The Electrochemical Society

# INTERFACE

VOL. 27, NO. 1
Spring 2018

## Sunlight in a HYDROGEN Bottle

### IN THIS ISSUE

# ECS Institutional Members

The Electrochemical Society values the support of its institutional members. Institutional members help ECS support scientific education, sustainability, and innovation. Through ongoing partnership, ECS will continue to lead as the advocate, guardian, and facilitator of electrochemical and solid state science and technology.

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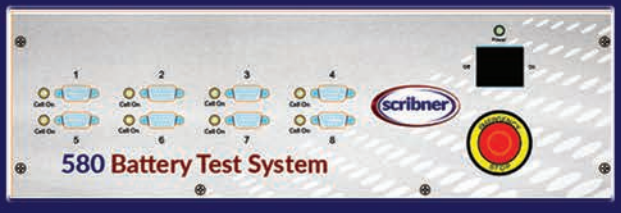


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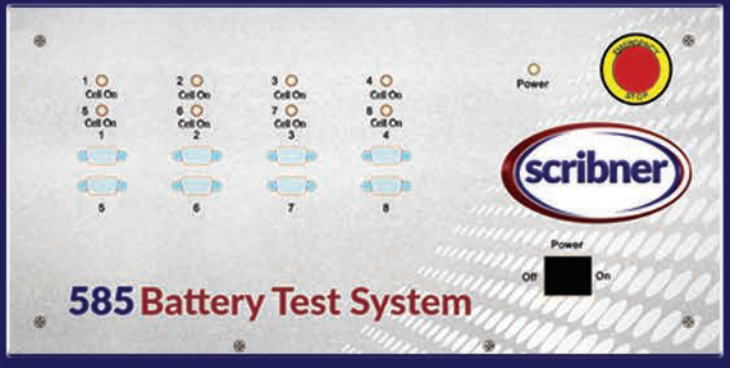


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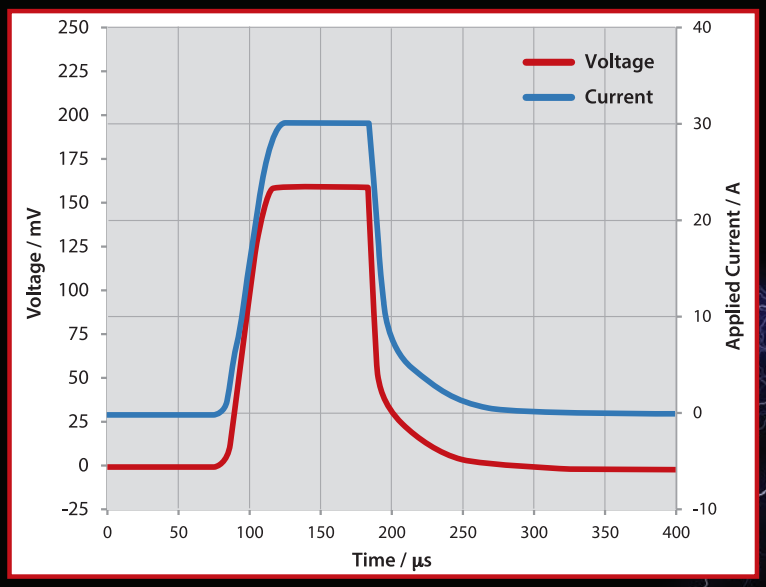


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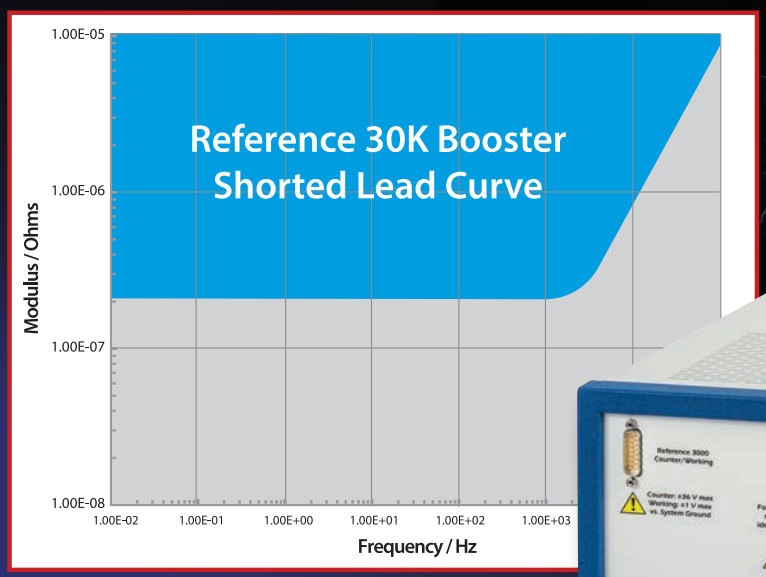


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# Déjà vu? Certainly Not All Over Again!

Many of you perusing the masthead page of this particular issue must be wondering what my moniker is doing under the title of Editor. I daresay, a few of you may even be perturbed by this? Rest assured, this is only a temporary assignment; I am back on the saddle only till such time as the Society finds a good candidate to take up the editorial reins from me. We can all agree that this magazine fulfills a very important function for our Society, and it is incumbent upon us to do the due diligence and find the "right" person as its editor. Thus, you may or may not be aware that the search process is well-underway and we do have eminently qualified candidates who have expressed an interest in leading this magazine into the future. By the time you are reading this, the candidate interviews will have been held and we will be close to naming a new editor. In this vein, I could not but help reflect on the fact that our wonderful Society, in a broader vein, is also in an interesting state of flux at this moment. The Society has engaged a search firm to find a successor to Roque Calvo, our executive director, and those are indeed big shoes to fill. The Society has evolved in its role of championing the cause of electrochemical and solid state science and technology, and the next executive director will be called upon to help guide the organization in ways not imagined decades ago. While meetings have, especially in recent years, been the Society's strong suit, publications continue to be a formidable challenge to tackle—one that is certainly at the forefront of many other professional societies' and for-profit publishers' agendas as well. All in all, interesting times ahead, and if I may end this segment with another quote form our erstwhile American philosopher (well, professional baseball player): "The future ain't what it used to be!"

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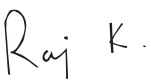
This special issue of the magazine features the juxtaposition of two technologies poised to make considerable inroads in the future, namely: solar energy conversion and hydrogen production. Climate change naysayers (like gun control opponents) can continue to make all the foolish arguments about lack of proof etc. However, I would invite them to set their skepticism aside and make a trip to Beijing or New Delhi or Bengaluru (or any other Asian city for that matter!) and experience firsthand, peak hour traffic conditions. The population growth, combined with an improved standard of living in these locales, have conspired to produce environmental conditions that are no longer sustainable, and could even be hazardous in a chronic sense. Why, even an international cricket match had to be suspended in New Delhi recently for a few hours because the players started getting breathless and sick on the field from inhaling the toxic air! The book and the companion documentary, *Merchants of Doubt*, come to mind here and serve as a warning as to what can happen if we all continue to literally bury our heads in the sand, and not pay heed to these warning signals.

This is certainly not the first time that this magazine has featured the above two topics. For example, the fall 2004 issue of *Interface* (Vol. 13, No. 3) featured hydrogen production and storage. However, in this dawning era of electric cars and windmill farms, the time is surely ripe for us to reexamine where we are, in the business of solar energy conversion and hydrogen production. Stay tuned.



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The Electrochemical Society
INTERFACE

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The Electrochemical Society is an educational, nonprofit 501(c)(3) organization with more than 8,500 scientists and engineers in over 75 countries worldwide who hold individual membership. Founded in 1902, the Society has a long tradition in advancing the theory and practice of electrochemical and solid state science by dissemination of information through its publications and international meetings.

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The Electrochemical Society
# INTERFACE
Vol. 27, No. 1
Spring 2018



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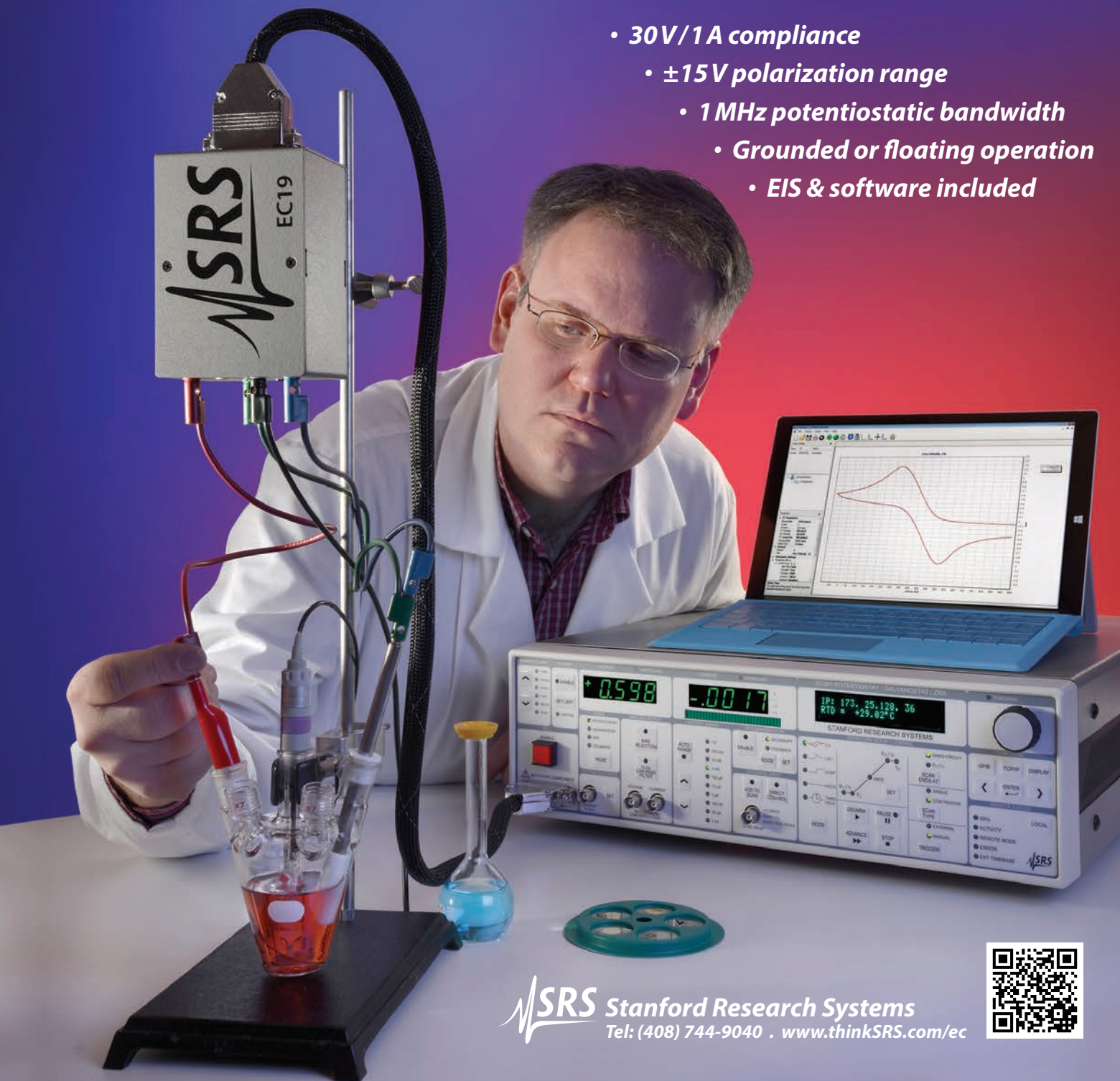


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# The Journey

The great Spanish author Cervantes observed that "the journey is better than the end." Being of Spanish descent myself and now arriving at the end of my ECS journey, Cervantes' words are an affirmation of the wonderful journey that I've experienced. So, after writing the first Pennington Corner column more than 26 years ago for the inaugural issue of *Interface*, this one is my last.

My ECS journey began in 1980. After serving in various positions, the Board appointed me as the fourth executive secretary (later changed to executive director) in 1991. My first major initiative was to launch the magazine you are reading. From its beginnings in 1992, *Interface* has featured the Pennington Corner providing the executive director the opportunity to share with our community insights into what's happening at ECS. In the first column, I wrote, "*Interface* gives me a forum to inform the members about Society benefits, programs, and activities … and helps you recognize the advantages of membership and will hopefully enable you to maximize your personal affiliation through contact with the staff, board, divisions, and sections." (Student chapters were not chartered until 2004.)

The Pennington Corner has tracked the transformations of the Society, which have amplified as the years have passed. The latest transformation is described in my previous column, entitled "We Choose to Go to the Moon." It describes the research publishing revolution that has placed ECS in the midst of a transformational initiative called *Free the Science*, which is enabling unprecedented progress toward our mission to advance electrochemistry and solid state science. This transformation began seven years ago and with the clearest vision and strongest commitment ECS has made enormous progress. And now that ECS has taken this Moon Shot and embarked on a path to open science, it is necessary for me to begin my own transformation, and toward that end the Board of Directors approved a transition arrangement stipulating that my service as executive director will conclude this summer.

**"Threaded through my nearly 38 years of service to ECS is the increasing relevance of electrochemical and solid state science and technology."**

During my tenure as executive director, ECS has experienced many challenges and three significant transformations that have been shared in this column. In the first decade, ECS experienced tremendous international development and growth thanks to strategic partnerships. That growth transformed our programs and governance structure. As we entered the new millennium, the digital revolution drove technological advancements in communication. Tools for discovery and dissemination produced new opportunities for information exchange and the creation of advanced databases, electrochem.org, and the ECS Digital Library. Since 2010, the open science revolution has led to transformational improvement in our dissemination, which is democratizing access to our important research and ultimately enabling extraordinary advancement of the ECS mission.

Threaded through my nearly 38 years of service to ECS is the increasing relevance of electrochemical and solid state science and technology. The role our science has in advancing communications, transportation, energy technology, human health and welfare, and the sustainability of our planet cannot be overstated. With the world battling climate change, ECS is at a crescendo. Our steadfast stewardship of these critical scientific and engineering disciplines has dramatically increased the importance of our mission.

**"The knowledge and friendships that I've acquired at ECS are gifts that I'll value forever."**

As I look back on the anecdotes I shared in the Pennington Corner, I find they act as diary entries. Our challenges and successes have provided me with a career of immense inspiration and satisfaction. Over the years, the leadership has offered thoughtful mentoring and support leading to lifelong friendships. People and relationships are the driving force behind the success and longevity of ECS. Through many years of hard work together, we have prepared for a future where the organization continues to grow in global influence and impact.

Being so engulfed in our recent transformation has left little time to reflect on the next phase of my life and the best use of my time and experience. The knowledge and friendships that I've acquired at ECS are gifts that I'll value forever and intend to share, and they will accompany me on my journey wherever it takes me.

**Roque J. Calvo**
*ECS Executive Director*
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# Focus on Focus Issues

*ECS publishes focus issues of the* Journal of The Electrochemical Society *and the* ECS Journal of Solid State Science and Technology *that highlight scientific and technological areas of current interest and future promise. These issues are handled by a prestigious group of ECS technical editors and guest editors, and all submissions undergo the same rigorous peer review as papers in the regular issues. As begun in 2017, all focus issue papers are published open access at no cost to the authors. ECS waives the article processing charge for all authors of focus issue papers as part of the Society's ongoing* Free the Science *initiative.*

## Recent JES Focus Issues

- ***Lithium-Sulfur Batteries: Materials, Mechanisms, Modeling, and Applications.*** [JES **165**(1) 2018] Doron Aurbach, JES technical editor, guest editor. This issue includes papers from the Li-SM$^3$ 2017 Conference (April 26-27, 2017, IET Savoy Place, London) and invited papers on Li-S batteries. Most of the important technical challenges of Li-S batteries are dealt with in this focus issue, including development of new sulfur cathodes, protected Li anodes, new electrolyte systems including solid state electrolytes, study of degradation mechanisms, in situ spectroscopic efforts, surface, and structural aspects. A number of papers provide overviews including practical aspects of the possible commercialization of Li-S batteries. Several papers describe mechanistic and theoretical aspects of these batteries. This focus issue is a suitable epilogue for a successful and fruitful meeting on a very *hot* topic in modern electrochemistry in general and advanced batteries in particular.


- ***Processes at the Semiconductor-Solution Interface.*** [JES **165**(4) 2018] David Cliffel, JES technical editor; Colm O'Dwyer, Robert Lynch, and Hans J. Lewerenz, guest editors. This issue addresses the recent developments in processes at the semiconductor-solution interface including etching, oxidation, passivation, film growth, electrochemical and photoelectrochemical processes, water splitting, electrochemical surface science, electroluminescence, photoluminescence, surface texturing, and compound semiconductor electrodeposition, for photovoltaics, energy conversion, and related topics. It includes papers on both fundamental and applied topics of both bulk and nanoscale materials. The issue covers device and system-level results where the semiconductor-solution interface plays a crucial role, including bioelectrochemical processes and electrochemically driven science and technology.

## Recent JSS Focus Issues

- ***Visible and Infrared Phosphor Research and Applications.*** [JSS **7**(1) 2018] Kailash Mishra, JSS technical editor; John Collins, Anant Setlur, and Alan Piquette, guest editors. Among the topics covered in this issue are narrow band emission from $Eu^{2+}$ in nitride phosphors and that from $Mn^{4+}$ in oxide and fluoride hosts from theoretical and experimental perspectives; nanophosphors and quantum dots and their applications; persistent phosphors, infrared phosphors, organic lighting diodes, solar cells and quantum dots as bio-markers; synthesis issues relating to both micron-sized and nanophosphors. It also addresses new areas of research that include light extraction from within materials with high refractive index through surface structuring (photonics), laser liftoff of thin conversion layers for possible integration into micro-pixelated LEDs, and flicker in LED lamps. This issue includes several critical review (CRES$^3$T) articles providing an overview of topical research in luminescence where rapid developments are in progress.

*Phosphors emitting in the visible region.*

## Current and Upcoming Focus Issues

The following focus issues are currently in production with many papers already published in the ECS Digital Library (http://ecsdl.org).

- **JES Focus Issue on Proton Exchange Membrane Fuel Cell Durability.** [JES **165**(6) 2018] Thomas Fuller, JES technical editor; Jean St-Pierre, Deborah Myers, and Rodney Borup, guest editors.
- **JES Focus Issue on Ubiquitious Sensors and Systems for IoT.** [JES **165**(8) 2018] Rangachary Mukundan, JES technical editor; Ajit Kholsa, Praveen Kuman Sekhar, Peter Hesketh, Charles Henry, and Luca Magagnin, guest editors.
- **JSS Focus Issue on Semiconductor-Based Sensors for Application to Vapors, Chemicals, Biological Species, and Medical Diagnosis.** [JSS **7**(7) 2018] Fan Ren, JSS technical editor; Yu-Lin Wang, Ajit Khosla, Rangachary Mukundan, and Toshiya Sakata, guest editors.

The following focus issue is open for submissions. Manuscripts may be submitted at http://ecsjournals.msubmit.net.

- **JES Focus Issue on the Brain and Electrochemistry, in Honor of R. Mark Wightman and Christian Amatore.** Janine Mauzeroll, JES technical editor; Lili Deligianni, Michael Wolfson, Nick Langhals, and Mekki Bayachou, guest editors.

The following focus issues are in the planning stages. Look for their calls for papers to come out soon.

- **JES Focus Issue on Electrocatalysis, in Honor of Radoslav Adzic**
- **JES Focus Issue on Advances in Electrochemical Processes for Interconnect Fabrication in Integrated Circuits**

**Visit**
**www.electrochem.org/focusissues**
**for more information.**

# Opening the Floor, ECS Hosts a Reddit Ask Me Anything

On December 14, 2017, ECS President **Johna Leddy** and *ECS Transactions* Editor **Jeffrey Fergus** hosted a Reddit Ask Me Anything as part of the /r/Science community's Science AMA Series, offering ECS members and nonmembers alike an opportunity to engage in open online discourse with Society leadership.

Prearranged topics for the AMA included open science, the *Free the Science* initiative, and the launch of ECSarXiv, but participants were encouraged—in keeping with AMA tradition—to ask about anything. Soon after the event began, the spirited discussion expanded to encompass associated subjects, from net neutrality to global warming and the enduring importance of science.

Leddy and Fergus addressed questions with care and precision. By the event's conclusion, they had provided thorough responses to every inquiry that had been posted.

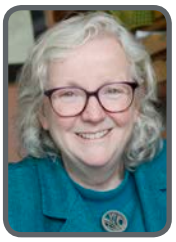
The majority of the questions the two received were in reference to ECS's preprint server, ECSarXiv, which Leddy described as "the newly introduced forum for presentation of ideas and content that are evolving."

Regarding the value of having both a meeting proceedings and a preprint server, Fergus said, "There is overlap but some differences. … Although the first use of ECSarXiv will be for sharing work presented at an ECS meeting, eventually, the plan is to also include work that is not presented at an ECS meeting."

ECS Chief Content Officer and Publisher Mary Yess, who helped field questions during the AMA, elaborated upon the rationale behind the server's development.

"We started ECSarXiv because we want to provide another open access outlet for researchers to publish other types of research outputs, such as datasets, Python notebooks, slide decks, etc.," Yess said. "These other research outputs are becoming important to funding agencies like the NIH and Wellcome Trust. About three years ago, NIH changed its grant report requirements to say that these other outputs were just as important as publications in peer-reviewed journals."

JEFFREY FERGUS



JOHNA LEDDY

Interspersed among inquiries about ECSarXiv were broader questions about the state of open science. In the face of such questions, Leddy and Fergus were optimistic.

"By making well-reviewed information about electrochemical and solid state science and technology available through open access and open science," Leddy said, "more researchers worldwide have access to the tools needed to advance the technology and fundamental science critical to overcoming critical societal issues in health, the environment, energy, water, communications … With open access and open science, more researchers are equipped to tackle critical problems, and the public in general will be better informed."

The most heartwarming inquiry of the event arose from a conscientious father, who asked how best to cultivate his seven-year-old daughter's budding interest in science.

"I think it is important to point out the places where science is making an impact on people's lives," Fergus said, "so she can see that it is not only interesting but has a positive impact on society. This could be through medical breakthroughs, providing clean water and energy, or many other impacts."

Reflecting fondly upon her own experience as the daughter of a chemist, Leddy advised, "Be there in the everyday things, listen, and promote address of queries through thinking."

Want to read the full discussion? Visit www.reddit.com/r/science and search *ECSarXiv*.

# 2018 Changes to *ECS Transactions*


*ECS Transactions*, the Society's official meeting proceedings publication, will be undergoing some exciting changes over the course of 2018.

At the start of 2018, ECS debuted the newly redesigned cover of ECST. The refreshed design is streamlined and modern, prominently branded with the Society's colors, green and blue. Adding to ECST's improved look and feel, all hard copy (CD or USB) editions of ECST purchased from the upcoming 233rd ECS Meeting in Seattle, WA, will feature brand-new premium hardboard packaging.

Also beginning with the Seattle meeting, ECST will no longer be available in a CD/USB combination pack. Instead, those who are interested in purchasing a hard copy edition will be able to purchase either the CD or USB edition. This small change has been made in order to reduce waste, while ensuring that attendees will still be able to purchase ECST issues in their preferred format. Full issues of ECST will continue to be made available for sale in PDF format through the ECS Online Store with individual articles available in the ECS Digital Library.

Lastly, as previously announced, beginning with AiMES 2018 (September 30 – October 4, 2018), ECS will no longer publish *standard* issues of ECST for its biannual meetings. Instead, this content will be eligible for submission to ECS's new preprint server platform, ECSarXiv. Although the *enhanced* issues of ECST will remain unchanged, *enhanced* authors will also have the opportunity to submit slideshows, posters, or data based on their AiMES presentation to the preprint server.

If you have questions or comments about these forthcoming changes, ECS would like to hear from you. Please feel free to reach out to the ECST staff at ECST@electrochem.org, or contact ecsarxiv@electrochem.org for more information about the forthcoming preprint server.

# Five Questions with Technical Editor Charles Hussey

**Charles L. Hussey** is Associate Dean for Research and Graduate Education in the College of Liberal Arts at the University of Mississippi and professor of chemistry. He is a fellow of ECS and a recipient of the Society's Max Bredig Award in Molten Salt and Ionic Liquid Chemistry. His scientific research with molten salts/ionic liquids has been directed at the electrochemistry and spectroscopy of d- and f-block elements, the electrodeposition of aluminum and corrosion-resistant aluminum-transition metal alloys, the electrodissolution of metals and alloys, and the electrochemical processing of spent nuclear fuel. Hussey was recently reappointed as technical editor of the *Journal of The Electrochemical Society* in the area of electrochemical/electroless deposition.

**What has your experience as a JES editor been like?**

I was appointed as an associate editor in 2000 and continued in that role until 2011. As an associate editor, I handled manuscripts on all topics for JES and *Electrochemical and Solid-State Letters*. Handling a variety of topical manuscripts for JES and ESL was the job that needed to be done, and it was a very challenging and sometimes uncomfortable assignment, but also highly educational. After the reorganization of the ECS Editorial Board in 2011 and reassignment of the board members to specific topical interest areas, I became technical editor for electrochemical/electroless deposition. This is a much more focused and comfortable assignment because it is closer to my own research interests. No doubt, this reorganization has led to better quality evaluation of manuscripts on the part of all of our editors. In addition, I now split this editorial work with Takayuki Homma at Waseda University. Taka serves as the associate editor for this area and does a fantastic job. I should also mention that during the 18 years that I have served on the board, I have had the pleasure of working directly with several great editors, Dennis Hess, Paul Kohl, Dan Scherson, and Bob Savinell. ECS publications have prospered under their guidance.

**What have been some of the biggest changes you've seen in ECS publications during your time as editor?**

Undoubtedly, the biggest change during my long service as a board member has been the switch in 2003 from paper manuscripts to the first digital interface platform PXP. Now we use ECSxPress. The digital platform is so much more efficient, requires less manpower, and gives us access to numerous digital tools for reviewing and copyediting. For example, we also have a vibrant and growing online reviewer database, and we always welcome new members! Did I mention digital graphics? Our younger readers may not realize that once upon a time, each manuscript was prepared on paper in triplicate and sent by the editors to reviewers through postal mail, even reviewers outside the U.S. In fact, I had a part-time secretary at the University of Mississippi whose only job was to handle the processing of paper manuscripts! Once accepted for publication, each manuscript was retyped by hand in duplicate with special word processing software for cross-checking purposes. It is hard to imagine this now.

**Why is the peer review process such an important piece of scholarly publications?**

There is so much to say about this that I hardly know where to begin. To have scientific manuscripts evaluated before publication anonymously by impartial experts in the field is an essential tool to check for quality and to help ensure the integrity of scientific results reported to the world. It goes a long way toward preventing the publication of fallacious results and eliminating duplicate submissions. Sadly (and rarely), authors do submit their work to two journals simultaneously or try to republish data. We count on our expert reviewers to catch these problems. Unfortunately, as we editors all know, the peer review process does not completely eliminate these problems, but it is the best tool we can imagine.

**What separates ECS journals from other journals in the field?**

I think that it is the careful selection of editorial board members who are outstanding scientists and experts in their own areas of electrochemistry and/or solid state science as well as the careful thought and planning that goes into the whole ECS journal publication enterprise. The Society's *Free the Science* initiative, which democratizes the publication process, serves as an example. Rather than being part of some large organization that hosts many different and disparate journals, ECS is laser-focused on one big idea, the publication of the leading work in all aspects of electrochemical and solid state science and technology.

**Why should authors publish in ECS journals?**

To me, ECS journals represent the scientific standard for the publication of new results in electrochemical and solid state science. They are the go-to journals in these disciplines. In fact, these are the venues where the leading scientists in the Society choose to submit much of their own work. The very large and growing number of manuscript submissions from all over the world that Takayuki and I have processed over the past few years also bear this out, as does the steady rise in the impact factors of our journals. It is obvious that many authors come to us first for the publication of their best work. Regrettably, we cannot publish all of the high-quality reports that we receive because we are looking specifically for high-impact contributions that significantly advance the field. ■

*Charles Hussey may be reached at chclh@olemiss.edu.*

# Five Questions with Technical Editor Doron Aurbach

**Doron Aurbach** is professor at Bar-Ilan University in Israel, where he leads a research group focused on developing rechargeable, high energy density batteries and EDL capacitors. His work in fundamental battery research has received recognition worldwide, including at ECS where he was awarded the 2017 Allen J. Bard Award in Electrochemical Science. Aurbach was recently reappointed as technical editor of the *Journal of The Electrochemical Society* in the area of batteries and energy storage.

**What role has ECS played in your life?**

ECS is the home of many scientists working in electrochemistry and related fields. The meetings give opportunities to researchers and allow people to express themselves. As technical editor of JES, I work closely with ECS's publications department. It's such a pleasure to work with that department, with people who feel that they're working to fulfill a mission. Fortunately, a lot of good scientists all over the world are affiliated with the Society, so there is a tradition of collaboration and creating a good atmosphere. ECS is a home to thousands of scientists, including myself.

**How did your career in electrochemistry begin?**

I did my postdoctoral studies with an electrochemistry group in the U.S. with Ernie Yeager. He ran, at that time, one of the best groups in electrochemistry in the world at Case Western Reserve University. I was privileged to do my postdoctoral research with him. Interestingly, I did my PhD in organic chemistry and my first degree in chemical engineering, but I fell in love with electrochemistry. It turned out that I was able to proceed with an academic career if I brought electrochemistry to Bar-Ilan University in Israel. It was a new topic for the university. They were pointing out several fields that were missing there at the time, and one was electrochemistry.

**What made you chose electrochemistry as a scientific discipline?**

I always liked chemistry. With chemistry, you're in the heart of the science. In fact, everything is chemistry. Whatever you touch is chemistry. We're also chemical entities; the chemistry of life is amazing. By doing chemistry, you're connected to all pieces of science: mathematics, physics, biological, engineering. Doing chemistry is really doing interdisciplinary science. I fell in love with chemistry when I was in college, but then I had to spend four years in the army. When I finished in the army, I still wanted to study. Eventually I fell in love with electrochemistry. Electrochemistry is also very interdisciplinary. It's a beautiful field because you have to touch so many other areas of science.

**How important has the development of the lithium-ion battery been for society?**

All mobile electronics are powered by lithium-ion batteries. This is one of the greatest successes of modern electrochemistry. The story looks simple, but just apparently simple. There are a lot of fine details and a lot of basic science that has to be well-understood, and that is the beauty of the field. This is why the community flourishes. So many people are attracted to working on batteries because there's a lot of science that has to be understood in order to ensure a lithium-ion battery works, to make sure your battery can store enough energy for an entire day and you can recharge the battery more times than the electronic lasts, so you can use your phone several years with the same battery. This was a great success and it's because we struggled a lot with many details; there were a lot of fine details.

**What's next for battery technology?**

Right now we are working on the frontier. After gaining prestige with mobile electronics and the success of lithium-ion battery technology, we want to go further. Now the challenge is electromobility. Electromobility is business. We have reliable batteries and we can be successful with electromobility with the current technology. We can fill cars with batteries. The most important thing is to have reliable technology with safety and durability. I convey a very optimistic message about the possibility of electrochemistry to promote electromobility. We have solutions and I think the carmakers understand it. If we have a problem with global warming and we can no longer burn fossil fuels the way we've done in the past, we can charge our car batteries from renewables like solar and reduce pollution and gas emissions, resulting in better energy economy. ■

*Listen to our podcast with Doron Aurbach at www.electrochem.org/aurbach. He may be reached at doron.aurbach@biu.ac.il.*


# ECS Thanks 2017 Reviewers

The Electrochemical Society relies upon the technical expertise and judgment of the many individuals who, as reviewers, help to maintain the high standards characteristic of the Society's peer-reviewed journals (*Journal of The Electrochemical Society* and *ECS Journal of Solid State Science and Technology*). We greatly appreciate the time and effort put forth by these individuals and express our sincere thanks for their hard work and support.

**For a complete list of the 2017 reviewers, please go to:**
**www.electrochem.org/reviewers_2017**

# Five Questions with Technical Editor Peter Mascher

**Peter Mascher** is a professor in the Department of Engineering Physics and holds the William Sinclair Chair in Optoelectronics at McMaster University in Ontario, Canada. There, he leads a research group specializing in the fabrication and characterization of nanostructures. Mascher was recently named technical editor of the *ECS Journal of Solid State Science and Technology* in the area of dielectric science and materials.

**What made you want to take on an ECS editorial role?**

I've been a member of the ECS Dielectric Science and Technology Division for many years and we've had many discussions on how to raise the quality of submissions to JSS and by extension, the quality of the journal overall. At some point in time, when the opportunity arises, one should try to make a contribution rather than just discussing it. I think there are avenues toward increasing the profile of the journal and I hope I can make a contribution there.

**What do you hope to accomplish in your new role as JSS technical editor?**

I would like my colleagues who contribute to the ECS meetings in the various symposia to be much more aware of the journal and the opportunity to publish in JSS, which will help increase the overall quality. There should be a strong connection between the excellent presentations that are given at the various symposia at ECS meetings and the manuscripts that are being submitted to the journal.

**What are the biggest barriers in the current scholarly publishing model?**

The biggest barrier to both authors and readers is the exorbitant cost of journals. A library budget cannot possibly keep up with the escalation of costs by a handful of major international publishers. At the same time, many funding agencies—certainly Canadian funding agencies—are moving down a path towards ultimately demanding that publications be made open access, which puts that price back on the authors. Of course, research funding doesn't increase by such large percentages, so there is a real problem with how to finance the dissemination of knowledge in reputable journals. From this, predatory journals emerge that offer essentially free publication with some make-believe reviewers and these journals suddenly look very attractive, until you take a closer look at what they actually are. I think that's a real danger, especially for junior researchers and faculty members who might not be quite as experienced.

**What role do you believe open access has in the future of scholarly publishing?**

I think open access is very important, especially if you believe that scientific disciplines should be for the benefit of a global good. There are countries that are just in the stage of really developing their research infrastructure and simply do not have the money to buy subscriptions. For them, open access is the only way to gain access to high-level publications internationally, and affordable open access is their only way to publish their own work. I think there's an obligation to some extent by the scientific communities in Europe and North America and some other areas of the world to make their knowledge available to areas where the research infrastructure isn't as well-developed.

**What is the importance of dielectric science and materials in today's society?**

Dielectric materials find their way into many, many areas of application. One example is my own research. We are working on silicon-based nanostructures for optoelectronic applications. If you look at the field of silicon photonics, for instance, while the core material is the semiconductor, you need to have several layers that usually have very distinct dielectric properties such as silicon oxides, silicon nitrides, or silicon carbides to make that device. Without those layers and without these structures, you couldn't actually manufacture a device. The very same argument holds for many of the microelectronic structures. Somewhere in the structure, you'll always find the dielectric for particular reasons.

*Peter Mascher may be reached at mascher@mcmaster.ca.*

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# New Division Officer Slates

New officers for the spring 2018–spring 2020 term have been nominated for the following divisions. All election results will be reported in the summer 2018 issue of *Interface*.

## ECS Dielectric Science and Technology Division

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Dennis Hess, Georgia Institute of Technology
Zia Karim, Eugenus, Inc.
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Dolf Landheer , G-Camria Co.
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## ECS Nanocarbons Division

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Tomas Torres, Universidad Autonoma de Madrid
Shangfeng Yang, University of Science and Technology of China
Ming Zheng, National Institute of Standards and Technology

# Advancement News

## Divisions Attracting New Support from Haddon and Mercedes-Benz

ECS divisions have long been responsible for finding outside funding to support symposia and special events. In the past couple of years, divisions have also been successful in securing money to create travel grant funds (i.e., the ECS Battery Division's K. M. Abraham Travel Award) and help fund awards (i.e., Bio-Logic's five-year sponsorship of the ECS Energy Technology Division's Graduate Student Award). This trend is continuing in 2018, and ECS hopes to further interest among other divisions to seek this very important type of outside support.

The ECS Nanocarbons Division recently received a $50,000 gift from Elena Haddon, the widow of renowned scientist Robert C. Haddon, to recognize excellence in advancing understanding and applications of carbon materials. Haddon was a distinguished professor of chemistry and of chemical and environmental engineering and director of the Center for Nanoscale Science and Engineering at the University of California, Riverside. He is best known for the prediction and discovery of superconductivity in alkali-metal-doped carbon-60, for his preparation and characterization of a stable crystal of phenalenyl radicals, and for his pioneering research in nanotechnology. He was an elected member of several scholarly societies and, in 2014, was named by Thomson Reuters as one of the "best and brightest minds of our times." Nanotechnology is "the final frontier in miniaturization, at least on the surface of the planet," Haddon once said. "It encompasses all of the scientific disciplines, including chemistry, engineering, physics, biology, computers, and medicine." He was a member of ECS for almost 10 years and an active member of the Nanocarbons Division.

The ECS Battery Division is pleased to announce a five-year, $25,000 sponsorship from Mercedes-Benz Research & Development North America, Inc. for its Student Research Award. Beginning in 2018, the support will allow the Battery Division to give up to two awards per cycle, each of which will include a $1,000 prize, a meeting registration, and travel support.

Mercedes-Benz
Research & Development North America, Inc.

"We are thrilled to create this partnership with Mercedes-Benz," said Jie Xiao, chair of the Battery Division's fundraising efforts and chief scientist at Pacific Northwest National Laboratory. Xiao is also an associate professor in the Department of Chemistry and Biochemistry at the University of Arkansas. "It is an honor to have such a formidable company associated with our division and for them to recognize the incredible work being done by our younger colleagues," she continued. "With companies like Mercedes-Benz focusing on battery technology, we are working together to not only support science but also better transportation and a cleaner environment. And that benefits everyone."

To discuss ideas on how your division might put together a proposal for outside support, or just to brainstorm, please contact development@electrochem.org.

## India Section Confers First S. K. Rangarajan Graduate Student Award

### Thank You to the Founding S. K. Rangarajan Award Donors

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Ramesh Satyalakshmi
Ashok Shukla

In December 2017, Prashant Kamat of the University of Notre Dame led the two-day ECS India Section School for 80 students at the Amrita Vishwa Vidyapeetham University, Coimbatore, Tamil Nadu, India. It was, once again, a great success, and planning is already beginning for the end of this year.

During the gathering, the India Section bestowed the first ECS India Section S. K. Rangarajan Graduate Student Award on **Anantharaj S**, who is currently in the research group of Subrata Kundu at the Central Electrochemical Research Institute. The S. K. Rangarajan Award was established to recognize and support a student pursuing a career in electrochemistry and/or solid state science and technology in India. Sarukkai Krishnamachari Rangarajan, the award's namesake, was an exceptional scientist whose diverse research investigations ranged from functional analysis and stochastic modelling to ion transport across membranes and bipolar cells. His electrochemistry career started in 1955 and continued until his death in 2008 with work at Alagappa Chettiar College of Engineering and Technology, the Central Electrochemical Research Institute, Indian Institute of Science in Bangalore, Institute of Mathematical Sciences in Chennai, Raman Research Institute in Bangalore, and National Aerospace Laboratory in Bangalore.

*Award winner* **Anantharaj S** *(left) received a ceremonial shawl from* **Prashant Kumat** *(right), 2017 India School keynote speaker, while accepting the inaugural award.*

This first award consisted of a $500 prize, a one-year membership to ECS, and a certificate. ECS continues to raise money for this award to increase the prize money and provide travel funds for the winner to attend an ECS biannual meeting to further his/her exposure and networking and to be recognized by a wider community.

If you would like to make a gift towards the S. K. Rangarajan Award Fund, or set up a recurring gift plan, please contact development@electrochem.org.

## JES 2018 Volume Named for Chung Chiun Liu

CHUNG CHIUN LIU

ECS is pleased to announce that a donor has made a $20,000 gift to create a leadership collection for the 2018 volume of the *Journal of The Electrochemical Society* in honor of **Chung Chiun Liu**. Liu is the Wallace R. Persons Professor of Sensor Technology and Control at Case Western Reserve University. He has been an ECS member for over 50 years, during which he has given many oral presentations and organized several symposia for Society meetings. In addition to numerous forms of recognition, he is also the recipient of the 2008 ECS Sensor Division Outstanding Achievement Award.

Currently, there are two opportunities to support and create collections in the ECS Digital Library to help *Free the Science*. Donors can name an entire volume year in either journal, or collections of articles can be gathered under the name of a single author. Examples of each of these can be found by visiting the JES page in the ECS Digital Library and clicking on the collections link (http://jes.ecsdl.org/cgi/collection/).

## Access Corporate Program Benefits through Institutional Membership

Are several members of your organization involved with ECS? The **ECS Institutional Membership Program** offers a holistic partnership between ECS and your organization. Institutional membership allows your organization to take advantage of the outstanding benefits available through ECS corporate programs.

Your institutional membership allows your organization to choose benefits that are best suited to meet your business needs—ranging from discounts on advertising, digital library subscriptions, and sponsorships/exhibits to meeting registration waivers, member representatives, and more!

Reach out to Shannon Reed, director of membership services, to learn more about how your organization can benefit by becoming an institutional member: Shannon.Reed@electrochem.org.

## How to Give to ECS

**There are many ways to give to ECS and we hope you will consider one of these ideas:**

- Donate $115 to ECS in honor of our 115th Anniversary
- Make a gift of stock to ECS by contacting development@electrochem.org
- Give a gift at checkout time when you're registering for your next ECS meeting
- Donate your stipend, royalties, or speaker fees to ECS
- Make a small recurring gift each month
- Make a planned gift by leaving a bequest in your will, transferring life insurance, or making an IRA charitable rollover. All planned gifts are recognized through the Carl Hering Legacy Circle

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## IRA Charitable Rollover Opportunity for U.S. Taxpayers

If you're a U.S. taxpayer and 70.5 years or older, now is the time to start thinking about your required minimum distributions for the year. You can take advantage of the IRA Charitable Rollover provision which means you can transfer money directly to ECS as a philanthropic gift. Although the gift will not generate an income tax charitable deduction, it will be free from income tax, making it a clear tax win for most donors.

**For more information contact development@electrochem.org or 609.737.1902 ext. 100.**

## *In the* NEXT *issue of* INTERFACE

- The summer 2018 issue of *Interface* will feature the **ECS Electrodeposition Division**. The issue will be guest edited by **Stanko Brankovic** and has the tentative title of "Electrodeposition as Surface Limited Redox Replacement Process." It will include the following technical articles (titles are tentative) that highlight activities of interest to the division: "Fundamentals of Electrodeposition via Surface Limited Redox Replacement of UPD Monolayer," by **Stanko Brankovic**; "Surface Limited Redox Replacement of Cu UPD Monolayer by Pd in One-Cell: Pros, Cons, and Critical Comparison with Other Approaches," by **Nikolay Dimitrov**; "Electrodeposition of Pt-Bimetallic Model Systems for Electrocatalysis and Electrochemical Surface Science," by **Natasa Vasiljevic**; and "Selective Electrodesorption Based Atomic Layer Deposition of Bismuth under Morphological Control," by **Massimo Innocenti**.
- **Highlights from the ECS Spring 2018 Meeting in Seattle**. Don't miss all the photos and news from this, the largest spring meeting ever held by ECS.
- **2017 Annual Report and Year in Review** will provide a look back at the Society's highlights and achievements from 2017.

# Staff News

**John Lewis** has recently been promoted to the director of meetings and corporate programs. John will be responsible for overseeing all aspects of the development, organization, and management of ECS biannual meetings, satellite conferences, and other ECS events. He will work with other senior staff and volunteer leaders to ensure the meetings support the Society's goals and objectives.

John joined ECS in 2005 as the manager of *ECS Transactions*, and then as the associate director of conference publications. During this time he was responsible for the publication of *ECS Meeting Abstracts* and all facets of ECST, from guiding authors and editors through the online process, to producing and marketing the finished issues. In 2015, John became the associate director of meetings, responsible for all aspects of the technical programming of ECS biannual and ECS satellite and sponsored meetings, from the development of calls for papers through the abstract submission and scheduling to the final publication and production of all accepted presentations.

ECS Executive Director Roque Calvo commented that, "John has done an excellent job working for the Society in both publications and meetings positions over the past 12 years. He has a tremendous ability to work with organizers and editors to develop technical programs and publications. Considering the complexities of our technical activities this is a great skill to apply to his new role as director of meetings and corporate programs."

Prior to ECS, John spent seven years working in the Publication Technologies Department of Random House Inc., and more than five years doing concert production and artist management in the music business. This intersection of events, publications, technology, and personal service has given him a well-rounded skill set that has been of great value to the Society through the years.

**Bianca Kovalenko** joined ECS in August 2017 as the meetings program specialist. In this role she will be responsible for developing, organizing, and planning ECS meetings, with specific responsibilities managing the development and execution of the technical programs. She will work closely with ECS division chairs, symposium organizers, session chairs, and authors of technical papers to ensure the value of the ECS meetings and promote successful planning, all while providing the highest level of customer service.

Bianca attended Rutgers University and studied communications with a focus on information technology. She also worked for the university just under 10 years as an event planner for the Department of Continuing Professional Education. While working at Rutgers, Bianca built a strong foundation in her program and event coordination skills.

"We are very fortunate to have Bianca join the ECS staff," said John Lewis, ECS director of meetings. "Her previous experience and advanced knowledge of what it takes to plan and execute successful meetings have made her a valuable addition to the Meetings Department team."

Bianca prides herself on her ability to build and maintain strong client relationships and is excited to implement her skills and experience through her work at ECS.



## Erratum

In the winter 2017 issue of *Interface*, on page 22, the Candidate for President column contained an error. It should be correctly stated that before Yue Kuo joined Texas A&M University, he worked in the IBM T. J. Watson Research Center and Data General Semiconductor Division in Silicon Valley. The error was corrected in the online version of *Interface*. ECS regrets this error.

## Upcoming ECS Sponsored Meetings

In addition to the ECS biannual meetings and ECS satellite conferences, ECS, its divisions, and its sections sponsor meetings and symposia of interest to the technical audience ECS serves. The following is a partial list of upcoming sponsored meetings. Please visit the ECS website (http://www.electrochem.org/upcoming-meetings/) for a list of all sponsored meetings.

### 2018

- **Next Generation Electrochemistry** (NGenE); June 4-8, 2018; University of Illinois at Chicago; https://energyinitiative.uic.edu/energy/ngene
- **25th International Workshop on Active Matrix Flat Panel Displays and Devices** (AM-FPD); July 3-6, 2018; Kyoto, Japan; http://www.amfpd.jp
- **1st Conference on 4D Materials and Systems**; August 26-30, 2018; Yamagata, Japan; https://ecs.confex.com/ecs/4dms18/cfp.cgi
- **69th Meeting of the International Society of Electrochemistry**; Bologna, Italy; September 2-7, 2018; http://annual69.ise-online.org; **ECS–ISE Joint Symposium**: "Theory: From Understanding to Optimization and Prediction"
- **International Conference on Solid State Devices and Materials** (SSDM); September 9-13, 2018; Tokyo, Japan; http://www.ssdm.jp/index.html
- **III Colombian Congress of Electrochemistry**; October 2-5, 2018; Cali, Colombia; https://sites.google.com/view/cceq2018
- **7th Baltic Electrochemistry Conference: Finding New Inspiration** (BEChem 2018); November 4-7, 2018; Tartu, Estonia; http://BEChem2018.ut.ee

To learn more about what an ECS sponsorship could do for your meeting, including information on publishing proceeding volumes for sponsored meetings, or to request an ECS sponsorship of your technical event, please contact ecs@electrochem.org.

# websites of note

by Alice H. Suroviec

## Software Carpentry

- Software Carpentry has a large library of lesson materials available for those researchers who would like to learn how do basic research computing. Data collection and analysis is a critical part of science, but most scientists are never taught how to build, use, and validate software well. Software Carpentry's stated goal is to teach those skills through free lessons so scientists can spend less time wrestling with software and more time doing useful research. Their core topics include structured programming in Python, R, and MATLAB.

  **https://software-carpentry.org**

## Battery University

- Battery University is a free educational website offering battery information to engineers, educators, media, students, and battery users alike. The tutorials evaluate the advantages and limitations of battery chemistries, advise on best battery choice, and suggest ways to extend battery life. The information is compiled from specifications and independent test laboratories as well as crowdsourcing.

  **http://batteryuniversity.com/learn**

## ChemCatBio

- The Chemical Catalysis for Bioenergy Consortium leverages unique U.S. Department of Energy national lab capabilities to address technical risks associated with accelerating the development of catalysts and related technologies for the commercialization of biomass-derived fuels and chemicals. This website is working to establish an integrated and collaborative portfolio of catalytic technologies and enabling capabilities to push products to market faster.

  **www.chemcatbio.org**

## About the Author

**Alice Suroviec** is an associate professor of bioanalytical chemistry and chair of the Department of Chemistry and Biochemistry at Berry College. She earned a BS in chemistry from Allegheny College in 2000. She received her PhD from Virginia Tech in 2005 under the direction of Mark R. Anderson. Her research focuses on enzymatically modified electrodes for use as biosensors. She is currently the chair of the ECS Physical and Analytical Electrochemistry Division and an associate editor for the physical and analytical electrochemistry, electrocatalysis, and photoelectrochemistry topical interest area of the *Journal of The Electrochemical Society*. She may be reached at asuroviec@berry.edu.




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## The ECS Lecture

***Monday, May 14***

### "Linking Brains to Machines: From Basic Science to Neurological Neurorehabilitation"

**Miguel Nicolelis, *Duke University***

**Miguel Nicolelis**, MD, PhD, is the Duke School of Medicine Distinguished Professor of Neuroscience at Duke University, professor of neurobiology, biomedical engineering, neurology, neurosurgery and psychology and neuroscience, and founder of Duke's Center for Neuroengineering. He is founder and scientific director of the Edmond and Lily Safra International Institute for Neuroscience of Natal. Nicolelis is also founder of the Walk Again Project, an international consortium of scientists and engineers dedicated to the development of an exoskeleton device to assist severely paralyzed patients in regaining full-body mobility. He is the author of *Beyond Boundaries: The New Neuroscience of Connecting Brains with Machines and How It Will Change Our Lives* and coauthored *The Relativistic Brain: How It Works and Why It Cannot Be Simulated by a Turing Machine*.

## Award Winning Speakers

***(Check the meeting app for times.)***

### SOCIETY AWARD WINNING SPEAKERS

**Hariklia (Lili) Deligianni**, IBM T. J. Watson Research Center
*ECS Vittorio de Nora Award*

**Ralph White**, University of South Carolina
*ECS Henry B. Linford Award for Distinguished Teaching*

### DIVISION AWARD WINNING SPEAKERS

**Yasser Ashraf Gandomi**, University of Tennessee, Knoxville
*Industrial Electrochemistry and Electrochemical Engineering Division Student Achievement Award*

**Tae-Yeon Seong**, Korea University
*Electronics and Photonics Division Award*

**Flavio Maran**, University of Padova
*Organic and Biological Electrochemistry Division Manuel M. Baizer Award*

**Michael Arnold**, University of Wisconsin-Madison
*Nanocarbons Division SES Young Investigator Award*

**Yushan Yan**, University of Delaware
*Energy Technology Division Research Award*

**Soo Kim**, Northwestern University
*Industrial Electrochemistry and Electrochemical Engineering Division H. H. Dow Memorial Student Achievement Award*

**Deijun Xiong**, Dalhousie University
*Energy Technology Division Graduate Student Award Sponsored by Bio-Logic*

**Maria Escudero-Escribano**, Technical University of Denmark and Stanford University
*Energy Technology Division Supramaniam Srinivasan Young Investigator Award*

# Short Courses

***Sunday, May 13***

ECS short courses are all-day classes designed to provide students or the seasoned professional with an in-depth education on a wide range of topics. Taught by academic and industry experts, the small classes make for excellent opportunities for personalized instruction, helping both novices and experts advance their technical expertise and knowledge.

### SHORT COURSE 1

**Advanced Impedance Spectroscopy**
Mark Orazem, *Instructor*

### SHORT COURSE 2

**Rechargeable Battery Materials**
Shirley Meng and Boryann Liaw, *Instructors*

### SHORT COURSE 3

**Electrodeposition Fundamentals and Applications**
Stanko Brankovic and Giovanni Zangari, *Instructors*

# Professional Development Workshops

***(Check the meeting app for times.)***

Offered at each of the biannual Society meetings, the professional development workshops help to serve our members. These workshops are available to you whether you are a student looking for some help with your resume or a mid-career researcher looking for a refresher on team management.

- **Essential Elements for Employment Success**
- **Managing and Leading Teams**
- **Refresh & Connect: An ECS Mentoring Session**
- **Resume Review**
- **Grant Writing 101**
- **An Introduction to Intellectual Property**
- **Running an Effective Meeting**

# Career Expo

Enjoy career enhancement opportunities through the ECS Career Expo that support employers and candidates through resume services, professional and career development. The expo is the premier opportunity for employers, job seekers, and postdoctoral candidates to engage. Meeting attendees receive full access to the ECS Career Expo in the exhibit hall.

# ECS Data Sciences Hack Week

ECS Data Sciences Hack Week is the Society's foray into building an electrochemical data sciences and open source community from the ground up. The critical need is to build a community of electrochemical data scientists, the people who will contribute to a growing library of shared experimental and computational datasets, and who develop and adapt open source software tools. See page 26 for more.

# Special Events

***(Check the meeting app for times.)***

### Opening Reception

All attendees are welcome to this event that kick-starts the week with tasty desserts and ample time to mingle.

### Student Mixer

Join distinguished members and staff of ECS for an evening of networking and socializing. Always one of the most popular events of the meeting, this is a must for all student attendees!

### Annual Society Business Meeting and Luncheon

Join us as we celebrate the many successes of 2017 and look forward to an even brighter future!

### General Student Poster Session

A long standing ECS tradition, with cash prizes awarded for the top presentations by eligible students.

### Reception in Honor of Radoslav Adzic

Join us to honor Radoslav Adzic's great achievements in the field of electrocatalysis and celebrate his retirement after more than five decades of research.

### Field Trip to Microsoft SOFC Powered Data Center

Join us for an excursion to see Microsoft's state of the art data center, powered by solid oxide fuel cells (SOFC).

# Symposium Topics, Organizers, and Sponsoring Divisions

## A — Batteries and Energy Storage

A01 — **Battery and Energy Technology Joint General Session**
Mani Manivannan, S. R. Narayan, Marca Doeff
*Battery, Energy Technology*

A02 — **Large-Scale Energy Storage 9**
Trung Nguyen, Wei Wang, Adam Weber, Jean St-Pierre, Jay Whitacre, Claire Xiong, Christopher Johnson
*Electronics and Photonics, Battery, Industrial Electrochemistry and Electrochemical Engineering*

A03 — **Li-ion Batteries and Beyond**
John Vaughey, Ying Meng, Jihui Yang, Pawel Kulesza, Vito Di Noto
*Battery, Physical and Analytical Electrochemistry*

A04 — **Materials Recycling for Energy Conversion and Storage**
Linda Gaines, E. Taylor, Douglas Riemer, Michael Slater, John Staser, Andrew Herring, Scott Calabrese Barton, William Mustain
*Battery, Energy Technology, Industrial Electrochemistry and Electrochemical Engineering*

## B — Carbon Nanostructures and Devices

B01 — **Carbon Nanostructures for Energy Conversion and Storage**
Jeffrey Blackburn, Vito Di Noto, Plamen Atanassov, Michael Arnold, David Cliffel, Christina Bock
*Nanocarbons, Physical and Analytical Electrochemistry*

B02 — **Carbon Nanostructures in Medicine and Biology**
Daniel Heller, Fotios Papadimitrakopoulos, Ardemis Boghossian, Mekki Bayachou, James Burgess, Larry Nagahara, Tatiana DaRos
*Nanocarbons, Organic and Biological Electrochemistry, Sensor*

B03 — **Carbon Nanotubes—From Fundamentals to Devices**
Stephen Doorn, Yury Gogotsi, Pawel Kulesza, Ming Zheng, Slava Rotkin, R. Bruce Weisman, Shigeo Maruyama, Benjamin Flavel
*Nanocarbons, Physical and Analytical Electrochemistry*

B04 — **International Symposium on Nanomaterials: Focus—Korea**
Hiroshi Imahori, Nazario Martin, Shigeo Maruyama, Slava Rotkin, Doo-Hyun Ko, Sang Bok Lee, Ho Seok Park, Yuanzhe Piao, Jaejoon Lee, Richard Martel
*Nanocarbons, Dielectric Science and Technology, Electronics and Photonics, Industrial Electrochemistry and Electrochemical Engineering*

B05 — **Fullerenes—Endohedral Fullerenes and Molecular Carbon**
Shangfeng Yang, Alan Balch, Francis D'Souza, Luis Echegoyen, Dirk Guldi, Nazario Martin, Steven Stevenson
*Nanocarbons*

B06 — **2D Layered Materials from Fundamental Science to Applications**
Michael Arnold, Stefan De Gendt, Zia Karim, Colm O'Dwyer, Slava Rotkin, Lain-Jong Li, Yaw Obeng
*Nanocarbons, Dielectric Science and Technology, Electronics and Photonics, Industrial Electrochemistry and Electrochemical Engineering*

B07 — **Inorganic/Organic Nanohybrids for Energy Conversion**
Hiroshi Imahori, Prashant Kamat, Kei Murakoshi, Tsukasa Torimoto, Takanori Fukushima
*Nanocarbons*

B08 — **Porphyrins, Phthalocyanines, and Supramolecular Assemblies**
Karl Kadish, Roberto Paolesse, Tomas Torres, Nathalie Solladie, Diane Smith, Norbert Jux
*Nanocarbons, Organic and Biological Electrochemistry*

B09 — **Engineering Carbon Hybrids—Carbon Electronics 3**
Rodrigo Martinez-Duarte, Andrew Hoff, Marc Madou, Richard Martel, Chunlei Wang, D. Landheer, Michael Carter, Robert Kostecki, Oana Leonte
*Dielectric Science and Technology, Battery, Electronics and Photonics, Nanocarbons, Sensor* CD/USB

## C — Corrosion Science and Technology

C01 — **Corrosion General Session**
Sannakaisa Virtanen, Masayuki Itagaki
*Corrosion*

C02 — **High Temperature Corrosion and Materials Chemistry 13**
Paul Gannon, Torsten Markus, Makoto Nanko, Dev Chidambaram, E. Opila, Jeffrey Fergus, Jan Froitzheim, Gregory Jackson
*High Temperature Materials, Corrosion* CD/USB

## D — Dielectric Science and Materials

D01 — **Nanoscale Luminescent Materials 5**
Peter Mascher, David Lockwood, Federico Rosei
*Dielectric Science and Technology, Luminescence and Display Materials* CD/USB

D02 — **Plasma and Thermal Processes for Materials Modification, Synthesis, and Processing 2**
Sreeram Vaddiraju, Uros Cvelbar, Mahendra Sunkara, Dennis Hess, Peter Mascher, Michael Carter, Manfred Engelhardt, Oana Leonte
*Dielectric Science and Technology, Sensor*

## E — Electrochemical/Electroless Deposition

E01 — **Electrodeposition of Micro and Nano Materials for Batteries and Sensors**
Philippe Vereecken, Nianqiang Wu, James Rohan
*Electrodeposition, Battery, Sensor*

E02 — **Surfactant and Additive Effects on Thin Film Deposition, Dissolution, and Particle Growth**
Thomas Moffat, Peter Broekmann, Rohan Akolkar, Ji-Guang Zhang, Benjamin Wiley
*Electrodeposition*

## F — Electrochemical Engineering

F01 — **Industrial Electrochemistry and Electrochemical Engineering General Session**
John Staser, Douglas Riemer
*Industrial Electrochemistry and Electrochemical Engineering* CD/USB

F02 — **Multiscale Modeling, Simulation and Design – From Conventional Methods to the Latest in Data Science**
John Harb, Michael Lowe, Gerardine Botte, Jean St-Pierre, Venkat Subramanian
*Industrial Electrochemistry and Electrochemical Engineering, Energy Technology* CD/USB

## G — Electronic Materials and Processing

G01 — **Silicon Compatible Materials, Processes, and Technologies for Advanced Integrated Circuits and Emerging Applications 8**
Fred Roozeboom, Paul Timans, Evgeni Gusev, Zia Karim, Stefan De Gendt, Hemanth Jagannathan, Kuniyuki Kakushima
*Electronics and Photonics, Dielectric Science and Technology* CD/USB

## H — Electronic and Photonic Devices and Systems

H01 — **Wide Bandgap Semiconductor Materials and Devices 19**
Jennifer Hite, Vidhya Chakrapani, John Zavada, Travis Anderson, Steve Kilgore
*Electronics and Photonics* CD/USB

H02 — **Advanced CMOS-Compatible Semiconductor Devices 18**
Joao Martino, Jean-Pierre Raskin, Siegfried Selberherr, Hiromu Ishii, Francisco Gamiz, Bich-Yen Nguyen, Akira Yoshino
*Electronics and Photonics* CD/USB

H03 — **Solid-state Electronics and Photonics in Biology and Medicine 5**
Yu-Lin Wang, Andrew Hoff, Chih-Ting Lin, Wenzhuo Wu, Lluis Marsal, M. Deen, Toshiya Sakata, Zong-Hong Lin, Zoraida Aguilar
*Electronics and Photonics* CD/USB

H04 — **Wearable and Flexible Electronic and Photonic Technologies**
Colm O'Dwyer, Wei Gao, Durgamadhab Misra, Shelley Minteer, Scott Calabrese Barton, Lain-Jong Li, Sheng Xu, Jong-Hyun Ahn, Sang-Woo Kim, Yu-Lun Chueh, Jessica Koehne, Ajit Khosla
*Electronics and Photonics, Dielectric Science and Technology, Energy Technology, Physical and Analytical Electrochemistry, Sensor, Interdisciplinary Science and Technology Subcommittee*

## I — Fuel Cells, Electrolyzers, and Energy Conversion

I01 — **State of the Art Tutorial in Low Temperature Fuel Cell Electrocatalysis: The Challenge of High Current Density Performance at Low Platinum Loading**
Adam Weber, Peter Strasser, Karen Swider-Lyons
*Energy Technology, Industrial Electrochemistry and Electrochemical Engineering, Physical and Analytical Electrochemistry* e

I02 — **Electrosynthesis of Fuels 5**
John Staser, William Mustain, Gessie Brisard, John Flake, Xiao-Dong Zhou, Turgut Gur, Mogens Mogensen, Hui Xu
*Industrial Electrochemistry and Electrochemical Engineering, Energy Technology, High Temperature Materials, Organic and Biological Electrochemistry, Physical and Analytical Electrochemistry* CD/USB

I03 — **Oxygen or Hydrogen Evolution Catalysis for Water Electrolysis 4**
Hui Xu, Katherine Ayers, Pawel Kulesza, Gang Wu
*Energy Technology, Industrial Electrochemistry and Electrochemical Engineering, Physical and Analytical Electrochemistry* CD/USB

I04 — **Materials for Low Temperature Electrochemical Systems 4**
Minhua Shao, Gang Wu, Robert Mantz, Wei Gao, Vito Di Noto
*Energy Technology, Industrial Electrochemistry and Electrochemical Engineering, Physical and Analytical Electrochemistry* e

I05 — **Renewable Fuels via Artificial Photosynthesis or Heterocatalysis 3**
Nianqiang (Nick) Wu, Heli Wang, Nicolas Gaillard, Frank Osterloh, Mani Manivannan, Jae-Joon Lee, Pawel Kulesza, Eric Miller, Bunsho Ohtani, Vaidyanathan Subramanian
*Energy Technology, Organic and Biological Electrochemistry, Physical and Analytical Electrochemistry* e

I06 — **Mechano-Electro-Chemical Coupling in Energy Related Materials and Devices 3**
Jason Nicholas, Nicola Perry, Kejie Zhao, Gery Stafford, Ahmet Kusoglu
*High Temperature Materials, Battery, Electrodeposition, Energy Technology* e

I07 — **Energy Conversion Systems Based on Nitrogen**
Gang Wu, Yuyan Shao, Julie Renner, Lauren Greenlee, Hui Xu
*Energy Technology* e

## K — Organic and Bioelectrochemistry

K01 — **13th Manual M. Baizer Memorial Symposium on Organic Electrochemistry**
Diane Smith, Graham Cheek
*Organic and Biological Electrochemistry* e

K03 — **Oxidation and Reduction: Exploring Electron Transfer Reactions in Chemistry and Biology**
Kevin Moeller, James Rusling, Mekki Bayachou, Hugh De Long
*Organic and Biological Electrochemistry, Physical and Analytical Electrochemistry* e

## L — Physical and Analytical Electrochemistry, Electrocatalysis, and Photoelectrochemistry

L01 — **Physical and Analytical Electrochemistry, Electrocatalysis, and Photoelectrochemistry General Session**
Alice Suroviec, Anne Co
*Physical and Analytical Electrochemistry* e

L02 — **Electrocatalysis 9: Symposium in Honor of Radoslav Adzic**
Minhua Shao, Gessie Brisard, Mekki Bayachou, Nenad Markovic, Miomir Vukmirovic, Piotr Zelenay, Kotaro Sasaki, Stanko Brankovic, Junliang Zhang, Jia Wang
*Physical and Analytical Electrochemistry, Electrodeposition, Energy Technology* CD/USB

L03 — **Biological Fuel Cells 8**
Shelley Minteer, Scott Calabrese Barton, Plamen Atanassov
*Physical and Analytical Electrochemistry, Energy Technology* e

L04 — **Charge Transfer: Electrons, Protons, and Other Ions 3**
Stephen Paddison, Vito Di Noto, Andrew Herring
*Physical and Analytical Electrochemistry, Energy Technology* e

L05 — **Oxygen Reduction Reactions**
Pawel Kulesza, Vito Di Noto, Robert Mantz, Piotr Zelenay, Plamen Atanassov, Yang Shao-Horn, Hui Xu, Minhua Shao, Sanjeev Mukerjee
*Physical and Analytical Electrochemistry, Energy Technology* e

L06 — **Nanoporous Materials**
Roseanne Warren, Anne Co, Bo Zhang, Kunal Karan
*Physical and Analytical Electrochemistry, Energy Technology* e

## M — Sensors

M01 — **Sensors, Actuators, and Microsystems General Session**
Larry Nagahara, Nianqiang Wu, Aleksandr Simonian, Jin-Woo Choi, Ajit Khosla, Leyla Soleymani, Milad Navaei, Mekki Bayachou, Bryan Chin, Daniel Heller
*Sensor* e

M02 — **Microfluidics, Sensors, and Devices 2**
Jessica Koehne, Raluca-Ioana Stefan-van Staden, Chris Salthouse, Shekhar Bhansali, Ajit Khosla, Peter Hesketh, Praveen Sekhar
*Sensor, Nanocarbons* e

## Z — General Topics

Z01 — **General Student Poster Session**
Venkat Subramanian, Kalpathy Sundaram, V. Chaitanya, P. Pharkya, Alice Suroviec
*All Divisions* e

Z02 — **Nanotechnology General Session**
Oana Leonte, Z. Chen, Christina Bock, Jessica Koehne
*All Divisions, Interdisciplinary Science and Technology Subcommittee* e

Z03 — **Solid State Topics General Session**
Kalpathy Sundaram, Meng Tao, Oana Leonte, Hiroshi Iwai, Michael Carter
*Dielectric Science and Technology, Electronics and Photonics, Energy Technology, Luminescence and Display Materials, Nanocarbons, Organic and Biological Electrochemistry, Sensor* e

ECS will publish issues of *ECS Transactions* with papers from each symposium. Issues will be available in CD/USB CD or USB format or as e Electronic (PDF) editions. Pre-ordered CD or USB editions will be available for pick up at the meeting.


# ECS Data Sciences Event Grows to a Full Week

***May 14-19, 2018***

**Application Deadline: March 30, 2018**

Building on the success of the first ECS Data Sciences Hack Day (October 2017), ECS is pleased to offer another opportunity at the ECS spring meeting in Seattle. In May 2018, the program will be expanded to an entire week as the next stage in ECS supporting a growing electrochemical data science and open source community. The goal of this event is to increase awareness and impact of data science tools, open source software, and shared datasets in electrochemistry and solid state science and technology, by bringing together people from different backgrounds to collaborate.

Hack Week will again be led by the very capable and engaging team from University of Washington: Dan Schwartz, David Beck, and Matt Murbach. The program will kick off on Monday, May 14 and have sessions all day Wednesday through Friday, as well as optional software training tutorials during the week. The activities will culminate with project presentations and an optional clamming expedition on Saturday, a traditional activity in the Puget Sound area.

## Meet the Organizers

Daniel Schwartz

David Beck

Matthew Murbach

**Daniel Schwartz** is the Boeing-Sutter Professor of Chemical Engineering and director of the Clean Energy Institute at the University of Washington, and brings electrochemistry and modeling expertise to the team. **David Beck** is a senior data scientist with the eSciences Institute at the University of Washington, and leads regular hackathons; he is associate director of the NSF Data Intensive Research Enabling CleanTech PhD training program. **Matthew Murbach** is past-president of the ECS University of Washington Student Chapter, and an advanced data sciences PhD trainee; he has been leading the student section software development sessions on the UW campus, and has practical experience coaching electrochemical scientists and engineers in software development.

## Who Should Attend?

All electrochemical engineers can benefit from this workshop, whether experimentally or theoretically focused. Learning how to create, share, use, and improve open source software tools and public datasets is one way to accelerate research progress in our field.

## Selection of Attendees

The goal of this event is to increase awareness and impact of data science tools, open source software, and shared datasets in electrochemistry by bringing together people from different backgrounds to collaborate. We expect to have 42 slots for attendees, and will seek to build a cohort comprised of people with a diverse mix of experimental and theoretical electrochemical expertise, as well as a range of prior experiences creating and using open source software and python programing.

## Travel Grants

A number of travel awards made possible by generous grants from the Army Research Office and the University of Washington Clean Energy Institute will be available. Please indicate your interest in being considered for a travel award when completing your ECS Hack Week application.

## Interested?

The attendees of Hack Week are innovators, leaders, and emerging leadership in their fields, all interested in accelerating research progress through data science. If you or one of your colleagues would like to learn more, please contact Mary.Yess@electrochem.org. If you would like to sponsor Hack Week, please contact Ashley.Moran@electrochem.org to learn about opportunities.

**Learn more about Hack Week at**
**www.electrochem.org/233/hack-week**

# ecstransactions

## ECS Members Receive 20% Off

www.electrochem.org/ecst

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85 12 — Electrocatalysis 9: Symposium in Honor of Radoslav Adzic
CD or USB.....$158.00

## Issues from the 233rd ECS Meeting in Seattle, WA
## Now Available for Pre-Order

# Future ECS Meetings

## AiMES 2018

CANCUN, MEXICO
September 30-October 4, 2018
*Moon Palace Resort*

AiMES 2018
AMERICAS INTERNATIONAL MEETING ON ELECTROCHEMISTRY AND SOLID STATE SCIENCE

## 235th ECS Meeting

DALLAS, TX
May 26-May 31, 2019
*Sheraton Dallas*

**2019**

## 236th ECS Meeting

ATLANTA, GA
October 13-17, 2019
*Hilton Atlanta*

**2019**

## 237th ECS Meeting

*with the 18th International Meeting on Chemical Sensors (IMCS 2020)*

MONTREAL, CANADA
May 10-15, 2020
*Palais des congress de Montreal*

**2020**

ECS www.electrochem.org/meetings

# ECS Student Member Named to Forbes 30 Under 30 2018

**Matthew Murbach**, founding president of the ECS student chapter at the University of Washington and motivating force behind the launch of the ECS Data Sciences Hack Day, has been named to the Forbes 30 Under 30 2018 list in the area of energy. According to Forbes, Murbach was recognized for his work "to commercialize battery management breakthroughs to enable faster charging, finer control over degradation and longer lifetimes."

Murbach is cofounder of Battery Informatics, Inc. and a PhD student in chemical engineering at the University of Washington. Murbach's PhD research is exploring new ways to diagnose the state of health in batteries, a critical and expensive asset in the emerging low carbon energy economy.

Battery Informatics is a next-generation battery management company focused on capturing the maximum value of energy storage through software solutions. The company is licensing University of Washington intellectual property to extract the maximum value from these battery assets over the whole battery life cycle. A few months ago, the company completed its first customer installation.

During the recent 232nd ECS Meeting in National Harbor, MD, Murbach co-organized the Society's first ever Data Sciences Hack Day, providing a forum for building an electrochemical data sciences and open source community from the ground up.

"Hack Day is an opportunity to get people together to build software, learn how to program, and eventually build a community of data science at ECS," Murbach said. "We're trying to build a repository for software that people use in their daily lives as electrochemists, except we want it to be open. We want people to contribute to packages that other researchers can use and have the ability to build tools and analysis techniques that are reproducible."

Additionally, as founding president of the ECS University of Washington Student Chapter, Murbach helped establish a network of young researchers working in electrochemical and solid state science. The group was recently awarded the ECS Chapter of Excellence Award at the 232nd ECS Meeting.

David Crane, one of the Forbes 30 Under 30 2018 judges, added, "If there is any common thread in my picks, you will see that I have a bias for those who have sought to put together all the elements of whatever endeavor they are engaged in—technological, financial, commercial—more than being strong in just one. I also have a bias towards those who have actually gotten things over the finish line."

# ECS Member a Winner of 2017 Bell Labs Prize

Nokia recently announced the top three winners of its fourth annual Bell Labs Prize, which recognizes disruptive technology innovations with the potential to solve the critical challenges humanity faces within the next 10 years. Joint second prize was awarded to ECS member **Colm O'Dwyer**, professor in chemical energy at University College Cork, Ireland, and chair of the ECS Electronics and Photonics Division, for his invention of a new class of 3D-printed batteries that could be incorporated into virtually any form factor, enabling new kinds of wearable devices with medical, health, communications, and other future applications.

This year's competition attracted more than 330 proposals from 35 countries, which were narrowed down to around 20 semifinal applications shortlisted for collaboration with Bell Labs researchers over a two-month period. These refined semifinal proposals were then reviewed by the Bell Labs leadership team, and the nine finalists were selected, with each finalist having the chance to extend their collaboration with leading researchers at Bell Labs.

The nine finalist applications covered a range of topics, including new approaches to machine learning, new materials synthesis, new human sensory technologies, new distributed computing paradigms, new battery technologies, and new programmable radio and antenna technologies. The final judging event took place with a group of seven luminaries in the STEM fields.

"Being one of the winners of this prize is not only an honor, but it is motivating to see how our ideas and research dovetails with an integral part of the vision of Bell Labs for human-centric technology," O'Dwyer said. "This rethink of the design of a battery allows a 3D printable battery power inspired by its use and its user and offers complete design freedom of battery shape for wearables and a range of other applications where the battery power can be inbuilt at the design stage as part of the device, instead of needing a separate battery. New thinking for the battery was part of our goal to enable technologies that conform to natural human movement and how we process and interact with the information around us. Our research is looking at how this can be done, starting with all-plastic 3D printed rechargeable batteries."

Marcus Weldon, president of Nokia Bell Labs and Nokia CTO, added, "Each year the Bell Labs Prize produces a set of outstanding innovations that have the potential to solve critical problems confronting humanity. This year was no exception and produced one of the finest groups of finalists we have seen, with each of the nine having the potential to profoundly disrupt and enhance the technology or solution domain they were addressing. It was a difficult decision, but the judges were unanimous in their support for the three winners, based on the novelty of the work and the disruptive potential. We look forward to continuing to work with all of these rising stars to help make their vision a reality."


*From left to right: President of Nokia Bell Labs and Nokia CTO* **Marcus Weldon** *presented the Bell Labs Prize to joint second prize winners* **Colm O'Dwyer**, **Jason Azoulay**, *and* **Tse Nga (Tina) Ng**.

# ECS Fellows Enter National Academy of Engineering

**Raymond J. Gorte**, **Yang Shao-Horn**, and **M. Stanley Whittingham**, all of whom are ECS fellows, were recently elected to the National Academy of Engineering. Election to the NAE is one of the most prestigious professional distinctions bestowed upon engineers.

According to the NAE, academy membership honors individuals who have made outstanding contributions to "engineering research, practice, or education, including, where appropriate, significant contributions to the engineering literature" and to "the pioneering of new and developing fields of technology, making major advancements in traditional fields of engineering, or developing/implementing innovative approaches to engineering education."

Raymond J. Gorte

**Gorte** is the Russell Pearce and Elizabeth Crimian Heuer Professor of the Department of Chemical and Biomolecular Engineering and the Department of Materials Science and Engineering at the University of Pennsylvania. He is also an associate editor of the *Journal of The Electrochemical Society*.

The NAE recognizes Gorte "for fundamental contributions and their applications to heterogeneous catalysts and solid state electrochemical devices."

**Shao-Horn** is the W. M. Keck Professor of Energy of the Department of Mechanical Engineering and the Department of Materials Science and Engineering at MIT. The NAE recognizes her "for contributions to design principles for catalytic activity for oxygen electrocatalysis for electrochemical energy storage for clean energy."

Yang Shao-Horn

**Whittingham** is a distinguished professor of chemistry and materials science and engineering at Binghamton University, NY. The NAE recognizes him "for pioneering the application of intercalation chemistry for energy storage materials."

M. Stanley Whittingham

The three will be formally inducted during a ceremony at the annual NAE meeting in Washington, DC, on September 30, 2018.

## *In Memoriam*

# Israel Rubinstein
## (1947 – 2017)

**Israel Rubinstein** passed away at the age of 70 on October 21, 2017, in Rehovot, Israel. Rubinstein completed his PhD in chemistry at Tel-Aviv University (1975-1979). He then joined the laboratory of Allen Bard at the University of Texas at Austin for postdoctoral studies (1979-1981). After two years at the General Electric Research Center in Schenectady, NY, he moved on in 1983 to the Weizmann Institute of Science in Rehovot, Israel, becoming a full professor in 1996. Rubinstein joined ECS in 1983 as a member of the Society's Physical and Analytical Electrochemistry Division and was named an ECS fellow in 2002.

After joining the WIS, Rubinstein's main scientific focus was on polymer- and monomolecular layer-modified electrodes. During this early period, he published a series of seminal papers on the electrochemistry of modified electrodes. In the early 1990s, Rubinstein, in collaboration with Gary Hodes, pioneered the field of epitaxial deposition of semiconductor nanoparticles on single crystal surfaces. In further studies, Rubinstein and Alexander Vaskevich, who joined his group, turned to the development of plasmonic nanostructures based on gold island films. They were able to demonstrate the high sensitivity of the optical properties of these films to adsorption of very few molecules, thereby establishing a general platform for applications in biosensing and environmental monitoring.

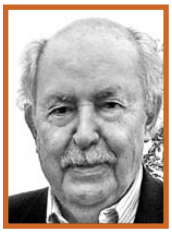
Many of Rubinstein's students become leaders in their own fields in academic research and in the high-tech industry, both in Israel and abroad. Rubinstein was among the founding faculty members of the WIS's Department of Materials and Interfaces, which was established in 1991. He served on the advisory board of several international and national scientific organizations and served as chairperson of numerous national and international conferences.

Hodes describes him as "a perfect example of how it is possible to balance a highly successful scientific career with a full family life and with other interests." Indeed, Rubinstein was a talented musician who played guitar, piano, and accordion and gained a black belt in karate at the age of 52. He continued his scientific activities while struggling with illness to the last days of his life. Rubinstein is survived by his wife, Beverly, and his four children. Rubinstein was, for us, both a great colleague and friend, and we will sorely miss his sense of humor and his sharp mind.

*Contributed by Reshef Tenne and David Cahen, Department of Materials and Interfaces, Weizmann Institute of Science.*

## In Memoriam

### Jose Domingo Giner
### (1928 – 2017)



Jose Domingo Giner passed away at the age of 89 on November 4, 2017, in the quiet company of his family. A resident of Brookline, MA, Giner was the founder and chairman of Giner, Inc. In 1986, Giner made the decision for his institution to join ECS as a sustaining member, forging a connection that has lasted decades; Giner, Inc. has remained a sustaining member of the Society for over 31 years.

Giner earned his PhD in electrochemistry in Madrid. He conducted postdoctoral work in Germany before moving with his family to the U.S. in 1961. There, he worked on fuel cells for the Apollo Space Program at United Technologies. In 1973, he founded Giner, Inc. Throughout his career, Giner directed extensive research in the fields of electrocatalysis, electrochemical kinetics, fuel cells, batteries, electrochemical sensors, and corrosion. He was the inventor or coinventor of 30 U.S. patents.

Giner is remembered by colleagues, friends, and family for his sharp mind and benevolent nature.

"Those that worked for Jose greatly appreciated the freedom to pursue their ideas and projects," says Cortney Mittelsteadt, CEO of Giner, Inc.

Among the things Giner enjoyed were Spanish music, traveling, and dining. Most of all he cherished his family. He kept in regular contact with his siblings in Spain and visited their families often. Giner is survived by his longtime partner, Renate Kollrack, five children, and four grandchildren, who will miss his humor, wit, and loving presence.

## In Memoriam

### Allen Louis Solomon
### (1922 – 2017)

Allen Louis Solomon passed away at the age of 95 on November 7, 2017. Solomon was an emeritus member of the Society who had been an ECS member for 60 years. He was a member of the ECS Electronics and Photonics Division.

After graduating valedictorian of Taylor Allderdice High School in Pittsburgh, PA, Solomon was admitted to Yale University. There, he studied chemistry and graduated in 1943. During World War II, Solomon served as a lieutenant in the U.S. Navy—a radar specialist stationed in Guam, Wake Island, and Hawaii. Once the war ended, Solomon returned to Yale to earn his PhD in chemistry.

Solomon was first employed as a research chemist at RCA Laboratories in Princeton, NJ, where he was an associate of media pioneer David Sarnoff. Later, Solomon worked as an engineering specialist for Sylvania Electric Products Inc. In the 1970s, Solomon moved with his family to California. In Silicon Valley, he developed a number of cutting-edge technologies. Over the course of his lifetime, Solomon acquired over 30 patents.

In retirement, Solomon traveled the world with his wife, Elaine Miller Solomon. He spent his free time collecting stamps, gardening, and studying history. Solomon is survived by his wife, two children, and four grandchildren. He will be remembered for both his brilliance and his devotion to his family.

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– Researcher and 12-year ECS member

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## Important Dates

| | |
|---|---|
| Technical Program Published Online | June |
| Meeting Registration Opens | June |
| Travel Grant Applications Due | June 18 |
| Meeting Sponsor and Exhibitor Deadline | June 20 |
| Hotel and Early Bird Meeting Registration Deadline | August 27 |

# Portable Biosensor Warns of Heart Attack and Stroke

A team of researchers from National Tsing Hua Uni-versity and National Cheng Kung University, both in Taiwan, has developed a low-cost, portable medical sensor package that has the potential to alert users of medical issues ranging from severe heart conditions to cancer, according to a new study published in the *ECS Journal of Solid State Science and Technology*.

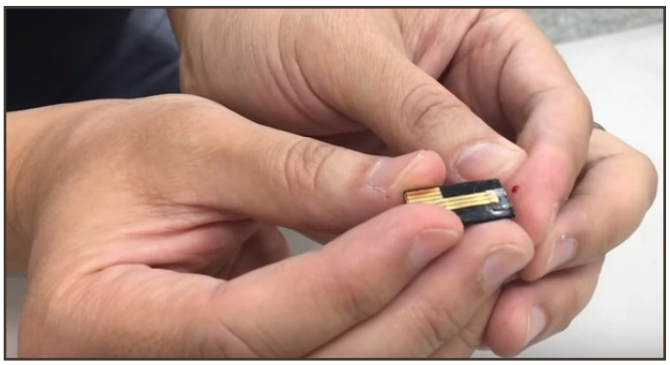
Portable medical devices have become an integral part of holistic health care, exhibiting huge potential in monitoring, medical therapeutics, diagnosis, and fitness and wellness. When paired with benchtop point-of-care instruments used in hospitals and urgent care centers, individuals are able to both increase preventative care measures and gain a more complete picture of their health.

According to the open access paper, "Field-Effect Transistor-Based Biosensors and a Portable Device for Personal Healthcare" (*ECS J. Solid State Sci. Technol.*, **6**, Q71 [2017]), researchers have reported the design, development, fabrication, and prototyping of a low-cost transistor-based device that can measure the C-reactive protein (CRP) in bloodstreams, which, when elevated, indicates inflammation that could be linked to heart attack, stroke, coronary artery disease, and a host of other medical diagnoses.

"This device will eventually be made as a small handheld device, which can easily connect with a smartphone through Bluetooth or Wi-Fi," said Yu-Lin Wang, professor at National Tsing Hua University and coauthor of the study. "The data can be collected in an app and users can send that data to their doctors. The operation is just as simple as the blood sugar meter, where anyone can do the test with one drop of blood anywhere, anytime."

Because of the high salt concentration in blood samples, the accuracy and performance of silicon-based field-effect transistor (FET)-based biosensors often suffers. Wang and the team of researchers recognized this issue and developed a GaN-based high electron mobility transistor (HEMT) in response, which does not suffer from the same performance degradation due to the chemical inertness of GaN. While GaN is more expensive than silicon, advances in micro-fabrication allow for the development of an extremely small HEMT, greatly reducing cost and paving the way for an affordable device upon mass production.

While FET-based biosensors exhibit a host of potential benefits, there are significant technological barriers to overcome before the devices are applicable. Because FETs are extremely sensitive, yet have the potential to be unstable, it is often difficult to develop a sensor that produces consistent results. In order to make their device reliable on top of being affordable, the team began pursuing new, innovative ways to cause the least amount of disruption as possible. This was achieved by using a measurement system of very short pulses.



*The portable biosensor can test specific cardiac markers in five minutes with a single drop of blood. Photo credit: Yu-Lin Wang*

"We also developed a methodology to overcome the charge-screening effect, which is frequently seen in FET-based biosensors," Wang said. "This methodology allows us to detect the target protein without needing to dilute or de-salt the clinical samples. Thus, we do not need to use automatics in our sensor or device, which can make the system simple and cost-effective. The operation is simple and everyone can do it. Just drop and click."

Through these efforts, the research team was able to develop a system that is not only accurate and affordable, but incorporates a new methodology on the sensor itself.

"I believe that what we have created is a technology that has the potential to be used by billions of people," Wang said.

The device's ability to alert individuals of elevated CRP levels could be potentially lifesaving. Currently, individuals who would most benefit from this technology would be those with or at risk for cardiovascular disease, such as heart attack or heart failure. For example, some individuals may not have hallmark symptoms, such as crushing chest pain or discomfort, when it comes to heart attacks. However, the portable biosensor can instantly test specific cardiac markers in the blood that could alert individuals that they are having a heart attack, even without displaying symptoms. Alternatively, this device could be used by first responders to quickly and accurately diagnose patients.

Individuals with chronic heart failure can monitor biomarkers with this device, which if elevated, can indicate your risk of heart failure. Routinely monitoring these biomarkers could be effective at reducing hospital readmission rates, which could lead to improved quality of life and lower hospital medical expenses.

"The test only takes five minutes and one drop of blood, and everybody can just intuitively know how to use this device," Wang says. "The cost of the device will be very low, so this device is affordable for everyone. When the immobilized receptors, such as aptamer or antibody, are changed, then different biomarkers can be tested. Many disease markers can be detected with this device."

Because of its significance and the transformative work demonstrated in this paper, ECS editors designated it as an Editors' Choice article. Editors' Choice articles show new direction, a new concept, and a new way of tackling issues in the related field.

"This work is a demonstration of a low-cost, portable medical sensor package," says Fan Ren, technical editor of the electronic and photonic devices and systems topical interest area of the *ECS Journal of Solid State Science and Technology*. "With a single drop of blood of plasma, this novel sensor package can be used to detect a heart attack or even a tumor."

The team has already developed a handheld device prototype, which has successfully demonstrated accurate, consistent results. Wang believes that within one year, the device will be compatible with smartphones and cloud computing.

"We are collaborating with hospitals and industries, and trying to make this device become a real product," Wang says. "I think in the future this device will collect huge data, which will be analyzed by artificial intelligence and become part of the ecosystem of the Internet of things. This device will play an important role." ■

*This article was written by ECS staff and was first published in the ECS Redcat blog on Feb. 20, 2018.*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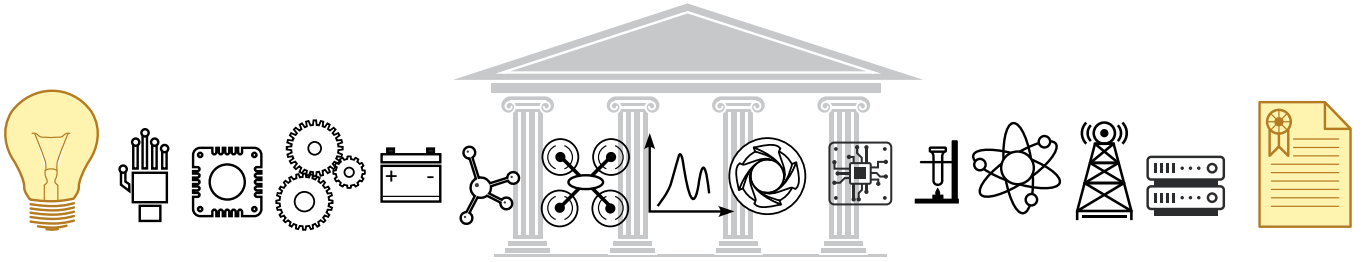
# Looking at Patent Law: A Case Study Regarding the Patenting of a Plating Cell Invention

## *Part I – From Conception to Published Patent Application*

***by E. Jennings Taylor and Maria Inman***



**In this two-part article, we present a case study of an electrochemical plating cell invention. Part I of the case study begins with the initial concept as described in the Invention Disclosure and highlights key steps in the prosecution of the patent application by the U.S. Patent & Trademark Office (USPTO).**

Recall from our previous article,[1] the prosecution history of a patent application is publically available in the file wrapper on the USPTO Patent Application Information Retrieval (PAIR) system and is the basis for this case study.[2] We chose this invention as particularly illustrative of a diverse number of prosecution "events" an inventor may encounter during the prosecution of their inventions. Table I summarizes this journey from the initial documentation and filing of the invention, through various interactions with the USPTO, to the issue of four separate but related patents. As noted in the legend of Table I, we use four different colors to highlight the events related to the four patents which issued from the single patent application. The following events that will be described in this case study occurred in chronological order:

- Creation of an Internal Invention Disclosure
- Inclusion of Patent Drawings in the Invention Disclosure to better describe the invention
- Establishment and Maintenance of a Filing Date
- Submission of an Information Disclosure Statement and Duty of Candor
- Acknowledgement of Federal Funding Sources
- Notice of the 18th Month Publication Requirement
- Restriction/Election Requirement Leading to Divisional Patent Applications
- Submission of Continuation-in-Part Applications based on on-going research activities, and types of continuing applications
- Request for Continued Examination of Original Application with Affidavits
- Submission of Divisional Applications

## The Patenting Process Starts with an Internal Invention Disclosure

Documenting the invention begins with the submission of an Invention Disclosure (ID) by the inventor(s) to the appropriate parties within their organization. Most organizations have their own specific ID, but generally included are:

1. Inventor Names
2. Working Title of the Invention
3. References related to the Invention (Notebooks, Reports, Proposals, Publications)
4. Funding sources if appropriate
5. Date of Public Disclosure or Anticipated Date of Public Disclosure
6. Problem-Solution Statement
7. Detailed Description of the Invention

As previously discussed, the "named inventors" must be correctly represented on a U.S. patent.[3] Specifically, *inclusion* of a colleague as a co-inventor who did not participate in the conception of the invention is known as a *misjoiner* and invalidates an otherwise valid patent. Similarly, *exclusion* of a co-inventor who participated in the conception is known as a *nonjoiner* and also invalidates an otherwise valid patent.

The "working title" of the invention initiates the disclosure of the invention to the appropriate parties within the inventor's organization. The "references related" to the invention provide documentation regarding the known prior art. The identification of the "funding

*(continued on next page)*

sources" are important to document contractual obligations and in the case of government funding to acknowledge government *"march-in rights"* to the subject invention.[4]

**Table I. Timeline of steps in the subject case study.**

| |
|---|
| Internal Invention Disclosure |
| Mar 19, 2004: Application filed |
| Jun 3, 2004: Notice to File Missing Parts |
| Jul 26, 2004: Submitted Information Disclosure Statement |
| Apr 4, 2005: Acknowledged federally sponsored research |
| Sep 25, 2005: Application published |
| Dec 1, 2006: USPTO required Restriction/Election |
| Elected Appl. 10/804,841: Apparatus |
| Elected Div. Appl. 12/431/030: Process |
| Mar 23, 2007: Non-Final Rejection |
| Jun 25, 2007: Examiner Phone Interview |
| Aug 10, 2007: Filed C-I-P Application |
| Sep 21, 2007: Final Rejection |
| Jan 22, 2008: Request for Continued Examination |
| Aug 10, 2007: Filed C-I-P Application |
| Apr 2, 2008: Non-Final Rejection |
| Sep 30, 2008: Submitted Affidavit |
| Jan 8, 2009: Final Rejection |
| Feb 20, 2009: Amended Claims |
| Mar 16, 2009: Notice of Allowance |
| Apr 28, 2009: Application Filed |
| May 21, 2009: Paid Issue Fee |
| Jun 30, 2009: 7,553,401 Patent Issued |
| Aug 20, 2009: Application Published |
| Sept 10, 2010: Non-Final Rejection & Restriction/Election |
| Elected C-I-P Appl. 11/836/,903 Apparatus |
| Elected Div. Appl. 13/086,683: Process |
| Apr 14, 2011: Application Filed |
| Sep 11, 2011: Application Published |
| May 24, 2011: 7,947,161 Patent Issued |
| Jul 24, 2012: 8,226,804 Patent Issued |
| Dec 11, 2012: 8,329,006 Patent Issued |

**Legend**

| |
|---|
| Patent Application 10/804,841: Apparatus |
| Continuation-in-Part Application 11/836,903: Apparatus |
| Divisional Patent Application from 10/804,841: 12/431/030: Process |
| Divisional Patent Application from C-I-P Application 11/836,903: 13/086,683: Process |

Prior to the Leahy-Smith America Invents Act of 2011 (AIA), the U.S. awarded a patent to the *"first-to-conceive"* the subject invention. In these cases, witnessed notebook references were critical to document the inventors' contribution to the conception of the invention and the date of the invention. After the AIA, the U.S. patent system is in harmony with most of the world and awards the patent to the *"first-to-file"* the subject invention. The witnessed notebook references are still important to document those contributing to the conception of the invention, but are no longer relevant to establishing the *"first-to-conceive"* the subject invention. The *first-to-file* component of the AIA applies to patent applications filed on or after March 16, 2013.[5]

The "date of public disclosure" or "anticipated date of public disclosure" is important in that the inventor has one year from public disclosure to file a patent application in the U.S.[6] In essence, the U.S. could be considered as a *"first-to-publically-disclose"* patent jurisdiction. This one year grace period from public disclosure does not apply to most foreign jurisdictions as the ability to file a foreign patent is barred by public disclosure.

As previously noted, the "problem-solution" statement is a convenient way of forcing the inventor to concisely state the significance of their concept in view of the prior art:[7]

***"The problem(s) of … is (are) solved by …"***

The "problem-solution" statement forces the inventors to reduce their invention to this one, albeit long, statement. As a consequence, the elements of the invention are succinctly and broadly stated. The "problem-solution" statement and the "detailed description" of the invention become the basis of the claims and interaction with patent counsel.[8]

In our case study Invention Disclosure, the inventors of the subject electroplating cell disclosed the following "problem-solution" statement:

***The problem of …***
***non-uniform electrodeposition of a metal such as copper on an approximately planar workpiece such as a printed circuit board wherein the plating electrolyte is agitated using air sparging and/or educator directed solution flow in a perpendicular or angular orientation against the workpiece***
***is solved by …***
***positioning eductors below the workpiece and directing the electrolyte flow against a dampening element which guides the solution across the workpiece through a channel formed by the workpiece and a cloth between the workpiece and the counter electrodes resulting in uniform electrodeposition of a metal such as copper on the workpiece.***

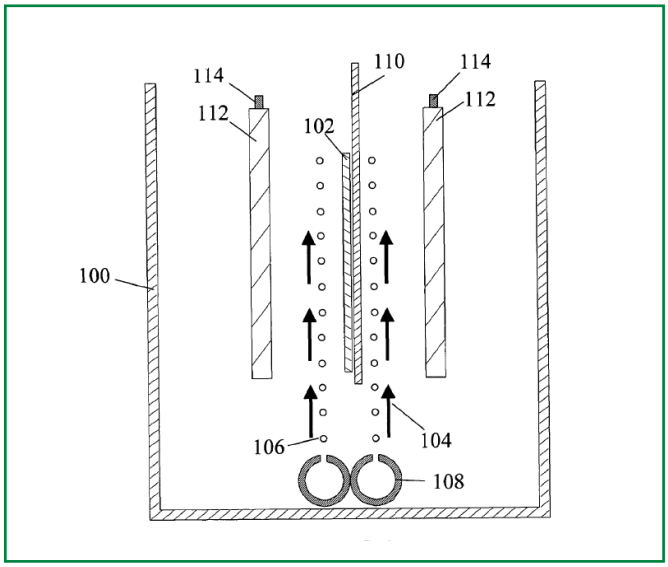



**Fig. 1.** *Illustration of electrolyte agitation using air sparging.*

While the "problem-solution" statement is somewhat clumsy in terms of writing style, our experience is that it forces the inventor to concisely and precisely describe their invention and distinguish it from the prior art. This provides a "jump-start" for patent counsel as they review the detailed description and begin to draft the independent claims.

After careful drafting of the "problem-solution" statement, we began drafting of the "detailed description" of the invention that we briefly describe herein. A detailed description of the subject electroplating cell technology being discussed in this case study is contained in a recent publication.[9]

## Use of Patent Drawings in the Invention Disclosure

We begin our drafting process with creation of the figures, as we generally believe it is valuable to illustrate the prior art to distinguish our invention. So as to facilitate better communication of the nature of the invention between Faraday Technology, Inc. and the patent attorney, Faraday scientists and engineers have been trained in the basic mechanics of patent drawings illustrating the key elements of the invention.[10]

In Fig. 1 and 2, we illustrate the prior art electrolyte agitation using air sparging and eductors, respectively. Notice how the drawings are derived from the "problem" component of the "problem-solution" statement. Further note that the drawings distinctly point out the key elements in the prior art drawings using a numbering system. We find it helpful, although not required, to include a glossary of the key elements (Table II) in the "detailed description" of the invention. In Fig. 3 and 4, we illustrate the non-uniform boundary layer resulting from educator directed solution flow impinging the workpiece perpendicularly and angularly, respectively. We disclosed the experimental results within the "detailed description" illustrating the non-uniformity of an electrodeposited metal foil plated onto a planar workpiece using the prior art approaches.

In Fig. 5, we illustrate the key elements of our invention wherein the eductors are positioned below the workpiece and the electrolyte flow is directed against a dampening element that guides the solution across the workpiece. Notice how the drawing is derived from the "solution" component of the "problem-solution" statement. The key elements in Fig. 5 are depicted in red and include:

1. Variable high velocity eductor agitation (116);
2. Shaped guides to direct eductor flow across the cathode (136);
3. Use of anode chamber (126) with porous polymeric cloth (128) creating a channel for electrolyte flow;
4. Baffles beneath anode chamber to isolate eductor flow to cathode (138);
5. Non-conductive shielding to eliminate edge effects (130); and
6. Lateral oscillation (154) and vibration (152) to help facilitate solution flow into board features.

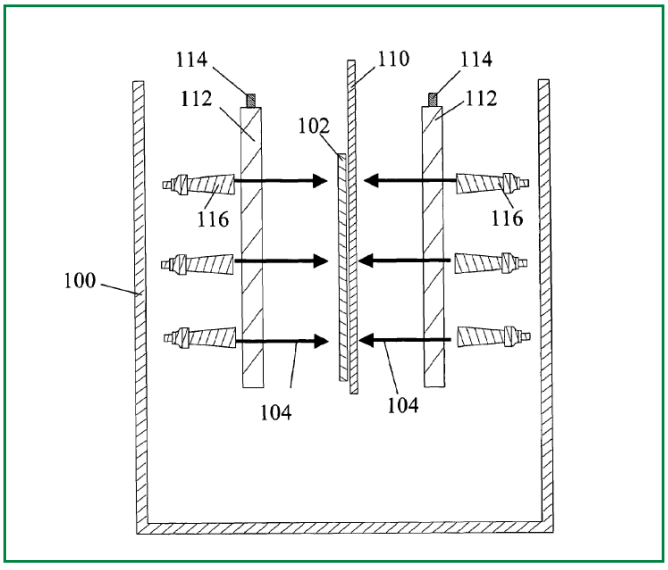



**Fig. 2.** *Illustration of electrolyte agitation using impinging eductors.*

These key elements were referred to in the claims of the patent application. In addition, the patent application included two statutory classes of invention, apparatus and process.[8]

## Establishment of a Filing Date

The patent application was filed March 19, 2004 in accordance with U.S. patent laws. Specifically, in order to *establish* a filing date, we submitted a patent application including:

1. Specification[11]
   *"A written description of the invention, and the manner and process for making it … to enable any person skilled in the art … to make and use [the invention]"*
2. A Minimum of one claim[12]
   *"Particularly pointing out … the subject matter … as the invention"*
3. Drawings[13]
   *"Where necessary for understanding the subject matter … to be patented"*

*(continued on next page)*

**Table II. Glossary of key terms.**

| |
|---|
| 100. Plating cell |
| 102. Workpiece |
| 104. Arrow indicating electrolyte flow |
| 106. Air bubbles |
| 108. Pipe |
| 110. Rack |
| 112. Anode |
| 114. Rail |
| 116. Eductor |
| 118. Impingement point |
| 120. Fluid flow profile |
| 122. Jet centerline |
| 124. Velocity profile |
| 126. Anode chamber |
| 128. Porous fiber cloth |
| 130. Non-conducting shielding |
| 132. Pump |
| 134. Manifold |
| 136. Guide |
| 138. Baffle |
| 140. Arrow indicating electrolyte flow |
| 142. Arrow indicating electrolyte flow |
| 144. Hole |
| 146. Baffle |
| 148. Side chamber |
| 150. Outlet hole |
| 152. Arrow indicating vertical vibration |
| 154. Arrow indicating oscillation |

On June 3, 2004, correspondence from the USPTO assigned patent application number 10/804,841 to the invention. In addition, our attorney of record received a "Notice to File Missing Parts of an Application" from the USPTO with a two month response date. In order to *maintain* the filing date, the following additional material is required:

1. Filing fee in accordance with the current USPTO schedule[14]
2. Inventor oath or declaration asserting[15]
   a. The patent application was authorized by the inventor(s),
   b. The inventor(s) believe he/she is the original inventor or they are the original joint inventors.

We paid the filing fee and submitted a declaration within the two month period. The declaration must be notarized and per the Code of Federal Regulations (CFR):[16]

> ***"False statements are punishable by fine or imprisonment … and may jeopardize the validity of … any patent application issuing thereon."***

## Submission of an Information Disclosure Statement and Duty of Candor

On July 26, 2004, we submitted an "Information Disclosure Statement" (IDS) in accordance with U.S. patent laws. The IDS is the submission of relevant background art or information to the USPTO by the applicant. The "Duty of Candor" requires that the inventor submit an IDS within a reasonable time of submission of the patent application or at least prior to the first office action:[17]

> ***"Disclose to the Office [USPTO] all information known to that individual to be material to patentability."***

The "Duty of Candor" is specific to any existing claim and requires that the IDS be continually updated while the claim is pending. The "Duty of Candor" ceases only when the claim is allowed and the issue fee is paid.

The "Duty of Candor" extends to any individual *associated* with the filing of the patent application including: 1) Inventor(s); 2) Patent Counsel; or 3) those persons who are substantially involved in the preparation or prosecution of the patent application. Substantial involvement could include technical assistants, collaborators or colleagues. Substantial involvement would generally not extend to clerical workers. Furthermore, the inclusion of a reference in an IDS:[18]

> ***"Is not taken as an admission that the reference is prior art against the claims."***

If a finding of a violation of the "Duty of Candor" resulting in "inequitable conduct" regarding any claim in a patent application or patent is determined, then all the claims are rendered invalid.[19] Finally, in spite of the requirement of the "Duty of Candor", the applicant is cautioned not to "bury" the examiner with a long list of non-material references in hopes that the examiner will not notice the material references.

## Acknowledgement of Federal Funding Sources

On April 4, 2005, we submitted an amendment to acknowledge federally sponsored research in accordance with the Bayh-Dole Act.[20] As a consequence, any patents issuing from the 10/804,841 patent application will have the government rights acknowledgement:

> ***"The experimental work leading to this invention was funded in part by the Department of Defense SBIR Contract No. DASG60-01-C-0056."***

## Notice of the 18th Month Publication Requirement

On September 25, 2005, the 10/804,841 patent application was published eighteen months from the earliest filing date in accordance with U.S. patent laws.[21] The significance of the date of publication is that if the patent application eventually issues with a claim or claims that are substantially the same as in the published patent application, then the applicant may be able to collect reasonable royalties from any person who:[22]

> ***"During the period beginning on the date of publication … and ending on the date the patent is issued makes, uses, offers for sell, or sells … [and] had actual notice of the published patent application."***

Note, the person using the invention must be notified of the pending patent application.

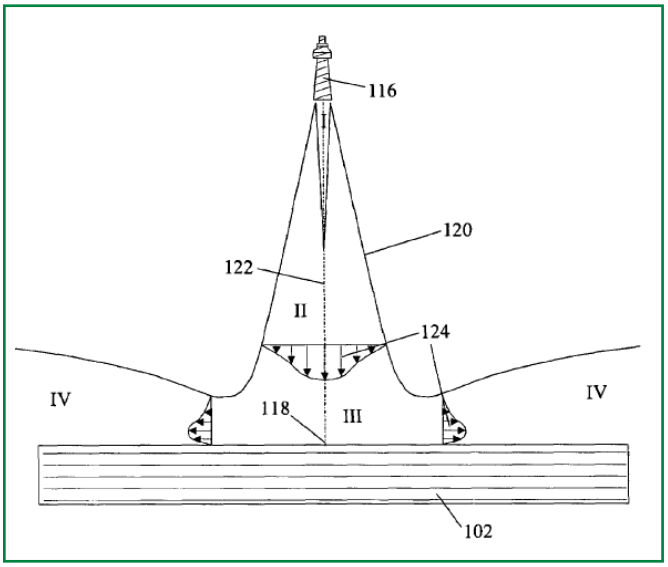



**Fig. 3.** *Illustration of perpendicular impinging eductor electrolyte flow.*

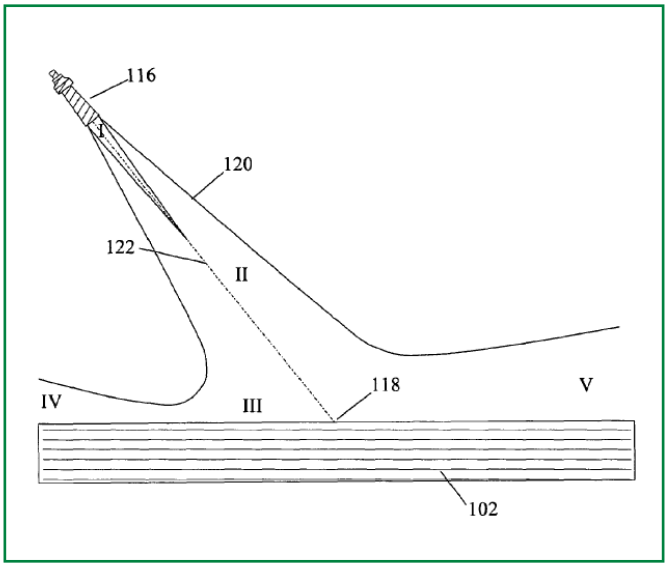



**Fig. 4.** *Illustration of angular impinging eductor electrolyte flow.*

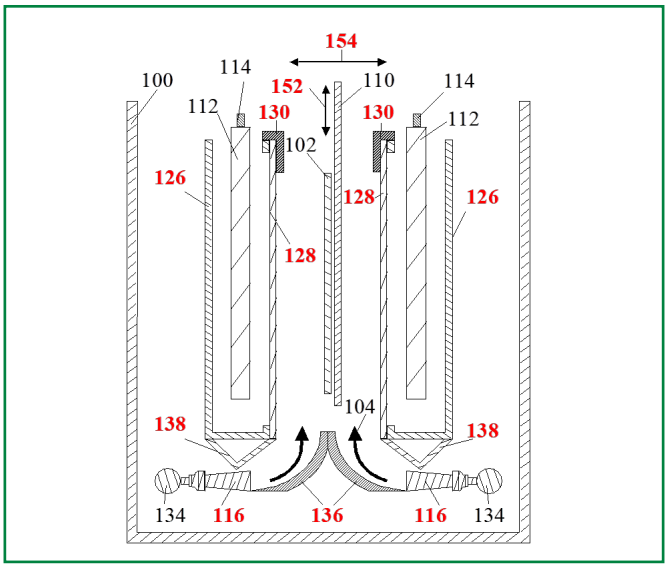



**Fig. 5.** *Illustration of the subject plating cell invention.*

## Concluding Remarks

In this Part I installment of our "Looking at Patent Law" series, we presented a case study of the conception and preparation of a patent application related to an electrochemical plating cell invention. The case study begins with an "Invention Disclosure" (ID) including the basic items required therein including: 1) inventors; 2) title; 3) references; 4) funding source; 5) public disclosure if any; 6) problem-solution statement; and 7) detailed description. We particularly illustrated the value of the problem-solution statement with regards to drafting the patent drawings, detailed description and claims of the invention. We provided examples of patent drawings and their effectiveness in distinguishing the subject invention vis-à-vis the prior art. We described the patent application submission requirements to establish a filing date and the additional submission requirements to maintain the filing date. We introduced the requirement for an "Information Disclosure Statement" (IDS) and the associated "Duty of Candor" in interacting with the USPTO. We touched on the requirement to acknowledge federal funding sources. We discussed the eighteen month publication requirement of patent applications. Part II will continue with the office actions and responses that eventually resulted in the issuance of four U.S. patents.

 *DOI: 10.1149/2.F01181if.*

## About the Authors

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## Influence of Anode Materials on the Electrochemical Performance of $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ Cathodes

$LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (NMC) continues to attract a great deal of attention as a cathode material for Li-ion batteries due to its enhanced specific capacity and lower cost compared to $LiCoO_2$. Typically electrode materials are evaluated in half cells against Li metal and, surprisingly, reports on full Li-ion cells remain quite uncommon. Full cell testing is a crucial step to determine the true value of promising electrode materials. Researchers from Uppsala University have prepared full Li-ion cells with NMC cathodes paired with three commonly used anodes. Galvanostatic cycling of NMC samples paired with Li, $Li_4Ti_5O_{12}$ (LTO) and graphite revealed that the capacity retention of NMC-based cells is significantly influenced by the choice of the anode material. NMC-LTO and NMC-graphite cells demonstrated gradual capacity fading over 200 cycles, whereas NMC-Li cells suffered from rapid capacity fading, despite having an excess of lithium. The declining capacity is attributed to an increased overpotential when cycled vs. Li, which causes the cutoff potential to be reached before the cell is fully lithiated/delithiated. This investigation of NMC cathodes paired with commonly used anode materials offers valuable insight for the optimization of full Li-ion cells.

*From: E. Björklund, D. Brandell, M. Hahlin, et al.,* J. Electrochem. Soc., ***164****, A3054 (2017).*

## Field Trials of Hydrogen Safety Sensors at Hydrogen Filling Stations in California

EDITORS' CHOICE

The initiative to reduce greenhouse gas emissions has driven rapid changes in the automotive industry, including the widescale introduction of new vehicle technologies that include fuel cell vehicles (FCVs). Given the significant hazards for gaseous hydrogen fuel (highly flammable, high pressure storage, rapid propagation if released), publically-available hydrogen filling stations for hydrogen-fueled FCVs have been engineered with multiple levels of safety features. Researchers at Los Alamos National Laboratory and Lawrence Livermore National Laboratory partnered with an owner of hydrogen filling stations (Hydrogen Frontier, Inc.) to conduct extensive, two-year field trials of hydrogen sensors (based on mixed potential electrochemical principles) to determine the efficacy of these sensors for accurate, precise, sensitive, and reproducible measurement of hydrogen at two filling stations in California. The authors briefly describe the approximately 9-year research program that led to the development of an electrochemical sensor with a yttria-stabilized zirconium oxide electrolyte and either a tin-doped indium oxide or strontium-doped lanthanum chromite electrode. The sensors detected numerous hydrogen releases over two years of field trials. None of the releases approached the 4% lower flammability limit, and all releases correlated well with customers filling their FCVs or with normal station maintenance activities.

*From: E. L. Brosha, C. J. Romero, D. Poppe, et al.,* J. Electrochem. Soc., ***164****, B681 (2017).*

## Effect of Galvanic Current on the Physicochemical, Electrochemical and Mechanical Properties of an Aerospace Carbon Fiber Reinforced Epoxy Composite

Carbon fiber reinforced epoxy composites are attractive for use in the aerospace and automobile industries due to their high strength-to-weight ratio. When joined to aluminum metallic structures, however, the overall assembly can form a galvanic cell. Oxidation occurring on the metal and reduction of oxygen to $H_2O_2$ on the carbon fibers could cause the epoxy in the assembly to degrade, leading to water ingress and an eventual decrease in the mechanical strength of the composite. To examine this hypothesis, researchers at Michigan State University exposed standard airframe composites joined to AA2024-T3 to neutral salt spray and moist $SO_2$ environments. They also probed the electrochemical properties of the composite after application of cathodic and anodic currents. Lastly, they exposed composite samples to $H_2O_2$ environments and measured the peak load during a horizontal shear test. Testing revealed that salt-spray exposure, applied cathodic currents, and $H_2O_2$ environments led to epoxy degradation, while applied anodic currents induced carbon corrosion and did not significantly degrade the epoxy. A decrease in mechanical strength was observed after $H_2O_2$ exposure at elevated temperatures. Implications of a local pH increase with oxygen reduction on epoxy degradation could be considered.

*From: B. Whitman, D. Miller, et al.,* J. Electrochem. Soc., ***164****, C881 (2017).*

## Investigation and Review of the Properties of Atomic Layer Deposited High-k Dielectrics

Atomic layer deposited (ALD) high-dielectric-constant (high-*k*) materials have broad applications in the complementary metal–oxide–semiconductor (CMOS) industry. To facilitate material selection, a group of researchers from academia and industry in the USA have carried out a thorough investigation of the thermal, mechanical, electrical, optical, and structural properties of ALD high-*k* materials including $Al_2O_3$, AlN, $HfO_2$, and BeO. The reported thin film materials show higher dielectric permittivity and electrical resistance and similar extraordinary thermal and mechanical properties compared to those of $SiO_2$ and SiN:H grown via thermal oxidation and PECVD. Especially ALD BeO displays a Young's modulus over 300 GPa and thermal conductivity over 15 W/m·K, along with ALD $HfO_2$ displaying the highest thermal conductivity of 4.1 W/m·K among all $HfO_2$ reported so far. It is found, despite the low growth temperature, the existence of crystallinity and high purity of ALD films significantly contribute to excellent thermal and mechanical properties, while the ratio of ionic to covalent bonds dominates the electrical and optical properties. This review provides valuable insight to ALD high-*k* materials as high-performance CMOS, leaving establishing correlations between thermal/mechanical and electronic/optical properties of ALD high-*k* films attractive for next stage study.

*From: J. T. Gaskins, P. E. Hopkins, D. R. Merrill, et al.,* ECS J. Solid State Sci Technol., ***6****, N189 (2017).*

## Review—The Current and Emerging Applications of the III-Nitrides

High-end applications involving the use of III-Nitride materials, such as GaN AlN and InN, are possible due to the versatility of their material characteristics, in particular tunable direct bandgaps coupled with beneficial thermal/optoelectronic attributes. Through the use of alloying and doping techniques it is possible to utilize and fine-tune these materials for LEDs, electronics, thermoelectrics and solar cells. In a comprehensive review article, researchers from Missouri and Indiana in the United States have summarized and outlined the numerous roles and applications of a number of III-Nitride materials with particular emphasis on their uses for improvements in sustainable and renewable energy technologies. The particular use of InGaN materials for solar cell applications is examined in detail by the authors where the bandgaps of InGaN-based materials can range from low (0.7 eV) to high (3.4 eV) values by altering the elemental composition of In, Ga and N. Examples of III-Nitrides use in novel applications such as nuclear detection and photonic/plasmonic arrays are also presented, demonstrating the versatility of the materials. This review is essential reading for both prospective and current researchers involved with III-Nitride materials.

*From: C. Zhou, A. Ghods, V. G. Saravade, et al.,* ECS J. Solid State Sci. Technol., ***6****, Q149 (2017).*

*Tech Highlights was prepared by Colm Glynn of Analog Devices International, Xiaodan Cui of Louisiana State University, Mara Schindelholz and Mike Kelly of Sandia National Laboratories, David McNulty of University College Cork, Ireland, and Donald Pile of Rolled-Ribbon Battery Company. Each article highlighted here is available free online. Go to the online version of Tech Highlights in each issue of* Interface, *and click on the article summary to take you to the full-text version of the article.*

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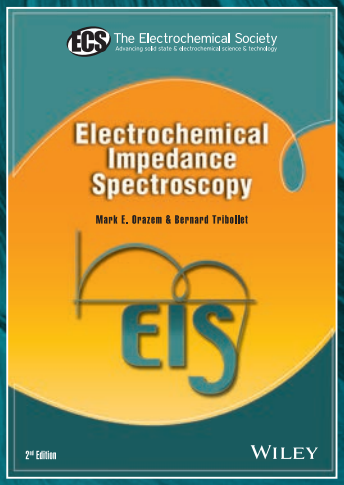


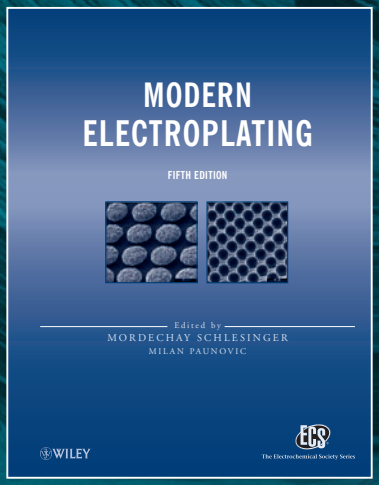


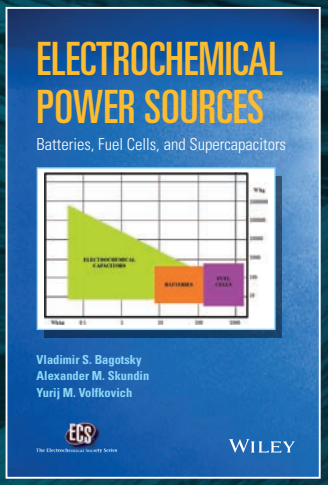


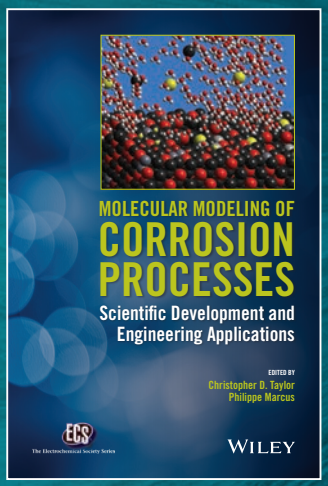


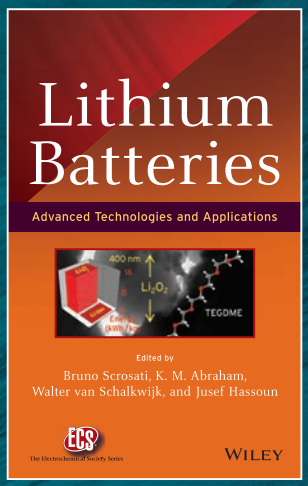


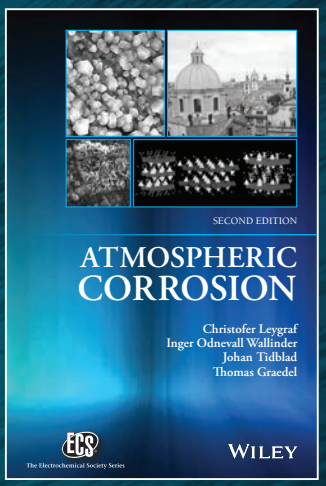


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# Solar Energy: An Enabler of Hydrogen Economy?

*by John W. Weidner*

Worldwide energy consumption continues to rise, but unfortunately, fossil fuels continue to make up an outsized share of the energy portfolio. The effects of continued widespread use of fossil fuels are clear: energy insecurity, and harm to the environment in the form of climate change, and deleterious impacts on human health. It is imperative that the use of renewable energy expand rapidly across all energy-consuming sectors. One problem facing widespread adoption of renewable energy, of course, is the nature of electricity coupled with the intermittency of renewable energy sources. Electricity, once generated, must be used immediately or stored in some other form (i.e., chemical or mechanical energy storage). This makes renewable energy, as currently generated, less reliable than fossil fuel-derived energy because its output is highly dependent on weather conditions (i.e., cloudy day, no wind) and time (i.e., at night). For renewable energy to be practical at very large scale, some efficient and reliable form of energy storage must be developed. One promising chemical storage pathway is to use renewable energy to generate hydrogen, which then can later be burnt in an oxygenated atmosphere (to generate water and close the loop). Alternately, it can be electrochemically converted to water and electricity in a fuel cell to recover the stored energy.

A collaborative article by Pivovar et al. from the National Renewable Energy Laboratory (NREL) and the U.S. Department of Energy, first discusses the critical role hydrogen will play in our energy future; the authors make the case that the hydrogen economy is not dead. Of course that will only be true if we can generate clean, $CO_2$-free hydrogen at an affordable price. Hydrogen can be generated via water electrolysis using electrons from the grid, although significant inefficiencies arise in that route. Alternatively, solar thermochemical hydrogen (STCH) processes have the potential to generate clean hydrogen efficiently and on a very large scale, as discussed by Gorensek et al. Like water electrolysis, hybrid STCH processes involve an electrochemical step, which will also require the renewable generation of electrons.

The final two articles in this special issue present the opportunities and challenges facing solar energy in general, and photovoltaics in particular. Subramanian and Pathak provide an overview of photovoltaics technology and Davis and Schoenfeld discuss the particular challenges of engineering the interfaces in silicon solar cells. With continued progress in photovoltaics and increasingly more efficient ways of generating hydrogen, the hydrogen economy will be alive and well, at least if electrochemistry has any say in it.

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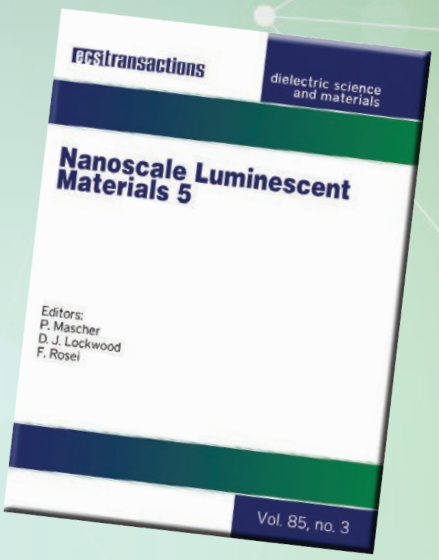


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# Hydrogen at Scale ($H_2$@Scale) Key to a Clean, Economic, and Sustainable Energy System

*by Bryan Pivovar, Neha Rustagi, and Sunita Satyapal*

Much of hydrogen's value to the energy-system lies in its ability to be *cleanly and efficiently converted between chemical and electrical energy*, while also possessing the *high energy density and long-term storage potential of chemical bonds*. For these reasons, hydrogen's importance is expected to grow substantially in the coming decades, providing cross-sector and cross-temporal impact through clean, efficient processes. Many of these processes are electrochemical in nature, such as electrolysis of water and electricity production using fuel cells. Hydrogen also offers significant flexibility in how it can integrate into the energy system as a function of scale (from W to GWs), source (fossil fuels, nuclear, biomass, solar, wind, thermal), and end use (grid, buildings, industry, transportation). This flexibility, along with the ability to be used as a dispatchable load or power generation source, allows hydrogen and hydrogen-based processes to couple with the overall energy system in an integrated or hybridized fashion, offering system optimization potential. However, achieving the scale necessary to have impact—the vision of Hydrogen at Scale ($H_2$@Scale)—still has research challenges, many of which center around electrochemistry.

## $H_2$@Scale Vision

The role that hydrogen can play as a clean, energy carrier is illustrated in Fig. 1. As shown, hydrogen can be produced from diverse feedstocks, including natural gas, coal, water, electricity, and high-temperature heat. Electricity can be obtained directly from the grid, or from off-grid power generators, such as wind, solar, or geothermal power. Similarly, high-temperature heat can be obtained from various sources, such as nuclear power or concentrated solar power. Today, the primary demand for hydrogen is as a chemical feedstock in petroleum refining and ammonia production. Hydrogen can also be used, however, to provide thermal energy (e.g., in conventional heating applications) or power generation, or it can be blended in existing natural gas infrastructure. Hydrogen can additionally be coupled with fuel cells to generate electricity electrochemically, which can be used as backup power, easily dispatchable remote power, or on the grid. An emerging application for hydrogen and fuel cells today is in transportation, where they allow for high performance vehicles both in the light-duty and heavy-duty sectors with zero-emissions, while enabling fueling times and ranges that are comparable to conventional technologies.

Hydrogen can *cleanly and cheaply couple with multiple power generation inputs*, while also servicing *all of society's energy demands*, including grid, industrial, and transportation sectors. $H_2$@Scale accomplishes this while also increasing energy security (domestic supply, resiliency) and providing positive economic impact (manufacturing competitiveness, jobs). Each of these benefits individually is valuable, but $H_2$@Scale offers the potential of all of these benefits in a single energy system, removing the need to compromise and representing a case where the whole is greater than the sum of its parts.

## Why Hydrogen?

Much of the benefit of hydrogen comes from its *electrochemical properties*; the value of *high energy density, covalent, chemical bonds* as a mechanism to store and move energy or create products; and hydrogen's ability to serve as a *feedstock for other products*. Since the start of the industrial revolution, our energy system has been based on fossil fuels, harvesting existing chemical bonds from nature, to meet society's demands for electricity, transportation and industrial products (through chemical transformations, often combustion based processes). Our energy system is now evolving at an astonishing pace. In the last decade, the cost of wind power has declined over

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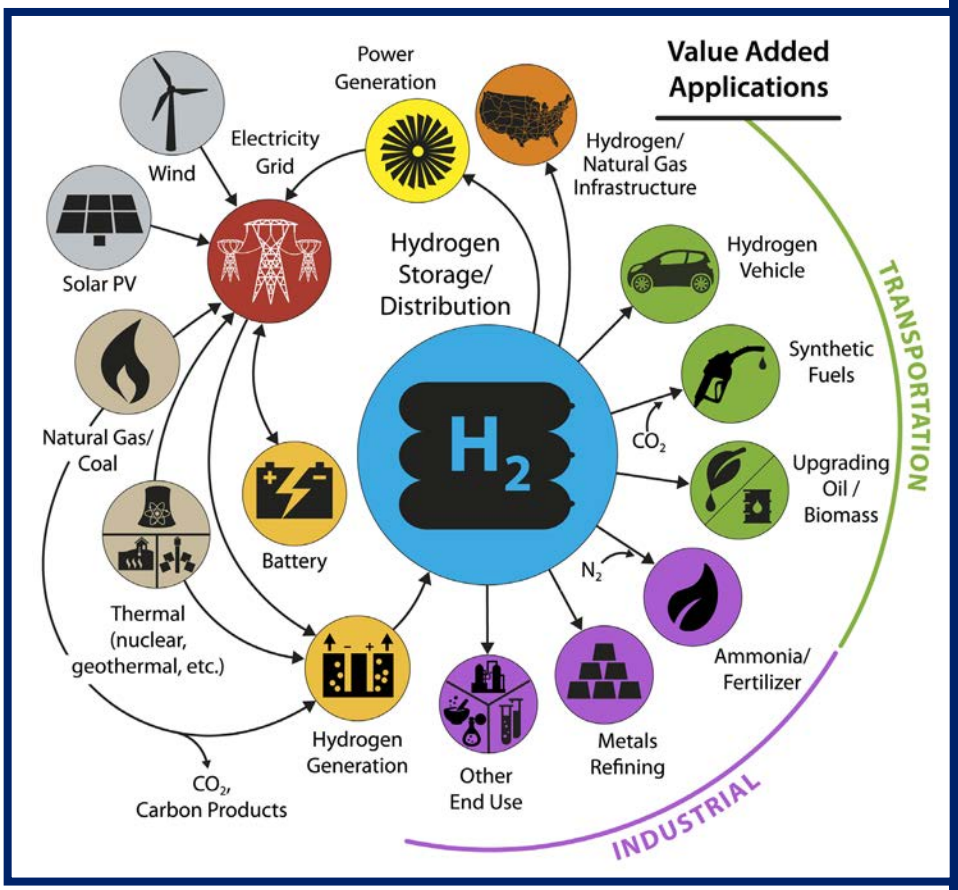


**Fig. 1.** *Illustrative schematic of $H_2$@Scale energy system.*

40%, the cost of solar power has been cut by over 60%, and the price of natural gas has declined over 60%.[1,2] These changes are creating stress on power generation and the grid, in some cases leading to the shuttering of nuclear and coal power plants, as the electrical grid seeks to become more dynamic and responsive. To ensure grid reliability as penetrations of solar and wind power increase, the energy system of the future will include processes that transform "electrons to bonds" at utility scale, taking electrical energy and creating high energy density, long storage duration molecules or end-products for a variety of applications.

When considering different chemical (covalent) bonds to hold energy, four options quickly distinguish themselves: hydrogen-hydrogen (HH); carbon-hydrogen (CH); carbon-carbon (CC); and nitrogen-hydrogen (NH). These bonds can be created by the reduction of $H_2O$, $CO_2$, and/or $N_2$. Electrochemically speaking, the reduction of $H_2O$ is far simpler (less potential for side reactions), faster (kinetic advantage), and more efficient (lower activation barrier) than either $CO_2$ or $N_2$. For $CO_2$ reduction, there are additional constraints as to where and how the $CO_2$ is sourced, as $CO_2$ concentrations in air (~400 ppm) are too low for easy separation, while water and $N_2$ can be simply obtained at large scale from the environment with modest separation or processing costs.

The Gibbs free energy change (ΔG), cell voltage (V cell), and number of electrons generated per reaction are presented in Table I for a handful of reactions selected to compare the energy contained within different chemical bonds. The first three reactions are the equivalent of burning $H_2$ (HH bonds); $CH_4$ (natural gas, CH bonds); and C (coal, CC bonds). The fourth reaction is the partial oxidation of ammonia to water and $N_2$ (avoiding the formation of $NO_x$, a criteria air pollutant with human health implications). These reactions represent reversible potentials and free energy changes for both the forward and reverse processes. For example, water electrolysis is the reverse of the first reaction, requiring input energy rather than delivering energy. Representing the reactions this way, allows for the comparison of bond energy on a per electron basis (V cell). Notably, HH bonds have the most energy per electron (1.19 V), followed by NH bonds (1.13 V), CH bonds (1.04 V), and CC bonds (1.02 V). It is slightly exothermic (downhill) going from $H_2$ plus $CO_2$ to hydrocarbons (including the Sabatier process, fifth reaction, for methane generation or Fischer-Tropsch chemistry for liquid fuels or other multiple carbon, hydrocarbon products) or going from $H_2$ plus $N_2$ to ammonia (Haber-Bosch process, sixth reaction). Through these established, large-scale industrial processes (Sabatier, Fischer-Tropsch and Haber-Bosch), $H_2$ can serve as the energy-containing intermediate leading to fuels or products, with enough energy to drive processes, but not so much excess energy that product formation "wastes" an excessive amount of the input energy. These hydrogen-based intermediate routes are currently the most energetically favorable and economically viable pathways to other chemical bonds, and major breakthroughs (to significant scientific challenges) are required to make either the direct electrochemical reduction of $CO_2$ or $N_2$ competitive with hydrogen-intermediate based routes, particularly for large scale energy applications. In this way, $H_2$ brings added flexibility to the energy system as it can either be used directly (for example, as a fuel in fuel cell vehicles) or as a stepping stone to other fuels or products.

**Table I. The Gibbs free energy change (ΔG), cell voltage (V cell), and number of electrons generated for select chemical bond energy storing gas-phase reactions.**

| Rxn | ΔG (kJ/mol) | V cell (V) | # e– |
|---|---|---|---|
| $H_2 + 1/2O_2 \rightarrow H_2O$ | –228.6 | 1.19 | 2 |
| $CH_4 + 2O_2 \rightarrow 2H_2O+CO_2$ | –800.8 | 1.04 | 8 |
| $C + O_2 \rightarrow CO_2$ | –394.4 | 1.02 | 4 |
| $NH_3 + 3/2O_2 \rightarrow 1/2N_2 + 3/2H_2O$ | –326.5 | 1.13 | 3 |
| $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ | –113.6 | 0.15 | 8 |
| $N_2 + H_2 \rightarrow NH_3$ | –16.4 | 0.06 | 3 |

From an electrochemical standpoint, hydrogen is unique in its ability to be cleanly and efficiently converted between chemical bonds and electrical energy, particularly at low temperatures. This conversion occurs in fuel cells (the combination of $H_2$ and $O_2$ yields water and electrical potential) through half reactions involving hydrogen oxidation and oxygen evolution reactions, as well as water electrolyzers (water and electrical potential yields $H_2$ and $O_2$) through hydrogen and oxygen evolution reactions. The hydrogen oxidation and hydrogen evolution reactions are two of the most facile electrochemical processes known, often with kinetic rates so high and overpotentials so low that they are difficult to measure accurately.[3,4] The ability to perform these reactions quickly and efficiently at low temperatures is important because it enables their use in applications with requirements for dynamic, variable operation and frequent start-ups and shut-downs.

A benefit of electrochemical generation of electricity using hydrogen is that it allows for substantially greater efficiencies than achievable through conventional processes that combust fuels to generate heat that is then converted into electricity through mechanical motion. Use of hydrogen in fuel cells relies on hydrogen that is stored, along with oxygen from the air. Production of hydrogen via electrolyzers requires relatively small amounts of water due to the high energy density of the HH bond; for example, a single toilet flush is more than 0.5 kg $H_2$ by mass. 1 kg of hydrogen enables over 60 miles of travel in fuel cell vehicles or provides approximately 12 hours of electricity to the average U.S. household (assuming 50% fuel cell efficiency).[6,7] These electrochemical processes have fast dynamics (capable of responding to power system needs like grid frequency fluctuations), and are scalable ranging from the sub-Watt to the GW scale. While the focus here, is largely on the electrochemical routes for hydrogen production and use, hydrogen also has multiple non-electrochemical generation and end uses routes (steam methane reforming, high temperature chemical cycles, ammonia or steel production) and offers added flexibility to adjust and adapt within the energy system as power generation and demand shift over time.

Our energy system has been based on (and all of nature runs on) chemical bonds as a mechanism of energy storage and conversion due to high energy density and long-term storage efficiency. However, today's batteries have made significant advances in both energy density and cost allowing for deeper penetration into markets while providing many of the same positive electrochemical attributes discussed for hydrogen above (clean and efficient). While batteries will continue to play an ever-growing role in our energy system, hydrogen technology is a complement with potential benefits in certain operating conditions. The optimal markets and costs for both technologies will evolve over time, as technology advances and manufacturing levels further develop. Batteries tend to have advantages in areas where frequent, short duration needs favor electron to electron storage and efficiency is a key metric (the daily storage of solar energy for grid balancing, and short distance, light duty transportation are two specific examples). Hydrogen tends to have advantages in areas where longer duration, multiple sector needs favor the energy density of chemical bonds (seasonal storage of energy, heavy duty, long haul transportation, and industrial processes). With hydrogen-based systems, the energy carrier (hydrogen) is distinct from the energy conversion unit (fuel cell or electrolyzer), offering intrinsic advantages in safety, refueling versus recharging (rates), footprint, and geographic distribution.

## Background of Hydrogen and $H_2$@Scale

Hydrogen is a critical industrial feedstock, with the U.S. producing more than 10 million metric tons per year, an energy equivalent greater than 1% of all U.S. energy use and roughly 1/6th of global production, primarily for oil refining and ammonia production.[8]

There are over 1,600 miles of dedicated hydrogen pipeline in the U.S. and three geologic facilities for $H_2$ storage, including the world's largest hydrogen storage salt cavern.[9-11] Today, over 95% of hydrogen produced is generated via reforming of natural gas.[12] Electrolysis is currently favored where the quantities of hydrogen required are small, purity demands are stringent, natural gas options are limited, and/or grid services are valued. The area of hydrogen production from electrolysis has seen significant recent growth with multiple examples of in-place or planned demonstrations, including projects in Germany, France and other countries with over 100 MW of electrolyzers to produce $H_2$ for various applications (including blending $H_2$ in natural gas pipelines, as fuel for fuel cell vehicles, and upgrading of oil).[13-17]

The past two decades have seen a growing emphasis on hydrogen with tens of billions of dollars invested by government and private industry largely focused on hydrogen fuel cells for transportation. Through research and engineering advances based on these large investments, fuel cell vehicle technology has demonstrated the ability in large scale projections to approach cost-parity with competing technologies. Today, in California, there are nearly 3,500 commercial light duty fuel cell vehicles[18] and over 30 hydrogen fueling stations open to the public[19] with most major auto manufacturers adding production capacity. Fuel cells have also established themselves in materials handling applications (over 16,000 units of material handling equipment that use fuel cells have been ordered in the U.S. since 2009)[20] and in stationary applications (in Japan, there are over 200,000 household fuel cell units providing heat and electricity to homes, using natural gas to produce onsite hydrogen).[21] The commercial viability of end-use applications and the technology to support them has been a major achievement in the past several years.

With demonstrated commercial viability of fuel cells, $H_2$@Scale is focused on the central role that $H_2$ can play in the energy system, but this concept is far from new. The term "Hydrogen Economy" was termed in the 1970s, focused largely on hydrogen's potential to displace petroleum from transportation applications due to oil shortages and the impact of oil embargoes. Going back even further, the concept of hydrogen produced from water and renewable sources dates back to at least the 19th century (from 1891 to 1908 Poul la Cour used wind energy and electrolysis to split water into hydrogen and oxygen which were collected and later used for lighting).[22] On Feb. 4, 1923, J.B.S. Haldane in a paper read to the Heretics Society at Cambridge University, hypothesized about "rows of metallic windmills working electric motors which in their turn supply current at a very high voltage to great electric mains. At suitable distances, there will be great power stations where during windy weather the surplus power will be used for the electrolytic decomposition of water into oxygen and hydrogen." These examples clearly show that the positive attributes and potential of hydrogen had been recognized long ago, although economic factors and/or technical limitations have limited hydrogen's impact to a few, select, but sizable, markets.

There is significant information available on the U.S. Department of Energy (DOE) $H_2$@Scale website[24] including workshop reports and presentations, and a detailed R&D roadmap available for public comment to be finalized in 2018. The contributors to the development of the $H_2$@Scale concept and initiative included multiple national labs, various DOE program offices, and multiple industrial stakeholders. $H_2$@Scale is related to other efforts that often include descriptive terms such as power to gas, power to X, and hydrogen energy storage. Power to gas and power to X are based on hydrogen as the pathway to gas (hydrogen or methane) and a variety of other end-uses (X). $H_2$@Scale integrates these concepts with the potential for hydrogen production to capture excess electricity from the grid, as well as from power generation resources that are distant from electricity transmission. The term $H_2$@Scale was in part chosen to highlight the central role that hydrogen can play in addressing energy system challenges, including grid reliability, energy storage, and domestic competitiveness, as well as emissions or pollution reduction without negative economic impact.

A particularly compelling, recent effort relevant to $H_2$@Scale, has been the establishment of the Hydrogen Council, and the release of a roadmap, titled "Hydrogen, Scaling Up".[23] According to its website, the Hydrogen Council is currently the largest industry-led effort to develop the hydrogen economy. Launched in January 2017 its members include leading companies with over $10 billion in investments along the hydrogen value chain, including transportation, industry, and energy exploration, production, and distribution. The report shows that by 2050, hydrogen could meet 18% of the world's final energy demands, create a market with revenues of 2.5 trillion dollars, provide 30 million jobs, and reduce $CO_2$ in sectors like transport, industry, and residential by between 40% and 60%. The engagement of multiple stakeholders, and specifically large industry is critical for such a major energy-system transition.

> ***Potential Impacts from Hydrogen Council Roadmap Study. By 2050:***
> - *$2.5 trillion in global revenues*
> - *30 million jobs*
> - *400 million cars, 15-20 million trucks*
> - *18% of total global energy demand*

## Challenges and R&D Needs of $H_2$@Scale

While significant momentum is growing for hydrogen as its energy system-wide benefits become clear, challenges remain for hydrogen to achieve its full potential, including:

- Cost, performance, and durability of hydrogen systems: key components in the hydrogen value chain (production, distribution, and end use) are currently highly capital intensive, and lower-cost alternatives (e.g., catalysts that eliminate the use of precious metals) are still in early stages of research.
- Technological, regulatory, and market barriers to the integration of hydrogen with the conventional energy systems: examples include the availability of standardized power electronics to integrate electrolyzers with the electricity grid, regulatory structures to enable electrolyzers to participate in markets for grid services, code compliant methods of integrating hydrogen fueling within available land area, and regulations that allow for hydrogen blending into natural gas infrastructure.
- Aggregation of disparate sources of hydrogen supply and demand: existing and emerging sources of large-scale supply and demand are often geographically distant, challenging the development of economies of scale. For example, a currently growing source of large-scale supply is hydrogen that is produced as a by-product of petrochemical cracking. While cracking is heavily concentrated around the U.S. Gulf Coast, emerging large-scale demands for transportation are concentrated along the East and West coasts.
- Demonstration of value proposition: in-depth analyses are necessary to characterize the investments necessary for hydrogen energy systems, and the benefits possible in several areas such as job creation, grid impacts, regional energy storage, and the supply chain.

Of the challenges listed above, those associated with R&D are of the most interest for the *Interface* audience. While the focus on hydrogen for use in fuel cells has been significant, the research on hydrogen as part of the energy system has been orders of magnitude less, resulting in a significant lag in technology and manufacturing capabilities. Figure 2 highlights the specific areas of $H_2$@Scale research needs separated into research pillars and cross-cutting areas.

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The pillars of research identified for $H_2$@Scale are:

- Advanced hydrogen generation
- Storage and distribution
- Hydrogen end-use and systems integration

The cross-cutting research needs of $H_2$@Scale are:

- Analysis
- Foundational Science
- Integration in the Future Electric Grid and Across Sectors

These research needs are focused on the cost-competitive production, distribution, and use of hydrogen. These specific areas have been explored in depth during DOE's $H_2$@Scale workshops, and reported in much greater detail elsewhere.[24] Each one of the pillars has significant challenges associated with electrochemistry. The areas of low and high temperature hydrogen generation through electrochemical routes are of high interest, and are areas where fuel cell investments have resulted in dramatic improvements of related technology. Specific aspects of hydrogen storage and distribution including mitigation of corrosion and hydrogen embrittlement of materials have electrochemical relevance. Many processes that could consume, compress, or use hydrogen are also electrochemical in nature. The cross-cutting research needs are also of relevance to The Electrochemical Society, as knowledge of electrochemistry is required for proper analysis and grid integration, and all research areas are built upon foundational science which includes electrochemistry. Electrochemistry and electro-chemists are needed to address these challenges and help hydrogen maximize its impact.

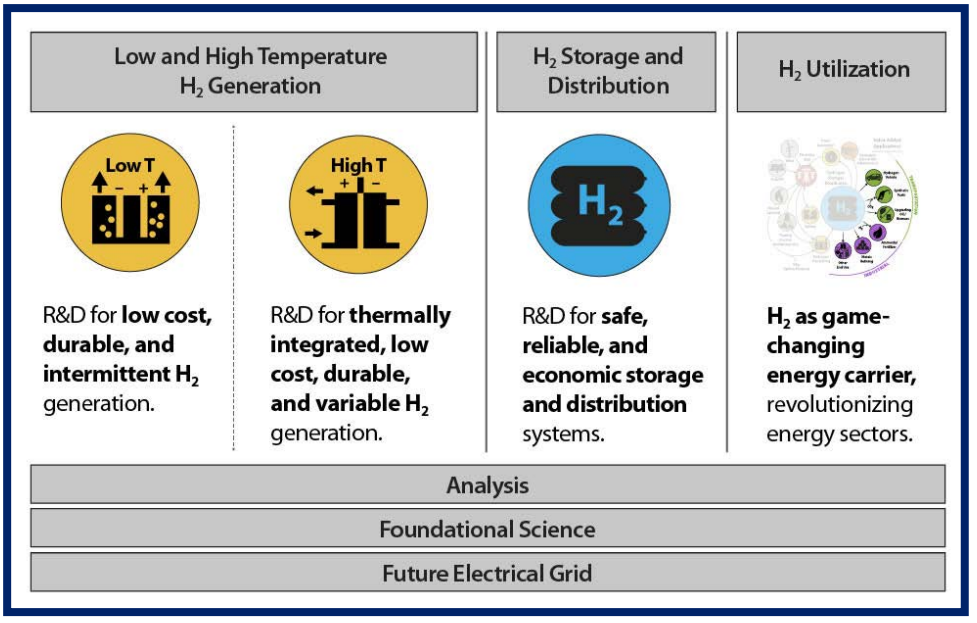


**Fig. 2.** *Priority areas of research to enable $H_2$@Scale.*

Hydrogen production costs are central to market adoption. As part of ongoing techno-economic analysis on $H_2$@Scale concepts, Fig. 3 compares the levelized costs of hydrogen production from electrolysis to the dominant incumbent technology, steam methane reforming (SMR), under various assumptions of capital and operating costs. The first column represents projections of today's technology and operating mode, consistent with DOE's independent panel review of the state-of-the-art in hydrogen production.[25] The projected cost of hydrogen today ($4.20/kg) is dominated by the cost of electricity ($3.46/kg). The second column (intermittent integration) of Fig. 3 investigates the impact of low cost (1 or 2 cent/kWh), intermittent (40% capacity factor down from 95%) electricity on $H_2$ production costs. Low cost electricity results in much lower hydrogen production cost, $2.24/kg or $2.77/kg, even at the lower capacity factor. In the third column, the combined impact of R&D advances and access to low-cost electricity are shown where the impacts of decreasing capital cost to $100/kW with a decrease (10% relative) in efficiency are investigated. In this scenario, hydrogen production costs become favored over SMR. The advancements that have already been achieved in similar electrochemical processes to date suggest that the necessary cost reductions in hydrogen production are achievable. For example, PEM fuel cells for vehicles, which operate in reverse of electrolysis systems, are designed to operate longer than 10 years and turn on and off multiple times a day, have declined in projected costs (at scale) from $275/kW in 2003 to ~$50/kW today.[26,27]

Figure 4 describes key contributors to the capital and operating costs of electrolysis. Materials research in the areas of electrolysis catalysts, membranes, and cell components can strongly influence both capital and operating costs. Additional water splitting pathways are also being researched. For example, photoelectrochemical hydrogen production uses semiconductors to directly split water into

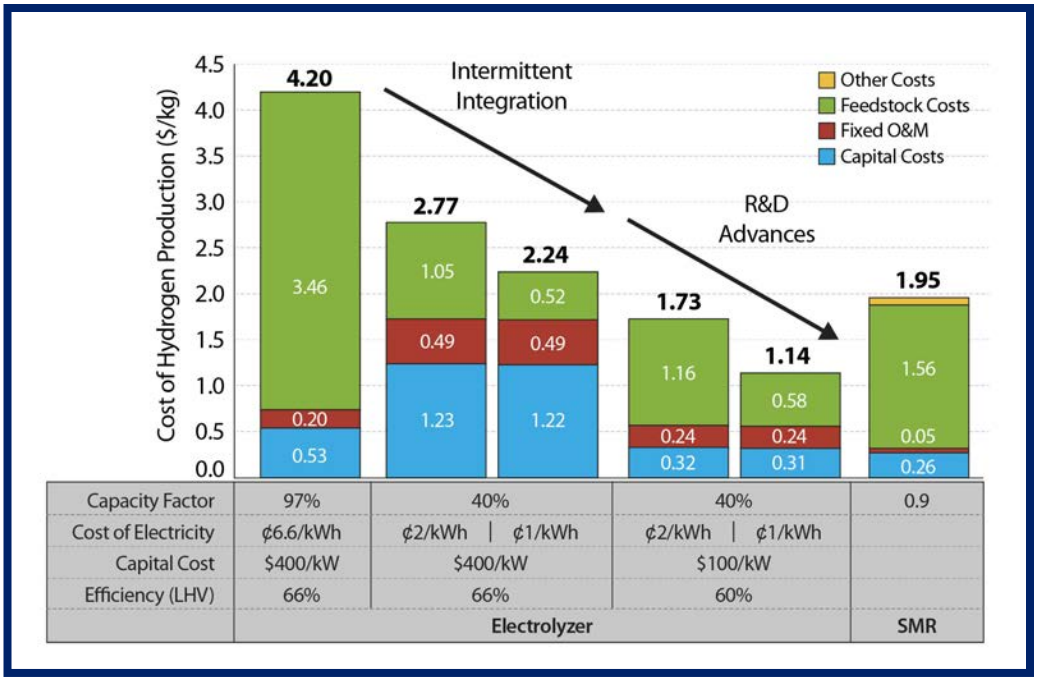


**Fig. 3.** *Techno-economic analysis of electrolyzer-based hydrogen production costs as a function of capacity factor, cost of electricity, capital cost, and efficiency compared to steam methane reforming (SMR), using H2A models.*[28]

hydrogen and oxygen. Thermochemical hydrogen production is another approach being explored where high-temperature heat (e.g., >1,000 °C) is used to drive water splitting through repeated reduction-oxidation cycles. Each of the approaches above will require strategic R&D investments to enhance their viability, and are currently being pursued as part of the DOE's new Energy Materials Network consortium, HydroGEN – Advanced Water Splitting Materials.[30]

In order to achieve wide-scale deployment of hydrogen, research is also necessary to reduce the costs and improve durability of hydrogen infrastructure and end uses. One cross-cutting area of interest is the performance of metallic materials in hydrogen. Infrastructure components, such as pipelines, compressors, and storage vessels, are currently designed to account for the potential of hydrogen embrittlement. The design and operation of these technologies could be optimized for lower cost and higher reliability through research that enhances the fidelity of predictive computational models. Specific research needs include the experimental characterization of relationships between the mechanisms of steel failure, microstructures of steel, and morphologies of steel grains. Finally, novel end-use applications where low-cost hydrogen is a potentially enabling element of market competitiveness and job creation also need to be developed (steel manufacturing, metal industry, modified ammonia synthesis, biofuel production, natural gas/hydrogen infrastructure, electrical generation, use of hybrid fuel cell/battery electric vehicles, etc.).

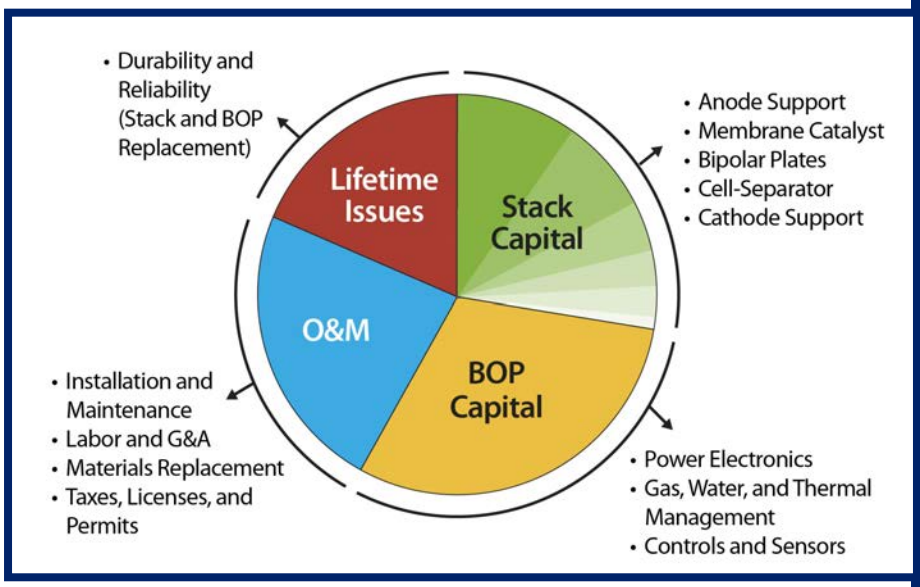


**Fig. 4.** *Key Contributors to capital and operating costs of electrolysis, excluding electricity.*[29]

## The Future of $H_2$@Scale

The 21st century is becoming a turning point for electrochemical processes as the advantages of efficient, clean, flexible, and sustainable electrochemical systems become increasingly valued by society. As these trends are projected into the future, a clear opportunity exists for hydrogen to play a major role, as a clean, energy carrying intermediate (paralleling and in some cases, surpassing electricity in function). However, improving the economics of hydrogen—its production, distribution, storage, and utilization—is critical.

Success of $H_2$@Scale efforts will result in decreasing costs and increased implementation of hydrogen in many major energy sectors, addressing key issues that include grid resiliency, energy security, employment, manufacturing, environmental benefits, and innovation. Achieving the $H_2$@Scale vision will be greatly facilitated by research advances that focus on materials and systems improvements, many of which will be electrochemical in nature. In this way electrochemists will play a central role in enabling $H_2$@Scale, and providing a pathway for society to a clean, economic, and sustainable energy system. ■

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# Solar Thermochemical Hydrogen (STCH) Processes

*by Maximilian B. Gorensek, Claudio Corgnale, John A. Staser, and John W. Weidner*

In a companion article in this issue on Hydrogen at Scale, Pivovar et al. outline the role hydrogen could play in our energy future. A key element of this vision is the need to generate $CO_2$-neutral hydrogen efficiently and at a large scale.[1,2] Potential processes to do this can be broken out into four categories: 1) electrolytic processes; 2) biological processes, e.g., microbial biomass conversion, photobiological; 3) direct solar water-splitting processes, e.g., photoelectrochemical; and 4) thermochemical processes, e.g., hydrocarbon reforming and coal or biomass gasification with carbon capture, water-splitting cycles. This article focuses on thermochemical water-splitting cycles, especially when coupled with solar energy. There are hundreds of possible thermochemical cycles, but only a few have been considered commercially viable. Commonalities among thermochemical cycles are a series of reactions that split water at lower temperatures (~500–1000 °C) than thermal dissociation (>2500 °C), with other species recycled in the system. Thermochemical cycles can be direct (all chemical steps) or hybrid (i.e., a combination of chemical and electrochemical steps) processes. If concentrated solar energy is used for the thermal dissociation step, all thermochemical cycles can be classed as solar thermochemical hydrogen (STCH) processes. This article will focus on two cycles: 1) a direct thermochemical cycle (zinc oxide cycle), and 2) a hybrid cycle (hybrid sulfur cycle). The latter combines a chemical thermal dissociation step with an electrochemical step. As two-step cycles, their appeal is in their relative simplicity.

## Direct Thermochemical Cycle—Zinc Oxide Cycle

One promising direct thermochemical cycle is based on Zn/ZnO redox reactions.[3] Zn is abundant and relatively inexpensive, and species separation and recovery within the process is somewhat straightforward.[4] The two-step process involves reduction of ZnO at 2000 °C, quenching to Zn particles with generation of oxygen, followed by an exothermic hydrolysis step at 425 °C to generate ZnO with the formation of hydrogen.[5] The reactions are outlined below:[3]

$$ZnO \rightarrow Zn + 1/2O_2 \quad (1)$$

$$Zn + H_2O \rightarrow ZnO + H_2 \quad (2)$$

Generally speaking, the zinc oxide cycle involves carrying out Reaction 1 in a high-temperature tubular reactor; the dissociation reaction is relatively fast, but possible recombination of Zn and $O_2$ limits overall conversion.[4] Reaction 2, recovery of ZnO, can also be carried out in a tubular reactor, and research has demonstrated that this reaction can be driven nearly to completion with increased residence time.[4]

Efficiencies around 40% have been demonstrated for the zinc oxide cycle,[6] with quenching under an inert atmosphere (typically Ar) critical to recovery of Zn (i.e., Zn(g) and $O_2$ may coexist, but quenching avoids recombination and aids Zn recovery).[7] In fact, this aspect is one of the primary challenges of the ZnO cycle; recombination of Zn and $O_2$ (back-reaction 1) limits overall conversion, and the necessity of quenching limits recovery of sensible heat from the solar reactor.[4] Issues related to separating Zn and $O_2$ represent a primary barrier toward achieving efficiencies very close to the theoretical limit.[4,8,9]

Despite these challenges, a 100-kW system has been developed to demonstrate the zinc oxide process on a pilot scale.[7] In this study, the solar reactor was designed for concentrated solar radiation up to 4761 kW/m$^2$. Critical to system design is a reactor capable of extremely high reaction temperatures necessary to carry out dissociation of ZnO (Reaction 1, around 2000 °C, interlocking $Al_2O_3$ bricks lined with a thin layer of sintered ZnO in the present example).[6] In general, given the high temperature of Reaction 1 (common to metal oxide thermochemical cycles), materials selection is important and a key metric over process feasibility.[10] A quartz window separates the solar reactor from the atmosphere, and the entire reactor rotates to uniformly expose ZnO to the concentrated solar radiation. Rotation also allows the ZnO powder to be evenly distributed inside the reaction chamber, leading to relatively high rates for Reaction 1. The products (Zn and $O_2$) leave the reaction vessel, followed by quenching to Zn particles using Ar gas.

Typical operation of this pilot-scale thermochemical reactor involved first heating the reaction vessel via concentrated solar radiation, followed by injection of the ZnO powder to the reaction vessel. Low Zn yield typically resulted in low solar-to-fuel efficiency, often an order of magnitude lower than the recorded solar-to-chemical efficiency. For example, the research group reported solar-to-fuel efficiencies approaching 0.03% on average, with the potential upon process optimization of 0.06% on average. The maximum recorded solar-to-fuel efficiency was 0.17%.[6] On the other hand, solar-to-chemical efficiency was typically on the order of 3%. Low Zn yield was attributed primarily to damage to the reactor during operation. In fact, in addition to the already mentioned difficulty with product recovery, thermal shock and fatigue of reactor materials could sideline further development of zinc oxide process.[5] Demonstrated efficiency of the process in the pilot-scale study was significantly lower than calculated efficiencies using detailed process modeling,[5,6] an indication of the significant engineering barriers that must be overcome to make the zinc oxide process economically feasible. For example, a recent U.S. Department of Energy report recommended that the zinc oxide cycle not be considered for further development given the unlikelihood of achieving target hydrogen costs.[5] At this juncture, therefore, the status of the zinc oxide cycle is in question.

Significant advances in reactor materials to avoid damage at high temperatures must occur before development is likely to resume, and the process may be doomed from the outset due to the already mentioned reduction in efficiency that results from the necessary rapid quenching step. A more promising option is to use alternative nonstoichiometric metal oxide systems such as perovskites that could release oxygen at lower temperatures than ZnO does,[11] although this approach is still in its infancy. There are, however, many other thermochemical cycles from which to choose, and several of these may have more tractable material and economic considerations. We will now turn our attention to one such cycle.

## Hybrid Thermochemical Cycle—Hybrid Sulfur Cycle

The hybrid sulfur (HyS) cycle was developed by Westinghouse in the 1970s as a combination thermochemical and electrochemical cycle for large-scale hydrogen production.[12-14] The HyS process consists of two steps: 1) a high-temperature (~850 °C) decomposition of sulfuric acid to $SO_2$ and $O_2$, and 2) a low-temperature (~100 °C) electrolysis step oxidizing $SO_2$ to sulfuric acid at the anode and generating pure hydrogen at the cathode of an $SO_2$ depolarized electrolyzer (SDE). Overall, like other thermochemical cycles, oxygen and hydrogen are

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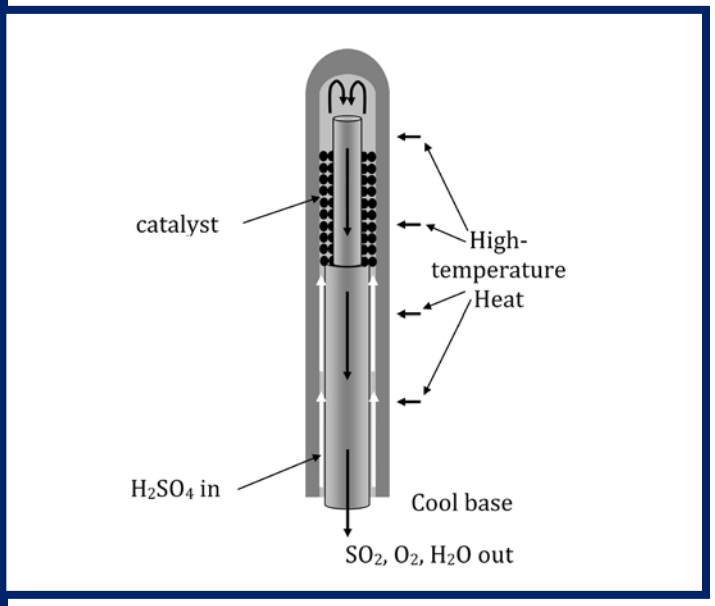


**Fig. 1.** *Schematic drawing of bayonet reactor for high-temperature sulfuric acid decomposition.*

generated as products and, in this case, the sulfur compounds are recycled within the process loop. The reactions are as follows:[15-18]

$$H_2SO_4 \rightarrow H_2O + SO_2 + 1/2O_2 \quad (3)$$

$$SO_2 + 2H_2O \rightarrow H_2SO_4 + 2H^+ + 2e–,\ U^0 = 0.158\ \text{V vs. SHE} \quad (4)$$

$$2H^+ + 2e– \rightarrow H_2,\ U^0 = 0.0\ \text{V vs. SHE} \quad (5)$$

where Reaction 4 is the oxidation of $SO_2$ at the electrolyzer anode and Reaction 5 is hydrogen generation at the cathode. Originally envisioned as part of nuclear-driven hydrogen production,[19,20] the HyS process has more recently garnered attention due to the possibility of coupling it with solar receiver arrays (much like the previously discussed zinc oxide cycle).[21,22] With the required temperature of the decomposition reaction significantly lower than the zinc oxide process, one could envision more tractable materials concerns with this hybrid process, although the corrosiveness of concentrated sulfuric acid would present challenges in its own right. Recent reactor designs for the high-temperature decomposition step (Reaction 3) have focused on a bayonet reactor (Fig. 1) consisting of nested SiC tubes that form two concentric, countercurrent flow paths.[23,24] This design provides corrosion resistance while allowing for simultaneous external heating and internal recuperation to maximize energy efficiency.[25-27]

The efficiency of the hybrid sulfur process depends on two features: 1) the energy required to concentrate the sulfuric-acid solution leaving the electrolyzer, heat it to the decomposition temperature (~850 °C), and carry out the endothermic decomposition reaction; and 2) the efficiency of the electrochemical process, primarily manifested as the resistance of the membrane and the overpotential required to oxidize $SO_2$. Therefore, high overall process efficiency is achieved when the electrolyzer can produce concentrated sulfuric acid at low voltage. The follow discussion will primarily focus on the electrochemical step of the hybrid sulfur process, and issues pertaining to operation and cell efficiency.

Considerable progress was made in the last decade in lowering the operating voltage and increasing the current density of the SDE by moving from a microporous rubber diaphragm separator used by Westinghouse in the late 1970s[13,14] to a perfluorinated sulfonic acid membrane (e.g., DuPont's Nafion).[15-17] However, water management was quickly identified as a key driver of electrolyzer performance.[15] Water sent to the electrolyzer cathode diffuses toward the anode due to a concentration difference, while at the same time, water is transported back across the membrane from the cathode to the anode due to electro-osmotic drag with $H^+$. Water transport can also be driven by a difference in pressure across the membrane.[15] Therefore, water transport, and hence the resulting acid concentration, can be varied by changing the thickness of the membrane and the pressure differential across the cell.

Unfortunately, the problem with using membranes like Nafion that rely on water for their proton conductivity is that high acid concentrations dehydrate the membrane and dramatically increase membrane resistance.[17,28] Decreasing the membrane thickness will lower the voltage, but it will also decrease the acid concentration. Figure 2 illustrates the tradeoff between the two performance metrics of the electrolyzer.[18] When there is no differential pressure across Nation ($\Delta P = 0$), minimal water crosses from the cathode to the anode, resulting in high acid concentrations but high cell voltages (7.0 M and 0.90 V at 80 °C and 0.5 A/cm$^2$ respectively). The high voltage results from high membrane resistance. When a differential pressure is created ($\Delta P = 600$ kPa) additional water crosses over the membrane, lowering the cell voltage at 0.5 A/cm$^2$ from 0.9 V to 0.72 V through an increase in the membrane conductivity. However, this additional water results in a decrease in the acid concentration from 7.0 M to 4.5 M at the anode.

Recently, sulfuric acid-doped polybenzimidazole (s-PBI) membranes have been developed that provide an alternative to membranes like Nafion because they do not rely on water for their proton conductivity.[18,29-31] Figure 2 also shows the voltage and acid concentration for an SDE with s-PBI operated at 110 °C and 0.5 A/cm$^2$, where 0.66 V with an acid concentration of 7.0 M was achieved. The acid concentration was varied by metering the water fed to the anode, which had little effect on the cell voltage. Consequently, these two performance metrics can be varied independently. The cathode chamber in this case was pure hydrogen gas (i.e., no liquid water).

In addition, s-PBI membranes can operate at higher temperatures than Nafion, thus further decreasing the voltage of the cell. Figure 3 shows the cell voltage as a function of temperature, and the contributions of anodic overpotential ($\eta_a$), equilibrium potential ($U_{eq}$), and membrane resistance ($iR_a$) to this voltage.[18] Membrane

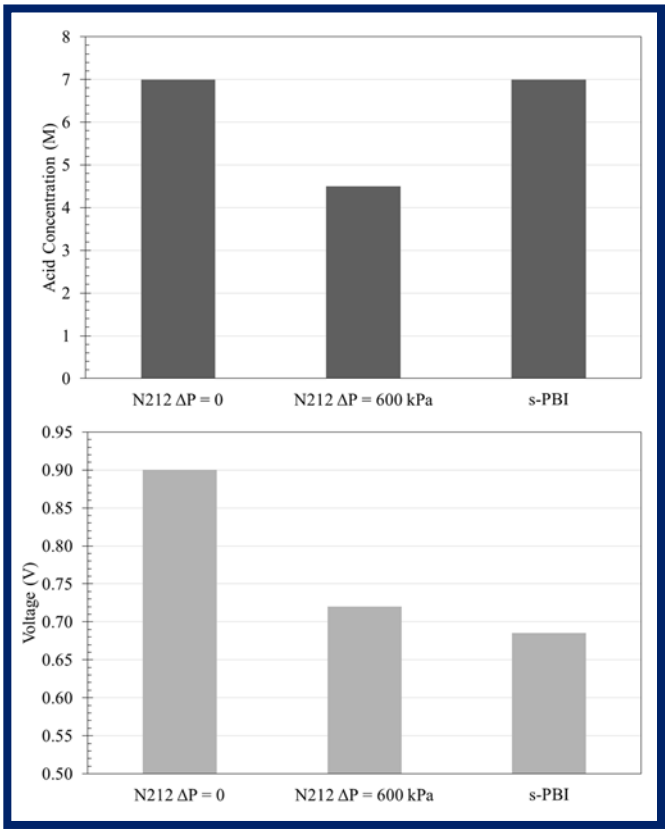


**Fig. 2.** *a) Sulfuric acid concentration and b) cell voltage at 0.5 A/cm$^2$ for: Nafion at 80* °C and two pressure differentials (ΔP),[15] *and sulfonated polybenzimidazole (s-PBI) at 110* °C.

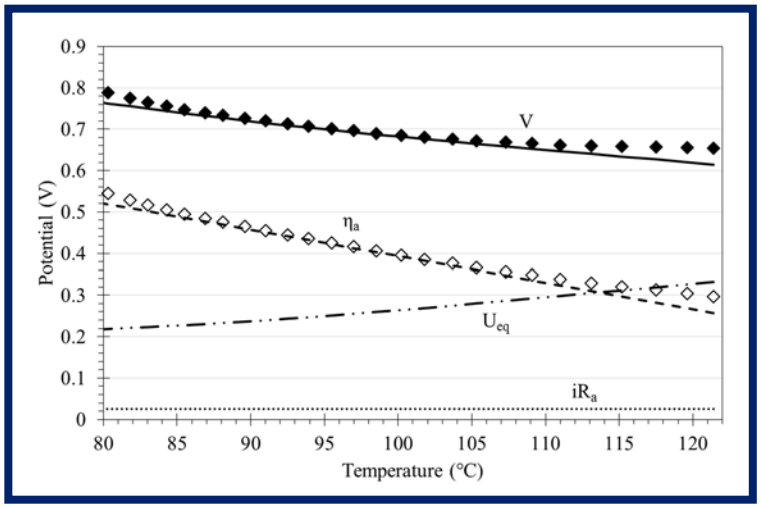


**Fig. 3.** Contributions towards total operating voltage across a range of temperatures in the HyS electrolyzer at a current density of 0.5 A/cm$^2$. Lines represent model predictions and the symbols are the cell voltages (filled symbols) and anodic overpotentials (open symbols) data.[18]

resistance was measured to be relatively independent of temperature and acid concentration in the range of conditions studied here, and it contributes a relatively small amount to the cell voltage. The two dominant contributions to the cell voltage are the equilibrium potential and the anodic overpotential. The amount of water fed to the cell was constant, so at the fixed current density shown here, the acid concentration increased due to increased evaporation. Hence some of the increase in the equilibrium potential was due to an increase in acid concentration, which is desirable. The most significant result from Fig. 3 is the decrease in the anodic overpotential with an increase in temperature. Further improvements in electrolyzer operation can be achieved by optimizing the temperature and developing more active electrocatalysts.

## Conclusions and Outlook

There is a significant opportunity to store solar energy using hydrogen if a suitable thermochemical process can be developed. Although there are literally hundreds of cycles to choose from, most have three or more equilibrium-limited steps, which incur the need for separations and concomitant efficiency losses. Only a handful have any real shot at technical and economic feasibility. This article has outlined two such cycles. One, the direct thermochemical cycle based on zinc oxide, has garnered significant attention in recent years, and development has proceeded far enough that a pilot-scale reactor has been developed. However, extremely high temperatures required (near 2000 °C) present significant materials challenges that may not be solvable in the near-term, and the rapid quenching step limits process efficiency.

The second, the hybrid thermochemical cycle based on sulfur dioxide, combines a low-temperature electrolysis step with a higher temperature (~850 °C) decomposition step. Significant efforts have been made to develop the high-temperature decomposition reactor, with parallel work on the electrolyzer development. The feasibility of this cycle has been demonstrated with operating cell voltages low enough to efficiently generate hydrogen. Recent techno-economic studies demonstrate solar to hydrogen efficiencies on the order of 15-20%[32] and costs on the order $4.80/kg[21,22] with potential to reach values of $2.00/kg[33] for large scale solar hydrogen production using the HyS cycle. In the future, additional advances in materials and operating parameters for all feasible thermochemical cycles will need to be demonstrated for commercial adoption of these processes. Although probably several years away, the outlook for solar thermochemical hydrogen generation is strong, especially with continued research and development.



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# With Photovoltaics, Solar Energy Is Here to Stay

*by Vaidyanathan (Ravi) Subramanian and Pawan Pathak*

Until the turn of the 20th century, mankind was content with exploiting wood, coal, and petroleum for meeting all of its energy needs. Since the last century it began to dawn upon us that fossil fuels can be a finite resource. The last century has also seen notable advancements in technology leading to significant changes in our life style that has made us more energy dependent. Due to this ever increasing and aggressive dependence on fossil fuels, by several estimates we have reached a point where we cannot expect to continue using fossil fuels in the same manner to power our economy. For example, the availability of petroleum and its economical production will ultimately become a challenge, although we are not there yet. Coal can be regarded as a longer term fuel source compared to petroleum if we consider all grades and availability around the globe. However, in recent decades it has became abundantly clear that continued use of fossil based fuels can interfere with the environment leading to potentially irreversible climate change.

These changes can negatively alter our way of life. Therefore, there is an urgent need to examine alternative sources of energy, provided that their use is sustainable and contributes to maintaining our lifestyle without any drastic changes. Since the turn of the 20th century the notion that coal and petroleum will be *the* sources of energy to support our economies and be the driver that sustains our way of life and our environment, is slowly being replaced (Fig. 1).

From an energy standpoint, the challenges to the present and future generations are two-fold. The first is to identify energy sources that are sustainable and the second is to develop technologies that can harness these sources efficiently. Eco-friendly solutions to energy generation must become an integral part of the energy generation process in the future. This mindset will guide us to seek a lasting solution for meeting our energy needs and ensure that future generations do not wait until reaching a precipice that could force us to consider a lifestyle altering decision.

## Solar Energy and Its Overarching Benefits

Solar energy has been available for billions of years, ever since the Sun came into existence. The moment the planetary system formed, the planets began to evolve by interacting with the energy from the Sun. Once the Earth was created and the conditions started to become conducive for sustaining life, evolution started to take root. The environment became conducive for the formation of the earliest and rudimentary microorganisms. In due course, these microorganisms, mostly simple and unicellular, began to thrive in all parts of nature. Later, complex cell structures began to evolve in the Earth's environment. At some point plants began to take shape. The plants and microorganisms began to thrive by interfacing directly with sunlight or using the nutrients available in the Earth's environment. These are the earliest and natural examples of the Sun's participation in Earthly evolution. Steadily the evolution of variants of these microorganism and more complex cellular structures (trees and animals) began to occur, much earlier than primitive man evolved. Other attempts, primarily manmade, to leverage the potential of the Sun to date is summarized in this retrospective of solar power as a one-stop-shop for all our energy needs.

## Evolution of the Use of Solar Energy

The ancient Greeks are generally believed to be the first to realize the potential of the Sun's energy and to utilize it in an organized manner. They were able to design buildings in such a manner that light was allowed in to illuminate the living quarters. The Romans built upon this concept and were able to use glass as a medium to regulate the Sun's energy for domestic purposes. They were also able to leverage solar energy using the concept of green houses. Since then there have been several applications that have evolved around the use of solar energy as a primary power source.[1] Figure 2 provides a comprehensive list of efforts that are currently being pursued to harness energy from the Sun. This article focuses on the use of the Sun's energy for electricity generation. In the subsequent pages, we present some of the current state-of-the-art technologies in harnessing solar power as a sustainable and long term energy source using photovoltaics as a platform.

## Solar to Electricity Conversion or Photovoltaics

The generation of electricity using solar energy was brought to the fore by French physicist, Edmund Becquerel, who developed the photovoltaic cell in 1839. The photoelectric effects, the phenomena in the cell, were explained by Nobel Prize winner Albert Einstein. When a photon of energy $E = h\nu$ ($h$ = Planck's constant and $\nu$ = frequency of light) strikes a semiconductor surface, electron-hole pairs are generated in the material; the flow of these electrons constitutes an electric current. Since this discovery, research into photovoltaics has seen steady progress leading to the evolution of new materials, their assembly, and advancements in processing techniques, resulting in cells that produce power in a sustainable manner for a distributed supply.[2]

The technology of the photovoltaic (PV) solar cell is considered to have evolved across three generations.[3] The first generation represents the traditional solar cell and mainly focuses on silicon as the primary

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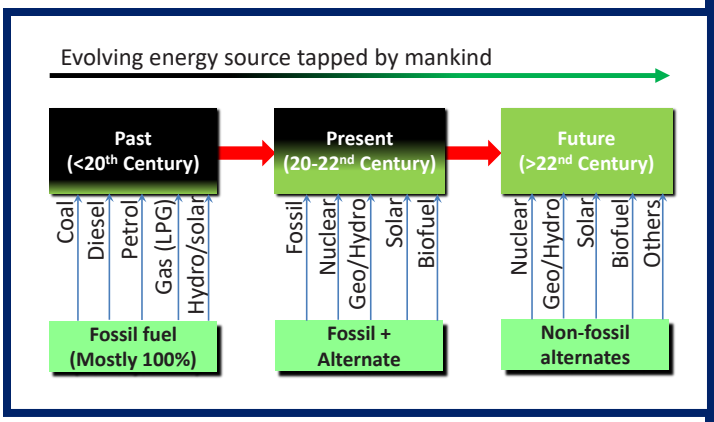


**Fig. 1.** *The major contributors towards the energy portfolio accessible to mankind in the past and present and the options available to us in the foreseeable future.*

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material. Silicon is a unique element with four electrons in its outmost orbital and forms tetravalent bonds with other neighboring silicon atoms. The performance of a silicon-based device depends on the atomic arrangement of silicon.[4] The common arrangements are crystalline (ordered) or amorphous (disordered) as indicated in Fig. 3(i) and (ii) respectively.

Intrinsic or undoped Si is not as effective in demonstrating PV response and therefore an impurity is often added (or doped) in the Si to alter its electronic properties.[5] Pentavalent or trivalent atoms such as phosphorus or boron that give it a characteristic n-and p-type behavior respectively, are used for this purpose as shown in Fig. 3(i). The n- and p-type silicon can be integrated to form a single p/n junction solar cell with or without an intermediate intrinsic silicon layer as shown in Fig. 3(iii). Photoillumination of such a cell produces a DC current that can be used in the external circuit to power a device. The Shockley Queisser efficiency (SQE) analysis provides a theoretical limit of the performance of a single junction cell by correlating the spectral absorbance range and the possible bandgap energy required to the maximum efficiency of the cell. For a solid state single p/n junction crystalline silicon solar cell, this value is estimated to be ~33% under 1 sun (normal solar irradiance of ~100 mW/cm$^2$) as indicated in Fig. 3(iv).[6] Practically reported numbers are ~25% for a crystalline device.[7] This decrease is attributable to surface reflection and charge recombination/thermal losses.[8] The efficiency generally reduces as the crystallinity of the Si reduces. An increase in solar radiance typically achieved by solar concentration improves the single junction device performance across the spectral range of interaction. However, there are other approaches, where one can leverage structural design to achieve efficiencies beyond the SQE.[9] Further, one can assemble multiple absorber layers together that can interact with a broad spectral range to improve cell performance.

Silicon is the preferred material of choice because it offers advantages such as wide availability (produced from silica or sand). Broad ranging applications based on the extent of its crystalline characteristics are possible. Silicon solar cells are classified as monocrystalline, polycrystalline, amorphous, or hybrid. The techniques used for preparing the silicon depend on the crystallinity, dopant level, and type of substrate (hard surface or flexible ribbon-type) in the device. Based on the type of silicon and its physical features (hard or flexible) they can be used to produce power for various applications. Modular panels containing several of these silicon based cells can be assembled together in series/parallel configurations to generate a significant amount of electricity from the Sun. The technology for this class of material has matured over the last several decades. Today, silicon-based solar cells continue to be the dominant and most dependable of all solar cell technologies.[10] They produce energy for a broad range of applications from extraterrestrial (space) to residential and commercial complexes.

Second-generation devices are a class of cells that evolved to be recognized as very thin films comprising of a few to several layers of different materials that still lead to thicknesses that are in the order of several micrometers. Amorphous silicon-based cells are also included here since it is possible to produce them on a flexible substrate with the expenditure of relatively less energy than crystalline Si solar cells. Other representative examples include cadmium telluride (CdTe) cells or multi-component copper indium sulfide or copper indium gallium sulfide/selenide (CIGS) cells.[11] These cells are also single junction devices and are generally cheaper compared to first-generation crystalline solar cells due to lower processing cost. The raw materials for these cells could be an issue as noted recently or lead to environmental problems.[12] They are less efficient than some of the top performing single generation crystalline silicon cells but are catching up with efficiencies in the 20% range.[13]

The third-generation devices represent several organic, inorganic, and hybrid material classes that demonstrate unique optoelectronic properties. These cells are classified based on the type of light absorber materials as organic dyes, quantum dots, polymer, and the more recent organic perovskites cells. The key components of these cells are two conducting substrates that sandwich a semiconductor (optional in some cases), a light absorber, a redox medium and/or a hole transport medium in a configuration as shown in the exploded schematic of Fig. 4(i). Substrates are hard and inflexible such as indium or fluorine doped tin oxide glass or flexible and conducting polymer with at least the illumination side transparent. The substrate material is often a large bandgap oxide which shows good adhesion to the substrate, offers high surface area (usually due to a porous structure), and facilitates the transport of electrons once they are generated in the sensitizer. The photosensitive component absorbs light and injects electrons into the underlying semiconductor. Although each of the four sensitizer type is slightly different, the general cell operation involves the transport of the generated electrons through the external circuit constituting a photocurrent. A suitable redox medium that is matched to the sensitizer energetics serves as the medium for regeneration of the photosensitizer. Titanium dioxide is the most popular of the large bandgap semiconductor used as the substrate.

A characteristic aspect of the dye is it absorbs visible light and transition from a ground state, also called lowest unoccupied molecular orbital (LUMO), to an exited state, or the highest occupied molecular orbital (HOMO).[14] After attaining this excited state, the electron is injected into the semiconductor as indicated in Fig. 4(ii). It is reduced by the redox couple as it transitions to the ground state while the oxidized couple collects the electron from the cathode completing the circuit. Ruthenium-based dyes (e.g., N719), its variant, or N719 with additives are considered promising photo absorbers in the dye solar cell class.[15] These dye-based cells have been extensively developed and are at a point where they are considered competitive in the commercial domain.

Quantum dots are unique in that they display size dependent opto-electronic properties. The physics of quantum confinement principles state that when an object is confined and limited in its mobility to a small space, it demonstrates the property of an isolated atom, where the energy levels are discretized. Adhering to this principle are some semiconductor nanoparticles that absorb light to produce electron-hole pairs in discretized conduction and valence bands that are set based on the size of the nanoparticle. For example,

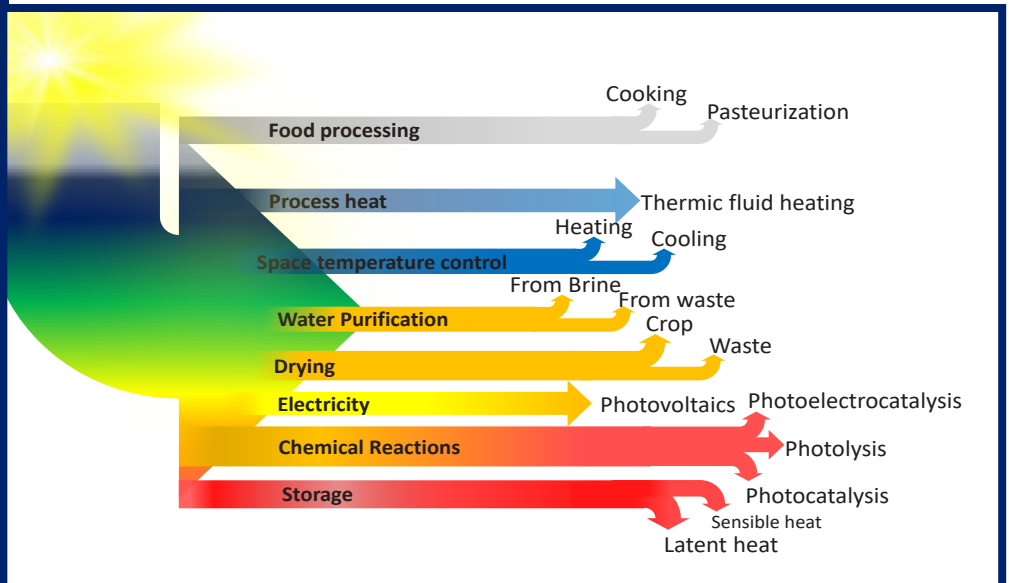


**Fig. 2.** *The omnipresent nature of solar energy has led to the development of broad overaching application.*

the chalcogenide CdS can be assembled as a heterostructure with $TiO_2$ to form a heterogeneous photoresponse electrode.[16,17] The choice of the semiconductor and its size is determined such that its conduction band is more negative to the conduction band edge of the substrate to allow photogenerated electrons to cascade to the oxide and exit at the substrate generating photocurrent as indicated in Fig. 4(iii). Chalcogenides are a class of semiconductors that demonstrate interesting size dependent optical/electronic responses and multiple exciton generation which can allow for theoretical cell efficiencies in ~40% range.[18] Nanoparticles of these material classes demonstrate widening bandedge positions as the physical size reduces allowing one to tune the bandgap to facilitate absorbance of light of various wavelengths spanning the visible and IR domain. An appropriate electrolyte redox couple is used to replenish the electron to the semiconductor. CdX (X = S, Se, or Te), PbX (X = S, Se, or Te) are materials that are photo responsive as well as demonstrate size quantization effects in the visible and IR domain.[19]

The polymer cells are very similar to the dye-sensitized solar cells (DSSCs). The electron donors are of various types ranging from photo responsive fullerene derivatives to conjugate polymers. Just as in the DSSCs these photoresponsive materials absorb light and produce electron-hole pairs. An oxide layer serves as the electron receptor. It may be optional if the photo responsive component and the hole transporter form an effective heterojunction and the in-built potential can drive the charges to separate. Examples of hole transport polymer are Poly(3,4-ethylenedioxythiophene) Polystyrene sulfonate (PEDOT:PSS).[20] The conducting hole transport may also be used with DSSCs to avoid using an expensive counter electrode such as platinum. The salient features of this class of cells include low processing temperatures, production on flexible substrates (roll-to-roll processing), light, and scalability.[21] Their efficiencies are however lower than the DSSCs.

Organic perovskites are a recently identified new class of inorganic-organic hybrid compounds comprised of an alkyl-halogen complex with a metal center and halogen moiety. Their role is very similar to organic dye. The small band gap, high charge carrier mobility, apparent tolerance of defects, and high exciton coefficient of perovskites materials have made them ideal for photovoltaic devices. Once the excitons are generated, the electron transport occurs by a pathway similar to the DSSC. However, the specific hole transporting agent is juxtaposed next to the perovskite and intimately mixed to enhance the efficiency of exciton separation, as indicted in Fig. 4(iv). Alkyl $NH_4$.MX (where M = Pb, X = Br, Cl, I) or halide perovskite cells have been extensively tested for their photo responsiveness.[22] They are coupled with with Spiro-MeOTAD (abbreviated name) as the hole transporting agent. However, stability is one of the major issues of perovskite solar cells and research groups around the world are intensively working to address this issue.[23] The contents of the cell require full encapsulation because moisture can significantly impede cell performance. Research in this type of solar cell has been dramatic with overall cell efficiencies close to ~22%. Other cells that are included in this third generation category are the tandem and multifunction cells. These devices consist of several absorber materials that principally broaden the spectral range to improve device efficiencies.

## Conclusions and Future Outlook

Harnessing the power of the Sun using photovoltaics is a very real and practical option for sustainable energy generation. The development of photovoltaic technology has opened several avenues across three generations of photovoltaic technologies that can be considered as successful pathways for electricity generation. The

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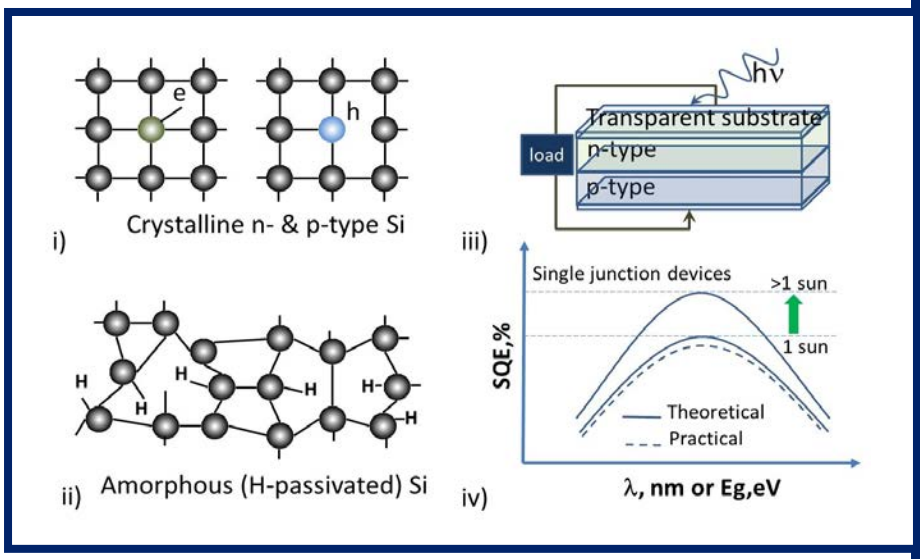


**Fig. 3.** *Lattice structure of (i) crystalline and (ii) amorphous silicon, (iii) structure of a pn junction silicon solar cell, and (iv) sketch of the Shockley Queisser efficiency plot with reference to wavelength or bandgap of photoresponse material forming single junction devices.*

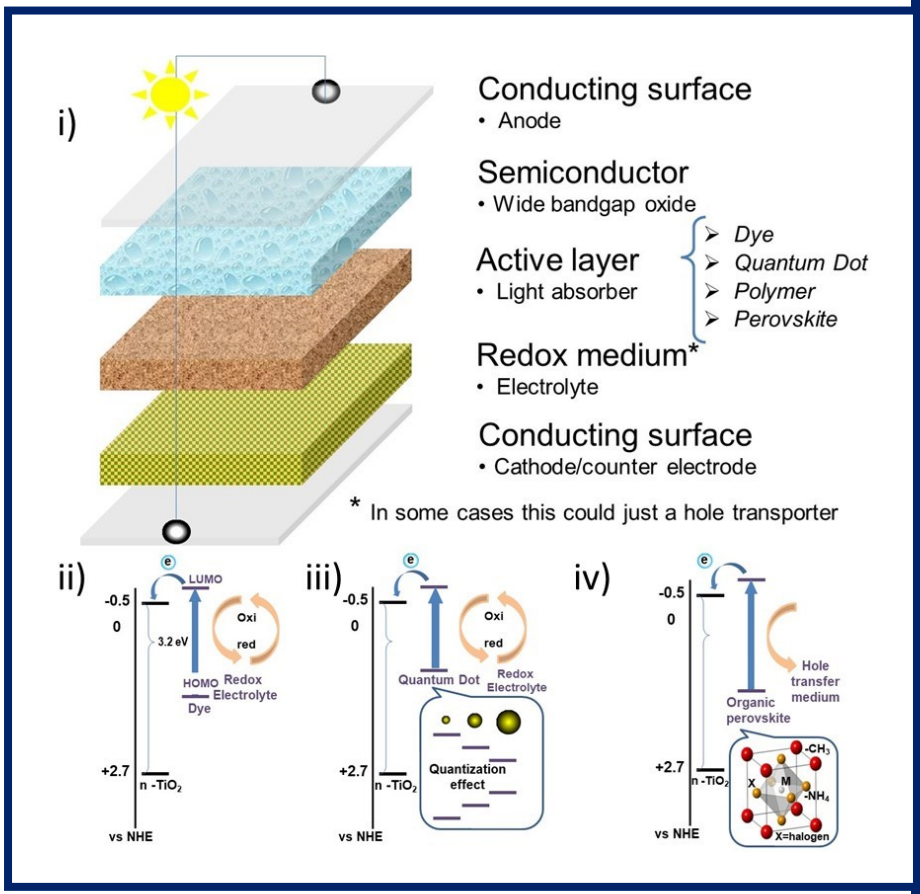


**Fig. 4.** *(i) The exploded view of the different layers in a typical third generation solar cell. The energetics of the (ii) dye sensitized,(iii) quantum dot (inset) size quantitation effect, and (iv) organic perovskite solar cells (insert) structure of an organic sensitizer.*

success of single crystalline solar cells for space applications set the standard for photovoltaics and continues to be implemented as evident from the recent Mars missions. However the traditional dominance of silicon is now being challenged by second- and third-generation cells. CdTe, CIGS, quantum dot, and perovskite solar cells provide unique properties that can be leveraged for niche applications and are expected to make inroads into applications ranging from off-grid power, portable devices, smart textiles, and building integrated photovoltaics. From a price standpoint as well the solar cell producing power well below a dollar per kW has made photovoltaics increasingly attractive and less dependent on government subsidies for market penetration. Some of the key future challenges include lowering of manufacturing cost, improving cell performance efficiency, and addressing material stability. Together these technologies will ensure that photovoltaic technology continues to be a relevant pathway for sustainable energy generation.

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# Engineered Interfaces Using Surface and Contact Passivation in Silicon Solar Cells

*by Kristopher O. Davis and Winston V. Schoenfeld*

Silicon solar cells have enjoyed significant advancement in the past decade with manufacturing costs dropping considerably in tandem with measurable increases in absolute cell efficiency. As cell efficiencies have climbed, surface passivation has quickly become a key factor in realizing higher efficiencies. The first silicon solar cells to exceed efficiencies above 24% relied on covering the majority of the front and rear surfaces with insulating dielectrics, primarily silicon oxide ($SiO_2$), to reduce surface recombination, only placing the metal contacts required for carrier collection at a small fractional area of the total surface.[1] Figure 1 provides a cross- section of an advanced cell architecture that has recently transitioned into high-volume manufacturing, the passivated emitter rear contact (PERC) cell. As noted in the figure, the top surface includes a front contact grid that contacts the emitter in specific regions while the backside is comprised of a full metal contact that makes contact to the wafer backside at specific sites where the passivation is omitted.

More recently, researchers have realized the potential for engineering the passivation/silicon and contact/silicon interfaces using fixed charge. This article provides an overview of the role of surface passivation in silicon solar cells and presents current advanced passivation approaches that enable designed engineering of the cell interfaces for increased efficiency.

## Recombination Loss and the Role of Surface Passivation

The role of surface passivation is best understood by assessing recombination loss in a silicon solar cell. Recombination loss is characterized by the total saturation current density ($J_0$) of the cell, roughly approximated as the sum of the individual $J_0$ values of the front surface ($J_{0f}$), bulk ($J_{0b}$), and rear surface ($J_{0r}$). Current values of $J_{0b}$ are roughly 50 fA·cm$^{-2}$ for high quality p-type Czochralski (Cz) wafers and even lower for n-type Cz wafers, as compared to 200 fA·cm$^{-2}$ for $J_{0f}$ of PERC cells today.[2] Thus, recent silicon wafer advancements that have increased the bulk lifetime of the wafers resulting in a lower $J_{0b}$, have made recombination loss at the silicon/passivation interface a limiting factor. While $J_{0b}$ is primarily driven by silicon wafer quality, the $J_0$ of the front and rear surfaces are more complex and can be approximated as the weighted average of the surface passivated regions and contacted regions,[2] denoted as Regions I and II in Fig. 1:

$$J_{0f} = J_{0fp} \cdot (1 - A_{fc}) + J_{0fc} \cdot A_{fc} \quad (1)$$

$$J_{0r} = J_{0rp} \cdot (1 - A_{rc}) + J_{0rc} \cdot A_{rc} \quad (2)$$

where $J_{0fp}$ and $J_{0rp}$ are the front and rear recombination parameters for the passivated regions, $J_{0fc}$ and $J_{0rc}$ are the front and rear contact recombination parameters, and $A_{fc}$ and $A_{rc}$ are the fractional area of the front and rear surface covered by metal contacts. Typical values for the insulating, passivated regions (Region I) of industrial cells ($J_{0fp}$ and $J_{0rp}$) are below 10-20 fA·cm$^{-2}$ for undiffused surfaces and in the range of 50-100 fA·cm$^{-2}$ for diffused surfaces.[2,3]

Recombination at metal/silicon interfaces (Region II) is normally much higher, with values for industrial cells ranging greatly from 500 to over 10,000 fA·cm$^{-2}$ for both $p^+$ and $n^+$ surfaces depending on the doping concentration, depth and microstructure of the metal contacts.[2,4,5] While Region I passivation is sufficient to reach the $J_{0b}$ values of typical wafers, the high saturation current density, $J_{0c}$, of the contacted regions increases the net surface $J_0$ for the front and back surfaces of the cell to much higher values. Thus, it is desirable to identify ways in which to further increase passivation quality in Region I, and more importantly Region II under the contacts. The following paragraphs present recent approaches towards further reducing $J_0$ values at the cell surface through engineered interfaces, often utilizing fixed charge.

## Surface Passivation

As noted earlier, with rising cell efficiencies surface passivation has become increasingly more important to reduce carrier loss at the cell surface that would otherwise limit absolute efficiencies. Extremely low surface recombination levels can be achieved when *both* chemical and field effect passivation are utilized effectively at the surface. Chemical passivation refers to the traditional passivation of surface states via saturation of dangling bonds, often measured by the interface defect density near midgap ($D_{it\text{-}midgap}$, or $D_{it}$ for short), while field effect passivation refers to a deliberate reduction in the concentration of electrons or holes, preferably the minority carrier for highly doped silicon surfaces.[3,6] It is the latter, electronic passivation, that has enabled engineered interfaces at the silicon solar cell surface.

A thermally grown $SiO_2$ layer accompanied by a hydrogenation step (e.g., forming gas anneal) can drastically reduce $D_{it}$, and lightly doped surfaces, called front and back surface fields, can be used to manipulate carrier concentrations near the surface. More recently, the deposition of thin dielectric films with inherent fixed charges

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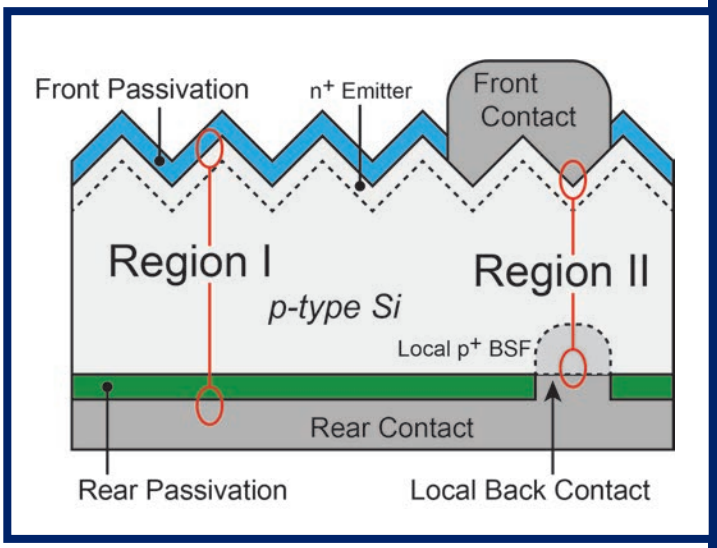


**Fig. 1.** *Illustration of a PERC solar cell with front and rear surface passivation. Regions I and II refer to the passivation and contact regions for the front surface, respectively.*

near the interface, measured as a total fixed charge, $Q_{tot}$, have been used to provide both chemical and field effect passivation without surface doping to create the front and back surface fields. In typical silicon solar cells, the front and rear surfaces differ in their minority carrier type. For example, in Fig. 1 the front surface has a diffused $n^+$ emitter while the rear surface is the undiffused p-type silicon wafer. Thus, field effect passivation at the front surface requires a positive fixed charge while the rear surface requires a negative fixed charge. This is demonstrated in Fig. 2 where the impact of the magnitude and polarity of the interface charge on $J_0$ for both $n^+$ and $p^+$ emitters is presented. Fortunately, both negative and positive fixed charge interfaces can be achieved on silicon by selection of the proper passivation material, with silicon nitride ($SiN_x$) providing a large positive $Q_{tot}$[7] and aluminum oxide ($Al_2O_3$ or $AlO_x$) a large negative $Q_{tot}$.[8] It should be noted that in addition to the inherent interfacial fixed charge of a given passivation material, extrinsic field effect passivation has also been demonstrated using corona charging or the deliberate incorporation of ionic species into the thin films at the interface.[3] This can be used to enable materials with typically poor passivation quality, but other desired qualities, to achieve very low levels of surface recombination.[9] Thin $SiO_2$ or $SiO_x$ layers can be used to further reduce $D_{it}$ for $SiN_x$,[10] but is not necessary for $Al_2O_3$ due to the natural formation of a ≈1-2 nm $SiO_x$ layer.[11] While $SiN_x$ has been used for many years as an anti- reflection coating and to passivate the front side $n^+$ emitter of p-type aluminum back surface field (Al-BSF) cells, the development of $Al_2O_3$ surface passivation has helped usher in a large transition from Al-BSF to rear passivated PERC cells since it provides great passivation of the rear p-type surface.

## Contact Passivation

A silver top contact grid is typically employed on the surface of silicon solar cells to collect carriers. The use of a grid allows shading by the top contact to be reduced to only about 3% of the cell and the geometry of the grid (finger density and width) is optimized for the best tradeoff of contact recombination and series resistance for the cell. On the rear side, local contacts are also formed, representing a small fraction of the rear surface. In both cases, the metal contacts make direct contact with the underlying silicon (Region II in Fig. 1). The resultant metal/silicon interfaces have a very high $D_{it}$, and thus contribute strongly to recombination loss and must be minimized. An obvious mitigation path is to lower the contact fraction (area) of the metal with the cell's surface. However, this also results in an increased series resistance due to carriers having to travel further distances to the contacts that nullifies the benefits of this simple approach. Additionally, the small dimensions (finger width of the contact) required to achieve these low contact fractions can be difficult to translate to high-volume solar cell manufacturing where photolithography is incompatible.

Recently, researchers have worked on developing passivated contact heterostructures with various materials, where passivation of the surface below the contact region is possible by using a thin layer (e.g. tunneling $SiO_2$ or intrinsic amorphous silicon). When properly designed, the thin layer can lower $D_{it}$ without introducing measurable contact resistance in the cell. These passivated contact heterostructures are normally made of a stack of films that can accomplish the following functions:[13] (1) lower $D_{it}$ at the silicon surface with the thin passivation layer; (2) limit minority carrier flow, while enabling transport of majority carriers through the stack (i.e., carrier selectivity); and (3) provide lateral transport, in the case of all front contacts and some rear contact designs, like bifacial cells. The carrier selectivity functionality is obtained using materials with appropriate band offsets or by induced band bending due to the work function of the material. Three carrier selective technologies have emerged as promising candidates for contact passivation in silicon solar cells: doped amorphous silicon; doped polycrystalline silicon; and transition metal oxides. The basic band diagrams for each of these is shown in Fig. 3.

In each case, the band offset is designed to enable carrier selectivity that allows easy majority carrier transport while creating a barrier for minority carriers. The following paragraphs provide a general overview of each approach.

## Doped Amorphous Silicon

Hydrogenated amorphous silicon (a-Si:H) was first explored as heterojunction with crystalline silicon by Fuhs et al. in 1974.[14] By doping a-Si:H with phosphorus or boron, the films can be made electron or hole selective, respectively, and can therefore by used to form the junction or the back surface field of solar cells. Doped a-Si:H is most commonly used with an intrinsic a-Si:H layer for surface passivation on high quality n-type wafers, which is the approach that has been commercialized by Panasonic[15] and the approach used in the recent world record efficiency silicon solar cells from Kaneka (confirmed 26.7% efficiency at standard test conditions).[16] A basic band diagram of this approach is provided in Fig. 3(a) for a n-type surface, where a barrier is created for holes but electrons are easily able to transverse the interface. An undoped thin a-Si:H layer is used at the surface to obtain good chemical passivation of the silicon surface. This is followed by a n-type a-Si:H layer that offers good electrical transport for electrons and a significant barrier in the valence band for minority carrier holes. Normally, a transparent conducive oxide is also used above the doped a-Si:H layer to provide lateral transport to the metal fingers. The key challenges associated with this technology are degradation of the passivation at temperatures above 300 °C, parasitic optical absorption in the intrinsic and doped a-Si:H layers, and process complexity (e.g., number of deposition steps, precise thickness requirements, special surface preparation steps, more expensive metal contact pastes).[17]

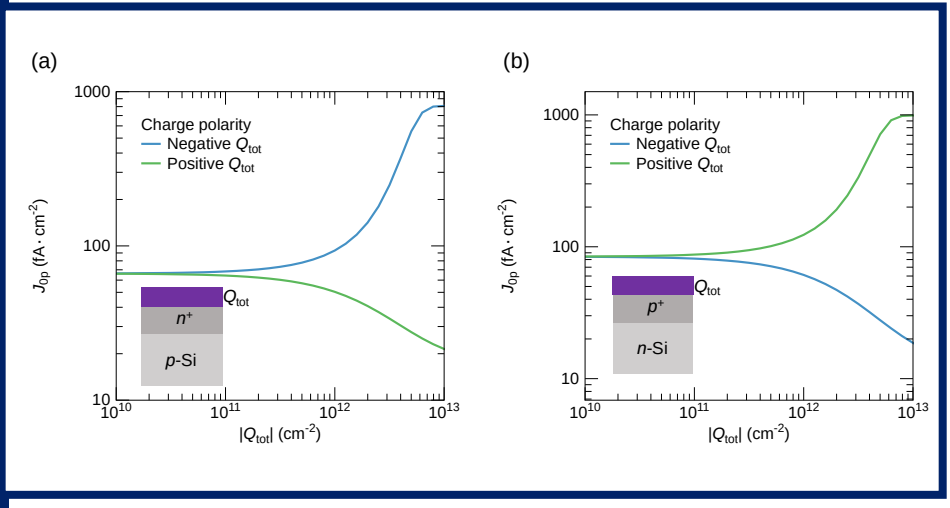


**Fig. 2.** *$J_{0p}$ as a function of the magnitude of the dielectric charge at the interface for negative and positive charges on two types of surfaces: (a) $n^+$ emitter on a p-type wafer; and (b) $p^+$ emitter on a n-type wafer. $J_{0p}$ was calculated using EDNA 2[12] and comparable bulk wafer resistivity (1.5 Ω·cm) and sheet resistances (Ω/square) were used for the $n^+p$ and $p^+n$ structures.*

## Doped Polycrystalline Silicon

Doped polycrystalline silicon films were investigated by Yablonovitch et al. back in 1985, where very high open-circuit voltages were obtained ($V_{OC}$ = 720 mV).[18,19] This work was later improved by Feldmann et al. using a thin $SiO_2$ passivation layer[20] and has recently achieved a confirmed 25.7% efficiency at standard test conditions.[16] As with amorphous silicon, the polysilicon films can be doped

with phosphorus or boron to make them electron or hole selective. The band diagram for this approach on a n-type silicon surface is provided in Fig. 3(b), showing the case of a hole selective design that allows for efficient hole transport across the interface while creating a barrier for minority carrier electrons. Here, the $SiO_2$ layer is used at the interface for chemical passivation and a thicker n-type polycrystalline silicon (pc-Si) layer provides carrier selectivity, forming the heterojunction in this case, and serves as the transport layer for majority carriers. Advantages of this design over a-Si:H are improved thermal stability and bulk film conductivity, as well as some simplification of the process sequence since the $SiO_2$ or $SiO_x$ passivation layer can be grown chemically.[21] However, the films suffer from even greater parasitic optical absorption, limiting their applicability on the front side of cells and potentially reducing the light trapping performance of cells when used on the rear side.

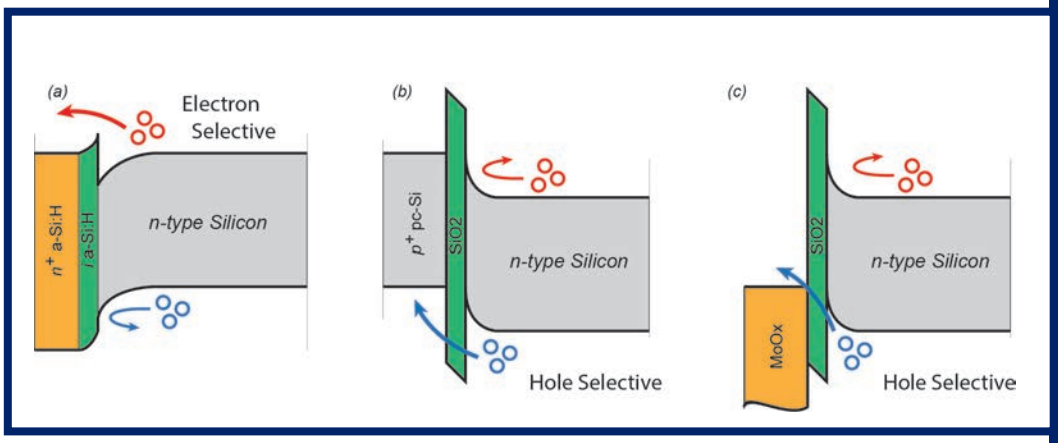


**Fig. 3.** *Current approaches to passivated contacts: (a) doped amorphous silicon, (b) doped polycrystalline silicon, and (c) transition metal oxides such as $MoO_x$.*

## Transition Metal Oxides

Transition metal oxides utilize a thin metal oxide layer that serves as an electron-selective or hole-selective layer that blocks minority carriers at the interface. This is depicted in Fig. 3(c) for a hole selective contact that utilizes $MoO_x$ due to its large work function. A key advantage of these metal oxides is that their wider band gaps lead to less parasitic optical absorption, and by using atomic layer deposition these metal oxides can be deposited with very precise thickness (a critical parameter in ensuring efficient majority carrier transport). Additionally, the work function and band structure can be modified by controlling the stoichiometry, allowing for a some tuning of the electronic properties after deposition.

Different metal oxides accomplish carrier selectivity in different ways. Titanium oxide ($TiO_2$) serves as an effective hole-blocking layer due to its small conduction band offset ($\Delta E_c \approx 0.05$ eV), enabling electrons to pass through the $TiO_2$ layer while blocking holes with a large valence-band offset ($\Delta E_v \approx 2.0$ eV).[22,23] Recently, Yang et al. demonstrated cell efficiencies up to 21.6% for a n-type Si solar cell with a full area $TiO_2$ rear contact featuring a thin silicon oxide passivation layer.[22] Subsequently, Allen et al. achieved a 21.8% efficiency using a local $TiO_2$ rear contact with a low work function calcium layer to facilitate electron transport.[24]

Conversely, sub-stoichiometric molybdenum oxide ($MoO_x$),[25-27] tungsten oxide ($WO_x$),[2628] and vanadium oxide ($VO_x$)[27] have recently been used as electron-blocking layers due to their high work function that induces band bending at the silicon surface that helps accumulate holes and deplete electrons. Geissbühler et al. achieved a 22.5% efficiency with a silicon solar cell consisting of a $MoO_x$ heterojunction.[29] One challenge associated with these high work function metal oxides is instability in the work function upon annealing, thought to be caused by oxygen defects.

## Future Direction and Outlook

Silicon solar cell passivation has evolved greatly, with recent approaches enabling interface engineering for carrier selectivity and effective suppression of recombination, or $J_0$, under contacted regions of the cell. Future advanced silicon solar cell designs will certainly adopt passivated contact approaches given the strong experimental evidence demonstrating their benefits. In particular, metal oxide approaches appear to offer considerable promise for both n- and p-type interfaces where efficient carrier collection and low surface recombination velocities can be achieved in both contacted and non-contacted regions. The ability to adjust the work function of the metal oxide interfacial tunnel layer, a critical parameter in determining the efficiency of the contact, has proven to be a valuable attractive attribute. However, widespread adoption of metal oxide passivated contact approaches will require a considerable amount of further work to understand the stability and long-term reliability of such structures. Much of the near-term work must focus on the role of oxygen vacancies in determining the work function and transport properties across the interfacial layer with additional focus on processing methods to engineer such interfaces for optimal silicon solar cell efficiency.

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## About the Authors

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**Winston V. Schoenfeld** is the director of the Solar Technologies Research Division at the Florida Solar Energy Center and a professor at CREOL, the College of Optics & Photonics at the University of Central Florida. He received his PhD in materials science from the University of California, Santa Barbara, and holds an MS and BS in materials science and engineering from the University of Florida. He has authored

*(continued on next page)*

or coauthored more than 120 refereed journal publications in the areas of photovoltaics, the epitaxial growth and properties of oxide semiconductors, oxide and nitride-semiconductor light emitting diodes, solid state ultraviolet detectors, self-assembled quantum dots, quantum information/networks, and solid state nuclear material detection. He is a fellow of SPIE, the International Society for Optics and Photonics, and serves as a principal editor for the *Journal of Materials Research*. He may be reached at winston@creol.ucf.edu.

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## India Section

The **ECS India Section** hosted the sixth installment of its annual school, which has come to be recognized as India's most prestigious and most sought-after electrochemistry teaching program for researchers. This year's school was conducted by Prashant V. Kamat of the University of Notre Dame, USA. The three-day school was held at the serene and sylvan campus of Amrita Vishwa Vidyapeetham University, Coimbatore, Tamil Nadu, India, December 26-28, 2017. The theme of the school was "Applications of Functional Materials for Electrochemical Energy Conversion."

The school was attended by 102 participants drawn from industry and academia across the country. The spectacular success of the school was underlined by the fact that although no advertisement was made, the demand for participation was heavy. Participation, as usual, was restricted by invitation to particular groups and individuals specialized in the school's theme. The three-day discourse covered an entire gamut of fundamental and applied topics: clean energy challenges, advanced energy materials and their characterization, photoinduced processes in semiconductor nanostructures, quantum dot solar cells, solar cell characterization, metal halide perovskite solar cells, solar fuels, and photoinduced processes in mixed halide perovskites. Kamat also gave a special lecture on effective scientific publication, highlighting what it takes to get a manuscript of publishable standards. The chair of the India Section, Vijayamohanan K Pillai, contributed a lecture on semiconductor electrolyte interfaces in order to lend variety to the discourse.

The school saw the presentation of the first India Section S.K. Rangarajan Graduate Student Award. The award was presented by Kamat to Anantharaj S of the Central Electrochemical Research Institute. Prior to the presentation of the award, T. Prem Kumar, previous cochair of the India Section, outlined the genesis of the award and gave a kaleidoscopic overview of Rangarajan as a multitasking and multifaceted personality. A dinner at an ITC WelcomHotel and a trip to the Isha Yoga Center served as pleasant getaways for the delegates and accentuated the school's exceptional blend of education and relaxation.

As usual, the organization of the school was made possible by generous logistical and monetary support from ECS. Sponsorship from Sun Teknolozy, Electrodes and More, Adilab Technologies, BioLogic Science Instruments, and VB Ceramics helped embellish the program. The office-bearers, particularly S. Vasudevan, secretary, and M. Sathish, treasurer, place on record their appreciation for the altruistic support they received from Amrita University. The phenomenal success of the sixth India Section school should inspire other ECS sections to emulate its program.

*Delegates of the sixth ECS India Section school.*

# Singapore Section

The recently formed **ECS Singapore Section** successfully conducted the first installment of the Singapore ECS International Symposium on Energy Materials, December 6-9, 2017, at Nanyang Technological University, Singapore. SESEM 2017 aimed to promote interaction and the generation of new ideas to advance research in the electrochemical community.

The organizing committee constituted professors from prominent universities in Singapore: Qingyu (Alex) Yan (NTU), Zhichuan (Jason) Xu (NTU), Jason Yeo Boon Siang (National University of Singapore), Yizhong Huang (NTU), Hongjin Fan (NTU), Shuzhou Li (NTU), Huiying Yang (Singapore University of Technology and Design), and Hanbin Liao (NTU), with the distinguished international advisory board consisting of Shirley Y. Meng, Adrian Fisher, Guenter Scherer, Gregory Jerkiewicz, Shizhang Qiao, Xin Wang, Harry Hoster, Yang Shao-Horn, Marc Koper, Jingguan Chen, and Edman Tsang.

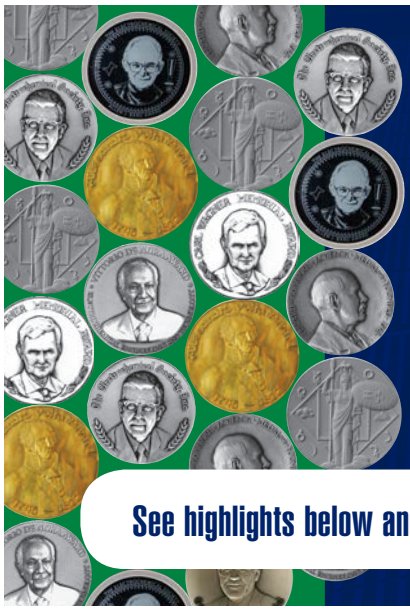
Bor Yann Liaw, department manager of Idaho National Laboratory, presented Yan and Xu with the formal certificate of the formation of the ECS Singapore Section and delivered the welcome speech for the official commencement of the symposium. The meeting was attended by nearly 100 participants drawn from industry and academia across Asia and Europe. The spectacular success of the symposium was evidenced by heavy participation although no advertisement was made. There was a rigorous selection process for the speakers, who consisted of elite researchers and scientists specialized in the field of electrochemistry. The four-day interaction covered an entire gamut of fundamental and applied topics: in situ characterizations, electrochemical sensors, advanced energy storage, electrocatalysis, membranes/electrolytes, nanostructured electrodes, electrochemical synthesis, modelling, simulations, and bioelectrochemistry.

The organization of the symposium was made possible due to generous logistical and monetary support from ECS and NTU's School of Materials Science and Engineering. In addition, Metrohm and Nano-Micro Letters served as sponsors.

SESEM 2017, through its remarkable success, honored ECS's reputation and laid the foundation for future initiatives in the field of electrochemistry.

*From left to right:* **Bor Yann Liaw** *presented the ECS Singapore Section certificate to* **Qingyu (Alex) Yan** *and* **Zhichuan (Jason) Xu**.

*ECS delegate* **Bor Yann Liaw** *(front row, second from left) and* **Qingyu (Alex) Yan** *(front row, first from left) with the prominent speakers and participants at SESEM 2017.*



# Awards, Fellowships, Grants

ECS distinguishes outstanding technical achievements in electrochemistry, solid state science and technology, and recognizes exceptional service to the Society through the **Honors & Awards Program**. Recognition opportunities exist in the following categories: Society Awards, Division Awards, Student Awards, and Section Awards.

ECS recognizes that today's emerging scientists are the next generation of leaders in our field and offers competitive **Fellowships** and **Grants** to allow students and young professionals to make discoveries and shape our science long into the future.

**See highlights below and visit www.electrochem.org for further information.**

## Society Awards

The **ECS Carl Wagner Memorial Award** was established in 1980 to recognize mid-career achievement and excellence in research areas of interest of the Society, and significant contributions in the teaching or guidance of students or colleagues in education, industry, or government. The award consists of a silver medal, wall plaque, Society life membership, complimentary meeting registration, and travel assistance of up to $1,000.

**Materials are due by October 1, 2018.**

The **ECS Olin Palladium Award** was established in 1950 to recognize distinguished contributions to the fields of electrochemical or corrosion science. The award consists of a palladium medal, wall plaque, a $7,500 prize, Society life membership, and complimentary meeting registration.

**Materials are due by October 1, 2018.**

## Division Awards

The **ECS Dielectric Science and Technology Division Thomas D. Callinan Award** was established in 1967 to encourage excellence in dielectrics and insulation investigations, to encourage the preparation of high-quality science and technology papers and patents, to encourage submission to ECS publications, and to recognize outstanding contributions to the field of dielectric science and technology. The award consists of a certificate and a $1,500 prize.

**Materials are due by August 1, 2018.**

The **ECS Electronics and Photonics Division Award** was established in 1968 to encourage excellence in electronics research and outstanding technical contribution to the field of electronics science. The award consists of a framed certificate, a $1,500 prize, and the choice between travel assistance of up to $1,000 or Society life membership.

**Materials are due by August 1, 2018.**

The **ECS Energy Technology Division Research Award** was established in 1992 to encourage excellence in energy-related research. The award consists of framed certificate, a $2,000 prize, and membership in the Energy Technology Division for as long as the recipient is an ECS member.

**Materials are due by September 1, 2018.**

The **ECS Energy Technology Division Supramaniam Srinivasan Young Investigator Award** was established in 2011 to recognize and reward an outstanding young researcher in the field of energy technology. The award consists of a framed certificate, a $1,000 prize, and complimentary meeting registration.

**Materials are due by September 1, 2018.**

The **ECS Nanocarbons Division Richard E. Smalley Research Award** was established in 2006 to encourage excellence in fullerenes, nanotubes, and carbon nanostructures research. The award is intended to recognize, in a broad sense, those persons who have made outstanding contributions to the understanding and applications of fullerenes. The award consists of a framed certificate, a $1,000 prize, and assistance up to a maximum of $1,500 to facilitate attendance of the meeting at which the award is to be presented.

**Materials are due by September 1, 2018.**

The **ECS Physical and Analytical Electrochemistry Division David C. Grahame Award** was established in 1981 to encourage excellence in physical electrochemistry research and to stimulate publication of high-quality research papers in ECS journals. The award consists of a framed certificate and a $1,500 prize.

**Materials are due by October 1, 2018.**

The **ECS Corrosion Division Herbert H. Uhlig Award** was established in 1972 to recognize excellence in corrosion research and outstanding technical contributions to the field of corrosion science and technology. The award consists of a framed certificate, a $1,500 prize, and possible travel assistance.

**Materials are due by December 15, 2018.**

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## Student Awards

The **ECS Georgia Section Outstanding Student Achievement Award** was established in 2011 to recognize academic accomplishments in any area of science or engineering in which electrochemical and/or solid state science and technology is the central consideration. The award consists of a $500 prize.

**Materials are due by August 15, 2018.**

The **ECS Energy Technology Division Graduate Student Award sponsored by Bio-Logic** was established in 2012 to recognize promising young engineers and scientists in fields pertaining to this division. The award consists of a framed certificate, a $1,000 prize, complimentary student meeting registration, and complimentary admission to the ETD business meeting.

**Materials are due by September 1, 2018.**

The **ECS Industrial Electrochemistry and Electrochemical Engineering Division H. H. Dow Memorial Student Achievement Award** was established in 1990 to recognize promising young engineers and scientists in the field of electrochemical engineering and applied electrochemistry. The award consists of a framed certificate and a $1,000 prize to be used for expenses associated with the recipient's education or research project.

**Materials are due by September 15, 2018.**

The **ECS Industrial Electrochemistry and Electrochemical Engineering Division Student Achievement Award** was established in 1989 to recognize promising young engineers and scientists in the field of electrochemical engineering and to encourage the recipients to initiate careers in this field. The award consists of a framed certificate and a $1,000 prize.

**Materials are due by September 15, 2018.**

## Section Awards

The **ECS Europe Section Heinz Gerischer Award** was established in 2001 to recognize an individual or a small group of individuals (no more than three) who have made an outstanding contribution to the science of semiconductor electrochemistry and photoelectrochemistry including the underlying areas of physical and materials chemistry of significance to this field. The award consists of a framed certificate and a EUR 2,000 prize and, if required, financial assistance for un-reimbursed travel expenses incurred to receive the award, not to exceed EUR 1,000.

**Materials are due by September 30, 2018.**

# Awards Winners

*Allow us to introduce the award winners who will be recognized at the Society's 233rd meeting in Seattle in May. Join us as we extend sincere congratulations.*

## Society Award Winners

### Henry B. Linford Award for Distinguished Teaching

**Ralph E. White** is a professor of chemical engineering and a distinguished scientist at the University of South Carolina. He graduated from the University of South Carolina with a BS in chemical engineering in 1971. He then attended the University of California at Berkeley and completed his PhD in 1977 under the direction of John Newman.

White began his teaching career at Texas A&M University in 1977. In 1993 he moved to the University of South Carolina, where he served as the chair of the Department of Chemical Engineering for seven years and then as the dean of the College of Engineering and Computing for five years. In 1995 he founded the Center for Electrochemical Engineering.

White has published 338 peer-reviewed journal articles and has graduated 50 PhD and 39 MS students. He is a past treasurer of ECS (1990-1994) and a fellow of ECS, the American Institute of Chemical Engineers, and the American Association for the Advancement of Science. White has received several international awards, including the American Electroplaters and Surface Finishers Society Scientific Achievement Award (2000) for mathematical modeling of the electrodeposition of alloys, the ECS Olin Palladium Award (2013) for contributions to the science of electrochemistry, and the ECS Vittorio de Nora Award (2016) for contributions to the field of electrochemical engineering and technology. He has served as a consultant to several major companies, including Energizer and General Electric.

### Vittorio de Nora Award

**Hariklia (Lili) Deligianni** is a research scientist in IBM's Thomas J. Watson Research Center. Her current research interests include materials and devices for power electronics, bioelectronics, biosensors, and brain-inspired computing.

Deligianni has played a key role developing the solder bump technology that became the standard for the joining of silicon chips to packages. She coinvented copper electrodeposition for on-chip interconnects and was a corecipient of the 2006 Inventor of the Year Award from the New York Intellectual Property Law Association. For these technologies, IBM was recognized with the U.S. National Medal of Technology and Innovation. She has developed an electrodeposition route for the synthesis of solar thin film semiconductors and earth abundant solar materials and has been instrumental in the scale-up of thin film solar energy conversion technologies.

Deligianni holds PhD and MS degrees in chemical engineering from the University of Illinois at Urbana-Champaign and a BS in chemical engineering from Aristotelion University in Thessaloniki, Greece. She has coauthored 58 manuscripts and has 187 patents, with more than 30 patents pending with the United States Patent and Trademark Office. Deligianni is a member of the IBM Academy of Technology and an ECS fellow. In 2012, Deligianni was the first female recipient of the ECS Electrodeposition Research Award. She is a past secretary of ECS (2012-2016) and has served as chair of the ECS Education Committee, the ECS Ways and Means Committee, and the ECS Electrodeposition Division. She is a senior member of the Institute of Electrical and Electronics Engineers and the American Institute of Chemical Engineers and a member of the International Society of Electrochemistry, the American Chemical Society, the Association for Computing Machinery, and the American Association for the Advancement of Science.

## Division Awards Winners

### Electronics and Photonics Division Award

**Tae-Yeon Seong** received his PhD in materials science from the University of Oxford in 1992. After two years as a postdoctoral fellow, he joined the Gwangju Institute of Science and Technology, where he served as department chair and director for the Brain Korea 21 Centre for Advanced Materials.

In 2005, Seong moved to the Department of Materials Science and Engineering at Korea University, where he served as department chair and director for the Brain Korea 21 Centre for Advanced Device Materials (2011-2016). He also served as associate dean of research in the university's College of Engineering (2014-2015). Seong was president of the Korea Society of Optoelectronics in 2014. He was also an advisory committee member of the Ministry of Education of Korea (2005-2008). His current research interests include integration of HEMT (TFT) and μ-LEDs, LEDs for general illumination, displays, and biomedical applications.

Seong has authored or coauthored approximately 430 papers and holds 230 patents issued or pending. He is a fellow of ECS, the Institute of Physics (UK), and the International Society for Optics and Photonics. He is a life member of ECS and served as an editorial advisory committee member for the *ECS Journal of Solid State Science and Technology* and *ECS Solid State Letters*.

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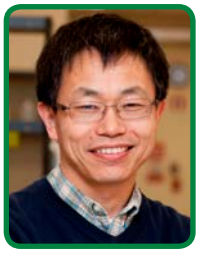
## Energy Technology Division Graduate Student Award Sponsored by Bio-Logic

**Deijun Xiong** completed his PhD in chemistry at Dalhousie University in October 2017 under the supervision of Jeff Dahn.

During his PhD studies, he mainly focused on understanding the failure of high-voltage $LiNi_xMn_yCo_{(1-x-y)}O_2$ (NMC) cells and developing functional electrolytes for high-voltage NMC cells. He put forward a novel *pouch bag* method to deepen understanding of the crosstalks occurring in Li-ion cells. He provided new evidence that oxygen can be released from charged polycrystalline NMC materials rather than single crystal NMC materials at mild temperature at high voltage. He also made contributions to develop ethylene carbonate-free electrolytes for high-voltage NMC cells.

In December 2017, Deijun joined Shenzhen Capchem Technology Co. Ltd. (one of the leading Li-ion battery and supercapacitor electrolyte companies in the world) as vice director of research and development to develop functional electrolytes for Li-ion batteries and supercapacitors.

## Energy Technology Division Research Award



**Yushan Yan** joined the University of Delaware as the Distinguished Engineering Professor in the Department of Chemical and Biomolecular Engineering in 2011. He became the Founding Associate Dean for Research and Entrepreneurship in 2014. Before joining UD, he held the positions of department chair at the University of California, Riverside and senior staff engineer at Allied Signal.

His recognitions include the Nanoscale Science and Engineering Forum Award from the American Institute of Chemical Engineers, the Donald Breck Award from the International Zeolite Association, fellow of the American Association for the Advancement of Science, University of California presidential chair, and the inaugural UCR University Scholar. He has been an inventor on over 20 issued or pending patents. His research has led to more than 200 widely cited publications and extensive news coverage.

Yan earned a BA in chemical physics at the University of Science and Technology of China, studied heterogeneous catalysis at the Dalian Institute of Chemical Physics of the Chinese Academy of Sciences, and earned a doctoral degree in chemical engineering at the California Institute of Technology.

## Energy Technology Division Supramaniam Srinivasan Young Investigator Award

**María Escudero Escribano** studied chemical engineering at the University of Extremadura in Spain. She obtained her PhD in electrocatalysis and surface nanostructuring from the Autonomous University of Madrid in 2011, supervised by Angel Cuesta. Her PhD was named the "Best PhD in Chemistry in the Region of Madrid" by the Spanish Royal Society of Chemistry and the "Best PhD Thesis Related to Hydrogen Energy and Fuel Cells" by the Spanish Hydrogen Association and Spanish Association of Fuel Cells.

In 2012, she started her postdoctoral research with Ib Chorkendorff at Danmarks Tekniske Universitet. In 2014, she was awarded the Sapere Aude: Research Talent Grant from the Danish Council for Independent Research. Thanks to this grant, she spent two years in Thomas Jaramillo's group at Stanford University.

Since March 2017, Escudero Escribano has been an assistant professor of the Department of Chemistry at the University of Copenhagen, where she leads the NanoElectrocatalysis Group. Her research has been recognized by numerous awards for young researchers, including the European Young Chemist Award (2016) and the CIDETEC Award (2016).

## Industrial Electrochemistry and Electrochemical Engineering Division H. H. Dow Memorial Student Achievement Award

**Soo Kim** received his PhD in materials science and engineering at Northwestern University in 2017, specializing in research and development of advanced battery materials. He received his BS in chemical engineering at the University of Michigan in Ann Arbor in 2008 and his MS in chemical engineering at Carnegie Mellon University in 2009.

Before pursuing a doctorate degree in computational materials research, he worked at Samsung to develop Li-ion battery cathodes at industrial-scale (2010-2011) and as a staff scientist at the Korea Institute of Science and Technology with Byung-Won Cho and Kyung Yoon Chung (2011-2013) to experimentally synthesize more advanced cathode materials.

Kim has coauthored over 30 patents and peer-reviewed journal papers and has been a recipient of multiple awards, including the ECS Edward G. Weston Summer Research Fellowship (2016), Northwestern Computational Research Day Poster Competition Award (2016), ECS Battery Division Travel Grant (2014), and Fifty for the Future Award from the Illinois Technology Foundation (2013). Kim is currently a postdoctoral researcher at MIT and is supervised by Yang Shao-Horn. He is concentrating on synthesis in conjunction with performing density functional theory calculations to design functional materials for electrochemical energy conversion and storage applications.

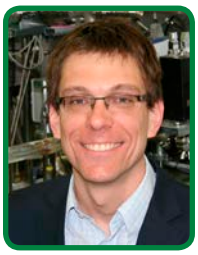
## Industrial Electrochemistry and Electrochemical Engineering Division Student Achievement Award

**Yasser Ashraf Gandomi** is currently a PhD candidate at the University of Tennessee, Knoxville and a member of the Electrochemical Energy Storage and Conversion Laboratory. He also received his MS in mechanical engineering with a minor in computational sciences from UTK. He holds BS and MS degrees in mechanical engineering from the University of Tabriz.

Ashraf Gandomi has worked on multiple projects funded by the Department of Energy and industry. His research has focused on the design, engineering, modeling, and prototyping of electrochemical conversion devices, including redox flow batteries, polymer electrolyte fuel cells, and electrochemical sensors.

His accomplishments have been recognized via several institutional awards at UTK. Ashraf Gandomi also won a best presentation award at the Fifth International Education Forum on Environmental and Energy Science in 2016. He is the recipient of a University of Tennessee Chancellor's Graduate Fellowship and an International Alliance of Healthcare Educators Fellowship. He plans to continue in academia after graduation and expand the advances made in his doctoral studies to such broadly impactful technologies as water desalination, energy storage and conversion, and related electrochemical devices.

## Nanocarbons Division SES Young Investigator Award



**Michael S. Arnold** is currently a professor of materials science and engineering at the University of Wisconsin-Madison. There, he has directed the Advanced Materials for Energy and Electronics Group since 2008.

Arnold graduated summa cum laude from the University of Illinois at Urbana-Champaign with a BS in electrical engineering in 2001. He earned his PhD in 2006 from Northwestern University in materials science and engineering under Mark Hersam and Sam Stupp. He conducted postdoctoral research at the University of Michigan at Ann Arbor from 2006 to 2008 with Stephen Forrest.

Arnold has been a recipient of various awards throughout his career, including the National Science Foundation CAREER Award (2014) and the American Chemical Society's Arthur K. Doolittle Award (2012). His work addresses fundamental challenges—in controlling the growth, processing, ordering, and heterogeneity of nanomaterials and in understanding phenomena beyond the scale of single nanostructures—that must be overcome to exploit nanomaterials in technology. Arnold's research has resulted in 95 journal publications and 15 patents/patent applications.

## Organic and Biological Electrochemistry Division Manuel M. Baizer Award

**Flavio Maran** is a professor of physical chemistry in the Department of Chemistry at the University of Padova, where he leads the Molecular Electrochemistry and Nanosystems Group. He obtained his PhD in chemistry at the University of Padova in 1980. Maran has been a visiting scientist and professor at the National Research Council of Canada, University of Western Ontario, Université de Sherbrooke, Utah State University, University of La Laguna, Temple University, Princeton University, Okayama University, and Kyoto University.

Maran is a fellow of the Japan Society for the Promotion of Science and is the recipient of the 2014 Jaroslav Heyrovsky Prize for Molecular Electrochemistry awarded by the International Society of Electrochemistry. He is on the editorial board or acts as section editor of various scientific journals and is a regular organizer of ECS and International Society of Electrochemistry symposia. His mentor was the late Elio Vianello, one of the fathers of molecular electrochemistry.

Maran has always been an advocate of the molecular approach to address scientific problems and thus of the importance of explaining the fine details of electrochemical processes on a true molecular basis. His research focuses on molecular and organic electrochemistry, monolayer-protected gold clusters, electron-transfer reactions, monolayers and biomimetic membranes on electrodes, and electrochemical biosensors.

## ECS Introduces the First Winner of the ECS India Section S. K. Rangarajan Graduate Student Award: Anantharaj S of the Council of Scientific & Industrial Research

The S. K. Rangarajan Graduate Student Award was established last year to assist a deserving student in India in pursuing a career in disciplines related to electrochemistry and solid state science and technology. The award consists of a certificate, a $500 prize, and a complimentary one-year ECS membership. Moving forward, the ECS India Section will recognize one such winner annually at its acclaimed India School, which is a weeklong teaching program in electrochemistry for young researchers. The recipient may be invited to speak at that meeting about his or her work or on another topic of interest to the field of electrochemistry.

Anantharaj S has shown his excellence from secondary school level to his MS in chemistry by securing CGPAs always higher than 8.3. Later, he qualified for the state and national level eligibility tests for lectureship by simultaneously securing the award of junior research fellowship from the Council of Scientific and Industrial Research while concluding his MS coursework. He subsequently joined the research group of Subrata Kundu at CSIR (2014).

His research interests are mainly focused on the synthesis and self-assembly of transition metals-based nanostructures for their application in the fields of energy, environment, and catalysis. The primary focus of his PhD thesis is the design and application of nanostructured inorganic materials as electrocatalysts for water splitting to enable energy and cost-efficient $H_2$ production.

In his research career, he has published 24 research articles and 2 review articles with an average impact factor of 5.635. In addition, he has also edited a book chapter on the recent advances in the field of transition metals-based electrocatalysts for catalytic water splitting.

The award namesake, Sarukkai Krishnamachari Rangarajan, was an exceptional scientist whose diverse research investigations ranged from functional analysis and stochastic modelling to ion transport across membranes and bipolar cells.

Thank you to all of the donors who supported the creation the award. The goal is to increase the award prize to include travel and conference registration so that future award winners are recognized at ECS biannual meetings. If you would like to continue to help grow the fund, please consider making a gift. ECS appreciates your recognizing the good work that is being done following the legacy of SKR.

# NEW MEMBERS

*ECS is proud to announce the following new members for October, November, and December 2017.*

## Members

Robbyn Anand, Ames, IA, USA
Juan Carlos Arevalo, USAF Academy, CO, USA
Thomas Barbarich, Rochester Hills, MI, USA
Ronald Birke, New York, NY, USA
Sivasambu Bohm, Cambridge, Cambridgeshire, UK
Michael Cason, Manchester, NH, USA
Kyuhwan Chang, Austin, TX, USA
Renkun Chen, La Jolla, CA, USA
Yuming Dai, Nanjing, Jiangsu, China
Dong Ding, Idaho Falls, ID, USA
Denis Fauteux, West Palm Beach, FL, USA
Thomas Ferrier, Chicago, IL, USA
Christian Fischer-Walchshofer, Wien, Austria
Andrew Fisk, Quakertown, PA, USA
Jeremy Gilbert, Charleston, SC, USA
Risei Goto, Houston, TX, USA
Tieshi He, Jinzhou City, Liaoning Province, China
Peter Hoffmann, Detroit, MI, USA
Zhaozhao Hou, Beijing, China
Simon Joshi, Oakville, ON, Canada
Howard Katz, Baltimore, MD, USA
Hyoung Woo Kim, Changwon, South Korea
Sebastian Kirsch, Wolfsburg, NI, Germany
Konstantin Klyukin, Lincoln, NE, USA
Peter Lamberg, Rochester, NY, USA
Feng Li, St Catharines, ON, Canada
Jun Liu, Richland, WA, USA
Wei Liu, Guangzhou, Guangdong, China
Daryl Ludlow, Lake George, NY, USA
Kazuhiro Manseki, Gifu City, Gifu, Japan
Luis Carlos Martínez, Lystrup, Denmark
Matthew Mayer, Berlin, BE, Germany
Melissa Menard, Garnerville, NY, USA
Danijela Milosevic, Independence, OH, USA
David Mitlin, Potsdam, NY, USA
Yukio Miyaki, Koriyama-shi, Fukushima, Japan
Shuji Nakanishi, Toyonaka, Osaka, Japan
Viktor Nemykin, Winnipeg, MB, Canada
Kerstin Neuhaus, Muenster, NW, Germany
Haryo Oktaviano, Jakarta Selatan, Indonesia
Cem Ornek, Stockholm, Sweden
Satoshi Oya, Sakai, Osaka, Japan
Geletu Qing, East Lansing, MI, USA
Abitha Ramesh, Education City, Doha, Qatar
Jorge Seminario, College Station, TX, USA
JIhoon Seo, Potsdam, NY, USA
Ashok Sharma, Gurgaon, HR, India
Yue Shen, Wuhan, Hubei, China
Nirala Singh, Santa Barbara, CA, USA
Sefik Suzer, Ankara, Turkey
Masao Suzuki, Toyota, Aichi, Japan
Takahisa Suzuki, Nagakute, Aichi, Japan
Youkun Tao, Shenzhen, Guangdong, China
Suqing Wang, Guangzhou, Guangdong, China
Zonghua Wang, Qingdao, Shandong, China
Wei Wu, Pittsburgh, PA, USA
Bingjun Xu, Newark, DE, USA
Fei Yao, Buffalo, NY, USA
Huaxiang Yin, Beijing, China
Greg Yoder, Sammamish, WA, USA
Seung-il Yoo, Huzhou City, China
Qibo Zhang, Kunming, China
Viktor Zhdankin, Duluth, MN, USA

## Student Members

Jonathan Adsetts, London, ON, Canada
Baian Almusned, London, ON, Canada
Alireza Amadianyazdi, Chicago, IL, USA
Hatem Amin, Oxford, Oxfordshire, UK
Mackenzie Anderson, Los Angeles, CA, USA
Martin Badley, London, ON, Canada
Mohsen Bahrami, London, ON, Canada
Nicole Bauer, Carrboro, NC, USA
Thomas Beckmann, Saint Louis, MO, USA
Matthew Bird, Nottingham, Notts, UK
Justin Bui, Fairfax, VA, USA
Dinara Burkhanova, London, UK
Karen Butler, Raleigh, NC, USA
Xiaosheng Cai, Oxford, Oxfordshire, UK
Sarah Calhoun, Raleigh, NC, USA
Joseph Carabetta, Liege, Liege Wallonie, Belgium
Korbua Chaisiwamongkhol, Oxford, Oxfordshire, UK
Pingping Chen, Manhattan, KS, USA
Yixi Chen, Bryan, TX, USA
Cameron Cheyne, Salt Lake City, UT, USA
Xinyi Chia, Singapore, Singapore
Christopher Choi, La Mirada, CA, USA
Stuart Cornes, Oxford, Oxon, UK
Filipe da Cruz, Diamantina, Minas Gerais, Brazil
Dany Danhausen, Kankakee, IL, USA
Vahid Dehnavi, Lonodn, Canada
Thao Do, Leamington, ON, Canada
Guillaume Dolphijn, Louvain-la-Neuve, Belgium
Jesse Dondapati, Thunder Bay, ON, Canada
Shuyu Dong, Kowloon, Hong Kong, China
Laszlo Eifert, Ulm, BW, Germany
Joseph English, Vancouver, BC, Canada
Hamideh Eskandari, Calgary, AB, Canada
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Narges Goudarzi, London, ON, Canada
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Ludwig Kraft, Muenchen, BY, Germany
Lea Kremer, Ulm, Germany
Joseph Lambert, Plainfield, IL, USA
Katelyn Lanasky, Plainfield, IL, USA
Heather Lange, Downers Grove, IL, USA
Hiu Ming Lau, Oxford, Oxfordshire, UK
Haonan Le, Oxford, Oxfordshire, UK
Mandy Le, London, ON, Canada
Pedro Leal, Teresina, Piaui, Brazil
Dongcheul Lee, Suwon, South Korea
Jiadong Li, Hong Kong, Hong Kong
Kun-Che Li, Taichung, Taiwan, Taiwan
Tiehuai Li, Hong Kong, Hong Kong
Xiuting Li, Oxford, Oxfordshire, UK
Meng Lin, Renens, VD, Switzerland
Zhiqiang Lin, Kowloon, Hong Kong, China
Abigail Linhart, Harvard, IL, USA
Paulette Loichet, Garching bei München, BY, Germany
Julia Long, Burke, VA, USA
Malin Ly, London, ON, Canada
Simon Malifarge, Vandoeuvre-les-Nancy, France

# NEW MEMBERS

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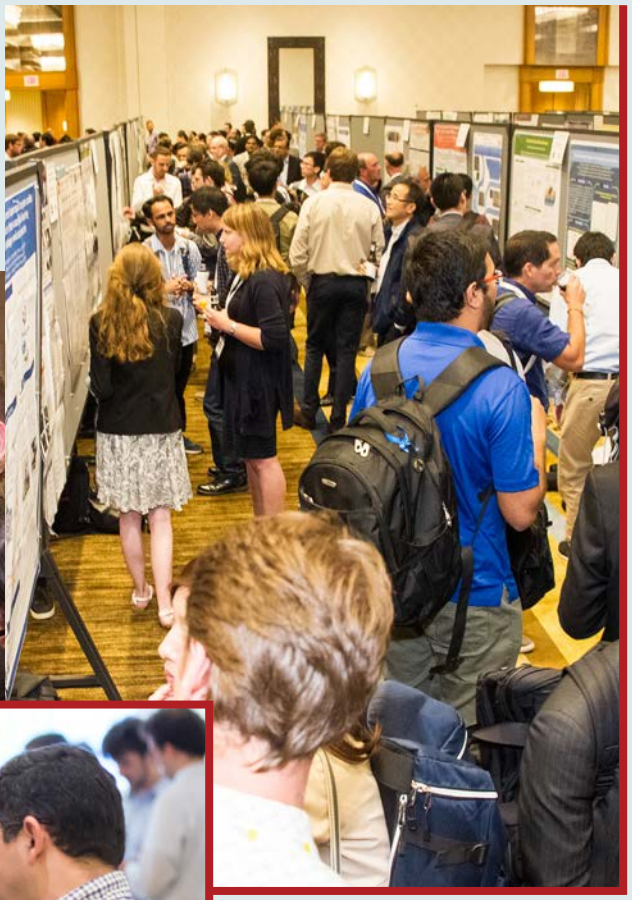
Zachary Messegee, Newport News, VA, USA
James Mitchell, Raleigh, NC, USA
Maryam Mohammad, London, ON, Canada
James Moulton, Stillwater, OK, USA
Advaith Murali, Los Angeles, CA, USA
Ehsan Nasr Esfahani, Seattle, WA, USA
Mojdeh Nikpour, Provo, UT, USA
Demian Njoku, Shenyang, Liaoning, PR, China
Benoit Notredame, Gembloux, Namur, Belgium
Amin Nouri Khorasani, Vancouver, BC, Canada
Edgar Olivera, Van Nuys, CA, USA
Maedeh Pahlevaninezhad, Calgary, AB, Canada
Mei-Chin Pang, London, UK
Bumjun Park, Notre Dame, IN, USA
Ana Flavia Petro, Bloomington, IN, USA
Victoria Petrova, La Jolla, CA, USA
Quang Hieu Pham, Daejeon, South Korea
Jason Quinn, Pefferlaw, ON, Canada
Amin Rabiei Baboukani, Miami, FL, USA
Elizabeth Raine, Oxford, Oxon, UK
Ilija Rasovic, Oxford, Oxfordshire, UK
Hang Ren, Salt Lake City, UT, USA
Yuxun Ren, Hong Kong, Hong Kong
Karsten Richter, Stuttgart, BW, Germany
Thomas Rickhoff, Homewood, IL, USA
Mylène Robert, Nancy, France
Griffin Ruehl, Seattle, WA, USA
Maria Salinas, Cicero, IL, USA
Christoph Schmidt, Garching bei Muenchen, BY, Germany
Shaghayegh Shajari, Calgary, AB, Canada
Jordan Shanahan, Alsip, IL, USA
Brian Sherry, Joliet, IL, USA
Jennifer Shin, London, ON, Canada
Sapna Sinha, Oxford, Oxfordshire, UK
Rebecca Skelton, Jetersville, VA, USA
Kirk Smith, Oxford, Oxfordshire, UK
Sean Smyth, Lemont, IL, USA
Michael Spencer, Raleigh, NC, USA
Matteo Stefanoni, Zurich, ZH, Switzerland
Matthew Stewart, Cambridge, MA, USA
Michael Striednig, Garching, BY, Germany
Akshay Subramaniam, Seattle, WA, USA
Vinsensia Sugiawati, Marseille, France
Aaron Taggart, Chapel Hill, NC, USA
Ran Tao, Kowloon, Hong Kong, China
Andrew Thompson, Oakland, CA, USA
Shruthi Tiruchirapalli Kumar Raj, East Lansing, MI, USA
Guelen Tok, Garching bei Muenchen, BY, Germany
Claire Tully, London, ON, Canada
Hannes Van Avermaet, Ghent, Oost-Vlaanderen, Belgium
Peter VanNatta, Salt Lake City, UT, USA
Ian VonWald, Chapel Hill, NC, USA
Frank Vukaj, Davison, MI, USA
Yong Wang, Singapore, Singapore
Yeting Wen, Columbia, SC, USA
Lauren Werth, Lockport, IL, USA
Jonathan Wong, Mississauga, ON, Canada
Katherine Wortman-Otto, Minneapolis, MN, USA
Yuan Xu, Kowloon, Hong Kong
Liuqing Yang, London, ON, Canada
Tianrang Yang, Columbia, SC, USA
Bin Yao, Santa Cruz, CA, USA
Lina Yao, London, ON, Canada
Yalda Zamani Keteklahijani, Calgary, Canada
Benjamin Zhang, Somerville, MA, USA
Jingtian Zhang, Seattle, WA, USA
Tao Zhang, Kowloon, Hong Kong, China
Zongliang Zhang, Salt Lake City, UT, USA
Dan Zhu, Los Angeles, CA, USA
Ziyan Zhu, London, ON, Canada
Tala Zubi, Tinley Park, IL, USA
Tanja Zuend, Garching, BY, Germany

# ECS STUDENT PROGRAMS



## Awarded Student Membership

ECS Divisions offer Awarded Student Memberships to qualified full-time students.

To be eligible, students must be in their final two years of an undergraduate program or enrolled in a graduate program in science, engineering, or education (with a science or engineering degree). Postdoctoral researchers are not eligible.

Memberships include generous meeting discounts, an article pack with access to the ECS Digital Library, a subscription to *Interface*, and much more.

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**▶Deadline**
Renewable yearly

**▶Note**
Applicants must reapply each year

## Travel Grants

Several of the Society's divisions and sections offer Travel Grants to students, postdoctoral researchers, and young professionals presenting papers at ECS meetings.

Please be sure to review travel grant requirements for each division and section. In order to apply for a travel grant, formal abstract submission is required for the respective meeting you wish to attend.

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## Summer Fellowships

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Please visit the ECS website for complete rules and nomination requirements.

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**▶Deadline**
*January 15*

# Student Chapter News

## Belgium Student Chapter

In its last group activity of the year, the **ECS Belgium Student Chapter** paid a visit to Umicore—more specifically, to the corporate R&D department and the Rechargeable Battery Materials business unit formerly known as Union Minière. While the headquarters of this multinational materials technology company is based in Brussels, the chapter was offered a visit at the Olen site near Antwerp, Belgium.

Umicore graciously hosted a lunch and on-site tour for the chapter. In exchange, Umicore asked only that the ECS members describe their PhD or postdoc research topics. The visit began with an introductory presentation of Umicore by Daniël Nelis and Randy De Palma, which was followed by a short presentation by each of the ECS members present.

Following these interesting discussions, the group was guided through parts of the site to observe the various stages of precious metal recycling, including the purification of germanium and its processing into either high-purity crystals or Ge semiconductor wafers through the Czochralski crystal pulling method. Umicore has been acquiring vast knowledge and know-how in precious metal recycling since the beginning of the twentieth century, when Union Minière's primary occupations consisted of mineral mining and refinement. On top of that, the chapter was introduced to the energy storage activities at Umicore, since Umicore is one of the leading companies in the development and manufacturing of battery cathode materials.


*ECS Belgium Student Chapter members visited the Umicore facility in Olen, Belgium.*

## Calgary Student Chapter

**Dr. Hector Abruna** *presented a talk to the attendees of the workshop on in operando electroanalytical techniques at the University of Calgary.*

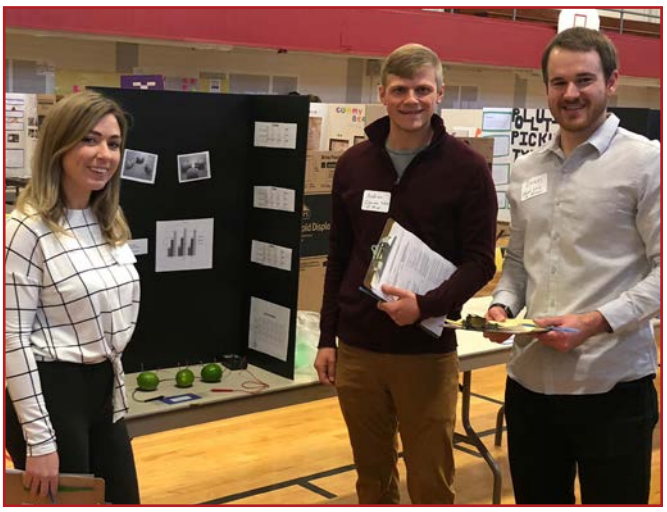
The **ECS Calgary Student Chapter** organized several events for Dr. Hector Abruna's visit in February 2017. Dr. Abruna is the Emile M. Chamot Professor of chemistry and the director of the Energy Materials Center at Cornell University. The morning workshop covered in operando electroanalytical techniques, including a refresher of electrochemistry fundamentals. Over 40 people attended the workshop, along with 9 new members, mainly from the Department of Chemistry and the Schulich School of Engineering at the University of Calgary.

In the evening, 20 graduate students and postdoctoral fellows participated in a social event during which they met with Dr. Abruna to discuss their current research as well as possible career pathways in electrochemistry.

## Colorado School of Mines Student Chapter

On January 19, 2018, members of the **ECS Colorado School of Mines Student Chapter** volunteered as science fair judges at Colorado STEM Academy in Westminster, CO. One of the chapter's goals and collective interests is community outreach—discussing science with the next generation of scientists. The chapter was pleasantly surprised to encounter several electrochemistry projects at the fair, including one observing the rate of electrolysis in different electrolyte solutions and another involving a lime battery. Many of the middle school students were enthusiastic about learning. The chapter believes in the importance of supporting and encouraging the students of the future and found it rewarding to see the progress schools and students are making in science.

The chapter also hosted a social event this past fall to say farewell to its previous student chapter president, Tara Pandey, as he moved on from graduate school to start his career. The event was graciously sponsored by ECS and served as a great setting for bringing together graduate students from different departments to discuss electrochemistry and graduate student life. The chapter found that this provided a great opportunity for members to learn from one another and build upon each other's ideas and successes.



*At Colorado STEM Academy's science fair, judges from the ECS Colorado School of Mines Student Chapter came across a battery made from limes. From left to right:* **Jessica Hoffman**, **Andrew Motz**, *and* **Evan Reznicek**.

## Hong Kong University of Science and Technology Student Chapter

On November 29, 2017, the **ECS Hong Kong University of Science and Technology Student Chapter** had the pleasure of hosting Prof. Peter Pintauro from Vanderbilt University and Dr. Adam Weber from Lawrence Berkeley National Laboratory. During their visit, Prof. Pintauro and Dr. Weber gave lectures in a themed workshop on fuel cells, electrolyzers, and flow batteries.

Before the workshop, Prof. Pintauro and Dr. Weber met with some members of the student chapter. The faculty advisor of the student chapter, Prof. Minhua Shao, hosted the meeting. The students shared their current research projects on energy conversion and storage. Prof. Pintauro and Dr. Weber also shared their insights on career development.


*Members of the ECS Hong Kong University of Science and Technology Student Chapter with their guest speakers (left to right):* **Shangqian Zhu**, *chapter vice president,* **Sitong Jia**, **Yao Yao**, **Yuze Yao**, **Prof. Minhua Shao**, **Prof. Peter Pintauro**, **Dr. Adam Weber**, **Wai Leong Mickey Chan**, **Jiadong Li**, *and* **Gabriel Nambafu**.

## University of Kentucky Student Chapter

The **ECS University of Kentucky Student Chapter** hosted Tobias Glossmann from Mercedes-Benz on October 8, 2017. His seminar, titled "Battery Research Opportunities Today and in the Future—Mercedes-Benz Perspective," gave insights into fast charging liquid electrolytes versus solid state electrolytes, mechanical analysis of cells, and battery thermal management. Glossmann also discussed energy storage research with Prof. Y. T. Cheng's group and visited the advanced pouch cell facilities at the Center for Applied Energy Research of the University of Kentucky. Glossmann's seminar was a campus-wide event attended by faculty and students from both the College of Engineering and the College of Arts & Sciences at the University of Kentucky.

*ECS University of Kentucky Student Chapter members with their guest speaker (left to right):* **Doo Young Kim**, *chapter faculty advisor,* **Yan Sun**, **Dingying Dang**, **Jiazhi Hu**, *chapter secretary,* **Xiaowen Zhan**, *chapter president,* **Tobias Glossmann**, *guest speaker,* **Yikai Wang**, **Shuang Gao**, *chapter vice president, and* **Andrew Meyer**.

## Montreal Student Chapter

On December 1, 2017, the **ECS Montreal Student Chapter** hosted a unique mini-symposium that focused on electrochemical flow systems. The event was designed both for people taking their first steps into the world of flow electrochemistry as well as for seasoned electrochemists wishing to broaden their knowledge and learn new tricks. Over 40 registered attendees enjoyed two talks by invited speakers Dr. Tomer Noyhouzer and Dr. Samuel C. Perry at the Notman House, one of Montreal's leading innovation hubs.

Dr. Noyhouzer covered all fundamental aspects associated with developing an experimental electrochemical flow system, including common troubleshooting techniques and up-to-date examples. Dr. Perry focused on the theoretical side, explaining how to approach the topic from a simulation point of view and the advantages it can provide. The event concluded with a stimulating Q&A session and a successful networking event.

*ECS Montreal Student Chapter committee members with their invited speakers (left to right):* **Lisa I. Stephens**, **Dr. Samuel C. Perry**, **Samantha M. Gateman**, **Dr. Tomer Noyhouzer**, *and* **William Odette**.

## Missouri University of Science and Technology Student Chapter

The Society officially welcomed the **ECS Missouri University of Science and Technology Student Chapter** on October 5, 2017. The new chapter currently has 12 student members and 3 faculty advisors. Since the chapter's foundation, its members have been hard at work making their presence known within their academic community and the ECS community. To learn more, contact them at ecsmst@gmail.com.

In November 2017, the chapter held its first seminar in the Chemistry Department of Missouri S&T. Invited speaker Dr. Jay A. Switzer, a senior investigator in electrochemistry in the Materials Research Center at Missouri S&T, delivered a talk about epitaxial lift-off of electrodeposited single-crystal gold foils for flexible electronics. The seminar was open to undergraduate and graduate students, faculty, and research staff.

During the 60-minute talk, the seminar was filled with lively discussions amongst students and researchers on the aspects of electrodeposition of epitaxial single crystals.

The student chapter is grateful for Dr. Switzer's time and presentation. The chapter would also like to thank all the supporters of this seminar.

**Dr. Jay A. Switzer** *engaged in a seminar talk.*


*Members of the ECS Missouri University of Science and Technology Student Chapter (left to right):* **Apurv Saxena**, **Yufang He**, **Susmita Sarkar**, *chapter secretary*, **Jie Li**, **Meagan Kelso**, **Siddesh Umapathi**, **Dr. Jay A. Switzer**, **Prashanth Sandineni**, *chapter treasurer*, **Dr. Manashi Nath**, **Dr. Amitava Choudhury**, **Umanga de Silva**, **Xi Cao**, *chapter president*, **Maalavan Arivu**, *chapter vice president*, **Charles Abbey**, *and* **Qingzhi Chen**.

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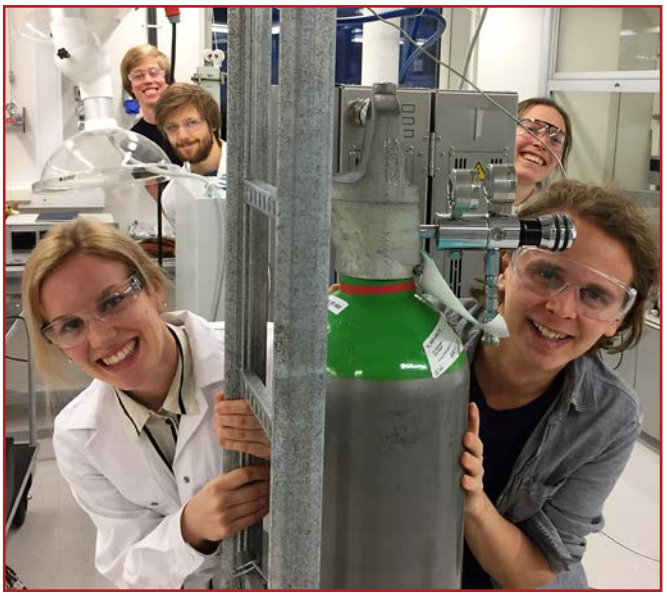
## Norwegian University of Science and Technology Student Chapter

Big things are happening for the **ECS Norwegian University of Science and Technology Student Chapter** in Trondheim, Norway. The university's battery group is growing fast, with five new PhD candidates and seven master's students starting last fall and additional scholars coming this spring. Some of the new PhD candidates proved themselves by producing a Mg/Li-ion hybrid battery cake during the annual department cake contest, held on December 18, 2017. The Mg chocolate anode and spinel-LMO carrot cathode demonstrated excellent gastronomical performance and won the prestigious contest.

With a brand new battery lab up and running, it is possible that this is not the last ECS will hear from these aspiring PhD candidates.


*The winning hybrid battery cake.*



*The creators of the hybrid battery cake (left to right):* **Elise Ramleth Østli**, **Henning Kaland** *(back)*, **Daniel Tevik Rogstad**, **Ingeborg Treu Røe**, *and* **Jacob Hadler-Jacobsen**.

## Ohio University Student Chapter

The **ECS Ohio University Student Chapter** has been active since May 2011. In its nearly six and a half years as a chapter, Dr. Gerardine G. Botte, distinguished professor at Ohio University, director of the Center for Electrochemical Engineering Research, and ECS fellow, has served as the chapter's advisor.

The chapter has maintained its goals of (1) educating students in the field of electrochemistry and solid state science and technology and keeping them informed of the latest trends in the field, (2) attracting the next generation of students into science and engineering with emphasis in electrochemical science and technology, and (3) serving


*Center for Electrochemical Engineering Research students and faculty with Dr. Daniel Scherson after his talk at Ohio University (left to right):* **Ali Yazdani**, **Dr. John Staser**, **Fazel Bateni**, **Ben Sheets**, **Behnaz Jafari**, **Dr. Daniel Scherson**, **Ashwin Ramanujam**, **Dr. Gerardine Botte**, **Dr. Madhivanan Muthuvel**, **Mohiedin Bagheri**, **Mahtab Naderi**, **Mohammedreza Rostami**, **Xiang Lyu**, **Raziyeh Ghahremani**, **Davoud Ghazanfari**, *and* **Payman Sharifi**.

as an entity to promote activities related to the field of electrochemistry within the university and the community. The chapter also performs activities that encourage discussion and interaction with leading scientists in electrochemistry and electrochemical engineering.

On September 22, 2017, the chapter hosted Dr. Daniel Scherson, a Frank Hovorka Professor of Chemistry from Case Western Reserve University in Cleveland, OH. Dr. Scherson gave a seminar lecture for the Russ College of Engineering's chemical and biomolecular engineering graduate students and faculty. The title of the lecture was "Biofuel Cell Powered Autonomous Insect Cyborgs." After the lecture, Dr. Scherson joined the student chapter committee over lunch for an informal discussion during which he shared his cognizance in electrochemistry. The overall experience was extremely educational, providing the chapter new perspectives about the field of electrochemistry. The chapter is grateful that Dr. Scherson was able to volunteer his time amidst his busy schedule.

Also, on October 13, 2017, an election was held to elect the new student chapter officers for the 2017-2018 term. The newly elected chapter office-bearers are Behnaz Jafari, president; Ashwin Ramanujam, vice president; Mohiedin Bagheri, treasurer; and Davoud Ghazanfari, secretary. The officers meet on a weekly basis to organize lectures, events, and tours that will help educate members and spread knowledge of electrochemistry to society. The newly appointed committee thanks the members of the previous committee for their valuable service during their tenure.

## Research Triangle Student Chapter

The **ECS Research Triangle Student Chapter** is an intercollegiate student chapter shared between the University of North Carolina-Chapel Hill, North Carolina State University, and Duke University. The chapter continued its tradition of hosting an annual student poster competition. The fifth annual Triangle Student Research Competition was held on October 4, 2017, in the Frontier building in Research Triangle Park. This year, over 60 poster presenters from UNC, NCSU, and Duke met to showcase their work relating to materials science and/or electrochemistry.

The competition's mission is to bring together students from universities within the Research Triangle area as well as industry partners to discuss their recent scientific findings and network. The evening was broken up into two 45-minute sessions, allowing time for networking and a buffet-style dinner provided by Mediterranean Deli and scheduled during the interim. Top prizes were awarded for posters selected in five categories: (1) biomaterials, (2) electrochemistry, devices and sensors, (3) modeling computation and theoretical simulations, (4) materials characterization, and (5) methods for making new materials.

This event would not have been possible without help from multiple sources. The chapter worked with local chapters of the Materials Research Society in organizing and sponsoring this intercollegiate event. Major funding sources for the event included the NCSU Chemistry Department, the UNC Chemistry Department, and Duke's Electrical and Computer Engineering Department. Becton Dickinson and Eastman Chemical Company were the major industrial partners of this event; they provided funding as well as poster judges. Other judges for this year's event included scientists from local industrial companies, such as Additive Medical Technologies, LLC, inSeption Group, Allergen, and Liquidia, as well as professors and postdocs from NCSU, UNC, and Duke.

## University of Maryland Student Chapter

On January 14, 2017, the **ECS University of Maryland Student Chapter** sent representatives Griffin Godbey, Nico Eidson, Dr. Yaoyu Ren, and Yevgeniy Ostrovskiy to team up with researchers at the National Institute of Science and Technology to participate in the youth educational program Adventures in Science. AIS is a volunteer program sponsored on the NIST campus in Gaithersburg, MD, in which participants design and run a demonstration for grade school students to promote interest in science and engineering. The chapter collaborated with Dr. Trevor Braun to demonstrate electroplating using pennies and copper/brass plates using a 9V battery as a power source based on the success of last year's demonstration at AIS. The students measured the current supplying the electroplating reaction to attempt to backwards calculate Faraday's constant. Additionally, students got to experience the electroplating of pennies with zinc. Further quenching allows the zinc and copper to produce a gold colored penny, so each student got to take home a silver and gold penny. By participating in AIS, the chapter hopes to nurture young students' interest in science and, more specifically, in electrochemistry.

## University of Washington Student Chapter

For the past two summers, the **ECS University of Washington Student Chapter** has hosted the Coffee & Electrochemistry book series, which encourages students and faculty members to get together and learn electrochemistry. Each week, the members met in the library for coffee and a student-led discussion focused on chapters of Prof. Newman and Dr. Thomas-Alyea's *Electrochemical Systems*. Coming together to discuss a range of important electrochemical engineering topics—from thermodynamics to electrode kinetics and mass transport—helped students learn and/or relearn electrochemical basics while also building a community across departments at the University of Washington.

In October 2017, the chapter held its first voting elections since its founding in 2015, and Jerry Chen took over as president of the chapter. The chapter experienced explosive growth and interest that propelled the chapter to become of the 2017 ECS Chapters of Excellence. The chapter plans to expand on the biweekly educational meetings, outreach to K-12 students, and professional development events that were held in the past year to grow its reach across campus and the Pacific Northwest.

The first Coffee Talk event was held in November 2017, when visiting instructor Prof. Daniel Steingart from Princeton University met with over 20 students for questions and discussion that covered topics from his work with multiple start-up companies to future trends in electrochemistry. The Coffee Talk event planned for December 2017 featured Prof. Elizabeth J. Biddinger from the City College of New York, whose exciting work applies green chemistry and sustainability to electrochemistry applications. Also in December 2017, the chapter hosted a workshop on creating a personal website for building a professional online presence.

**Jonathan Michael Witt** *(left) and* **Brian Gerwe** *(right) led the Coffee & Electrochemistry book series discussion.*

**Prof. Daniel Steingart** *from Princeton University shared his research and start-up experience with the ECS University of Washington Student Chapter.*

## University of Western Ontario Student Chapter

The **ECS University of Western Ontario Student Chapter** was established in October 2017. The chapter held its inaugural event on December 15, 2017, in the form of its first annual graduate student symposium. The event featured 20-minute presentations from two of the section's faculty advisors, Dr. Jamie Noël and Dr. David Shoesmith. Dr. Noël opened the symposium by giving an orientation to ECS, including an explanation of all the benefits and opportunities offered by the Society. Dr. Shoesmith gave a more technical talk to begin the afternoon session, in which he explained the different surface analytical techniques available at the university to augment electrochemical studies. Graduate students and postdoctoral fellows provided the rest of the oral presentations. The presentations ranged between 10 and 15 minutes and featured 2 presentations by postdocs, 6 by PhD candidates, and 3 by MS candidates. Various topics were covered, including but not limited to corrosion, solar cell optimization, scanning electrochemical microscopy, and electrogenerated chemi-luminescense of both carbon and graphene-based quantum dots. After each presentation, the presenters and symposium attendees engaged in a discussion regarding the presented material to ensure a thorough understanding of the techniques displayed and an inclusive learning atmosphere. This format allowed for discussion of various electrochemical and surface analytical techniques along with problems these techniques can be used to solve. Discussions stimulated ideas for each of the symposium attendees for possible future experiments. The symposium also included a lunch social with food provided by the chapter. This allowed members to socialize and enabled conversations to continue during the lunch period.

At the conclusion of the symposium, the members of the chapter participated in an organizational meeting to discuss the future direction of the student chapter. Ideas were brainstormed for future events to ensure that members receive the greatest possible benefit from chapter events. An election process was also established for replacing members of the executive committee when current committee members graduate. Overall, the symposium's huge success should promote further participation in chapter events and foster an atmosphere that creates membership growth in the future.

The chapter would like to acknowledge the financial and technical support of ECS, Surface Science Western, and the Surface Science Division of the Chemical Institute of Canada.

*Executive committee of the ECS University of Western Ontario Student Chapter (left to right):* **Jeff Henderson**, *president,* **Joseph Turnbull**, *vice president,* **Dan Guo**, *secretary, and* **Matthew Turnbull**, *treasurer.*

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