Institute for Soldier Nanotechnologies

Founded in 2002, the Institute for Soldier Nanotechnologies (ISN) is a three-member team designed to leverage the unique capabilities of the US Army, industry, and MIT. The ISN mission is to help the army dramatically improve the survivability of its soldiers by working at and extending the frontiers of nanotechnology through basic research, and by transitioning promising outcomes of that research in collaboration with our army and industry partners. This mission includes not only decreasing the weight that soldiers carry but also improving blast and ballistic protection, creating new methods of detecting and detoxifying chemical and biological threats, and providing physiological monitoring and medical treatment. The ultimate goal is to help the army create integrated systems of nanotechnologies that combine high-tech protection and survivability capabilities with low weight, increased comfort, improved performance, and better compatibility with the end user.

Army funding for ISN basic research is approximately $135 million over 15 years dispensed through renewable five-year contracts administered by the US Army Research Office (ARO). There is also substantial co-investment by industry partners and MIT. Following a series of reviews by the army, ISN was approved for its third five-year contract in 2012. The contract for ISN-3 was signed on December 27, 2012. The renewal process for ISN-4 is currently underway. If awarded, the new contract will begin on January 1, 2018.

Approximately 30 faculty members from 12 MIT academic departments, as well as more than 100 graduate students and postdoctoral associates, participate in ISN research. ISN research results in more than 125 refereed publications annually in distinguished scientific journals including *Science*, *Advanced Materials*, *Nature*, *Physical Review Letters*, and the *Proceedings of the National Academy of Sciences*. Additionally, more than 350 people have visited ISN over the past year for briefings on research endeavors and tours of ISN facilities. Most notably, General Dennis Via, Commanding General of the US Army Materiel Command, visited ISN headquarters in February 2016, while in April 2016, the ISN director was selected to brief US Secretary of Defense Dr. Ashton Carter during his visit to the MIT campus.

Research

ISN's signature interdisciplinary research agenda evolved over the course of its first 10 years into a focused program reflecting the areas where ISN and the army see the potential for especially strong soldier impacts. For ISN-3, this structure is further updated and redefined to better align with and more efficiently respond to guidance from the army while working within the constraints of army budget reductions. Team-based innovation is a hallmark of ISN's intellectual course, with new ideas and collaborations emerging frequently. The ISN research portfolio is currently divided into three strategic research areas (SRAs) that are, in turn, further divided into research themes.

Strategic Research Area 1: Lightweight, Multifunctional Nanostructured Materials and Fibers

Strategic Research Area 1 emphasizes the creation of nanoscale and nanostructured building blocks to provide diverse protective capabilities.

- Theme 1.1: Optoelectronic Phenomena in Nanoparticles
- Theme 1.2: Photonic Structure in Atomic Monolayers
- Theme 1.3: Elementary Excitations and Dynamics in Fiber Platforms
- Theme 1.4: Optical Resonance Phenomena in Nanostructured Materials
- Theme 1.5: Novel Photonic Crystal and Metamaterial Phenomena

Strategic Research Area 2: Soldier Medicine—Prevention, Diagnostics, and Far-Forward Care

Strategic Research Area 2 focuses on medical diagnostics and treatment for soldiers with particular emphasis on enabling far-forward and remote area care. Far-forward and remote area care include immediate as well as longer-term treatment of battlefield injuries.

- Theme 2.1: Cellular Immune Response and Nanoengineered Drug Delivery
- Theme 2.3: Synthesis and Characterization of Therapeutic Nanoengineered Materials

Strategic Research Area 3: Multiple Blast and Ballistic Threats—Materials Damage, Human Injury Mechanisms, and Lightweight Protection Systems

The aim of Strategic Research Area 3 is to develop new, lighter-weight protective materials systems for improved protection from blast, ballistic, and blunt trauma, as well as to obtain increased understanding of materials failure and human injury caused by blast and other forms of mechanical energy. This understanding is used to guide the design and formulation of novel protective materials with potential applications for the dismounted and the mounted soldier.

- Theme 3.2: Grain and Phase Boundary Manipulation in Nanocrystalline Metal Alloys
- Theme 3.3: Physical, Biological, and Physiological Mechanisms of Injury
- Theme 3.5: Novel Carbon-Based Nanostructured Materials

Transitioning

ISN places a strong emphasis on basic research. However, the transitioning of promising outcomes of that research is also a crucial component of our mission. To this end, ISN works with the army, industry partners, startups and other companies, and with the MIT Technology Licensing Office to help assure that promising ISN innovations leave the lab and make it into the hands of soldiers and first responders as rapidly and efficiently as possible. ISN is pleased to count an army research laboratory officer—Army Research Office Technology Transfer Officer (TTO)—among our full-time headquarters team. It is the TTO's charge to help maximize the effectiveness and efficiency with which ISN technologies progress from the laboratory bench to more advanced stages of development.

Over the past year, ISN has been the source of several highly important technology transitions. Very notable is the recently announced Advanced Functional Fabrics of America (AFFOA) Manufacturing Innovation Institute, founded by the US Department of Defense in response to a team proposal led by MIT. AFFOA is a part of the National Network for Manufacturing Innovation championed by the Obama Administration, and is based on foundational ISN research led by ISN-affiliated MIT faculty member Professor Yoel Fink.

A Small Sampling of ISN Research Accomplishments

Miniature Quantum Dot-Based Spectrometer

Optical spectrometers are fundamental tools for materials analysis across many scientific fields. Challenges exist, however, in making these devices small, simple, and inexpensive. ISN faculty member Moungi Bawendi, working with former postdoctoral associate Jie Bao—now a professor at Tsinghua University in Beijing—has devised a possible solution to these challenges. By using a planar array of quantum dots, Professor Bawendi's device obviates the need for complex optics, allowing different spectra to be distinguished using hundreds of quantum dot materials that each filter a specific set of wavelengths of light. Further details of this work have been published in a scholarly article in the journal Nature (Jie Bao and Moungi G. Bawendi, "A Colloidal Quantum Dot Spectrometer," *Nature* 523, no. 7558 [2015]: 67–70, doi: 10.1038/nature14576).

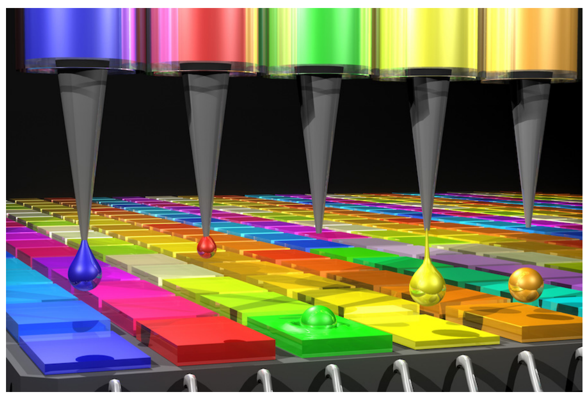

Fig. 1: Filters are a necessary component of spectrometers. Illustrated here, the QD spectrometer prints these filters out of liquid droplets. Image: Mary O'Reilly.

The Experimental Observation of Weyl Points

Despite their theoretical prediction by noted German physicist and mathematician Hermann Weyl in 1929, building on earlier work by English physicist Paul Dirac, "Weyl points," as they came to be known—massless subatomic particles—escaped experimental observation for some 86 years. In early 2015, an international team of scientists led by Professor Marin Soljačić and Professor John Joannopoulos, director of ISN, was able to announce the detection of Weyl points through a process relying upon a gyroid photonic crystal precisely designed to produce such particles. While the full ramifications of the observation of Weyl points are not yet known, they could lead to improved high-power single frequency lasers as well as optical materials that provide angular selectivity for filtering light regardless of its 3-D angle of incidence. Further details of this work have been published in a scholarly article in the journal *Science* (Ling Lu, Zhiyu Wang, Dexin Ye, Lixin Ran, Liang Fu, John D. Joannopoulos, and Marin Soljačić, "Experimental Observation of Weyl Points," *Science* 349, no. 6248, [2015]: 622–624, doi: 10.1126/science.aaa9273).

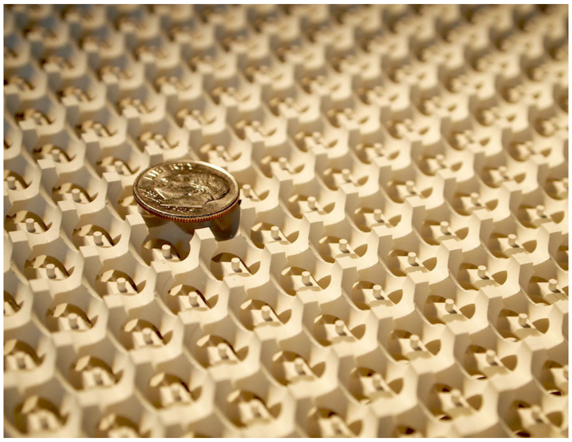

Fig. 2: A novel photonic crystal design, shown above with a dime for scale, was critical to the manifestation of Weyl points. Image courtesy of the researchers.

Implantable Sensor for Real-Time Cancer Treatment Monitoring

Despite rapid advancements in chemotherapy agents, radiation, and other cancer-fighting treatments, physicians' means of monitoring the efficacy of these treatments has failed to progress at a similar rate. In most cases, oncologists rely on tissue biopsies to gauge the state of a tumor and the progress of treatment. These biopsies can provide very accurate information, but that information is locked to a single point in time, and the invasive nature of biopsies makes multiple measurements a risky proposition. Now, a team led by ISN-affiliated MIT professor Michael J. Cima has developed an implantable sensor that can measure the pH level and oxygen content of a tumor, providing real-time monitoring to better determine the effectiveness of therapy and allow for rapid adjustments to the treatment plan. Further details of this work have been published in a scholarly article in the journal *Lab on a Chip* (Christophoros C. Vassiliou, Vincent H. Liu, and Michael J. Cima, "Miniaturized, Biopsy-Implantable Chemical Sensor with Wireless, Magnetic Resonance Readout," *Lab on a Chip* 15, no. 17 [2015]: 3465–3472, doi: 10.1039/c5lc00546a).

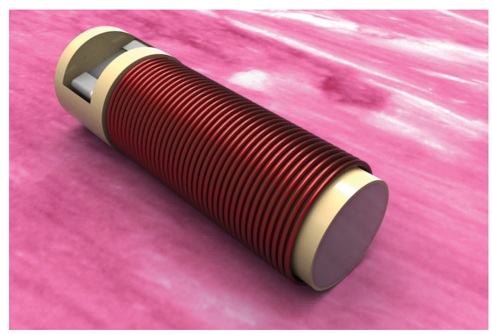

Fig. 3: An illustration of the newly developed sensor, which could be implanted in a patient for real-time monitoring of treatment. Image courtesy of the researchers.

Plasmonic X-Ray Generation

X-rays, nearly ubiquitous in a variety of imaging applications, have been produced by the same means for over a century. Now, a team of scientists led by Professor John Joannopoulos, director of ISN, and ISN-affiliated Professor Marin Soljačić has theoretically demonstrated that it should be possible to efficiently generate X-rays by harnessing the unique properties of graphene, a honeycomb-structured form of carbon one atom thick. Similar to lasers, the X-rays produced should be both very uniform in their wavelengths and very tightly aligned. This ISN research implies that this plasmonic generation method should be able to produce types of X-rays that typically require large and expensive equipment to create. The method should also be capable of generating light at wavelengths outside the X-ray regime, leading to a host of additional potential applications. Work is underway to achieve experimental confirmation of the theoretical work. Further details of this research have been published in a scholarly article in the journal *Nature Photonics* (Liang J. Wong, Ido Kaminer, Ognjen Ilic, John D. Joannopoulos, and Marin Soljačić, "Towards Graphene Plasmon-Based Free-Electron Infrared to X-Ray Sources," *Nature Photonics* 10, no. 1 [2016]: 46–52, doi: 10.1038/nphoton.2015.223).

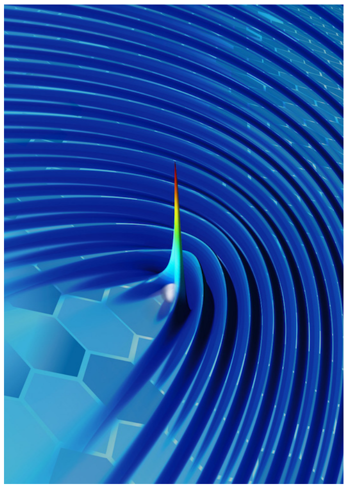

Fig. 4: Laser irradiation of a graphene sheet can generate surface waves called plasmons, which can in turn "wiggle" a free electron to generate a sharp pulse of light that can be tuned to wavelengths from infrared to X-rays. Image courtesy of the researchers.

Hydrogel Bandages Equipped with Sensors and Drug Reservoirs

A team of researchers led by ISN-affiliated Professor Xuanhe Zhao has devised a new type of hydrogel-based wound dressing that could be equipped with a variety of sensors, lights, and drug delivery tools. Professor Xuanhe Zhao's hydrogel material is more than 90% water and boasts an impressive degree of biocompatibility, so that the material could not only be used on the body's surface, but eventually for implantable systems. A *smart* bandage of electronic devices embedded in a hydrogel matrix could detect changes in a patient's status, administer medications as needed, and send signals to caregivers. Further details of this work have been published in a scholarly article in the journal *Advanced Materials* (Shaoting Lin, Hyunwoo Yuk, Teng Zhang, German A. Parada, Hyunwoo Koo, Cunjiang Yu, and Xuanhe Zhao,

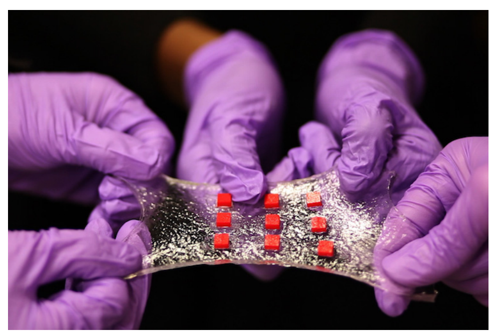

Fig. 5: Tough, water-based hydrogel bandages could be equipped with a variety of sensors and drug-containing wells. Image: Melanie Gonick/MIT.

"Stretchable Hydrogel Electronics and Devices," *Advanced Materials* 28, no. 22 [2016]: 4497–4505, doi: 10.1002/adma.201504152).

Historically Black Colleges and Universities and Minority Institutions Program

In 2007, with Professor Paula Hammond as program director, ISN began a program to engage faculty and students from historically black colleges and universities and minority institutions (HBCU-MIs) in research in support of the ISN mission. This program funds peer-reviewed basic research projects at HBCU-MIs and facilitates collaborations between HBCU-MIs and ISN scientists. Also, visiting faculty and students from HBCU-MIs utilize ISN research facilities. Currently, ISN funds two faculty-led projects through its HBCU-MI program; one at the City College of New York, the other at Howard University.

Army Collaboration

Army research partners are vital to the ISN mission. They collaborate on basic and applied research, provide guidance on the soldier relevancy of ISN projects, and participate in transitioning (i.e., the technological maturation and scale-up of the outcomes of ISN basic research). ISN has collaborated with many army science and technology laboratories and centers, including:

- Armament Research, Development, and Engineering Center at Picatinny Arsenal
- Army Research Laboratory (including the Army Research Office, Computational and Information Sciences Directorate, Human Research and Engineering Directorate, Sensors and Electron Devices Directorate, and Weapons and Materials Research Directorate)
- Aviation and Missile Research, Development, and Engineering Center
- Communications-Electronics Research, Development, and Engineering Center
- Defense and Veterans Brain Injury Center
- Edgewood Chemical/Biological Center
- Madigan Army Medical Center
- Natick Soldier Research, Development, and Engineering Center
- Program Executive Office—Soldier
- Tank Automotive Research, Development, and Engineering Center
- US Army Corps of Engineers
- US Army Research Institute of Environmental Medicine
- Walter Reed Army Institute of Research

Other Department of Defense and Government Collaboration

While ISN's first customer remains the soldier, many research projects have broad appeal to not only the Department of Defense but also other government agencies.

Collaborations and interactions have occurred with a number of the army's sister services and other US government entities, such as:

- Camp Roberts
- Deployed Warfighter Protection Program
- Naval Postgraduate School
- Naval Sea Systems Command
- US Air Force Medical Service
- US Air Force Special Operations Command
- US Department of Agriculture
- US Food and Drug Administration
- US Special Operations Command
- Walter Reed National Military Medical Center

Industrial Collaboration

Industry partners are critical to the ISN mission, helping turn innovative results of basic research into real products and scale them up for affordable manufacture in quantities needed by various end users. ISN industry partners include:

- Center for Integration of Medicine and Innovative Technology
- FLIR Systems
- JEOL USA
- Lockheed Martin
- Nano-C
- Raytheon
- Total American Services
- Triton Systems
- VF Corporation
- Xtalic

Outreach Activities

Soldier Design Competition

The ISN Soldier Design Competition (SDC) was established in 2003 to engage MIT undergraduates in the activities of ISN and, in 2004, was expanded to include cadets from the United States Military Academy at West Point (USMA). The SDC provides a unique opportunity for students to apply their knowledge and creativity, while gaining hands-on experience in the design and prototyping of technology solutions to problems faced by today's soldiers and first responders. Teams compete for prize money donated by industry companies that have included Boeing, General Dynamics, L-3 Communications, Lockheed Martin, QinetiQ North America, Raytheon, and W. L. Gore and Associates. Each year, a panel of leaders from the army, industry, and MIT determines the winning prototypes.

SDC participants meet active duty soldiers and marines, and develop perspective on how modern technology can help the US military as well as fire fighters, law enforcement officers, and other emergency response personnel. Army mentors provide SDC team members with advice on the military relevancy and technical viability of proposed technology solutions. Finalists are judged according to the technical design practicality, innovativeness, likely military benefit, and logistical supportability of their prototypes. Competitors are encouraged to further develop and commercialize their inventions.

The winning team at the SDC13 Finals in May 2016 was a group of USMA cadets who developed a device that minimizes the muzzle jump of the army's standard M249 light machine gun. The Recoil Annihilators team took home the first place prize of $5,000 for their work. An MIT team took second place, and a $4,000 prize, for their development of light, potentially disposable sensors that can not only detect hazardous chemicals such as nerve agents but also track soldiers' exposure to those agents over time.

Army Nanotechnology Seminar Presentations

The ISN Army Nanotechnology Seminar (ANTS) series is designed to foster the exchange of information related to research on soldiers' protection, equipment, health, and other needs. These seminars, held during the fall and spring semesters, also offer ISN researchers, graduate students, and postdoctoral associates the opportunity to learn more about research underway at army labs and other facilities.

To help our colleagues at other locations participate, ANTS presentations are webcast using collaboration software that facilitates real-time interaction. Remote participants can watch and listen to presentations, and are able to engage in question-and-answer sessions.

Contributions to the MIT Community

ISN has over 40,000 square feet of space in a dedicated facility located in the northeast sector of the MIT campus within Cambridge's Technology Square (NE47). Approximately 500 registered users from across MIT have access to ISN facilities that include wet and dry labs, computer clusters, and mechanical testing and other research instrumentation, including equipment for low- and high-rate mechanical

Fig. 6: ISN headquarters and labs occupy the fourth and fifth floors of 500 Technology Square (NE47) in Cambridge, MA.

characterization of the dynamic response of materials, electron microscopy, and femtosecond laser spectroscopy.

Additionally, since the start of the second ISN contract in August 2007, ISN has provided more than $7.5 million in seed and augmentation funding for MIT research projects, supporting research in a variety of different academic departments and research centers.

Future Plans

The ISN mission remains extremely relevant to the needs of the soldier and the nation. In the short term, ISN looks forward to further revising its research portfolio to be even more responsive to the army's needs and to further align itself with the army's research and technology roadmap. Over the coming years, ISN will seek to build and further strengthen partnerships with the army, other US military services, and industry while refocusing and streamlining our portfolio of basic research projects in response to new opportunities and evolving customer needs. Working as an army-industry-university team, ISN will continue to perform basic research and transitioning to improve soldiers' protection and survivability.

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