Microscale Thermal Engineering of Electronic Systems

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Mechanical Engineering Department
Stanford University
Key Points

1. Self Heating of Transistors and Interconnects

2. Nanothermal Devices for Information Technology

3. Microscale Technologies for Heat and Power Management
Microprocessor Thermal Challenges

**ESD**

Siemens

**Metal Heating**

Texas Instruments

Metal 1 (AlCu)

W-plug

Silicon Dioxide

Thermal damage

n+ Silicon Diffusion Region

**Novel Materials**

IBM

Strained Silicon / Si Ge

**Novel Geometries**

UC Berkeley/AMD
Nanotransistors

Classic Bulk FET

Strained-Si FET

Thin Body SOI

Double-Gate SOI (Purdue, IBM)

FinFET (UC Berkeley, AMD, IBM)
Transistor Electrothermal Physics

Approximate Impact of Device Scaling on Peak Phonon Temperatures

\[ \Delta T \text{ Increase (K)} \]

\[ \text{Power } Q' \text{ (µW/µm)} \]

Channel Length L (nm)

Pop, Banerjee, Dutton, Goodson, *Proc. IEDM 2001*
Transistor Simulation Regime Map

Nanotransistor Regime

<table>
<thead>
<tr>
<th></th>
<th>electrons</th>
<th>phonons</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFP</td>
<td>~5 nm</td>
<td>~100 nm</td>
</tr>
<tr>
<td>λ</td>
<td>~5 nm</td>
<td>~1 nm</td>
</tr>
</tbody>
</table>

Research needs for the future

Lattice

Atomistic

BTE with Wave models

BTE or Monte Carlo

Diffusion

Isothermal

Drift Diffusion

BTE

Monte Carlo

Monte Carlo with Quantum Models

In progress

Full Quantum

Datta, Lundstrom (1995)

Wachutka (1994)

Stratton (1962)

Sverdrup Ju, Goodson (2000)

Shur (1990)

Apanovich (1995)


Baccarani (1985)

Rudan (1986)

Fischetti (1988)

Jacoboni (1983)

Datta, Lundstrom (1995)

Shur (1990)

Apanovich (1995)

Sverdrup, Ju, Goodson (2000)

Shur (1990)

Apanovich (1995)


Baccarani (1985)

Rudan (1986)

Fischetti (1988)

Jacoboni (1983)

Datta, Lundstrom (1995)

Research needs for the future
Electron Drift & Phonon Generation at 40kV/cm

Thesis work of Eric Pop, 2003

- Monte Carlo, 300 electrons at 300 K
- Electric Field starts at 0.5 ps
- $E_{\text{avg}}$ jumps from 39 meV to 290 meV
The temperature rise in interconnects is small now, but compounding trends in the ITRS roadmap lead to a tremendous increase at the 70 nm node beyond low-k dielectric materials, increasing current densities and aspect ratios, and increasing number of interconnect layers.

\[
\Delta T \sim \frac{j^2 d_{\text{MET}} \rho_{\text{MET}} d_{\text{ILD}}}{k_{\text{ILD}} \eta} N^{1.7}
\]
Nanoscale Thermal Data Storage

IBM Zurich: Vettiger, Binnig  Stanford: King, Kenny, Goodson.
See King et al., Applied Physics Letters 78, 1300 (2001)

Data Writing

\[ I_{bias} \]

\[ \Delta T \sim 300 \text{ K} \]

Data Reading

\[ I_{bias} \]

\[ \Delta T \sim 5 \text{ K} \]

\[ \Delta T \text{ reduced} \]

“0”

“1”

Cantilever Array

100 nm

Stanford University

Micro- and NanoMechanics
Zurich Research Laboratory
Microrocessor Thermal Management

Microprocessor heat sinks are 3000 times larger and heavier than the chip. They crowd away power delivery components, ASICs, RAM, and Video.
Interdisciplinary Grand Challenge: Integrated Power Delivery & Heat Removal

Groups of Goodson, Kenny, Santiago, Saraswat, Stanford Mechanical Engineering
Groups of Thompson & Troxel, MIT Materials and Electrical Engineering

Thermofluidic Mixed-Signal Power Module (Sponsors: SRC/MARCO & DARPA)

Thermofluidic Module with Solid-State Pump (Sponsors: Intel & DARPA)
ElectroOsmotic Microchannel Cooler

PIs: Goodson, Santiago, Kenny, Stanford ME

- 2001: 30 W Demo, 1 cm² (Intel)
- 2002: 100 W Demo, 1 cm² (Intel)
- 2002: 150 W Demo, 4 cm² (Intel)
- 2002: Laptop Demo
- 2002: Apple Dual Processor Demo
- 2003: AMD Demo

**ElectroOsmotic Pump**

- Silicon dioxide wall
- Charge double-layer
- High-Pressure Liquid Pumping ~ 50 nm

**Microchannel Heat Sink**

- Channels in silicon
- Thermal attach
- Pyrex seal

Stanford/Intel 100 W Demo
EO Pump Flowrate ~ 20 ml/min
ElectroOsmotic Pumps

With groups of Santiago and Kenny, Stanford Mechanical Engineering
Sponsor: SRC/MARCO, DARPA

Idealized pore channel:
Glass or fused-silica capillary wall

Charge double-layer

Deprotonated silanol groups

\[
u(r) = \frac{\varepsilon \zeta E}{\mu} - \frac{dp}{dx} \frac{(a^2 - r^2)}{\mu}
\]

\[
Q_{\text{max}} = \frac{\varepsilon \zeta VA}{\mu l}
\]

\[
\Delta p_{\text{max}} = \frac{32 \varepsilon \zeta V}{d^2}
\]

• Very high volume to flowrate ratio
• Stanford pump performance (Feb 2002)

\[P_{\text{max}} \sim 2 \text{ atm}, Q_{\text{max}} \sim 40 \text{ ml/min}, \text{Vol.} \sim 2 \text{ cm}^3\]
Cooligy develops thermal management components based on electro-osmotic pumps and novel microscale heat exchangers

• Founded in 2001 by Stanford Profs. Ken Goodson, Tom Kenny, Juan Santiago, Mechanical Engineering

• 24 employees (Feb 2003) with engineering expertise including chemical, mechanical, packaging, thermal, & fluidic specialties

• Experienced management and directors drawn from Intel, Dell, Corning, Silicon Light Machines.

• Focussing on reliability demonstration, product implementation, collaboration with computer manufacturers
Concluding Remarks

• The next decade of IC research & development will bring solutions to “secondary” challenges associated with Moore’s Law, such as power delivery, heat removal, and package integration.

• IC thermal management problems will have lengthscales spanning six orders of magnitude, from 10 nm in nanotransistors to more than 10 cm at the package level.

• Novel materials and geometries are increasing micro/nanoscale on-chip thermal resistances, leading to hotspots in metallization and interconnects.

• Circuit design focuses computation on the chip, yielding mm-scale hotspots that dramatically increase the thermal resistance from the chip to the package.
Goodson Microscale Heat Transfer Group
Thermosciences Division, Mechanical Engineering Department, Stanford

Current Students and Post-Docs (AY 2002/2003)

<table>
<thead>
<tr>
<th>Dachen Chu (Physics)</th>
<th>Monikka Mann (ME)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xuejiao Hu (ME)</td>
<td>Sanjiv Sinha (ME)</td>
</tr>
<tr>
<td>Sungjun Im (Materials Science)</td>
<td>Evelyn Wang (ME)</td>
</tr>
<tr>
<td>Kevin Ness (ME)</td>
<td>Ankur Jain (ME)</td>
</tr>
<tr>
<td>Jae-Mo Koo (ME)</td>
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<tr>
<td>Yue Liang (ME)</td>
<td>Dr. Linan Jiang</td>
</tr>
<tr>
<td>Angie McConnell (ME)</td>
<td>Dr. Abdullahel Bari</td>
</tr>
<tr>
<td>Eric Pop (Electrical Engineering)</td>
<td>Dr. Samuel Graham (Visitor from SNL)</td>
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Alumni (1999-2002)

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<thead>
<tr>
<th>Prof. Mehdi Asheghi</th>
<th>Carnegie Mellon University (ME)</th>
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<tbody>
<tr>
<td>Prof. Dan Fletcher</td>
<td>UC Berkeley (Bioengineering)</td>
</tr>
<tr>
<td>Prof. Bill King</td>
<td>Georgia Tech (ME)</td>
</tr>
<tr>
<td>Prof. Katsuo Kurabayashi</td>
<td>University of Michigan (ME)</td>
</tr>
<tr>
<td>Prof. Sungtaek Ju</td>
<td>UCLA (ME) – with IBM until Fall 2003</td>
</tr>
<tr>
<td>Prof. Kaustav Banerjee</td>
<td>UC Santa Barbara (EE)</td>
</tr>
<tr>
<td>Dr. Uma Srinivasan</td>
<td>Xerox</td>
</tr>
<tr>
<td>Dr. Per Sverdrup</td>
<td>Intel</td>
</tr>
<tr>
<td>Dr. Peng Zhou</td>
<td>Cooligy</td>
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<tr>
<td>Dr. Maxat Touzelbaev</td>
<td>AMD</td>
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