Energy in Nanoelectronics and Nanomaterials

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(previously with University of Illinois at Urbana-Champaign)
What Motivates Us

20 Watts

(IBM Watson, Jeopardy! champion)

200 kiloWatts

10,000x

(conventional Moore’s Law size scaling can get us ~10x)
Electronics Use (and Waste) Much Power


Electronics, limited by power & heat since 2005!

http://phys.ncku.edu.tw/~htsu/humor/fry_egg.html

energy limits performance from processors, to mobile devices, to data centers
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Calibrating: 1 GW ~ 1 nuclear power plant
12 GW ~ all electricity used by Argentina

J. Koomey (Stanford)
• In 2007 “cloud computing” was 5th among electricity use by countries (other sources have put it at 12th among countries = Italy or Spain)
• Expected growth is ~12% per year
Cooling Electronics in Outer Space

NASA Troubleshoots Growing ISS Thermal Control System Leak
Aviation Week - May 9, 2013

Emergency spacewalk required to fix leaky space station, NASA says
Fox News - May 10, 2013

Spur-of-the-moment spacewalk a first for NASA, space station
CNET - May 11, 2013

Space Station Leak Repaired by Emergency Spacewalk
Science World Report - May 12, 2013
Electronic Energy Use Closer to Home

• My old house: electronics active non-stop
  – 150 W refrigerator (time-average)
  – 50 W digital video recorder (DVR), no sleep mode
  – ...
  – 15 W backup PC (custom-built for low power)

about 50M in U.S.

2.5 GW use
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• One Google search = 1 kJ*
  ≈ car in 0.01 sec.
  ≈ body in 10 sec.
  ≈ laptop in 1 min.

about 50M in U.S.
2.5 GW use

100k searches per second
0.1 GW use

*http://googleblog.blogspot.com/2009/01/powering-google-search.html
Our Work: Two Sides of the Same Coin

Lower power at its source
(devices, sensors, circuits)

Harvest and manage heat
(energy, thermo-electrics)

fundamental understanding
practical applications
Some Nanomaterials We Work With

- **0D**
  - Carbon nanotubes
  - Devices, heat spreaders
  - \( \approx 2 \text{ nm} \)

- **1D**
  - Graphene
  - Devices, sensors

- **2D**
  - BN
  - Insulators
  - Ge\textsubscript{2}Sb\textsubscript{2}Te\textsubscript{5}

- **3 + “2”D**
  - Phase transition materials
  - Amorphous
  - GeSb
  - Crystalline
  - VO\textsubscript{2}

- Atomic dimensions automatically address size scaling issues…
Abundance of Nanomaterials vs. Silicon

source: http://pubs.usgs.gov/fs/2002/fs087-02
IR Thermal Imaging of Graphene Transistors


IR thermal imaging

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**Graphene Transistor Diagram**

- **Drain Voltage** ($V_D$) Applied
- **Source Voltage** ($V_S$) Applied
- **Gate Voltage** ($V_G$) Applied
- **Thermal Imaging Data**
- **Current-Voltage (I-V) Characteristics**
  - Linear
  - Saturation
  - Ambipolar

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**Thermal Imaging Data**

- **Temperature ($T_{im}$)** vs. **Voltage** ($V$)
- **Concentration** vs. **Position** ($X$)
- **Carrier Mobility** vs. **Voltage**

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**References**

Simulation: Ambipolar + Poisson + Heating

model “GFETTool” available on http://nanoHUB.org
Need for Low-Power Data Storage


Modern processor memory consumes much power

Full Power Breakdown
Total - 125.3W
- Clocking: 1.9W
- Routers: 12.1W
- Cores: 87.7W
- MCs: 23.6W
- Global Clocking: 2%
- MC & DDR3-800: 19%
- Cores-1GHz, Mesh-2GHz, 1.14V, 50°C

Low Power Breakdown
Total - 24.7W
- Clocking: 1.2W
- Routers: 1.2W
- Cores: 5.1W
- MCs: 17.2W
- Global Clocking: 5%
- MC & DDR3-800: 69%
- Cores-125MHz, Mesh-250MHz, 0.7V, 50°C

ITRS 2010

trade-off between speed vs. energy
Phase-Change Memory (PCM) Materials

- Chalcogenide compound: Ge$_2$Sb$_2$Te$_5$ (GST)
- Used in RW-DVDs
- Crystalline vs. amorphous: fast phase change (~1 ns)
- Large change in resistance (>100x)
- Promising candidate for memory, BUT... high programming current (>0.1 mA at Intel, IBM, Samsung)

PCM Device with Nanotube Electrodes


- Key idea: CNTs are smallest possible electrodes (2 nm diameter)
- Use CNT to contact sub-10 nm bits of phase-change material
- Switching at \(~100x\) lower power than conventional memory!
How Can We Improve on This Design?


- Create “marshmallow” device
  - Nanowire self-aligned with CNT electrodes (thermally confined bit)
- Create “cross-bar” device (smallest possible area, \~2x2 nm²)

- Are we switching individual PCM filaments? (must take a look…)
- Theoretical possibility of operating at 10-100 atto-Joules
Where This Work Fits In

- These memory devices are highly scalable with electrode and bit size
- Lowest power $<1 \mu W$, energy $<1 \text{ fJ/bit}$ (with $\sim 1 \text{ ns}$ pulse)
- We have **not hit fundamental limits yet** ($\sim 10$-100x more to go!)

also see: J. Liang, H.S.P Wong et al, IEEE-TED (2012)
Our Work: Two Sides of the Same Coin

Lower power at its source
(devices, sensors, circuits)

Harvest and manage heat
(energy, thermo-electrics)

fundamental understanding
practical applications
Peculiar Energy Transport at Nanoscale

• Macroscale, $R$ is additive: $1 + 1 = 2$

• **Nanoscale**, $R$ is quantized: $1 + 1 = 1$
  – Occurs when system size is comparable to the electron or phonon (heat) wavelengths and collision distance (10-100 nm)
  – Both electrical and thermal resistance expected to behave this way
Peculiar Energy Transport at Nanoscale


- Has quantized nanoscale resistance been measured?
- Electrically, in quantum point contacts at low temperature
  - In carbon nanotubes up to room temperature: $6.5 \text{k}\Omega = \frac{h}{4e^2}$
- Thermally, in a “hero” experiment near zero Kelvin*

Wanted rigorous assessment of nanoscale graphene heat flow

Built arrays of graphene ribbons between heater & sensor

Control samples with SiO₂ only (no graphene)

Built computational models of test structure and of phonon transport
Nanoscale Heat Flow in Graphene


**Control heat flow** by manipulating nanoscale dimensions even at room T!
- Quasi-ballistic heat flow in short devices
- Strong edge scattering in narrow devices

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Energy Harvesting from Waste Heat

- Almost everything we do wastes heat
  - Power generation
  - Transportation (engine + friction)
  - Computing

- 15 TW wasted as heat in the world*
- Most is “low-grade” $T \leq 200 \, ^\circ C$
- Recovering even a few percent would be HUGE, equivalent of several power plants (GW)

Possible Solution: Thermoelectrics

*Dept. of Energy (2008)
• Use junction (ΔS) and current to electrically heat or cool
  – Peltier effect: \( P_{heat,cool} = \pm I \Delta ST \)

• Used in small refrigerators, cooled car seats, cup holders

• No moving parts (=quiet and reliable), no freon (=clean)
How Thermoelectrics Work

Fig. 9.1 Thermoelectric devices. **Left:** Cooler based on Peltier effect. **Center:** Power generator based on Seebeck effect. **Right:** An actual module (sources: A. Shakouri, G. Snyder)

- Use temperature gradient ($\Delta T$) to generate power
  - Seebeck effect: $\Delta V \equiv S\Delta T$
- Used in car engines & exhaust, Mars rover (~100 W)
- No moving parts (=quiet and reliable), no freon (=clean)
New Materials for Thermal Energy Harvesting

- Traditional thermoelectrics: Bi, Te, Pb → rare, expensive, toxic, brittle

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G. Snyder, *Nature Mat.* (2008); S. Yee et al. (2013)
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- Start with **low-cost polymers** that already have low $k$, high $\sigma$
- Use nanostructuring (nanotubes, nanowires) to increase $S$

collaborator: Prof. Zhenan Bao (Stanford ChemE)

Bonus:
- mechanically flexible
- solution processable
What Is 10,000x Power Reduction?

10 GW
(all data centers in US)

+ 10,000

1 MW
(2 Ferrari F430)
(solar power from 1 parking lot)

50 mW
(iPhone average)

+ 10,000

5 μW
(watch powered by body heat)
Energy Harvesting From Us(ers)

- up to $50 \text{ mW}$ (iPhone average)
- up to $5 \mu\text{W}$ (watch powered by body heat)
- up to $\sim 4 \text{ W}$ walking (piezoelectricity)
- up to $\sim 1 \text{ W}$ body heat (thermoelectrics)

Flexible, organic composite thermoelectrics; Yu et al, ACS Nano (2011); Lian et al (in preparation)
Summary

- Moore’s Law ~10x → slowing down
- Energy scaling & harvesting ~$10^4$x → exciting

- Opportunity for convergence of:
  - Low power electronics
  - Energy harvesting
  - Novel nanomaterials

- Towards fundamental limits of energy use
  (up to 10,000x improvements may be possible)

MUCH room for optimization of energy dissipation, use, and harvesting from the “atomic” level
• **Alumni:**
  - Dr. Z.-Y. Ong, Dr. A. Liao, Dr. D. Estrada
  - 7 M.S. and 8 B.S. theses

• **Post-docs:**
  - Dr. Ashkan Behnam, Dr. Myung-Ho Bae

• **Grads (EE + Physics + ME):**
  - E. Carrion, V. Dorgan, C. English
  - K. Grosse, S. Hong, S. Islam, Z. Li, F. Lian
  - A. Serov, F. Xiong, N. Wang, J. Wood

• **Undergrads:**
  - Akshay, Chris, Daifeng, Dominic, Maryann, Yuan

• **Sponsors:**
  - NRI, MARCO-MSD, ONR, NSF-CCF, NSF-EPMD, NASA
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