Electro-Thermal Interaction in Nanoscale Devices: Carbon Nanotubes and Phase-Change Memory

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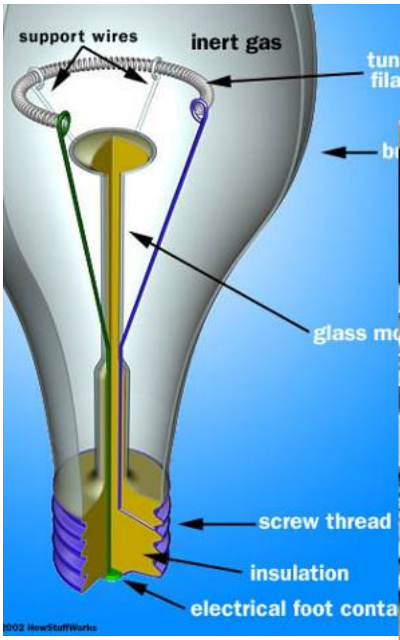
http://nanoheat.stanford.edu/epop/research.html

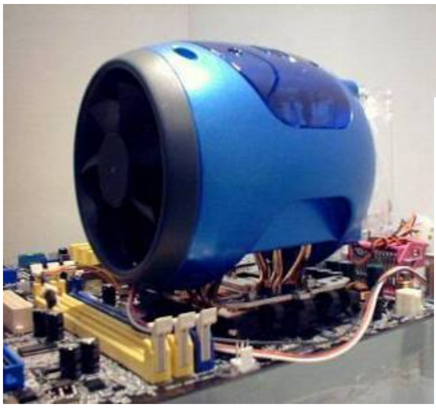
Joule (Self-Heating) in Electronics

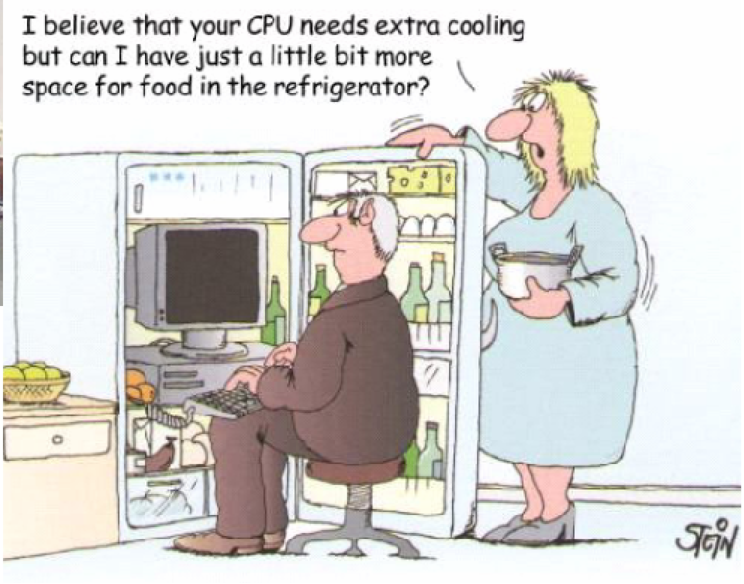
Portables: batteries
Reliability + Performance
CPU Power Density ~ 100 W/cm^2



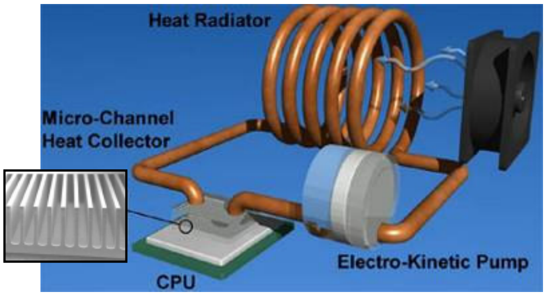
http://phys.ncku.edu.tw/~htsu/humor/fry_egg.html

Thermal Management Methods

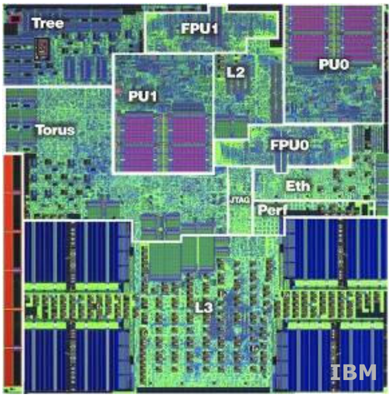




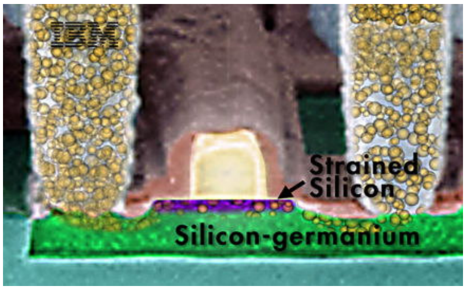
Thermal Management Methods



System Level
→ Active Microchannel Cooling (Cooligy)

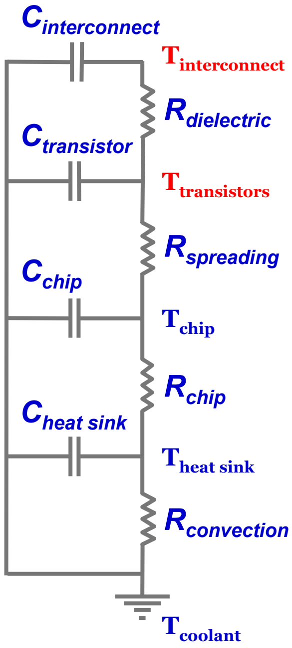


Circuit + Software Level
→ active power management
(turn parts of circuit on/off)

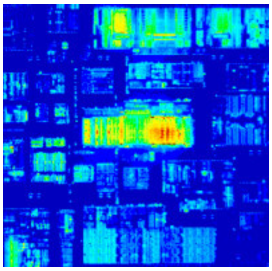


Transistor Level
→ electro-thermal device design

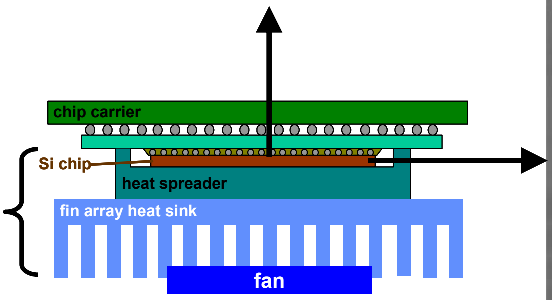
Chip-Level Thermal Network



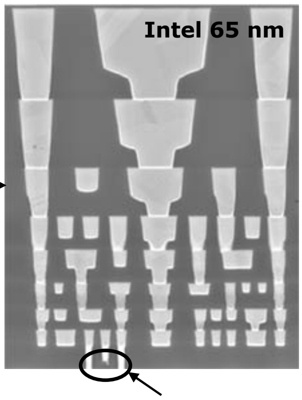
Intel Itanium



Top view
Hottest spots > 300 W/cm^2



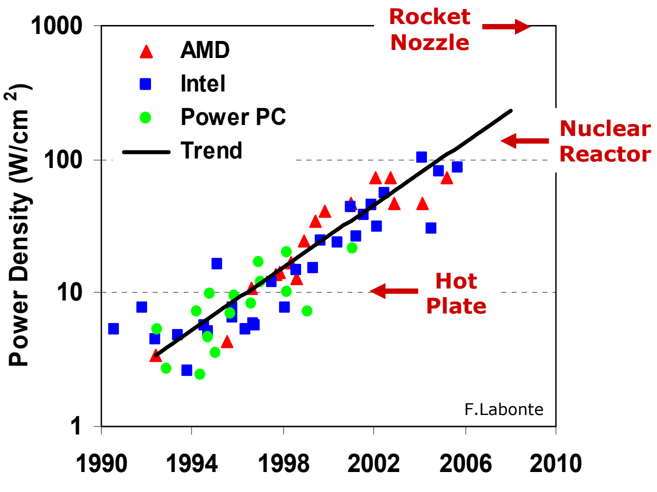
Cross-section
8 metal levels + ILD



Transistor < 100 nm

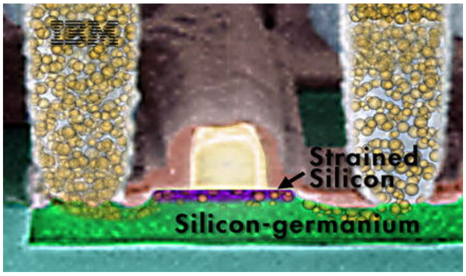
Chip-Level Thermal Trends

E. Pop *et al.*, Proc. IEEE 94, 1587 (2006)



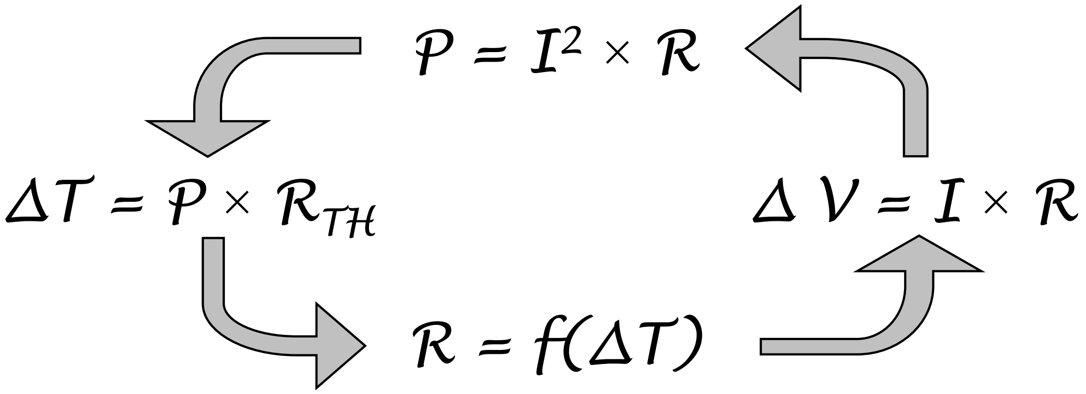
Sun surface: 6000 W/cm^2

Device Level:
Confined Geometries, Novel Materials



Material	*k_{th} (W/m/K)*
Si	148
Ge	60
Silicides	40
Si (10 nm)	13
SiO_2	1.4

Thermal Resistance, Electrical Resistance



$P = I^2 \times R$

$\Delta T = P \times R_{TH}$

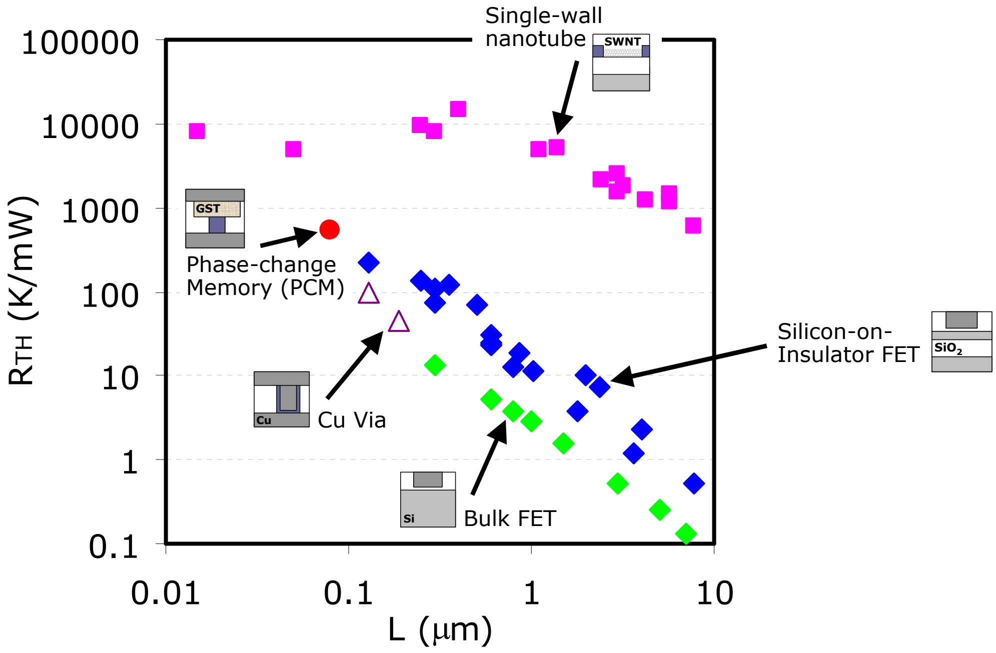
$\Delta V = I \times R$

$R = f(\Delta T)$

Fourier's Law (1822)

Ohm's Law (1827)

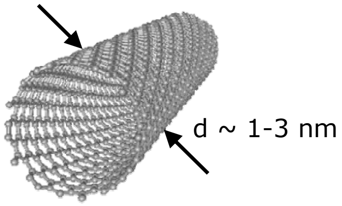
Thermal Resistance at Device Level



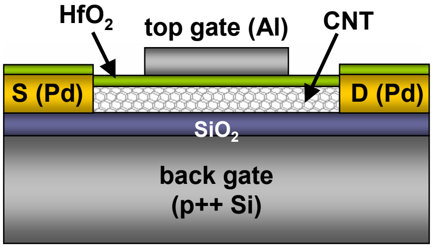
Sources: Mautry (1990), Bunyan (1992), Su (1994), Lee (1995), Jenkins (1995), Tenbroek (1996), Jin (2001), Reyboz (2004), Javey (2004), Seidel (2004), Pop (2004-6), Maune (2006).

Carbon Nanotubes for Electronics

- Carbon nanotube = rolled up graphene sheet
- Great electrical & thermal conductors
  - Semiconducting → transistors
  - Metallic → interconnects
  - $\sigma \approx 100 \times \sigma_{Cu}$; $k \approx k_{Diamond}$



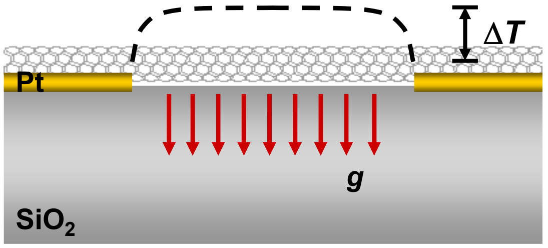
- (Some) open questions:
  - Thermal conductivity of single-walled carbon nanotubes (SWNTs)
  - Great thermal conductivity k, low thermal *conductance* (small *d*)
  - Optimizing high-field transport



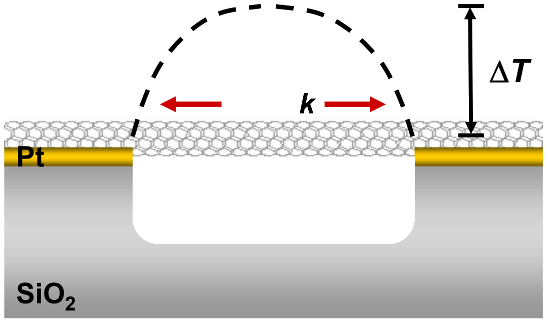
Back-of-the-Envelope Estimates

E. Pop *et al.*, Phys. Rev. Lett. 2005; Proc. IEDM 2005

- Typical *L* ~ 2 μm, *d* ~ 2 nm
- *On insulating solid substrate*
- Heat dissipated into substrate
  - Moderate power ~ 10 μW/μm
  - Peak Δ*T* ~ 60 K

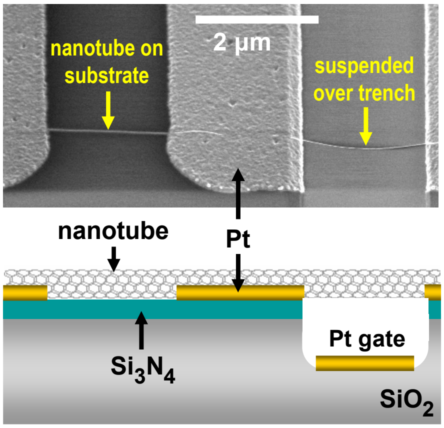


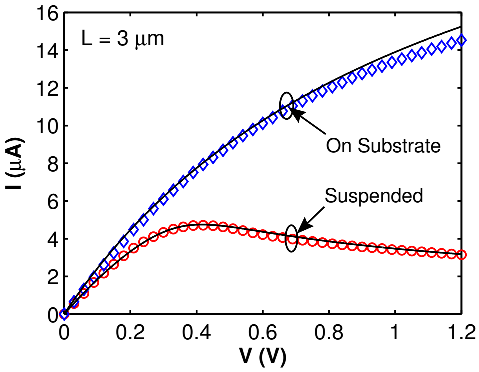
- Thermal conductivity *k* ~ 3000 W/m/K
- *Freely suspended nanotube*
- Heat dissipated along tube length
  - Moderate power ~ 10 μW (10 μA @ 1 V)
  - Peak Δ*T* ~ 400 K!



Transport in Suspended Nanotubes

E. Pop *et al.*, Phys. Rev. Lett. 95, 155505 (2005)

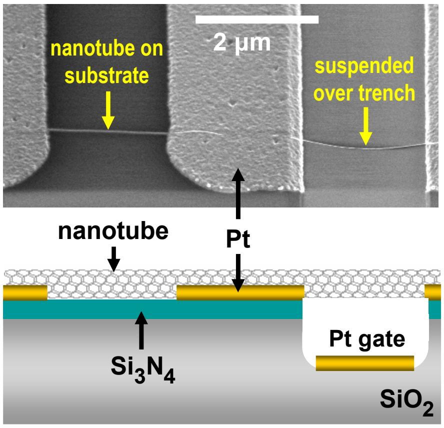


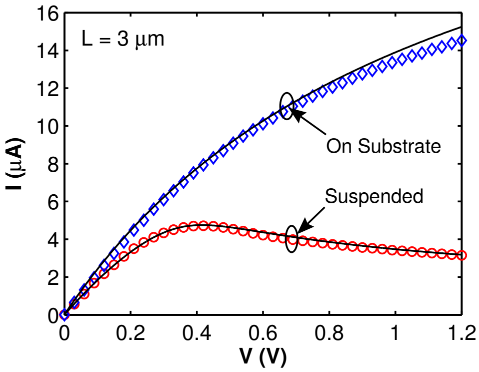


- Observation: significant current degradation and negative differential conductance at high bias in suspended tubes
- <u>Question</u>: Why? <u>Answer</u>: Tube gets HOT (how?)

Transport in Suspended Nanotubes

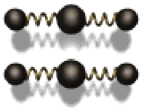
E. Pop *et al.*, Phys. Rev. Lett. 95, 155505 (2005)





- Evidence for much longer *phonon* lifetimes in suspended SWNTs:
  - Narrower Raman linewidths of suspended tubes *(Dresselhaus in APL '04)*
  - Observed 50x lifetime for suspended RBM mode *(Dekker in Nature '04)*
  - Why? Substrate interface provides phonon relaxation channels
  - Consequence: hot optical phonons in suspended SWNTs under high bias

Quick Recap of Phonons

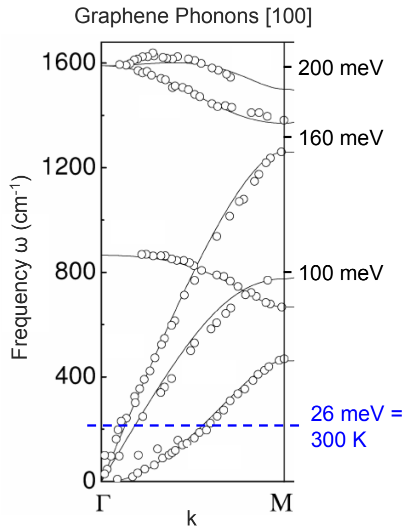


CO_2 molecule vibrations

transverse small k

transverse max k=2π/a

$$\mathbf{u}(\mathbf{r},t) = \mathbf{A}\exp[i(\mathbf{k}\cdot\mathbf{r} - i\omega t)]$$



- Phonons = quantized atomic lattice vibrations
- Transverse ($u \perp k$) vs. longitudinal modes ($u \parallel k$), acoustic vs. optical
- “Hot phonons” = highly occupied modes above room temperature

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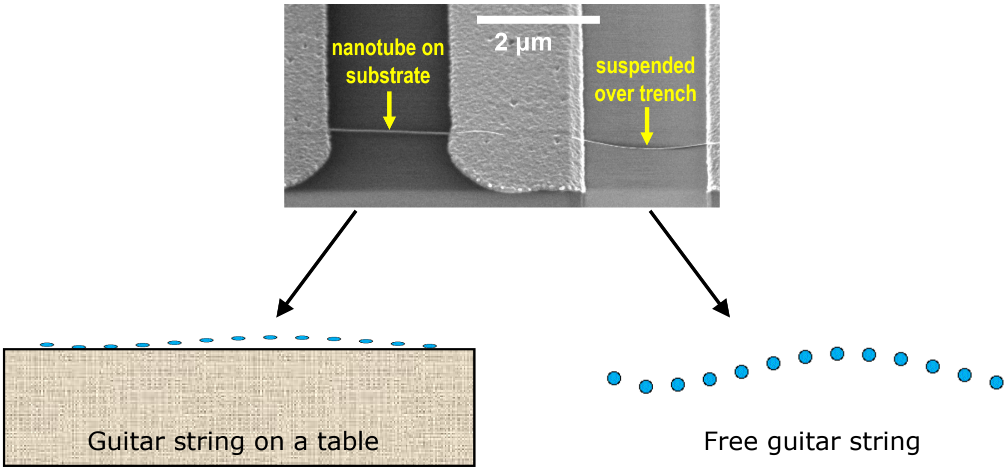
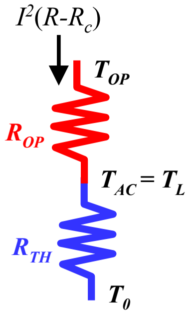
Phonons and Guitar Strings



- Phonons = quantized lattice vibrations
- Transverse ($u \perp k$) vs. longitudinal modes ($u \parallel k$), acoustic vs. optical
- “Hot phonons” = highly occupied modes above room temperature

Transport Model Including Hot Phonons

E. Pop *et al.*, Phys. Rev. Lett. 95, 155505 (2005)

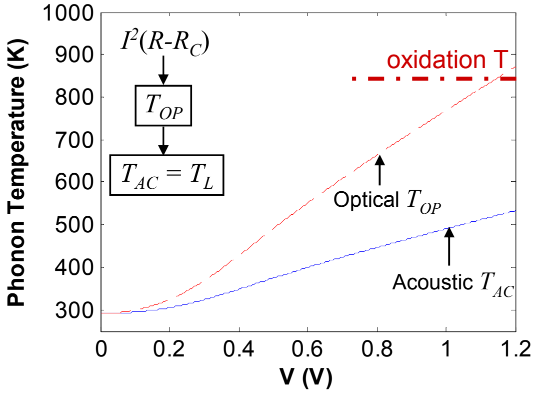


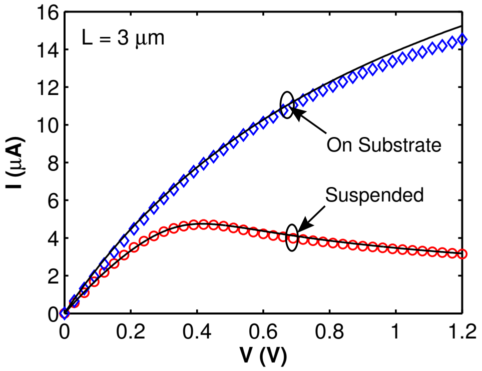
Non-equilibrium OP:

$$\boxed{T_{OP} = T_{AC} + \alpha(T_{AC} - T_0)}$$

Heat transfer via AC:

$$\boxed{A\nabla(k\nabla T) + I^2(R - R_C)/L = 0}$$





Landauer electrical resistance

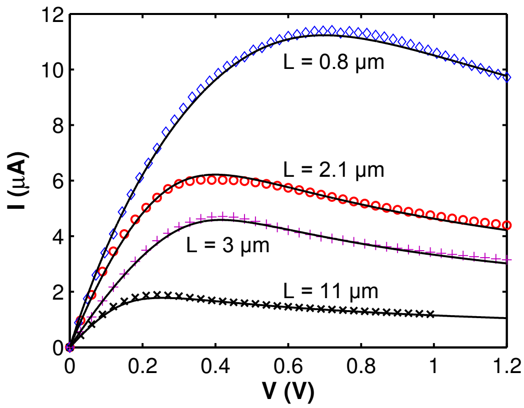
$$\boxed{R(V,T) = R_C + \frac{h}{4q^2}\left[\frac{L + \lambda_{eff}(V,T)}{\lambda_{eff}(V,T)}\right]}$$

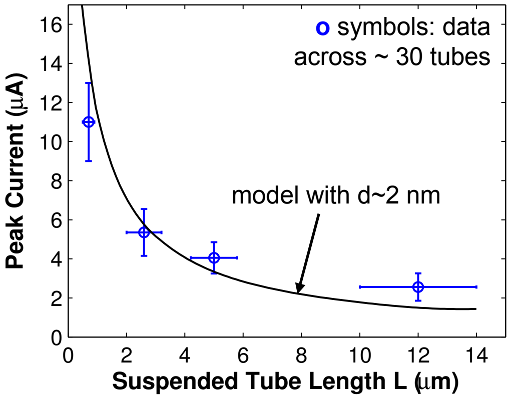
Include OP absorption:

$$\boxed{\lambda_{eff} = \left(\frac{1}{\lambda_{AC}} + \frac{1}{\lambda_{OP,ems}} + \frac{1}{\lambda_{OP,abs}}\right)^{-1}}$$

All Suspended Tubes Exhibit NDC

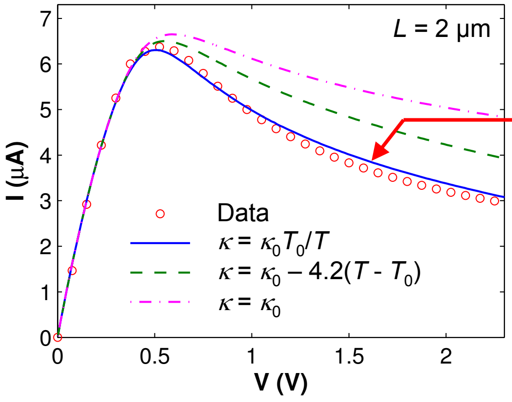
E. Pop *et al.*, Phys. Rev. Lett. 95, 155505 (2005)

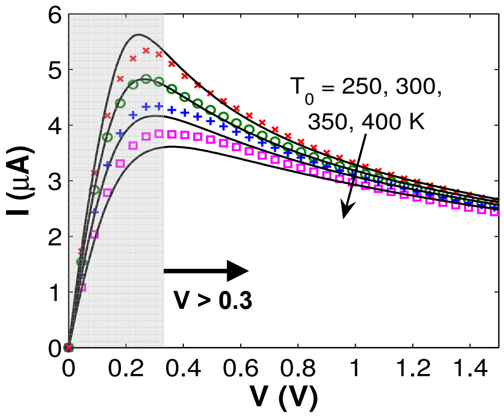




- First experimental observation of *Negative Differential Conductance (NDC)*
  - ALL *suspended* tubes show NDC; longest *at fields as low as 200 V/cm*
  - Previous work predicts velocity saturation at *E-fields* > 5 kV/cm (isothermal)
- Peak current: I_{max} ~ 1/*L*, which scales as the *thermal conductance*
  - Compare to I_{max} > 20 µA for same *L* tubes on substrate

Effect of κ_{th} at High Temperature, Bias

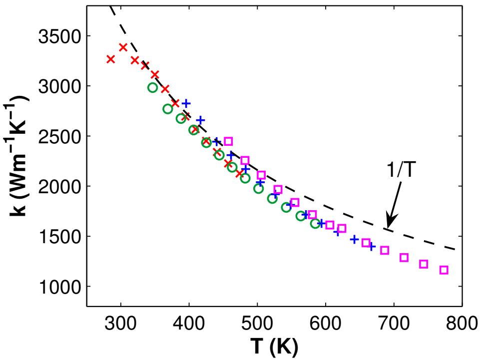


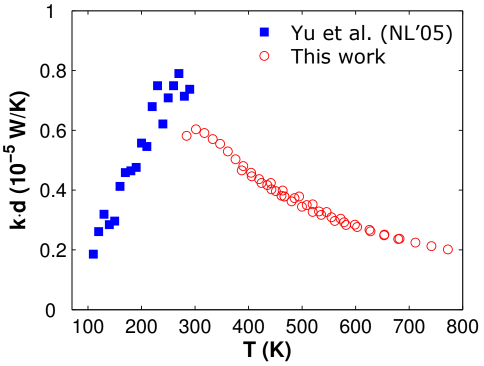


- Current at high bias: $I \sim \lambda_{op} \sim 1/N_{op} \sim 1/T \sim \kappa_{th}$
- Thermal conductivity $\underline{\kappa_{th} \sim 1/T}$ at high T (Umklapp phonon scattering)
- *I-V* curve at high bias indirectly measures $\kappa_{th}(T)$ at high T !
- Back out to T ~ 300 K → $\boxed{\kappa_0 \sim 3600 \text{ W/m/K}}$

Extracting SWNT Thermal Conductivity

E. Pop *et al.*, *Nano Letters* 6, 96 (2006)

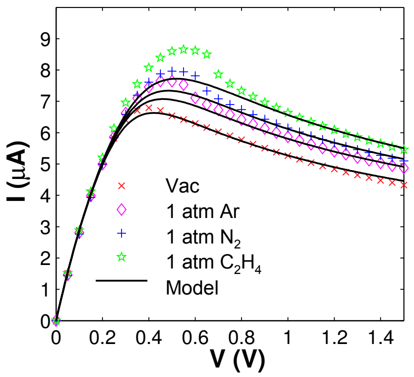


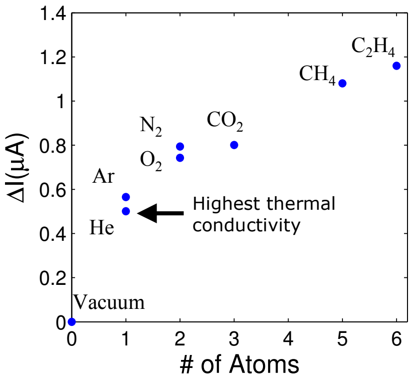


- Numerical extraction of *k* from the high bias (*V* > 0.3 V) tail
- Subtle second-order effect of three-phonon scattering introduces $1/T^2$ temperature dependence (N. Mingo, *NL Jun'05*)
- Comparison to data from 100-300 K of UT Austin group (C. Yu, *NL Sep'05*)
- Result: first "complete" picture of SWNT thermal conductivity from 100 – 800 K

Gas Environment Dependence of NDC

D. Mann *et al.*, *J. Phys. Chem. B* 110, 1502 (2006)





- Current enhancement (ΔI) in ambient gases does not scale with thermal conductivity of gas
- It scales with the number of atoms in the physisorbed gas molecules
- Physisorbed gases act like "weak substrates" for suspended SWNTs, providing more vibrational modes for OP decay

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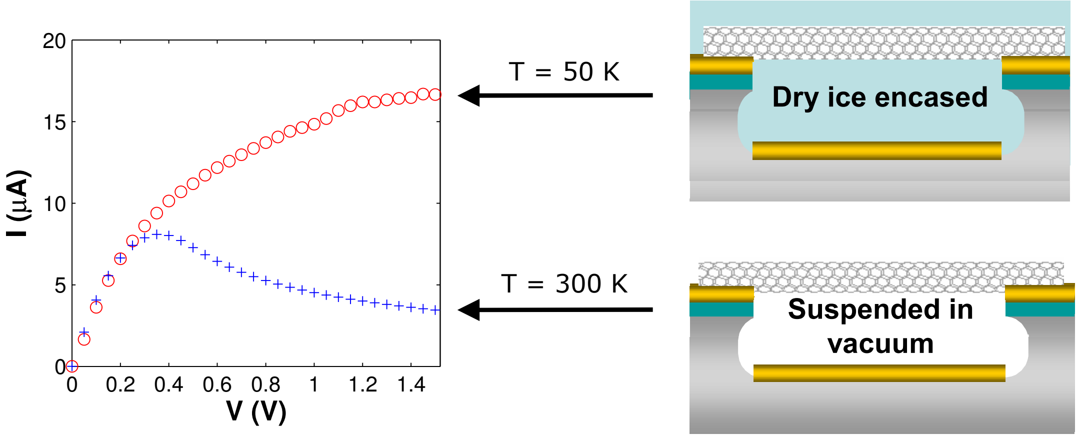
Effects of Extreme Environment

D. Mann *et al.*, *J. Phys. Chem. B* 110, 1502 (2006)

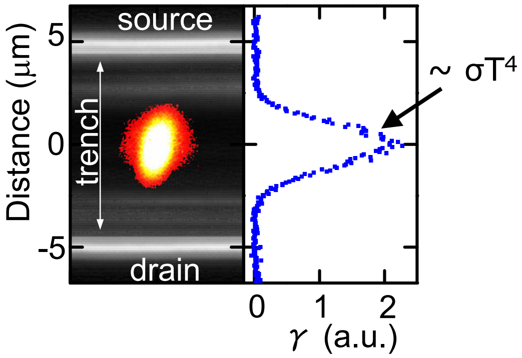


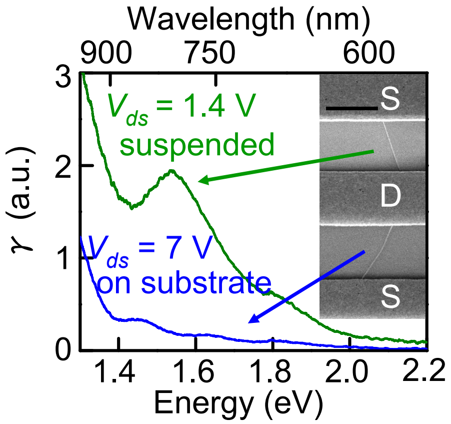
- If the surrounding molecules are dense enough, they act as a substrate, dissipating heat and relaxing optical phonons
- Environment can be engineered to modify properties of devices

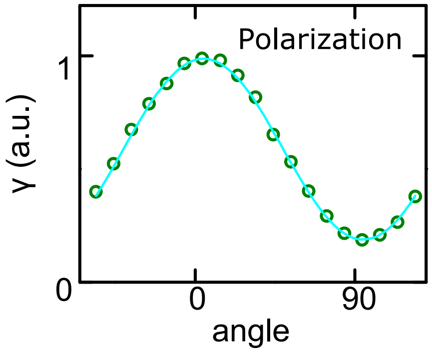
Light Emission from Suspended SWNTs

D. Mann *et al.*, *Nature Nano* (2007)

- HOT metallic tubes emit light
  - Comes from center
  - Highly polarized
  - Emitted photons @ higher energy than applied bias



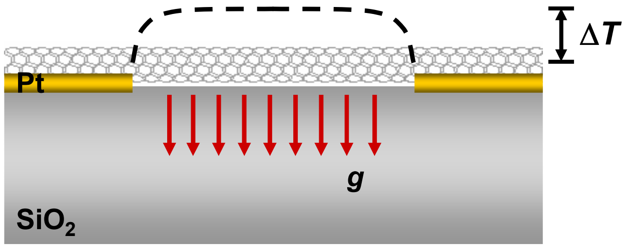




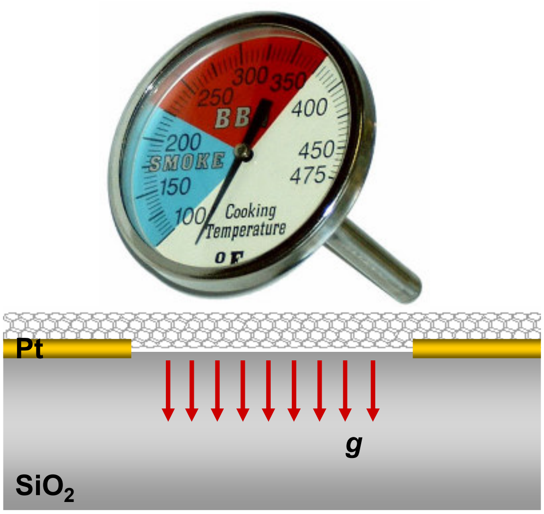
Return to SWNTs On Substrates

E. Pop *et al.*, Proc IEDM 2005; Proc IEEE 2006

- SWNT on insulating solid substrate
- Heat dissipated into substrate rather than along tube length
- What is the heat loss coefficient *g*?
- [A: need some gauge of the tube temperature]

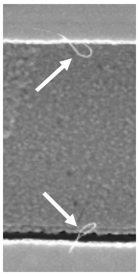


Nanotube Temperature Gauge



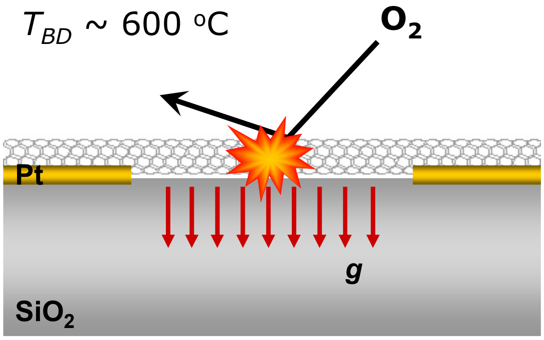
~~Nanotube Temperature Gauge~~

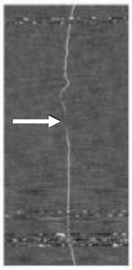
- Doesn't exist
- But… oxidation (burning) temperature is known



Suspended

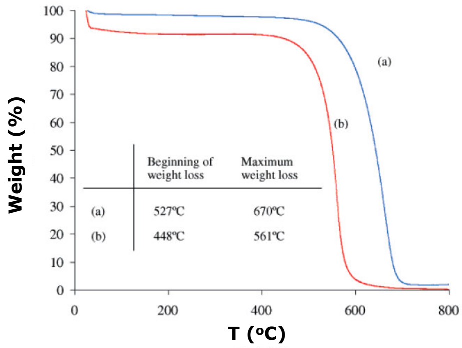
T_{BD} ~ 600 °C



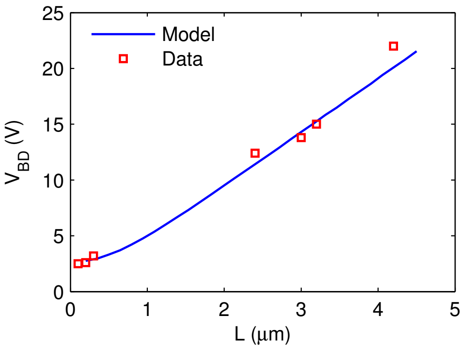


On substrate

Breakdown of SWNTs in Air (Oxygen)



K. Hata, *Science* 306, 1362 (2004)
I. Chiang, *JPCB* 105, 8297 (2001)



E. Pop, *Proc. IEDM* (2005)
A. Javey, *PRL* 92, 106804 (2004)

- Thermogravimetric (TGA) data shows SWNTs exposed to air break down by oxidation at 500 < T_{BD} < 700 °C (800–1000 K)
- Joule breakdown voltage data shows V_{BD} scales with *L* in air
- Supports cooling mechanism *along* the length, into the substrate

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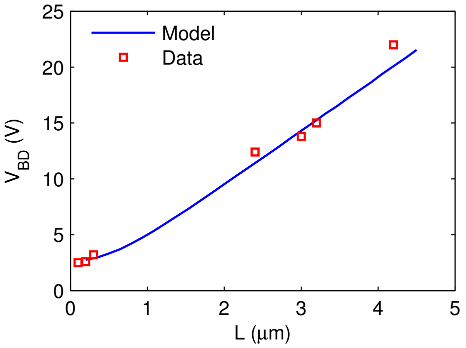
Breakdown of SWNTs: Analysis

E. Pop *et al.*, *Proc. IEDM* (2005)

$$A\nabla(k\nabla T) + p' - g(T - T_0) = 0$$

At breakdown: $p' = I_{BD}V_{BD}/L$

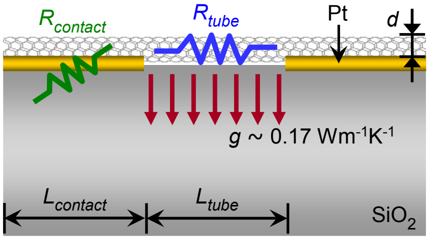
$$\boxed{V_{BD} = \underset{\uparrow}{g}L\left(T_{BD} - T_0\right)/I_{BD}}$$

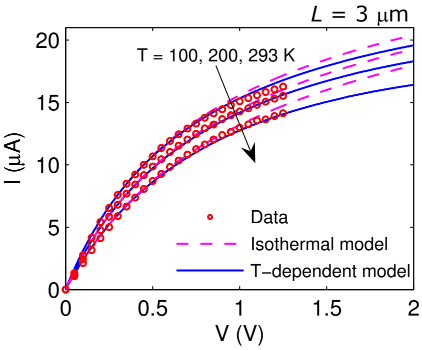


- For *on-substrate* tubes, empirically note that:
  - V_{BD} vs. *L* in air scales linearly, as about 5 V/μm
  - Breakdown currents for *L* > 1 μm always around $I_{BD} \approx 20$ μA
- Analytic solution of heat conduction equation
  - Heat loss per unit length: $g \approx 0.17 \pm 0.03$ WK^{-1}m^{-1}
- *No* assumption was made about electrical transport model

Electro-Thermal Model for m-SWNTs

E. Pop *et al.*, *Proc. IEDM* (2005)





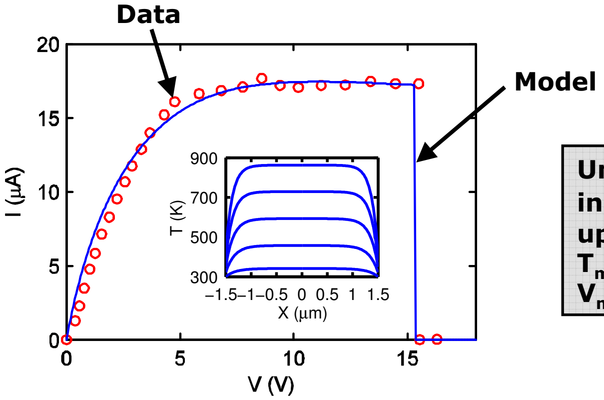
- Same model as that used for suspended SWNTs
- Include Joule heating, couple with heat conduction equation
- Self-consistent solution

$$\boxed{A\nabla(k\nabla T)+p'-g(T-T_0)=0}$$

- No assumptions of hot phonons needed

Modeling Long SWNTs up to Breakdown

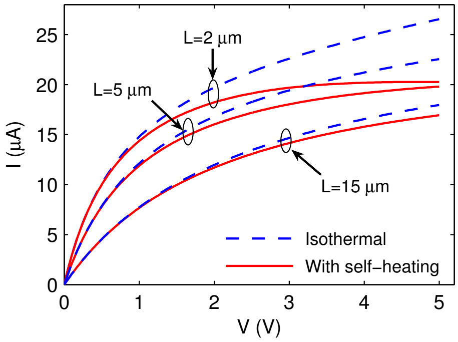
E. Pop *et al.*, submitted to JAP, pre-print cond-mat/0609075

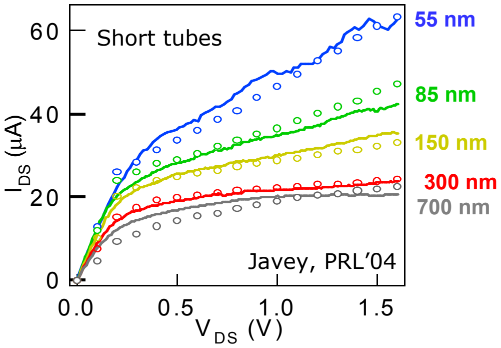


Understanding transport in a 3 μm metallic SWNT up to breakdown:
T_{max} ~ 600 ºC = 873 K
V_{max} ~ 15 V

- Thermal "healing length" along SWNT ~ 0.25 μm
- Current saturation ~ 20 μA in long tubes (> 1 μm) *due to self-heating*
- Self-heating not significant when *p*' < 5 μW/μm (design goal?)

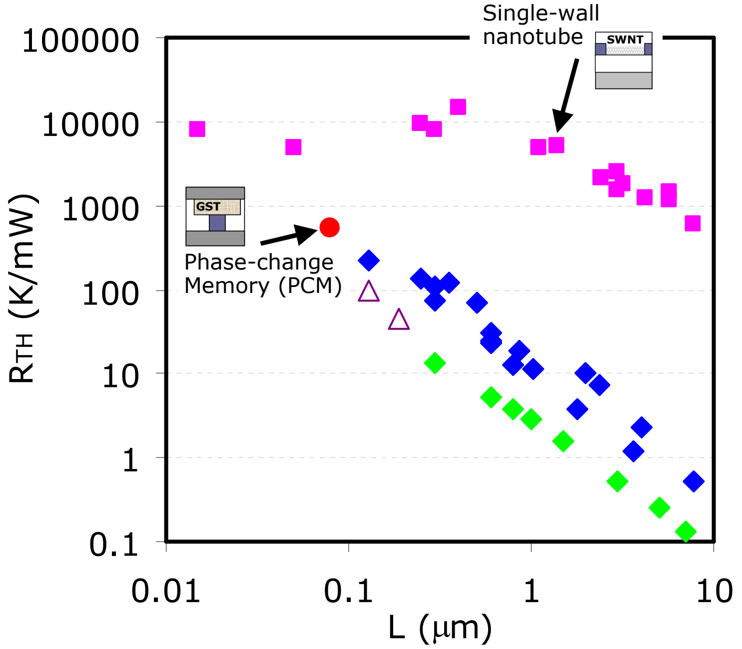
Some Notes on *Shorter* SWNTs





- Thermal "healing length" along SWNT ~ 0.2 μm
- Current saturation ~ 20 μA in long tubes (> 1 μm) *due to self-heating*
- Self-heating not significant when *p*' < 5 μW/μm (design goal?)
- **In short (< 1 μm) tubes current enhancement (> 20 μA) very likely aided by Joule heating shifting towards the contacts**

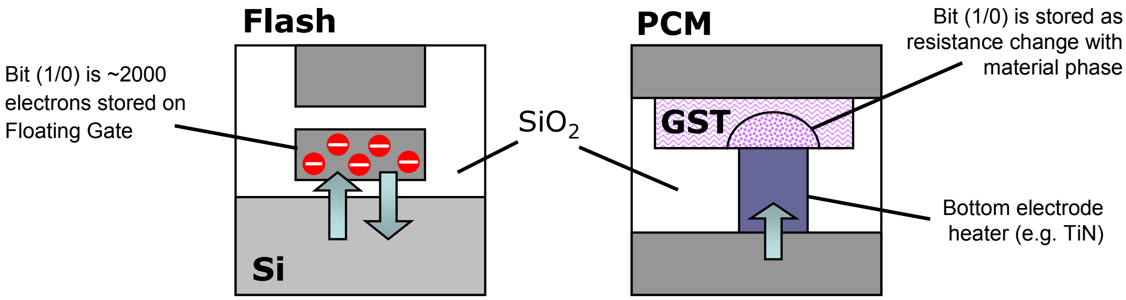
From Nanotubes to Phase-Change Memory



High thermal resistance:

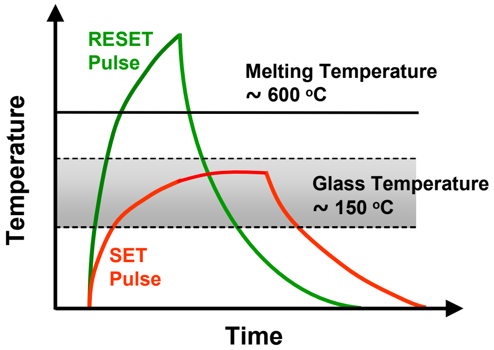
- SWNT due to small thermal conductance (very small d ~ 2 nm)
- PCM due to low thermal conductivity materials (SiO_2, $Ge_2Sb_2Te_5$)

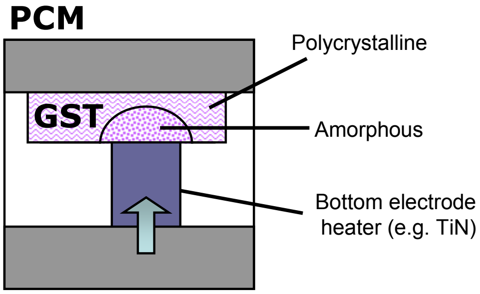
What Is Phase-Change Memory?



- PCM: Like Flash memory (non-volatile)
- PCM: Unlike Flash memory (resistance change, not charge storage)
- Faster than Flash (100 ns vs. 0.1–1 ms), smaller than Flash (which is limited by ~1000 electrons stored/bit)
- For: iPod nano, mobile phones, PDAs, solid-state hard drives…

How Phase-Change Memory Works

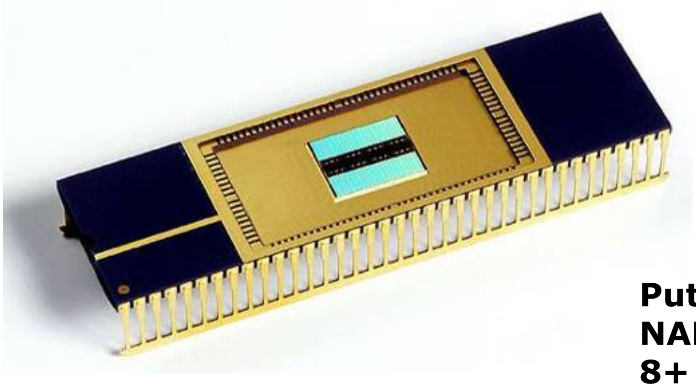




- Based on $Ge_2Sb_2Te_5$ reversible phase change: $R_{amorph} / R_{xtal} > 100$
- Short (10 ns), high pulse (0.5 mA) melts, amorphizes GST
- Longer (100 ns), lower pulse (0.1 mA) crystallizes GST
- Small cell area (sits on top of heater), challenge is reliability and lowering programming current (BUT, helped by scaling!)

Samsung 512 Mb PCM Prototype

Sep 11, 2006

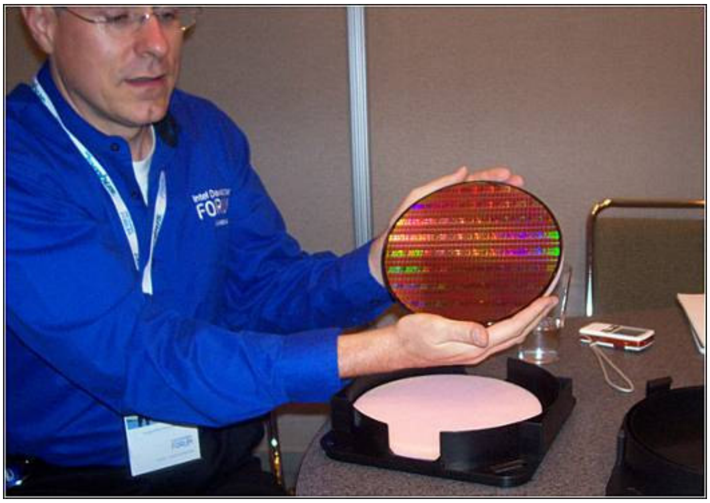


Put in perspective: NAND Flash chips of 8+ Gb in production

"Samsung completed the first working prototype of what is expected to be the main memory device to replace high density Flash in the next decade – a Phase-change Random Access Memory (PRAM). The company unveiled the 512 Mb device at its sixth annual press conference in Seoul today." Source: *http://samsung.com/PressCenter/PressRelease/PressRelease.asp?seq=20060911_0000286481*

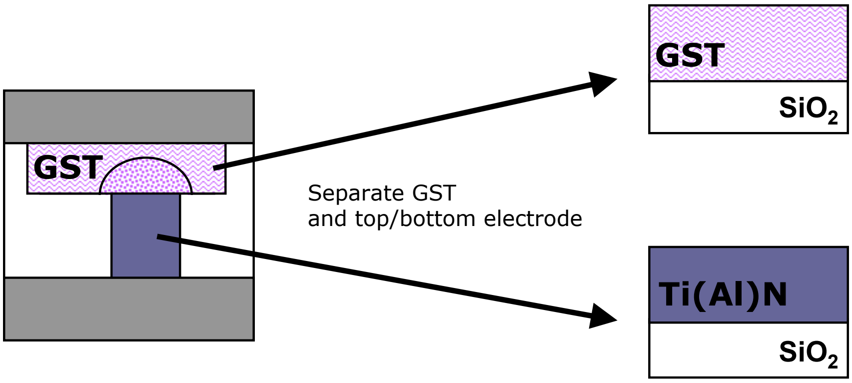
Intel/ST Phase-Change Memory Wafer

Sep 28, 2006



"Intel CTO of Flash Memory Ed Doller holds the first wafer of 128 Mbit phase change memory (PCM) chips, which has just been overnighted to him from semiconductor maker STMicroelectronics in Agrate, Italy. Intel believes that PCM will be the next phase in the non-volatile memory market." Source: *http://www.eweek.com/article2/0,1895,2021841,00.asp*

PCM Material Challenges

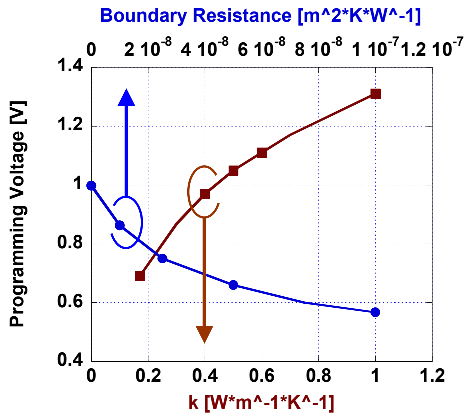


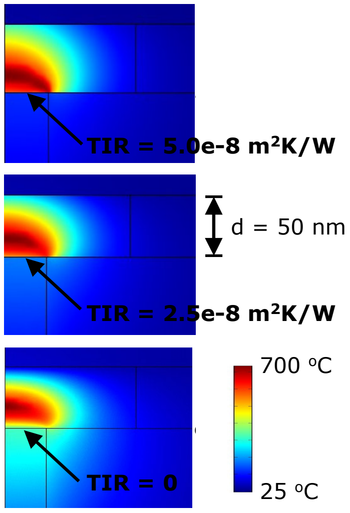
Separate GST
and top/bottom electrode

- Thermal and electrical conductivities 25 – 625 °C
- Thermal resistance of *interfaces* between materials (high surface to volume ratio)
- Phase change physics – thermal and temporal evolution
- (Practical goal: memory cell with lower programming current)

GST Thermal Conductivity and Interface

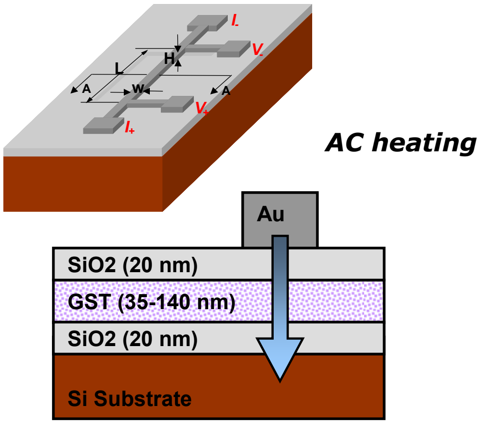
J. Reifenberg *et al.*, ITHERM 2006

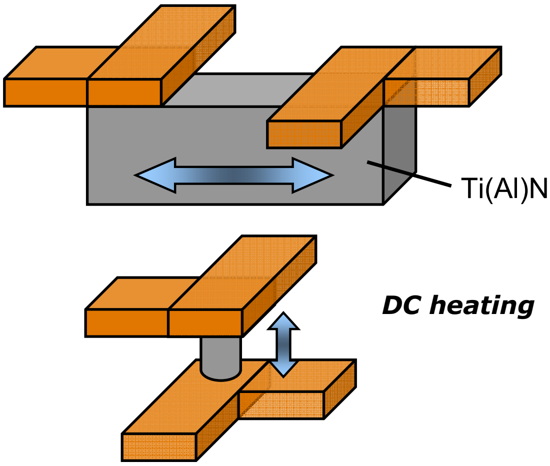




- GST thermal conductivity 0.2–1.0 W/m/K (SiO_2 ~ 1.3 W/m/K)
- Thermal interface resistance (TIR) ≈ equivalent to 10-20 nm GST
- TIR alters temperature profile and may be *key* to device operation

AC and DC Thermal Measurements





- AC harmonic heating of thin GST films (3-ω method)
  - 35-70-140 nm thin GST films, capped by SiO_2
- DC electrical thermometry of electrode metals
  - Transport physics (electrical, thermal) in *amorphous materials*

Conclusions

Summary:

- Self-heating due to small dimensions or thermal insulation
- *HOT* metallic single-wall carbon nanotubes at high bias:
  - Hot phonons and thermal conductivity of SWNTs
  - Light emission and breakdown (burning) of SWNTs in air
- Role of interface thermal resistance and material properties (amorphous vs. crystalline) in phase-change memory

Publications (see http://nanoheat.stanford.edu/epop/research.html)

- E. Pop, D. Mann, J. Cao, Q. Wang, K. Goodson, H. Dai, *Phys. Rev. Lett*. **95**, 155505 (2005)
- E. Pop, D. Mann, J. Reifenberg, K. Goodson, H. Dai, *Proc. IEDM*, Washington DC (2005)
- J. Reifenberg, E. Pop, A. Gibby, S. Wong and K. Goodson, *ITHERM* 106 (2006)
- D. Mann, E. Pop, Q. Wang, K. Goodson, H. Dai, *J. Phys. Chem. B* **110**, 1502 (2006)
- E. Pop, D. Mann, Q. Wang, K. Goodson, H. Dai, *Nano Letters* **6**, 96 (2006)
- D. Mann *et al.*, to appear in *Nature Nano* (2007)

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