Electro-Thermal Transport in Metallic Single-Wall Carbon Nanotubes

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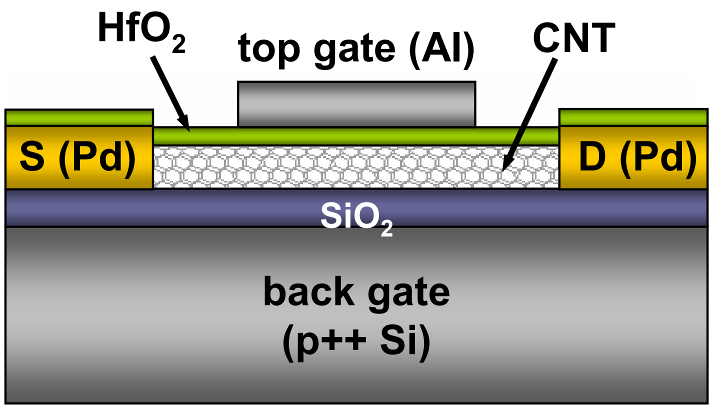
Carbon Nanotubes for Electronics

- Great <u>electrical</u> & <u>thermal</u> conductors
  - – Semiconducting → transistors
  - – Metallic → interconnects

- (Some) open questions:
  - – Thermal conductivity of single-walled carbon nanotubes (SWNTs)
  - – Great thermal conductivity, poor thermal conductance (small *d*)
  - – Transport issues

Carbon nanotube transistor



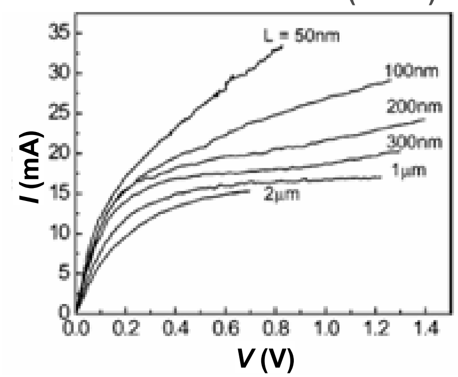
1995 2000 2005 2010 2015 ?

Properties of Metallic SWNTs

(what we know so far)

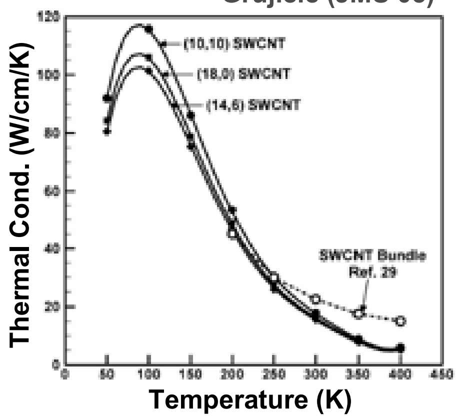
- Electrical properties (on insulating substrates)
  - Yao (PRL'00), Javey (PRL'04), Park (NL'04)
  - Current saturation near 20 μA for tubes longer than 1 μm
  - Larger currents (up to 100 μA) for short ~10 nm tubes

Park (NL'05)



- Thermal properties
  - Yu (NL'05), Mingo (NL'05), Pop (PRL '05)
  - Thermal conductivity dominated by phonon transport
  - 3500 $Wm^{-1}K^{-1}$ around 300 K, decreases as 1/*T* above

Grujicic (JMS'05)



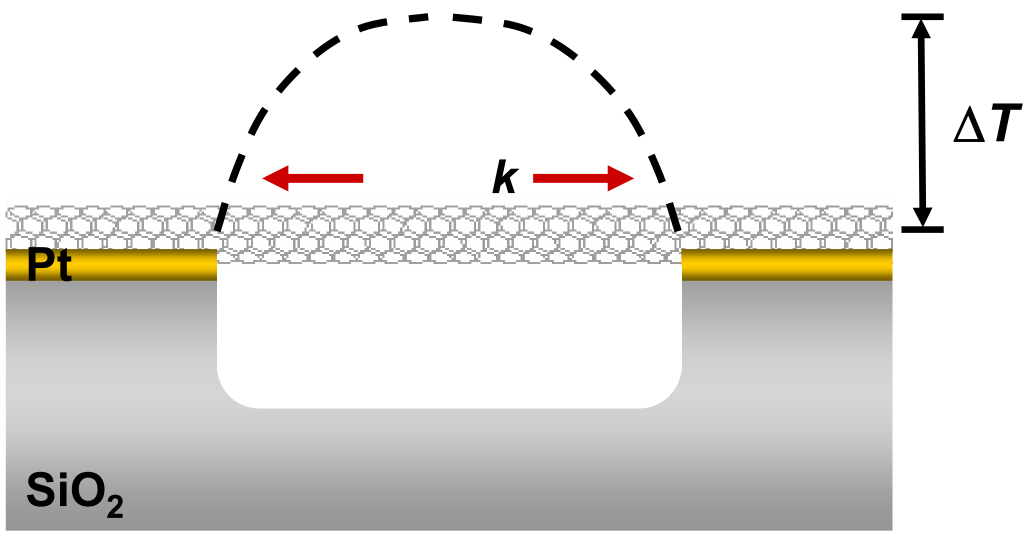
Summary of This Talk

- Metallic single-wall nanotubes
  - On insulating substrate (silicon nitride or oxide)
- Coupled electrical *and* thermal transport
  - Essential for predicting breakdown voltage of SWNTs on substrates exposed to air (oxygen)
  - Use breakdown voltage scaling to find heat loss coefficient
- Unified electro-thermal model
  - Must include optical phonon *absorption* (usually neglected) to explain “upkick” in *low-bias* resistance vs. T

Back-of-Envelope Estimate (Suspended)

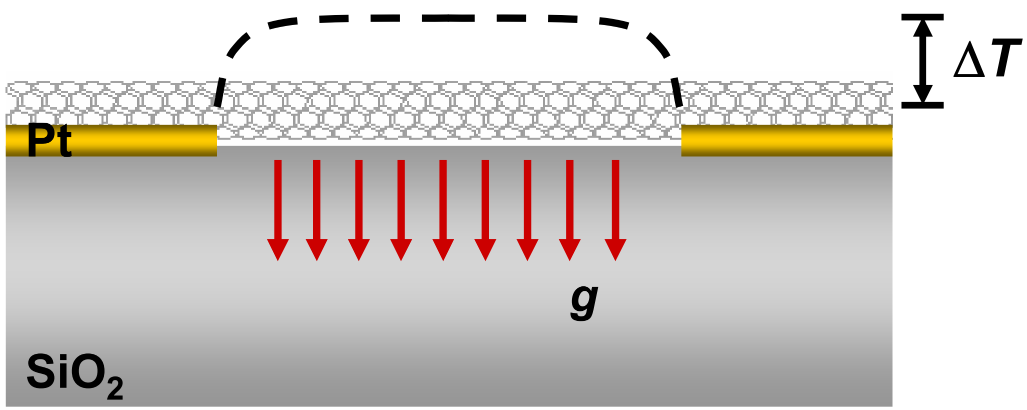
E. Pop *et al.*, Phys. Rev. Lett. 95, 155505 (2005)

- Thermal conductivity k ~ 3000 W/m/K
- Typical L ~ 1 μm, d ~ 1 nm suspended nanotube:
  - Thermal conductance ~ 25 nW/K
  - Thermal resistance ~ 40 K/μW
- Moderate power ~ 10 μW (10 μA @ 1 V) → ΔT = 400 K!

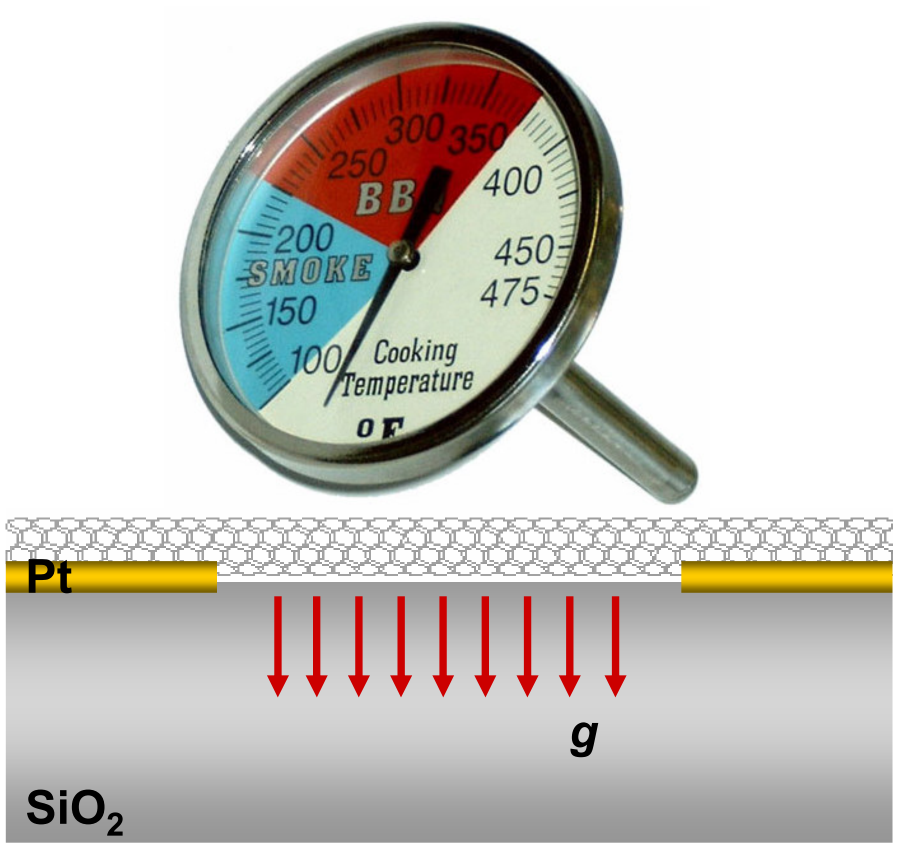


Back-of-Envelope Estimate (On-Substrate)

- 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]

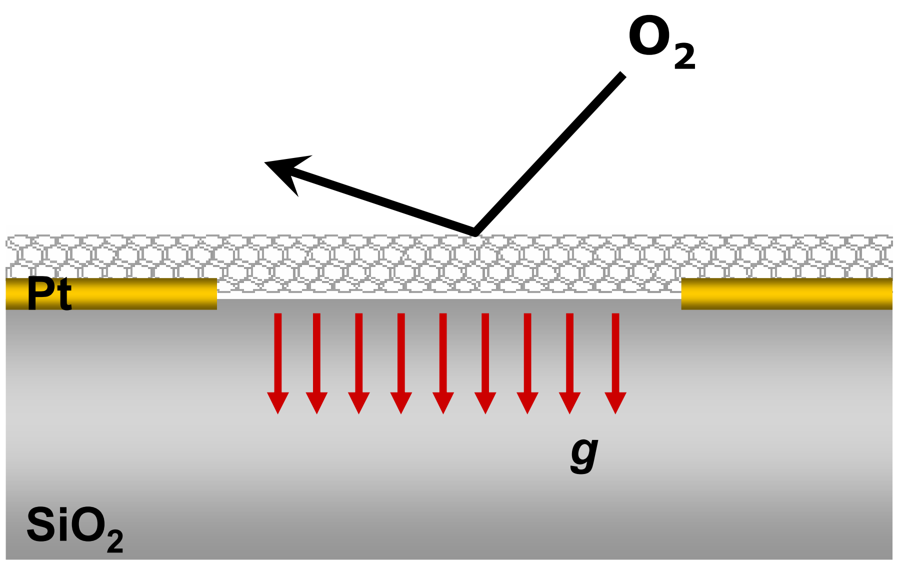


Nanotube Temperature Gauge

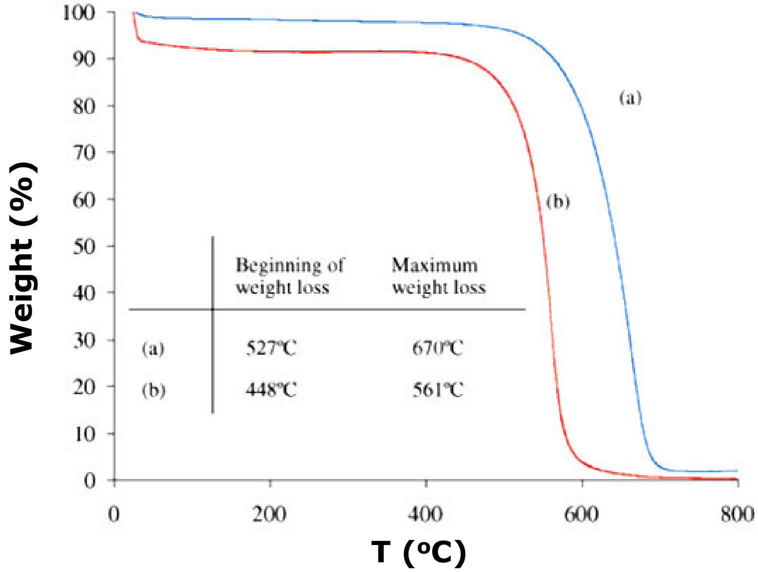


Nanotube Temperature Gauge

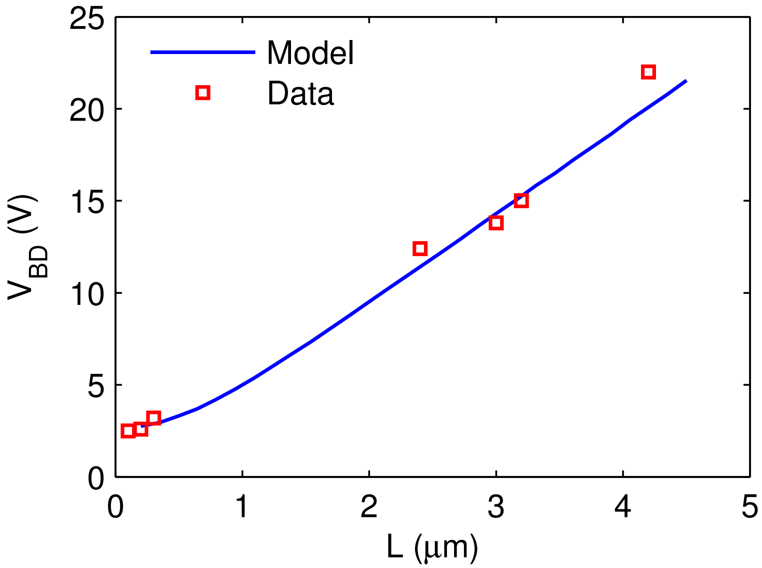
- Doesn’t exist
- But… oxidation (burning) temperature is known



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)

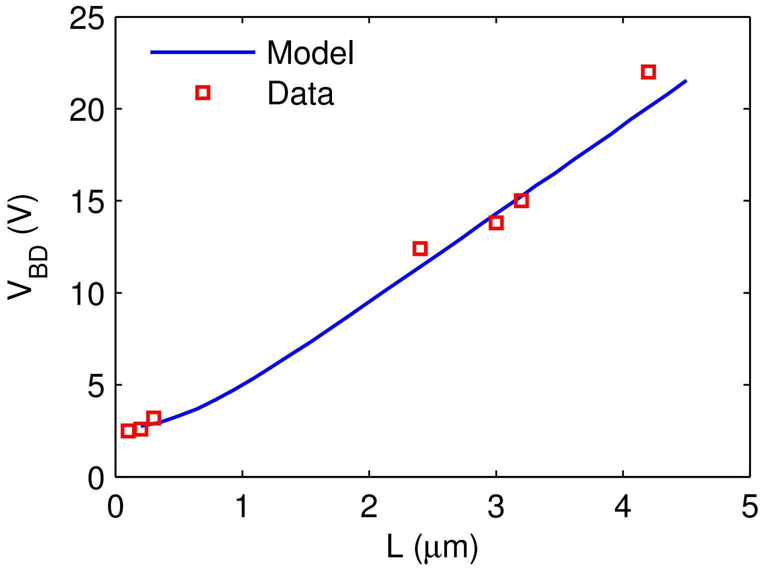
- Thermogravimetric (TGA) data shows SWNTs exposed to air break down by oxidation at 500 < T_{BD} < 700 °C (800–1000 K)
- Joule breakdown voltage data shows V_{BD} scales with L in air
- Supports cooling mechanism *along* the length, into the substrate

Breakdown of SWNTs: Analysis

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

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

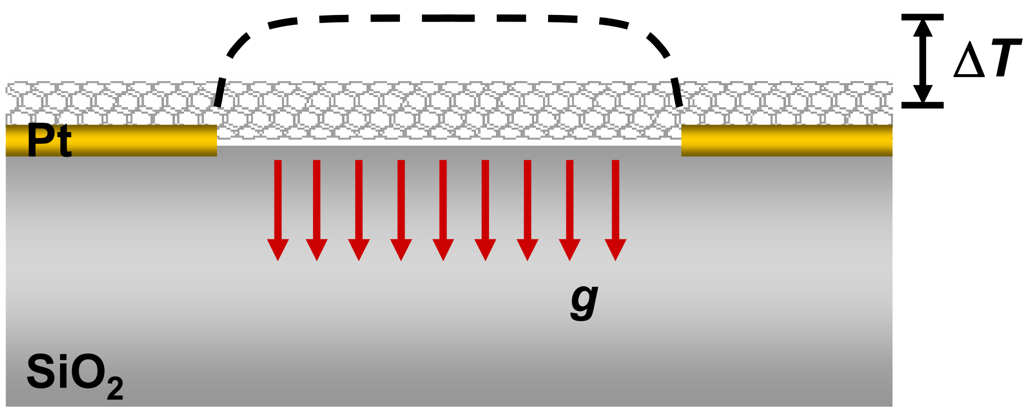
$$\boxed{V_{BD} = gL\left(T_{BD} - T_0\right) / I_{BD}}$$



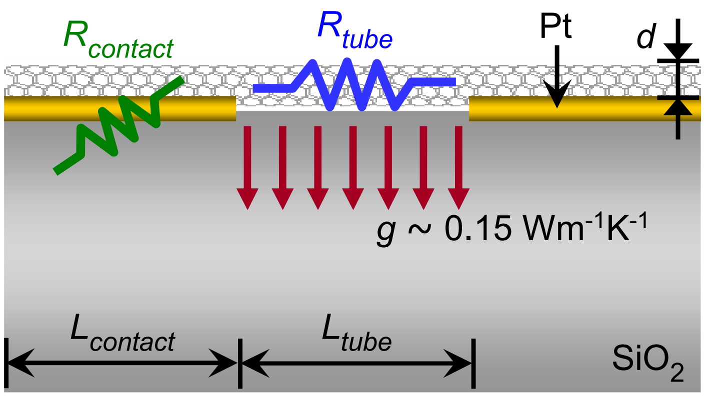
- Empirically note that:
  - V_{BD} vs. L in air scales approx. 5 V/μm
  - Breakdown currents for L > 1 μm always about $I_{BD} \approx 20$ μA
- Analytic solution of heat conduction equation
  - Heat loss per unit length: $g \approx 0.14 – 0.2$ WK^{-1}m^{-1} given range of T_{BD}
- *No* assumption was made about electrical transport model

Back-of-Envelope Estimate (Revisit)

- Using $g \approx 0.15\ \mathrm{WK^{-1}m^{-1}} \rightarrow 1/g \approx 6\ \mathrm{K\mu m/\mu W}$
- Consistent with typical solid-solid thermal interface resistance values, given the SWNT-substrate contact area (~Lxd)
- At moderate power per length $p' \approx 10\ \mu\mathrm{W}/\mu\mathrm{m} \rightarrow \Delta T \approx 60$ K



Combined Electro-Thermal Model



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

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

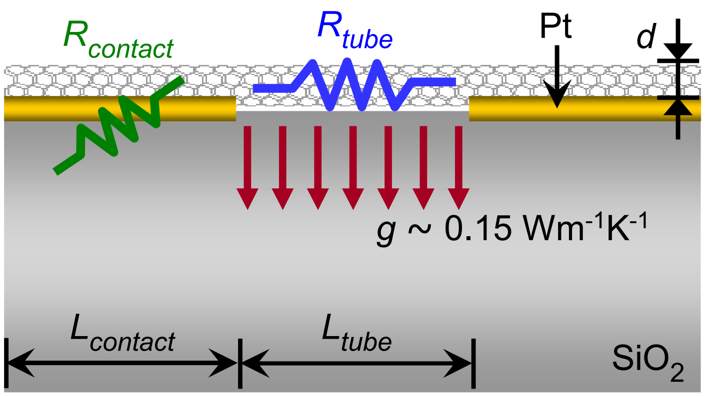
where

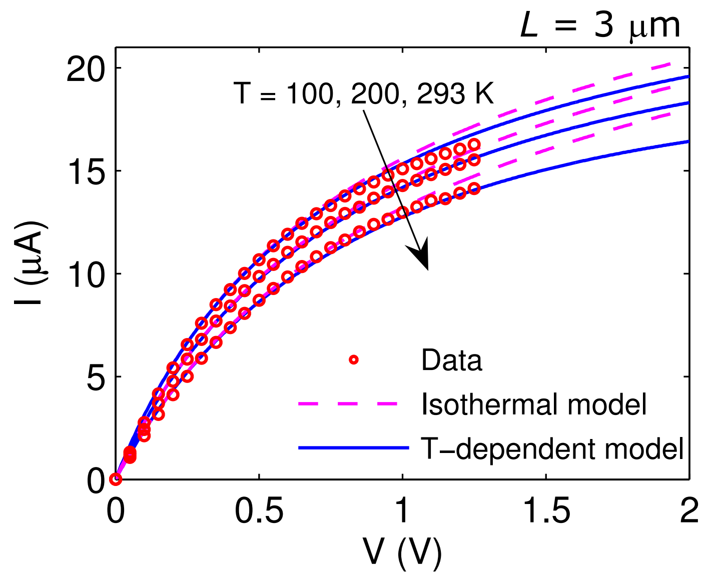
$$p' = I^2(R - R_C)/L$$

$$k(T) = 3500(300/T)$$

- Landauer-type electrical resistance
- Include Joule heating, couple with heat conduction equation
- Self-consistent solution
- Need temperature-dependent mean free paths (MFPs)

Combined Electro-Thermal Model





- Landauer-type electrical resistance
- Include Joule heating, couple with heat conduction equation
- Self-consistent solution
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Temperature Dependence of MFPs

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

$$\lambda_{AC} = \lambda_{AC,300}(300/T)$$

$$\lambda_{OP,abs}(T) = \lambda_{OP,300}\frac{N_{OP}(300)+1}{N_{OP}(T)}$$

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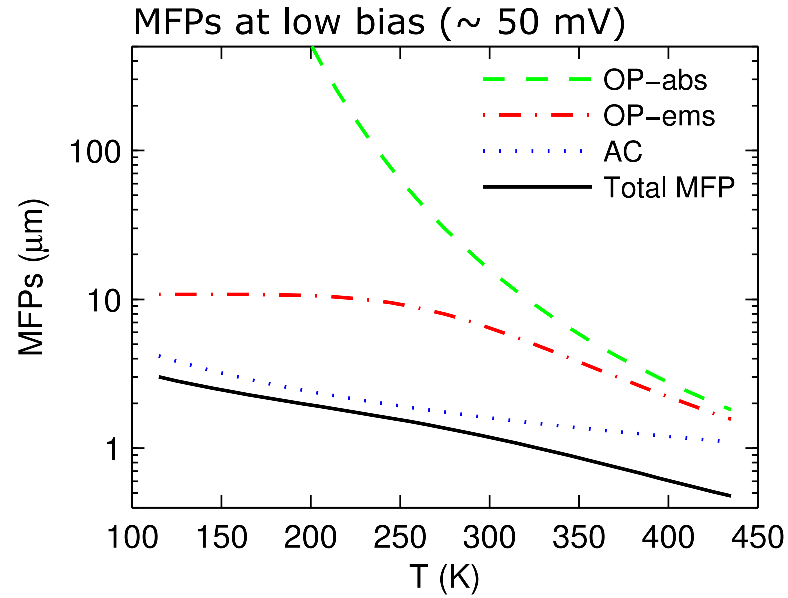
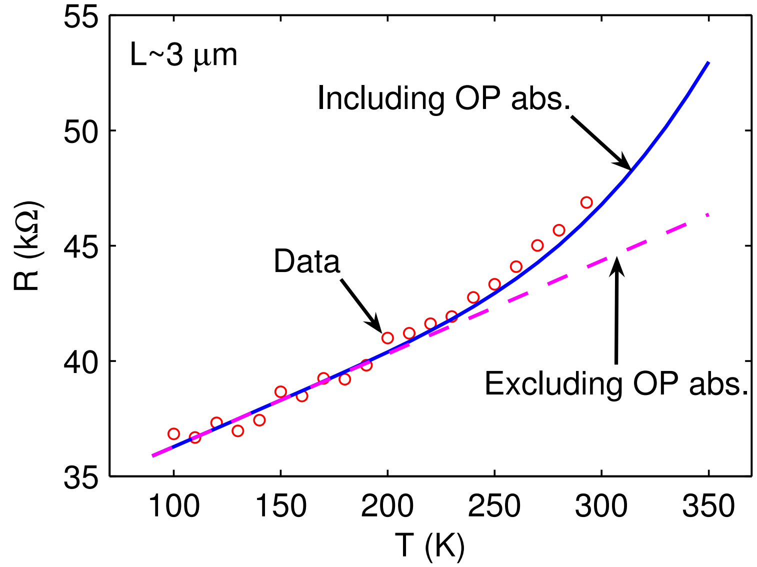
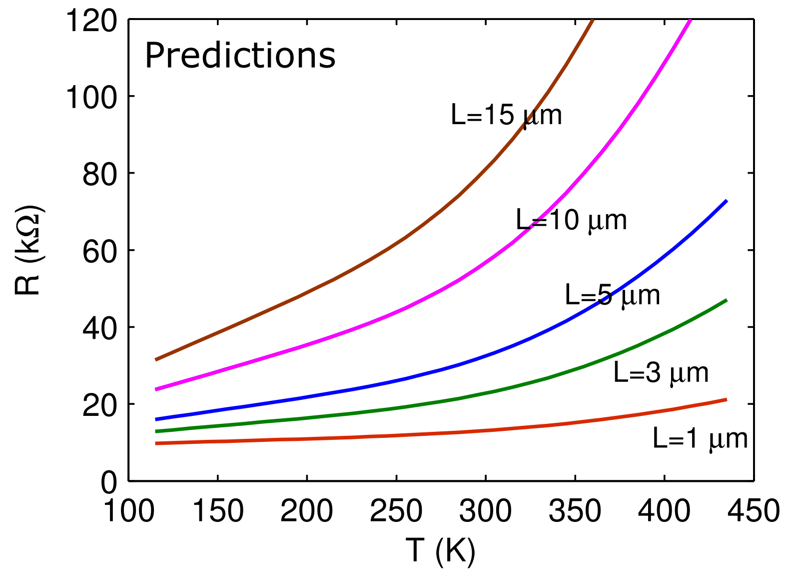


- Include scattering by optical phonon (OP) absorption
- Note OP *emission* may occur after:
  - (1) A carrier gains enough energy ($\hbar\omega_{OP}$ ~ 0.18 eV) from E-field
  - (2) An OP absorption event
- OP absorption is a strong function of T via $N_{OP} = [\exp(\hbar\omega_{OP}/k_B T) - 1]^{-1}$

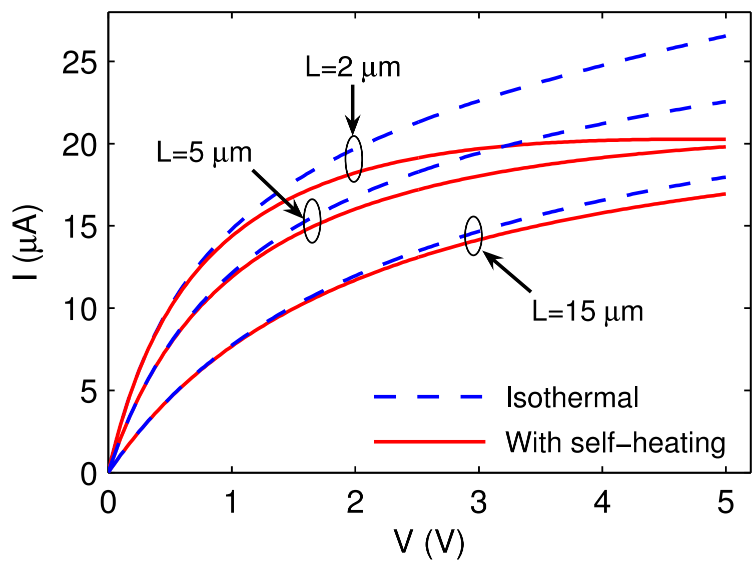
Role of Optical Phonon *Absorption*

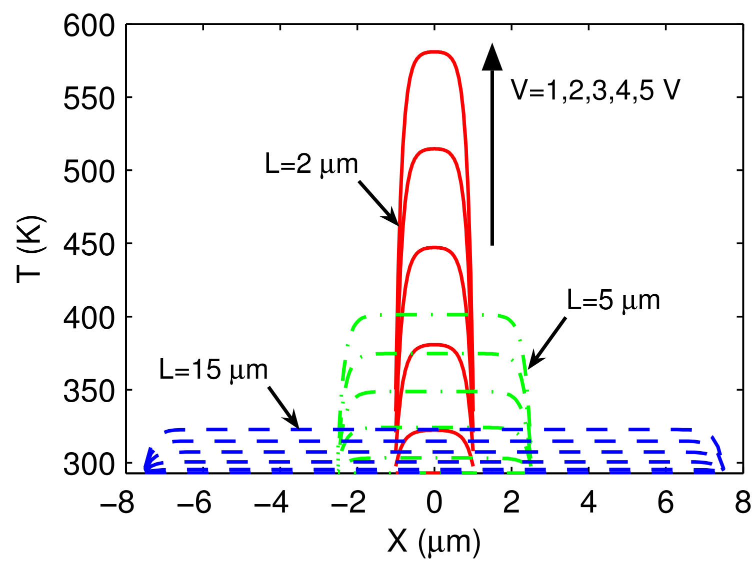




- ***Low-bias*** resistance of metallic SWNTs
- Subtle effect in the "up-kick" of SWNT ***low-bias*** resistance near room *T*
- Important for temperature coefficient of resistivity (TCR) of SWNT interconnects: ~0.0026 K^{-1}, comparable to 40 nm Cu vias

Electro-Thermal Modeling of SWNTs





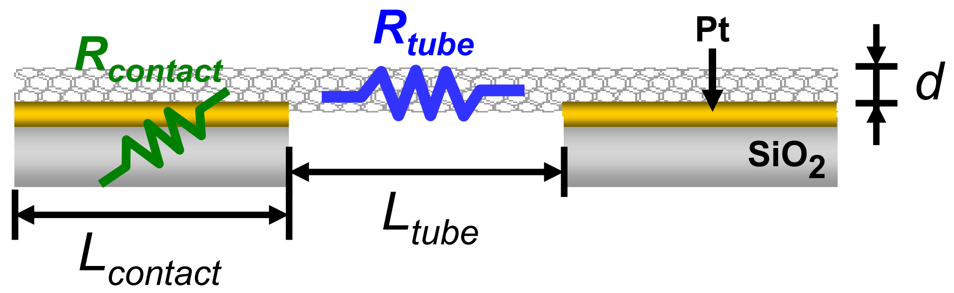
- *Long tubes heat up less*: better heat-sinking, lower power density
- Model suggests current saturates near 20 µA due to self-heating
- Self-heating may be neglected when *p*' < 5 µW/µm (design goal?)
- Current enhancement (> 20 µA) in shortest (< 1 µm) SWNTs very likely aided by Joule heating shifting towards the contacts

Metallic SWNT Resistance Components

$k \approx 3500\ \mathrm{Wm^{-1}K^{-1}}$

$L_{tube} \approx 2\ \mu m$, $d \approx 2\ nm$

$L_{contact} \approx 2\ \mu m$



	Thermal Res. Phonons	Thermal Res. Electrons		Electrical Res. Electrons
Tube	3×10^8 K/W	2×10^9 K/W	← WFL	~ 15 kΩ
Contacts	6×10^6 K/W	2×10^9 K/W	←	~ 15 kΩ

- $R_{elec.} \sim 10 \times R_{phon.}$ → phonons dominate heat conduction
- $R_{contact} < 0.1 \times R_{tube}$ as long as $L_{contact} > 0.8/L_{tube}$ (μm)

Conclusions

- High-bias breakdown in air (oxidation)
  - Extract thermal conductance to substrate along SWNT length
  - $g \approx 0.15$ $Wm^{-1}K^{-1}$, limited by nanotube-substrate interface
- Electro-thermal model for transport in metallic SWNTs
  - Estimate MFPs(T) and include optical phonon absorption
  - Relevant in long (> 1 μm) SWNTs even at *low bias* ($T > 300$ K)
  - Can we break the 20 μA current saturation "limit" for long metallic SWNTs by engineering (increasing) g ?
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