Metal-Carbon Nanotube Contacts

Patrick Wilhite and Cary Y. Yang

February 20, 2014

Santa Clara University
Center for Nanostructures

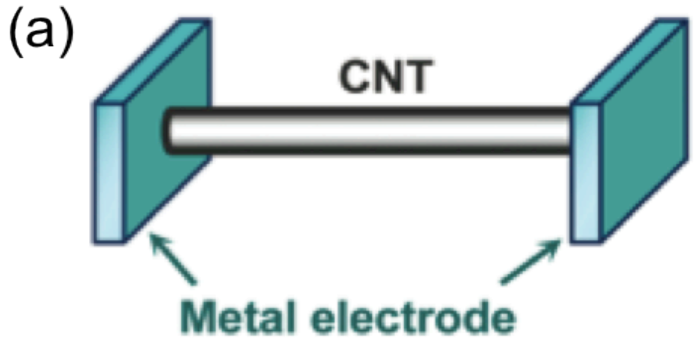
Outline

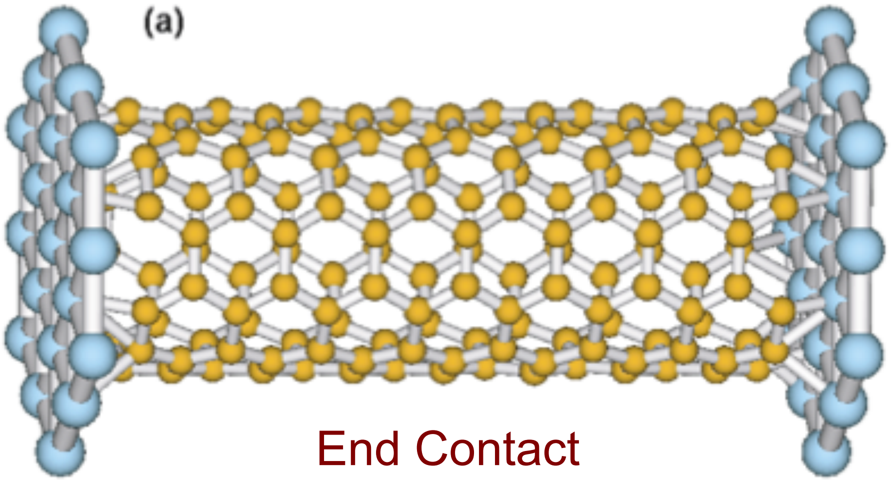
- Introduction: Contact Types and Applications
- Metal-CNT Contact Models
- CNT Nanoscale Probing
- Contact Engineering
- Summary

Outline

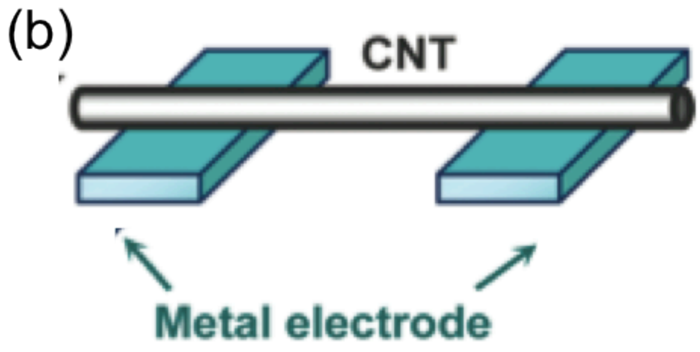
- Introduction: Contact Types and Applications
- Metal-CNT Contact Models
- CNT Nanoscale Probing
- Contact Engineering
- Summary

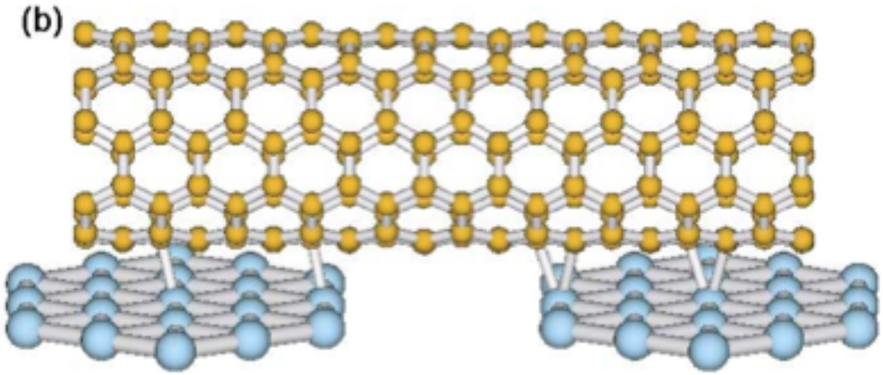
Contact Schematics





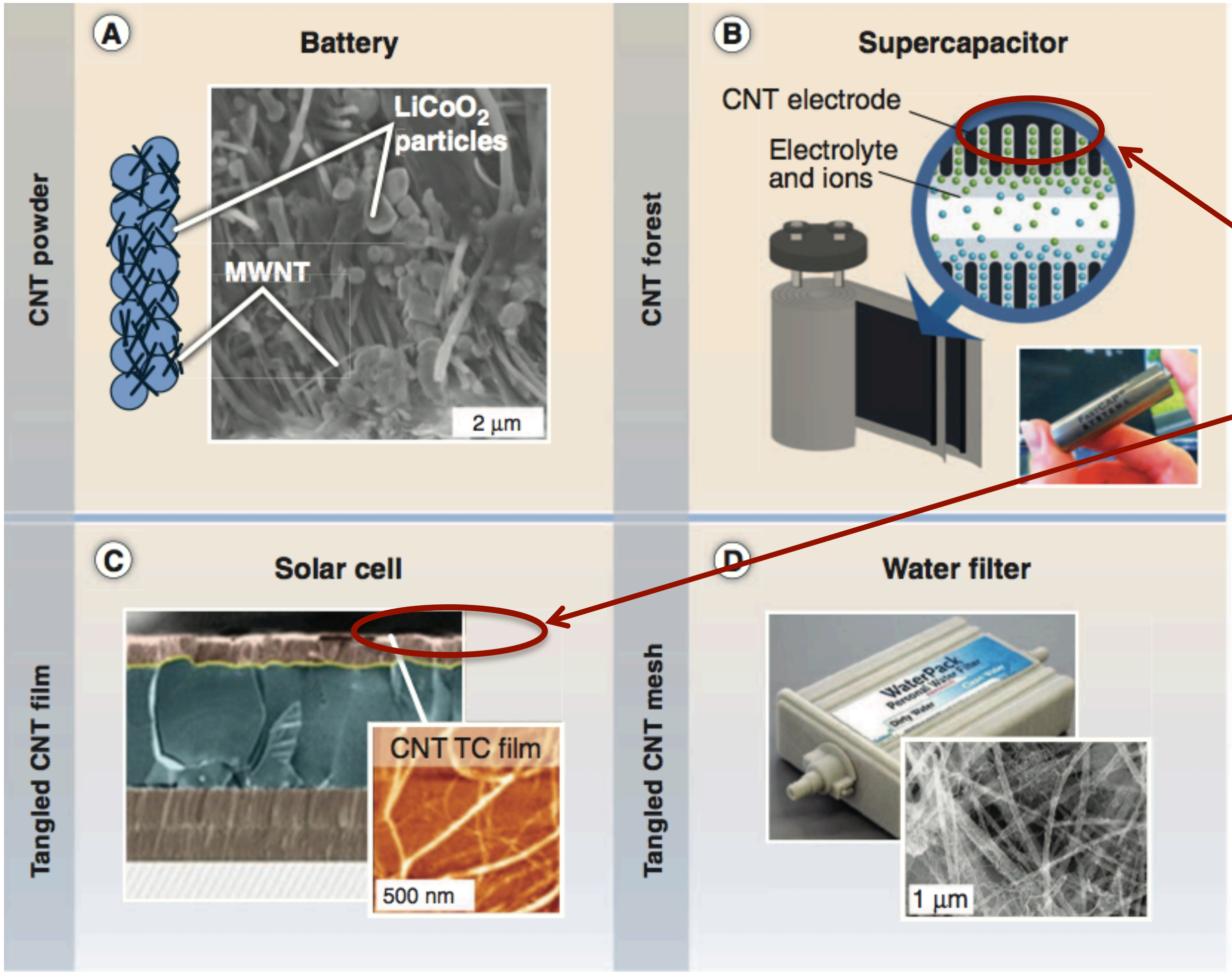
End Contact





Side Contact

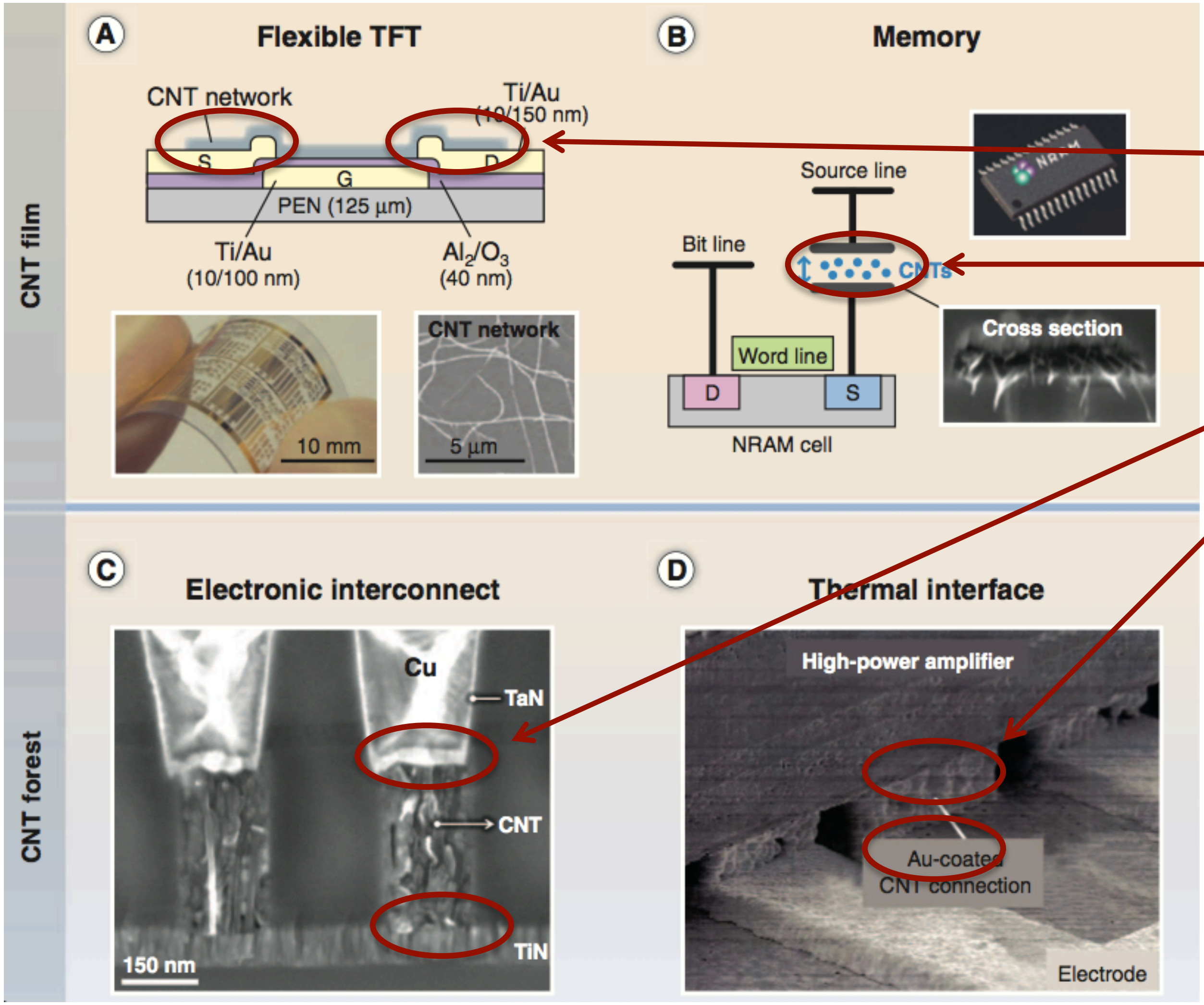
Applications



Metal-CNT contact resistance impacts performance

De Volder *et al.*, *Science* 339, 535–9

Applications



Metal-CNT contact resistance impacts performance

De Volder *et al.*, *Science* 339, 535–9

Outline

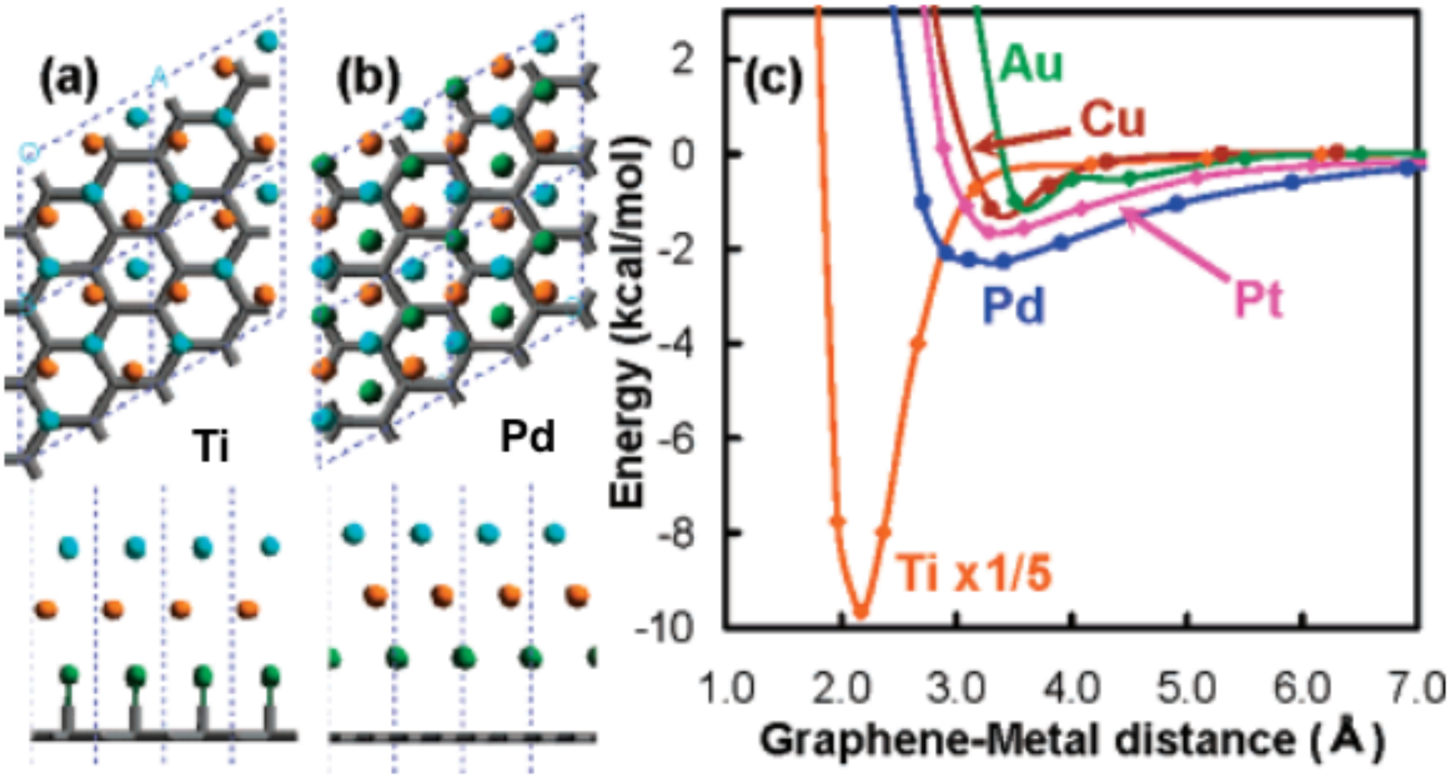
- Introduction: Contact Types and Applications
- Metal-CNT Contact Models
- CNT Nanoscale Probing
- Contact Engineering
- Summary

Contact Resistance Limits

- Quantum conductance for ballistic transport, $G_0 = 2e^2/h$
- *Ab initio* calculations predict contact resistivities $\geq 24.2\ \mathrm{k\Omega \cdot nm^2}$ for a side-contacted graphene layer*
- For near-ballistic transport and optimum metal-CNT interfaces, contact resistance can be minimized for device functionalization

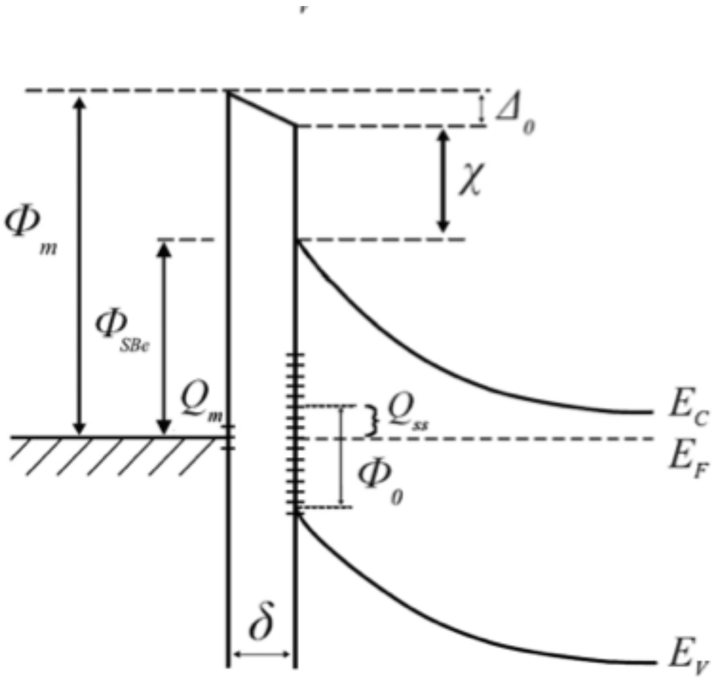
*Matsuda *et al., J. Phys. Chem. C* **2010,** *114,* 17845

DFT/Green's Function



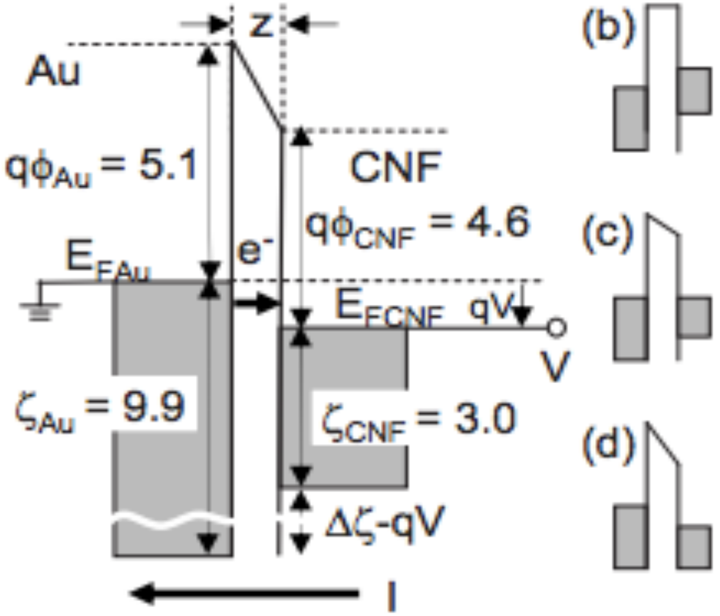
Matsuda *et al., J. Phys. Chem. C* **2010,** *114,* 17845

Tunneling



Schottky barrier (metal-semiconducting SWCNT)

Svensson and Campbell, *J. Appl. Phys*. **110**, 11110 (2011)



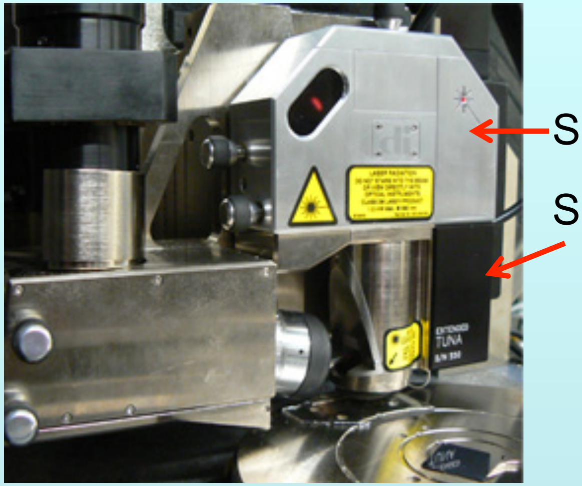
Tunneling barrier (metal-MWCNT)

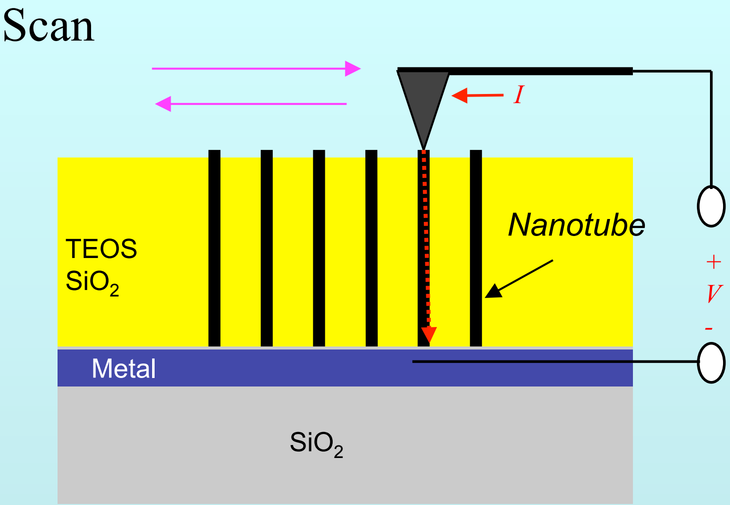
Yamada *et al*., *J. Appl. Phys*. **107,** 044304 (2010)

Outline

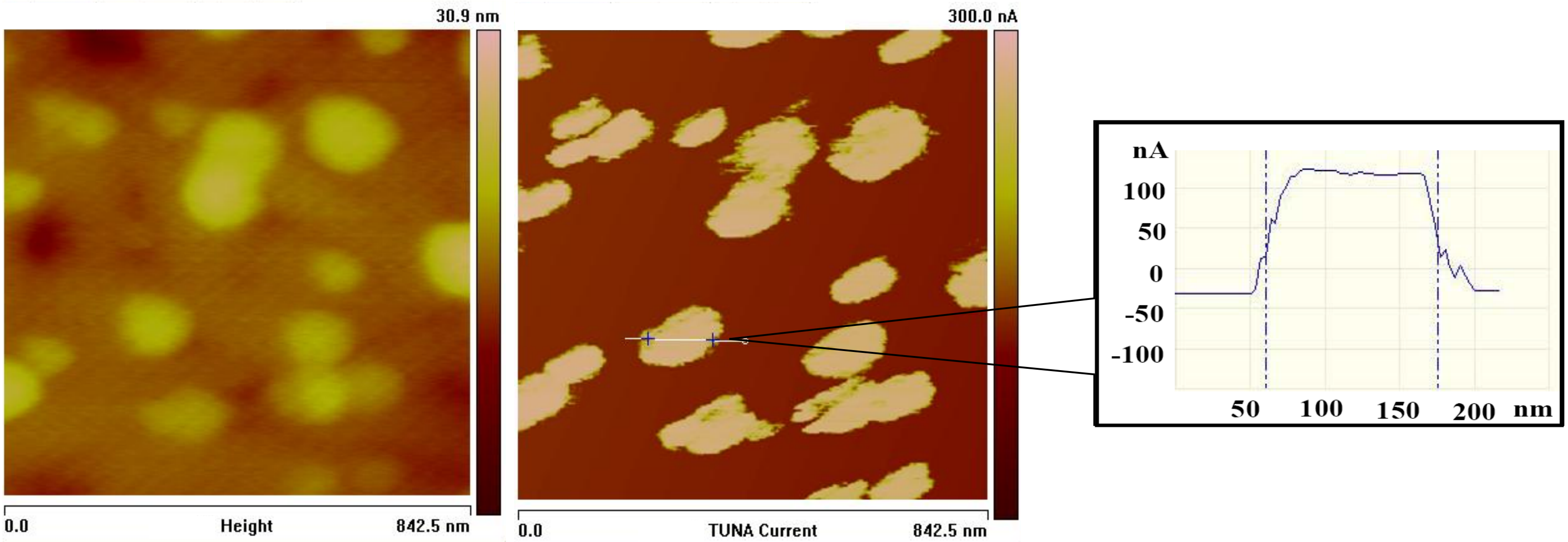
- Introduction: Contact Types and Applications
- Metal-CNT Contact Models
- CNT Nanoscale Probing
- Contact Engineering
- Summary

Conductive – Atomic Force Microscopy (C-AFM)





C-AFM Results

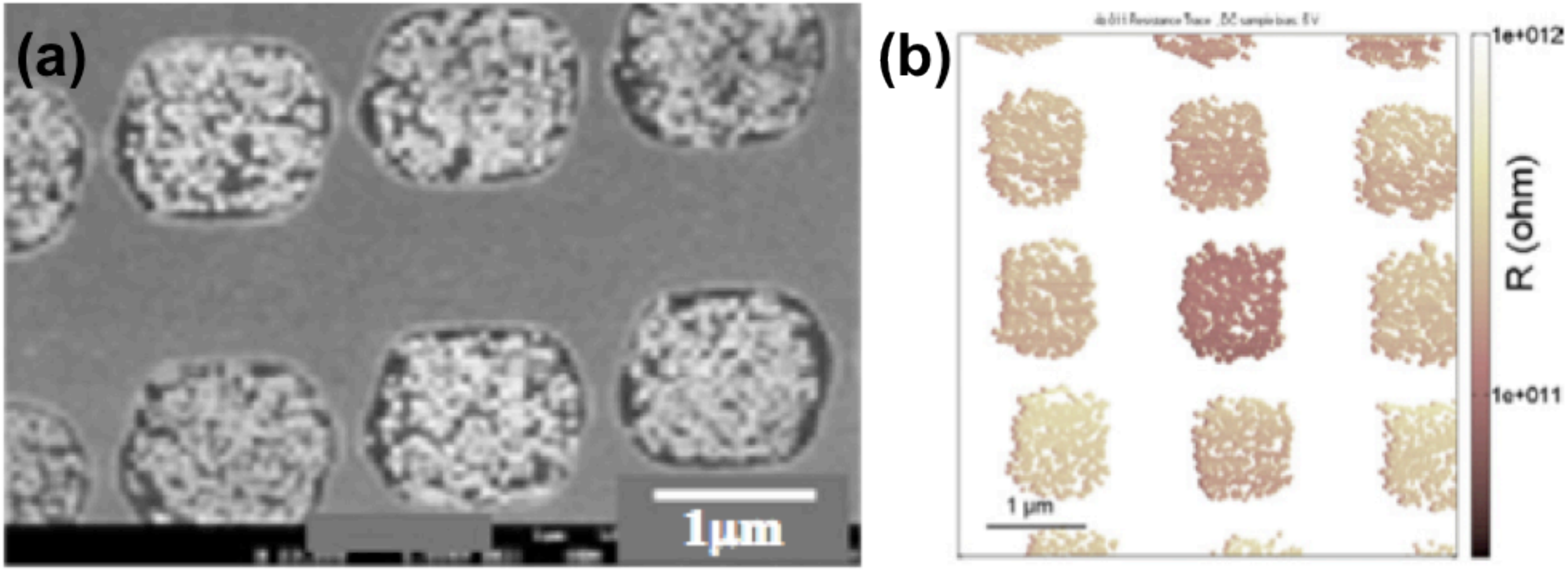


Surface topography

Current map

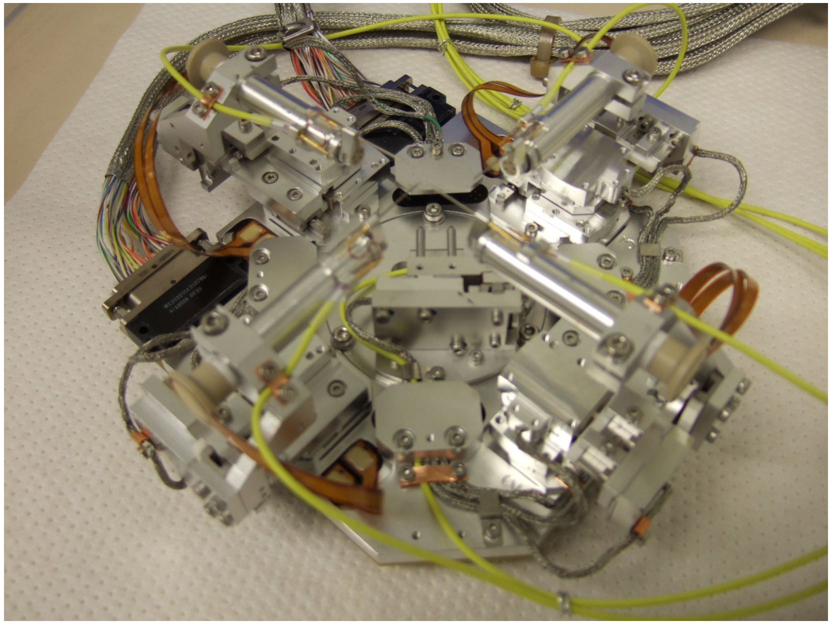
- Current through every single CNT sensed for fixed *V*
- Locate precisely individual CNT and measure electrical characteristics
- Position tip for *I*-*V* sweeps

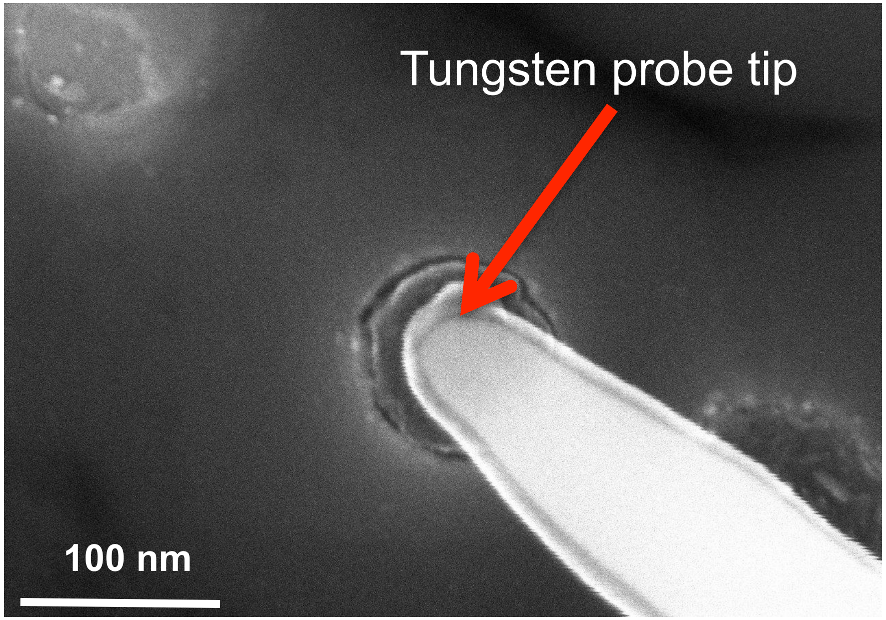
Scanning Spreading Resistance AFM

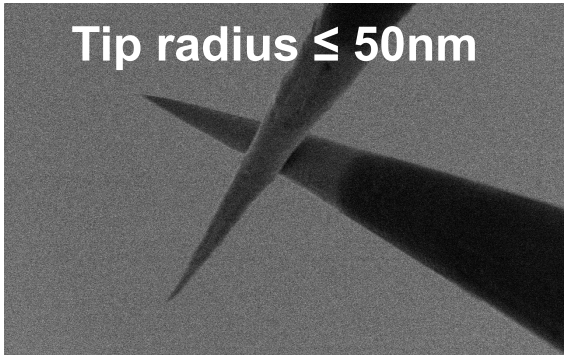


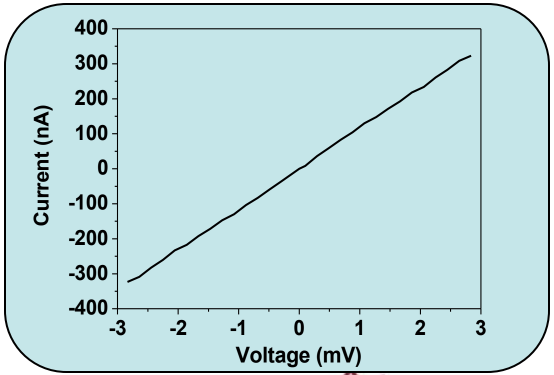
M. Fayolle *et al*., *Microelectronic Engineering* **88,** 833 (2011)

In Situ Nanoprobing inside SEM







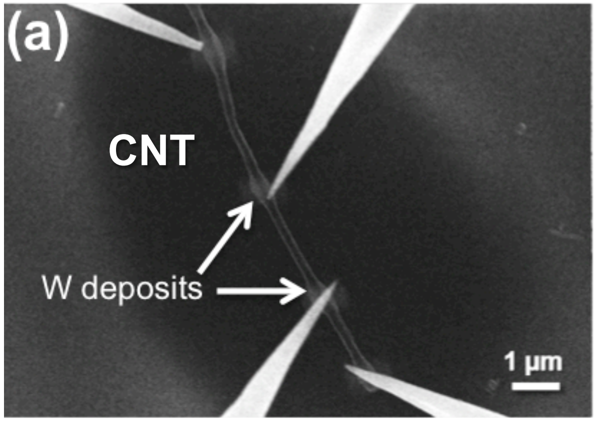


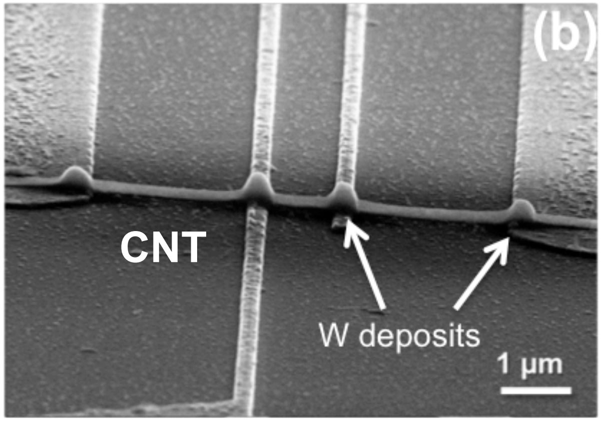
Typical ***I-V*** for single CNT

Santa Clara University
Center for Nanostructures

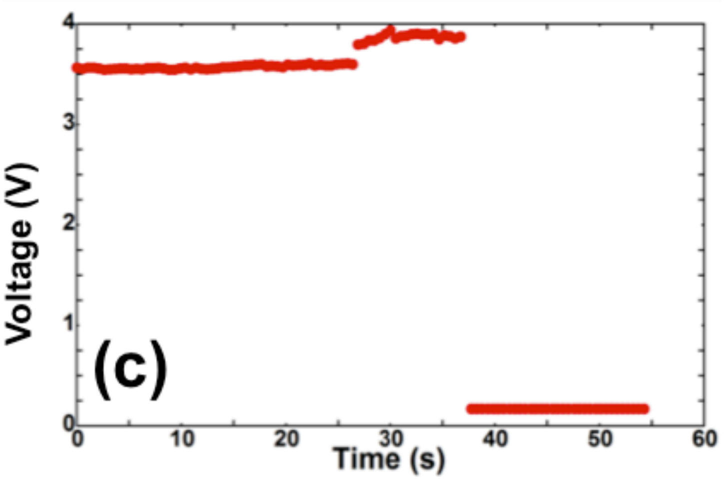
Nanoprobing Measurements

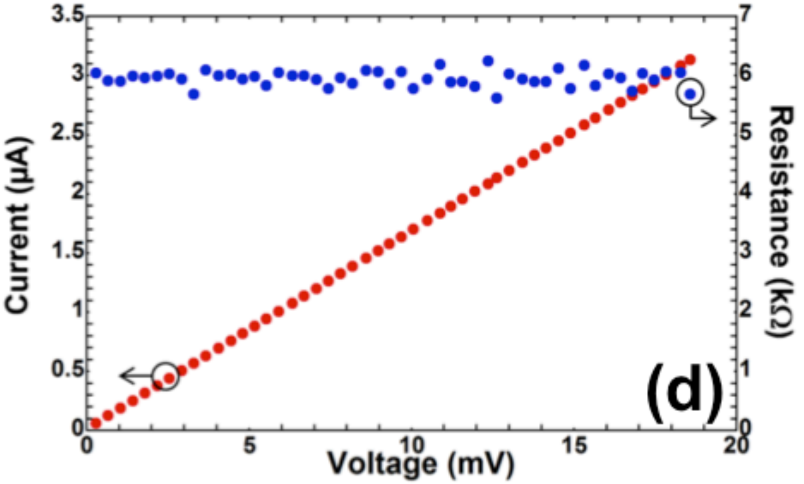
Direct probe contact with W deposits





Probes interfaced with Au electrodes

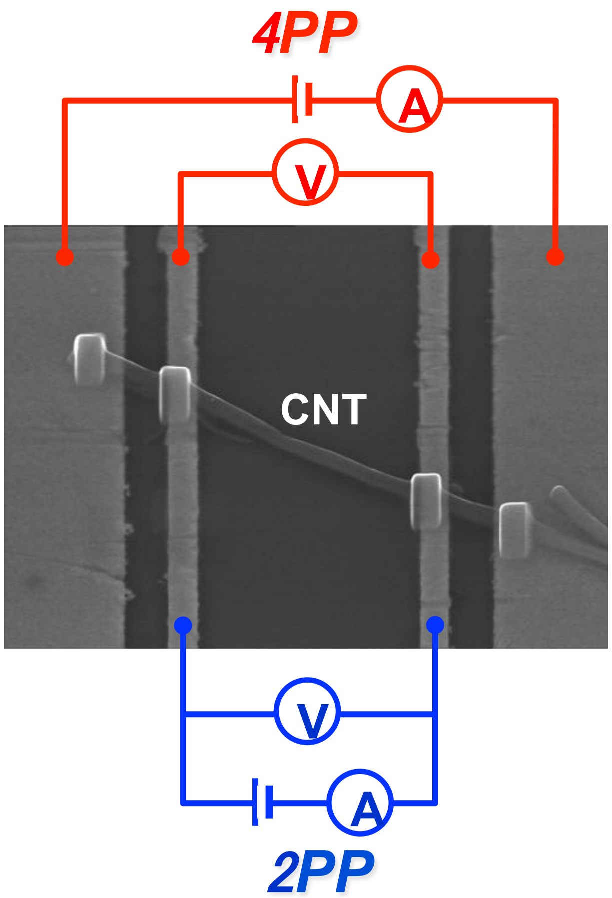


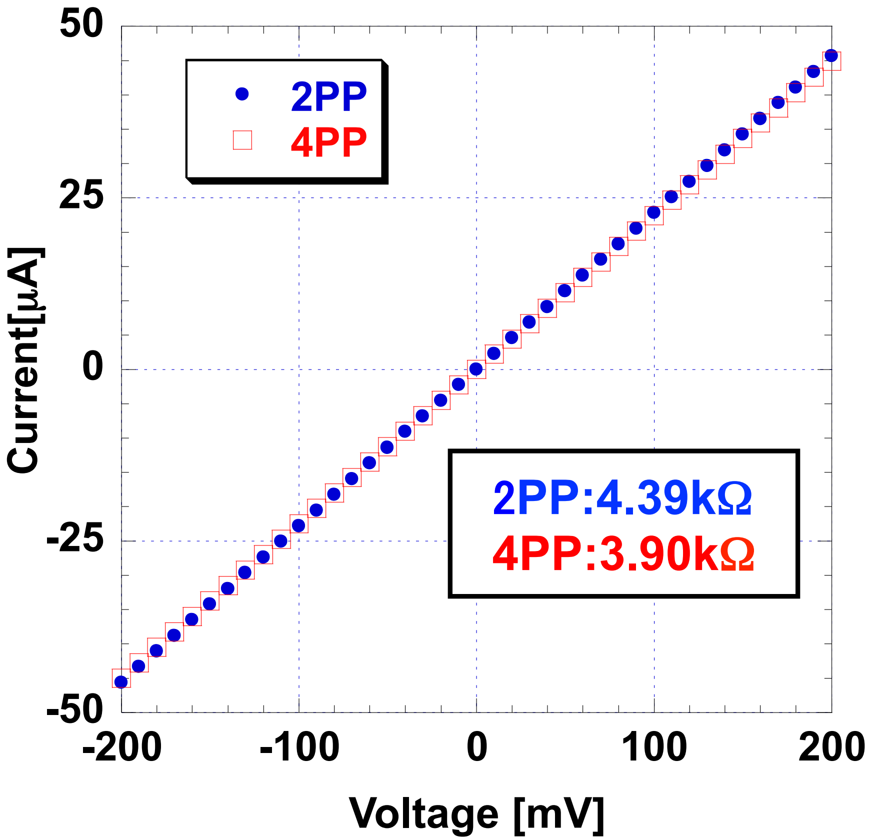


(c) Constant current through outer probes

(d) 4PP resistance remains constant

Contact Resistance Extraction





R_C = 0.49 kΩ

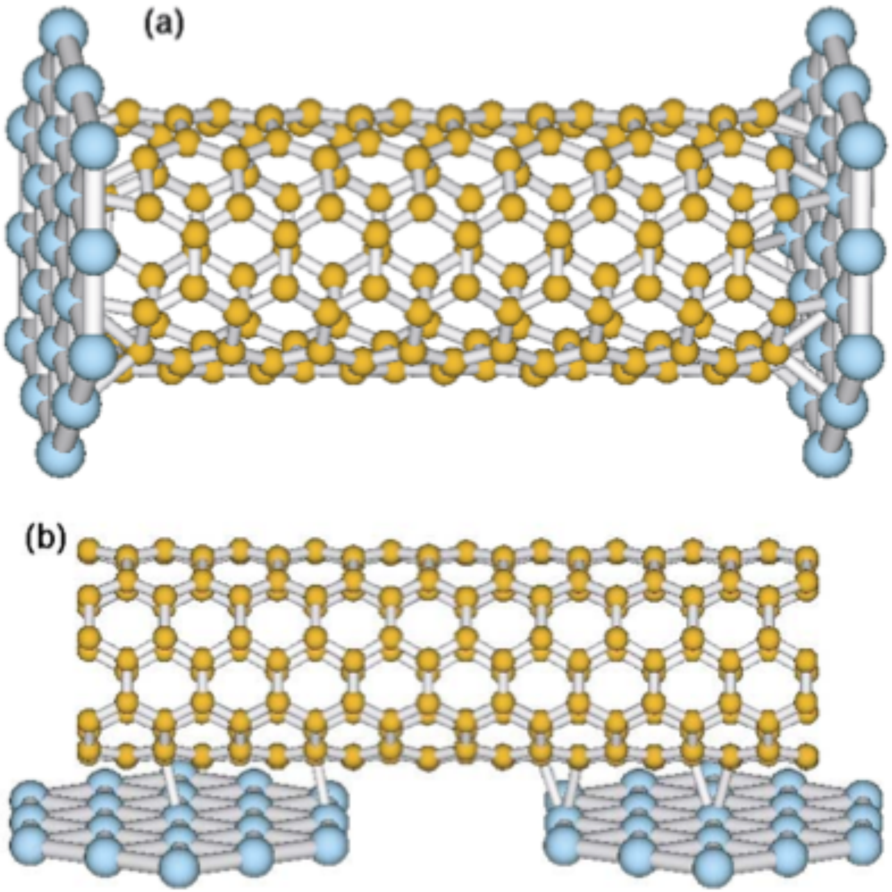
Outline

- Introduction: Contact Types and Applications
- Metal-CNT Contact Models
- CNT Nanoscale Probing
- Contact Engineering
- Summary

Contact Engineering

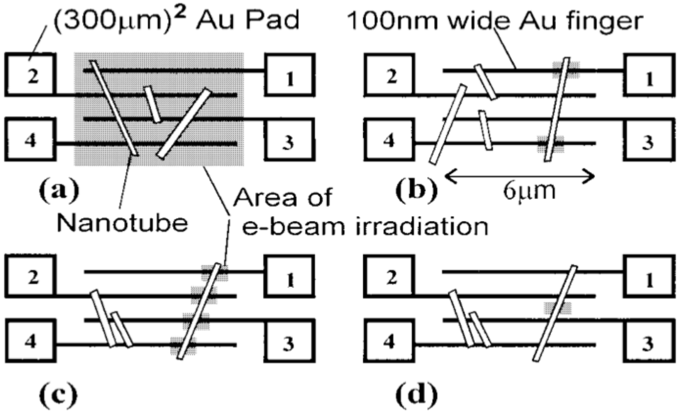
- Contact Geometry consideration
  - End contact vs. side contact
- Joule Heating
- E-beam Treatment
- Contact Encapsulation
  - Electrode contact deposition
  - Contact area
- As-grown interface vs. metal deposition

End vs. Side Contacts

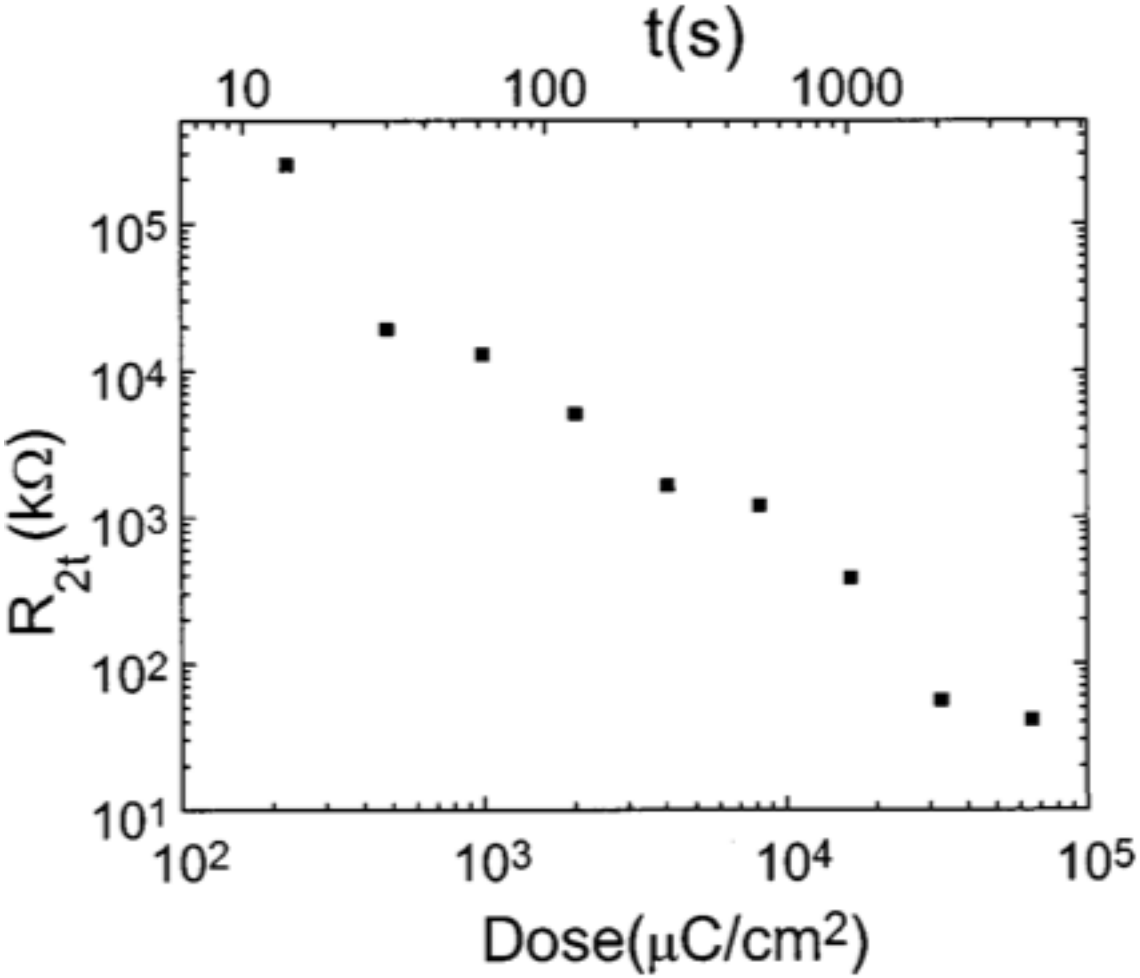


- Chemical bonding at end contact
  - Saturated C-bonds
  - Conduction modes of graphitic structure is unaffected
  - Interface with concentric walls
- Van der Waals bonding at side contact
  - Larger interfacial separation
  - C-bonds remain unsaturated, inhibiting conduction
  - Interface with outermost wall only

E-beam Irradiation

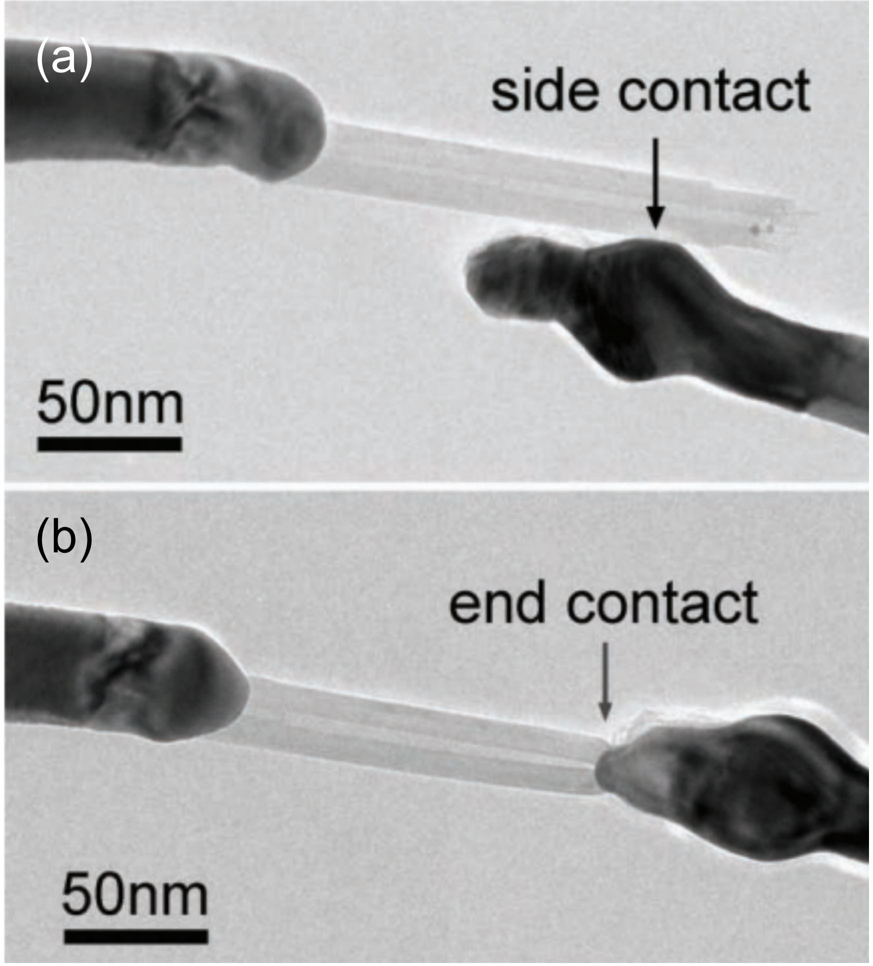


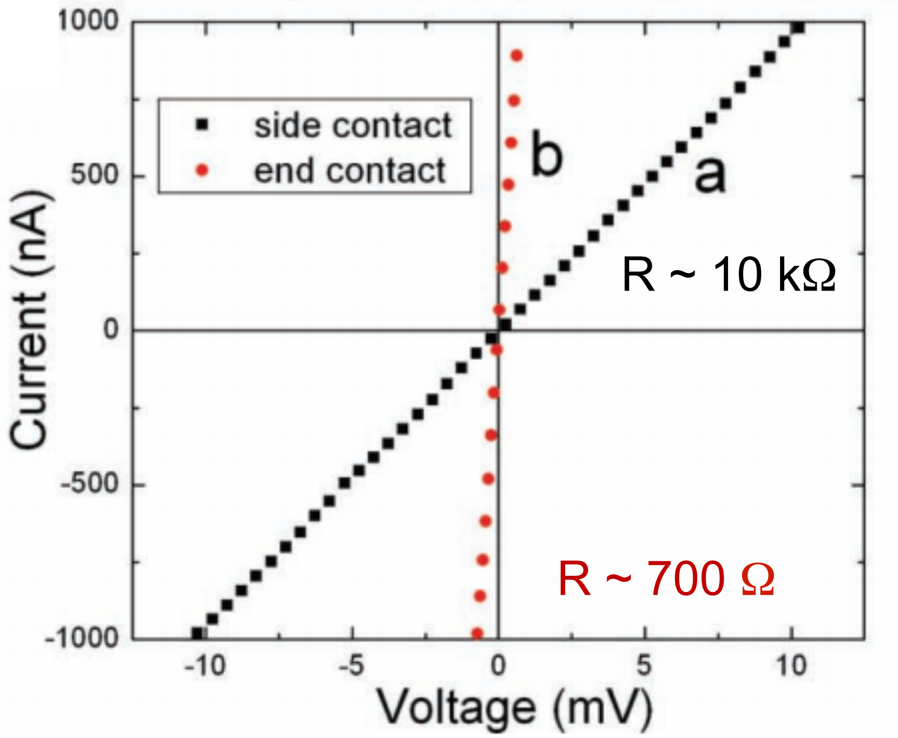
- Results in a-C depo
    - Non-conductive
- 4PP unaffected by exposure
- Does not affect CNT



Bachtold *et al., Appl. Phys. Lett.*, **73**, 274 (1998)

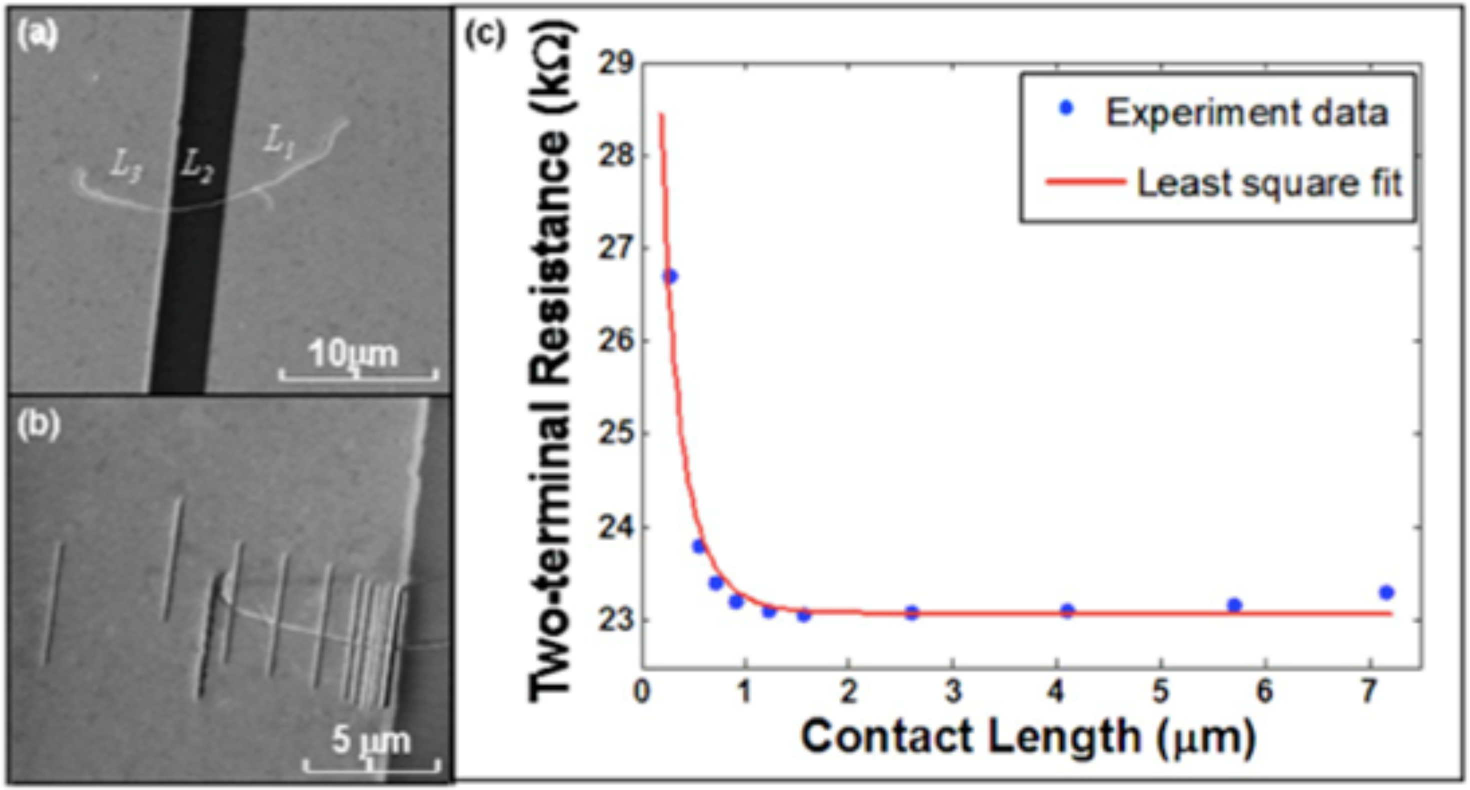
E-beam Fused Contacts





Wang *et al.*, *Adv. Mater.* **22**, 5350 (2010)

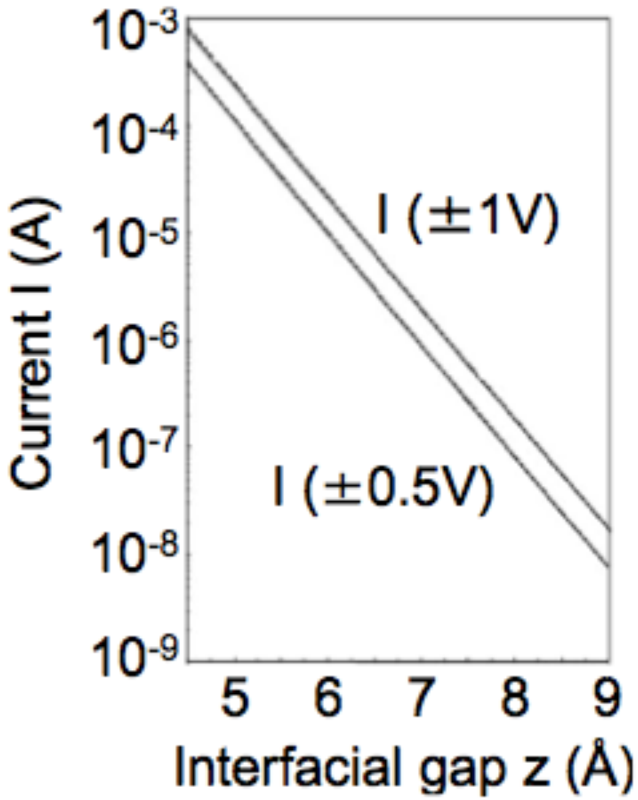
Contact Area Enhancement

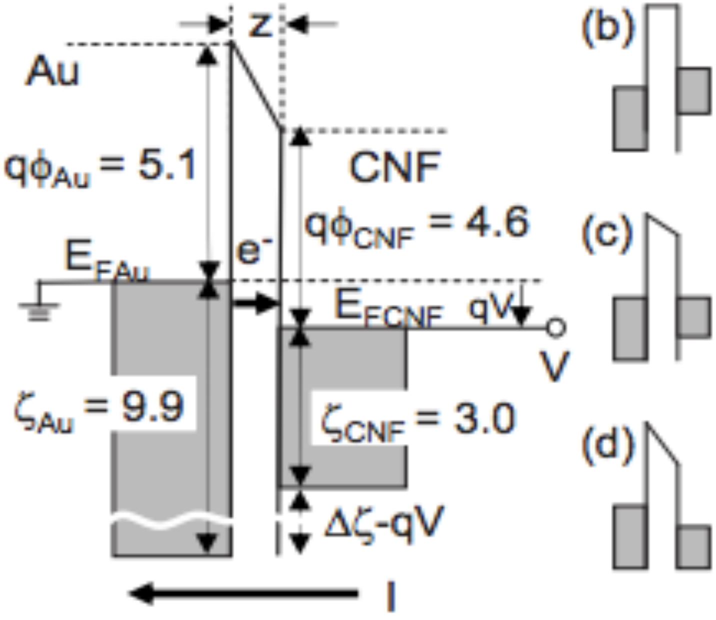


R_C appears to be area independent for contact longer some characteristic length

Lan *et al.*,*Appl. Phys. Lett.* **92,** 213112 (2008)

Tunneling

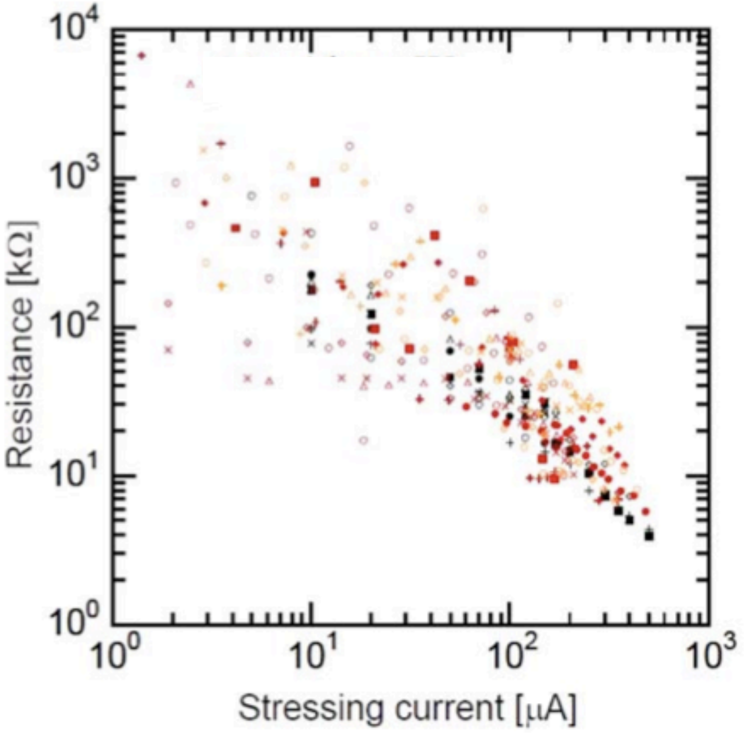


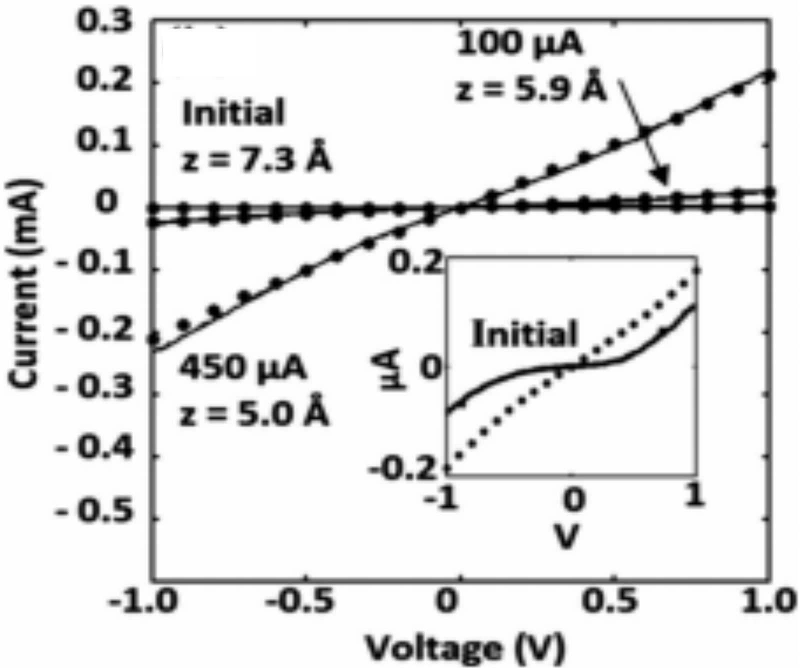


Tunneling barrier (metal-MWCNT)

Yamada *et al., J. Appl. Phys.* **107,** 044304 (2010)

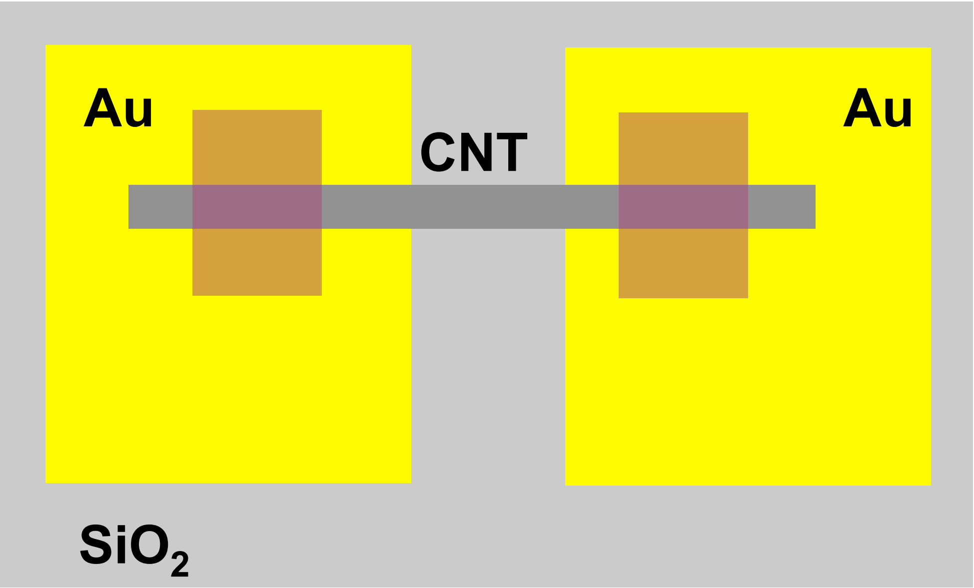
Joule Heating

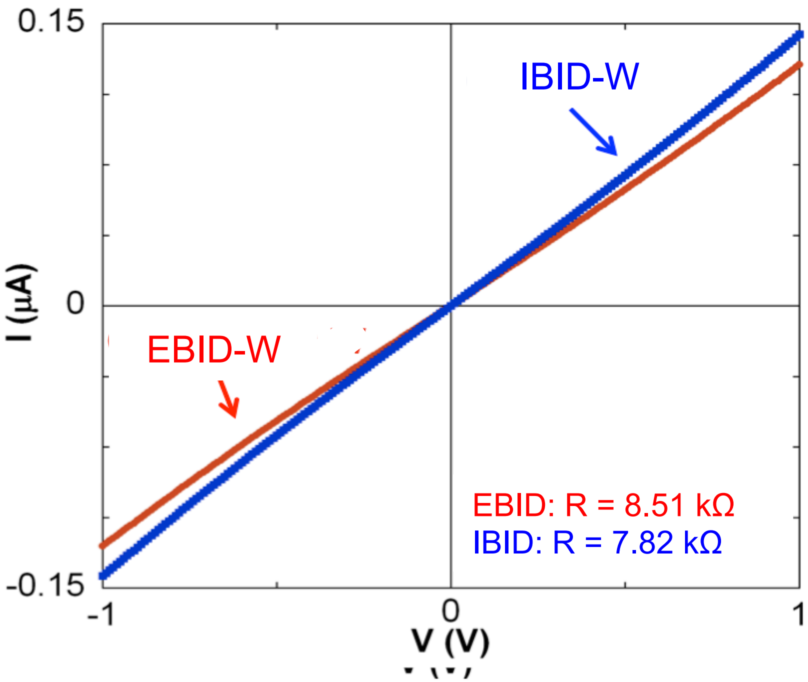




- I-V nonlinearity reduced by stress current
- Interfacial gap remains large
- Contact resistance ~ few kΩ

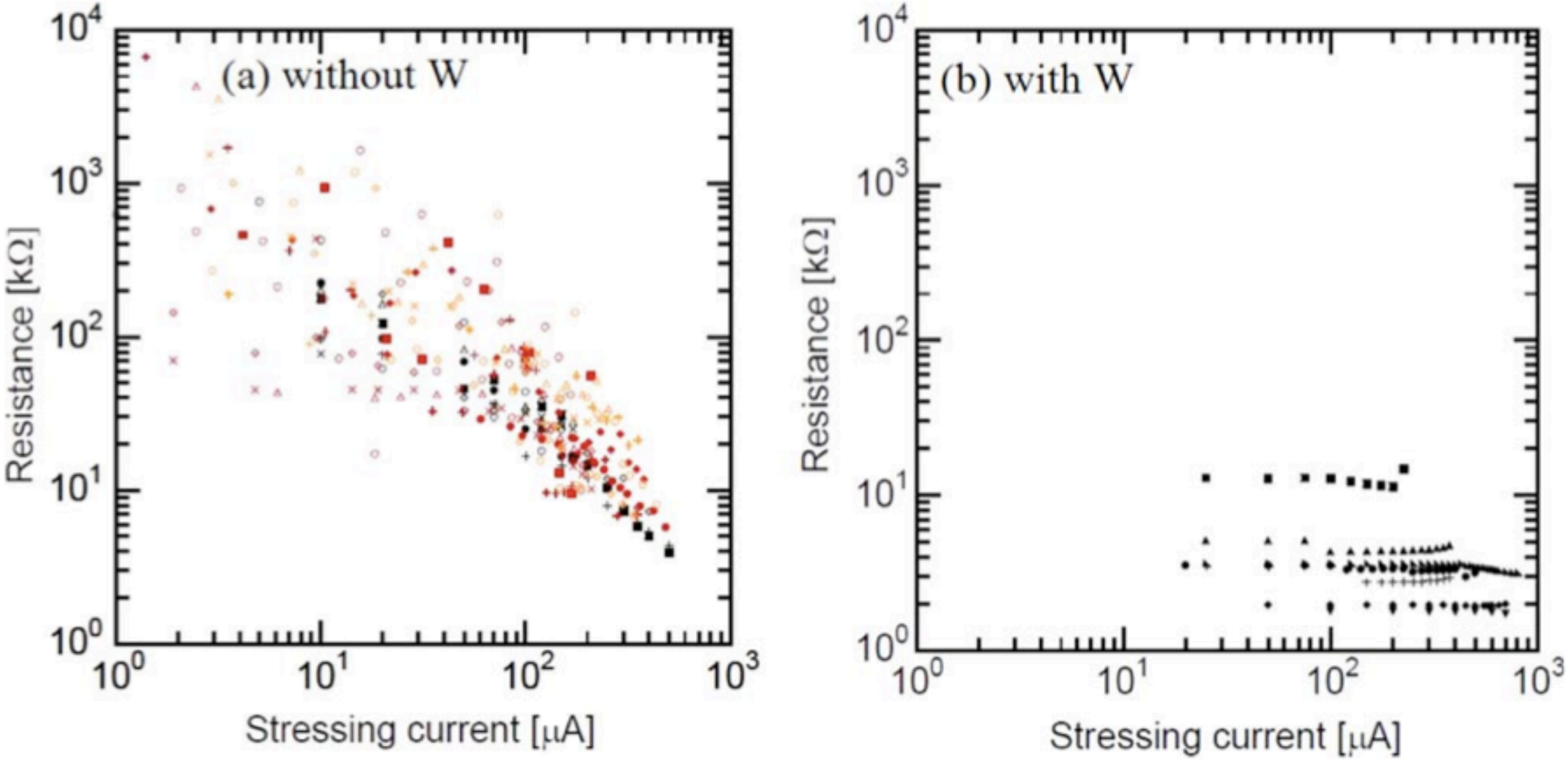
Metal Deposition on Electrode Contacts



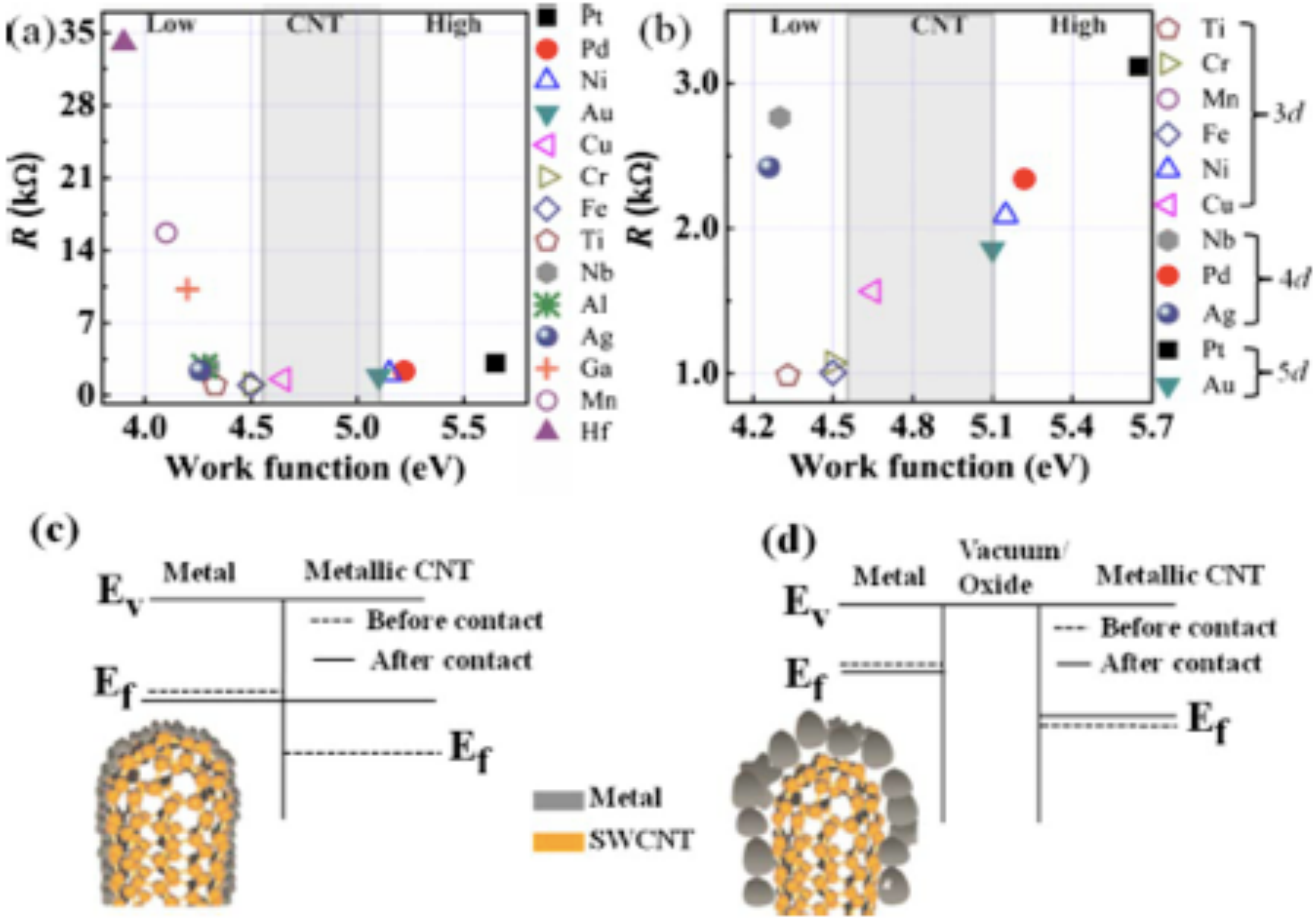


- CNTs exhibit high contact resistance
- CNT contact resistance can be reduced with metal deposition on contacts

Resistance with & without W-deposited contacts

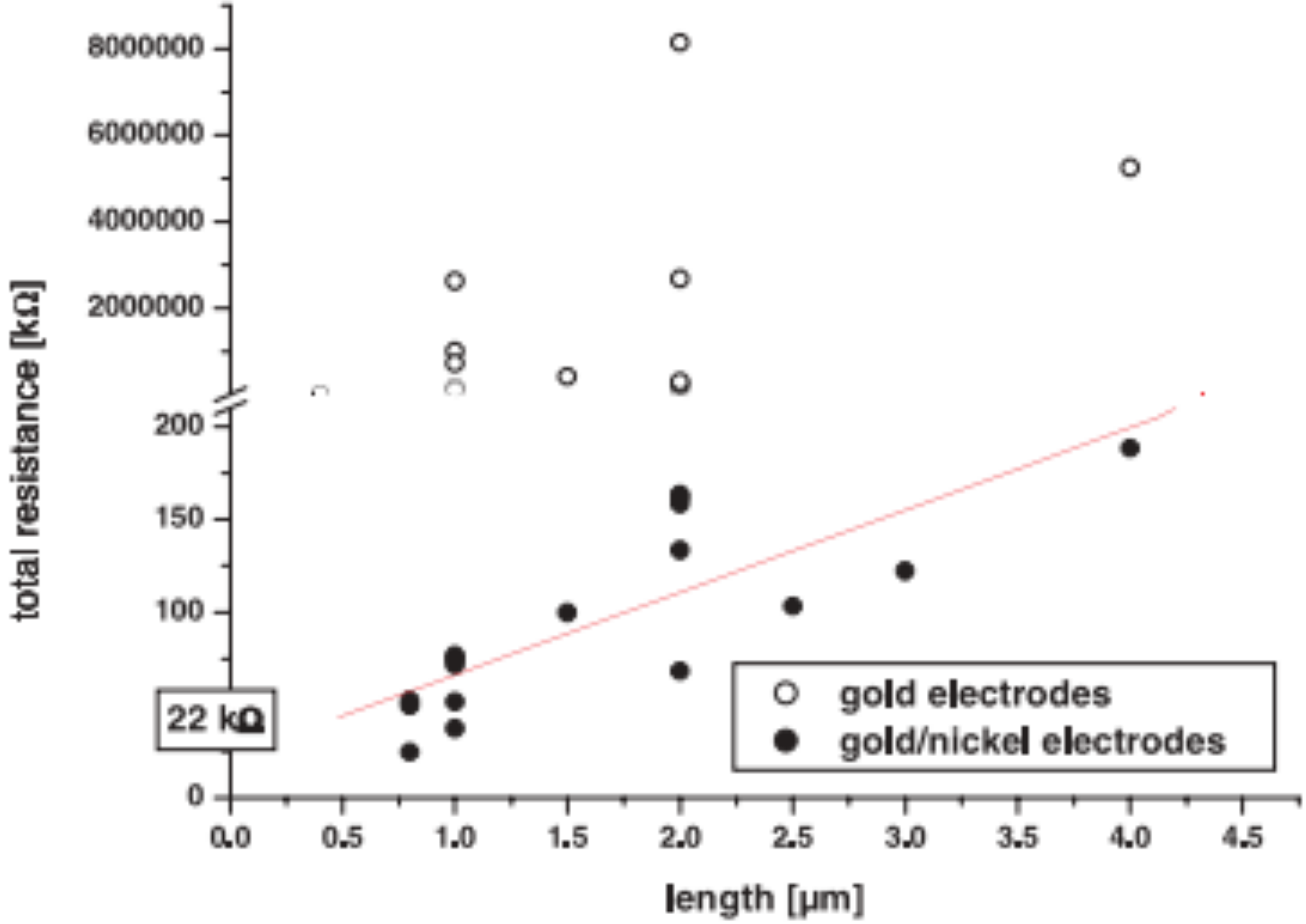


Work Function and Wettability



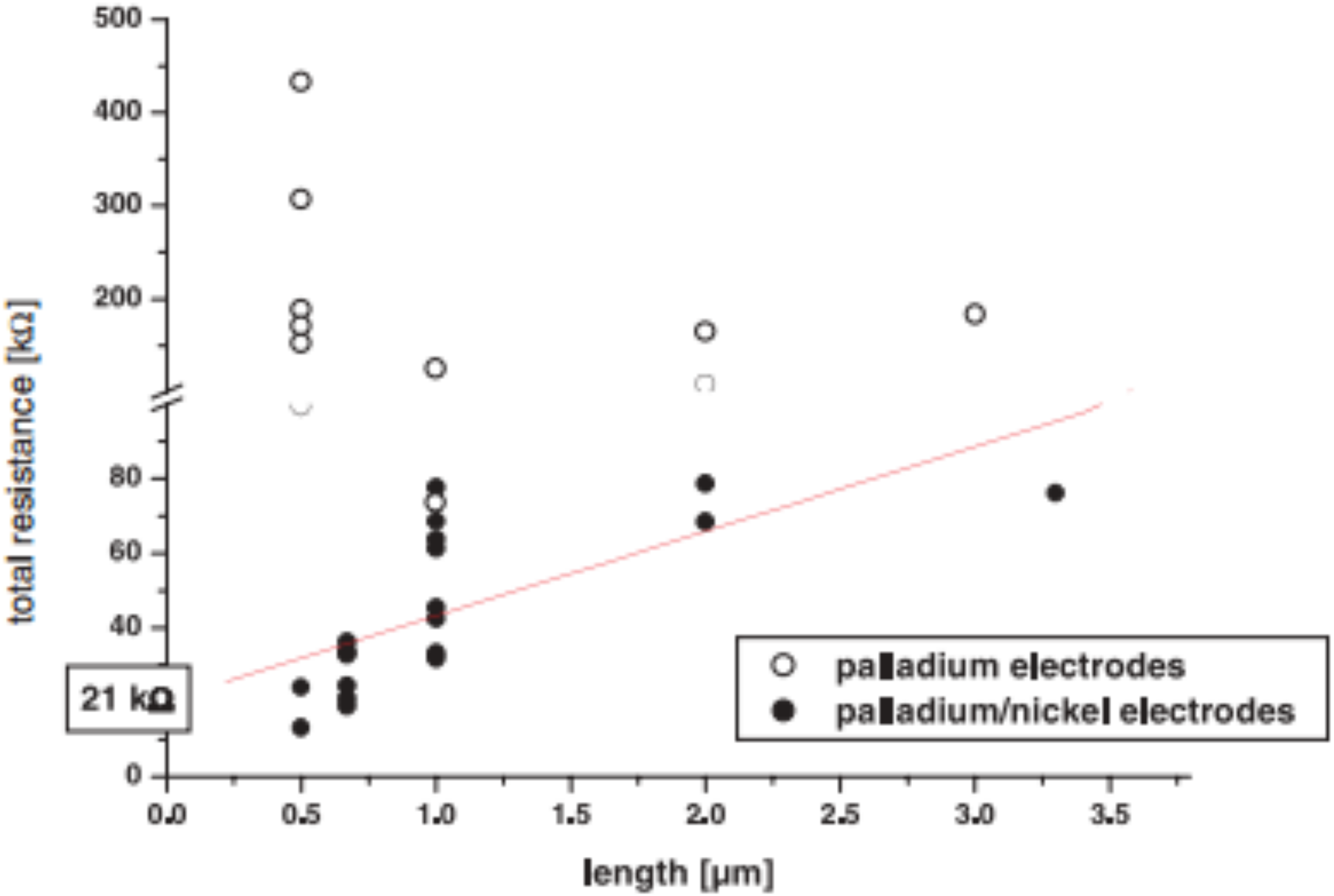
Lim *et al., Appl. Phys. Lett*. **95,** 264103 (2009)

Metal-CNT Contact Encapsulation



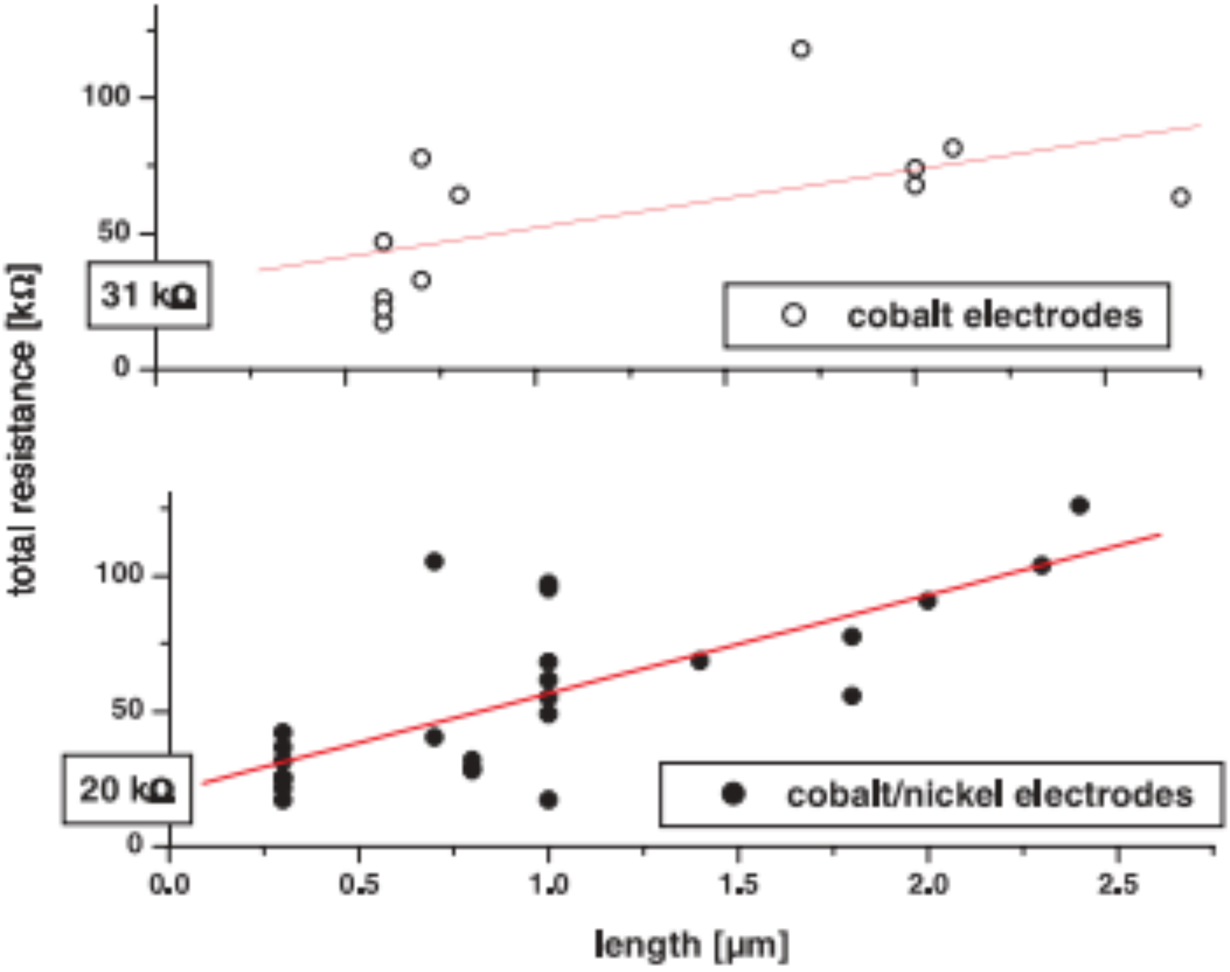
Liebau *et al., Appl. Phys. A* **77**, 731 (2003)

Metal-CNT Contact Encapsulation



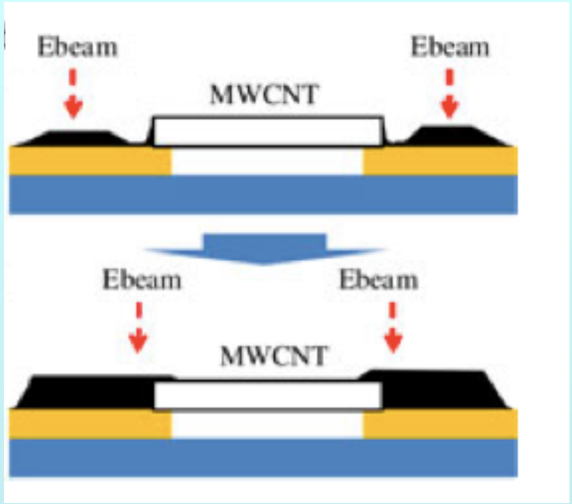
Liebau *et al.*, *Appl. Phys. A* **77**, 731 (2003)

Metal-CNT Contact Encapsulation

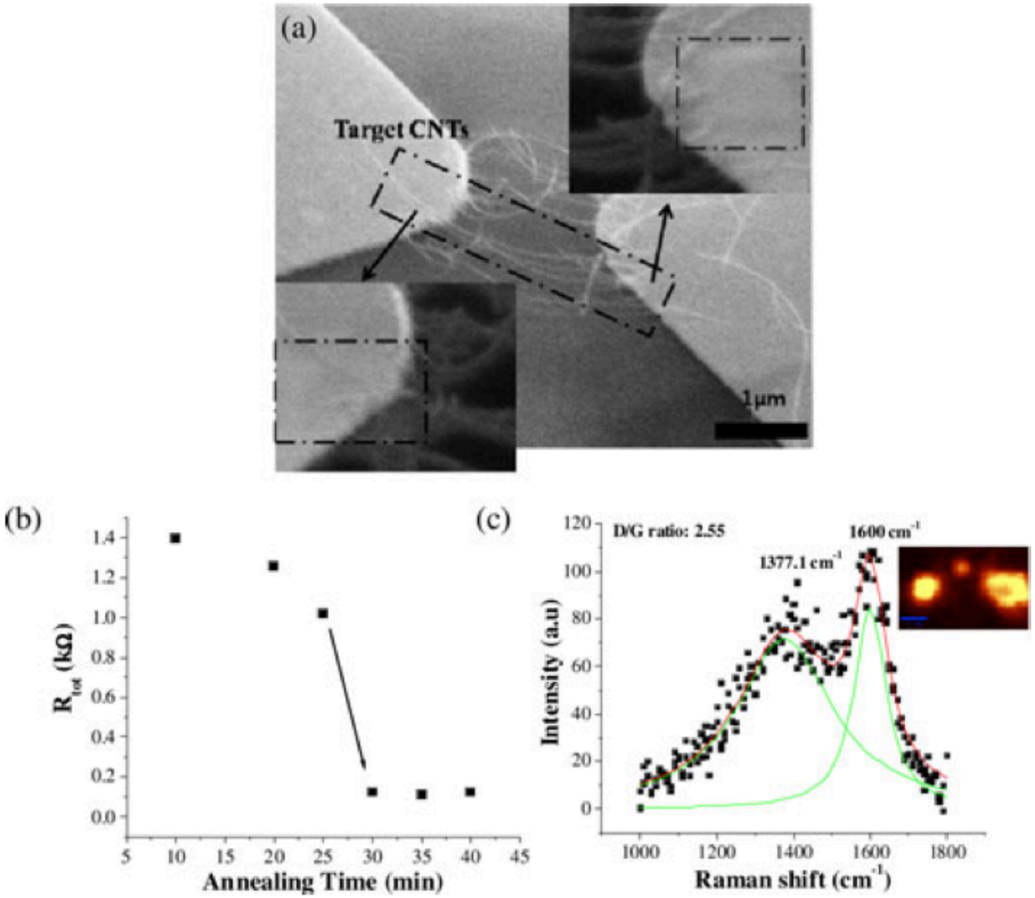


Liebau *et al.*, *Appl. Phys. A* **77**, 731 (2003)

EBID-C + Joule heating



EBID-C deposition at edges



Total resistance reduced
from 300 kΩ to 116 Ω

Kim *et al.,IEEE Trans Nanotech.* **11**, 1223 (2012)

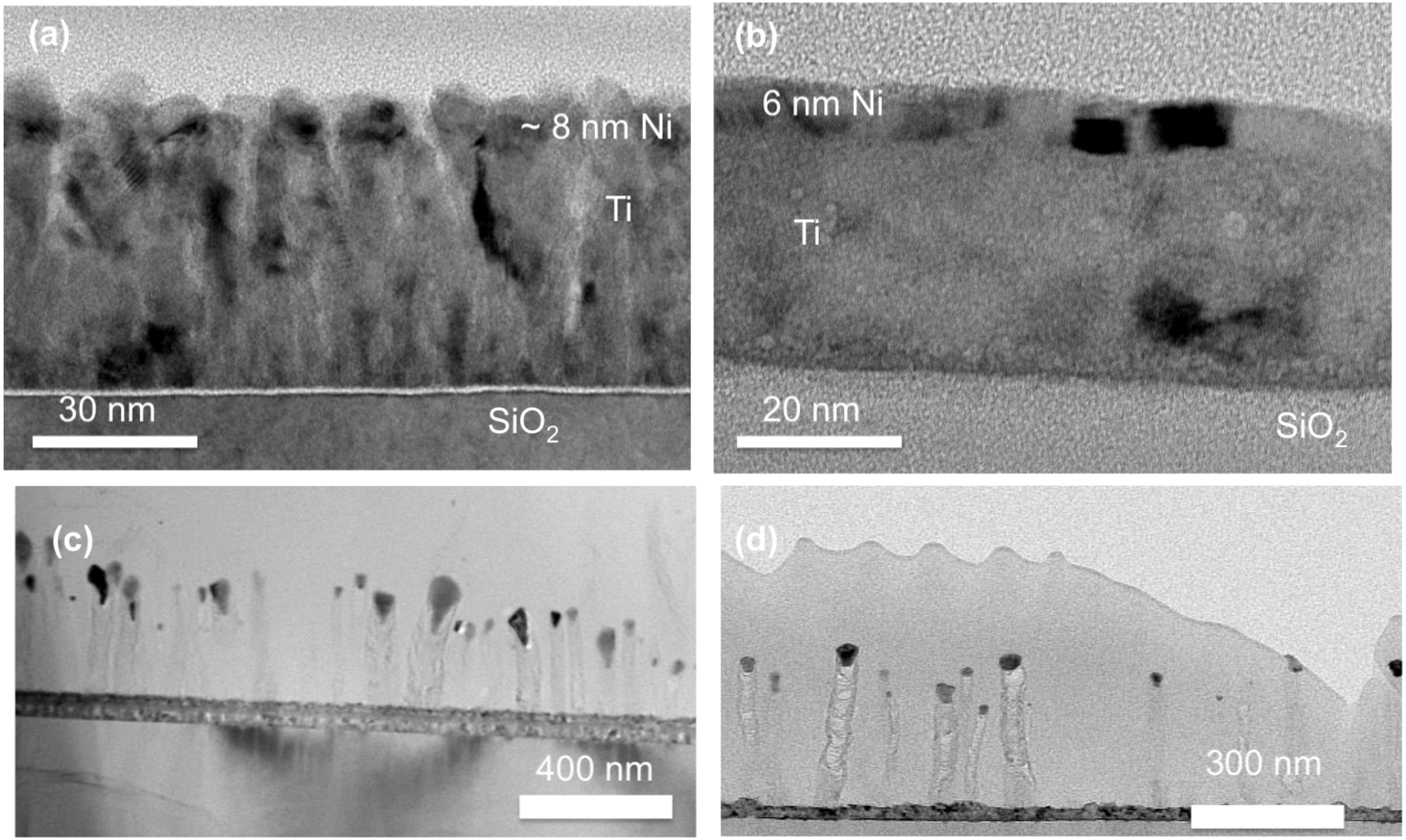
Contact Engineering

- Contact Geometry consideration
  - End contact vs. side contact
- Joule Heating
- E-beam Treatment
- Contact Encapsulation
  - Electrode contact deposition
  - Contact area
- As-grown interface vs. metal deposition

Contact Engineering

- Contact Geometry consideration
  - End contact vs. side contact
- Joule Heating
- E-beam Treatment
- Contact Encapsulation
  - Electrode contact deposition
  - Contact area
- As-grown interface vs. metal deposition

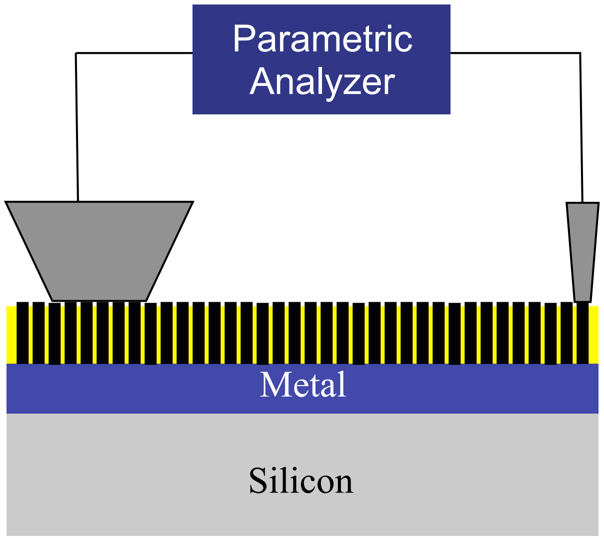
As-grown Interface

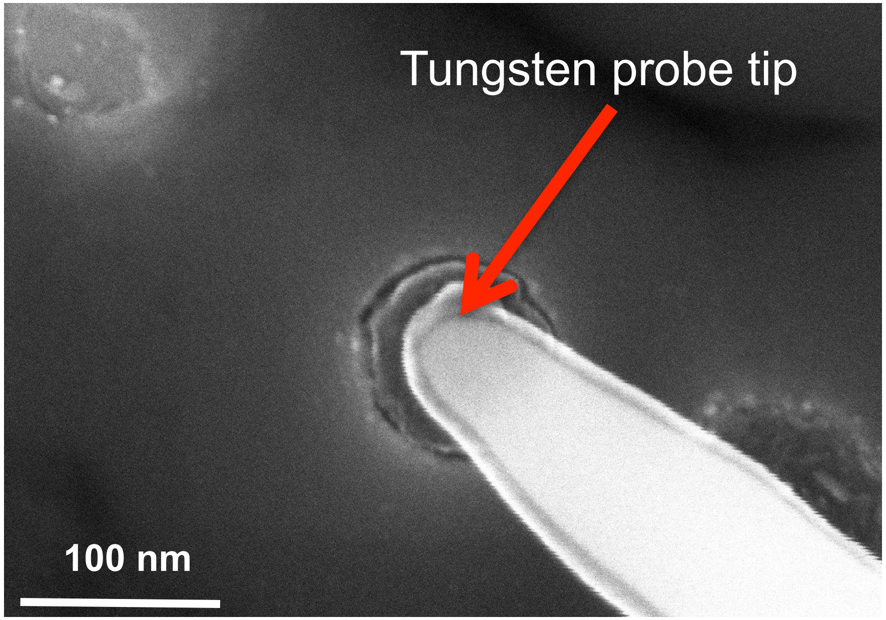


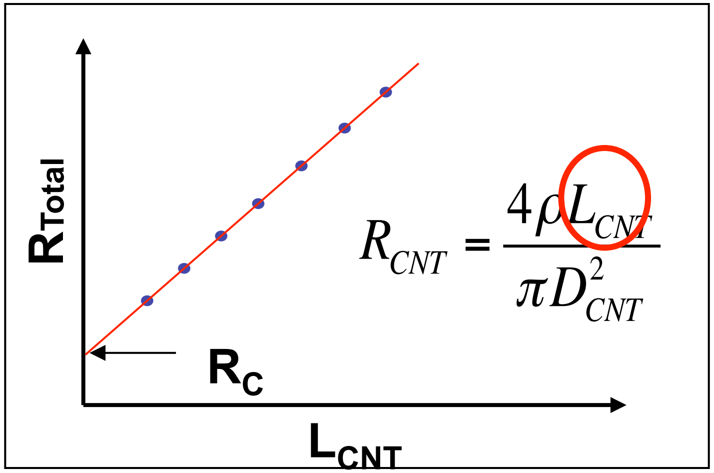
Grainy substrate

Smooth substrate

Measurement Setup





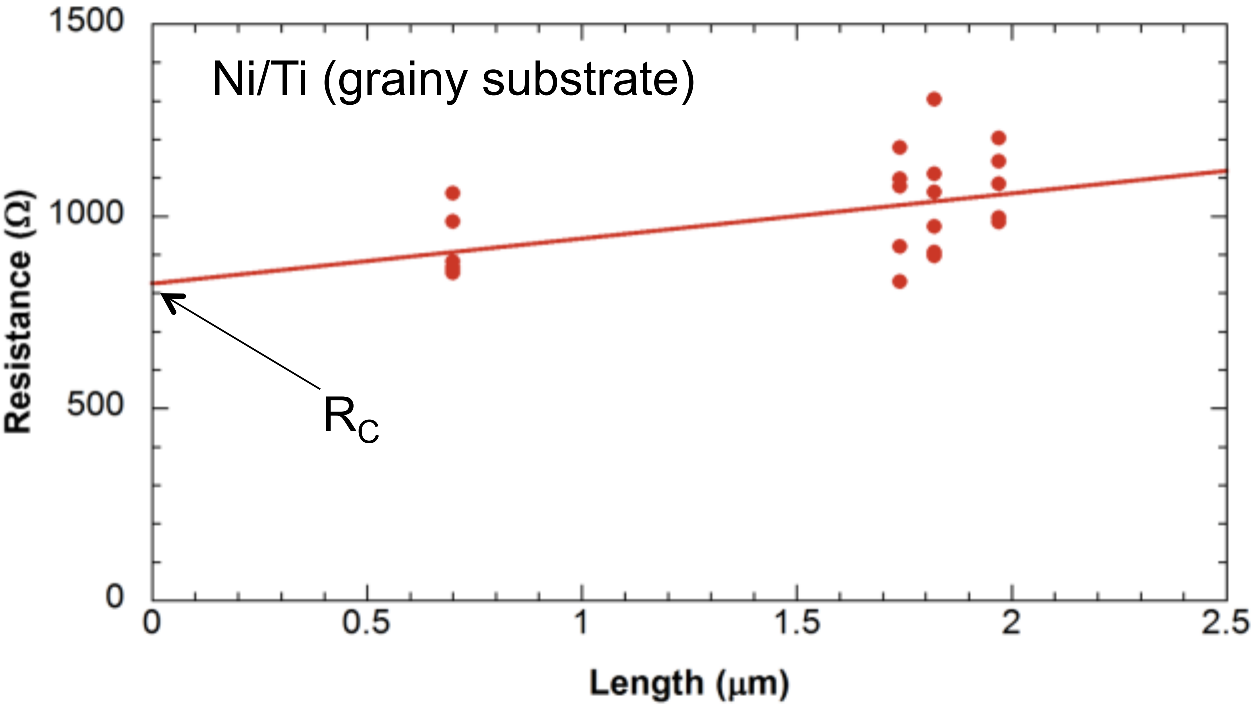


$$R_{CNT} = \frac{4\rho L_{CNT}}{\pi D_{CNT}^{2}}$$

$$R_{total} = (R_{bundle} + R_{CNT/m} + R_{p/CNT} + R_{m}) + R_{CNT}(L)$$

$$\equiv R_{C} + R_{CNT}(L)$$

Resistance vs. Length

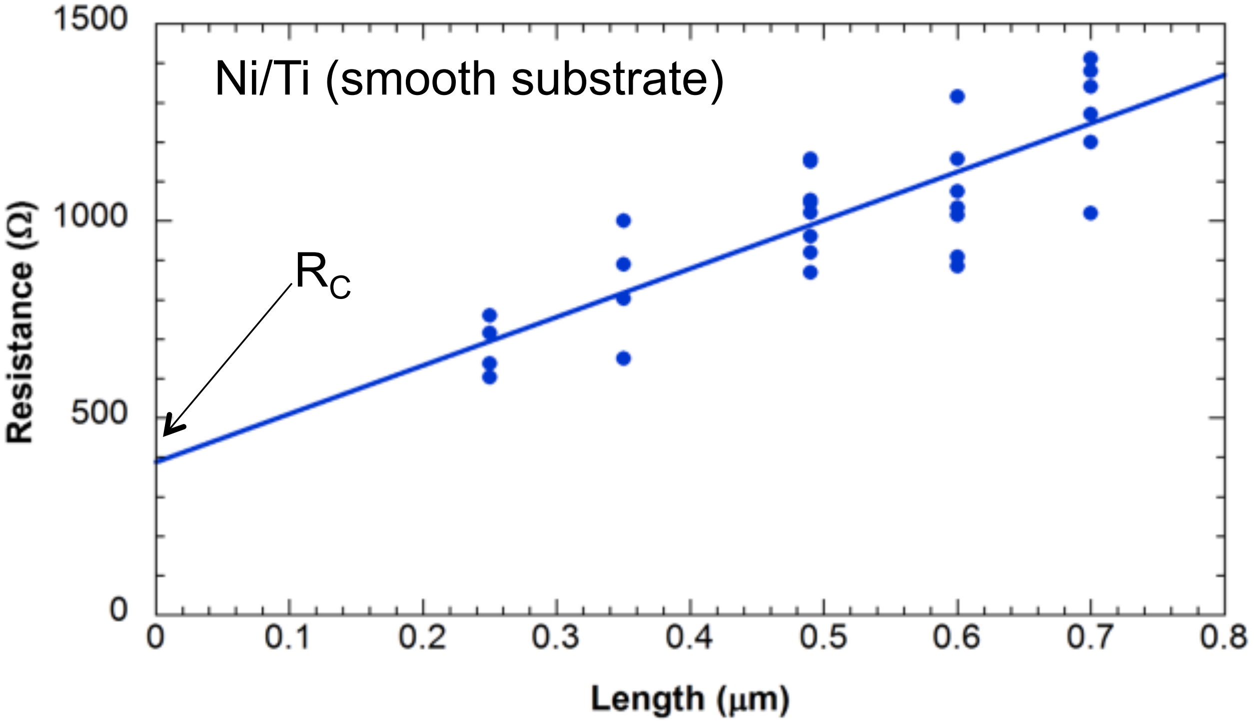


ρ (Ω-cm)	R_C (Ω)
1.66 - 1.85 x 10^{-4}	825

Diameter range of probed samples: 90 – 100 nm

$$R_{Total} = R_C + R_{CNT} = R_C + \frac{4\rho}{\pi D_{CNT}^2} L_{CNT}$$

Resistance vs. Length

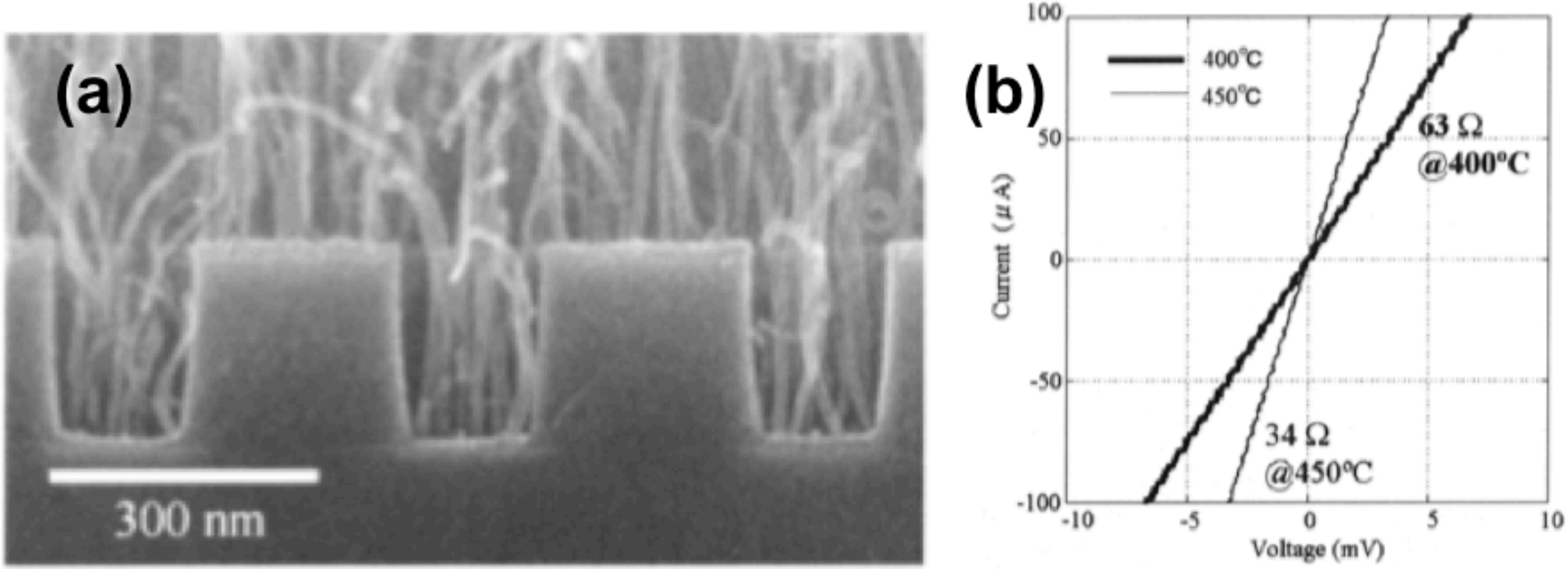


ρ (Ω-cm)	R_C (Ω)
2.4×10^{-4}	388

Diameter of probed samples: ~50 nm

$$R_{Total} = R_C + R_{CNT} = R_C + \frac{4\rho}{\pi D_{CNT}^2} L_{CNT}$$

Resistance measurements for CNT via



Nihei *et al., (ICSICT),* 541-543 (2008)

Outline

- Introduction: Contact Types and Applications
- Metal-CNT Contact Models
- CNT Nanoscale Probing
- Contact Engineering
- Summary

Summary

- Metal-CNT contact resistance critically affects device performance, but can be engineered to yield desirable outcomes
- End-contacted vertical structures typically result in lower contact resistance due to strong bonding between edge carbon and surface metal atoms
- Contact engineering can result in sub-kΩ contact resistance values, which still need to decrease considerably before device functionalization
- Contact resistance can be drastically reduced by Joule heating and contact metallization using selection criteria governed by wettability metal-CNT work-function difference.
- As-grown interface between CNT and underlayer metal can yield very low contact resistance under the best growth conditions, such as catalyst and underlayer metal depositions without ambient adsorbates trapped at the interfaces

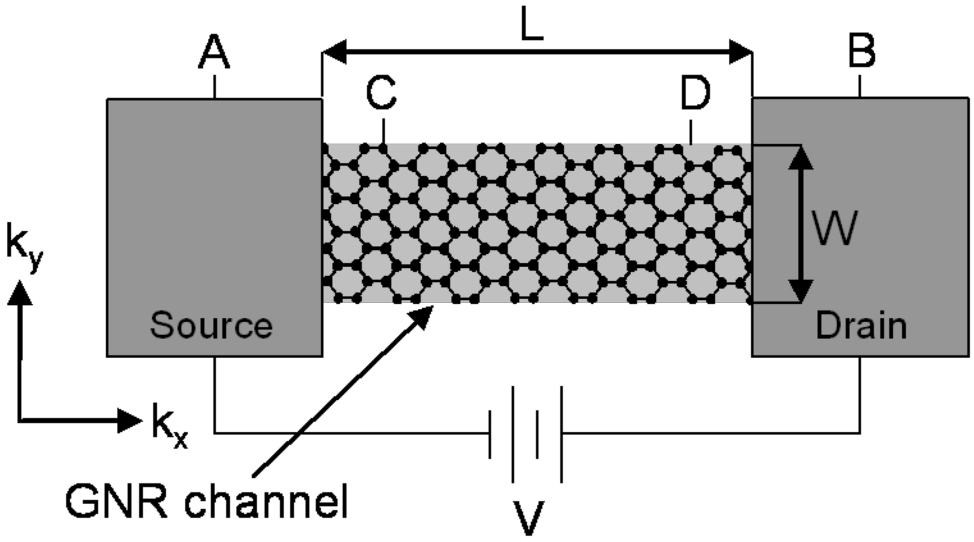
Acknowledgements

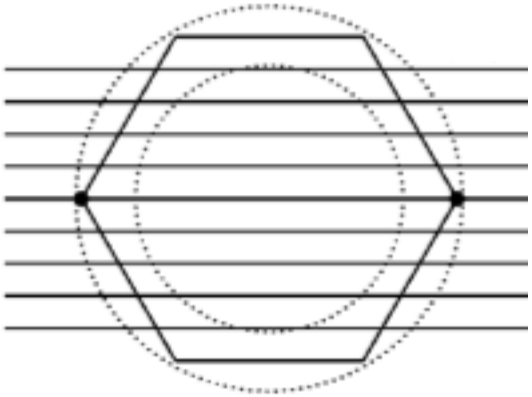
Toshishige Yamada
Anshul Vyas

Phillip Wang
Jeongwon Park

Jessica Koehne

Landauer (quantum limit)





- 2-D surface to 1-D conduction

$$G = \frac{2e^2}{h} MT$$

  - Materials and engineering independent
  - $\lambda_{MFP} \geq L$
- Conservation of momentum (Bloch symmetry) violation
  - Conduction through surface scattering
  - Van der Waals?

Tersoff, *APL* **74**, 2122 (1998)