Carbon Nanofibers for On-chip Interconnect and Integrated Circuit Applications

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Outline

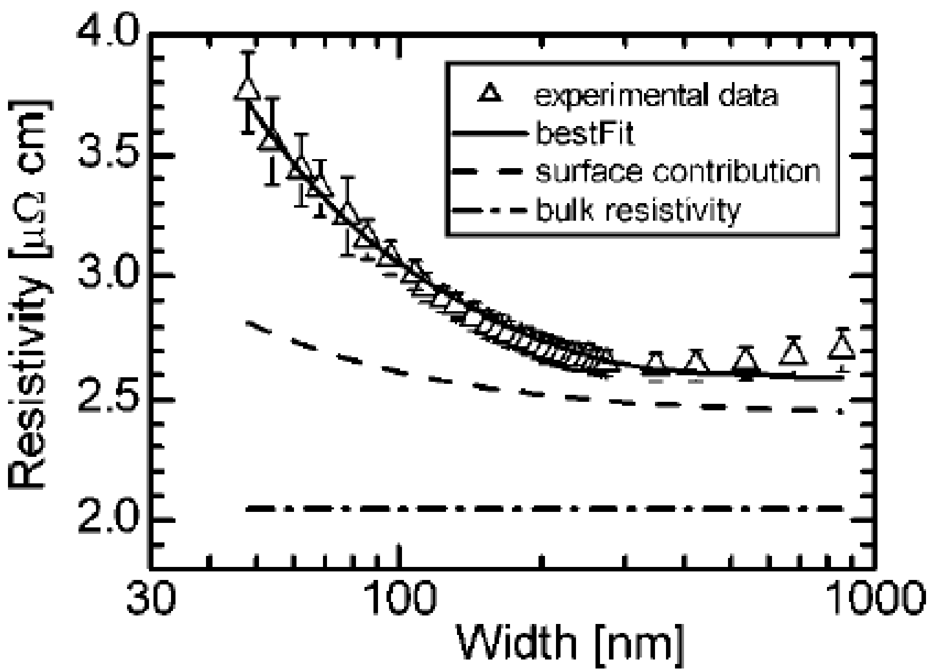
- Overview
- On-chip interconnects/vias
  - Synthesis
  - DC characterization
- Multi-layer structures
  - IC concepts using multi-layer CNF
- High-resolution microscopy analysis
- CNF-Cu composites for thermal management
- Continuing work

Overview

- On-chip interconnects to replace copper
  - Carbon nanofiber synthesis using PECVD
  - DC measurements of CNF arrays and multi-layer nanofibers
- Microstructural analysis
  - Sample preparation for TEM/STEM imaging
  - Elemental analysis (EDX)
- Thermal Interface Materials (TIMs)
  - Fabrication
  - Thermal resistance characterization

Motivation: Resistivity concerns

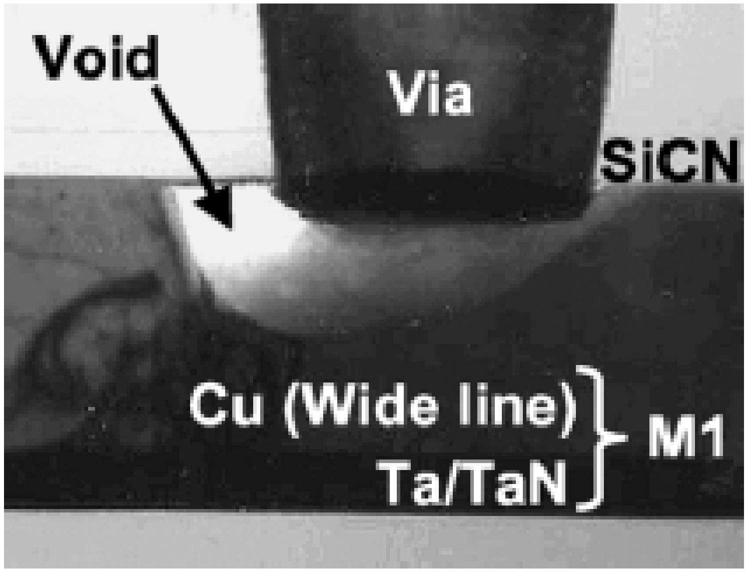
- Resistance copper interconnects and vias will soon be reached if scaling trends continue
- CNFs can meet both performance requirements for interconnects in next generation ICs



Steinhogl et al., *J. Appl. Phys.* **97**, 023706 (2005)

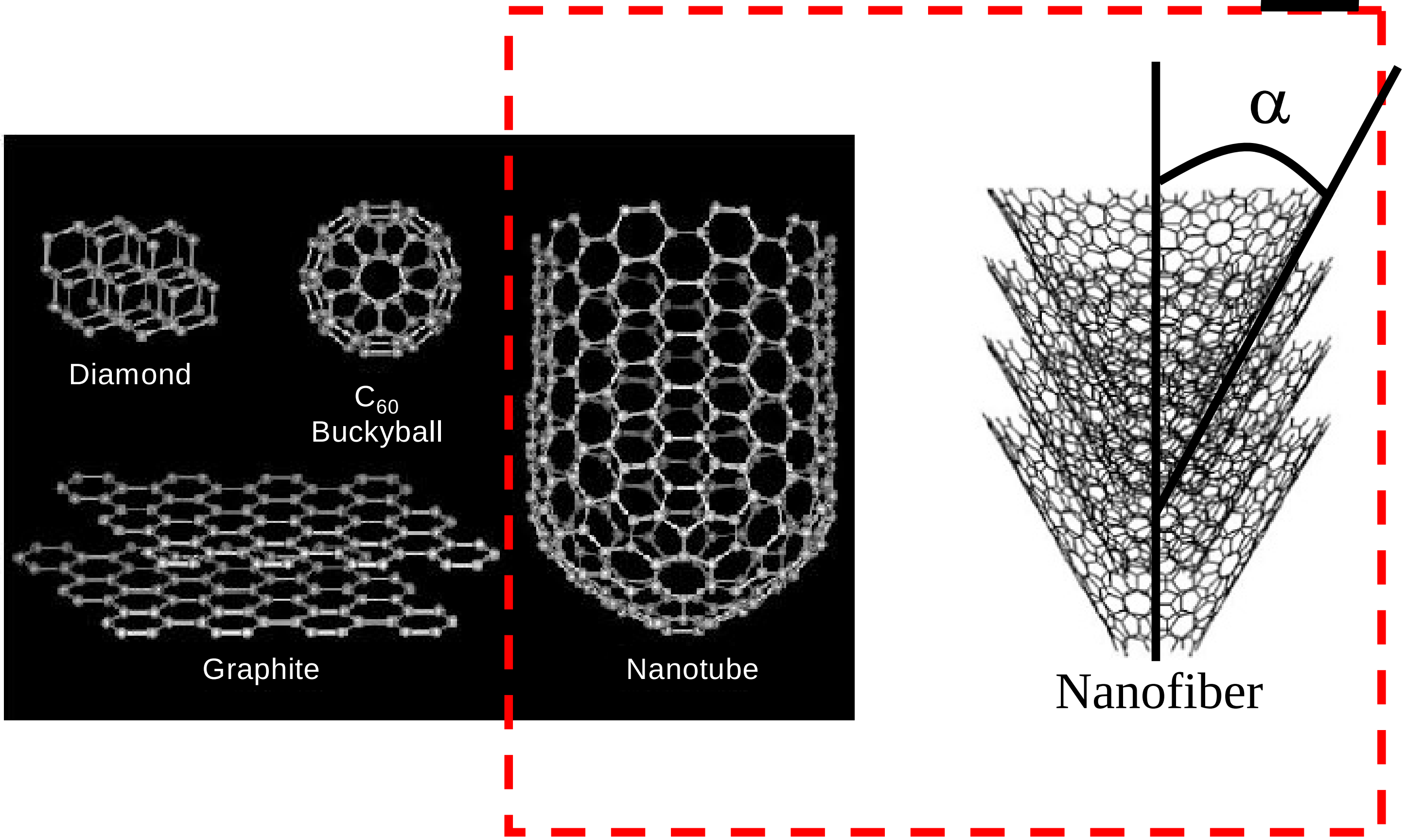
Motivation: Electromigration

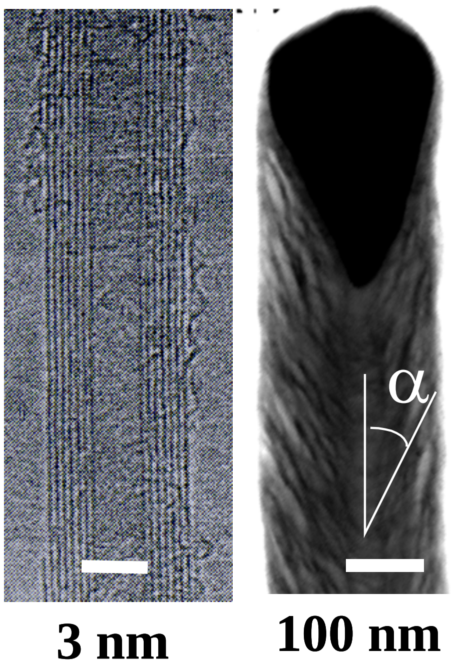
- Electromigration is the failure of an interconnect line or via due to high current stress
- Main source of reliability failures in back-end structures



Saito et al., *IEEE Trans. Elec. Dev.* **51**, 2129 (2004)

Carbon Systems



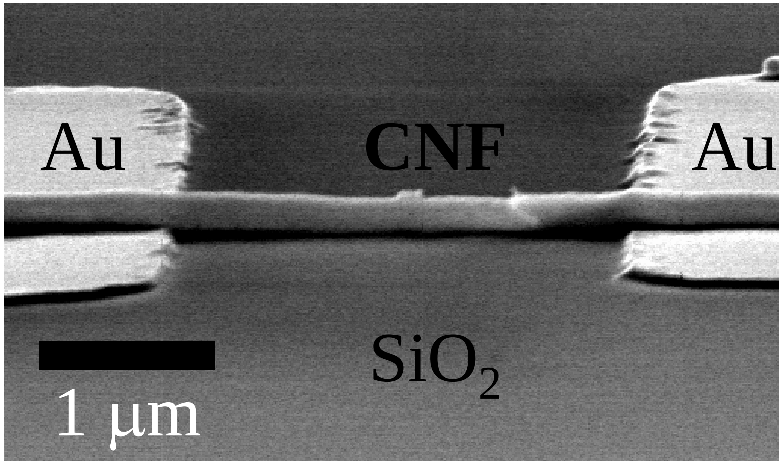


Iijima et al., *Nature* **354**, 56 (1991)

CNF Architectures:

Side-contacted geometry

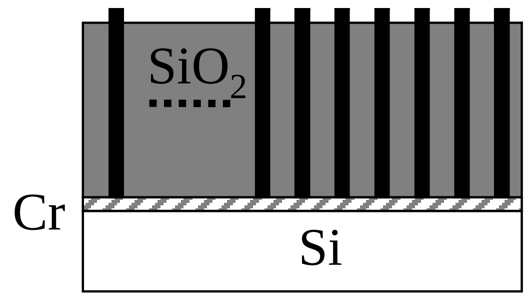
- Contacts are either pre-patterned on the substrate, or deposited after the nanofiber or nanotube has been dispersed onto a substrate
- Contact is made on the sidewall

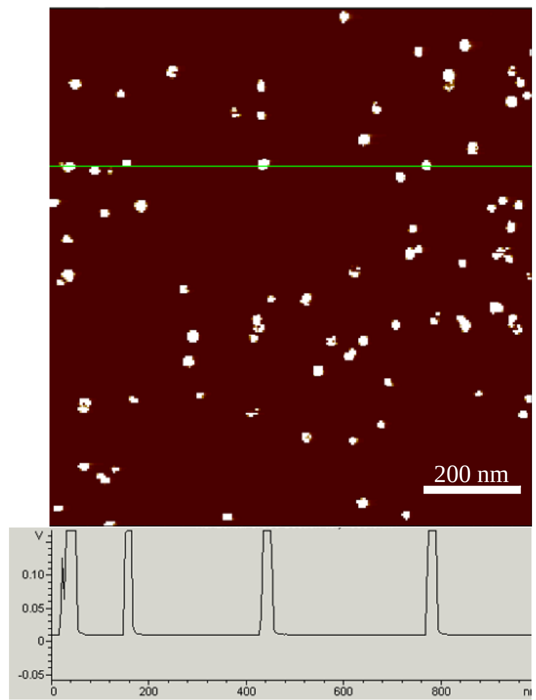


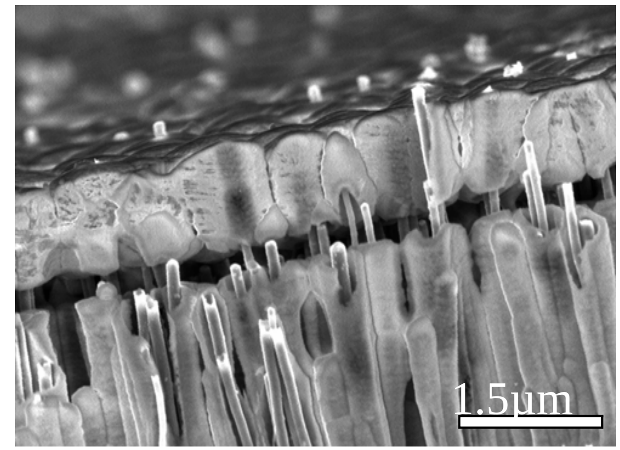
CNF Architectures:

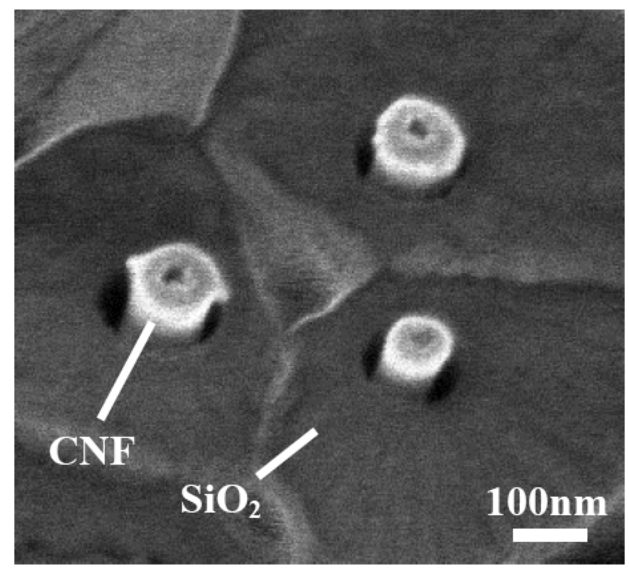
End-contacted geometry

- Nanofibers are grown by plasma-enhanced CVD (PECVD) vertically from a patterned catalyst film
- Contact is made with ends of nanofibers





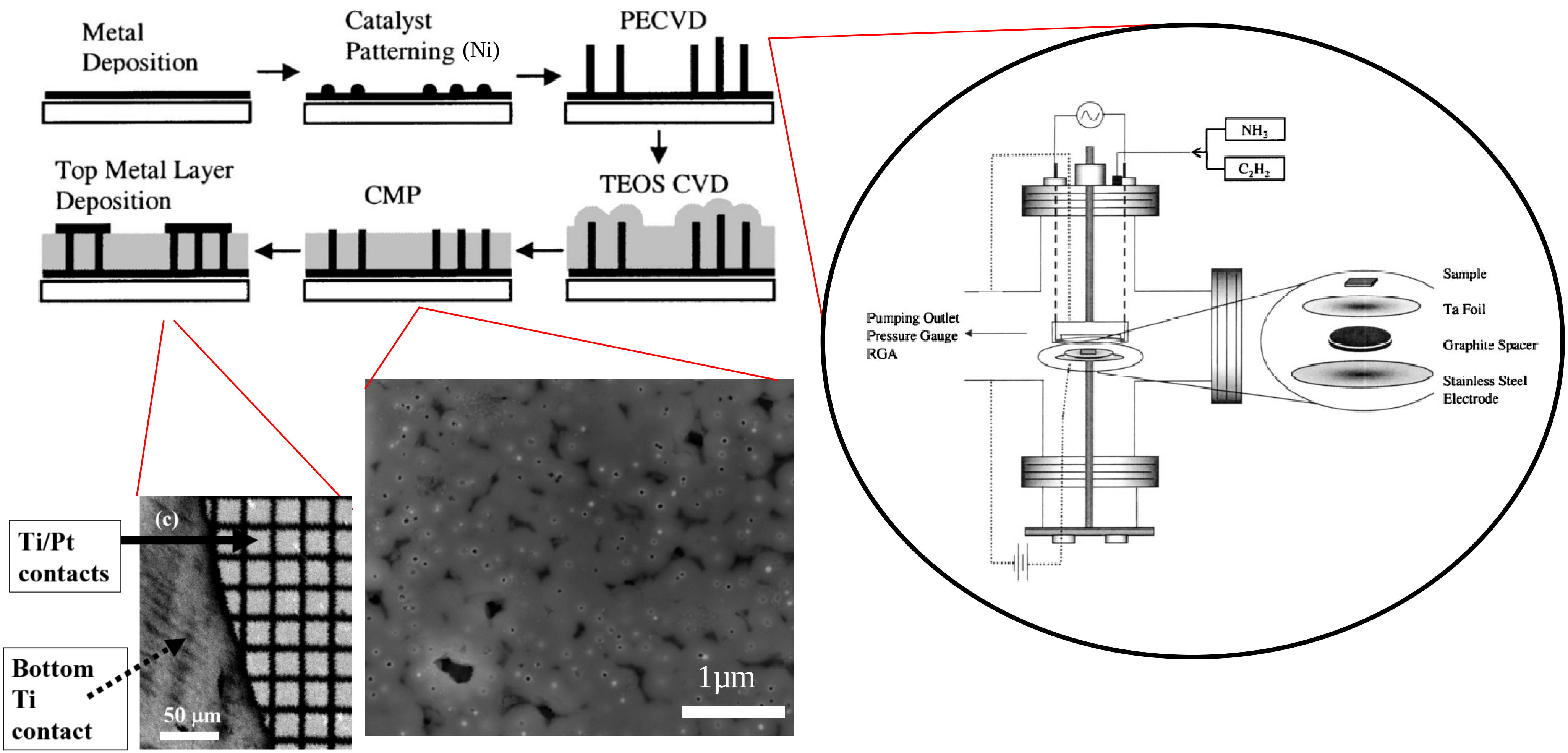




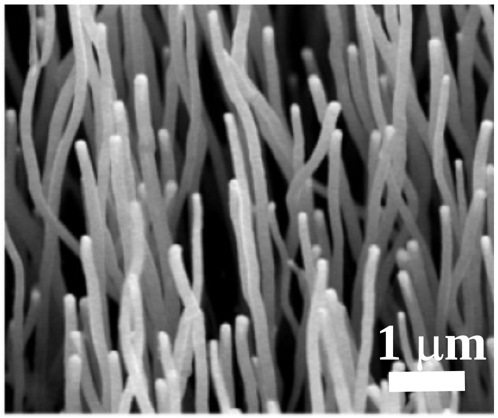
Current sensing AFM and SEM characterization

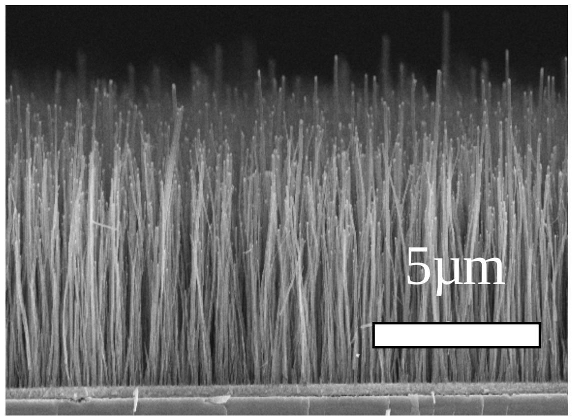
Process flow for PECVD-grown CNFs

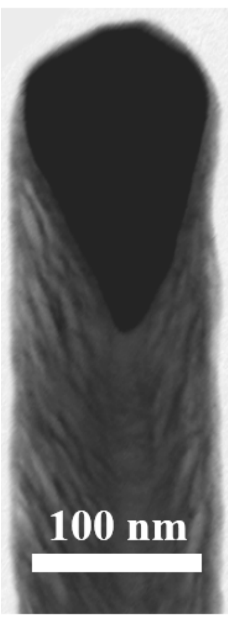
Li et al., *Appl. Phys. Lett*, **82**, 2491 (2003)
Cruden et al., *J. Appl. Phys.* **94**, 4070 (2003)

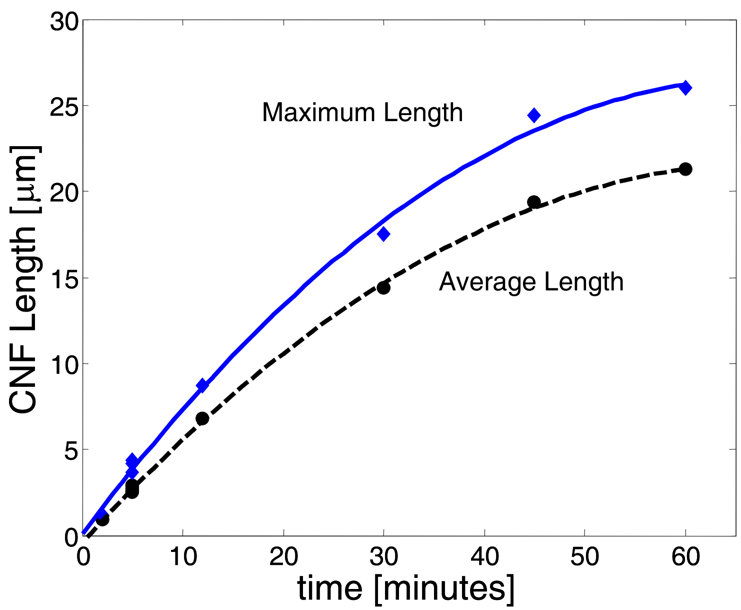


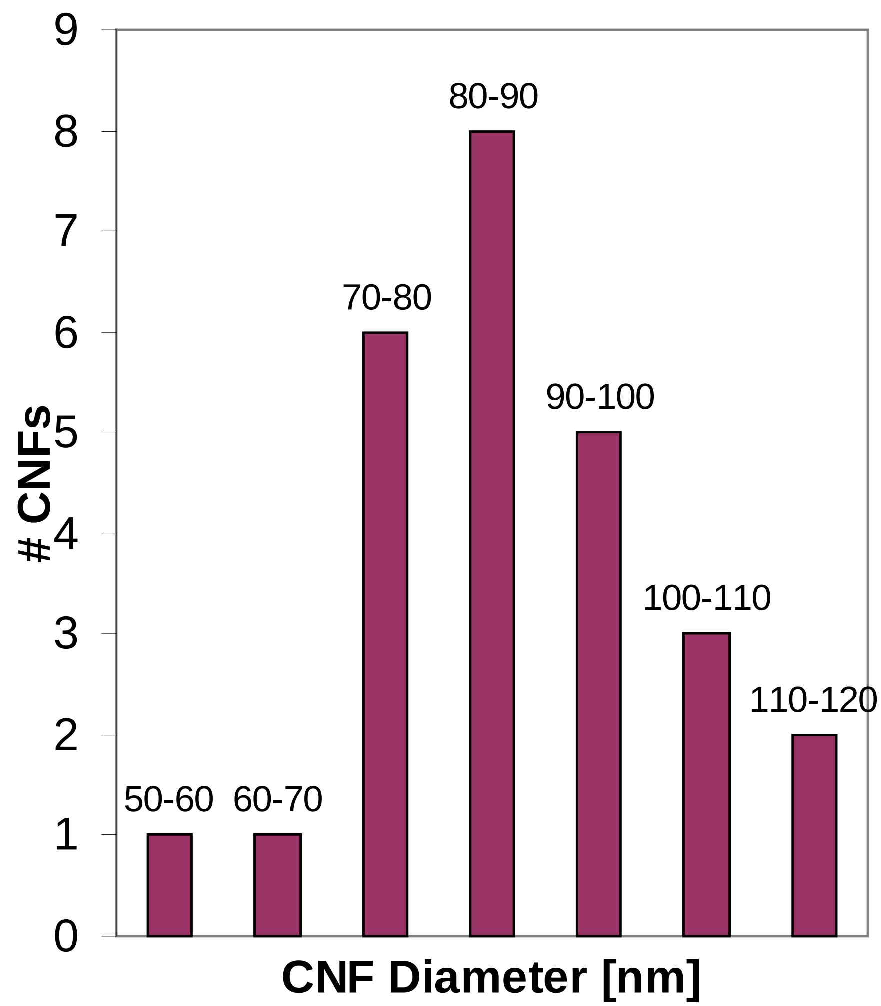
CNF Process Control









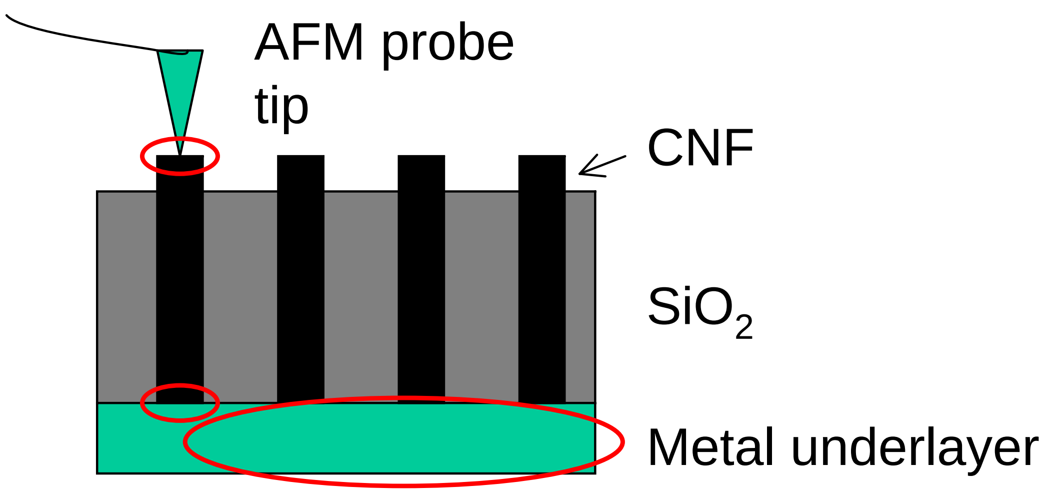


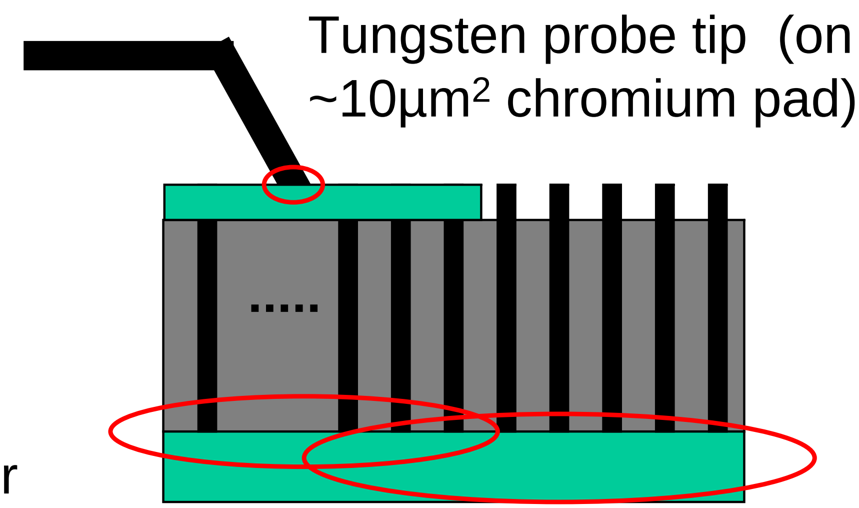
DC Characterization of CNF Vias

Collaborators: J. Li, A. Cassell, M. Meyyappan
Center for Advanced Aerospace Materials and Devices,
NASA Ames Research Center, Moffett Field, CA

Collaborators: A. J. Austin
Center for Nanostructures,
Santa Clara University, Santa Clara, CA

Mechanisms of End-contact Resistance





Single CNF Resistance:

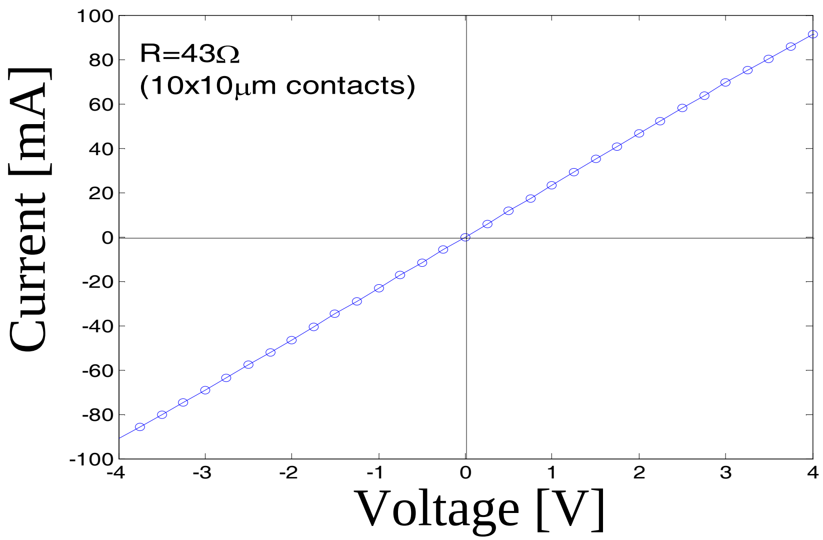
- AFM tip to CNF (contact)
- CNF to metal underlayer
- Metal underlayer sheet resistance

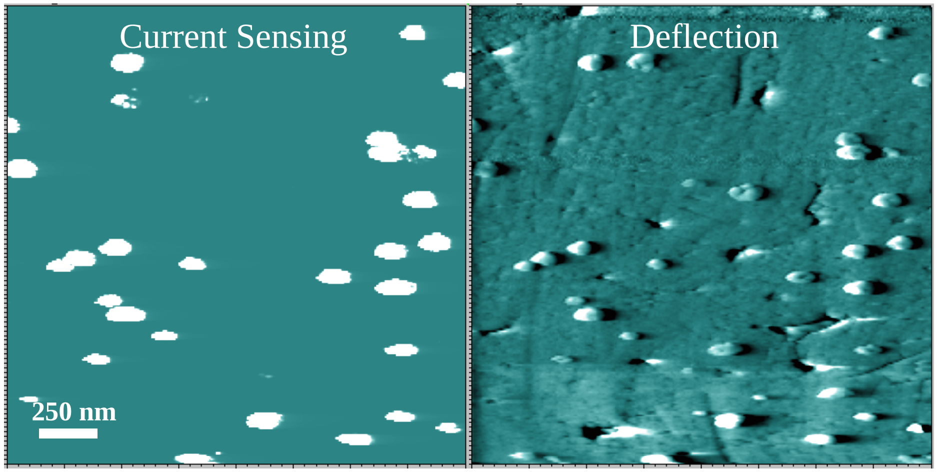
Parallel CNF Resistance:

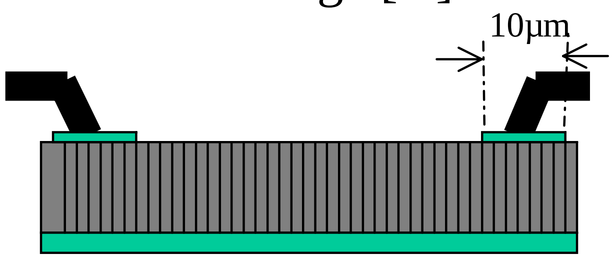
- Probe tip/metal to CNF(contact)
- CNFs to metal underlayer
- Metal underlayer sheet resistance

I-V Characteristics of CNF Array Vias

- A statistical approach can be taken for calculating resistance of a single CNF by measuring many CNFs in parallel





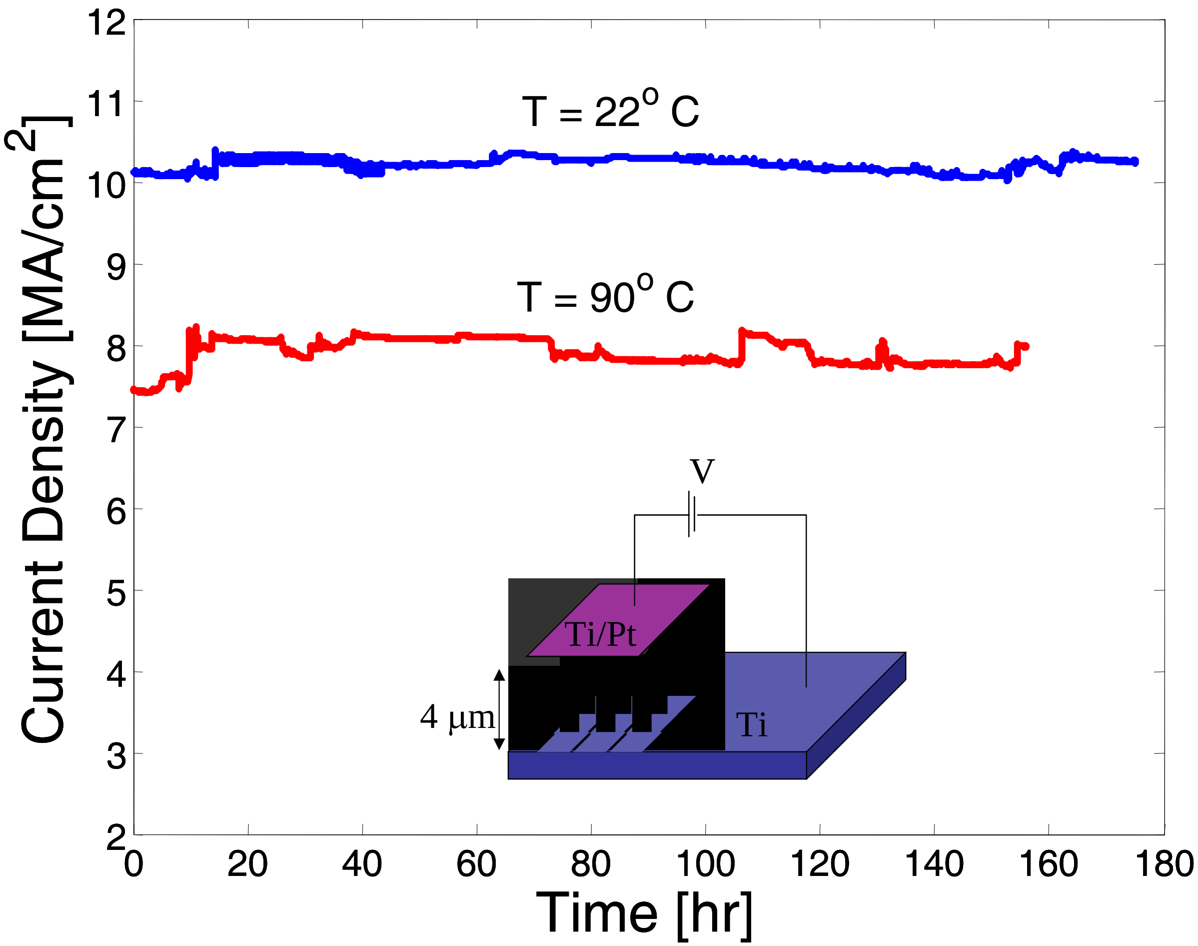


Ngo et al., *IEEE Trans. Nanotechnology* **3**, 311-317 (2004)

- Nanofiber diameters = 50-100nm
- ~5-6 CNF per 1μm^2
- 100μm^2 contains ~500-600 CNF

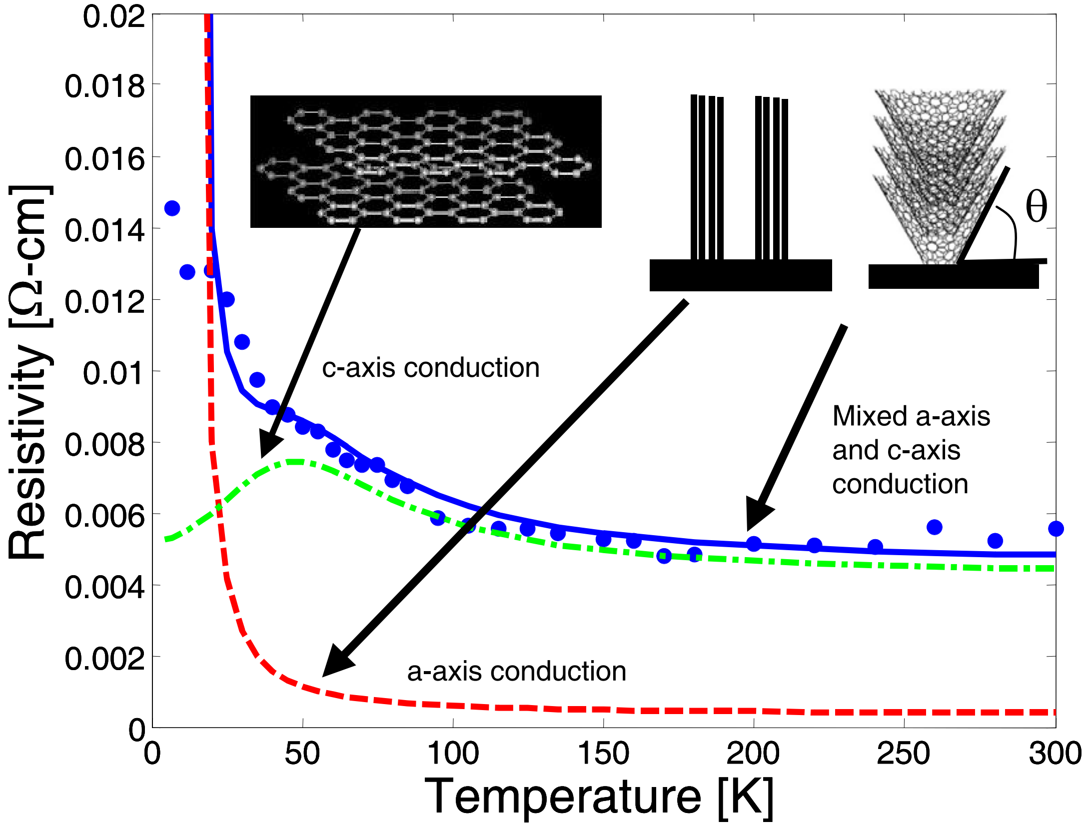
R(single CNF) ≈ 12-15kΩ

Reliability Measurement of CNF Via



ITRS Roadmap for 32 nm node: $J_{MAX} = 4\ MA/cm^2$

Modeling of Temperature-dependent Resistivity



Ngo et al., *Elec. Dev. Lett.* **27**, 221 (2005)

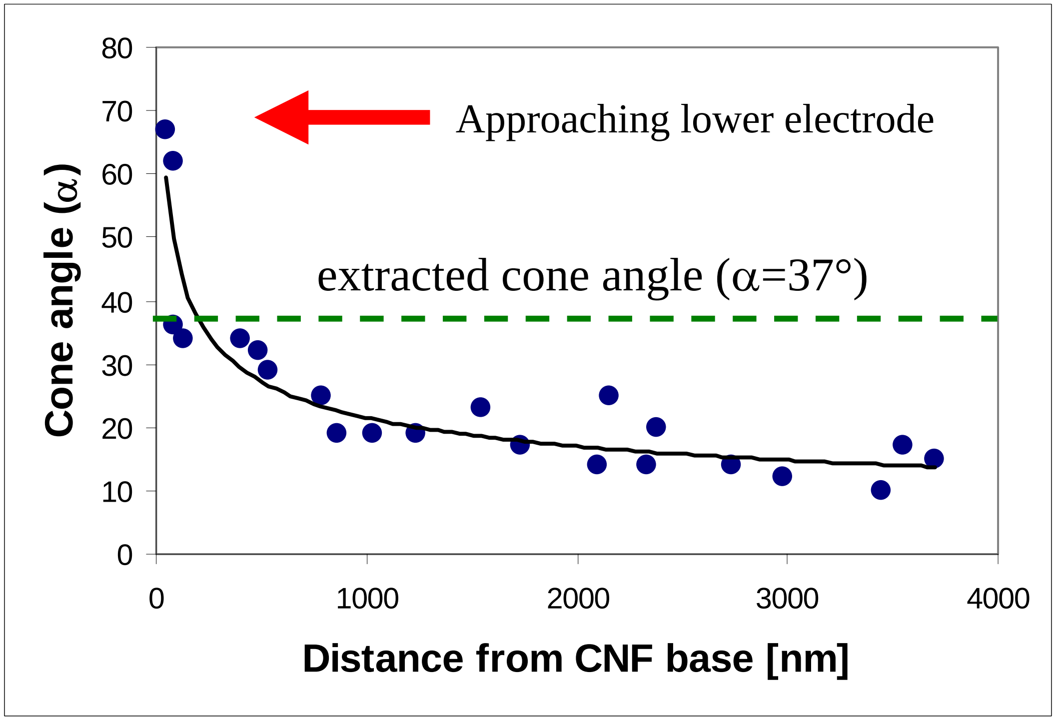
- Model incorporates both a-axis [1] and c-axis [2] graphite resistivity components
- Two fitting parameters, θ (complimentary cone angle) and ρ_0 (equilibrium resistivity) provide a good fit to the resistivity data
- All other model parameters assume pure graphite values from measurements [1,2]

$$\rho(T) = \rho_0 + (\rho_a \sin^2\theta)\exp\left(\frac{-E}{kT}\right) + (\rho_c \cos^2\theta)\left(\frac{1}{gT^2 + \frac{b}{T^2 + c}}\right)$$

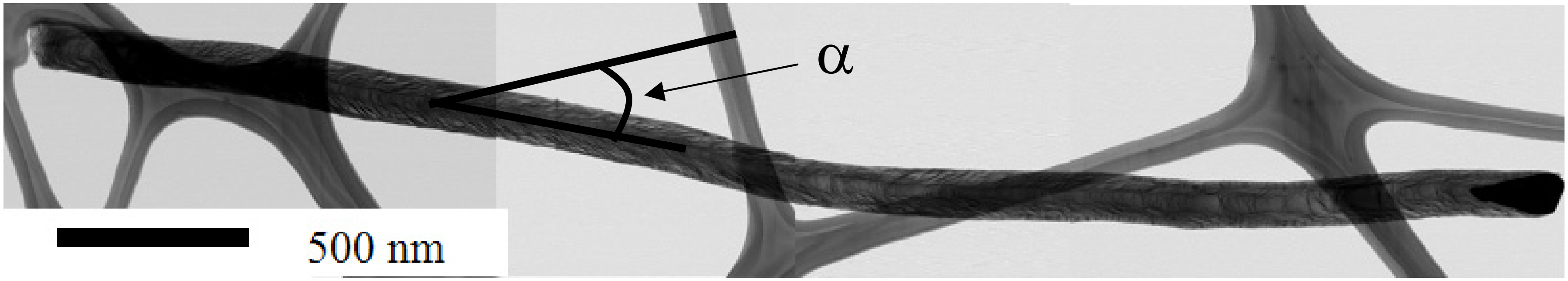
[1] S. Ono et al., J. Phys. Soc. Jap. **21** (861) 1966

[2] C. Uher et al., Phys. Rev. B **35** (4463) 1987

Cone-angle variation

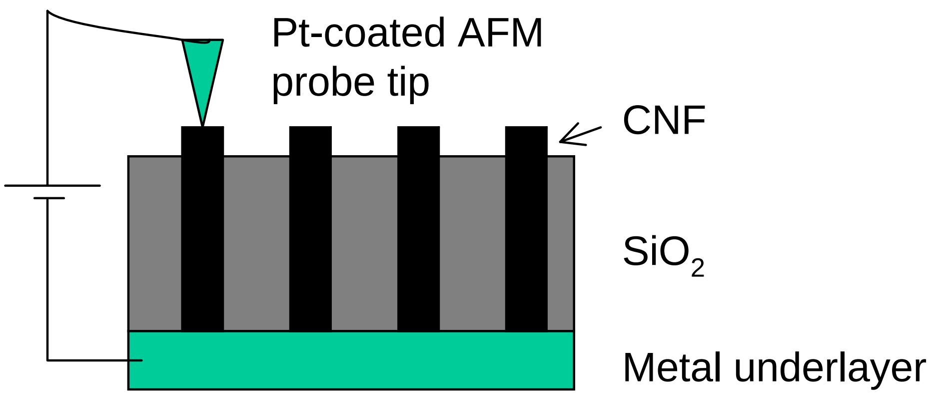


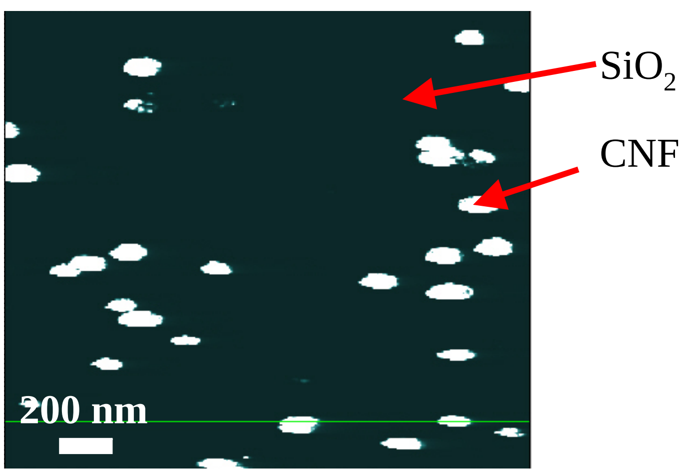
- Cone angle α=(90-θ)=37° extracted from the model equation
- Lower electrode influences resistivity, consistent with STEM analysis

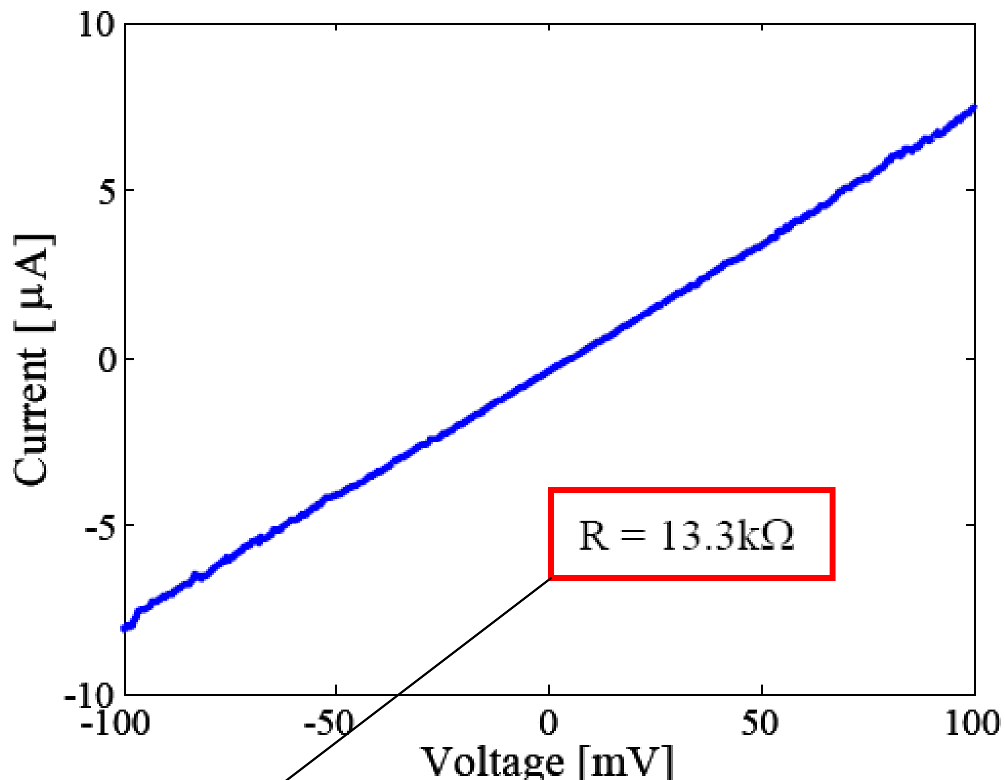


I-V Characteristics of a single CNF

- Characterization of single CNFs using CSAFM confirms the result obtained from the statistical approach





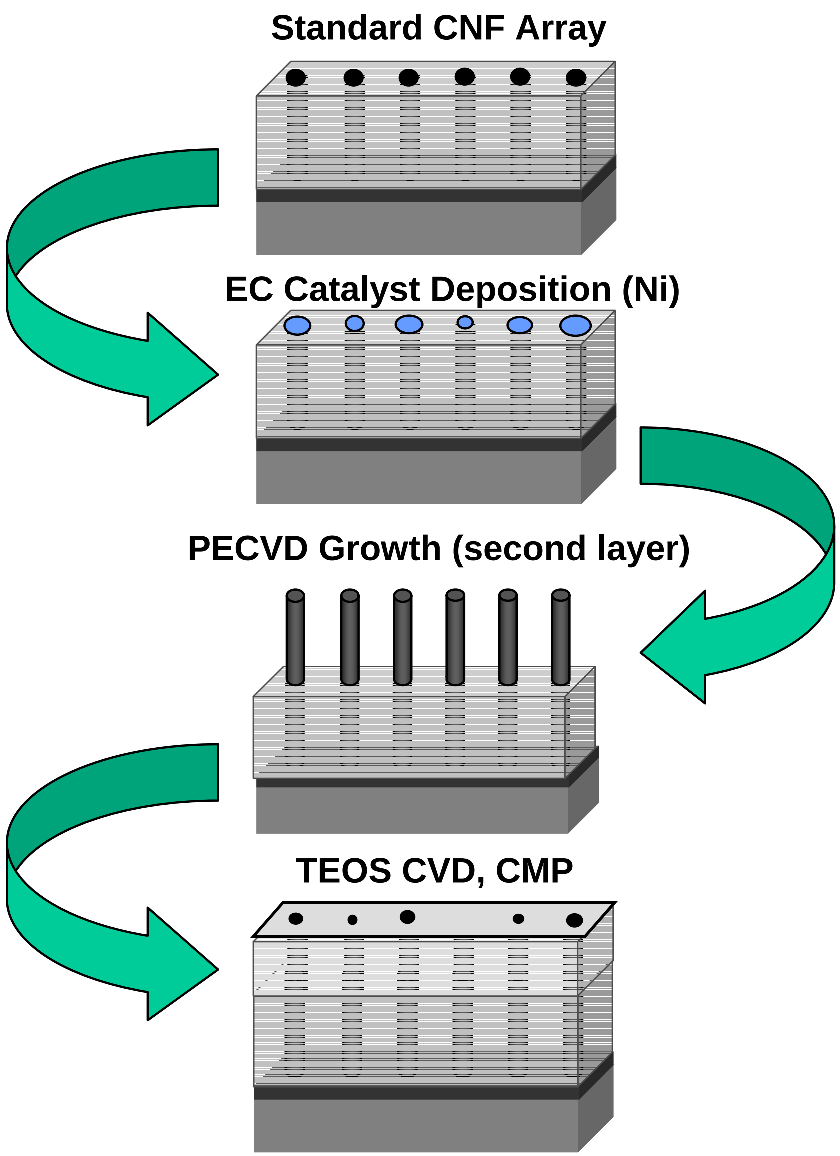


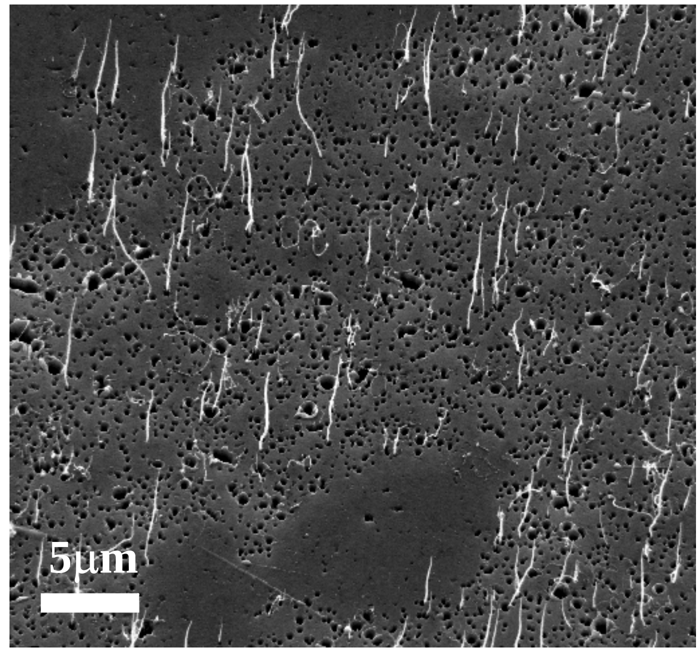
Consistent with bulk measurement

Multi-layer CNF Structures

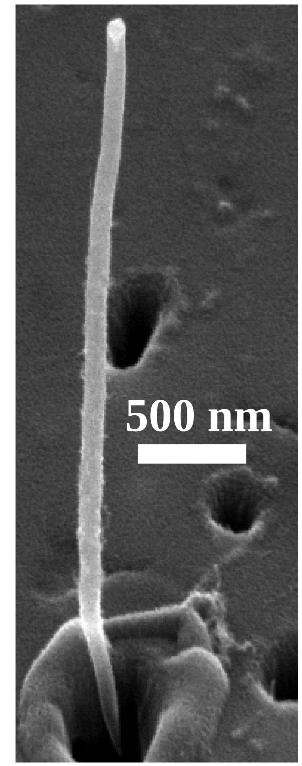
Collaborators: J. Li, A. Cassell, M. Meyyappan
Center for Advanced Aerospace Materials and Devices,
NASA Ames Research Center, Moffett Field, CA

Process flow for CNF multi-layer growth



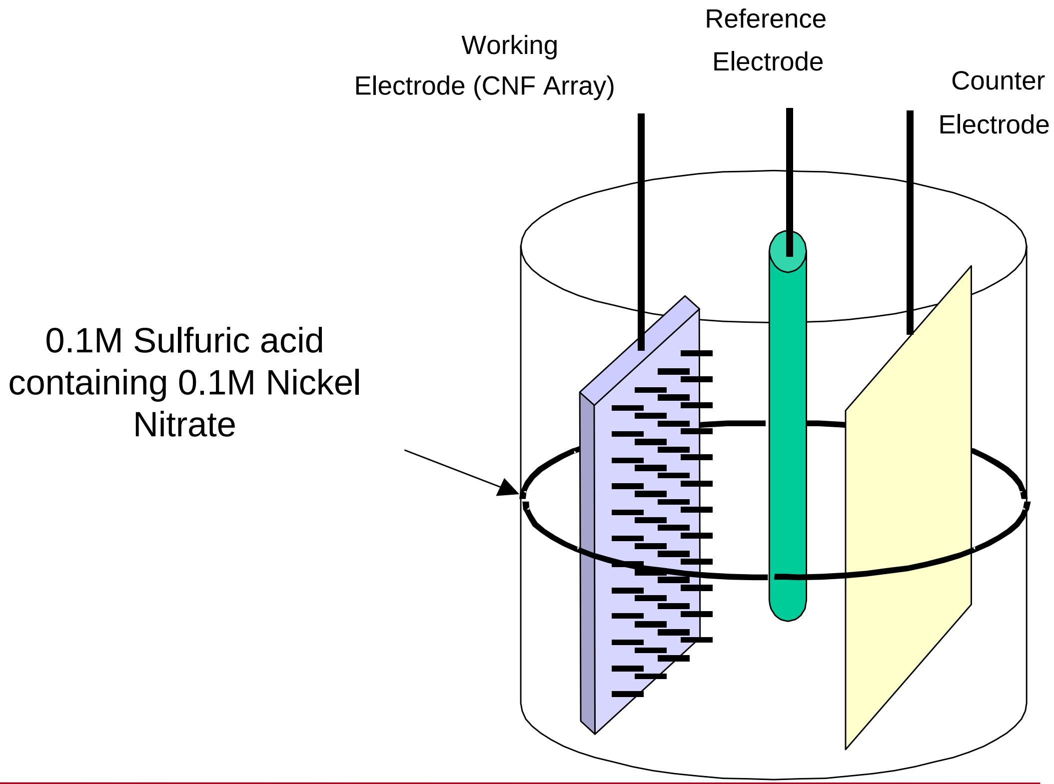


Post second-layer growth



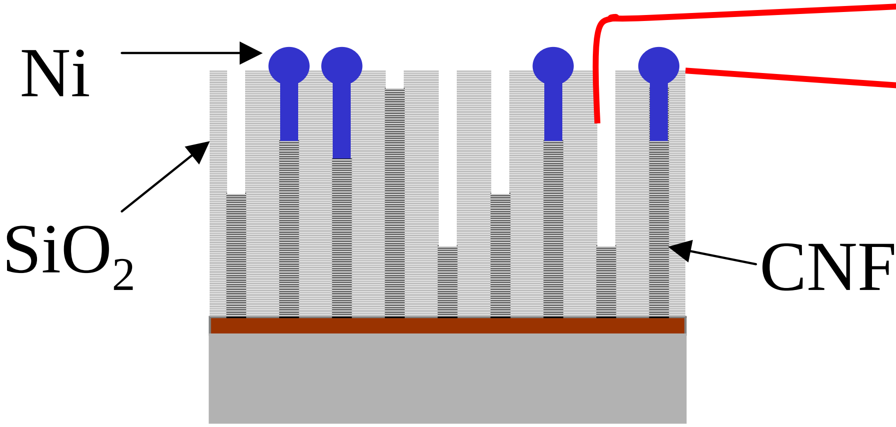
Second-layer Catalyst Deposition (I)

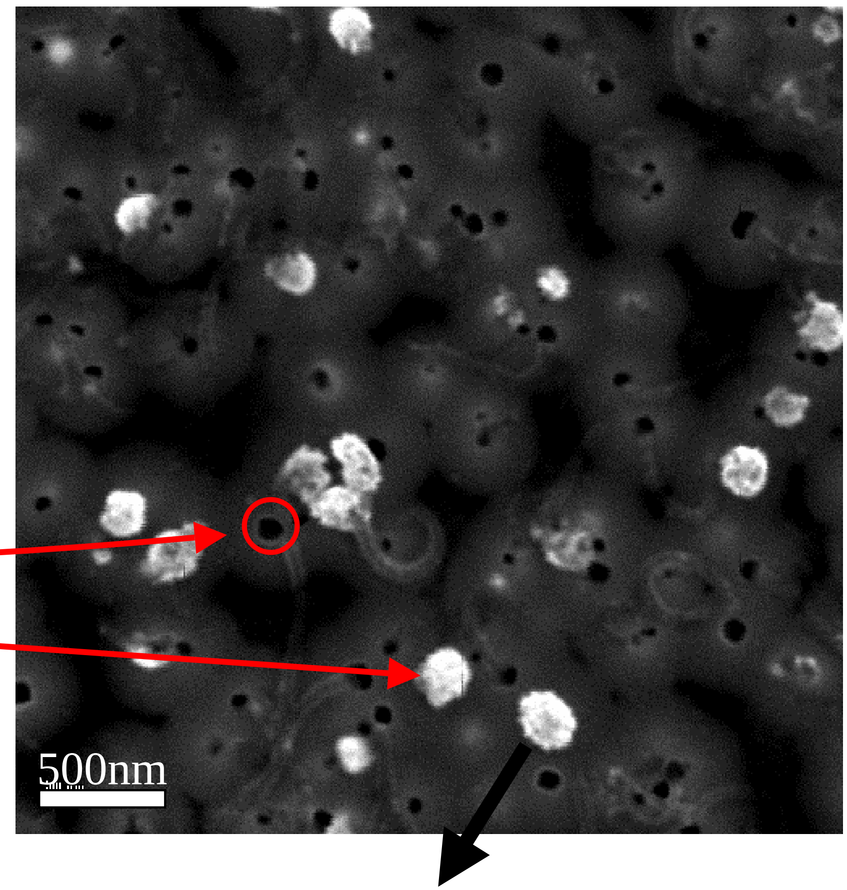
- Tubes are etched in NaOH solution to recess them into SiO_2 layer and expose -OH and -COOH groups at CNF ends
- Provides a good carbon electrode for selective Ni catalyst growth
- Deposition is optimized at -0.70V vs. SCE for 45-60 minutes



Second-layer Catalyst Deposition (II)

- Not all first layer nanofibers can form heterojunctions
- Some nanofibers are recessed deep in SiO_2 after NaOH etch (preventing Ni deposition)



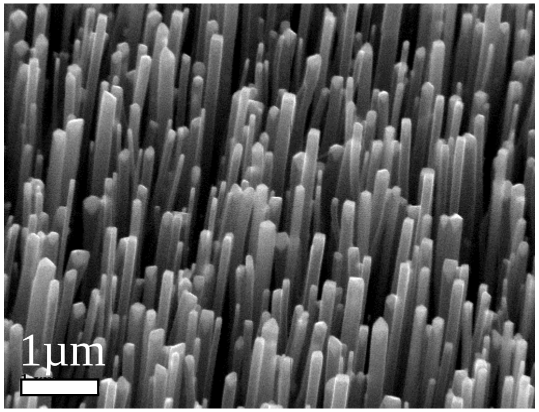


Average Ni cluster size: 200nm

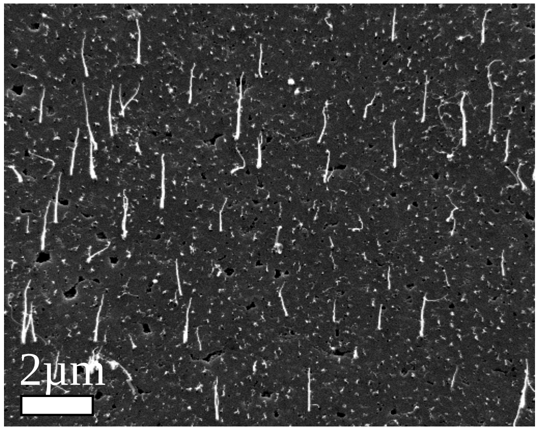
Second-layer Nanofiber Growth (I)

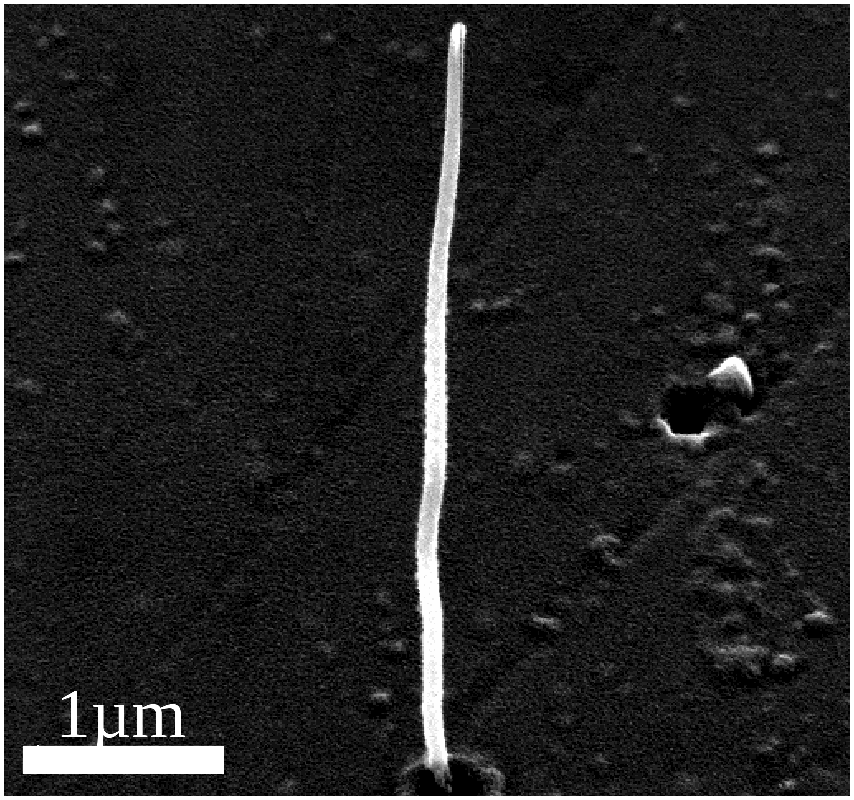
- Same PECVD growth conditions were used for second layer

First-layer CNF array growth



Second-layer CNF array growth



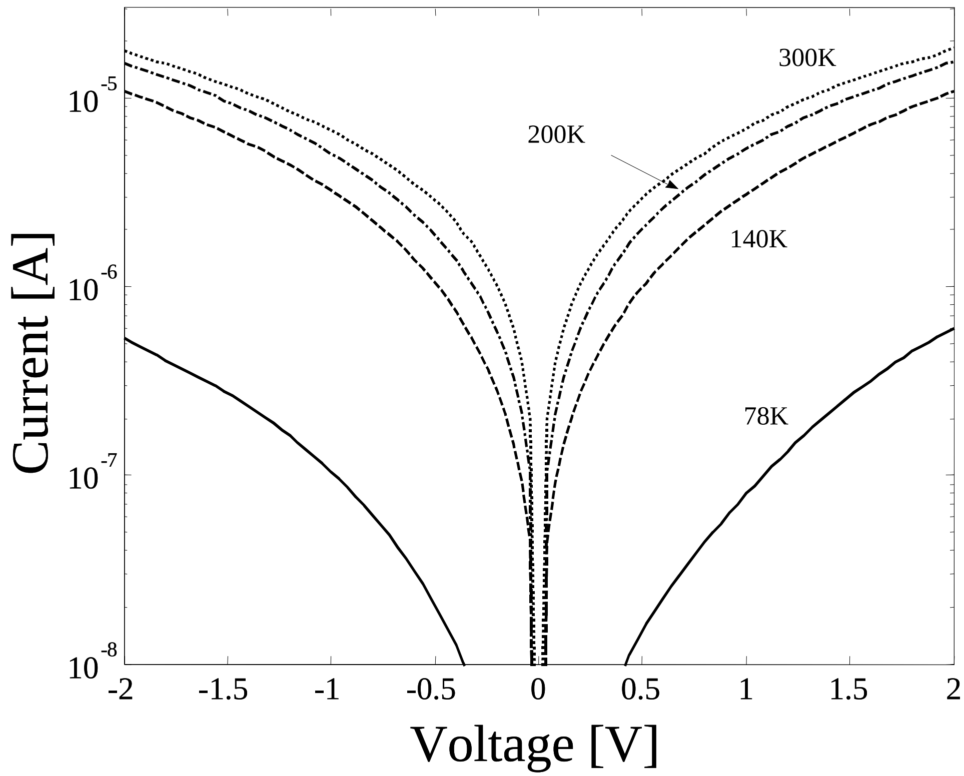


Second-layer Nanofiber

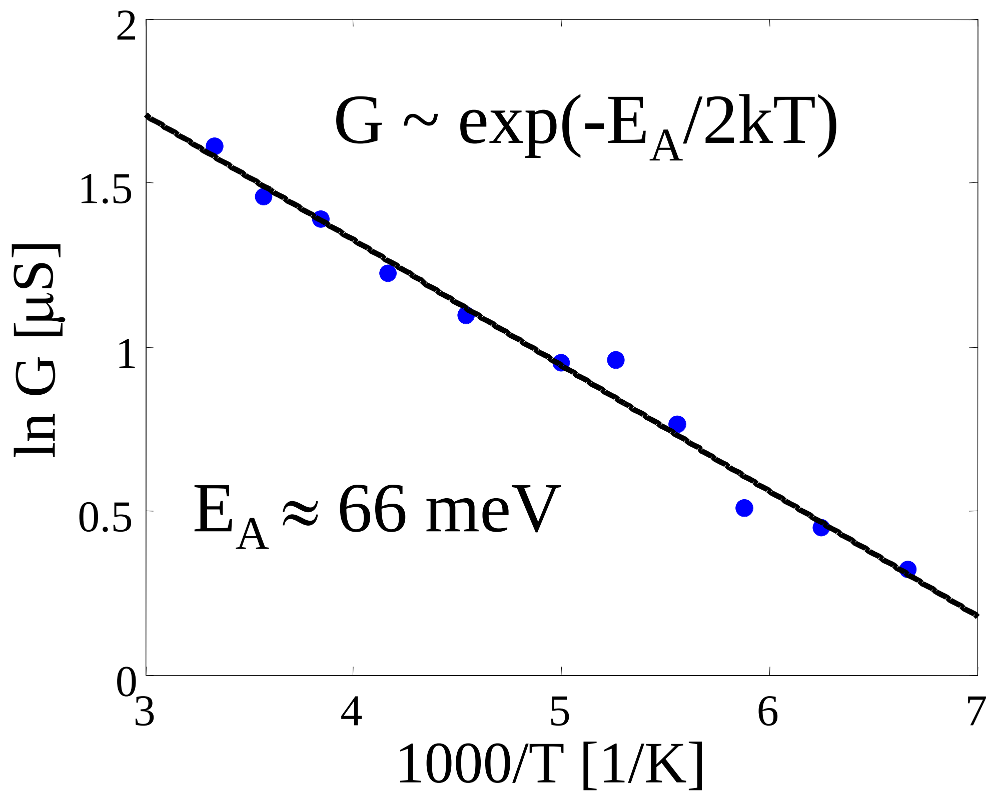
Summary of CNF Multi-layer Growth

- Ni cluster size can be well controlled using nickel nitrate $Ni(NO_3)_2$
  - Parameters: deposition potential, deposition time, nickel concentration
- Morphology of second-layer nanofibers depends on Ni cluster geometry
- Density of second-layer nanofibers is low

I-V Characteristics of Multi-layer CNF Array



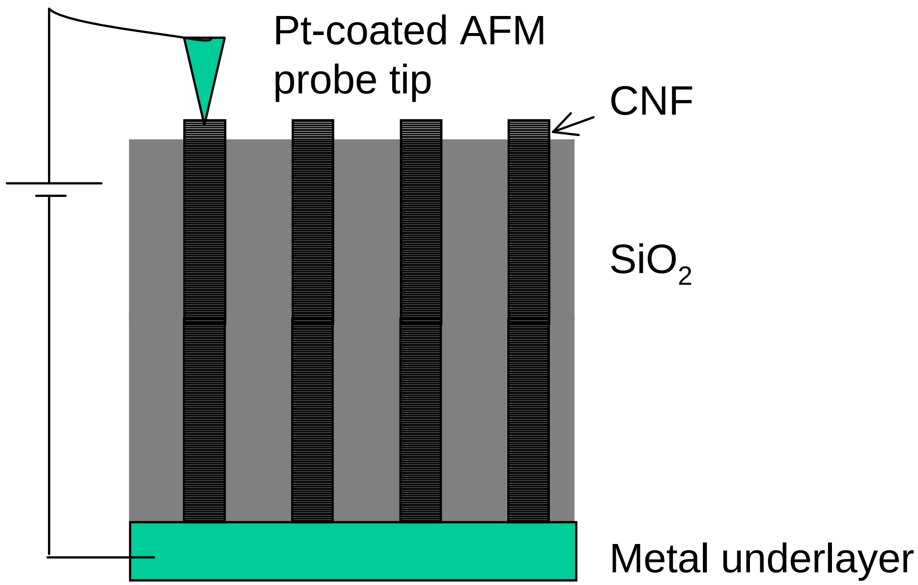
Tunnel junction-like behavior of Multi-layer CNF Array

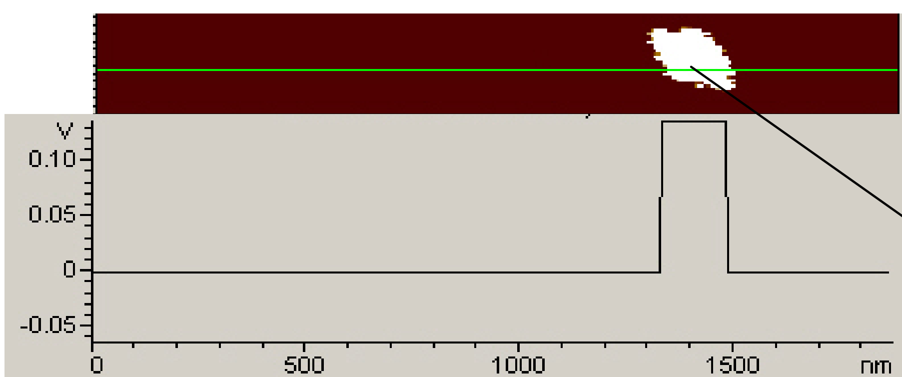


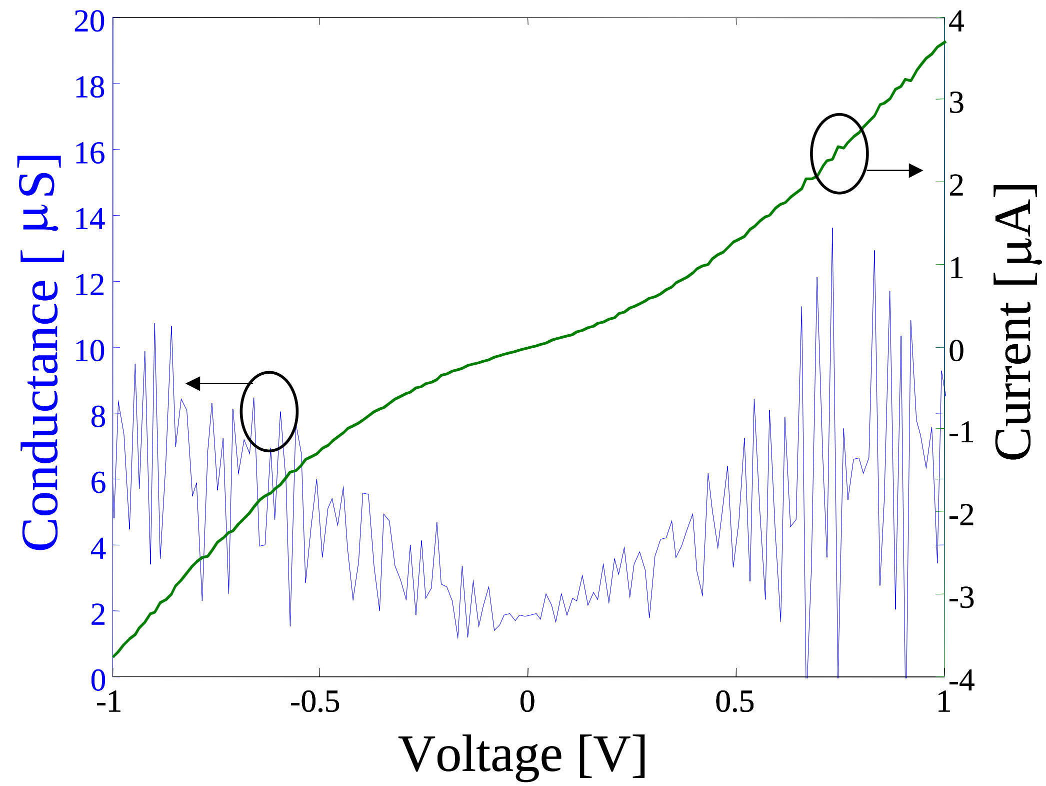
Temperature dependence of differential conductance G at V=0

Ngo et al., *Proc. IITC* 2005, 153-155

I-V Characteristics of Single Multi-layer CNF

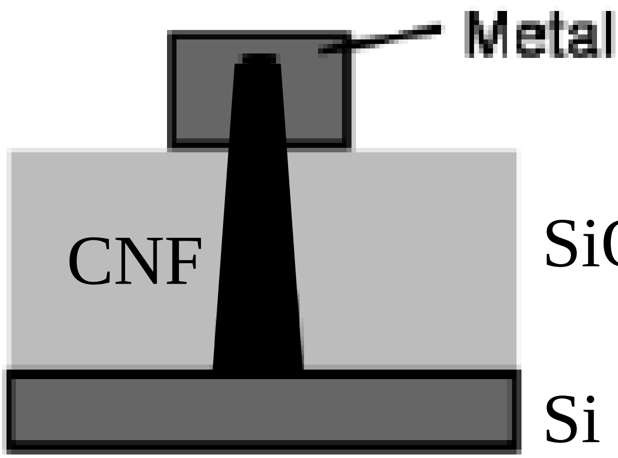




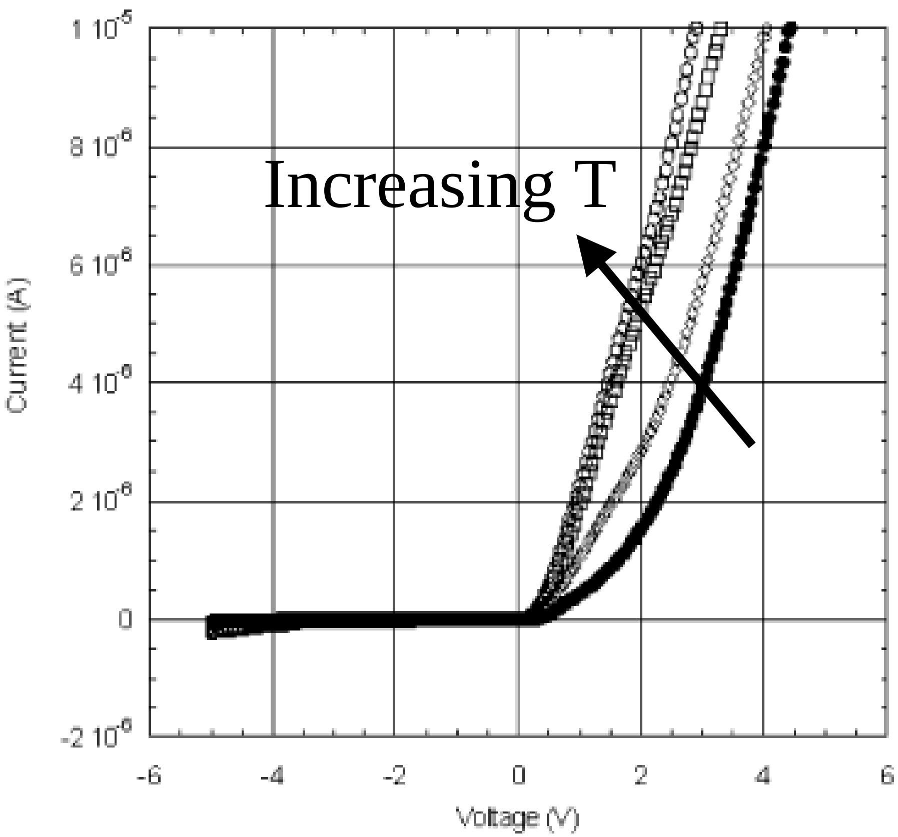


Second layer CNF diameter ≈ 200 nm

Potential Multi-layer CNF devices

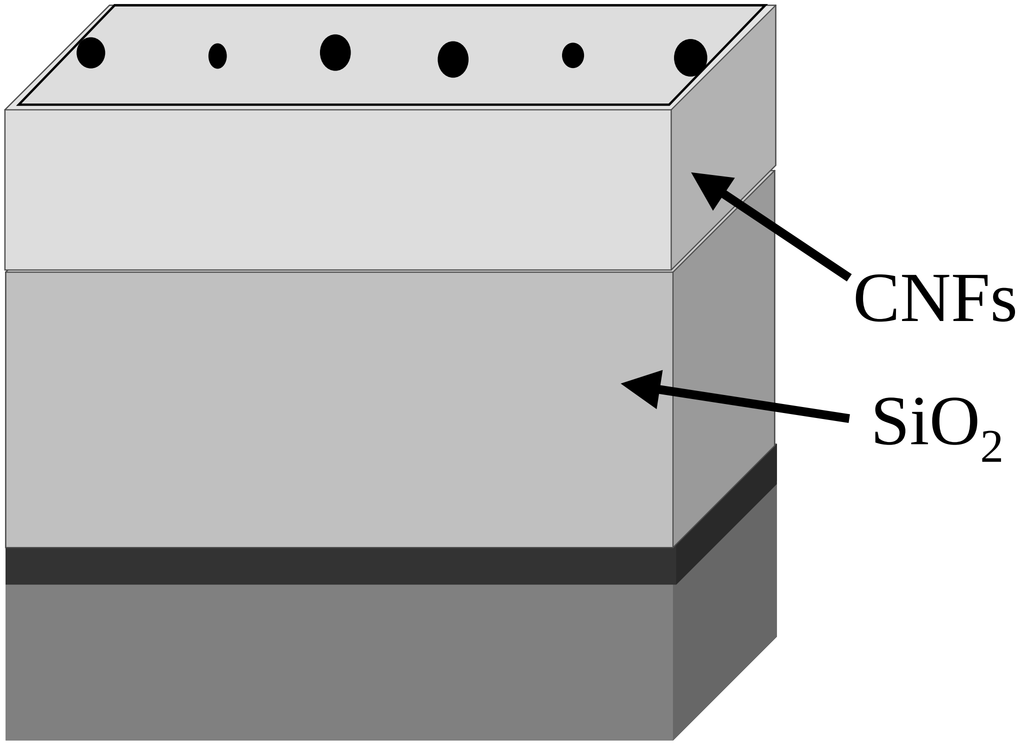


Si-based Schottky Barrier Diode

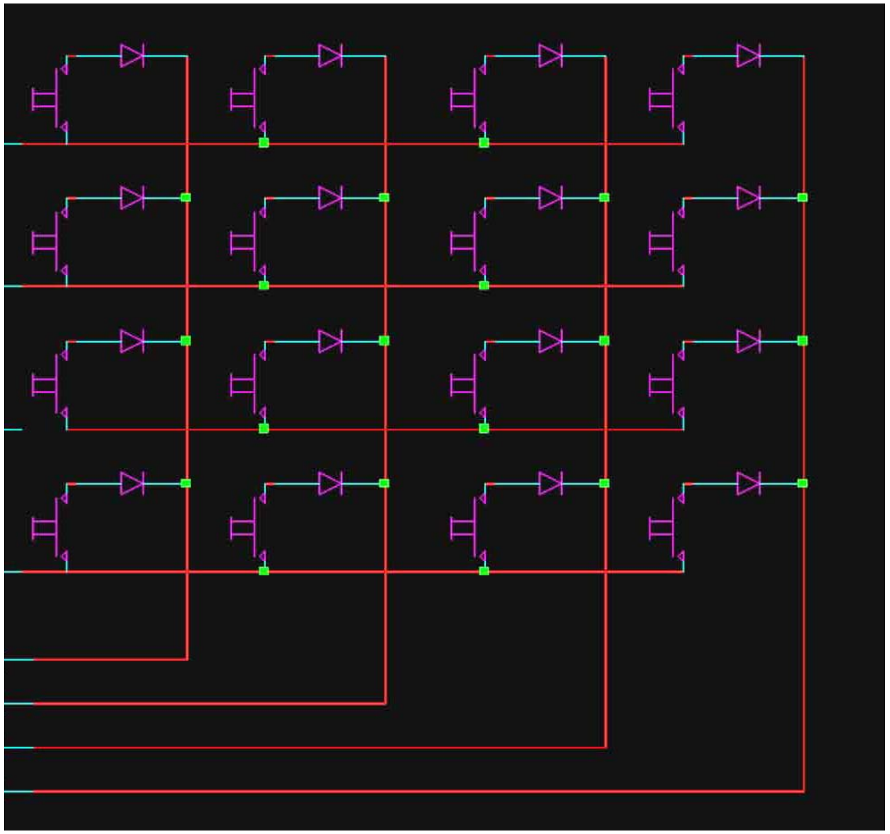


X. Yang et al., *Nano Lett.* **3**, 1751 (2003)

Potential Multi-layer CNF devices



CNF diode array



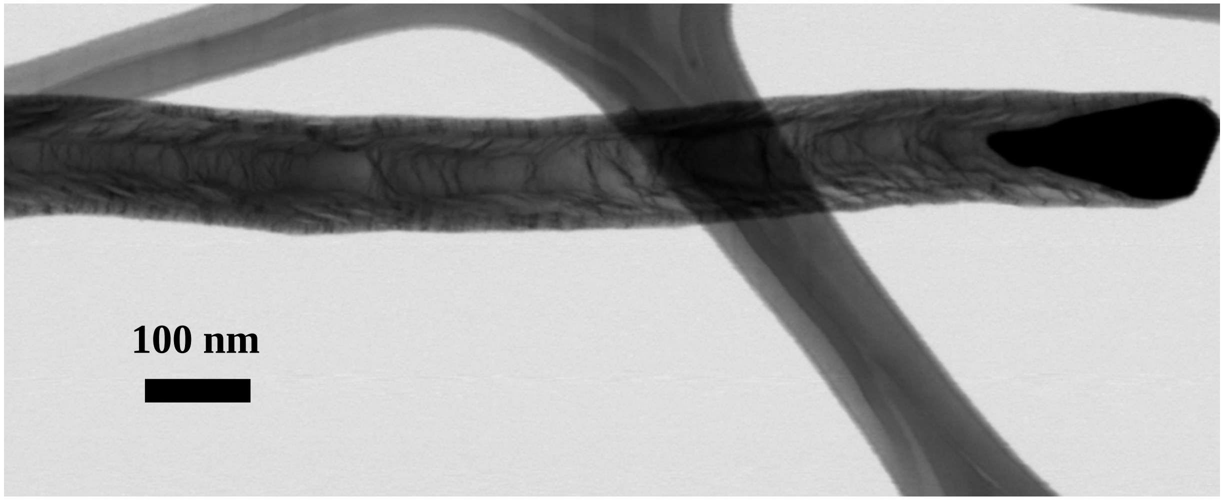
TEM/STEM Analysis of Individual CNFs

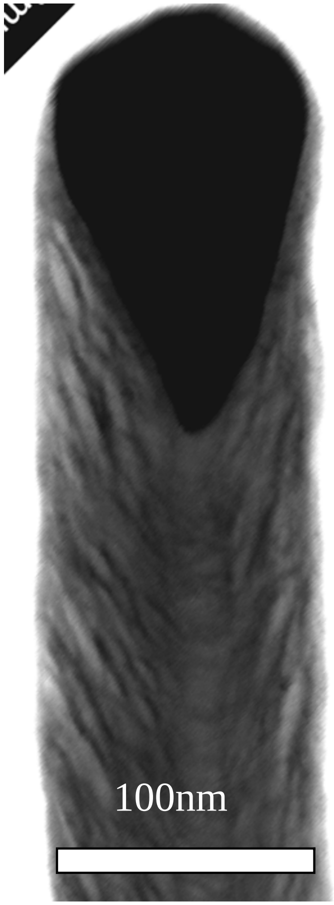
Collaborators: Y. Ominami, M. Suzuki
Hitachi High Technologies America (HHTA)
Pleasanton, CA

Collaborators: V. R. Radmilovic
National Center for Electron Microscopy (NCEM)
Lawrence Berkeley National Laboratory
Berkeley, CA

STEM analysis of Ni-catalyzed CNFs (I)

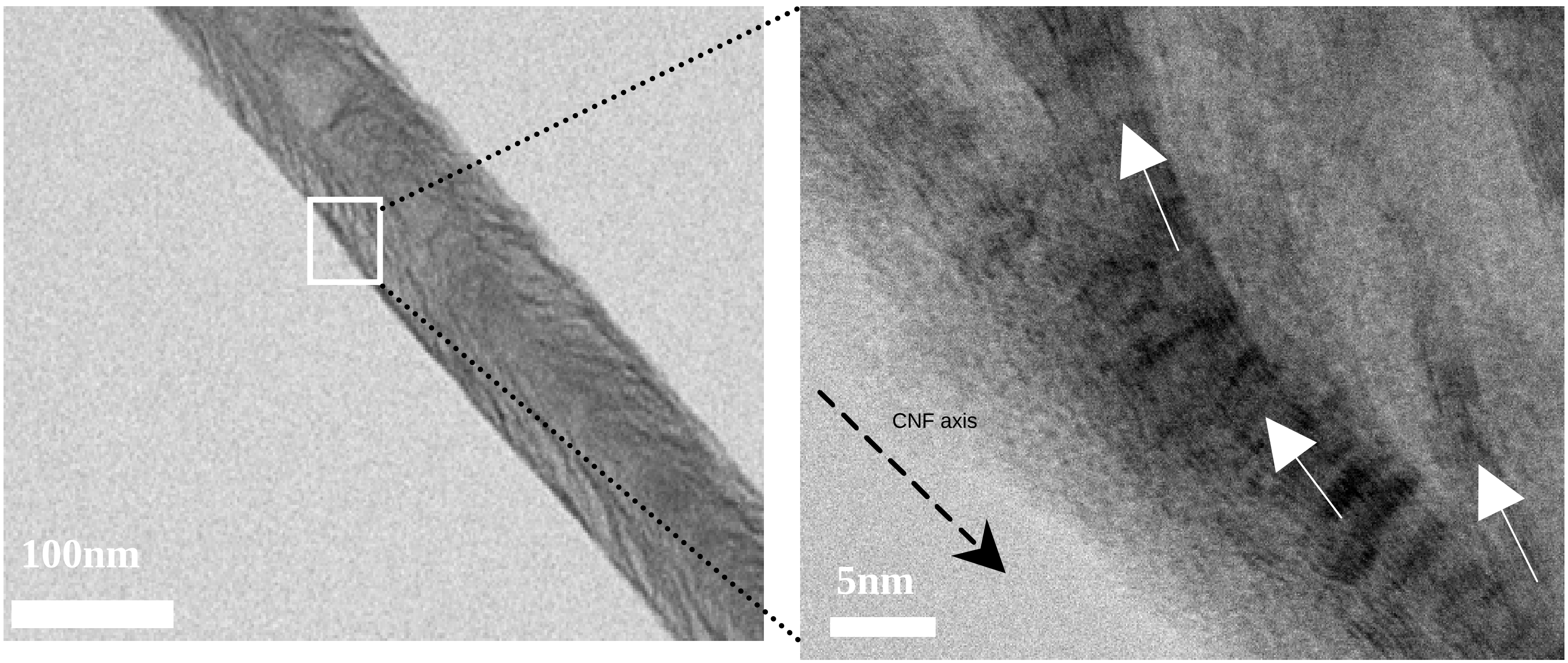
- Nickel-catalyzed CNFs show stacked cone morphology
- Scanning Transmission Electron Microscopy (STEM) using Hitachi S-4800





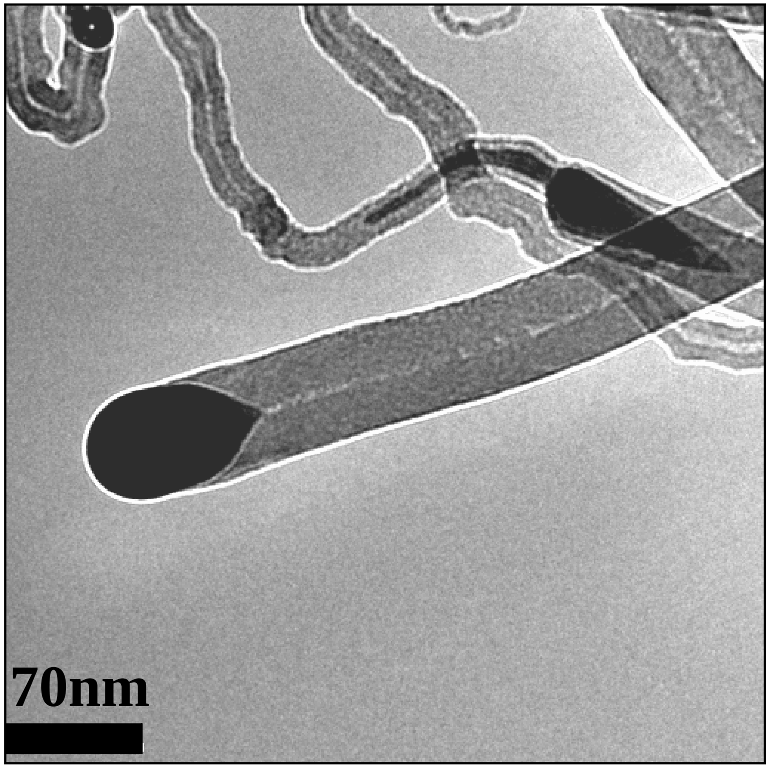
STEM analysis of Ni-catalyzed CNFs (II)

- High-resolution STEM shows stacked cone morphology observed on the outer regions of CNF

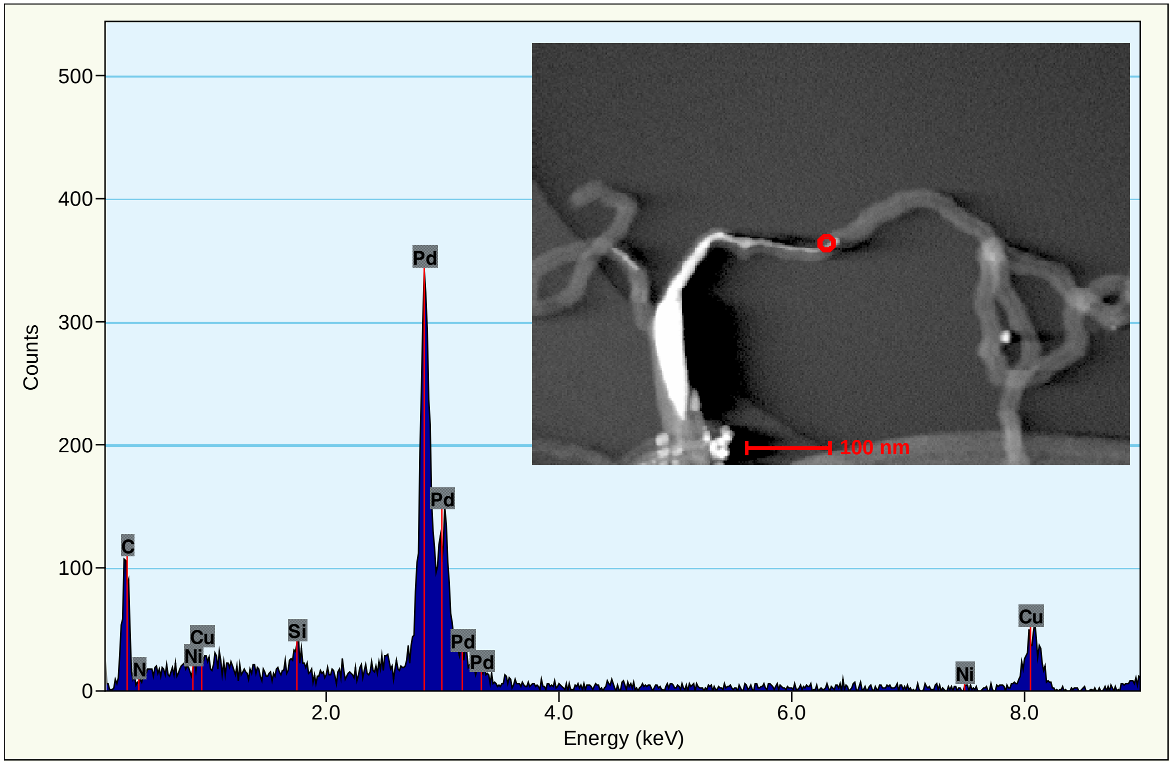


TEM analysis of Pd-catalyzed CNFs

- Secondary growth anomalies in Pd-catalyzed CNFs
  - [Ngo et al., *Carbon*, in press (2006)]

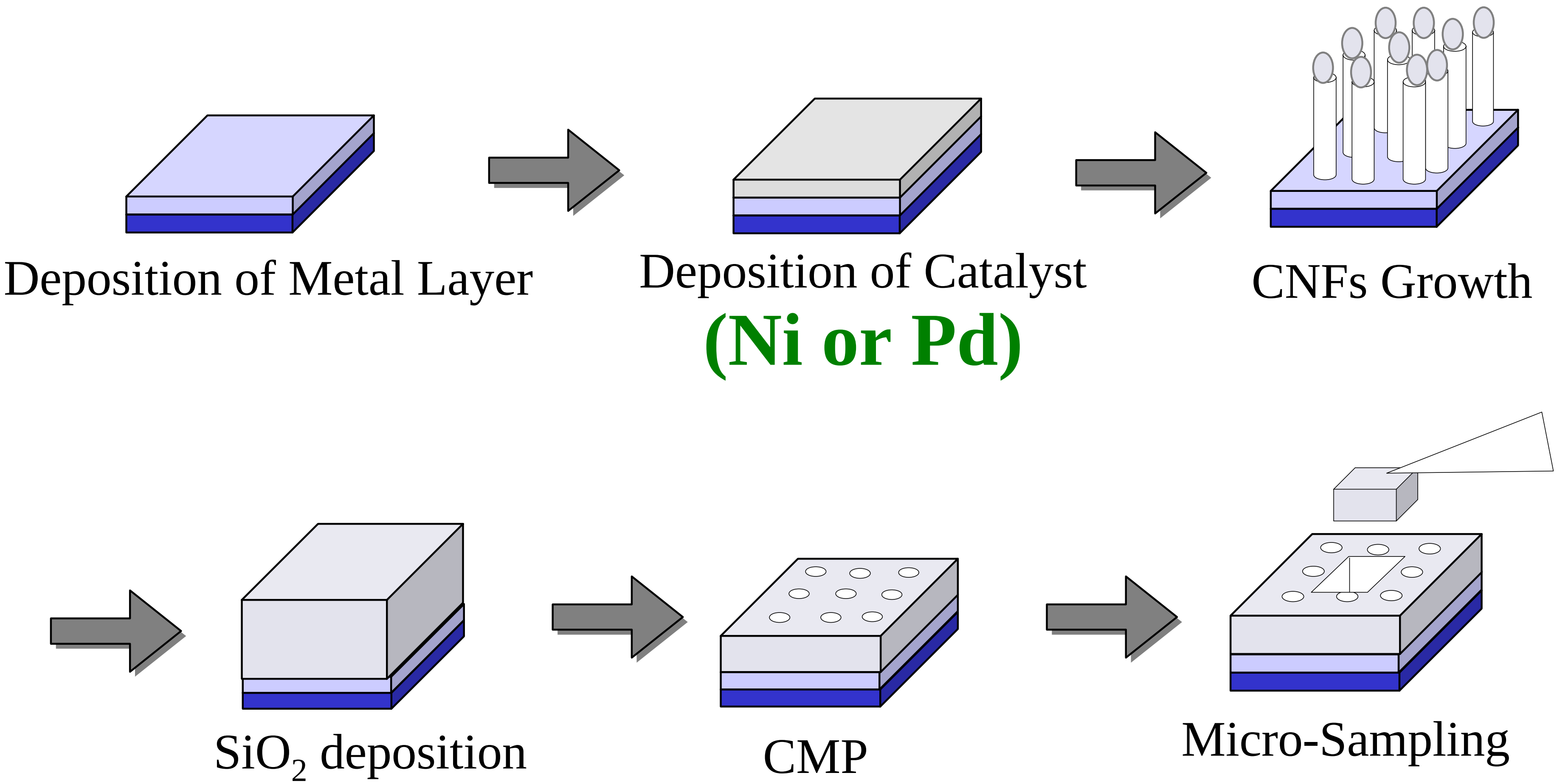


TEM image of secondary CNF growth

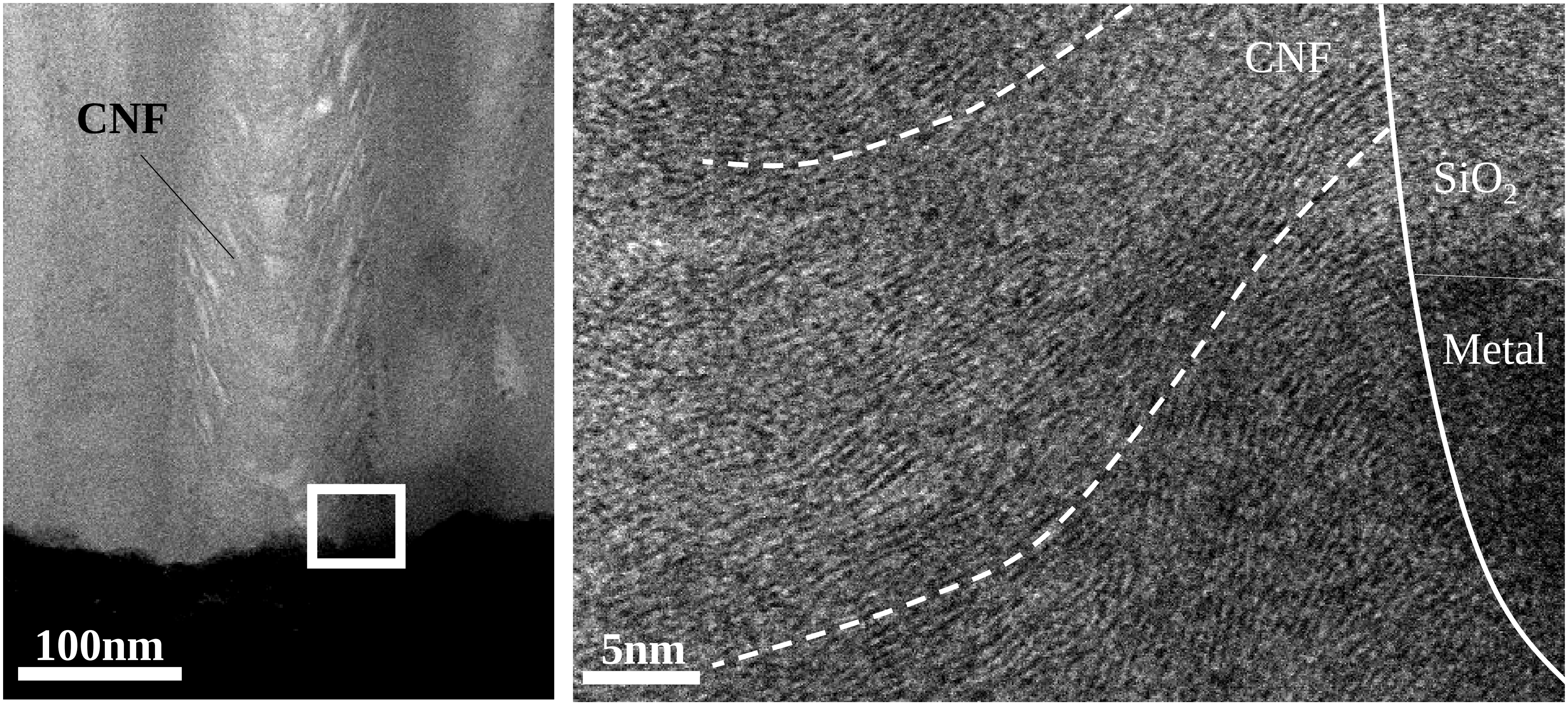


Energy Dispersive X-Ray Spectrum (EDX)

Sample Preparation



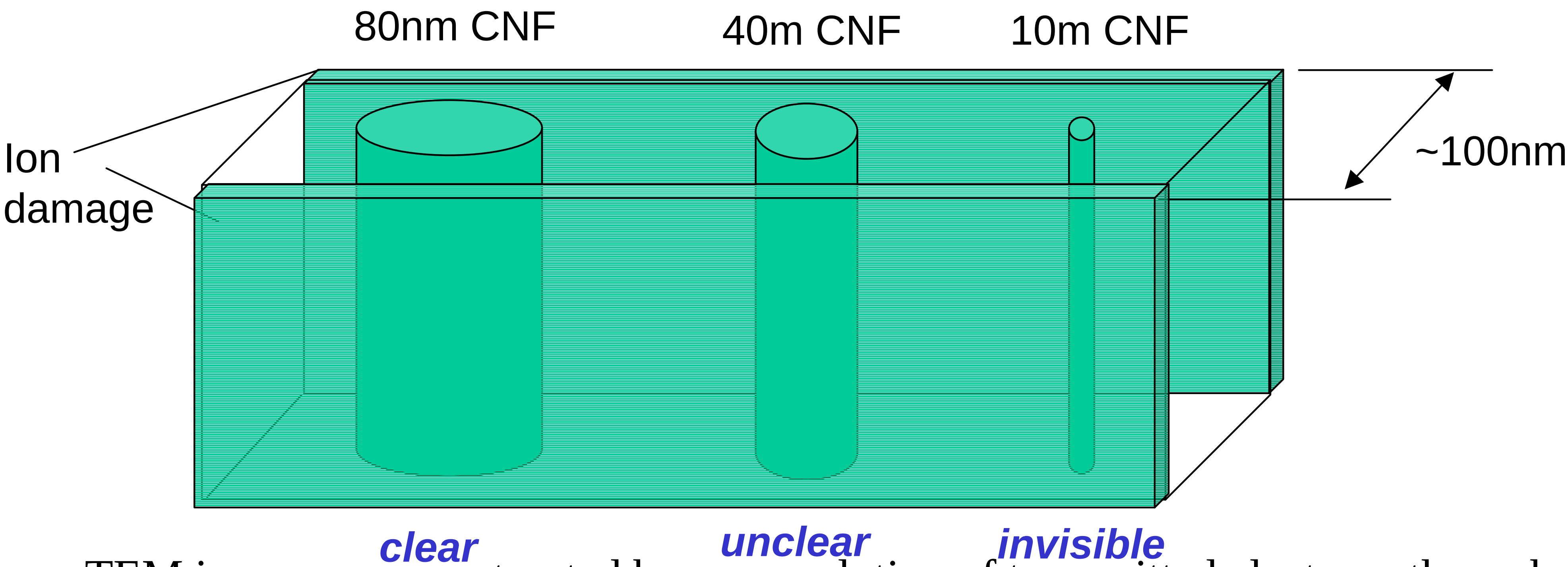
STEM (HD-2300) Images



The interface images of Ni-catalyzed CNF

Y. Ominami et al, *Appl. Phy. Lett.* **87**, 233105 (2005)

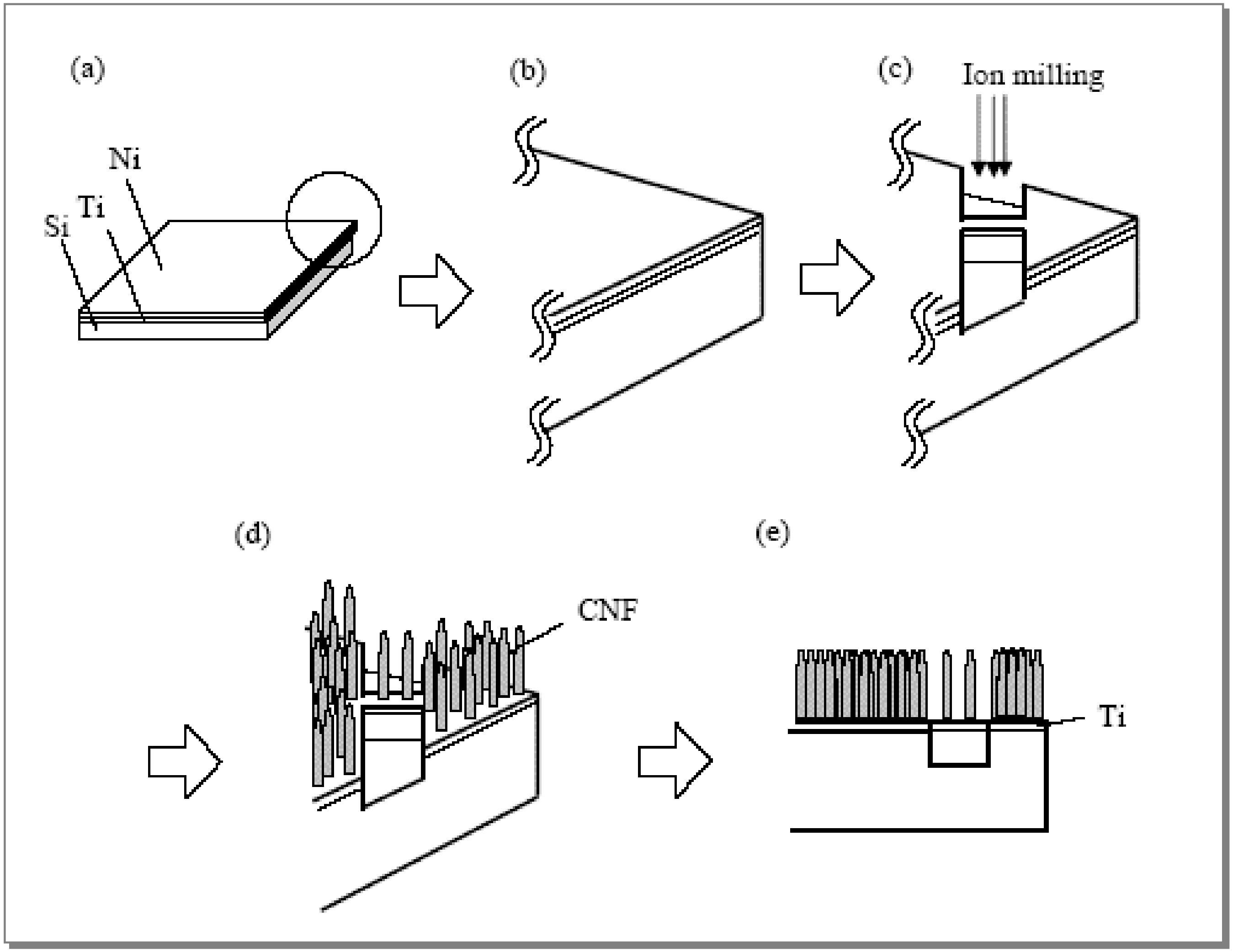
Issues with sample preparation



- TEM images are constructed by a convolution of transmitted electrons through both CNFs and materials around CNFs.
- Ion beam may destroy CNF structure in the process to make a thin foil (100nm or less) due to ion scattering in the foil.
- CNFs cannot be easily found in a prepared thin foil due to their small diameters.

Solution

“Bottom-up sample preparation”

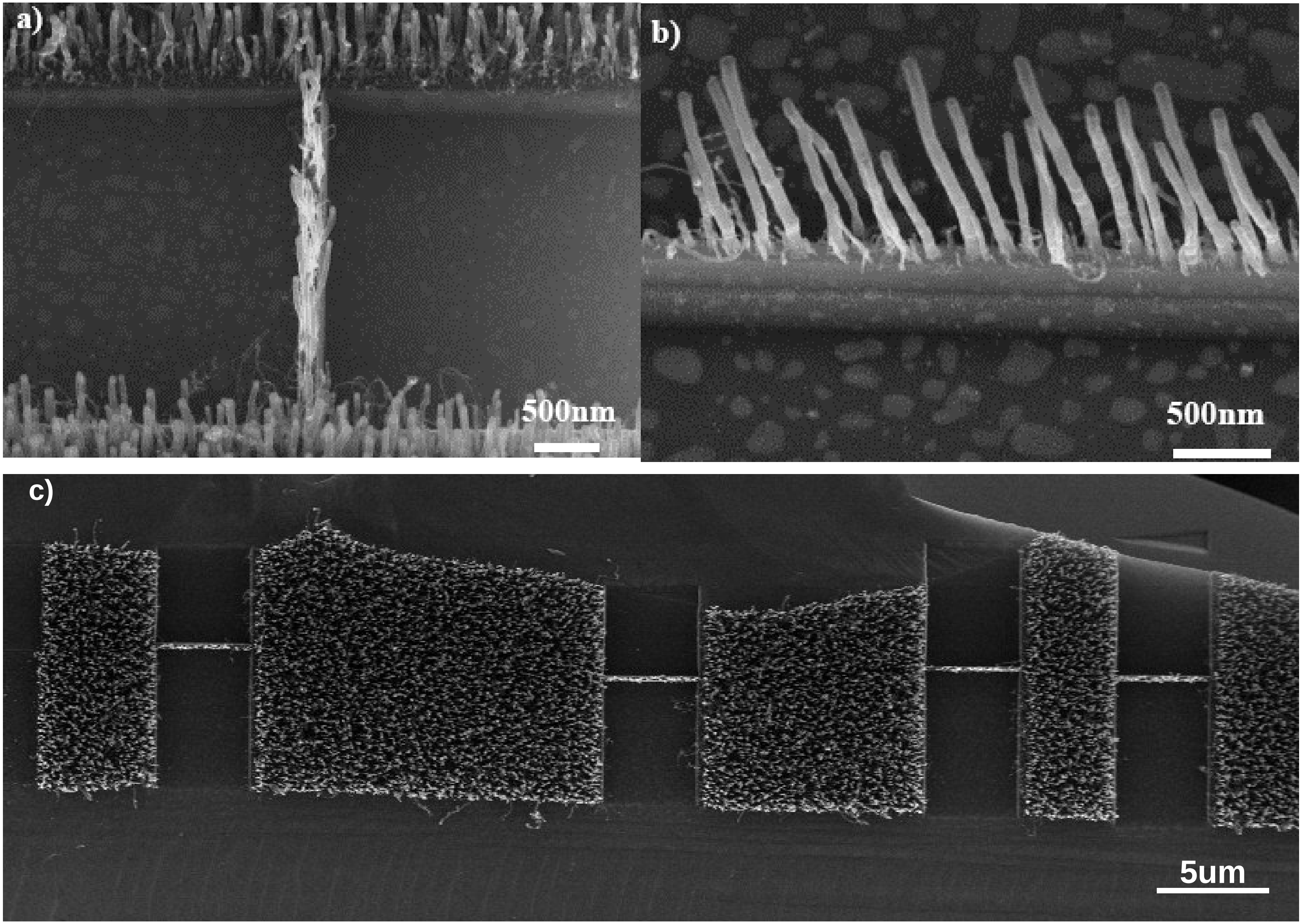


Y. Ominami et al., *Ultramicroscopy* **106**, 597 (2006)

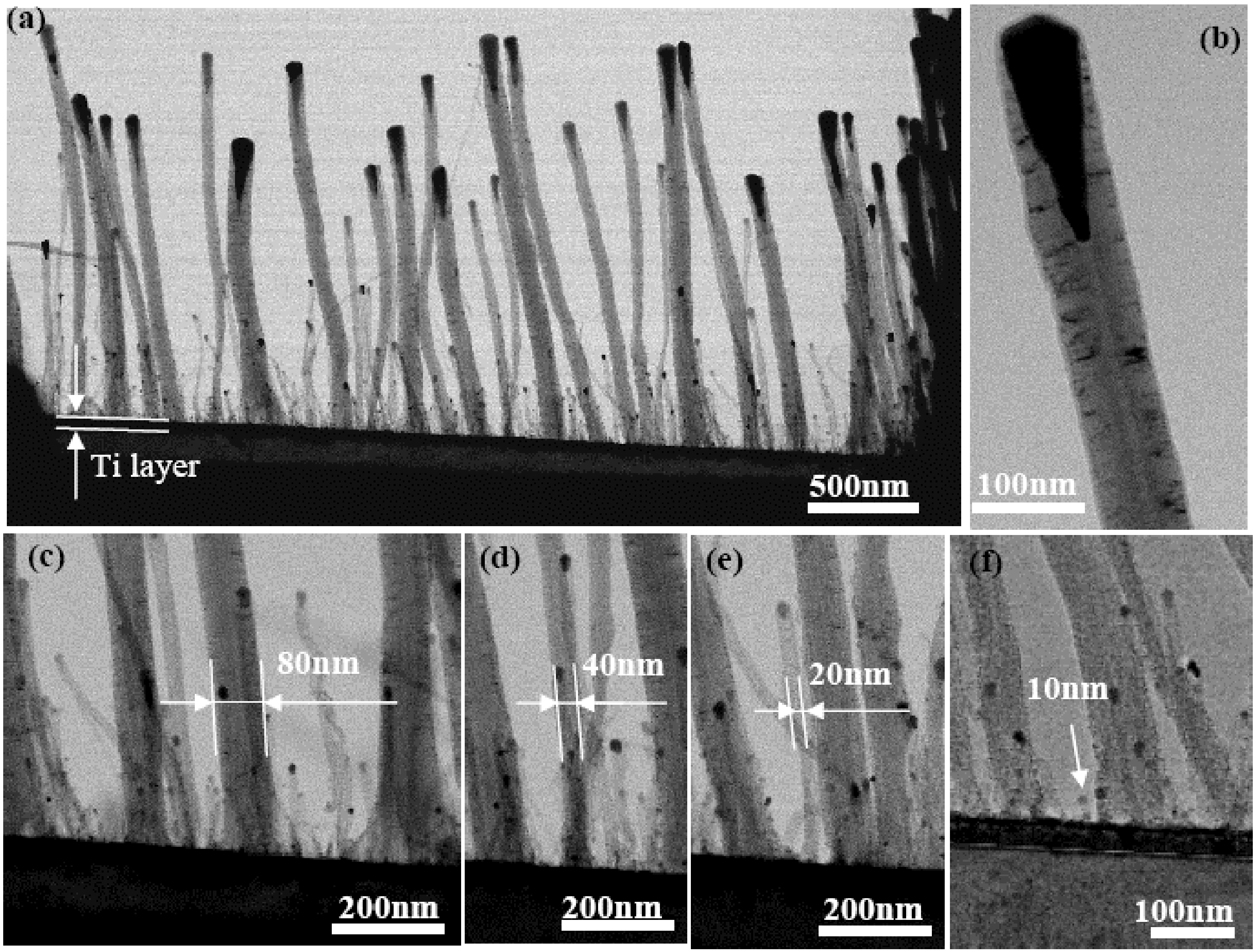
Ion milling **before** CNF growth

- No protective material around CNFs

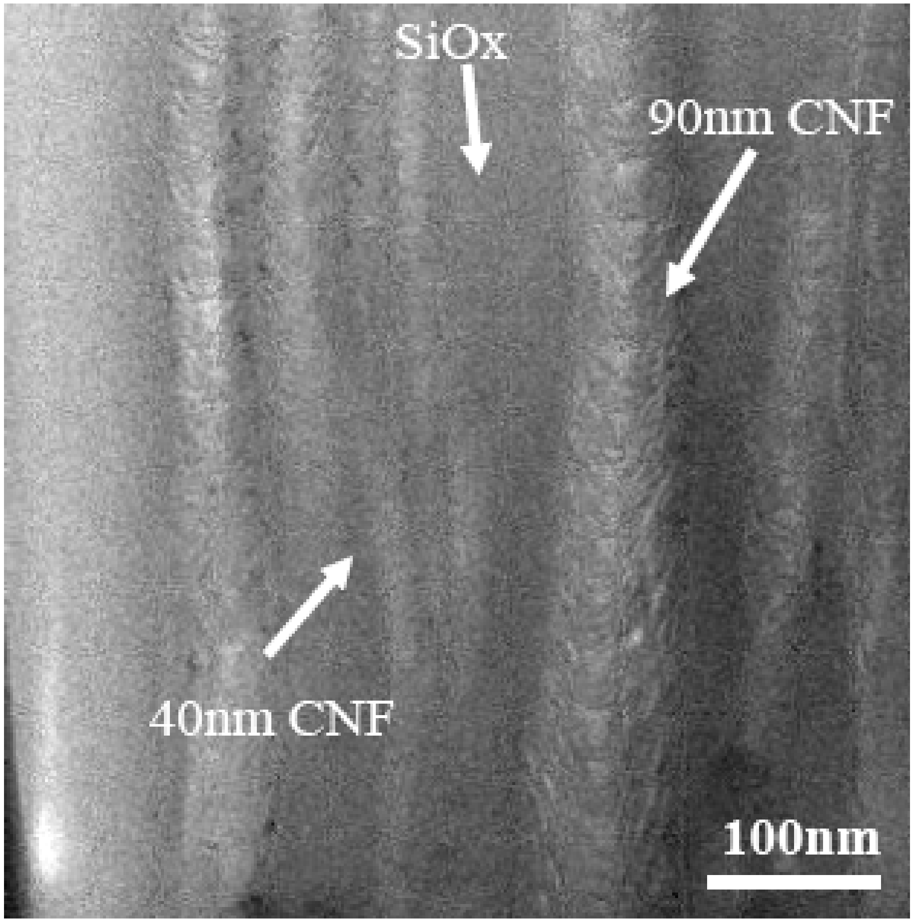
- Applicable to other vertically grown materials, such as nanowires


a)
500nm
b)
500nm
c)
5um

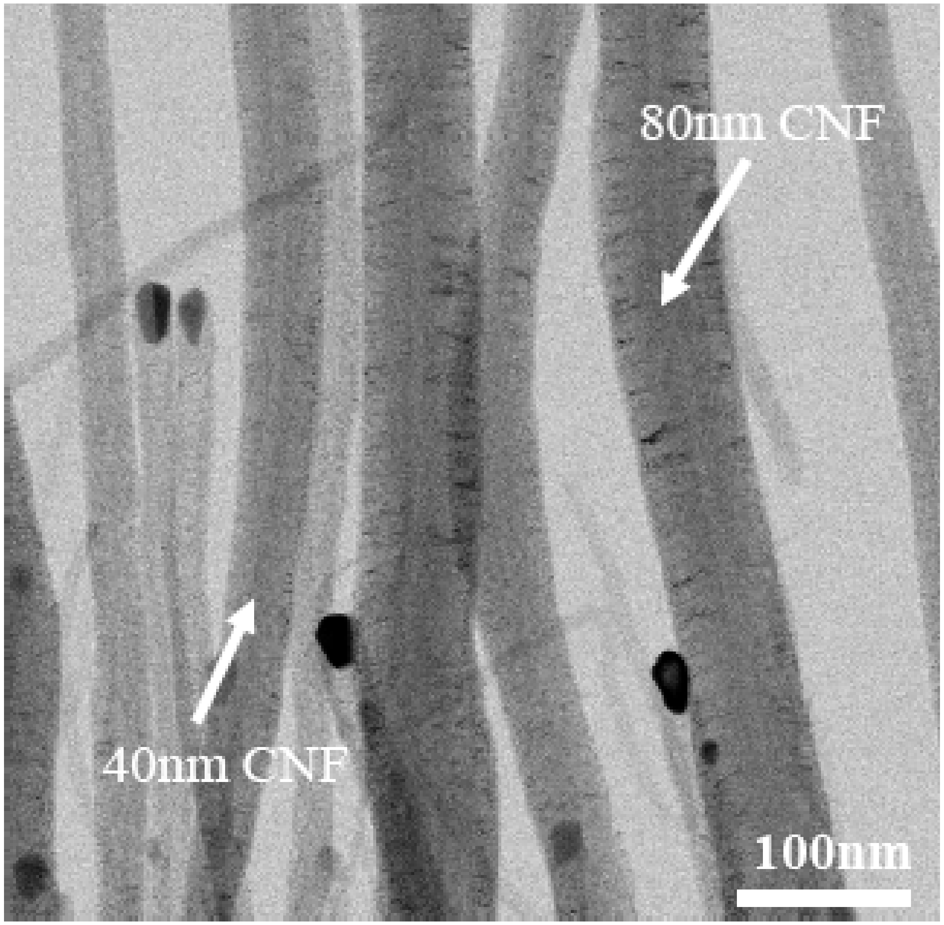
STEM images of CNFs on narrow strip



Comparison of preparation methods

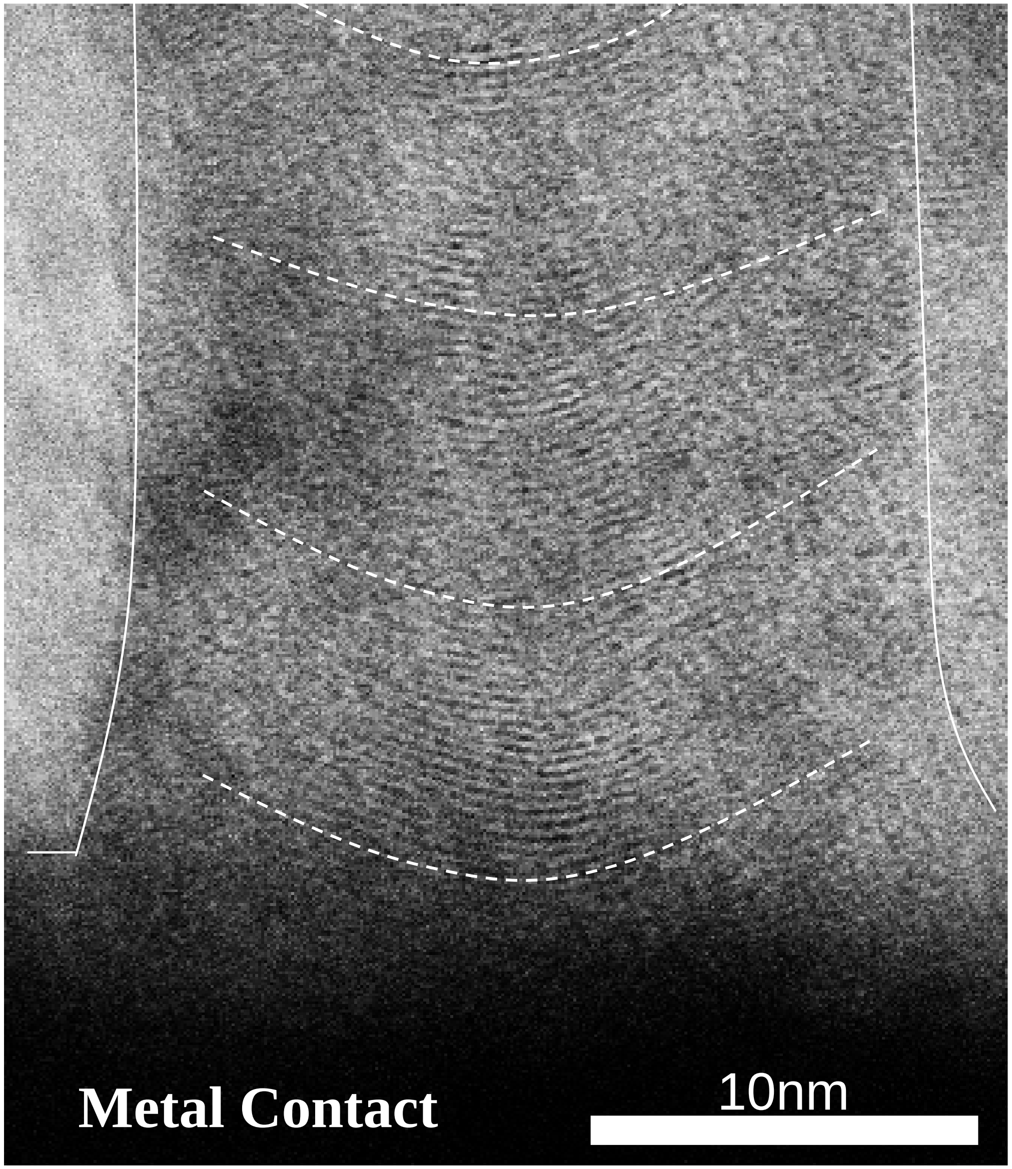


Sample prepared by Conventional Sample Preparation

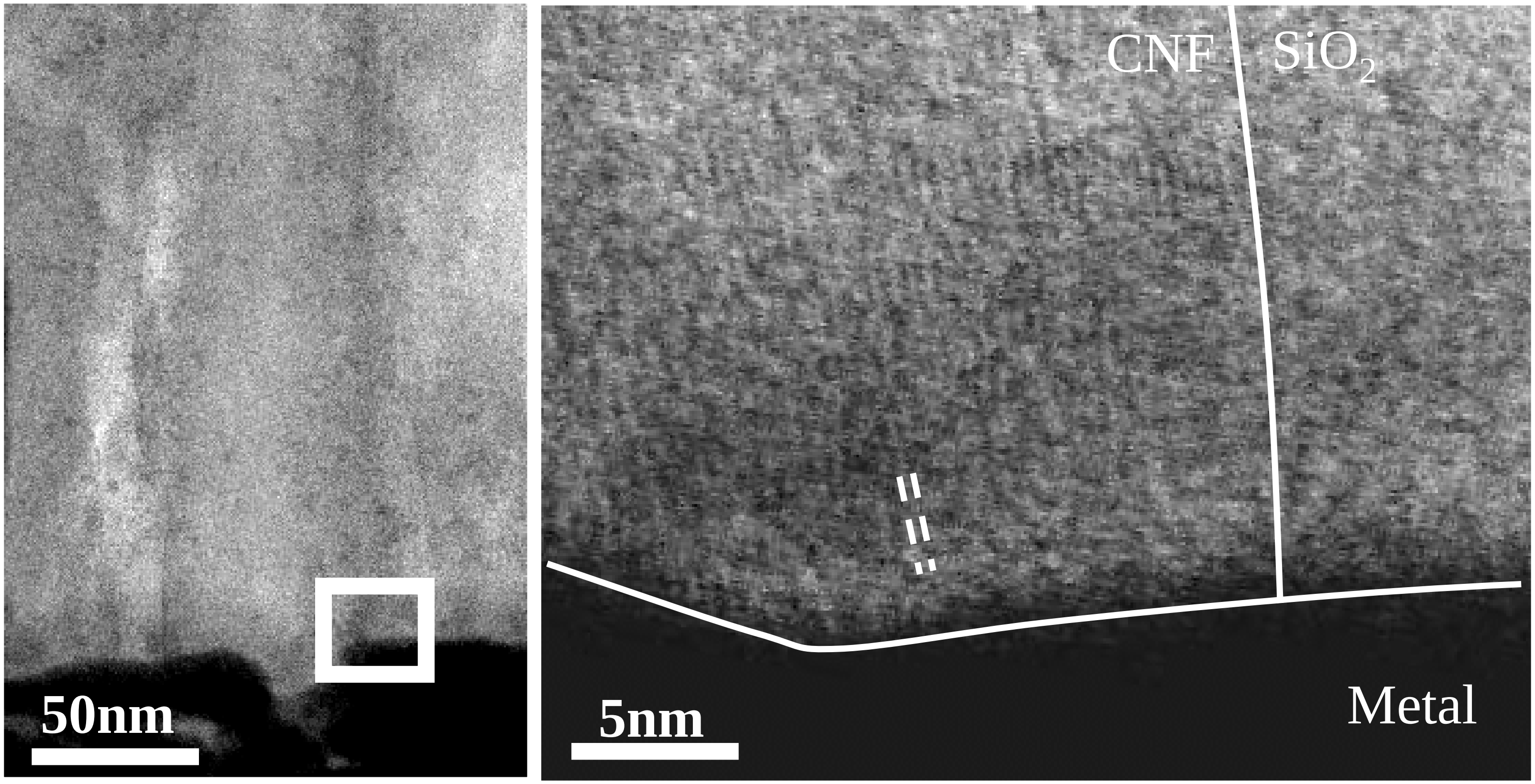


Sample prepared by Bottom-up Sample Preparation

CNF-metal contact interface



STEM (HD-2300) Images of Pd-catalyzed CNF



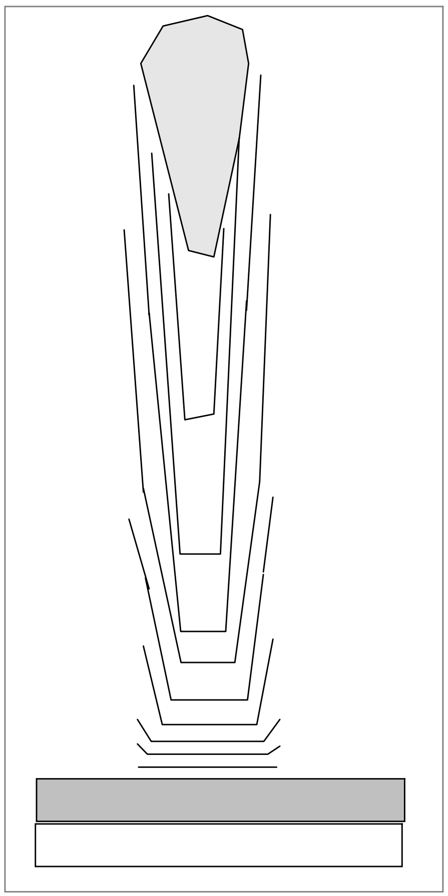
The interface images of Pd-catalyzed CNF

Y. Ominami et al, *Appl. Phy. Lett.* **87**, 233105 (2005)

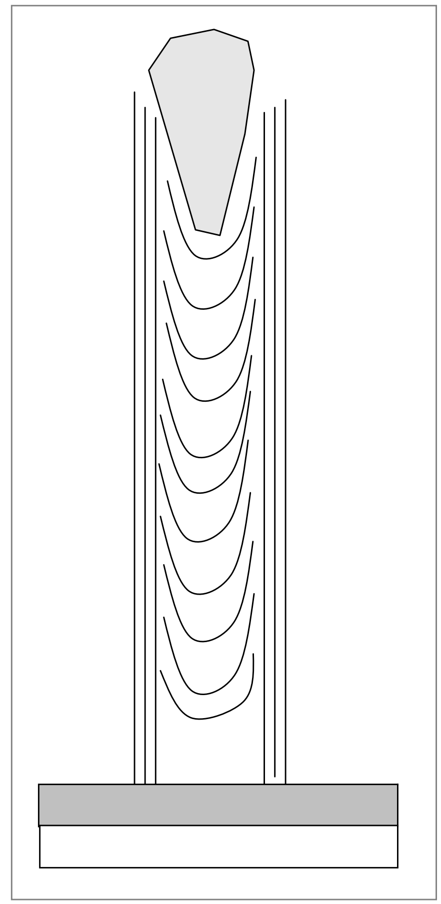
Structural Model

Ni-catalyzed CNF

Pd-catalyzed CNF

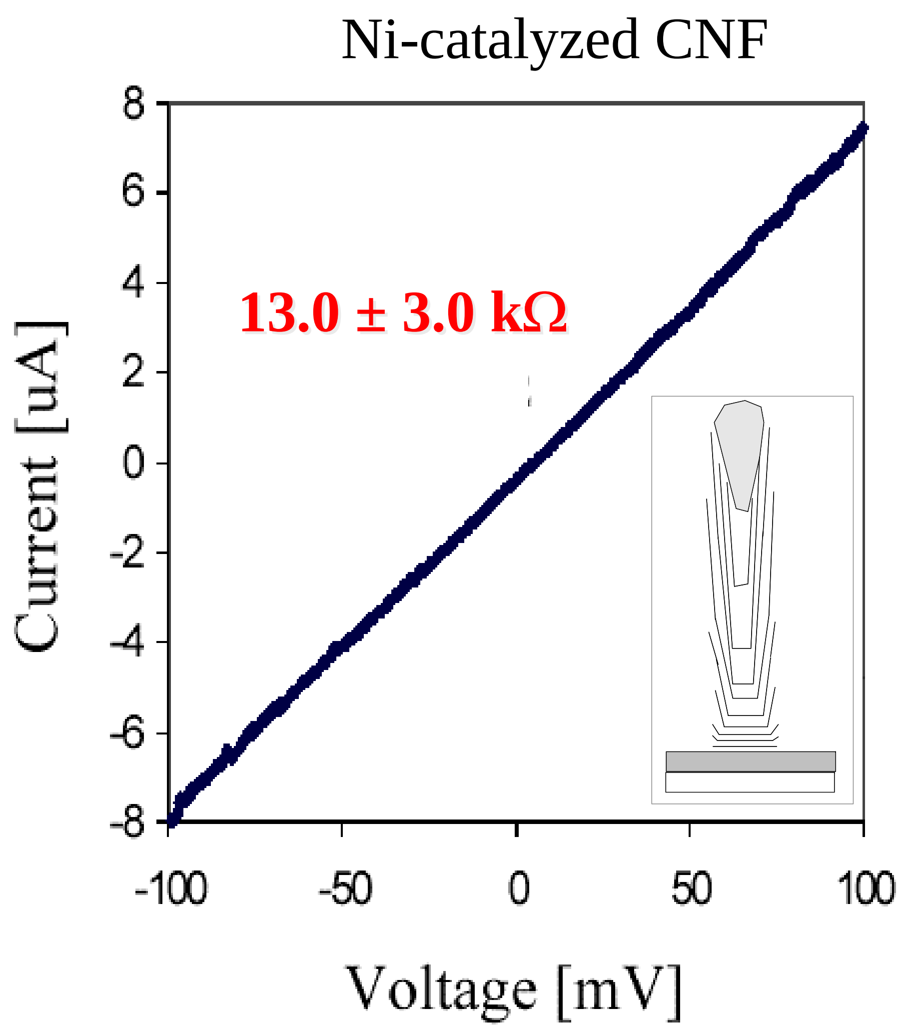


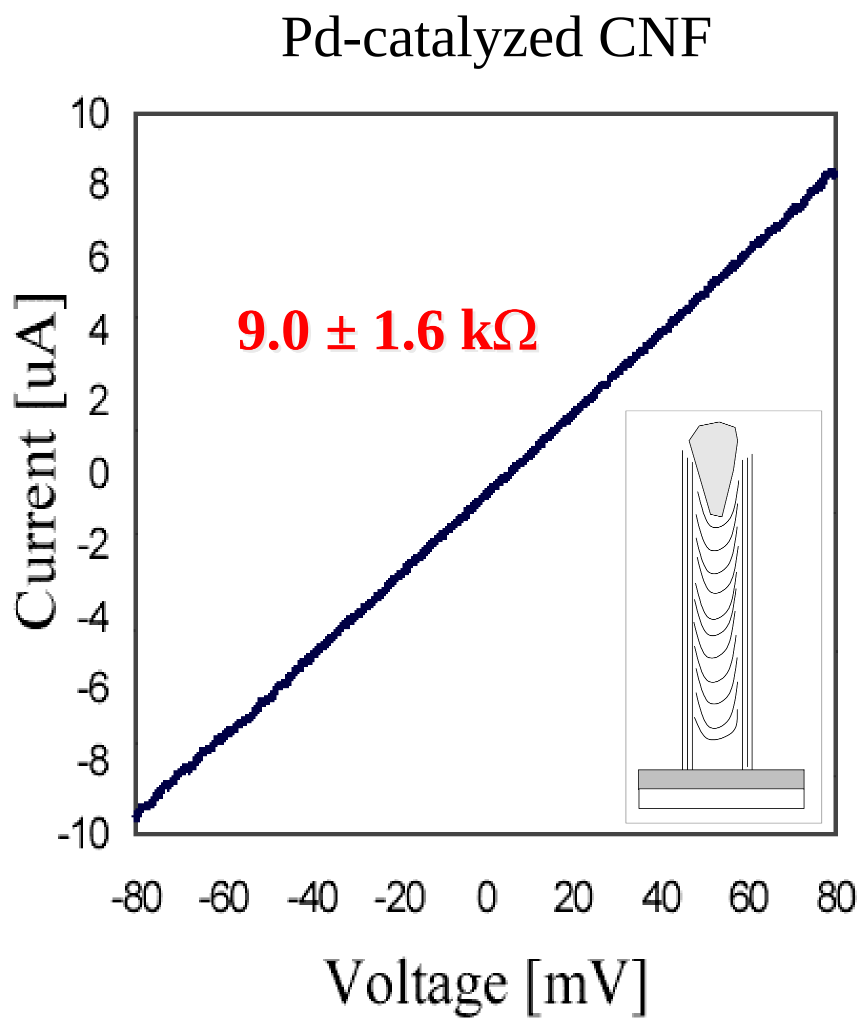
Ni-catalyzed CNFs have <u>stacked graphitic layers</u> near the CNF-metal interface.



Pd-catalyzed CNFs have <u>MW-like structure</u> spanning the entire CNF.

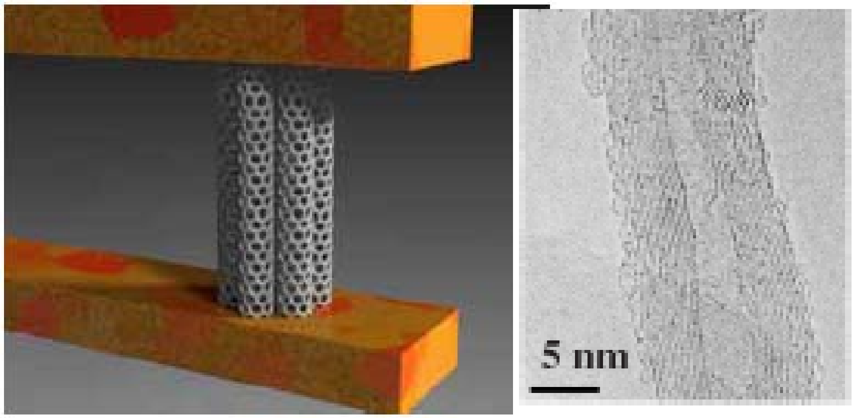
Resistance measurement using AFM





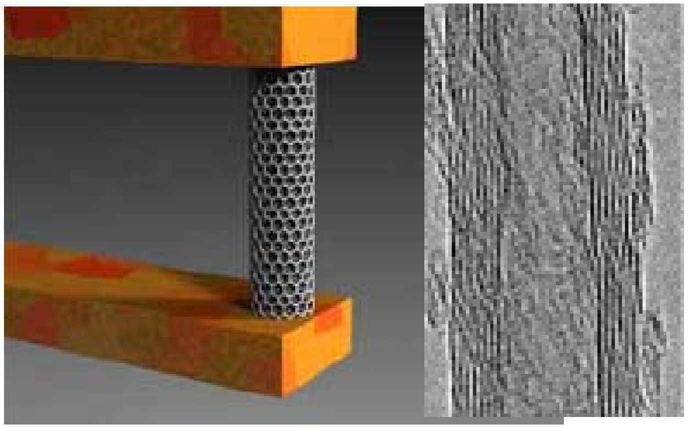
Ominami et al., *Proc. IEEE NANO* vol. **2**, 665 (2005)

Fujitsu, Samsung



Nihei *et al*. Jpn. J. Apl. Phys. **44**, 1626 (2005)

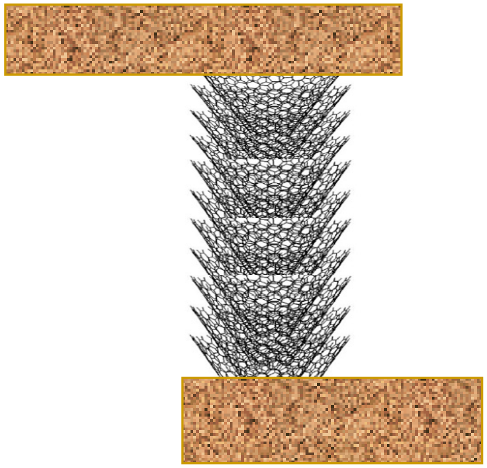
Infineon

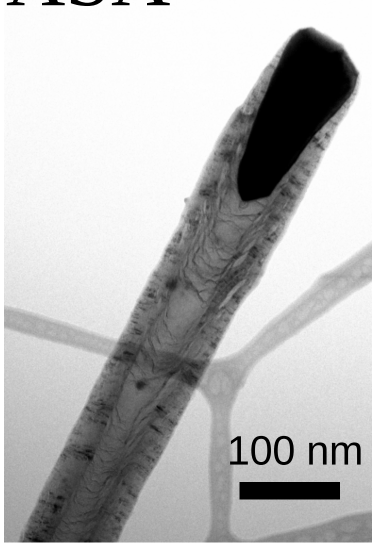


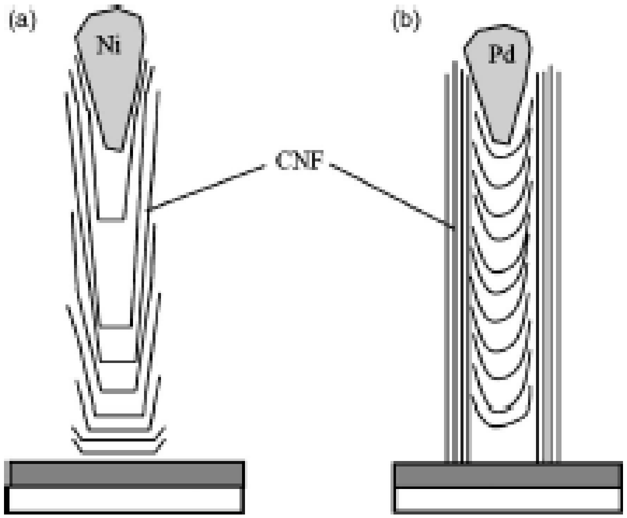
Kreupl *et al*. IEDM 2004

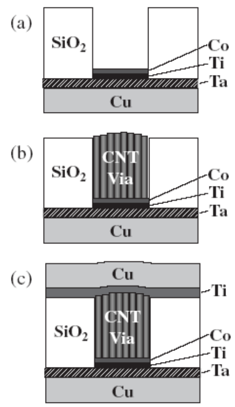
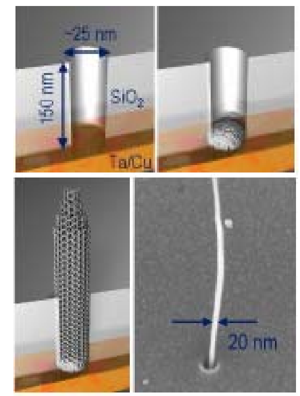
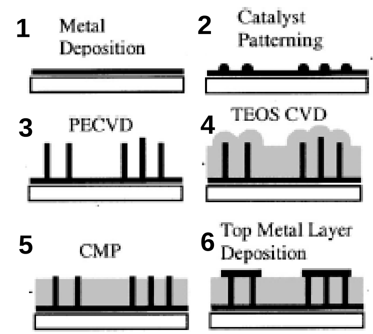
SCU & NASA

Ominami *et al*. Appl. Phys. Lett **87**, 233105 (2005)
Ngo *et al*. Elec. Dev. Lett **27**, 221 (2006)







Institute	Fujitsu	Samsung	Infineon	SCU & NASA
Material	MWNT bundles	MWNT bundles	Single MWNT	Single CNF
Fabrication process				
Via diameter [nm]	2000	700	20	50
Via height [nm]	350	1000	150-200	4000
R [Ω/via]	0.59	1.2 k	7.8 k	9 k (Pd), 13k (Ni)
Resistivity [Ω·cm]	2.1×10^{-3}	4.6×10^{-2}	1.4×10^{-3}	4.4×10^{-4}
Max. J [A/cm²/via]	$> 2 \times 10^{6}$	---	$> 5 \times 10^{8}$	$> 1 \times 10^{7}$
Reference	Nihei *et al.* Jpn. J. Apl. Phys. 44, 1626 (2005)	Choi *et al.* IEEE NANO 2006	Kreupl *et al.* in IEDM 2004	Ngo *et al.* IEEE Electron Device Lett. 27, 221 (2006)

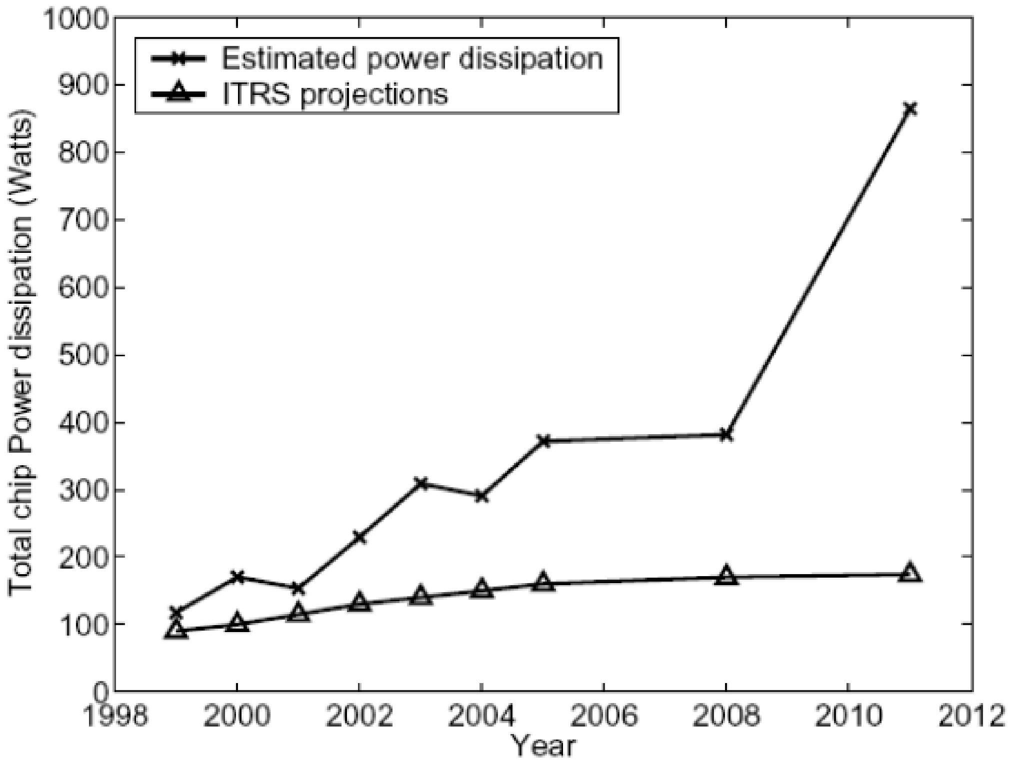
CNFs for Thermal Interface Materials (TIM)

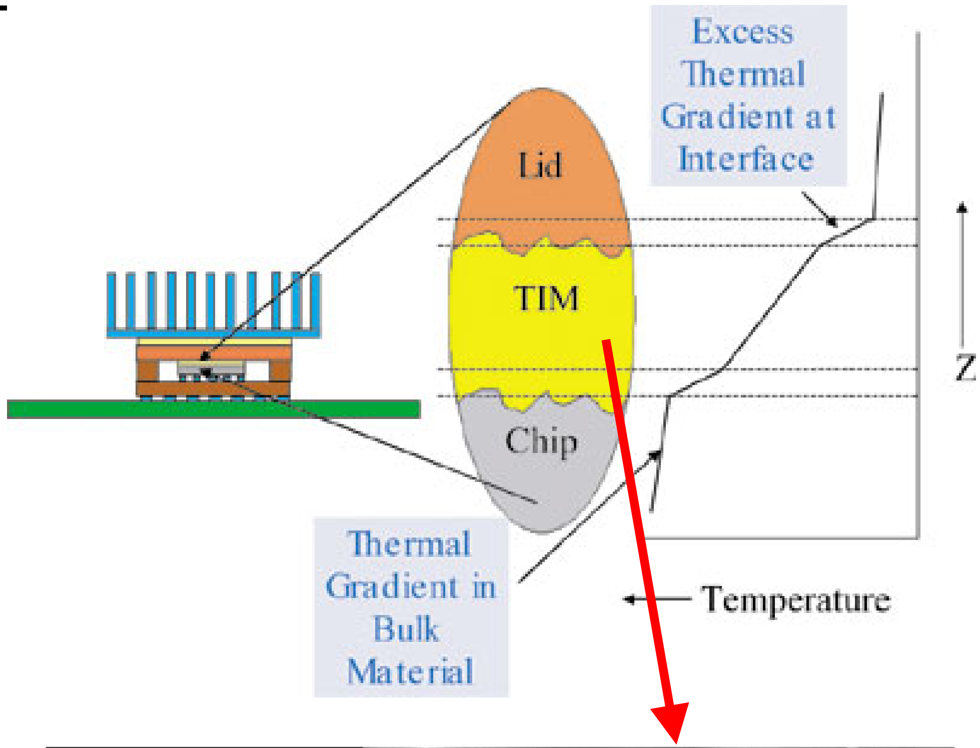
Collaborators: B. A. Cruden, J. Li, A. Cassell, M. Meyyappan
Center for Advanced Aerospace Materials and Devices,
NASA Ames Research Center, Moffett Field, CA

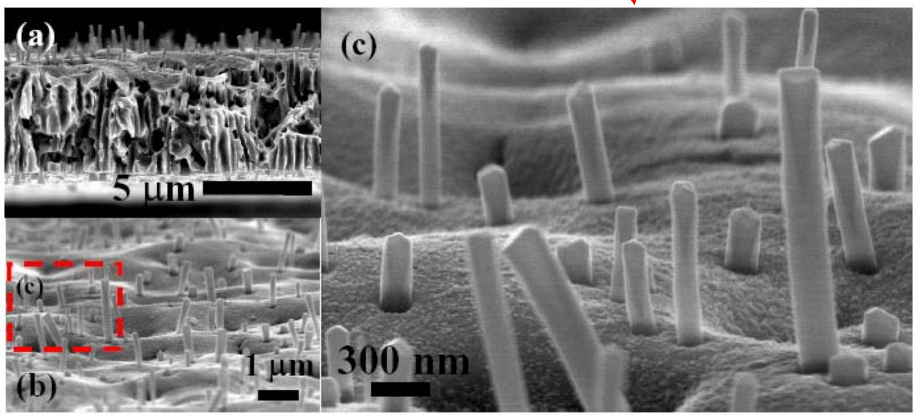
Collaborators: Y. Zhang
Nanoconduction Inc., Sunnyvale, CA

Need for new TIM

G. Chandra et al., IITC 2002



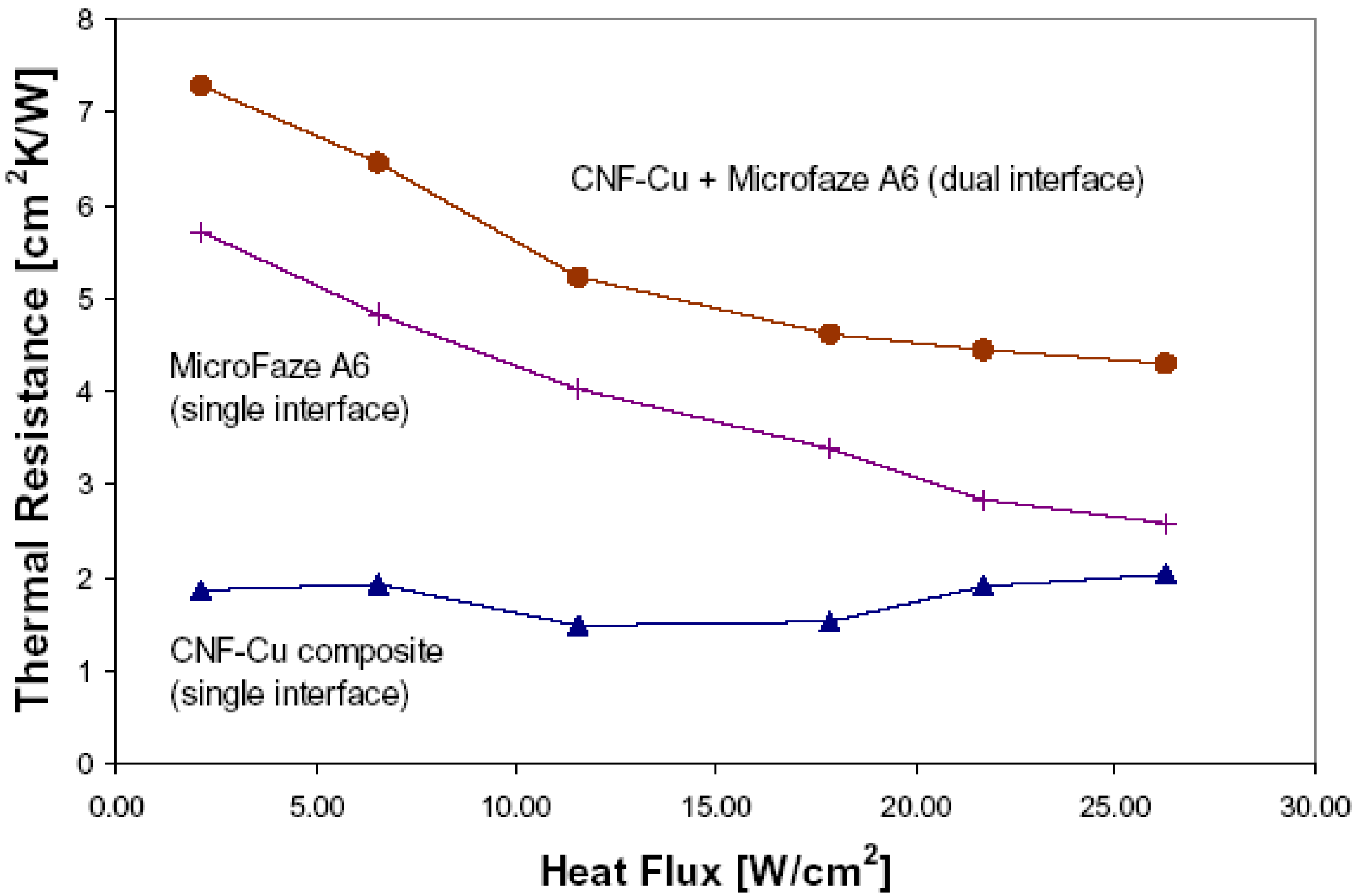




Ngo et al., *Nano Lett.* **4**, 2403 (2004)
Ngo et al., *Proc. ICCE-14* (2006)

Thermal Resistance of CNF-Cu Composite:

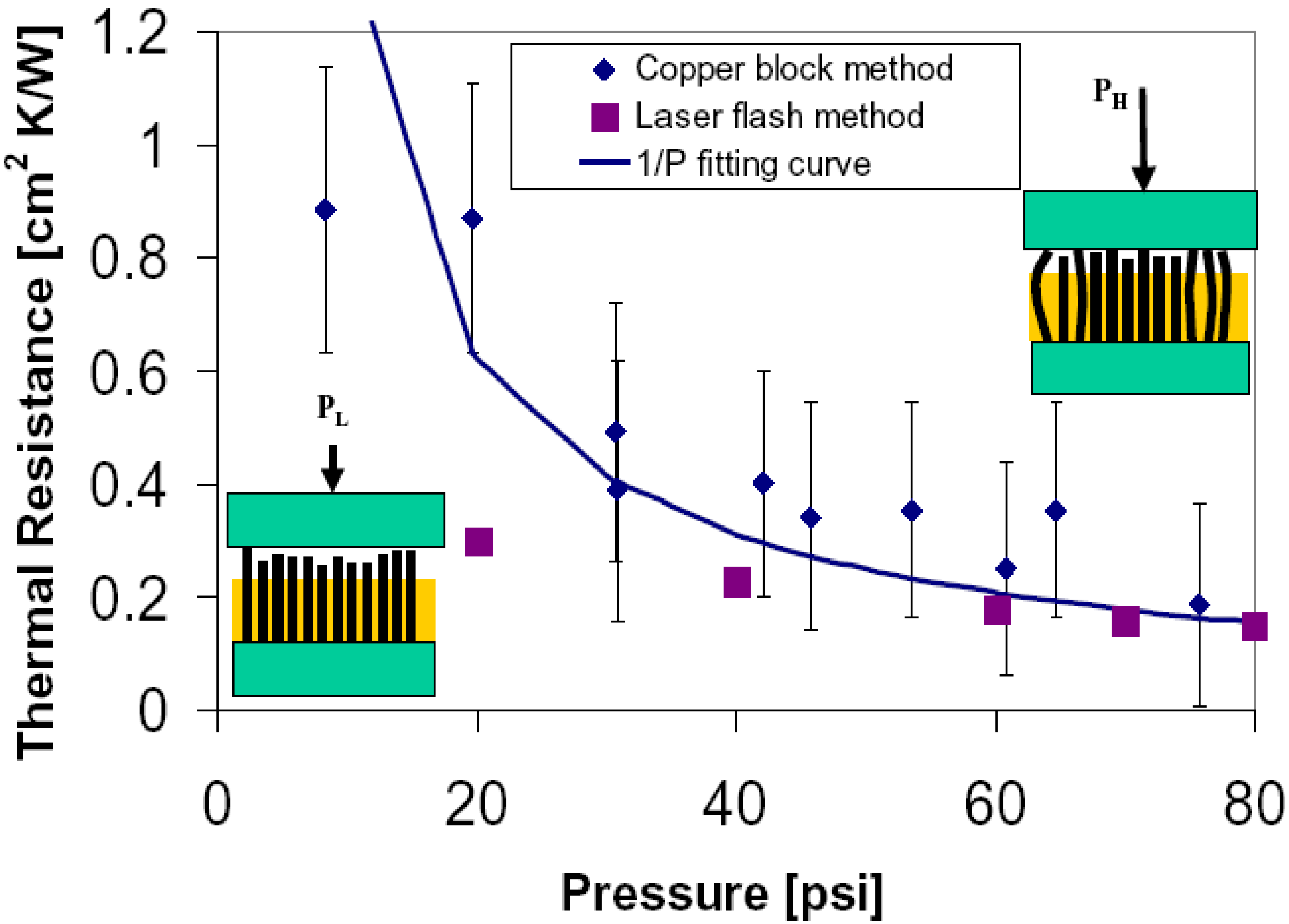
Power-cycling of CNF-Cu TIM



Ngo et al., *Nano Lett.* **4**, 2403 (2004)

Thermal Resistance of CNF-Cu Composite:

Pressure-dependence of CNF-Cu TIM



Continuing Work

- Design and fabrication of new CNF interconnect test structures
- Additional via reliability measurements at high temperature
- Optimization of CNF-Cu TIM for improved thermal resistance
- Electrothermal modeling of thermal effects on electrical characteristics of carbon nanodevices

Thank You!