Fabrication and Characterization of Sub-100 nm Carbon Nanotube Vias

Changjian Zhou[1], Anshul Vyas[2], Patrick Wilhite[2], Phillip Wang[3], Mansun Chan[1], and Cary Y. Yang[2]

[1]Hong Kong University of Science and Technology, Hong Kong

[2]Santa Clara University, Santa Clara, CA, USA

[3]Applied Materials Inc. Santa Clara, CA, USA

Outline

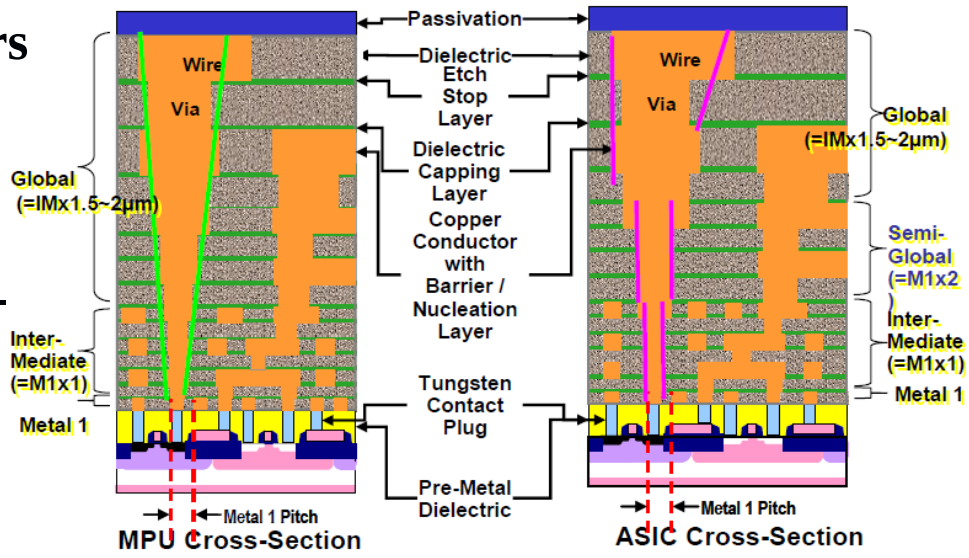
- Introduction
- CNT Via Test Structure
- Electrical Characterization
- Results and Discussion
- Summary

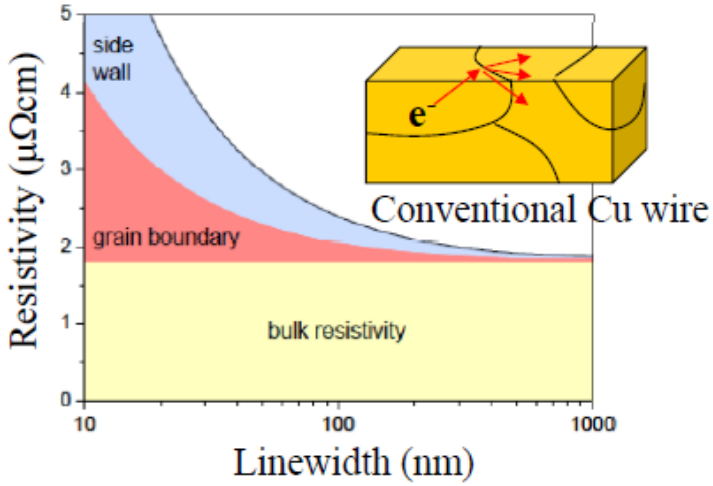
Outline

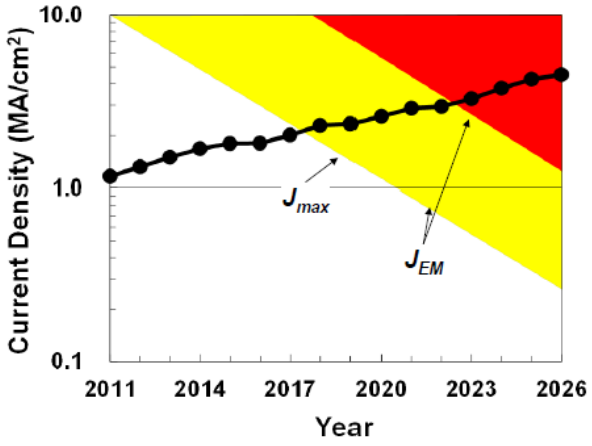
- Introduction
- CNT Via Test Structure
- Electrical Characterization
- Results and Discussion
- Summary

New interconnect materials needed

- **Current copper interconnect suffers from electromigration at current density ~ 1 MA/cm^2**
- **Increase of resistivity due to width-dependent scattering**

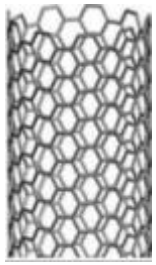
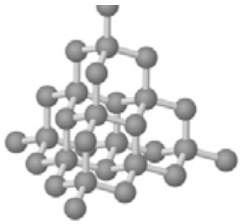
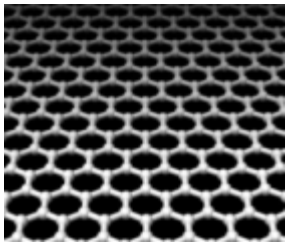
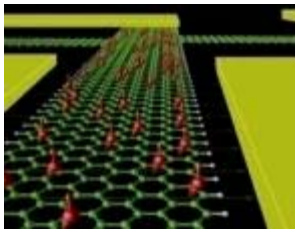






Source: ITRS 2011

Nanocarbons

~2000

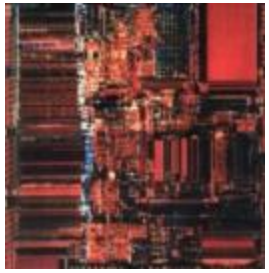
~1960

~1947

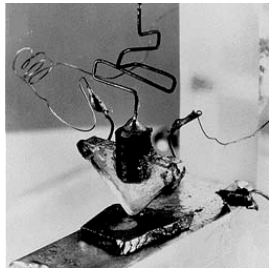
5	6	7
2 3	2 4	2 5
B	C	N
Boron	Carbon	Nitrogen
10.811	12.0107	14.00674

13	14	15
2 8 3	2 8 4	2 8 5
Al	Si	P
Aluminum	Silicon	Phosphorus
26.981538	28.0855	30.973761

31	32	33
2 8 18 3	2 8 18 4	2 8 18 5
Ga	Ge	As
Gallium	Germanium	Arsenic
69.723	72.64	74.92160



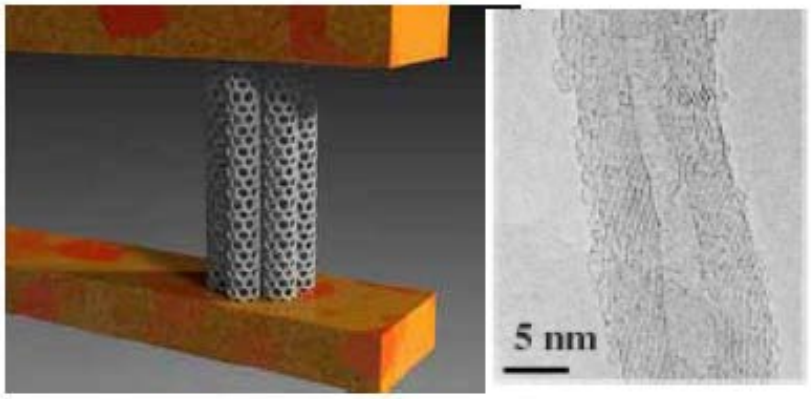
Intel CPU



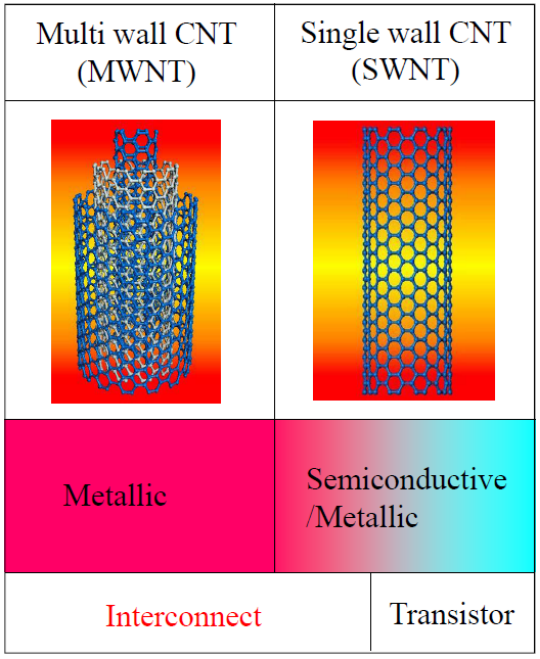
The first transistor

Nanocarbons as Interconnect Materials

- **Physical properties of CNT:**
  - **High current carrying capability**
    $> 10^7$ A/cm^2 (Cu ~ 10^6 A/cm^2) ⟹ Electromigration resistant
  - **High mobility and ballistic transport (6.45 KΩ/shell) ⟹ Low resistance**
  - **High thermal conductivity ~3000 W/K.m (Cu ~ 400 W/K.m)**



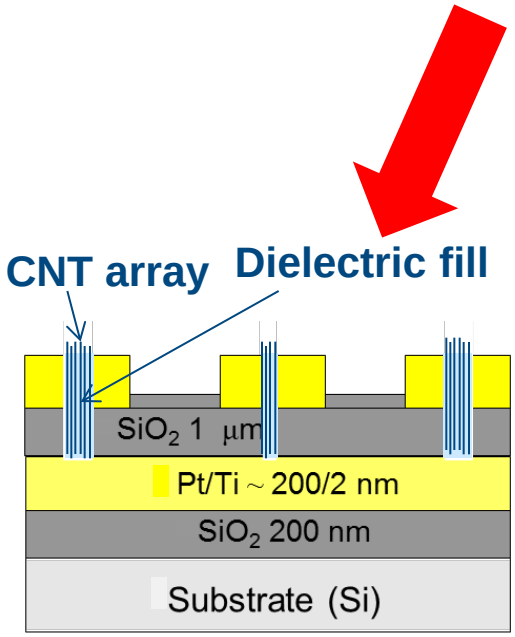
Nihei *et al*. Jpn. J. Apl. Phys. **44**, 1626 (2005)



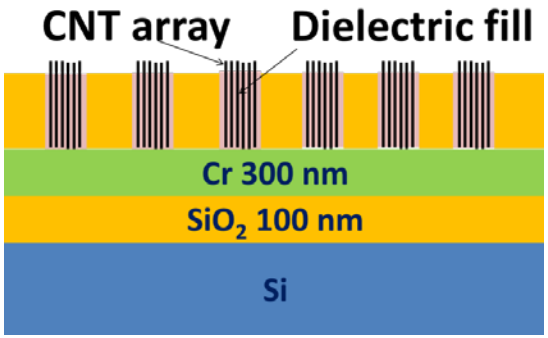
Objective and Approach

- **Objective**: To determine electrical characteristics of CNT on-chip via interconnects as a potential replacement for Cu.

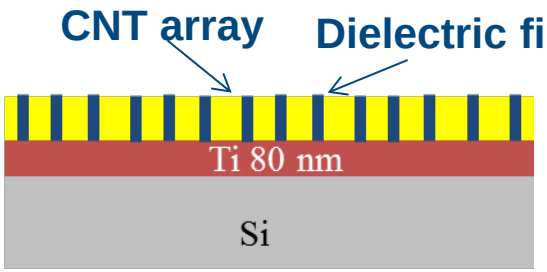
CNT Via Interconnect Analysis for Advanced Nodes



Sub-1000 nm vias



Sub-150 nm Vias

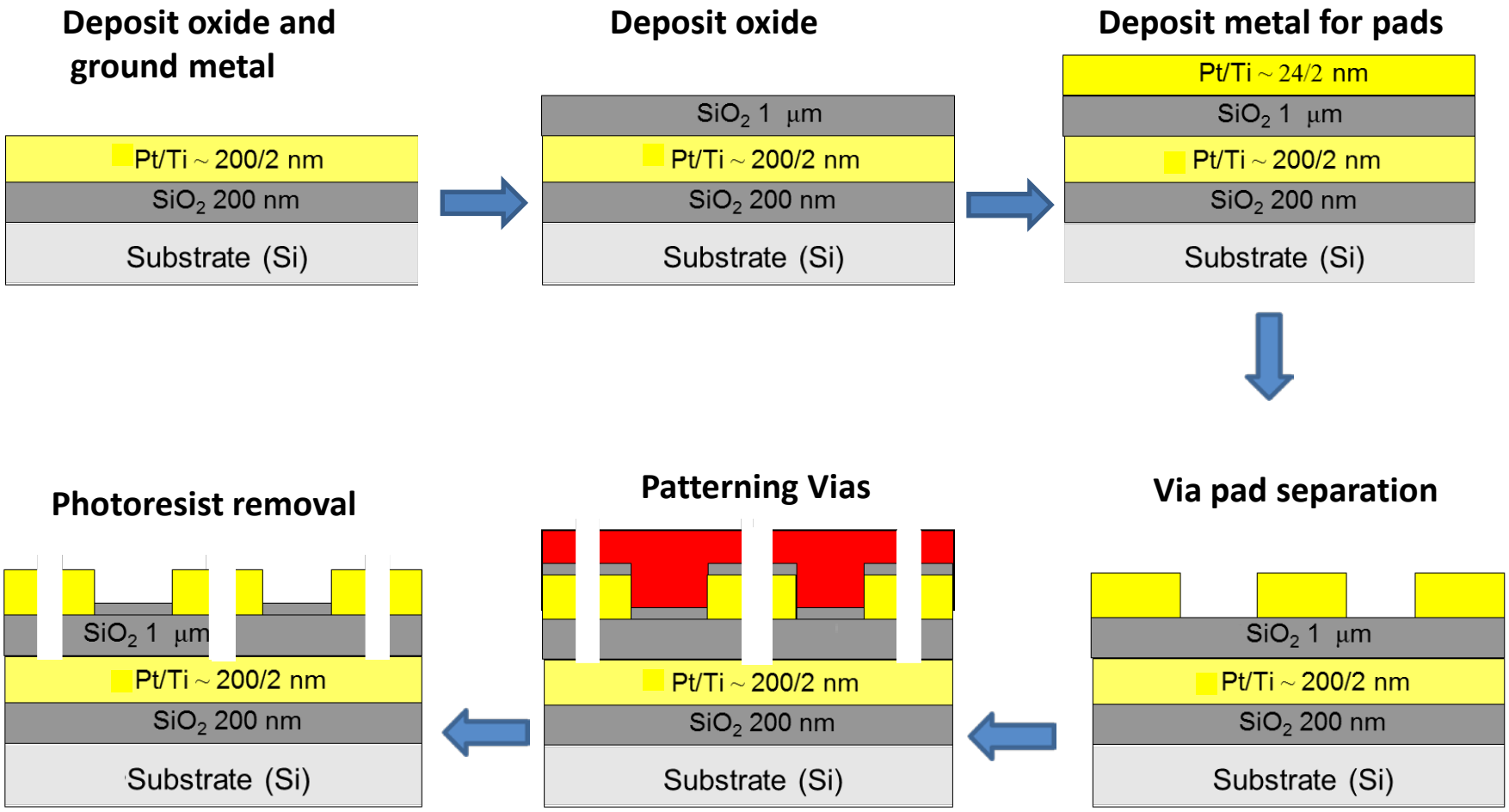


Individual CNTs

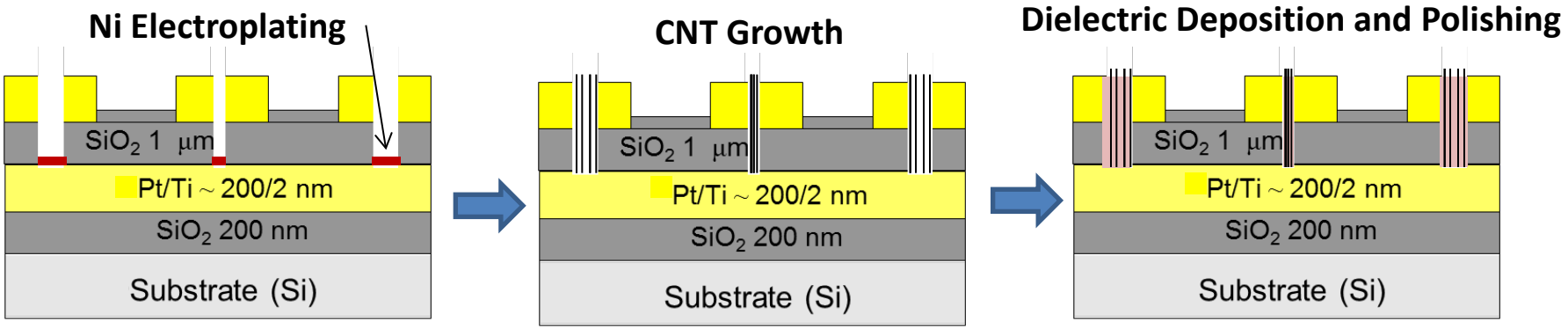
Outline

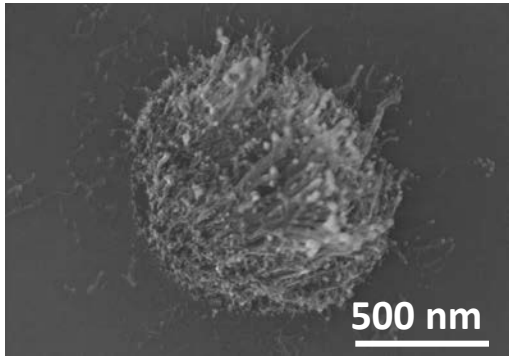
- Introduction
- **CNT Via Test Structure**
- Electrical Characterization
- Results and Discussion
- Summary

Fabrication of Sub-1000 nm Vias

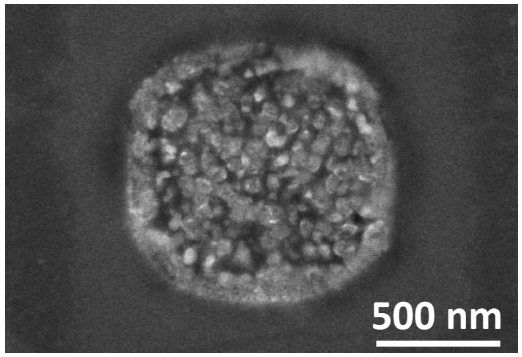


Fabrication of Sub-1000 nm Vias



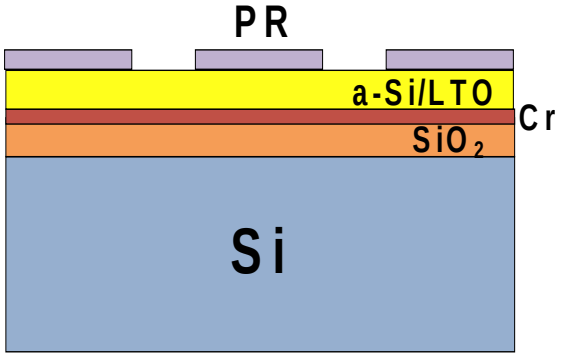


SEM image after CNT growth

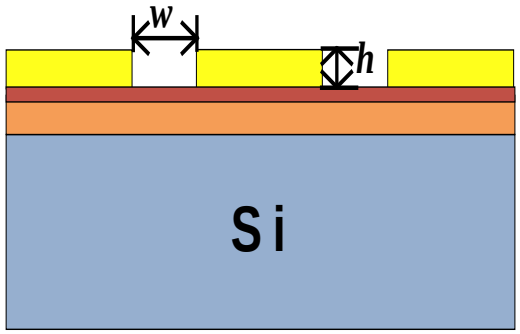


SEM image after polishing

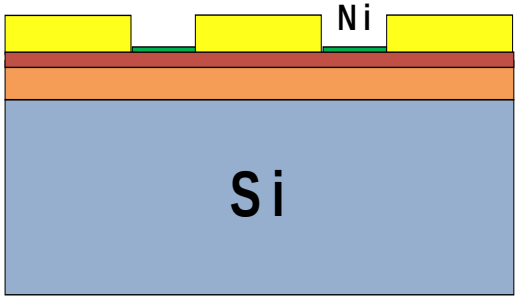
Fabrication of Sub-150 nm Vias



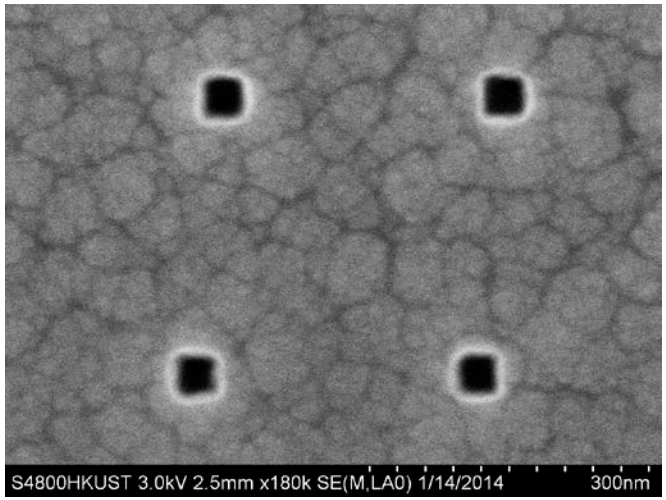
(a) Via patterning

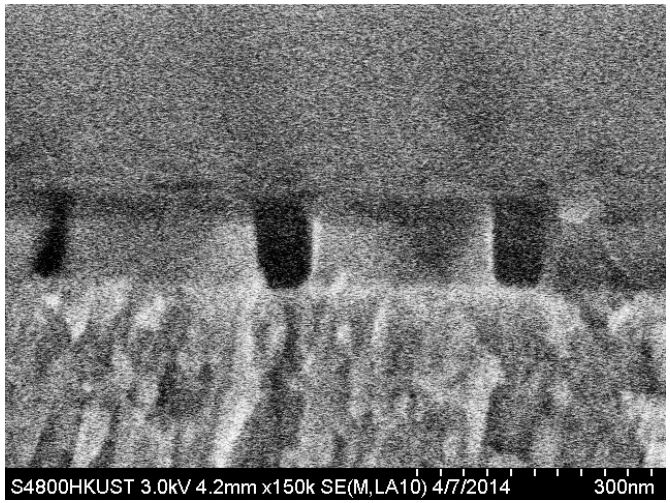


(b) Dry etching and PR removal



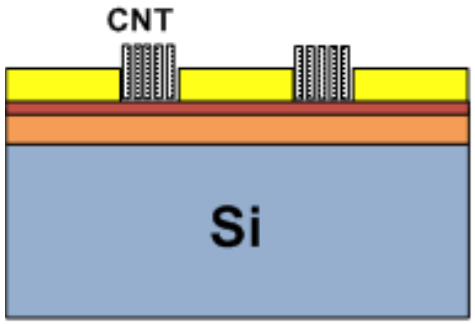
(c) Catalyst deposition and polishing



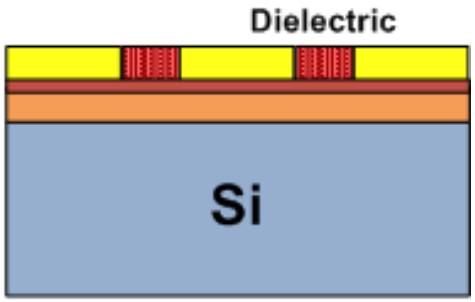


Top-view and cross-sectional SEM image of 60 nm vias for CNT growth

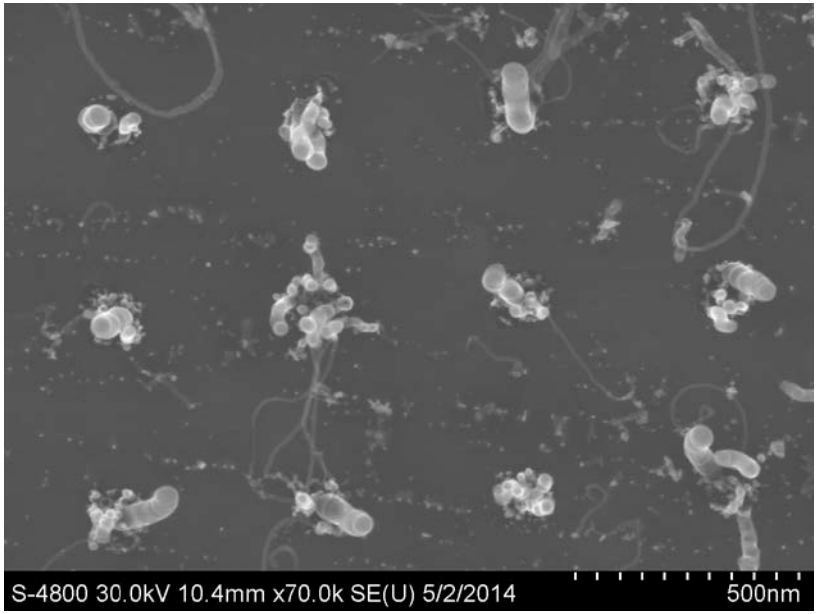
Fabrication of Sub-150 nm Vias

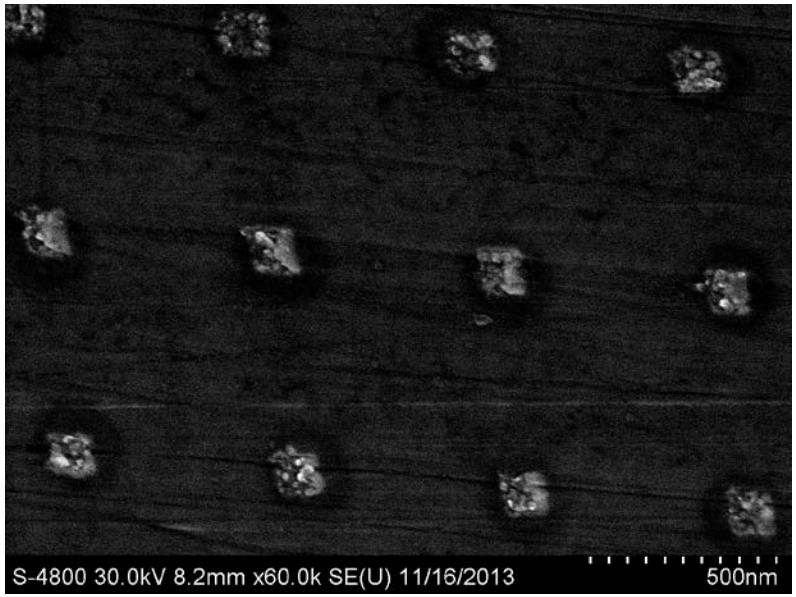


(4) CNT growth



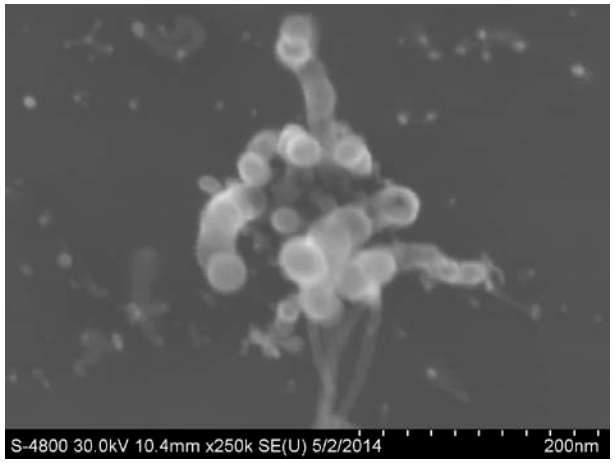
(5) Dielectric filling and CMP





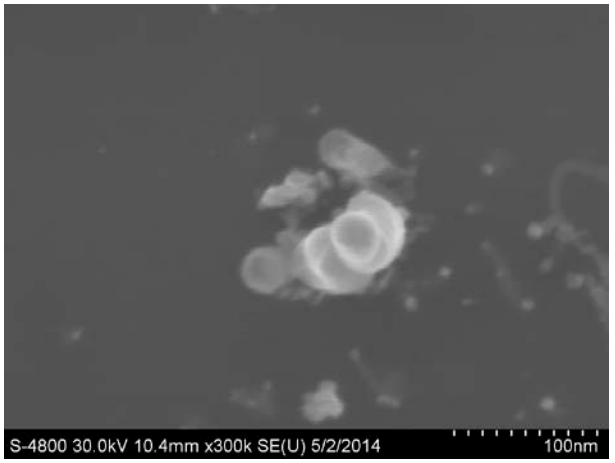
Fabrication of Sub-150 nm Vias

- **Estimation of CNT areal density in via, D_{CNT}**



90 nm CNT via

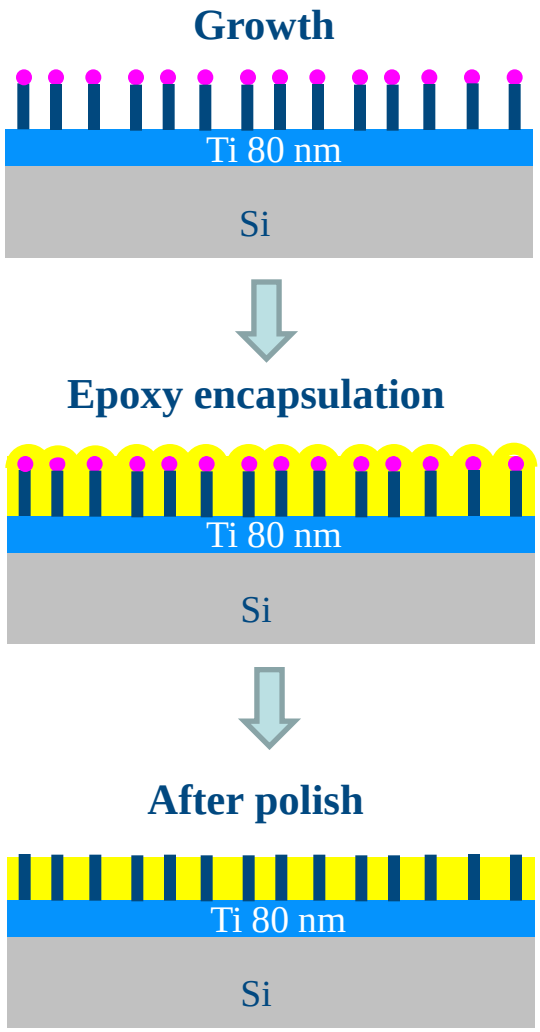
~2.2×10^{11}/cm^2

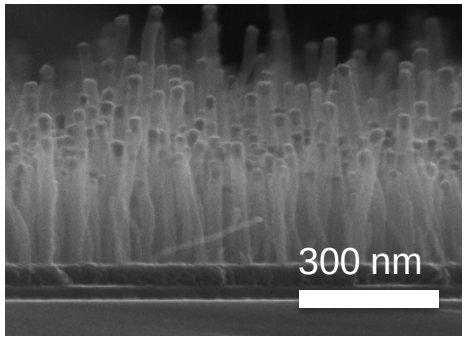


60 nm CNT via

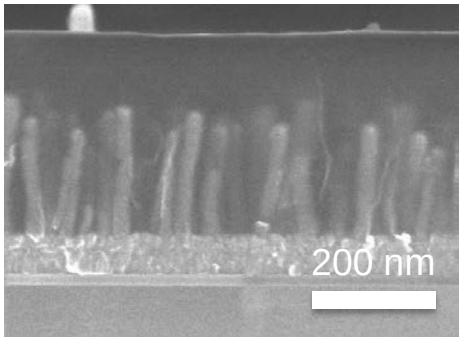
~1.7×10^{11}/cm^2

Fabrication for Individual CNT Probing

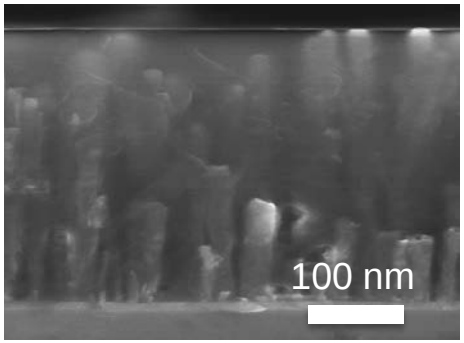




CNT grown on Ti/Si



After encapsulation & partial polish



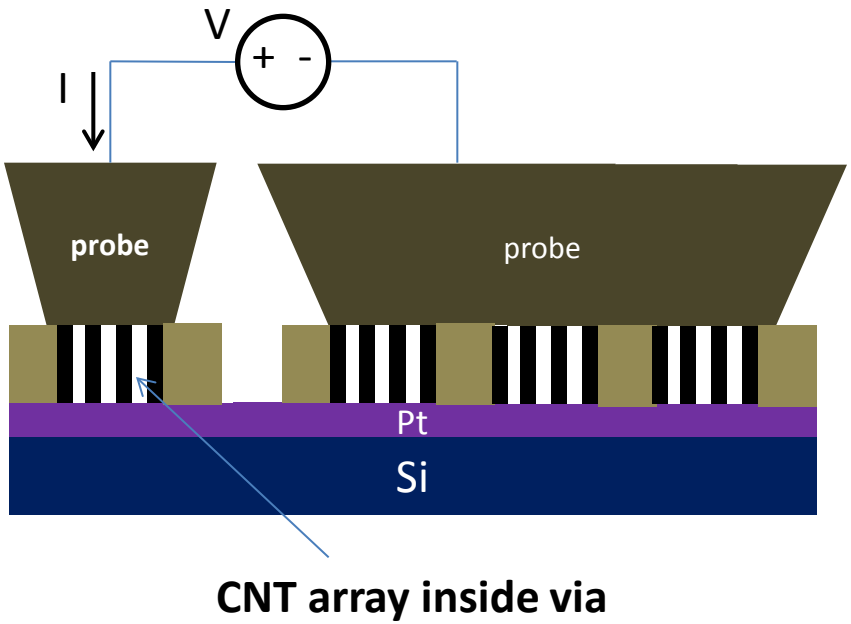
After final polish

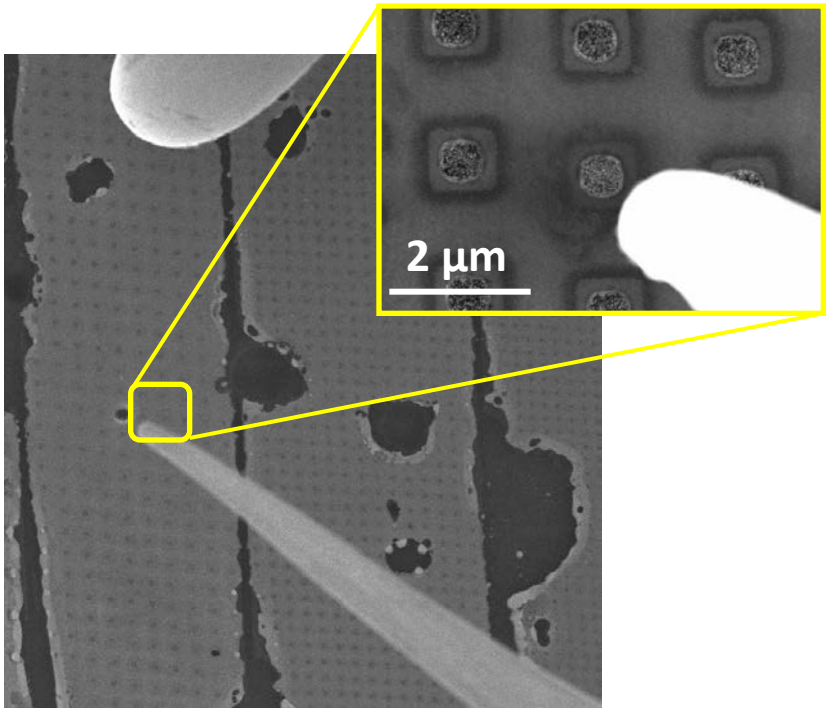
Outline

- Introduction
- CNT Via Test Structure
- **Electrical Characterization**
- Results and Discussion
- Summary

Measurement setup for Single CNT Via

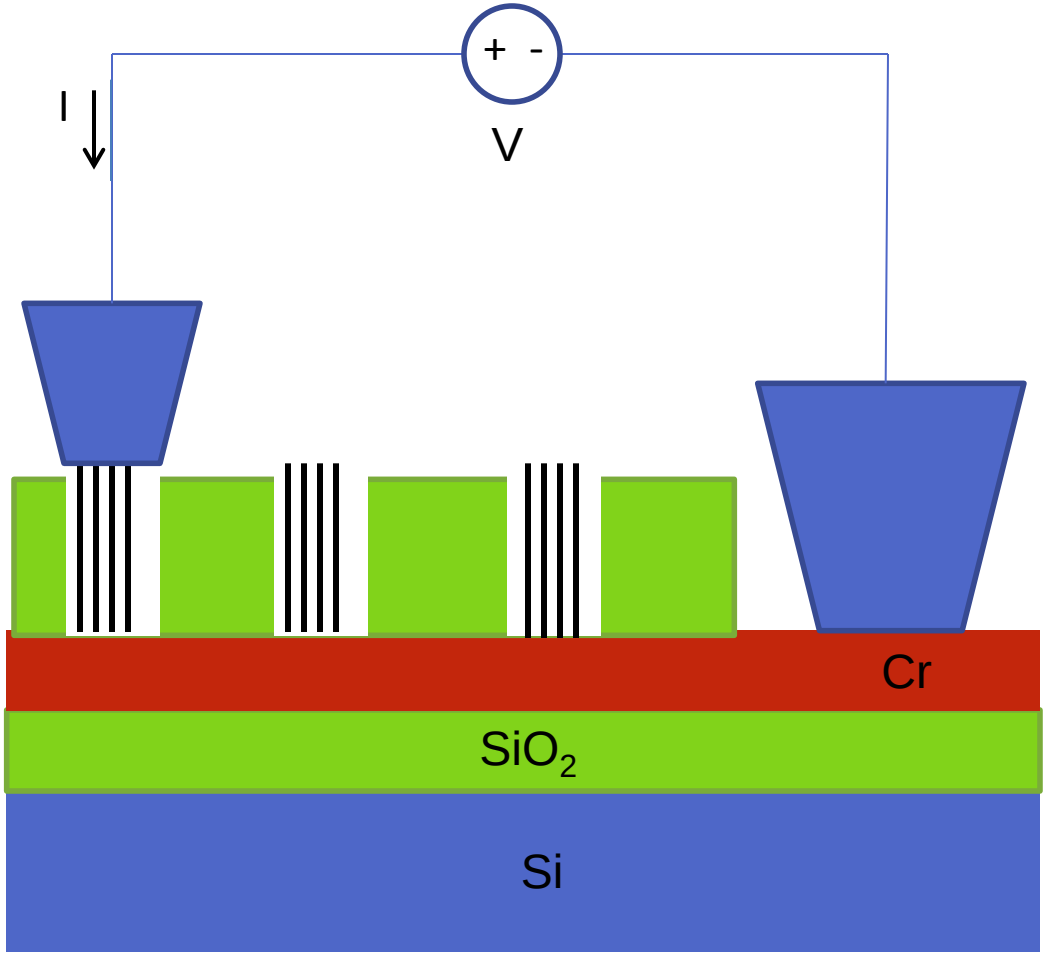
- ***In situ* nanoprobing inside SEM**
  - **Sub-1000nm CNT via**

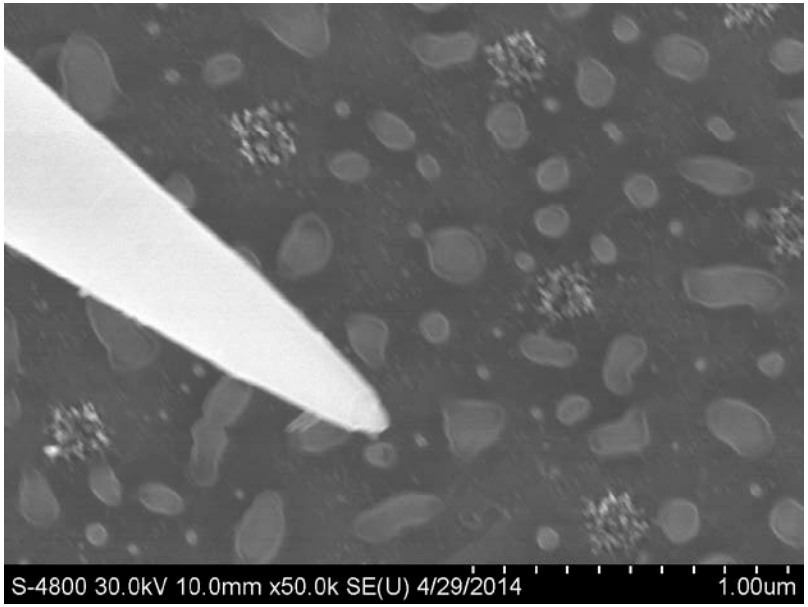




Measurement setup for Single CNT Via

- ***In situ* nanoprobing inside SEM**
  - **Sub-150nm CNT via**



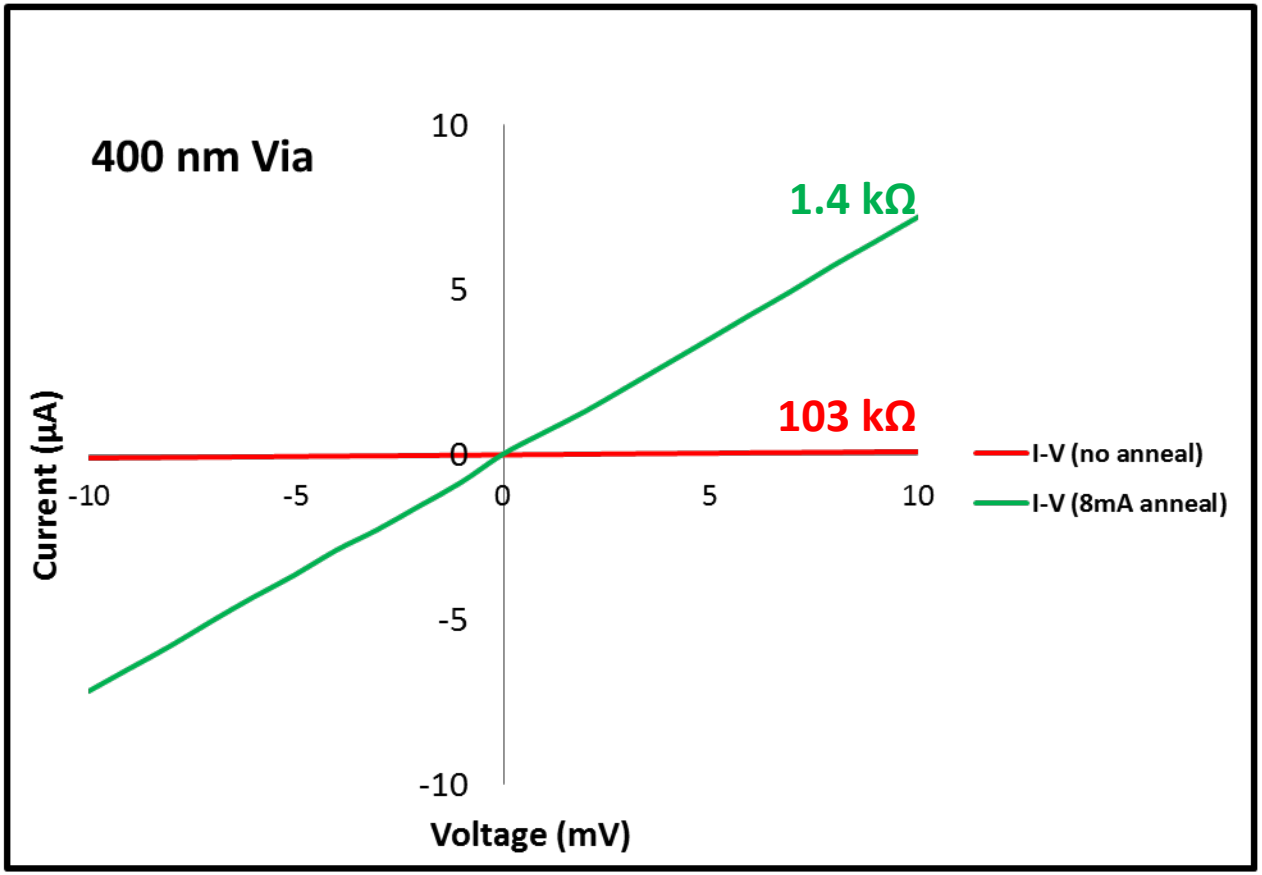


Probing a single CNT Via

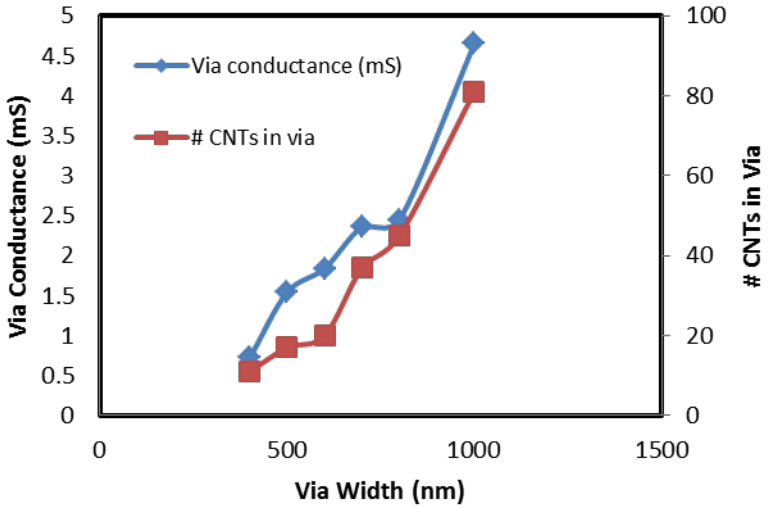
Outline

- Introduction
- CNT Via Test Structure
- Electrical Characterization
- **Results and Discussion**
- Summary

Electrical Characteristics of Sub-1000 nm Vias

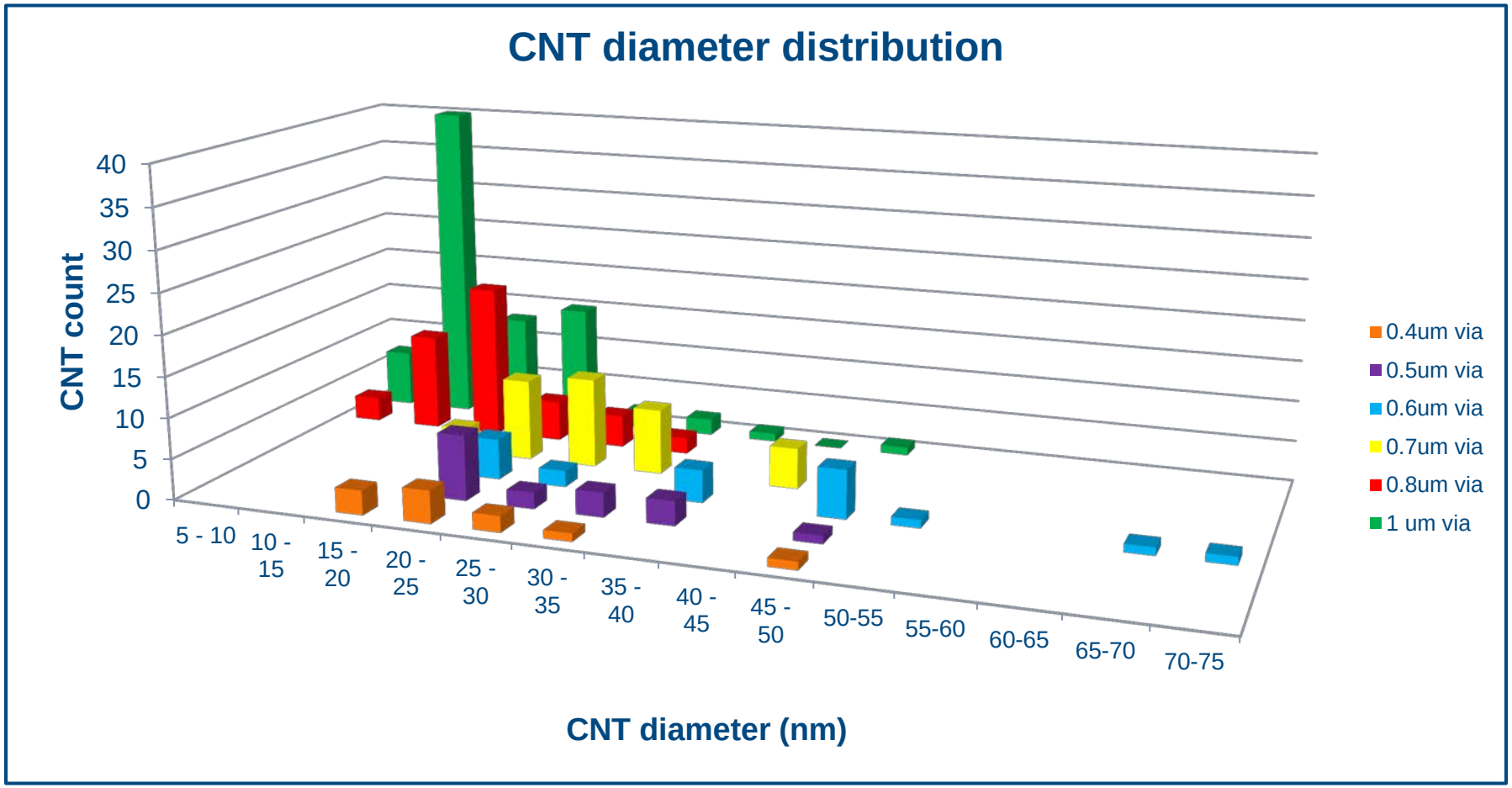


Electrical Characteristics of Sub-1000 nm Vias

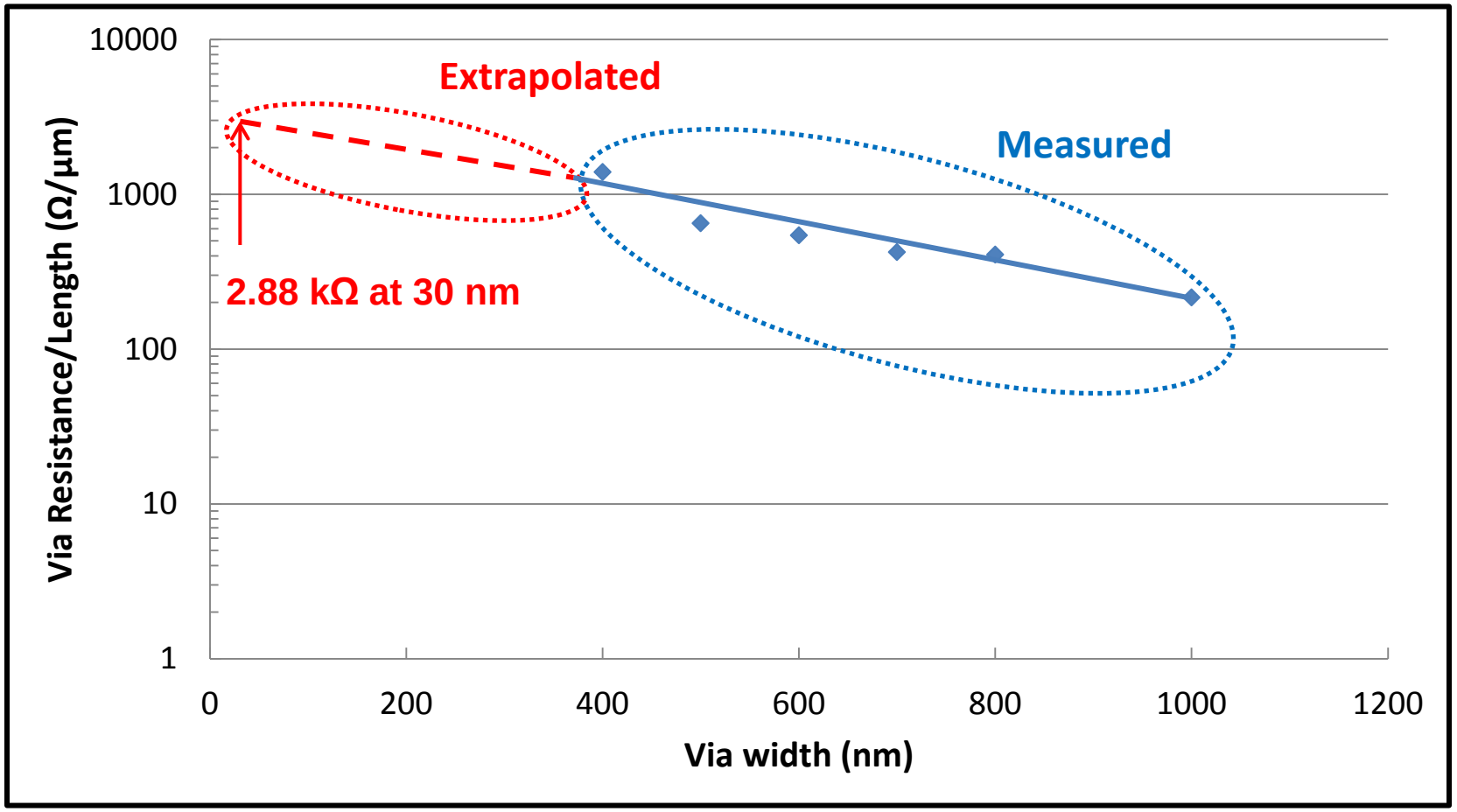


Via width (nm)	Via height (nm)	CNT diameter (nm)	# CNTs in via	CNT packing density (cm^{-2})	Via resistance (Ω)	Via conductance (mS)
1000	1000	16.56	81	8.10E+09	215	4.65
800	1000	17.74	45	7.03E+09	408	2.45
700	1000	27.85	37	7.55E+09	423	2.36
600	1000	39.44	20	5.56E+09	543	1.84
500	1000	29.29	17	6.80E+09	649	1.54
400	1000	26.05	11	6.88E+09	1394	0.72

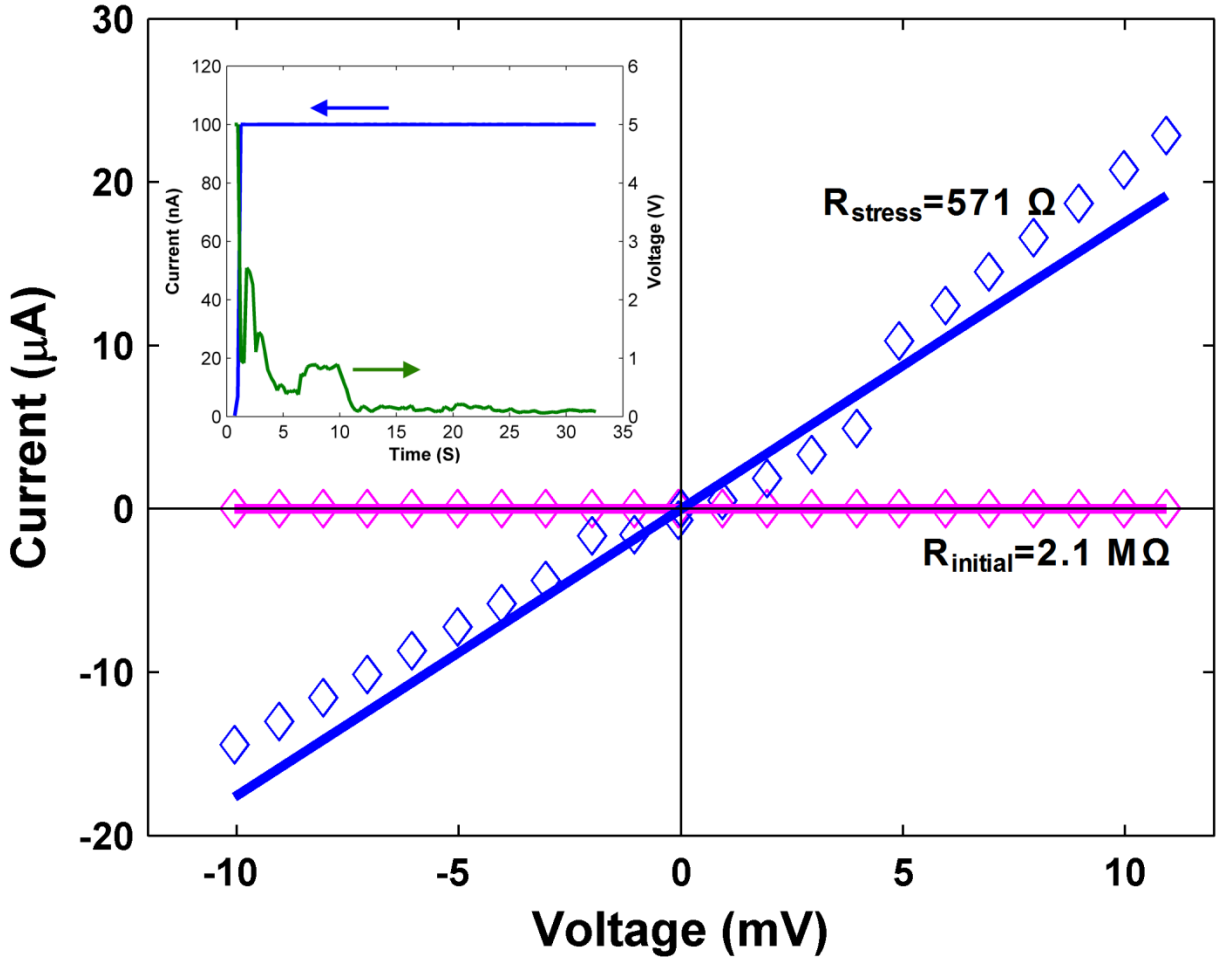
CNT diameter distribution in Sub-1000 nm Vias



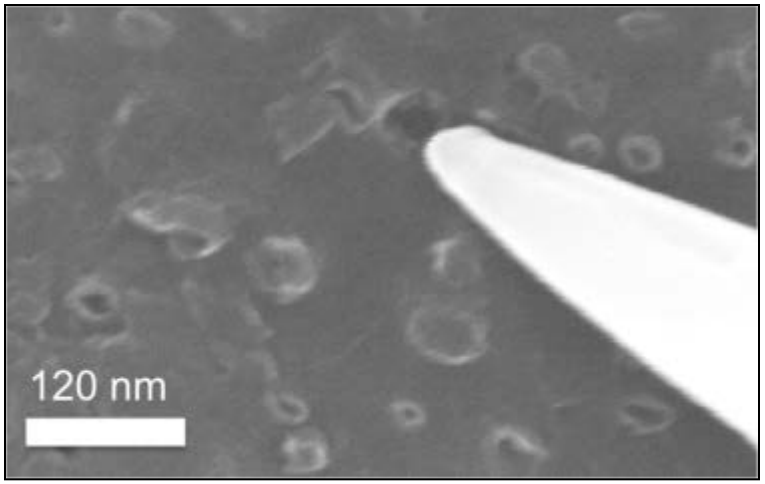
Projected resistance from Sub-1000 nm Vias

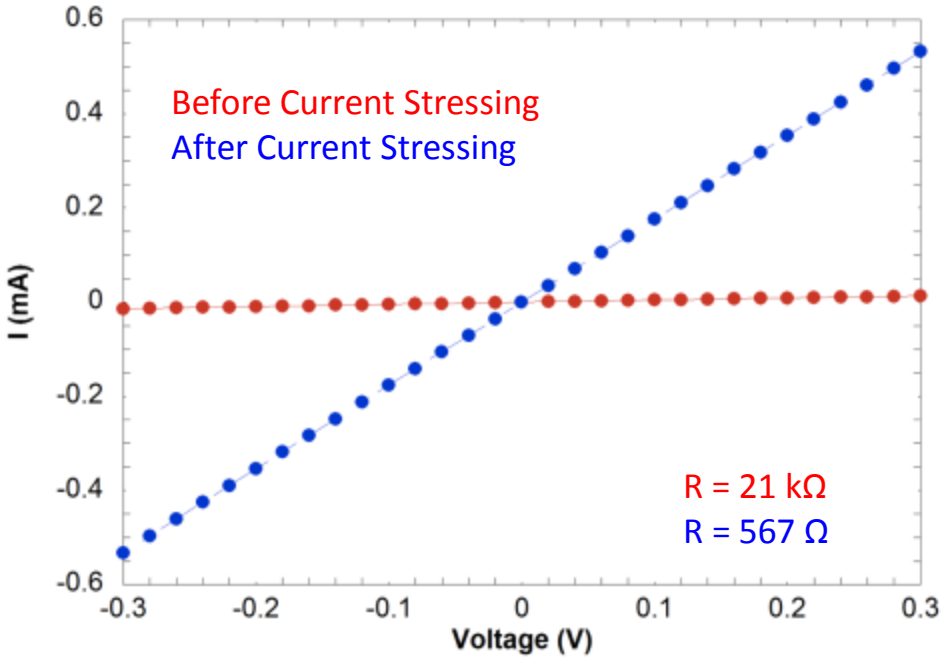


Electrical Characteristics of a 60 nm Via



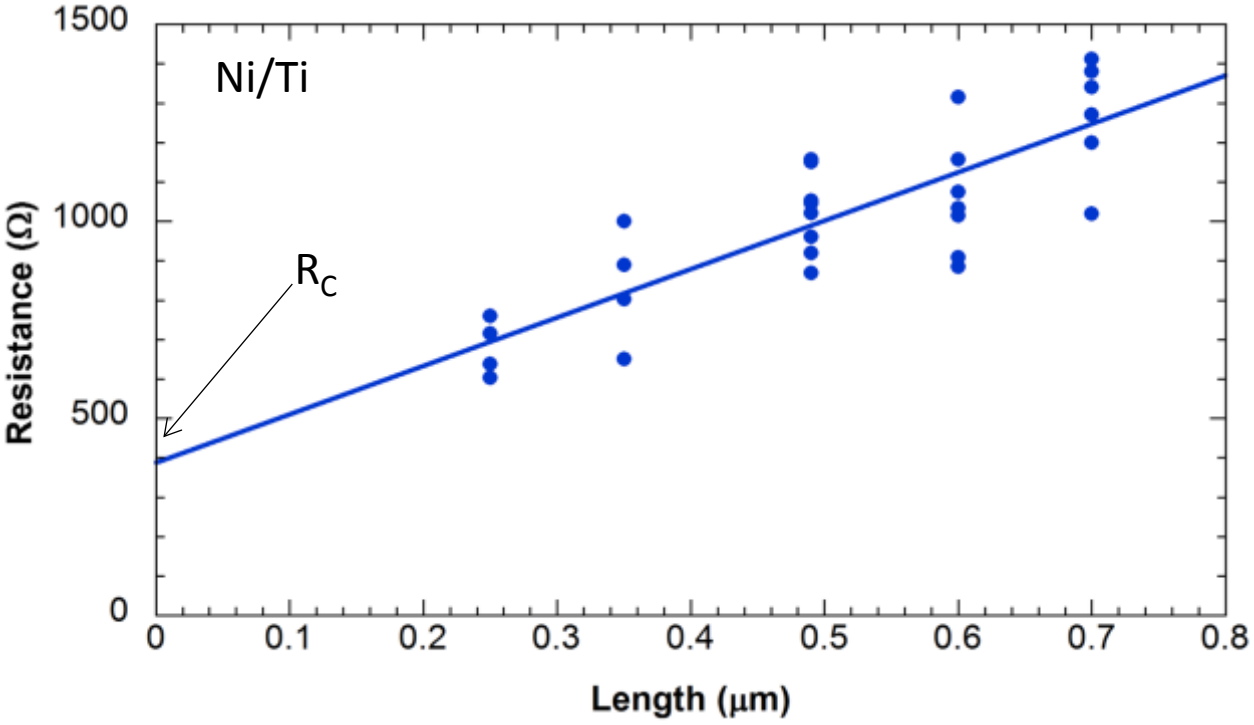
Electrical Characteristics of Single CNT





- **W-probe enlarges during probing**
- **High-current annealing (~3.5 mA) improves probe contact**

Electrical Characteristics of Single CNT

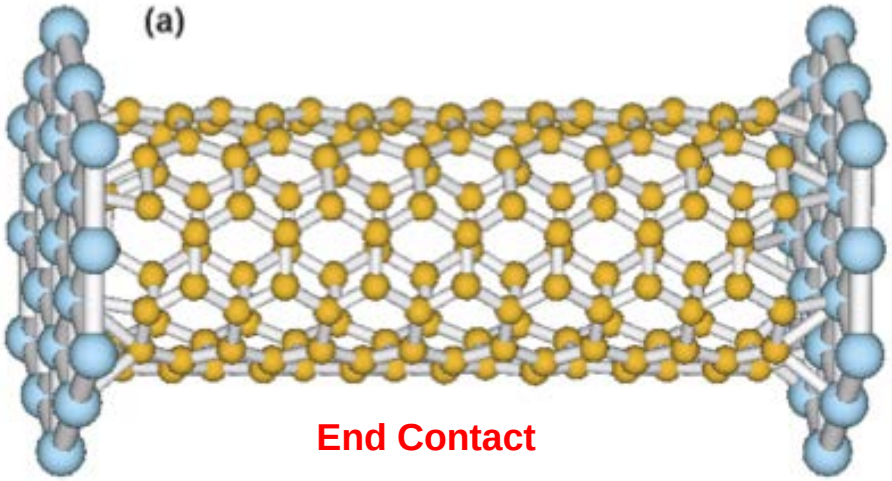


ρ (Ω-cm)	R_C (Ω)
2.4×10^{-4}	388

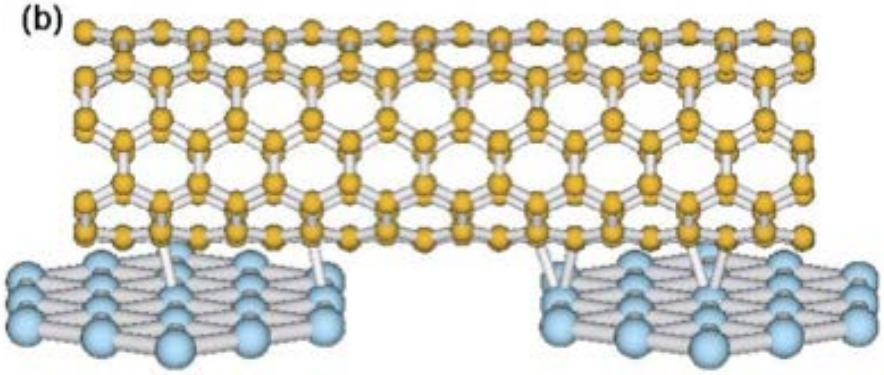
Diameter of probed samples: ~50 nm

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

Further Consideration – Metal-CNT Contact



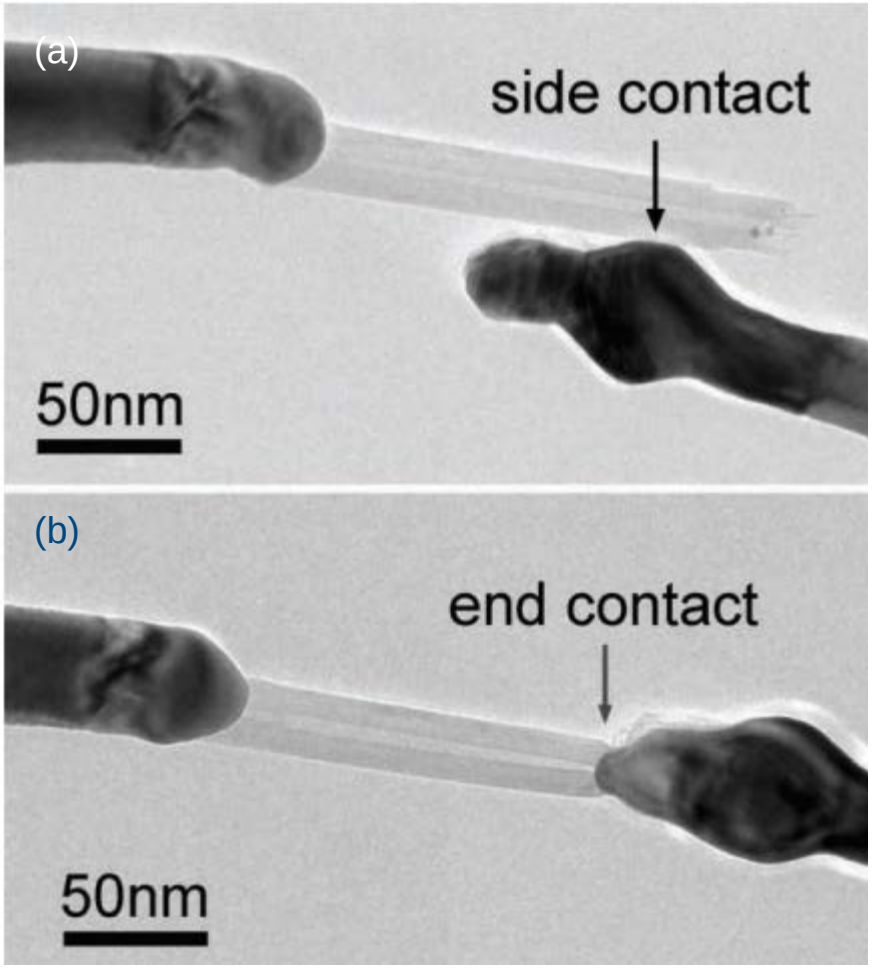
End Contact

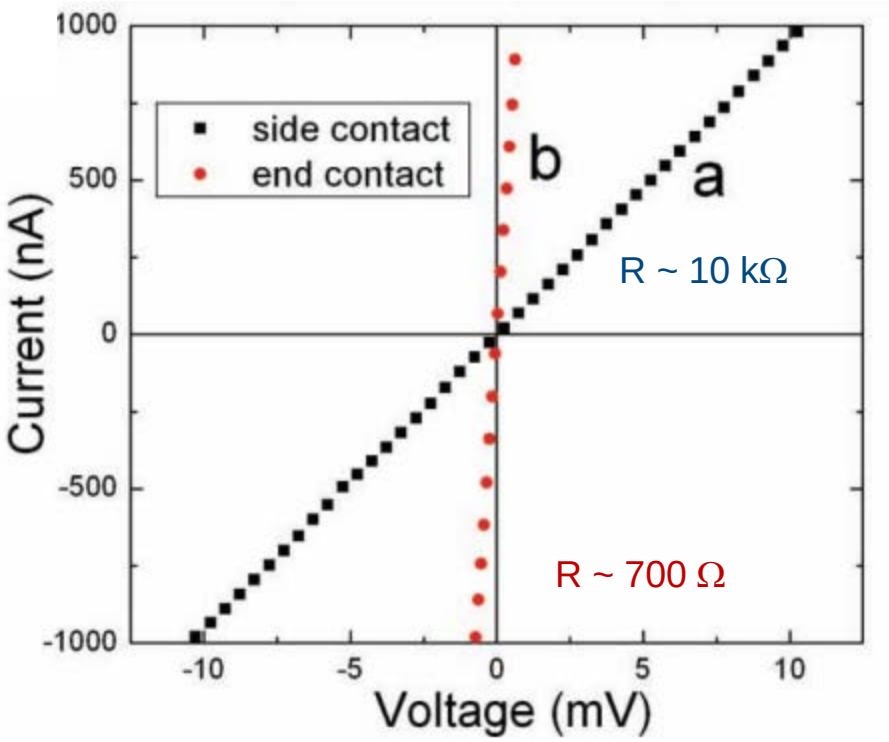


Side Contact

- **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

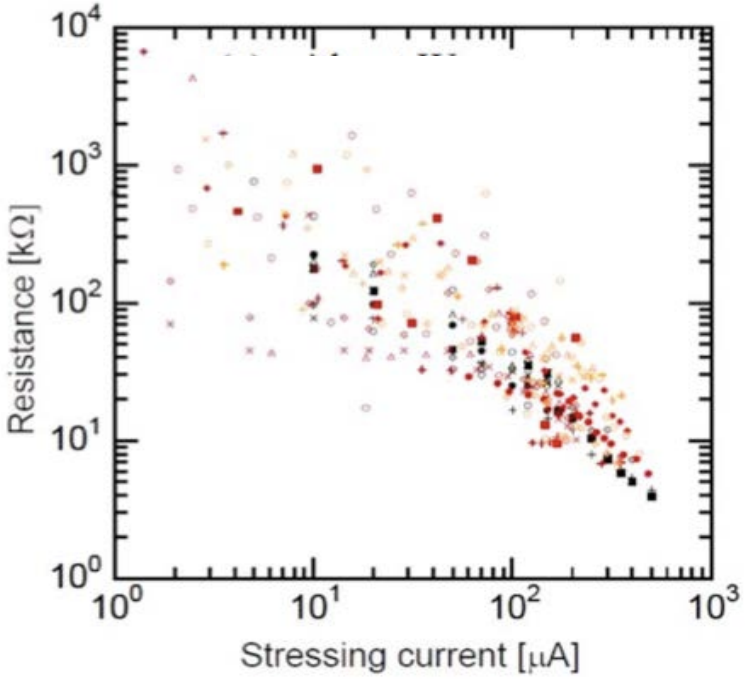
Side and End Contacts



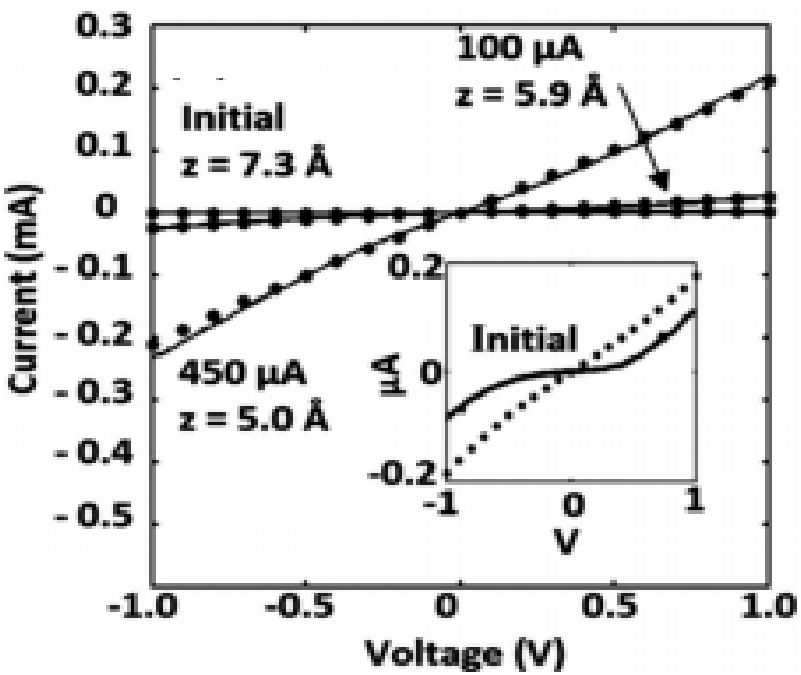


Wang *et al.*, *Adv. Mater.* **22**, 5350 (2010)

Contact improvement – Joule Heating



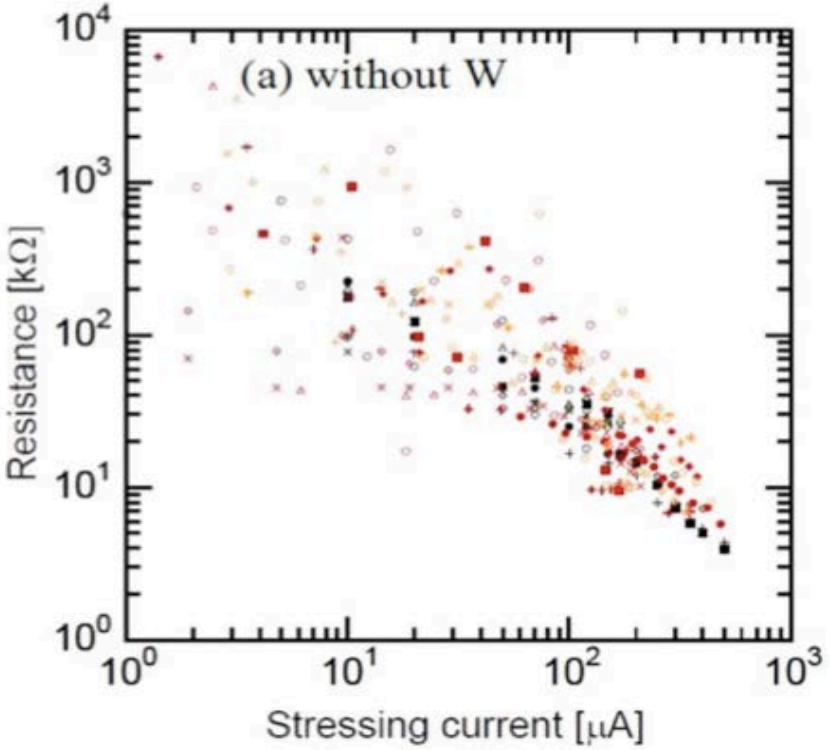
Kitsuki *et al, APL* **92**, 173110 (2008)



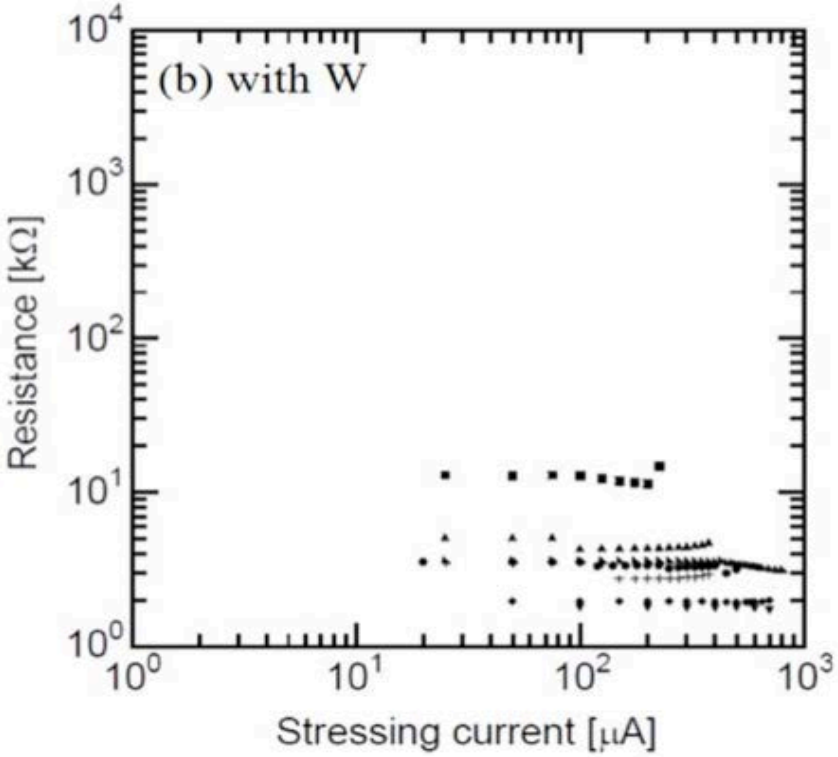
Yamada *et al, JAP* **107**, 044304 (2010)

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

Contact improvement – Deposited Tungsten



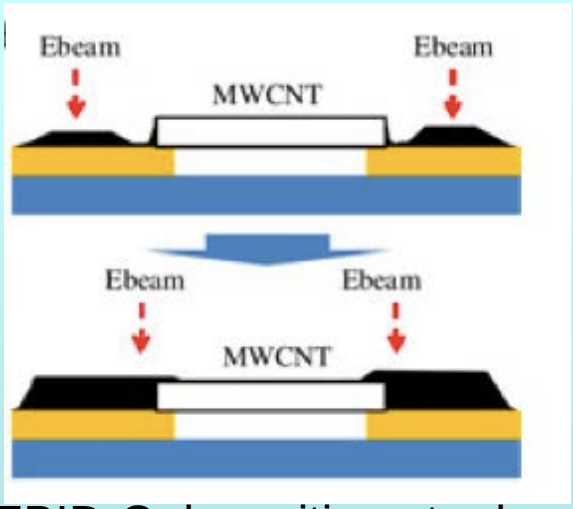
Kitsuki *et al, APL* **92**, 173110 (2008)



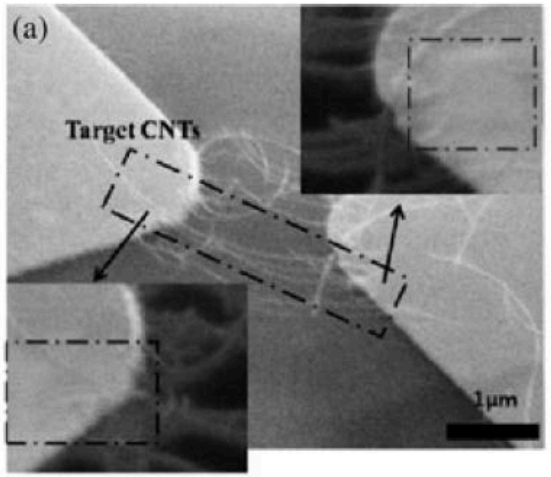
Saito *et al, APL* **93**, 102108 (2008)

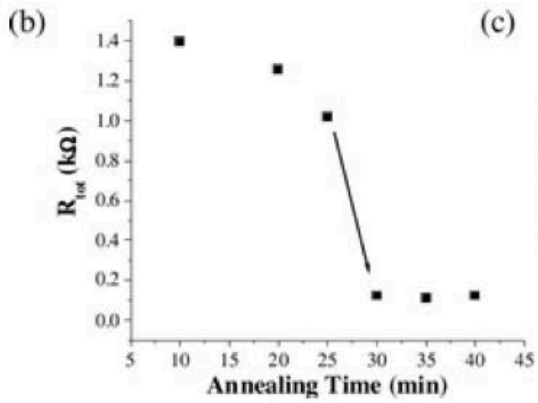
- **Resistance with W-deposited contacts reduced significantly and independent of stress current**
- **Contact resistance minimized**

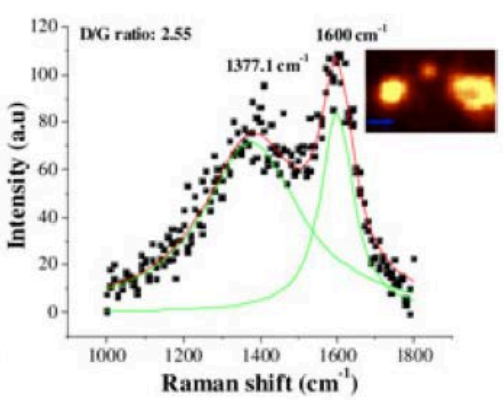
Contact improvement – EBID-C + Joule Heating



EBID-C deposition at edges







Total resistance reduced from 300 kΩ to 116 Ω

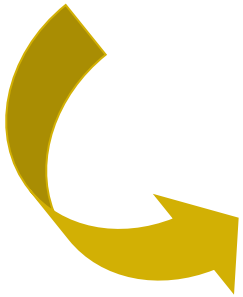
Kim *et al, IEEE Trans Nanotech.* **11**, 1223 (2012)

Outline

- Introduction
- CNT Via Test Structure
- Electrical Characterization
- Results and Discussion
- **Summary**

Summary

- CNT vias down to 60 nm width fabricated and characterized
  - Linear I-V characteristics for vias and individual CNTs
  - "Best" projected resistance for 30 nm CNT via ~ 5 x W via resistance
- Ongoing efforts to decrease CNT diameter and increase CNT packing density to reduce via resistance
- Additional contact engineering needed to reduce overall resistance
- Further considerations on contact resistance reduction with CNT growth process improvements



Thank You…