# Contact Improvement using E-beam and FIB-deposited tungsten in carbon nanofiber interconnects

Patrick Wilhite, Nobuhiko Kanzaki, Shusaku Maeda,Toshishige Yamada, and Cary Y. Yang

# Outline

- Background and motivation
- Comparison of CNF measurements between e-beam and FIB-deposited W contacts
- Measurement of CNF resistivity using 4PP
- Comparison of CNF resistance change in ambient and in vacuum
- Summary

# Motivation

**Resistivity concerns**

- As scaling trends continue, Cu interconnect resistance increases exponentially with decreasing line-width due to
  - Grain boundary scattering
  - Surface scattering

**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

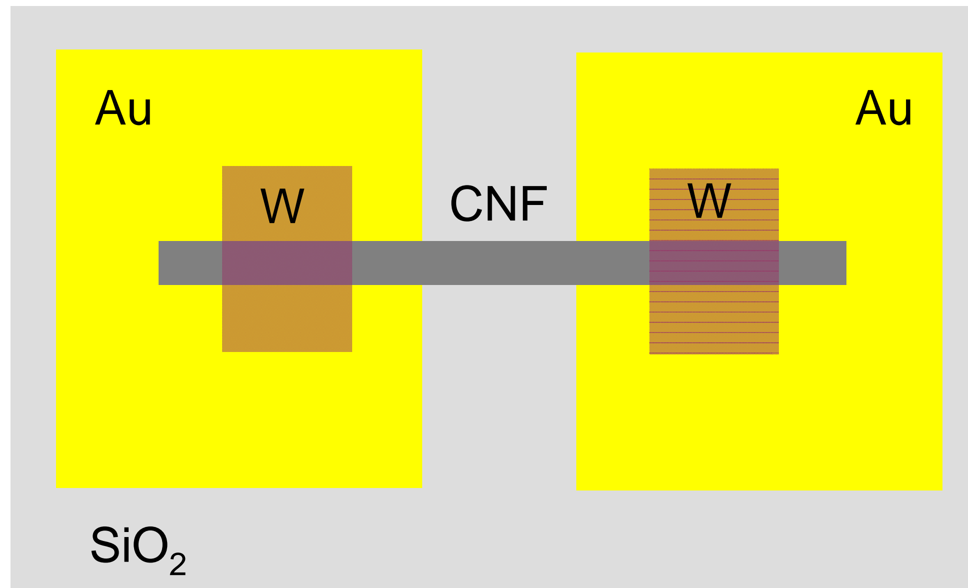
**Power concerns**

- As packing density and frequency of IC components increase, excessive power dissipation is becoming a reliability concern

New interconnect materials are needed

Carbon to replace Cu?

# CNF test device

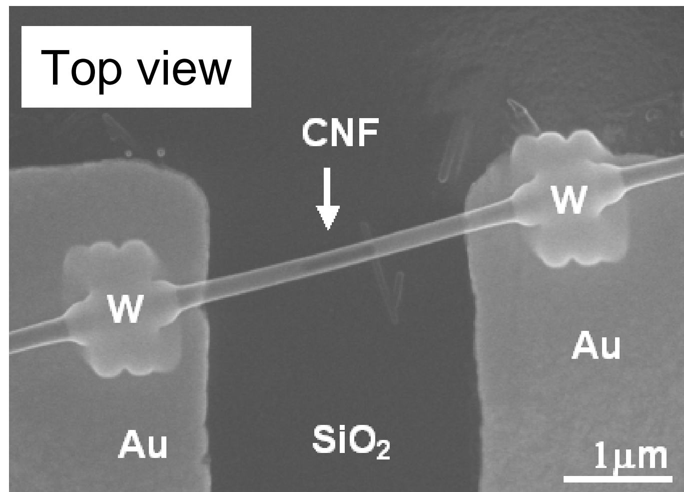


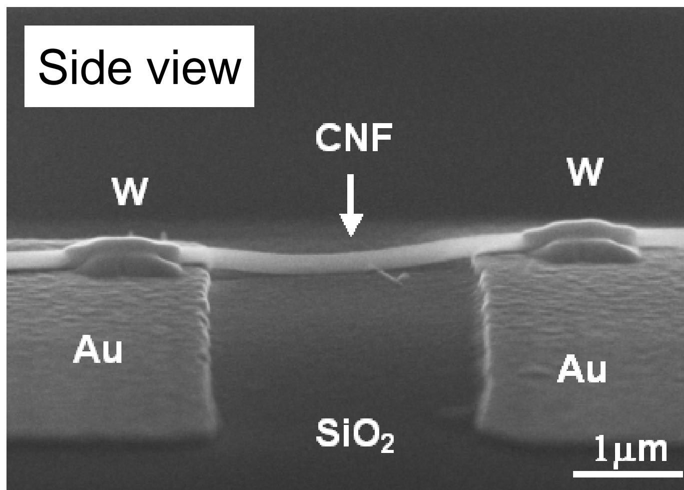

## *Test device fabrication*

- CNF growth by PECVD*
- Drop-cast CNF on patterned Au
- W deposition on test device

*Cruden, Cassell, Ye, and Meyyappan, *J. Appl. Phys.* 94(2003) 4070.

# FIB-deposited W contacts




**Resistance**

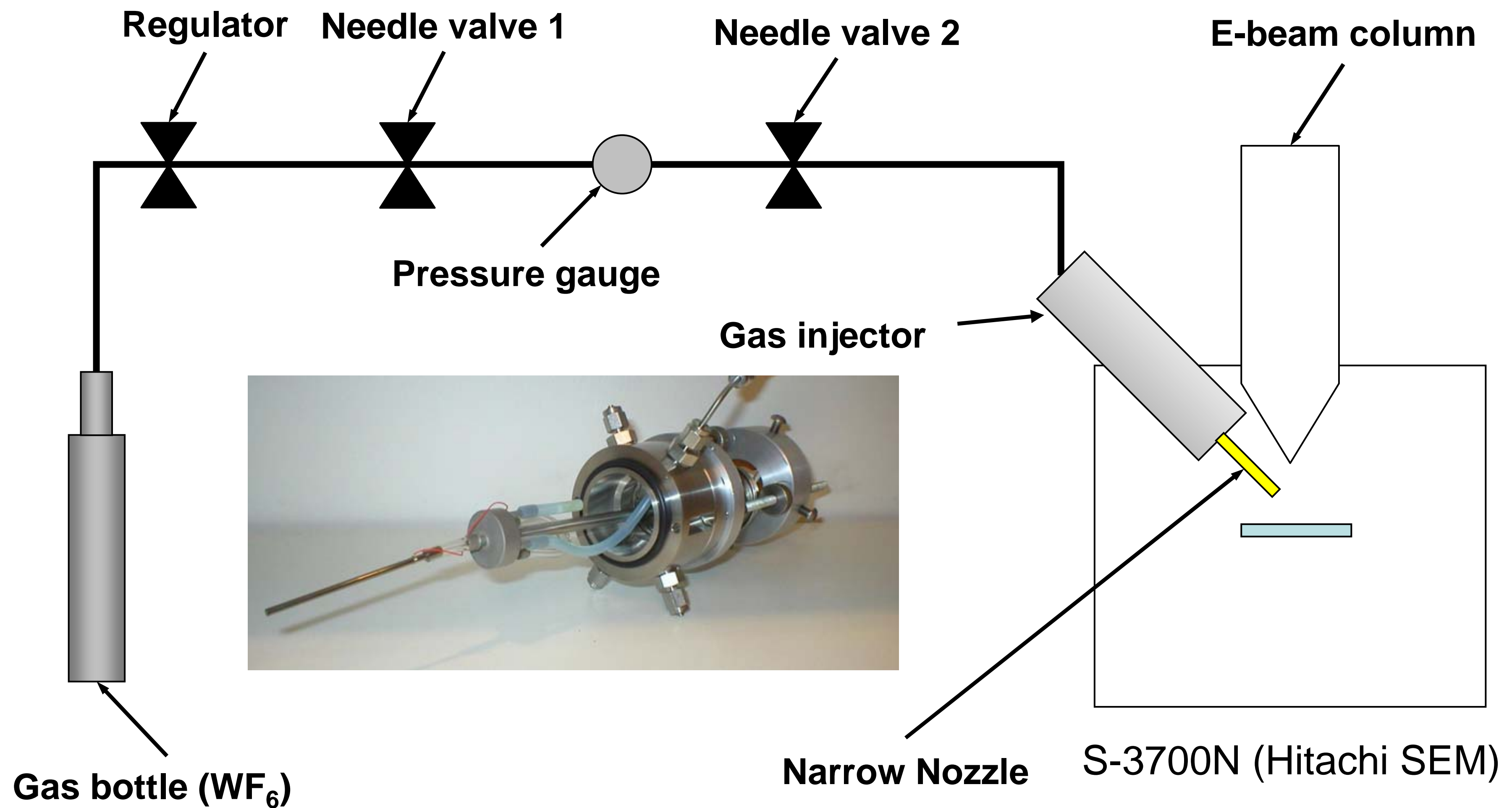
| Without W | With W |
| --- | --- |
| ~MΩ | ~kΩ |

Saito, Yamada, Fabris, Kitsuki, Wilhite, Suzuki, and Yang, *Appl. Phys. Lett.*, 93(2008) 102108.

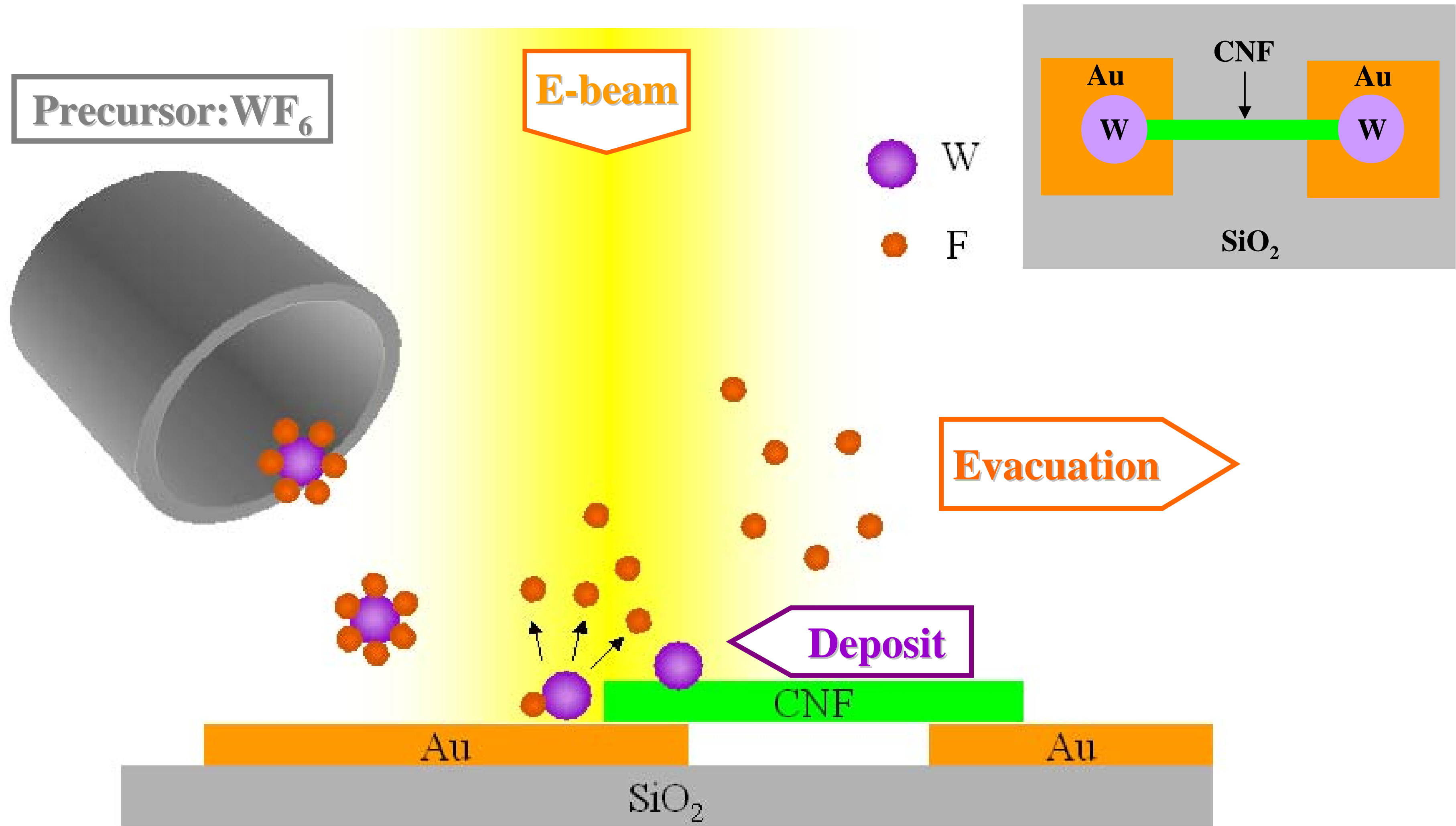
- **Radiation damage**
- **Ga contamination**
- **Spatial resolution and control**
- **Cost-effectiveness**

**E-beam deposition**

# Gas Injection System (GIS)

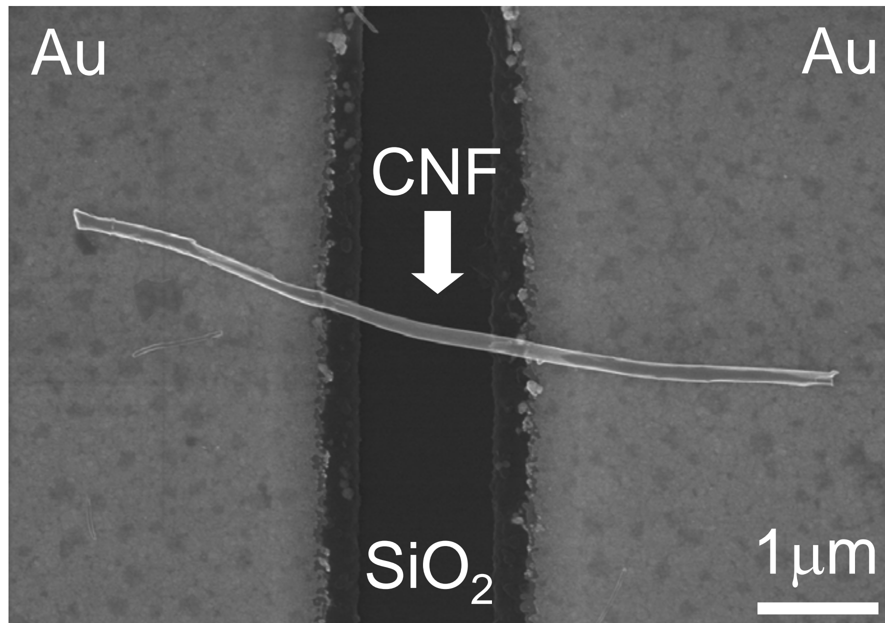


# Model of W deposition by e-beam

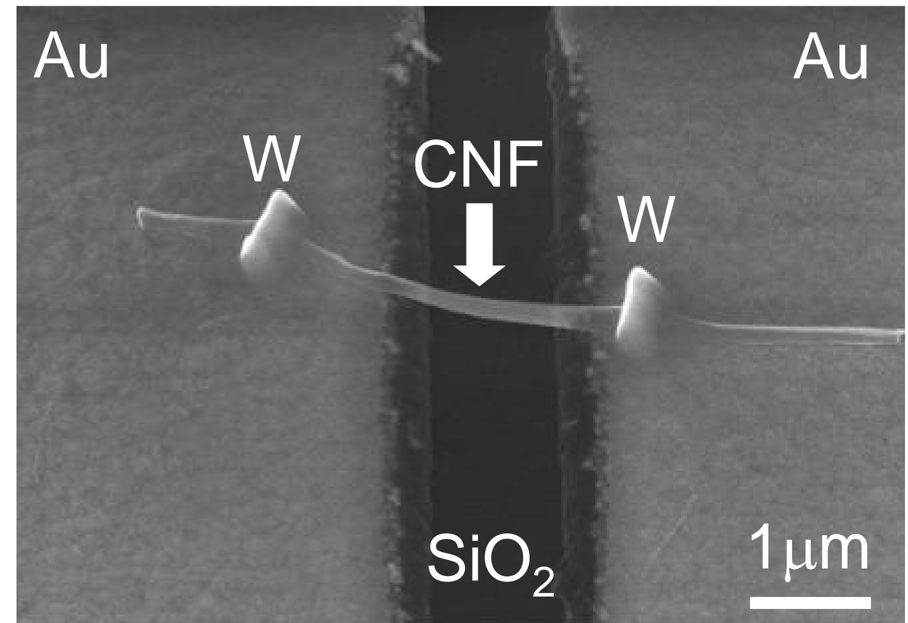


# E-beam deposited W contacts

**Before W-deposition**

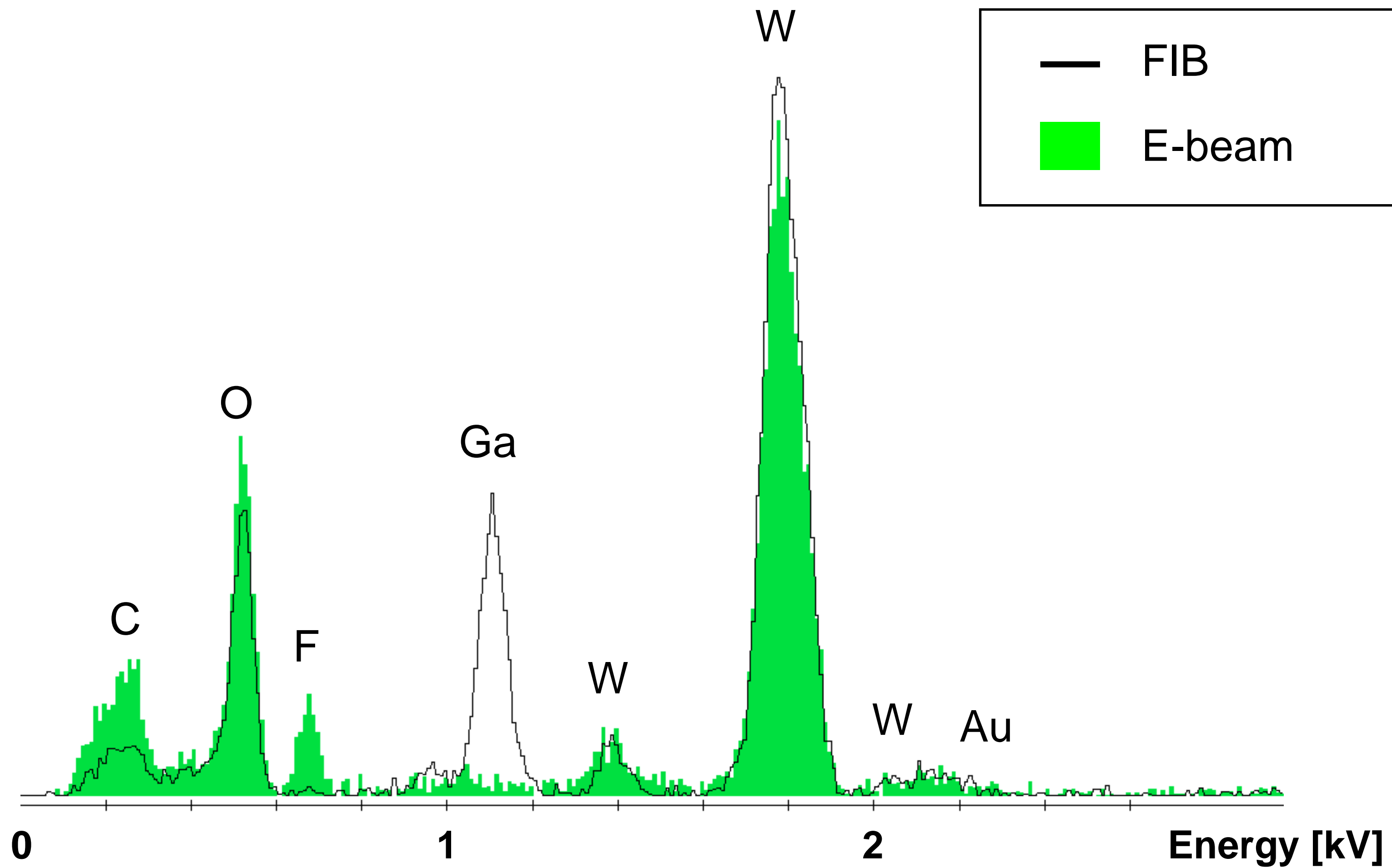



**After W-deposition**



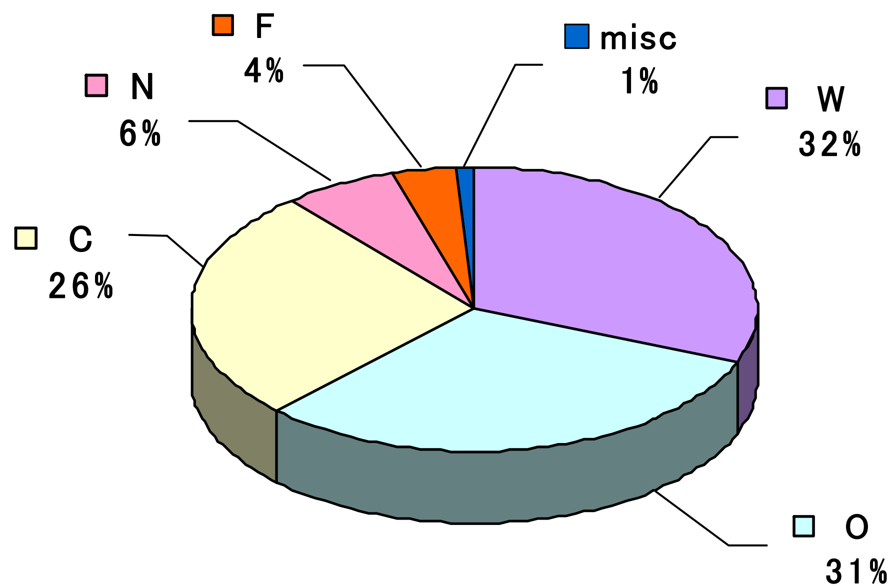

| Voltage | Beam current | Working Distance | Time | Scan |
|---|---|---|---|---|
| 30 kV | 29 pA | 25 mm | 30 min | area mode |

# EDS spectra of deposited W by E-beam and FIB

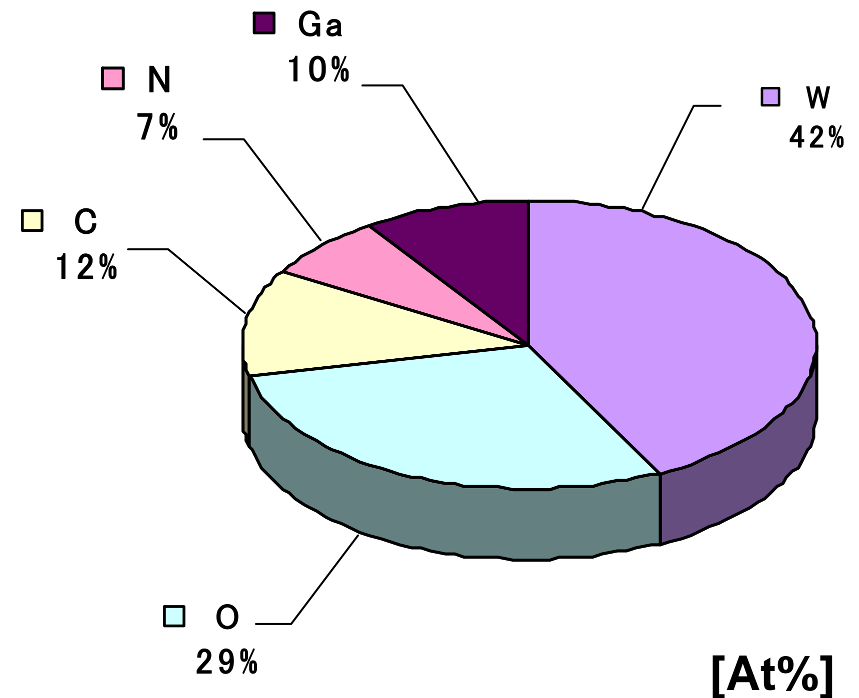


# Composition of W deposited by e-beam and FIB

**E-beam**

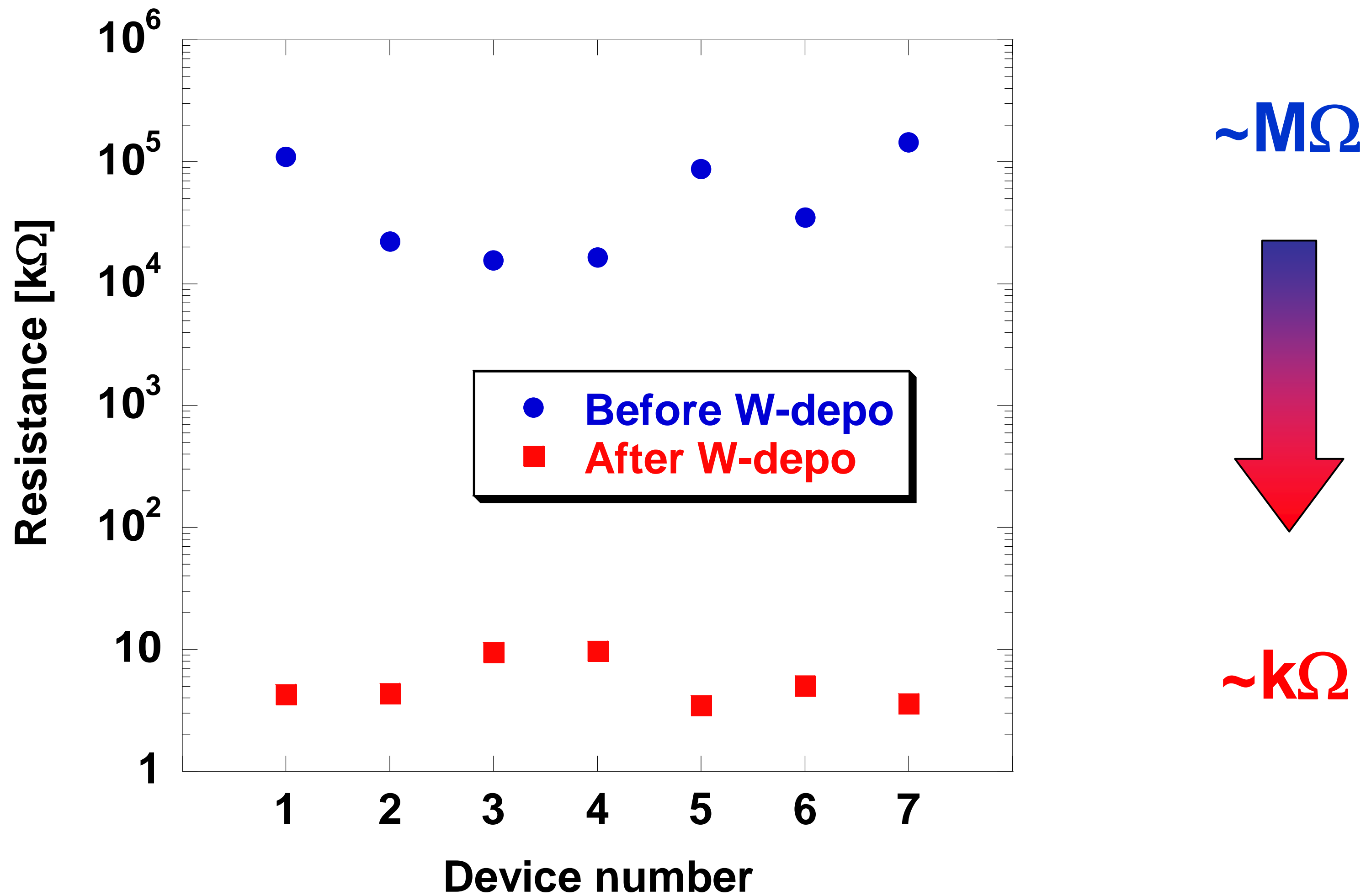



**FIB**

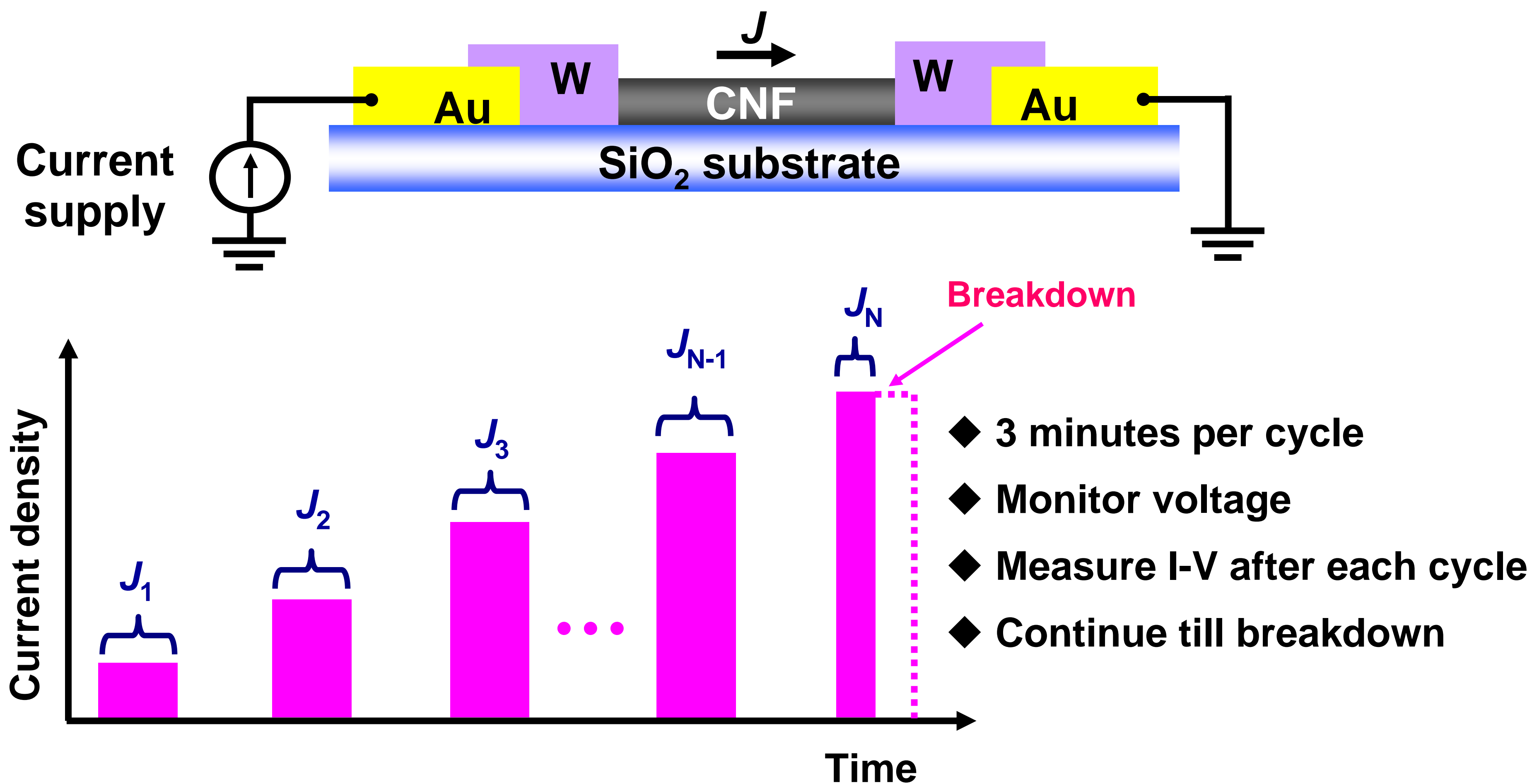



[At%]

# Change in resistance before and after W deposition

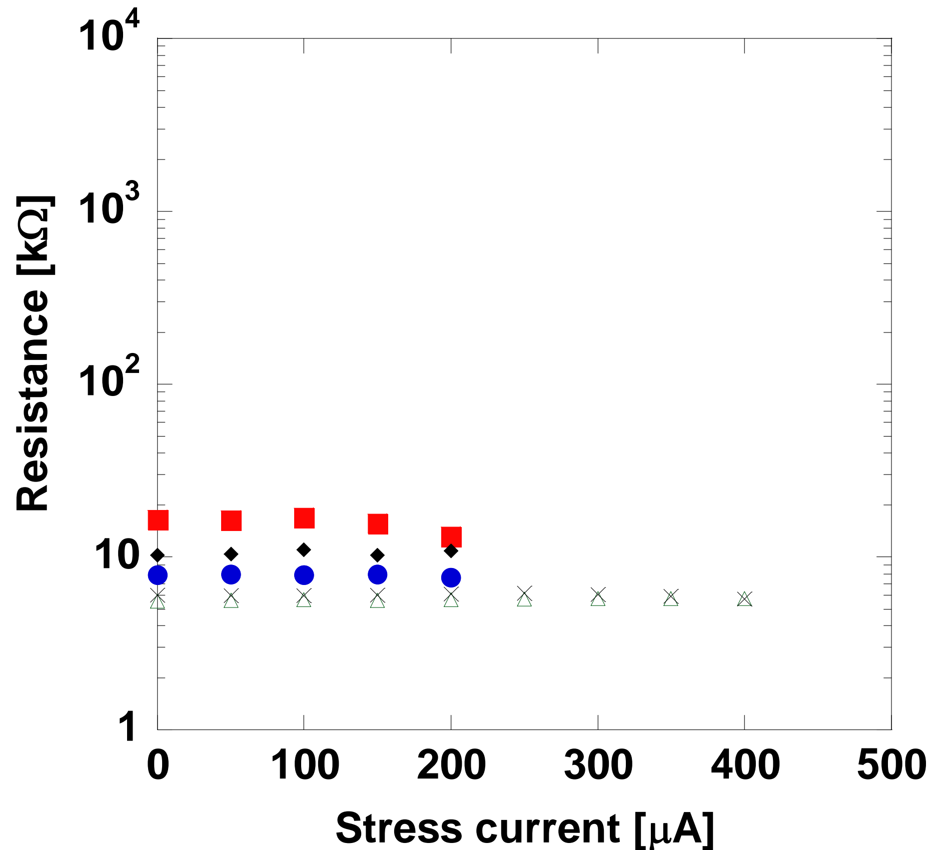


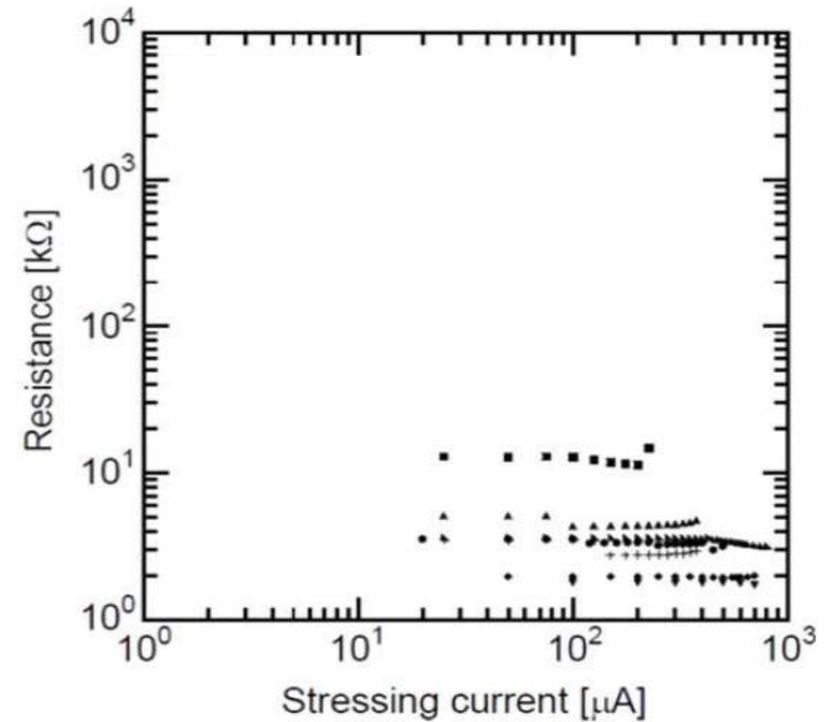
# Current stressing experiments




Kitsuki, Yamada, Fabris, Jameson, Wilhite, Suzuki, and Yang, *Appl. Phys. Lett.,* 92 (2008) 173110.

# Resistance *after* stress cycle

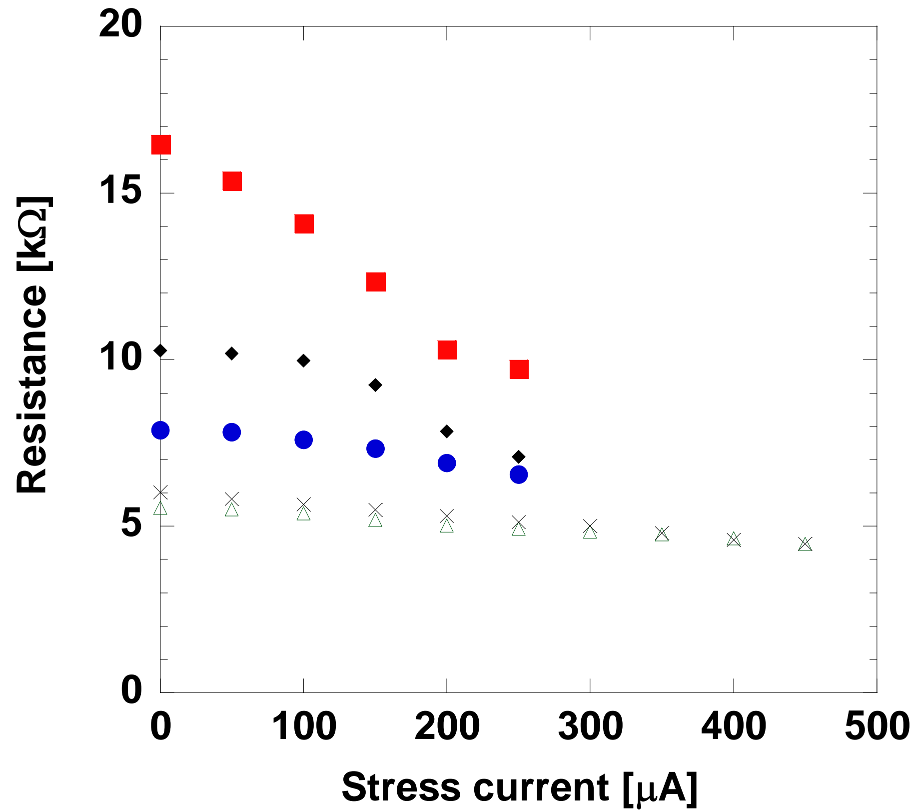


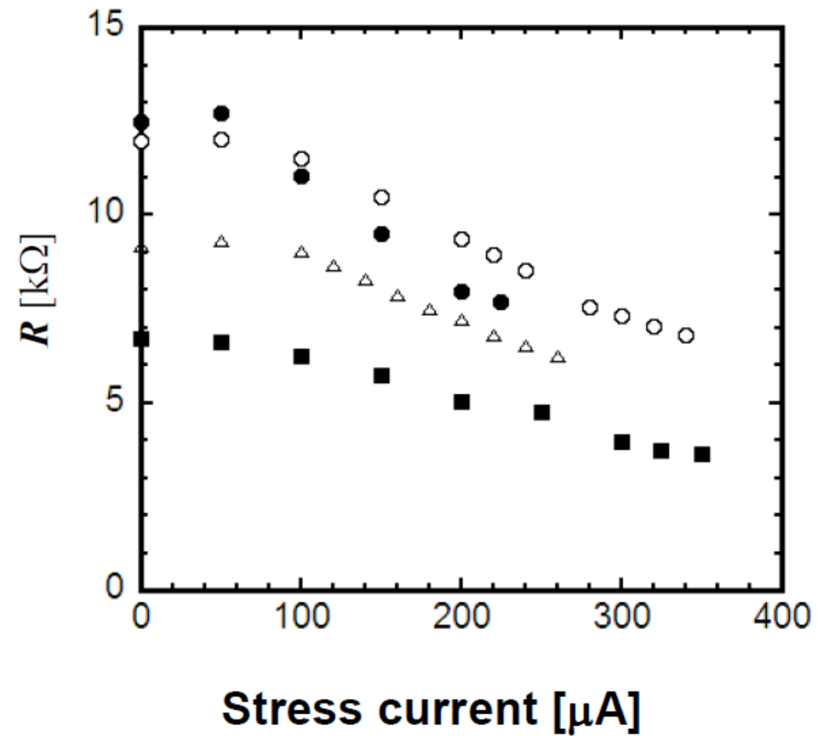

Saito, Yamada, Fabris, Kitsuki, Wilhite, Suzuki, and Yang, *Appl. Phys. Lett.*, 93 (2008) 102108.

# Resistance *during* stress cycle

## E-beam-deposited W

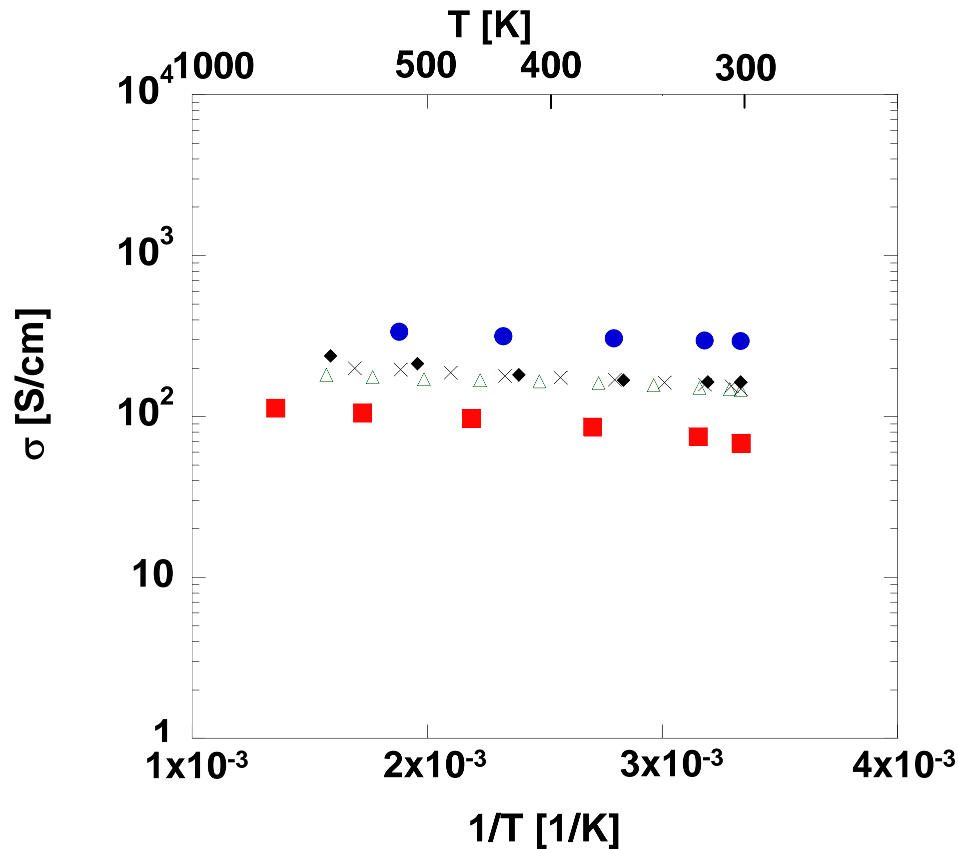



## FIB-deposited W




Yamada, Yabutani, Saito, and Yang, *Nanotechnology,* 21 (2010) 265707.

# Activation energy extraction




Converting stress current to temperature

Yamada, Saito, Fabris, and Yang, *IEEE Electron Dev. Lett.* 30 (2009) 469

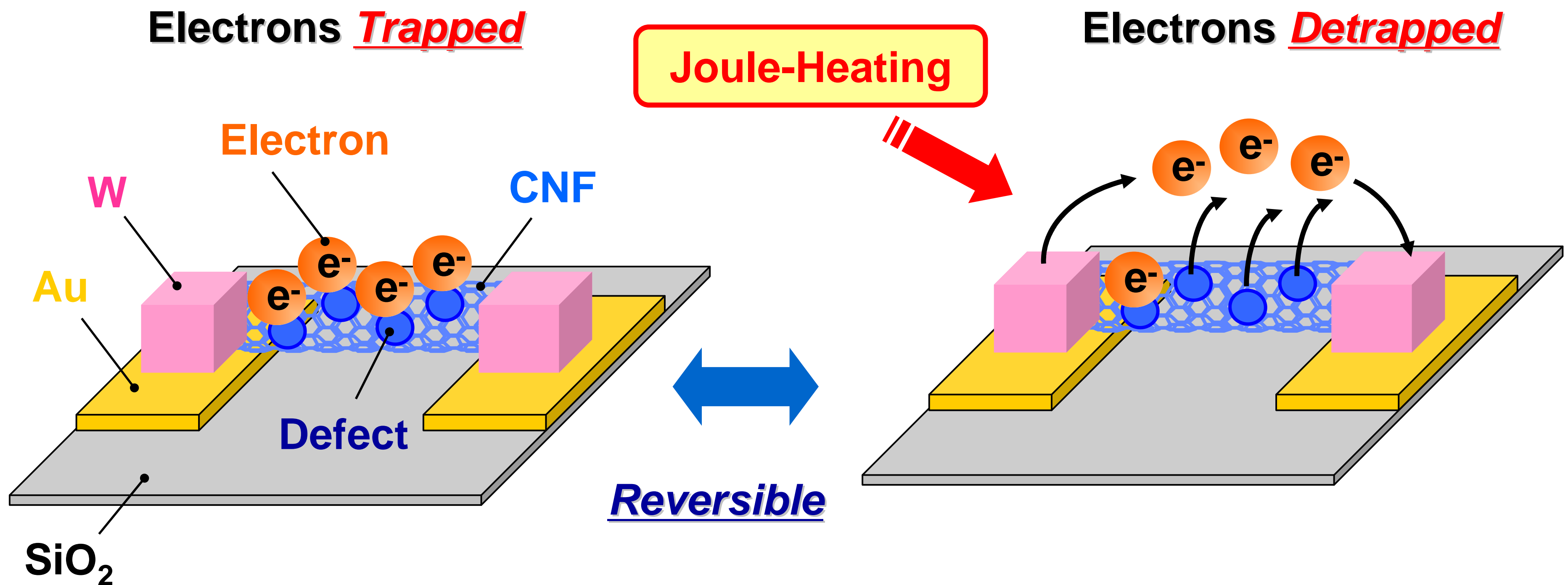
$$\sigma_{\mathrm{CNF}} = \sigma_0 \exp\left(-\frac{E_a}{k_{\mathrm{B}} T}\right)$$

| | | |
|---|---|---|
| $\sigma_0$[S/cm] | : | Device-dependent parameter |
| $E_a$[eV] | : | Activation energy |
| $k_B$ [JK$^{-1}$] | : | Boltzmann constant |
| $T$ [K] | : | Temperature |

*E-beam:* $E_a = 8.6 \sim 18.6$ *meV* cf. FIB: $E_a = 22 \sim 35$ *meV*

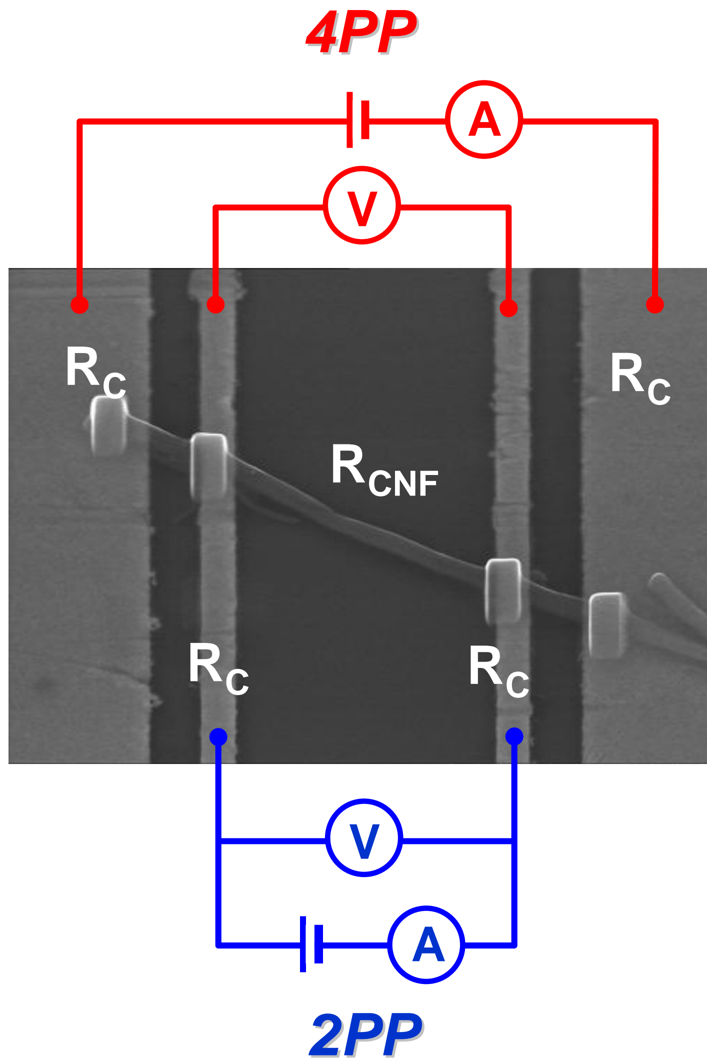
Yamada, Yabutani, Saito, and Yang, *Nanotechnology* 21 (2010) 265707

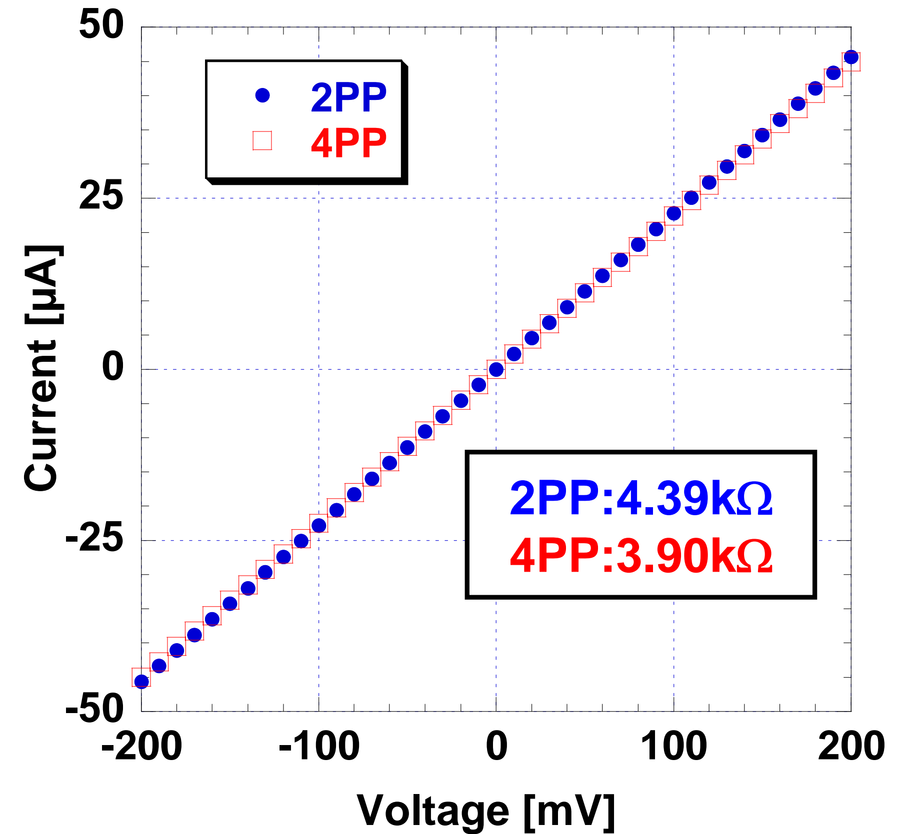
# Model of resistance change with temperature




- Defects in CNF give rise to electron traps
- Joule heating activates trapped electrons
- More carriers are generated, resulting in resistance decrease

# 4PP resistance measurement



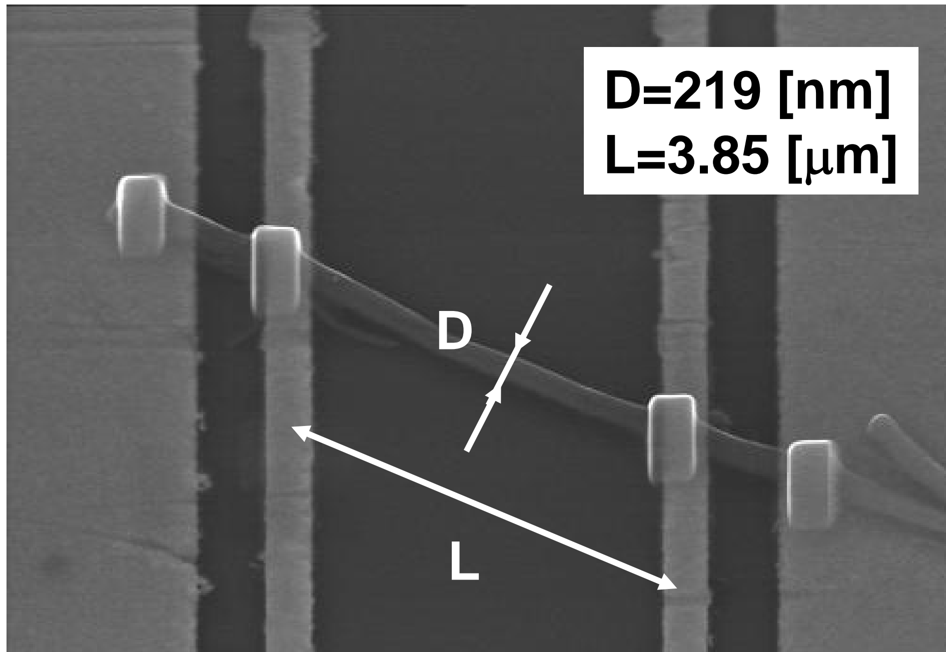




**Total Contact resistance: 0.49kΩ**



Santa Clara University
Center for Nanostructures

# CNF Resistivity




**Resistivity**

$$\rho = R \times \frac{S}{L}$$

**$\rho$: Resistivity**
***R*: Resistance**
***S*: Cross section area**
***L*: Length**

**$\rho$ = 3.83x10$^{-3}$ [Ωcm]** cf. **3.2~4.6x10$^{-3}$ [Ωcm]***

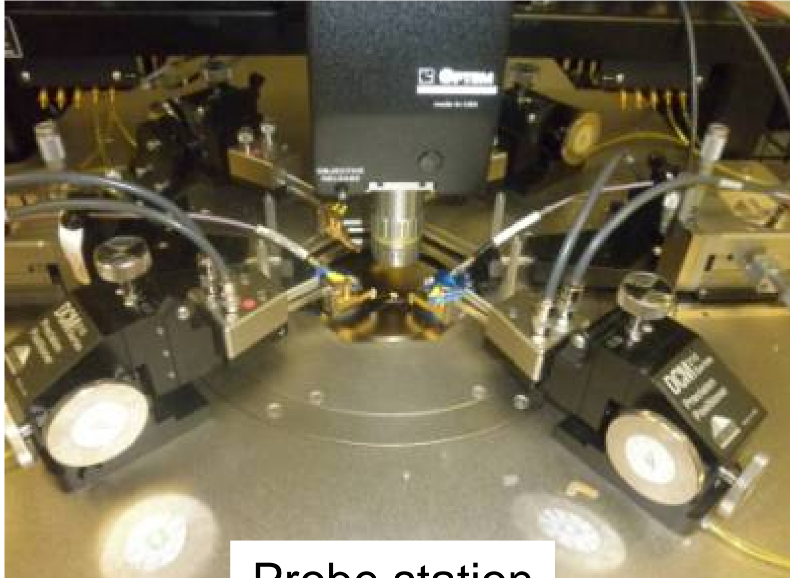
*Zhang, Austin, Merkulov, Meleshko, Klein, Guillorn, Lowndes and Simpson, *APL., 84*(2004)3972.


Santa Clara University
Center for Nanostructures

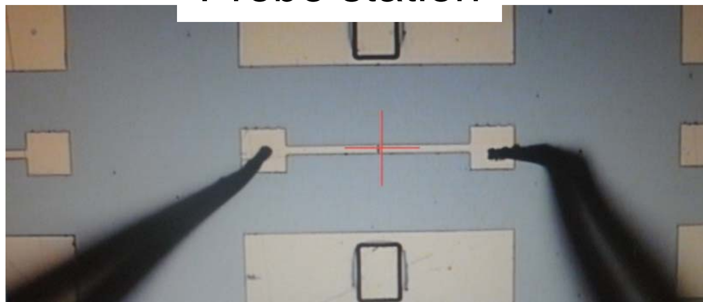
# Ambient vs Vacuum

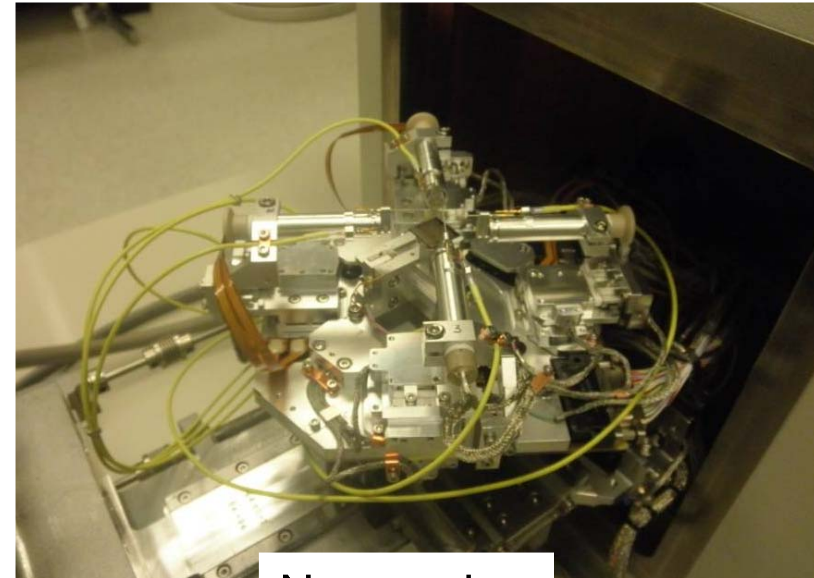
***Ambient***

***Vacuum***

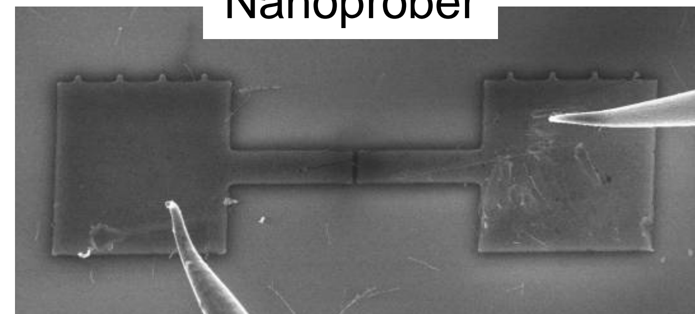


Probe station

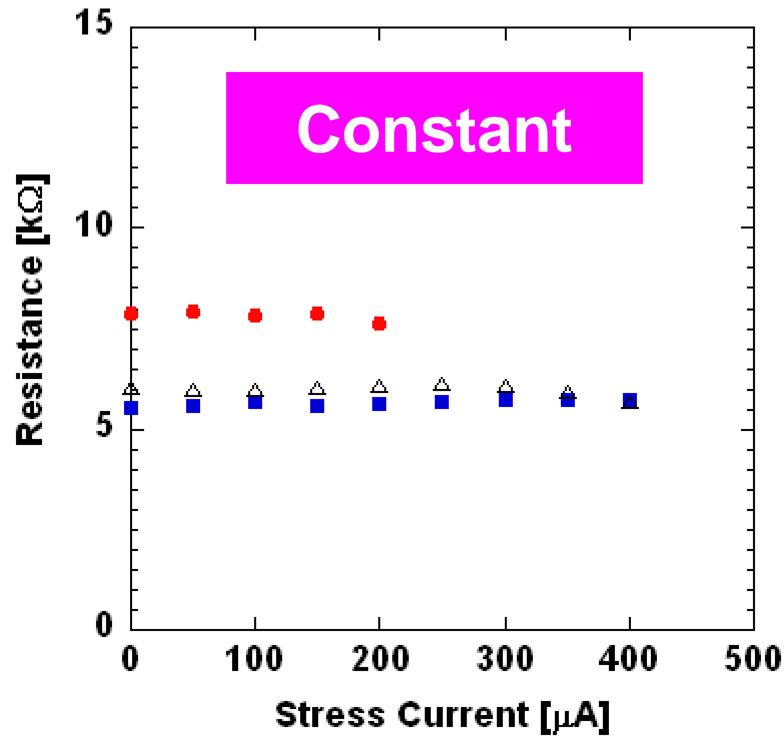


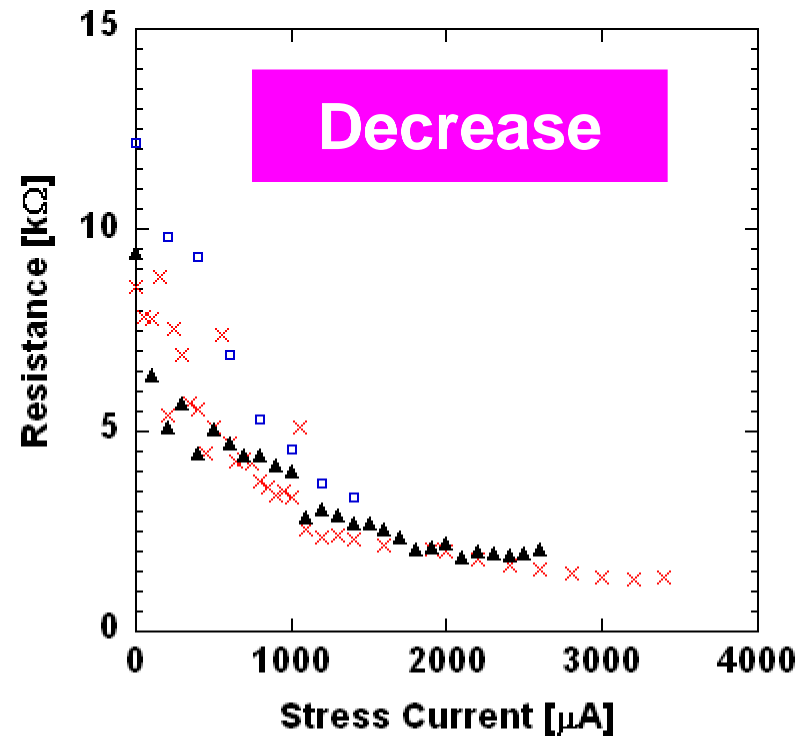


Nanoprober



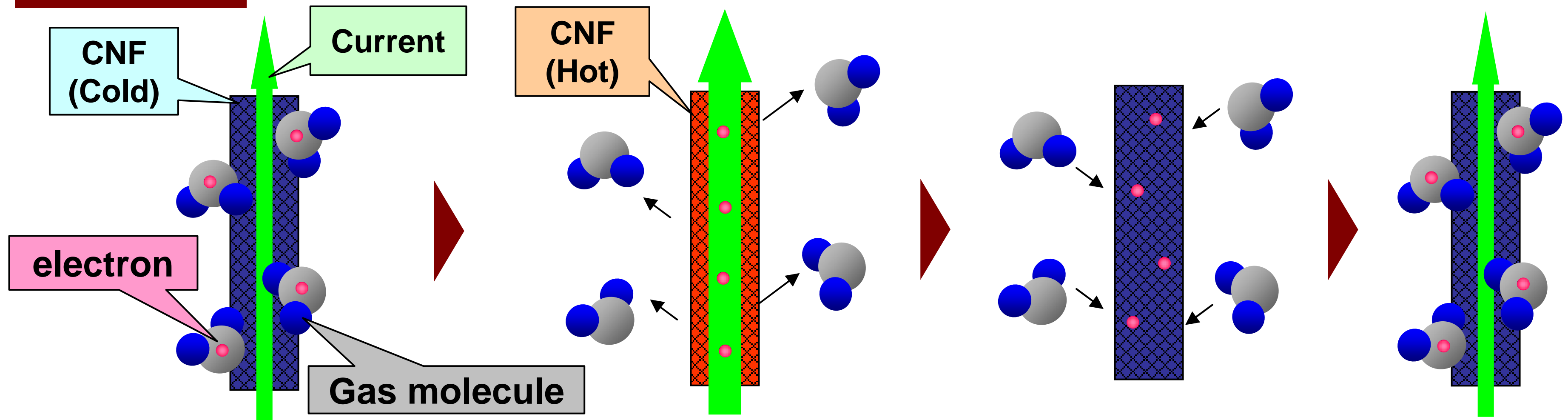
# Resistance *after* stress cycle

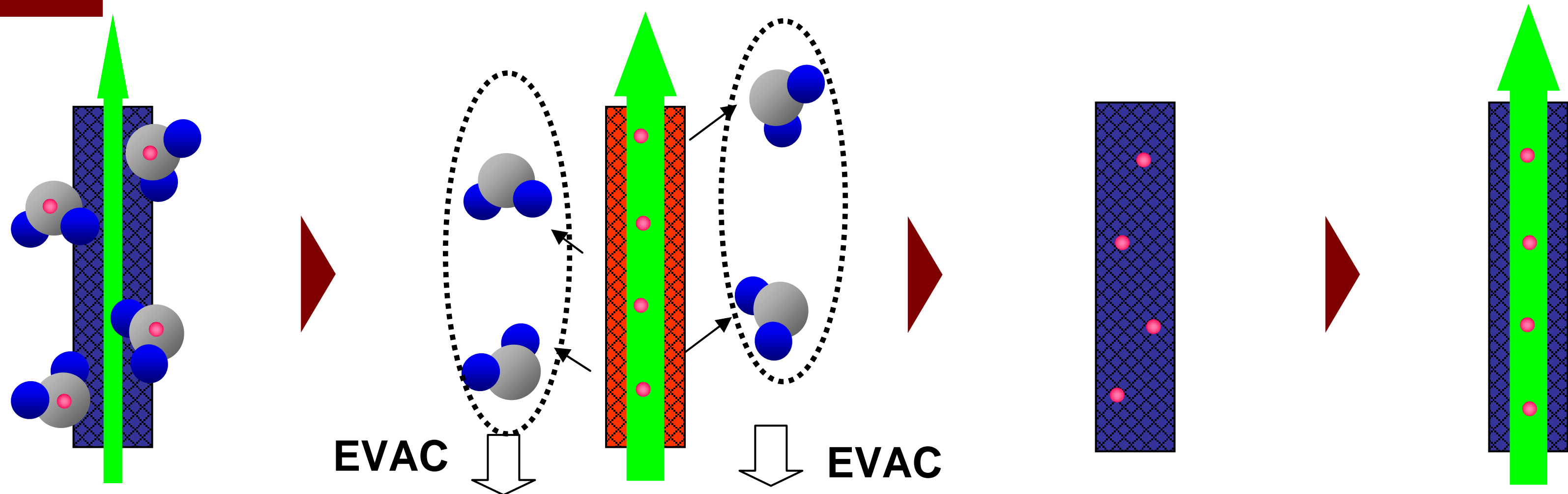


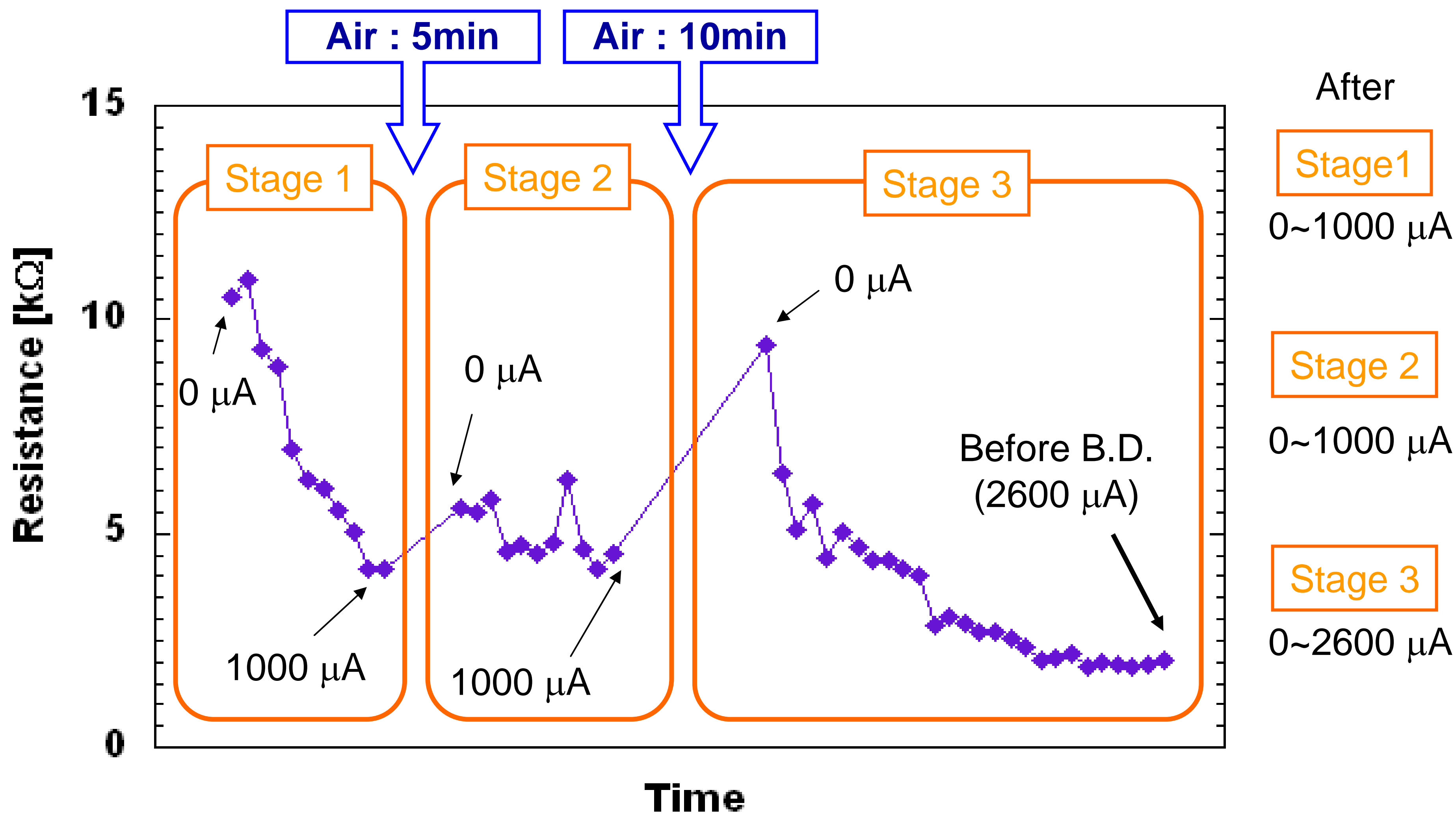

**Breakdown current: In ambient < In vacuum**

# Ambient gas adsorption/desorption model



# Effect of air exposure



# Summary

- Low-energy e-beam W-deposition technique developed using novel gas injection system
- Contact resistance of CNF test devices substantially improved by deposited W as in previous study using FIB
- CNF conductivity vs temperature behavior suggests electron trapping/detrapping
- EDS analysis suggests that purity of W can be improved by further cleaning of sample and chamber
- 4PP measurement provides more accurate CNF resistivity
- Resistance behavior in vacuum suggests gas adsorption/desorption

# Acknowledgements


- *Hitachi High-Technologies Corporation*

Hitachi High-Tech

**Mr. J. Clarke** **Mr. S. Nozaki**
**Mr. M. Betts** **Mr. A. Masunaga**

- *University of Tennessee*

**Dr. D. C. Joy**
**Dr. P. D. Rack**

***Thank you for your attention!***





25