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# Atomic Force Microscopy Study of High Electric Field Breakdown Through Thin Oxide Layers on Copper

**R.E. Kirby, C.H. Back, and I. Ben-Yaacov**
**Stanford Linear Accelerator Center**

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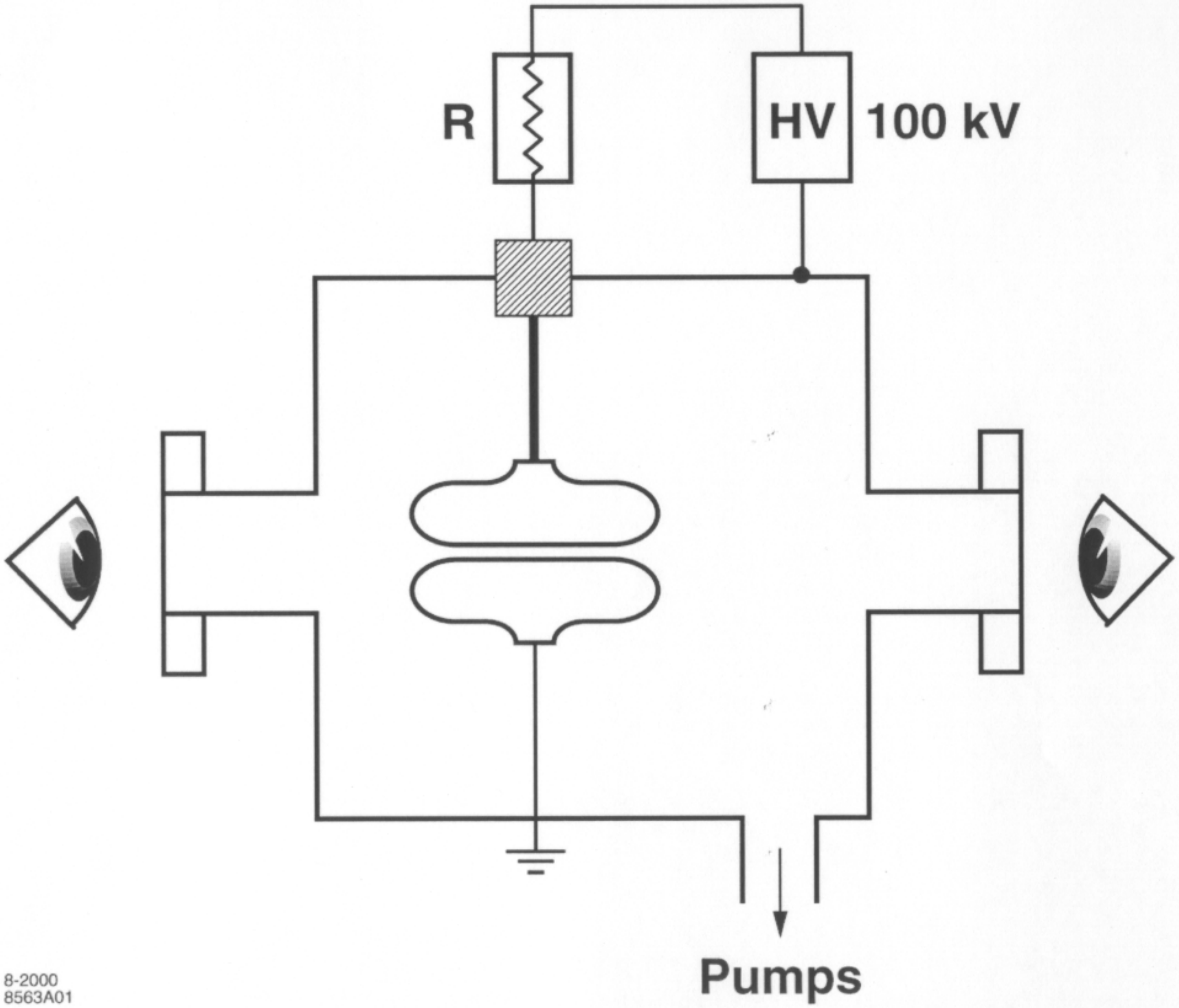
# Characterizing HV Breakdown

- HV breakdown and topography are linked
- A little history:
    - The UHV HV breakdown apparatus
    - Results - Raising the work function doesn't help
        - Degassed and Mechanically polished is good
        - E-P is not better than M-P
        - Dielectric coating raises the threshold, but…
- What broke down anyway?
    - Multiple sites
    - Are some sites more important than others?
    - How can $\beta$ be reduced?

# High Voltage Breakdown System



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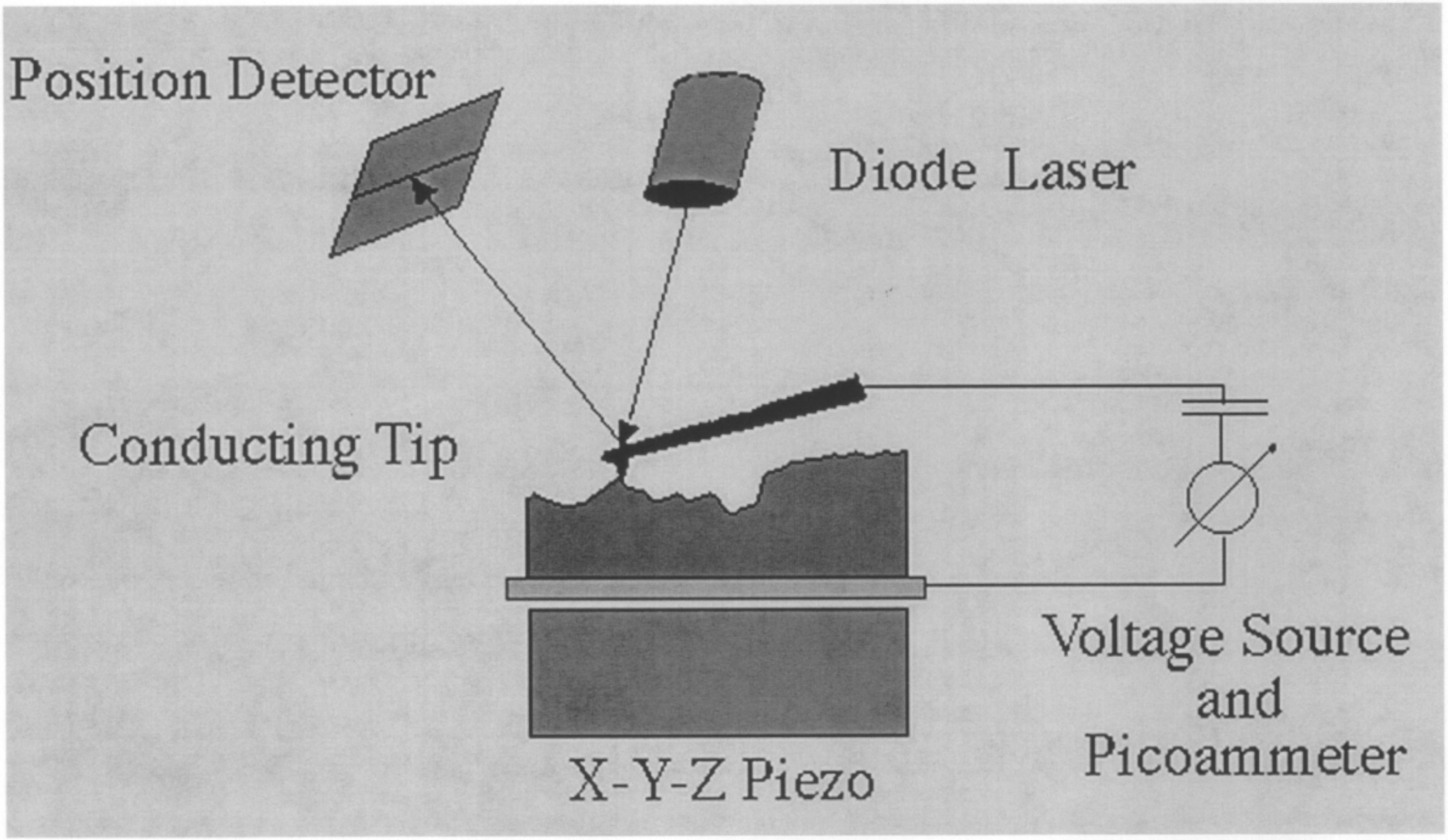
# Hard Carbon-Coated S/S

# Microscopy - the “Topography”

- **Optical**
  - **Useful for locating large sites**
  - **M < 1000x, poor vertical resolution**
- **SEM**
  - **Great resolution, wide magnification range**
  - **Poor contrast on smooth surfaces**
  - **Misleading images on dielectrics**
  - **Poor vertical resolution, vacuum only**
- **AFM/STM**
  - **Excellent xyz topographic resolution, to 10 nm**
  - **Ambient atmosphere**
  - **Small samples, but tip within 1-2 nm of the surface**

# High-Field Breakdown AFM



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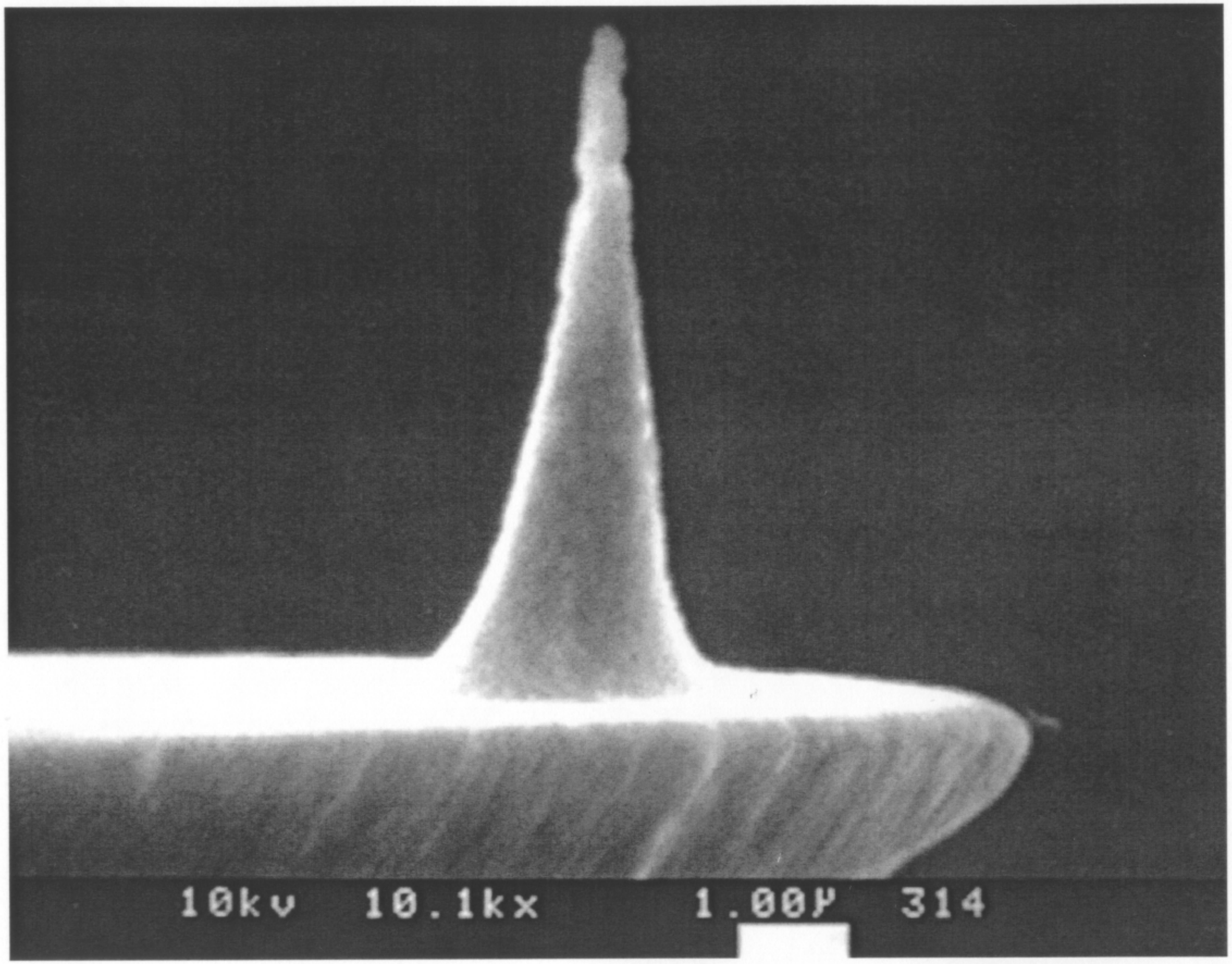
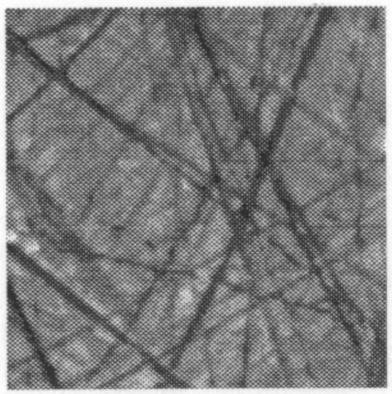
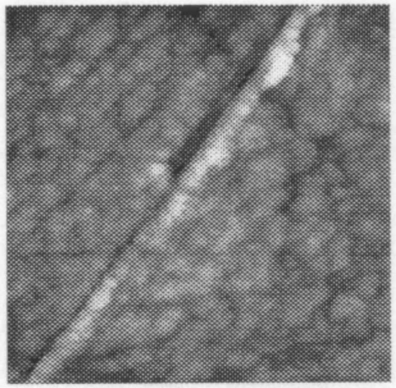


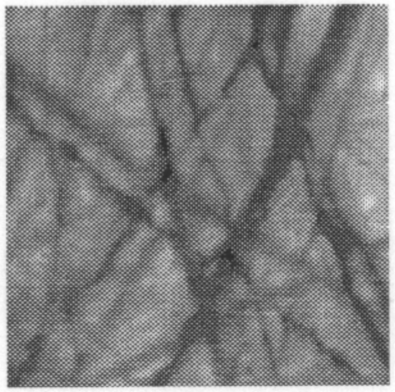
# Atomic Force Microscope Imaging - Cu



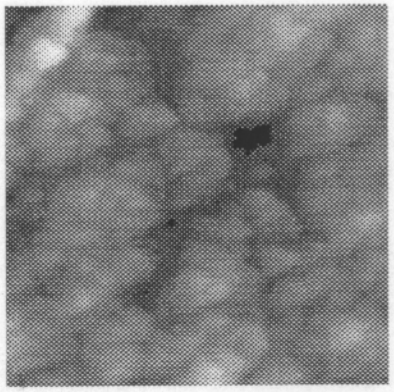
3.5 x 3.5 (μm)$^2$



3.5 x 3.5 (μm)$^2$



1.4 x 1.4 (μm)$^2$



1.4 x 1.4 (μm)$^2$

**Before UPW Rinse** **After UPW Rinse**

# Now Where?

-Can we do coatings, where many iterations (e.g., thickness) are involved, more quickly?

-But…we need topography identification for efficient determination of sites.

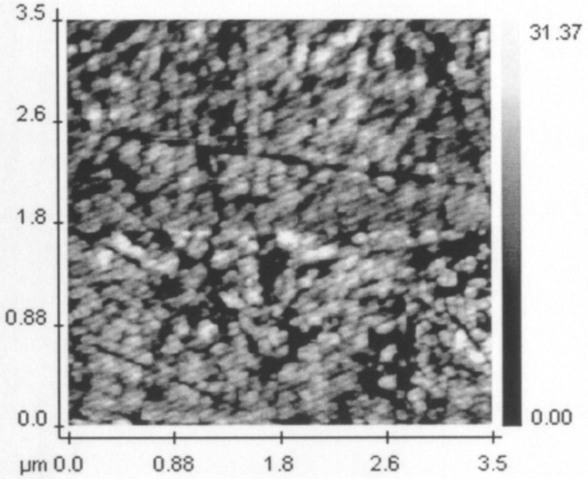
-And…could we be more surgical in choosing sites to measure before we attempt to F-N them (again efficiency).

-And…does UHV, or even vacuum, matter that much, to first order?

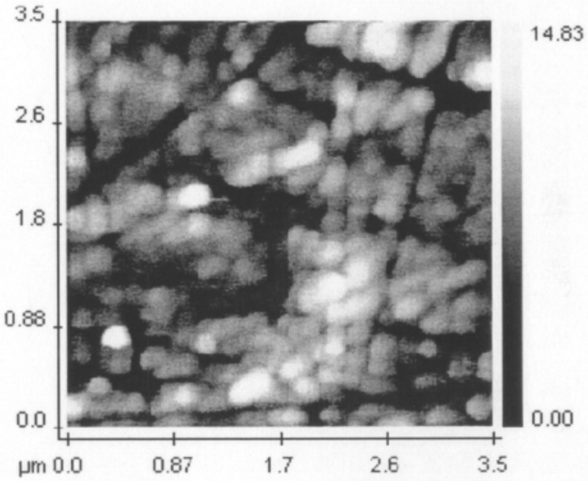
# Putting It Together, AFM + F-N

- Generating the breakdown:
  - Electrical circuit
  - Tunneling
  - Breakdowns
- F-N plots at the sites:
  - Identify the sites at which breakdowns occur
  - Acquire an F-N plot
  - Make an AFM topographic image
- Investigations:
  - Surface quality, processing, hardness
  - Material quality - inclusions, dislocations, boundaries, dielectric coatings

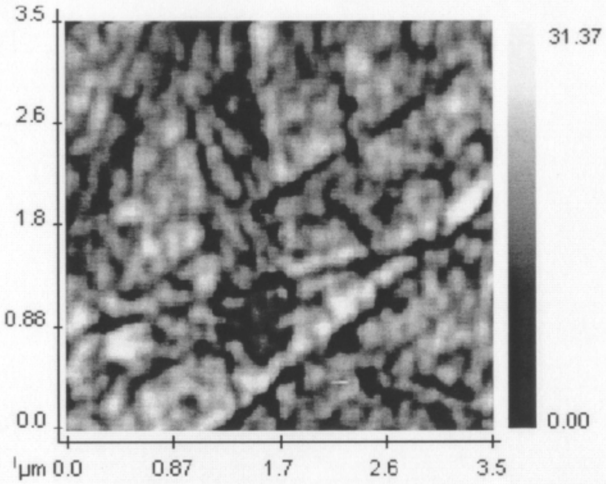
# AFM Images - Copper



**Clean OFE Cu**



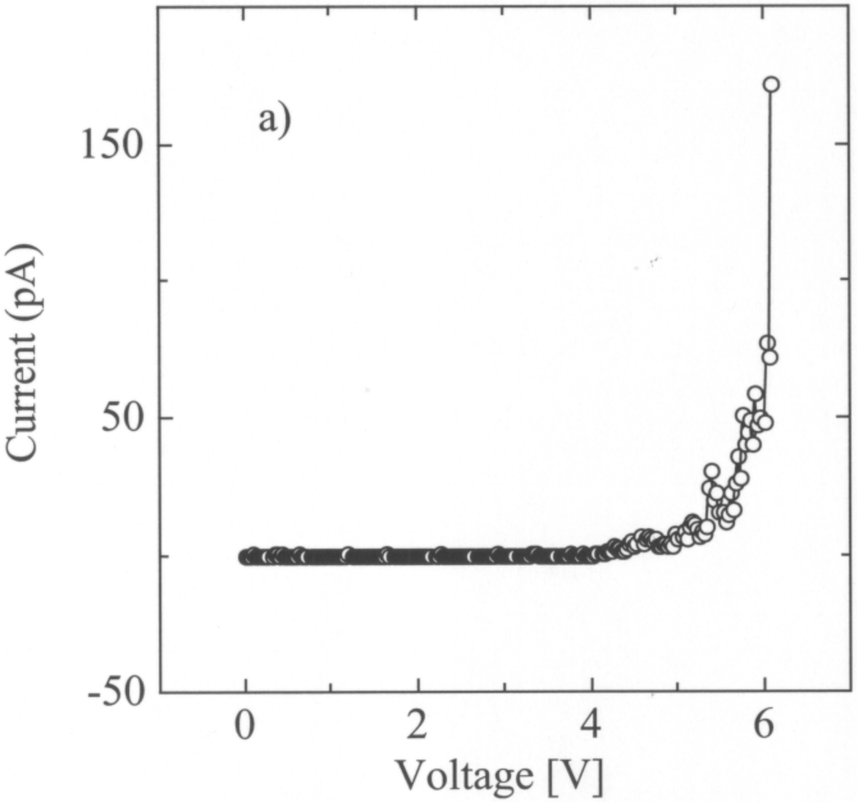
**2.5nm $Al_2O_3$/Cu**



**2.5nm $Al_2O_3$ /10nm Pt/Cu**

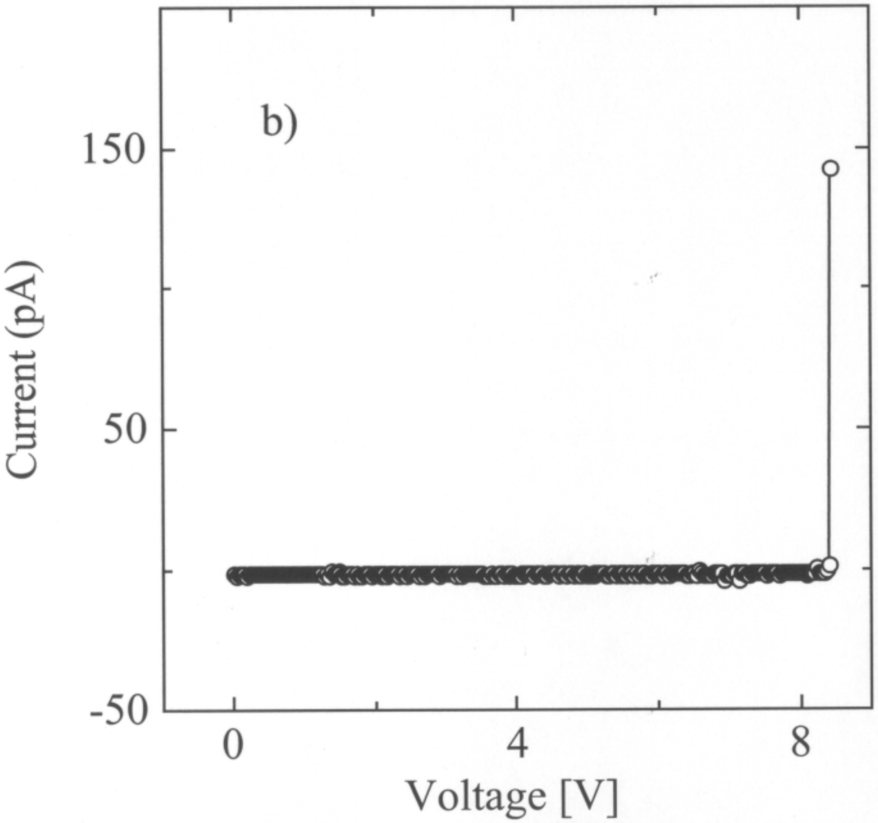
# Native Oxide/OFE Copper

## “Tunneling”



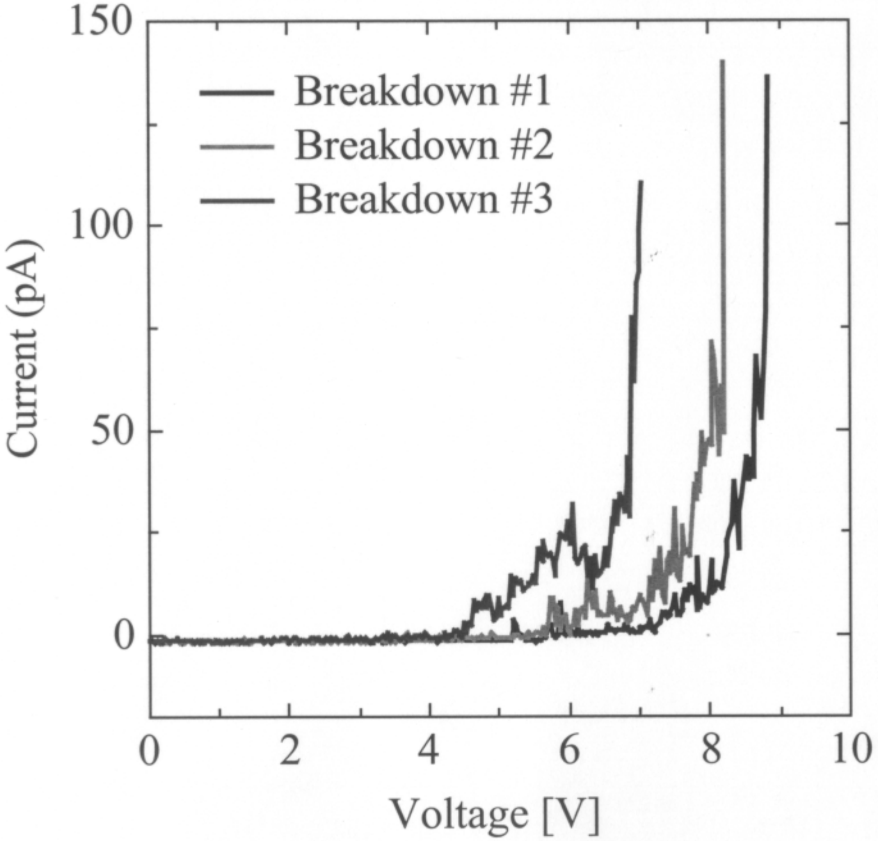
# 2.5nm $Al_2O_3$/20nm Mg/OFE Copper

## "Breakdown"



# Successive Voltage Scans

## 2.5nm $Al_2O_3$ on OFE Copper



# Fowler-Nordheim Equation

$$\frac{I_{FN}}{\alpha} = \frac{q^2}{8\pi h}\frac{m_0}{m^*}\frac{1}{t(E)}\frac{\beta^2 V^2}{\phi s^2}\exp\left\{-\frac{8\pi}{3}\frac{\sqrt{2m^* q}}{h}\mathrm{v}(E)\frac{s}{\beta V}\phi^{3/2}\right\}$$

**$\alpha$ - Effective emission area**

**s - Oxide thickness**

**$\phi$ - Barrier height at emitter**

**m* - Electron effective mass**

# Reducing Fowler-Nordheim

**The problem: Too many parameters**

**The partial solutions: Eliminate some by choosing surfaces with known known properties**

**- Effective emission area: Look in the SEM at the tip**

**- Oxide thickness: Deposit known thicknesses**

**- Barrier height: Deposit surfaces with known work functions**

**- Geometry: Use parallel plate geometry (Oxide thickness is small compared to tip radius, so**

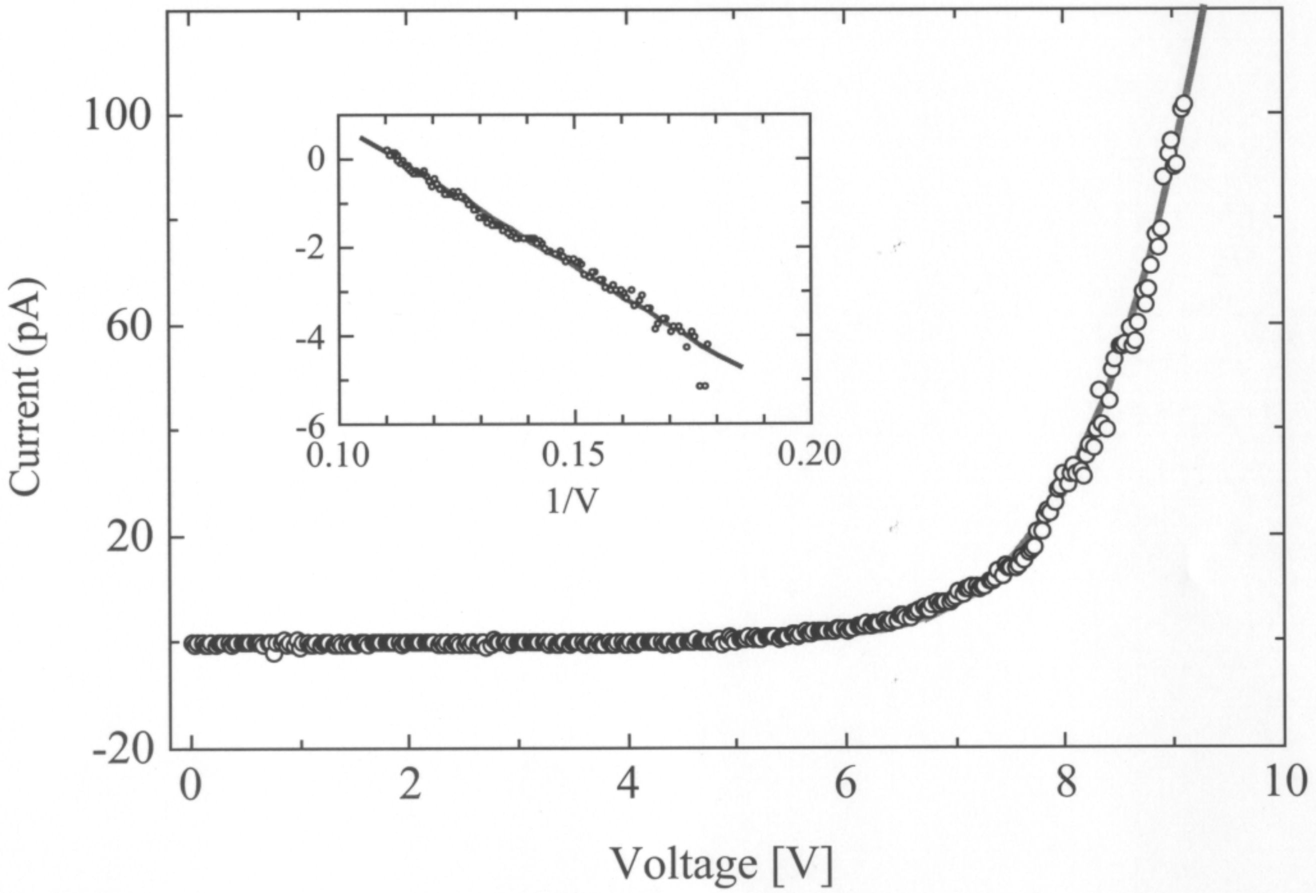
$$E = \beta\ V/S$$

**where $\beta$ is the “field enhancement factor**

**S is the oxide thickness**

# 2.5nm $Al_2O_3$/20nm Pt/OFE Copper

## Fit: $\varphi = 4.5$ eV, $\beta = 1$



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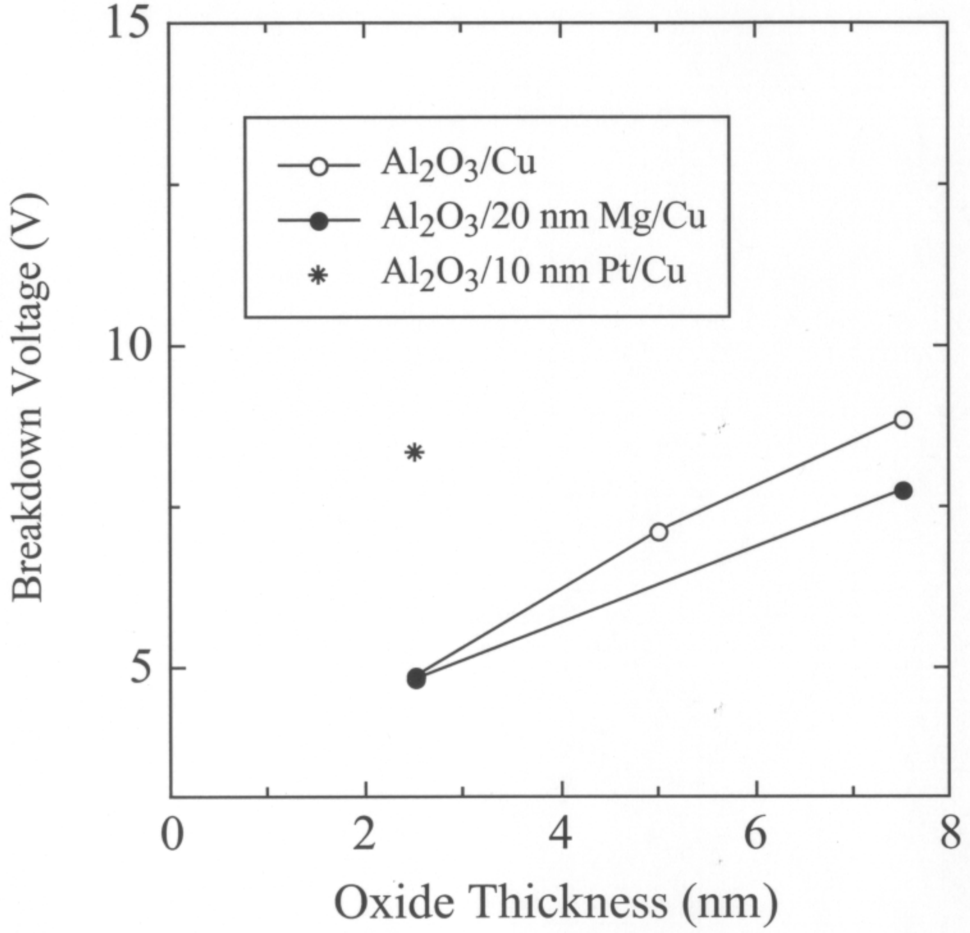
Robert E. Kirby


15
10
5
0
2
4
6
8
Breakdown Voltage (V)
Oxide Thickness (nm)
$Al_2O_3$/Cu
$Al_2O_3$/20 nm Mg/Cu
$Al_2O_3$/10 nm Pt/Cu

# Some Early Results

- Copper with oxide inclusions breakdowns easily
- On good copper, grain bodies and boundaries behave similarly and well

- Break downers: Poor Cu, Al oxide/Cu, Al oxide/Mg/Cu
- Non-break downers: Native oxide/Cu, Al Oxide/Pt/Cu

- Successive breakdowns at the same place occur at successively lower fields
- Non-breakdown I-V plots give single-digit betas