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

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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

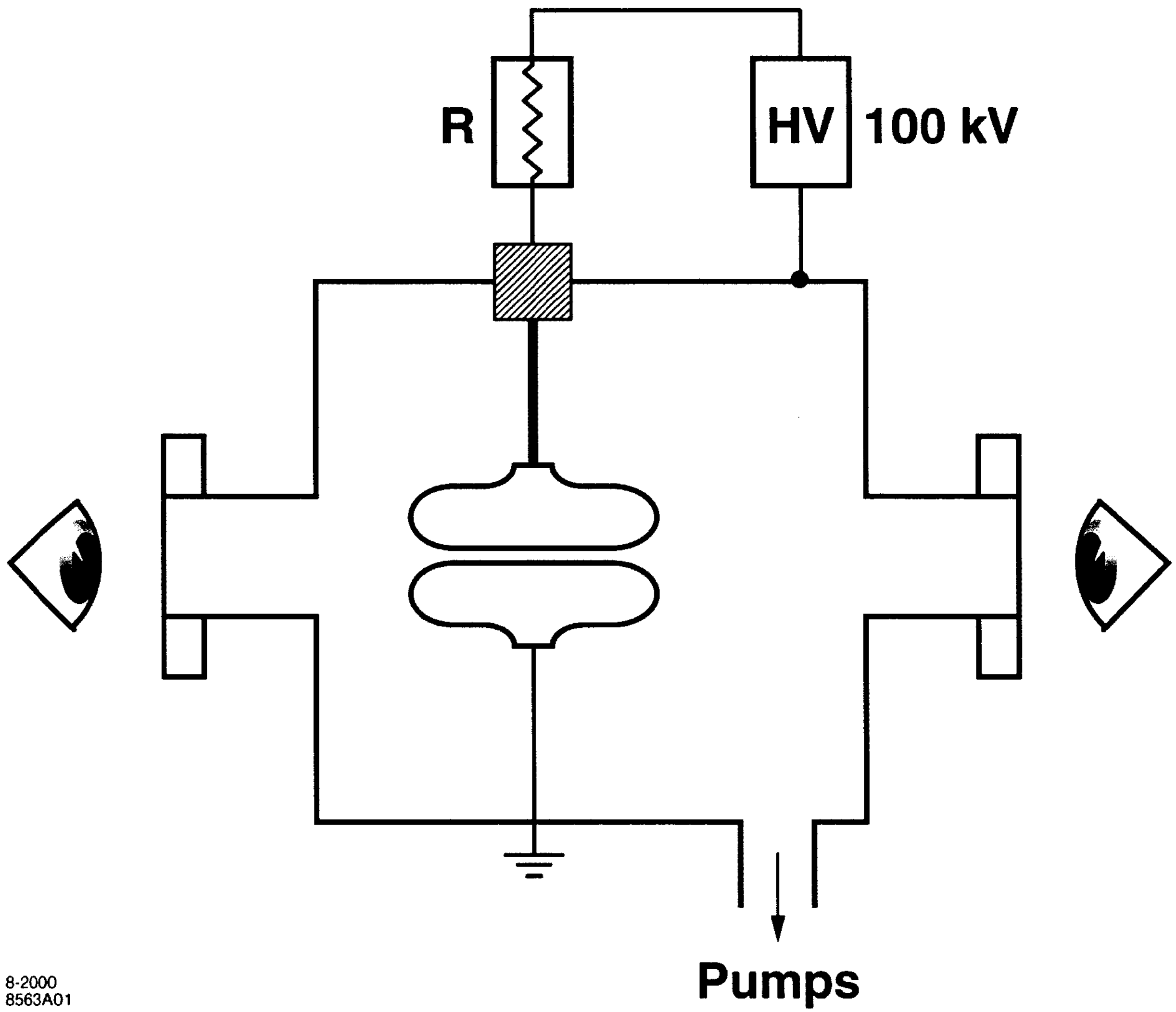
  Dielectric coating raises the threshold, but…
- What broke down anyway?

  Multiple sites

  Are some sites more important than others?

  How can β be reduced?

High Voltage Breakdown System

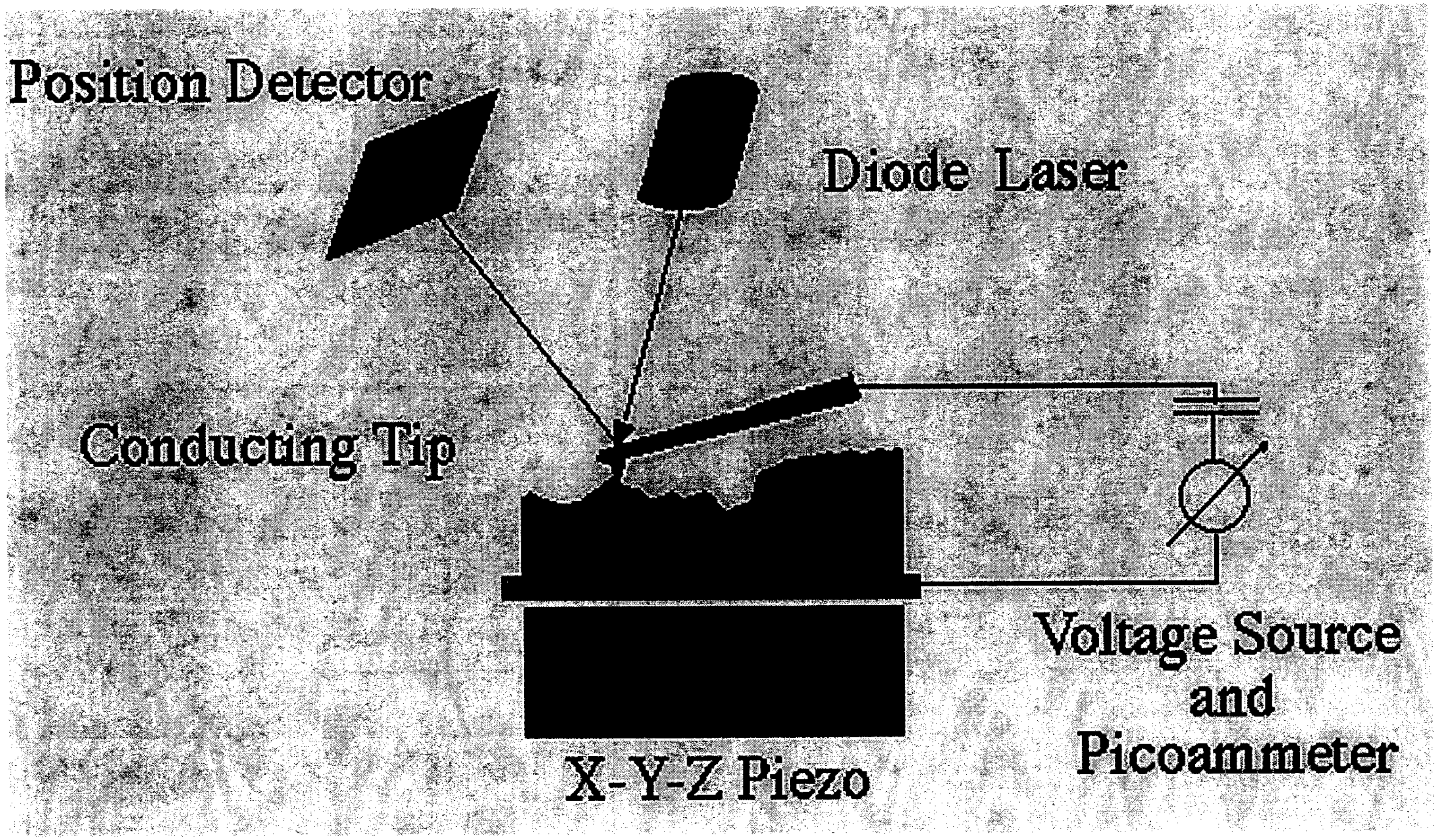


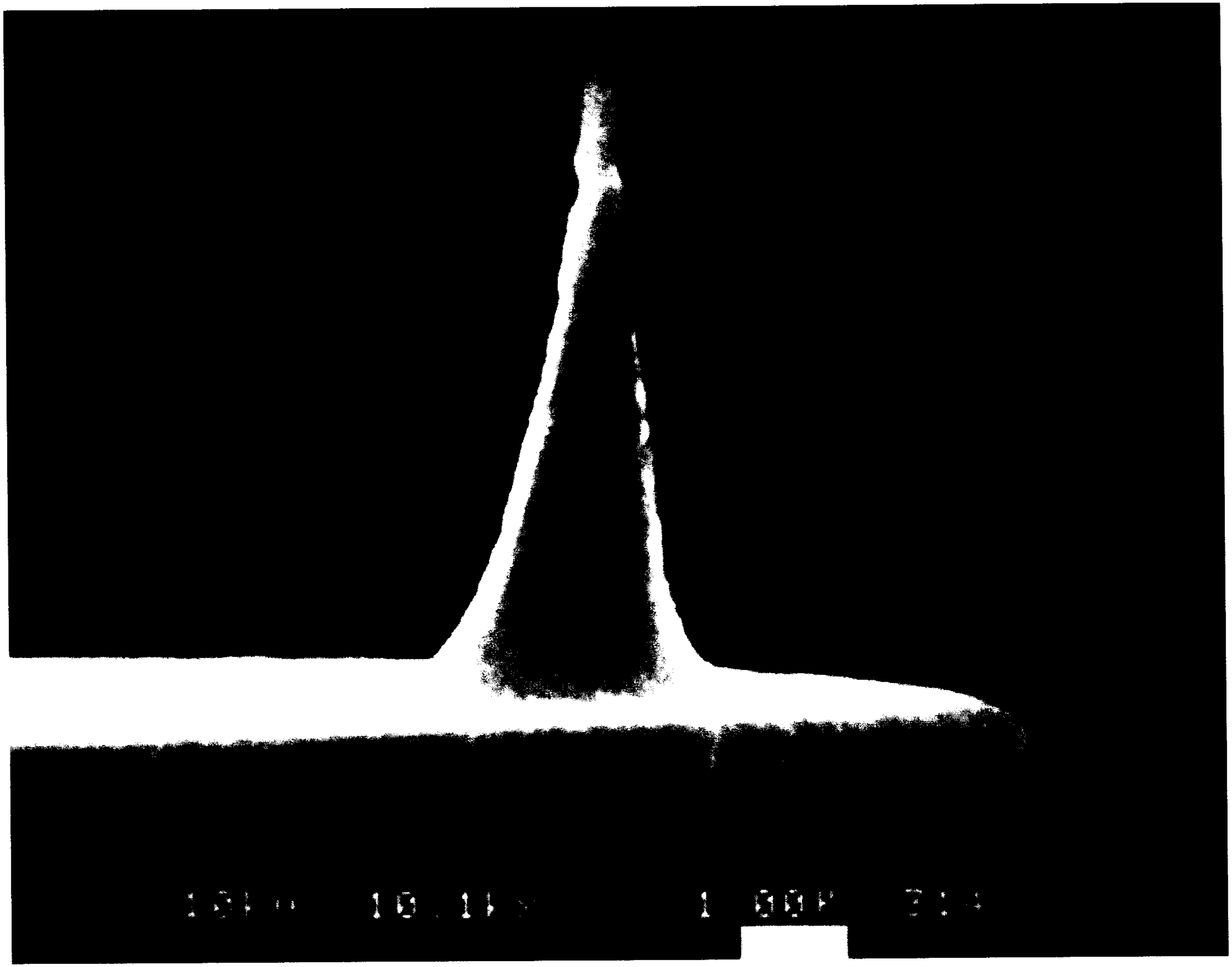
Hard Carbon-Coated S/S

Microscopy - the "Topography"

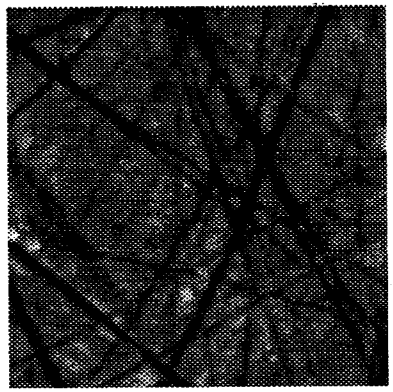
- Optical
  - Useful for locating large sites
  - M < 1000x, poor vertical resolution
- SEM
  - Great resolution, wide magnification range
  - Poor contrast on smooth surfaces
  - Misleading images on dielectrics
  - Poor vertical resolution, vacuum only
- AFM/STM
  - Excellent xyz topographic resolution,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

High-Field Breakdown AFM

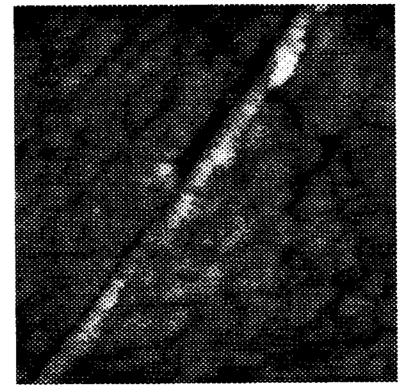




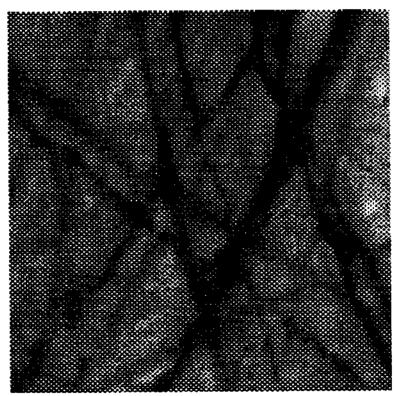
Atomic Force Microscope Imaging - Cu



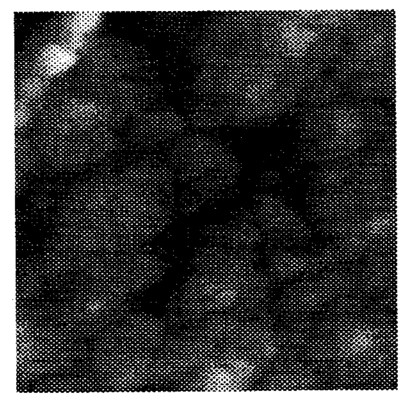
3.5 x 3.5 (μm)^2



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.

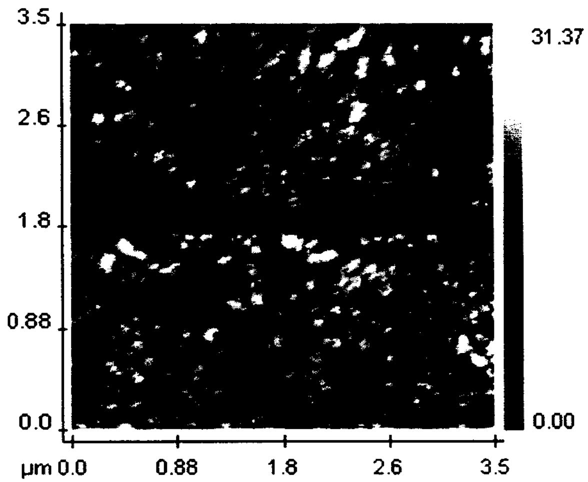
-And…could we be more surgical in choosing sites to measure before we attempt to F-N them (again efficiency).

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

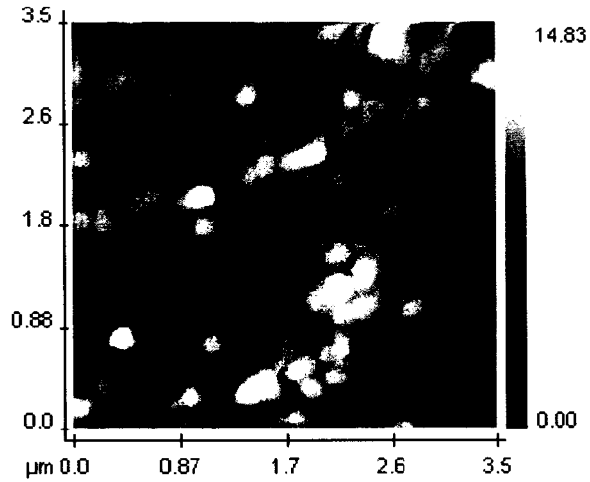
Putting It Together, AFM + F-N

- 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

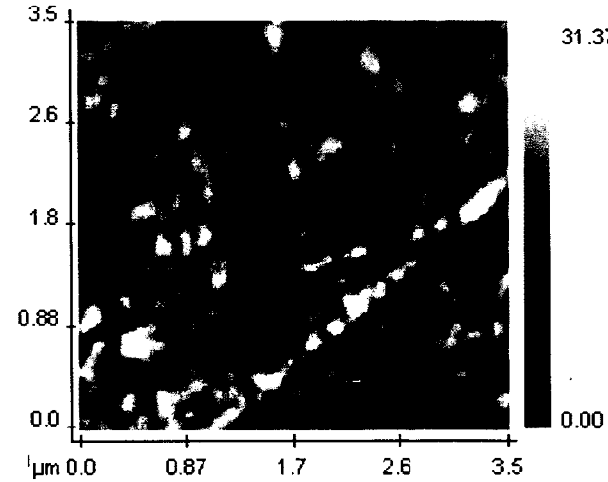
AFM Images - Copper



Clean OFE Cu



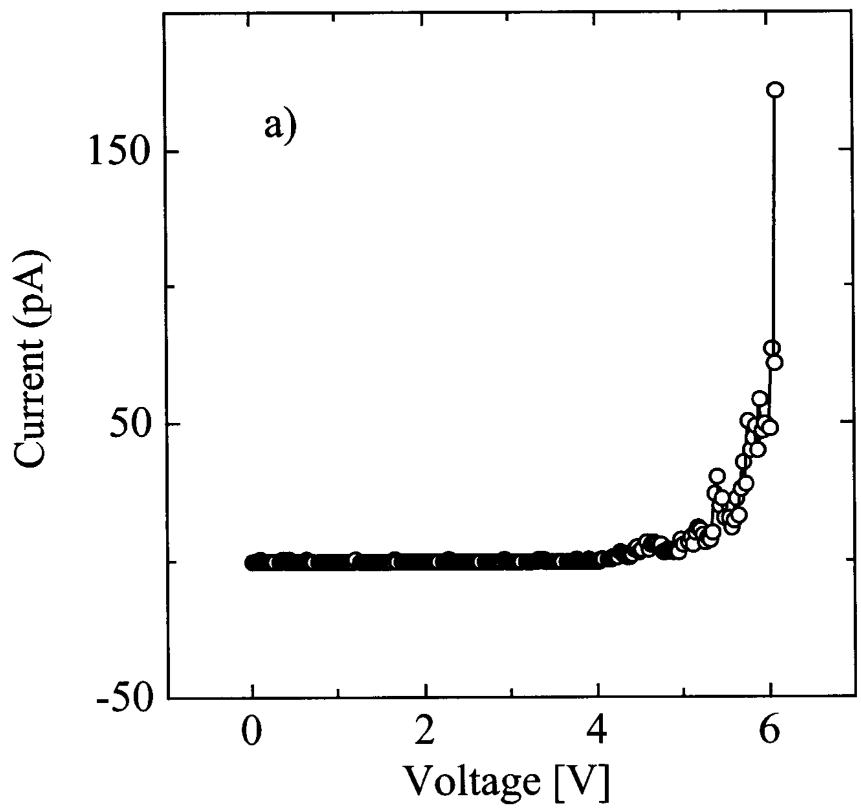
2.5nm Al_2O_3/Cu



2.5nm Al_2O_3 /10nm Pt/Cu

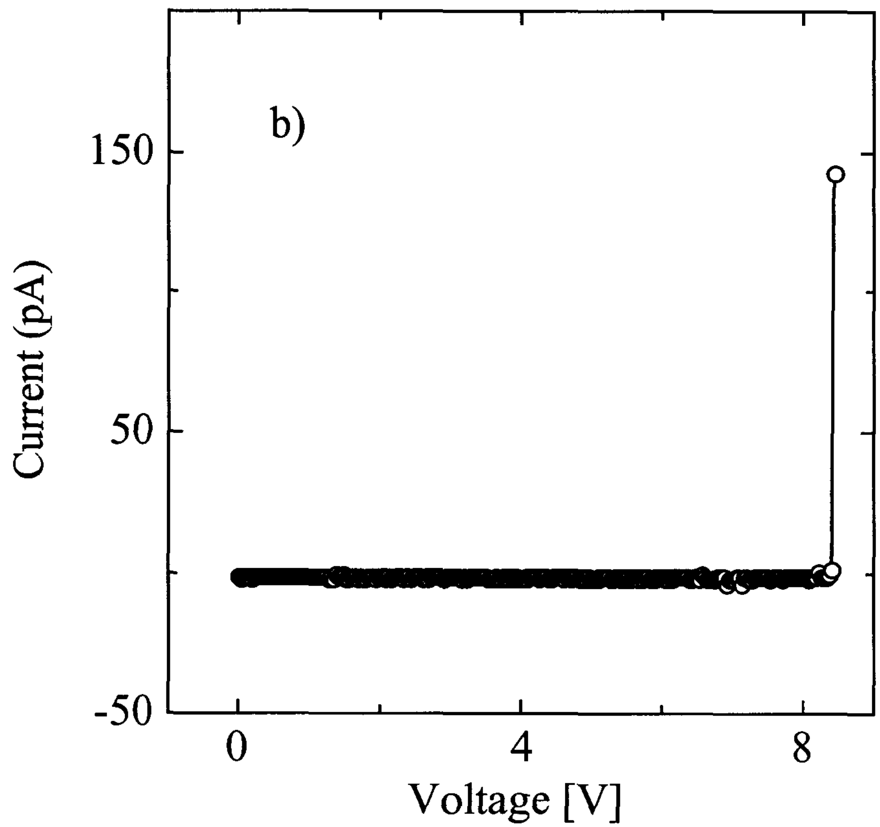
Native Oxide/OFE Copper

"Tunneling"

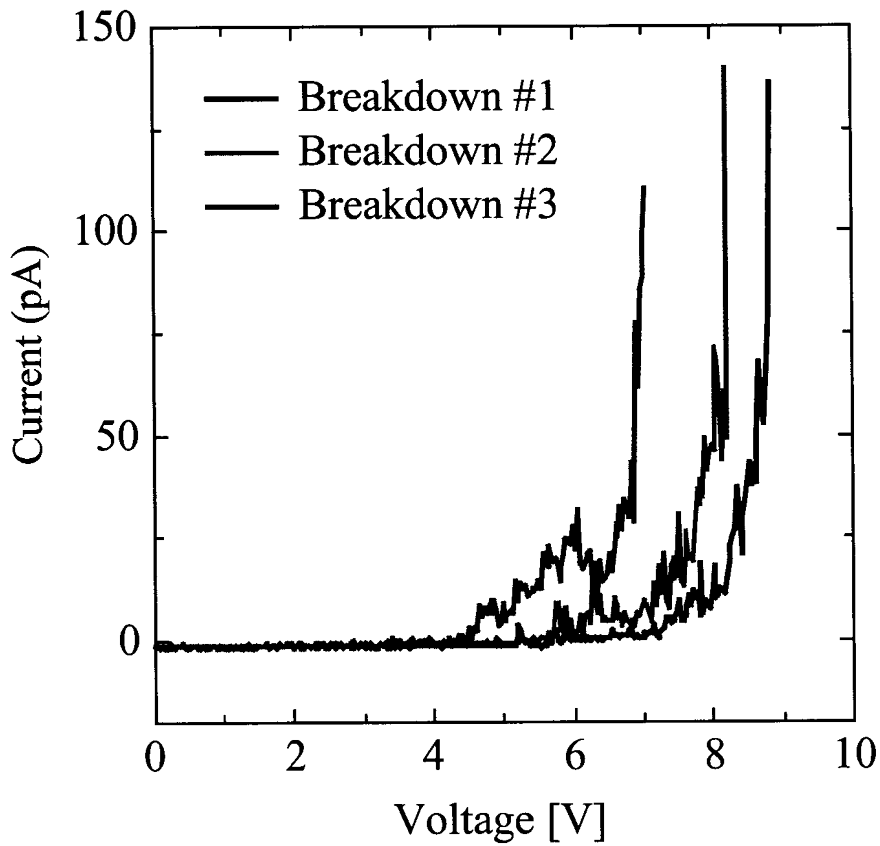


2.5nm Al_2O_3/20nm Mg/OFE Copper

"Breakdown"



Successive Voltage Scans
2.5nm Al_2O_3 on OFE Copper



Fowler-Nordheim Equation

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

α - Effective emission area

s - Oxide thickness

ϕ - 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

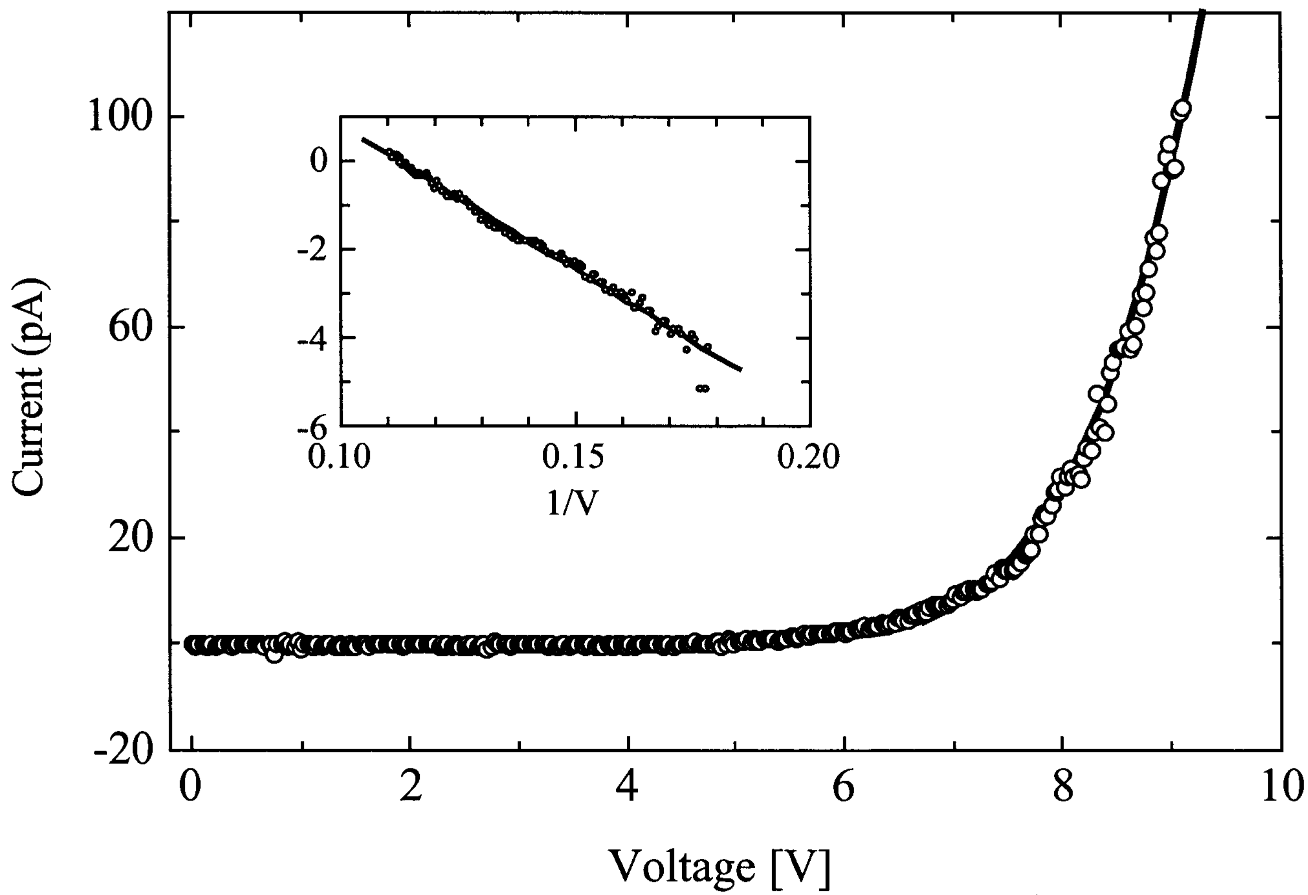
$$E = \beta V/S$$

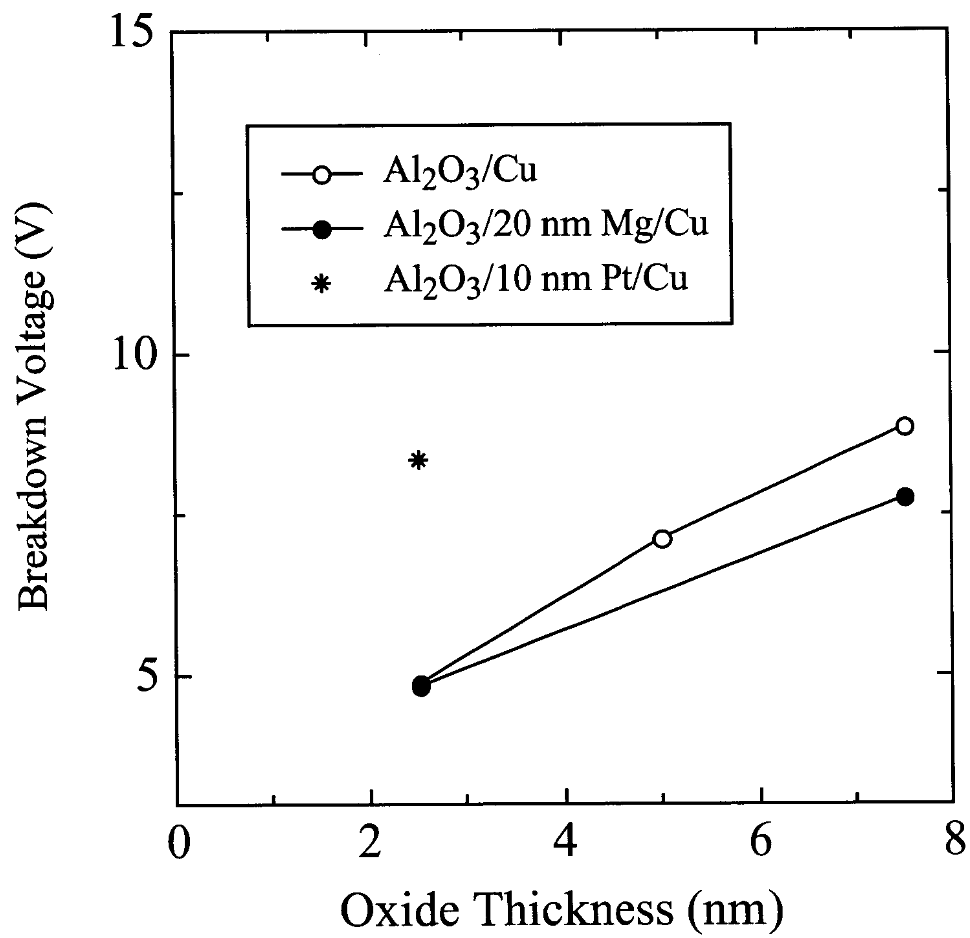
where β is the "field enhancement factor

S is the oxide thickness

2.5nm Al_2O_3/20nm Pt/OFE Copper

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





15
10
5
0
2
4
6
8
Breakdown Voltage (V)
Oxide Thickness (nm)
Al2O3/Cu
Al2O3/20 nm Mg/Cu
Al2O3/10 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