Georgia Tech

# ECE 4813

# Semiconductor Device and Material Characterization

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**Georgia Institute of Technology**

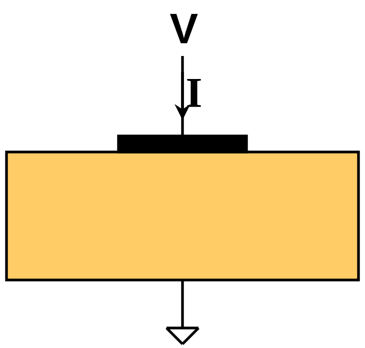
As with all of these lecture slides, I am indebted to Dr. Dieter Schroder from Arizona State University for his generous contributions and freely given resources. Most of (>80%) the figures/slides in this lecture came from Dieter. Some of these figures are copyrighted and can be found within the class text, *Semiconductor Device and Materials Characterization*. ***Every serious microelectronics student should have a copy of this book!***

# Charge-Based Measurements
# Probe Characterization

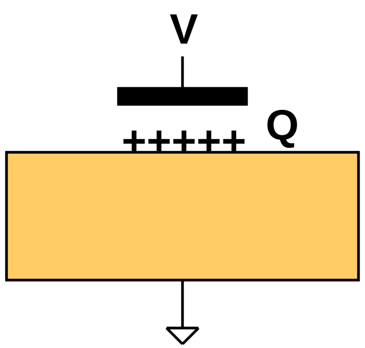
## Scanning Tunneling Microscopy
## Atomic Force Microscopy

# Charge-Based Measurements

- ***Traditional***
  - **Current – voltage**
  - **Capacitance – voltage**
  - **Current, voltage, capacitance – time**
  - **Usually need test structure with contacts**

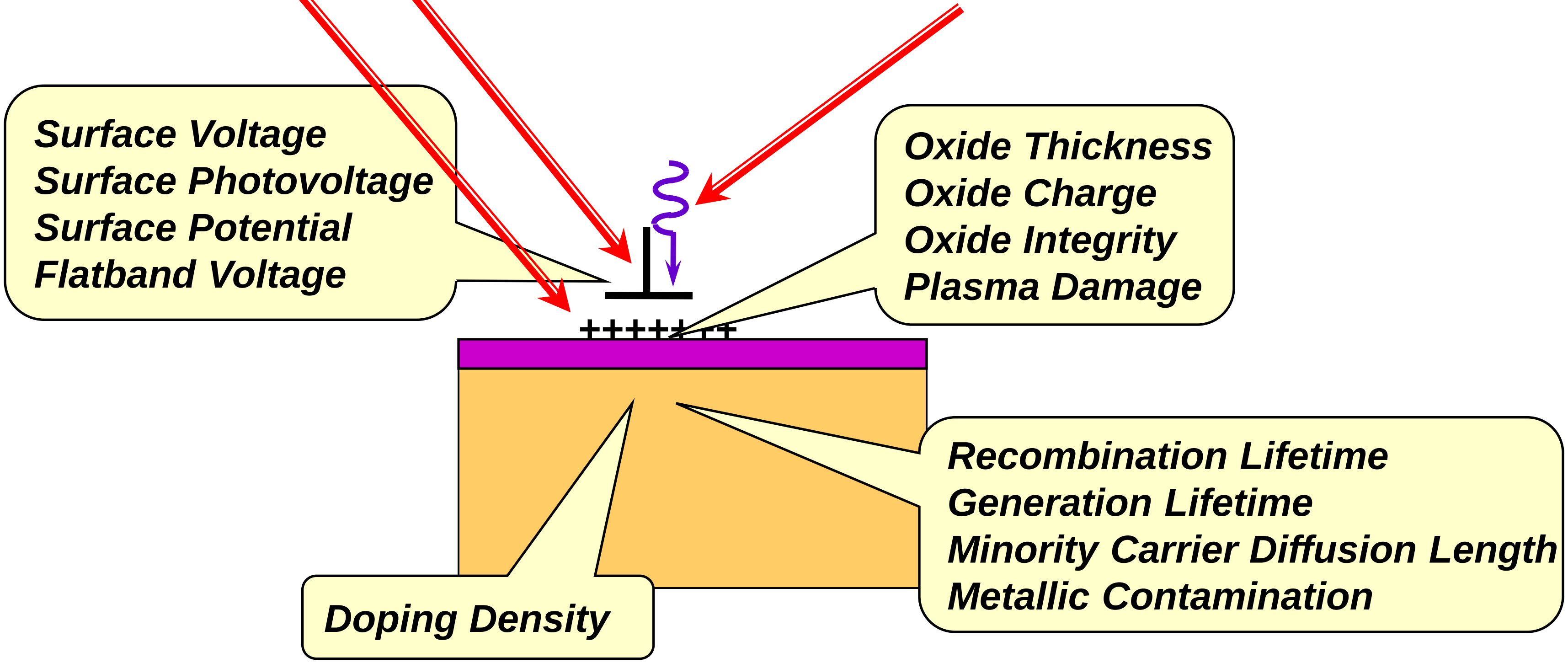



- ***New***
  - **Deposit charge**
  - **Measure surface voltage, surface photovoltage**
  - **Use charge, light**
  - **Usually contactless**



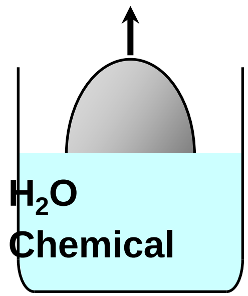
# Charge-Based Measurements

- Charge is deposited on the wafer *chemically* or by *corona charge*
- *Contactless* surface voltage/surface photovoltage is measured
- Measurement can be augmented with *light*



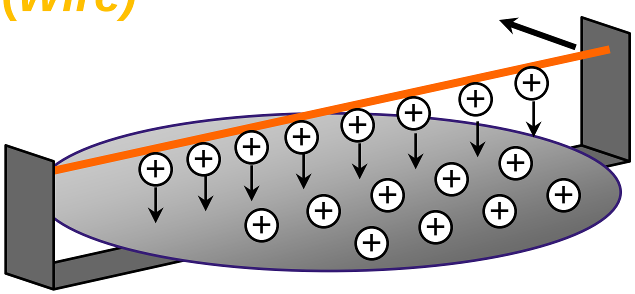
# Surface Charging

## Chemical Rinse



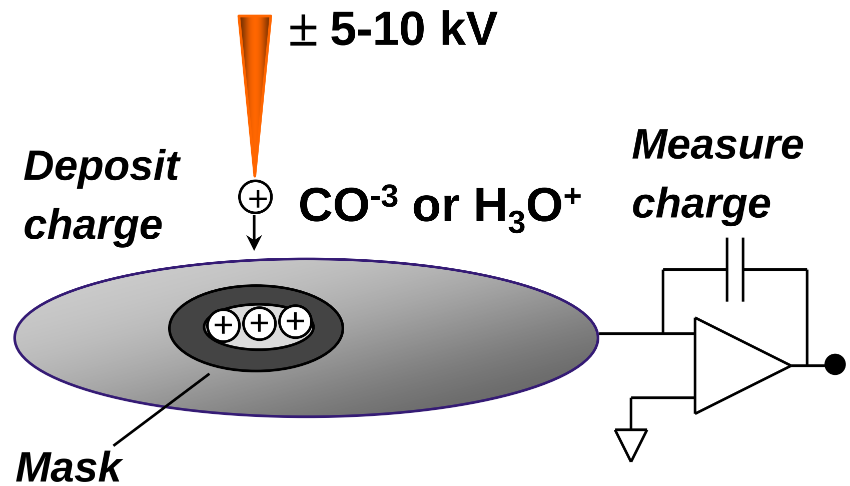

## Blanket Corona Charging

## (*Wire*)



## Localized Corona Charging

## (*Point source* with/without *mask*)



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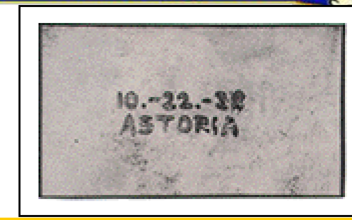
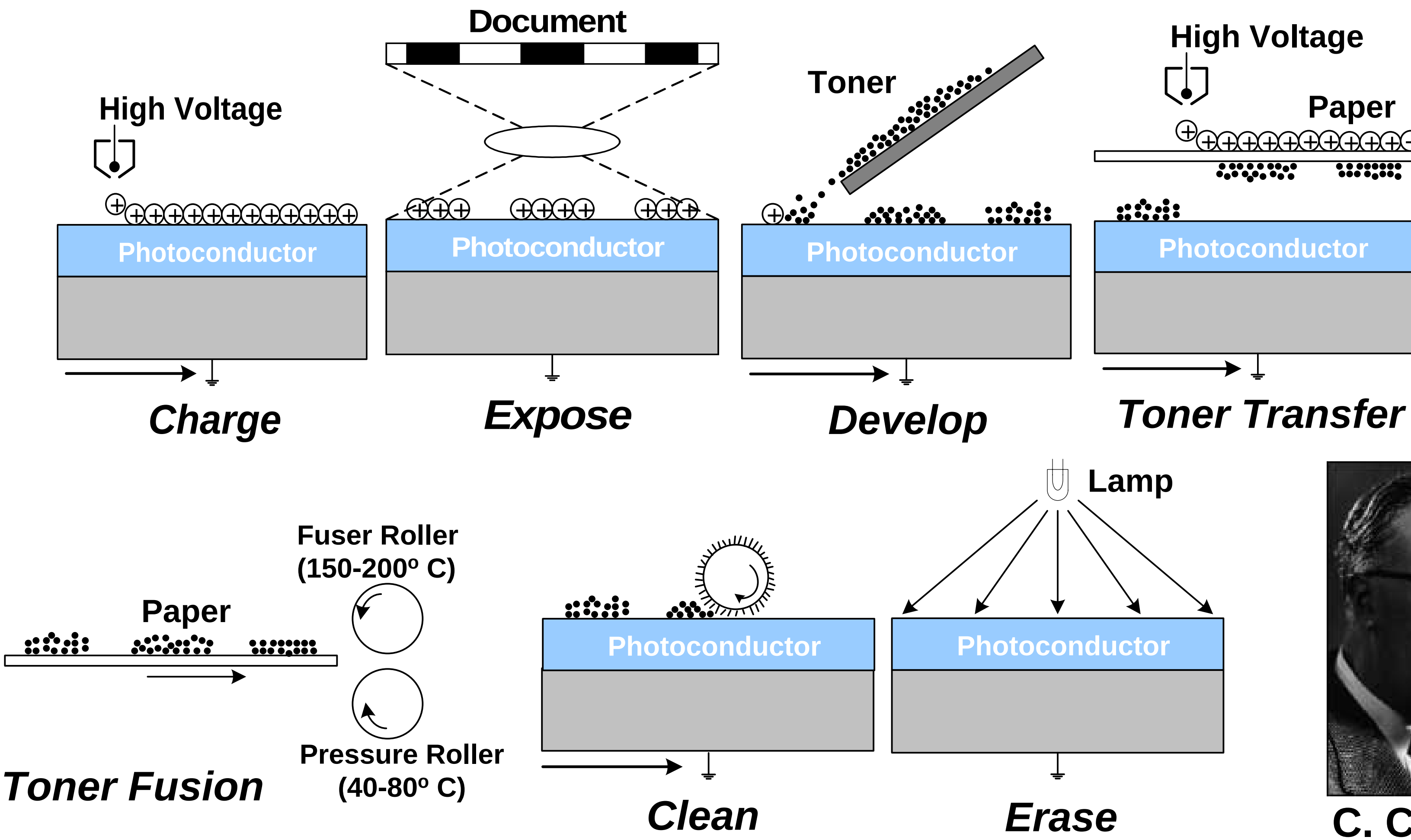
# Xerography

**First Xerographic Image**
**Oct. 22, 1938**

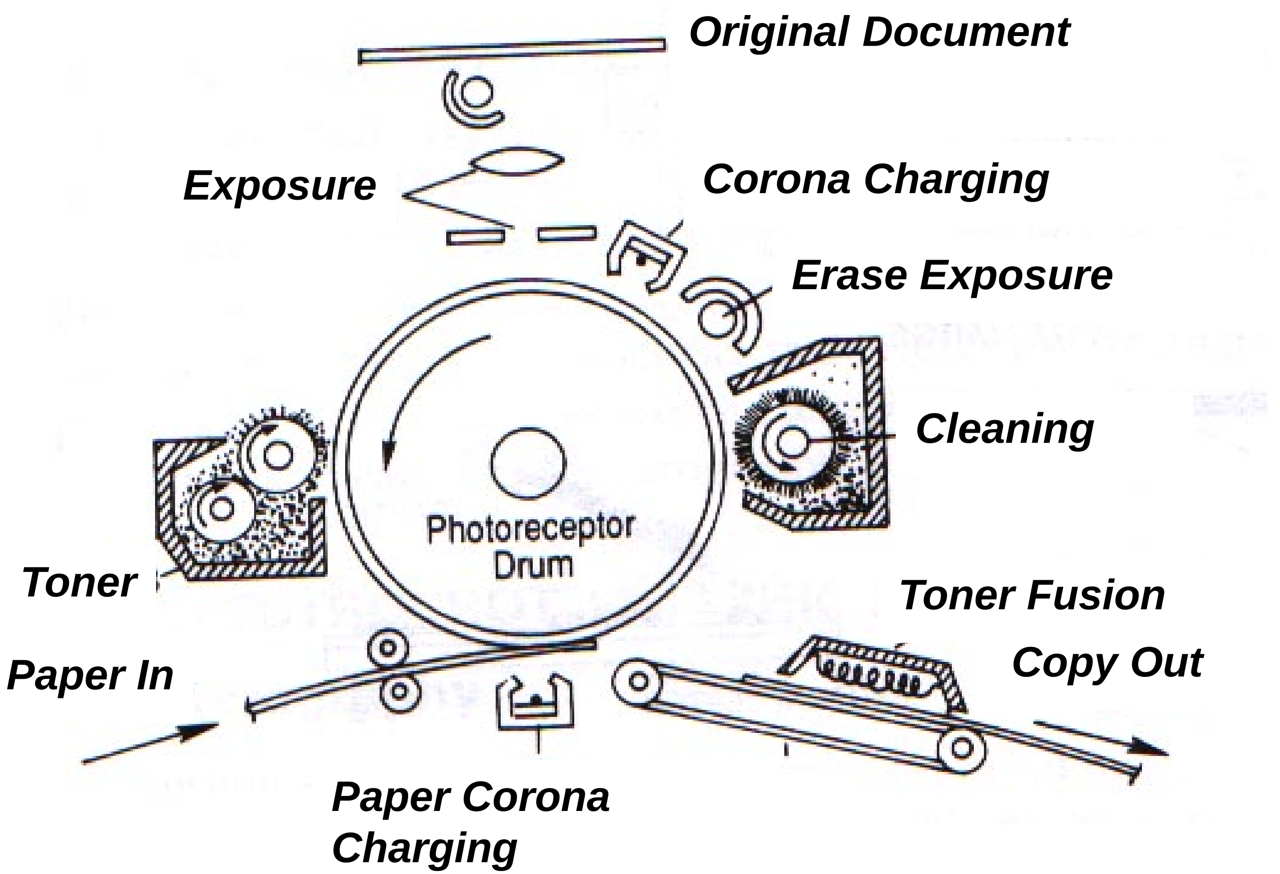



- Chester Carlson experimented with creation of electrostatic images on surfaces of photoconducting insulators



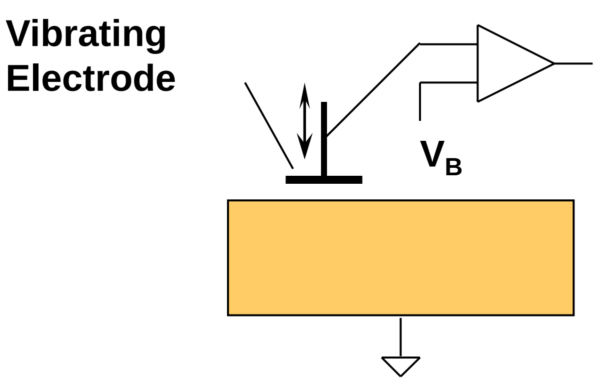

C. Carlson

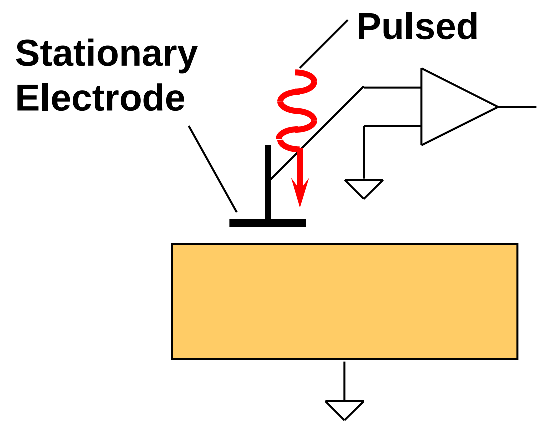
# Xerography


Original Document
Exposure
Corona Charging
Erase Exposure
Cleaning
Photoreceptor Drum
Toner
Toner Fusion
Paper In
Copy Out
Paper Corona Charging

# Voltage Measurement

- *Vibrating* probe: probe is moved mechanically leading to current flow; current is calibrated or voltage $V_B$ is applied until current is zero
- *Stationary* probe: probe is stationary, pulsed light produces time-varying voltage



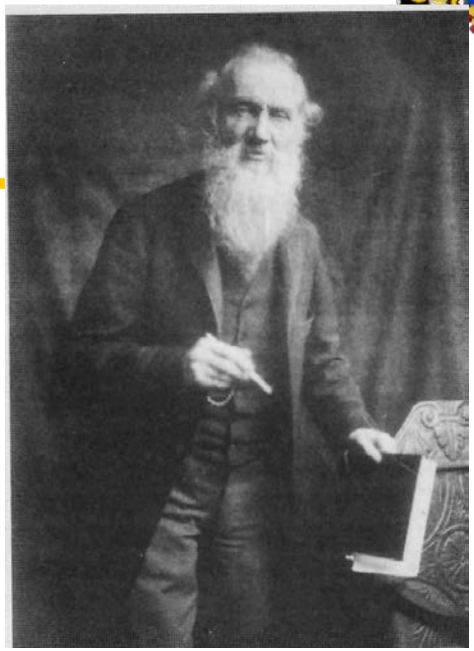

$$I = \frac{d(CV)}{dt} \approx V\underbrace{\frac{dC}{dt}}$$

Capacitance change due to vibrating electrode/gap

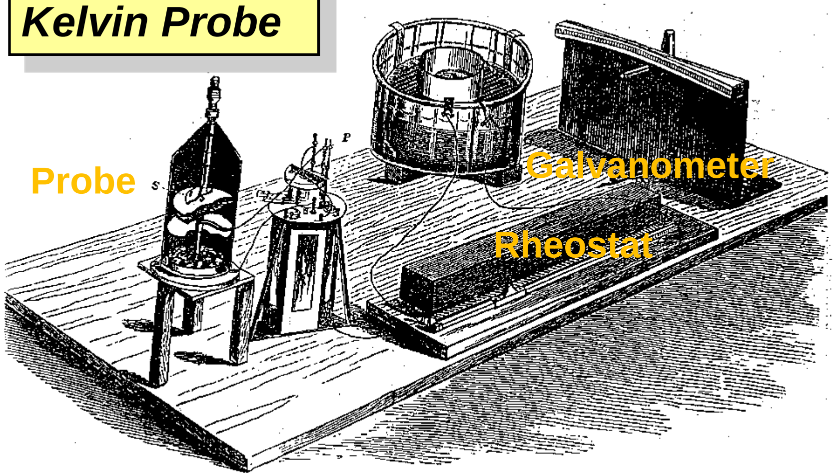
$$I = \frac{d(CV)}{dt} \approx C\frac{dV}{dt}$$

# Kelvin Probe

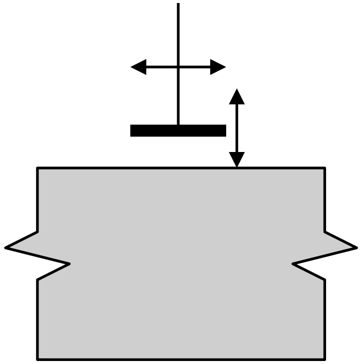
- Probe vibrates *vertically* or *horizontally*
- Piezo drive, ~ 100 – 1000 Hz
- 1 – 60 μm displacement
- Voltage or current is measured



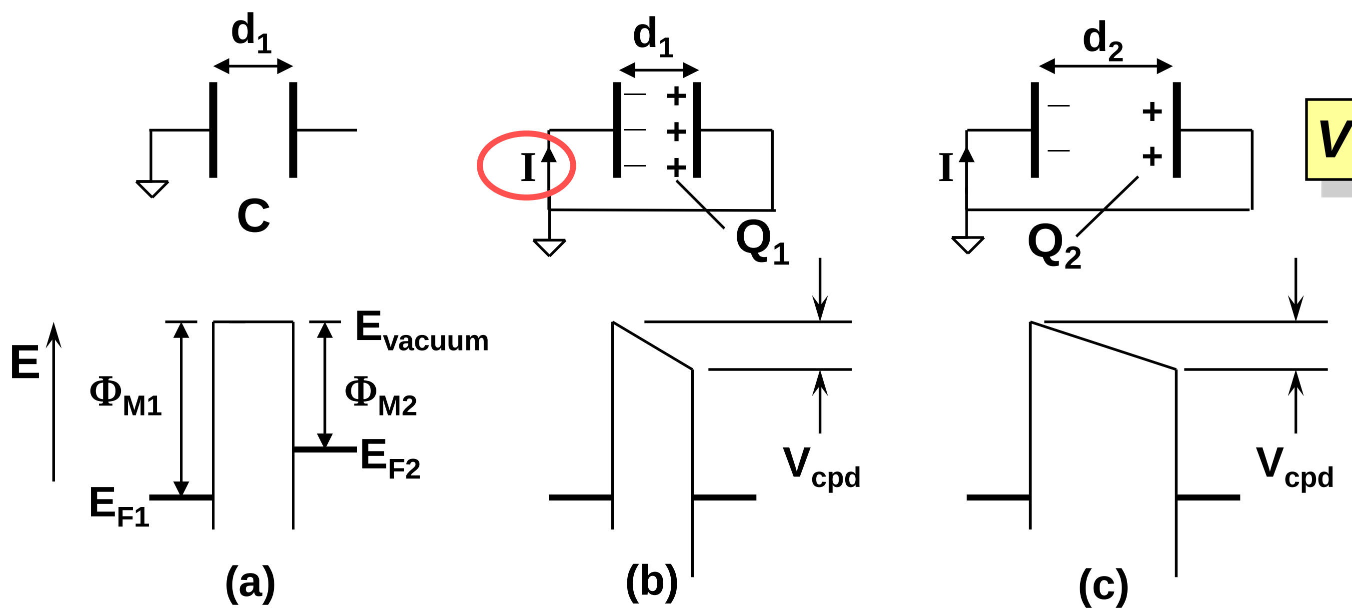

*Original 1898 Kelvin Probe*




Lord Kelvin, *Philos. Mag*. **46**, 82 (1898)



# Vibrating Kelvin Probe: Zero Voltage Mode




$V = Q/C = Qd/\varepsilon_o$

- (a): Open circuit, spacing d = $d_1$, $Q = 0$, $\varepsilon = 0$
- (b): Short circuit, $d = d_1$, $Q = Q_1$, $V = 0$, $\varepsilon = \varepsilon_1$
- (c): Short circuit, $d = d_2 > d_1$, $Q = Q_2 < Q_1$, $V = 0$, $\varepsilon = \varepsilon_2 < \varepsilon_1$

No applied voltage, current flows as plate vibrates

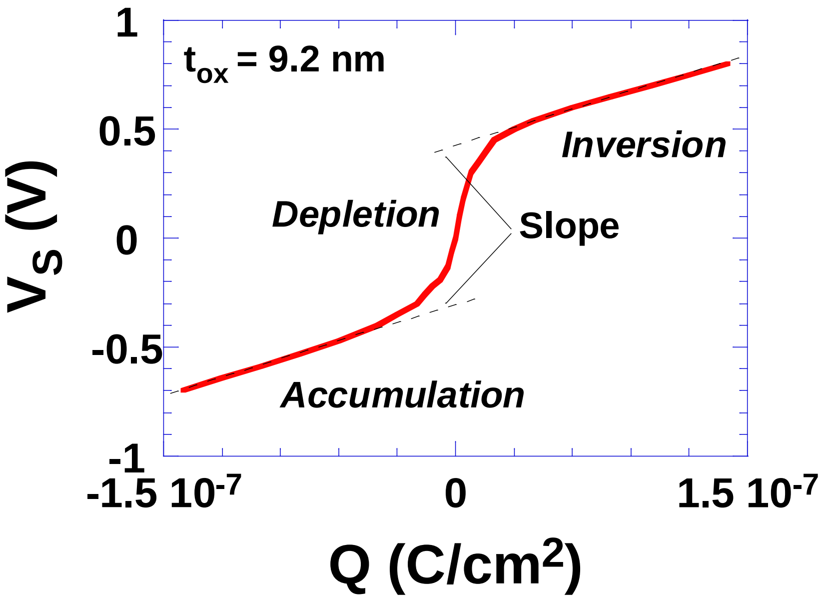
$$I = \frac{dQ}{dt} = V\frac{dC}{dt} = -V\frac{\varepsilon_o}{d^2}\frac{d(d)}{dt}$$

# Oxide Thickness

- Measure the surface voltage as a function of corona charge *Q*
- In inversion/accumulation $\phi_s \approx$ constant
- Slope gives oxide thickness
  - No poly-Si gate depletion
  - Not affected by probe punchthrough
  - Relatively insensitive to oxide pinhole leakage currents

$$V_s = \phi_{MS} + V_{ox} + \phi_s$$

$$C_{ox} = \frac{dQ}{dV_{ox}} \approx \frac{dQ}{dV_s};\ t_{ox} = \frac{K_{ox}\varepsilon_o}{C_{ox}}$$



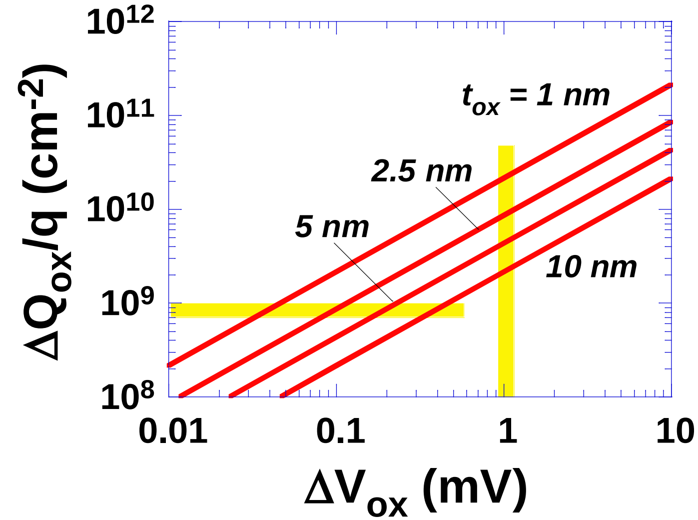
# Errors Associated with Voltage Versus Charge Measurements

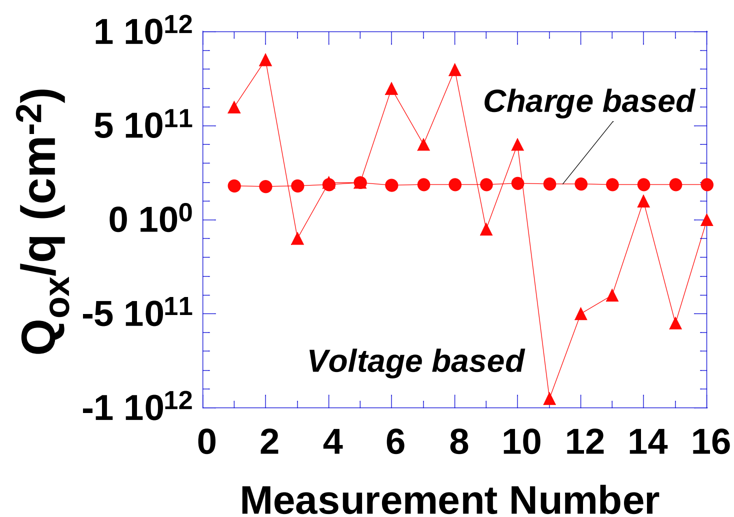
- The oxide charge is related to the oxide voltage through the relationship $Q_{ox} = C_{ox}V_{ox}$
- A voltage uncertainty $\Delta V_{ox}$ leads to a charge uncertainty of

$$\Delta Q_{ox} = \frac{K_{ox}\varepsilon_o \Delta V_{ox}}{t_{ox}}$$

- Voltage-based measurements
  - Large uncertainty in oxide charge
  - Uncertainty is dependent on oxide thickness
- Charge-based measurements
  - Less uncertainty in oxide charge ($\Delta Q_{ox} \approx 10^9$ cm$^{-2}$)
  - Uncertainty independent of oxide thickness

$$\Delta Q_{ox} = \Delta Q_{ox}$$



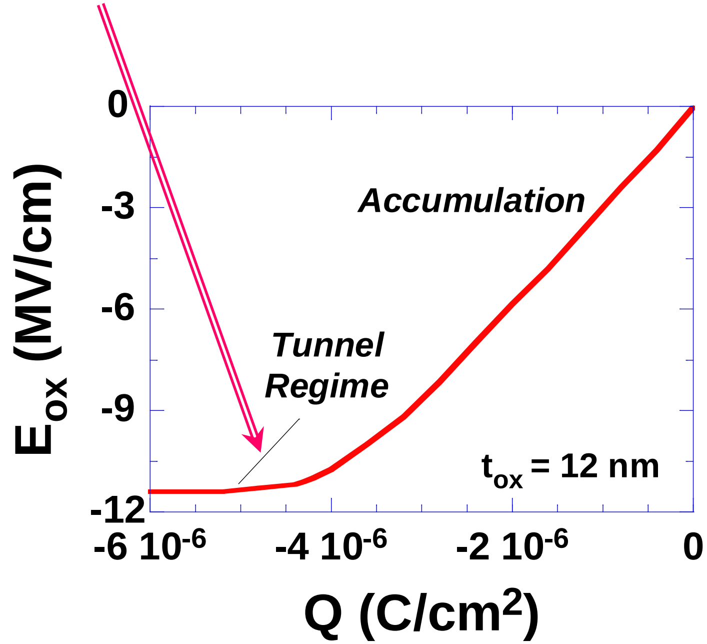
# Gate Oxide Integrity

- Deposit charge on an oxidized wafer
- Some charge leaks through the oxide
- Measure surface voltage as a function of time

$$I_{leak} = C_{ox}\frac{dV}{dt} \Rightarrow V(t) = \frac{I_{leak}}{C_{ox}}t$$

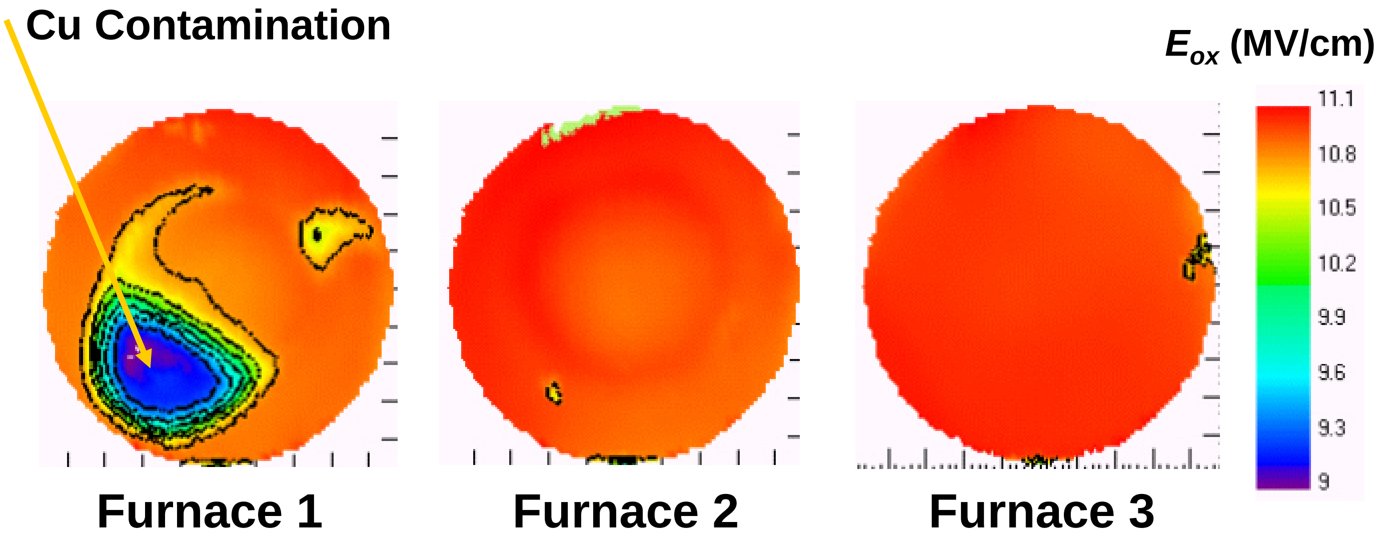
- When the charge density is too high, the charge tunnels through the oxide
- $SiO_2$ breaks down at electric fields of 10-14 MV/cm and $E_{ox}$ saturates

$$Q = K_{ox}\varepsilon_o E_{ox} = 3.45x10^{-13}E_{ox}$$
$$\approx 4x10^{-6}\ C\ for\ E_{ox} = 12\,MV/cm$$



# Gate Oxide Integrity

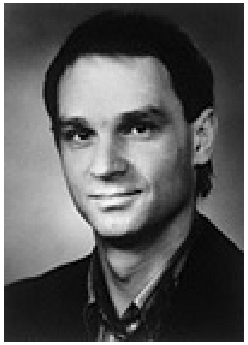
- **3.8 nm production oxide, localized GOI degradation detected**
- **Source: Cu contamination**
- **Missed by TXRF (measured only in 5 spots)**



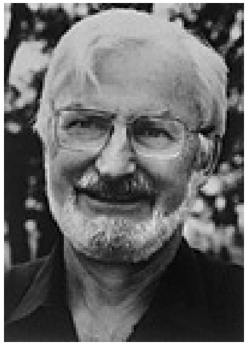

Courtesy of S. Weinzierl, KLA-Tencor.

# Probe Microscopy

- Probe microscopy was invented in 1980 By Binnig and Rohrer at IBM Labs. in Zürich, Switzerland
- They devised a clever way of bringing a sharp metal tip very close (within 1-2 nm) to a conducting sample, applied a voltage and measured the current
- This technique is known a scanning tunneling microscopy
- For this work they were awarded the Nobel prize in 1986



G. Binnig



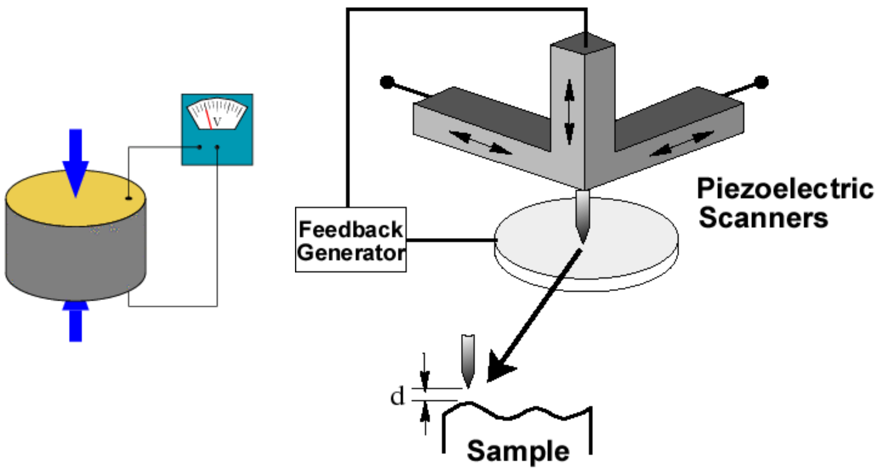
H. Rohrer

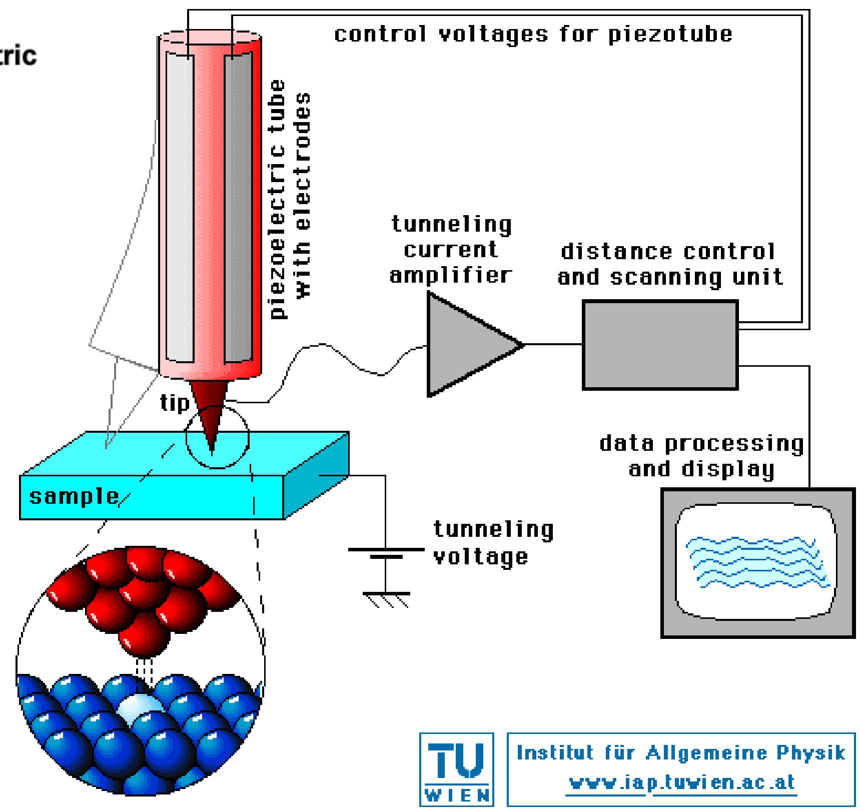
# Probe Microscopies

| | |
|---|---|
| **AFM** | **Atomic force microscope** |
| BEEM | Ballistic electron emission microscope |
| CAFM | Conducting AFM |
| CFM | Chemical force microscope |
| IFM | Interfacial force microscope |
| **MFM** | **Magnetic force microscope** |
| MRFM | Magnetic resonance force microscope |
| MSMS | Micromagnetic scanning microprobe |
| Nano-Field | Nanometer electric field gradient microscope |
| Nano-NMR | Nanometer nuclear magnetic resonance microscope |
| **NSOM** | **Near field scanning optical microscope** |
| **SCM** | **Scanning capacitance microscope** |
| SCPM | Scanning chemical potential microscope |
| SEcM | Scanning electrochemical microscope |
| SICM | Scanning ion conductance microscope |
| **SKPM** | **Scanning Kelvin probe microscope** |
| SThM | Scanning thermal microscope |
| STOS | Scanning tunneling optical spectrometer |
| STM | Scanning tunneling microscope |
| TUNA | Tunneling AFM |

# Scanning Tunneling Microscopy (STM)

- **STM relies on electron tunneling through an air gap**




$$I = \frac{C_1 V}{d} \exp\left( -2d \sqrt{\frac{8\pi^2 m \bar{\phi}_M}{h^2}} \right)$$

$$= I_o \exp(-Kd\sqrt{\bar{\phi}_M}) \;\; (K = 1.025 \; \mathring{A}^{-1} eV^{-1/2})$$

$$\bar{\phi}_M = \frac{\phi_{M,probe} + \phi_{M,substrate}}{2}$$

$$\textit{For } \bar{\phi}_M = 4eV \textit{ and } \Delta I / I = -10\%$$

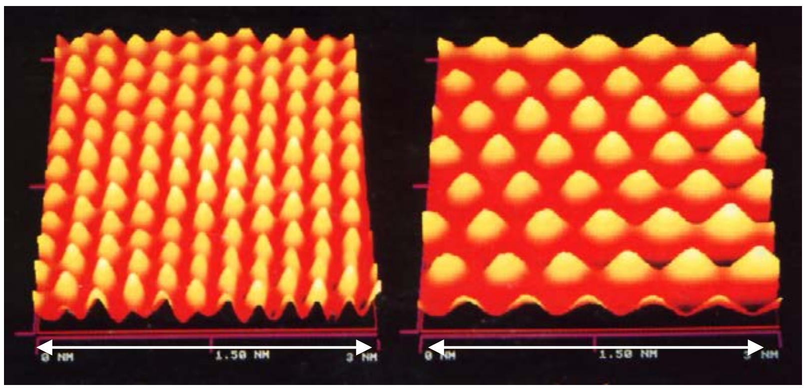
$$\Delta I / I = -K\sqrt{\bar{\phi}_M}\,\Delta d \Rightarrow \Delta d = 0.05 \; \mathring{A}$$

# STM Images

- **STM images can have atomic resolution**

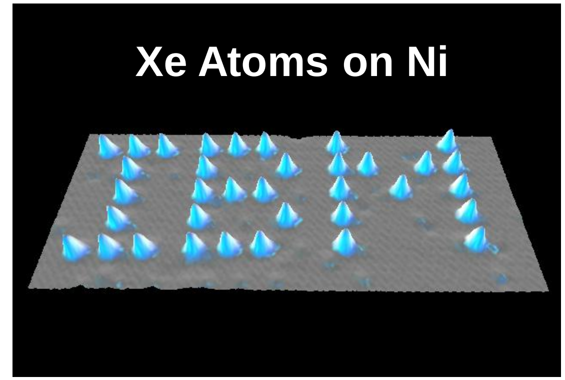
***Au Lattice***

***Au Lattice With 1/3 Monolayer Cu***

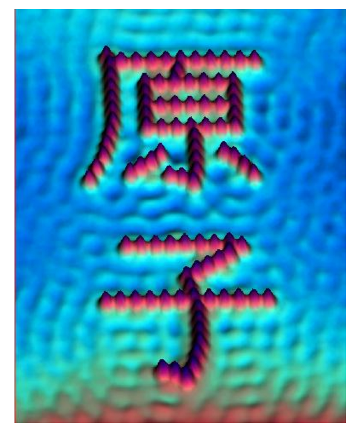


**3 nm** **3 nm**

**Courtesy of Topometrix**



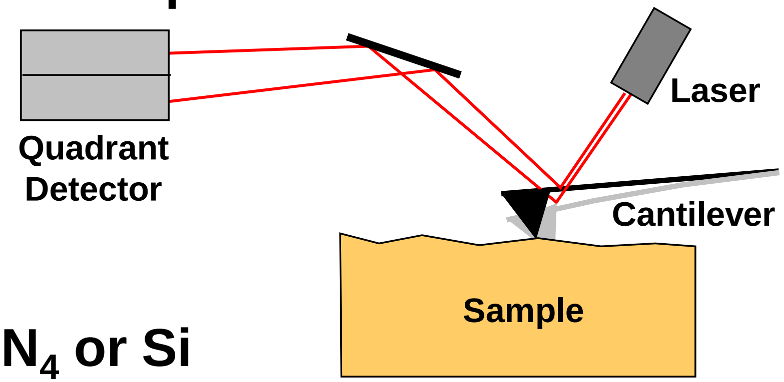

**www.almaden.ibm.com/vis/stm/gallery.html**



**Fe Atoms on Cu Surface “Atom”**

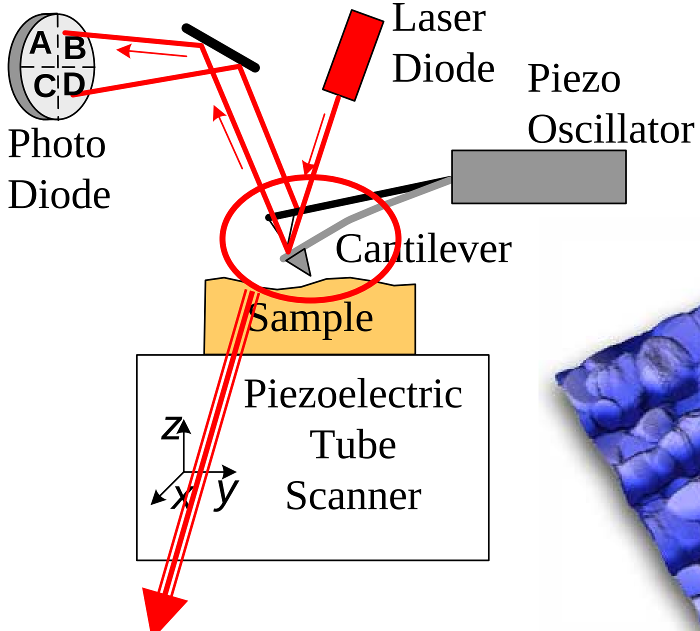
# Atomic Force Microscopy (AFM)

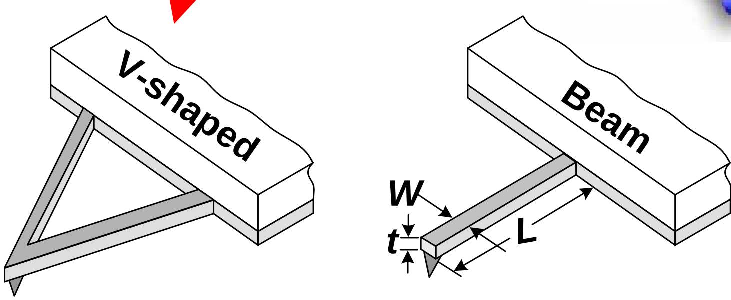
- A sharp tip is scanned over a surface with feedback
- Piezo-electric scanners maintain the tip at
- *Constant force*
  - Height information
- *Constant height*
  - Force information
- Tips are typically made from $Si_3N_4$ or Si
- The detector measures the difference in light intensities between the upper and lower photodetectors
- Feedback from the photodiode difference signal enables the tip to maintain either a *constant force* or *constant height*

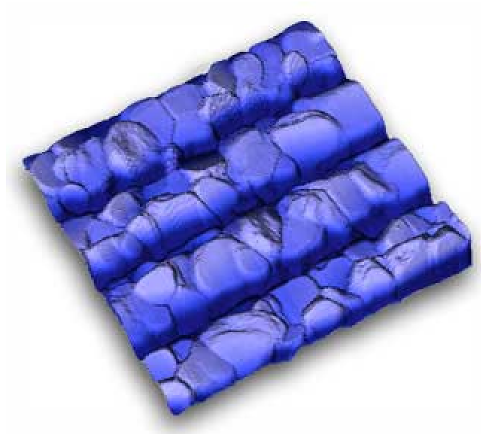


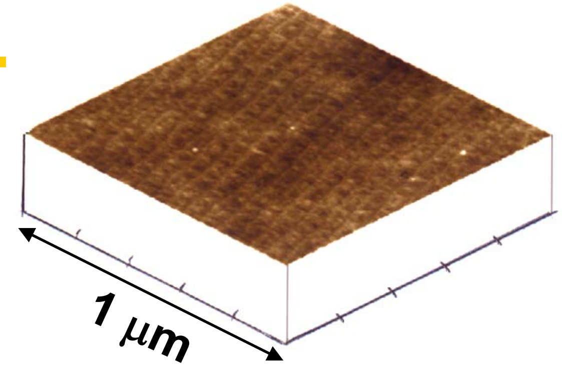

http://www.chembio.uoguelph.ca/educmat/chm729/afm/firstpag.htm

# AFM

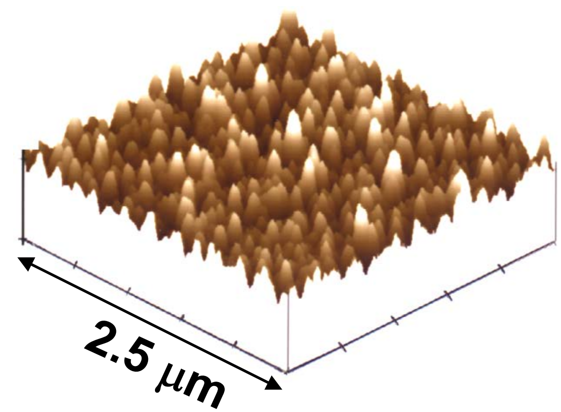





**Epi Si; rms ~ 0.7 Å**



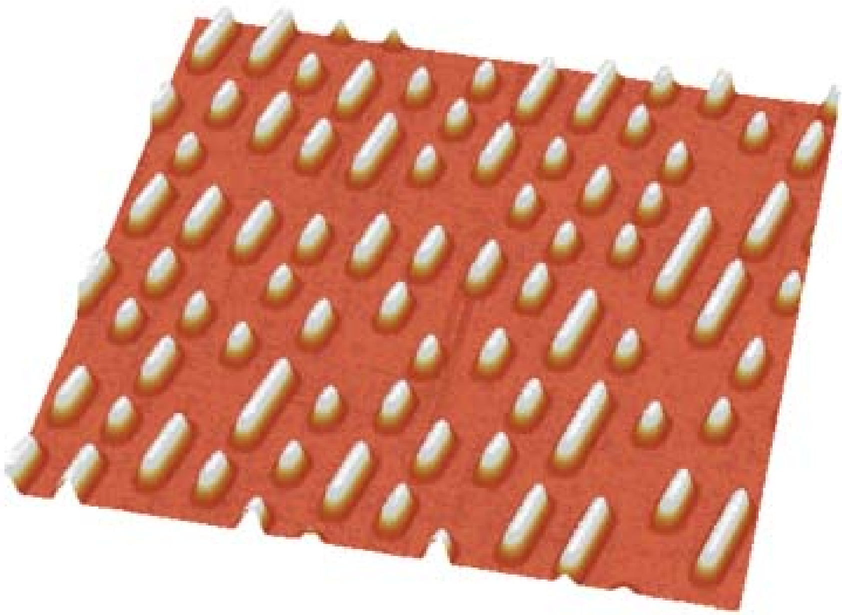

**Poly Si; rms ~ 60 Å**

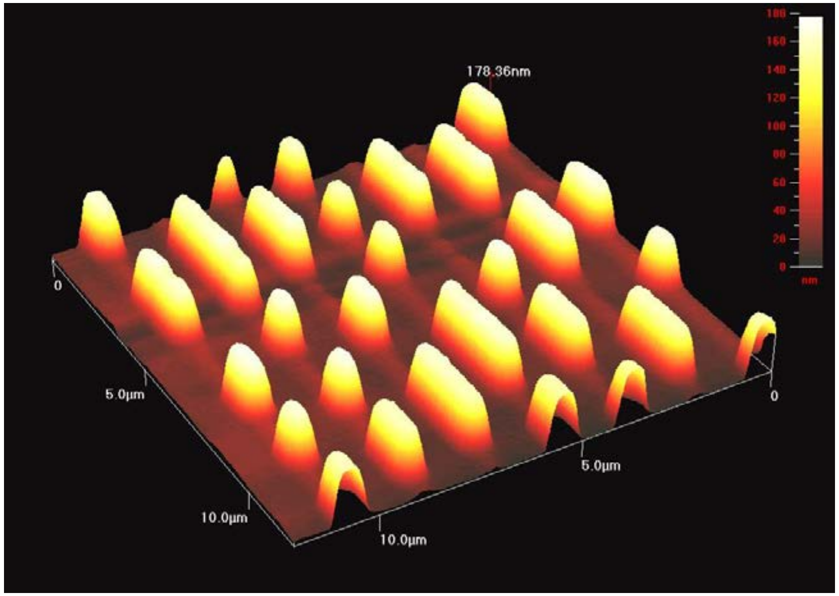
**AFM images courtesy of W. Chen, Motorola**

# Atomic Force Microscopy

- Contact mode
  - Tip scans the sample in close contact with the surface
  - The repulsive force on the tip is around $10^{-8}$ N
  - This force is set by pushing the sample against the cantilever with a piezoelectric element
  - The piezo voltage is proportional to sample height
- Non-contact mode
  - Tip is 5-15 nm above the sample surface. Attractive Van der Waals forces acting between the tip and the sample are detected, and topographic images are constructed by scanning the tip above the surface
- Tapping mode
  - Cantilever oscillates at its resonant frequency (50-500 kHz)
  - The cantilever oscillates with a high amplitude (around 20nm) when the tip is not in contact with the surface
  - The oscillating tip is then moved toward the surface until it begins to lightly touch, or tap the surface
  - Oscillation amplitude is reduced
  - The reduction in oscillation amplitude is used to measure surface features

# AFM Images

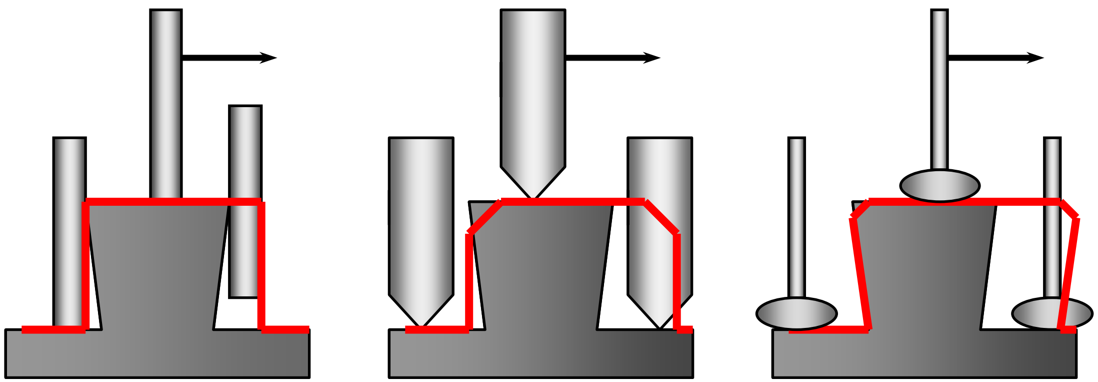


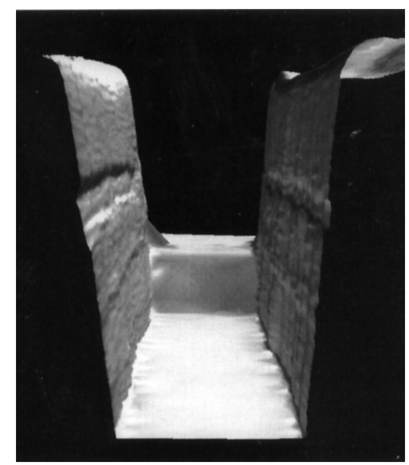



**Digital Video Disk** **CD Stamper**

# Atomic Force Microscopy

- Measured line width is probe shape dependent
  - Tip shape obtained from profiling standard samples
  - True profile is obtained from known probe tip shape
- Probe shape, flexing stability
- Piezoelectric scan linearity
- Low throughput



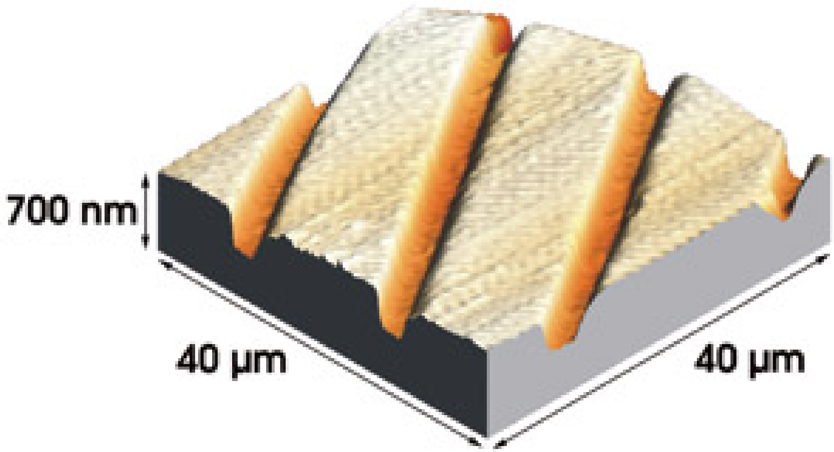


0.45 µm

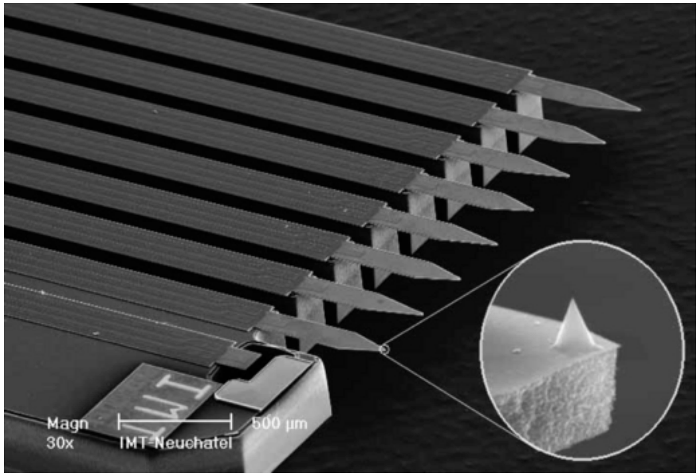
Courtesy of IBM

# AFM Images of Mars

- **AFM on Mars Phoenix Lander**
  - **8 AFM points**
  - **Can be broken off**
  - **Height sensed by piezoresistors**


**The first AFM image taken on Mars of Martian soil; 40 × 40-µm, grooves are 300 nm deep and 14 µm apart.**

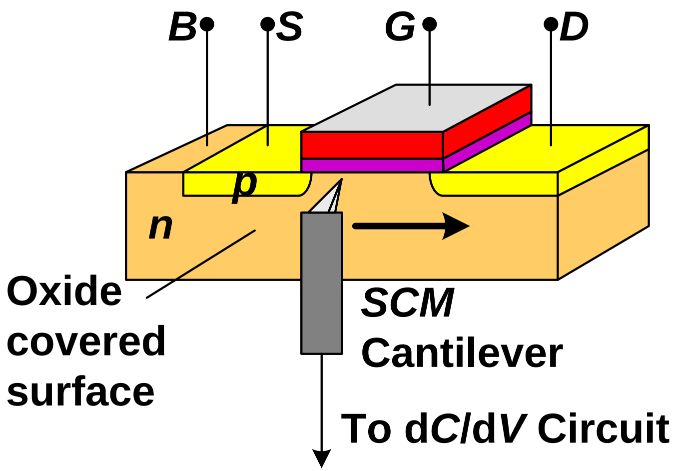


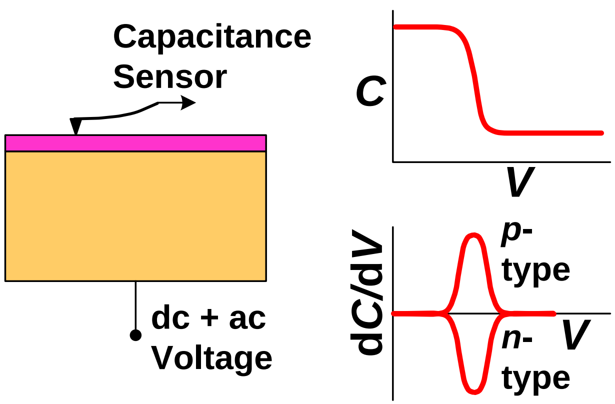

**AFM needles**

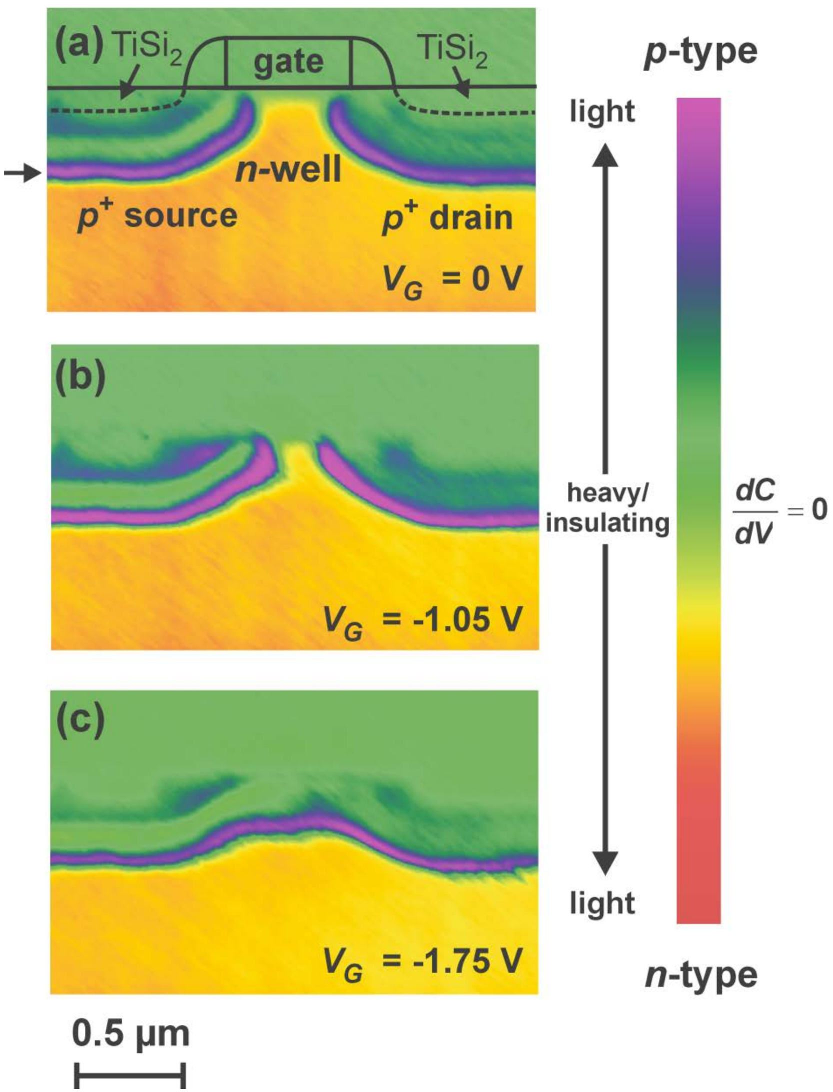
*Photonics Spectra*, **42,** 68, Dec. 2008

# Scanning Capacitance Microscopy

- **Capacitance is analyzed to yield doping densities**



# Review Questions

- What advantages do charge-based measurements have over voltage-based measurements?
- How is the charge deposited?
- How is the voltage measured?
- Why are charge-based measurements less sensitive to oxide pinholes than conventional oxide integrity measurements?
- How do Kelvin probes work?
- What is the principle of scanning tunneling microscopy?
- What is the principle of atomic force microscopy?
- What materials can be measured with STM?
- What materials can be measured with AFM?
- Why does the probe shape matter in AFM?
- What is measured with scanning capacitance?