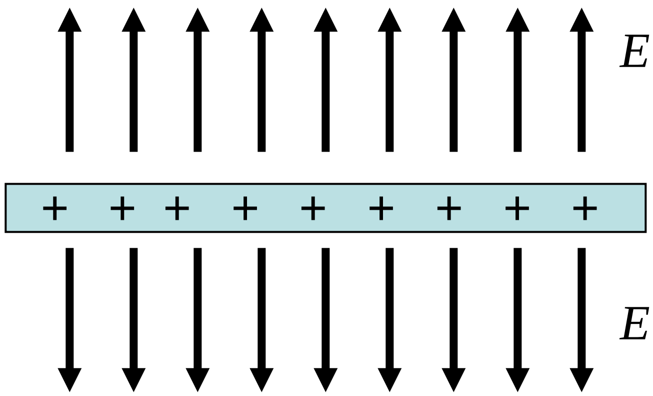
ME597/PHYS57000
Fall Semester 2010
Lecture 24

Using the AFM to Measure Electrostatic Forces

Electrostatics of Charged Plates

Charge +Q added to plate of area A



$$E = \frac{\sigma}{2\varepsilon_o}$$

$$\sigma = \frac{Q}{A}$$

$$E = \frac{\sigma}{2\varepsilon_o}$$

$$E = 0$$

$$E_{net} = \frac{\sigma}{\varepsilon_o}$$

$$E = 0$$

2 clicks

Standard results – Parallel Plates

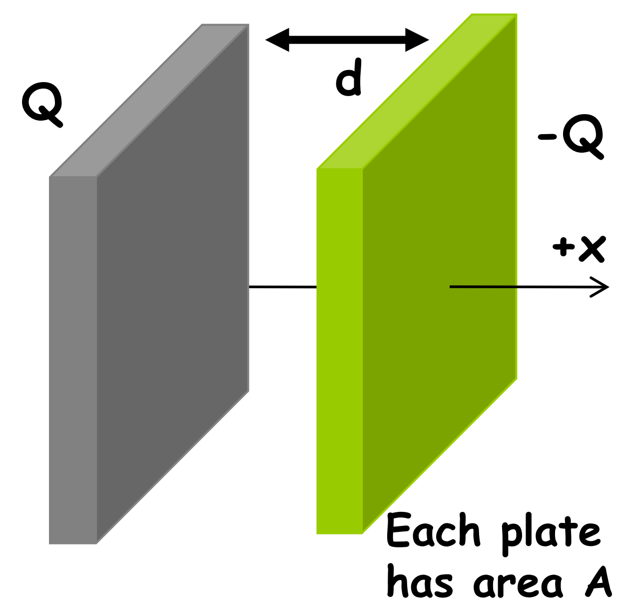
aka ΔV

$$E_{net} = \frac{\sigma}{\varepsilon_o} = \frac{Q}{\varepsilon_o A}; \quad V = E_{net} d = \frac{Q}{\varepsilon_o A} d$$

$$Q = \varepsilon_o A \frac{V}{d}; \quad C \equiv \frac{Q}{V} = \frac{\varepsilon_o A}{d};$$

$$\Rightarrow \quad C = \frac{\varepsilon_o A}{z}; \quad \left[\frac{dC}{dz}\right]_{z=d} = \left[-\frac{\varepsilon_o A}{z^2}\right]_{z=d} = -\frac{\varepsilon_o A}{d^2}$$

$$|F| = \left|q_{right\ plate} E_{left\ plate}\right| = \left|(-Q)\right| \frac{1}{2} \frac{Q}{\varepsilon_o A} = \frac{1}{2}\left(\frac{\varepsilon_o A}{d^2}\right) V^2 \quad (attractive)$$

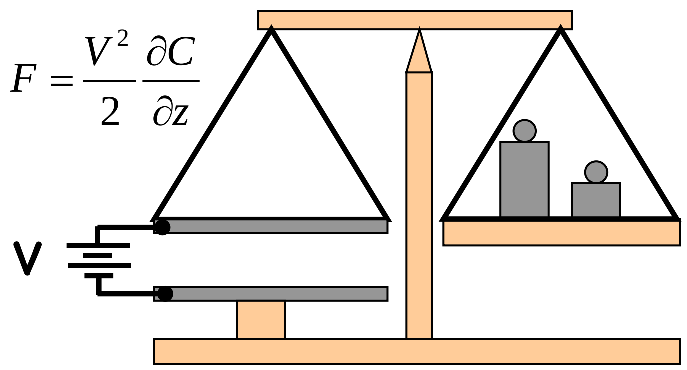


(for finite size, circular plates with separation d and diameter D):

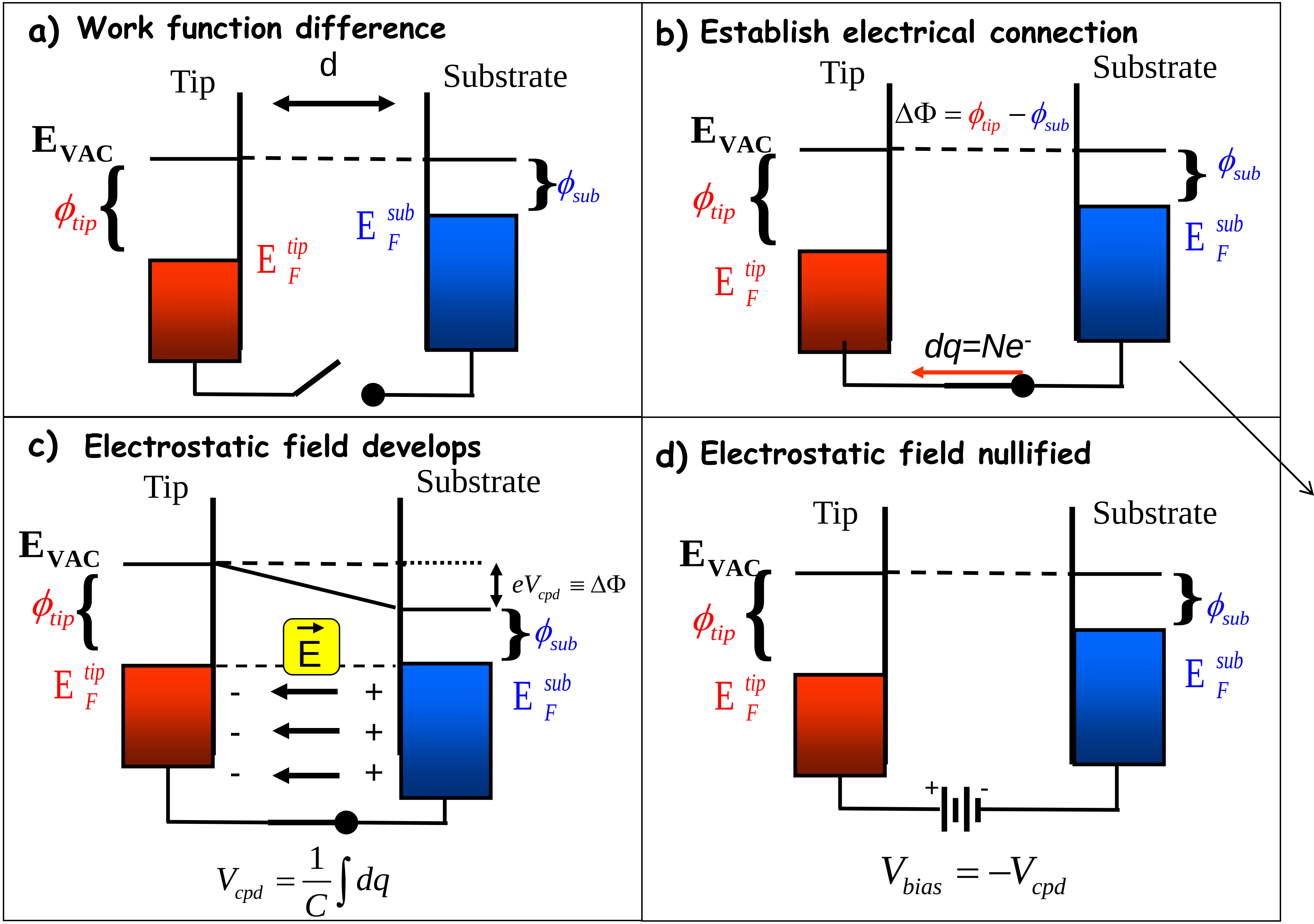
$$F \approx \frac{\varepsilon_o A V^2}{2d^2}\left(1 + \frac{2d}{D} + ...\right)$$

in general

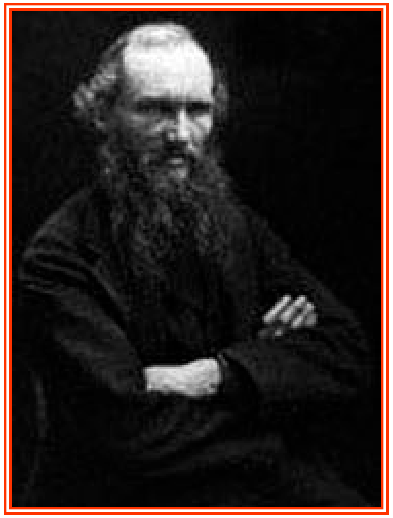
$$F = -\frac{1}{2} \frac{dC}{dz} V^2$$



Contact Potential Difference (CPD)



Macroscopic Kelvin Probe Measures CPD

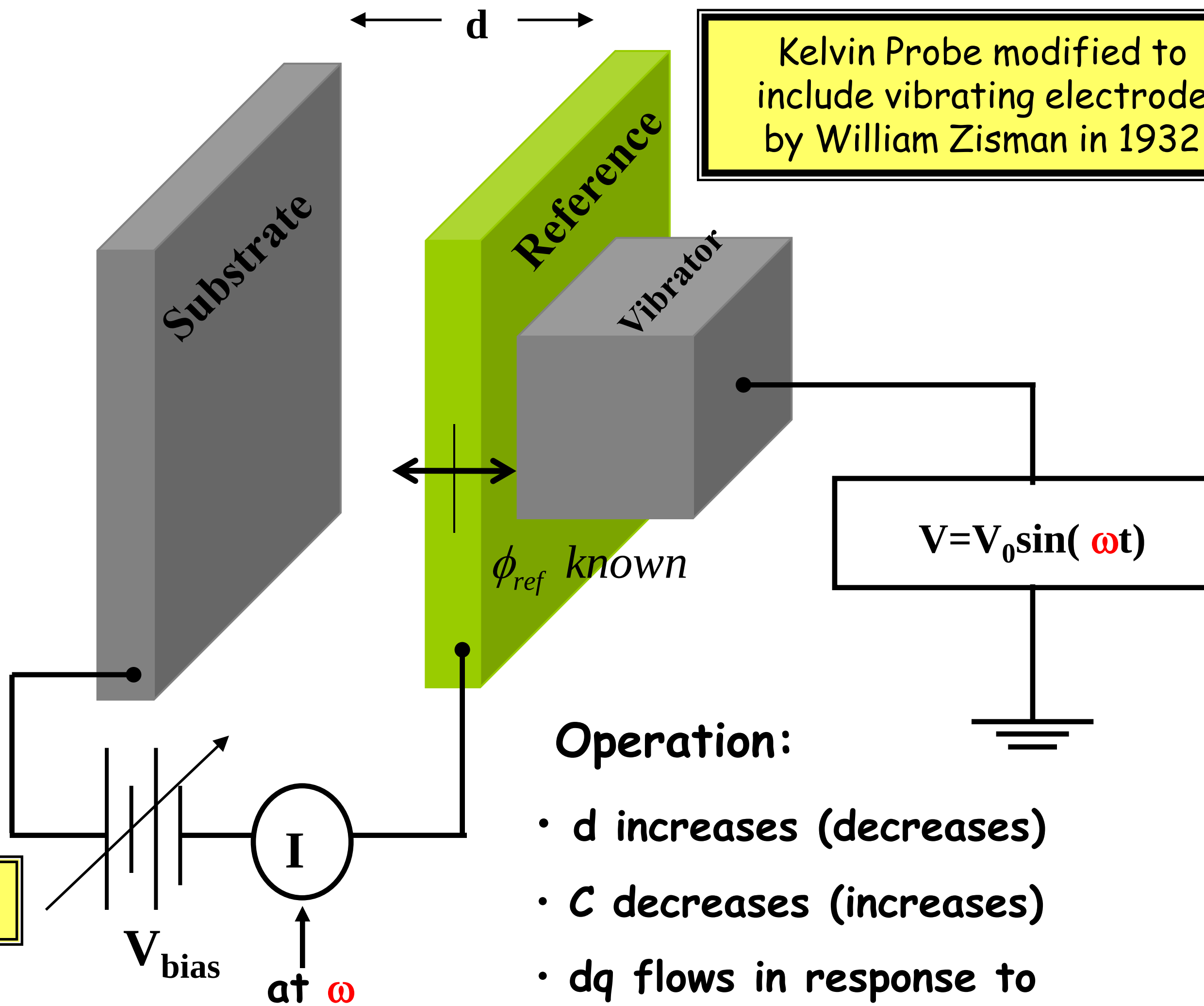


- Sir Wm. Thomson, Lord Kelvin, 1861
- Non-contact
- Non-destructive
- ~1 mV resolution (best case)

Adjust V_{bias} so I =0

$$C = \frac{Q}{V_{cpd}} = \varepsilon_o \frac{A}{d}$$

Kelvin Probe modified to include vibrating electrode by William Zisman in 1932



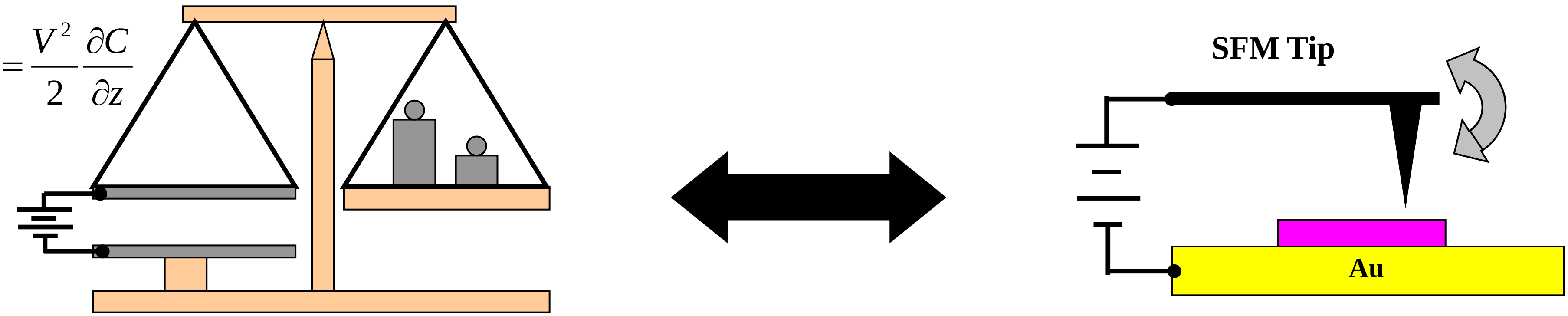
Operation:

- d increases (decreases)
- C decreases (increases)
- dq flows in response to change in C

Electrostatic Force Microscopy
The Basic Idea

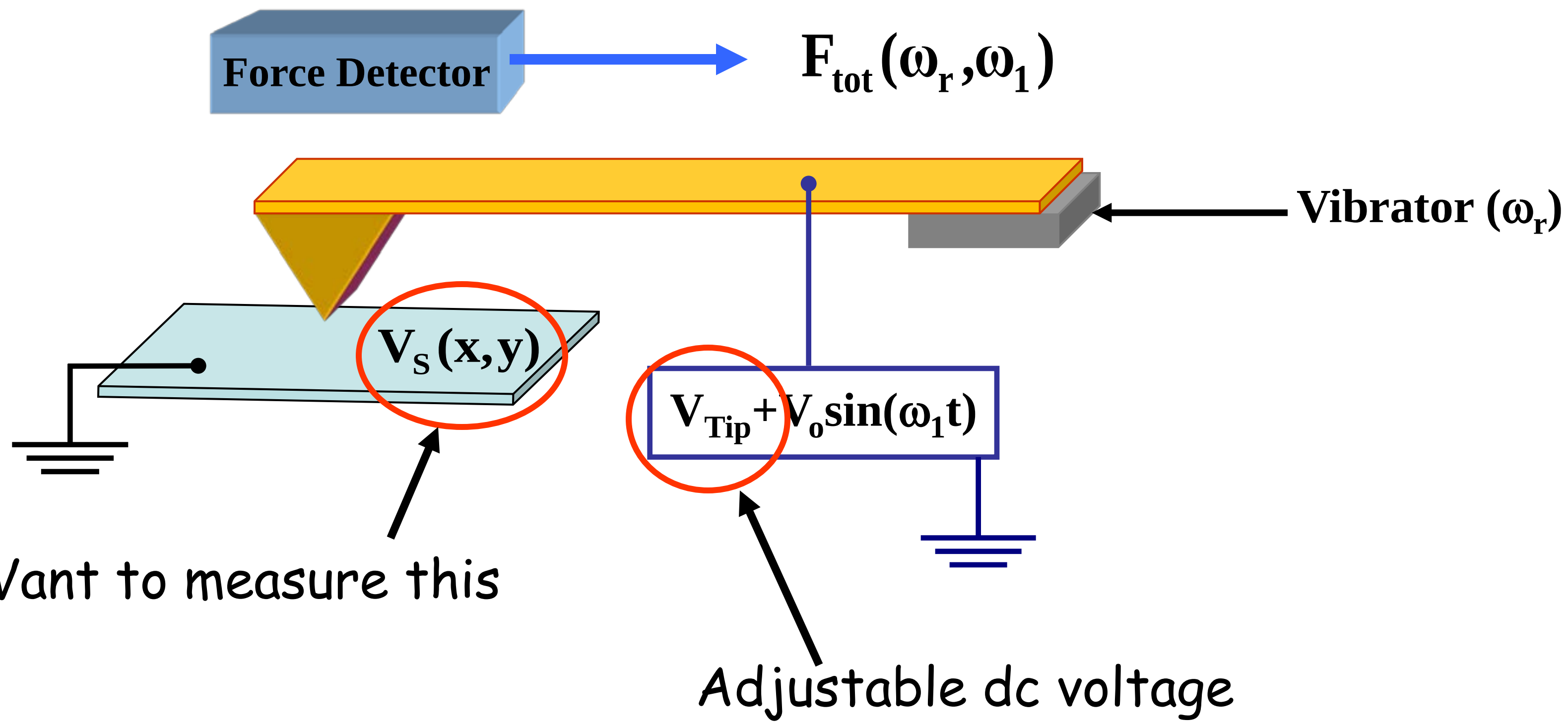
Macroscale | Nanoscale

$$F = \frac{V^2}{2}\frac{\partial C}{\partial z}$$



M. Nonnenmacher, M. P. O'Boyle, and H. K. Wickramasinghe, *Appl. Phys. Lett.* **58**, 2921 **(1991)**.

The Basic Idea



The tip-sample potential difference (cpd) is:

$$\Delta V=V_S(x,y)-[V_{Tip}+V_o\sin(\omega_1 t)]$$

The force acting on the cantilever due to the tip-sample capacitance gradient is:

$$F_{electrostatic} = -\frac{1}{2}\frac{dC}{dz}(\Delta V)^2$$

$\Delta V = V_S(x,y) - [V_{Tip} + V_o \sin(\omega_1 t)]$

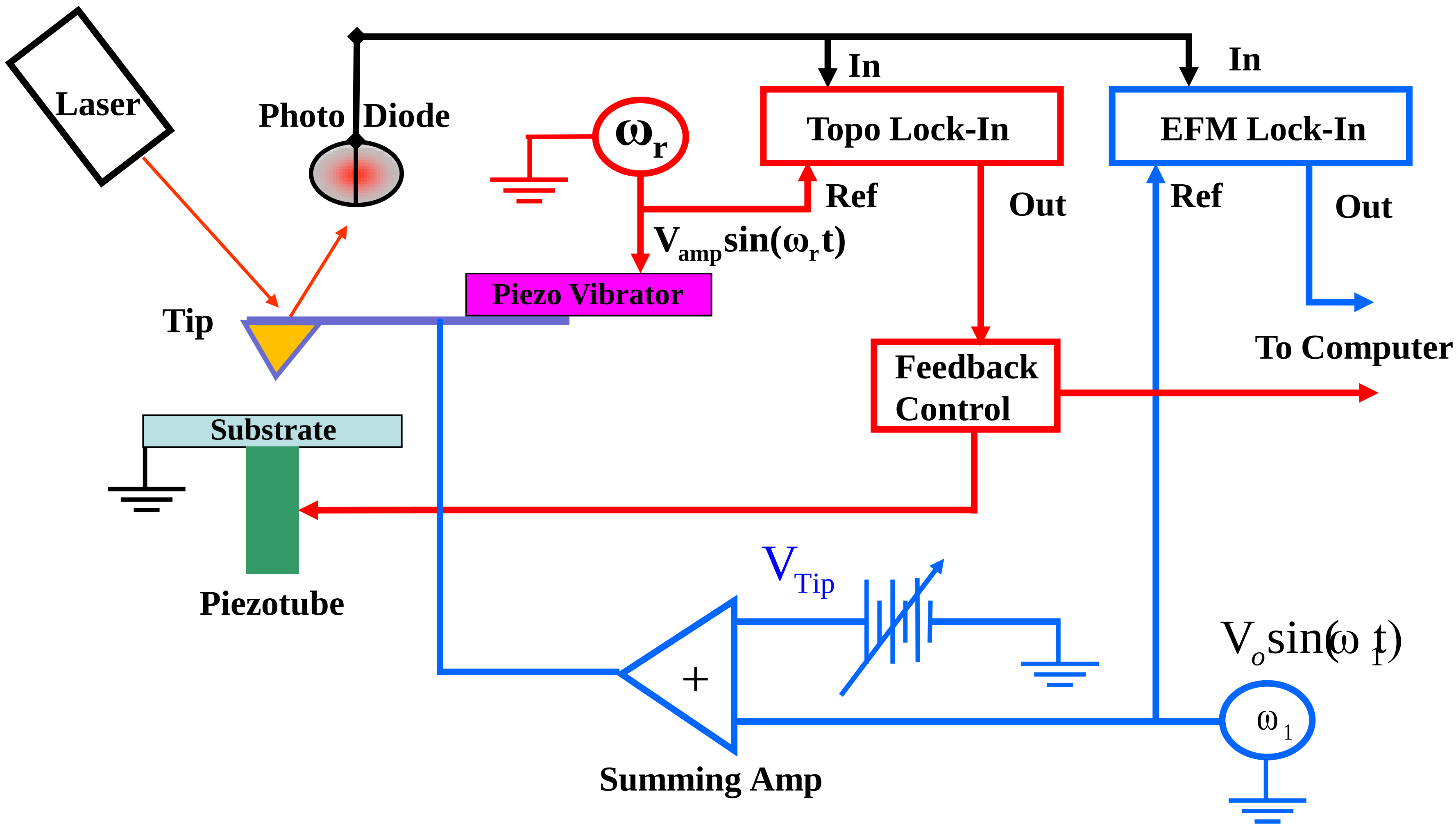
$$= -\frac{1}{2}\frac{dC}{dz}\left[V_s(x,y) - \left(V_{tip} + V_o \sin(\omega_1 t)\right)\right]^2$$

$$= -\frac{1}{2}\frac{dC}{dz}\left[\underbrace{\left(V_s(x,y) - V_{tip}\right)^2}_{\text{dc term}} + \underbrace{V_o^2 \sin^2(\omega_1 t)}_{2\omega_1 \text{ term}} - \underbrace{2\left(V_s(x,y) - V_{tip}\right)V_o \sin(\omega_1 t)}_{\omega_1 \text{ term}}\right]$$

dc term **$2\omega_1$ term** **ω_1 term**

$$F_{electrostatic}\Big|_{\omega_1} = \frac{\mathrm{dC}}{\mathrm{dz}}\left(V_s(x,y) - V_{tip}\right)V_o \sin(\omega_1 t)$$

Experimental Set-Up (Dual Probe)



The EFM lock-in measures the amplitude of the ω_1 component:

$$\text{Amplitude}(\omega_1) = \frac{dC}{dz} V_o [V_s(x,y) - V_{tip}]$$

Operational Modes

1) EFM Imaging Mode:

No controlled adjustment of V_{Tip} (V_{Tip} is held constant).

Passively record the output of the **EFM lock-in** (the detected electrostatic force) as a function of position. Detect phase shifts vs. (x,y).

2) KFM Imaging Mode:

A feedback circuit adjusts V_{Tip} to minimize the output of the **EFM lock-in** (eliminating the ω_1 component of the electrostatic force).

Recording V_{Tip} as a function of position produces a map of the electrostatic surface potential.

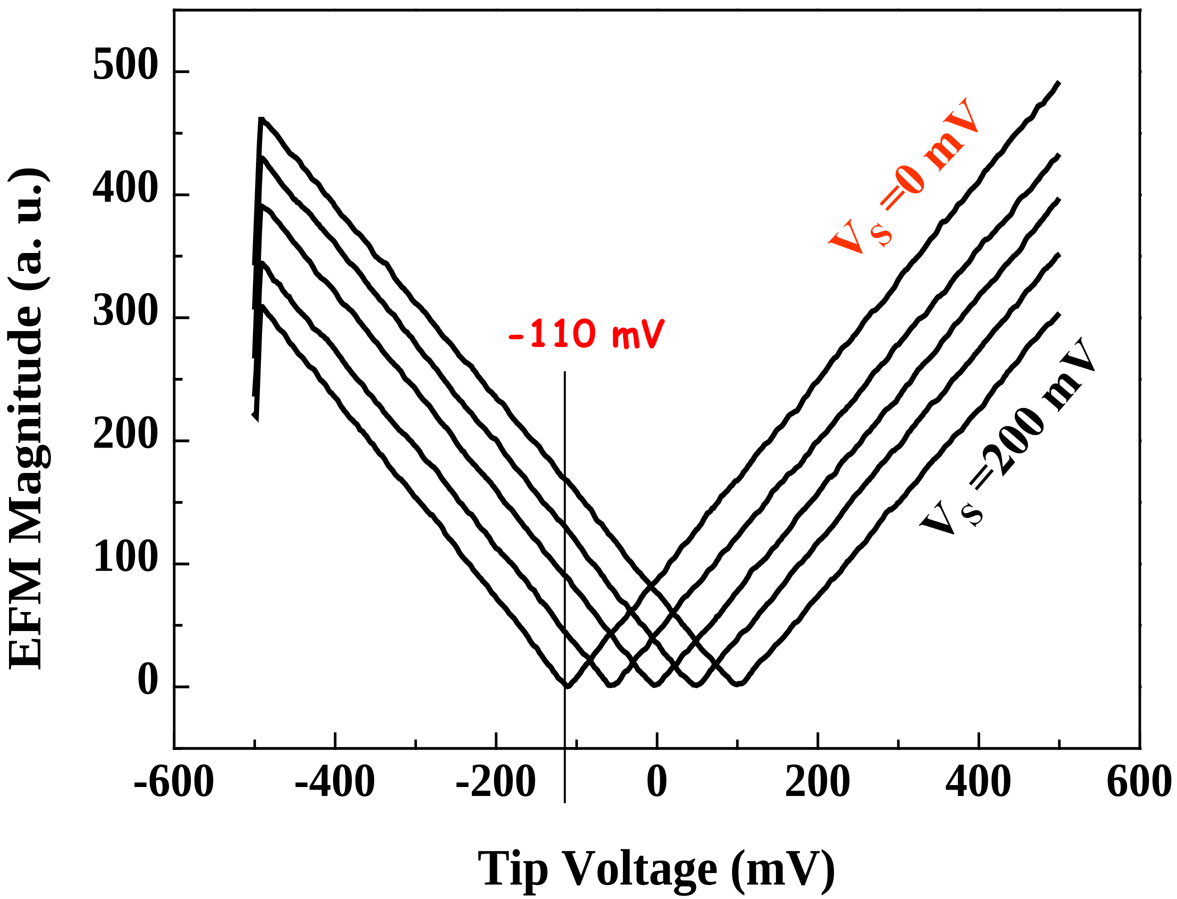
3) Electrostatic Force Curve:

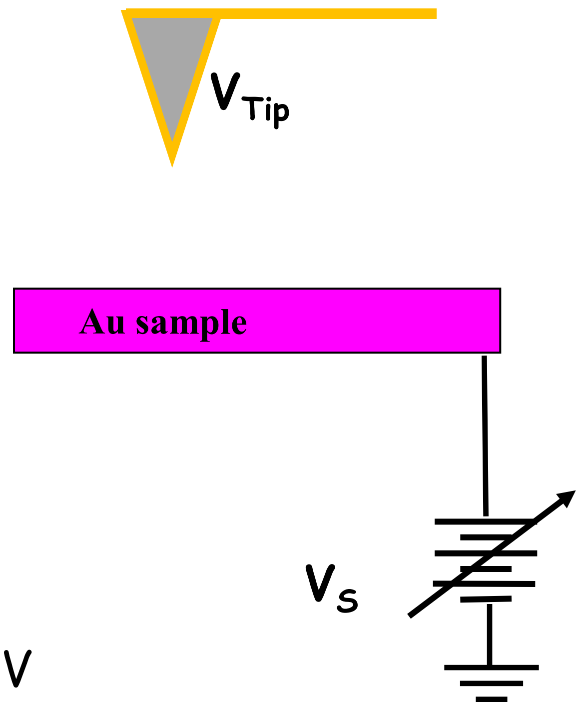
Tip is positioned over a region of the sample.

The output of the **EFM lock-in** (the magnitude of the ω_1 component) is measured as a function of V_{Tip}.

Testing the Experimental Technique

(no scan)

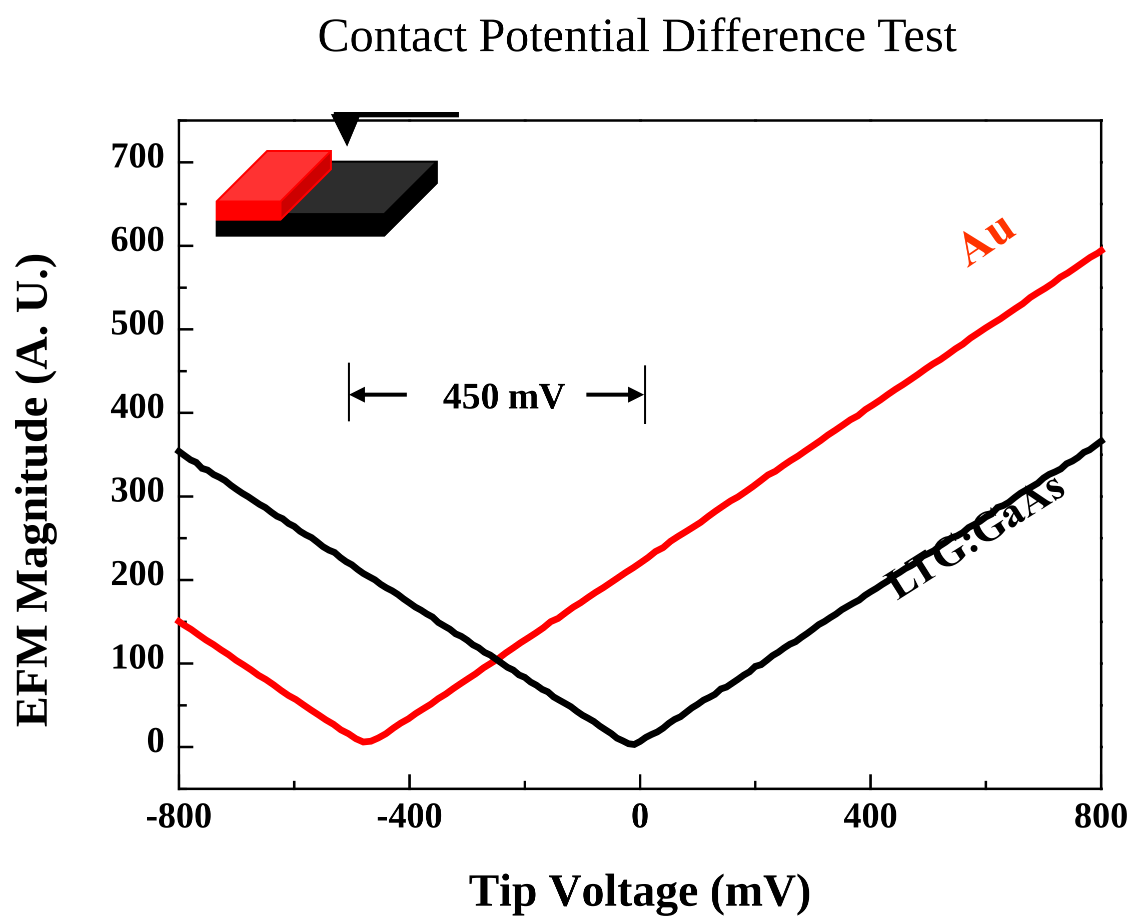




- Sample potential was intentionally increased by +50 mV increments by connecting it to a voltage source V_s.

S. Howell, PhD thesis, Purdue University (2001)

Comparison Between Different Regions
(no scan)

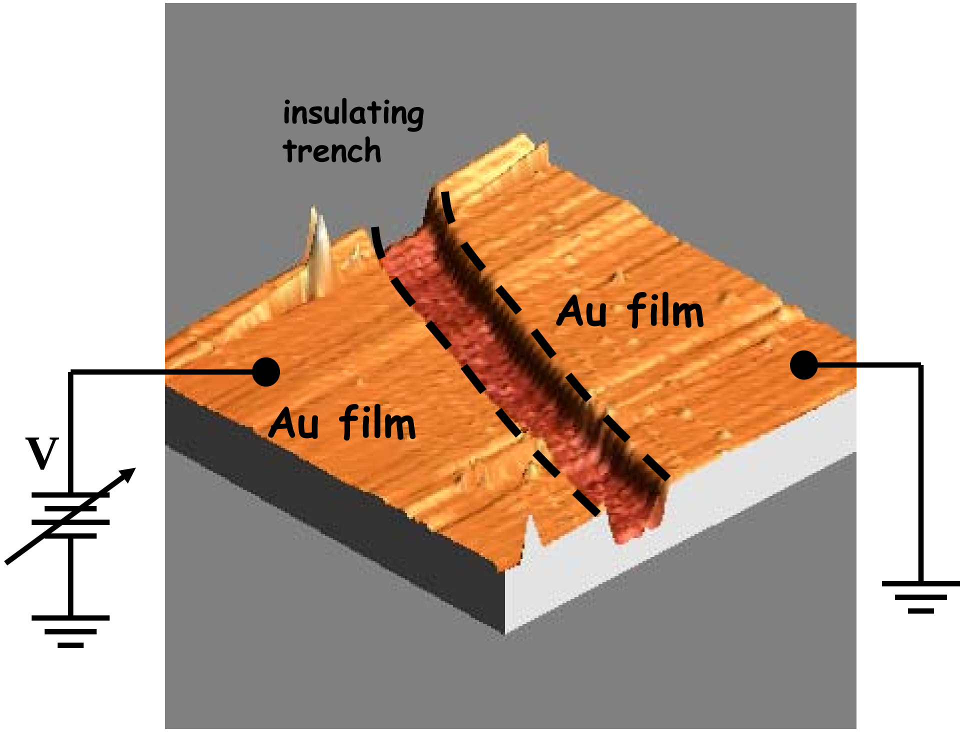


Work function difference between different regions on same sample can be determined using the same tip.

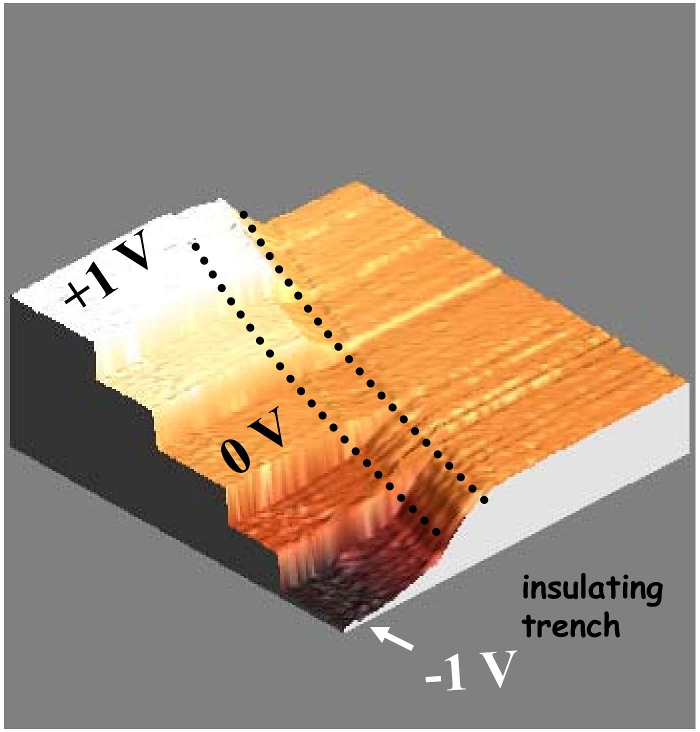
S. Howell, PhD thesis, Purdue University (2001)

Scanning Test Between Two Au Electrodes (voltage offset adjusted by hand)

Topography



KFM Image



Scan Size: 30 μm x 30 μm

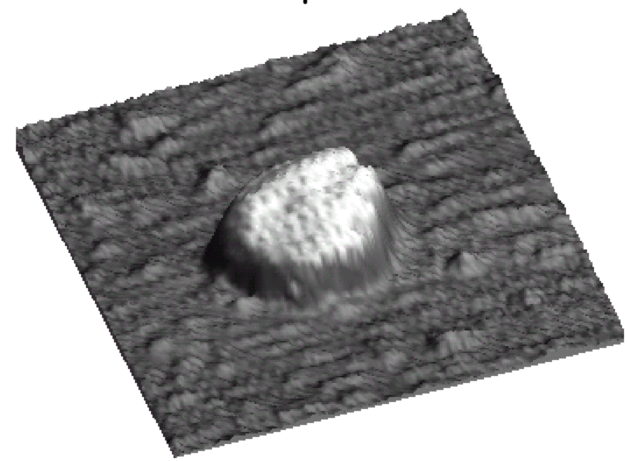
S. Howell, PhD thesis, Purdue University (2001)

Topographic and Electrostatic Force Scans of a single 20 nm Au cluster on LTG:GaAs

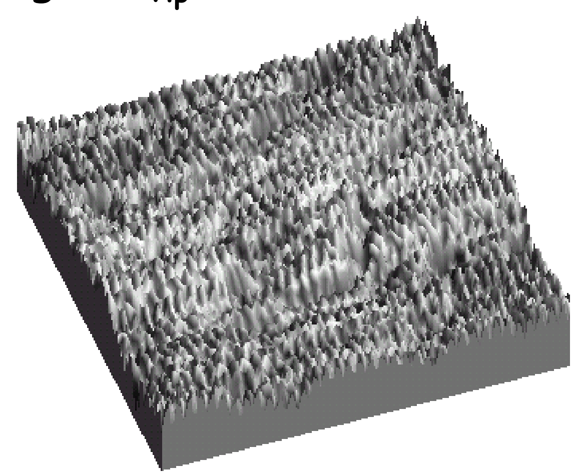
Topography

Scan Size: 100 nm x 100 nm

EFM Image: V_{Tip} = +670 mV



EFM Image: V_{Tip} = -230 mV

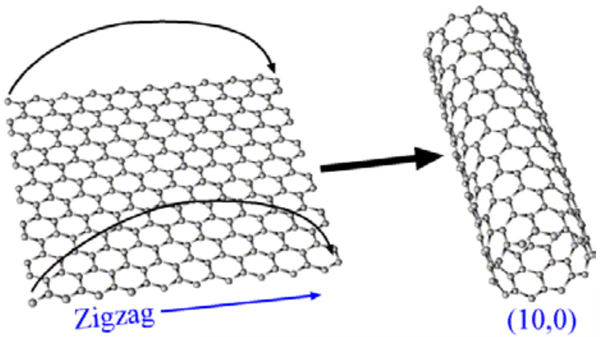


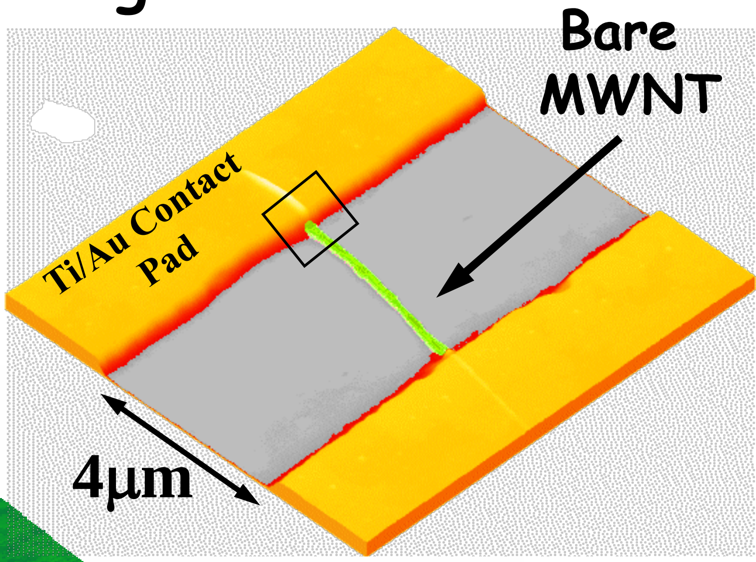
When V_{Tip} = -230 mV, the electrostatic force over the substrate is the same as over the cluster .

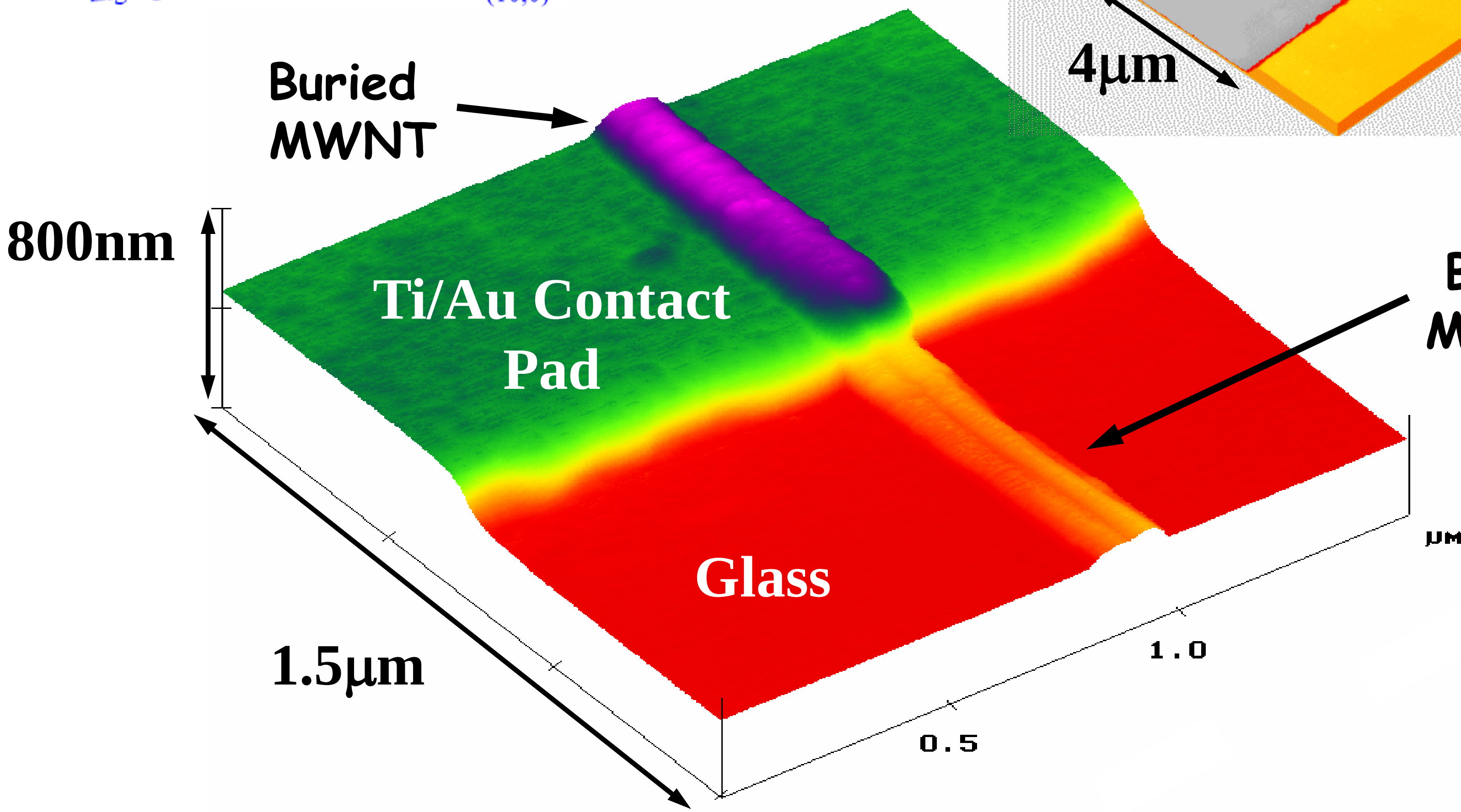
The estimated charge on the cluster is ~ 1.1×10^{-18} C. This corresponds to 7 electron charges.

S. Howell, PhD thesis, Purdue University (2001)

Electrically Contacting Nanotubes

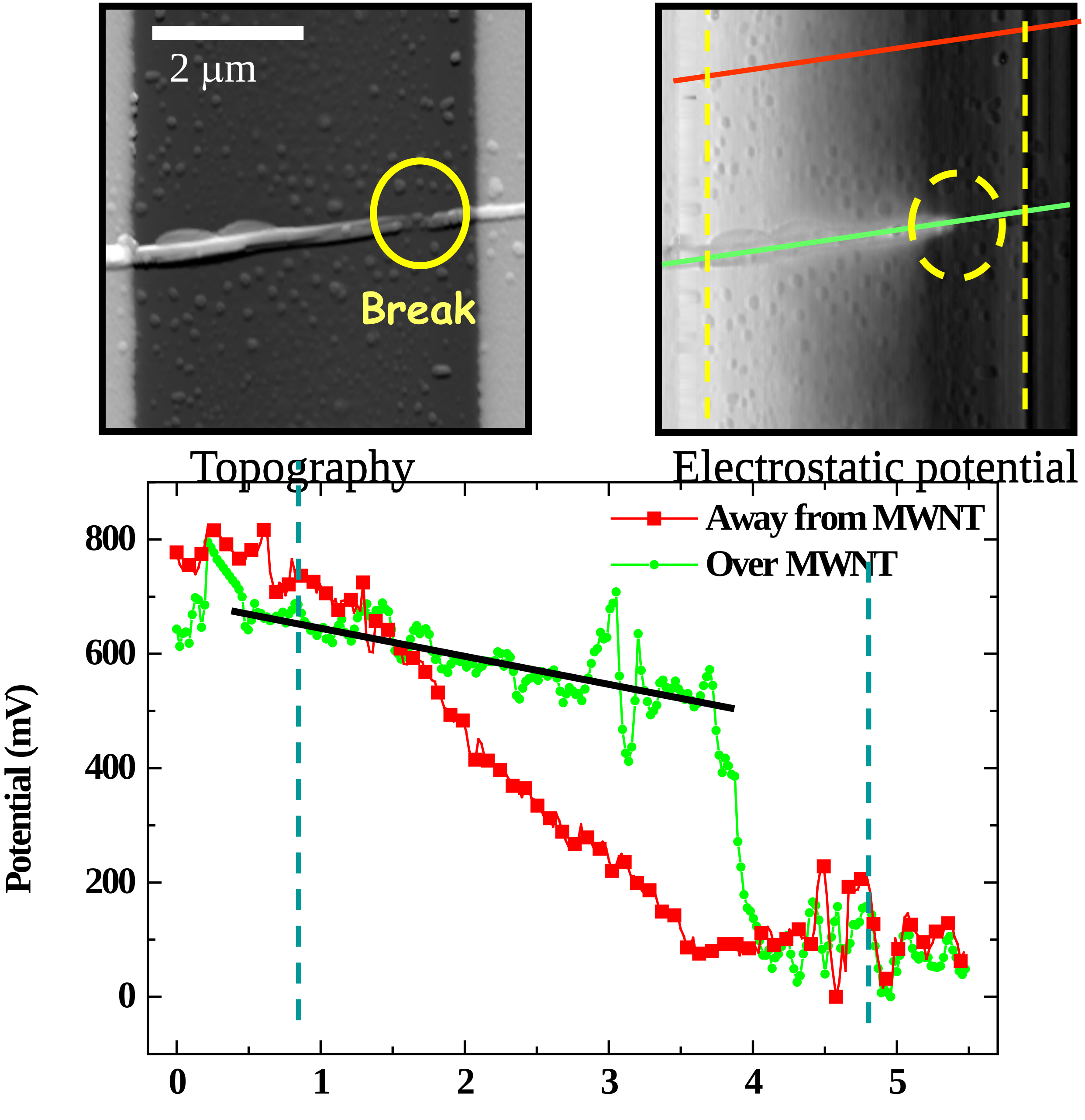






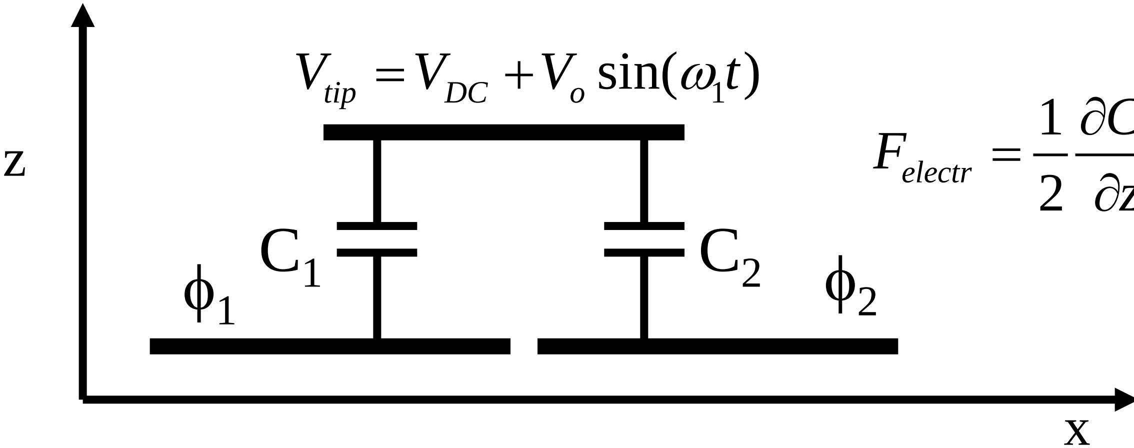
de Pablo, et al., Appl. Phys. Lett. **74**, 323 (1999).

Measuring the voltage drop along a MWCNT



B. Walsh, MSc thesis, Purdue University (2000)

Convolution Effects



$$F_{electr} = \frac{1}{2}\frac{\partial C_1}{\partial z}(\phi_1 - V_{tip})^2 + \frac{1}{2}\frac{\partial C_2}{\partial z}(\phi_2 - V_{tip})^2$$

$$\left|F_{electr}(\omega_1)\right| = \frac{1}{2}\frac{\partial C_1}{\partial z}(\phi_1 - V_{DC})V_o + \frac{1}{2}\frac{\partial C_2}{\partial z}(\phi_2 - V_{DC})V_o = 0$$

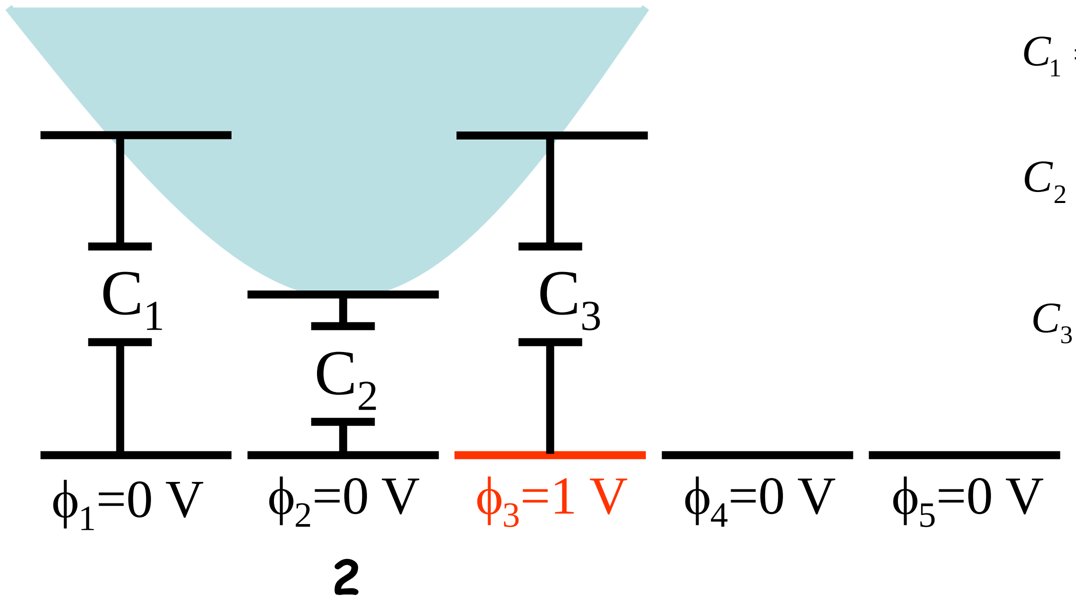
$F_{electr} = 0$ when

$$V_{DC} = \frac{\frac{\partial C_1}{\partial z}\phi_1 + \frac{\partial C_2}{\partial z}\phi_2}{\frac{\partial C_1}{\partial z} + \frac{\partial C_2}{\partial z}}$$

Measurements of the electrostatic potential will be distorted due to the non-uniform capacitive coupling between the tip and various parts of the surface.

Jacobs et al., J. Appl. Phys. 84, 1168 (1998)

Effects of Convolution
- Simple Model -



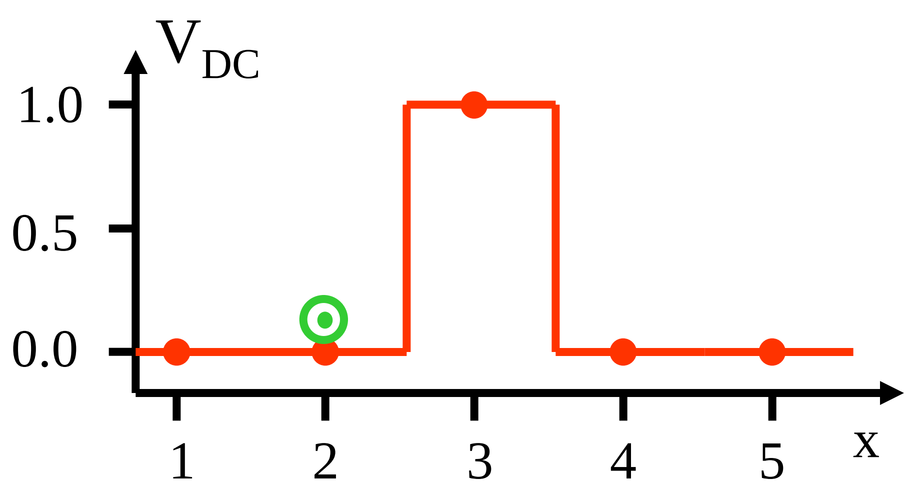
$$C_1 = \frac{\varepsilon_0 A}{z_1};\ \ z_1 = 2\ \mu\text{m}$$

$$C_2 = \frac{\varepsilon_0 A}{z_2};\ \ z_2 = 1\ \mu\text{m}$$

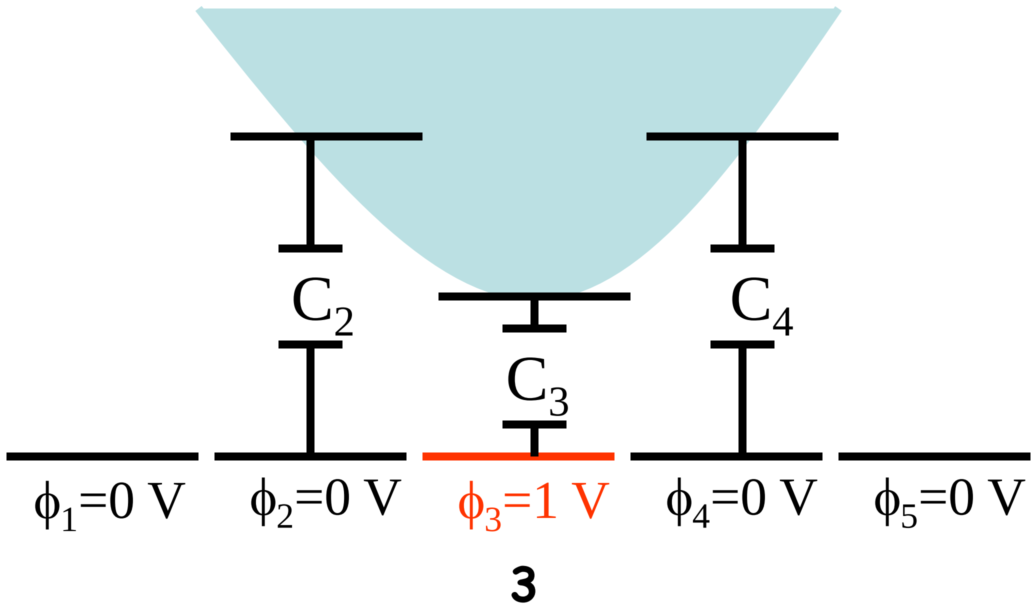
$$C_3 = \frac{\varepsilon_0 A}{z_3};\ \ z_3 = 2\ \mu\text{m}$$

$$V_{DC} = \frac{\frac{1}{2}\frac{\partial C_1}{\partial z}\phi_1 + \frac{1}{2}\frac{\partial C_2}{\partial z}\phi_2 + \frac{1}{2}\frac{\partial C_3}{\partial z}\phi_3}{\frac{1}{2}\frac{\partial C_1}{\partial z} + \frac{1}{2}\frac{\partial C_2}{\partial z} + \frac{1}{2}\frac{\partial C_3}{\partial z}} = \frac{\frac{1}{4}\cdot 0 + \frac{1}{1}\cdot 0 + \frac{1}{4}\cdot 1}{\frac{1}{4} + \frac{1}{1} + \frac{1}{4}} = \frac{0.25}{1.5}$$

V_{DC}=0.17 V



Effects of Convolution
- Simple Model -



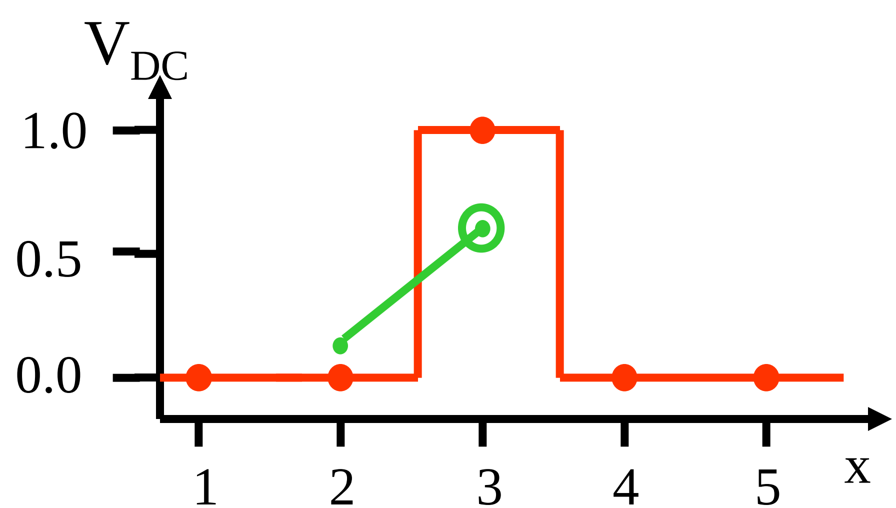
$$C_2 = \frac{\varepsilon_0 A}{z_2} \quad ; z_2=2\ \mu\text{m}$$

$$C_3 = \frac{\varepsilon_0 A}{z_3} \quad ; z_3=1\ \mu\text{m}$$

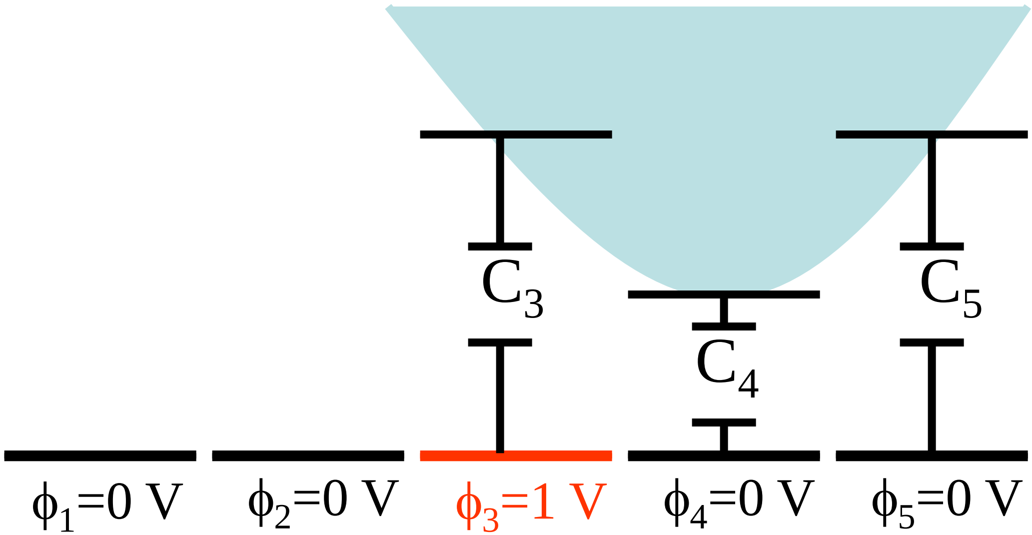
$$C_4 = \frac{\varepsilon_0 A}{z_4} \quad ; z_4=2\ \mu\text{m}$$

$$V_{DC} = \frac{\frac{1}{2}\frac{\partial C_2}{\partial z}\phi_2 + \frac{1}{2}\frac{\partial C_3}{\partial z}\phi_3 + \frac{1}{2}\frac{\partial C_4}{\partial z}\phi_4}{\frac{1}{2}\frac{\partial C_2}{\partial z} + \frac{1}{2}\frac{\partial C_3}{\partial z} + \frac{1}{2}\frac{\partial C_4}{\partial z}} = \frac{\frac{1}{4}\cdot 0 + \frac{1}{1}\cdot 1 + \frac{1}{4}\cdot 0}{\frac{1}{4} + \frac{1}{1} + \frac{1}{4}} = \frac{1}{1.5}$$

V_{DC}=0.67 V



Effects of Convolution
- Simple Model -



$$C_3 = \frac{\varepsilon_0 A}{z_3} \quad ; \; z_3 = 2\ \mu\text{m}$$

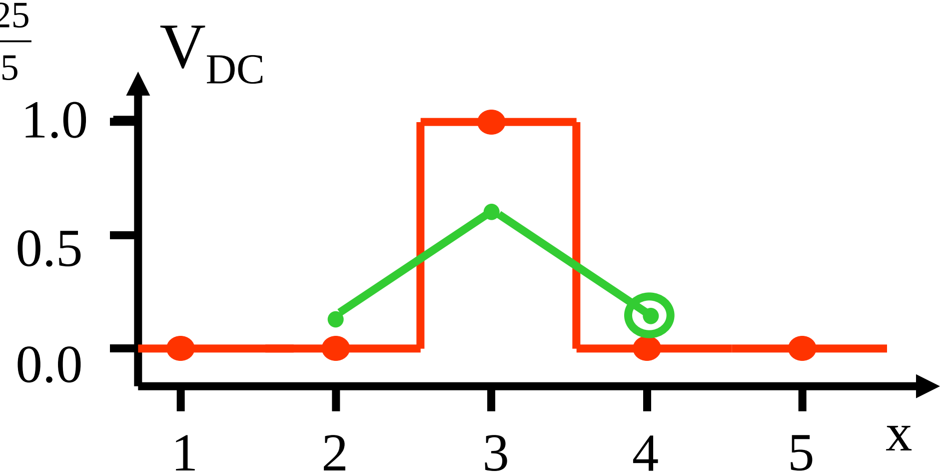
$$C_4 = \frac{\varepsilon_0 A}{z_4} \quad ; \; z_4 = 1\ \mu\text{m}$$

$$C_5 = \frac{\varepsilon_0 A}{z_5} \quad ; \; z_5 = 2\ \mu\text{m}$$

4

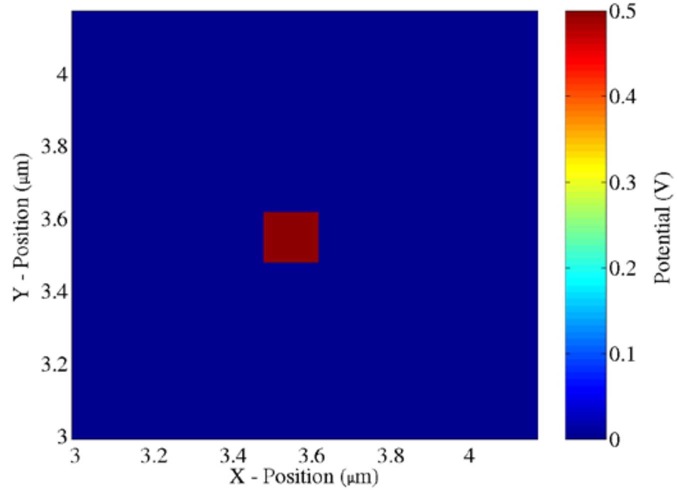
$$V_{DC} = \frac{\frac{1}{2}\frac{\partial C_3}{\partial z}\phi_{23} + \frac{1}{2}\frac{\partial C_4}{\partial z}\phi_4 + \frac{1}{2}\frac{\partial C_5}{\partial z}\phi_5}{\frac{1}{2}\frac{\partial C_3}{\partial z} + \frac{1}{2}\frac{\partial C_4}{\partial z} + \frac{1}{2}\frac{\partial C_5}{\partial z}} = \frac{\frac{1}{4}\cdot 1 + \frac{1}{1}\cdot 0 + \frac{1}{4}\cdot 0}{\frac{1}{4} + \frac{1}{1} + \frac{1}{4}} = \frac{0.25}{1.5}$$

V_{DC}=0.17 V



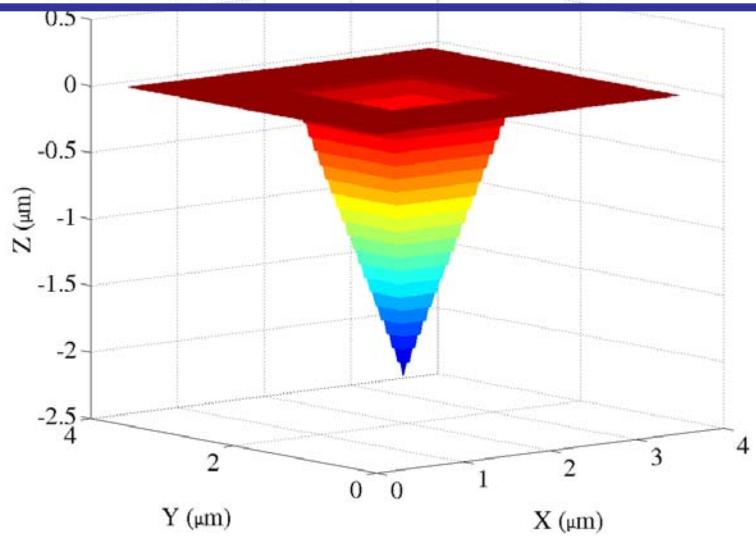
B. Walsh, MSc thesis, Purdue University (2000)

More Realistic Model

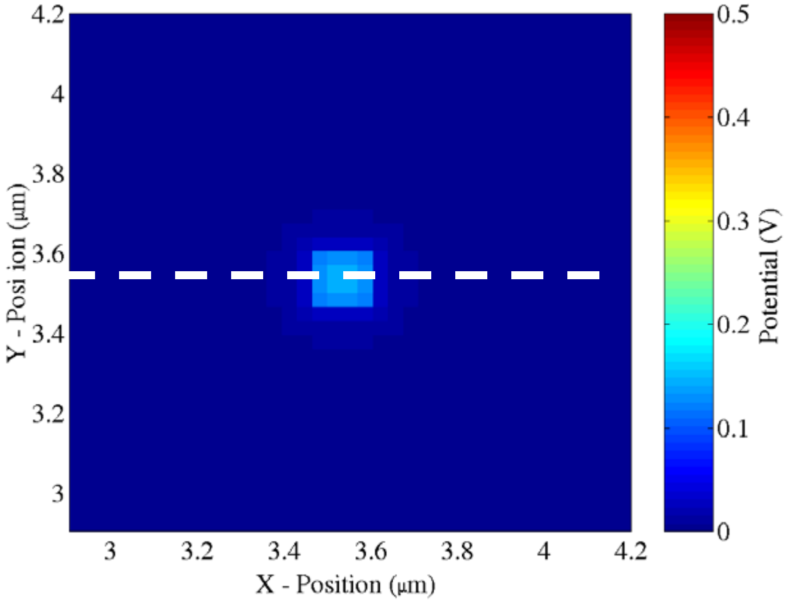


The electrostatic potential is specified in two dimensions by V(x,y)

The tip is moved relative to the specified potential, and the weighted average is calculated at each point.

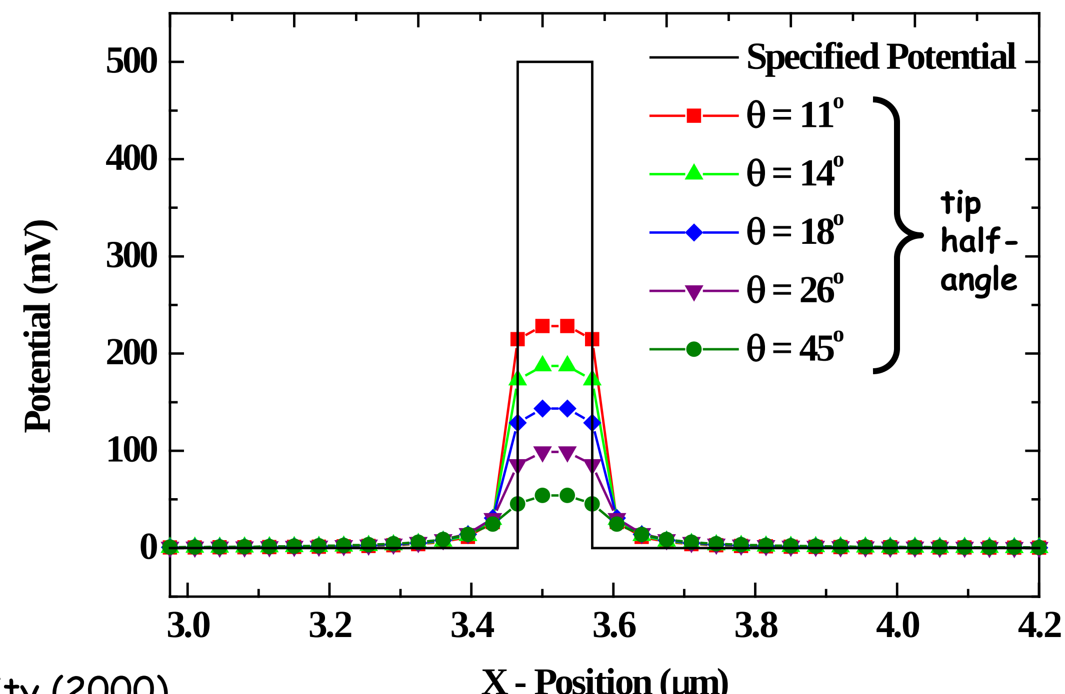


$$V_{DC} = \frac{\sum_{surface}^{i} \left(\frac{\partial C_i}{\partial z} \cdot \phi_{surface} \right)}{\sum_{surface}^{i} \left(\frac{\partial C_i}{\partial z} \right)}$$



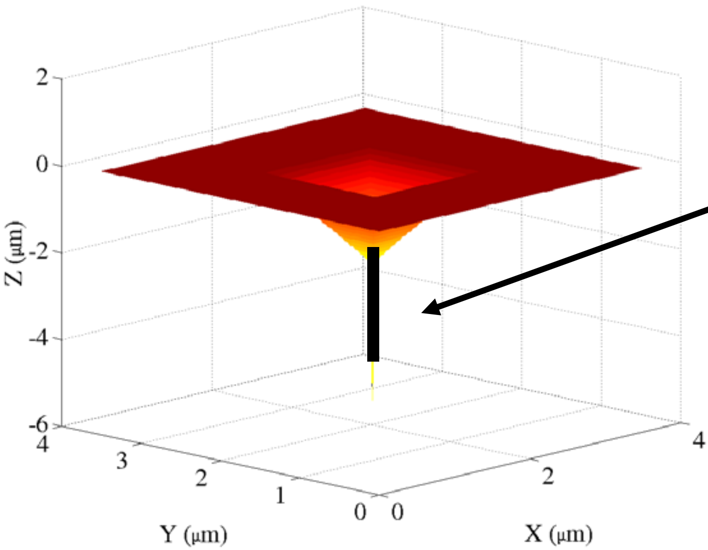
The output of the convolution program is a 2-D electrostatic potential map.

Plot of profiles of the electrostatic potential along dotted white line.

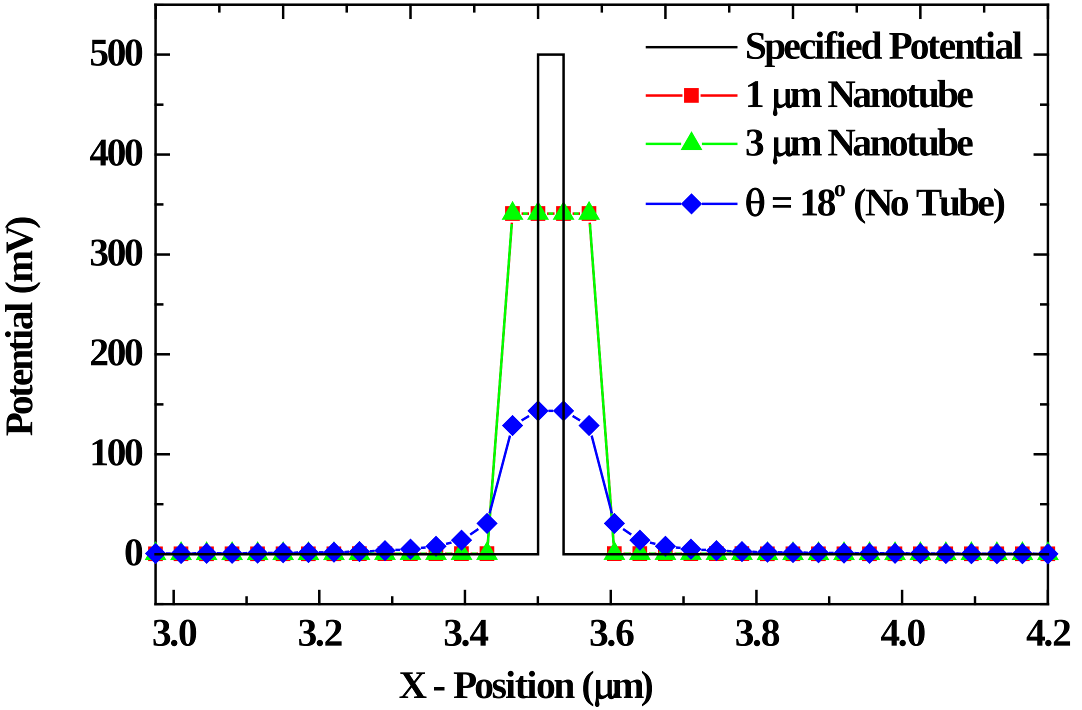


B. Walsh, MSc thesis, Purdue University (2000)

Improving the Situation

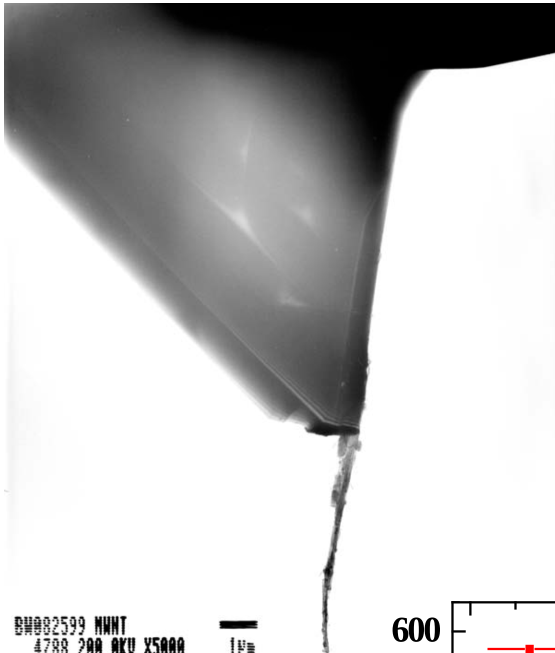


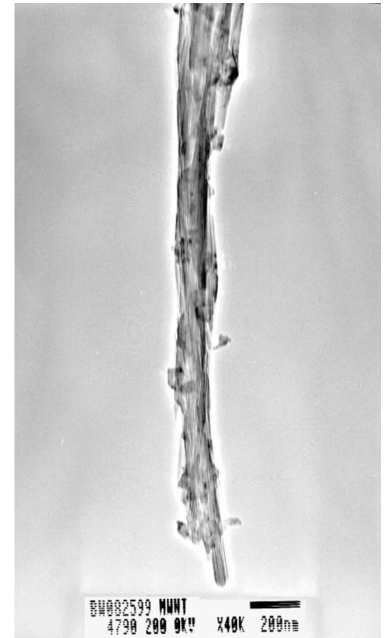
1 µm and 3 µm long extensions to the tip were modeled.

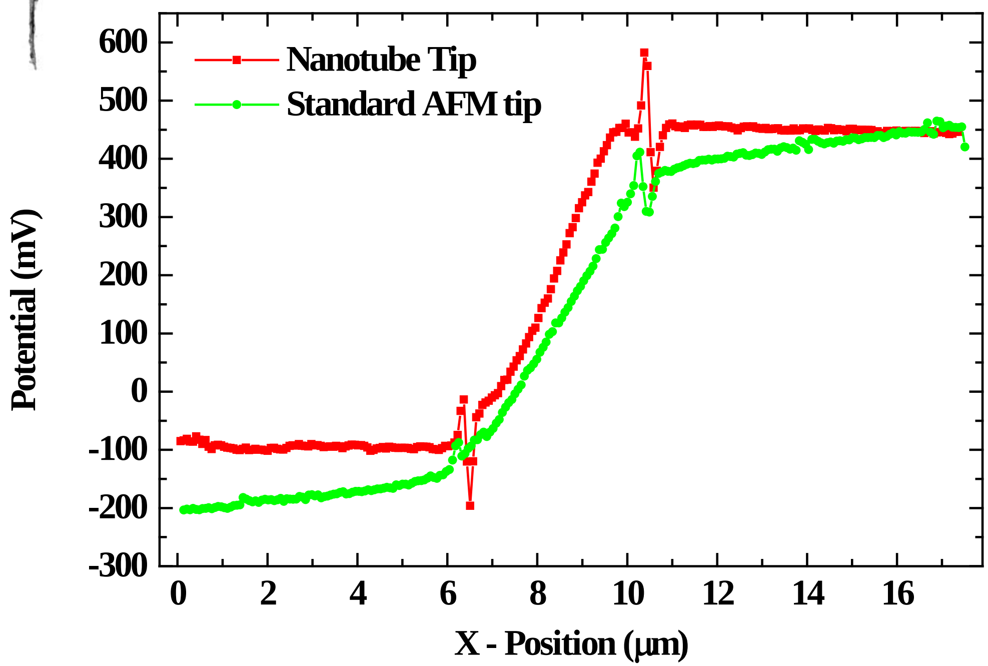


B. Walsh, MSc thesis, Purdue University (2000)

Experiment: MWCNT tip

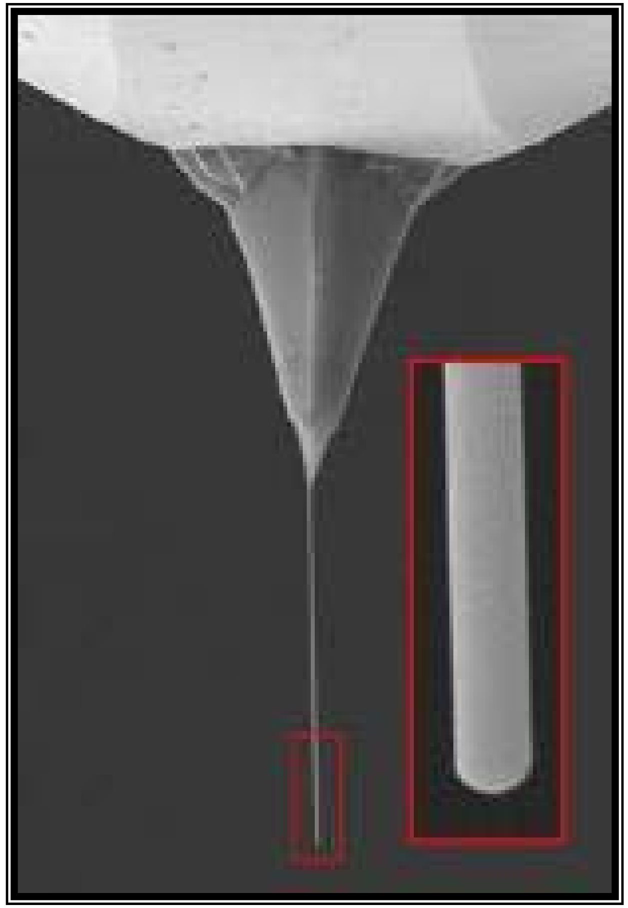






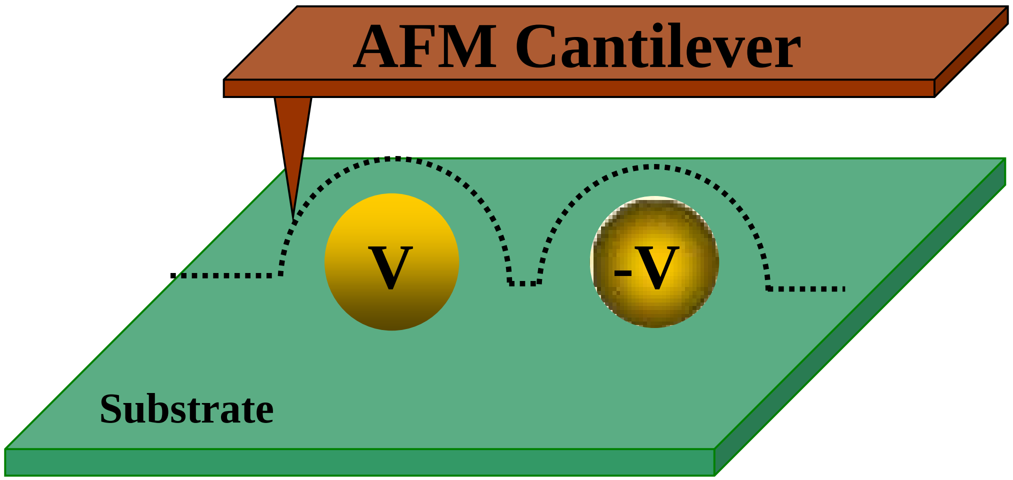
B. Walsh, MSc thesis, Purdue University (2000)

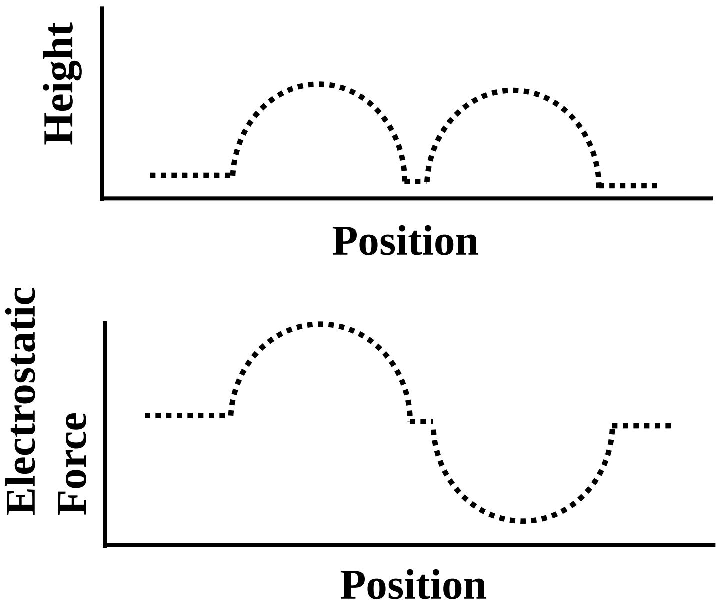
Recent Development: sharp tips with high aspect ratio



http://www.nauganeedles.com/

Summary





- Modified atomic force microscope
- Capable of simultaneously measuring topography and surface potential
- Correlate surface morphology with surface potential
- Measures variations in the electrostatic force with ~50 nm resolution