Fundamentals of Atomic Force Microscopy
Part 2: Dynamic AFM Methods

Week 5, Lecture 1
Measuring Electrostatic Forces I

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From the last lecture

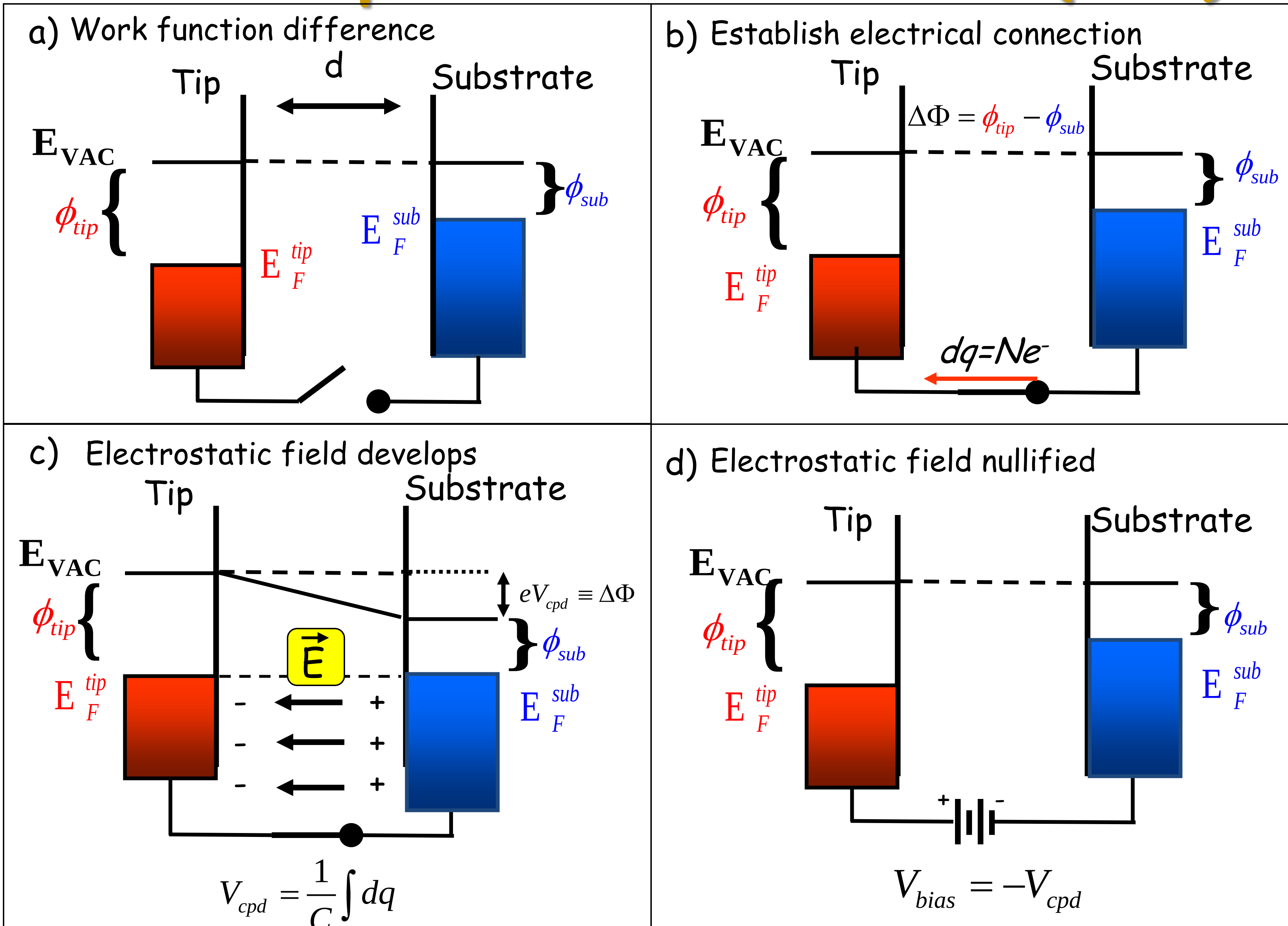
- Force reconstruction from dynamic approach curves on surfaces
- Reconstruction using both FM-AFM and AM-AFM

Electrostatic force microscopy methods

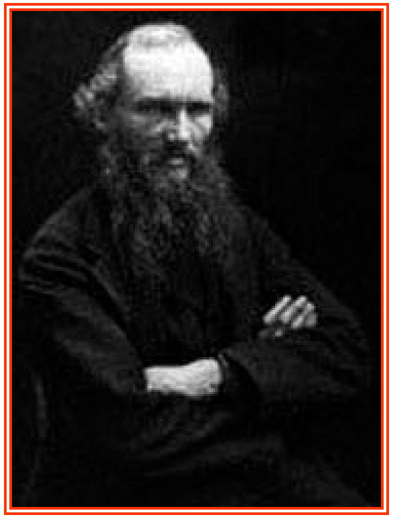
Using oscillating metal coated AFM tip to measure or map

- Local charges on surface *
- Local dielectric constants *
- Film thickness of insulating layers *
- Photo-induced voltage *
- Contact potential difference *

Contact potential difference (CPD)

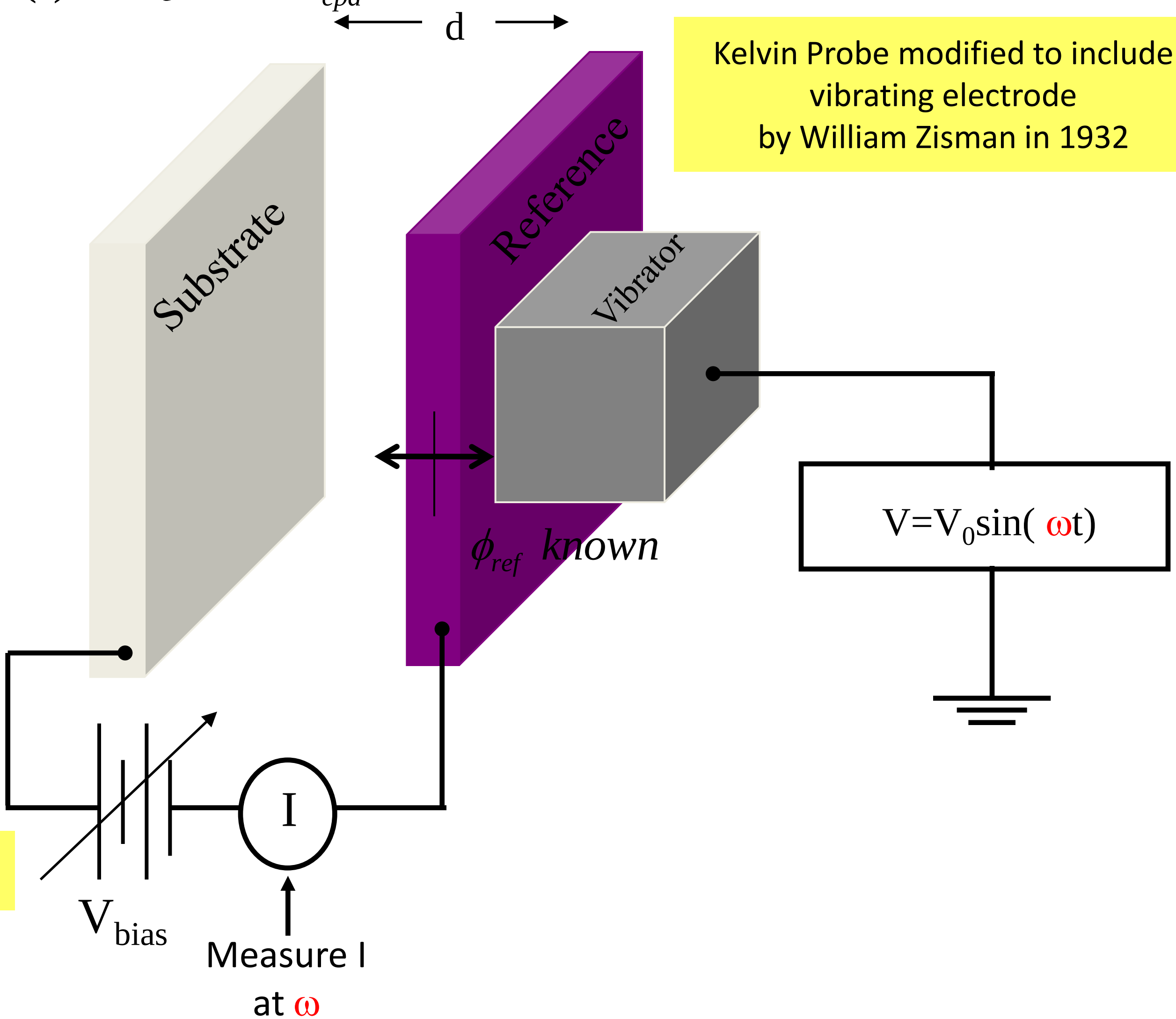


Macroscopic contact potential measurements



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

$$i(t) = dQ/dt = V_{cpd}\ dC/dt$$



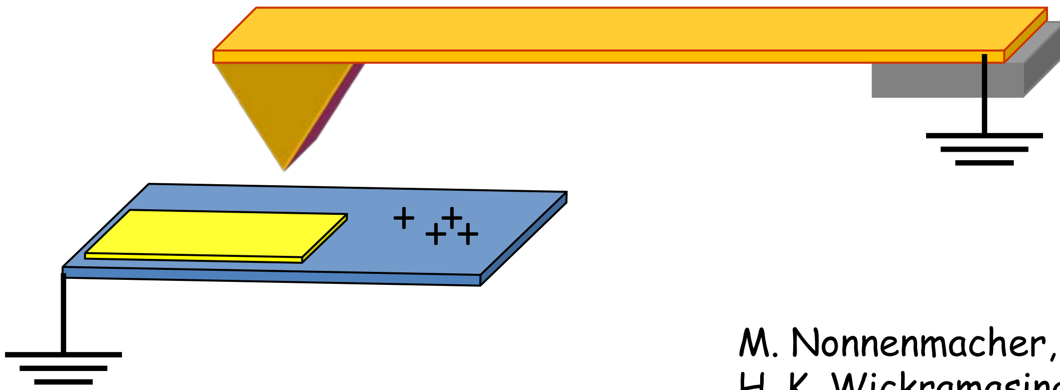
Kelvin Probe modified to include vibrating electrode by William Zisman in 1932

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

Adjust V_{bias} so I =0

Nanoscale contact potential measurements

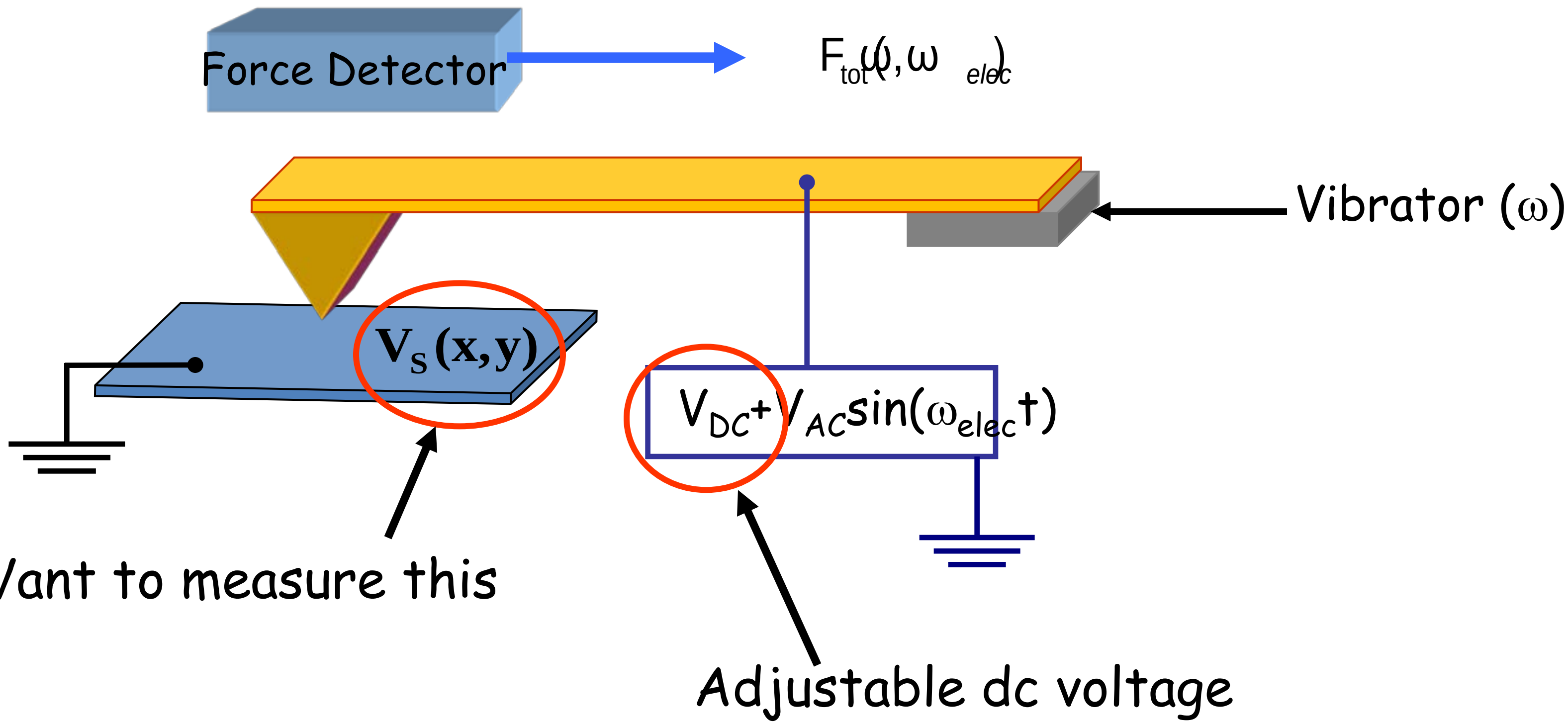
AFM cantilever -Metal coated tip or highly doped Si



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

- For more complex samples V_{cpd} can be regarded as the Voltage required to null the electric field that develops between the tip and a local volume of the substrate. Then V_{cpd} depends on many factors
  - Surface contamination of metal
  - Presence of dielectrics with trapped charges
  - Doping of semiconducting sample
  - Thickness of dielectric layer, its dielectric constant
- For well prepared conducting samples this technique measures CPD due to difference in work-function. For more complex samples it could measure a convolution of all the above effects

Nanoscale contact potential measurements



The tip-sample potential difference (cpd) is:

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

- The mechanical excitation scans the topography of the sample in AM or FM-AFM while electrostatic information is collected from the electrical excitation

The electrostatic force channels

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

$$= -\frac{1}{2}\frac{dC}{dz}\left[V_s(x,y) - \left(V_{DC} + V_{AC}\sin(\omega_{elec}t)\right)\right]^2$$

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

Usually $\omega_{elec} << \omega$

$$F_{electrostatic}\Big|_{\omega_{elec}} = \frac{dC}{dz}\left(V_s(x,y) - V_{DC}\right)V_{AC}\sin(\omega_{elec}t)$$

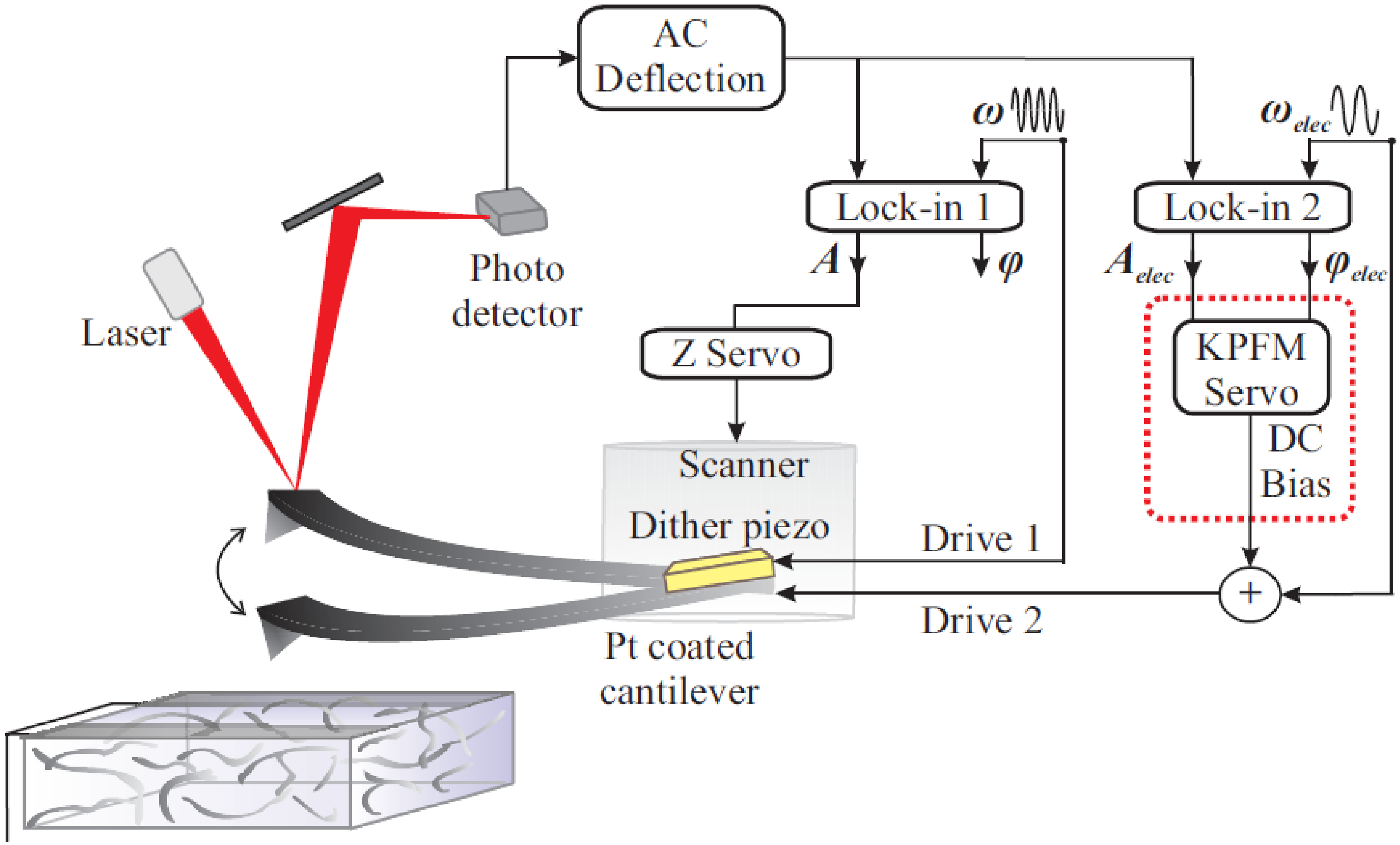
$$F_{electrostatic}\Big|_{2\omega_{elec}} = \frac{1}{4}\frac{dC}{dz}V_{AC}^2\sin(2\omega_{elec}t)$$

- These forces oscillate far below the resonance frequency of the cantilever so the cantilever response at these frequencies can be written as (Appendix)

$$q_{elec}(t) = A|_{\omega_{elec}}\sin(\omega_{elec}t - \phi_{elec}) + A|_{2\omega_{elec}}\sin(2\omega_{elec}t - \hat{\phi}_{elec}) = \frac{1}{k}\left[F_{electrostatic}\Big|_{\omega_{elec}} + F_{electrostatic}\Big|_{2\omega_{elec}}\right]$$

- By adjusting V_{tip} to null the vibration at ω_{elec} one can map $V_s(x,y)$
- Mapping the $2\omega_{elec}$ signal allows mapping of $\frac{dC}{dz}$ over the sample

Schematic KPFM technique



- This is for the single-pass implementation (single-pass and two-pass is discussed later)
- Lock in amplifier 1 tracks the tip oscillation amplitude at the cantilever resonance
- Lock in amplifier 2 tracks the tip oscillation amplitude at the electrical excitation frequency ω_{elec}
- The KPFM servo applies a DC bias to null the tip oscillation at ω_{elec}
- Sometimes a 3rd lock-in amplifier is used to track the signal at 2 ω_{elec}

Early results

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

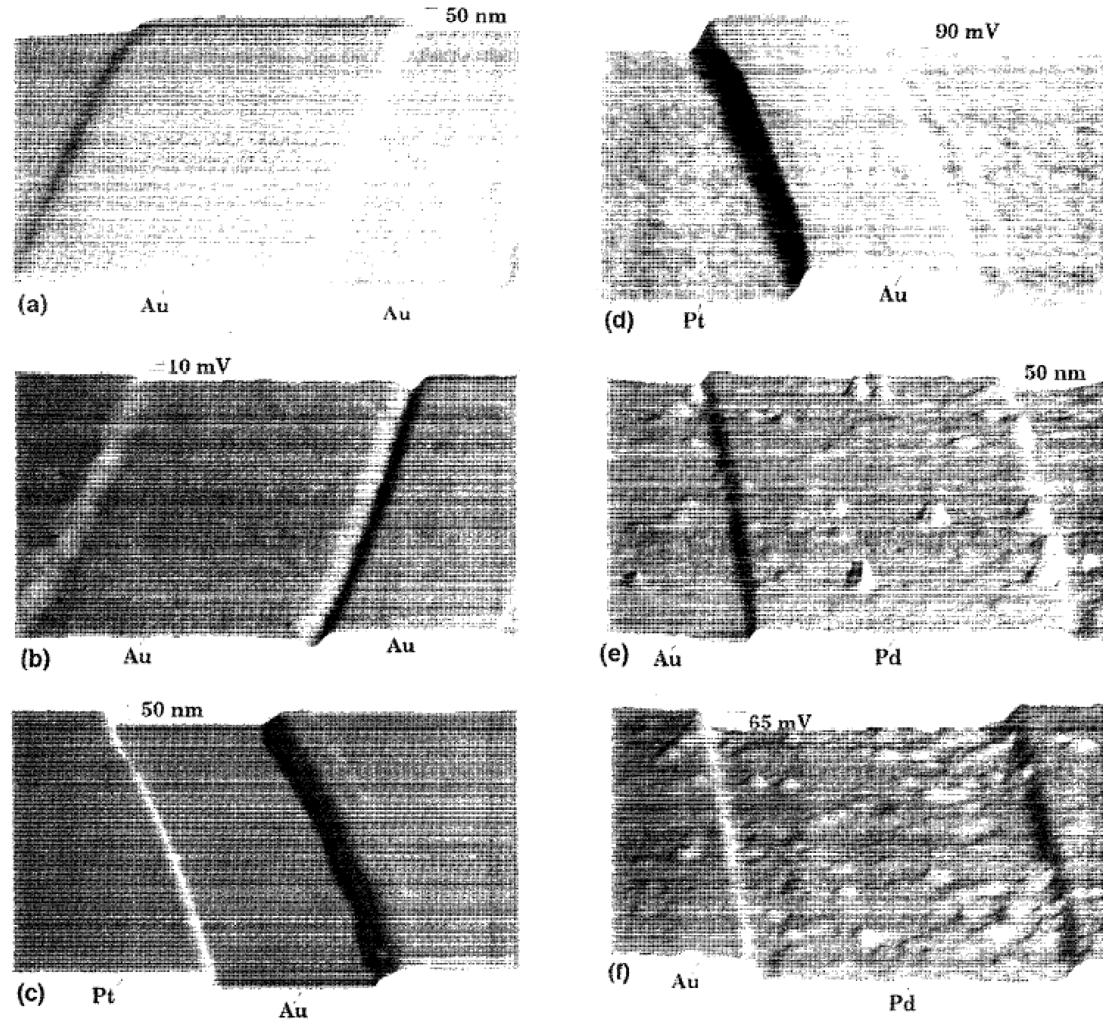


FIG. 2. Comparison of topographic and CPD images (8 μm × 6 μm) of different samples: (a) and (b) gold on gold, (c) and (d) platinum on gold, (e) and (f) palladium on gold.

- Capable of detecting 0.1 mV of CPD!

Appendix