Lecture: P1_Wk4_L6

Lateral Force Microscopy (LFM)

Ron Reifenberger
Birck Nanotechnology Center
Purdue University
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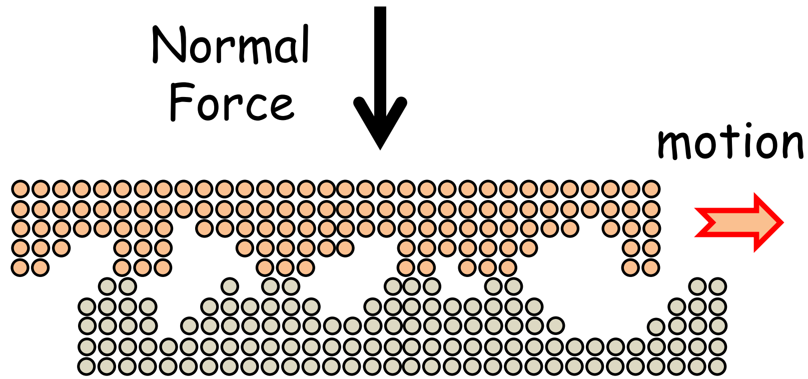
PURDUE UNIVERSITY

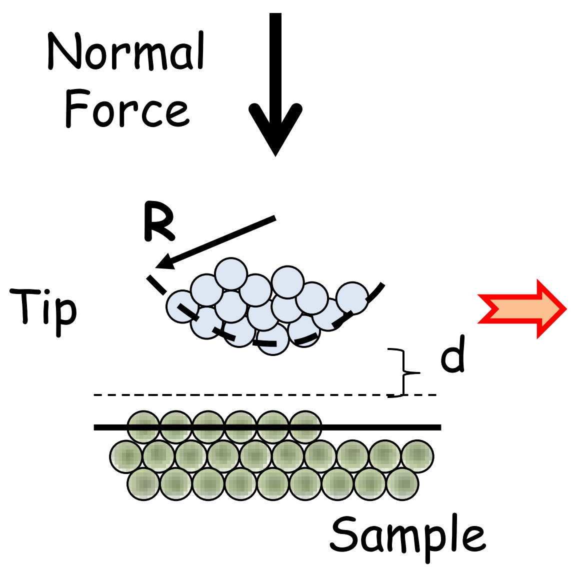
Friction

Macroscale Friction – dominated by surface roughness



True contact area is small fraction of apparent contact area

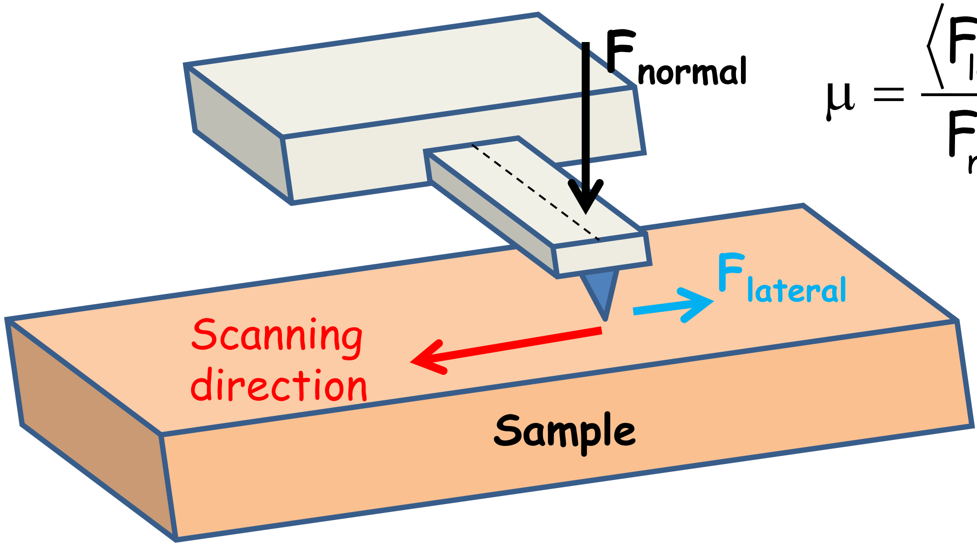
Friction at the Nanoscale – single asperity contacts



At what value of d does the "onset of friction" appear?

Lateral Force Microscopy

Measure the twist of the cantilever as it scans



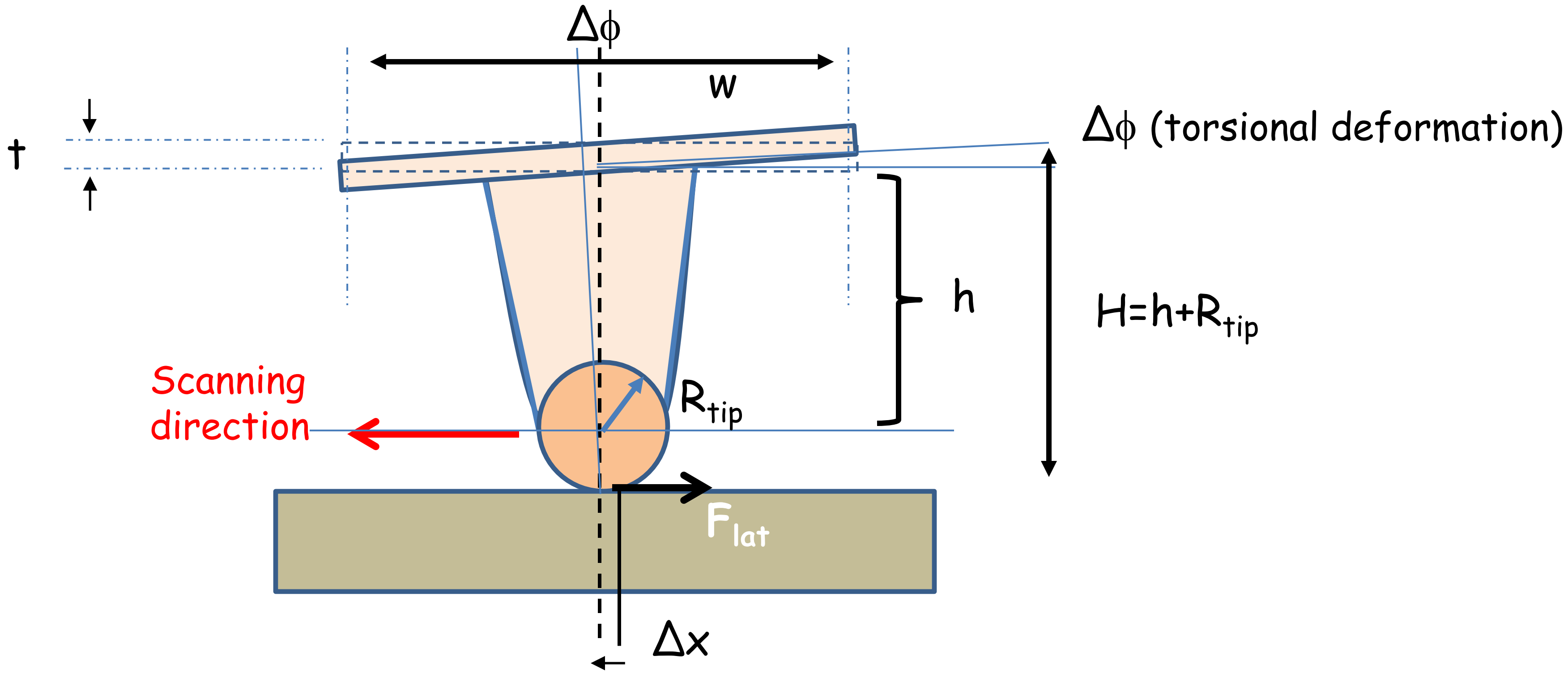
$$\mu = \frac{\langle F_{lateral} \rangle}{F_{normal}} = \frac{\langle F_{friction} \rangle}{F_{Load}} = \text{coef. of friction}$$

Typically, $0.01 < \mu < 1$
for $F_{normal} = 100$ nN,
1 nN < $F_{lateral}$ < 1 00 nN

What influences friction at the nanoscale?

- Maximize twist: use long cantilevers with a small thickness having long tips
- Forward and backward scans will be different
- Calibration more difficult than for the normal force signal

Twisting a Cantilever



$$\Delta\phi \propto torque \times cantilever\ length$$

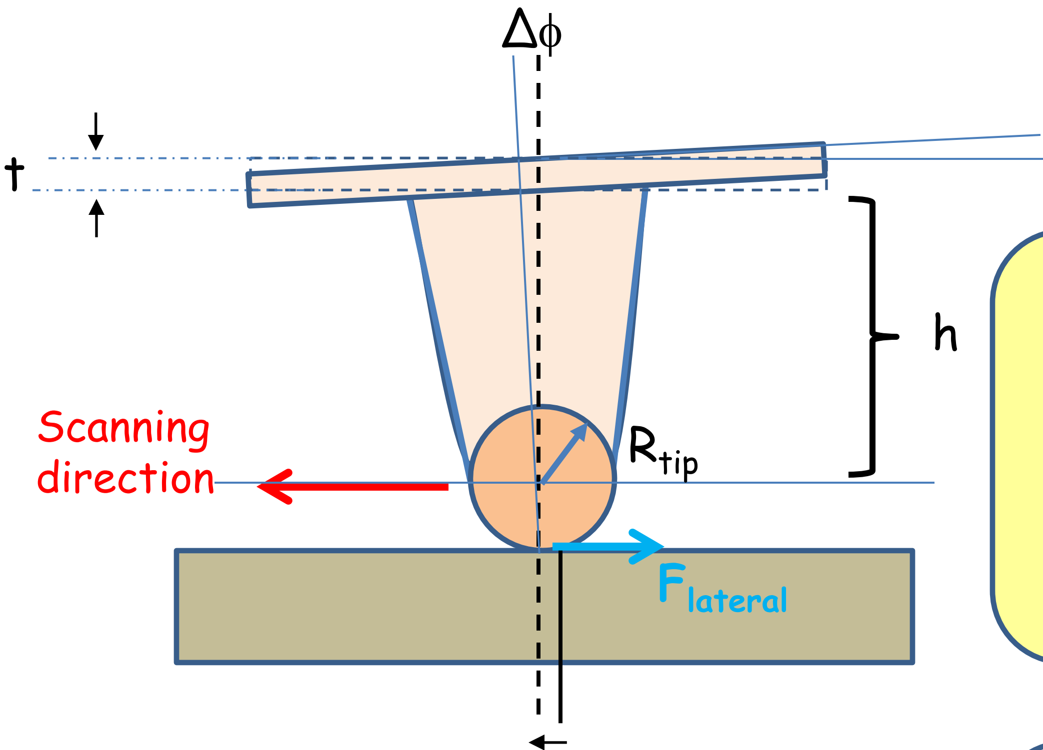
$$\Rightarrow \quad K_{tor}\Delta\phi = \tau L$$

$$for\ t \ll w; \quad K_{tor} = \frac{Gwt^3}{3}; \quad G = shear\ modulus$$ (see P1_Wk2_L4)

$$\tau = F_{lat}H$$

$$F_{lat} = \frac{K_{tor}}{HL}\Delta\phi = \frac{K_{tor}}{HL}\frac{\Delta x}{L} = \frac{Gwt^3}{3HL^2}\Delta x = k_x\Delta x$$

Spring Constants for Lateral Force



lateral spring constant

$$F_{lat} = k_x \Delta x$$

$$k_x = \frac{Gwt^3}{3HL^2}$$

$$\left[units : k_x = N/m \right]$$

Δx=displacement of sample that causes a torsional deformation Δϕ =($h+R_{tip}$) Δϕ = H Δϕ

torsional spring constant

$$\tau = k_\phi \Delta\phi = F_{lat} H$$

$$k_\phi = \frac{K_{tor}}{L} = \frac{Gwt^3}{3L}$$

$$\left[units : k_\phi = Nm/rad \right]$$

Comparing Spring Constants

For homogeneous **rectangular cantilever** of length L, width w, thickness t, and having a tip height $H=h+R_{tip}$, the lateral spring constant is given by

$$k_x = \frac{Gwt^3}{3LH^2}$$

where G is the shear modulus of the cantilever material.

Recall, the spring constant of the cantilever when a normal force is applied is given by

$$k = \frac{Ewt^3}{4L^3}$$

The ratio of the spring constants is therefore given by

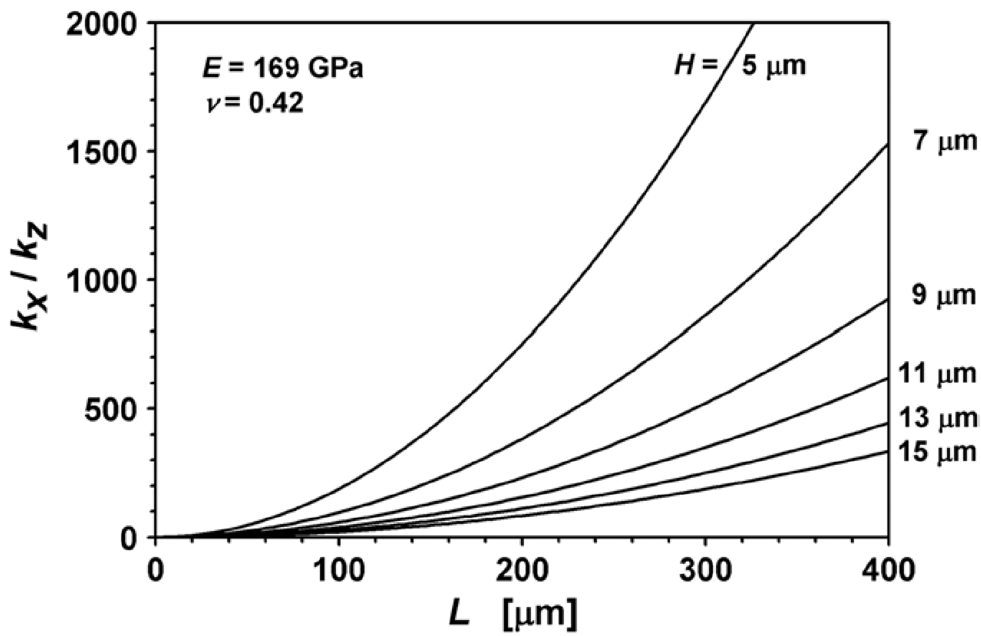
$$\frac{k_x}{k} = \frac{4G}{3E}\left(\frac{L}{H}\right)^2$$

Assuming a perfectly **isotropic and homogenous material**, G is related to E by

$$G = \frac{E}{2(1+\nu)}$$

giving

$$\frac{k_x}{k} = \frac{2}{3(1+\nu)}\left(\frac{L}{H}\right)^2 \gg 1$$

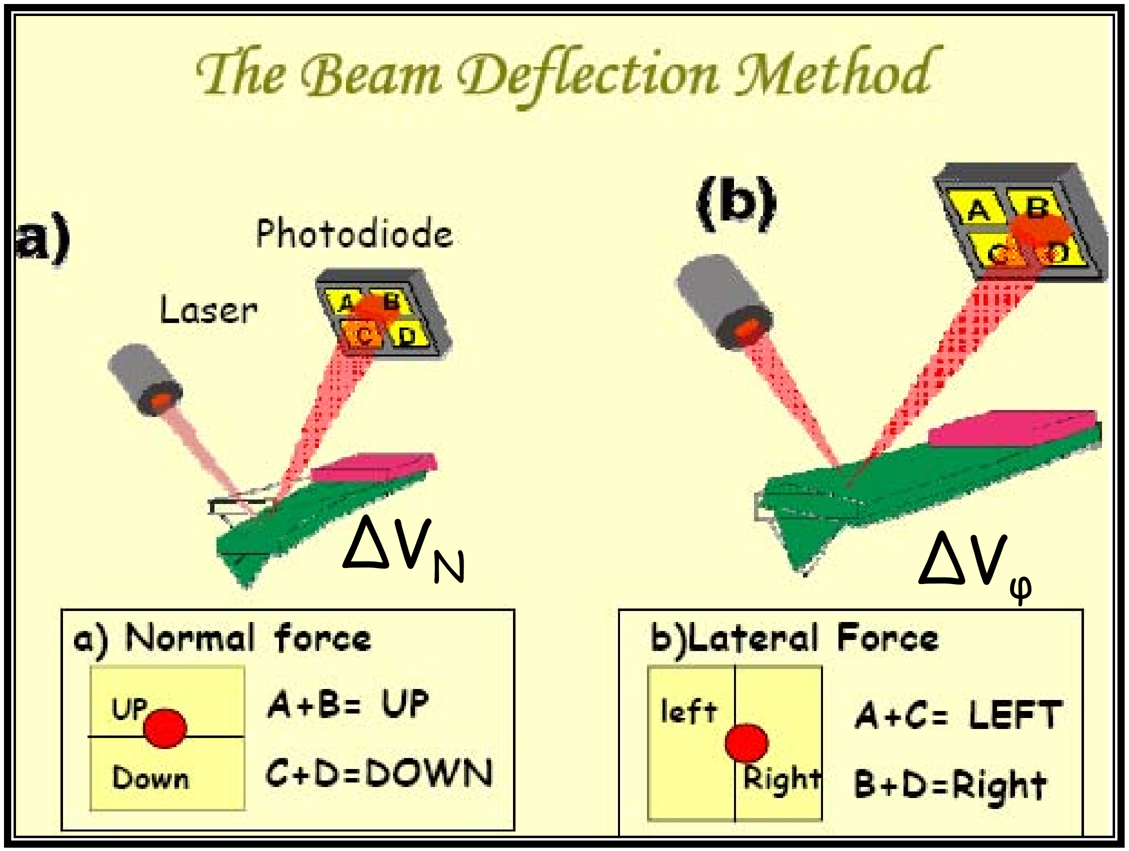


M. Munz , *J. Phys. D: Appl. Phys.* **43,** 063001 (2010).

Two Issues in Lateral Force Microscopy

1. Calibrating the lateral spring constant of the cantilever

2. Calibrating the lateral sensitivity of the photodiode



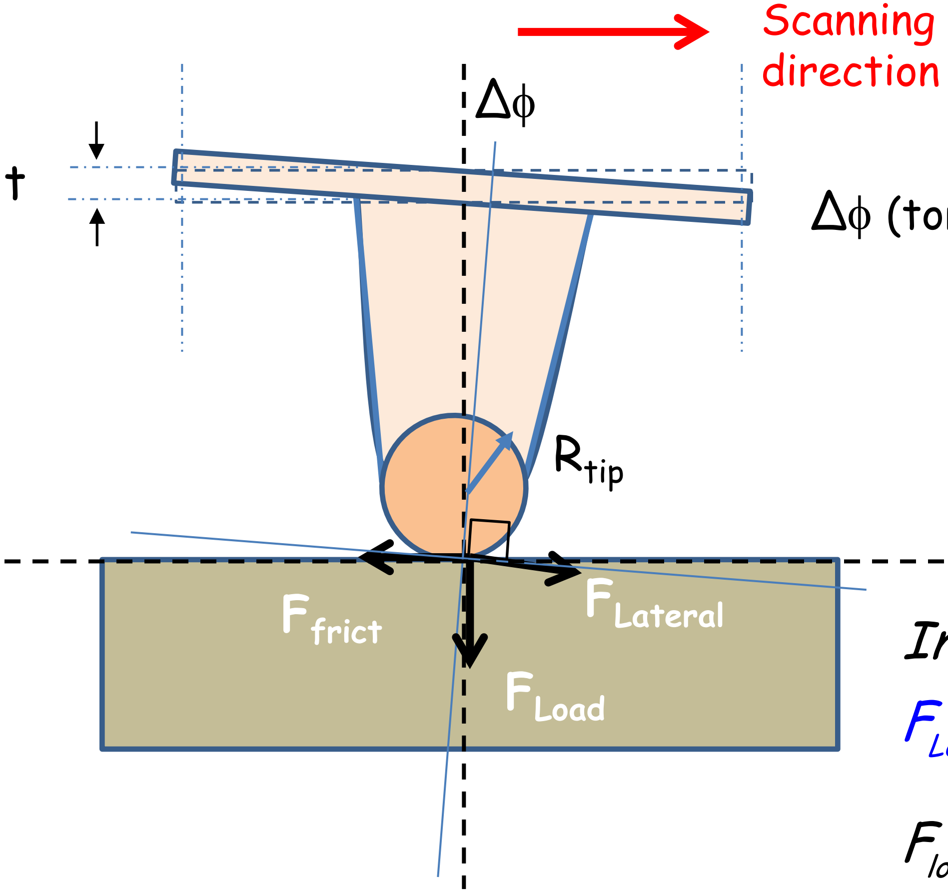
graphic courtesy of J. Gomez-Herraro

How does the PSD respond as a function of torsional deformation?

Maybe same response as for normal displacements?

If the shape of the reflected laser spot is asymmetric, the torsional response will **not** be the same as the normal response.

Accounting for All the Forces



In equilibrium:

$$F_{Load}\sin(\Delta\phi) + F_{friction}\cos(\Delta\phi) = F_{Lateral}$$

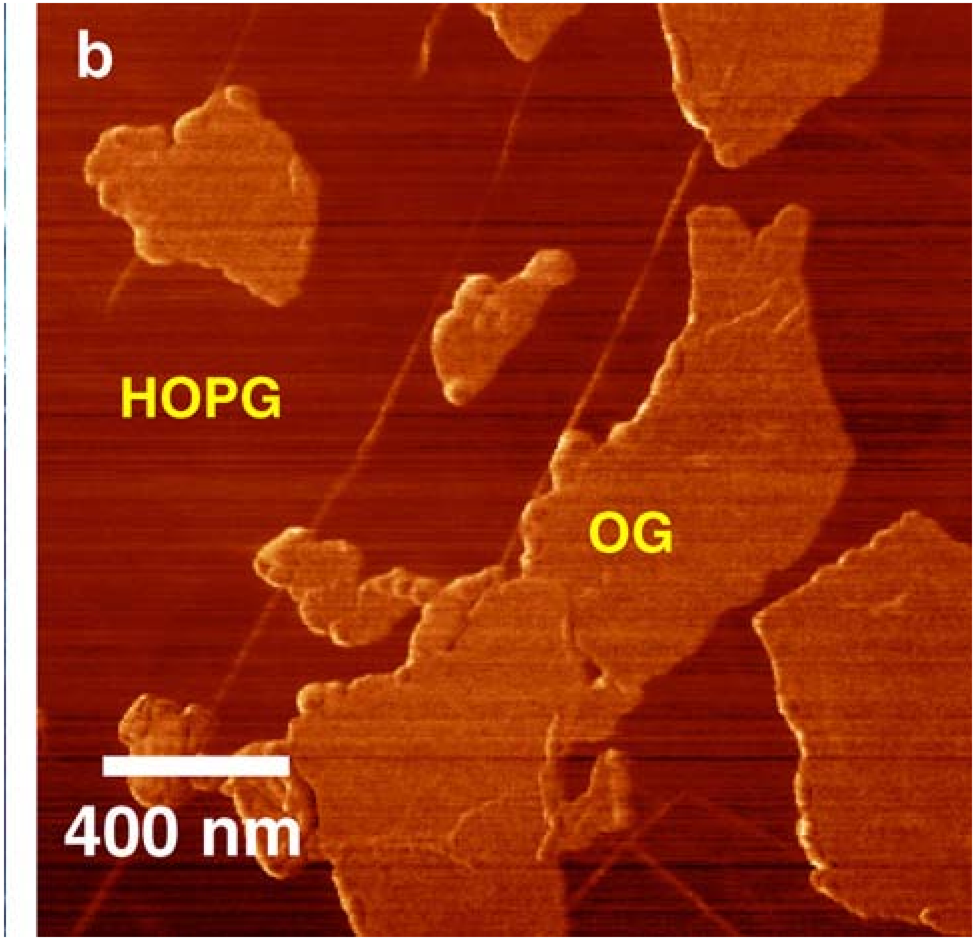
$$F_{load} = kq = \frac{Et^3w}{4L^3}q$$

$$F_{friction} = \mu F_{load}$$

$$F_{Lateral} = \frac{Gt^3w}{3LH}\Delta\phi$$

One equation, one unknown:
If Δφ is measured, then μ can be found.

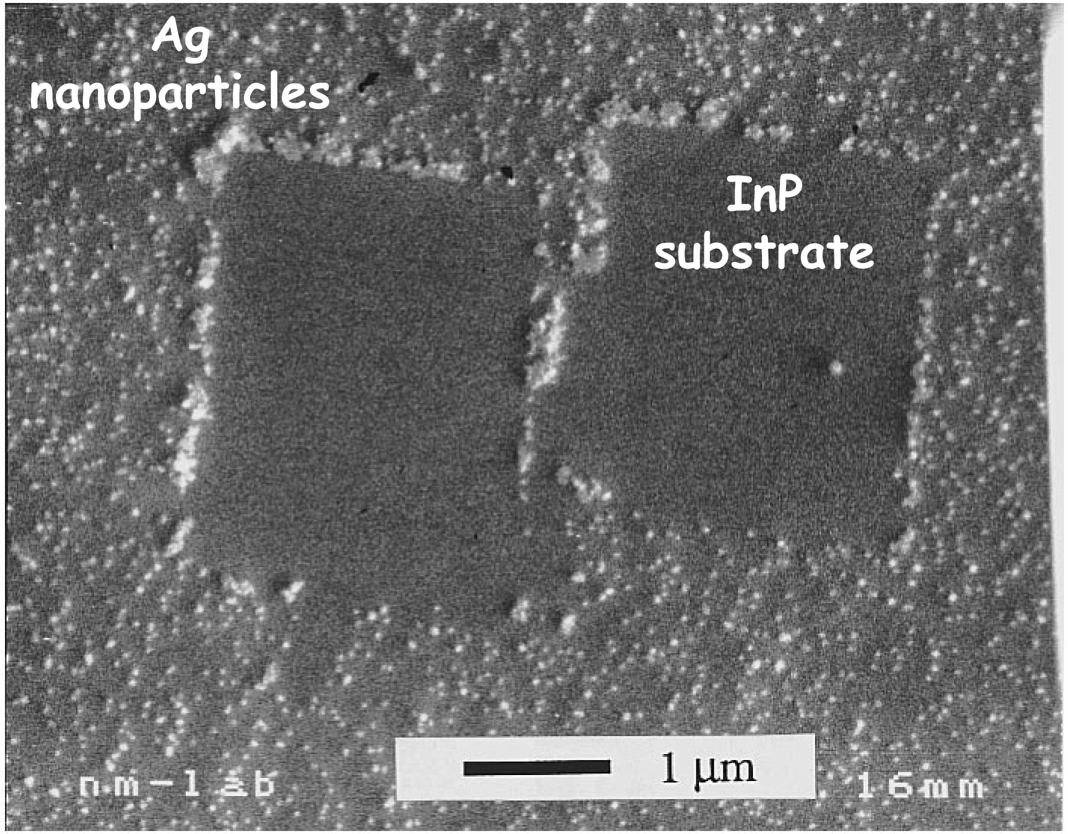
Uncalibrated Frictional Force Maps



Different frictional forces when tip is scanning over HOPG and flakes of deposited oxidized graphene (OG).

D. Pandey *et al.*, Surface Science **602** 1607 (2008) .

The lateral forces can be large



SEM image showing the result of AFM scanning of an InP surface covered with nm-sized Ag aerosol particles. The AFM probe has cleaned the two scanned areas of particles.

T. Junno, *et al.*, Appl. Phys. Lett. **66,** 3295 (1995).

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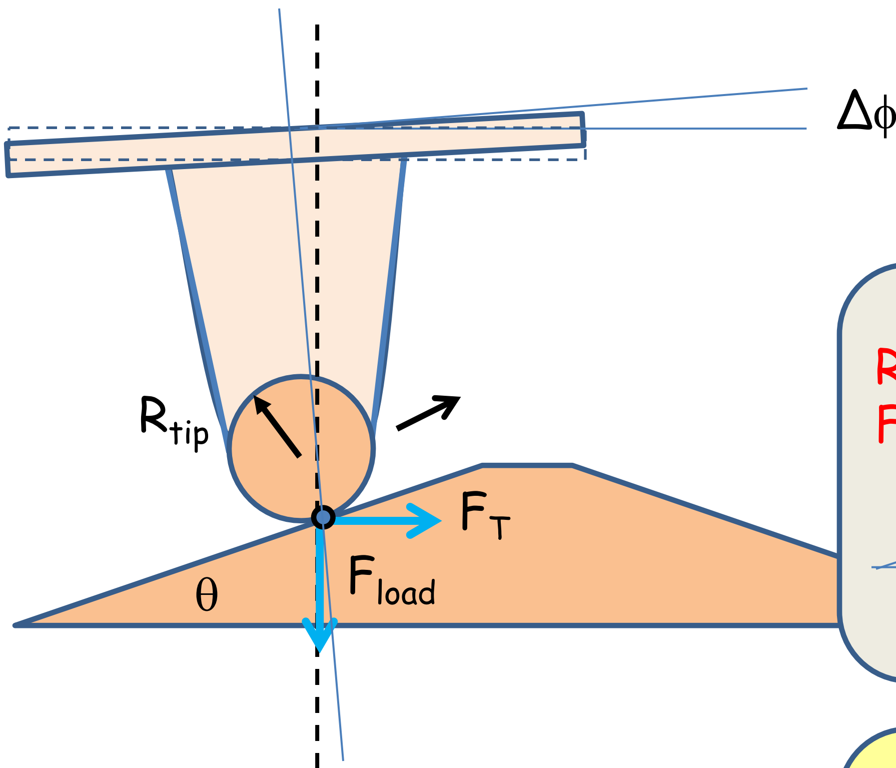
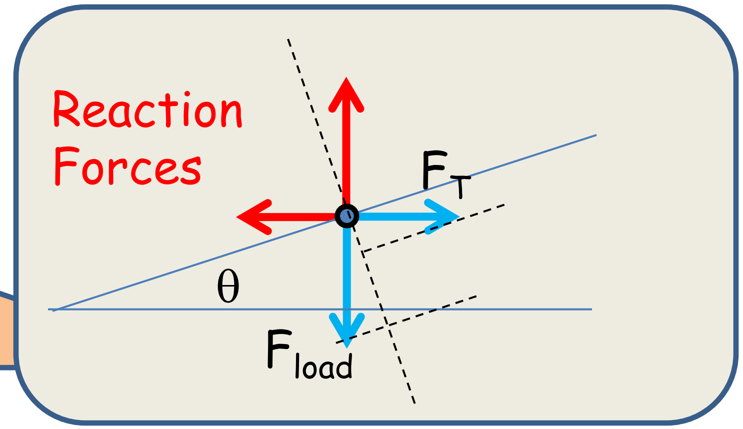
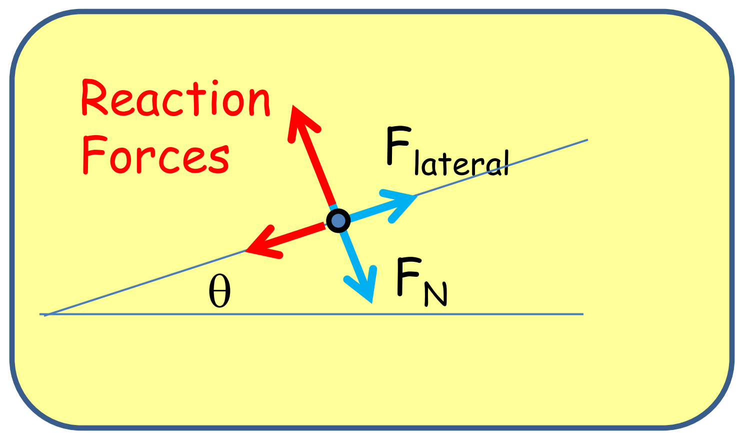
How to Generate a Known Lateral Force?



Force balance after
<u>static contact</u> with
a rigid structure

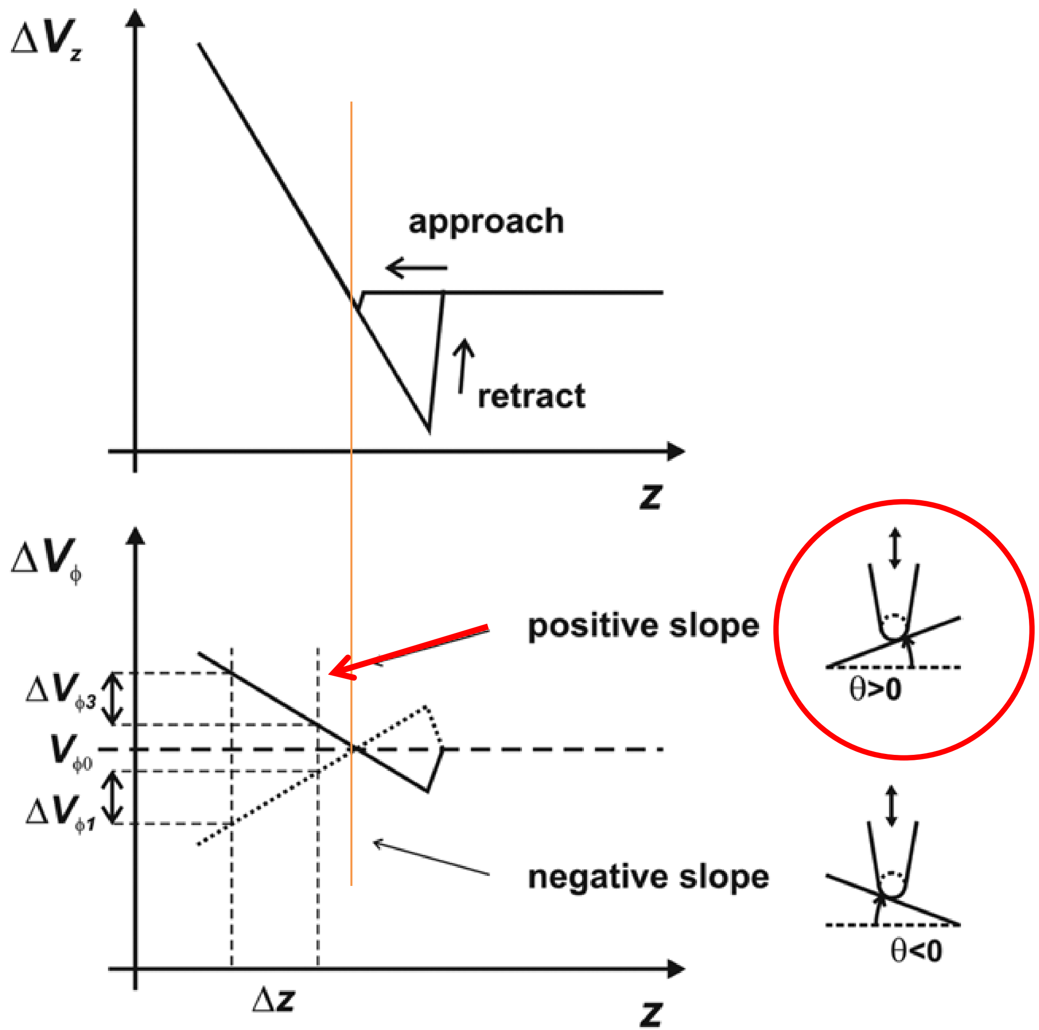




$$F_N = F_{load} \cos\theta + F_T \sin\theta$$

$$F_{lateral} = F_T \cos\theta - F_{load} \sin\theta$$

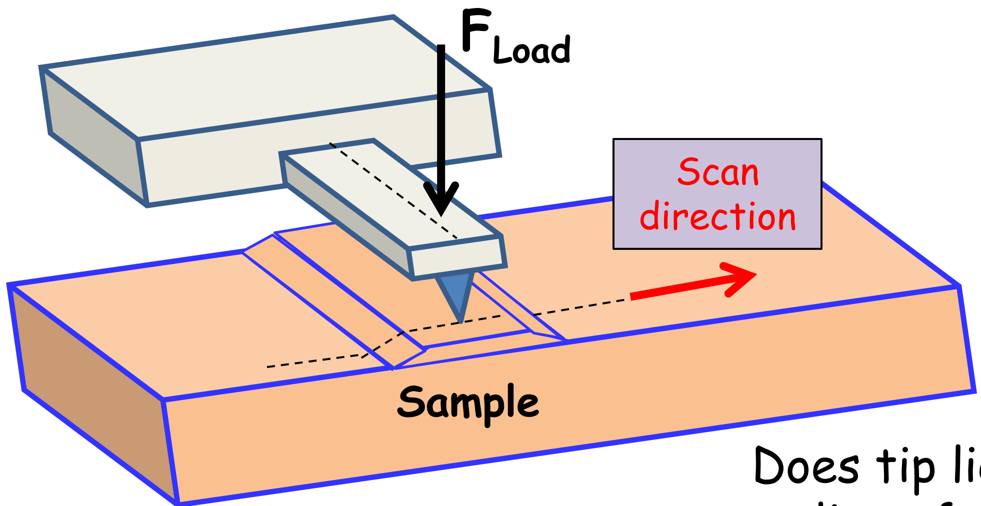
Lateral Signal vs. Loading Force



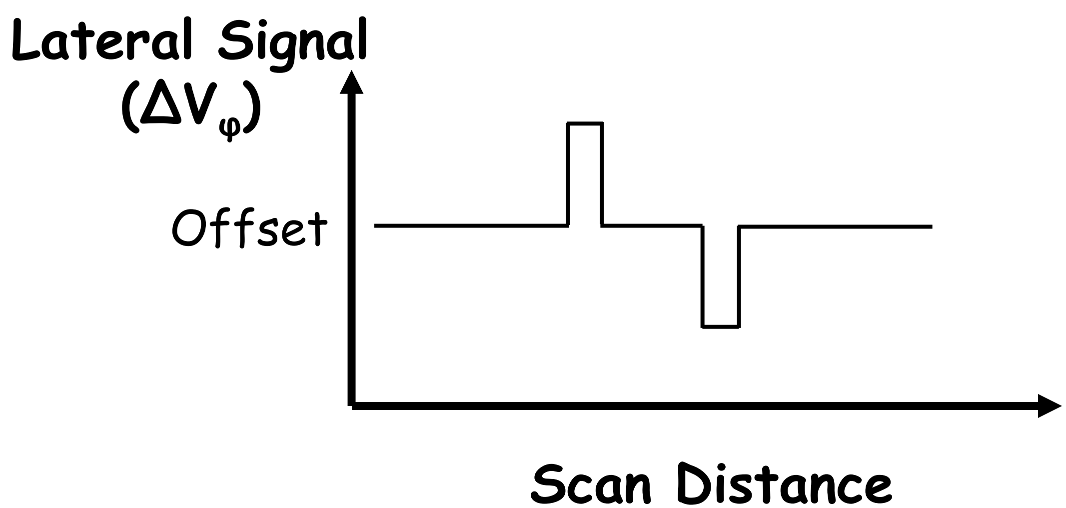
M. Munz , *J. Phys. D: Appl. Phys.* **43**, 063001 (2010).

Calibration relies on many assumptions

Wedge scanning technique

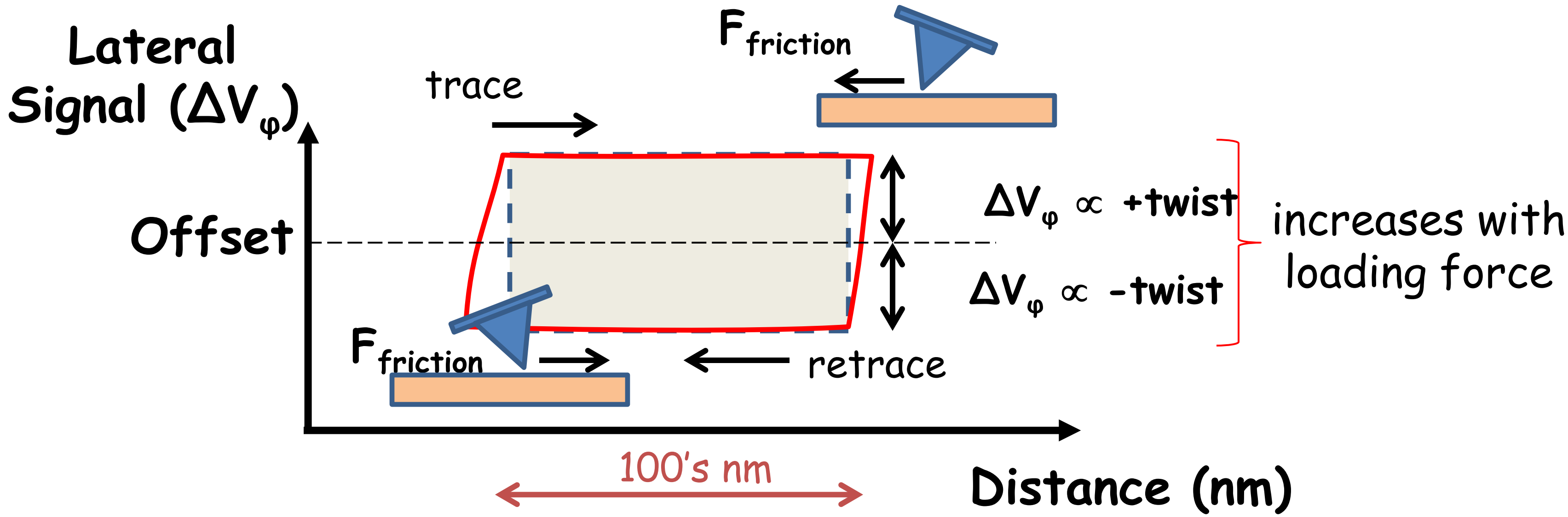


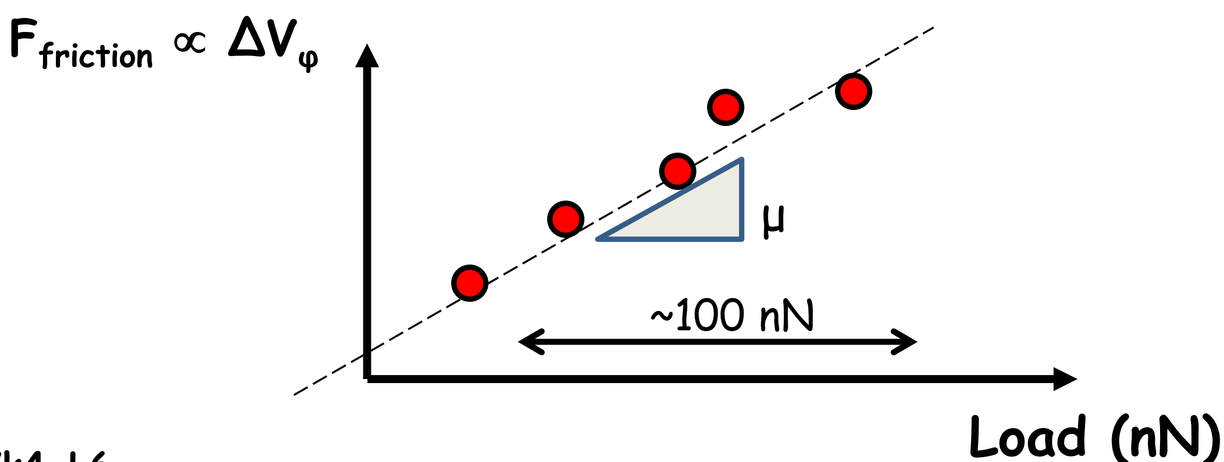
Does tip lie along centerline of cantilever?



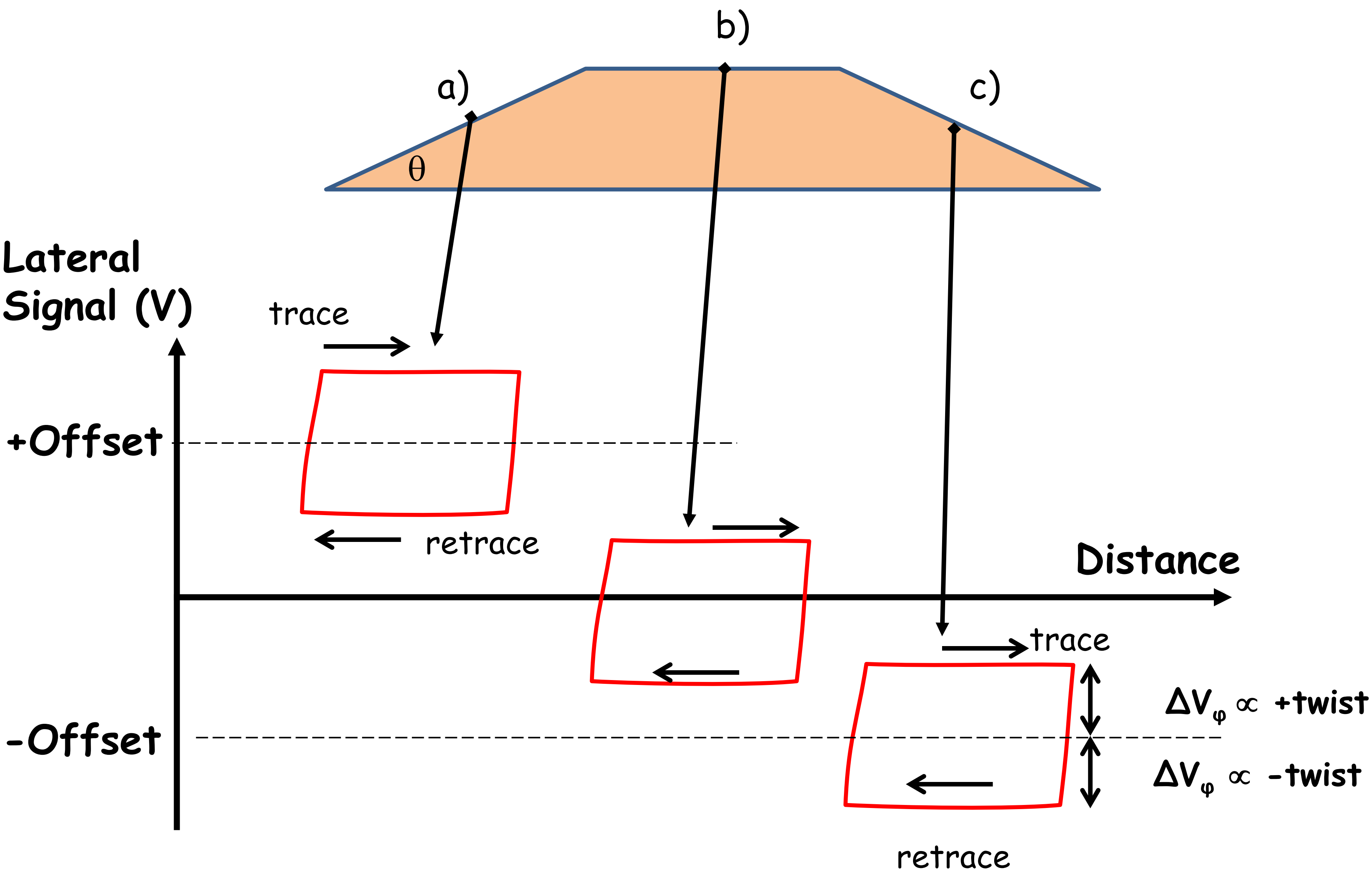
The Friction Loop

For a preset loading force F_{Load}





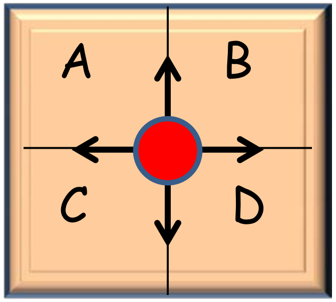
Friction Loops on Sloped Surfaces



Ogletree et al., Rev. Sci. Instrum. **67** (1996),

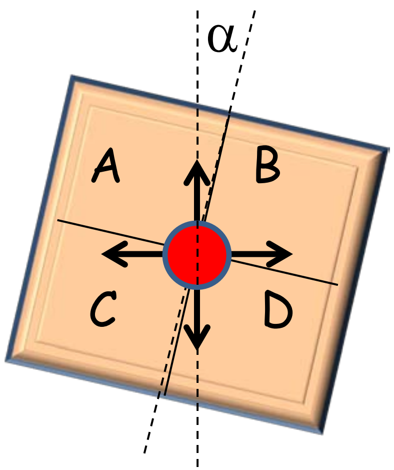
Alignment of photodiode is important

Perfectly aligned:



$$\begin{bmatrix} V_N \\ V_L \end{bmatrix} = \begin{bmatrix} \dfrac{(V_A + V_B) - (V_C + V_D)}{(V_A + V_B) + (V_C + V_D)} \\ \dfrac{(V_A + V_C) - (V_B + V_D)}{(V_A + V_B) + (V_C + V_D)} \end{bmatrix}$$

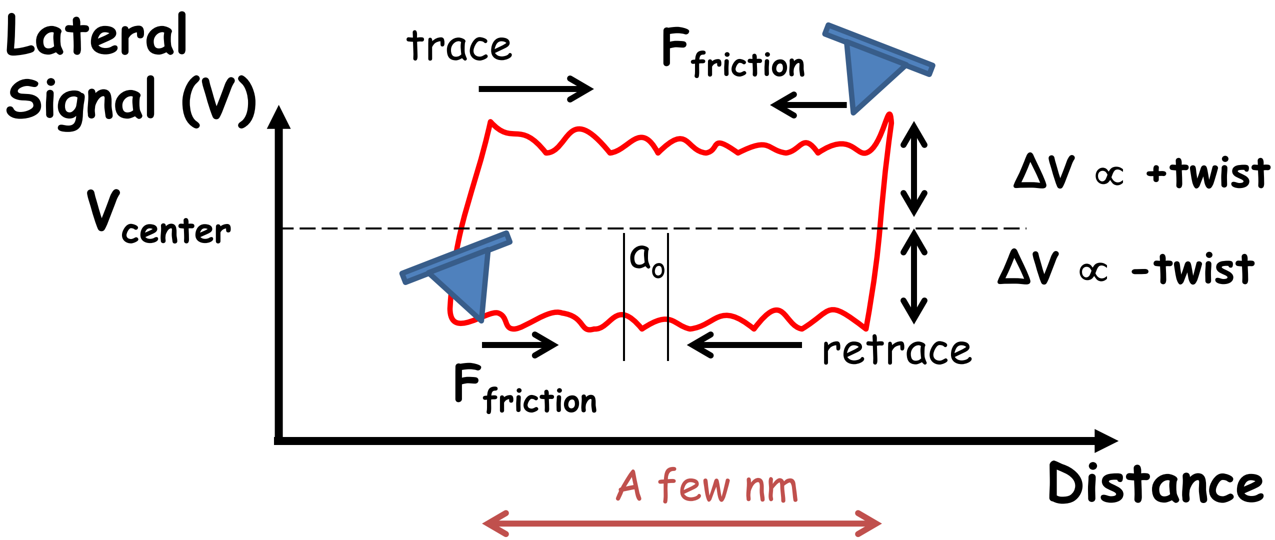
Misaligned:



$$\begin{bmatrix} V_{N,measured} \\ V_{L,measured} \end{bmatrix} = \begin{bmatrix} V_N \\ V_L \end{bmatrix} \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix}$$

Atomic scale friction: Stick/Slip

For a preset loading force $F_n = N$



First observation of atomic-scale stick-slip behavior:
C.M. Mate et al., Phys. Rev. Lett. **59**, 1942 (1987).

Up Next: Week 5 - VEDA Simulations

Appendix

Silicon elastic moduli often required in many calculations. For polycrystalline structures:

- Young's modulus, $E=1.60 \times 10^{11}$ N/m^2 =160 GPa
- Poisson's ratio, ν=0.22
- mass density, ρ = 2330 kg/m^3
- Shear modulus, $G=0.65 \times 10^{11}$ N/m^2 =65 Gpa

But it's more complicated (it always is)! Check out M.A. Hopcroft, D. Nix and T.W. Kenny, J. Microelectromechan. Systems **19**, 229 (2010).