iemn Institut d'Electronique, de Microélectronique et de Nanotechnologie

Principle of Electrostatic Force Microscopy and Applications

Thierry Mélin

thierry.melin@univ-lille1.fr

I – Introduction

II – Electrostatic Force Microscopy (EFM)

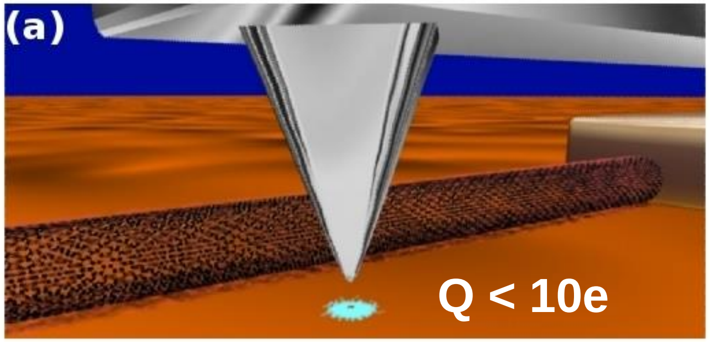
III – Kelvin Probe Force Microscopy (KPFM)

I – Introduction

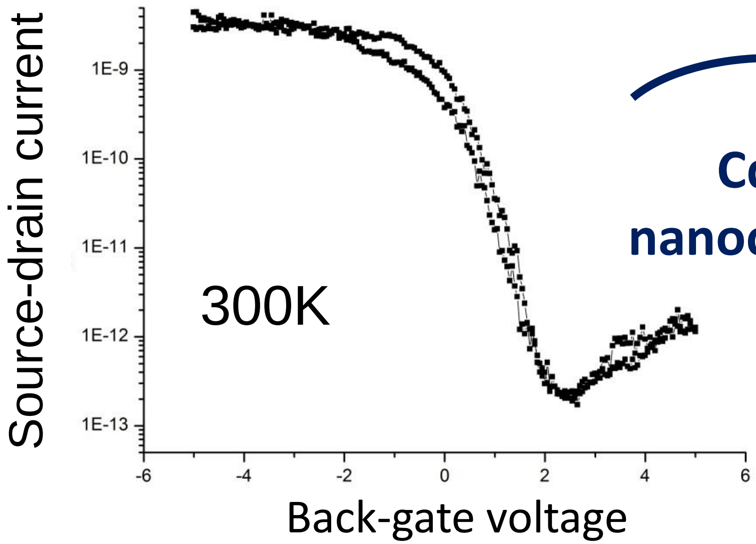
A few motivations

EX 1 : Imaging the operation of CNT-FETs as charge sensors

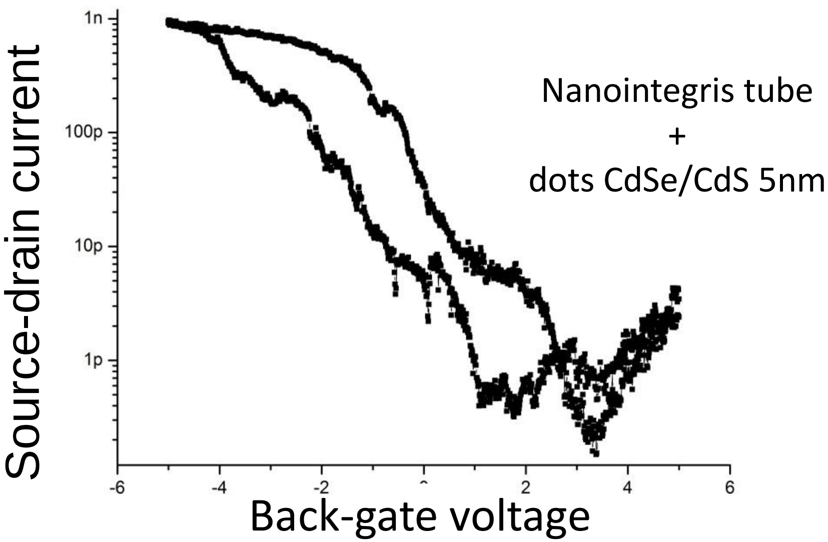
[D. Brunel et al., ACS Nano 2010]



EX 2 : coupled CNTFETs and nanocrystals



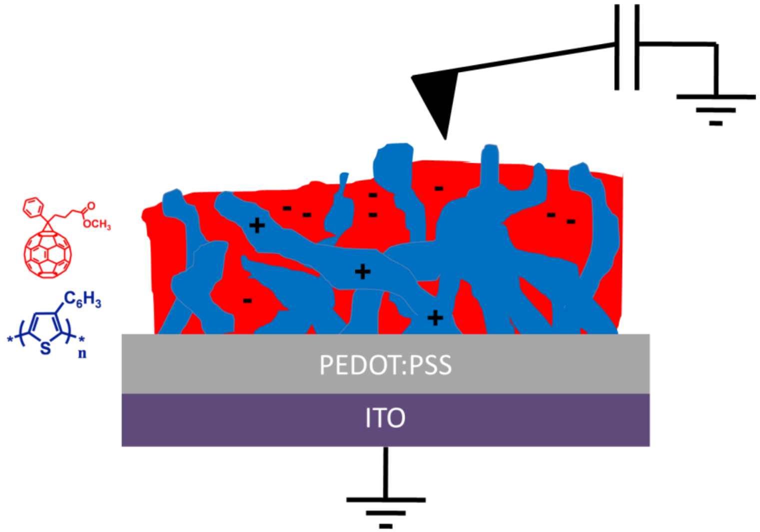
+ CdSe nanocrystals



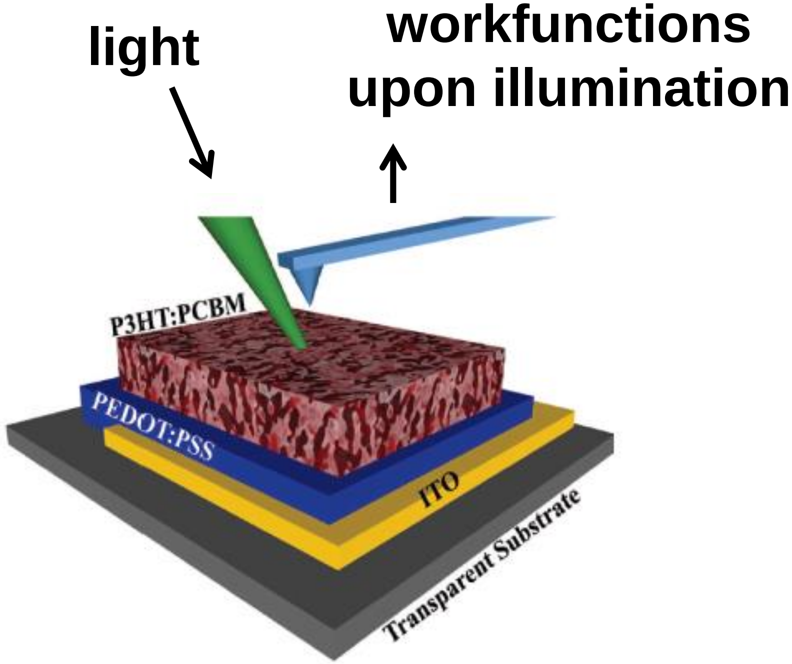
un(re)solved using AFM – Nanoletters 2015

A few motivations

EX 3 : photovoltaic materials



P3HT:PCBM blend
molecular D/A junction



cf Ł. Borowik / B. Grévin

EFM | KPFM

Electrostatic Force Microscopy | **Kelvin Probe Force Microscopy**

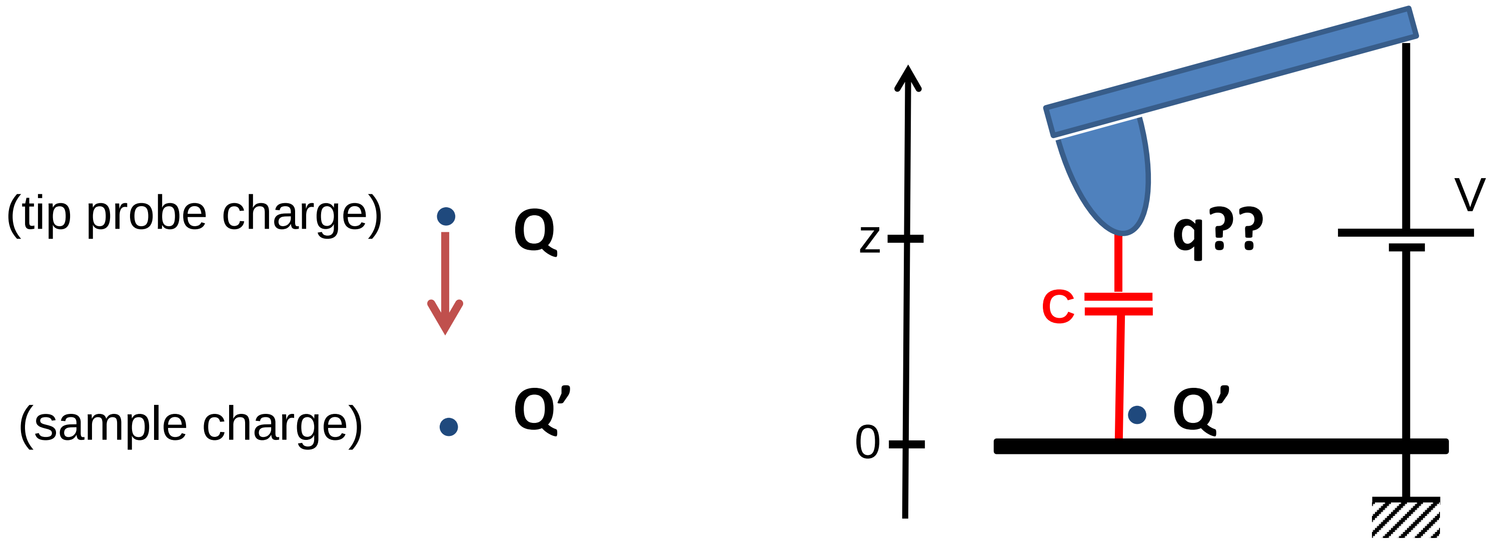
Measurement of electrostatic force gradients | *Compensation of electrostatic forces*

Units : Hz or N/m | Units : V

Charge detection ↔ *Probing local surface potentials*

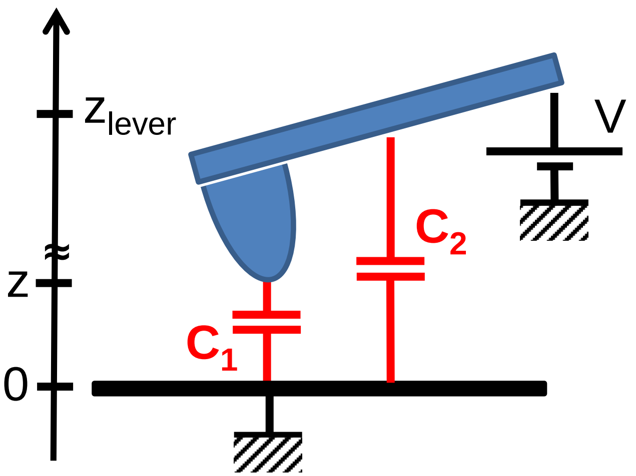
Basics

Charge detection



charges in vacuum → charges in a capacitor

Charge {≡ capacitance}



$$Q = C.V$$

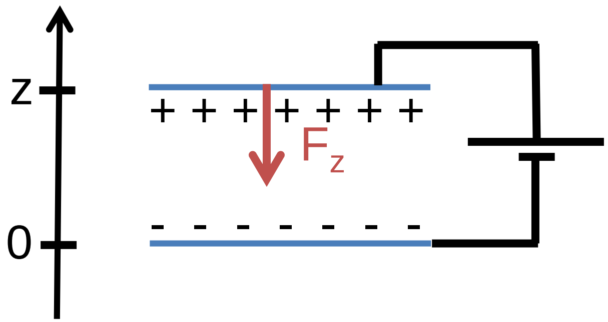
Tip apex	Cantilever
$C_1 \approx 4\pi\varepsilon_0 R_{apex}$	$C_2 \approx \varepsilon_0 \; S_{lever} \; / \; z_{lever}$
R_{apex}=20nm	S_{lever} = 30µm×100µm
$z >> R_{apex}$	z_{lever} =15µm
↓	↓
$Q_1 \approx 20$ e	$Q_2 \approx 10^4$ e

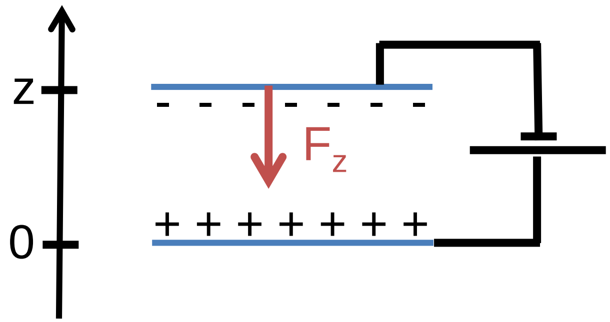
[V=1V]

Energy stored in a capacitor $\frac{1}{2} C V^2$

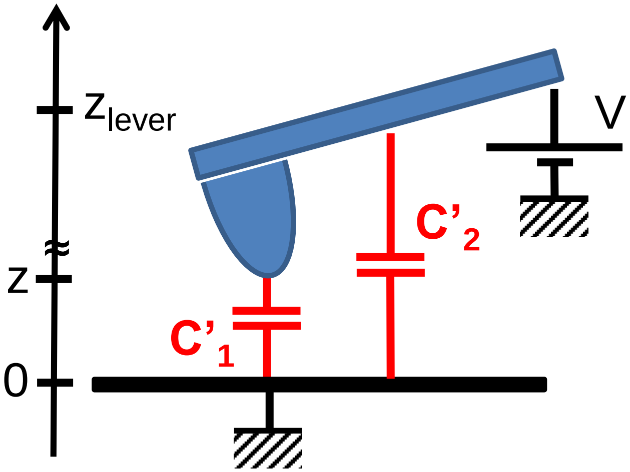
Attractive force between capacitor plates

$$F_z = + \frac{1}{2} \underbrace{\frac{dC}{dz}}_{<0} V^2 \quad (<0)$$





Electrostatic Force {≡ capacitance gradient}



Energy stored in a capacitor $\frac{1}{2} C V^2$

Attractive force between capacitor plates

$$F_z = + \frac{1}{2} \, dC/dz \; V^2 \quad (<0)$$

Tip apex	Cantilever
$\lvert dC_1/dz \rvert \approx 4\pi\varepsilon_0 R^2_{apex}/z^2$	$\lvert dC_2/dz \rvert \approx \varepsilon_0 \; S_{lever} \; / \; z^2_{lever}$
R_{apex}=20nm	S_{lever} = 30µm×100µm
z=100nm	z_{lever} =15µm
↓	↓
$F_1 \approx 5$ pN	**$F_2 \approx 100$ pN**

[V=1V]

iemn
Institut d'Electronique, de Microélectronique et de Nanotechnologie
UMR CNRS 8520

Force gradient detection

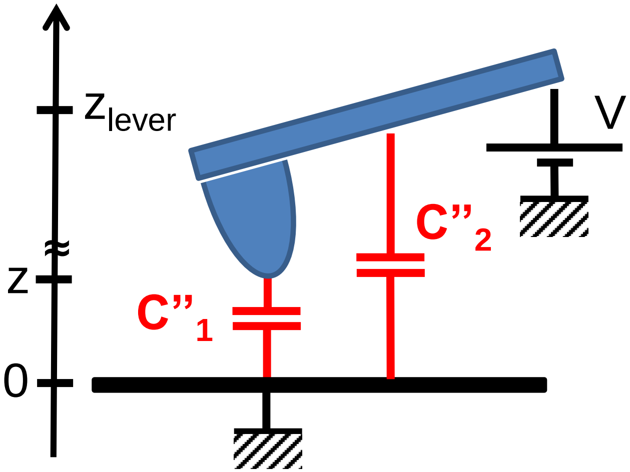
$$F_z = F_z(z_0) + (z-z_0).\ \underbrace{F'_z(z_0)}$$

frequency shift : $df = -\ f_0/2k.\ F'_z(z_0)$

- Here: long-range forces [ambient air / UHV]

- Short-range electrostatic forces disregarded here

Force gradient {≡ capacitance 2nd derivative}



force gradient $dF_{z/}/dz = \frac{1}{2}\, d^2C/dz^2\, V^2$

Tip apex

$d^2C_1/dz^2 \approx 8\pi\varepsilon_0 R^2_{apex}/z^3$

R_{apex}=20nm
z=100nm

Cantilever

$d^2C_2/dz^2 \approx 2\varepsilon_0\ S_{lever}\ /\ z^3_{lever}$

S_{lever} = 30µm×100µm
z_{lever} =15µm

[V=1V] $dF_1/dz \approx 10^{-4}$ N/m $dF_2/dz \approx 2.10^{-5}$ N/m

dF_1/dz (apex) exceeds dF_2/dz (cantilever)

We could almost stop the presentation now …

- due to tip apex size → sensitivity to few or single charge events
  provided the signal to noise ratio is sufficient

- typically sub-pN forces or 10^{-5} N/m force gradients (z=100nm)

- force gradients at the tip apex can exceed force gradients at the cantilever

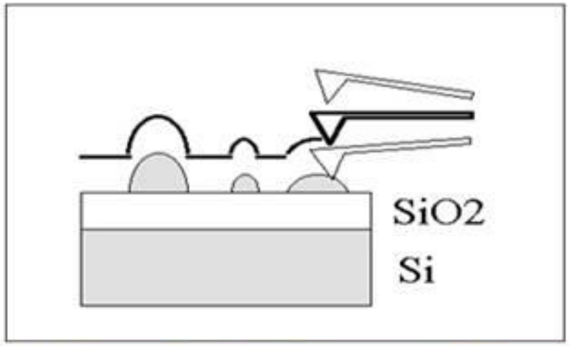
Frequency Modulation (FM) modes already appear better than Amplitude Modulation (AM) modes with this respect

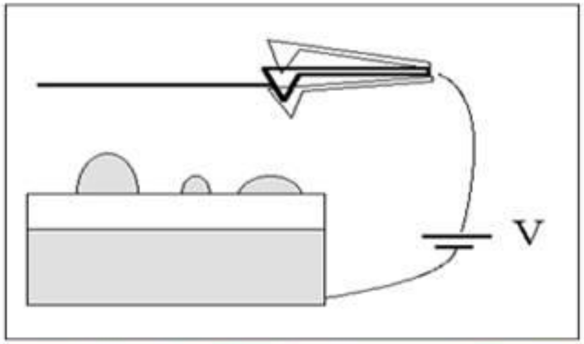
II - Electrostatic Force Microscopy

capacitive forces

Capacitive forces 1/2

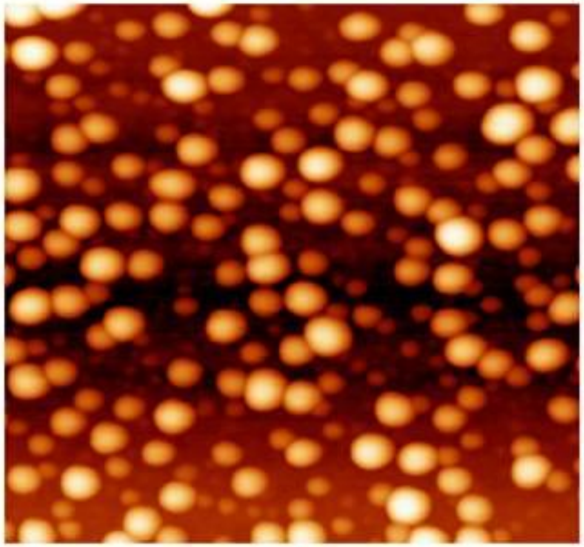
Capacitive signals associated with topgraphic features



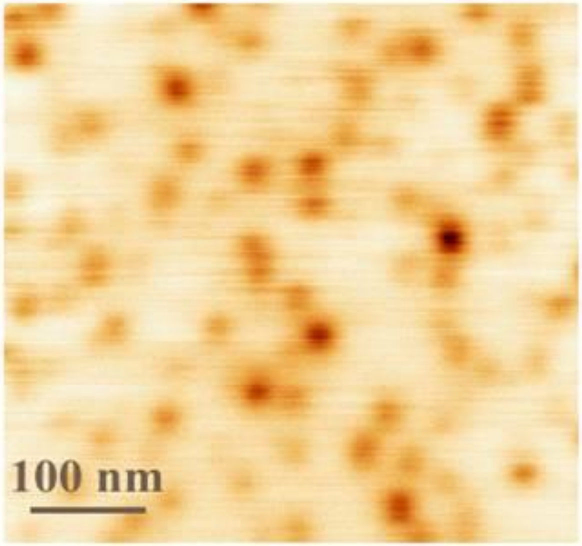


Linear mode [constant height]

z scale 50 nm



Topography image



EFM (frequency shift) image

V=-8V, freq. scale 40 Hz

Capacitive forces 2/2

Capacitive signals associated with sub-surface nanostructures

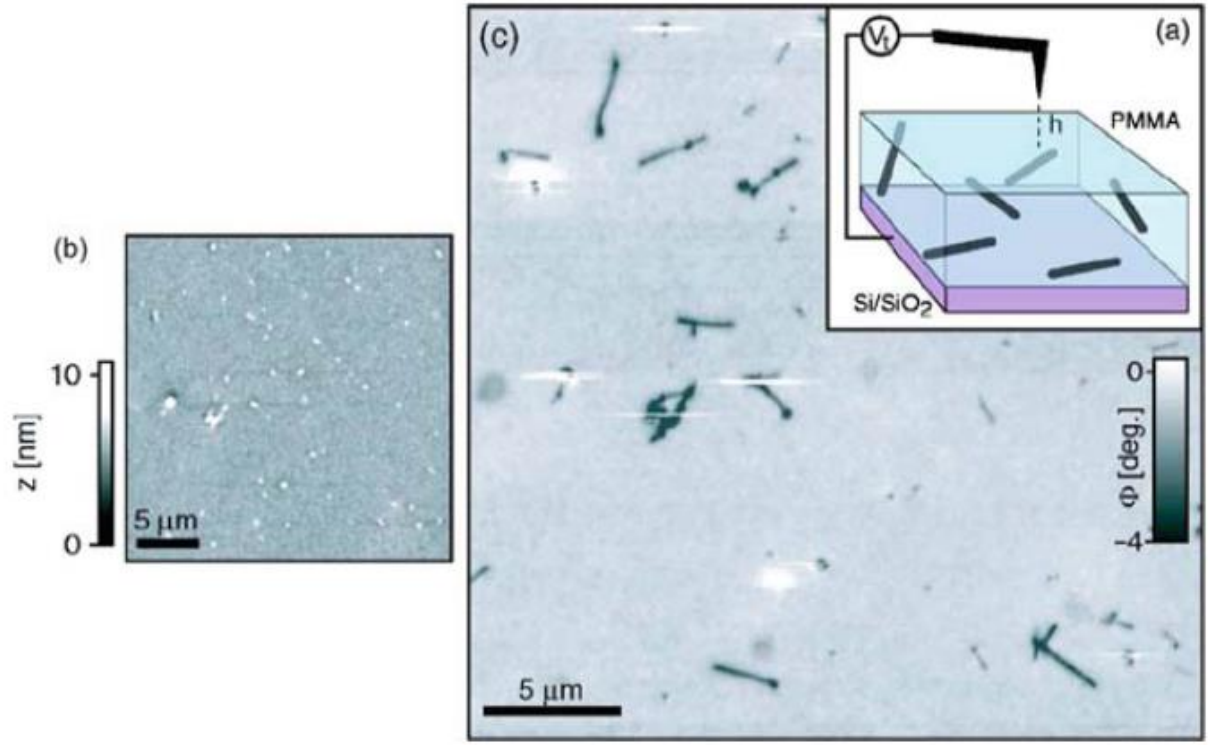
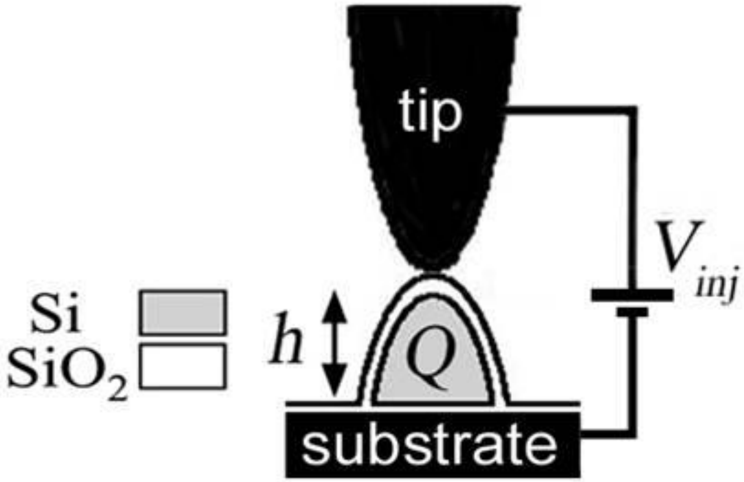


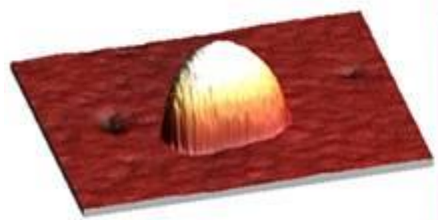
Fig. 4.6. (a) Schematic illustration of the polymer/SWCNT sample and EFM operation. (b) Topography image of the 60 nm-thick film of PMMA/SWCNT composite. Because of the polymer, the tubes cannot be observed. (c) Corresponding EFM image (tip-substrate distance $h = 35$ nm, tip biased at $+7$ V), in which individual SWCNTs are clearly seen as dark lines (negative phase shifts). Adapted from [23]

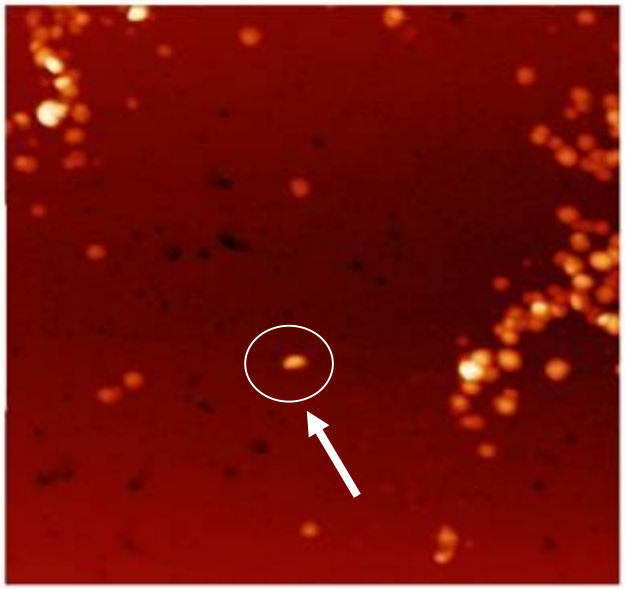
J. Nygard *et al.* Appl. Phys. Lett. 90 183108 (2007)

charge manipulation

Charge manipulation





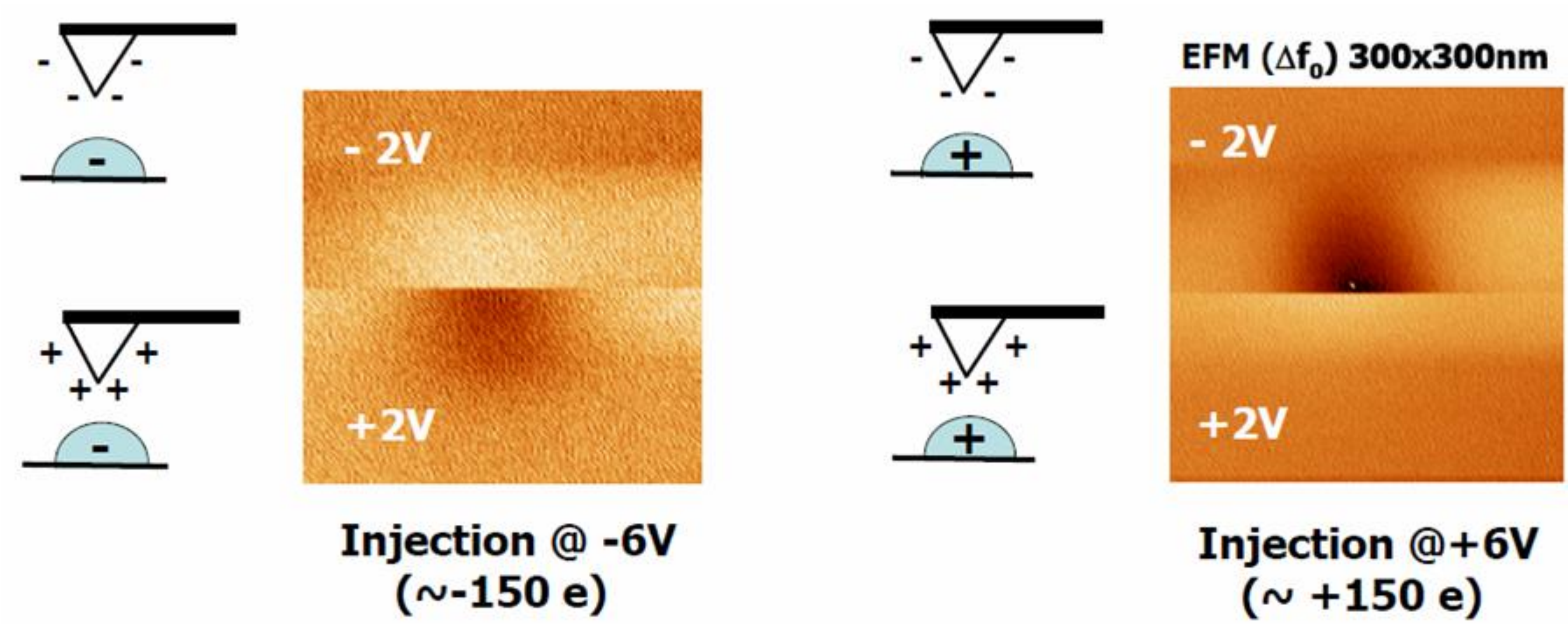


AFM Image 2500 x 2500 nm²

Contact force : a few nN

Charge retention time : of few 10 min (dry N_2)

Imaging charged nanocrystals

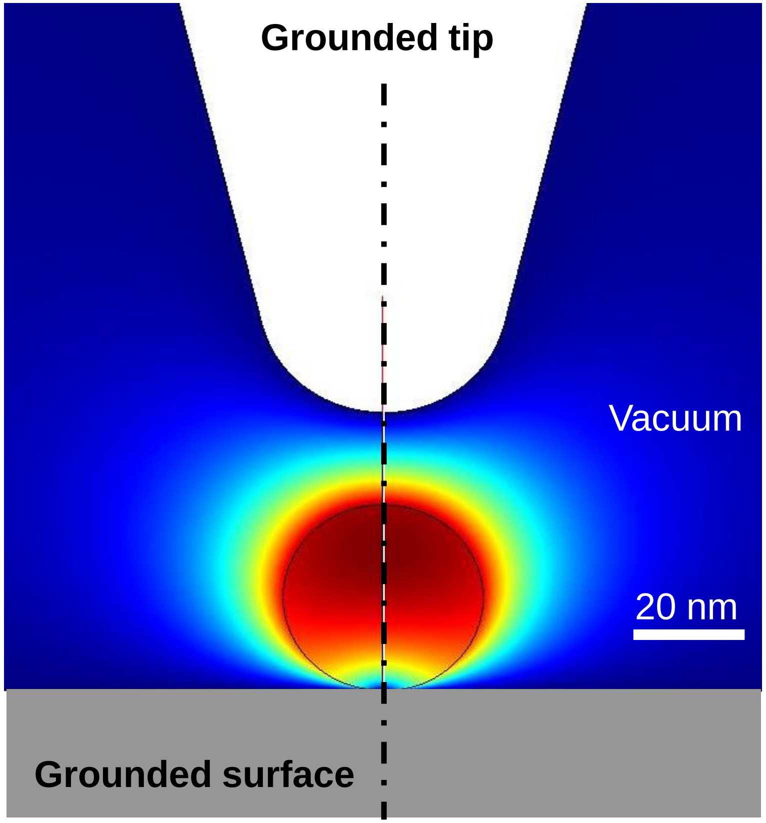


iemn
Institut d'Electronique, de Microélectronique et de Nanotechnologie
UMR CNRS 8520

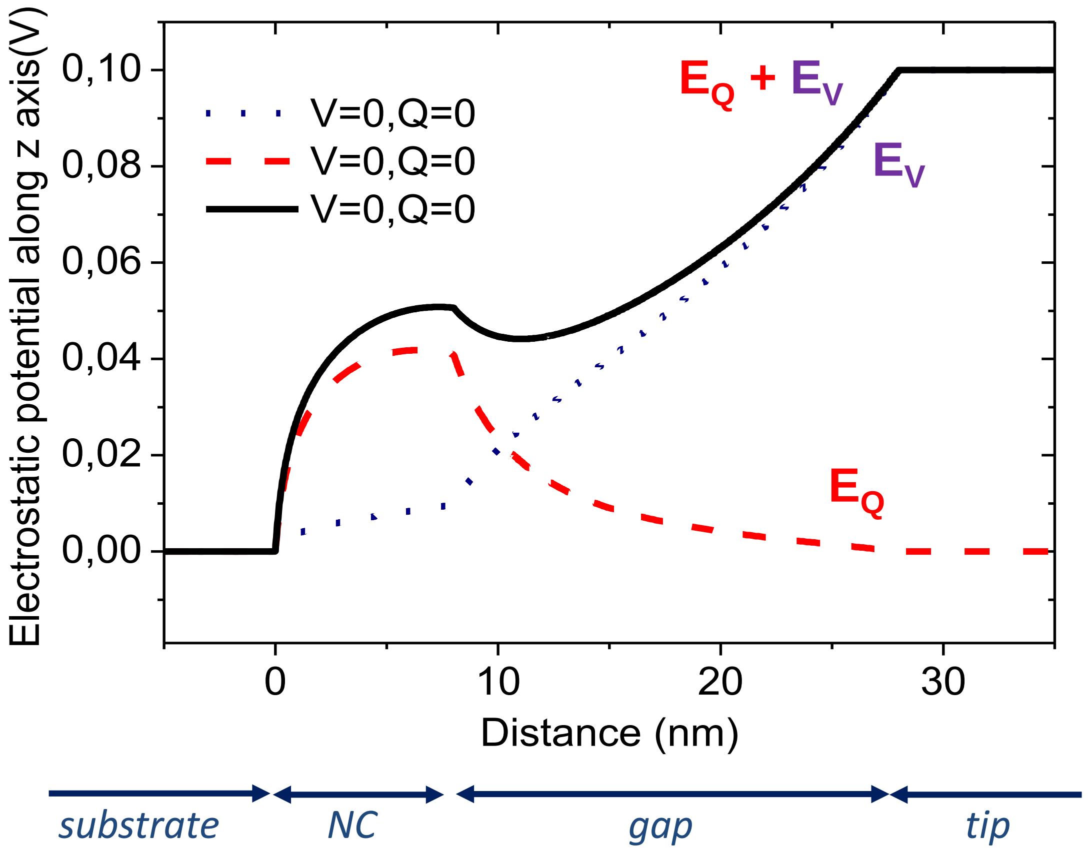
Appl. Phys. Lett., 78 5054 (2002)

electrostatic force analysis

Electrostatic forces



Isopotential map of a charged dielectric sphere with grounded substrate and tip



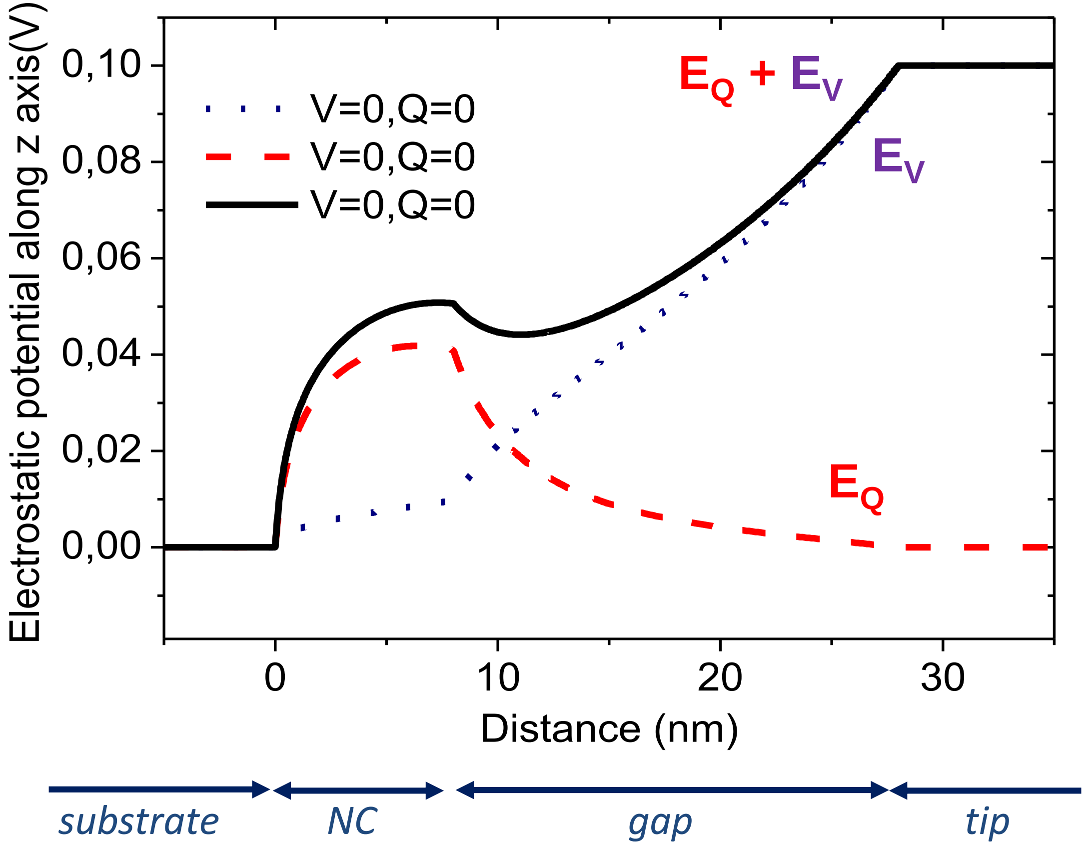
Electrostatic forces

electric field at the tip ?

[superposition theorem]

$$E_{Q\neq0,V\neq0} = \underbrace{E_{Q=0,V\neq0}}_{E_V} + \underbrace{E_{Q\neq0,V=0}}_{E_Q}$$

$$a.V + b.Q$$



iemn
Institut d'Electronique, de Microélectronique et de Nanotechnologie
UMR CNRS 8520

Electrostatic forces

electric field at the tip ?

[superposition theorem]

$$E_{tip} = E_{Q=0,V\neq 0} + E_{Q\neq 0,V=0}$$

$$E_V + E_Q$$

$$a.V + b.Q$$

force applied to the tip ?

[electrostatic pressure]

$$F_{tip} = \tfrac{1}{2}\,\varepsilon_0 \iint [E_{tip}]^2.dS$$

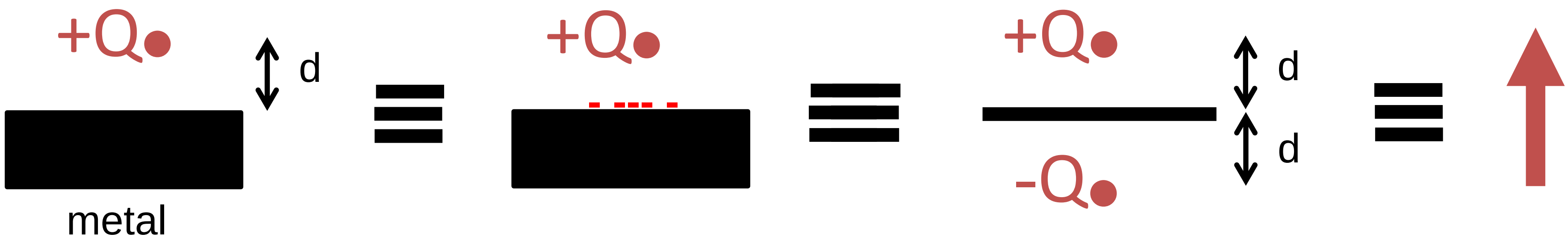
proportional to $[a.V + b.Q]^2$

$A.V^2$ + **$B.Q.V$** + **$C.Q^2$**

capacitive force — mixed term — image force

OK — OK — ??

Charge screening



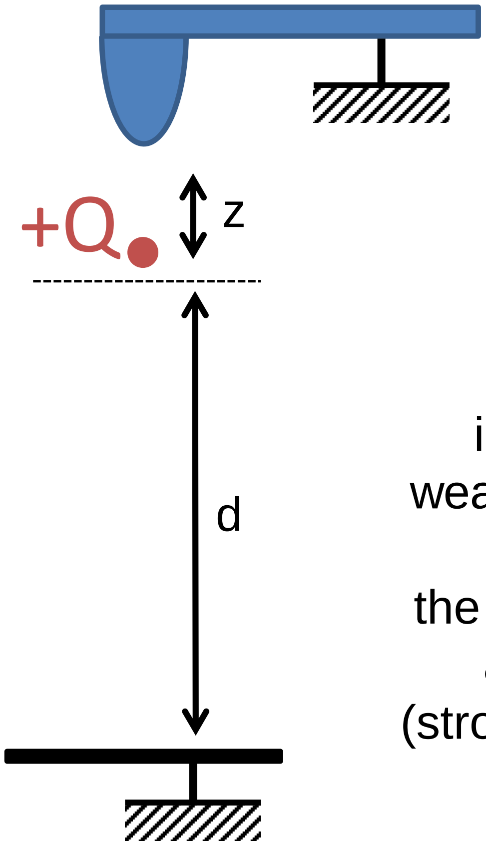
charge in the vicinity of a conductive plane

screened charge

charge +Q + image charge -Q

dipole prop. to Q

Two opposite situations



z<<2d

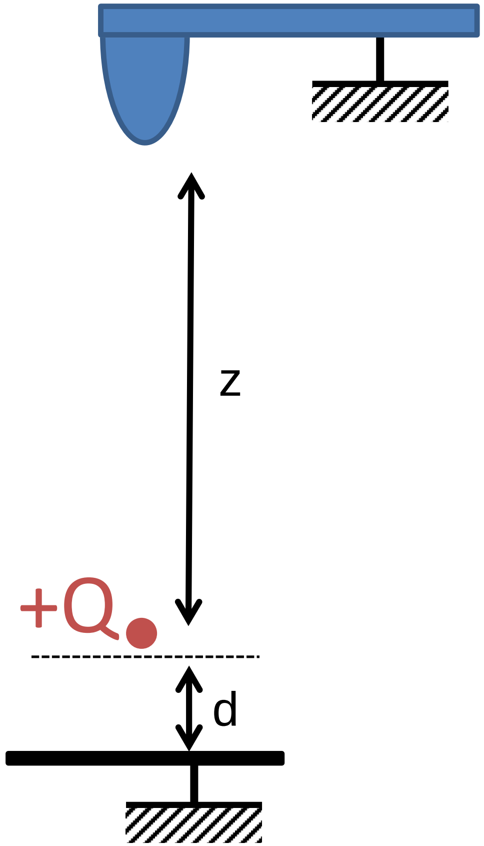
insulators
weak screening

the tip « feels »
a charge
(stronger forces)

z>>2d

conductors
strong screening

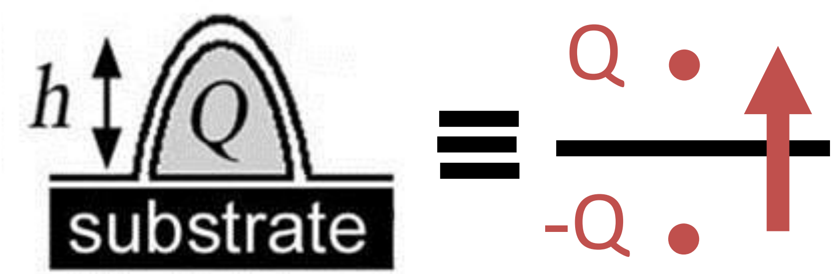
the tip « feels »
a dipole
(weaker forces)

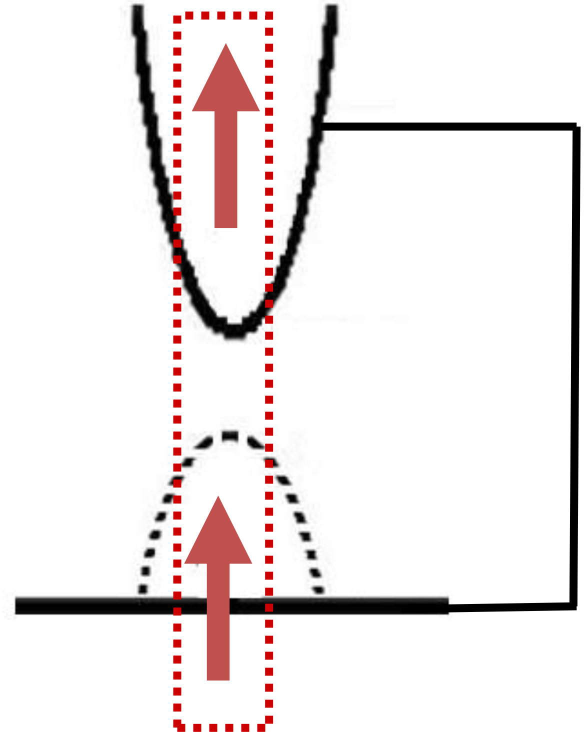


Electrostatic forces without energy diagrams

effective surface dipole

$Q\,h\,/\,\varepsilon$





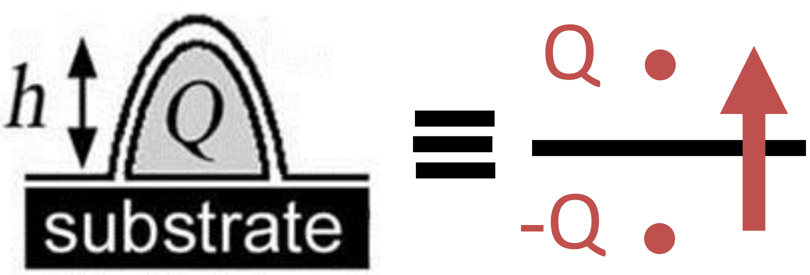
charged nanoparticle (V=0)

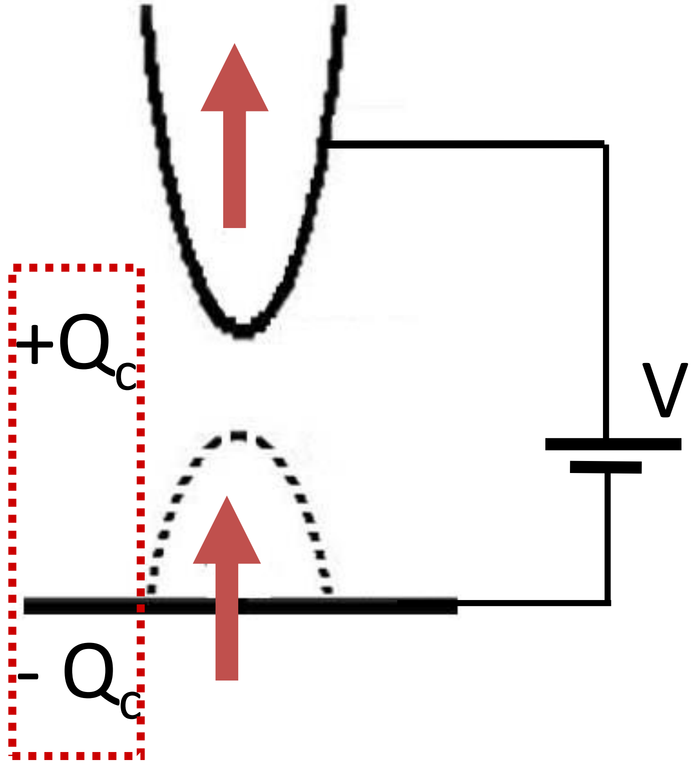
dipole-dipole interaction $\alpha\ Q^2$

Electrostatic forces without energy diagrams

effective surface dipole

Q h / ε





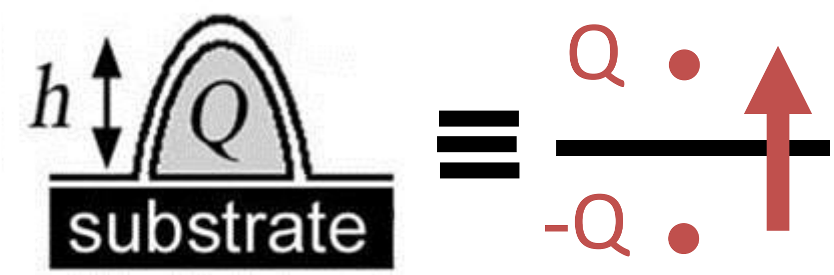
charged nanoparticle (V=0) — dipole-dipole interaction α Q²

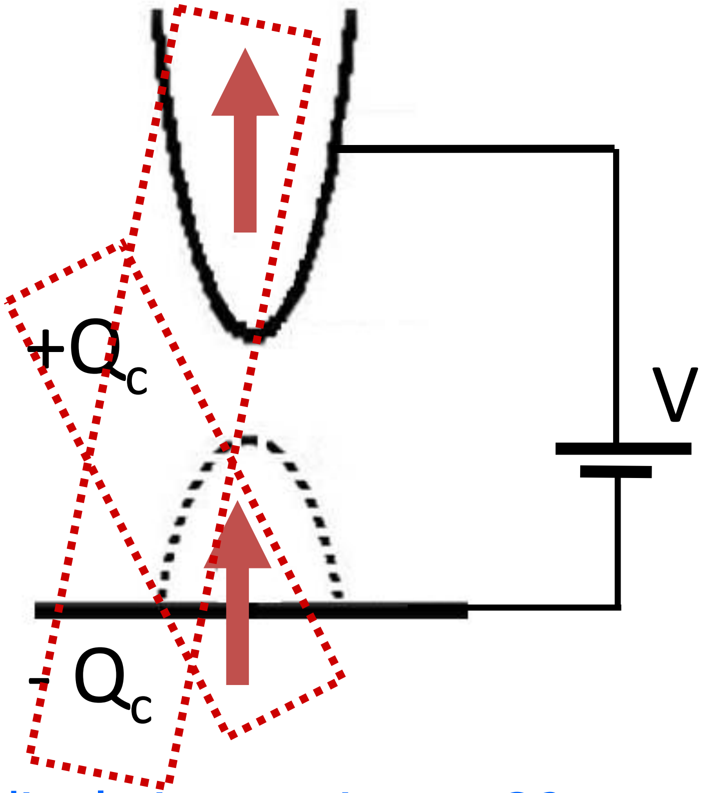
uncharged nanoparticle (V≠0) — capacitive interaction α V²

Electrostatic forces without energy diagrams

effective surface dipole

Q h / ε

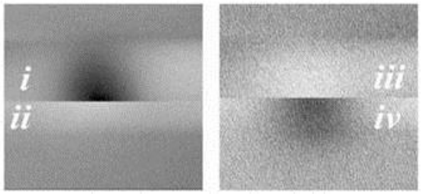


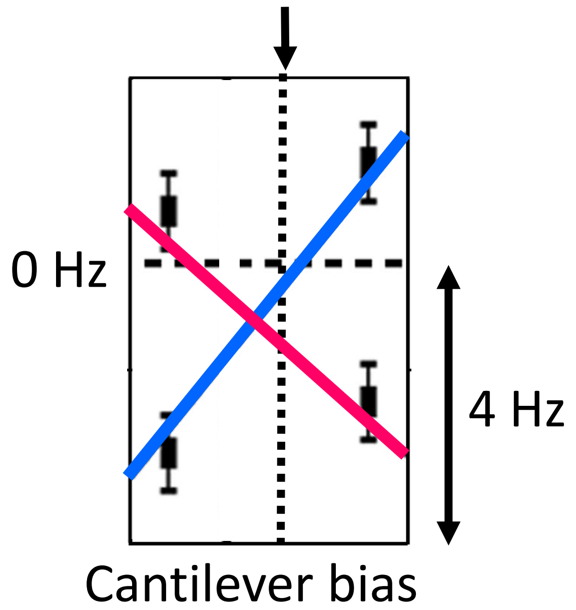


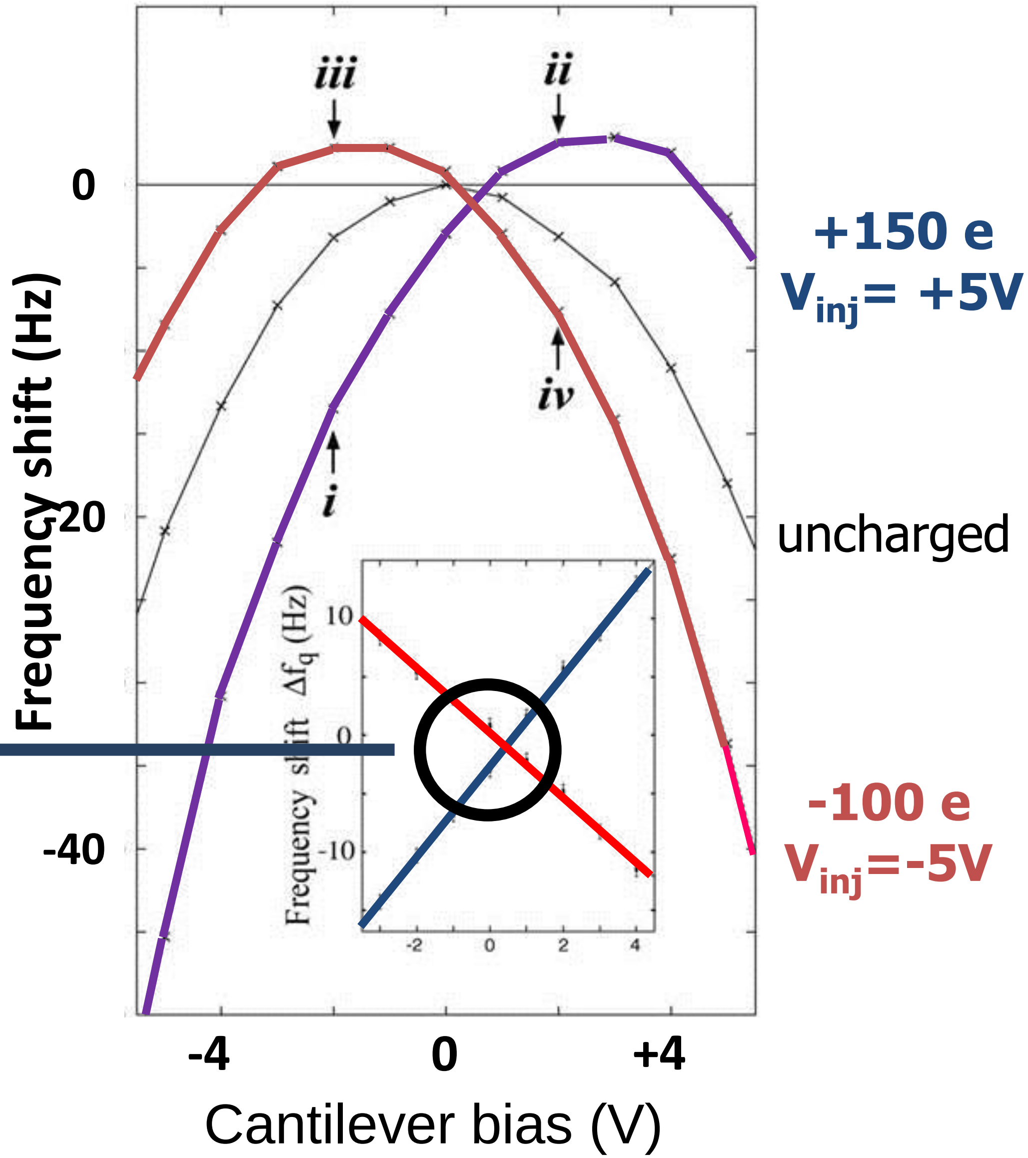
charged nanoparticle (V=0)	dipole-dipole interaction α Q²
charged nanoparticle (V≠0V)	dipole-charge interaction α Q.V
uncharged nanoparticle (V≠0)	capacitive interaction α V²

Experimental spectroscopic analysis
[here : screened charges above a conducting plane]

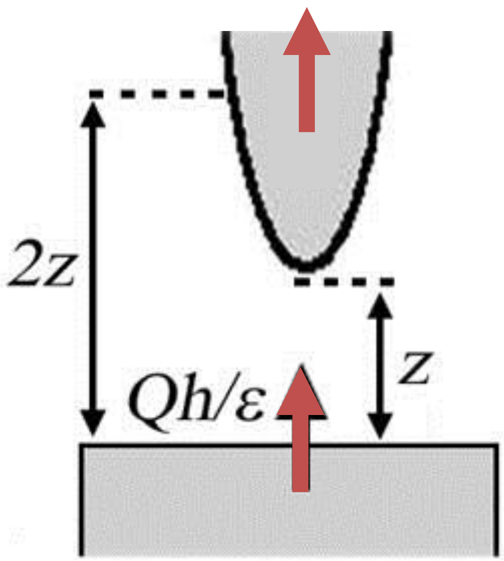
Spectroscopic analysis of charge signals

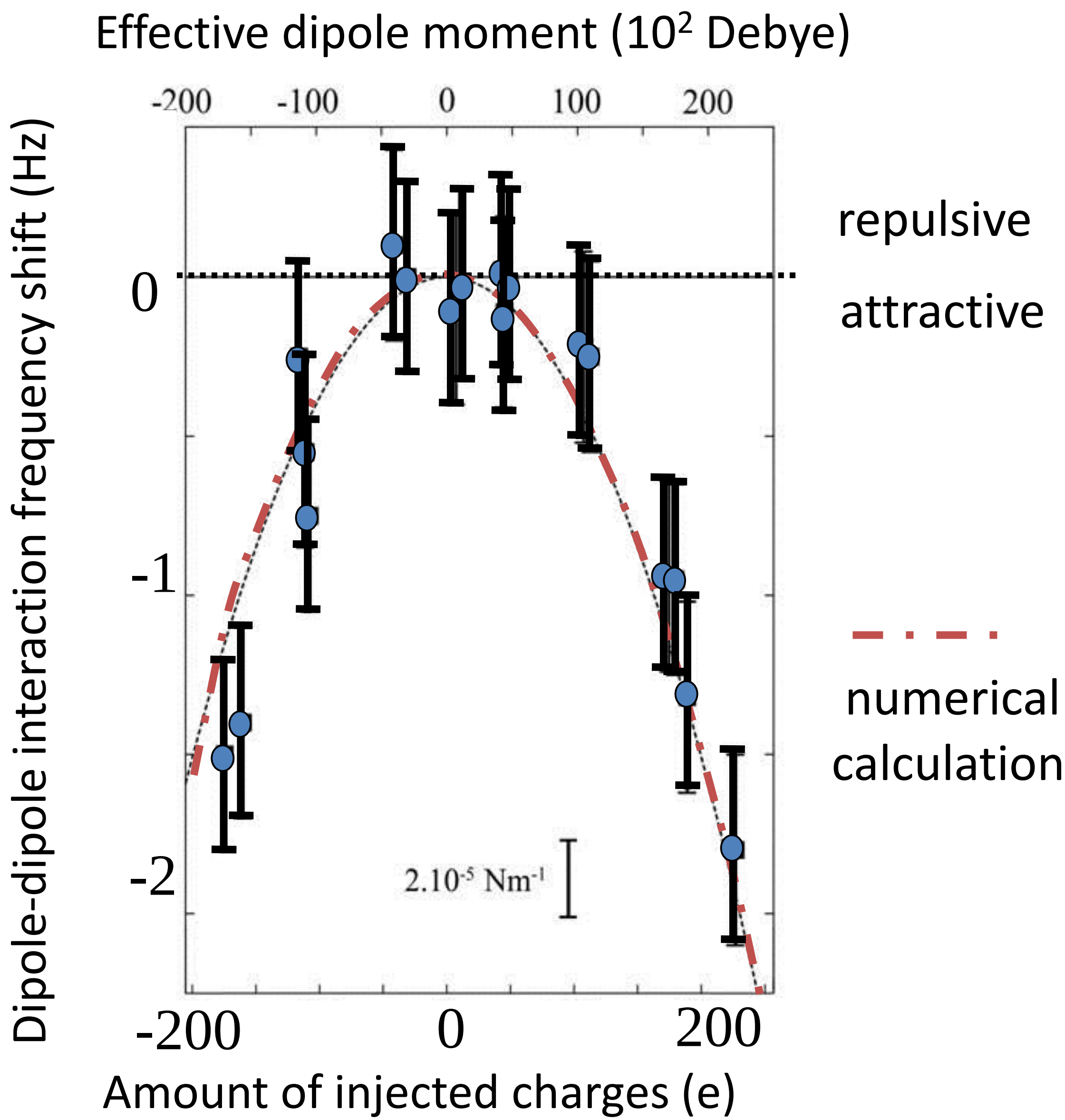






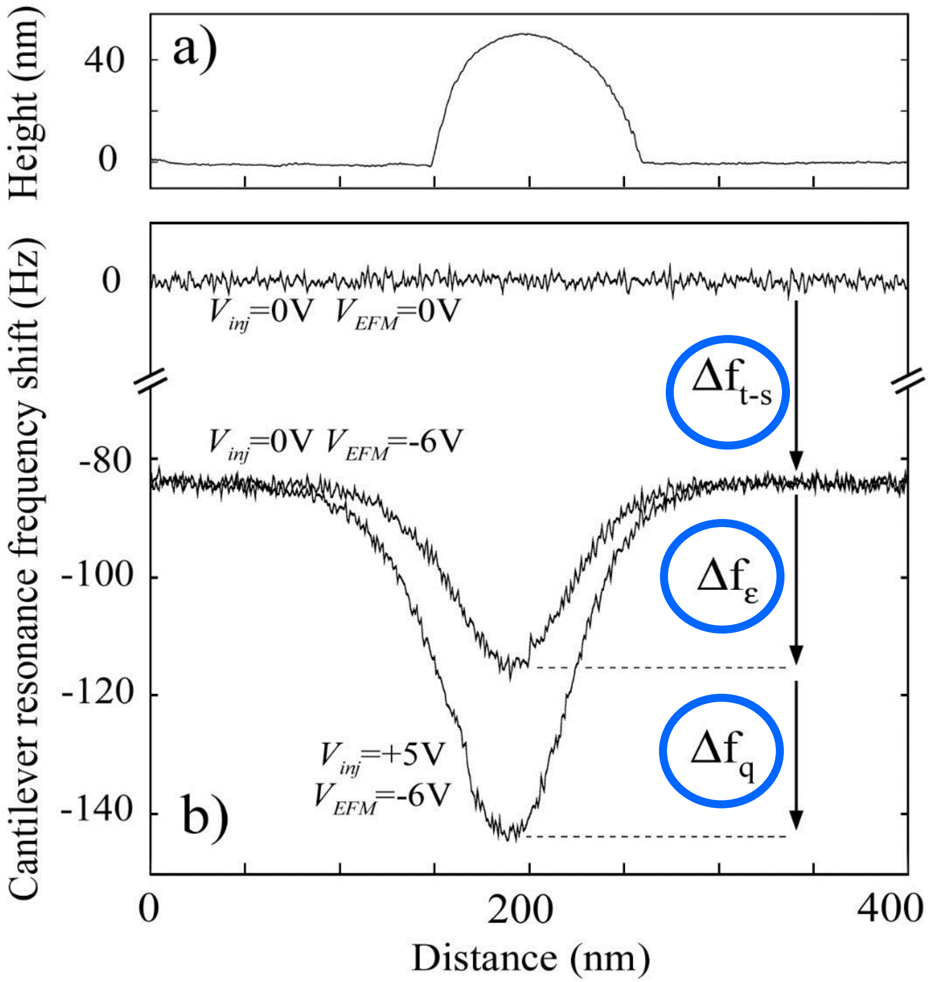
dipole-dipole interactions





Charges or dipoles ?

Probing a charge or a dipole ?



- tip-substrate capacitance

  prop. to $\mathbf{V_{EFM}^2}$

- nanoparticle capacitive effect

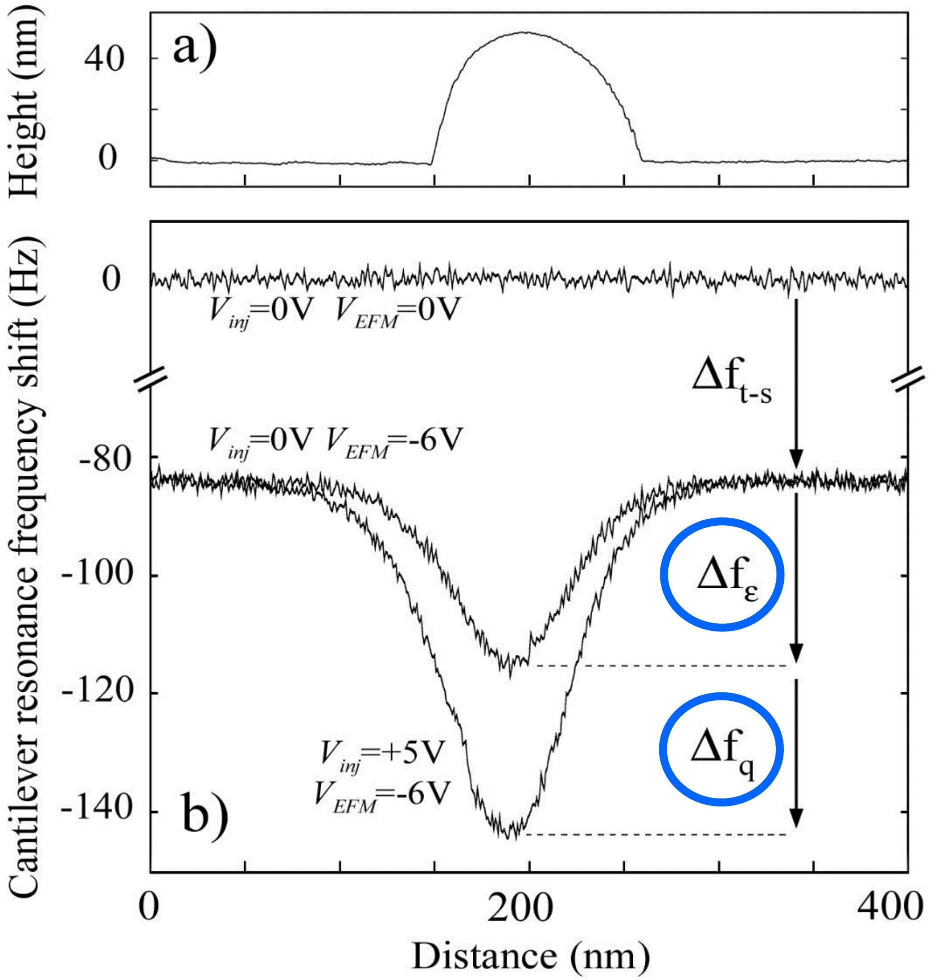
  prop. to $\mathbf{V_{EFM}^2}$

- charge perturbation

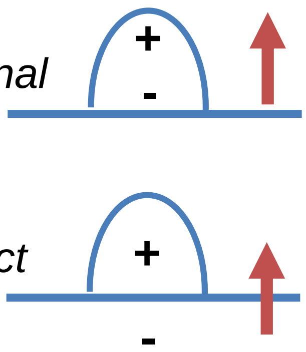
  prop. to $\mathbf{Q \cdot V_{EFM}}$ **(+Q^2 contribution)**

iemn
Institut d'Electronique, de Microélectronique et de Nanotechnologie
UMR CNRS 8520

Probing a charge or a dipole ?



Capacitive signal



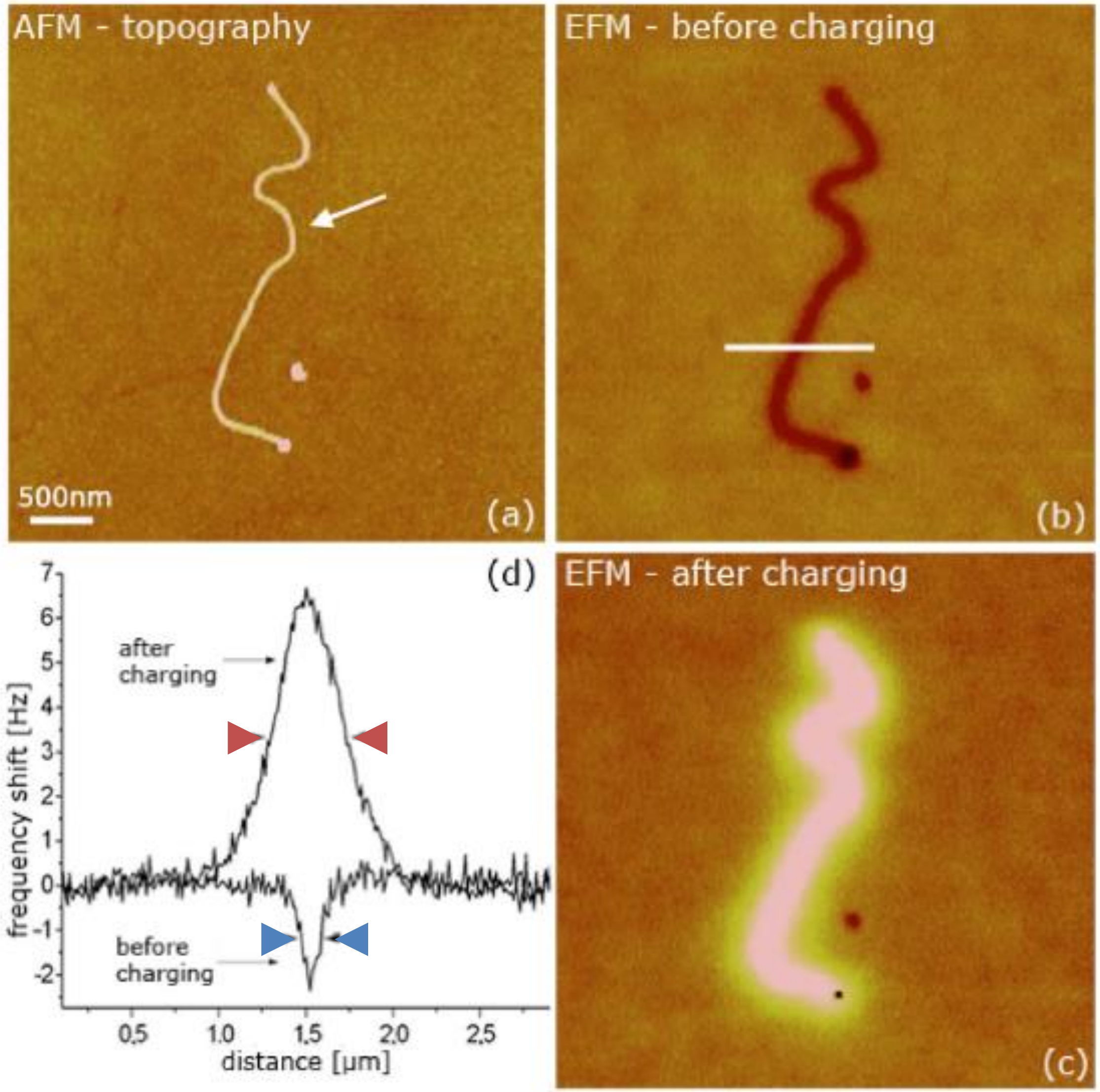
[polarization]

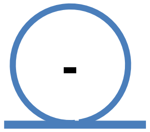
Charge effect

[surface dipole]

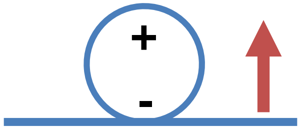
Probing a charge or a dipole ?

multiwalled carbon nanotube MWCNT
(~20nm diameter)
on 200nm thick SiO_2





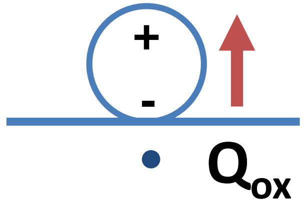
charge signal



capacitive signal

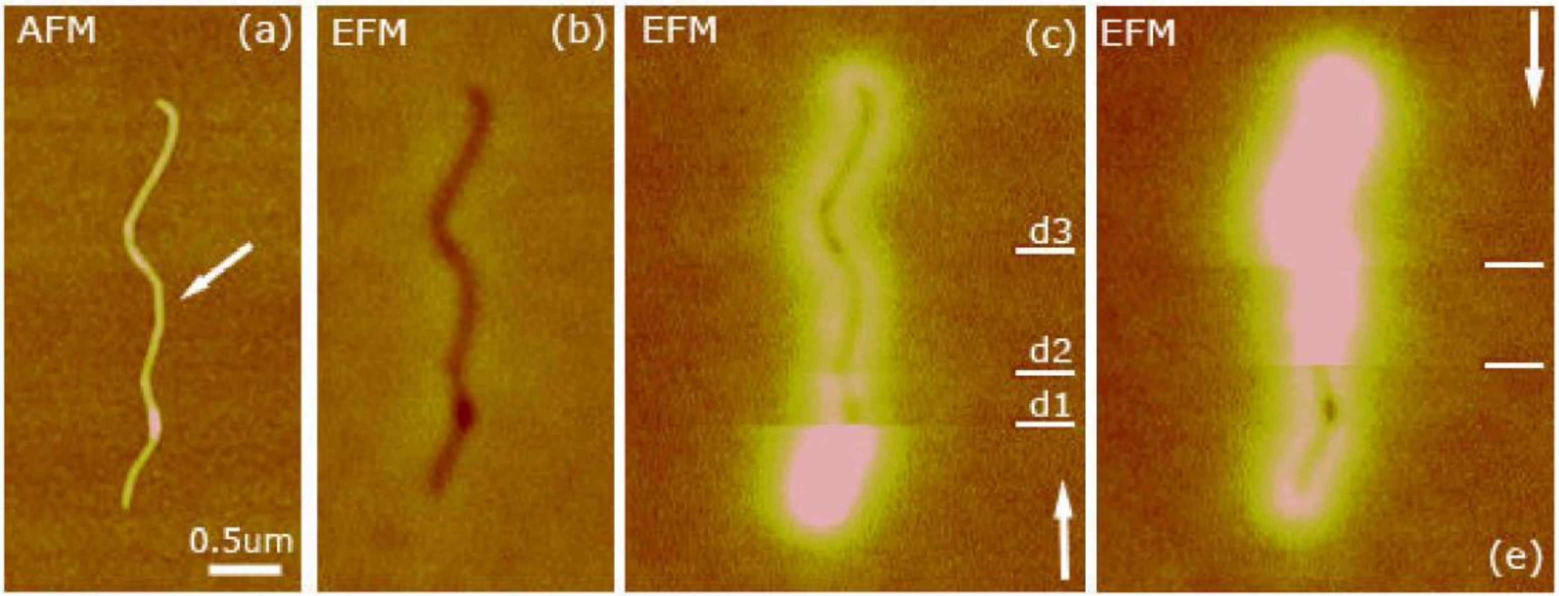
Probing a charge or a dipole ?

After discharge



capacitive signal

+ residual oxide charge



[MWCNT with 18 nm diameter, V_{inj}=-7V (3 min) detection V_{EFM}=-3V]

image force contributions

Apparent topography due to image forces

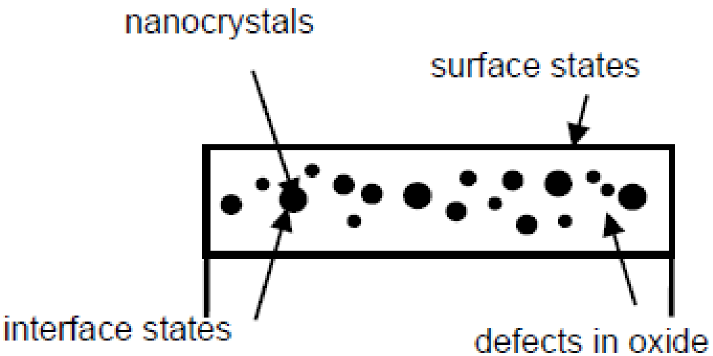


Figure 3.3: Possible locations of trapped charge.

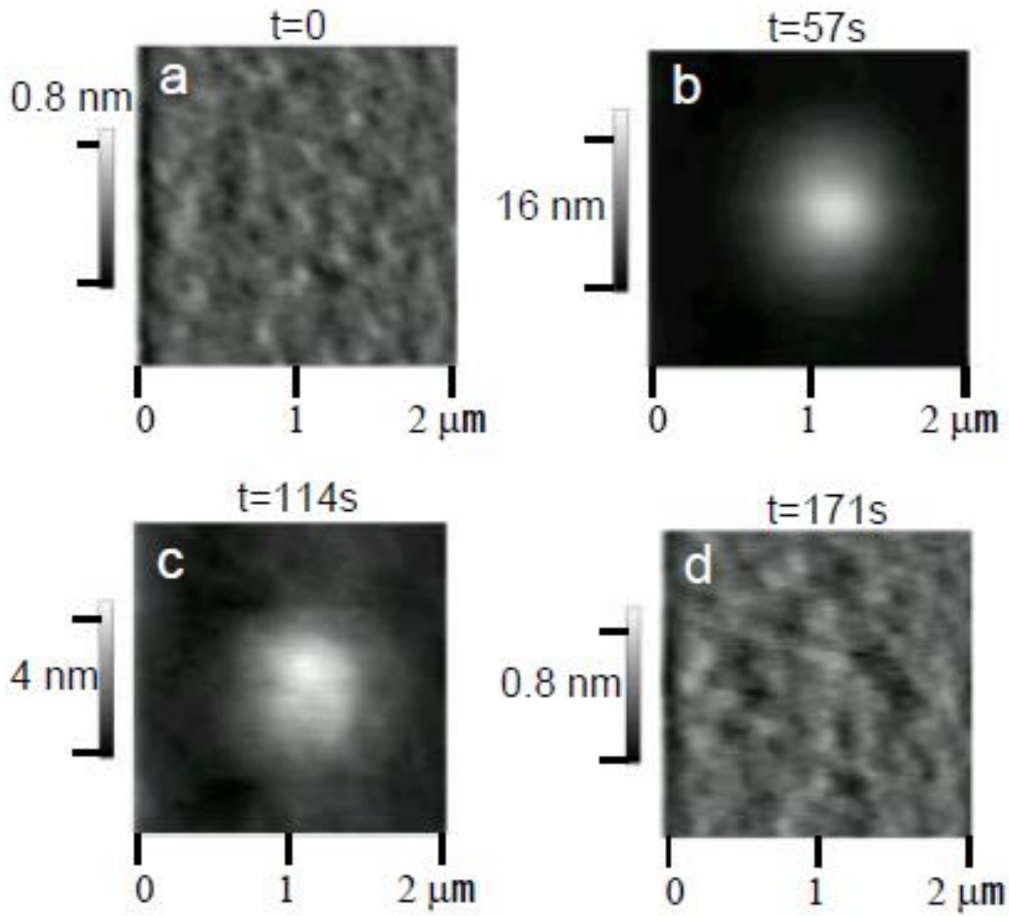
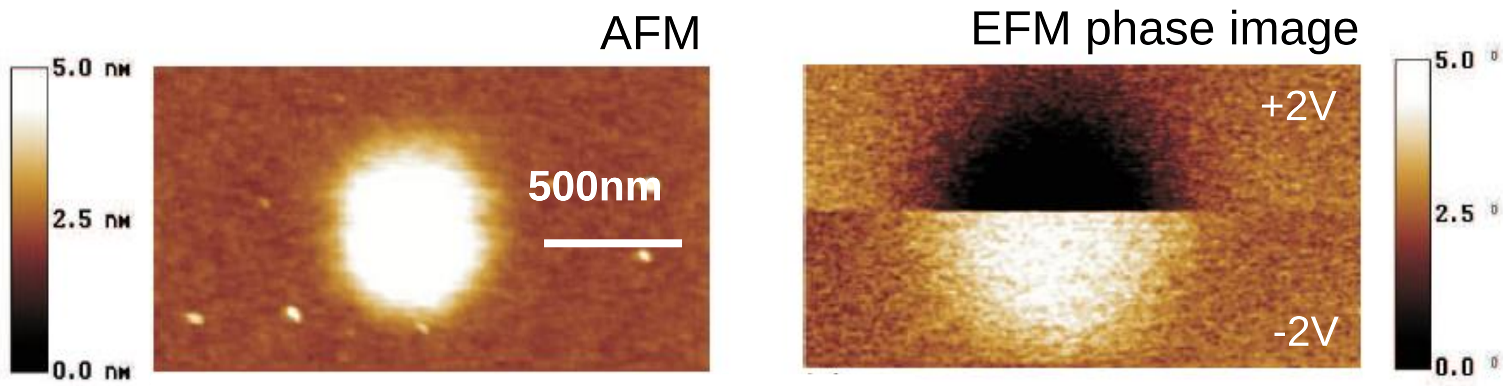


Figure 3.2: Charging of ion implanted samples—unetched.

E. Boer et al. - APL (2002)

Apparent topography due to image forces



Charge injection in a 7nm thick SiO_2 layer

R. Dianoux, PhD (2004)

Missing points

- sensitivity
- spatial resolution
- time resolution
- quantitative charge measurements ?

Sensitivity

Optical beam deflection EFM
with soft cantilevers ($k=3N/m; f_0=60kHz$)

	in air	in vacuum, 300K
F'_{min}	limited by thermal noise	
	~10^{-5} N/m B=100Hz, Q=200 A=25nm	**a few 10^{-6} N/m** B=50Hz, Q=20000 A=15nm
<z>	**50-100nm**	**10-20nm**

$$F'_{min} = \sqrt{\frac{4\,k\,.\,k_B T\,.\,B}{\pi\,f_0\,.\,A^2\,.\,Q}}$$

[F. Giessibl et al., Phys. Rev. B 2011 + references therein]

Sensitivity

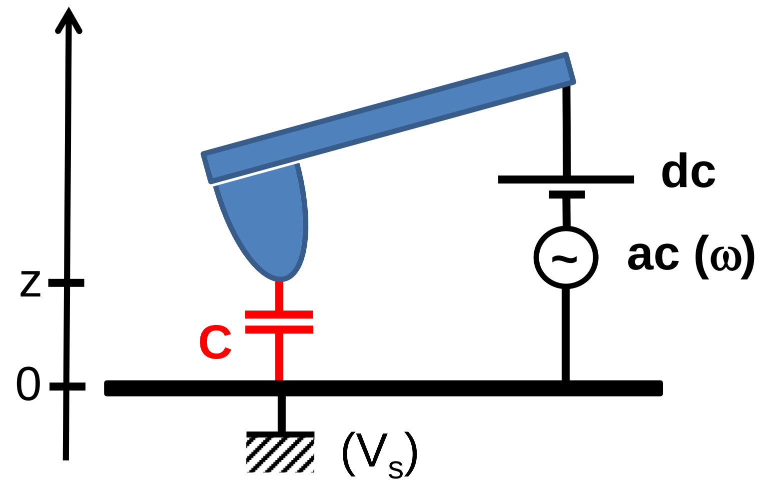
	Optical beam deflection EFM with soft cantilevers ($k=3N/m; f_0=60kHz$)		Qplus, LER
	in air	in vacuum, 300K	vacuum, 1-5 K
	limited by thermal noise		deflection noise, thermal noise, …
F'_{min}	**~10^{-5} N/m** B=100Hz, Q=200 A=25nm	**a few 10^{-6} N/m** B=50Hz, Q=20000 A=15nm	**~ 10^{-3} N/m** B=25Hz, Q=20000 A=200pm
<z>	**50-100nm**	**10-20nm**	**< 1 nm**
	Long-range (LR)	LR + SR	Short-range (SR)

single charge detection in air

ω/2ω EFM

« modulated » EFM technique :

- mechanical excitation
- ac +dc bias at the tip
- $\omega \ll 2\pi f_0$ (quasistatic)



z-force gradient $\frac{1}{2}\, d^2C/dz^2\, V^2$

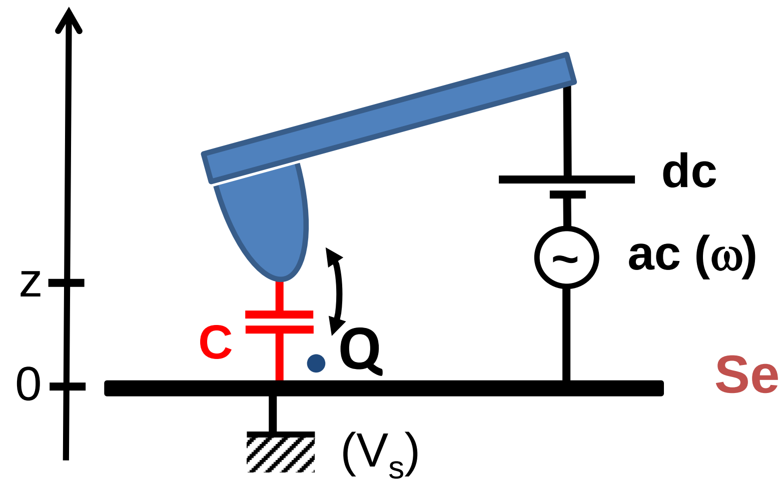
$V(t) = V_{dc} + V_{ac} \cos(\omega t)$
+ surface potential V_s (offset in tip bias)

$$F'_z(t) = \frac{1}{2}\, d^2C/dz^2\, [(V_{dc}-V_s)+V_{ac}\cos \omega t]^2$$

three force components

static	$F'_{0\omega} = \frac{1}{2}\, d^2C/dz^2\, [(V_{dc}-V_s)^2+V_{ac}^2/2]$	*not desired here*
ω	$F'_{\omega} = d^2C/dz^2$ ~~$(V_{dc}-V_s)$~~ $V_{ac}\cos(\omega t)$	*zero if $V_{dc}=V_s$*
2ω	$F'_{2\omega} = \frac{1}{4}\, d^2C/dz^2\, V^2_{ac}\cos(2\omega t)$	*capacitive interaction*

ω/2ω EFM



For $V_{ds}=V_s$, a surface charge Q will :

- interact with its image charges
- interact with ac charges at the tip

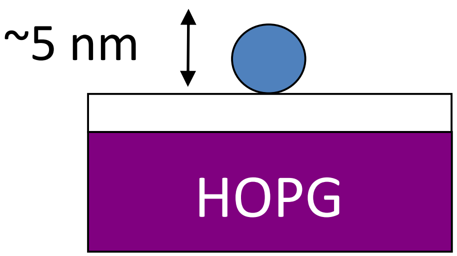
Separation of charge and dielectric images

three force components

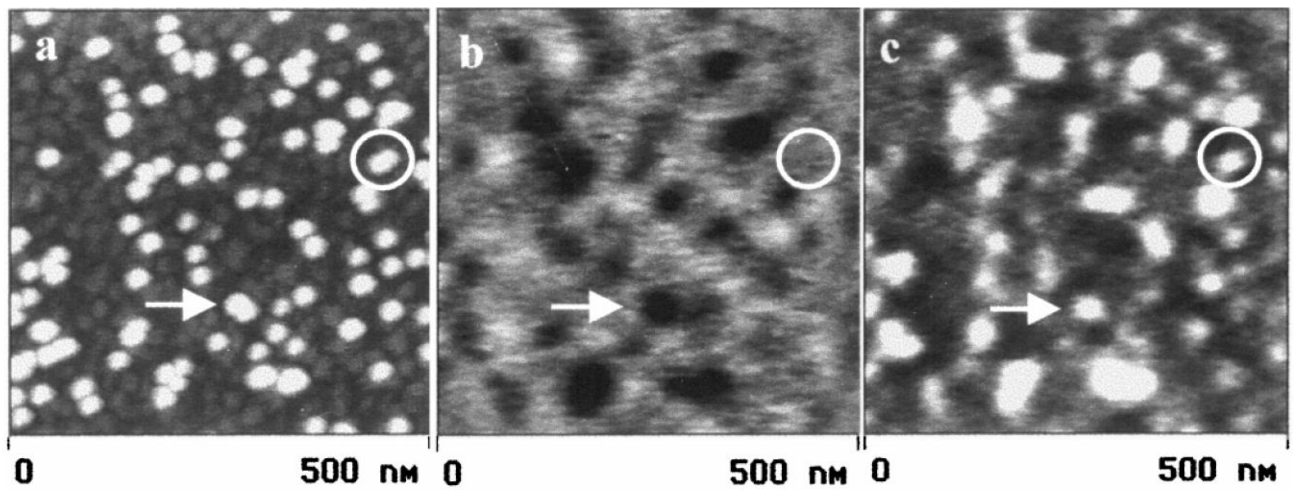
static	$F'_{0\omega} = \frac{1}{2}\, d^2C/dz^2\, [(V_{dc}-V_s)^2+V_{ac}^2/2]$	**+ image force contributions**
ω	$F'_{\omega} = d^2C/dz^2\, \cancel{(V_{dc}-V_s)}\, V_{ac} \cos(\omega t)$	**+ K(z) . Q . CV_{ac} cos(ωt)**
2ω	$F'_{2\omega} = \frac{1}{4}\, d^2C/dz^2\, V^2_{ac} \cos(2\omega t)$	**(no change)**

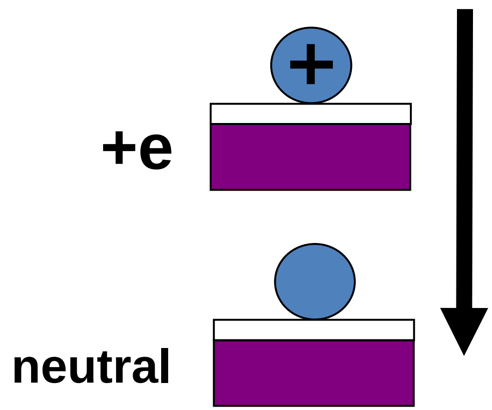
Single charge detection in ambient air

CdSe nanocrystals

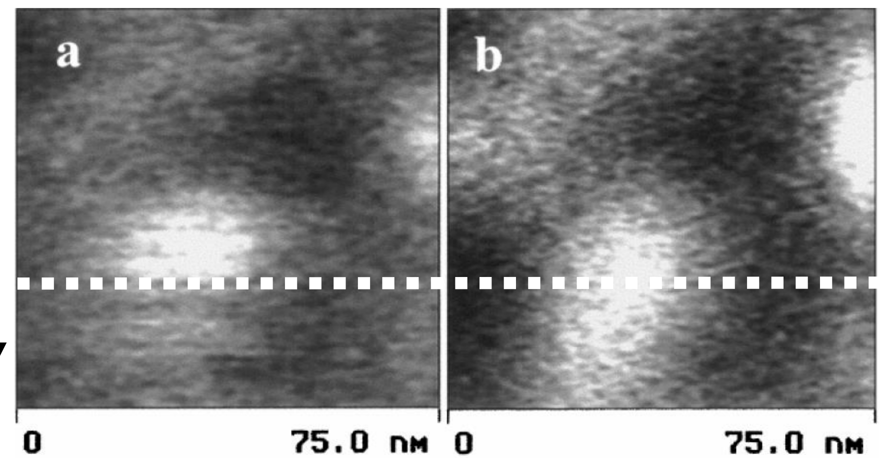


Topography | Charge image | Dielectric image





Charge image | Dielectric image



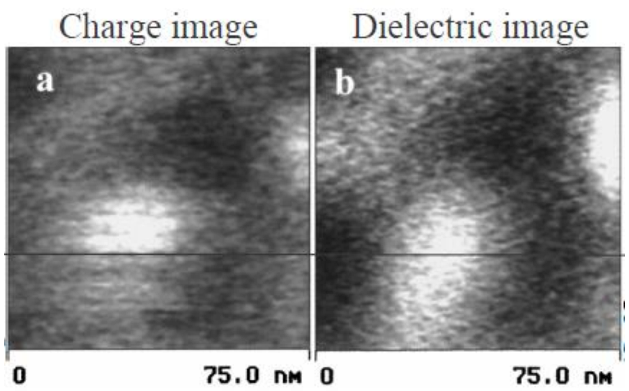
T. Krauss & L. Brus, PRL **83** 4840 (1999)

Single-charge sensitivity with sub-nm resolution

1999

Columbia Univ., *Phys. Rev. Lett.*

[ac-modulated EFM in air]



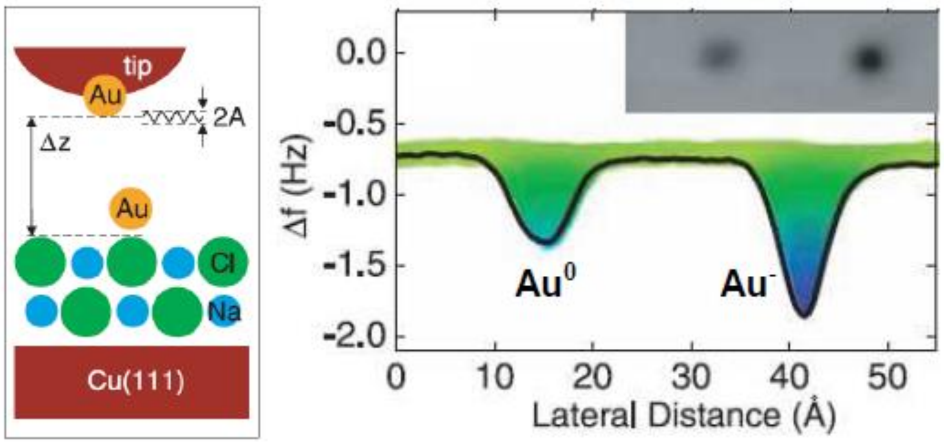
Single charge fluctuations in CdSe nanocrystals

resolution 25nm

2009

IBM Zürich, *Science*

[4K AFM]



Single charge state of Au adatoms

resolution < 1nm [UHV et 4K]

Figure 1: *(from [2]) Left: schematics of nc-AFM with sub-nm tip oscillation, here on Au adatoms on an ultra-thin NaCl layer. Right: tuning-fork frequency shifts above two adatoms (5K). The contrast difference between the Au0 and Au- adatoms corresponds to a single charge.*

iemn
Institut d'Electronique, de Microélectronique et de Nanotechnologie
UMR CNRS 8520

Time resolution

- in general, limited by the phase demodulation of the cantilever oscillation

- better resolution possible :
  - fast frequency shift demodulation,
  - oscillation transients (sub-µs see D. Ginger et al. Nanoletters 2012)
  - response under modulated illumination (see Ł. Borowik)

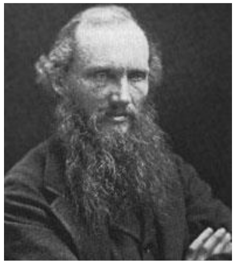
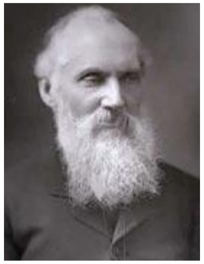
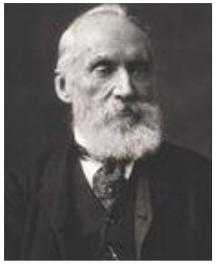
Quantitative charge measurements ?

- in general, semi-quantitative models only
- difficult due to the large variety of dielectric environments
- numerical simulations in most situations
- single charge events as calibration

III - Kelvin Probe Force Microscopy

surface potential and charge detection

Principle …

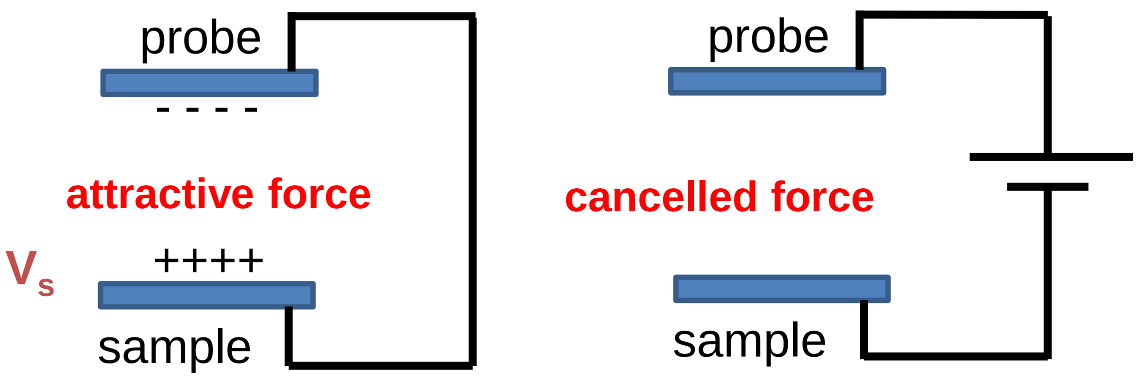




Measuring surface potentials from forces

- Lord Kelvin (1898)
- Zisman (1932) : vibrating Kelvin probe (down to mm size)
- Nonnenmacher (1991) : Kelvin probe **force** microscopy

different metals

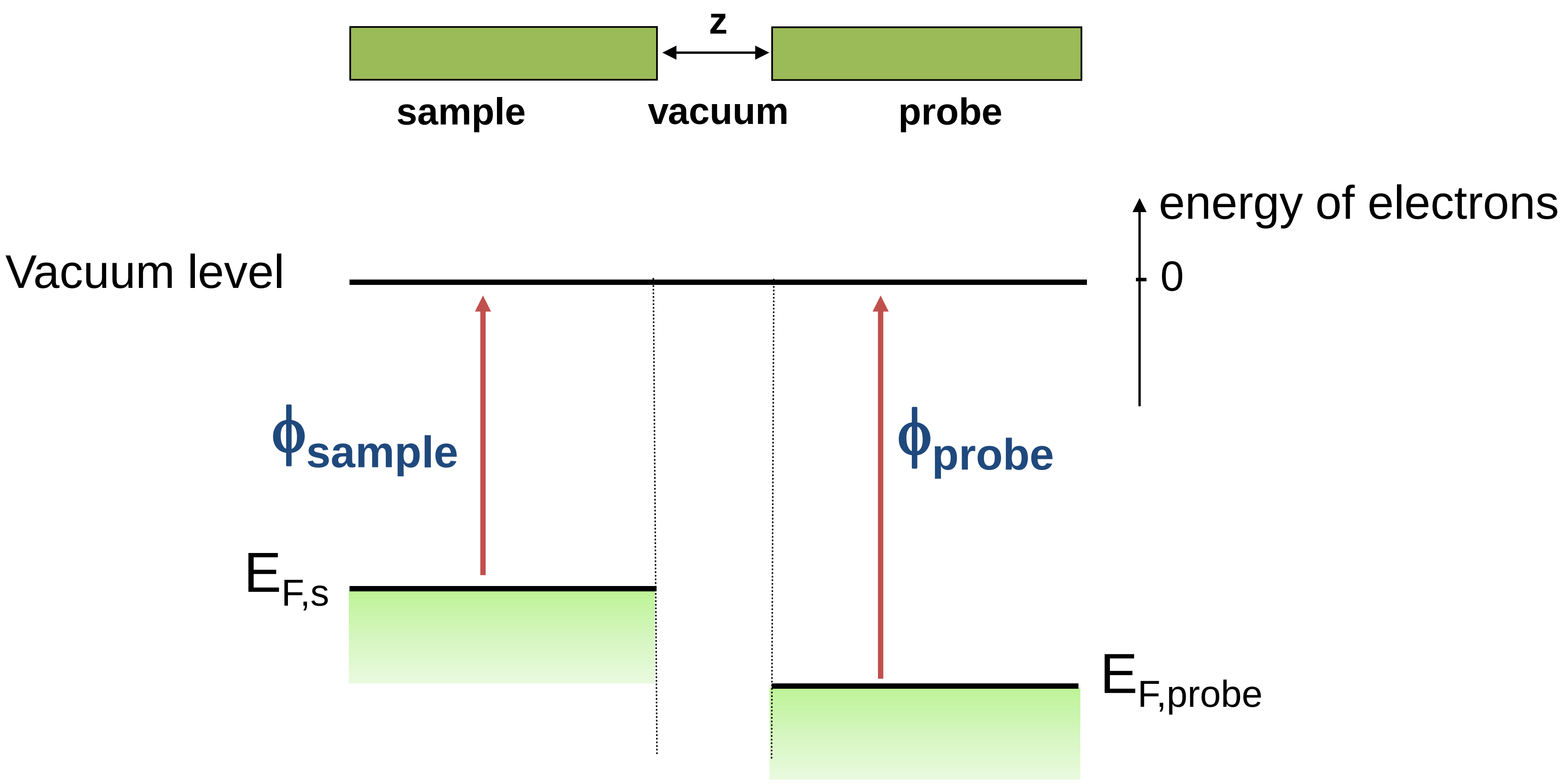
e.g. $\phi_{probe} > \phi_{sample}$



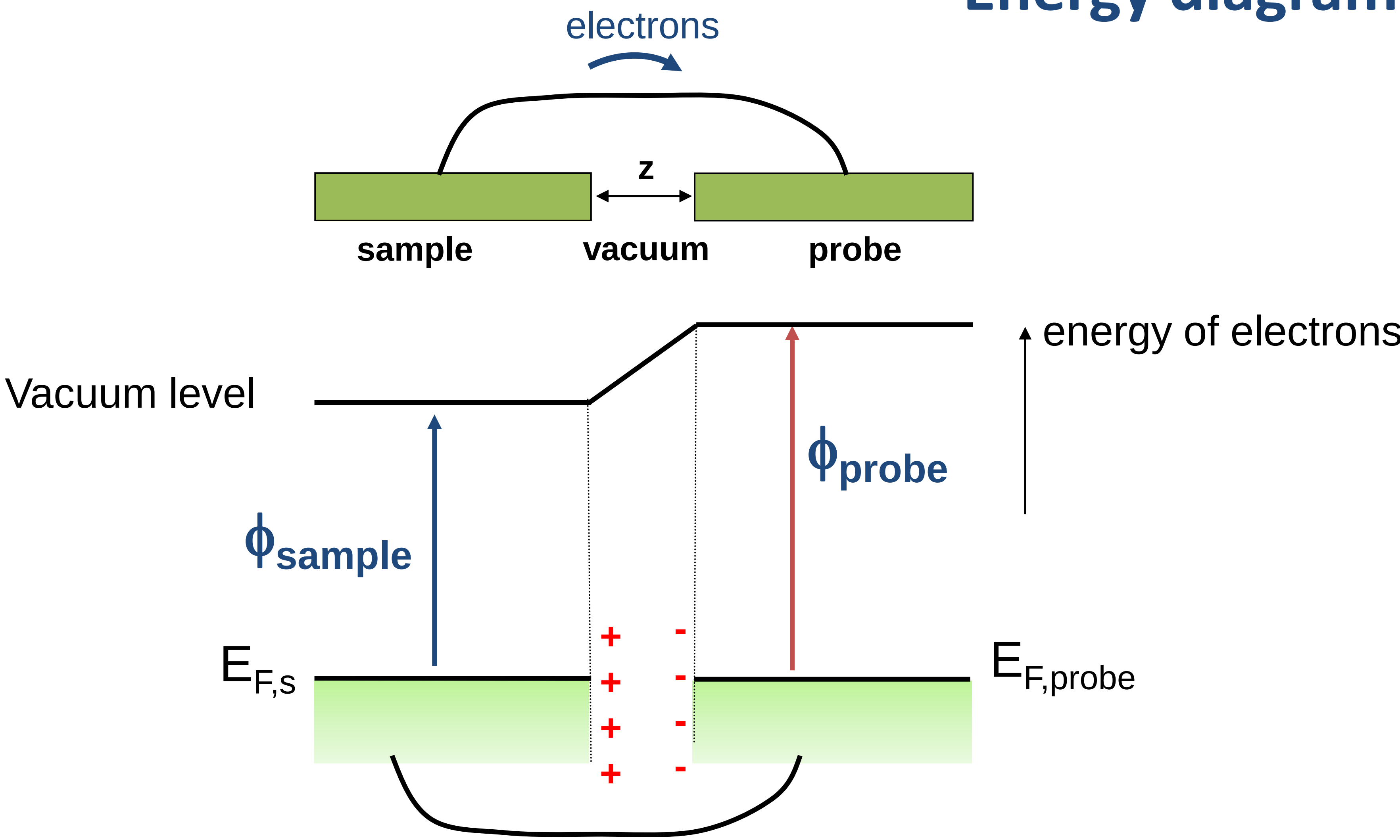
$$V_{dc} = \underbrace{(\phi_{probe} - \phi_{sample})}_{V_s} / |e|$$

Work function
measurement

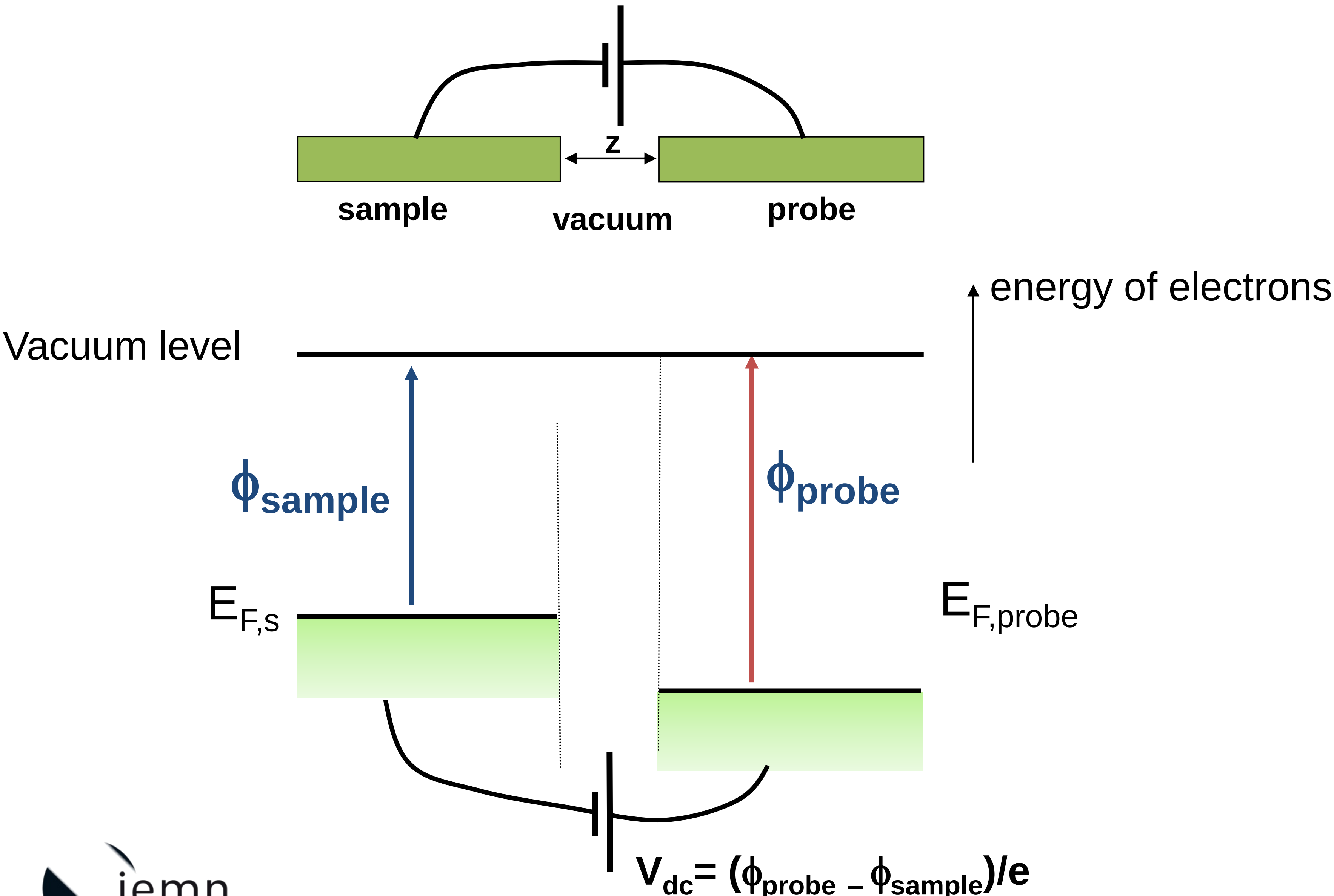
Energy diagrams



Energy diagrams



Energy diagrams



A few remarks …

- The sign of V_{dc} is user-dependent (V_{dc} at the tip, or at the sample)

- V_{dc} at the tip (and V_s at the surface)

  'electrostatics-friendly' convention :

  a positive charge or dipole (e.g. adsorbate) is 'seen' as a positive V_s

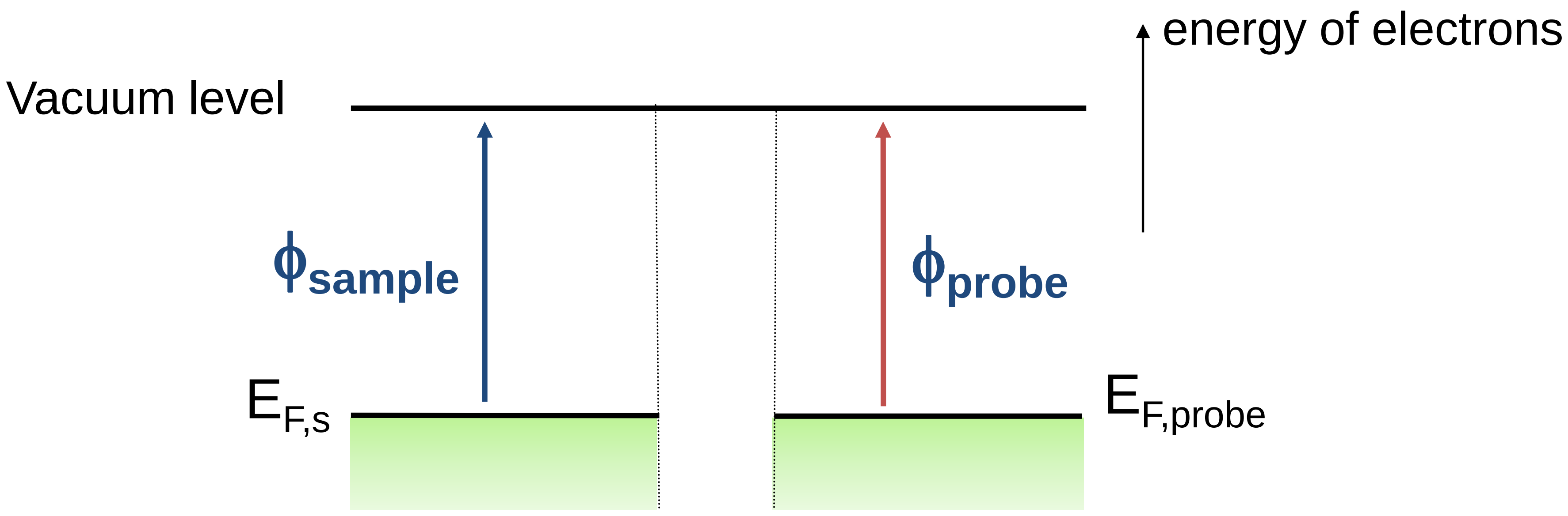
A few remarks …

- The sign of V_{dc} is user-dependent (V_{dc} at the tip, or at the sample)

- V_{dc} at the tip (and V_s at the surface)

'electrostatics-friendly' convention :

a positive charge or dipole (e.g. adsorbate) is 'seen' as a positive V_s

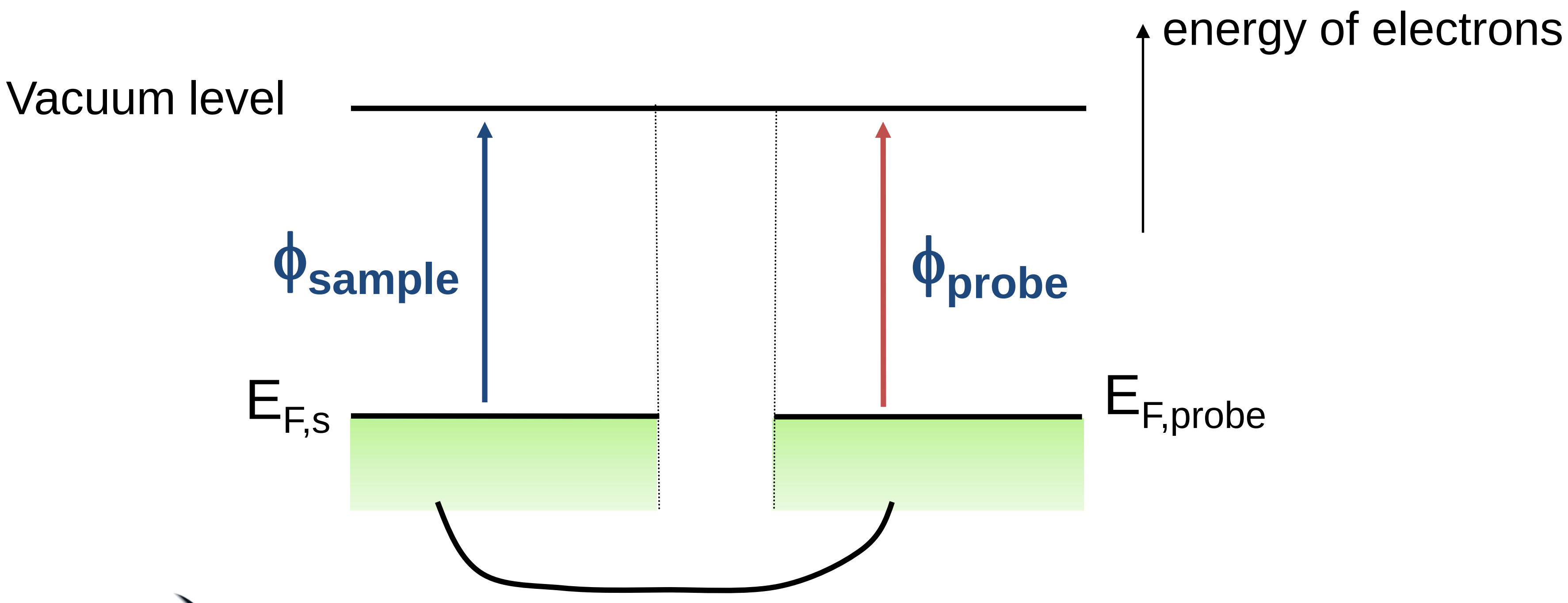


A few remarks …

- The sign of V_{dc} is user-dependent (V_{dc} at the tip, or at the sample)

- V_{dc} at the tip (and V_s at the surface)

'electrostatics-friendly' convention :
a positive charge or dipole (e.g. adsorbate) is 'seen' as a positive V_s



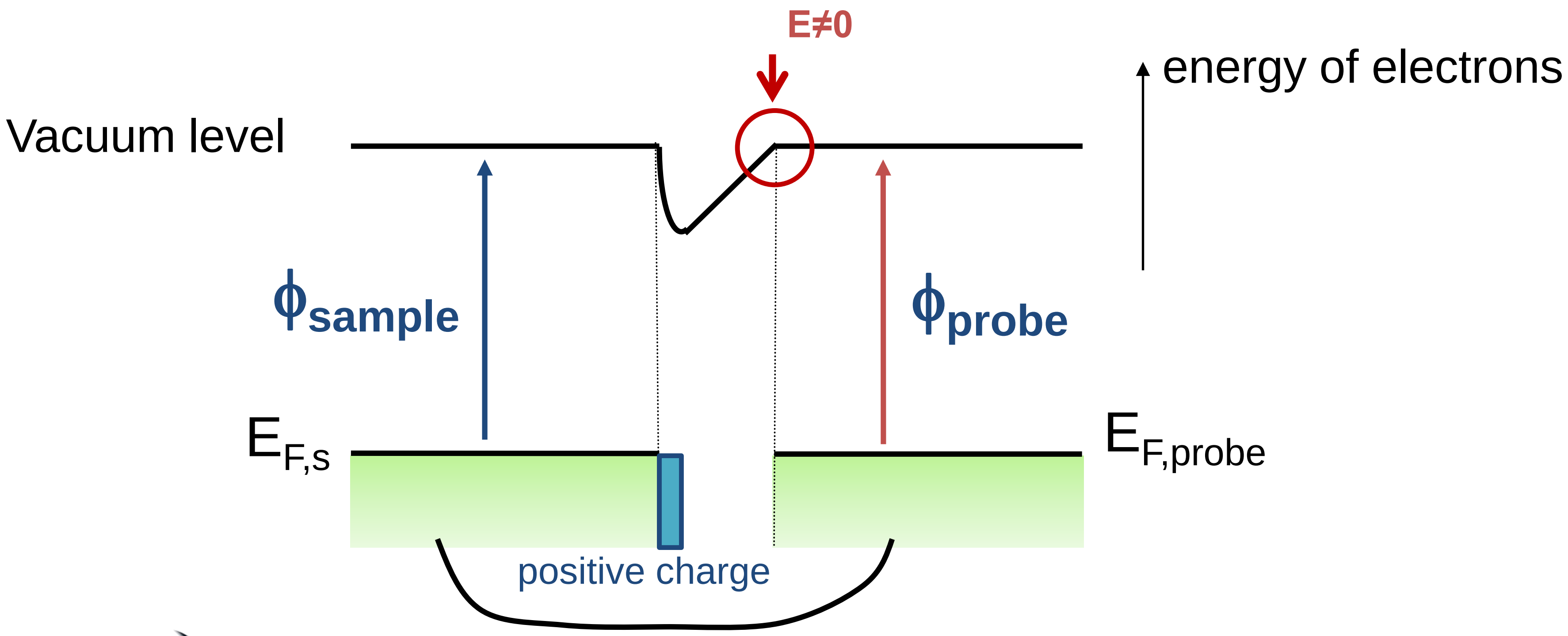
A few remarks ...

- The sign of V_{dc} is user-dependent (V_{dc} at the tip, or at the sample)

- V_{dc} at the tip (and V_s at the surface)

'electrostatics-friendly' convention :

a positive charge or dipole (e.g. adsorbate) is 'seen' as a positive V_s

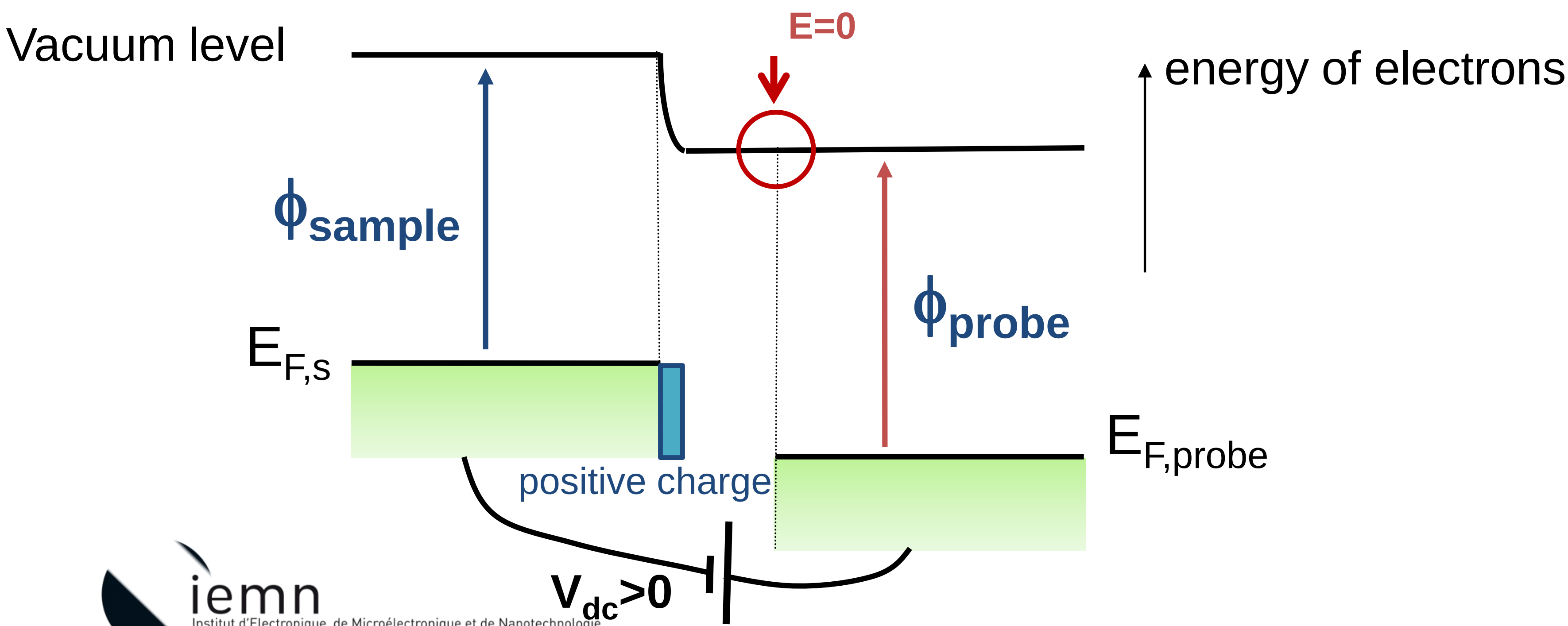


A few remarks …

- The sign of V_{dc} is user-dependent (V_{dc} at the tip, or at the sample)
- V_{dc} at the tip (and V_s at the surface)

‘electrostatics-friendly’ convention :

a positive charge or dipole (e.g. adsorbate) is ‘seen’ as a positive V_s



A few remarks …

- **The sign of V_{dc} is user-dependent** (V_{dc} at the tip, or at the sample)

- **V_{dc} at the tip** (and V_s at the surface)

  'electrostatics friendly' convention

  a positive charge or dipole (e.g. adsorbate) is 'seen' as a positive V_s

- **V_{dc} at the sample**

  'work-function friendly' convention :

  a material with a larger work-function will be imaged as « more positive » in KPFM images

Oscillating probe

Zisman method

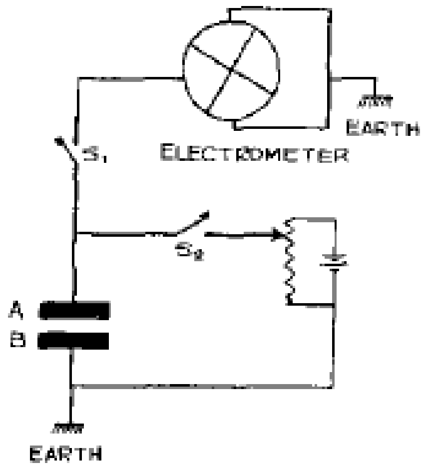
Rev. Sci. Instrum. **3**, 367 (1932)

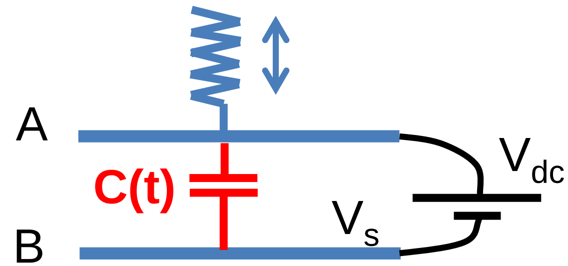
A NEW METHOD OF MEASURING CONTACT POTENTIAL DIFFERENCES IN METALS

By W. A. Zisman
[Jefferson Physical Laboratory, Harvard University, Cambridge, Mass.
Received March 5, 1932]

ABSTRACT

A new method is described for measuring the contact potential differences between dissimilar metals. It enables one to measure the p.d. to 1/1000 volt in a few seconds of manipulation. An apparatus is described for studying metals in air and another is described for high vacuum work.





$$C = C_0 + \Delta C.\sin \omega t$$

↓

$$i(t) = \Delta C.\omega.[\,V_{dc} - V_s\,].\cos(\omega t)$$

↓

to a loud speaker (!)
(ω in the audio range) :
zero sound for $V_{dc} = V_s$

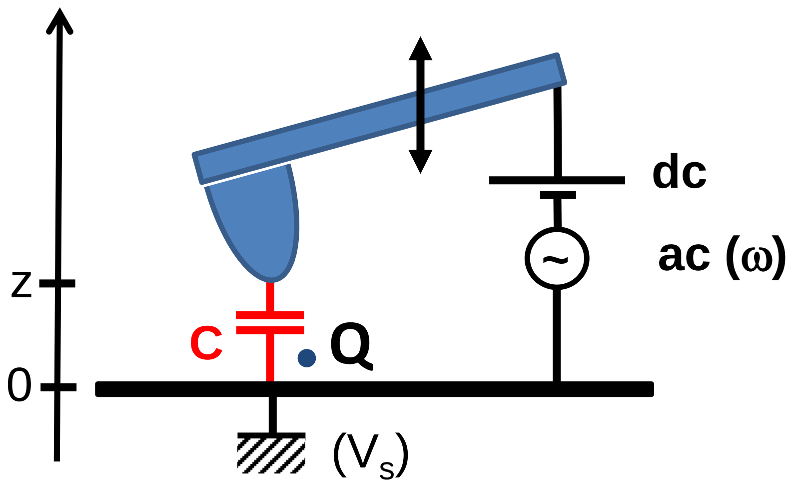
Kelvin method

Response of the electrometer deflection as a function of V_{dc} to find the zero force

iemn
Institut d'Electronique, de Microélectronique et de Nanotechnologie
UMR CNRS 8520

Frequency Modulation
Kelvin Probe Force Microscopy
(FM-KPFM)

FM-KPFM



Principal similar to modulated EFM

- **mechanical excitation**
- **ac +dc bias at the tip**
- **$\omega << 2\pi f_0$ (quasistatic)**

+ a feedback loop

three force components

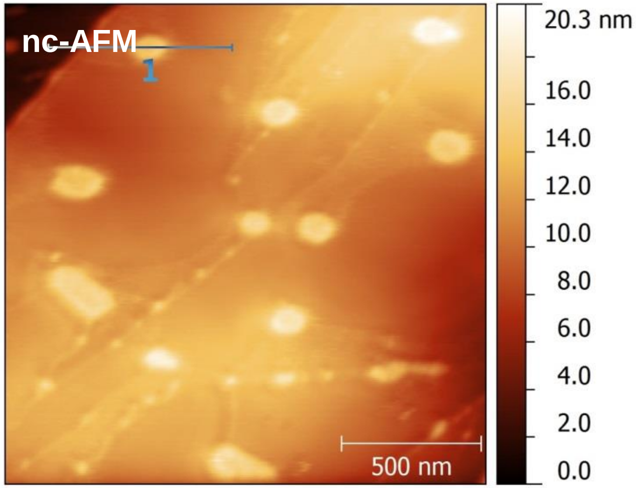
static	$F'_{0\omega} = ½\ d^2C/dz^2\ [(V_{dc}-V_s)^2+V_{ac}^2/2]$	**+ image force contributions**
ω	$F'_{\omega} = d^2C/dz^2\ (V_{dc}-V_s)\ V_{ac} \cos(\omega t)$	**+ $K(z)\ Q\ V_{ac} \cos \omega t$**
2ω	$F'_{2\omega} = ¼\ d^2C/dz^2\ V^2_{ac} \cos(2\omega t)$	

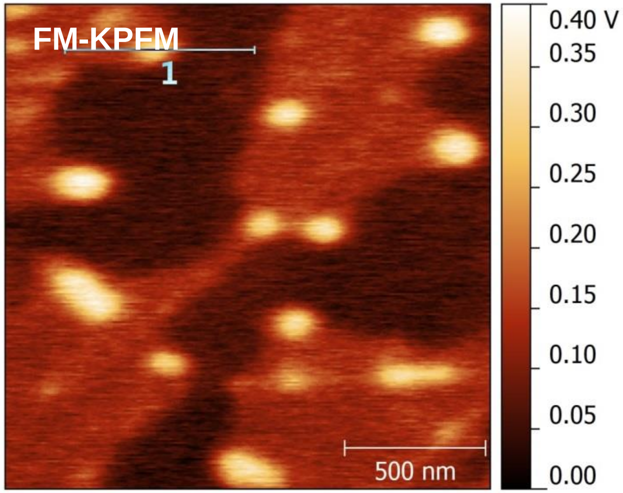
regulating F'_ω to zero (df_ω=0) gives :

$V_{dc} = V_s + V_Q$ (z-dependent)

Imaging …

Doped nanocrystals inducing charge transfers to the substrate



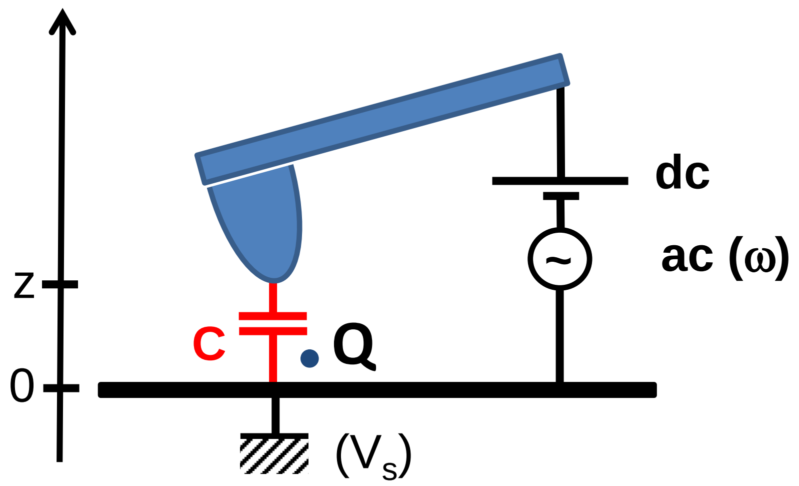


topo : $A_{pp} = 20\ nm$, Δf = - 5 Hz ;
1,7 µm * 1,7 µm; 512 *512 pixels;
tip-sample distance of 4-6 nm

FM-KPFM : f_{ac} ~ 300Hz; V_{ac} = 200 mV

Amplitude Modulation
Kelvin Probe Force Microscopy
(AM-KPFM)

AM-KPFM



ac+dc force excitation

- no mechanical excitation
- ac +dc bias (here) at the tip
- « free » ω

three force components

- static $F_{0\omega} = ½\ dC/dz\ [(V_{dc}-V_s)^2+V_{ac}^2/2]$ **+ image force contributions**
- ω $F_{\omega} = dC/dz\ (V_{dc}-V_s)\ V_{ac} \cos(\omega t) + K_1(z).Q.V_{ac} \cos(\omega t)$
- 2ω $F_{2\omega} = ¼\ dC/dz\ V^2_{ac} \cos(2\omega t)$

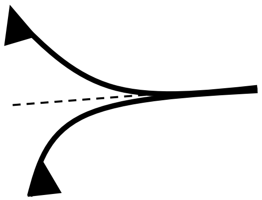
regulating F_ω to zero (i.e: A_ω=0) gives :

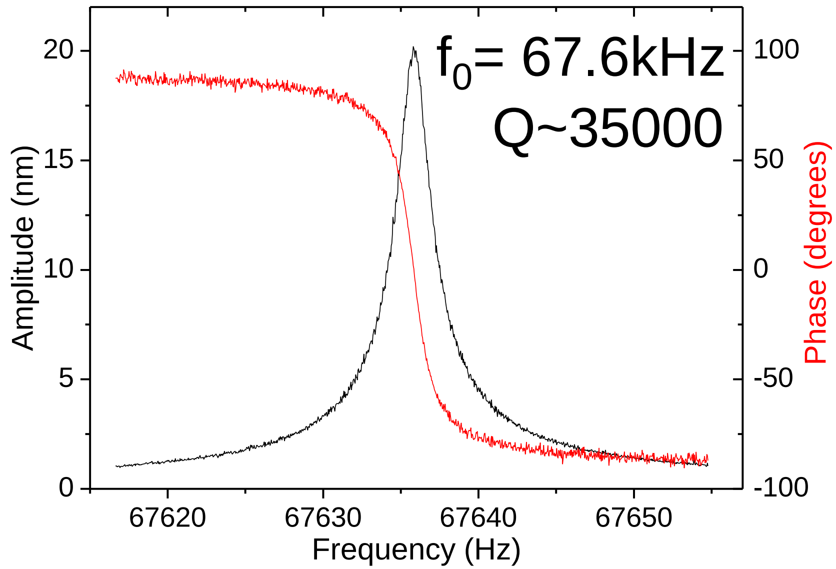
$V_{dc} = V_s + V_Q$ (z-dependent)

Example of a single-pass (UHV) AM-KPFM mode 1/2

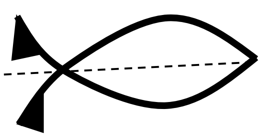
- **first resonance f_0**
- mechanical excitation
- **non-contact AFM**

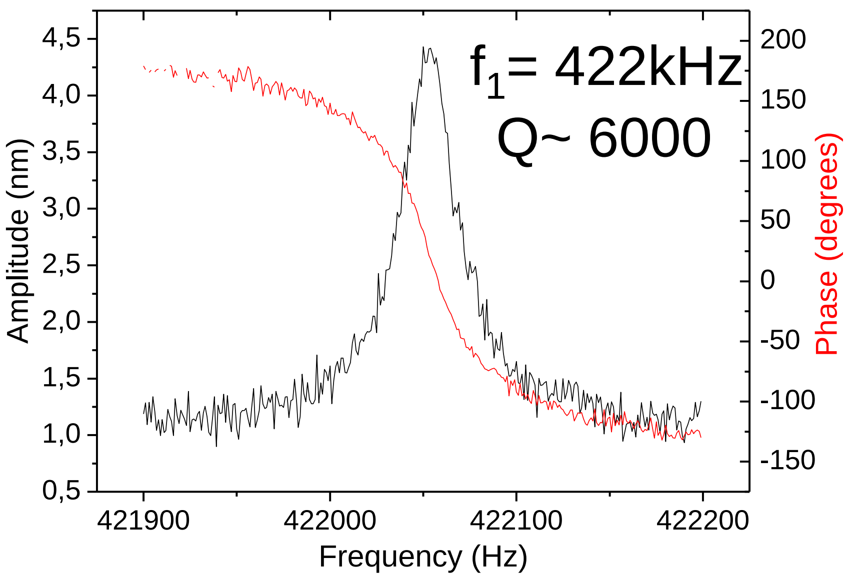
Δf = -5Hz oscillation amplitude 15 nm
minimum tip-substrate distance ~5nm





- **second resonance f_1~6.2×f_0**
- electrostatic excitation
- **KFM loop at f_1**

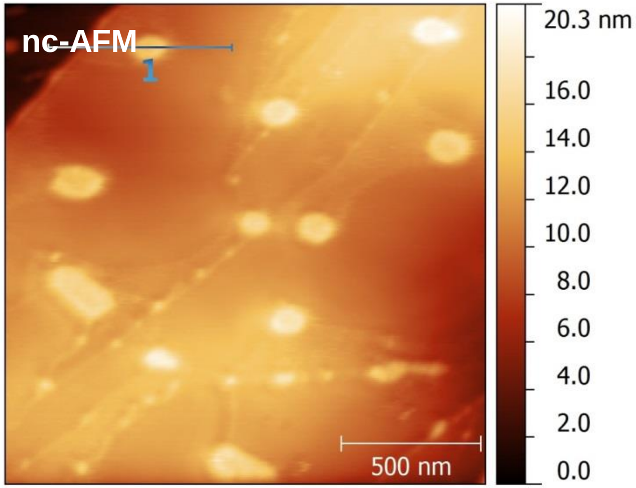




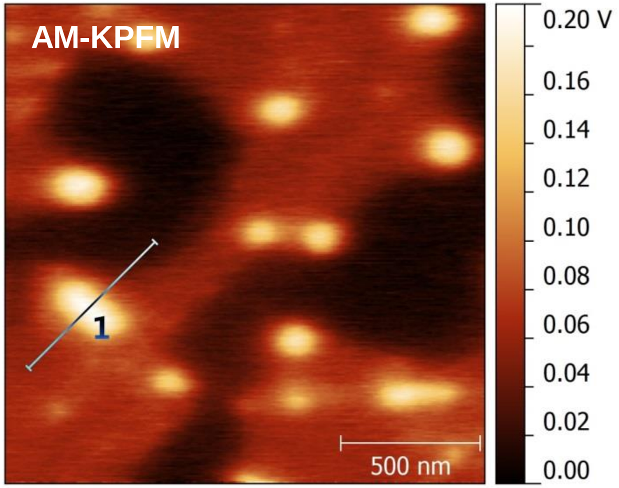
iemn
Institut d'Electronique, de Microélectronique et de Nanotechnologie
UMR CNRS 8520

AM-KPFM

Imaging …



topo : $A_{pp} = 20\ nm$, Δf = - 5 Hz ;
1,7 µm * 1,7 µm; 512 *512 pixels;
tip-sample distance of 4-6 nm



AM-KPFM : V_{ac} = 200 mV;
V_{dc} = 2 V; τ = 100 µs

Similar image as FM-KPFM

AM-KPFM

A [too] large variety of implementations …

► **ω can be chosen freely** :

- close to the cantilever resonance (increases the sensitivity by $Q^{1/2}$)
- at a cantilever higher eigenmode (e.g. f_1=6.2 f_0)
- at low frequency or high frequency, but out of resonance

► **in conjunction or separately from topography imaging**
(single-pass versus lift/linear modes)

► with feedback loop on … or off.

AM-KPFM versus FM-KPFM

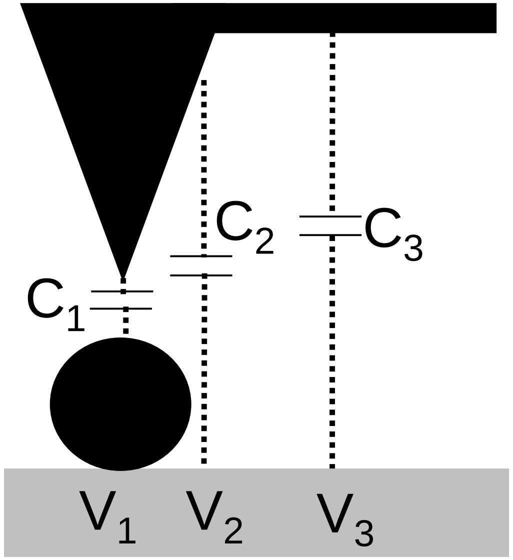
	signal to noise	resolution
AM-KPFM	+	-
FM-KPFM	-	+

↓

Side capacitance effects

iemn
Institut d'Electronique, de Microélectronique et de Nanotechnologie
UMR CNRS 8520

Side-capacitance effects in AM- and FM-KPFM – 1/5



Nullification of the ω force component (AM-KPFM)

$$dC'_1/dz\ V_{ac}\ (V_{dc}-V_1) + dC_2/dz\ V_{ac}\ (V_{dc}-V_2) + dC_3/dz\ V_{ac}\ (V_{dc}-V_3) = 0$$

$$V_{dc} = \frac{dC_1/dz\ .\ V_1 + dC_2/dz\ .V_2 + dC_3/dz\ .V_3}{dC_1/dz + dC_2/dz + dC_3/dz}$$

KPFM : averaging technique

iemn
Institut d'Electronique, de Microélectronique et de Nanotechnologie
UMR CNRS 8520

H. O. Jacobs *et al.* JAP (1998)

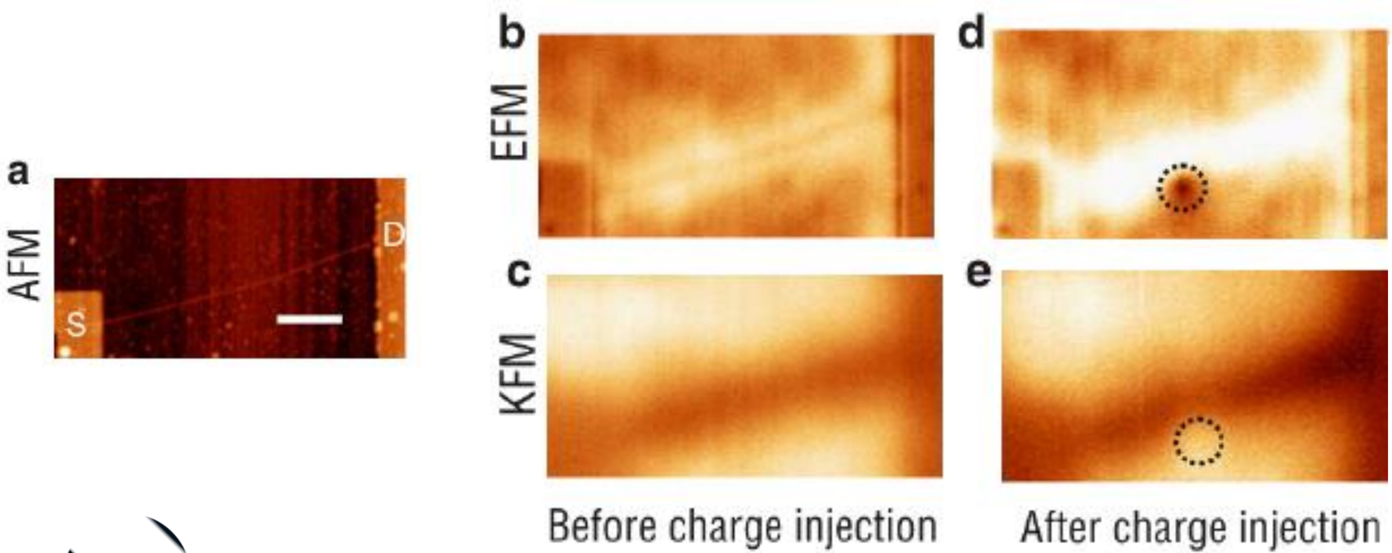
Side-capacitance effects in AM- and FM-KPFM - 2/5

gerenalization

AM-KPFM $V_{dc} = (\Sigma\, dC_i/dz\, .V_i\,) / (\Sigma\, dCi/dz)$

FM-KPFM $V_{dc} = (\Sigma\, d^2C_i/dz^2\, .V_i\,) / (\Sigma\, d^2Ci/dz^2)$

- intrinsic averaging effects in AM and FM modes
- dC_i/dz less ‘peaked’ at the tip than d^2C_i/dz^2 : less resolution in AM modes

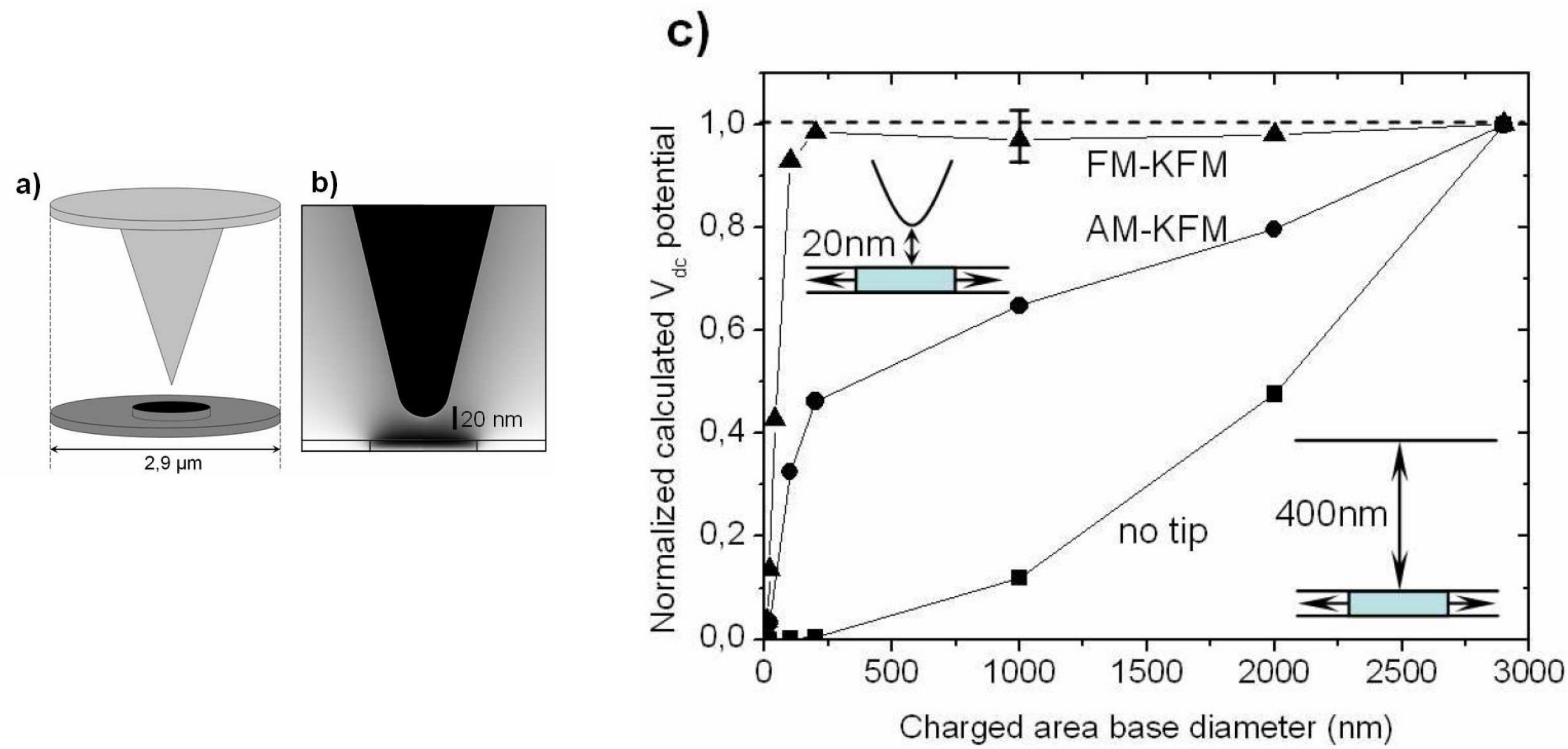


EFM≈FM-KPFM

AM-KPFM

D. Brunel et al. ACS Nano (2010) – ambient air imaging

Side-capacitance effects in AM- and FM-KPFM – 3/5



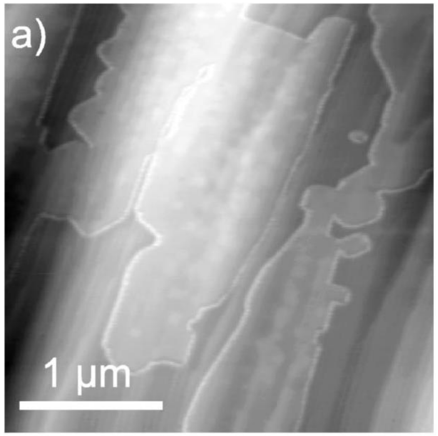
Both FM- and AM- modes are sensitive to side-capacitance effects at small size

Appl. Phys. Lett. **96** 103119 (2010)

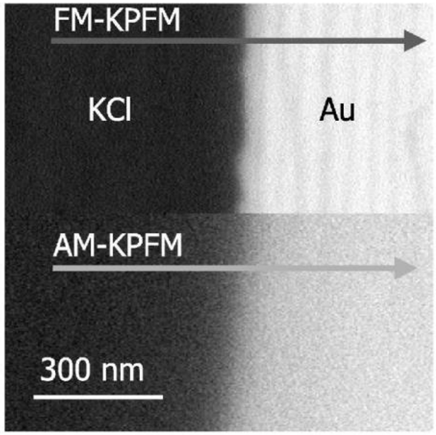
Side-capacitance effects in AM- and FM-KPFM – 4/5

	sensitivity	resolution
AM-KPFM	+	-
FM-KPFM	-	+

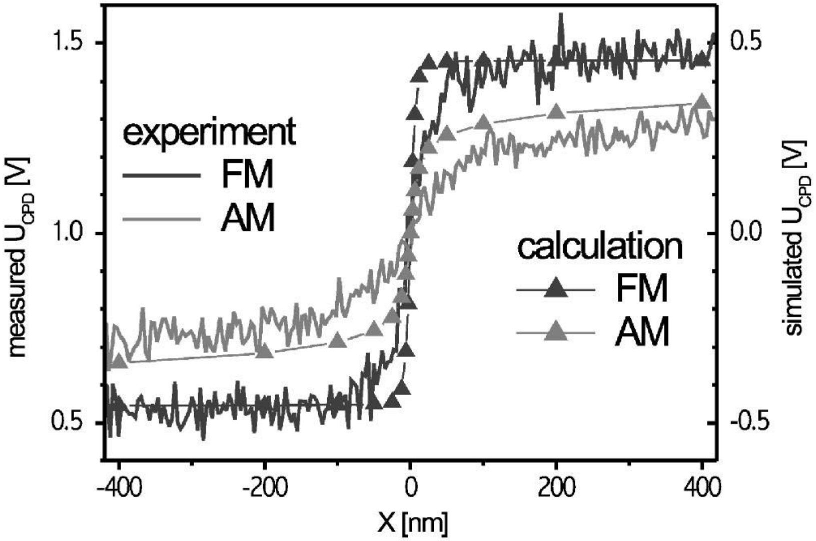
- less ac cross-talk
- no need for a 2nd resonance



KCl islands on Au 111 (topo)



KPFM accross KCl island boundaries



U. Zerweck et al., Phys Rev B 71 125424 (2005)

Side-capacitance effects in AM- and FM-KPFM – 5/5

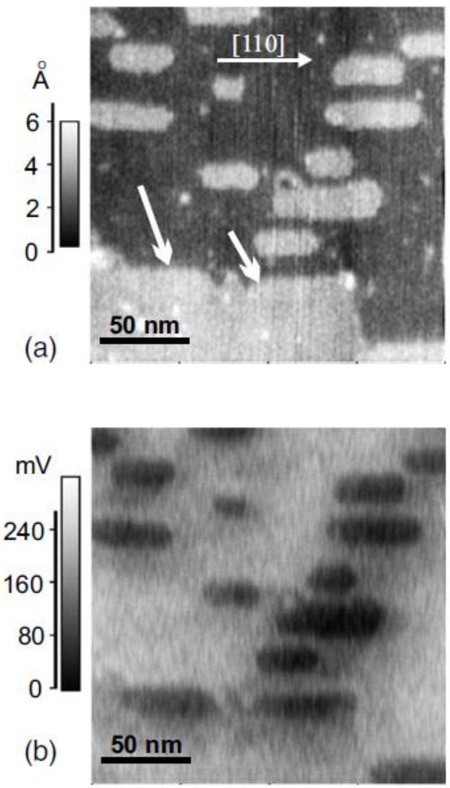
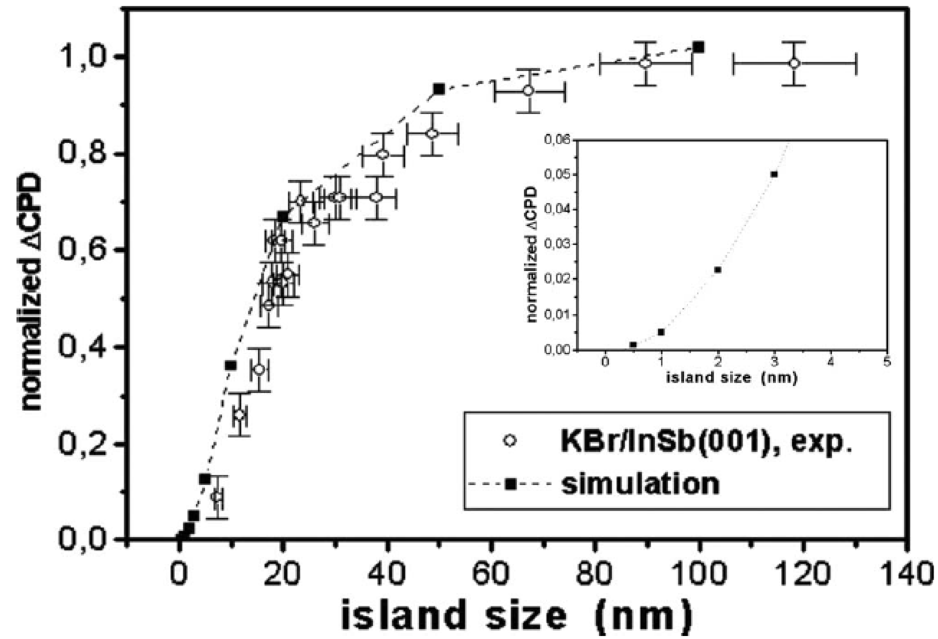


FIG. 1. (a) FM-KPFM topography and (b) ΔCPD images of KBr islands grown on InSb(001) surface (f_0=111, 1 kHz, Δf =−17 Hz). The white arrows indicate the KBr islands, which are topographically not resolved from the substrate terrace.



KBr on InSb(001)

FM-KPFM measurements

convolution in FM mode for structures with smaller size than the tip apex

F. Krok et al., Phys. Rev. B **77**, 235427 (2008)

iemn
Institut d'Electronique, de Microélectronique et de Nanotechnologie
UMR CNRS 8520

AM-KPFM versus FM-KPFM

	signal to noise	resolution
AM-KPFM	+	-
FM-KPFM	-	+

↓ « usually reported »

Justification, if AM and FM modes are performed on the same resonance (Q) :

$dC/dz \, . \, \Delta V_{dcmin,\, AM} \, . \, V_{ac,\, AM} = F_{min}$ (limited by thermal noise)

$d^2C/dz^2 \, . \, \Delta V_{dcmin,\, FM} \, . \, V_{ac,\, FM} = F'_{min}$ (limited by thermal noise)

for the same V_{ac} : $\Delta V_{dcmin,\, FM} / \Delta V_{dcmin,\, AM} = [\, \underbrace{dC/dz \, / \, d^2C/dz^2}_{z \, / \, |\alpha - 1|} \,] \, . \, [\underbrace{F'_{min} \, / \, F_{min}}_{\sqrt{2} \, / \, A}]$

if d^2C/dz^2 prop to $z^{-\alpha}$
(in air $\alpha \sim 1.5$)

AM-KPFM versus FM-KPFM

	signal to noise	resolution
AM-KPFM	+	-
FM-KPFM	-	+

« usually reported »

Justification, if AM and FM modes are performed on the same resonance (Q) :

$dC/dz \,.\, \Delta V_{dcmin,\,AM} \,.\, V_{ac,\,AM} = F_{min}$ (limited by thermal noise)

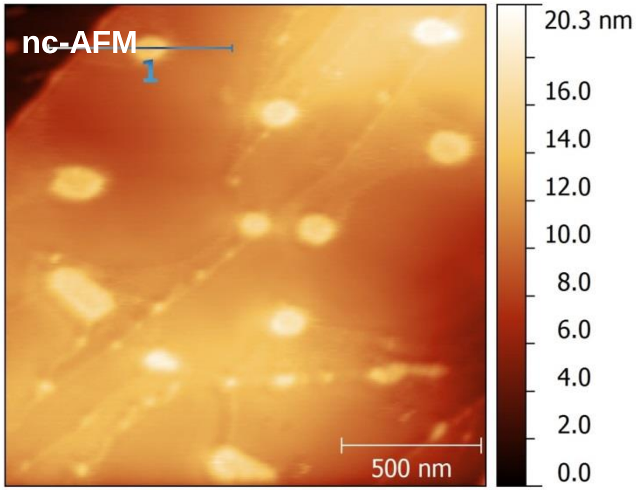
$d^2C/dz^2 \,.\, \Delta V_{dcmin,\,FM} \,.\, V_{ac,\,FM} = F'_{min}$ (limited by thermal noise)

for the same V_{ac} : $\Delta V_{dcmin,\,FM} / \Delta V_{dcmin,\,AM} = \underbrace{\frac{\sqrt{2}}{|\propto -1|}}_{>1} \; \underbrace{\frac{z}{A}}_{>1}$ **> 1**

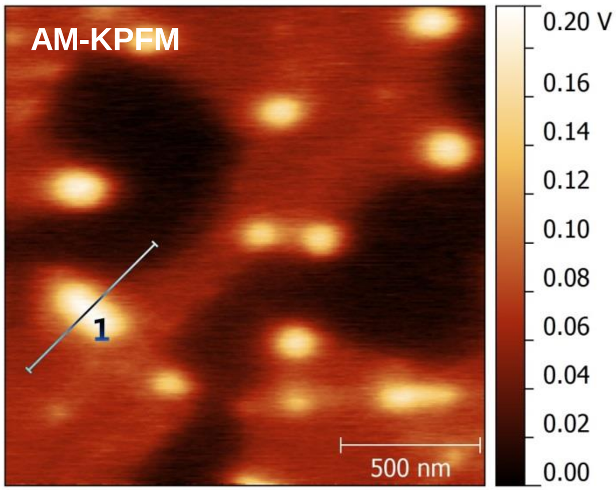
AM-KPFM versus FM-KPFM

	signal to noise	resolution
AM-KPFM	+	-
FM-KPFM	-	+

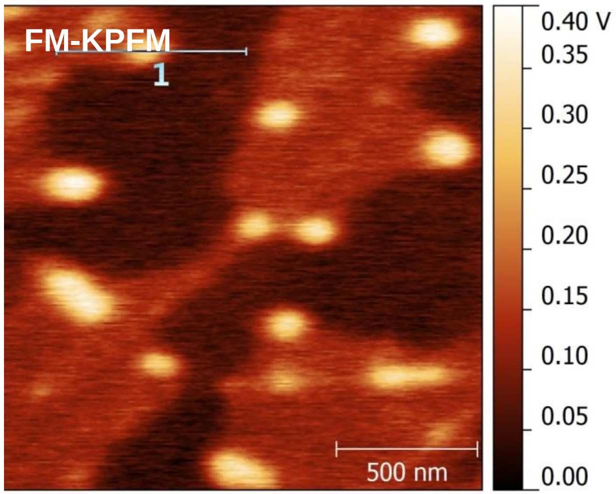
- less ac cross-talk
- no need for a 2nd resonance



topo : $A_{pp} = 20\ nm$, Δf = - 5 Hz ; 1,7 µm * 1,7 µm; 512 *512 pixels; tip-sample distance of 4-6 nm



AM-KPFM : V_{ac} = 200 mV; V_{dc} = 2 V; τ = 100 µs

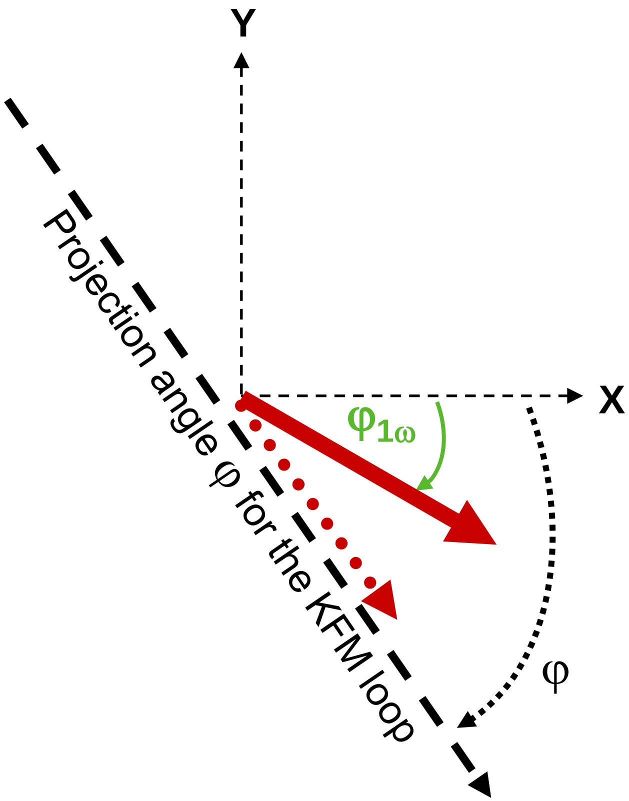


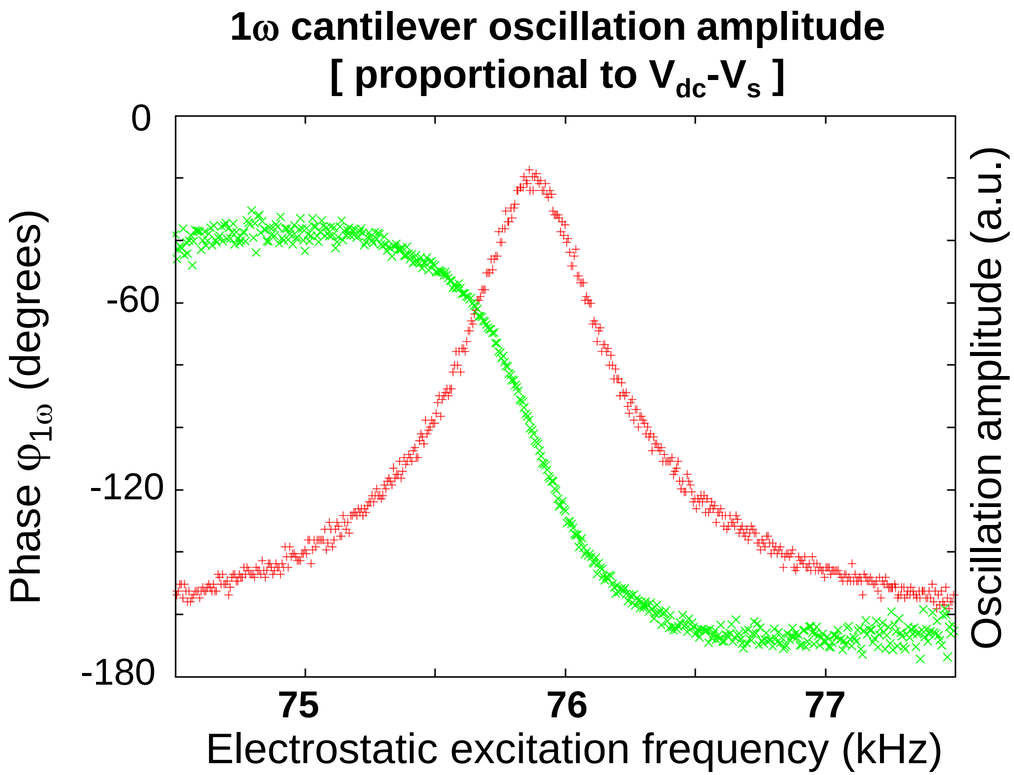
FM-KPFM : f_{ac} ~ 50Hz; V_{ac} = 200 mV

Can we measure quantitatively a work function difference ?

(ac-crosstalk issues – AM KPFM in air)

Practical operation principle

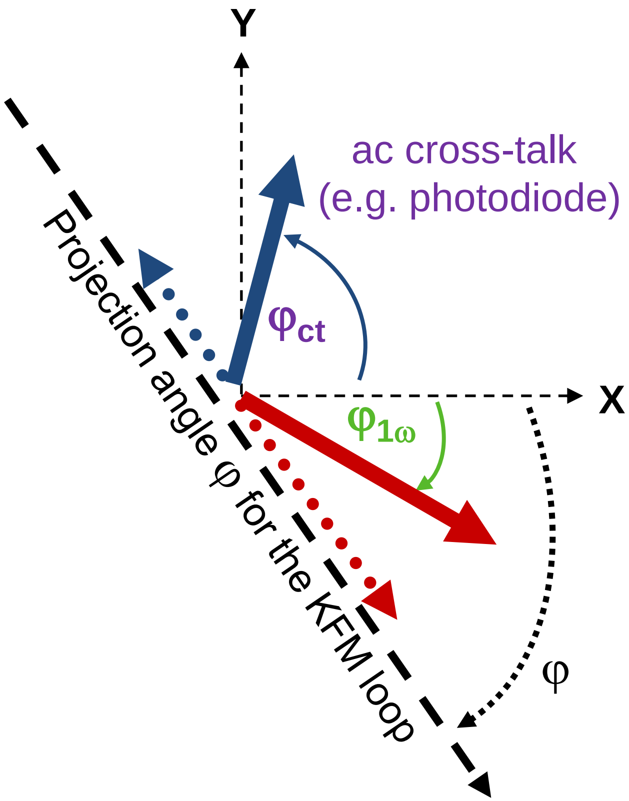




projection angle necessary for the KFM feedback loop

KFM "equation" : $dC/dz.\,(V_{dc}-V_s).V_{ac}.\,\cos(\phi_{1\omega}-\phi) = 0$

Practical operation principle … with ac cross-talks



KFM "equation"

$$dC/dz.\ (V_{dc}-V_s).V_{ac}.\ \cos(\phi_{1\omega}-\phi) + A_{ct}\ .V_{ac}\ .\ \cos(\phi_{ct}-\phi) = 0$$

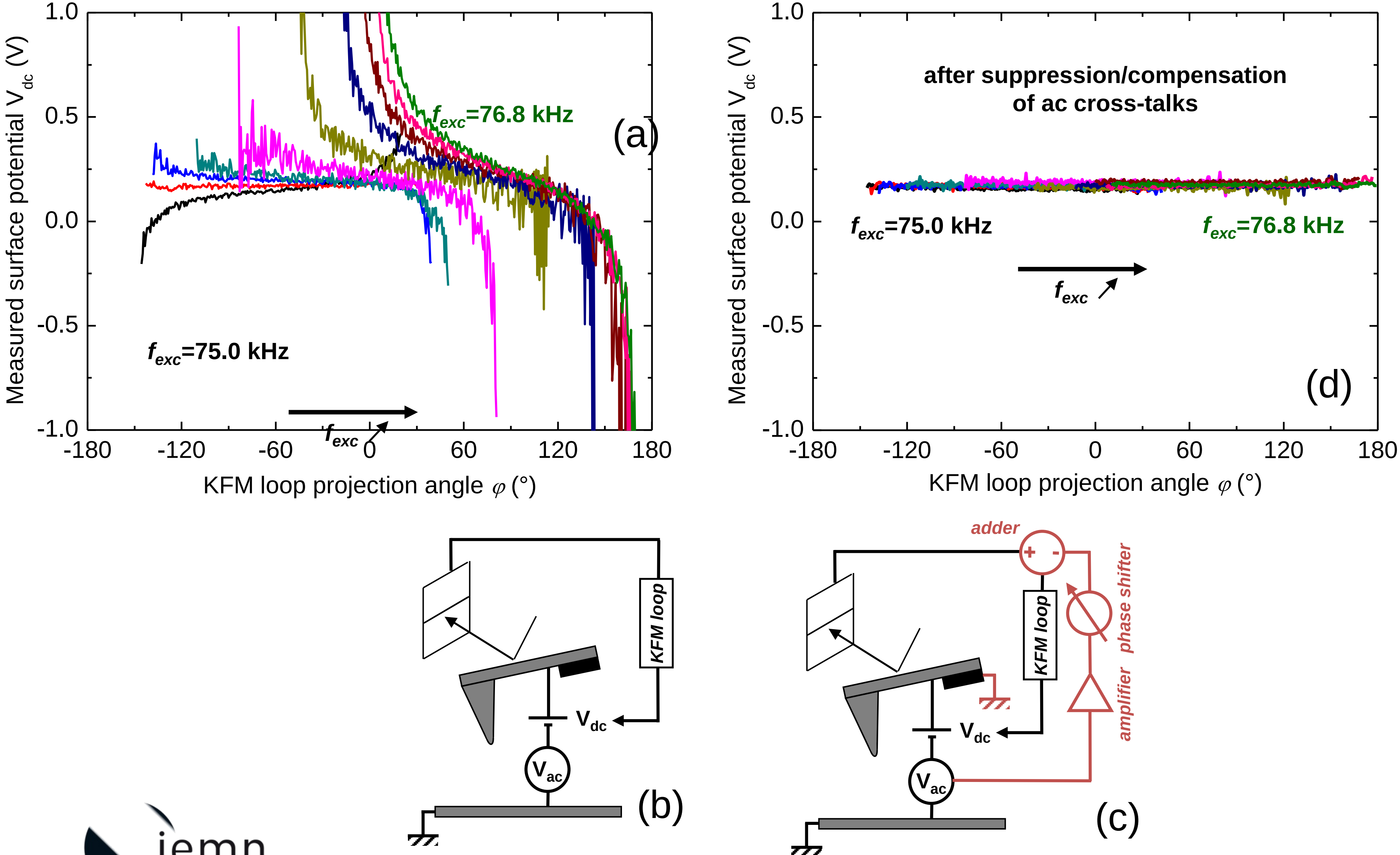
$$V_{dc}=V_s+ \underbrace{A_{ct}\ .\ \cos(\phi_{ct}-\phi)\ /\ dC/dz\ \cos(\phi_{1\omega}-\phi)}$$

This term depends ☹ ☹ ☹

- on ϕ ("drive phase")
- on $\phi_{1\omega}$ (excitation frequency)
- on z (via dC/dz)

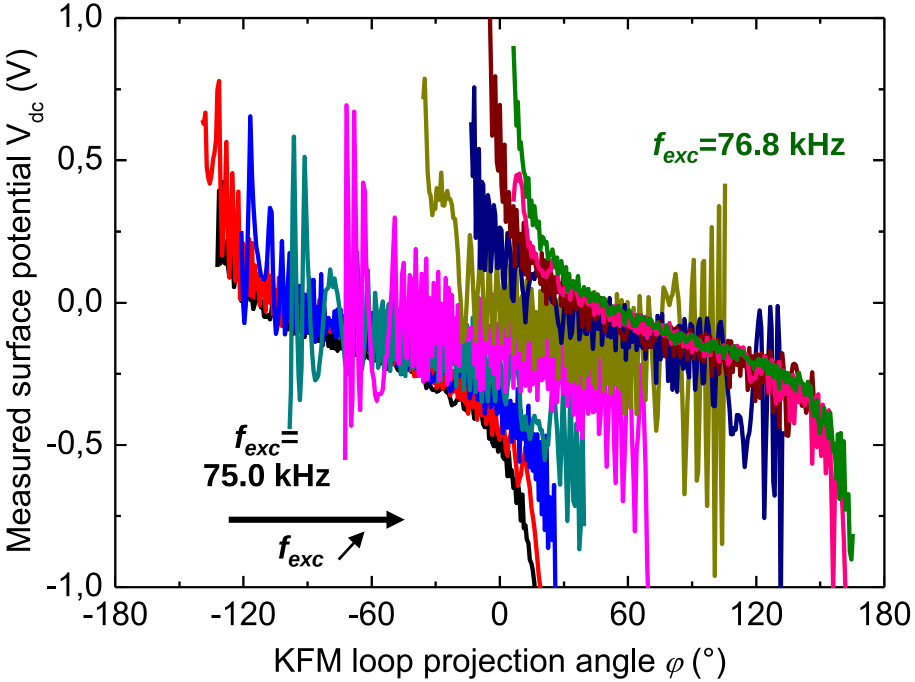
In practice (Brüker) : photodiode + mechanical ac-cross-talks

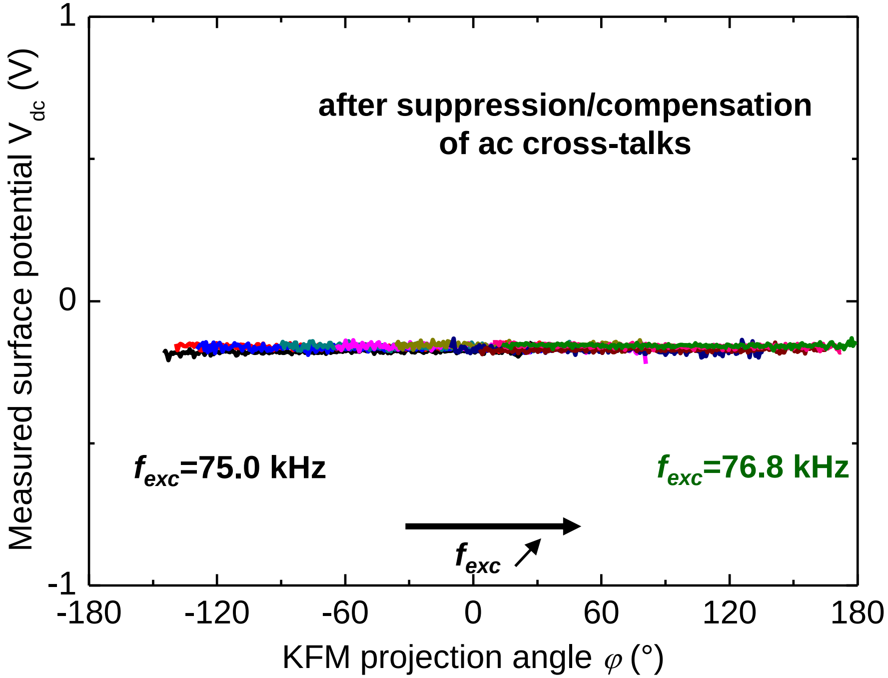
Cross-talk suppression/compensation

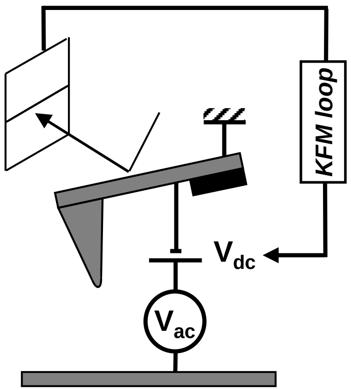


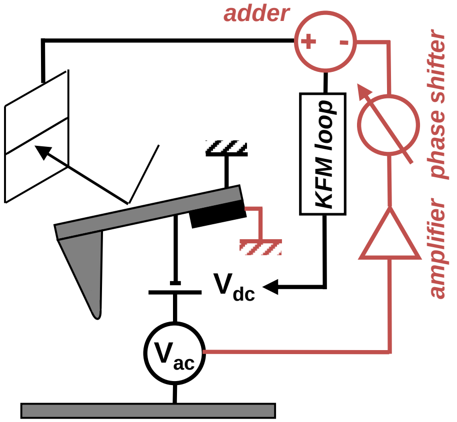
iemn
Institut d'Electronique, de Microélectronique et de Nanotechnologie
UMR CNRS 8520

Cross-talk suppression/compensation









iemn
Institut d'Electronique, de Microélectronique et de Nanotechnologie
UMR CNRS 8520

Rev. Sci. Inst. 2010

Conclusion

This was an introduction lecture on

- **Electrostatic Force Microscopy (EFM)**

  - spectroscopy of electrostatic forces
  - sensitivity and limits

- **Kelvin Probe Force Microscopy (KPFM)**

  - basic implementations
  - AM-KPFM vs FM-KPFM
  - quantitative work function measurement issues

Questions ?