Charge injection and detection in semiconducting nanostructures studied by Atomic Force Microscopy
Electrostatic Force Microscopy in dry atmosphere

- Principles of charge injection and detection
- Minimum detectable force gradient in a Brownian motion
- Electrostatic tip-sample interaction: the plane-plane approximation
- Method of charge estimation
- Limits of this model: numerical evidence of a repulsive force

Non-linear dynamic force curves

- Coupling with the higher oscillating modes of the cantilever
- Analytical treatment of the cantilever motion
- Adding of the electrostatic interaction

Charging experiments on semiconducting nanostructures

- Charging the oxide layer
- Si nanocrystals embedded in SiO$_2$
- Si nanostructures made by e-beam lithography
What is Electrostatic Force Microscopy?

The idea: use the AFM probe to:

- Inject charges locally AND Detect charges

Conditions:
- the tip must be metal-coated: W₂C, PtIr
  - Radius of curvature of the tip: ~35 nm
- the system must be electrically connected
- the tip must not touch the surface after injection
  - oscillating mode
**Charge injection with the tip**

1. Application of a voltage (-12 to 12 V) for 1ms to 10s

2. Decrease of the amplitude setpoint to near 0: contact with the surface

3. AFM in dynamic oscillating mode

4. The setpoint is returned to its original value

5. Resumes scanning

> Permanent N$_2$ flux

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**EFM**

- Injection and detection
- Min. force gradient
- Modelling
- Charge estimation
- Limits

**Dynamic force curves**

- Coupling to higher modes
- Analytical treatment
- Electrostatic interaction

**Charging experiments**

- SiO$_2$ layer
- Si-nanocrystals in SiO$_2$
- Lithography Si-nanostruc.
Detection of the injected charges

The double-pass method

1st pass: topography

1&2: Topography scan. Feedback on the amplitude of oscillation.

2nd pass: EFM signal

3: Raising of the AFM probe at a lift height $z_0$ of 30 to 100 nm. The feedback is cut off.

4&5: EFM scan: recording of the phase of oscillation. The tip is brought to potential $V_{EFM}$

The EFM signal is sensitive to electrostatic force gradients.
Injection and detection of charges

Example of charge injection on 7 nm of SiO$_2$ on Si

Topography

EFM signal

Conditions: -10V/ 10s

$V_{\text{EFM}} = +2 \text{ V}$

$V_{\text{EFM}} = -2 \text{ V}$

EFM can distinguish the sign of the deposited charges

BUT the tip-sample force is always attractive!

EFM signal $\propto - \text{(potential difference)}^2$
Mechanics of the cantilever

Single clamped beam

Euler-Bernouilly equation of movement:

\[
EI \frac{\partial^4 z(x,t)}{\partial x^4} + \rho A \frac{\partial^2 z(x,t)}{\partial t^2} = 0
\]

E : Young modulus
I : moment of inertia
\( \rho \) : density
A : section

Fundamental mode

- **EFM**
  - Injection and detection
  - Min. force gradient
  - Modelling
  - Charge estimation
  - Limits

- **Dynamic force curves**
  - Coupling to higher modes
  - Analytical treatment
  - + Electrostatic interaction

- **Charging experiments**
  - SiO\(_2\) layer
  - Si-nanocrystals in SiO\(_2\)
  - Lithography Si-nanostruc.
Detection of a force gradient

Point-mass model:

\[ \ddot{z}(t) + 2\beta_0 \dot{z}(t) + \omega_0^2 z(t) = \frac{F_{\text{exc}}}{m} \cos(\omega t) + \frac{f(z_0 + z)}{m} \]

where:
- \( \omega_0 \): angular resonance frequency
- \( k \): spring constant of the cantilever
- \( m \): effective mass
- \( \beta_0 \): friction coefficient /m

- Static deflection
- Shift of the resonance frequency

Attractive force = phase lag

\[ \Delta \omega = \omega_0 - \omega_1 \approx \omega_0 \left( \frac{1}{2k} \frac{\partial f}{\partial z}(z_0) \right) \]
Functioning point in amplitude feedback:

\[ \frac{d^2 A}{d\omega^2} = 0 \quad \Rightarrow \quad \omega_{s\pm} = \omega_0 \left( 1 \pm \frac{1}{\sqrt{8Q}} \right) \]

Q: quality factor of the oscillator = 100-300 \quad \omega_{s\pm} \approx \omega_0 !

\[ \frac{dA}{d\omega}(\omega_{s\pm}) = \pm A_m \frac{4Q}{3\sqrt{3}\omega_0} \]

\( A_m \): maximum amplitude of oscillation

\[ \Delta A = \frac{dA}{d\omega}(\omega_s) \cdot \Delta \omega = A_m \frac{2Q}{3\sqrt{3}k} \frac{\partial f}{\partial z}(z_0) \]
Minimum detectable force gradient in a brownian motion

Thermal noise = white-spectrum noise $\hat{R}(\omega)$

Langevin equation in Fourier space:

$$\left(-\omega^2 - i\beta_0 \omega + \omega_0^2\right)\hat{Z} = \frac{\hat{R}}{m}$$

The generalized susceptibility is defined as (Landau-Lifschitz):

$$\alpha(\omega) = \frac{\hat{Z}}{\hat{R}} = \alpha'(\omega) + i\alpha''(\omega)$$

The dissipation-fluctuation theorem provides:

Spectral density of the fluctuations:

$$\left\langle |\hat{Z}(\omega)|^2 \right\rangle = \frac{k_B T}{\pi \omega} \alpha''(\omega) = \frac{k_B T Q}{\pi k \omega_0} \cdot \frac{1}{Q^2 \left(1 - \frac{\omega^2}{\omega_0^2}\right)^2 + \frac{\omega^2}{\omega_0^2}}$$
Minimum detectable force gradient in a brownian motion

The standard deviation of movement N is:

\[ N = \sqrt{4\pi B \langle \hat{Z}(\omega)^2 \rangle} \]

where B is the bandwidth of the system (in Hz)

**Simplifications:**

- Near the resonance
  \[ N \approx \sqrt{\frac{4k_B T Q B}{k \omega_0}} \]
- Away from resonance
  \[ N \approx \sqrt{\frac{4k_B T B}{k \omega_0 Q}} \]

The minimum detectable force gradient is given when:

amplitude variation = standard deviation of movement

\[ \Delta A = N \]
Minimum detectable force gradient in a Brownian motion

One-dimensional, simple harmonic oscillator

Dissipation-fluctuation theorem:
Finite $Q^{-1} =$ dissipative system = source of noise

White spectral density of the noise force $f$:

$$S_f(\omega) = \frac{4k_B T \kappa}{Q \omega_0}$$

Units: N²/Hz

Standard deviation of the force:

$$N \propto \sqrt{BS_f(\omega)}$$

B = bandwidth of system

where:

$$N = \sqrt{\left\langle (k_{\text{eff}} z)^2 \right\rangle} \propto \left. \frac{\partial f}{\partial z} \right|_{\text{thermal}} \cdot A_m$$

$$\left. \frac{\partial f}{\partial z} \right|_{\text{thermal}} \propto \frac{1}{A_m} \sqrt{\frac{4k_B T \kappa B}{Q \omega_0}}$$
Minimum detectable force gradient in a Brownian motion

At the resonance:

$$ \frac{\partial f}{\partial z}_{\text{min}} = \frac{1}{A_m} \sqrt{\frac{27 k_B T k \omega}{\omega_0 Q}} $$

In our conditions:

- \( A_m = 10\text{-}20 \text{ nm} \)
- \( k_B T = 26 \text{ meV ambient temperature} \)
- \( Q = 100\text{-}300 \text{ ambient pressure} \)
- \( k = 0.1\text{-}1 \text{ N/m} \)
- \( \omega_0 = 20\text{-}100 \text{ kHz} \)
- \( B = 500 \text{ Hz} \)

Relation to min. detectable charge?

Plane-plane approximation
Modelling of the electrostatic tip-sample interaction

The electrostatic force is **capacitive**:

\[
f(z) = \frac{1}{2} \frac{\partial C}{\partial z}(z)V^2
\]

\[
\frac{\partial f}{\partial z}(z) = \frac{1}{2} \frac{\partial^2 C}{\partial z^2}(z)V^2
\]

**Capacitance C, C”=??**

Different capacitor geometries:

- Plane-plane
- Sphere-plane
- Cone-plane
- Truncated cone-plane
Modelling of the electrostatic tip-sample interaction

Plot of the 2nd derivative of capacitance vs. tip-sample distance

- Contribution of cantilever is negligible.
- Area of plane capacitor is adapted to fit $C''(z)$ of truncated cone-plane at a lift height of 100 nm.

The simplest geometry is chosen: plane-plane capacitor

$$C''(z) = 2\varepsilon_0\varepsilon_r \frac{A}{z^3}$$
Modelling of the electrostatic tip-sample interaction

The system is modelled as 2 plane capacitors in series

\[ f'(z) = \frac{\varepsilon_0 A}{\left( z + \frac{d}{\varepsilon_{SiO2}} \right)^3} \left( V_{EFM} - \frac{qd}{\varepsilon_0 \varepsilon_{SiO2} A} \right)^2 \]
Minimum detectable charge at $V_{EFM} = 0$

$$q_{\text{min}} = \sqrt{f'_{\text{min}} \left( z + \frac{d}{\varepsilon_{SiO_2}} \right)^3 \varepsilon_0 \varepsilon_{SiO_2}^2 A}$$

$q_{\text{min}}$ dependent on:
- $z$ : lift height
- $d$ : oxide thickness
- $A$ : effective plane area

$f'_{\text{min}} = 3 \times 10^{-5} \text{ N.m}^{-1}$

$z = 100 \text{ nm}, A = 14700 \text{ nm}^2$ (disc of 140 nm in diameter)

<table>
<thead>
<tr>
<th>$d$ (nm)</th>
<th>7</th>
<th>10</th>
<th>25</th>
<th>100</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_{\text{min}}$ (e-)</td>
<td>185</td>
<td>162</td>
<td>69</td>
<td>22</td>
<td>11</td>
</tr>
</tbody>
</table>

$z = 50 \text{ nm}, A = 6260 \text{ nm}^2$ (disc of 90 nm in diameter)

<table>
<thead>
<tr>
<th>$d$ (nm)</th>
<th>7</th>
<th>10</th>
<th>25</th>
<th>100</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_{\text{min}}$ (e-)</td>
<td>54</td>
<td>39</td>
<td>18</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>
Method of charge estimation

Imaging and relating the recorded phase to a charge

We established:

\[ \Delta \omega = \frac{\omega_0}{2k} \frac{\partial f}{\partial z}(z_0) \]

Moreover:

\[ q = \sqrt{\delta \phi \cdot k(z + \cdots)} \]

Charging experiments on 7 nm SiO\(_2\) (injection time: 10 s)

Charging experiments (injection time: 10 s)
Method of charge estimation

Relate the minimum of EFM signal vs. voltage to a charge

Before and after injection, voltage $V_{EFM}$ applied on tip is scanned

Minimum corresponds to $V_{EFM} = V_{surface}$

Conditions:
Injection -10V/10s
$d = 25$ nm
Lift height: 300 nm
$A = 13 \times 10^{-14} \text{ m}^2$
(disc 400 nm in diam.)

Here $q = 1500$ charges
Limits of the capacitor model

Capacitive force: always attractive

- Numerical evidence of a repulsive interaction (J.P. Julien, CNRS)

- Distribution of equivalent charge $q$ on the tip in rings
- Trapped charge $q_0$ is modelled above the symmetry plane
- Charges are adjusted to have a constant potential on the tip’s surface
- Screening charges are taken into account

Domain of repulsive force!

16 electrons!
= barely measurable
Non-linear dynamic force curves

What is a force curve:

- Scanning is stopped
- Feedback on amplitude is cut off
- Cantilever is mechanically excited near resonance frequency
- Tip is approached then retracted from the surface (height ~ 200 nm)
- Amplitude and phase of oscillation are recorded

Coupling to higher oscillating modes of the cantilever

Is the movement of the cantilever still that of a harmonic oscillator?

NO! Strong excitation

YES! Normal excitation
Non-linear tip-sample interaction

Deformation of the resonance curve with increasing tip-sample interaction

Amplitude and phase of oscillation undergo hysteresis
Non-linear tip-sample interaction

Deformation of the resonance curve with increasing tip-surface interaction

Amplitude and phase of oscillation undergo hysteresis
Analytical treatment of the movement of cantilever

Non-perturbative treatment (J.P. Aimé, CPMOH Bordeaux)

- Interaction is van der Waals: \( \frac{HR}{d^2} \) (attractive force)
- Amplitude and distance are normalized to free amplitude at resonance: \( a = A/A_0 \), \( d = z/A_0 \)

\[ d_{A\pm} = \sqrt{a^2 + \frac{k_{vdW}}{(u^2-1)^{\frac{1}{2}} \frac{1}{Q} \sqrt{a^2 - u^2}}}^{\frac{2}{3}} \]

- \( u = \frac{\omega}{\omega_0} \)
- \( k_{vdW} \): dimensionless parameter related with strength of van der Waals forces

\[ \phi_{A\pm} = \arctan \left( \frac{u^2}{Q(u^2-1) + Q \frac{k_{vdW}}{\left(d_{A\pm}^2 - a^2\right)^{\frac{3}{2}}}} \right) \]
Analytical treatment of the movement of cantilever

These analytical curves explain the hysteresis observed experimentally.

Analytical curves

Experimental curves

Experimental parameters used in the analytical curves:

\[ Q = 80 \]
\[ k = 2.3 \text{ N/m} \]
\[ \omega_0 = 57.85 \text{ kHz} \]
\[ u = 0.9939 \]
\[ A_0 = 13.5 \text{ nm} \]
Adding the electrostatic interaction

Capacitive tip-sample coupling taken into account

\[
d_{A^\pm} = \sqrt{a^2 + \left( \frac{k_{vdW} + k_{elect}V^2}{(u^2 - 1) + \frac{1}{Q} \sqrt{\frac{1}{a^2 - u^2}}} \right)^{2/3}}
\]

where

\[
k_{elect}V^2 = \frac{\varepsilon_0 A}{kA_0^3} V^2
\]

\[
\phi_{A^\pm} = \arctan \left( \frac{u^2}{Q(u^2 - 1) + Q \frac{k_{vdW} + k_{elect}V^2}{(d_{A^\pm}^2 - a^2)^2}} \right)
\]

We take advantage of the fact that the capacitive force for a plane capacitor has the same distance-dependence \(d^{-2}\) as the van der Waals force
Adding the electrostatic interaction

**Analytical curves**

**Normalized distance**

$A_0 = 14 \text{ nm}$

**Experimental curves**

**Dynamic force curves**

**Charging experiments**

SiO$_2$ layer

Si-nanocrystals in SiO$_2$

Lithography Si-nanostruc.
Quantitative charge measurement with force curves

Application to carbon nanotubes (M. Paillet, Uni Montpellier)

- Fitting the data before injection provides all parameters \((A_0, u, U_{vdW})\)
- After injection, the fit provides \(q=10\) electrons
**Charging experiments on semiconducting nanostructures**

**Objective:** not quantify charges but investigate charging behaviors
- charging of individual structures
- charging of collection of nanostructures

**Dynamic force curves**
- Coupling to higher modes
- Analytical treatment
- Electrostatic interaction

**Charging experiments**
- SiO$_2$ layer
- Si-nanocrystals in SiO$_2$
- Lithography Si-nanostr.

**Si-nc non-volatile memory**
Charging experiments on semiconducting nanostructures

3 types of samples:

- Reference SiO$_2$ layer on Si
  - charging behavior of an insulator
- Si-nanocrystals embedded in SiO$_2$
  - very small ~5 nm in diameter
  - collective behavior
- Si-nanostructures made by e-beam lithography
  - well-defined, ~100 nm in dimension
  - individual behavior
Charging insulators: the case of SiO$_2$

Large electric field (~$10^8$ V.m$^{-1}$) necessary to deposit only a few 100 charges

Charging of 25 nm of thermal oxide, conditions: -10 V/ 10s
Recording of the EFM signal

Characteristic retention time: 94 seconds = Low retention time
Charging insulators: the case of SiO$_2$

Charging of 25 nm of thermal oxide, conditions: -10 V/ 10s
Recording of the EFM signal

Absence of lateral spreading of the charges
Silicon nanocrystals embedded in SiO₂

**Elaboration:** (CEA Grenoble/LETI)
- deposition of a SiOₓ layer (x < 2) by LP-CVD
- annealing at 1000°C, 10 minutes
  = precipitation of Si nanocrystals in SiO₂ matrix

![TEM pictures](image)

**Typical dimension:** 3 nm

Density depends on x, varies from 3 \( \times 10^{11} \) to \( 10^{12} \) cm\(^{-2} \)
Silicon nanocrystals embedded in SiO$_2$

First behavior: very low Si-nc density

Circular shape of injected charges that does not evolve in time

Time retention: several hours

Estimation of one electron per nanocrystal

Any difference from reference SiO$_2$ sample?
Low-density Si-nanocrystals embedded in SiO$_2$

Same charging conditions: -10 V / 3 s

Si-nanocrystals

SiO$_2$ reference sample

Si-nanocrystals:
D \sim 200 \text{ nm}
\Delta \phi_{\text{max}} \sim 6.5 ^\circ

SiO$_2$ reference:
D \sim 350 \text{ nm}
\Delta \phi_{\text{max}} \sim 3 ^\circ

Smaller electron cloud
Higher surface density of electrons

\sim e \text{- density}
Evolution of the disc with the injection time

**Si-nanocrystals**
Reproducible experiment with homogeneous distribution of slopes

The disc’s diameter evolves as log (injection time)

Infinitely slow saturation

**Reference SiO$_2$**

Larger disc’s diameters = easier spreading of the charges

Inhomogeneous distribution of slopes: due to flawed tip-sample contact?
Low-density Si-nanocrystals vs. SiO\textsubscript{2} reference sample

- Same circular shape of the electron cloud for both samples
  - BUT
  - in the same charging conditions:
    - the electron cloud is **smaller** and **denser** for the Si-nanocrystal sample
    - and it remains much **longer** (hours vs. minutes)

- Same logarithmic injection-time dependence
  - BUT
  - Si-nanocrystals shows **homogeneous** distribution of slopes
  - whereas SiO\textsubscript{2} shows an **inhomogeneous** one

- Tip-sample contact resistance is dominant in SiO\textsubscript{2} sample
- Intercrystal-resistance is dominant in Si-nanocrystal sample
Tentative illustration of charge localization

Energetic diagrams

SiO₂ layer

Conduction band

Valence band

Traps

SiO₂ gap ~8 eV

Position

Si nanocrystals in SiO₂ layer

Conduction band

Valence band

Si gap ~1 eV

Position

EFM

Injection and detection
Min. force gradient
Modelling
Charge estimation
Limits

Dynamic force curves
Coupling to higher modes
Analytical treatment
+ Electrostatic interaction

Charging experiments
SiO₂ layer
Si-nanocrystals in SiO₂
Lithography Si-nanostruc.
**Silicon nanocrystals embedded in SiO₂**

- Typical dimension: 3 nm
- Density depends on x, varies from $3 \times 10^{11}$ to $10^{12}$ cm$^{-2}$
- 3 kinds of sample prepared, with varying densities

**Fitting of the ellipsometric measurements provides:**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Si(%)</th>
<th>SiO₂(%)</th>
<th>Fraction x</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>40</td>
<td>60</td>
<td>0.81</td>
</tr>
<tr>
<td>E2</td>
<td>8</td>
<td>92</td>
<td>1.67</td>
</tr>
<tr>
<td>E3</td>
<td>6</td>
<td>94</td>
<td>1.77</td>
</tr>
</tbody>
</table>

- **High Si-nc density**
- **Low Si-nc density**
- **Very low Si-nc density**
Silicon nanocrystals embedded in SiO$_2$

Sample E1: metallic behavior

EFM signal

- Charges spread away on a time scale of seconds

Si = 40 %
SiO$_2$ = 60 %

Si-nc touch one another, no confinement possible
Silicon nanocrystals embedded in SiO$_2$

Sample E3: strongly confining behavior

Si = 6 %  \hspace{1cm} \text{Very low Si-nc density} \hspace{1cm} \text{SiO}_2 = 94 %

Circular shape of injected charges that does not evolve in time

Estimation of \textbf{one electron per nanocrystal}
Silicon nanocrystals embedded in SiO$_2$

**Sample E2: partially confining behavior**

Si = 8 %
SiO$_2$ = 92 %

Charging conditions -10 V / 10 s

- Rough borderline
- Inhomogeneous distribution of charges inside the electron cloud

Reflects disorder in the distribution of Si-nc at nanoscale
Sample E2: time evolution of the electron cloud

EFM images

Profiles of EFM signal

Normalized profiles

Irregular spreading of the charges, on a time scale of hours = “kinetic roughening”
Sample E2: mechanism of charge spreading

Quenched disorder

Zone of charged Si-nc $V \approx 0.1 \, \text{V}$

Si-nc section: $S$

Intercrystal spacing: $d$

Electron transport is explained with the orthodox model of the Single Electron Transistor (SET) with $V_{\text{gate}} = 0$

Passage from one Si-nc to another occurs through **tunneling**

Percolation threshold related to intercrystal distances (=density)
Sample E2: mechanism of charge spreading

\[ S = \pi r^2 \text{ with } r \approx 3 \text{ nm} \]
\[ \rho_{\text{SiO}_2} = 10^{14} \text{ to } 10^{16} \Omega \text{ cm} \]
\[ d \approx 1 \text{ nm} \]

\[ C = \varepsilon_0 \varepsilon_{\text{SiO}_2} \frac{S}{d} \sim 1 \text{ aF} \]
\[ R_T = \rho_{\text{SiO}_2} d / S \sim 10^{19} \Omega \]

Tunneling of the electrons in the frame of orthodox model

Transition rate \( \Gamma = \tau^{-1} \) is:

\[ \Gamma = \frac{1}{R_T e^2} \frac{-\Delta F}{1 - \exp\left(\frac{\Delta F}{k_B T}\right)} \]

where:

- \( \Delta F = f(\Delta V, C) \) energy associated with the passage
  of one \( e^- \) from one Si-nc to its neighbor \( \sim -80 \text{ meV} \)

\[ \Gamma = 5 \times 10^{-2} \text{ s}^{-1} \text{ or } \tau = 20 \text{ s} \]

Progression of the borderline: 1 \( \mu \text{m/hour} \)

1 electron tunnels through \( \sim 200 \text{ Si-nc/hour} = 1 \text{Si-nc / 20s!} \)

Silicon nanostructures made by e-beam lithography

- Dots are polycrystalline Si deposited by LP-CVD
- 2 nm of SiO$_2$ is grown on top to protect the dots

- Dots are monocrystalline Si made from SOI
- 2 nm of SiO$_2$ is grown on top to protect the dots
AFM characterization

Most Si nanostructures are well-defined...

100 nm in diameter dots

... but some are more extravagant.

50 nm in diameter dots

EFM

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Charging experiments
SiO₂ layer
Si-nanocrystals in SiO₂
Lithography Si- nanostruc.
Influence of the oxide thickness

Charging conditions: -8V / 5s

For the same recorded phase shift, there are 7x less charges on thick oxide.
Existence of a voltage threshold for injection of charges

On thin-oxide sample:

Minimum electric field of $\sim 3 \times 10^8$ V.m$^{-1}$ is required
Propagation of the charges inside a ramified structure

Thin-oxide sample

Charging conditions: -10 V / 10 s

Amplitude  EFM signal

Injection is point-like
Charges extend immediately over several microns
Trapping of charges in the top oxide

Charging conditions: -7 V/ 10 S

Good quality oxide ("Rapid Thermal Oxide")
traps charges for more than 30 minutes
De-charging of the ramified structures

Thin oxide (7 nm)

Charging conditions: -10 V/ 10 s

Homogeneous de-charging of the structure, although 7 nm of oxide prevent direct tunneling

Strong repulsion between the electrons
(electronic density is high: $\sim 10^{17}$ cm$^{-3}$)

Existence of a Wigner crystal
(ordering of the electrons on a regular lattice?)
Silicon nanocrystals embedded in SiO$_2$

Sample E3: strongly confining behavior

Si = 6 %  
SiO$_2$ = 94 %

![AFM image](image1)

EFM images

t=0  t=4 hours

-6 V  +6 V

Very long retention time

Circular shape of injected charges that does not evolve in time

Estimation of one electron per nanocrystal
Electrostatic Force Microscopy in dry atmosphere:

- Powerful method to characterize electrical properties at the nanoscale
- Charge resolution: a few tens elementary charges
- Analysis of the non-linear tip-sample interaction

Semiconducting nanostructures:

- Reference SiO$_2$ sample shows low charge retention and low charge density
- Collective behavior of Si-nanocrystals show 3 regimes:
  - metallic
  - intermediate: observable spreading
  - confining

- Individual behavior of Si-nanostructures

Perspectives:

- Need for better resolution (charge, drift)
  - future experiments under vacuum, low temperatures
  - single electron detection
Acknowledgements

For the experiments

Henk-Jan Smilde                  CEA Grenoble/LETI
Martin Stark                     LEPES / LSP
Julien Pascal                    ESRF
Frederio Martin                  ESRF
Charlène Alandi                  ESRF
Emilie Dubard                    ESRF
Florence Marchi                  UJF / LEPES-CNRS
Fabio Comin                      ESRF
André Barski                     CEA Grenoble / DRFMC
Joël Chevrier                    ESRF / UJF / LEPES CNRS

For the samples

Denis Mariolle                   CEA Grenoble/LETI
Nicolas Buffet                   CEA Grenoble/LETI
Pierre Mur                       CEA Grenoble/LETI