

Electrostatic properties of carbon nanotubes and CNT-based devices using scanning force techniques

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CNRS research scientists

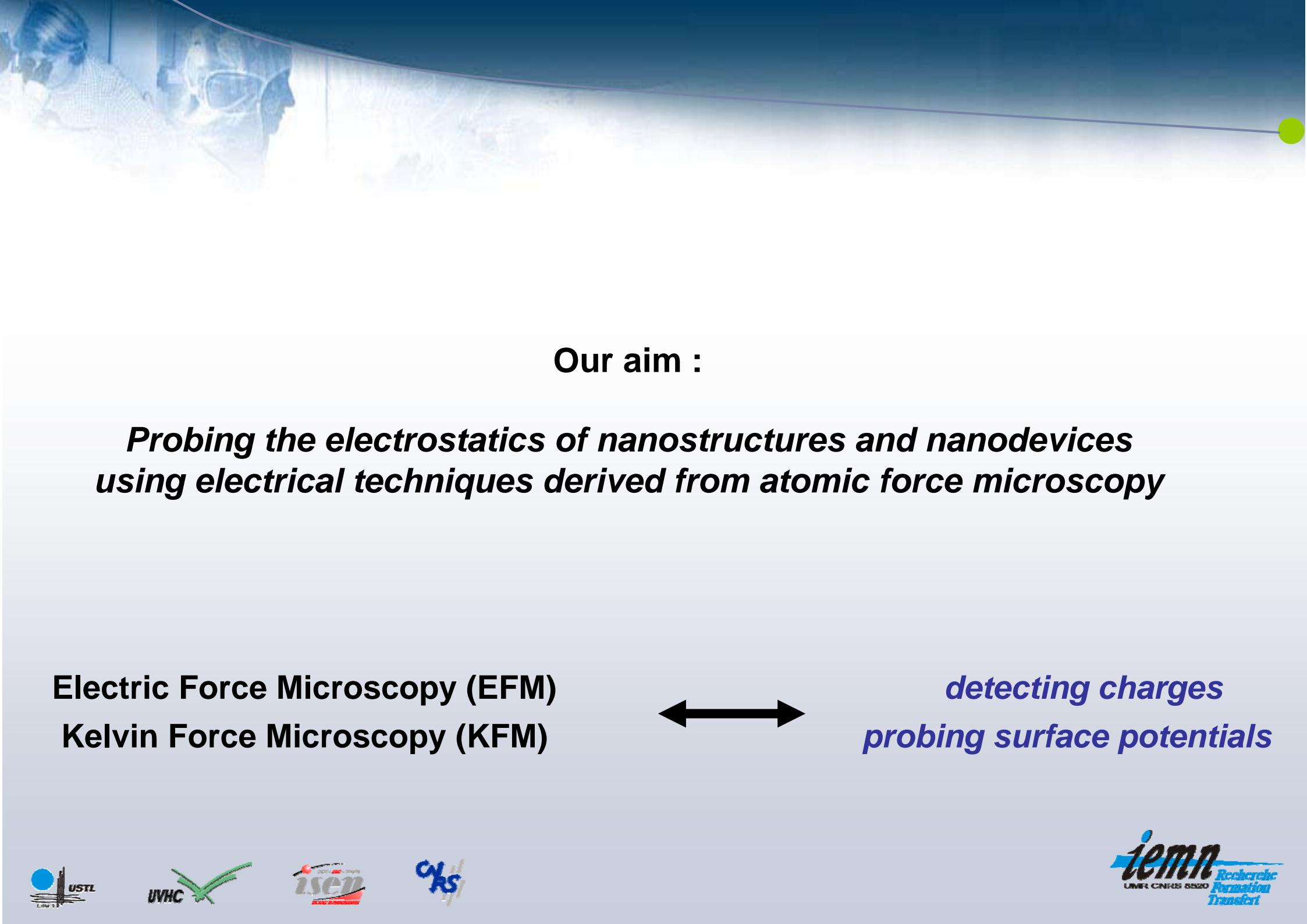
M. Zdrojek (2006), D. Brunel (2008)

PhD students

S. Barbet (2008), L. Borowik

D. Deresmes

Technical support



Our aim :

***Probing the electrostatics of nanostructures and nanodevices
using electrical techniques derived from atomic force microscopy***

**Electric Force Microscopy (EFM)
Kelvin Force Microscopy (KFM)**



*detecting charges
probing surface potentials*



- I - Electrostatics of individual nanotubes (SWCNTs, MWCNTs)
- II - Coupled transport and electrostatic measurements (SWCNTs)
[carbon nanotubes as memory devices]

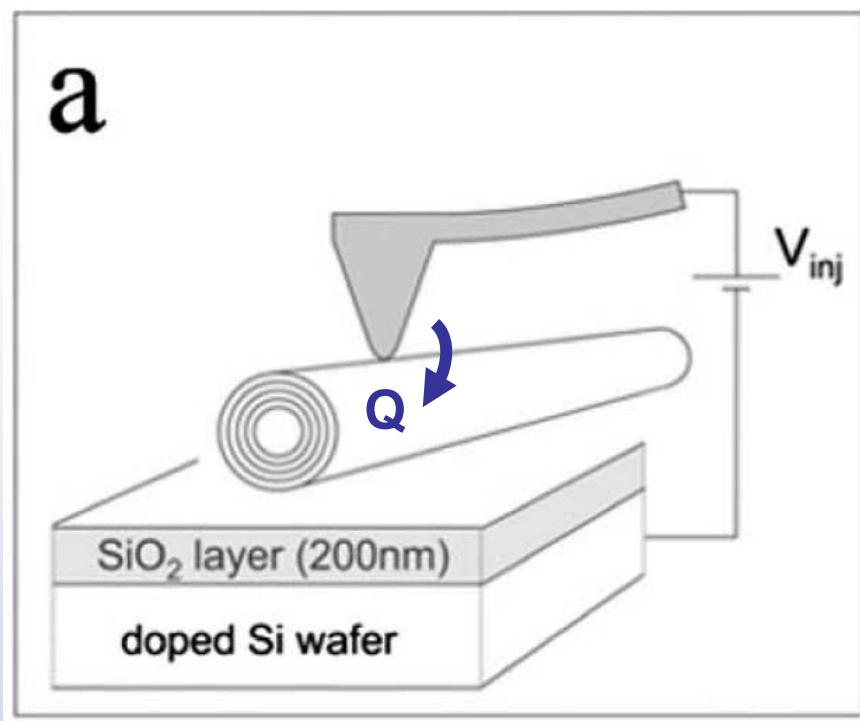


I - Electrostatics of individual nanotubes (SWCNTs, MWCNTs)

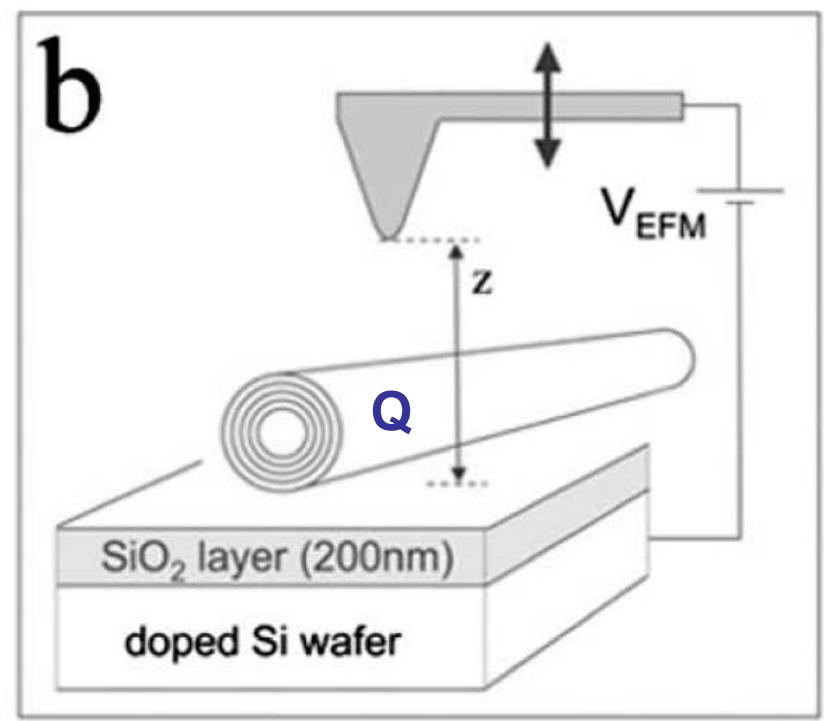
II - Coupled transport and electrostatic measurements (SWCNTs)

Charge injection - Charge detection

Charge injection



Charge detection (EFM)



$$F_z = F_z(z_0) + \underbrace{\text{grad}_z F_z}_{\text{" - } \Delta k \text{ "}} \cdot (z - z_0)$$

Force gradient on the tip

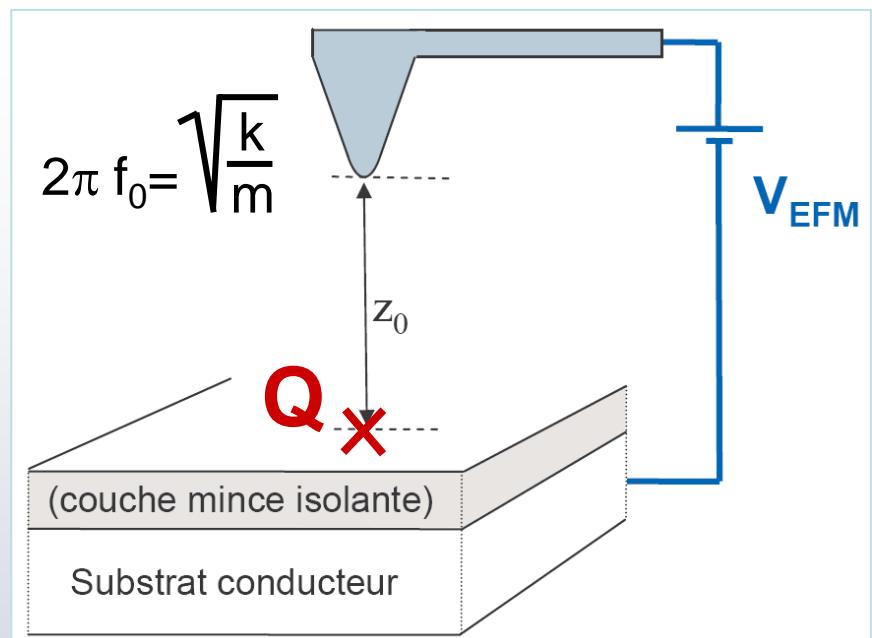


effective change in cantilever stiffness

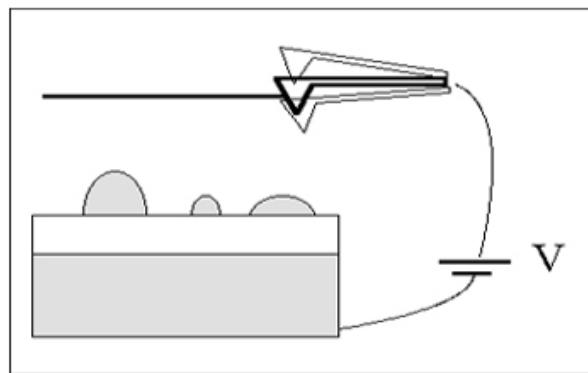
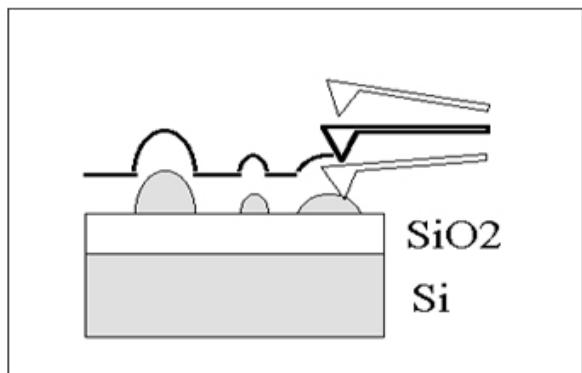


cantilever resonance frequency shift

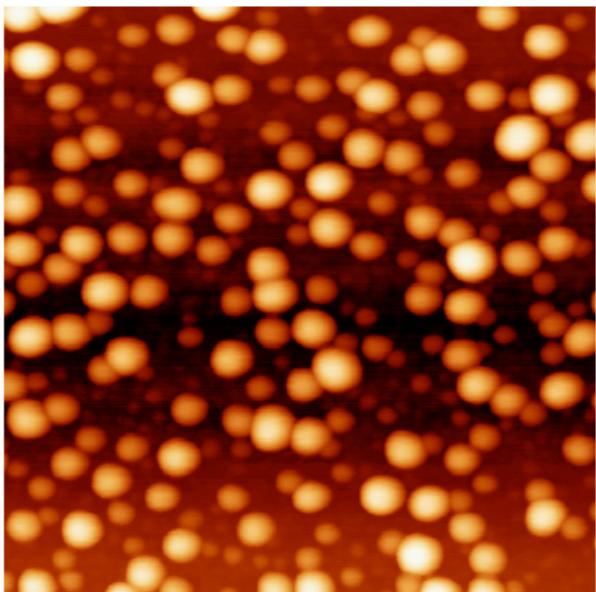
sensitivity down to 1e in specific cases



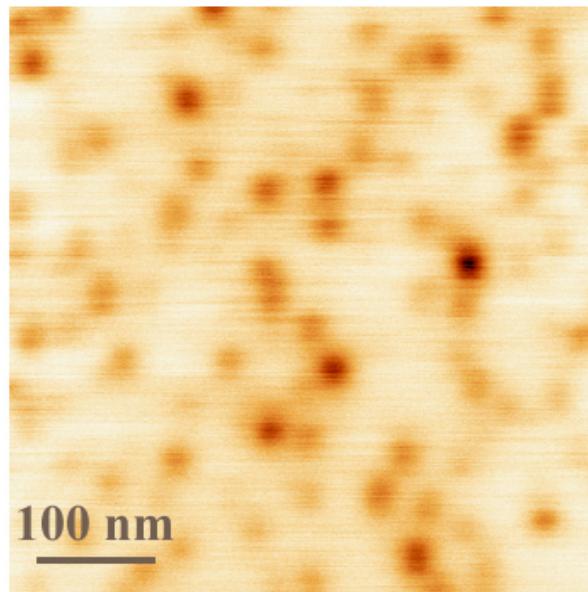
Uncharged silicon nanoparticles (capacitive interaction)



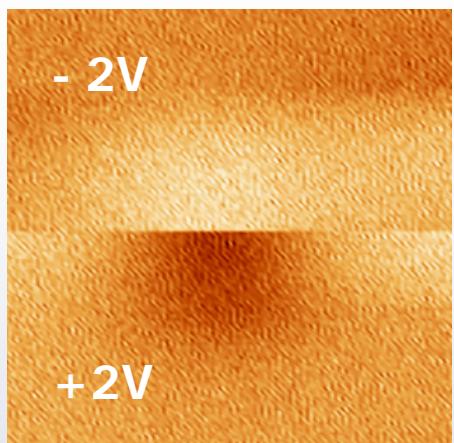
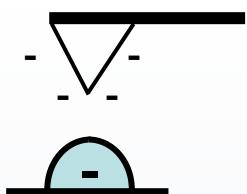
Topography
image
50 nm scale



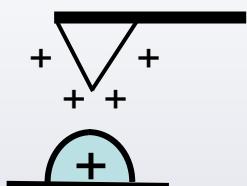
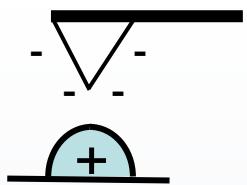
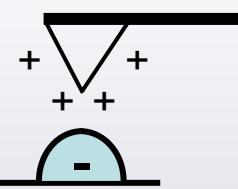
EFM image
($V_{\text{EFM}} = -8\text{V}$)
40 Hz scale



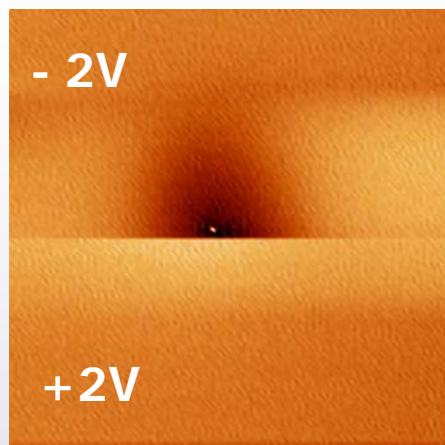
Silicon nanoparticles after charge injection



Injection @ -6V
(~ -170 e)

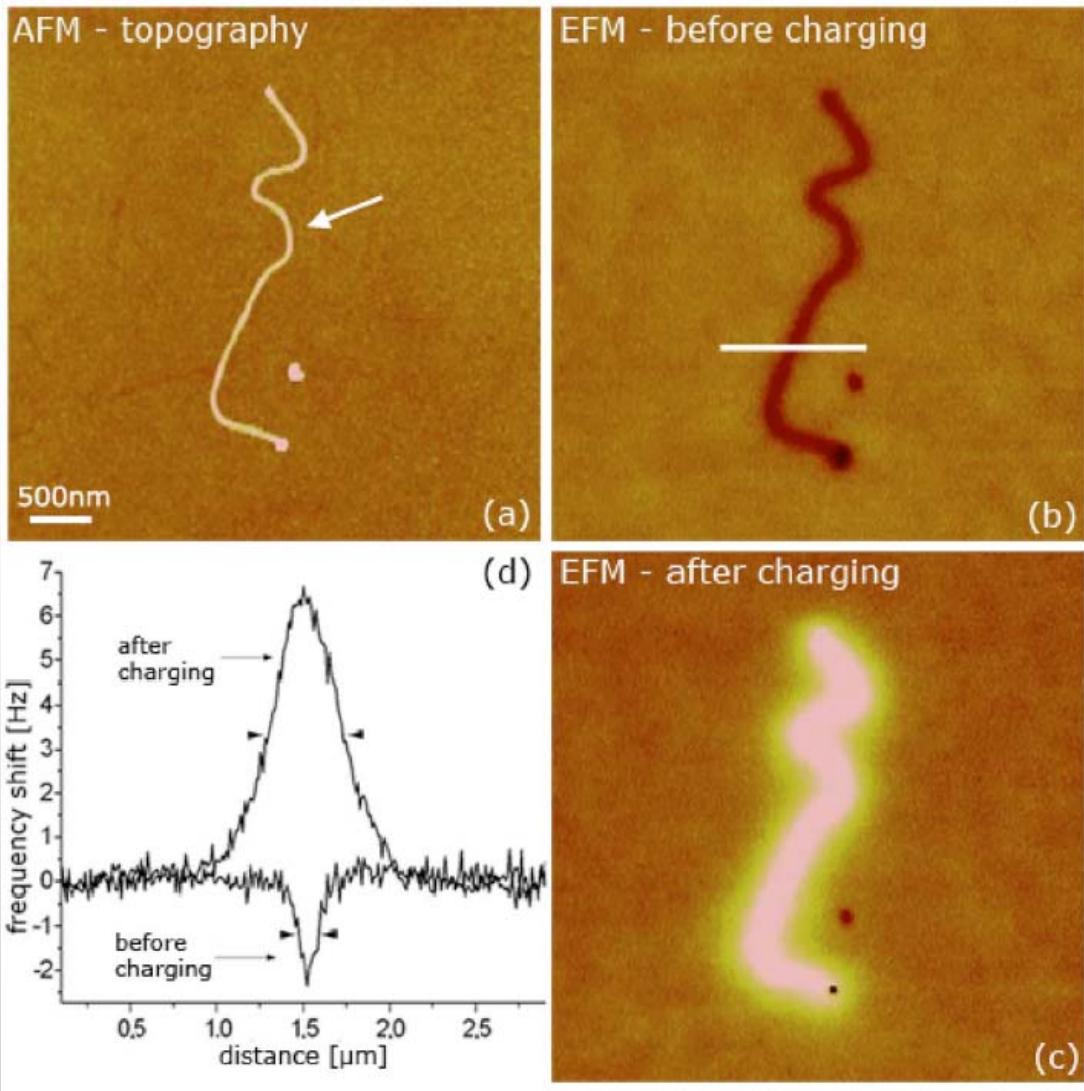


EFM (Δf_0) 300x300nm



Injection @ +6V
(~ +170 e)

Charge injection in carbon nanotubes



- Charge injection $V_{\text{inj}} = -5V$
- Delocalized charge pattern
- Different FWHMs between charge and capacitive EFM patterns

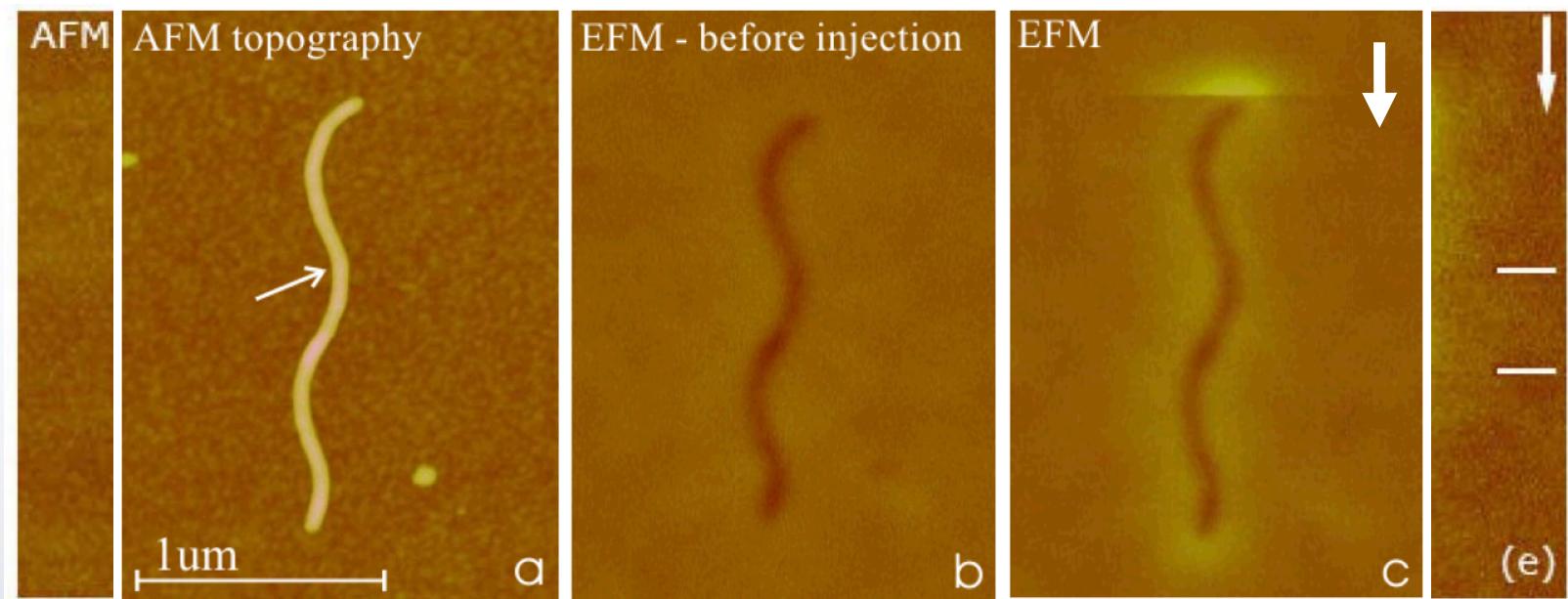
~30 nm diameter MWCNT
 $V_{\text{EFM}} = -3V$, 10Hz color scale

M. Zdrojek et al., J.Appl Phys (2006)



Abrupt discharge phenomena

- Abrupt discharges when scanning along the nanotubes

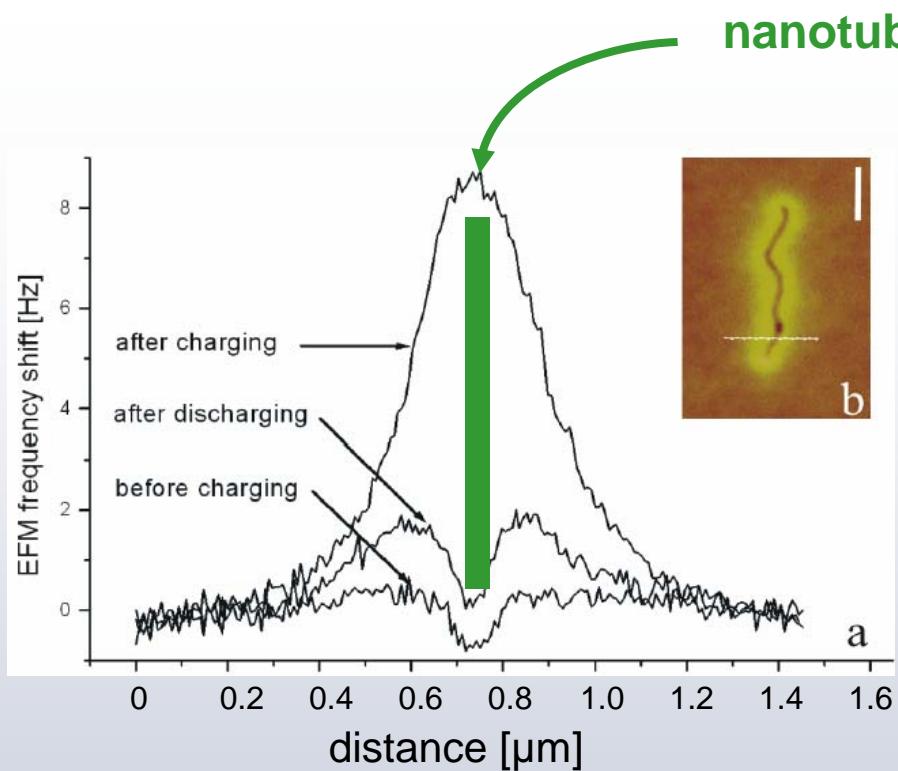


[MWCNT with 82 nm diameter, $V_{\text{inj}} = 7 \text{ V}$, $V_{\text{det}} = 5 \text{ V}$ (2 h), $V_{\text{EFM}} = 3 \text{ V}$, $V_{\text{EFM}} = -3 \text{ V}$]

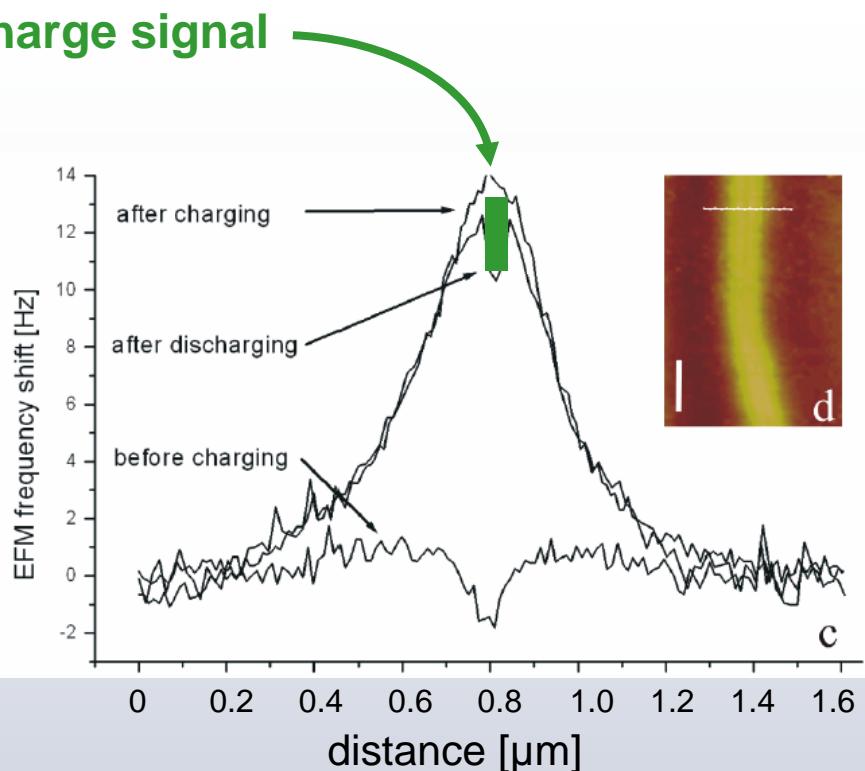
AFM : 50 nm color scale ; EFM : 20 Hz color scale

- Preferential charge emission sites with density : < a few μm^{-1}
- **MWCNTs can carry an out-of-equilibrium charge on SiO_2 !!**

MWCNT 15.0 nm diameter



SWCNT 3.0 nm diameter



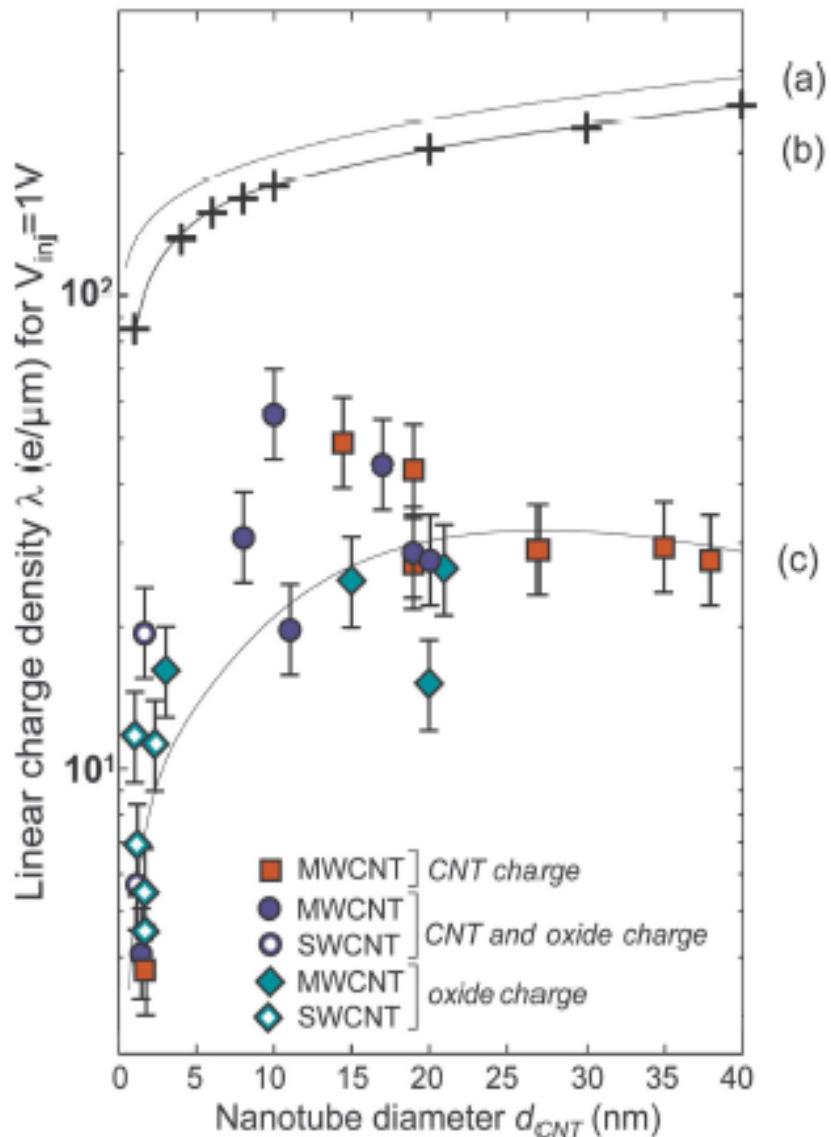
Charge injection : $V_{inj} = -6V$, 30s, charge detection : $V_{EFM} = -3V$

M. Zdrojek et al., Phys. Rev. Lett. 96 039703 (2006)



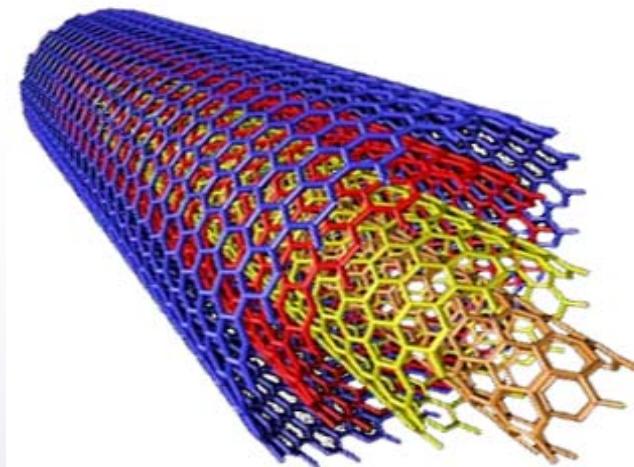
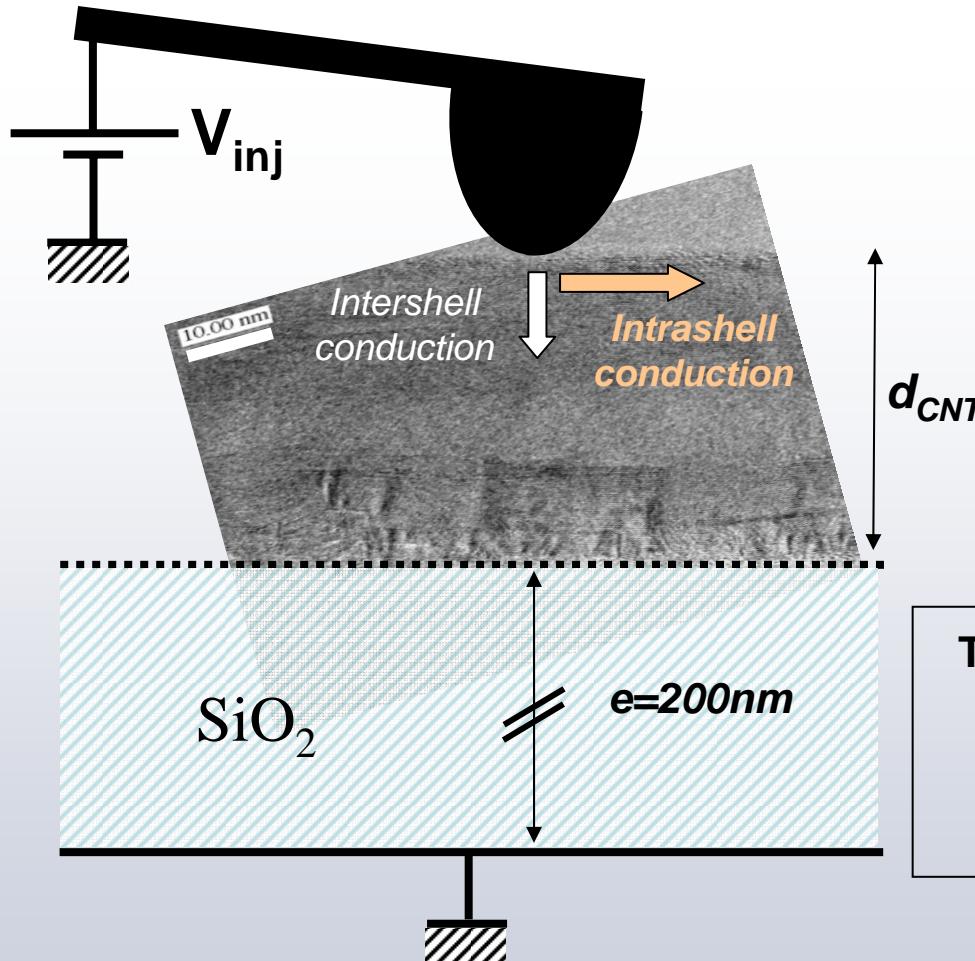
Charging mechanisms

Charging mechanisms ?



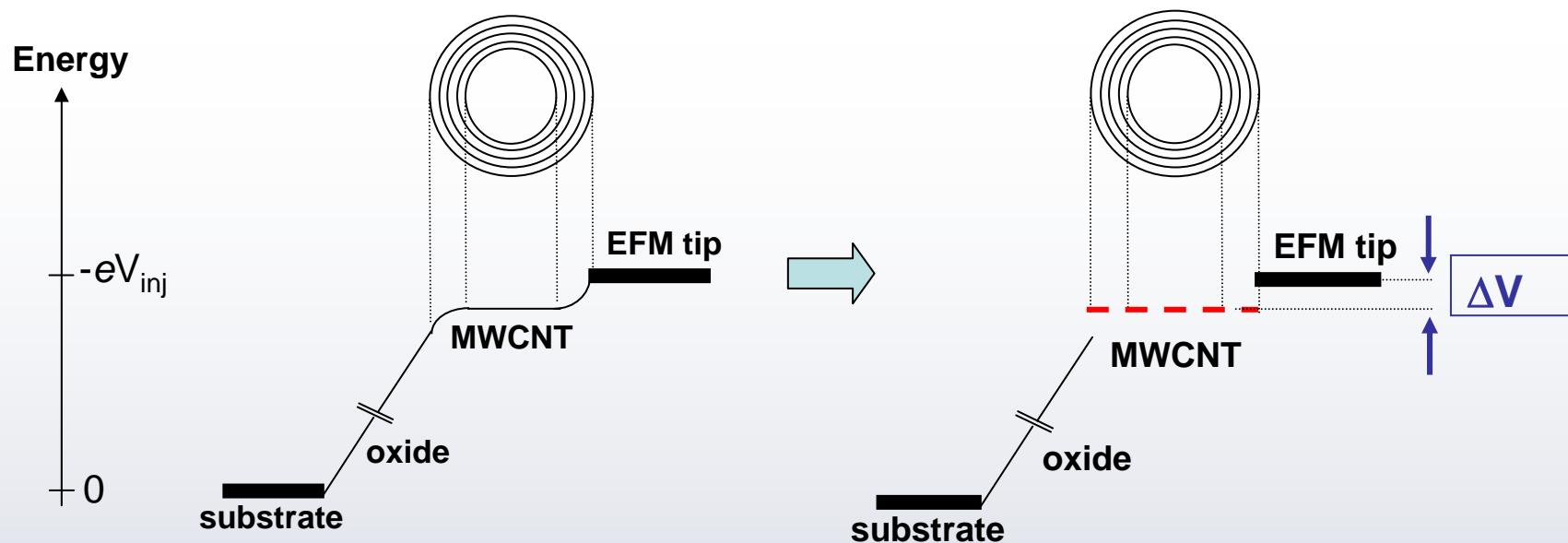
→ Capacitive response
to the tip bias

??

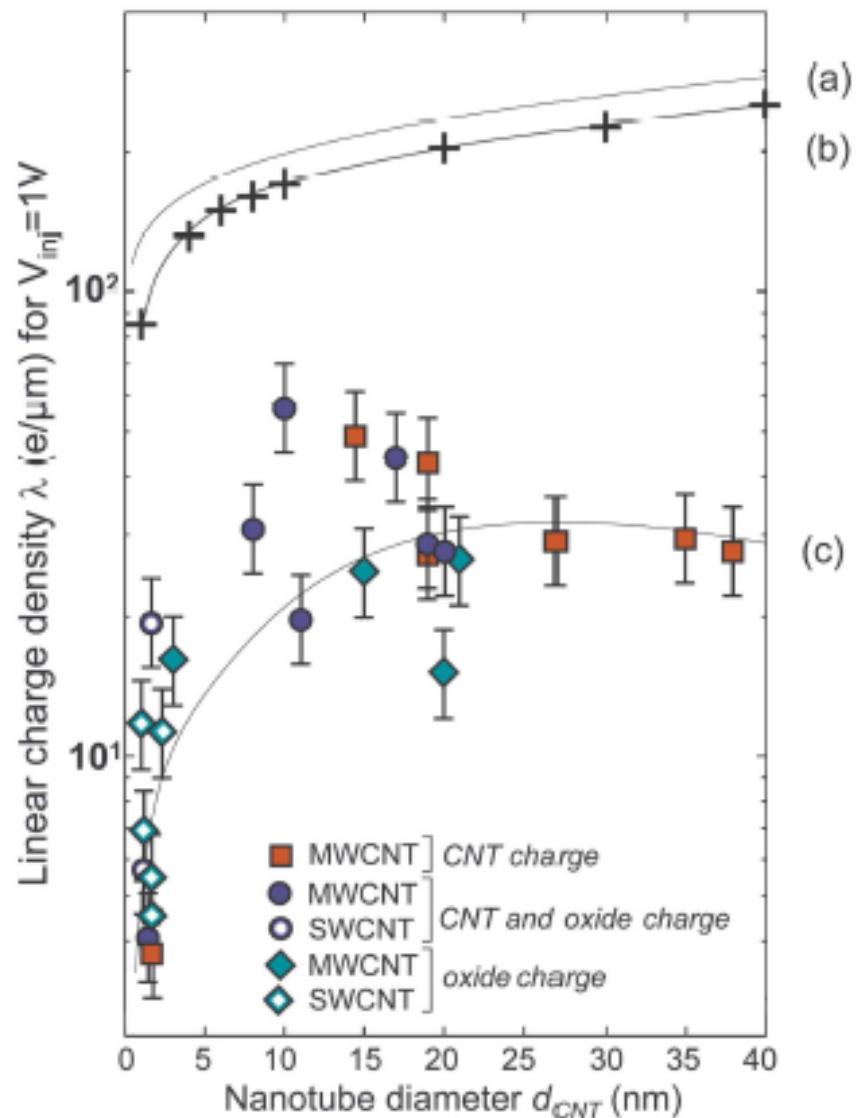


Transverse dielectric properties of nanotubes
 ⇒ Response to the electric field
 generated by the EFM tip

Energy diagrams during charge injection



Response to the electric field at the EFM tip : $\lambda = 2 \pi \epsilon_0 \epsilon / \ln(4e/d_{\text{CNT}}) \cdot \Delta V$



→ Capacitive prediction

$$\lambda = 2\pi\varepsilon_0 \varepsilon / \ln(4e/d_{CNT})$$

(a) analytical $\varepsilon = (\varepsilon_{ox} + 1)/2$
(b) numerical calculations

→ Experimental data points

and (c) :

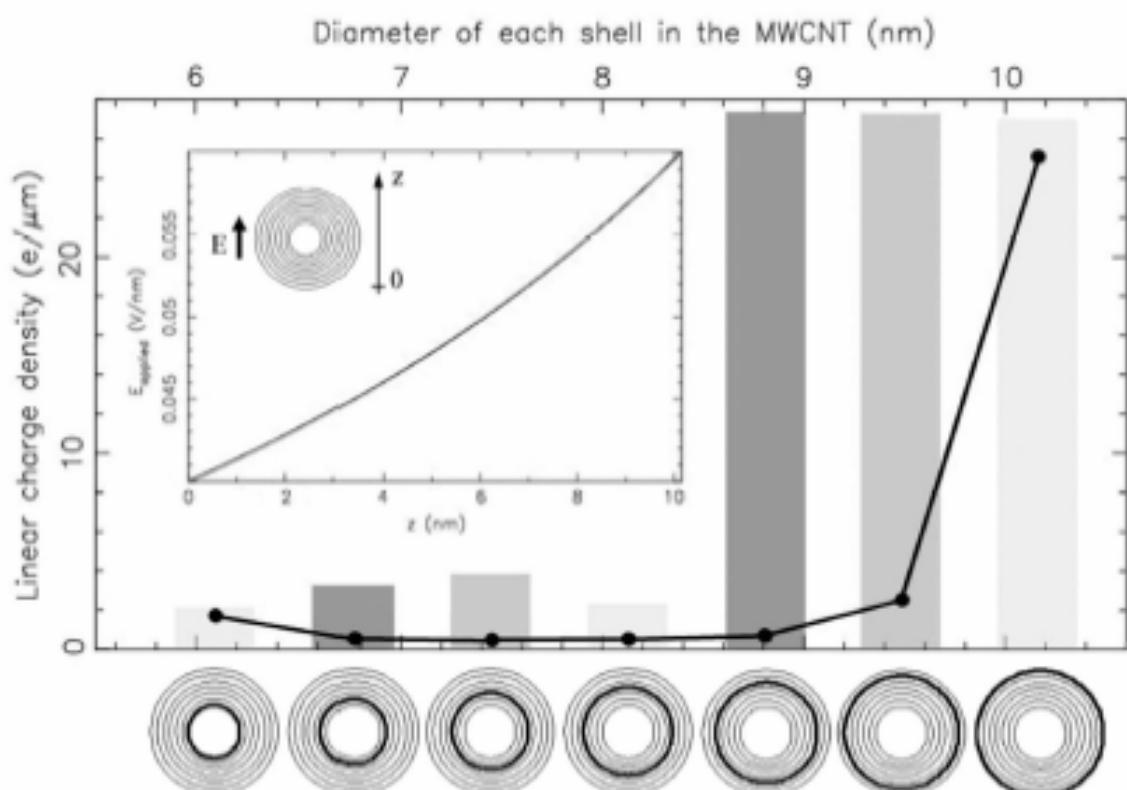
$$\lambda = \pi\varepsilon_0 \varepsilon / \ln(4e/d_{CNT}) \cdot E_{tip} \cdot d_{CNT}$$

M. Zdrojek et al., Phys. Rev. B 77 033404 (2008)



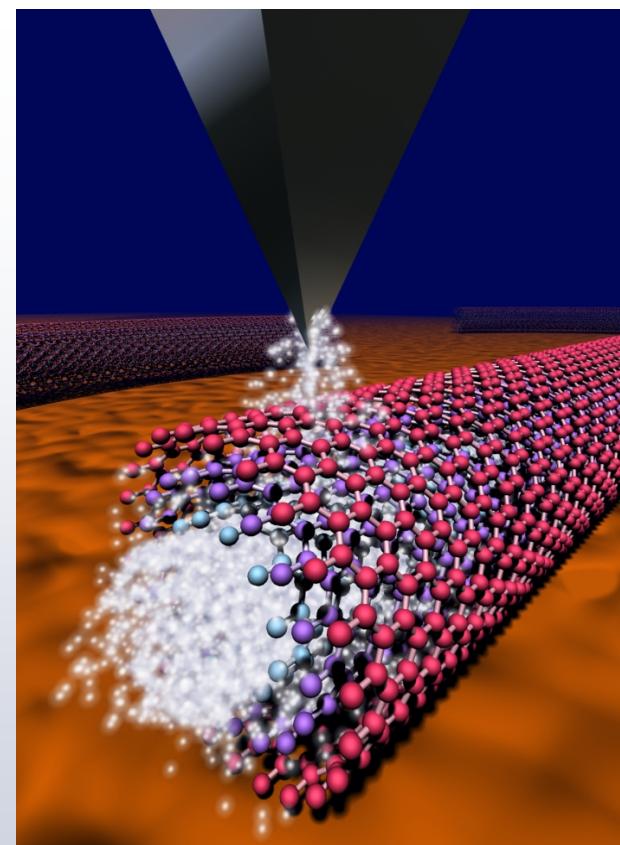
Inner-shell charging of MWCNTs

- Charge storage in the first inner metallic shells



(coll. A. Mayer, Univ Namur, Belgium)

M. Zdrojek et al., Phys. Rev. B 77 033404 (2008)



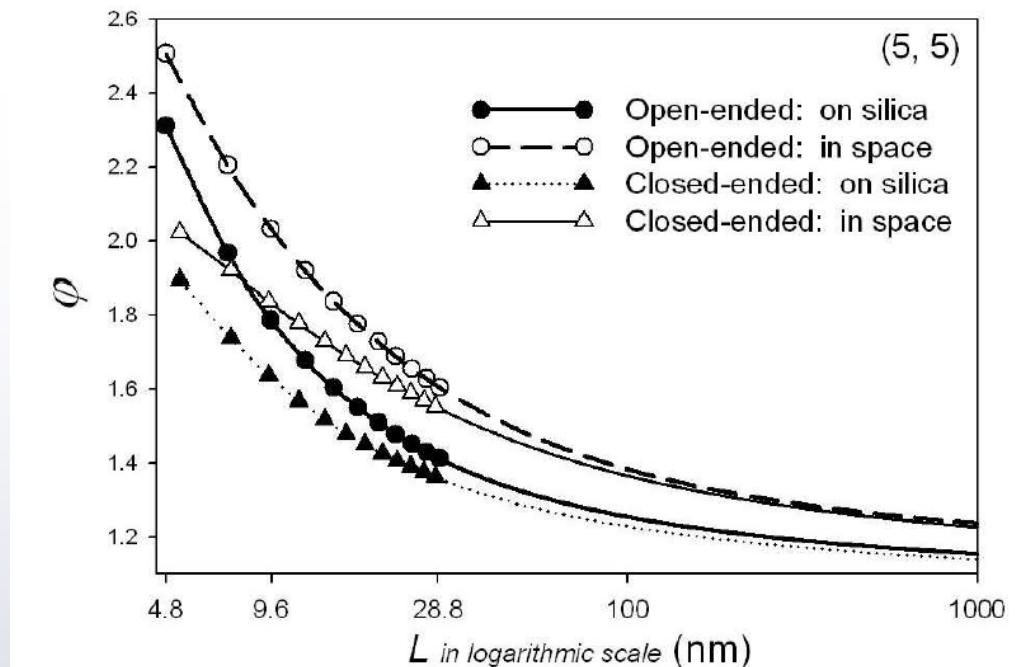


Electron interactions in SWCNTs



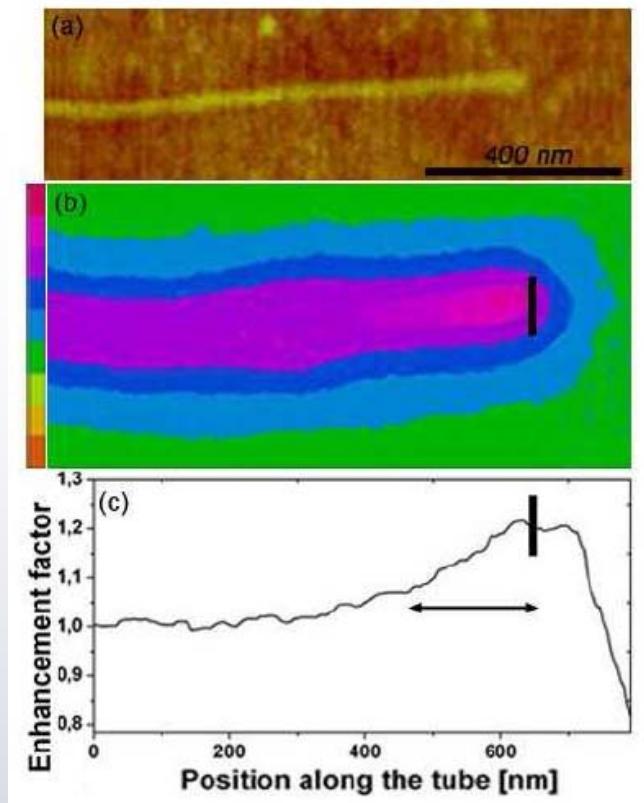
Charge accumulation
at the nanotube ends ?

[coll. Z. Wang, M. Devel,
Univ. Franche Comté France]



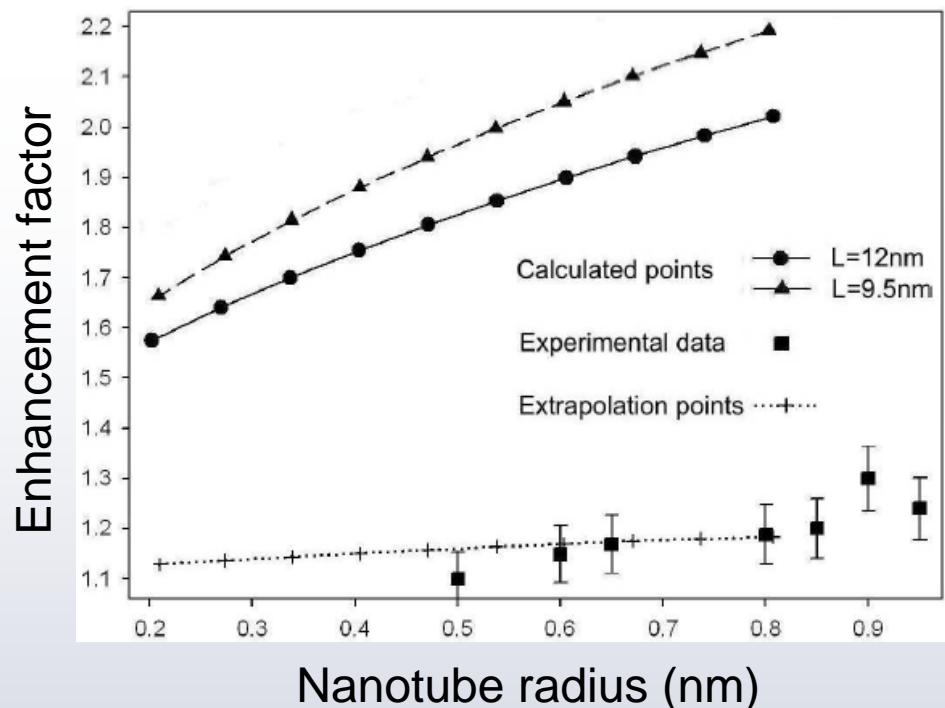
ϕ = charge enhancement factor

Ratio of the charge density
at the end of the CNT (10%L) with respect to its middle



*Experimental evidence
for charge enhancement at the CNT cap*

Z. Wang et al., Phys. Rev. B 78 085425 (2008)



Enhancement as a function of the CNT radius



I - Electrostatics of individual nanotubes (SWCNTs, MWCNTs)

II - Coupled transport and electrostatic measurements (SWCNTs)

- *description of experiments*
- *analysis of coupled transport and KFM measurements*
- *model*

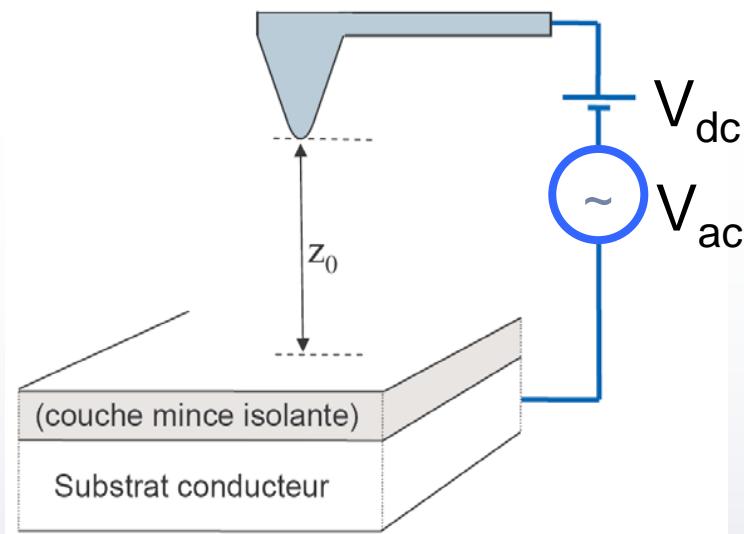


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Principle of surface potential measurements using Kelvin force microscopy



Electrostatic force

$$F = \frac{1}{2} \frac{\partial C}{\partial z} ((V_{DC} + V_{AC} \sin(\omega t)) - V_s)^2$$

1 ω force component

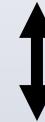
$$F_\omega = \frac{\partial C}{\partial z} (V_{DC} - V_s) V_{AC} \sin(\omega t)$$

Electrostatic excitation :
ac+dc voltage to the AFM tip

Nullification of the 1 ω force component



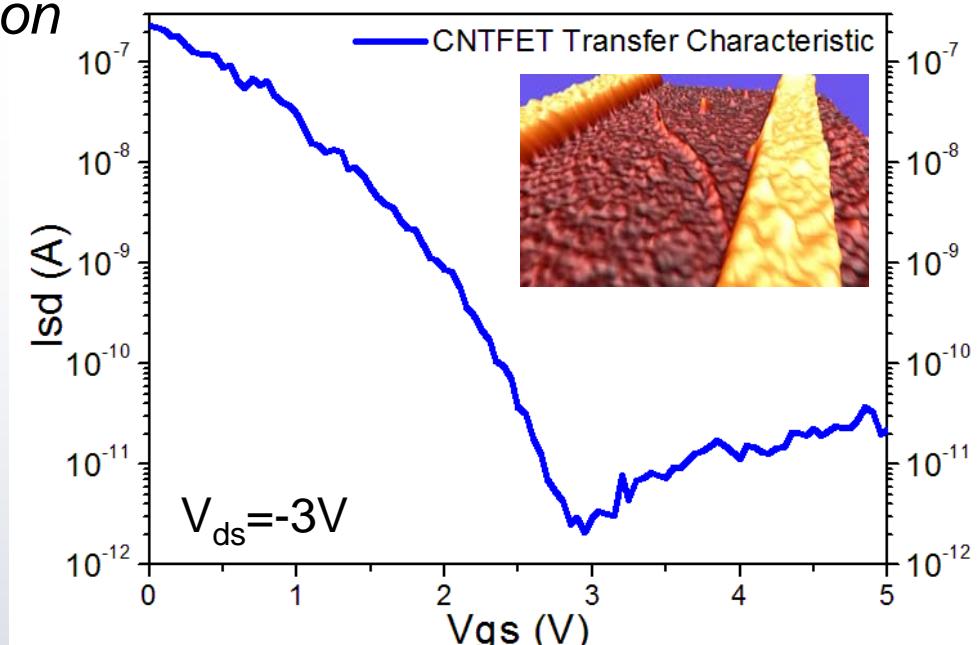
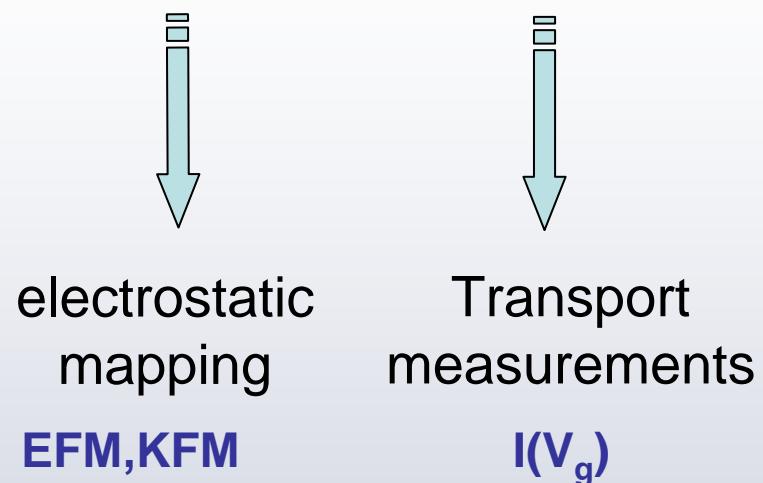
$$V_{dc} = V_s$$



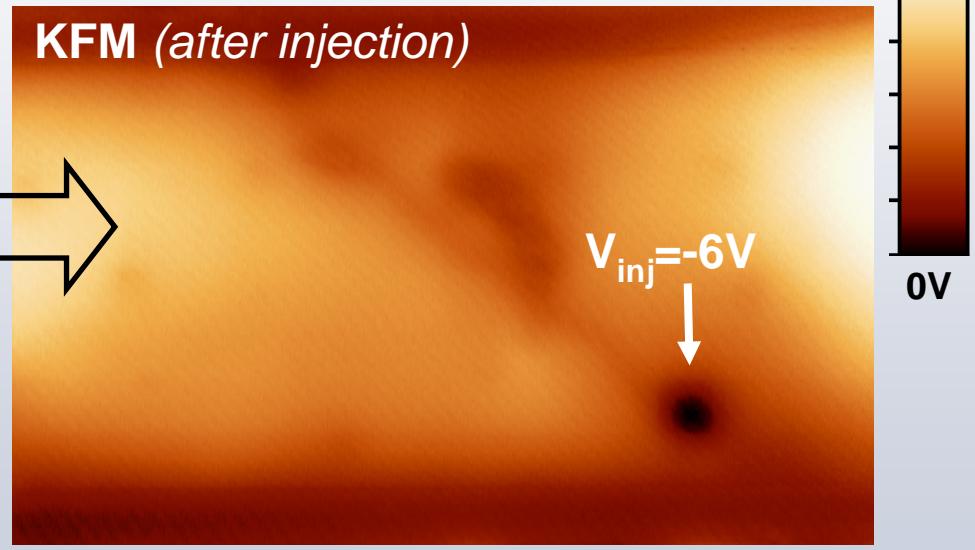
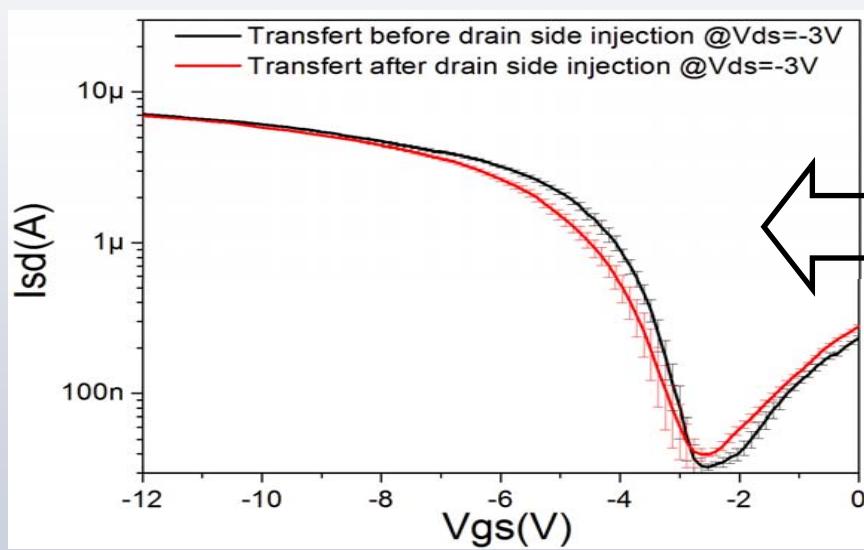
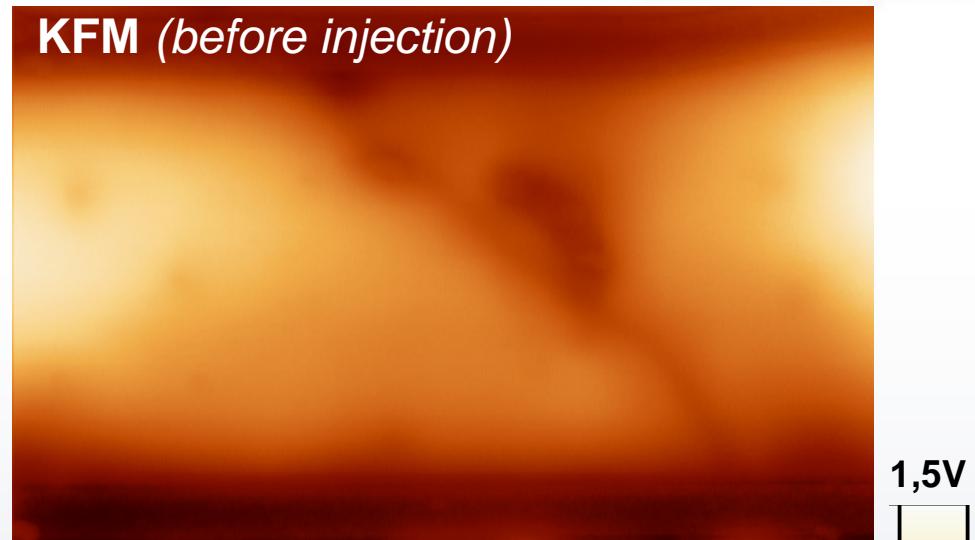
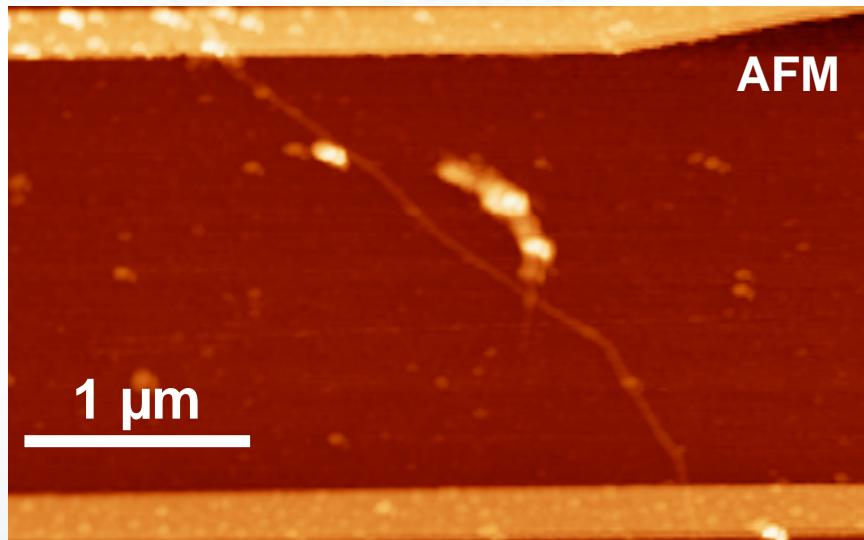
**Measurement
of the surface potential**

Coupled transport and KFM experiments

CNT-FET subjected to a local charge perturbation
charge injection in the SiO_2 layer



Experimental procedure



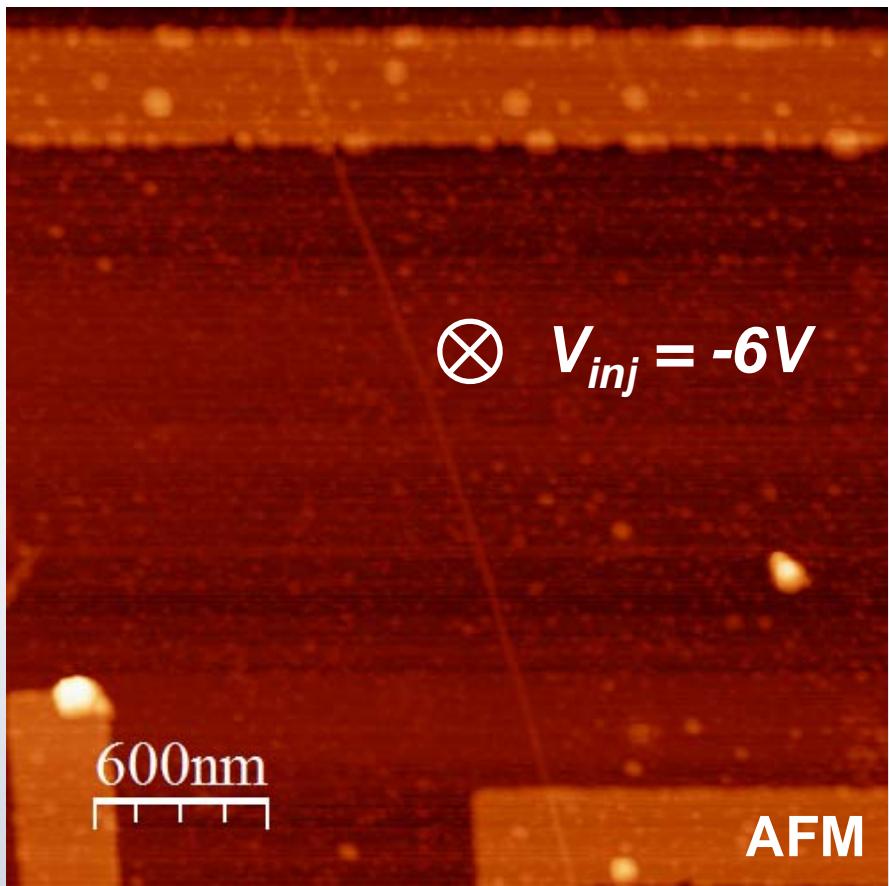


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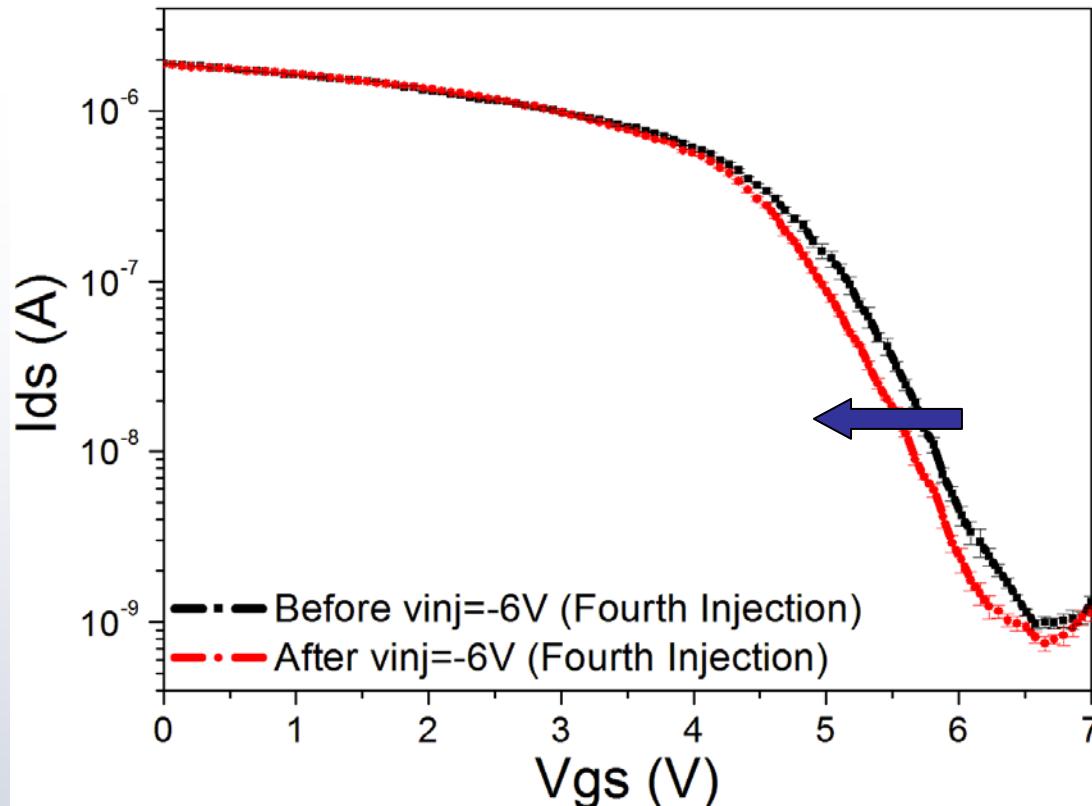
II - Coupled transport and electrostatic measurements (SWCNTs)

- *description of experiments*
- ***analysis of coupled transport and KFM measurements***
- *model*

Negative charge injection close to the CNT-FET

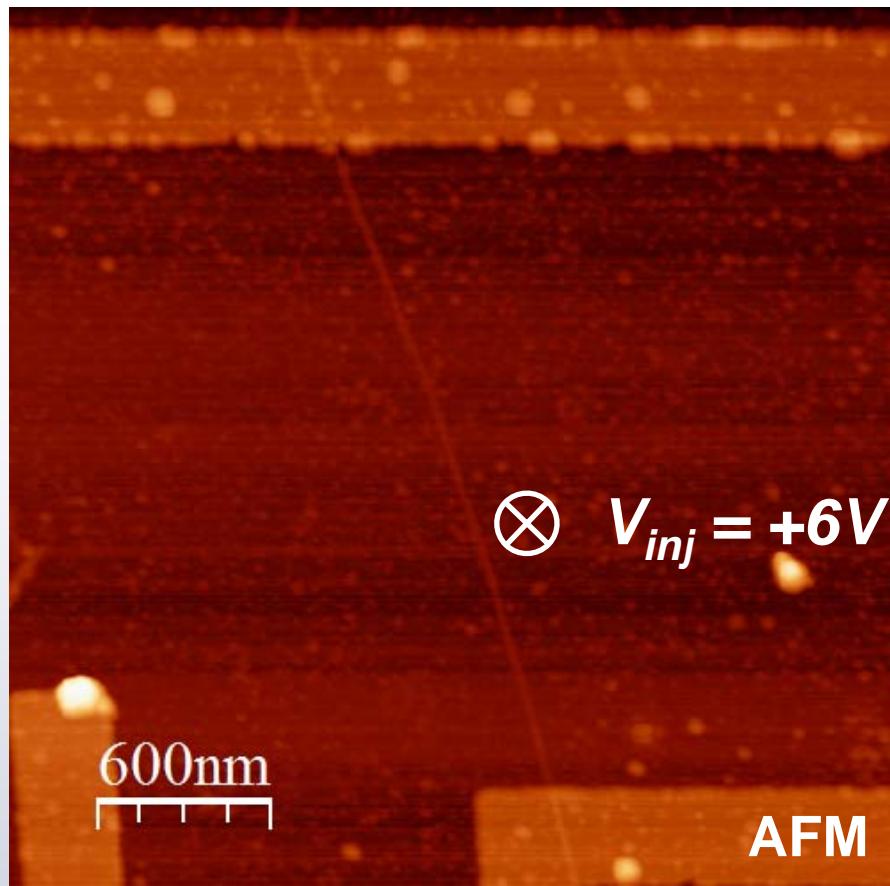


~200e at ~200nm from the CNT

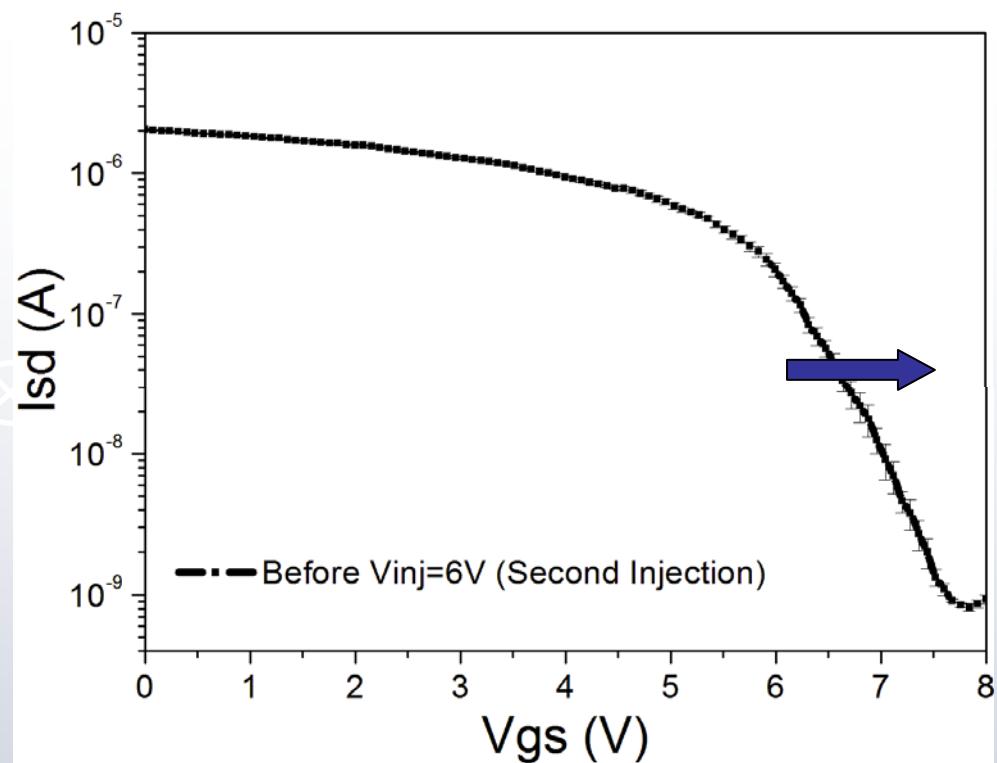


Positive effective gate voltage shift (!)

Positive charge injection close to the CNT-FET

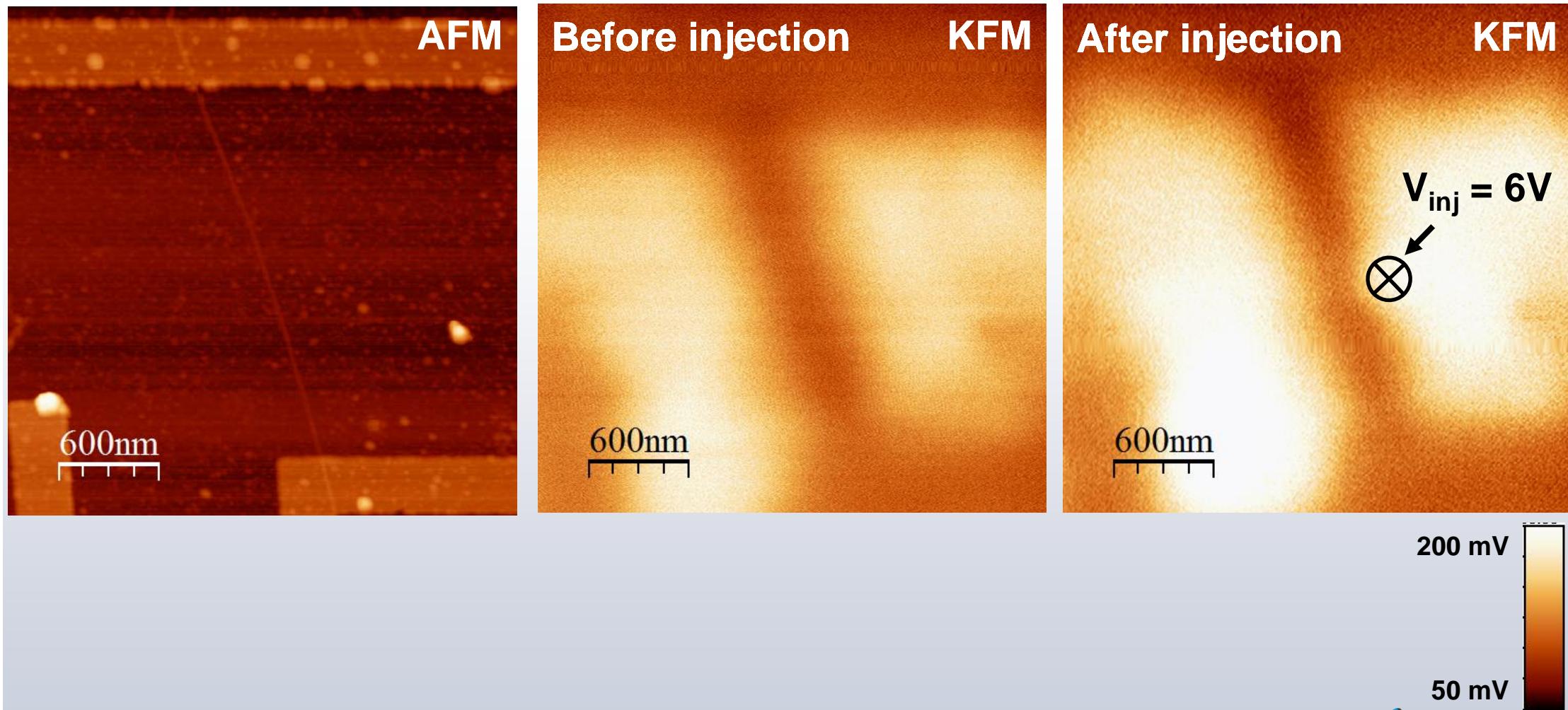


$\sim +200e$ at $\sim 200\text{nm}$ from the CNT

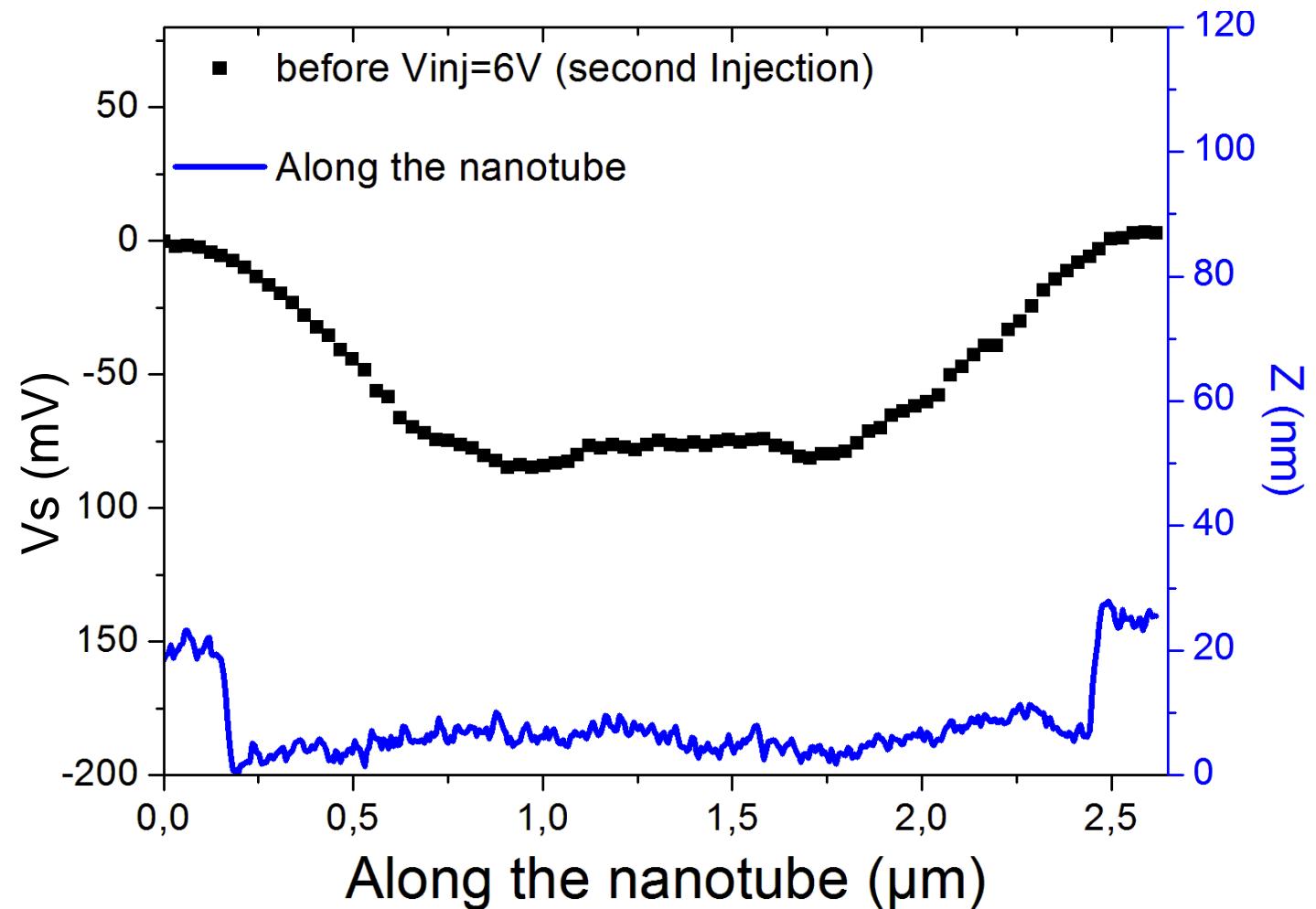


Negative effective gate voltage shift (!)

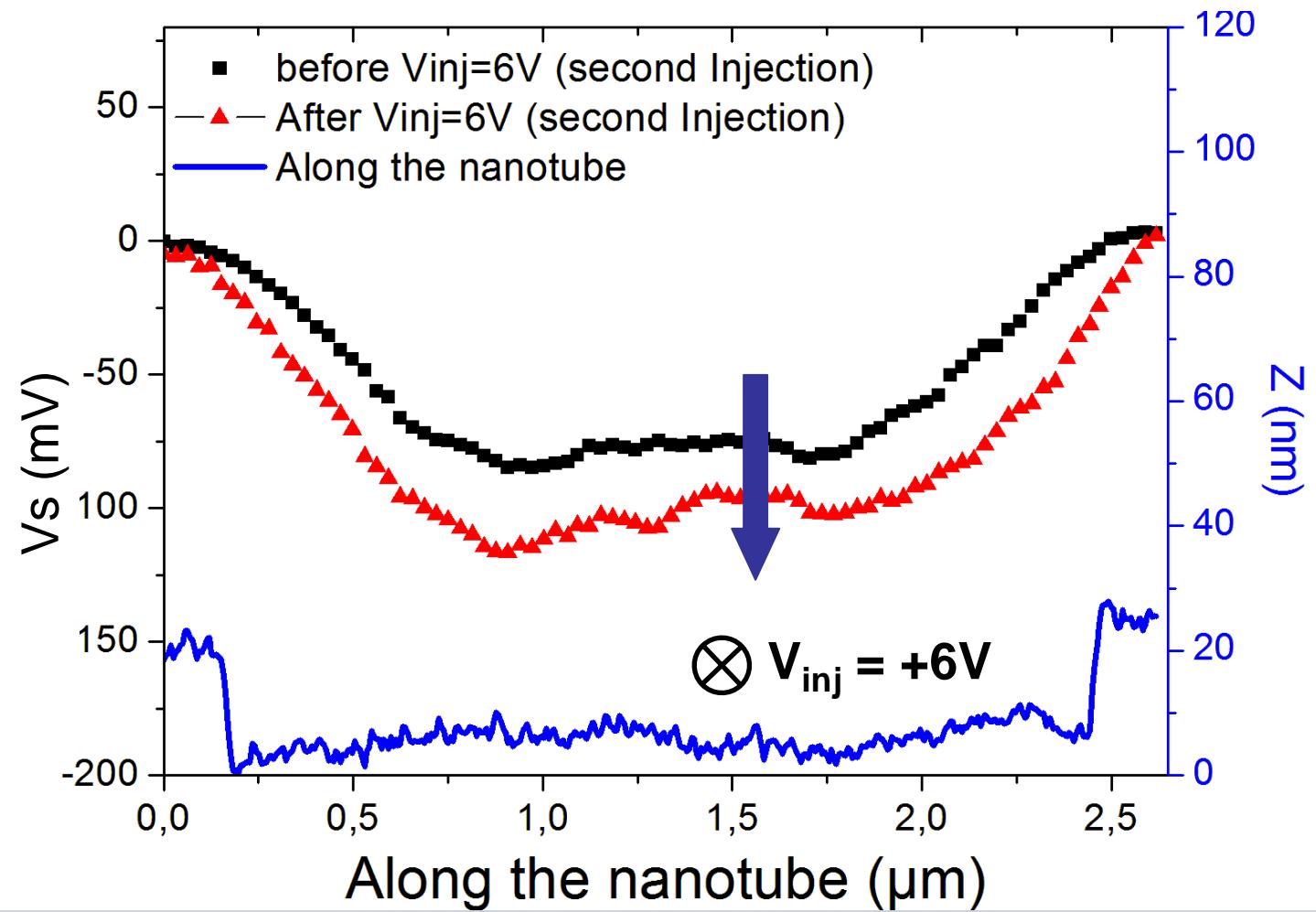
KFM images ($V_{inj} > 0$)



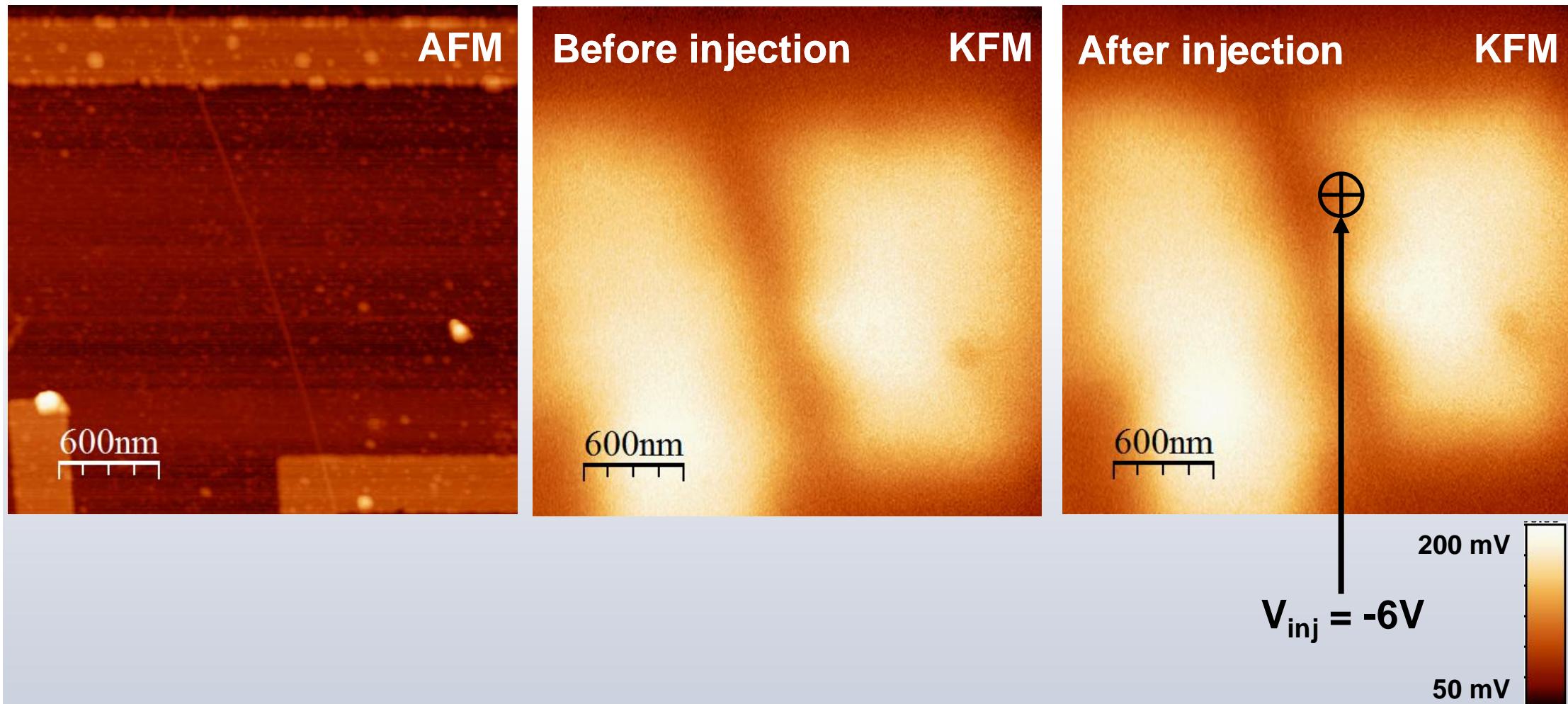
Nanotube response probed by KFM ($V_{inj}>0$)



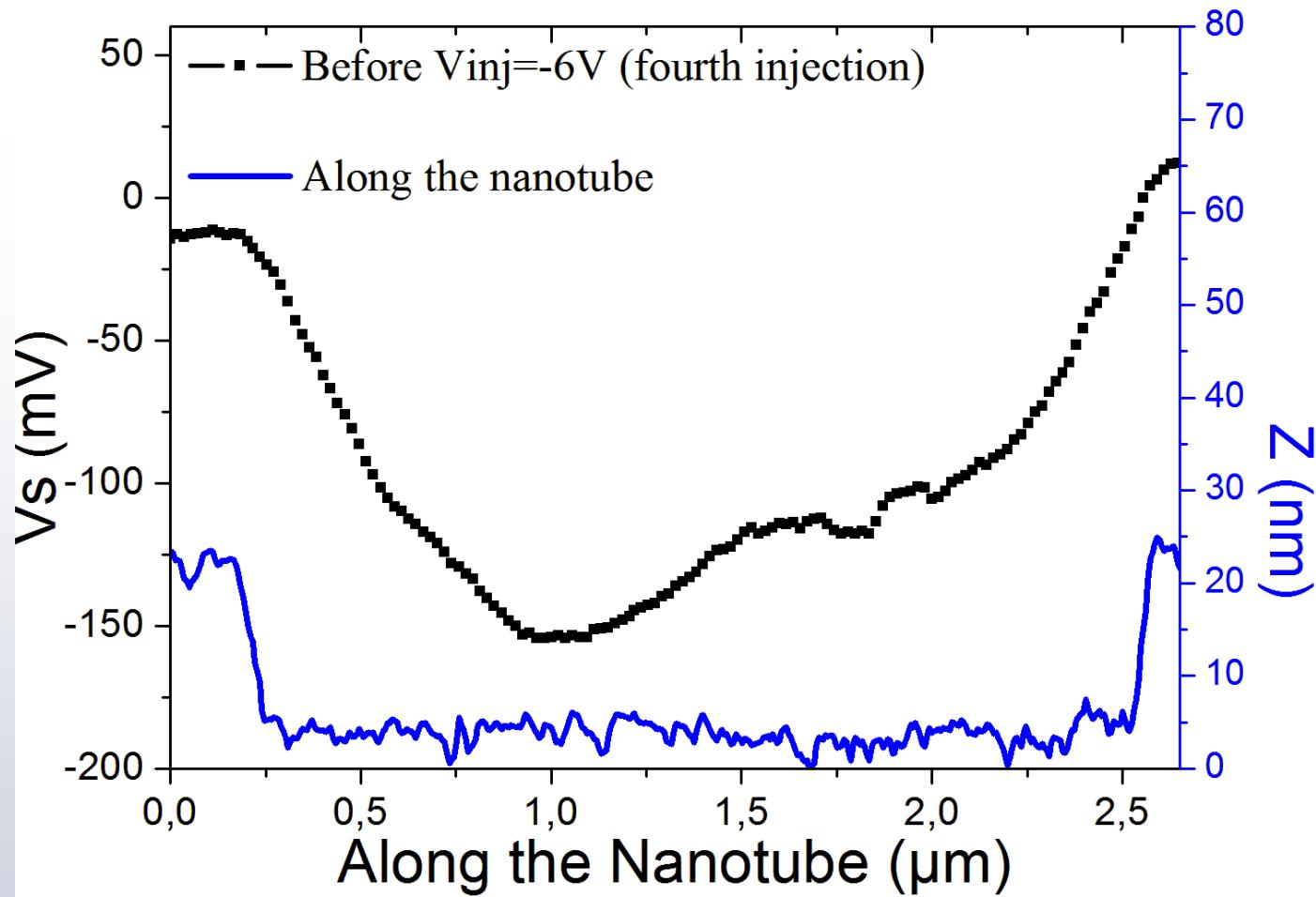
Nanotube response probed by KFM ($V_{inj}>0$)



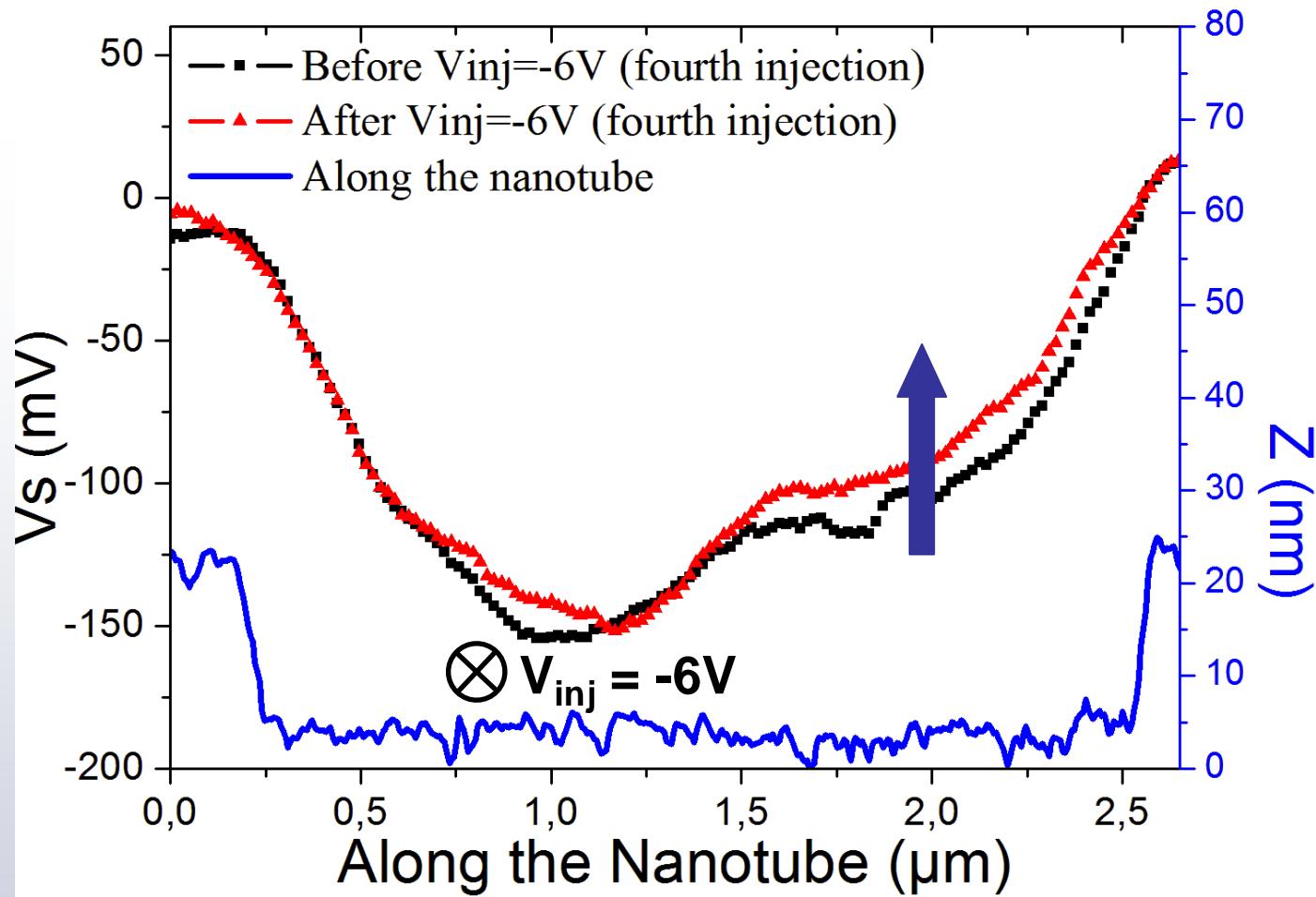
Injection at $V_{inj} = -6V$



Nanotube response probed by KFM ($V_{inj}<0$)



Nanotube response probed by KFM ($V_{inj}<0$)

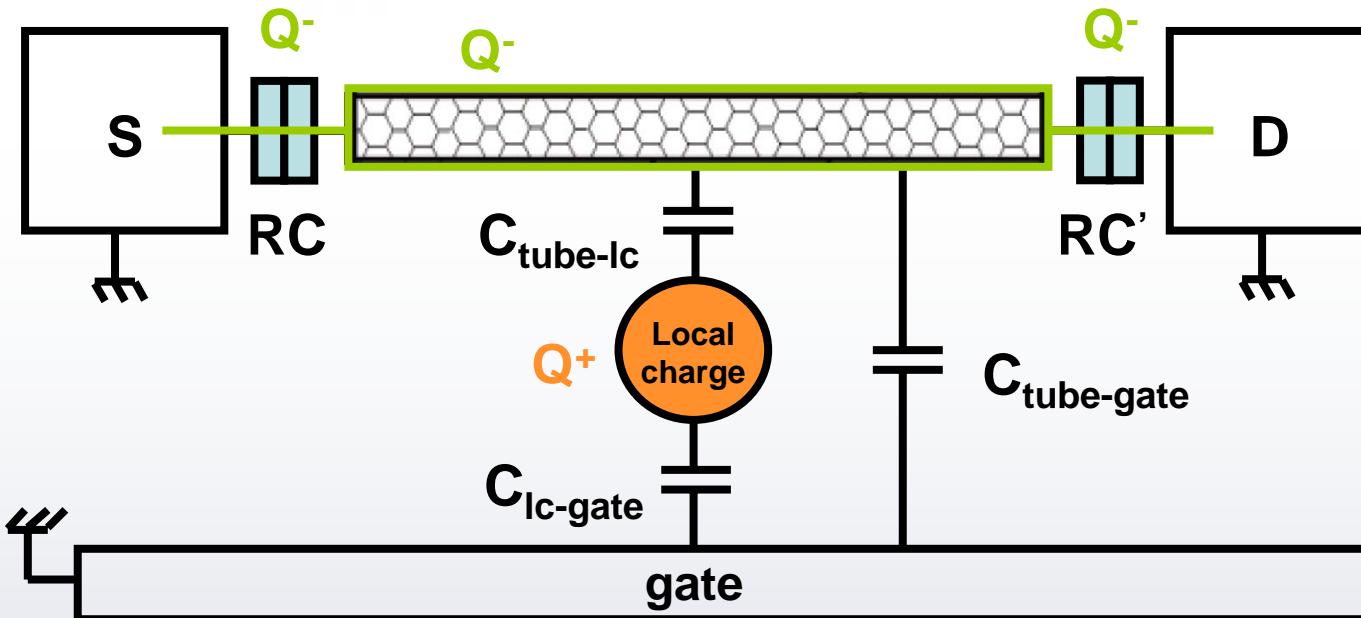




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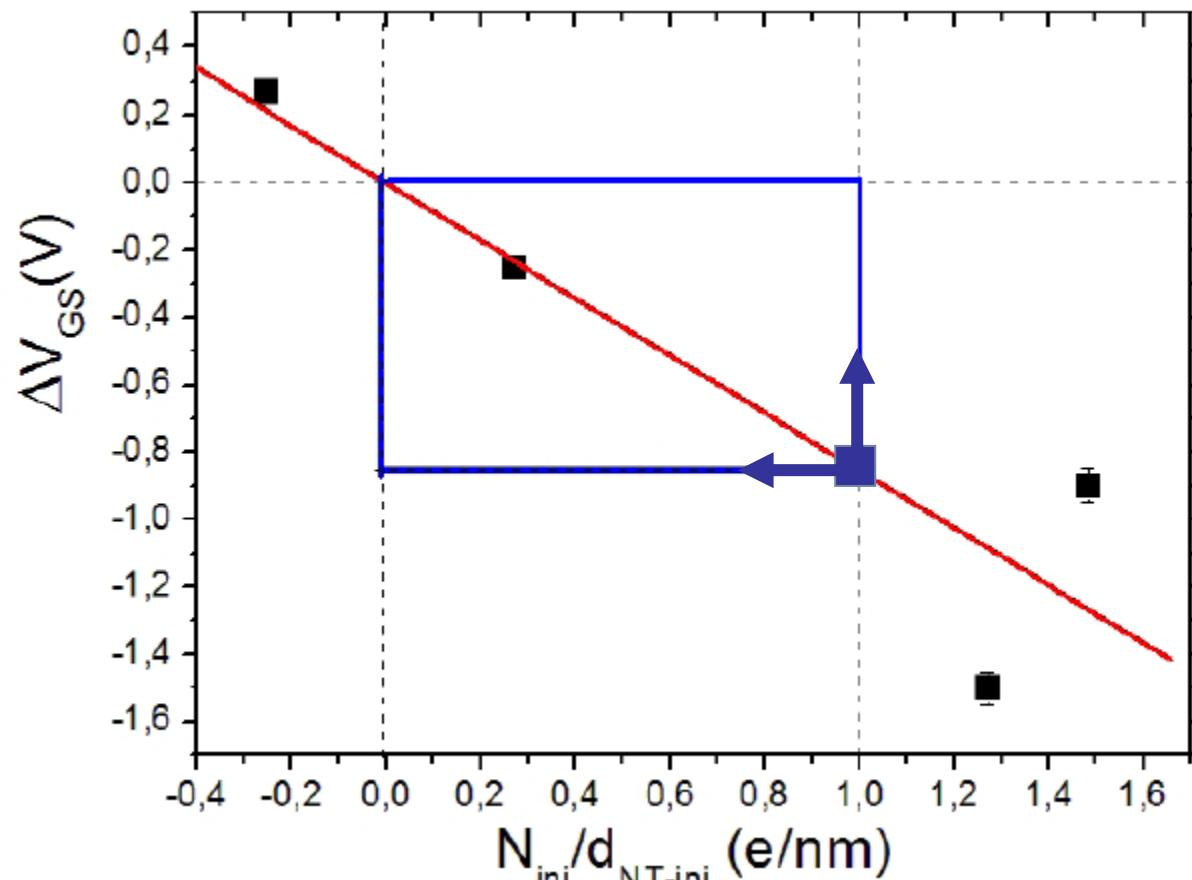
- *description of experiments*
- *analysis of coupled transport and KFM measurements*
- *model*



- Nanotube coupled to electrodes by tunnel contacts
- screening of the local (Q^+) charge by (Q^-) charges from the electrodes
- delocalized (Q^-) charge emission pattern along the nanotube

Sensitivity of CNTs as charge detectors

Gate voltage shift



Charge over distance

In our case :
 $100e@100nm$

Additional exp. point :
*Single charge
in a nanocrystal close
to the CNT channel
(1μm-thick oxide device)
[Gruneis et al. Nanolett. (2007)]*

Electrostatic properties of CNTs and CNT-devices using scanning force techniques

- Electrostatics of individual nanotubes (SWCNTs, MWCNTs)
- Coupled transport and electrostatic measurements
[carbon nanotubes as memory devices]

Prospects

UHV – AFM (EFM, KFM etc ...)
low-temperature measurements

