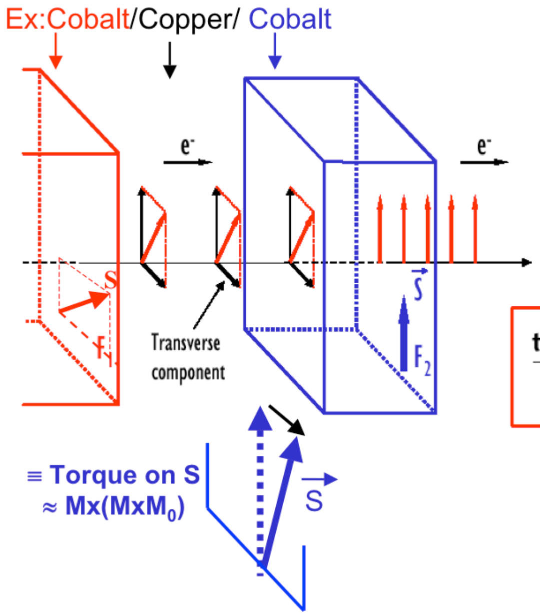
Spin transfer

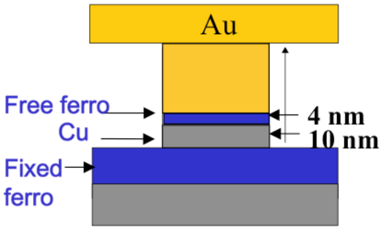
(J. Slonczewski, JMMM 1996, L. Berger, PR B 1996)



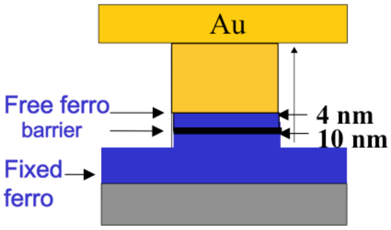
The transverse component of the spin current is absorbed and transferred to the total spin of the layer

$$\frac{\text{torque}}{\hbar} = \left(\frac{d\vec{S}}{dt}\right)_i = \text{absorbed transverse spin current} \propto j\, M \times (M \times M_0)$$

Experiments on pillars



Metallic pillar ≈ 50x150 nm²



Tunnel junction

E-beam lithography + etching

a) First regime (low H):
irreversible switching
(CIMS)

b) Second regime (high H):
steady precession
(microwave generation)

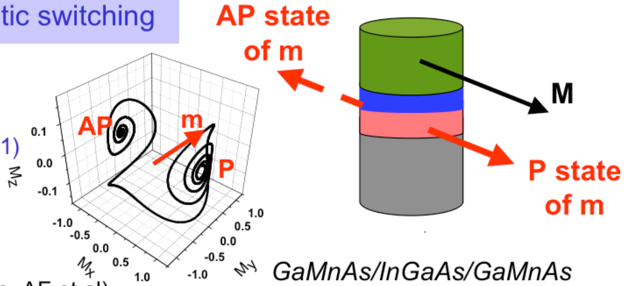
Regime of irreversible magnetic switching

First experiments on pillars:

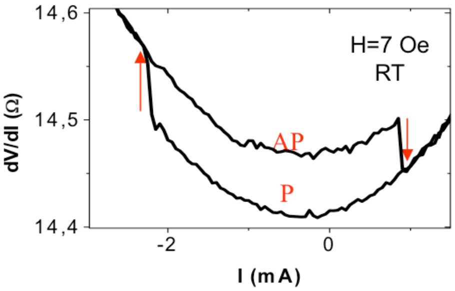
Cornell (Katine et al, PRL 2000)

CNRS/Thales (Grollier et al, APL 2001)

IBM (Sun et al, APL 2002)

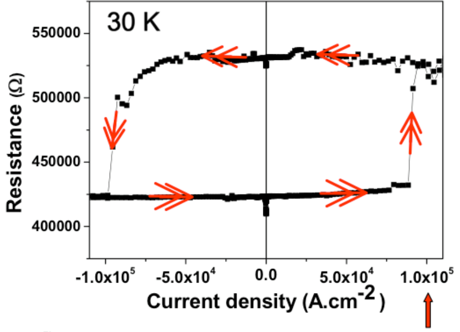


Py/Cu/Py 50nmX150nm (Boulle, AF et al)



GaMnAs/InGaAs/GaMnAs tunnel junction ***(MR=150%)***

(Elsen, AF et al, PR B 2006)



1 x 10^5 A/cm^2

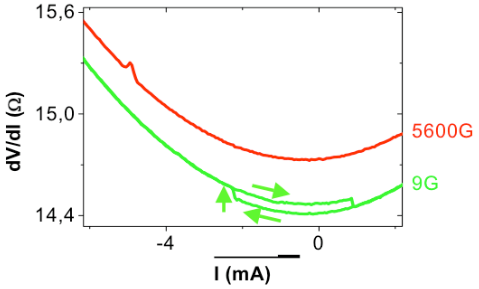
typical switching current ≈ 10^7A/cm^2

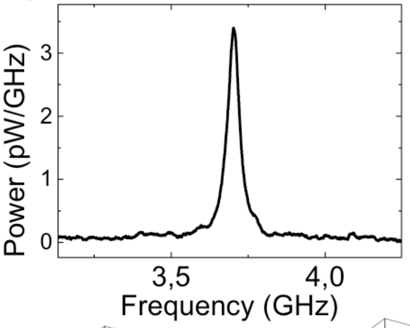
switching time can be as short as 0.1 ns (Chappert et al)

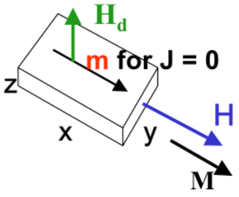
Regime of steady precession (microwave frequency range)

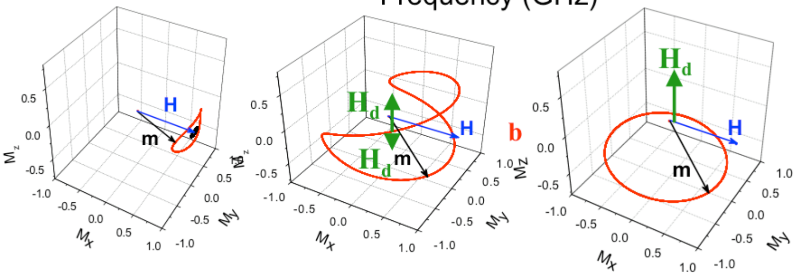
CNRS/Thales, Py/Cu/PY (Grollier et al)

(Py = permalloy)

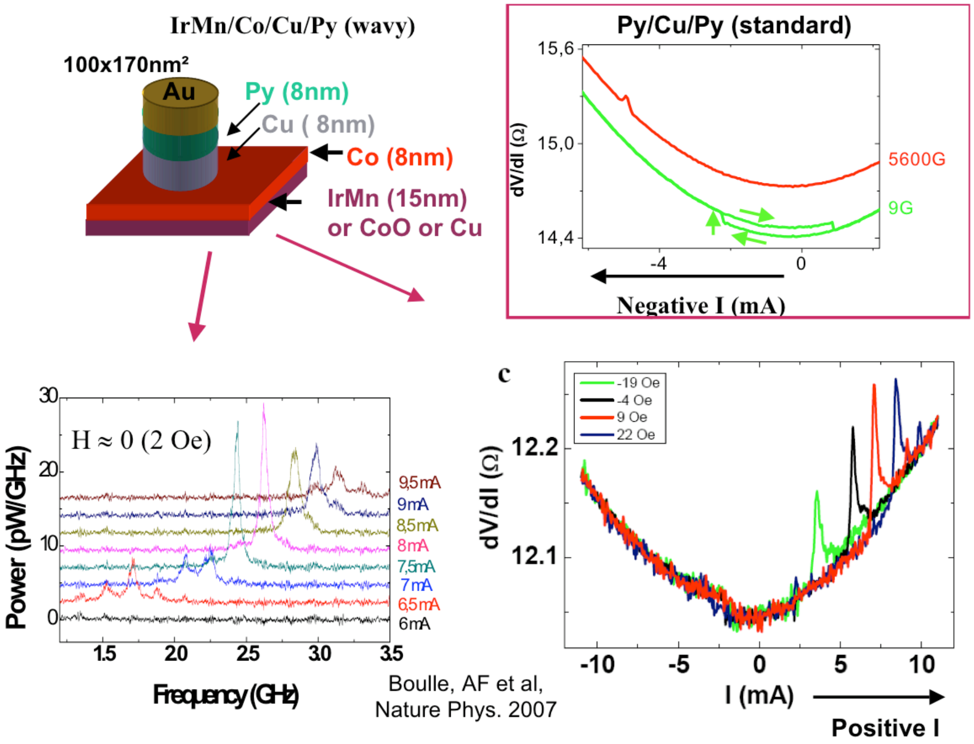








Increasing current

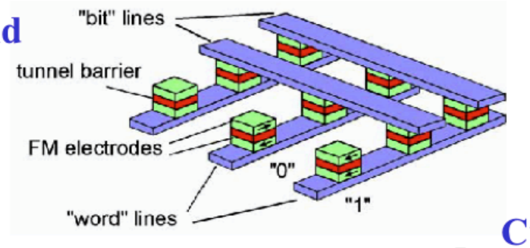


Boulle, AF et al,
Nature Phys. 2007

Switching of reprogrammable devices (example: MRAM)

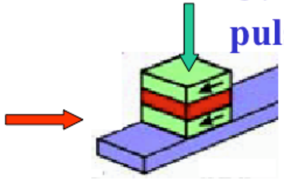
1) By external magnetic field

(present generation of MRAM, nonlocal, risk of « cross-talk » limits integration)



2) «Electronic» reversal by spin transfer from current

(for the next generation of MRAM, with already promising demonstrations by several companies)



Current pulse

Spin Transfer Oscillators (STO)
(communications, microwave pilot)

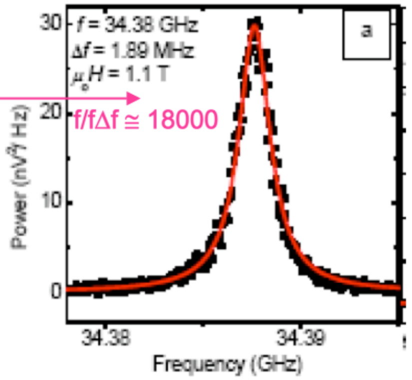
Advantages:

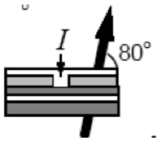
- direct oscillation in the microwave range
- agility: control of frequency by only dc current, frequency modulation , fast switching (5-40 GHz)
- high quality factor
- small size (≈ 0.1μm) and integration on chip (chip to chip communication)

-oscillations without applied field

-Needed improvements

- - increase of power by synchronization of a large of number of STO



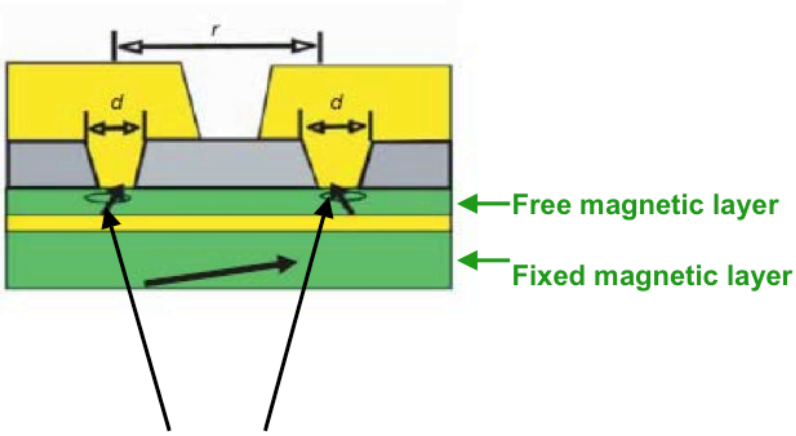


Rippart et al,
PR B70, 100406,
2004

Synchronization of STOs

Synchronization **by exchange coupling (**magnetic elasticity)

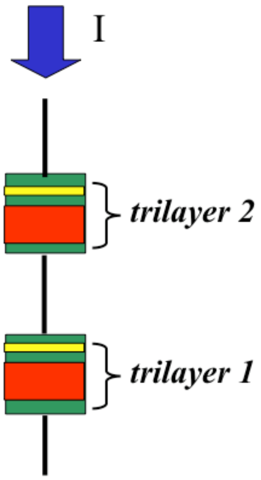
- **Kaka et al (NIST Boulder) Nature 2005**
  (similar results by Freescale)

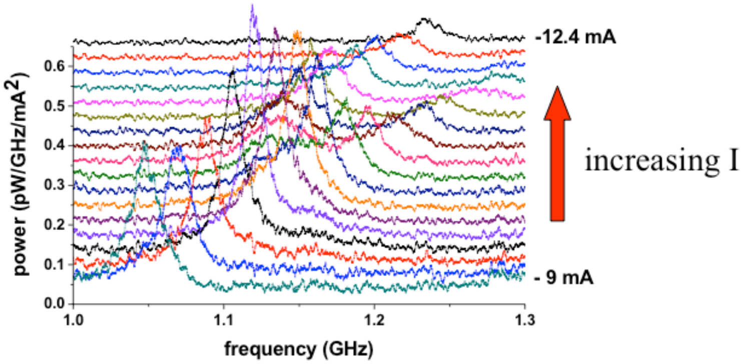


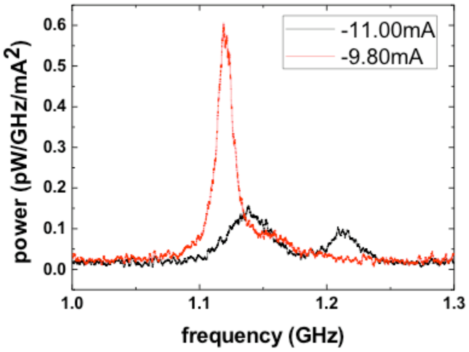
Phase locking of oscillations for r ≈ 500 nm

Self-synchronization experiments (preliminary results)

(B.Georges, AF et al, **CNRS/Thales and LPN-CNRS**)



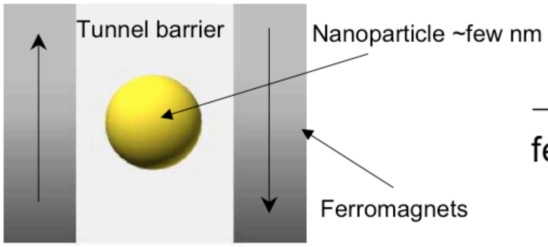




Spintronics with single electron devices

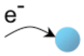
Nanospintronics

→ Connecting isolated nano-objects to ferromagnetic electrodes

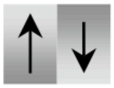


→ A lot of theoretical works but very few experimental realizations…

Single Electron transport + Ferromagnetism



Nanoparticle 2-3 nm in diameter



Cobalt Electrodes

→ Measure of Magnéto-Coulomb effects through a single nanoparticle

Introduction to **Coulomb blockade**

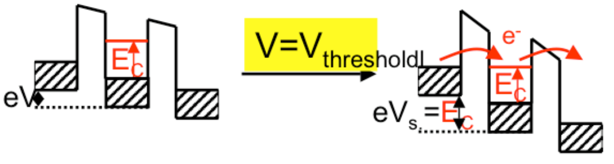
❶ It is not a quantum mechanics effects, just electrostatics!

❷ Translates the energy required to overcome the Coulomb repulsion in a reduced dimension system

→ $E_C = \frac{e^2}{2C}$ *Isolated sphere* : $C \propto d_{sphere}$

❸ if d small enough then $E_c >> kT$

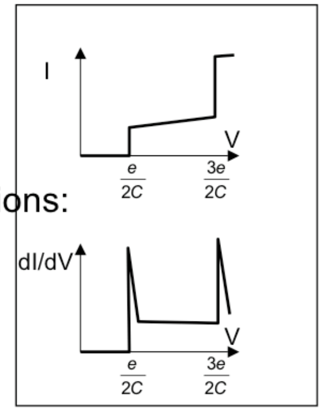
❹ No current if $V < V_T = \frac{e}{2C}$



V=V

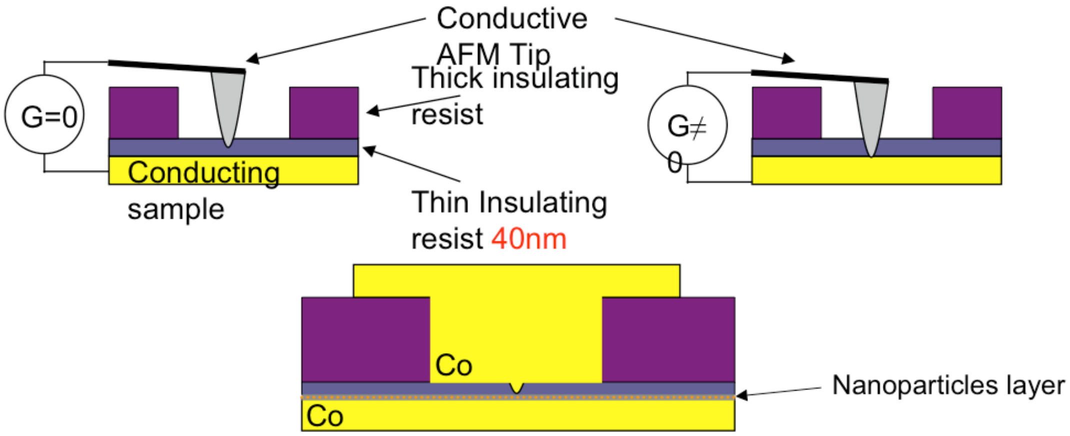
J. B. Barner et S. Ruggiero, PRL 59 (1987), p.109

Observations:



Our solution to obtain a contact on a single nanoparticle

Conductive tip AFM (CT-AFM) Nanoindentation: real time resistance monitoring



K. Bouzehouane et al., Nano Lett. **3**, 1599 (2003)

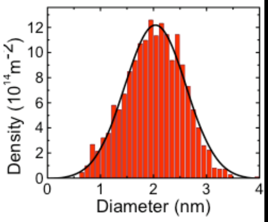
« AFM indenter makes holes for nanocontacts » http://nanotechweb.org/articles/news/2/10/14/1

Nanostructure elaboration

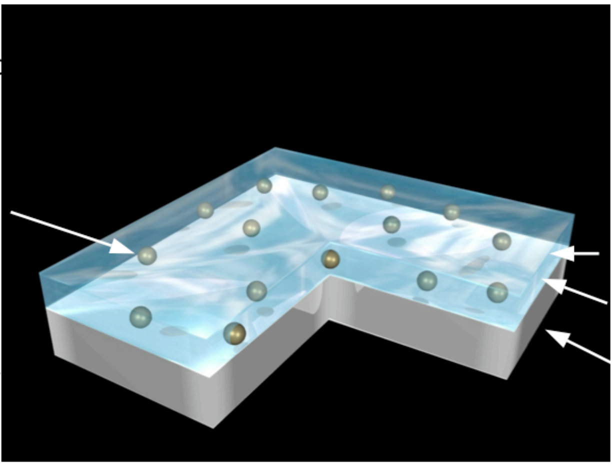
❶ Sputtering elaboration without top electrode

« Au self-assembled nanoparticles »

Au nominal~0.2nm



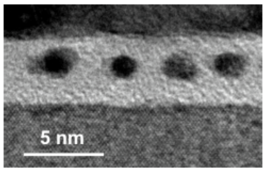
Cluster diam.~2nm



Al_20_3~1nm

Al_20_3~1nm

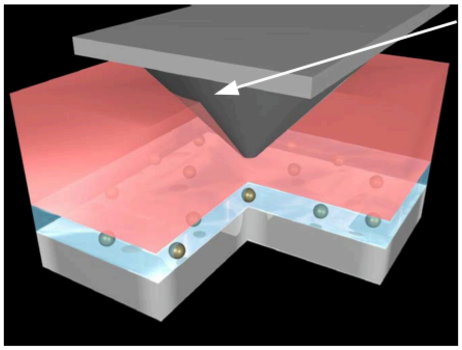
Cobalt

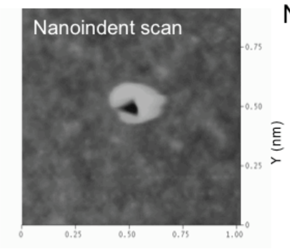


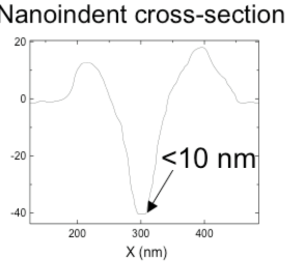
TEM cross section

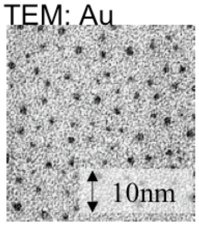
Nanostructure elaboration

❷ Nanoindentation: ConductiveTip-AFM indentation





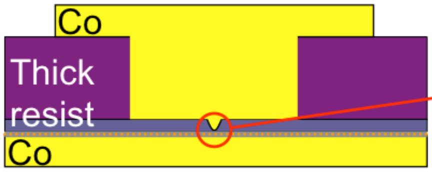


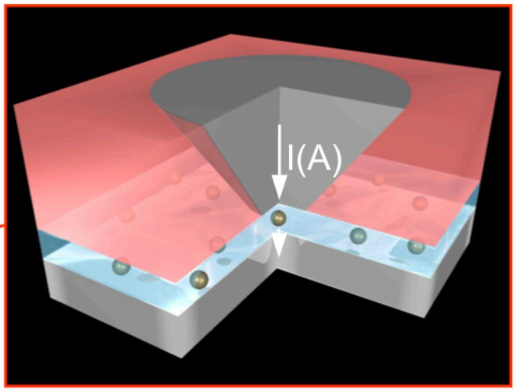


Contact surface smaller than
10nm x 10nm
=
Ability to connect a single cluster

MEASUREMENTS!

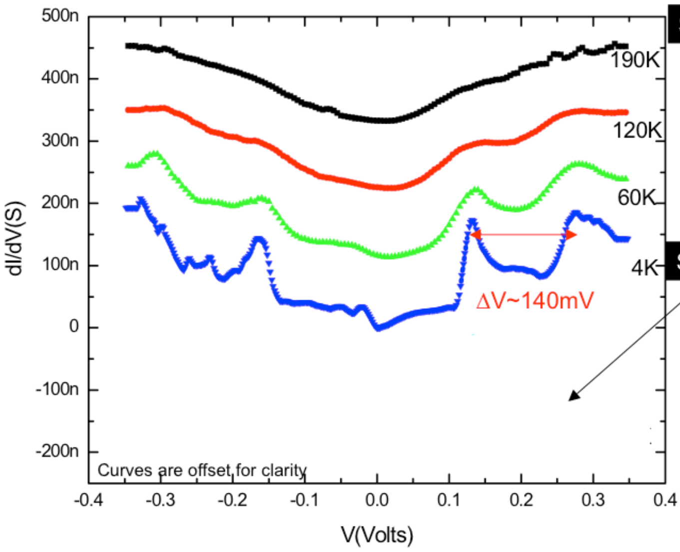
Co 15nm/Al_2O_3 ~1nm/Au cluster Φ_{mean}2~3nm/Al_2O_3 ~1nm/Co 50nm





Coulomb steps: decreasing temperature

$Co/Al_2O_3/Au$ cluster 2~3nm/Al_2O_3/Co



Simple parameter extraction

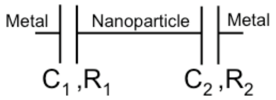
❶ $\Delta V \approx 140mV = \dfrac{e}{C_{max}}$

$\Rightarrow C_{max} \approx 1.15aF$

❷ $E_C = \dfrac{e^2}{2C_{Tot}} \geq 4kT_{120K} \approx 40meV$

Single nanoparticle monte-Carlo simulation

MOSES (Stony Brook, SUNY)



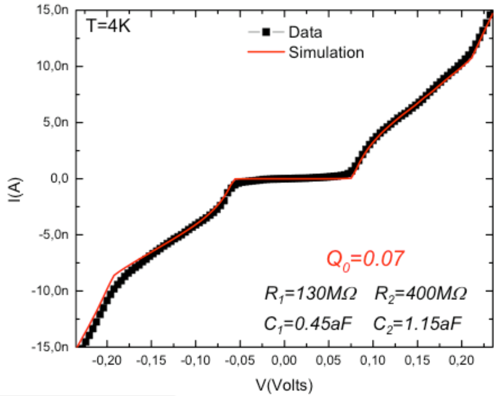
$R_1=130M\Omega$ $R_2=400M\Omega$

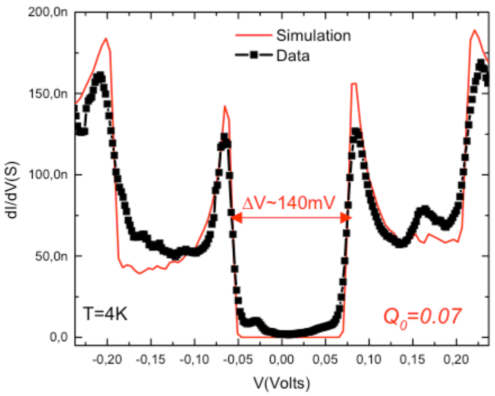
$C_1=0.45aF$ $C_2=C_{max}=1.15aF$

→ $Q_0=0.4$

Coulomb steps at 4K after high voltage cycling (change in Q0)

$Co/Al_2O_3/Au$ cluster 2~3nm/Al_2O_3/Co: same sample





Charging energy:

$$E_C = \frac{e^2}{2(C_1+C_2)} \approx 50meV$$

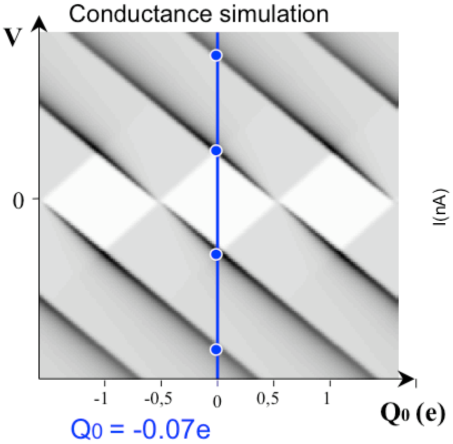
Cluster size?

Isolated sphere: $d \approx \dfrac{C_{Tot}}{2\pi\varepsilon} \approx 3.3nm$ More realistic (sphere+environment): $d \approx 2.5nm$

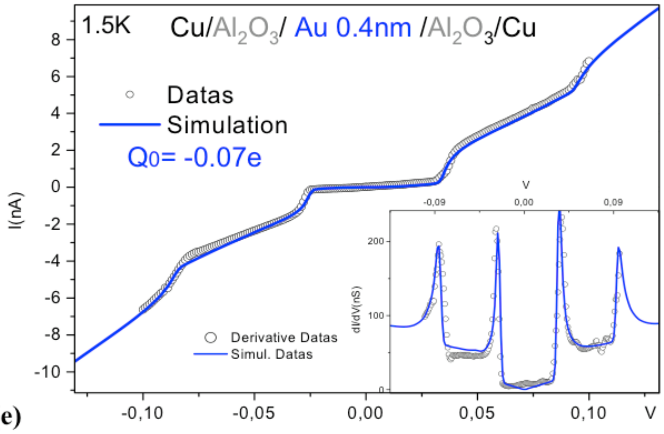
The same parameters fits the two sets of curves → we connect a single cluster

Background charge effect

Conductance simulation



Q_0 = -0.07e



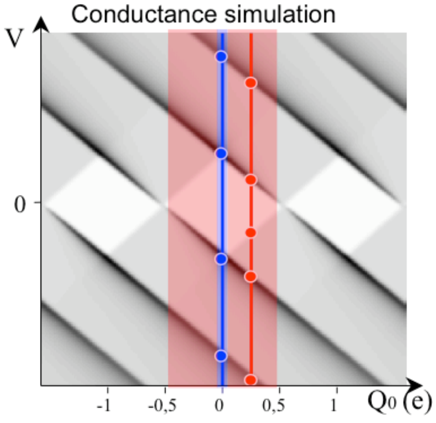
Tunnel junction parameters :

C_1= 2.5aF C_2= 2.7aF
R_1= 1MΩ R_2= 16MΩ

But this is not the most common situation !

Background charge effect

Conductance simulation



Q_0 = -0.07e Q_0 = 0.32e