Charging and discharging of Co/SiO_2 multilayer structures investigated by scanning force microscopy

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Outline

1. Motivation
2. Sample Structure and Experimental Procedure
3. Results and Discussion
4. Conclusion

1. Motivation

- Discontinuous ferromagnetic metal/insulator multilayers exhibit a variety of properties important for magnetic recording and other memory applications:
  - formation of metal nanoclusters separated by insulator
  - negative magnetoresistance due to spin-dependent tunneling
  - saturation of magnetoresistance at low magnetic fields
- Detailed study of electrical transport properties necessary to improve devices
- Scanning probe techniques allow local study in contrast to usual large scale electrodes
- Study of local charging/discharging of metal particles $\rightarrow$ insights in electrical transport properties of discontinous metal/insulator multilayers

2. Sample Structure and Experimental Procedure

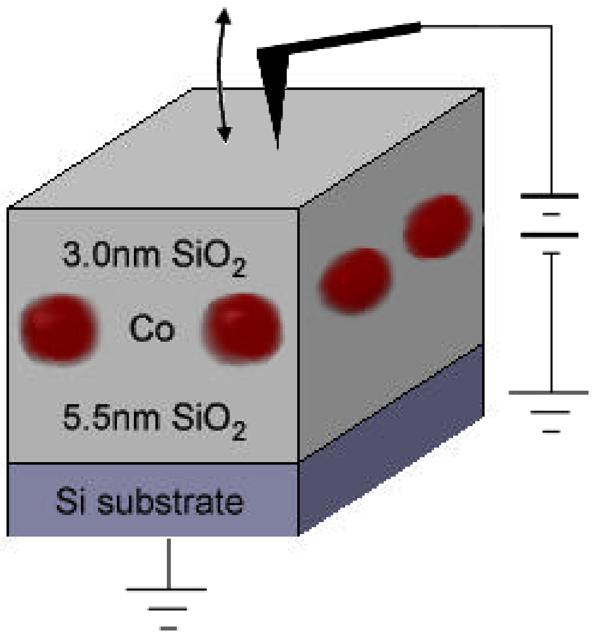
Sample Preparation and Structure

- Alternate sputtering from two separate targets on n-type Si substrate covered with ~2.5 nm native oxide
- Nominal deposited film structure: 3 nm SiO_2 / 1.4 nm Co / 3 nm SiO_2

Experimental Procedure

- Scanning Force Microscope
- Two pass method:
  1) Topography (via TappingMode™)
  2) Electrostatic Force Microscopy (EFM)

$$\Delta f = \frac{f_0}{2k}\frac{\partial F}{\partial z}$$



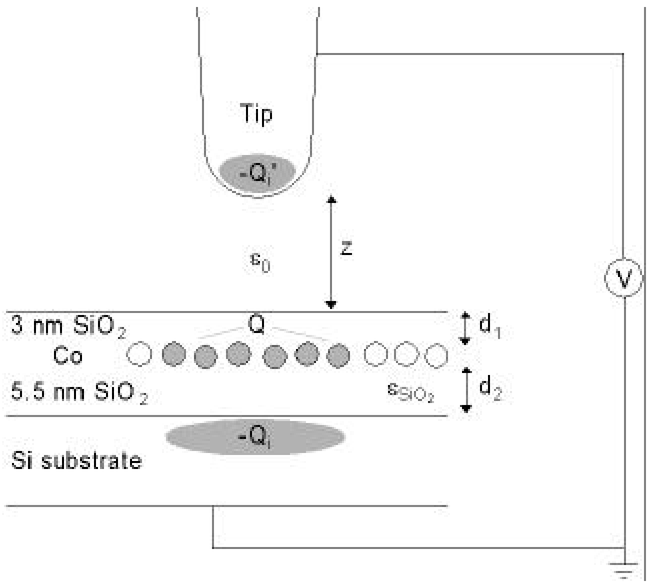
- Charging:
  Hold oscillating tip during first pass for 10 s in center of scan area and apply a voltage V_{ch} between tip and substrate

2. Sample Structure and Experimental Procedure

Measurement of stored charge via EFM:

Force on tip:

$$F(z) = \frac{1}{(z + (d_1 + d_2)/e_{SiO_2})^2} \times \left(-\frac{{d_2}^2 Q^2}{{e_{SiO_2}}^2 e_0 A} + \frac{2 d_2 Q V_{EFM}}{e_{SiO_2}} + \frac{e_0 A {V_{EFM}}^2}{2} \right)$$



- Model calculations + measurements show that first term in bracket is small and can be neglected
- last term constant for all points in scan area $\rightarrow$ does not contribute to contrast

Inserting parameters in *F*(*z*) and calculating Δf $\Rightarrow$ $Q \approx 18.4 \frac{e}{\mathrm{V\,Hz}} V_{EFM} \Delta f$

3. Results and Discussion

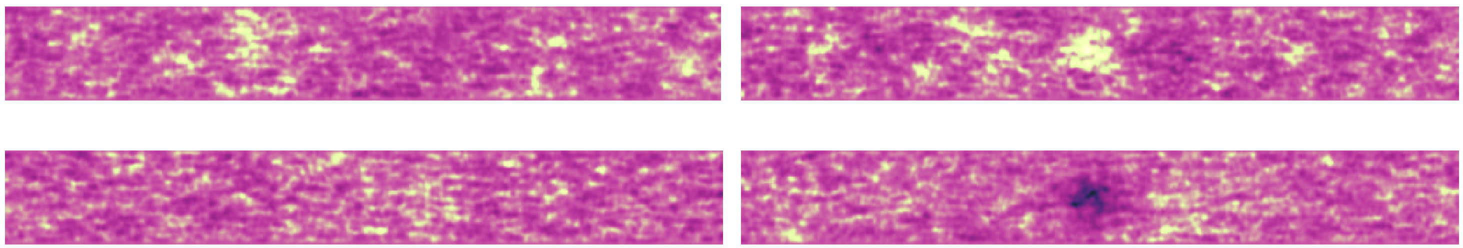
Charging

• Charging with +12 V for 10 s:

before after

V_{EFM} = 1 V

V_{EFM} = -1 V



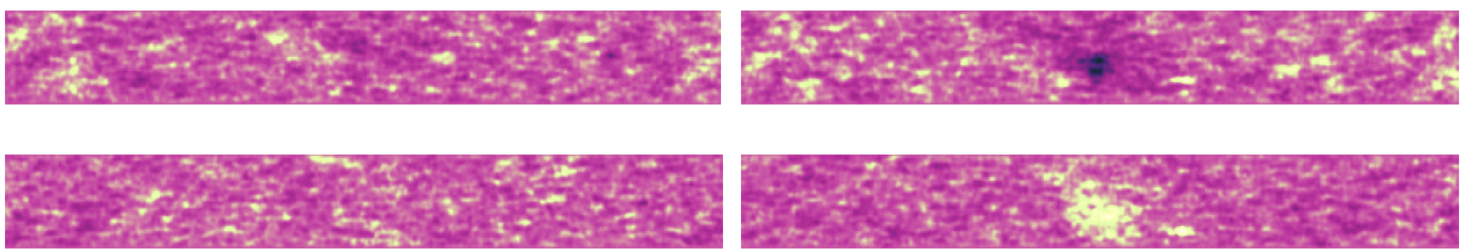
500 nm

• Charging with -12 V for 10 s:

before after

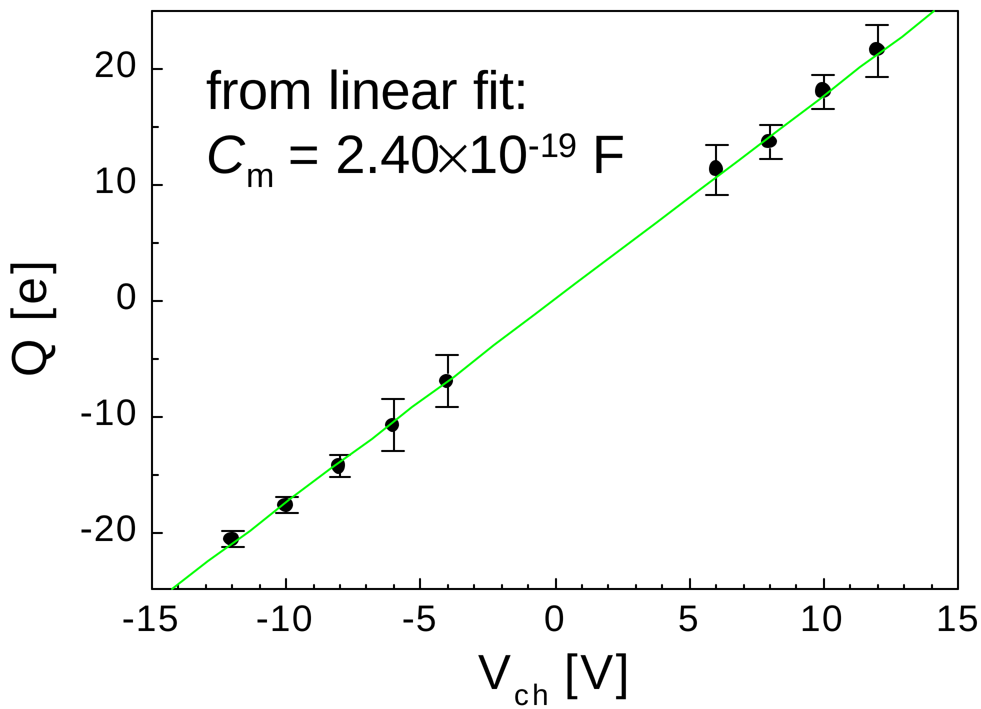
V_{EFM} = 1 V

V_{EFM} = -1 V



3. Results and Discussion

Dependence on voltage, charged area



Tip oscillates during charging with amplitude $B \rightarrow$ average capacitance:

$$\overline{C} = \frac{e_0 A}{2B}\int_0^{2B}\frac{1}{z+(d_1+d_2)/e_{SiO_2}}dz$$

$$= \frac{e_0 A}{2B}\ln\frac{2B+(d_1+d_2)/e_{SiO_2}}{(d_1+d_2)/e_{SiO_2}}$$

$$= 2.18\times10^{-8}\ \mathrm{F/cm^2}$$

$\Rightarrow$ Charged area: $A = \overline{C}/C_m = 1.10\times10^{-11}\ \mathrm{cm}^2$

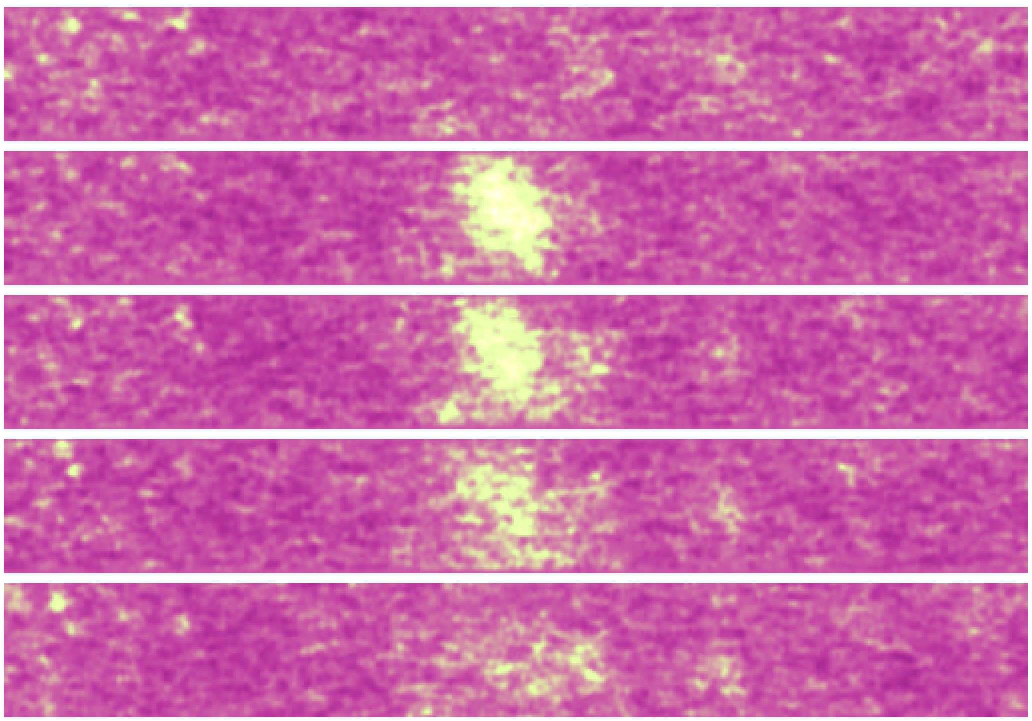
with $A = p r^2 \quad \Rightarrow \quad r \approx 20\ \mathrm{nm} \quad \Leftrightarrow \quad r_{Tip} \approx 10-20\ \mathrm{nm}$

compare with r_{Tip} and $r_{EFM} \approx 50\ \mathrm{nm} \quad \Rightarrow \quad r_{EFM} \approx r + r_{Tip}$

3. Results and Discussion

Discharging

500 nm



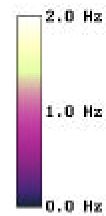
before

30 s after charging with +12V for 10s

90 s

210 s

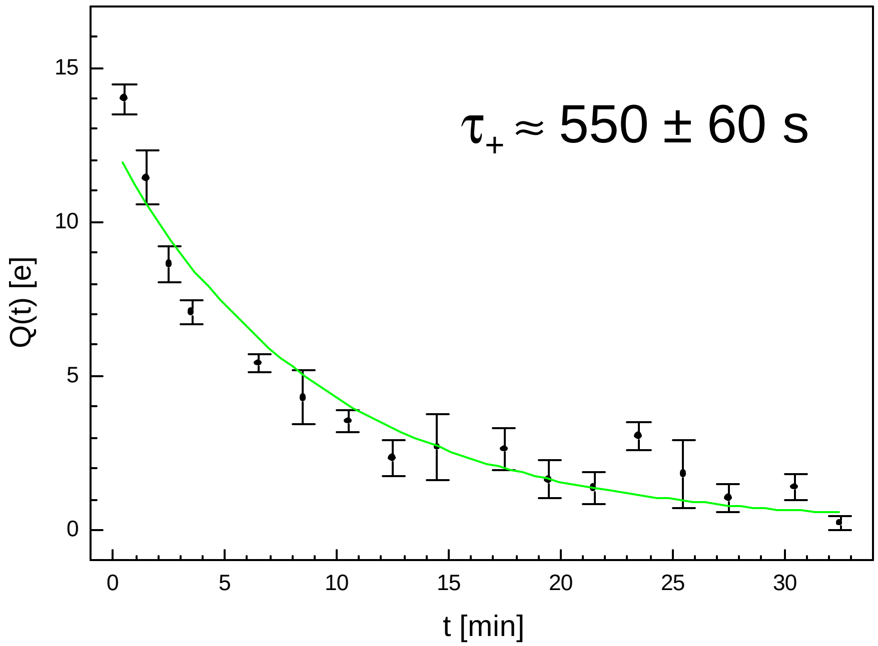
870 s



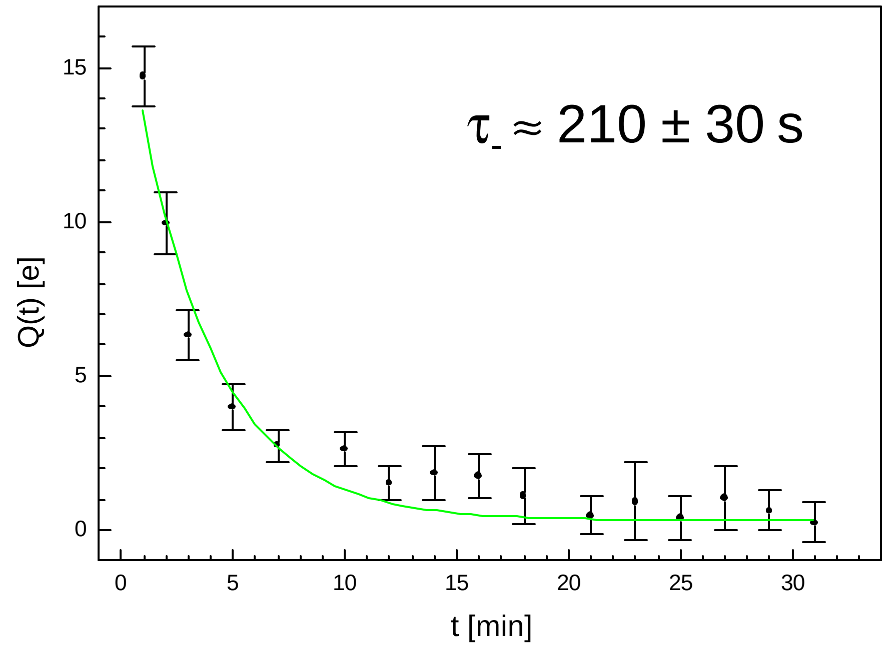
Gradual decrease in peak height, slight increase in area

⇒ Most of the stored charge tunnels into the Si substrate while part of it spreads out in the Co layer

3. Results and Discussion



Charging with +12 V for 10 s



Charging with -12 V for 10 s

- Exponential discharging with constant retention time $\tau_{\pm}$: $Q(t) = Q_0 e^{-t/t_{\pm}}$
- $\tau_{+} > \tau_{-}$

3. Results and Discussion

- Coulomb energy for cluster with capacitance C_{Co}: $E_0 = \frac{e^2}{2C_{Co}}$

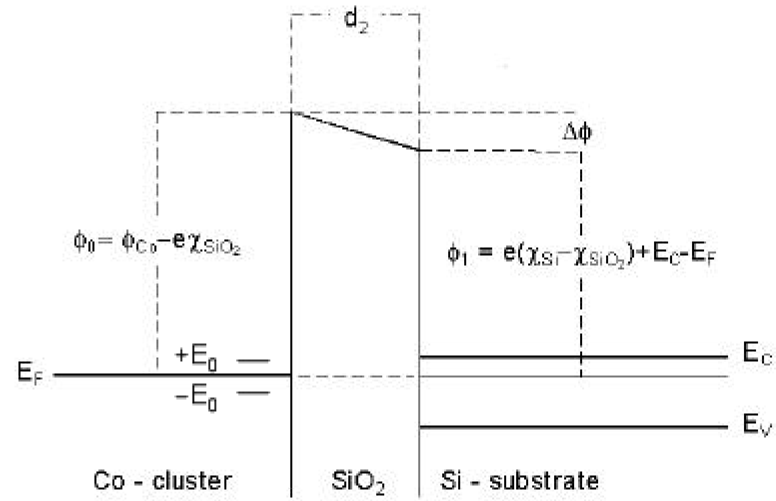
- Discharging from Co cluster into substrate

  Barrier heights:

  Positive charge on cluster: $f_+ = \bar{f} + E_0$

  Negative " " " : $f_- = \bar{f} - E_0$

  with average barrier height $\bar{f} = \frac{f_0 + f_1}{2}$



- Tunnel probability ~ $e^{-\frac{2d_2\sqrt{2mef}}{\hbar}}$ $\Rightarrow$ $\frac{t_+}{t_-} \approx e^{\frac{2d_2\sqrt{2me}}{\hbar}\left(\sqrt{f_+} - \sqrt{f_-}\right)}$

- d_2 and E_0 strongly dependent upon nominal Co layer thickness

- Additional discharging between Co cluster

4. Conclusions

- Controllable and reproducible charge deposition in Co clusters embedded in SiO_2
- Charge decays over several minutes with retention time τ_+ for positive charge larger than τ_- for negative charge
- Difference in retention times for positive and negative charge is explained by Coulomb blockade
- Retention times are strongly dependent upon film composition - implications for dynamics of charge transport in discontinuous multilayers and granular films
- Longer retention times can be achieved with thicker lower oxide and techniques such as nanoscale patterning to suppress discharging between Co cluster