Nanoscale charge transport properties of Co/SiO$_2$ multilayer structures and their application in a novel magnetic field sensor

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Motivation

- Discontinuous metal/insulator multilayers such as $[\text{SiO}_2/\text{Co}]_n\text{SiO}_2$ exhibit a variety of properties of importance for potential applications in data storage systems, notably:
  - possibility of charge storage
  - negative magnetoresistance
  - low saturation field

- A detailed study of the tunneling transport properties is of key importance to improve devices made of these multilayers.

- Scanning probe techniques allow localized studies of transport, in contrast to the usual measurements with large scale electrodes.

- Investigation of local charging of metal nanoclusters and subsequent charge dissipation yields insight into electric transport properties.

- Application: novel magnetic field sensor design
  Incorporation of granular tunnel-magnetoresistive material within the gate of a metal-oxide-semiconductor field-effect transistor (MOSFET) for amplified field sensitivity
Sample Preparation and Structure

- Alternate sputtering from a SiO$_2$ and a Co target onto n-type Si substrate covered with ~2.5 nm native oxide
- Nominal deposited film structure: 3 nm SiO$_2$ / 1.0 - 2.0 nm Co / 3 nm SiO$_2$
- Transmission micrographs show a discontinuous Co layer
- Microstructure strongly dependent on nominal Co film thickness

Experimental Procedure

- Scanning Force Microscope for charge injection and imaging
- Two pass method:
  1) Topography (via TappingMode™)
  2) Electrostatic Force Microscopy (EFM)
- 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
Charge transport experiments: Experimental Procedure

Measurement of stored charge via EFM

Frequency shift: \[ \Delta f = -\frac{f_0 F'(z_0)}{2k} \]

with resonant frequency \( f_0 \),
spring constant \( k \) and lift height \( z_0 \)

Force on tip:

\[
F(z) = \frac{1}{(z + (d_1 + d_2)/\varepsilon_{SiO_2})^2} \left( -\frac{d_2^2 Q^2}{\varepsilon_{SiO_2}^2 \varepsilon_0 A} + \frac{2d_2 QV_{EFM}}{\varepsilon_{SiO_2}} + \frac{\varepsilon_0 A V_{EFM}^2}{2} \right)
\]

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

Inserting parameters in \( F(z) \) and calculating \( \Delta f \):

\[
Q = 18.4 \frac{e}{V \text{Hz}} V_{EFM} \Delta f
\]
Charge transport experiments: Results

Charging on 3 nm SiO₂/1.4 nm Co/3 nm SiO₂

Charging with +12 V for 10 s:

- \( V_{\text{EFM}} = 1 \) V
- \( V_{\text{EFM}} = -1 \) V

Charging with -12 V for 10 s:

- \( V_{\text{EFM}} = 1 \) V
- \( V_{\text{EFM}} = -1 \) V
Charge transport experiments: Results

Quantification of charge injection into 3 nm SiO$_2$/1.4 nm Co/3 nm SiO$_2$

- Charged area $A$ is given by: $A = C_m \sqrt{\bar{C}} = 1.10 \times 10^{-15}$ m$^2$
- This corresponds to a disc with radius $r \approx 20$ nm which is on the order of the radius of curvature of the tip $r_{Tip} \approx 10-20$ nm
  $\Rightarrow$ initially, only Co clusters directly under the tip are charged
- These values are also in good agreement with the imaged radius $r_{EFM}$ of about 50 nm, since $r_{EFM} \approx r + r_{Tip}$

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

$$\bar{C} = \frac{\varepsilon_0}{2B} \int_{0}^{2B} \frac{1}{z + (d_1 + d_2) / \varepsilon_{SiO_2}} \, dz$$

$$= \frac{\varepsilon_0}{2B} \ln \frac{2B + (d_1 + d_2) / \varepsilon_{SiO_2}}{(d_1 + d_2) / \varepsilon_{SiO_2}}$$

$$= 2.18 \times 10^{-4} \text{ F/m}^2$$

from linear fit: $C_m = 2.40 \times 10^{-19}$ F
Charge transport experiments: Results

Charge decay on 3 nm SiO$_2$/1.4 nm Co/3 nm SiO$_2$

- gradual decrease in peak height
- slight increase in area

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

Charging with +12 V for 10 s

- exponential discharging with constant retention time $\tau_{\pm}$: $Q(t) = Q_0 e^{-t/\tau_{\pm}}$
- retention time $\tau_+$ for positive charge > retention time $\tau_-$ for negative charge
Charge transport experiments: Results

Dependence of retention times on nominal Co film thickness

- Retention times $\tau_+$ and $\tau_-$ are strongly dependent on nominal Co film thickness and thus on nanoscale structure (i.e. on Co cluster shape and spacing between Co cluster).
- Difference in retention times $\tau_+/\tau_-$ shows maximum for a nominal thickness of $d_{Co} = 1.6$ nm.
Charge transport experiments: Discussion

• Charging energy:

\[ E_0 = \frac{e^2}{2C_{Co}} \]

• Cluster capacitance:

\[ C_{Co} \approx 4\pi\varepsilon_0\varepsilon_{SiO_2}R \]

• Barrier heights:

- for positive charge: \( \phi_+ = \phi + E_0 \)
- for negative charge: \( \phi_- = \phi - E_0 \)

with average barrier height: \( \bar{\phi} = \frac{\phi_0 + \phi_1}{2} \)

• Tunnel probability \( \sim e^{-2d_2\sqrt{2m_\phi/\hbar}} \)

\[ \Rightarrow \frac{\tau_+}{\tau_-} \approx e^{\frac{2d_2\sqrt{2m_\phi}}{\hbar}(\sqrt{\phi_+} - \sqrt{\phi_-})} \]
Sensor: Design and Functionality

Sensor Design and Measurement Setup

- Incorporation of granular tunnel-magnetoresistive material within gate
- Fixed voltage $V_{MR}$ applied across magnetoresistive layer

Basic operation

- Current flow $I_{MR}$ through magnetoresistive film due to applied voltage $V_{MR}$
- $I_{MR}$ leads to stored charge in TMR layer $\rightarrow$ shift in transistor threshold voltage
- Applying or changing external magnetic field $H \rightarrow$ change in $I_{MR} \rightarrow$ change in charge in magnetoresistive film $\rightarrow$ change in threshold voltage

$\Rightarrow$ Modulation of transistor current with magnetic field via change in threshold voltage
Sensor: Transistor Characteristics

Current-voltage characteristics

Shift in threshold voltage as a function of current through the Co-SiO$_2$ layer

Subthreshold swing of ~ 400 mV / decade of current ↓
ideality factor $n \approx 7.5$

Threshold voltage varies monotonically with current $I_{MR}$ through magneto resistive layer
Sensor: Response to External Magnetic Field

- Current $I_{MR}$ through magnetoresistive layer is a function of magnetic field
- Threshold voltage $\Delta V_T$ shifts as $I_{MR}$ changes
  → Threshold voltage depends on magnetic field

- Zero magnetic field currents:
  $I_{MR} = 1.17 \ \mu A$, $I_{DS \text{ sat}} = 9 \ mA$, $I_{DS \text{ sub}} = -0.925 \ \mu A$

- Subthreshold region: $\sim 5$ $\%$ change in $I_{MR}$ leads to $\sim 20$ $\%$ change in $I_{DS \text{ sub}}$
- Saturation region: change in $I_{MR}$ of $\sim 60$ nA leads to change in $I_{DS \text{ sat}}$ of $\sim 30 \ \mu A$
Conclusions

- Scanning probe techniques were used to demonstrate and characterize local charge deposition and transport in Co nanoclusters embedded in an insulating SiO₂ matrix:
  - Controllably and reproducibly charge deposition, typically in quantities of ~5-20 electrons within areas ~ 20-50 nm in radius.
  - Charge decay occurs over a range of several minutes up to a few hours depending on Co/SiO₂ film composition.
  - Retention time $\tau_+$ for positive charge is larger than retention time $\tau_-$ for negative charge.
  - Difference in decay times for positive and negative charge is explained by Coulomb blockade

- New transistor-amplified magnetic field sensor (patent pending) has been proposed, experimentally demonstrated, and analyzed:
  - Key idea is incorporation of a granular tunnel-magnetoresistive film into the gate of a field-effect transistor structure.
  - Threshold voltage shift of 50 mV upon application of a 6 kOe magnetic field was obtained at room temperature.
  - Four-fold amplification of relative current response
  - Increase in absolute current response by a factor of ~500