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

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## Outline

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   - Results and Discussion
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# Motivation

- Discontinuous metal/insulator multilayers such as $[SiO_2/Co]_nSiO_2$ 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-magnetoresisitve material within the gate of a metal-oxide-semiconductor field-effect transistor (MOSFET) for amplified field sensitivity

# Charge transport experiments: Experimental Procedure

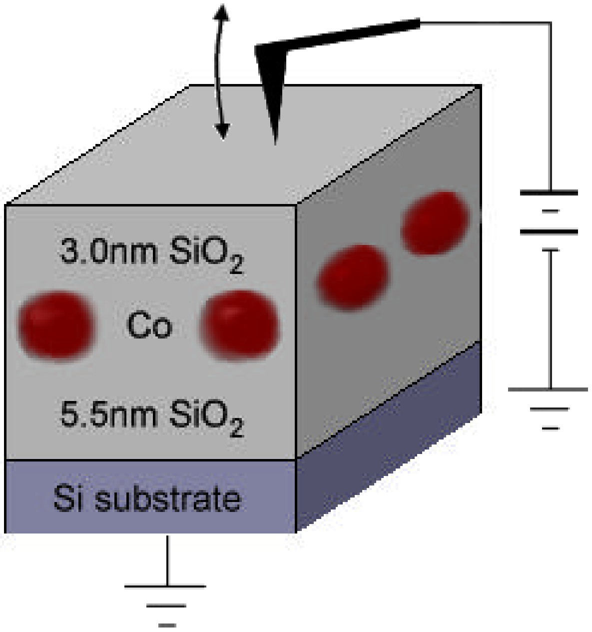
## Sample Preparation and Structure

- 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

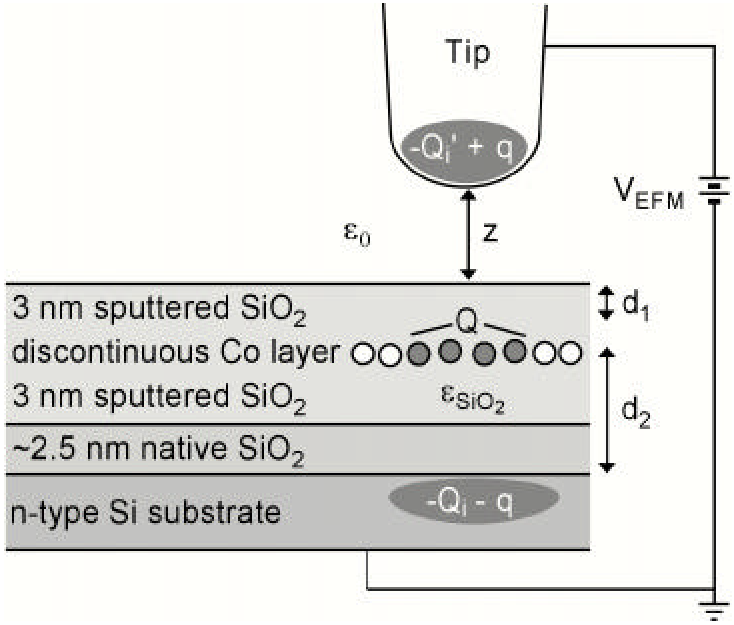
- Scanning Force Microscope for charge injection and imaging
- Two pass method:
  1) Topography (via TappingMode™)
  2) Electrostatic Force Microscopy (EFM)
- Charging:

  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: $\Delta f = -\dfrac{f_0 F'(z_0)}{2k}$

with resonant frequency $f_0$,
spring constant $k$ and lift
height $z_0$

Force on tip:

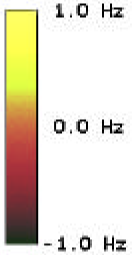
$$F(z) = \frac{1}{(z + (d_1 + d_2)/e_{SiO_2})^2}\left( -\frac{{d_2}^2 Q^2}{{e_{SiO_2}}^2 e_0 A} + \frac{2 d_2 Q V_{EFM}}{e_{SiO_2}} + \frac{e_0 A {V_{EFM}}^2}{2} \right)$$

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

Inserting parameters in $F(z)$ and calculating $\Delta f$ $\Rightarrow$ $\boxed{Q = 18.4 \dfrac{e}{\mathrm{V\,Hz}} V_{EFM} \Delta f}$

# Charge transport experiments: Results

Charging on 3 nm $SiO_2$/1.4 nm Co/3 nm $SiO_2$

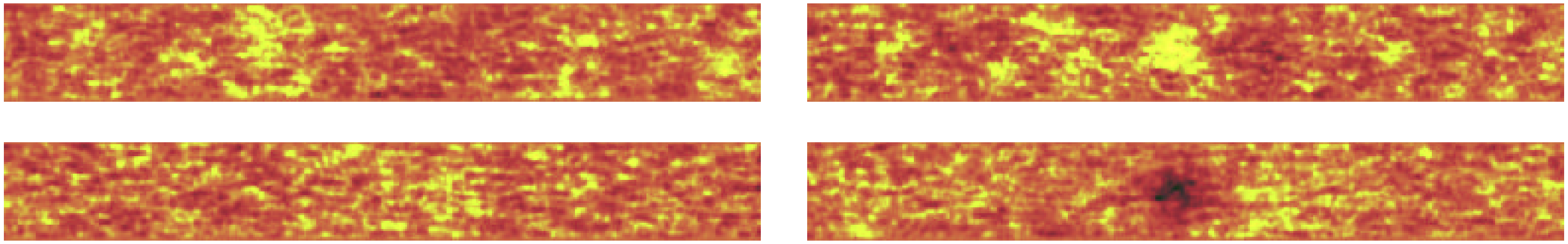


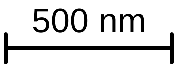
Charging with +12 V for 10 s:

before after

$V_{EFM}$ = 1 V

$V_{EFM}$ = -1 V



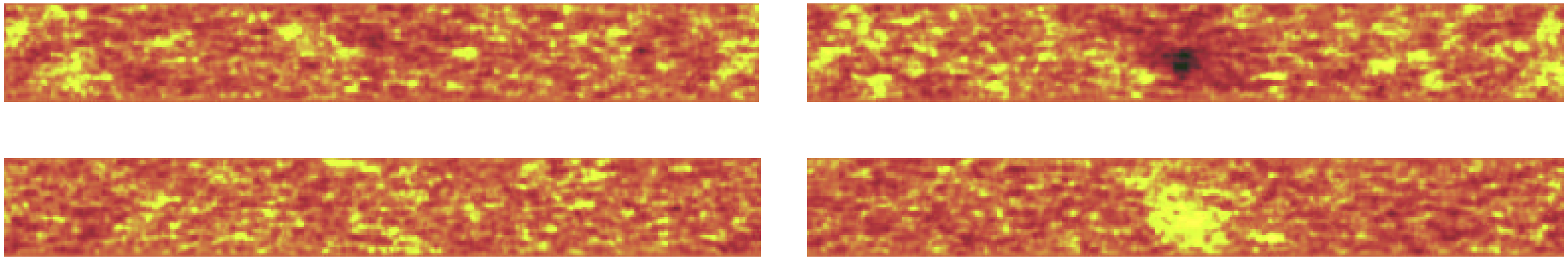


Charging with -12 V for 10 s:

before after

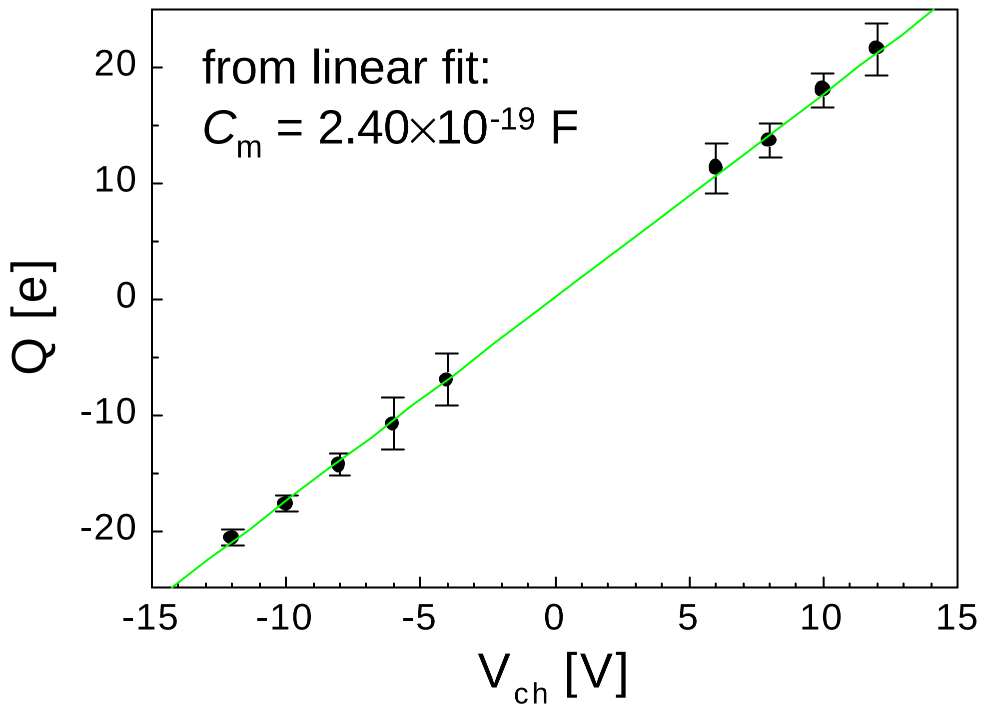
$V_{EFM}$ = 1 V

$V_{EFM}$ = -1 V



# Charge transport experiments: Results

Quantification of charge injection into 3 nm $SiO_2$/1.4 nm Co/3 nm $SiO_2$



Tip oscillates during charging with amplitude B → average capacitance:

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

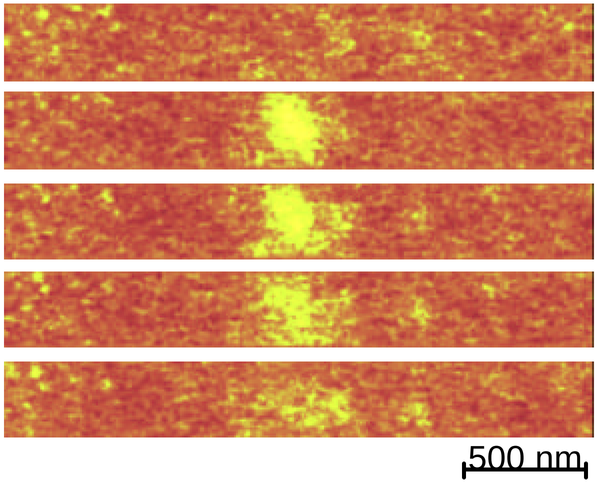
$$= \frac{e_0}{2B}\ln\frac{2B+(d_1+d_2)/e_{SiO_2}}{(d_1+d_2)/e_{SiO_2}}$$

$$= 2.18\times10^{-4}\ \mathrm{F/m^2}$$

- Charged area $A$ is given by: $A = C_m/\overline{C} = 1.10\times10^{-15}\ \mathrm{m^2}$
- This corresponds to a disc with radius $r \approx 20$ nm which is on the order of the radius of curvature of the tip $r_{Tip} \approx 10\text{-}20$ nm
  ⇒ 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 $r_{EFM} \approx r + r_{Tip}$

# Charge transport experiments: Results

Charge decay on 3 nm $SiO_2$/1.4 nm Co/3 nm $SiO_2$



before

30 s after charging with +12 V for 10 s

90 s

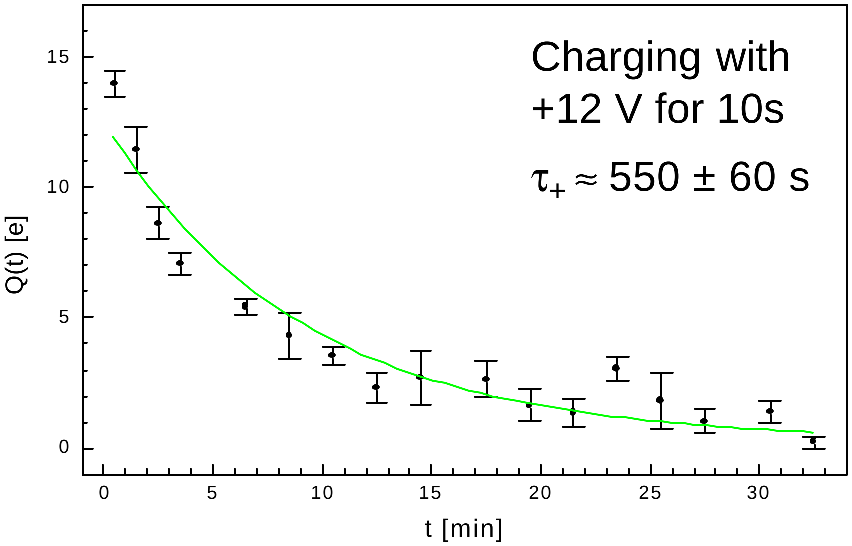
210 s

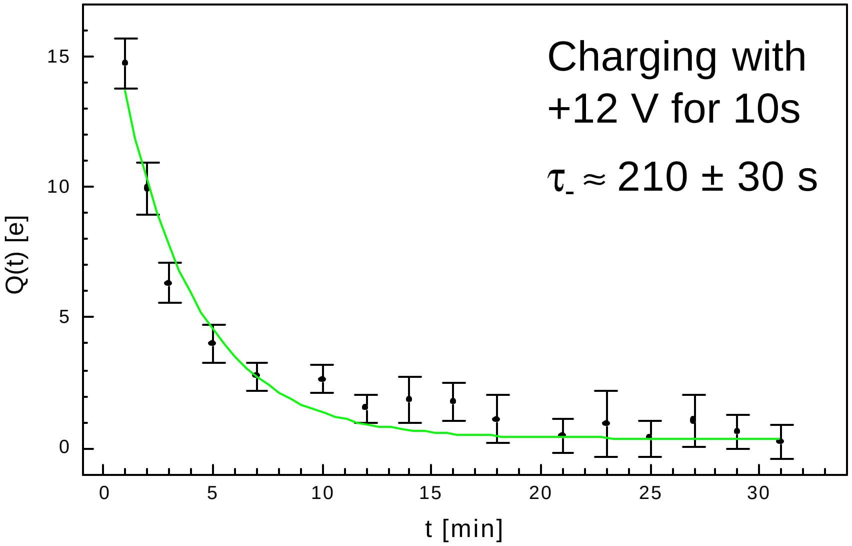
870 s

- 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

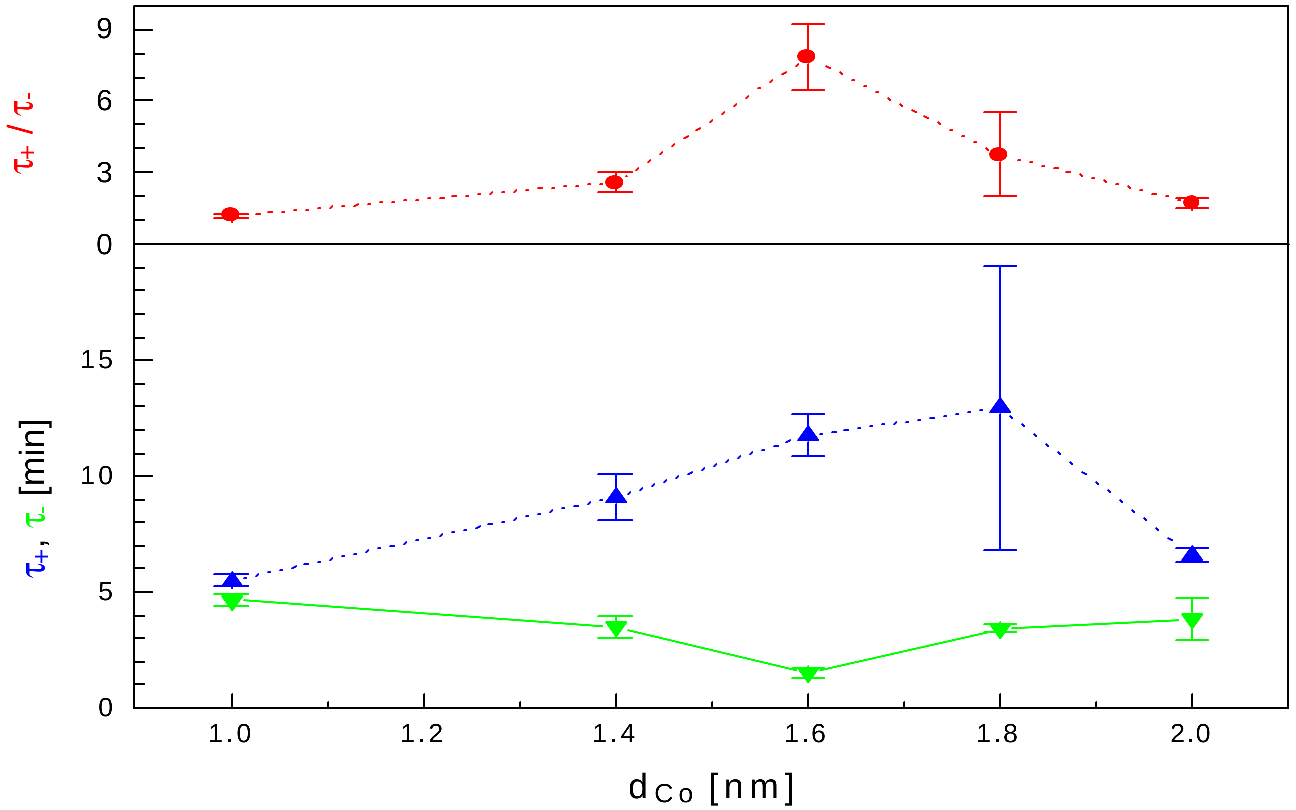




- exponential discharging with constant retention time $\tau_\pm$: $Q(t) = Q_0 e^{-t/t_\pm}$
- retention time $\tau_+$ for positive charge > retention time $\tau_-$ for negative charge

# 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

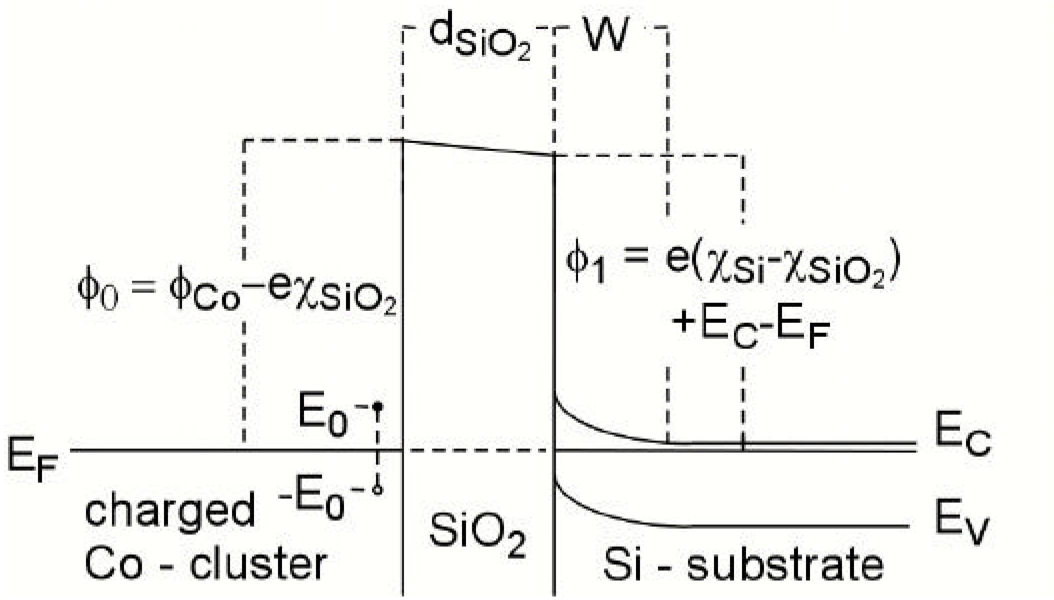
# Charge transport experiments: Discussion

- Charging energy:

$$E_0 = e^2 / 2C_{Co}$$

- Cluster capacitance:

$$C_{Co} \approx 4npe_0 e_{SiO_2} R$$



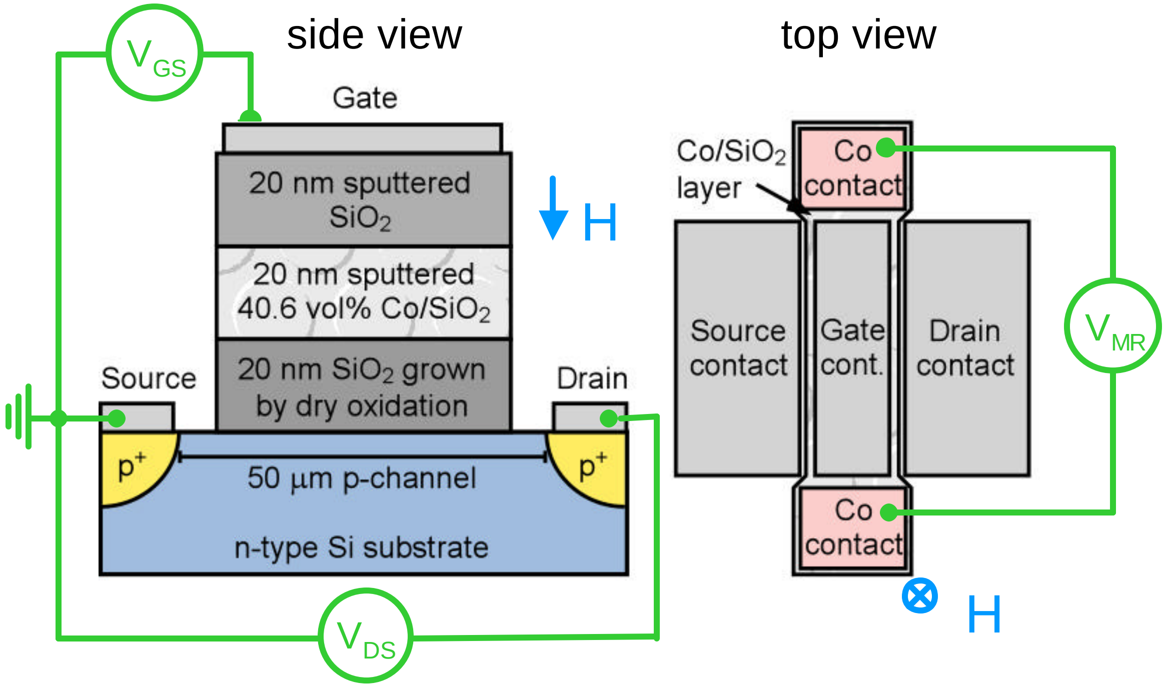
- Barrier heights:
  - for positive charge: $f_+ = \bar{f} + E_0$
  - for negative charge: $f_- = \bar{f} - E_0$

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

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

# 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

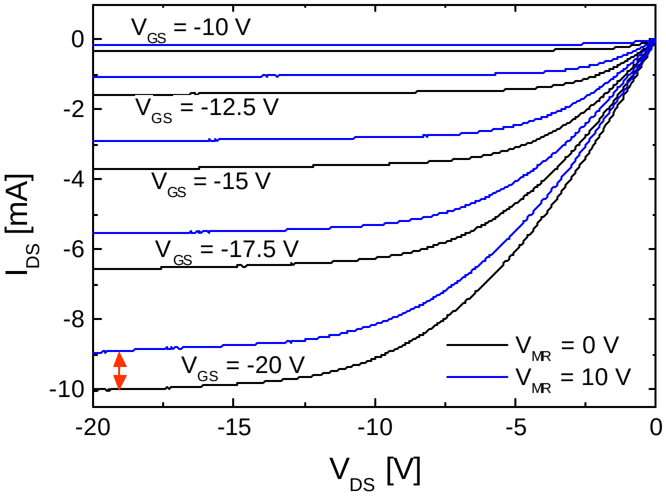
## Basic operation

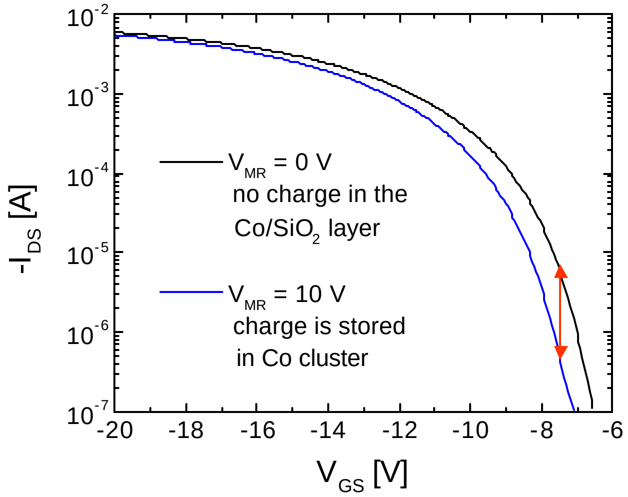
- Current flow $I_{MR}$ through magnetoresistive film due to applied voltage $V_{MR}$
- $I_{MR}$ leads to stored charge in TMR layer → shift in transistor threshold voltage
- Applying or changing external magnetic field $H$ → change in $I_{MR}$ → change in charge in magnetoresistive film → change in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

⇒ Modulation of transistor current with magnetic field via change in threshold voltage

# Sensor: Transistor Characteristics

## Current-voltage characteristics





Subthreshold swing of ~ 400 mV / decade of current

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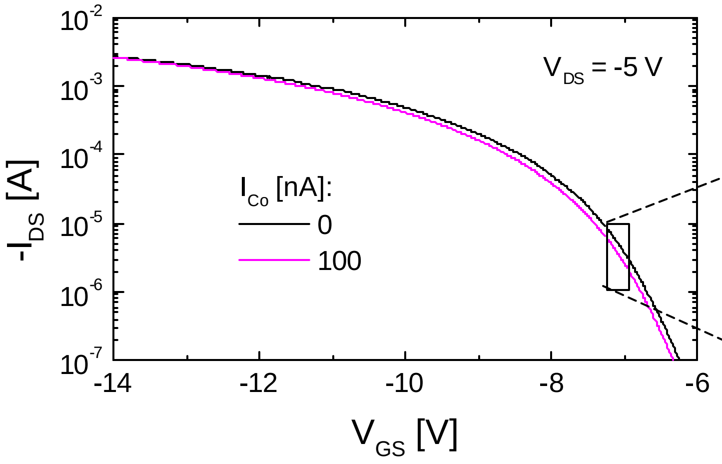
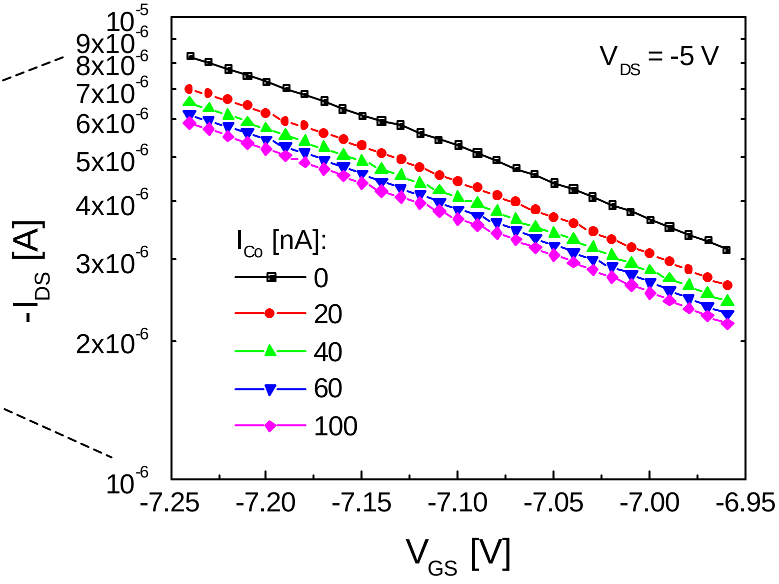
ideality factor *n* ~ 7.5

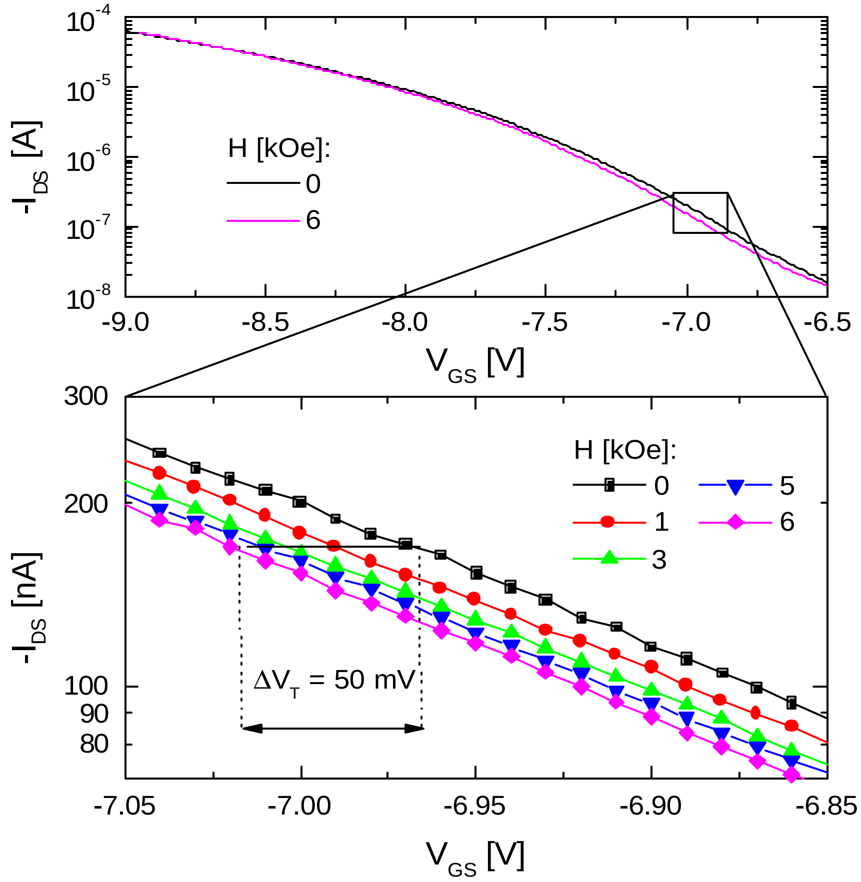
## Shift in threshold voltage as a function of current through the Co-$SiO_2$ layer

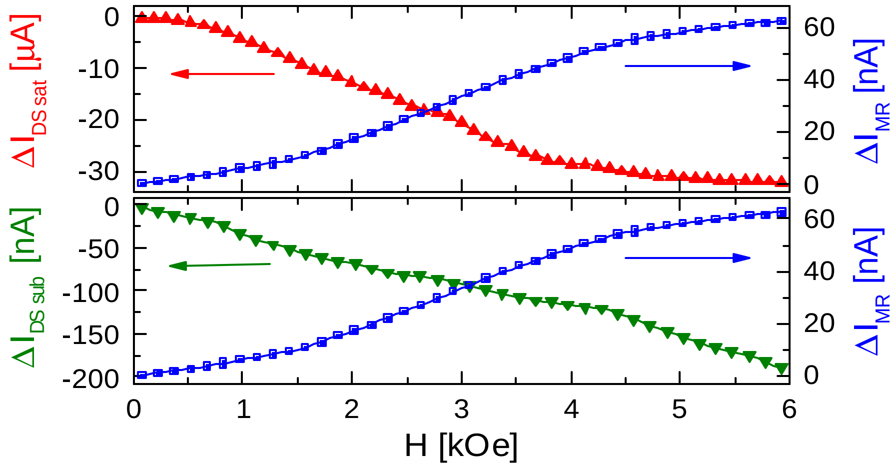


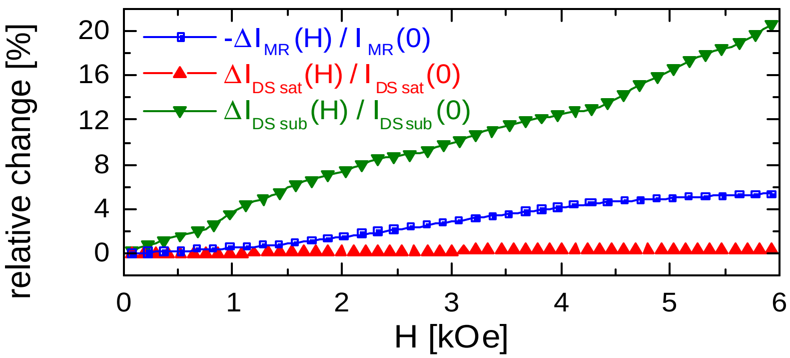


Threshold voltage varies monotonically with current $I_{MR}$ through magnetoresistive layer

# 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 µA, $I_{DS\,sat}$ = 9 mA, $I_{DS\,sub}$ = - 0.925 µA
- Subthreshold region: ~5 % change in $I_{MR}$ leads to ~20 % change in $I_{DS\,sub}$
- Saturation region: change in $I_{MR}$ of ~60 nA leads to change in $I_{DS\,sat}$ of ~ 30 µA

# Conclusions

- Scanning probe techniques were used to demonstrate and characterize local charge deposition and transport in Co nanoclusters embedded in an insulating $SiO_2$ 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 $Co/SiO_2$ 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