Novel hybrid magnetoelectronic device for magnetic field sensing

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Outline

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3. Sensor Characteristics
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1. Motivation

- Future magnetic data storage systems will benefit from magnetic field sensors with:
  - increased sensitivity
  - reliability in extreme environments
  - monolithic integration with semiconductor components for increased sensitivity and functionality
- Sensors based on giant-magnetoresistive materials are currently used
- Example of hybrid magnetic-electronic sensor device: spin-valve transistor

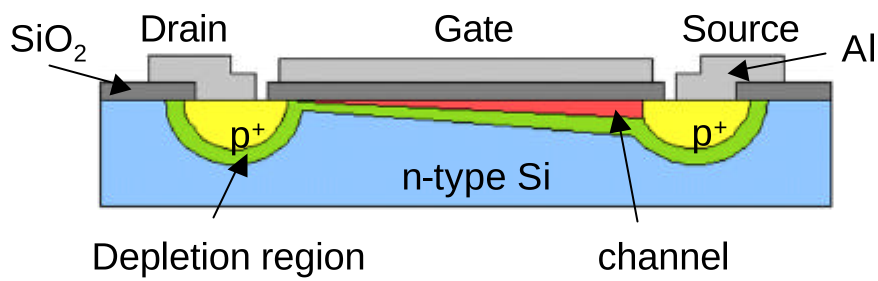
  [D. J. Monsma, R. Vlutters, and J. C. Lodder, *Science* **281**, 407 (1998)]
  - room temperature operation requires more complicated fabrication processes
  - problems with leakage currents

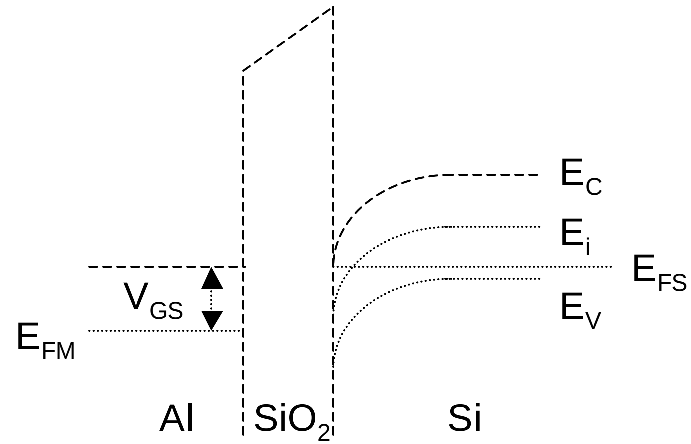
New device concept (patent pending) demonstrated here:

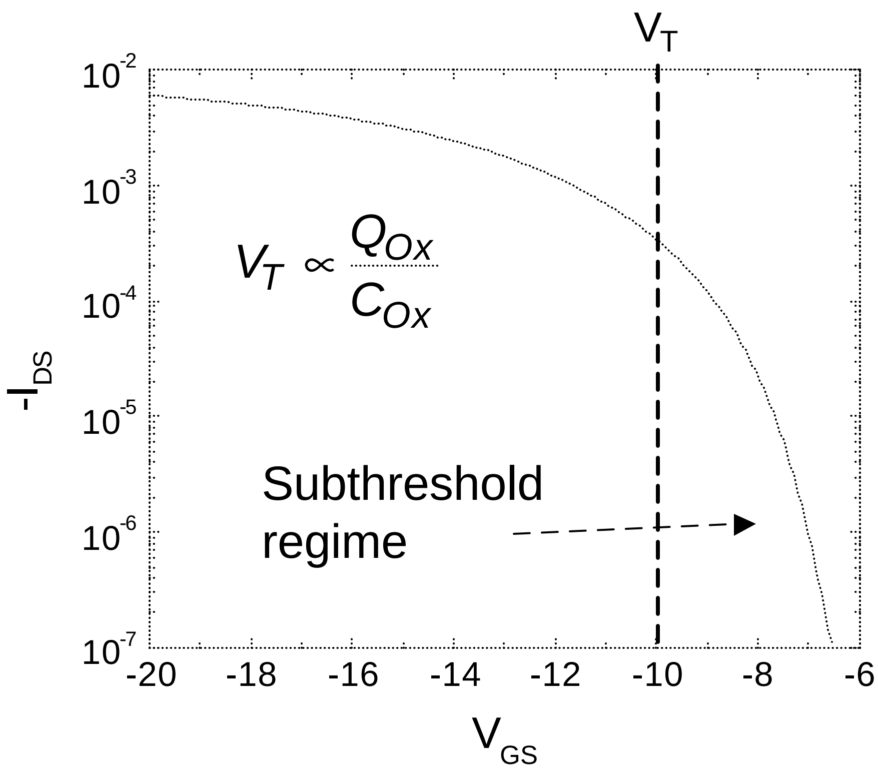
Incorporation of granular tunnel-magnetoresisitve material within the gate of a metal-oxide-semiconductor field-effect transistor (MOSFET) for amplified field sensitivity

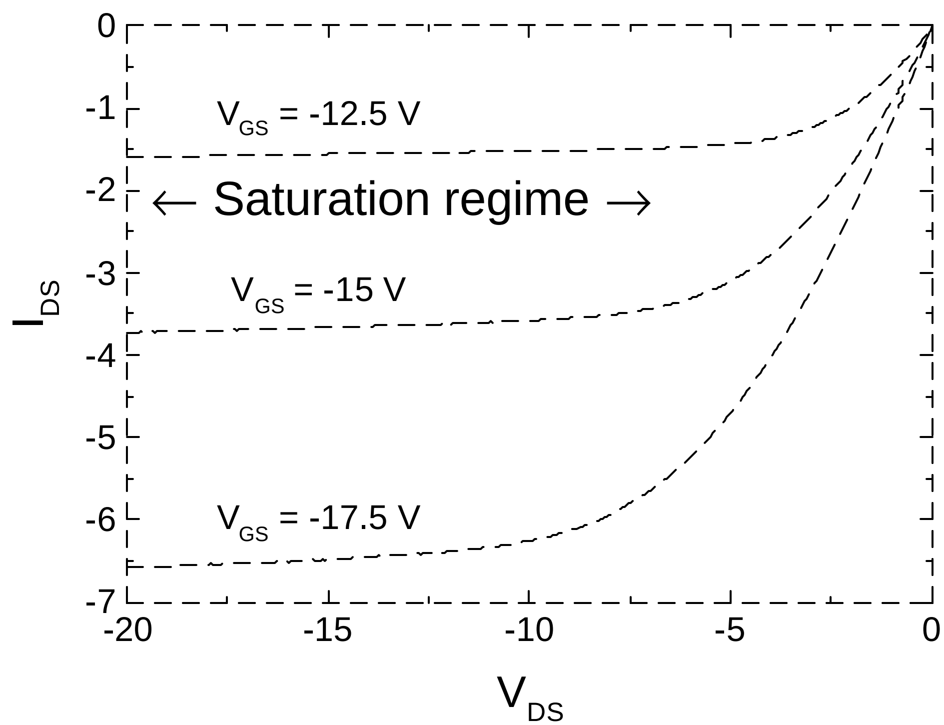
2. Sensor Design and Functionality

Introduction to MOSFET characteristics



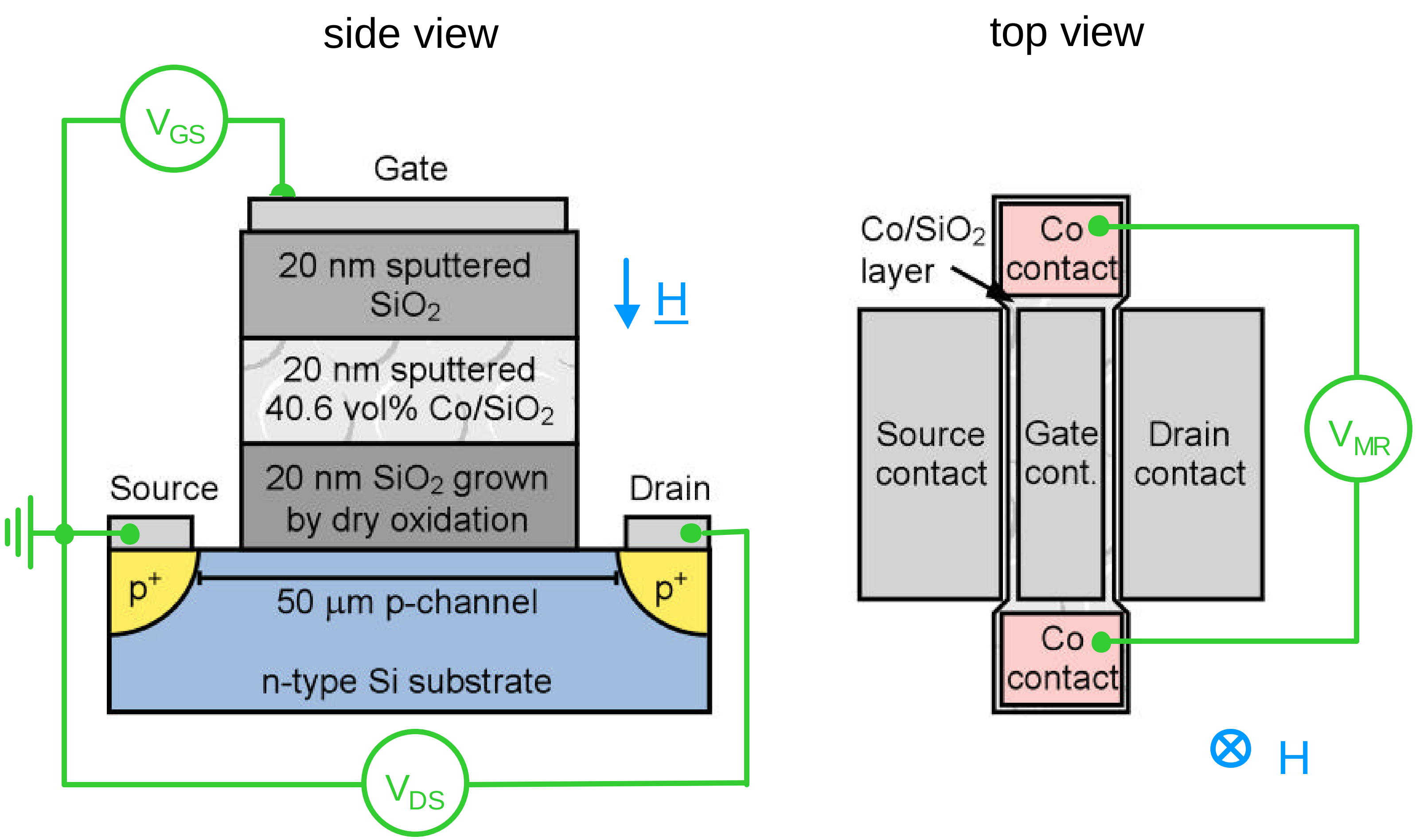






2. Sensor Design and Functionality

Sensor Design and Measurement Setup



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

2. Sensor Design and Functionality

Basic operation

- Current flow I_{MR} through magnetoresistive film due to applied voltage V_{MR}

- I_{MR} leads to stored charge Q_{MR} in the magnetoresisitve layer:

$$Q_{MR} \propto I_{MR}\, E_0$$ with E_0 Coulomb energy of a Co cluster

- Q_{MR} causes shift in transistor threshold voltage ΔV_T:

$$\Delta V_T = -\frac{Q_{MR}}{C_{ox}}$$ with C_{ox} capacitance of top oxide layer

- Applying or changing external magnetic field $H \rightarrow$ change in $I_{MR} \rightarrow$ change in charge $Q_{MR} \rightarrow$ change in threshold voltage ΔV_T

$\Rightarrow$ Modulation of transistor current with magnetic field via change in threshold voltage

2. Sensor Design and Functionality

Expected amplification in transistor drain-source current I_{DS} compared to I_{MR}:

- Exponential in subthreshold regime, limited by ideality factor n:

$$\frac{\Delta I_{DS}(H)}{I_{DS}(0)} = 1 - e^{-\frac{\Delta V_T(H)}{nkT}}$$

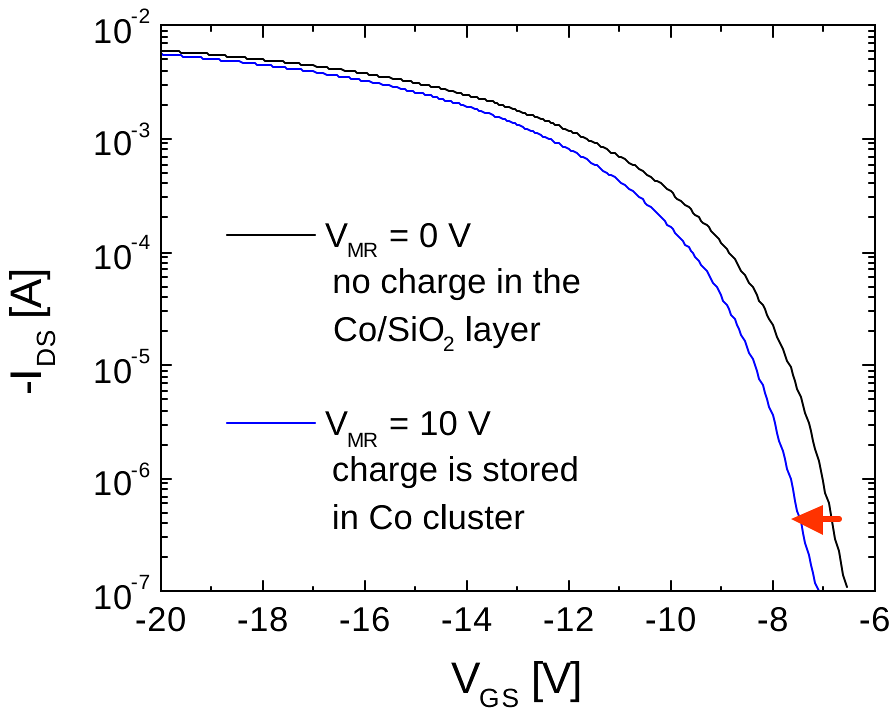
- Linear in saturation regime, large absolute change due to large saturation current:

$$\frac{\Delta I_{DSsat}(H)}{I_{DSsat}(0)} \approx \frac{2\Delta V_T(H)}{V_{GS} - V_T(0)}$$

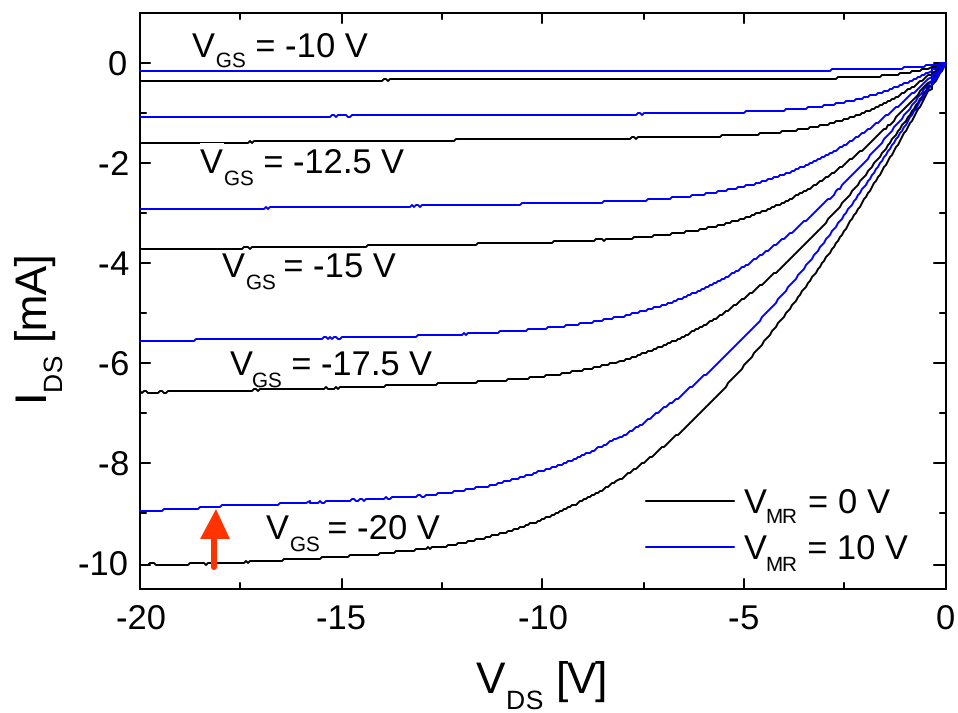
3. Sensor Characteristics

Current-voltage characteristics

Subthreshold regime



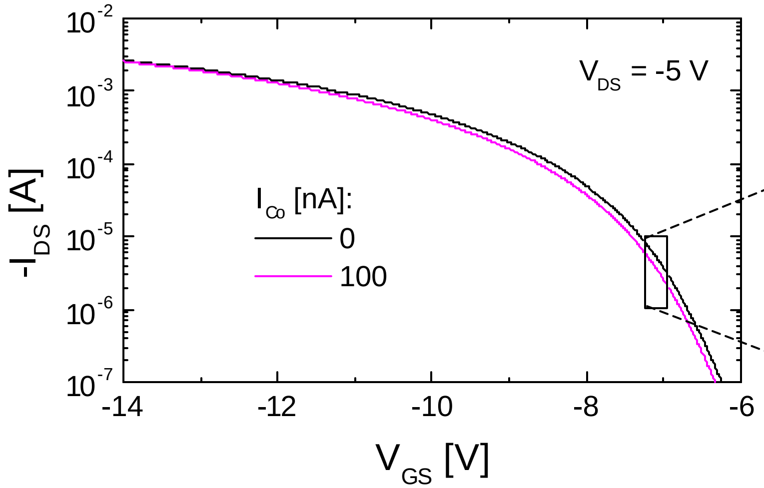
Saturation regime

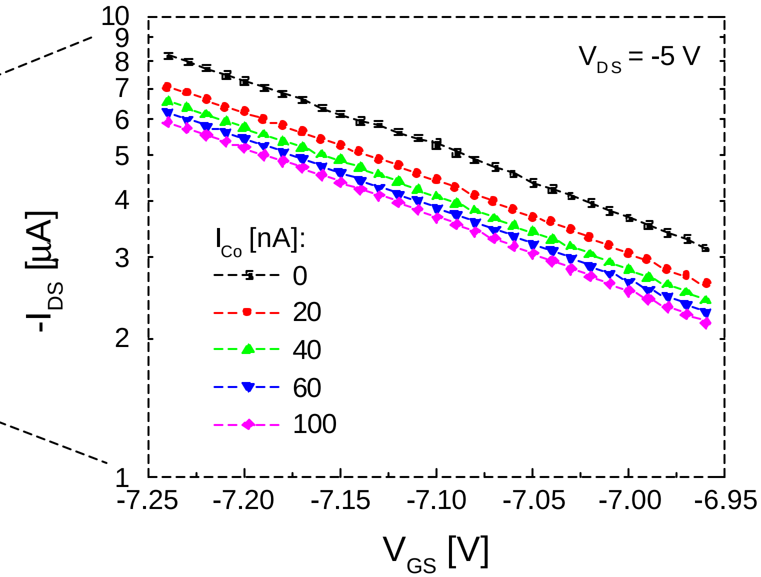


- Application of voltage V_{MR} = 10 V across magnetoresistive layer results in threshold voltage shift of ~ 0.6 V
- Subthreshold swing of ~ 400 mV / decade of current, corresponds to ideality factor *n* ~ 7.5

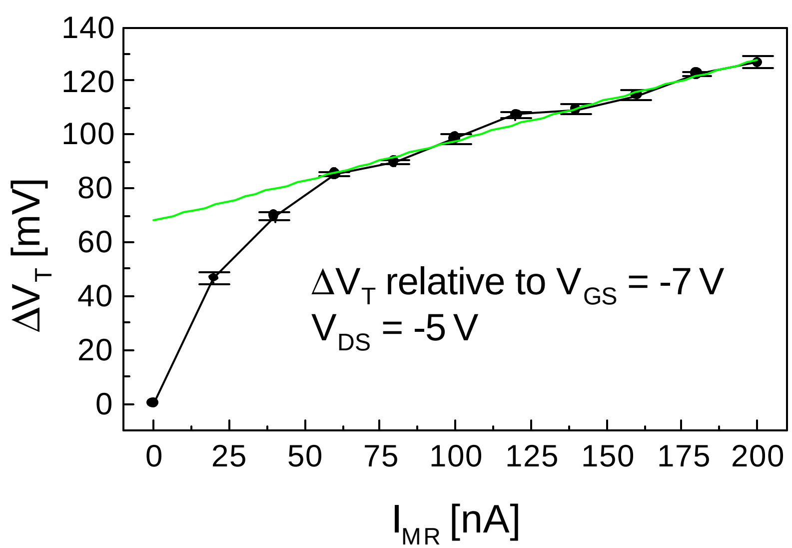
3. Sensor Characteristics

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





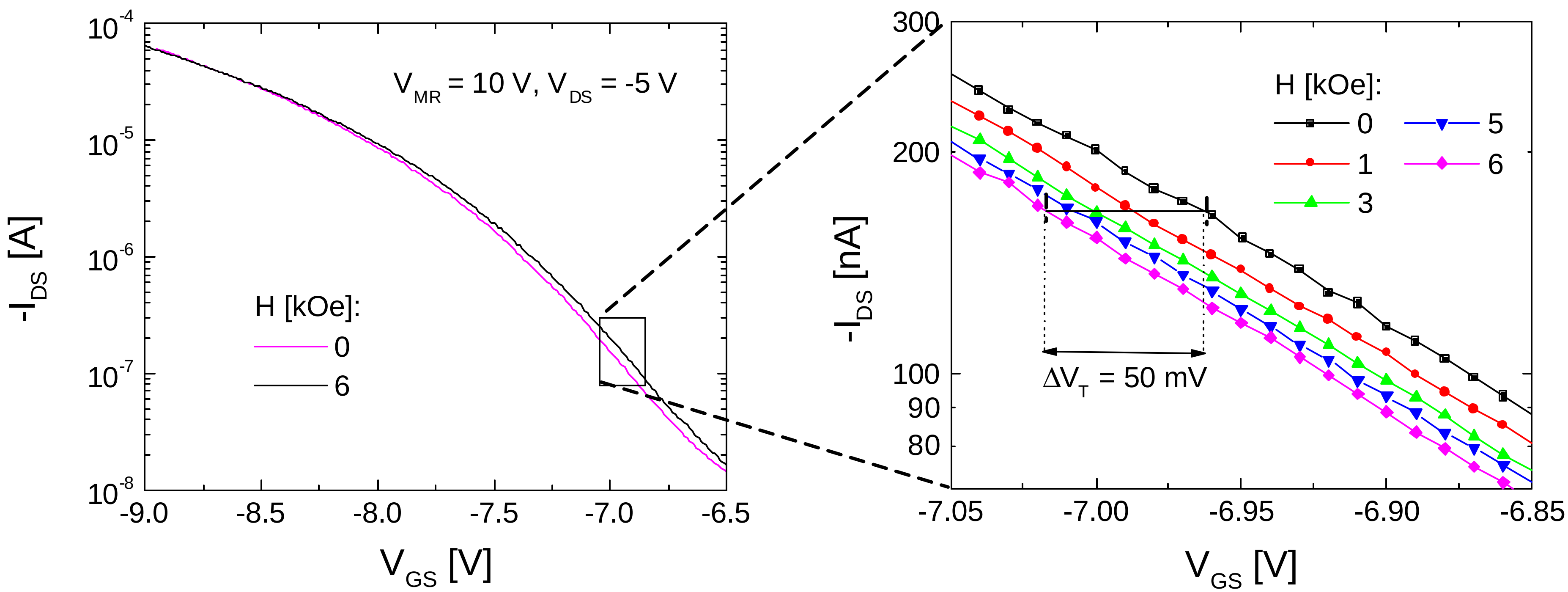
Threshold voltage varies monotonically with current I_{MR} through magnetoresistive layer



- Strong increase in ΔV_T for small I_{MR} values due to non-ohmic behavior of the contacts to the magnetoresistive layer
- Linear dependence of ΔV_T on I_{MR} for large I_{MR} values as expected from theory

3. Sensor Characteristics

Transistor characteristics as a function of magnetic field



- I_{MR} depends monotonically on magnetic field H
- ΔV_T depends monotonically on I_{MR}

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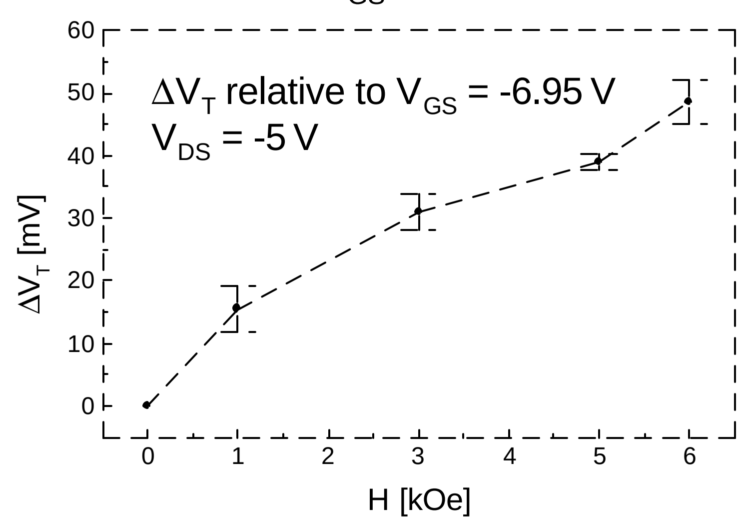
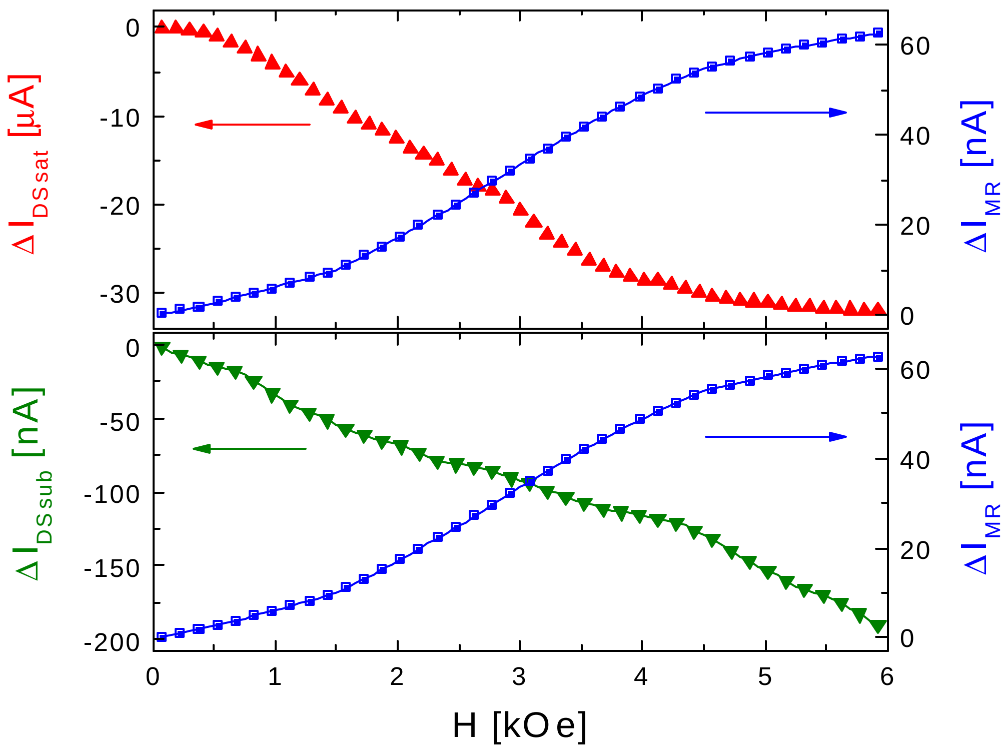
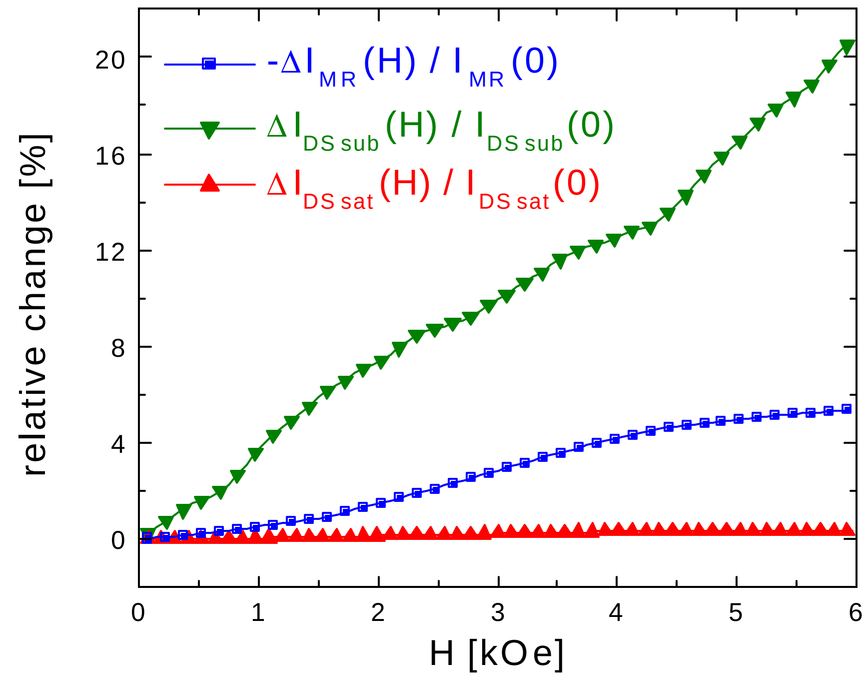
ΔV_T depends monotonically on H



3. Sensor Characteristics

Drain-source current as a function of magnetic field





	I_{MR}	$I_{DS\ sub}$	$I_{DS\ sat}$
Zero-magnetic field current $I(0)$	1.17 µA	-0.925 µA	-9 mA
Relative change $\Delta I(\mathrm{H}) / I(0)$	5 %	21 %	<1 %
Amplification factor $\Delta I(\mathrm{H}) / \Delta I_{MR}(\mathrm{H})$		3.3	500

4. Conclusions

- 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

- Expected change in subthreshold current for devices with optimal ideality factor of $n \sim 1.75$:

  - p-channel: $\Delta I_{DS\,sub}(H) / I_{DS\,sub}(0) \sim 67\,\%$, $I_{DS\,sub}(H) / I_{DS\,sub}(0) \sim 10$
  - n-channel: $\Delta I_{DS\,sub}(H) / I_{DS\,sub}(0) \sim 200\,\%$, $I_{DS\,sub}(H) / I_{DS\,sub}(0) \sim 30$