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Dynamic Observation of Magnetic Particles in Continuous Flow Devices by Ferromagnetic Tunneling Magnetoresistance Sensors

A. Weddemann,* A. Auge, C. Albon, F. Wittbracht, and A. Hütten

**corresponding author, elctronic address:* weddeman@physik.uni-bielefeld.de

D2 PHYSICS

Department of Physics, Bielefeld University, Postfach 100131, D 33501, Bielefeld

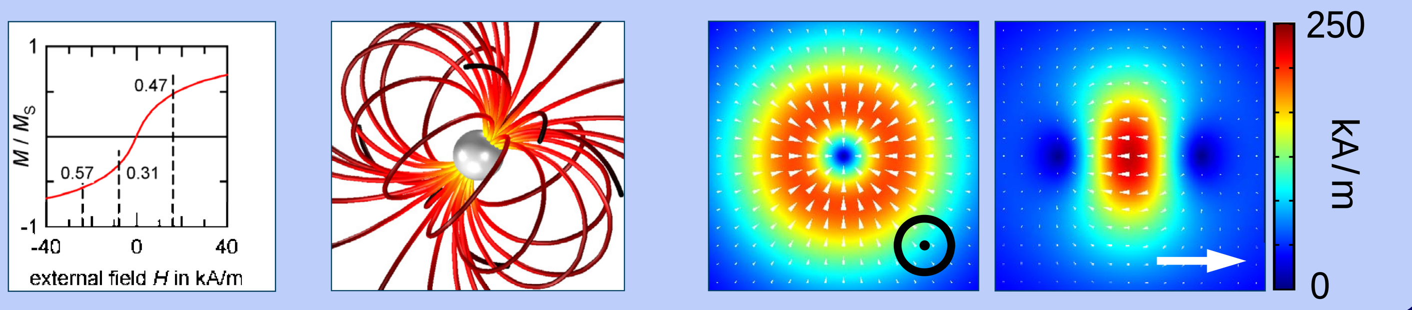
Bielefeld University www.spinelectronics.de

Motivation

Magnetic particles on the micro- or nanoscale have many different applications. In medical fields, a promising idea is to bind them to biomolecules enabling an indirect way to manipulate or detect these [1] – [3]. The focus of this work lies on the magnetoresistive recognition of magnetic markers by e.g. the following setup

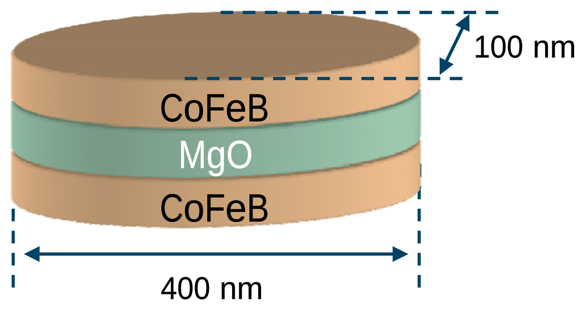
Magnetic particles

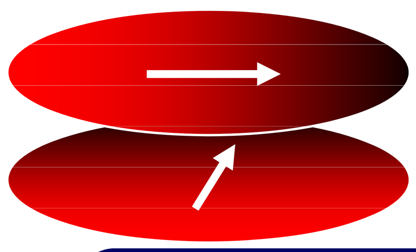
Magnetization **Stray field** **In-plane projection**



Material parameters:
- M_S = 1193.662 kA/m³
- A = 2.86 · 10⁻¹¹ J/m

Coupling parameters:
- h = 3 Å
- λ = 30 nm





Initial state

Grid:
x = -1.5 µm + 0.2 µm · (i - 1)
y = -1.5 µm + 0.1 µm · (j - 1)
z = 0.562 µm

i = 1, … , 16; j = 1, … , 31

Sensor consisting of two 4 nm ferromagnetic CoFeB-layers separated by a 2 nm insulating MgO-tunneling barrier.

Bottom electrode is pinned along the short ellipse axis by an antiferromagnet, the top one obtains its orientation by geometric anisotropy.

The resistance of the setup depends on the orientation of magnetization of both layers. Under the influence of an external (stray-)field a change is observed, quantified by the tunneling magnetoresistance(TMR)-ratio

$$\mathrm{TMR} = \frac{1}{3}\frac{1-\langle\alpha\rangle}{1+\langle\alpha\rangle/3} \quad \text{with} \quad \langle\alpha\rangle = \frac{1}{A_{\text{layer}}}\int_{A_{\text{layer}}} \langle \boldsymbol{m}_1, \boldsymbol{m}_2 \rangle \, dx$$

Theoretical approach

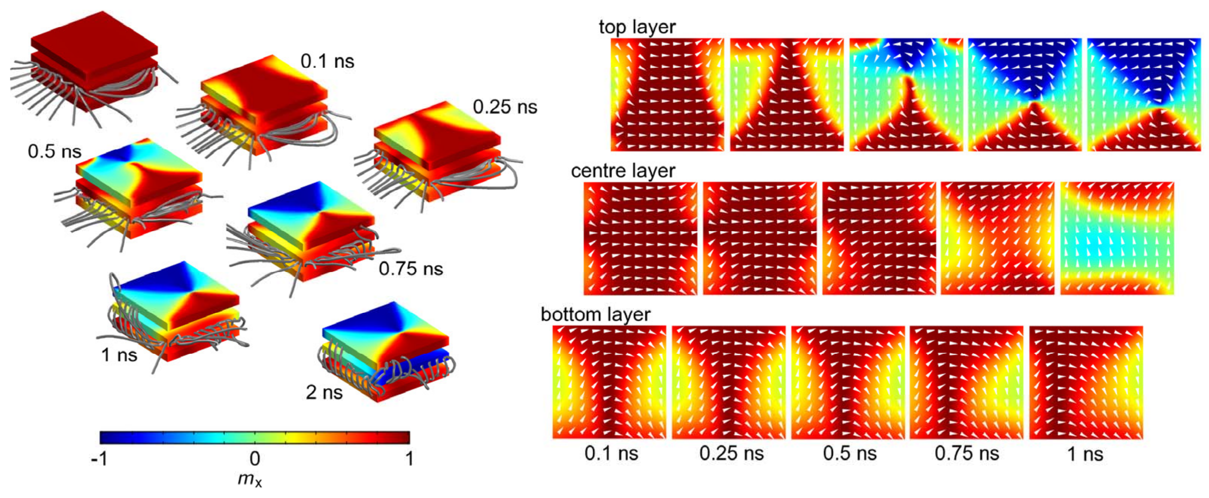
The dynamics of the magnetization vector $M_S m$ in a ferromagnetic layer or particle can be calculated from Landau-Lifshitz Gilbert equation:

$$\frac{\partial \boldsymbol{m}}{\partial t} = -\gamma \boldsymbol{m} \times \boldsymbol{H}_{\text{eff}} + \alpha \boldsymbol{m} \times \frac{\partial \boldsymbol{m}}{\partial t} \qquad |\boldsymbol{m}| = 1$$

$$\text{with} \quad \boldsymbol{H}_{\text{eff}} = \frac{2A}{\mu_0 M_S}(\nabla \boldsymbol{m})^2 - \frac{\delta f_{\text{ani}}(\boldsymbol{m})}{\delta \boldsymbol{m}} + \boldsymbol{H}_{\text{demag}} + \boldsymbol{H}_{\text{ex}}$$

γ: gyromagnetic ratio
A: exchange constant
M_S: saturation magnetization
f_{ani}: anisotropy energy functional
H_{ex}: external field H_{part} + H_{hom}
H_{hom}: hom. field to align particle moments

For the stray field H_{part} of the magnetic particles the analytic solution for homogeneously magnetized spheres is used. The demagnetization field H_{demag} from the magnetic layer is calculated in three dimensions assuming a two dimensional magnetization distribution. This enables a highly accurate calculation of the stray field coupling of different layers.



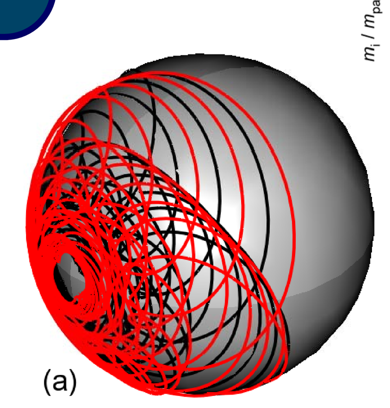
Magnetic thin films

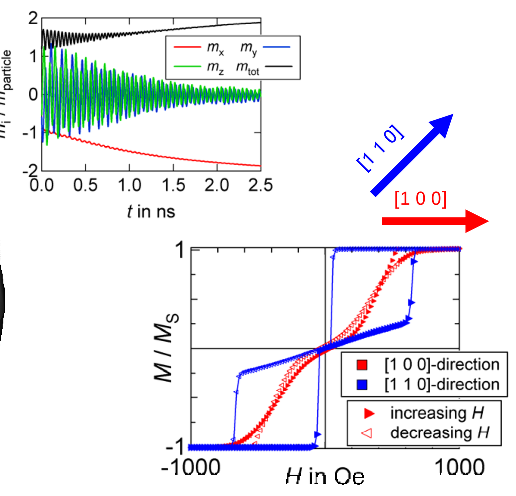
Dynamics of a ferromagnetic trilayer system; different electrodes form vortex, S- and C-state

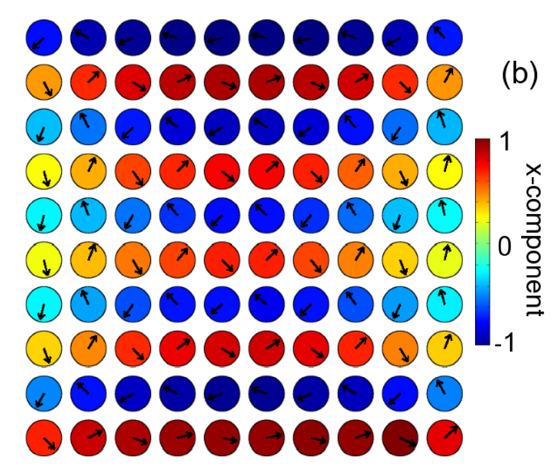
Magnetic particles

Dynamic behaviour of dipolar coupled single domain nanoparticles [4]

(a) dynamics of two interacting dipoles
(b) equilibrium state and hysteresis of a two-dimensional particle assembly



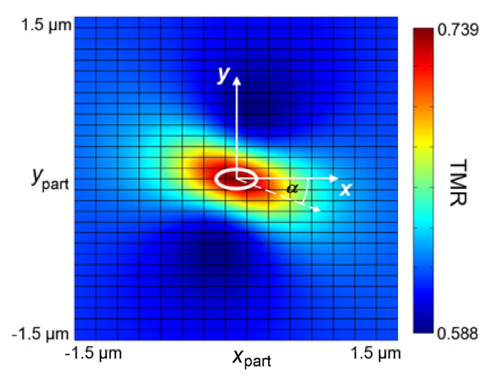




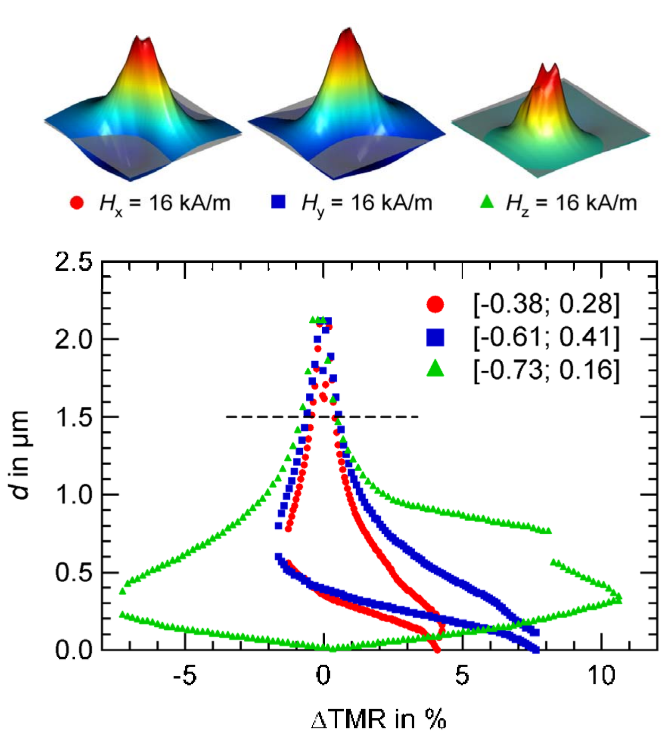
Single particle detection

$$\Delta\mathrm{TMR} = \frac{\mathrm{TMR}_{\text{part}} - \mathrm{TMR}_{\text{stack}}}{\mathrm{TMR}_{\text{stack}} + 1}$$

Typical TMR-map

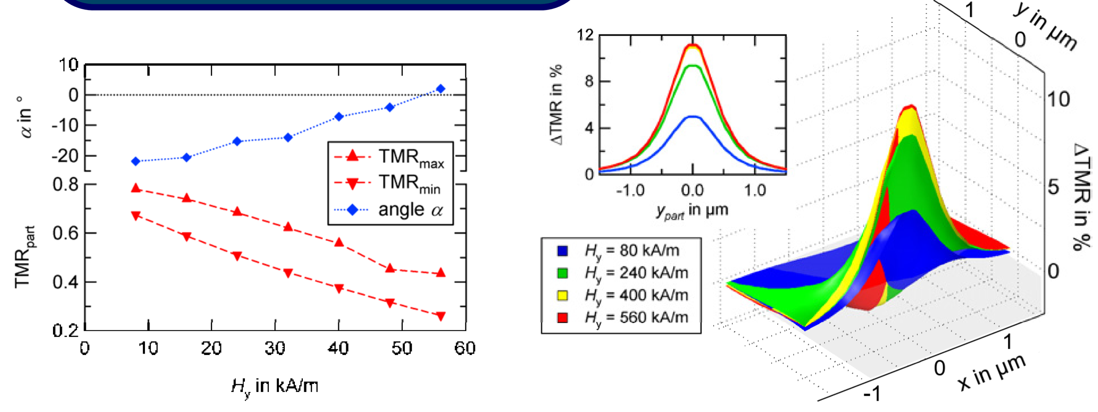


Measurements along several room directions allow an estimation of the distance between particle and sensor centre:



Combining measurements in x-, y- and z-direction the distance in an area of 1.2 µm diameter can be measured below an accuracy of 0.2 µm [5] – [7].

Influence of external field

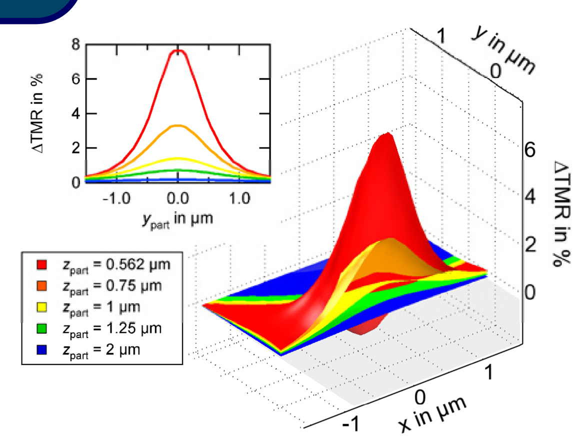


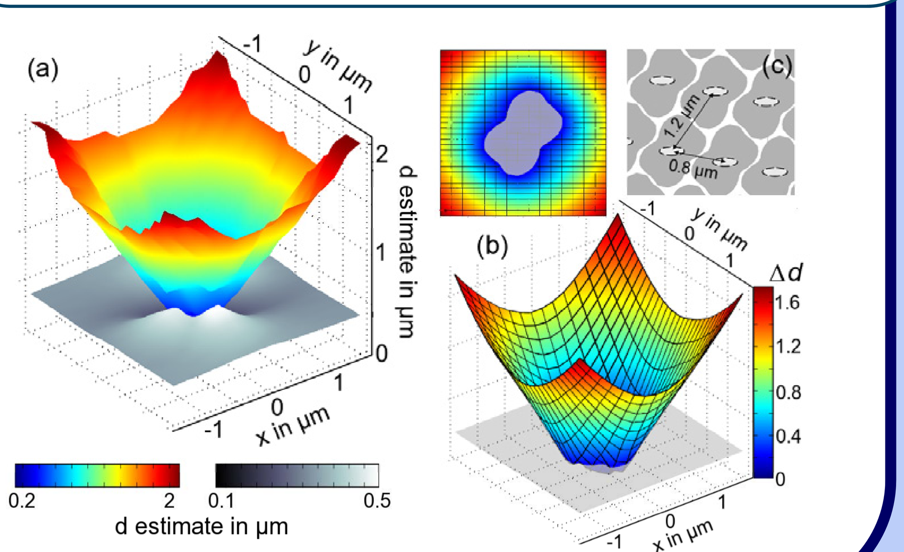
With higher magnetic field applied, a higher change ΔTMR can be observed (right), though the TMR-values themselves decrease (left). Higher fields therefore enable higher spatial resolution at the cost of a smaller visibility field!!

Influence of particle height

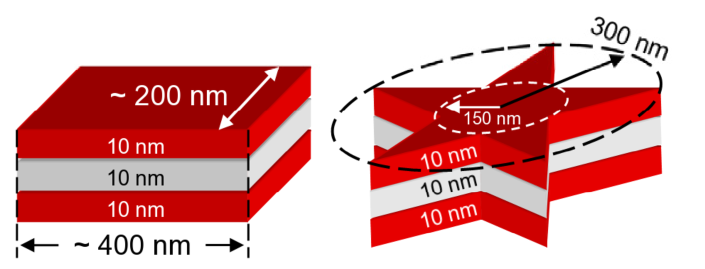
Sensor signal decreases rapidly with distance.

STRONG RESTRICTION FOR IN-FLOW MEASUREMENTS

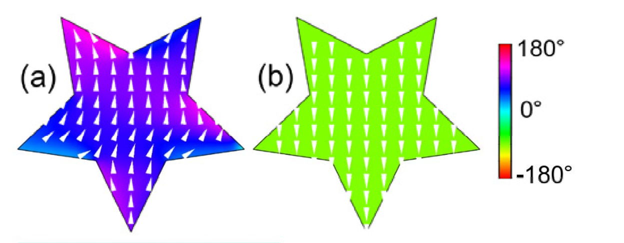




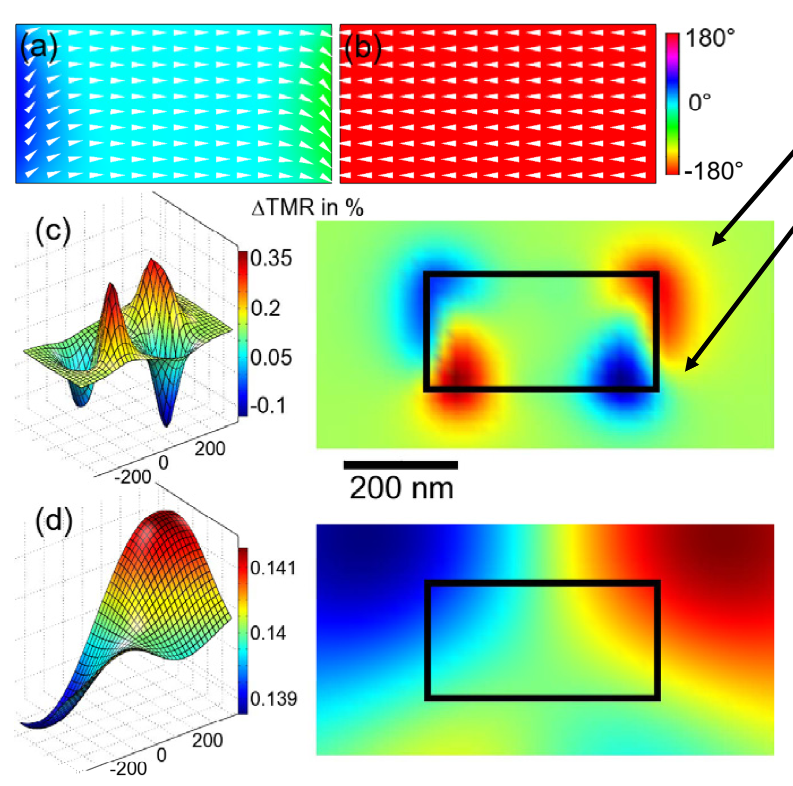
Sensor shape

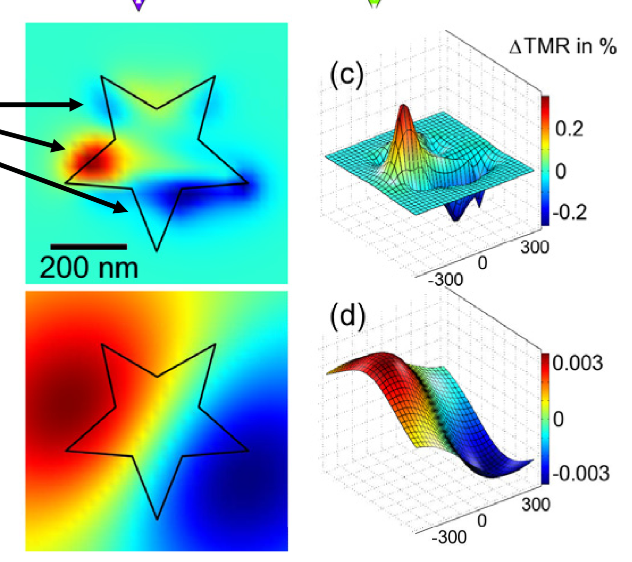


To overcome resolution limits and increase detection limits in respect to sensor-particle distance, modified geometries are employed.



New features!!
High resolution possible

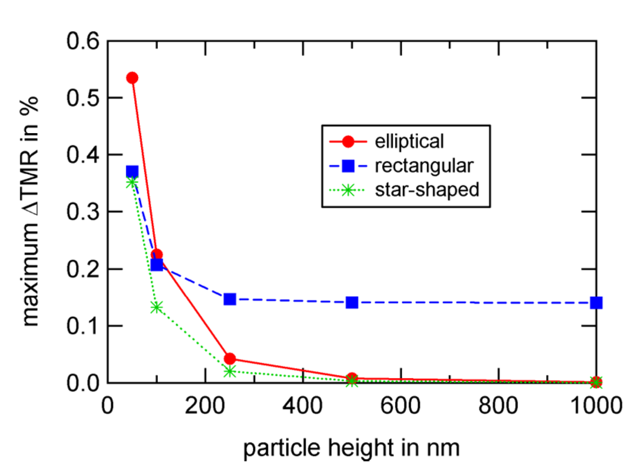




Significantly increased detection range for rectangular sensors!!
Areas along boundaries can easily be switched even by weak fields [8].

(a) initial state of top ferromagnetic electrode
(b) initial state of bottom ferromagnetic electrode
(c) ΔTMR-map for a distance of 50 nm
(d) ΔTMR-map for a distance of 500 nm

Shape comparison



The signal strength strongly benefits from the sensor shape.

IN-FLOW DETECTION LIMITS STRONGLY DECREASED

References and further information:

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[3] A. Weddemann et al., *Particle flow control by induced dipolar particle interactions*, submitted to Lab-Chip
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[6] C. Albon et al., *Tunneling magnetoresistance sensors for high resolutive particle detection*, Appl. Phys. Lett. **95** (2009)
[7] C. Albon et al., *Number sensitive detection and direct imaging of dipolar coupled magnetic nanoparticles by tunnel magnetoresistive sensors*, accepted for publication in Appl. Phys. Lett.
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[9] A. Weddemann et al., *Detection of agglomerated magnetic particle clusters*, in preparation

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