Magnetization Reversal in Granular Nanowires

Hermann Forster, Thomas Schrefl, Josef Fidler, Kornelius Nielsch, Herbert Hofmeister, Helmut Kronmüller, and Saskia Fischer

Abstract— **We simulate the switching process of granular Co nanowires using the finite element method. The wires have a diameter of 55 nm and a length of 1000 nm. TEM investigations show two different types of grains. One is randomly oriented in a plane perpendicular to the long axis of the wire and the other has the magnetocrystalline easy direction parallel to the long axis. The numerical results show that finite element micromagnetics can explaiin the influence of the microstructure in magnetic nano-systems.**

Keywords— **Style file, LaTeX, IEEE Transactions.**

I. Introduction

Progress in magnetic storage media is important for the information technology. One possibility to increase the areal density are patterned perpendicular media, where one bit of information corresponds to one single-domain nano-sized particle, a so-called nanomagnet. For example, an areal density of about 300 GBit/in^2 can be achieved by a hexagonal arranged array of nanomagnets with a lattice constant of about 50 nm [1].

In this work a array of Co nanowires is produced based on hexagonally-arranged porous-alumina templates [2]. The magnetzation is investigated by superconducting quantum interference device magnetometer measurements (SQUID). A TEM image is the starting point for the construction of a finite element model. The simulation is carried out in the framework of micromagnetics.

II. Finite element method in micromagnetics

Micromagnetics is a continuum theory for the description of magnetization processes in ferromagnetic materials. The theory starts from the total magnetic Gibbs free energy [3]:

$$E_t = \int \left[A \sum_{i=1}^{3} \left(\nabla \beta_i\right)^2 - K_u \left(\mathbf{u} \cdot \beta\right)^2 - \frac{1}{2}\mathbf{J} \cdot \mathbf{H}_\mathrm{d} - \mathbf{J} \cdot \mathbf{H}_\mathrm{ext} \right] dV \quad (1)$$

A is the exchange constant, β_i denotes the direction cosines of the magnetic polarization vector, $\mathbf{J} = (\beta_1, \beta_2, \beta_3)\mathbf{J}_\mathrm{s}$. K_u and $\mathbf{u}$ are the magneto-crystalline anisotropy constant and the anisotropy direction. $\mathbf{H}_\mathrm{ext}$ is the external field. The demagnetizing field, $\mathbf{H}_\mathrm{d}$, follows from a magnetic scalar potential. The magnetic scalar potential solves the magnetostatic boundary value problem and can be effectively computed using a hybrid finite element / boundary element method [4]. Since A, J_s and K_u are a function of space, we have the possibility to describe granular structures.

H. Forster, T. Schrefl and J. Fidler are with Vienna University of Technology, Wiedner Hauptstr. 8-10, A-1040 Vienna, Austria, phone: +43 1 58801 13729, fax:+43 1 58801 13798, email: hermann.forster@tuwien.ac.at. K. Nielsch and H. Hofmeister are with Max-Planck-Institute of Microstructure Physics, Halle, Germany. H. Kronmüller is with Max-Planck-Institute of Metal Research, Stuttgart, Germany. S. Fischer is with Dept. of Electrical Engineering, Ruhr University Bochum, Germany.
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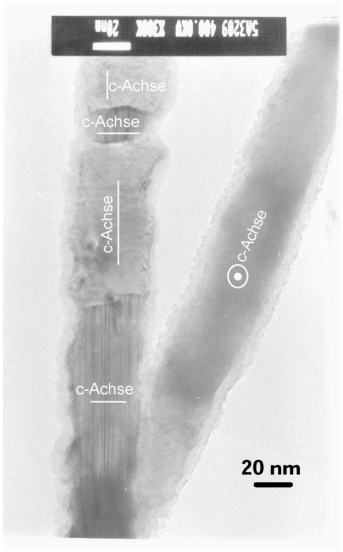

Fig. 1. TEM image of a Co-nanowire.

The actual path of the system towards a local minimum is obtained from the time integration of the Gilbert equation of motion [5]:

$$\frac{\partial \mathbf{J}}{\partial t} = -|\gamma| \mathbf{J} \times \mathbf{H}_\mathrm{eff} + \frac{\alpha}{\mathbf{J}_\mathrm{s}} \mathbf{J} \times \frac{\partial \mathbf{J}}{\partial \mathbf{t}} \quad , \quad (2)$$

The effective field $\mathbf{H}_\mathrm{eff}$, which provides the torque acting on the magnetization, is the negative variational derivative of the magnetic Gibbs free energy, $\mathbf{H}_\mathrm{eff} = -\delta \mathbf{E}_\mathrm{t} / \delta \mathbf{J}$. The first term describes the gyromagnetic precession, where γ is the gyromagnetic ratio. The second term describes the damping which is characterized by the Gilbert damping constant α. In equilibrium the torque, $\mathbf{J} \times \mathbf{H}_\mathrm{eff}$, vanishes and the magnetic polarization is at rest.

To solve the partial differential equations 2 for the whole sample we use the finite element method. Therefore we have to divide the magnetic sample into tetrahedral finite elements. Within each element the direction cosines β_i are interpolated by a linear function. The time integration is performed using a backward differentiation method (BDF).

III. Sample Geometry

Co nanowires were grown in highly-ordered anodic alumina templates using electrodeposition. This technique yields completely metal-filled alumina membranes. The nanowires are arranged in a hexagonal lattice. The diameter of one nanowire is 55 nm and the lattice spacing is 100 nm. The typical length is 1000 nm.

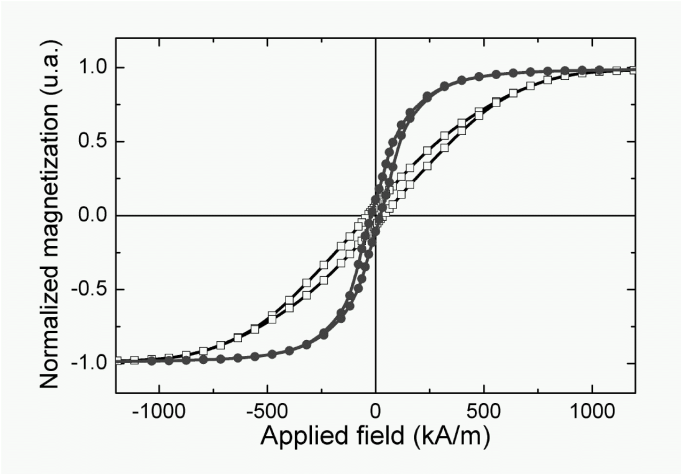

Fig. 2. Experimental result of the hysteresis curves for applied field parallel (full lines) and perpendicular (dashed lines) to the long axis.

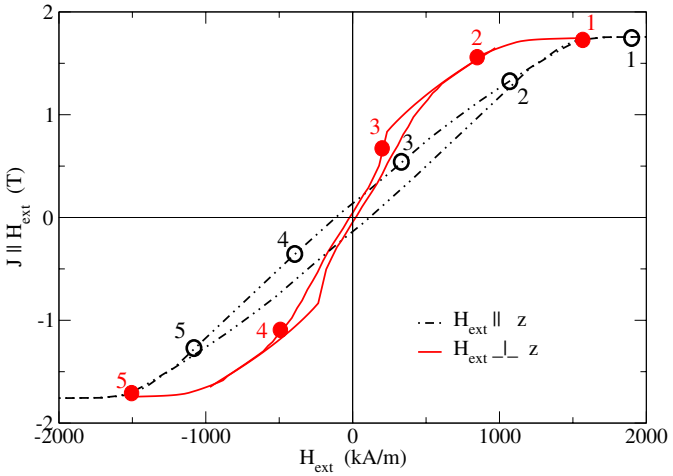

Fig. 3. Hysteresis curves for applied field parallel (dashed lines) and perpendicular (full lines) to the long axis. Numbered points correspond to snapshots in fig. 4 and fig. 5.

Fig. 1 shows a TEM image of one Co nanowire. Obviously there are two types of grains. The first type has a magnetocrystalline easy axis randomly oriented in a plane perpendicular to the long axis of the wire. The typical length of these grains is 100 - 250 nm. Grains of the second type have a length of less than 100 nm and a magnetocrystalline easy direction parallel to the long axis. The first kind of grains has a total volume fraction of the Co nanowire of 70 - 90 %.

The simulation of an array of nanowires would exceed computational power. Therefore we just model a finite element model of one nanowire. The influence of the other nanowires due to the strayfield is taken into account by a demagnetization factor. Our model of one nanowire consists of seven Co-grains. The material parameters are $J_\mathrm{s} = 1.76$ T, $A = 1.3\times10^{-11}$ J/m and $K_\mathrm{u} = 4.5\times10^{5}$ J/m^3 [6]. The total length of the sample is 1000 nm and the diameter is 55 nm. The grains are separated by a thin film (5 nm) of reduced exchange and saturation polarization to decrease coupling between the grains. Fig. 4 shows the geometry of our model. The smaller grains have a magnetocrysalline easy direction parallel to the long axis, instead in the bigger grains the easy axes are randomly distributed in a plane perpendicular to the long axis. The results haven't been dependent on the mesh size. Since we are only interested in equilibrium properties, it is enough to use a element size of 10 nm, which results in 4387 nodes and 16960 elements.

IV. Results

A. Experimental results

The magnetic properties of Co-filled nanopore arrays are carefully investigated by superconducting quantum interference device magnetometer measurements (SQUID). The external field is applied parallel and perpendicular to the long axis. The hystereses are measured parallel to the external field. Fig. 2 shows the result. Both orientations show just a little hysteretic behaviour resulting in small remanence ($J_\mathrm{R}/J_\mathrm{S} \leq 11$ %) and coercive field ($H_\mathrm{C}^{\parallel} \approx 40$ kA/m, $H_\mathrm{C}^{\perp} \approx 20$ kA/m). The result shows that the magnetic easy axis is perpendicular to the long axis of the nanowire. This effect can't be described only by the strayfield. We do have to take into account the grain structure. Since 70 - 90 % of the grains have a magnetocrystalline easy axis perpendicular to the long axis we have a reduced anisotropy of the whole nanowire.

B. Simulation

For the simulation we use the model described above. The external field is applied parallel and perpendicular to the long axis. Initial point is the Co nanowire totally saturated parallel to the long axis. Then the external field is instantanously applied with a strength of 1400 kA/m. For each applied field value we simulate till the equilibrium state is arrived. This is defined according to eq. 2, when the torque is less than 1×10^{-3}. Then the external field is reduced by 28 kA/m. After the simulation of the total hysteresis curves, we have to consider that we just simulate one nanowire, instead the experimental measurement is the result of the interaction of an array of nanowires. Therefore the demagnetizing effects have to be taken into account according to:

$$H_\mathrm{ext} = H_\mathrm{app} + N \cdot M \tag{3}$$

The resulting external field H_ext is the sum of the applied field H_app and a demagnetizing field $N \cdot M$. The demagnetizing factor N is dependent on the direction. In our case we have to distinguish between parallel to the long axis ($N_{\parallel}$)and perpendicular to the long axis ($N_{\perp}$). Because of the above mentioned grain structure of a Co-nanowire we have to consider the strong demagnetizing effects perpendicular to the long axis. Therefore we use $N_{\perp} = 0.9$. Instead for the parallel case we can neglect it more or less and use $N_{\parallel} = 0.1$.

The resulting hysteresis curves can be seen on fig. 3. Obviously is the good qualitative agreement with the ex-

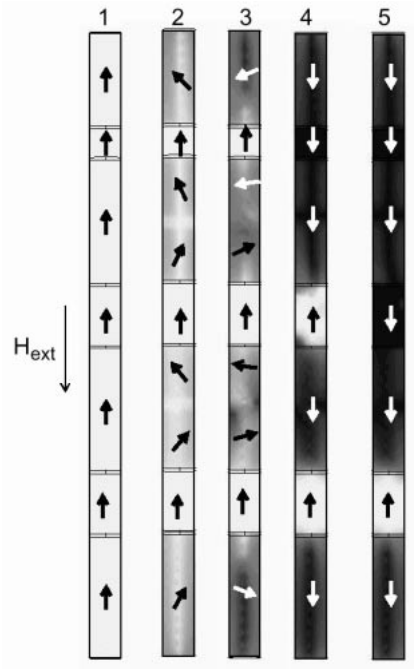

Fig. 4. Snapshots of the magnetization reversal according to the open points in fig. 3. The external field is applied parallel to the long axis. The greyscale represents the magnetizion parallel to the long axis.

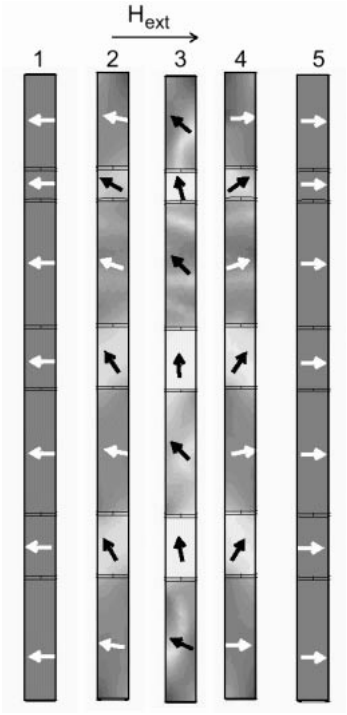

Fig. 5. Snapshots of the magnetization reversal according to the full points in fig. 3. The external field is applied perpendicular to the long axis. The greyscale represents the magnetizion parallel to the long axis.

perimental result of fig. 2. The nanowire shows just a small hysteretic behaviour. The values for the coercive fields are by a factor 2 bigger than the experimental values. Fig. 4 and 5 show snapshots of the magnetization distribution in the nanowire during the magnetic reversal. The greyscale represents the magnetization parallel to the long axis. For the perpendicular case the magnetization starts to turn in the smaller grains, which have a magnetocrystalline easy direction parallel to the long axis. As the external field is decreased enough also the magnetization in the bigger grains with magnetocrystalline easy direction perpendicular to the long axis start to rotate. But in these grains the reversal is finished faster, due to the fact that the external field has to be strong to rotate the magnetization out of the easy directin in the smaller grains. Contrary in the parallel case the reversal starts in the bigger grains.

We also performed simulations neglecting the granular structure of the Co nanowire. This means the nanowire is just one single crystal with uniaxial anisotropy either parallel or perpendicular to the long axis. The simulations clearly show that we do have to take into account the granular structure to achieve a good qualitative agreement with the experiment.

V. Conclusions

Numerical micromagnetic calculations have been carried out to investigate the influence of the granular structure of Co nanowires on the magnetization reversal. Therefore a model has been created from a TEM image. The TEM image has shown that there exist two kind of grains in the Co nanowires with different magnetocrystalline easy directions. The numerical results show that finite elment micromagnetics can explain the influence of the microstructure in magnetic nano-systems.

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