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Magnetization reversal process in thin Co nanowires

B. Hausmanns[a,*], T.P. Krome[a], G. Dumpich[a], E.F. Wassermann[a], D. Hinzke[b], U. Nowak[b], K.D. Usadel[b]

[a] *Tieftemperaturphysik, Gerhard-Mercator-Universität Duisburg, 47048 Duisburg, Germany*
[b] *Theoretische Tieftemperaturphysik, Gerhard-Mercator-Universität Duisburg, 47048 Duisburg, Germany*

Abstract

The magnetoresistance of single Co nanowires of various widths is investigated at low temperatures applying magnetic fields $\mu_0 H$ up to 4.5 T. The in-plane longitudinal magnetoresistance shows pronounced features at coercive fields H_c explained by the anisotropic magnetoresistance indicating the magnetization reversal process. Monte Carlo simulations present the magnetization distribution during the reversal process, revealing different mechanisms depending on the wire width.

Keywords: Numerical simulation studies; Magnetization reversal; Nanostructures

Recently, it has been proposed that magnetization reversal processes in magnetic nanostructures can be investigated by means of magnetoresistance (MR) measurements [1]. It has already been shown that the anisotropic MR (AMR) is sensitive to the domain structure and magnetization reversal process in nanostructures [2]. This is due to the fact that the resistance depends on the relative orientation between magnetization **M** and current direction **I** [3].

In contrast to many other experiments investigating ferromagnetic gratings [4] or electrodeposited nanowires [5] we are dealing with single Co nanowires prepared by electron beam lithography onto GaAs substrates. Their general dimensions are 40 nm in thickness and 30 μm in length while the width is varied between 200 nm and 4 μm. The morphology and the crystal structure are investigated by transmission electron microscopy. We find that the Co wires are polycrystalline with a typical grain size of about 7 nm. The crystal structure is mainly HCP. Using a four-probe DC technique the resistance is measured for magnetic fields applied in plane parallel to the current direction (longitudinal magnetoresistance ($MR_{\parallel}$)) as well as perpendicular (in plane and out of plane) to **I**. The experiments are carried out in a temperature range between 4.2 and 40 K. We find that the MR saturates for large magnetic fields ($B \simeq 4.5$ T). The saturation value $R_s(\alpha)$ decreases proportional to $\cos^2(\alpha)$ with α being the angle between **M** and **I** exhibiting the AMR [3]. By comparing the saturation resistances for the longitudinal case ($\alpha = 0^\circ$) which is interpreted as 0% transverse **M** and the perpendicular case ($\alpha = 90^\circ$) which is interpreted as 100% transverse magnetization, we get typical values of the relative resistance decrease of $\Delta R_s = (R_s(0^\circ) - R_s(90^\circ))/R_s(0^\circ)$ of the order of 1% (at $T = 4.2$ K). These results and experimental details are described elsewhere [6].

$MR_{\parallel}$ is almost constant for higher magnetic fields ($B \geqslant 0.3$ T) indicating that contributions caused by the classical Lorentz MR have not to be taken into account. However for low magnetic fields ($-0.3\,\mathrm{T} \leqslant B \leqslant 0.3\,\mathrm{T}$), we observe small negative resistance contributions indicating a hysteretic behavior. This is shown in Fig. 1, where we plot $\Delta R = (R(B, 0^\circ) - R_s(0^\circ))/R_s(0^\circ)$ in an extended scale versus the field $B = \mu_0 H$ for both field directions. The arrows indicate the measurement procedure.

As one can see from Fig. 1, we find the resistance suddenly decreasing at the coercive field H_c followed

*Corresponding author. Tel.: +49-293-379-2024; fax: +49-203-379-2098.

E-mail addresses: uli@thp.uni-duisburg.de (U. Nowak), britta@ttphysik.uni-duisburg.de (B. Hausmanns).

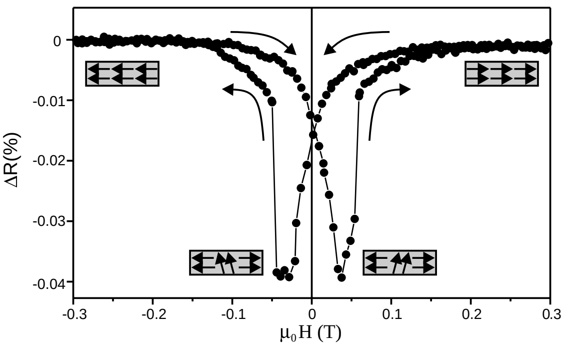

Fig. 1. Longitudinal magnetoresistance of a Co nanowire ($w = 529$ nm $T = 4.2$ K). It is shown the relative resistance value referring to the saturation value.

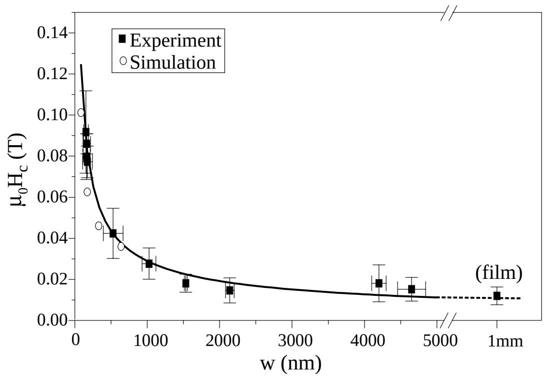

Fig. 2. Coercive field H_c as function of the wire width ($T = 4.2$ K). Theoretical values resulting from MC simulations at 4 K.

by a sharp positive resistance jump. Note that the resistance drop at H_c is of the order of $\Delta R \simeq 0.04\%$. However, if the magnetization would coherently change its direction when the external field is applied in the opposite direction the resistance drop at H_c should be of the order of 1%. We thus can exclude that coherent rotation is the dominating magnetization reversal process. Furthermore, we can estimate based on AMR that 'only' $\Delta R/\Delta R_s \simeq 4\%$ of the Co nanowire consist of domains with magnetization direction **M** perpendicular to the current direction **I** as indicated by the inset in Fig. 1. We observe similar behavior for smaller nanowires; however, the negative resistance peak broadens significantly indicating the onset of nucleation and propagation fields as already shown by Ebels et al. [5]. A detailed discussion of the experimental results of the wire width dependence of $MR_{\parallel}$ as well as the angular dependence of the MR is given in Ref. [6]. Thus, we explain the observed behavior by a nucleation process as will be discussed below on the basis of Monte Carlo (MC) simulations. We analyzed the longitudinal MR for Co nanowires of different width w. The result is shown in Fig. 2. The solid squares represent the experimental data including the value H_c of a Co film ($w = 1$ mm). The open circles reflect the results of Monte Carlo simulations carried out for a micromagnetic model explained below.

As one can see from Fig. 2 the coercive fields H_c show a reciprocal wire width dependence. The straight line in Fig. 2 is a fit to the experimental data with $H_c \sim 1/w$. This is in pretty good agreement with the results from the simulations and can be explained by the shape dependence of the stray field of the wire.

The reversal process plays a crucial role for understanding of the MR during hysteresis. In order to get a comprehension of the mechanism occurring during reversal processes in our Co nanowires numerical results which are based on a micromagnetic model are presented.

For the simulations we start with a classical Heisenberg Hamiltonian,

$$\mathcal{H} = -J \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j - \mu_s \mu_0 \mathbf{H} \cdot \sum_i \mathbf{S}_i - w \sum_{i<j} \frac{3(\mathbf{S}_i \cdot \mathbf{e}_{ij})(\mathbf{e}_{ij} \cdot \mathbf{S}_j) - \mathbf{S}_i \cdot \mathbf{S}_j}{r_{ij}^3}, \quad (1)$$

where the $\mathbf{S}_i = \mu_i/\mu_s$ are three-dimensional magnetic moments of unit length. The first sum represents the ferromagnetic exchange of the moments where J is the coupling constant, the second sum is the coupling of the magnetic moments to an external magnetic field **H**, and the last sum represents the dipolar interaction. The prefactor $w = \mu_0 \mu_s^2 / 4\pi a^3$ describes the strength of the dipole–dipole interaction with $\mu_0 = 4\pi \times 10^{-7}$ V s/Am. We do not consider any crystalline anisotropy, since the Co wires are polycrystalline so that in a first approximation — due to the random distribution of the easy axes — the influence of crystalline anisotropy is cancelled on larger length scales.

The Hamiltonian above is interpreted as the discretization of a continuum model on a length scale $a = 10$ nm which is of the order of the grain size in our sample. The transformation to the material parameters which are usually used in micromagnetism [7] is given by $J = 2aA_x$ where $A_x = 1.3 \times 10^{-11}$ J/m is the exchange energy and $\mu_s = M_s a^3$ where $M_s = 1.43 \times 10^6$ A/m is the spontaneous magnetization. Throughout this paper, we consider Co nanowires with fixed length $l = 1280$ nm and thickness $t = 40$ nm and we vary the width w from 80 to 320 nm. All our simulations start with a configuration where all spins are parallel to the wire. For the simulation we use a MC method with a heat bath algorithm and single-spin-flip dynamics. The methods are described in detail in Refs. [8,9]. In order to compute the long-range dipole–dipole interaction efficiently we use fast Fourier transformation methods [10]. The temperature T is 4 K.

Fig. 3 shows snapshots during the reversal process in a thin ($w = 80$ nm) and in a wider Co nanowire ($w = 320$ nm) close to the coercive field $\mu_0 H_c$. In the case of the thin wire two nuclei originate at the sample ends resulting in two 180° domain walls which pass the system during the reversal. For the wider wire a different reversal mechanism occurs. As shown before, this mechanism sets in at the sample ends but the domain structure during this reversal mode is rather complicated. Here, a domain structure consisting of several perpendicular in-plane domains fills up the inner part of the wire and 180° as well as 90° domain walls are formed. The crossover from this reversal by a complicated sample-filling domain structure to the quasi-one-dimensional behavior where two simple domain walls cross the sample is approximately at a wire width of 100 nm, a value which is little lower than the wire widths which we studied here experimentally. We hence conclude that the complicated domain structure shown here is relevant for the interpretation of our MR measurements.

Fig. 4 shows the corresponding simulated hysteresis curves. As was already demonstrated in Fig. 2 the coercive field is in good agreement with our experimental value. For the AMR the fraction of magnetic moments which are perpendicular to the current is relevant. Therefore, in addition to the longitudinal magnetization m_z, we also study the behavior of the magnetization perpendicular to the z axis which should directly be related to the AMR. In our data this perpendicular magnetization $m_\perp$ — as well as the longitudinal part — shows clearly a hysteresis where the peak of the perpendicular magnetization coincides with the coercive field. The peak value of $m_\perp$ is 48% of the saturation value, a value which is 12 times larger than the corresponding experimental drop of the MR (4% of

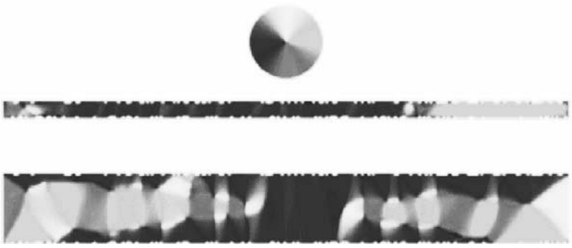

Fig. 3. Snapshots of simulated Co nanowires close to the coercive field $\mu_0 H_c$ for two different widths, $w = 80$ and 320 nm. The magnetization direction is gray scaled as shown in the circle (black: initial direction parallel to the wire).

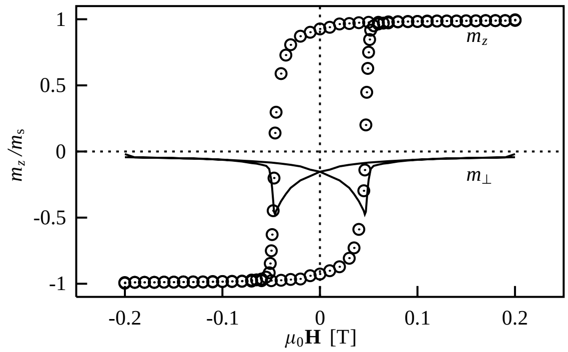

Fig. 4. Hysteresis curve for Co nanowire with a width of 320 nm. m_z is the longitudinal and $m_\perp$ the perpendicular magnetization. The latter is expected to resemble the anisotropic magnetoresistance.

the saturation value as discussed above). This deviation could be due to the fact that the experimentally investigated wires were 20 times longer so that it is less probable that the whole system is involved in the reversal at the same time. On the other hand, we cannot exclude MR contributions arising from domain wall scattering.

Thus, MC simulations determining the domain structure of Co nanowires with dimensions almost equal to those used for the experimental investigations allow us to characterize the magnetization reversal processes from which in turn the experimentally observed MR-date can be explained. Note that our interpretation is based on the simple assumption that the amount of perpendicular magnetization determines the MR due to AMR. Nevertheless, the close relation between $M(H)$- and $R(H)$-behavior shows that the magneto resistance is sensitive to magnetization reversal processes.

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