Domain wall resistance in (Co/Pt)₁₀-nanowires

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Abstract. – The clear separation of the domain wall magnetoresistance from the anisotropic magnetoresistance has been successfully achieved by investigating the transversal magnetoresistance of individual (Co/Pt)₁₀-nanowires. Since the magnetic easy axis of this nanowires is out of plane, the magnetization is always perpendicular to the current direction when applying a magnetic field transversally. Most importantly, even the domain walls do not give rise to an anisotropic resistance contribution by themselves under these conditions, and thus the pure domain wall magnetoresistance can be measured. The interpretation of the resistance behavior is confirmed by Monte Carlo simulations giving the magnetization distribution during the magnetization reversal process. It can be shown that the observed resistance behavior reflects the dependence of the domain wall magnetoresistance on the domain wall structure.

Introduction. – Since the experiments on iron whiskers showed that domain walls in a ferromagnet give rise to a positive resistance contribution [1], the effect of domain walls on the transport properties of ferromagnetic thin films and nanostructures became a topic of great interest. The first direct observation of the domain wall magnetoresistance (DWMR) was obtained by Gregg *et al.* [2]. They proposed that the positive resistance contribution of the domain walls is due to a combination of two effects: 1) The coincidence of the precessional behavior of the spins of the conduction electrons with the local variation of the exchange field while passing through the domain wall. 2) Spin-dependent scattering in the domain walls causing a mixture of majority and minority spins as has been described for the giant magnetoresistance (GMR) effect. This positive DWMR was theoretically explained [3,4] and observed in various experiments [5–8]. However, other experiments reveal negative domain wall resistance contributions [9,10] which have been explained by de-phasing effects in domain walls [11]. Up to now, a controversial discussion on whether the DWMR is positive or negative is still present even though recent investigations point out that the negative DWMR effect is mainly due to the anisotropic magnetoresistance of the domain wall itself [12]. The main difficulty in measuring the DWMR is that in most systems it is superposed by a strong anisotropic

magnetoresistance (AMR) [13], which depends on the direction of the magnetization relative to the current direction. A clear separation of both effects can hardly be achieved [6, 12] since even the domain walls themselves can give rise to AMR contributions.

To avoid this complication, we investigated individual (Co/Pt)₁₀-multilayer nanowires with a strong out-of-plane anisotropy [14]. In the remanent state these (Co/Pt)₁₀-nanowires show stripe or meander-like domains with alternating spin-up and spin-down magnetization, which is typical for thin films with out-of-plane anisotropy [8, 15]. Applying magnetic fields transversally to the wire axis forces the magnetization from out of plane to in plane, still perpendicular to the wire axis. Furthermore, the spins in the domain walls are also aligned parallel to the applied field. Therefore, all magnetic moments are oriented perpendicular to the current direction during the whole magnetization reversal process. Thus, a change in the resistance contributions due to the AMR can be excluded, which in turn provides a determination of the DWMR.

Experiment. – The nanowires are prepared using a special two-step electron beam lithography (EBL) technique in combination with electron beam evaporation. In the first step, individual (Co/Pt)₁₀-nanowires with lateral dimensions of a length of $l = 40\ \mu\text{m}$ and of a variable width of $100\ \text{nm} \leq w \leq 1\ \mu\text{m}$ are prepared. The (Co/Pt)₁₀-multilayers consist of a 15 nm thick Pt buffer layer followed by 10 bilayers of 0.3 nm Co and 1 nm Pt. Finally, the system is capped with a 1 nm thick Pt layer. The resulting film is polycrystalline with mean grain sizes of about $\Phi_K \simeq 7\ \text{nm}$ as obtained by transmission electron microscopy. The crystal structure of Co is fcc as determined by electron diffraction.

Since it has been shown that magnetic contacts influence the magnetization reversal process of nanowires [16], we use non-magnetic gold contacts, which are precisely attached to the magnetic wires in the second EBL step. The magnetoresistance measurements are carried out in a ⁴He-gas-flow-cryostat at a temperature of $T = 4.2\ \text{K}$ using an AC-4-point-probe resistance measurement technique with a resolution of $\Delta R/R \simeq 5 \times 10^{-6}$. Magnetic fields up to $B = 5\ \text{T}$ can be applied in the film plane. The longitudinal magnetoresistance is measured applying the field parallel to the wire axis. The transversal magnetoresistance is measured when the field is applied (in plane) perpendicular to the wire axis, *i.e.*, transversally. For magnetic characterization, magnetic force microscopy (MFM) as well as SQUID magnetometry have been used.

Magnetization measurements are carried out for (Co/Pt)₁₀-nanowire gratings consisting of 64000 single nanowires with a wire width of $w = 180\ \text{nm}$ and a distance between the nanowires of $d = 2\ \mu\text{m}$ using SQUID magnetometry. This distance has been chosen to minimize dipolar interactions between neighboring nanowires, which can be estimated to $B_{\text{dipole}} \simeq 0.3\ \text{mT}$. The magnetic field has been applied longitudinally, transversally and perpendicular to the wire axis. We find that for the three geometries the magnetization is saturated above $B = 1.5\ \text{T}$. The coercive field in the transversal geometry is $B_c(\text{transversal}) = 0.11\ \text{T}$, while for the longitudinal and polar geometry the measurements yield $B_c(\text{longitudinal}) = 0.135\ \text{T}$ and $B_c(\text{polar}) = 0.21\ \text{T}$. When the magnetic field is applied transversally, the value of the remanent magnetization, which is only about 30% of the saturation magnetization, indicates—in agreement with our MFM investigations—that the remanent state has a multi-domain structure. From these data we find in agreement with the shape of the hysteresis curves that the out-of-plane (polar) axis is the magnetic easy axis of the (Co/Pt)₁₀-nanowires, while the hardest axis is oriented transversally to the wire axis.

To check the magnetization state of the nanowires we investigated the domain structure using magnetic force microscopy (MFM) at room temperature. Figure 1 shows MFM images of the remanent state of a 400 nm wide (Co/Pt)₁₀-nanowire after applying a magnetic field of $B = 2\ \text{T}$ in longitudinal direction (fig. 1(a)) and in transversal direction (fig. 1(b)), respec-

Fig. 1 – (Color online): Magnetic force micrographs of an individual $(\text{Co/Pt})_{10}$ -nanowire with a wire width of $w = 400 \text{ nm}$ in remanence after a magnetic field of $B = 2 \text{ T}$ has been applied (a) longitudinally, (b) transversally. Both pictures show a comparable meander-like multi-domain remanent state with up and down magnetized domains.

tively. As one can see from fig. 1, the meander-like formation of dark and bright contrasts along the wire—which indicate the presence of out-of-plane stray fields—is rather similar in both cases. This means that the remanent state of the nanowire is almost independent of the direction of the saturation field, *i.e.*, independent of whether the field has been applied transversally or longitudinally. In both cases, meander-like domain patterns are created where the magnetization points up and down as expected for systems with perpendicular anisotropy [8, 15]. In these systems the shape anisotropy plays a minor role as compared to the magneto-crystalline anisotropy.

The magnetization behavior of individual nanowires can be probed by magnetoresistance measurements as has been shown earlier [17–19]. For the present $(\text{Co/Pt})_{10}$ -nanowires the magnetoresistance has been measured at $T = 4.2 \text{ K}$ applying magnetic fields in plane in the transversal as well as in the longitudinal direction. Typical results of the magnetoresistance measurements are given in fig. 2 for a $w = 110 \text{ nm}$ wide individual $(\text{Co/Pt})_{10}$ -nanowire. The open symbols describe the longitudinal magnetoresistance and the filled symbols the transversal magnetoresistance.

The *longitudinal* magnetoresistance in fig. 2 (open symbols) shows a hysteretic behavior with pronounced minima. This can be understood as arising from the anisotropic magnetoresistance (AMR) [17]. In the saturated state, the magnetization is aligned parallel to the applied field, *i.e.*, parallel to the wire axis and therefore parallel to the current direction corresponding to a high resistance value. When the magnetic field is reduced, the longitudinal magnetoresistance decreases, which is due to an increasing fraction of magnetization oriented perpendicular to the current direction. Passing through $B = 0 \text{ T}$, the resistance still decreases until it rapidly increases for magnetic fields $|B| > |B_c(\text{longitudinal})| \simeq 0.1 \text{ T}$.

The resistance behavior in the vicinity of the remanent state is shown in the right inset of fig. 2. As discussed above, the remanent state of the nanowires is characterized by the presence of spin-up and spin-down domains (see fig. 1). However, starting from the longitudinal saturated state the spins *inside* the domain walls still have (for $B = 0 \text{ T}$) longitudinal magnetization components. Applying a magnetic field in the opposite direction leads to a rotation of the spins inside the walls with components perpendicular to the current direction. This gives rise to a tiny negative anisotropic resistance contribution arising from the domain walls themselves at $B \simeq \pm B_c(\text{longitudinal})$.

The transversal magnetoresistance (filled symbols in fig. 2) shows a completely different behavior. In the saturated state the magnetization is aligned in plane perpendicular to the wire axis, *i.e.*, perpendicular to the current direction. Since in this state all spins are aligned perpendicular to the current direction, the AMR has its lowest value. Consequen-

Fig. 2 – Resistance of a single (Co/Pt)₁₀-nanowire ($w = 110$ nm) as a function of the applied field measured at $T = 4.2$ K. Longitudinal (open symbols) and transversal (filled symbols) magnetoresistance in a field range of $-2 \text{ T} \leq B \leq 2 \text{ T}$. The horizontal dashed line indicates the resistance value in the remanent state.

tially, the total amount of the AMR is indicated by ΔR_{AMR} in fig. 2. Reducing the applied field to $B \simeq 0$ T, we observe a continuous increase of the transversal magnetoresistance. Since the (Co/Pt)₁₀-nanowires have a perpendicular (out-of-plane) anisotropy, spins aligned in the transversal direction will coherently rotate from in plane to out of plane forming spin-up and spin-down domains when reducing the external field. Note that in this case the magnetization is *always* oriented perpendicular to the current direction. This means that AMR contributions arising from the domains are negligible.

The spins inside the domain walls are aligned transversally as long as the field is applied. Reversing the magnetic field causes a spin rotation inside the domain walls with longitudinal components which lead to a tiny increase of the magnetoresistance due to AMR (shown in the left inset in fig. 2 on an enlarged scale). Note that this resistance contribution is rather small (only of the order of 2% of ΔR_{AMR}) as compared to the total AMR and almost of the same amount as in the longitudinal case (see the right inset in fig. 2). This means that a small AMR contribution arising from the *domain walls* has to be taken into account *only* in the vicinity of the remanent state ($-B_c < B < B_c$), whereas for $|B| > |B_c|$ all AMR contributions can be neglected as confirmed by our simulations.

Increasing the transversal field above $B = |B_c|$ leads the up and down oriented spins in the domains to rotate coherently from out of plane to in plane, thereby increasing the domain wall widths. Since therefore all spins in the nanowire remain oriented perpendicular to the current direction during the whole magnetization reversal process, we experimentally observe a positive DWMR for the present (Co/Pt)₁₀-nanowires.

Simulation. – For a further confirmation of the considerations above, simulations have been performed, based on a micromagnetic model where the (Co/Pt)₁₀-multilayer is reduced to a homogeneous material with effective material parameters. We consider a classical Heisenberg Hamiltonian as in [18], interpreted as the discretization of a continuum model on a length

Fig. 3 – (Color online): Snapshots of the magnetization distribution during the reversal process of a single (Co/Pt)₁₀-nanowire ($w = 112$ nm) simulated for $T = 5$ K. The field is applied in plane perpendicular to the wire axis. The corresponding field values are (top to bottom): $B = -1.0$ T, $B = -0.8$ T, $B = -0.3$ T, $B = -0.2$ T, $B = 0.2$ T, $B = 0.3$ T, $B = 0.8$ T, $B = 1.0$ T. The magnetization direction is given in the color circle.

scale $a = 3.5$ nm which is well below the grain size of our samples. The material parameters which we use are an exchange energy $A_x = 6.5 \cdot 10^{-12}$ J/m, a saturation magnetization $M_s = 3.22 \cdot 10^5$ A/m, and a uniaxial out-of-plane anisotropy constant $K_u = 2.3 \cdot 10^5$ J/m³. The system size we consider is $512 \times 32 \times 4$ which corresponds to a length of 1792 nm, a width of 112 nm and a thickness of 14 nm.

We simulated transversal magnetization loops with field steps of 0.02 T, where we start with a configuration where all moments are parallel to the field. We used a Monte Carlo method with a heat-bath algorithm and single-spin-flip dynamics. In order to compute the long-range dipole-dipole interaction efficiently, we use fast Fourier transformation methods. All algorithms used are described in detail in [20]. The temperature is $T = 5$ K.

The magnetization component parallel to the applied transversal field shows a hysteresis behavior. We find a coercive field of $H_c \simeq 0.095$ T which is in good agreement with our experimental values. The magnetization component perpendicular to the applied field is almost zero and independent of the applied field. Since this component would give rise to the AMR effect, our simulations indeed show that AMR contributions can be neglected.

The snapshots of domain configurations during the reversal process in fig. 3 show which magnetization contributions occur during the reversal process. Starting with the magnetization aligned with the (negative) transversal field, first a stripe domain configuration arises upon increasing the field ($-0.8 \dots -0.2$ T) where the magnetization is oriented mainly out of plane within the domains and still aligned with the field within the domain walls. The remanent stripe domain structure results from the large magnetostatic energy for out-of-plane magnetization. At the coercive field the domain wall magnetization reverses with the field ($+0.2$ T). With increasing field values ($0.3 \dots 1$ T) the domain magnetization follows again the field into the transversal direction until saturation is reached.

Note that during the whole reversal process, the magnetization is either aligned parallel to the transverse field or is forced to rotate out of plane due to the strong crystalline anisotropy.

Note also that the number of domain walls remains constant after an initial arrangement where the domain walls try to find shapes with minimal length.

In contrast, the width of the domain walls changes during reversal, being minimal at the coercive field, while a further increase of the applied transverse field favors wider walls. At the same time, the angle of the domain walls varies from a 180° -wall at the coercive field to lower angles when the applied transverse field favors alignment with the field direction.

The zero-field domain wall width in CoPt can be estimated to be $\delta = 2\sqrt{A_x/K_u} \approx 10.6$ nm, a value which is rather small due to the high crystalline anisotropy.

Conclusion. – From these findings we conclude that we have indeed found a method where the AMR can be excluded as a source of the measured magnetoresistance effects. Resistance contributions arising from the Lorentz magnetoresistance (LMR) have not been detected within the resolution of our measurements of the order of 10^{-5} . This is in good agreement with Kohler’s plot [21], since we observe small grains sizes of about $\Phi_K \simeq 7$ nm and we find residual resistivity ratios of about $\text{RRR} \simeq 1.3$. Additional resistance contributions due to spin disorder scattering become only significant when approaching the Curie temperature [22, 23]. Since our resistance measurements are carried out at $T = 4.2$ K, these effects are not relevant.

The stripe domain structure which occurs in remanence provides a high number of domain walls leading to a measurable and well-defined, positive DWMR. To analyze the DWMR quantitatively, we determine the mean size of the remanent domains from an average over six simulations to about 300 nm. This is a rough estimation since we are using material parameters which are of course not known *a priori*. Moreover, the simulated domain configurations, even though calculated in the long-time limit, might still not resemble equilibrium properties. Nevertheless, the value of 300 nm is in agreement with the MFM data shown in fig. 1 and also those obtained for polycrystalline CoPt-films [24] and $(\text{Co}_x\text{Pt}_{1-x})_n$ -multilayers [25]. Hence, we estimate a number of approximately $n = 130$ domain walls for the investigated $(\text{Co/Pt})_{10}$ -nanowire with a length of $l = 40$ μm . As shown in fig. 2, the resistance contribution due to domain walls is $\Delta R_{\text{DWMR}} \simeq 1.9 \Omega$. The domain wall resistivity (per wall) is given by $\rho_w = \frac{1}{n} \Delta R_{\text{DWMR}} \cdot \frac{w \cdot t}{\delta}$. Using the experimental wire dimensions (wire width $w = 110$ nm, thickness of the $(\text{Co/Pt})_{10}$ -multilayer $t = 14$ nm), the calculated domain wall width $\delta = 10.6$ nm, and the estimated number of domain walls, we find a value of the domain wall resistivity of $\rho_w \simeq 0.23 \mu\Omega \text{ cm}$. This value is of the same order of magnitude as has been found for domain walls in a Co-film with $\rho = 0.52 \mu\Omega \text{ cm}$ [2] and in FePd-structures with $\rho \simeq 1 \mu\Omega \text{ cm}$ [8].

The calculated value of the DWMR is determined from the difference in resistance between the remanent and the saturated state (see fig. 2), *i.e.*, from the number of domain walls in the nanowire. Applying a magnetic field, one would expect that the number of domain walls decreases giving rise to specific jumps in the resistance behavior as has been observed in other experiments [8]. In contrast, as one can see from fig. 2, we observe a *continuous* decrease of the resistance with increasing field. Since our simulations show that the structure of the domain walls—their width as well as their angle—changes during the reversal process (and not the number of domain walls, see fig. 3), we propose that for the present $(\text{Co/Pt})_{10}$ -nanowires the continuous change of transversal magnetoresistance depends only on the change of the structure of the domain walls, rather than on a change of the number of the walls.

In conclusion, we found that $(\text{Co/Pt})_{10}$ -nanowires with a uniaxial out-of-plane anisotropy are suitable to investigate the DWMR without taking into account resistance contributions arising from the AMR. We clearly observe a positive DWMR in the remanent state which continuously decreases with increasing magnetic field. The latter behavior is probably due to a change of the width of the domain walls rather than of their numbers. This provides the possibility to study systematically the DWMR and its width dependence.

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