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Magnetotransport measurements as a tool to probe the micromagnetic configurations in epitaxial Co wires

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Abstract

The micromagnetic structure in epitaxial Co wires is investigated by using the magnetoresistance effect associated with the domain wall formation. This provides an efficient tool to monitor the magnetization reversal in systems with reduced lateral size. The influence of the lateral size and of the magnetic history on the micromagnetic configuration of the wires is considered. © 2002 Elsevier Science B.V. All rights reserved.

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The magnetic behavior of submicron systems has become a current topic of interest both from a technological and a scientific point of view. To study individual particles, new measurement techniques have been developed, such as Lorentz microscopy, electron holography, magnetic force microscopy (MFM) or microSQUID magnetometry. Magnetotransport measurements represent an alternative to these techniques since they show a good performance concerning the sensitivity and the spatial resolution at a large range of temperatures and applied field values. However, care has to be taken to differentiate between different magnetoresistance (MR) contributions, such as the anisotropic magnetoresistance (AMR), the Lorentz magnetoresistance or the domain wall magnetoresistance [1–3]. The contribution of these MR sources can be assessed by a proper orientation of the external field with respect to the crystallographic axes of the system.

In this paper, it is shown that the MR signal associated with the annihilation or the nucleation of individual domain walls can be monitored sensitively for flat rectangular Co wires, in which a regular stripe domain structure is stabilized.

The submicron wires were fabricated by electron-beam lithography and lift-off technique from epitaxial Co $(10\bar{1}0)$ thin films. The continuous films were deposited under ultrahigh vacuum conditions on (1 1 0) MgO substrates using a Mo–Cr buffer layer. Structural and magnetic investigations confirm their HCP structure and a strong and well defined in-plane uniaxial anisotropy [4]. The patterned configurations contain a right angle elbow (Fig. 1a), with wire segments which are oriented parallel, respectively, perpendicular to the easy axis. In this paper, only the latter configuration will be of interest (Fig. 1b). The whole conducting area (wire and contacts) is patterned from the Co film, with different 100 nm wide electrical contacts defined along the wire. A DC current of 0.5 mA is established through the ends of the wire ("I" contacts) and the ohmic potentials are measured between the voltage probes ("V" contacts), as shown in Fig. 1a. The MR hysteresis loops were studied for wires of different aspect ratios in the temperature range from 10 to 300 K and the resistivity of the wires was found to vary with the temperature from 2 to 15 $\mu\Omega$ cm.

Two characteristic types of MR hysteresis loops were found, which are described in the following for the case of (a) narrow (100 nm) and thick (90 nm) wires and (b)

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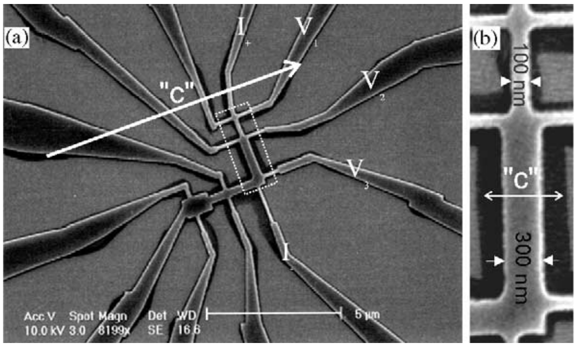

Fig. 1. (a) SEM image of the designed configuration. The crystal easy axis is indicated by "c"; the DC current is established through the contacts denoted by "I_+" and "I_-", while the voltage probes are denoted by "V_1", "V_2" and "V_3"; the white box indicates the part of the structure which is treated in the paper. A zoom of this part is shown in (b): two different lateral sizes were defined. The lengths of the segments are 1 μm, respectively, 2 μm, and the widths 100 and 300 nm.

wide (300 nm) and thin (30 nm) wires. For these dimensions, the competition between the magnetocrystalline anisotropy and the shape anisotropy induces a ground state stripe domain structure, whose periodicity lies on the order of 100–500 nm (in zero field, at room temperature). Typical magnetic force microscopy (MFM) images and a sketch of the stripe domain structure are shown in Figs. 2 and 3, respectively. Although the stripe domain state is the ground state, a single-domain state (SD) can be induced at remanence [5], depending on the wire width and thickness, but also on the magnetic history. In particular, after saturation in a field parallel to the easy magnetocrystalline anisotropy axis (perpendicular to the wire axis) a SD state occurs for wide and thin wires. This SD state corresponds to a local energy minimum, which is separated by an energy barrier from the stripe domain state. The barrier decreases, the narrower and the thicker the wires, due to the increase in the in-plane shape demagnetization fields, which favor the nucleation of reverse domains and thus stabilize a stripe domain structure at remanence.

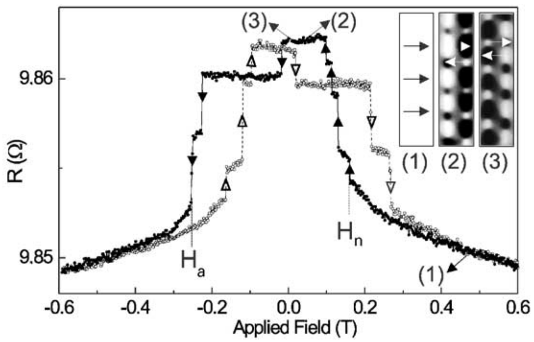

Fig. 2. The MR response of a 90 nm thick and 100 nm wide wire, at room temperature. Full circles and full line: the field is decreased from positive saturation (point (1)). Different stages along the cycle, after the nucleation of the walls (H_n) are illustrated by the MFM images (2) and (3). At the annihilation field (H_a), the walls are completely erased.

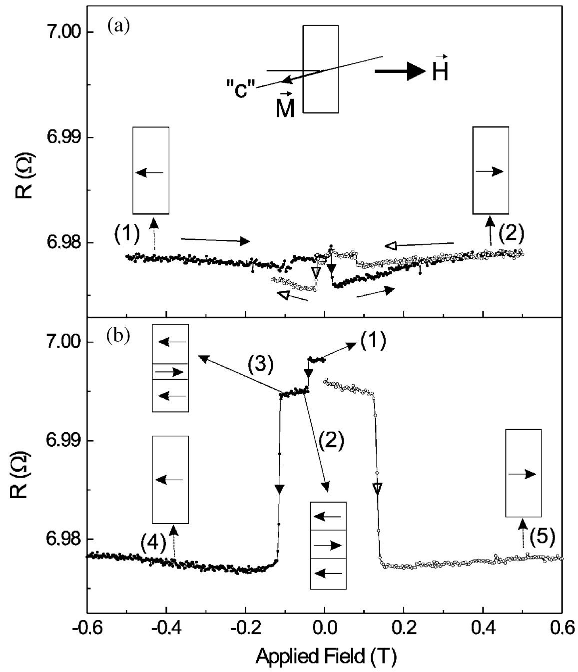

Fig. 3. (a) The MR hysteresis cycle of a 30 nm thick and 300 nm wide wire at 10 K. A schematic of the misalignment of the easy axis with respect to the normal to the wire axis. (b) MR curve corresponding to the remagnetization in a negative field (full circles) or in a positive field (open circles) applied perpendicular to the wire axis, after saturation in a field parallel to the wire axis.

The two different remanent states as a function of wire width and thickness are reflected in the magnetotransport measurements with the field applied along the easy axis. In this particular field configuration, the AMR contributions of the domains themselves are eliminated because the magnetisation inside the domains remains perpendicular to the current along the whole cycle. Hence, the variation of the magnetoresistive signal is related only to the nucleation/annihilation of the domain walls. Preliminary calculations indicate that the most important magnetoresistive contribution of the wall arises from the anisotropic magnetoresistance of the Néel-caps.

First, the MR hysteresis loop is discussed for a 100 nm wide and 90 nm thick wire in a field applied along the easy axis. A characteristic cycle at room temperature is shown in Fig. 2. Upon decreasing the field from positive saturation, the magnetic configuration evolves from a SD state—sketch (1)—to a stripe domain state—sketch (2). A first positive step in the resistance is observed at the field $H_n = 0.15\,T$, which is correlated with the nucleation of the first domain walls. Upon further decreasing the applied field, more domain walls are nucleated and a maximum in resistance is reached at about 0.1 T and maintained in zero applied field. As confirmed by MFM imaging, the number of walls remains constant in region (2)–(3). Only the size of the domains varies, but this has no effect on the MR signal. Reversing the field, the domain walls are successively erased (negative jumps at the annihilation fields H_a). The height of the jumps is directly proportional to the number of walls which are erased or nucleated. For the same wire, ten domain walls have been observed in the zero-field MFM images between the contacts. From this, it is concluded that the smaller jumps correspond to the annihilation/nucleation of two domain walls, and the other jumps are double or triple, corresponding to the annihilation/nucleation of four or six domain walls (the magnetoresistive contribution of a domain wall is about $0.001\,\Omega$).

In contrast to the previous situation, for a 300 nm wide and 30 nm thick wire, the remanent state after a saturation along the easy axis is a SD state [5] and the reversal takes place without the development of a stripe domain structure. The MR cycle in this case is shown in Fig. 3a, for $T = 10\,K$. The variation of the MR signal is mainly given by the Lorentz magnetoresistance, with small jumps occurring at low fields ($H = 0.02\,T$). These jumps are attributed to the reversal of the magnetization in the contacts and to a small misalignment of the "c" axis, as shown in the sketch of Fig. 3a.

For these wire dimensions, the ground state stripe domain structure is induced after saturation in a field applied along the wire axis, i.e. perpendicular to the "c" axis [5]. In this case the zero-field magnetoresistance, see point (1) in Fig. 3b, is much larger than the background signal shown in Fig. 3a for the SD state. Starting from the stripe domain structure, point (1), and applying a field along the easy axis into the negative direction—full circles, first the small drop due to the reversal of the contacts is seen ($H = -0.02\,T$), followed by a plateau—region (2)–(3). In this plateau, the number of walls remains constant, only the size of the domains varies, as indicated in the sketch of Fig. 3. Again, this has no effect on the MR signal. When the field exceeds a critical value ($H = -0.12\,T$), the resistance drops abruptly by a much larger amount (6 times larger than the small drop at $H = -0.02\,T$) due to the collapse of domain walls.

This low temperature reversal is consistent with field dependent MFM imaging at room temperature of the same sample. The difference between the micromagnetic configurations at low and room temperature is only the number of the walls: since at low temperatures the anisotropy energy and with this the wall energy is increased, the number of walls decreases.

Repeating this remagnetization procedure, but for fields applied along the positive direction (open circles, Fig. 3b), the small drop is absent, whereas the large jump due to the annihilation of the walls is present ($H = 0.15\,T$). The presence/absence of the small drop around 0.02 T in Fig. 3a and b is attributed to a variation of the AMR signal in the contacts arising from a small misalignment of the "c" axis as indicated in the sketch of Fig. 3a.

In conclusion, the micromagnetic configuration and the reversal process for Co $(1\,0\,\bar{1}\,0)$ submicron wires were monitored sensitively by magnetotransport measurements in accordance with MFM observations. This method is an alternative to the study of the magnetization in small systems, which can be hardly visualized by microscopy techniques under high applied magnetic fields and at low temperatures.

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References

[1] A.D. Kent, U. Rüdiger, J. Yu, L. Thomas, S.S.P. Parkin, J. Appl. Phys. 85 (1999) 5243.

[2] S.G. Kim, Y. Otani, K. Fukamichi, S. Yuasa, M. Nyvlt, T. Katayama, IEEE Trans. Magn. 35 (1999) 2862.

[3] U. Ebels, A. Radulescu, Y. Henry, L. Piraux, K. Ounadjela, Phys. Rev. Lett. 84 (2000) 983.

[4] I.L. Prejbeanu, L.D. Buda, U. Ebels, K. Ounadjela, Appl. Phys. Lett. 77 (2000) 3066.

[5] I.L. Prejbeanu, L.D. Buda, U. Ebels, M. Viret, K. Ounadjela, IEEE Trans. Magn. 37 (2001) 2108.