JOURNAL OF APPLIED PHYSICS VOLUME 85, NUMBER 8 15 APRIL 1999

Domain wall trapping probed by magnetoresistance and magnetic force microscopy in submicron ferromagnetic wire structures

Y. B. Xu, C. A. F. Vaz, A. Hirohata, C. C. Yao, W. Y. Lee, and J. A. C. Bland
Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, United Kingdom

F. Rousseaux, E. Cambril, and H. Launois
L2M/CNRS, 19 Avenue Henri Ravera, 92220 Bagneux, France

The magnetoresistance (MR) and domain structure of submicron NiFe wires and crosses fabricated using advanced electron beam lithography techniques have been studied in order to investigate the dependence of MR on the detailed domain configurations. While the 0.5 μm wire shows almost no longitudinal MR, the cross sample clearly shows a variation of the resistance upon sweeping the magnetic field, indicating an MR effect associated with the domain structures which form at the junction. By correlating the MR curves with the domain configurations obtained from magnetic force microscopy, we found that a 180° domain wall trapped in the junction of this 0.5 μm cross contributes a negative MR effect.
[S0021-8979(99)69708-0]

INTRODUCTION

Nanofabrication of mesoscopic magnets with size comparable to the critical diameter for a single domain particle ($\sim$10 nm-1 μm) has provided an opportunity to address key issues in nanomagnetism. One issue of great interest recently is the interplay of the electron transport and magnetic properties in mesoscopic magnets.[1–3] Studies of micron and submicron Ni,[1] NiFe,[2] and Fe[3]) wires have shown that the MR measurements yield detailed information concerning the behavior of the magnetization in these mesoscopic magnets. Hong and Giordano observed discontinuous changes of the resistance upon sweeping the field in Ni wires.[1] This was attributed to the nucleation and movement of domain walls (DW), which traverse the wire during magnetization reversal. Adeyeye *et al.*[2] found that the MR effect in FeNi wires can be interpreted in terms of the familiar anisotropic MR (AMR) effect. More recently, Ruediger *et al.*[3] has investigated the effect of the domain wall on the MR in micron Fe wires with controlled domain configurations. A negative DW contribution to the resistance was found. The effect of the domain wall on the MR was even observed in continuous ferromagnetic films at room temperature.[4] Theoretical models based on new physical mechanisms have been proposed very recently to interpret the MR due to DW scattering.[5,6] In this paper, we have designed and fabricated a structure which traps domain walls. The aim was to confine a limited number of domain walls in a junction with size comparable to the single domain width. The electric pads were fabricated as close as possible to the junction to probe the local MR response.

EXPERIMENT

Continuous films of Au(30 Å)/$Ni_{80}Fe_{20}$(300 Å)/GaAs (100) used for the patterning were deposited in an ultrahigh vacuum system. The deposition rate was 2 Å/min with a pressure of 6×10^{-9} mbar during growth. The substrate was held at 30 °C during growth and was then annealed at 120 °C for 30 min to remove the uniaxial anisotropy. Two sets of mesostructures were fabricated using electron beam lithography. One is a set of straight wires with width $w=0.5$, 1, 2, 5, and 10 μm and length fixed at 200 μm; the other one is a set of crosses with two wires of the same width joined perpendicularly together. Figure 1(a) is a scanning electron micrograph (SEM) of a 1 μm cross around the junction area.

Electrical contacts to the wires were made of Cr(20 nm)/Au(300 nm) for the transport measurements. Some of the electrical contacts were extended with large Al pads for better bonding. As shown in Fig. 1(b), there are eight pads connected to each cross sample for MR (four pads), as well as Hall effect measurements (other four pads). A dc current of 50 μA was passed through both ends of the wires and the voltage probes [as shown clearly in Fig. 1(a)] were placed very close (<2 μm) to the junction for four terminal MR measurements. The magnetic field was applied in the plane of the samples. The field was applied perpendicular and parallel to the current for the transverse MR (TMR) and longitudinal MR (LMR) measurements, respectively. All the measurements were carried out at room temperature. The domain imaging was carried out with a Digital II SPM using a low stray field tip for magnetic force microscopy (MFM). The

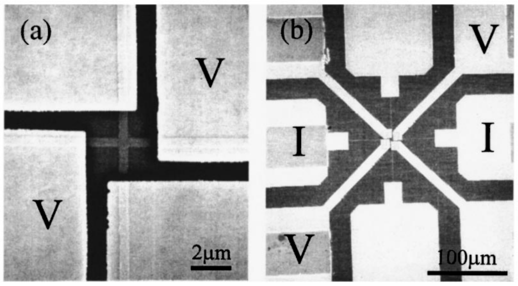

FIG. 1. (a) SEM micrograph around the junction area of a 1 μm width cross, and (b) large-scale micrograph showing the contact geometry.

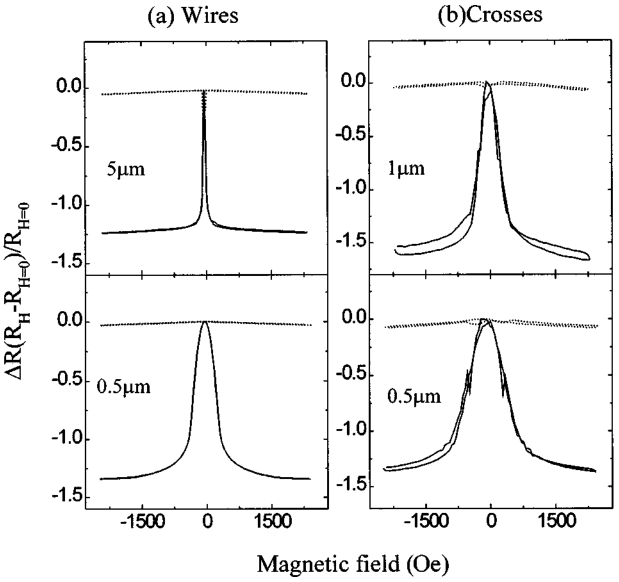

FIG. 2. The MR response of (a) 5 and 0.5 μm wires, and (b) 1 and 0.5 μm crosses. Solid lines: transverse MR, and dotted lines: longitudinal MR. The maximum applied magnetic field is 2.5 kOe.

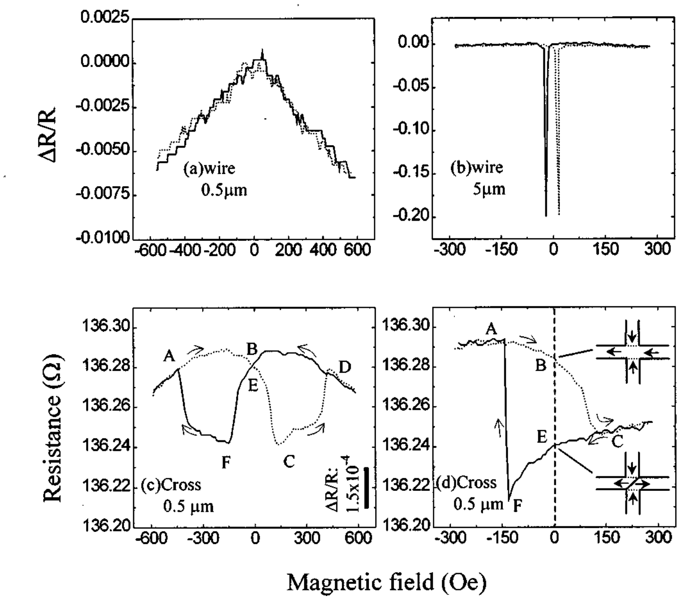

FIG. 3. The longitudinal MR of (a) 0.5 μm wire, (b) 5 μm wire, (c) 0.5 μm cross with applied field of 600 Oe, and (d) 0.5 μm cross with the applied field reduced to 300 Oe after the measurement (c). Inset in (d): schematics of the domain configurations at points B and E.

samples were imaged in the demagnetized state. We noticed that the stray fields from these submicron structures were rather weak in comparison with continuous film.

RESULTS

Figure 2 shows the MR curves of (a) wires of widths $w=5$ and 0.5 μm, and (b) crosses of widths $w=1$ and 0.5 μm for both the transverse and longitudinal configurations. The maximum applied field is about 2.5 kOe. The transverse MR of both the wires and crosses shows similar features to those seen previously in NiFe wires by Adeyeye *et al.*,[2] for which the dependence of TMR on the wire width has been studied in detail. The TMR response is determined by the AMR effect, as domain rotation dominates the magnetization process for the transverse measurements.

The longitudinal MR, however, is almost zero for both wires and crosses, as we can see from Fig. 2, in which both LMR and TMR values were plotted on the same scale. The resistance of the 0.5 μm wire varies linearly with magnetic field with a very small slope of about 1×10^{-5} per 100 Oe as shown in Fig. 3(a). No contribution from the magnetization reversal process to the MR is seen in this longitudinal configuration for 0.5 μm wire. The LMR of the 5 μm wire [as shown clearly in Fig. 3(b)] shows two sharp peaks of about 2×10^{-3}, much smaller than the TMR of 1.4×10^{-2}.

In contrast with the 0.5 μm wire, a significant LMR effect (a few 10^{-4}) upon sweeping the magnetic field was observed in the 0.5 μm cross as shown in Figs. 3(c) and 3(d). The characteristic of the MR of this 0.5 μm cross was found to depend on the detailed magnetization process. In Fig. 3(c) the field was swept between -600 and 600 Oe and in Fig. 3(d) the field was swept between -300 and 300 Oe starting from the remnant state (B) of Fig. 3(c). The MR curve in Fig. 3(c) is approximately symmetrical and the resistance values at zero field are almost the same for the two sweeps, namely, from $-H_{\max}$ to $+H_{\max}$, and from $H_{\max}$ to $-H_{\max}$. The MR response in Fig. 3(d) is strikingly different from that in Fig. 3(c). The MR curve is asymmetrical and the zero-field resistances are different for the two sweeps. The resistance difference between positions B and E is 0.04 ± 0.004 Ω, which is about 3×10^{-4} in terms of MR ratio.

Figure 4 shows the MFM image of the 0.5 μm cross around the junction area. A single domain state can be identified from the absence of contrast in the wire region, which is in agreement with a detailed MFM study of NiFe wires, which shows that the domain width in wires of this size is about 1 μm.[7] The domains of each wire are aligned along the

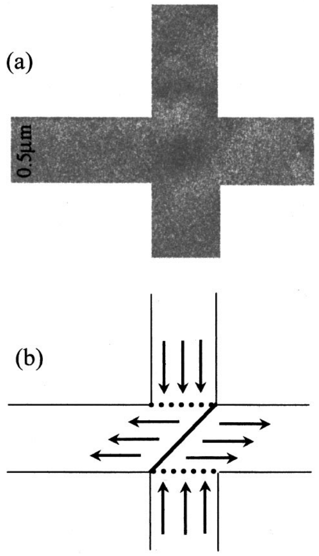

FIG. 4. (a) MFM image around the junction area of a 0.5 μm cross, and (b) schematic diagram of the domain configuration. The solid line across the junction and two dotted lines represent for a 180° wall and two 90° walls, respectively.

wire direction due to the strong shape anisotropy. The image of the junction area, however, shows significant contrast with a strong diagonal pattern visible, indicating the presence of domain walls. Figure 3(b) shows the schematics of the domain structure inferred from the MFM image. Three walls were formed in the junction area, one 180° wall (solid line) and two 90° walls (dotted lines). Thus we demonstrate that domain walls were created and trapped in the junction area in this ‘‘single domain width’’ structure. Micromagnetic simulations of the domain configurations of these crosses are underway.

DISCUSSION

The negative longitudinal MR around the coercive fields in the 5 μm wire is similar to that observed in multidomain wires and was attributed to the AMR effect.[8,9] In the case of a single domain wire, the magnetization **M** is either parallel or antiparallel to the current direction **I** and no AMR effect is expected. This was verified in the 0.5 μm wire, in which the resistance remains almost constant upon sweeping the field for the longitudinal measurement. The very slight variation of the resistance ratio of about 10^{-5} per 100 Oe may be due to the bulk like transverse MR effect, which is usually observed at high field.[2]

The significant LMR effect (a few $\times 10^{-4}$) observed in the 0.5 μm cross demonstrates the importance of the junction to the magnetotransport properties. The MR effect is clearly associated with a very limited number of domain walls in the junction area, as confirmed by the MFM images.

One question of fundamental interest is the contribution of domain wall scattering to the MR. The minimum resistances around points C and F in Fig. 3(c) correspond to the regions where the DWs appear, while points A and D mark where the walls are swept out of the system. When the maximum reverse field was reduced to a value large enough to create the wall, but not large enough to sweep the wall out of the sample, the wall will stay in the sample for a certain field range. In Fig. 4(d), the curve along C–F would correspond to the sample containing the walls created at point C. Based on the domain image of Fig. 4, the domain configurations at points B and E are shown in the inset of Fig. 3(d). For point B, the wire along the field (or current) direction was in a single domain state, and the wire along the perpendicular direction was split into two domains with two 90° walls near the junction. For point E, the 180° wall created at point C stayed in the sample along with the other two 90° walls. Therefore, the resistance difference between points B and E in Fig. 3(d) could be directly attributed to the MR effect of this single 180° wall across the junction area. The resistance of point E is smaller than that of point B. That means the wall made a negative contribution to the resistance.

The MR of the DW scattering has recently been observed in Fe[3] and Ni[1] wires, and continuous Co films[4] by controlling the domain structure and magnetization process. The work reported here is of particular interest in this context. By putting the voltage pads very close to the junction area, a significant MR effect was observed in the ‘‘single domain width’’ cross. The MR effect of a single 180° wall, confined in this submicron structure, has been found even at room temperature. The trapping of the domain walls has been confirmed by MFM imaging. It is interesting to note that the studies of Fe[3] and Ni[1] also show a negative MR contribution of domain walls. Based on a weak localization model, Tatara *et al.*[6] predicted a decrease in resistance associated with the nucleation of a wall. A detailed comparison between our experimental results and those of various theoretical models is beyond the scope of present paper. However, the MR effect associated with a simple controlled domain configuration as reported here should be of interest for theoretical simulations.

CONCLUSION

The MR and domain structures of submicron NiFe wires and crosses have been studied. Both MR and MFM measurements showed that a limited number of walls have been confined in the junction area in the ‘‘single domain width’’ cross-shaped structure. A negative MR effect of a 180° domain wall was observed in this submicron NiFe cross.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the EPSRC, Newton Trust (Cambridge), Toshiba and ESPRIT programme (‘‘MASSDOTS’’ project). C.A.F.V. is supported by Programa PRAXIS XXI—Fundação para a Ciência e Tecnologia (Portugal).

[1] K. Hong and N. Giordano, Phys. Rev. B **51**, 9855 (1995); Europhys. Lett. **36**, 147 (1996).

[2] A. O. Adeyeye, G. Lauhoff, J. A. C. Bland, C. Daboo, D. G. Hasko, and H. Ahmed, Appl. Phys. Lett. **70**, 1046 (1997).

[3] U. Ruediger, J. Yu, S. Zhang, A. D. Kent, and S. S. P. Parkin, Phys. Rev. Lett. **80**, 5639 (1998).

[4] J. F. Gregg, W. Allen, K. Ounadjela, M. Viret, M. Hehn, S. M. Thompson, and J. M. D. Coey, Phys. Rev. Lett. **77**, 1580 (1996).

[5] P. M. Levy and S. Zhang, Phys. Rev. Lett. **79**, 5110 (1997).

[6] G. Tatara and H. Fukuyama, Phys. Rev. Lett. **78**, 3773 (1997).

[7] A. Hirohata, Y. B. Xu, and J. A. C. Bland (unpublished).

[8] S. J. Blundell, C. Shearwood, M. Gester, M. J. Baird, J. A. C. Bland, and H. Ahmed, J. Magn. Magn. Mater. **135**, L17 (1994).

[9] R. Ferre, K. Ounadjela, J. M. George, L. Piraux, and S. Dubois, Phys. Rev. B **56**, 14066 (1997).