Magnetoresistance of Epitaxial Fe Wires with Varied Domain Wall Structure

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The low temperature negative domain wall (DW) contribution to the resistivity observed in epitaxial Fe microstructures has been investigated as a function of film thickness. The DW spin structure changes from Bloch to Neel-like with decreasing film thickness. Results suggest that an interplay between orbital effects in the internal magnetic fields near DWs and thin film surface scattering are at the origin of the observed negative wall contribution.

The effect of domain walls (DWs) on quantum and spin-dependent electron transport in magnetic nanostructures has been the subject of a number of recent theoretical and experimental studies [1–6]. In particular, detailed studies of the MR of epitaxial Fe wires with controlled stripe domains revealed a negative DW contribution to the resistivity at low temperature (< 80 K) [1,2]. This remarkable result was difficult to reconcile with existing theories of DW scattering [3] and an interesting model based on weak localization phenomena [4]. Here these effects are further studied in microfabricated wires of varied thickness and, hence, DW spin structure.

I. FABRICATION AND MAGNETIC CHARACTERIZATION

Epitaxial Fe (110) films of 25 nm, 50 nm, 100 nm, and 200 nm thickness were grown on a-axis (1120) sapphire substrates [1,2]. From these films Fe wires of 2 μm linewidth were microfabricated with the long axis perpendicular to the in-plane [001] uniaxial magnetocrystalline easy axis.

Magnetic Force Microscopy (MFM) images in Fig. 1 a) - c) show that the competition between magnetostatic, magnetocrystalline, and exchange interactions leads to a stripe domain pattern. All images were performed with a vertically magnetized tip in zero applied magnetic field after in-plane magnetic saturation parallel to the wire axis. The MFM images highlight the magnetic poles at the boundaries of the wire and above the DWs. Fig. 1 a) - c) show that there is a transition of the DW type as a function of thickness from Neel-like DWs (25 nm) to Bloch (50 to 100 nm) to canted Bloch Walls (200 nm). The transition from a Neel to a Bloch wall occurs when the thickness of the film is in the range of the DW width and is driven by the magnetostatic energy of the DW. If the wire is thinner than the DW width, the shape anisotropy of the DW favors a Neel-like DW in which the magnetization rotates in the plane. Following the same arguments, if the film thickness is greater than the DW width shape anisotropy favors Bloch-like DWs, with an out-of-plane rotation of the magnetization between adjacent stripe domains. Additionally, the subdivision of the DWs into sections of opposite chirality lowers the magnetostatic energy, as seen in Fig. 1 (a) and partly in (b). Canting of the walls as seen in Fig. 1 (c) further reduces the magnetostatic energy.

FIG. 1. MFM images in zero applied field of a (a) 25 nm, (b) 100 nm, and (c) 200 nm thick Fe wire of 2 μm width after longitudinal saturation.

II. TRANSPORT PROPERTIES

Low Field MR measurements were performed with an in-plane applied field oriented either longitudinal (||) or transverse (⊥) to the wire axis. The MR has the following general characteristics. There is structure to the MR in applied fields less than the saturation field (Hₛ), at which point the slope changes, and the resistivity then increases monotonically with field. Interestingly, the resistivity at Hₛ at high temperature (T > 70 K) is larger in the longitudinal than in the transverse field orientation (ρ⊥(Hₛ) > ρ∥(Hₛ)), while at low temperatures (T < 60 K), the situation is reversed (ρ∥(Hₛ) > ρ⊥(Hₛ)).
In these wires there are two predominant and competing sources of resistivity anisotropy. The first has its origins in the spin-orbit interaction and is known as anisotropic MR (AMR)–the resistivity extrapolated back to zero internal field \( (B = 0) \) depends on the angle between \( \mathbf{M} \) and \( \mathbf{J} \). The second effect is due to the anisotropy of the Lorentz MR, which generally depends on the angle of \( \mathbf{J} \) and \( \mathbf{B} \). Detailed MR measurements as a function of temperature and field angle have been used to determine these anisotropy contributions \( [2] \). At low temperatures, because of the large internal field in Fe \( (4\pi M = 2.2 \, \text{T}) \) and the decreased electron scattering rate, the anisotropy in the Lorentz MR is dominant, and leads to the observed reversal of the resistivity anisotropy.

For the purposes of this study it is sufficient to note that due to these competing effects there will be a temperature at which the in-plane resistivity anisotropy vanishes. We call this the compensation temperature \( T_{\text{comp}} \) and it is defined as the temperature at which \( \rho_\parallel(H = 0, T_{\text{comp}}) = \rho_\perp(H = 0, T_{\text{comp}}) \). This occurs close to 65 K for all the wires we have studied. Fig. 2 shows MR results at \( T_{\text{comp}} \) for wires of different thickness (a) 100 nm and (b) 200 nm. The slope in the MR above the saturation field is due to the Lorentz effect and the extrapolation of the high field MR to \( H = 0 \) (dashed lines) illustrates the resistivity compensation.

At this temperature the low field MR due to the magnetization reversal of the wires and, particularly, the in-plane reorientation of the magnetization should vanish. Fig. 2 (a) shows that a positive MR is associated with the erasure of DWs in the 100 nm thick wire, and is largest in the longitudinal field geometry in which the DW density at \( H = 0 \) is greatest \( [2] \). These results have been taken as evidence for a negative DW contribution to the resistivity. The DW MR is calculated as, \( \rho_d = \rho(H = 0) - \rho_{\text{eff}}(H = 0) \), where \( \rho(H = 0) \) is the resistivity measured at \( H = 0 \) and \( \rho_{\text{eff}}(H = 0) \) is the extrapolation to \( H = 0 \). The magnitude of \( \rho_d \) increases with increasing DW density \( [2, 3] \).

Fig. 2 (b) shows the MR of a 200 nm thick wire. The longitudinal MR is now negative at low fields and positive at higher fields. This low field negative MR is associated with a change in the magnetization reversal mode in thicker wires. The insets to Fig. 2 show MFM images of the magnetic structure in longitudinally applied fields at room temperature. In the 100 nm wire the reversal proceeds via the growth of favorably oriented longitudinally magnetized in-plane closure domains (inset Fig. 2(a)), whereas for the 200 nm thick film stripe domain configurations are observed (inset Fig. 2(b)). This latter image suggests that the magnetization has rotated out of the plane along \( \{100\} \) easy directions 45 degrees to the surface normal. The reduction in internal field (due to the strong demagnetization fields perpendicular to the film plane) is responsible for the low field drop in resistivity.

By establishing the magnetic state shown in Fig. 1(c) at room temperature by appropriate sample demagnetization and then cooling the sample to the MR measurement temperature (64.5 K), we find that the local maximum in the resistivity (longitudinal curve Fig. 2(b)) at \( H = 0 \) is associated with the canted DW structure (seen in Fig. 1(c)). Since the measured \( H = 0 \) resistivity is now observed to equal to the \( H = 0 \) resistivity extrapolated from the high field MR, \( \rho_d \) vanishes at this temperature for this wire.

**TABLE 1.** Characteristic data for 2 \( \mu \text{m} \) linewidth wires as a function of thickness.

| Thickness (nm) | 25     | 50     | 100   | 200   |
|---------------|--------|--------|-------|-------|
| \( \rho_d(1.5 \, \text{K})(\mu \Omega \cdot \text{cm}) \) | 1.2    | 1.48   | 0.71  | 0.45  |
| \( \rho_d(-65 \, \text{K})(\mu \Omega \cdot \text{cm}) \) | 1.84   | 2.14   | 2.1   | 0.98  |
| RRR           | 11.8   | 9.5    | 25.6  | 31.7  |
| Domain Size \( d (\mu \text{m}) \) | 0.64   | 0.45   | 0.45  | 0.58  |
| \( \rho_d/\rho_d(H=0, \, T=1.5 \, \text{K}) \) | -0.5 % | -0.75 %| -1.2 %| -0.6 %|
| \( \rho_d/\rho_d(H=0, \, T=65 \, \text{K}) \) | -0.06 %| -0.1 % | -0.1 %| 0.0 % |
| \( r = \rho_d(1.5 \, \text{K}) (\Omega \cdot \text{cm}^2) \) | -3.8 \times 10^{-7} | -4.9 \times 10^{-7} | -3.8 \times 10^{-7} | -1.6 \times 10^{-7} |

Varying the film thickness changes both the DW spin structure (Fig. 1) and the relative importance of bulk and thin film surface scattering on the resistivity. Table
1 summarizes the results of a systematic study of the effect of film thickness on $\rho_d$ and the film resistivity. It is seen that even in thin layers (25 nm films), in which the DWs are considerably broader and Neel-like, there is a large anomalous negative DW contribution. In fact, the magnitude of the DW interface resistance (which is negative) and given by $r = \rho_d d$ where $d$ is the domain size, is largest in the thinner films ($\leq 100$ nm).

\[ \lambda_{mfp} \]

FIG. 3. Cross-sectional view of the magnetic configuration of an Fe wire, showing the effect of internal fields and surface scattering on the trajectory of charge carriers within stripe domains and DWs.

These results suggest that the interplay between orbital effects in the internal magnetic fields near DWs and surface scattering are at the origin of the anomalous negative wall contribution. Fig. 3 illustrates a manner in which the trajectories of charge in the alternating internal magnetic field near a wall may lead to reduced surface interaction and hence an enhanced conductivity. Demagnetization fields in the wall will also act to increase the conductivity via the Lorentz effect. However, in thicker films, in which bulk scattering is dominant, we find the $r$ decreases. Altering the wall size and structure—which changes the demagnetization fields near walls—also is not critical to the observed effects. It appears that the magnetic structure within approximately a mean free path, $\lambda_{mfp}$ ($\sim 200$ nm at 1.5 K in a 100 nm thick film) is important to the observed phenomena.

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