Magnetoresistance in modulated width $Ni_{80}Fe_{20}$ wires

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The magnetization reversal processes and magnetoresistance behavior in micron-sized $Ni_{80}Fe_{20}$ wires with periodically modulated width have been studied. The wires were fabricated by electron beam lithography and a lift-off process. A combination of the magneto-optical Kerr effect and magnetoresistance measurements shows that the lateral shape of the wires greatly influences the magnetic and transport properties. For the field applied along the wire axis, the hysteresis loops are strongly influenced by the wire shapes. In contrast to the fixed width wires, the modulated width wires show an additional transverse magnetoresistance, which has been attributed to the shape-dependent demagnetizing fields and the inhomogeneous current density. The resistance of the modulated width wires is dominated by the contribution due to the narrow part of the wires; however, the inhomogeneous current density in the wide part of the wires contributes a significant transverse magnetoresistance. © *1999 American Institute of Physics.* [S0021-8979(99)00402-8]

INTRODUCTION

Recently, there has been much interest in artificially ''engineering'' the magnetic properties of thin film magnetic microstructures or even nanostructures by altering the lateral size.[1–12] The ability to design and control magnetic behavior is becoming increasingly important in technological applications as novel magnetic devices are miniaturized.[13,14] Extensive studies of size effects have been carried out on different geometric patterns, e.g., square dots,[8] circular dots,[1] holes,[15] and fixed width wires.[2–7] Adeyeye *et al.*,[2,3] Hong and Giordano[6,7] have extensively studied on the magnetic behavior in narrow ferromagnetic wires as a function of field orientation. Recently, a shape effect in magnetic nanostructures has also been studied by Kirk *et al.*,[16] who found that it is possible to control the domain structure and coercivity by altering the end shape and width of the structures. In this article, we report how the lateral shape affects the magnetic properties of micron-sized $Ni_{80}Fe_{20}$ wires. The magnetization reversal processes and magnetoresistance (MR) behavior have been found to change significantly in micron sized $Ni_{80}Fe_{20}$ wires with periodically modulated width. The width modulation modifies the shape-dependent demagnetizing fields, which strongly influence the magnetic behavior of the wires.

II. EXPERIMENTS AND DISCUSSIONS

The modulated width $Ni_{80}Fe_{20}$ wire arrays with different width modulation and a fixed width wire array were fabricated using high-resolution electron-beam lithography and a lift-off process. The Permalloy was electron-beam evaporated onto a GaAs substrate at a pressure of 2×10^{-8} Torr and a rate of 2.5 Å/min. All $Ni_{80}Fe_{20}$ wire arrays have a thickness of 300 Å. The geometry for the modulated width wire is shown in Fig. 1(a). The width of the wide part of the wires is denoted by W and the length is 5 μm. The width of the narrow part of the wires is 1 μm and the length is 5 μm. The modulation is repeated over a length of 200 μm. The separation between the centers of the wires is 15 μm. The width W ranges from 1 to 11 μm. The wires are fixed width when $W=1$ μm. Figure 1(b) shows the scanning electron microscope (SEM) image of the modulated width wire array with $W=11$ μm. The image shows that good edge definition has been achieved.

The magneto-optical Kerr effect (MOKE) magnetometry measurements were made in the longitudinal geometry using a stabilized HeNe laser source and a focused spot size at the sample of 0.2 mm. In Fig. 2, the results of the MOKE measurements performed on the wire arrays are shown with the field applied in-plane and parallel to the long axis of the wires. The data for the fixed width wire array ($W=1$ μm) are noisy, since this sample has the lowest total magnetic moment compared with other samples. Nevertheless, it is clear that some general trends can be observed. The fixed width wires show a rectangular hysteresis loop confirming that the easy axis is along the wire axis as expected from the shape anisotropy. For the modulated width wires, the hysteresis loops are rounded and the remanent magnetization decreases with the increasing width W, implying that the magnetic easy axis changes progressively away from the wire axis direction. It is possible to understand this behavior by considering the shape-dependent demagnetizing field which causes magnetically hard behavior.[17,18] For simplicity, we assume that there is a uniaxial anisotropy in the wide part of the modulated width wires induced by the demagnetizing fields. Since the demagnetizing fields are induced by the edge ''magnetic charge,'' it is legitimate to take the direction of the easy axis of this anisotropy as approximately parallel to the diagonal, and hence the angle between the shape induced easy axis and the wire axis is proportional to the width W in this case.

For MR measurements, electrical contacts to the arrays were made using standard optical lithography, metallization, and liftoff of 20 nm Cr/250 nm Au. The wire array extends over a distance of 250 μm but the voltage probes were separated by 160 μm. A dc sense current of 1 mA was passed

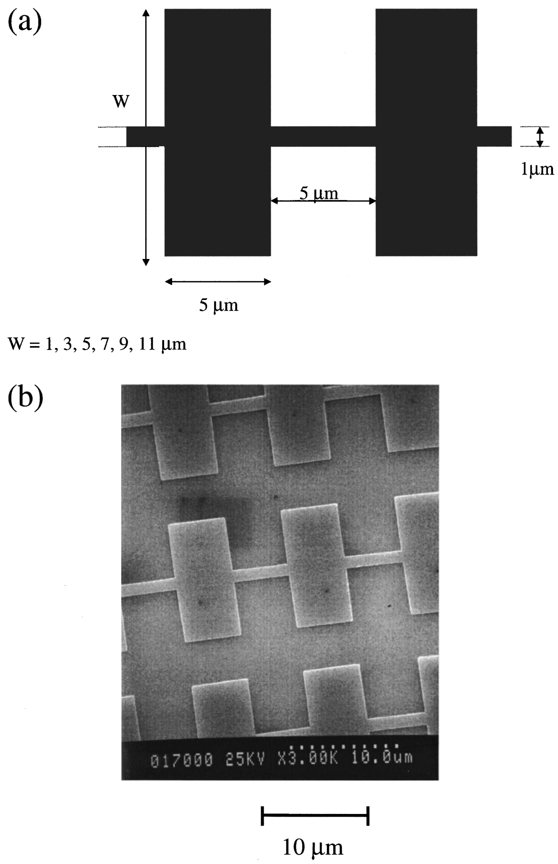

FIG. 1. (a) Schematic of the fabricated modulated width wires. (b) SEM image of the modulated width wire array with the width $W=11$ μm.

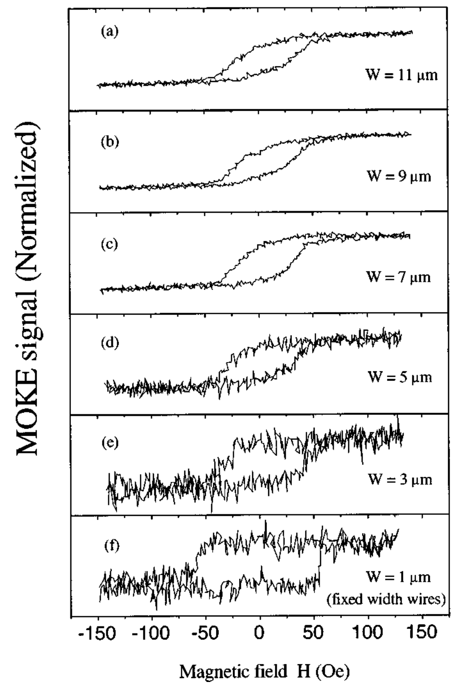

FIG. 2. MOKE hysteresis loops for the field applied along the wire axis.

along the wires and the room temperature resistance was recorded automatically using a four-terminal method as the in-plane magnetic field was swept. The MR ratio response to magnetic fields H applied along and perpendicular to the wire axis is defined as $[R(H)-R(H=0)]/R(H=0)$, where $R(H)$ is the resistance of the sample at a given magnetic field H.

The results of MR measurements performed on the fixed and modulated width wires with width $W=1$ and 11 μm, respectively, are presented in Fig. 3. For fields applied parallel to the wire axis, the maximum change in MR ratio is larger for the modulated width wires (0.22%), compared to the corresponding value for the fixed width wires (0.12%). By contrast, for fields applied perpendicular to the wire axis, the maximum change in MR ratio is smaller for the modulated width wires (0.99%), compared to the corresponding value for the fixed width wires (1.45%).

Figures 3(a) and 3(b) show the MR curves of fixed and modulated width wires for the fields applied parallel to wire axis, respectively. Figure 3(a) shows the typical longitudinal MR curve for fixed width wires,[2] in which the sharp resistance minimum corresponds to the switching of the magnetization in the wires, which is consistent with the MOKE hysteresis loop in Fig. 2(f). In Fig. 3(b), an additional transverse MR behavior and larger longitudinal MR behavior for the modulated width wires is observed. Even at the maximum applied field H (800 Oe), the resistance change is not saturated. As the applied field H is increased from the negative maximum, the resistance clearly increases and then drops abruptly before H reverses. At low positive fields, the resistance reaches a minimum and increases, and then decreases again at higher positive fields.

Since MOKE measures the component of the magnetization along the direction of the applied field, averaged over the focused spot size, this technique is essentially a measurement of $\langle\cos\theta_m\rangle$ when the field is applied along the wire axis, where θ_m is the angle of the magnetization with respect to the wire axis. The inset in Fig. 3(b) shows the value of $\langle\cos\theta_m\rangle^2$ over the field range from -150 to 150 Oe deduced from the corresponding MOKE measurement. The measured MR is mainly due to the anisotropic magnetoresistance (AMR) effect[19] which is proportional to $\langle\cos^2\phi\rangle$, where ϕ is the angle between the magnetization and the current density. In general, $\langle\cos\theta_m\rangle^2$ is not equal to $\langle\cos^2\phi\rangle$, unless all the current density is along the direction of the applied field and θ_m is uniform across the whole sample. It is interesting to note that the measured MOKE signal is dominated by the wide part of the wires and the measured resistance is dominated by the narrow part of the wires because of the width difference. However, the MR behavior and the $\langle\cos\theta_m\rangle^2$ behavior in Fig. 3(b) are similar at lower fields. The resistance drop before H reverses can be explained by the AMR effect due to the switching of the magnetization in the wide part of the wires.

The additional transverse MR behavior in Fig. 3(b) at higher fields can be explained by a combination of the AMR effect and the current density distribution in the wide part of the wires. From the hysteresis loop shown in Fig. 2(a), we observed that the magnetization reversal process is dominated by spin rotation at higher fields, suggesting that the transverse MR behavior is mainly due to the AMR effect in the wide part of the wires where some of the current flow is

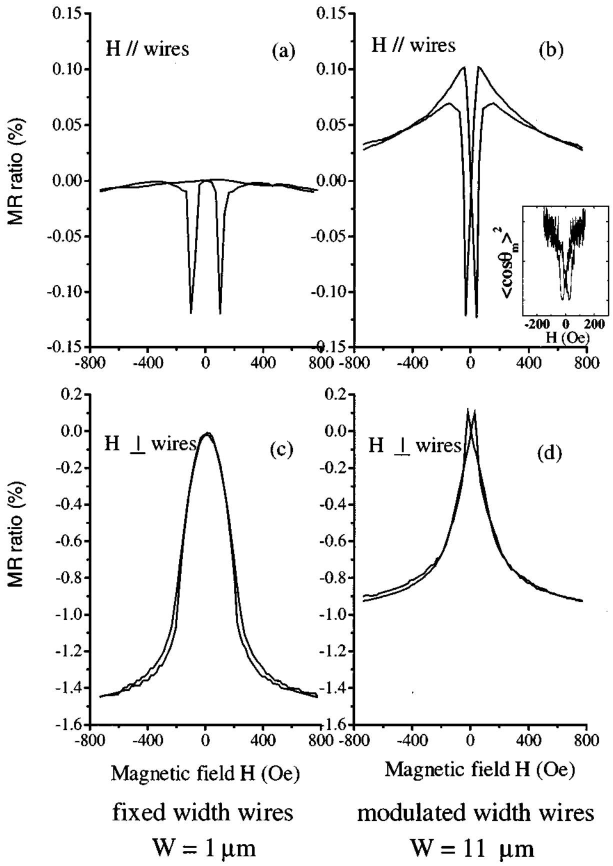

FIG. 3. MR ratio of the (a), (c) fixed width wires, and (b), (d) modulated width wires with the width $W=11$ μm for the magnetic field applied along and perpendicular to wire axis, respectively. The inset in (b) shows the value of $\langle \cos \theta_m \rangle^2$ over the field range from -150 to $+150$ Oe deduced from the corresponding MOKE measurement.

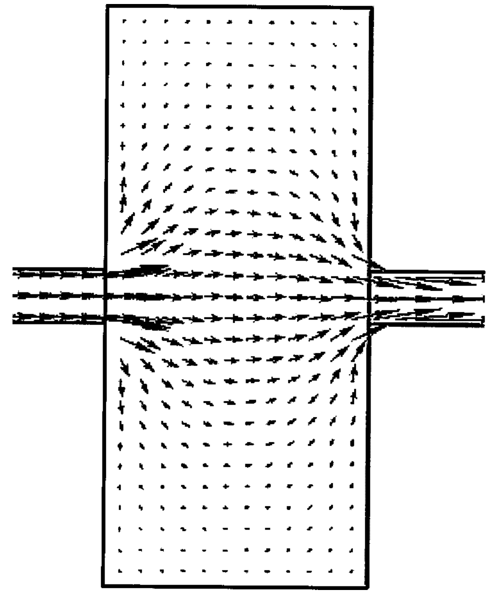

FIG. 4. Simulated current density distribution in the modulated width wires with a width of $W=11$ μm. The length of each arrow indicates the magnitude and direction of current.

not parallel to the wire axis.[20,21] The current density distribution in the modulated width is estimated numerically by solving the Poisson equation using a finite element method neglecting the galvanomagnetic effect.[14] The calculated current density distribution for the modulated width wires with the width$=11$ μm is shown in Fig. 4. The calculation indicates that there is an inhomogeneous current density distribution in the wide part of the wires, and also shows that 79.3% of the total resistance is due to the narrow part of the wires, and this is consistent with the experimental result of Fig. 3(b) in which that the MR ratio curve is dominated by the longitudinal MR.

Figures 3(c) and 3(d) show the MR curves for the fixed and modulated width wires for the fields applied perpendicular to the axis of the wires respectively. In Fig. 3(c), a typical negative transverse MR behavior,[2,3] nearly reversible and symmetrical with field strength, is observed. This behavior is consistent with the AMR effect arising from spin rotation dominating the reversal process and suggests that no domain develops across the width of the wires. In Fig. 3(d), two clearly separated peaks in the MR curve are observed, implying that domain wall motion occurs in the wide part of the wires. This MR behavior can still be explained in terms of the AMR effect with an inhomogeneous current density in the wide part of the wires. We can crudely estimate the demagnetizing field for the fixed width wires as $(t/w_n)M_s$, where t is the film thickness, w_n the wire width, and M_s is the saturation magnetization of the material. By inspection of Figs. 3(c) and 3(d), we can see that the MR characteristic is consistent with a demagnetizing field in the narrow part of the wires of ≈300 Oe estimated assuming the magnetization of bulk Permalloy.

III. CONCLUSION

In conclusion, the magnetic properties of novel magnetic microstructures fabricated by electron-beam lithography and lift-off techniques have been studied using MOKE magnetometry and magnetoresistive measurements. We have observed strong changes in magnetization reversal processes and MR behavior as the lateral shape of the wires changes. Our results have demonstrated that it is possible to use artificial layer structuring to engineering the magnetic properties of microstructures, with potential for device applications as well as basic studies in magnetism.

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