Magnetostatic interactions and magnetization reversal in ferromagnetic wires

A. O. Adeyeye,* J. A. C. Bland, C. Daboo, and D. G. Hasko
Cavendish Laboratory, Madingley Road, Cambridge, CB3 OHE, United Kingdom
(Received 14 August 1996; revised manuscript received 9 December 1996)

We have investigated the effect of magnetostatic interactions on the magnetization reversal behavior of $Ni_{80}Fe_{20}$ flat wire arrays using magnetoresistance (MR) measurements. The wires are fabricated from films of thickness 500 Å. As the separation s of a wire array of fixed width $w=2$ μm is increased, a crossover from the behavior characteristic of an interacting wire array to that of a single isolated wire is identified for $s/w\sim 1$. For the interacting limit, $s/w\leqslant 1$, a marked reduction in the coercive field occurs as the spacing of wires of fixed width are decreased. The shape of the MR response to fields applied along the hard axis is also found to be strongly dependent on the interwire separation. We attribute this behavior to the effect of interwire dipolar interactions. MR measurements were also made as a function of the orientation of the applied field relative to the axis of the wire, in order to investigate how the shape anisotropy affects the magnetization reversal process. In μm-size wires we find that ''one-jump'' switching of the magnetization can occur according to the orientation of the wires with respect to the applied field. [S0163-1829(97)00126-4]

I. INTRODUCTION

Studies of the magnetization reversal process and domain structure in small ferromagnetic elements provide an important opportunity to test micromagnetic predictions in new geometries.[1–6] Most experimental work on small magnetic structures have been carried out on powders,[7] suspensions,[8] and arrays[9–12] since it is difficult to characterize a single magnetic element using most conventional magnetometry techniques. The question of how the interelement spacing affects the magnetic properties of an array is therefore relevant in understanding and interpreting experimental results since the interelement spacing can influence both the magnetization reversal mechanism and the internal magnetic domain structures.[13–18] The effect of interparticle interactions is in general complicated by the fact that the dipolar fields depend upon the magnetization state of each element, which in turn depend upon the fields due to adjacent elements. The effect of the magnetostatic interactions is of practical interest because it may be used in optimizing device performance.[19,20]

Advances in lithographic and other controlled fabrication techniques have recently given rise to the possibility of exploring magnetism in laterally controlled magnetic structures down to the nanometer scale. A detailed understanding of the magnetization reversal processes and magnetoresistance (MR) response in small ferromagnetic elements is important in the design and optimization of miniature MR heads for ultrahigh-density data storage applications,[21] and also in proposed magnetoelectronic devices.[22,23]

We have previously reported the size dependence of the magnetoresistance in magnetically isolated submicron $Ni_{80}Fe_{20}$ wires.[11] At low field, we found a universal behavior of the MR vs applied field normalized to the average demagnetizing field and a strong increase in the coercive field H_c as the width of the wire is reduced. The evolution of the magnetoresistance behavior in these noninteracting wire arrays as the wire width is reduced from 200 to 0.3 μm corresponds to a transition from bulk to mesoscopic magnetic behavior:[24] beneath $\sim$2 μm, spin rotation processes are found to dominate and the MR curve is almost reversible, while above this wire width, domain-wall processes dominate.

In the present work, we have focused on studying the effect of magnetostatic interactions upon the magnetization reversal behavior in $Ni_{80}Fe_{20}$wire arrays. The arrays have a constant width of 2 μm and a variable spacing in the range between 0.5 to 15 μm. A crossover in the magnetic properties from the behavior characteristic of an interacting wire array to that of a single isolated wire is clearly identified for $s/w\sim 1$, which we discuss in terms of simple models of magnetostatic interactions. We have also carried out MR measurements as a function of the orientation of the applied field in order to explore the magnetization reversal processes.

II. FABRICATION AND MEASUREMENT TECHNIQUES

The structures consist of planar wire arrays with $w=2$ μm and variable separation s in the range from 0.5 to 15 μm and a single large wire of $w=200$ μm used as the reference material. The wires were each of length 250 μm and the array extends over a distance of 250 μm. The structures were fabricated from a continuous film structure of 30 Å Au/500 Å $Ni_{80}Fe_{20}$/GaAs(001). The polycrystalline continuous film was grown using electron-beam deposition in an ultrahigh vacuum system. A high-purity alloy source of the nominal $Ni_{80}Fe_{20}$composition was used. No attempt was made to verify the composition of the deposited film. The $Ni_{80}Fe_{20}$ layers were deposited at a rate of 2.5 Å/min. The pressure during growth was about 2.5×10^{-9} Torr, while the substrate was held at 30 °C. The film was annealed at 120 °C for 30 min to remove the uniaxial anisotropy induced during growth. The array structures were then fabricated using electron-beam lithography and optimized pattern transfer techniques based on a combination of dry and wet etching. Details of the fabrication process are described in Ref. 25.

For MR measurements, electrical contacts to the arrays were made using standard optical lithography, metallization and liftoff of 20 nm Cr/300 nm Au. An initial determination of the device resistance at zero applied field was made and it was found that the resistance scaled approximately inversely with the proportion of metal remaining after etching. A dc current of 1 mA was passed along the wires of each array and the resistance was recorded automatically using a four terminal method as the magnetic field was swept. In each array there are 15–100 wires which means that the current in each wire is in the range (0.1–0.6) μA. The magnetic field was applied in the plane of the structures for all the measurements reported since the magnetization of the continuous films lies in plane. The magneto-optic Kerr effect (MOKE) measurements on the 500-Å $Ni_{80}Fe_{20}$ unpatterned sample display almost identical M-H behavior in both in-plane orientations. This shows that there is negligible intrinsic anisotropy suggesting that magnetostriction effects are not significant in the films studied.

III. RESULTS

A. Magnetostatic interactions

To better understand the effect of magnetostatic interactions we carried out systematic studies of the effect of wire separation on the magnetic properties. MR measurements were used to probe the effect of magnetostatic interactions on the magnetic properties in wire arrays since it is difficult to measure the magnetic properties with magneto-optic Kerr effect (MOKE) when the separation s is large because of the increase in s/w ratio and paramagnetic contributions from the substrate. Measurements were carried out with the applied field parallel and perpendicular to the current direction to determine the coercive field and the average hard-axis saturation field, respectively.

The field at which the sharp minimum in the longitudinal MR curve occurs corresponds to the switching of the magnetization in the wire array, and therefore it is taken as the coercive field of the wire.[11,26] The average demagnetizing field was determined from the MR response to the field applied perpendicular to the direction of the sense current. The average hard-axis saturation field H_s can be estimated as[27]

$$H_s \approx H_k + \frac{3}{2} H_d ,$$

where H_d represents an estimate of the demagnetizing field at the wire center. In our film the magnetic anisotropy H_k is assumed to be zero. The average demagnetizing field was determined from the experimentally measured H_s values, using the equation above.

In Fig. 1, we show a plot of the coercive field as a function of s/w obtained from the MR measurements at room temperature when the applied field is parallel to the direction of the sense current along wire. A clear reduction in the coercive field for $s/w < 1$ is observed. Such behavior is consistent with the effect of interwire magnetostatic interactions. For the field applied parallel to the wire axis, there are local areas in the wire, i.e., at both ends of the wire, where domains can nucleate and then sweep through the wire as shown in Fig. 2. The charges created at the end of a wire can communicate with that of an adjacent wire due to dipole coupling between them. The interaction strength increases as

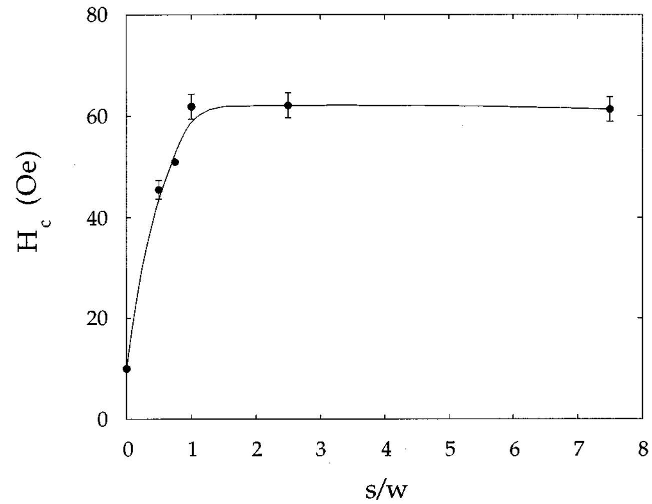

FIG. 1. A plot of the coercive field as a function of wire s/w obtained from the MR measurements at room temperature for a 500-Å thick $Ni_{80}Fe_{20}$wire array with $w = 2$ μm when the applied field is parallel to the easy axis of the wire array.

s is decreased. Although the actual coupling is at the end of the wire, the effect is propagated through the entire sample. This argument may explain the observed decrease in the coercive field for $s/w < 1$. The value of H_c in the noninteracting limit is ~60 Oe, as is consistent with the results in Ref. 11.

The experimental MR curves plotted as a percentage defined as

$$\frac{\partial R}{R} = \left[\frac{R(H) - R(H=0)}{R(H=0)} \right] \tag{1}$$

for fields applied perpendicular to the current direction for a 500-Å $Ni_{80}Fe_{20}$wire of constant width $w = 2$ μm but with 0.5 μm $\leqslant s \leqslant 15$ μm is shown in Fig. 3. For small s, i.e., $s/w < 1$, the MR response is hysteretic and saturates at lower applied field. However for $s/w > 1$, the hysteretic behavior observed at low s disappears and the MR curve retraces itself for $s \geqslant 2$ μm. For fields applied perpendicular to the wire axis, magnetic charges are formed along the edges of the wire which interact with charges from the adjacent wire depending on the spacing of the wire array. This results in an additional field produced by the adjacent wire which aids the applied magnetic field.

A simple model for calculating the effect of magnetostatic interactions on the demagnetizing field for fields applied along the width of the wire array has been developed by

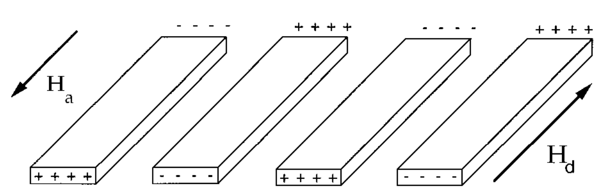

FIG. 2. Schematic of the charge distribution for field applied parallel to easy axis of the wire for the case of AFM alignment of adjacent wires.

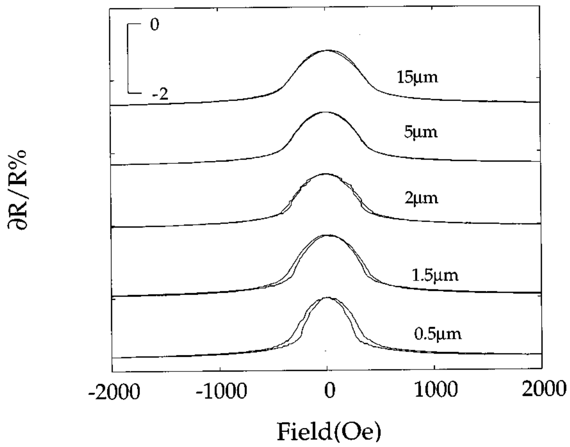

FIG. 3. The magnetoresistance (MR) response to field applied along the hard axis measured at room temperature for a 500-Å thick $Ni_{80}Fe_{20}$wire array with $w=2$ μm as a function of separation s.

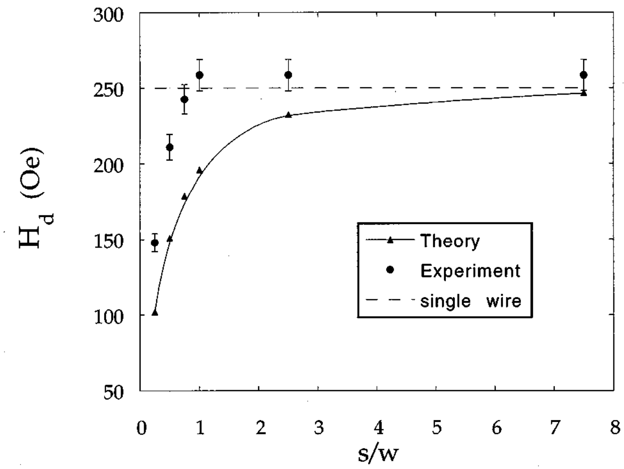

FIG. 4. A comparison of the experimental and theoretical demagnetizing field for field applied along the hard axis for a 500-Å thick $Ni_{80}Fe_{20}$ wire array with $w=2$ μm as a function of s/w.

Pant.[28] For an array of magnetic wires, the demagnetizing field of entire wire arrays is given in SI units as

$$H_d=M_s\frac{t}{w}\alpha(k),$$

$$\alpha(k)=\frac{2k}{1+2k}+\frac{k}{2(1+k)^2}\left(\frac{\pi^2}{2}-4\right), \tag{2}$$

where $k=s/w$, t is the film thickness. In the limit of $k\rightarrow 0$, the factor $\alpha(k)\rightarrow 0$; in the opposite limit of $k\rightarrow\infty$, $\alpha(k)\rightarrow 1$. In the first limit, the wires are assumed to be in physical contact corresponding to the continuous film, in which case there is no demagnetizing field. The second limit corresponds to the case of an isolated wire array. For $s/w>2$ the effect of magnetostatic interactions on the demagnetizing field is found to be negligible.

A comparison of the experimental and the theoretical demagnetizing fields is shown in Fig. 4. Both the experimental data and calculated values follow the same form, however, the experimental values are slightly higher than the calculated values. One of the assumptions in the theory is that magnetization is uniform in the wire arrays. This assumption is valid only for the case of an ellipsoidal sample. The difference in the two results may therefore be due to the nonuniformity of the magnetization in the wire studied. The theory also assumes a uniform edge definition of each wire; however there is a limitation imposed by the processing on how sharp the wire edge can be. Komine, Mitsui, and Shiiki[29] have carried out micromagnetic calculations of the role of edge defects on the magnetization reversal in soft magnetic thin films and observed that defects can trap a magnetic vortex wall. For the wire width studied, both the easy- and hard-axis results show that the magnetostatic interactions in a wire array are very important when the separation between neighboring wires in an array is less than or comparable to the width of the wires.

B. Orientation-dependent magnetization reversal

In this section, we present detailed studies of the magnetization and magnetoresistance (MR) as a function of the angular orientation ϕ of the applied field relative to the easy axis of the wires. The samples consist of wire arrays of $w=2$ μm; $s=5$ μm and a single large wire with $w=200$ μm. For MR measurements, the field was applied in the plane of film and at different in-plane orientations. In Fig. 5 we show representative MR curves for various field orientations relative to the easy axis of the wire for a 500-Å thick $Ni_{80}Fe_{20}$ wire array with (a) $w=2$ μm and separation $s=5$ μm (b) a single wire with $w=200$ μm. For $w=2$ μm, the MR response for $\phi=90°$ is seen to be almost reversible with no Barkhausen jumps. This is due to the fact that the component of the applied field along the easy axis is zero. Without the longitudinal component of the applied field, the central magnetization region within the wire will not undergo a domain-wall displacement and therefore, there is no domain formation. However, for $\phi<90°$, the MR response is characterized by irreversible jumps in both the forward and reverse cycles giving rise to sharp displacements in the MR curve. These jumps are due to the component of the applied field along the easy axis of the wire which forces the central region of the wire to undergo magnetization reversal. This results from the spatial varying demagnetizing field and the fact that the central region of the wire will have the smallest demagnetizing field H_d. This may lead to the formation of a structure which can be modeled as a three-domain state.[5,30] For the interior region, H exceeds H_d resulting in magnetization reversal. However, for the two edge regions, H is less than H_d, resulting in no magnetization reversal. The jumps in the MR response are due to sudden switching of the magnetization rather than domain-wall motion and annihilation.[31] For the single wire with $w=200$ μm, the MR curves show identical behavior of all applied field orientations [see Fig. 5(b)]. This is due to the fact that for such a large wire width, the demagnetizing field is too small to cause a significant change in the magnetization reversal process, and therefore the process is dominated by domain-wall motion, as in the continuous film.

In Fig. 6, the angular variation of the ''jump'' field for a wire array with $w=2$ μm and $s=5$ μm made from the 500 Å $Ni_{80}Fe_{20}$film is shown and compared with the equivalent measurements on a large single wire with $w=200$ μm. For

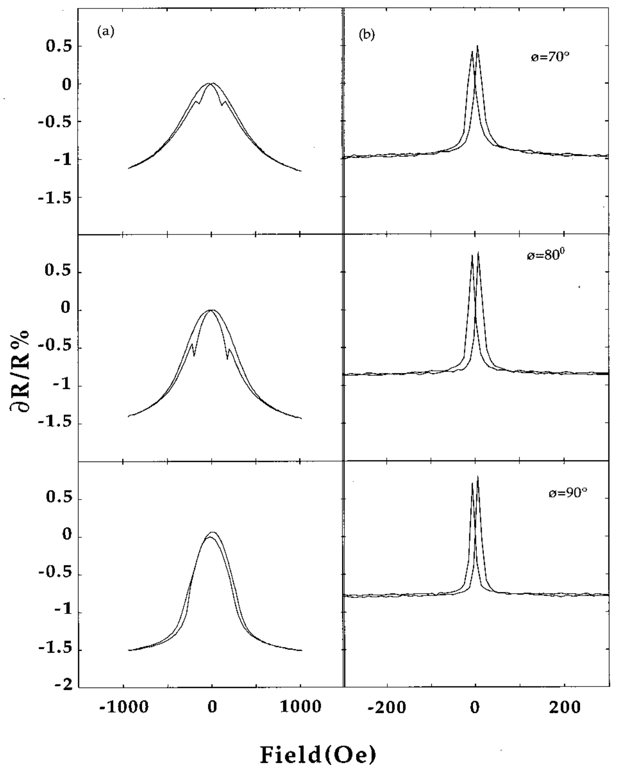

FIG. 5. Representative MR curves for various field orientations relative to the wire axis for a 500-Å thick $Ni_{80}Fe_{20}$ wire array with (a) $w=2$ μm and separation $s=5$ μm (b) $w=200$ μm measured at room temperature.

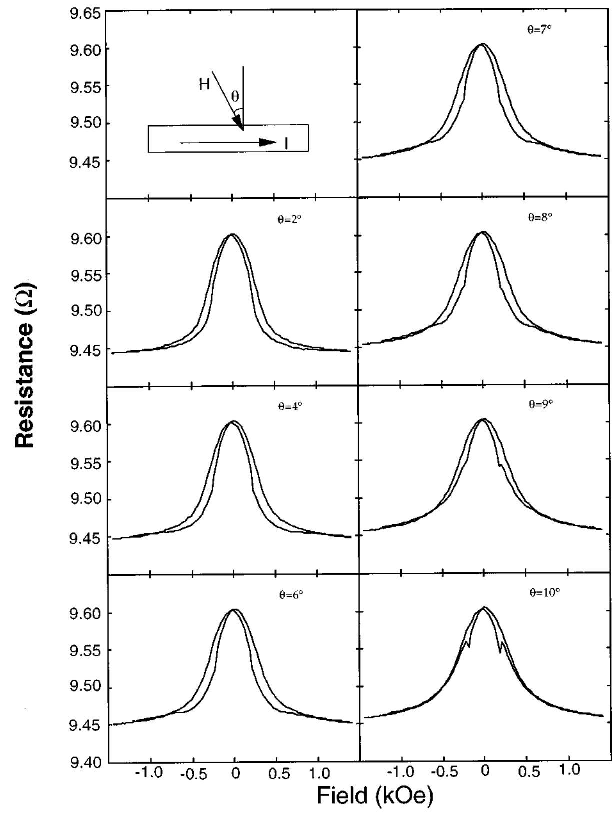

FIG. 7. R-H response to field applied at a few degree away from the hard axis measured at room temperature for a 500-Å thick $Ni_{80}Fe_{20}$wire array with $w=2$ μm and $s=5$ μm.

$w=2$ μm, the ''jump'' field increases with increasing field angle. This is likely to be due to an increase in the component of the applied field along the easy axis of the wire as ϕ increases. This orientation dependence of the ''jump'' field suggests that the magnetization reversal mechanism is incoherent,[32] i.e., that domain structures mediate the jump process, as occurs in continuous epitaxial films.[33] However

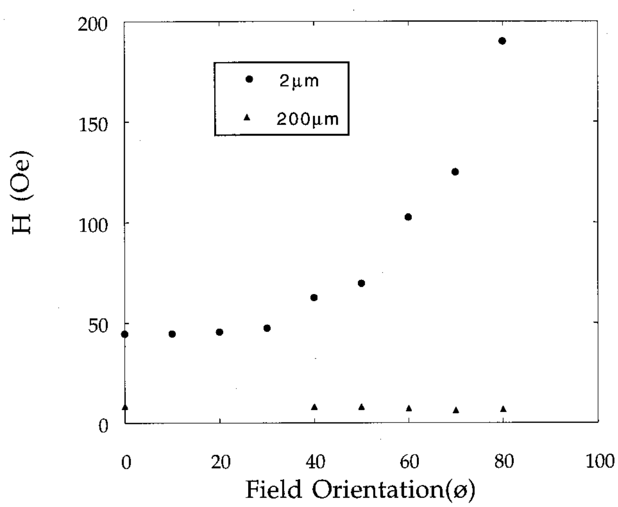

FIG. 6. The angular variation of the ''jump'' field for a 500-Å thick $Ni_{80}Fe_{20}$ wire array with $w=2$ μm and $s=5$ μm compared to that for which $w=200$ μm for the same field orientation measured at room temperature.

further studies with domain imaging are needed to determine the precise processes involved. As expected the ''jump'' field for $w=200$ μm as a function of the field angle remains almost constant.

In order to better understand the variation of the jump features seen in Fig. 5 for a wire array with $w=2$ μm, we carried out a careful measurement of the MR response as a function of the orientation ($\theta=\pi/2-\phi$) of the applied field angle only a few degrees from the hard axis of the wire. As shown in Fig. 7, the observed jump in the magnetization state developed gradually and became obvious at around $\theta=10°$ from the hard axis. The exact value of this angle varies depending on the film preparation conditions. The magnetization reversal process for an applied field a few degrees away from the hard axis of the wire has been described by Cross *et al.*[34] We have adopted this approach to describe the reversal process in the $w=2$ μm wire array. For an applied field angle $\phi=80°$, at point A in the MR curve as shown in Fig. 8, the magnetization is saturated along the field direction (i.e., the direction which minimizes the energy), which is at a maximum negative value. As the field is swept towards positive values, the magnetization rotates away from the field direction towards the nearest easy axis. At point B, ($H=0$) M is aligned parallel to the easy axis of the wire, resulting in maximum MR. At point C, the magnetization reaches an unstable configuration and jumps from M to M', resulting in a jump in the MR response from C to C'. The component of the applied field parallel to the current direction then drives the magnetization over to the new,

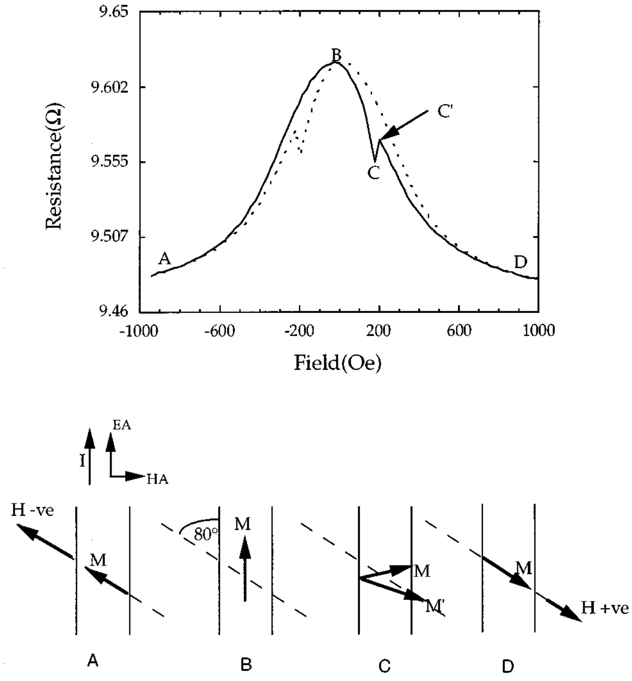

FIG. 8. Analysis and schematic diagram of the magnetic reversal process for a 500-Å thick $Ni_{80}Fe_{20}$ wire array with $w=2$ μm and $s=5$ μm for the field applied at $\phi=80°$ relative to the wire axis.

stable energy state. The magnetization is again saturated at point D along the field direction. The entire process is then repeated for the field sweep from positive to negative fields, with the jump now occurring for negative field values. While the jump process can be qualitatively predicted from considerations of the anisotropy energy, predicting the jump field is difficult since domain structures are likely to be involved.[33]

IV. CONCLUSION

We have used MR measurements as a probe of magnetostatic interactions and magnetization reversal processes in lithographically controlled $Ni_{80}Fe_{20}$ wire structures. Our systematic studies have shown that the reversal process is strongly dependent on the size and separation via internal and interwire dipolar fields. For the wire array with constant width $w=2$ μm and variable separation s in the range between 0.5 and 15 μm, a crossover is identified in the magnetic properties from the behavior characteristic of an interacting wire array to that of a single isolated wire when $s/w \sim 1$. The shape of the MR response to fields applied along the hard axis is also found to be strongly dependent on the magnetostatic interactions for $s/w<1$. Finally, we have presented detailed studies of MR as a function of the orientation of the applied field relative to the easy axis of the wire. We observed that for $w=2$ μm, the magnetization reversal is dominated by spin rotation for fields applied perpendicular to the wire axis in contrast to the wall motion and wall displacement processes observed for a single wire with $w=200$ μm. For fields applied at an angle to the wire axis, reversal proceeds by a combination of spin rotation and abrupt jumps, as evidenced by the additional features which appear in the angle-dependent MR curves. However at the jump field itself, the jump process is likely to involve domain formation, by analogy with studies of jumplike switching in continuous epitaxial Fe films.[33]

These studies show that magnetoresistance measurements provide a sensitive tool for probing the effect of magnetostatic interactions in ferromagnetic array structures. In the future, more detailed computational studies are needed to interpret the fine details in the magnetic response revealed by these studies.

ACKNOWLEDGMENTS

A.O.A. would like to thank Trinity College, Cambridge for their financial support. We would like to thank EPSRC for supporting this work. H. Ahmed and the Microelectronics Research Centre, Cavendish Laboratory are thanked for their help with this work.

---

*Present address: Data Storage Institute, NUS, 10 Kent Ridge Crescent, Singapore 119260.

[1] D. D. Awschalom and D. P. DiVincenzo, Phys. Today **48**, 43 (1995).
[2] R. Ferre, L. C. Sampaio, and B. Barbara, J. Magn. Magn. Mater. **140**, 249 (1995).
[3] M. E. Schabes and H. N. Bertram, J. Appl. Phys. **63**, 1347 (1988).
[4] J-G. Zhu and H. N. Bertram, J. Appl. Phys. **63**, 3248 (1988).
[5] N. Smith, J. Appl. Phys. **63**, 2932 (1988).
[6] T. R. Koehler, B. Yang, W. Chen, and D. R. Fredkin, J. Appl. Phys. **73**, 6504 (1993).
[7] A. H. Morrish and S. P. Yu, J. Appl. Phys. **26**, 1049 (1955).
[8] T. O. Paine, L. I. Mendelsohn, and F. E. Luborsky, Phys. Rev. **100**, 1055 (1955).
[9] A. D. Kent, S. Von Molnar, S. Gider, and D. D. Awschalom, J. Appl. Phys. **76**, 6656 (1994).
[10] J. F. Smyth, S. Schultz, D. R. Fredkin, D. P. Kern, S. A. Rishton, H. Schmid, and M. Cali, J. Appl. Phys. **69**, 5262 (1991).
[11] A. O. Adeyeye, J. A. C. Bland, C. Daboo, J. Lee, U. Ebels, and H. Ahmed, J. Appl. Phys. **79**, 6120 (1996).
[12] S. J. Blundell, C. Shearwood, M. Gester, M. J. Baird, J. A. C. Bland, and H. Ahmed, J. Magn. Magn. Mater. **135**, L17 (1994).
[13] A. H. Morrish and L. A. K. Watt, Phys. Rev. **105**, 1476 (1957).
[14] Y. Uesaka, Y. Nakatani, and N. Hayashi, J. Magn. Magn. Mater. **123**, 209 (1993).
[15] G. T. A. Huysmans, J. C. Lodder, and J. Wakui, J. Appl. Phys. **64**, 2016 (1988).
[16] L. Cheng-Zhang and J. C. Lodder, J. Magn. Magn. Mater. **88**, 236 (1990).
[17] C. Shearwood, S. J. Blundell, M. J. Baird, J. A. C. Bland, M. Gester, H. Ahmed, and H. P. Hughes, J. Appl. Phys. **75**, 5249 (1994).
[18] O. Geoffroy, D. Givord, Y. Otani, B. Pannetier, A. D. Santos, M. Schlenker, and Y. Souche, J. Magn. Magn. Mater. **121**, 516 (1993).
[19] B. B Pant, J. Appl. Phys. **67**, 414 (1990).
[20] U. Dibbern, Sens. Actuators **10**, 127 (1986).
[21] S. W. Yuan and H. N. Bertram, J. Appl. Phys. **73**, 6235 (1994).

[22] M. T. Johnson and R. H. Silsbee, Phys. Rev. Lett. **55**, 1790 (1985).
[23] G. A. Prinz, Phys. Today **48**, 58 (1995).
[24] A. O. Adeyeye, G. Lauhoff, J. A. C. Bland, C. Daboo, D. G. Hasko, and H. Ahmed, Appl. Phys. Lett. **70**, 1046 (1997).
[25] A. O. Adeyeye, J. A. C. Bland, C. Daboo, D. G. Hasko, and H. Ahmed, J. Appl. Phys. (to be published).
[26] M. H. Kryder, K. Y. Ahn, N. J. Mazzeo, S. Schwarzi, and S. M. Kane, IEEE Trans. Magn. **16**, 99 (1980).
[27] C. H. Bajorek, C. Coker, L. T. Romankiw, and D. A. Thompson, IBM J. Res. Dev. **18**, 541 (1974).
[28] B. B. Pant, J. Appl. Phys. **79**, 6123 (1996).
[29] T. Komine, Y. Mitsui, and K. Shiiki, J. Appl. Phys. **78**, 7220 (1995).
[30] R. W. Cross, A. B. Kos, C. A. Thompson, T. W. Petersen, and J. A. Brug, J. Appl. Phys. **28**, 3060 (1992).
[31] C. Tsang and S. K. Decker, J. Appl. Phys. **53**, 2602 (1982).
[32] H. J. Richter, IEEE Trans. Magn. **29**, 2188 (1993).
[33] C. Daboo, R. J. Hicken, E. Gu, M. Gester, S. J. Gray, D. E. P. Eley, E. Ahmed, J. A. C. Bland, R. Ploessl, and J. N. Chapman, Phys. Rev. B **51**, 15 964 (1995).
[34] R. W. Cross, J. O. Oti, S. E. Russek, and T. Silva, IEEE Trans. Magn. **31**, 3358 (1995).