Influence of crystalline structures on the domain configurations in controlled mesoscopic ferromagnetic wire junctions

A. Hirohata,[a] Y. B. Xu,[b] and J. A. C. Bland[c]
Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, England

S. N. Holmes
Cambridge Research Laboratory, Toshiba Research Europe Limited, 260 Cambridge Science Park, Milton Road, Cambridge CB4 0WE, England

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

A role of crystalline structures on domain wall formation is investigated by magnetic force microscopy (MFM) using mesoscopic wire junctions of both epitaxial bcc Fe and polycrystalline permalloy. Three sets of structures were fabricated with ferromagnetic wires (30 nm thick, $0.2 \leqslant w \leqslant 50\ \mu$m wide and 200 μm long); straight wires, two wires connected at the ends (L shapes), and crosses. Fe samples show complicated domain configurations due to magnetocrystalline anisotropy, while permalloy samples show simple domain with shape anisotropy. These results show that spin configurations at the junction can be precisely tuned by varying not only the shape and the size but also the crystalline structures of the sample.
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I. INTRODUCTION

The fundamental goal of studying micro/nanometer scale magnets is the precise control of a magnetic domain configuration (spin configuration) which can be achieved in artificially fabricated ferromagnets. In magnetic particles or patterned nano-structures,[1,2] a single domain state analogous to the ''giant spin'' can only be achieved when exchange interactions dominate over dipole interactions, requiring extremely small dimensions. In this case, experimental studies are prevented by challenges in fabrication and measurement techniques. However, for an appropriately designed mesoscopic structure, submicron/nanometer scale regions with aligned spins can be induced.

The resistivity associated with spin-dependent electron scattering at magnetic domain walls has recently attracted a great deal of attention.[3–9] The spin configurations in such regions have the same feature of noncollinearity found in antiferromagnetically coupled magnetic multilayers or magnetic granular systems, both of which display giant magnetoresistance effect. However, the experimental observations[3–7] reported so far are controversial and cannot prove the existence of such an effect. Namely, positive domain wall resistivity has been experimentally reported in Refs. 3, 6, and 7, which has been supported theoretically using spin-flip scattering,[8] while negative resistivity has been reported in Refs. 4 and 5 supported using weak localization theory.[9]

In this study, we use both bcc Fe[10] and polycrystalline permalloy[11] structures, which show a clear evolution of magnetic domain configurations with size previously. In order to control spin configurations precisely by varying shapes and sizes as well as crystalline structures, the differences in the domain configurations are studied here for 30 nm thick wire junction structures: straight wires of fixed length ($0.2 \leqslant w \leqslant 50\ \mu$m wide and 200 μm long), a set of two wires of the same size connected perpendicularly at the end (L shape), and crosses with two wires of the same size connected perpendicularly at the center. The structures were observed as grown (unmagnetized states) using magnetic force microscopy (MFM) (di Nanoscope III). With bcc Fe single crystal structures, the domain configurations are found to be much more complicated especially in the unmagnetized states. With the polycrystalline permalloy structures, on the other hand, for the case $0.2 \leqslant w \leqslant 2\ \mu$m, a single domain is observed in straight wires and a diagonal wall connected to one corner is seen at the cross junction.

II. EXPERIMENTAL PROCEDURES

A high quality epitaxial bcc Fe and polycrystalline $Ni_{80}Fe_{20}$ films (30 nm thick) were grown by molecular beam epitaxy on GaAs (100) substrates at room temperature. For the Fe film, the cubic anisotropy was dominant in this film as indicated by *in situ* magneto-optical Kerr effect measurements. Both films were then capped with a 5 nm thick Au

[a]Electronic mail: ah242@cam.ac.uk
[b]Present address: Department of Electronics, University of York, Heslington, York YO10 5DD, England.
[c]Author to whom correspondence should be addressed; electronic mail: jacb1@phy.cam.ac.uk

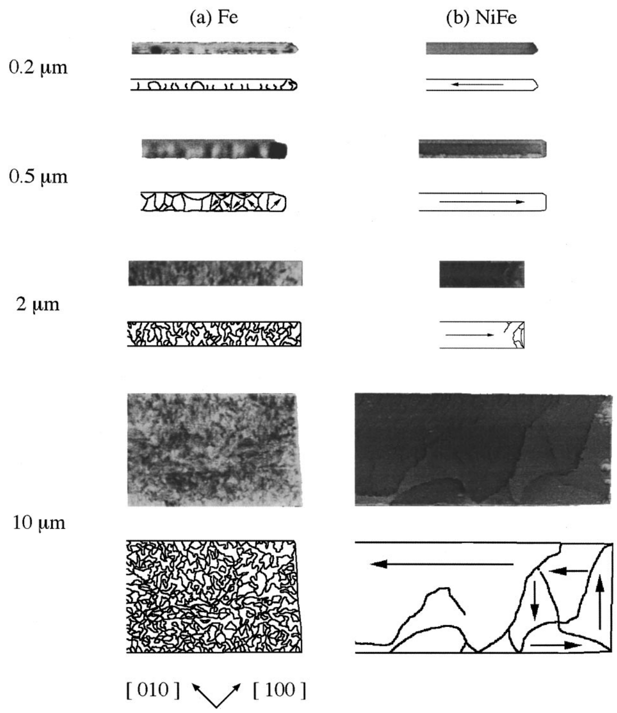

FIG. 1. MFM images and schematic diagrams of the domain configurations of the mesoscopic wires (30 nm thick, w μm wide and 200 μm long) of both (a) Fe and (b) NiFe as grown (unmagnetized states).

layer to prevent oxidation before the removal from the growth chamber. The wire junctions were fabricated using *e*-beam lithography (JEOL JBX5D2U) operated at 50 keV and ion-beam etching with an intermediate metallic mask of Al made by a lift-off process. The width of the wires w was varied from 0.2 to 50 μm and the length of them were fixed as 200 μm. Three sets of junctions were prepared: the first is a set of straight wires, the second is a set of two wires of the same size connected perpendicularly at the end (L shape), and the third is a set of crosses with two wires of the same size connected perpendicularly at the center. For bcc Fe samples, we expect to observe well-defined domain configurations at the wire junction using energy competition between the magnetocrystalline cubic anisotropy and the shape anisotropy as previously reported in Fe circular dots.[10] Accordingly, the Fe structures were positioned with the edge parallel to the $\langle 110 \rangle$ directions, and had in plane cubic anisotropy indicating that the easy axes along the two cubic directions, [100] and [010] as widely known.[12]

III. RESULTS AND DISCUSSION

Figure 1 shows MFM images and corresponding schematic diagrams of straight wires as grown (unmagnetized states). For bcc Fe wires, magnetic domains are seen even at $w = 0.2$ μm as shown in Fig. 1(a). These domains form a closure configuration with a 90° wall as clearly seen for the case of $w = 0.5$ μm. It should be noted that the magnetization direction in the domains are along the easy axes, i.e., either [010] and [100]. With increasing w, the Fe straight wires create complicated magnetic domain configurations.[13] Polycrystalline permalloy wires, on the other hand [see Fig. 1(b)], possess a single domain with the width range of $0.2 \leqslant w \leqslant 0.5$ μm. In this width range, magnetic poles are observed at the ends of the wires. Above $w = 1$ μm, the permalloy wires form magnetic domains at the ends of the wire to reduce the demagnetizing field. Upon increasing w further ($w > 10$ μm), the permalloy wires create domain configurations (not shown) in the middle of the wire, for which magnetization lies along the wire separated by 180° walls. It is important to mention that we observe qualitatively the same domain configurations for both Fe and permalloy structures in the remanent states (after the magnetization saturated along the wire using an external field of 1 T). This confirms that the domain configurations shown in Fig. 1 are very stable.

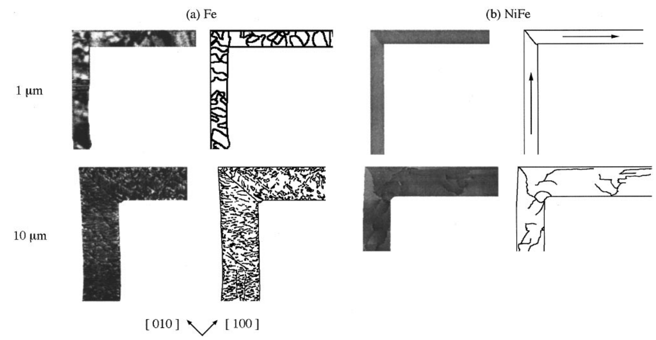

FIG. 2. MFM images and schematic diagrams of the domain configurations of the mesoscopic L shape structures (30 nm thick, w μm wide and 200 μm long) of both (a) Fe and (b) NiFe as grown (unmagnetized states).

In polycrystalline permalloy wires, only the shape anisotropy is present and is defined by the magnetostatic energy U_{mag}, which is proportional to the demagnetizing factor of the sample shape. The epitaxial Fe wires, on the other hand, possesses not only a shape anisotropy but also a cubic anisotropy, which is described by the cubic anisotropy energy U_{ca}. As the hard axes of the Fe wires are along the wires, preventing the magnetization pointing in the wire direction, the cubic anisotropy is expected to be dominant in the Fe wires ($U_{\mathrm{ca}} > U_{\mathrm{mag}}$). This is consistent with the MFM observation, which clearly indicates that the magnetocrystalline anisotropy plays a very important role in forming magnetic domains.

With connecting two straight wires perpendicularly at the end to form L shape structures, a major diagonal wall is observed in both bcc Fe and polycrystalline permalloy as shown in Fig. 2. Below $w = 2$ μm, the permalloy L shapes show only one diagonal 90° wall at the junction. The bcc Fe samples, however, possess many walls both at the junction and the wire regions, which is consistent with the domain configurations of straight wires. Above $w = 10$ μm, permalloy samples also show several walls but are much less complicated than Fe L shapes.

For the case of crosses, MFM images and corresponding schematic magnetic domain configurations are shown in Fig. 3. At the cross junctions, both $w = 0.2$ and 0.5 μm samples possess submicron regions with spins aligned diagonally for both bcc Fe and polycrystalline permalloy. Above $w = 2$ μm, new domain walls appear at the junction for both

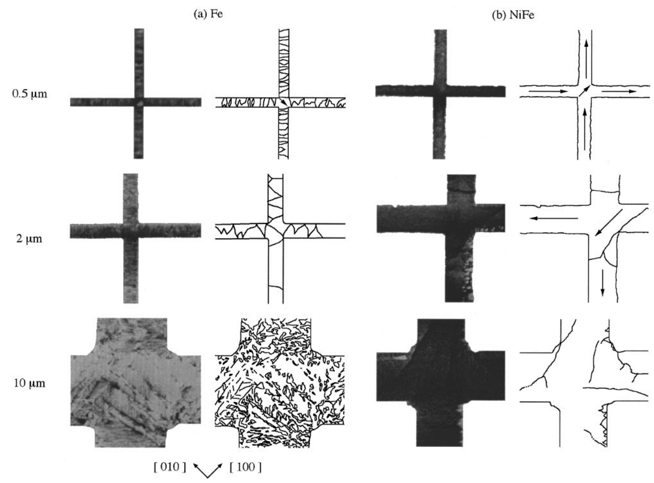

FIG. 3. MFM images and schematic diagrams of the domain configurations of the mesoscopic crosses (30 nm thick, w μm wide, and 200 μm long) of both (a) Fe and (b) NiFe as grown (unmagnetized states).

Fe and permalloy crosses. In wire regions, complicated domain configurations are seen with the width range of $0.2 \leqslant w$ μm for the bcc Fe crosses, while single domain states are observed with permalloy samples ($w \leqslant 2$ μm). The domain configurations in the wire area are the same as those observed in the straight wires. These domain configurations observed in polycrystalline permalloy cross junctions ($0.2 \leqslant w \leqslant 1$ μm) are the same as those seen in the previous study,[7] and show very few domain walls at the wire regions. This suggests that the permalloy crosses are especially suitable for quantum magnetotransport studies.

IV. CONCLUSION

Domain wall configurations in mesoscopic wire junctions of both epitaxial bcc Fe and polycrystalline permalloy were investigated using MFM. Three sets of structures were fabricated with ferromagnetic wires (30 nm thick, $0.2 \leqslant w \leqslant 50$ μm wide and 200 μm long); straight wires, two wires connected at the ends (L shapes), and crosses. Fe samples show complicated domain configurations due to the magnetocrystalline anisotropy, while permalloy samples show simple domain configurations induced by the shape anisotropy. These results show that the spin configuration around the junction can be precisely tuned by varying not only the shape and the size but also the crystalline structures of the samples. The simple and well defined spin configurations in submicron permalloy samples as compared with those in Fe indicate that permalloy is a suitable material to study quantum magnetotransport, such as spin-dependent domain wall scattering, in mesoscopic magnets. Epitaxial Fe could also be suitable depending upon the orientation of the easy axes.

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