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# Magnetic Domain Studies of Permalloy Wire-Based Structures with Junctions

A. Hirohata, C. C. Yao, H. T. Leung, Y. B. Xu, C. M. Guertler, and J. A. C. Bland

**Abstract**—Permalloy ( $\text{Ni}_{80}\text{Fe}_{20}$ ) wire-based structures (30 nm thick and  $1 \cdot w \cdot 10 \mu\text{m}$  wide) with junctions (crosses, networks, H-shapes, rectangular chains and ring chains) prepared on a GaAs (100) substrate were observed in both their demagnetized and remanent states by magnetic force microscopy (MFM) in order to investigate the role of junction geometry in domain formation. Except in ring chains, two classes of domain configuration are found at the junction: (i) a domain wall-like feature due to abrupt spin rotation and (ii) a triangle-shape domain consistent with a flux closure configuration. Ring chains, on the other hand, form vortex domains at every other junction. The MFM observations are compared with micromagnetic calculations which qualitatively support the magnetic domain configurations.

**Index Terms**—Mesoscopic structures, magnetic domain configuration, magnetic force microscopy, micromagnetic calculation.

## I. INTRODUCTION

LITOGRAPHICALLY defined mesoscopic structures have been attracting much interest for their possible applications for magnetoelectronic devices [1]. Network structures [2] are especially relevant to magnetic random access memory (MRAM), for example [3]. The mechanism of domain wall formation and trapping at junctions needs to be understood in order to develop magnetoresistive (MR) devices [4], [5]. There has also been extensive debate over whether the wall resistivity is positive [6] or negative [5], [7]. To investigate the role of the junction in trapping domains during the magnetization reversal process, the magnetic domain configurations at the junctions need to be clarified.

In the case of permalloy wire structures, since it is well known that the magnetic domain configurations are mainly dependent on the aspect ratio (length/width) [8], wires with a single domain are good candidates for creating domain wall trapping junctions. Combinations of simple wire structures therefore give rise to many possible domain configurations at the junction.

In this paper, we present magnetic domain studies of junction regions of various kinds of wire-based structures compared with micromagnetic calculations. A wide range of permalloy ( $\text{Ni}_{80}\text{Fe}_{20}$ ) mesoscopic wire-based structures with junctions were fabricated on GaAs (100) substrates. Scanning probe microscopy (SPM, Digital Instruments, Nanoscope III) was used to reveal the role of both the size and shape of the junctions in

the formation of domain walls, and micromagnetic calculations were carried out.

## II. EXPERIMENTAL PROCEDURE

A 3 nm Au/30 nm  $\text{Ni}_{80}\text{Fe}_{20}$  continuous film structure was deposited on a GaAs (100) substrate in ultrahigh vacuum (UHV). The NiFe films were grown at a rate of approximately one monolayer per minute by e-beam evaporation. The pressure during the growth was  $5.0 \times 10^{-9}$  Torr, while the substrate was held at 300 K. The permalloy mesoscopic wire-based structures (30 nm thick and  $1 \cdot w \cdot 10 \mu\text{m}$  wide) with junctions (crosses, networks, H-shapes, rectangular chains and ring chains) were fabricated by e-beam lithography and optimized pattern transfer techniques based on a combination of both dry and wet etching. The permalloy films do not have any magnetic easy axis according to our MOKE measurements.

The permalloy structures were observed in both their demagnetized (as grown) and remanent states by magnetic force microscopy (MFM) together with tapping mode atomic force microscopy (AFM). A commercial Si probe coated with CoCr (Digital Instruments, Pointprobe magnetic force sensor MESP) was used and the distance between probe and sample was set as 5 nm for tapping mode AFM and 100 nm for MFM measurements [9], [10]. The tip of the probe was magnetized before each observation.

## III. RESULTS AND DISCUSSION

Fig. 1 shows MFM images and corresponding schematic magnetic domain configurations at the junction regions of the permalloy cross structures ( $1 \cdot w \cdot 10$  and length  $l = 10 \mu\text{m}$ ). A cross with  $w = 1 \mu\text{m}$  possesses one domain wall-like feature in a diagonal direction as shown in Fig. 1(a). This feature is due to the divergence of the magnetization at the junction associated with the abrupt magnetization rotation. With increasing  $w$  and constant aspect ratio ( $l/w = 10$ ) in order to keep a single domain state in the 'arms' of the wire, this feature shifts toward one corner and so breaks the symmetry. In the case of  $w = 4 \mu\text{m}$ , finally, the junction region creates a triangle-shape domain as shown in Fig. 1(b) with  $w = 4 \mu\text{m}$ . This domain evolution occurs because the exchange energy of the magnetization at the cross junction becomes large enough to form a new domain. The wire arms of these crosses, on the other hand, remain in a single domain state in the range  $1 \cdot w \cdot 10 \mu\text{m}$ .

The MFM images and corresponding schematic domain configurations of the  $1 \mu\text{m}$  wide network and H-shape structure are shown in Fig. 2. At the junction of the network with the

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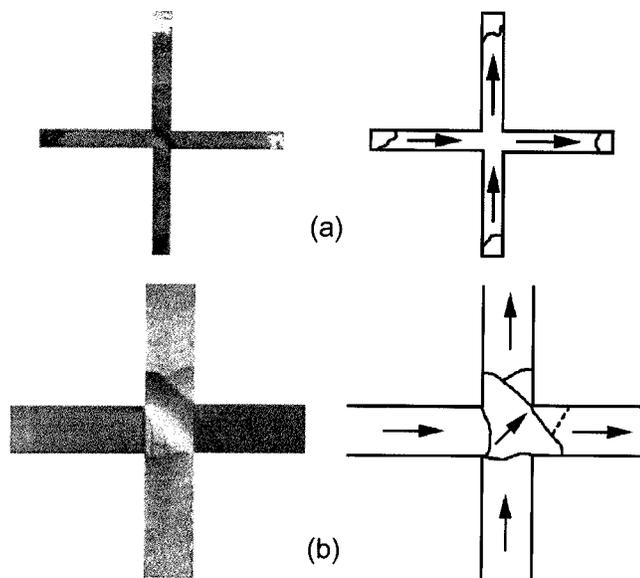


Fig. 1. MFM images associated with schematic magnetic domain configurations of permalloy wire-based structures with cross junctions: (a)  $w = 1$  and  $l = 10 \mu\text{m}$ , and (b)  $w = 4$  and  $l = 40 \mu\text{m}$ .

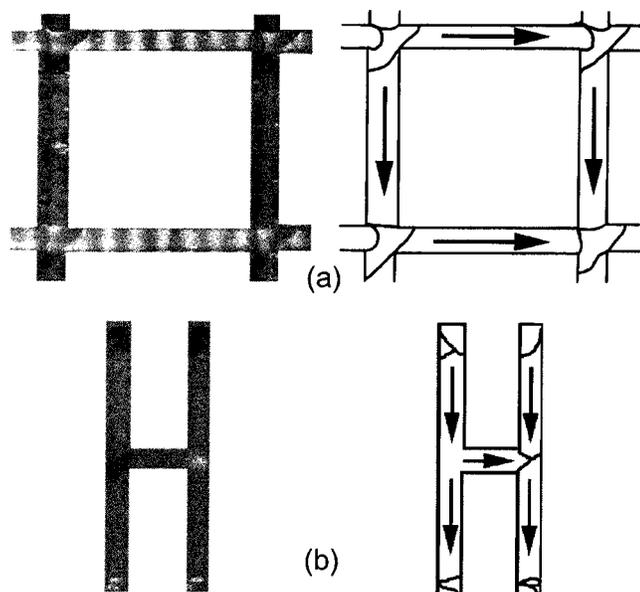


Fig. 2. MFM images associated with schematic magnetic domain configurations of permalloy wire-based structures with junctions: (a) network ( $w = 1$  and period  $p = 10 \mu\text{m}$ ) and (b) H-shape ( $w = 1$ ,  $l = 10$  and bridge length  $b = 5 \mu\text{m}$ ) in the demagnetized states. The periodical stripes in (a) are due to artificial noise.

$1 \mu\text{m}$  wide wires, a triangle-shape domain can also be seen [see Fig. 2(a)]. Such triangle-shape domains are observed with  $1 \cdot w \cdot 2 \mu\text{m}$ . The  $w = 1 \mu\text{m}$  H-shape (half-broken network structure), however, shows the wall-like feature to be the same as that observed in the  $1 \mu\text{m}$  cross as shown in Fig. 2(b). This asymmetrical domain configuration is due to the magnetic poles at the right-hand side of the junction in the H-shape. Since the MFM images of the  $w = 1 \mu\text{m}$  wire-based structures exemplify typical basic domain configurations at the junctions, the domain features of the  $1 \mu\text{m}$  structures are discussed below.

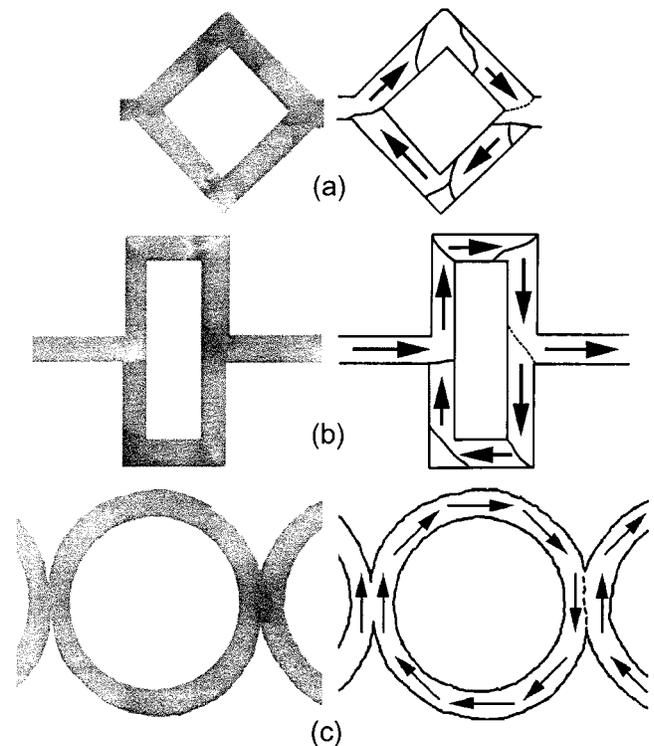


Fig. 3. MFM images associated with schematic magnetic domain configurations of permalloy chain structures: (a) diagonal square (rhombus) chain ( $w = 1$  and side length  $s = 10 \mu\text{m}$ ), (b) rectangular chain with wire ( $w = 1$ , longer side length  $l_1 = 10$ , shorter side length  $l_2 = 5$  and wire length  $l_w = 5 \mu\text{m}$ ) and (c) ring chain ( $w = 1$  and outer diameter  $r = 10 \mu\text{m}$ ) in the demagnetized states.

Two major domain configurations, a wall-like feature and a triangle domain, are formed in these wire-based domain wall trapping structures. For such simple structures, the corresponding MR behavior can be observed [4]. However, it is very difficult to detect very small resistivity signals related to a single domain wall. Therefore we have investigated the domain structures of periodically modulated wire structures with rhombus and rectangular extensions [11]. In such structures, the repetition of the domain walls should enable the domain wall contribution to the resistivity to be detected more easily. Since the magnetization reversal process in such structures always occur not only by wall movement but also by magnetization rotation, we fabricated chain structures to remove the wall-like feature which introduces the magnetization rotation contributions to the resistivity in MR measurements.

Fig. 3 shows MFM images and domain configurations of permalloy chain structures. Both the diagonally connected square (rhombus) chain and rectangular chain with wires form flux closure domain configurations with triangular shape domains at the corners. In particular, the rectangular chains create very clear and well defined domain walls connected to the corners of the structure, which corresponds to the walls observed in the modulated wire structures with extensions [11].

The ring chain also shows flux closure domains as observed in the circular dots [9] and single rings [see Fig. 3(c)]. It should be noted that the junctions in a chain of rings form a vortex closure domain (left-hand side) at every other junction (“8”-shape) and, in between, closure domains isolated by one wall (right-hand

side) are seen. Since this “8”-shape closure domain breaks into two circular vortex domains in the remanent state, we conclude that the pair of vortex domains is not stable and is easily rotated under a small applied field.

Both solid rhombus and solid rectangular chains were investigated previously by MFM and show flux closure domain configurations [11]. However, the current distribution needs to be considered in analyzing the MR behavior in these structures. With the chain structures, on the other hand, the domain walls are trapped at the junctions and the effect of the current distribution is much smaller due to the narrow width of the chains. From the application point of view, these structures are therefore potentially useful in MR devices.

#### IV. NUMERICAL CALCULATIONS

Micromagnetic numerical calculations were carried out to confirm the energetically stable magnetic domain configurations using a finite difference method [9]. The system was divided into 30 nm cubic cells, since we obtain reasonable domain configurations with this mesh size [2], [4], [9]. The demagnetization field, magnetic anisotropy field and the exchange field were calculated at the position of each cell. The cells were assumed to possess a constant magnitude of magnetization  $M_S$ . The magnetization was assumed to point in any direction.  $M_S$  was randomly aligned at first and each cell magnetization then rotated in such a direction as to reduce the total energy at the cell position. The total energy of the samples was also calculated and the stable domain configuration was defined at the minimum energy.

The results of numerical simulations are shown in Fig. 4. In these pictures, the magnitude of the divergence of the magnetization is shown by the gray scale. Since the magnetization in the domain walls is rapidly rotating, the walls are shown as a pair of white and black lines, corresponding to a high gradient value. A typical simulation result of a domain wall-like feature is shown in Fig. 4(a) with  $w = 1 \mu\text{m}$  cross. At the junction, the pair of white and black region is very large ( $\sim 1 \mu\text{m}$  wide) and corresponds to the MFM observation in Fig. 1(a). The conventional domain walls, on the other hand, show clear and sharp line between white and black regions as shown in Fig. 4(b). The walls are seen at each corner of the structure. The results for rhombus chain are qualitatively the same as those of the MFM image. With the simulation for the ring chain, as shown in Fig. 4(c), the results corresponds to a vortex state but do not show “8”-shape domain as observed in the MFM image. Fine structure is also seen which arises from the large mesh size.

#### V. CONCLUSION

We investigated the domain configurations in permalloy ( $\text{Ni}_{80}\text{Fe}_{20}$ ) small wire-based structures (30 nm thick and  $w \mu\text{m}$  wide;  $1 \leq w \leq 10 \mu\text{m}$ ) with a wide range of junctions (crosses, networks, H-shapes, rectangular chains and ring chains)

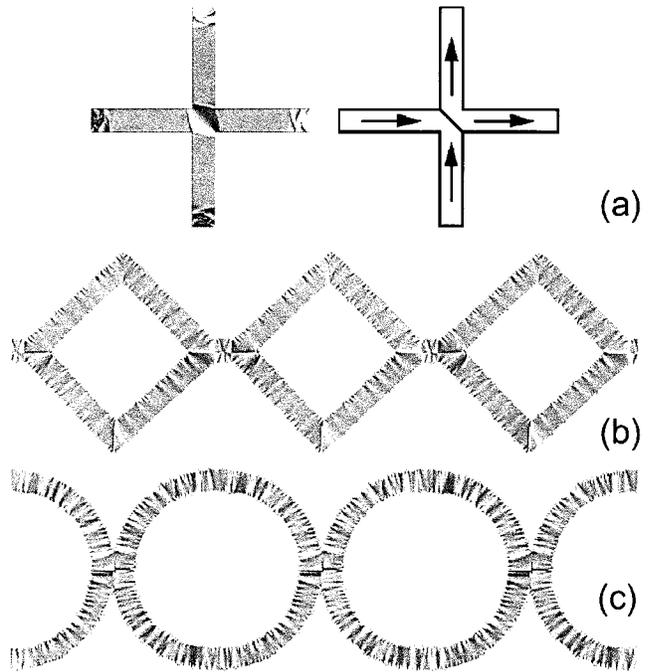


Fig. 4. Micromagnetic simulations for permalloy structures: (a) cross ( $w = 1$  and  $l = 10 \mu\text{m}$ ), (b) rhombus chain ( $w = 1$  and  $s = 10 \mu\text{m}$ ) and (c) ring chain ( $w = 1$  and  $r = 10 \mu\text{m}$ ). A pair of white and black lines connected with the corners correspond to magnetic domain walls. The fine structure is an art effect of the calculations which arises from the large mesh size.

prepared on a GaAs (100) substrate in both their demagnetized and remanent states using MFM. In wire-based junctions except ring chains, two classes of domain configuration are found: (i) domain wall-like feature due to abrupt spin rotation and (ii) a triangle-shape domain forming a flux closure domain configuration. With ring chains, on the other hand, vortex domains are observed to be in pair only in the remanent state. Using micromagnetic calculations, the effect of the existence of the junctions on domain wall formation was assessed. These domain studies indicate that wire-based junction structures could be useful in determining the MR of domain walls.

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