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Lee, W.Y., Hirohata, A. orcid.org/0000-0001-9107-2330, Leung, H.T. et al. (5 more authors) (2000) Magnetization reversal in mesoscopic Ni80Fe20 wires: A magnetic domain launching device. IEEE Transactions on Magnetics. pp. 3018-3020. ISSN: 1941-0069

https://doi.org/10.1109/20.908661

Magnetization Reversal in Mesoscopic $Ni_{80}Fe_{20}$ Wires: A Magnetic Domain Launching Device

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***Abstract*—The magnetization reversal process in mesoscopic permalloy ($Ni_{80}Fe_{20}$) wire structures has been investigated using scanning Kerr microscopy, magnetic force microscopy (MFM) and micromagnetic calculations. We find that the junction offers a site for reversed domain wall nucleation in the narrow part of the wires. As a consequence, the switching field is dominated by the domain nucleation field and the junction region initiates reversal by the wall motion following the nucleation of domains. Our results suggest the possibility of designing structures that can be used to "launch" reverse domains in narrow wires within a controlled field range.**

***Index Terms*—Magnetization reversal, mesoscopic wires, nucleation process, switching field.**

I. Introduction

In recent years, there has been great interest in the magnetization reversal and magnetoresistance (MR) behavior in ferromagnetic mesoscopic wires because of their importance in both MR devices and spin electronic devices [1]–[9]. It is well recognized that the switching field and magnetization reversal process depend strongly on the end shape as well as the width of ferromagnetic wire [1]–[4]. The effect of the end shape is attributed to the formation of end domains or edge domains, which are crucial in the magnetization reversal process [1]–[4]. Our previous work demonstrated that the shape of a wire structure has a decisive influence on the magnetic properties in the mesoscopic range [5]–[6].

In this paper, we present the effect of the junction geometry in extended permalloy ($Ni_{80}Fe_{20}$) wire structures for launching reverse domains in the wires. We demonstrate that it is possible to control the switching field by introducing a junction that facilitates magnetization reversal in the narrow part. Our results suggest the possibility of designing structures that can be used to "launch" reverse domains in narrow wires within a controlled field range. We discuss the geometrical effect of the junction on the magnetization reversal and switching field associated with domain configurations inferred from MFM imaging and micromagnetic calculations.

II. Experiment

A permalloy film was deposited at room temperature at a rate of ~2 Å/min by electron-beam evaporation in an ultrahigh vacuum (UHV) chamber with a pressure of 6×10^{-9} mbar and then annealed at 120°C for 30 min to remove the uniaxial anisotropy induced during deposition. A combination of electron beam lithography and a lift-off process has been utilized to fabricate wire array structures from a continuous film of 30 Å Au/300 Å $Ni_{80}Fe_{20}$/GaAs(001). Each wire consists of a narrow part (w_1 = 1 μm) and a wide part (w_2 = 5 μm): the widths of the wires change abruptly at the midpoint to create two 200 μm length regions with w_1 = 1 μm and w_2 = 5 μm (see the inset of Fig. 1). We also fabricated bridge-wire structures as shown in Fig. 3(a). The bridge wire is a single wire (l = 205 μm and w = 10 μm) which has a narrow region of length l = 5 μm and width w = 0.5–10 μm introduced in the center of the wire.

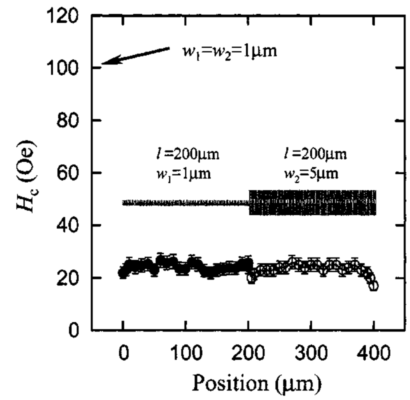

Fig. 1. The variation of the switching field as a function of position for the wire junction structure (w_1 = 1 μm, w_2 = 5 μm), measured every 10 μm along the wire length. The arrow indicates H_c in the fixed width wire ($w_1 = w_2$ = 1 μm) obtained by MR measurement.

The local hysteresis loops were obtained by scanning Kerr microscopy [7], [8]. Two objective lenses (×20, Numerical Aperture: 0.55, ×50, NA: 0.85) were used to focus the probing laser beam (~3 μm, ~1 μm spot size, respectively) on the wires. Magnetic force microscopy (MFM, Digital Instruments) has been carried out in order to observe domain configurations. The calculated magnetization pattern was also obtained by micromagnetic calculation based on the Labonte algorithm [10].

III. Results and Discussion

Scanning Kerr microscopy has been employed to measure microscopic MOKE hysteresis loops for the wire junction in order to investigate the magnetization reversal behavior and switching field, when magnetic fields were applied parallel to the wire axis. Fig. 1 presents that the switching fields of the narrow (w_1 = 1 μm) and wide part (w_2 = 5 μm) of the

Manuscript received February 14, 2000. This work was supported by the EPSRC (UK) and the ESPRIT (EU) programs ('Spider' and 'Massdots'). The work of W. Y. Lee was supported by the British Council Korea.

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Publisher Item Identifier S 0018-9464(00)08410-7.

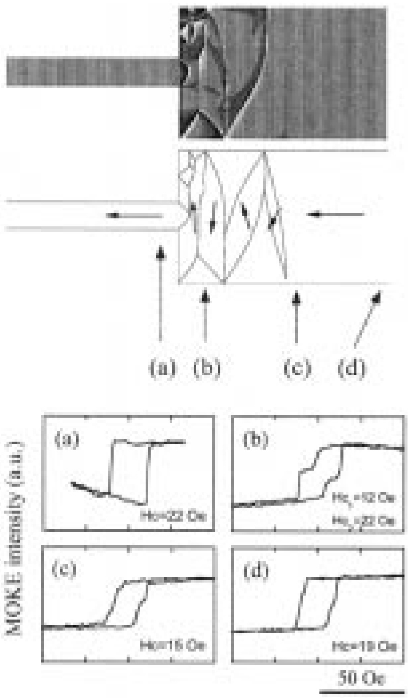

Fig. 2. MOKE hysteresis loops for the wire junction structure obtained at four different positions near the junction area. The inset shows the calculated and schematic domain patterns of the wire junction structure in the remanent state. In the calculated pattern, the magnitude of the divergence of the magnetization is shown by the gray scale.

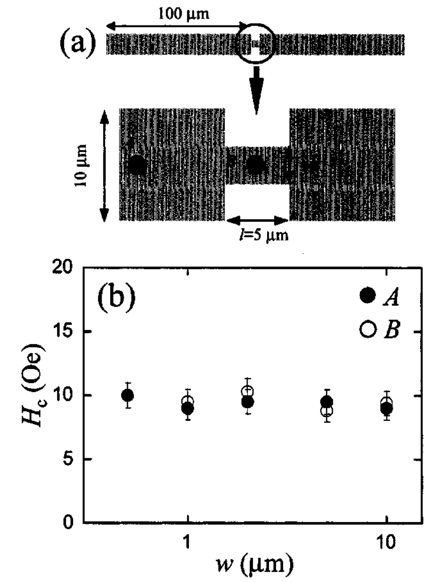

Fig. 3. (a) Schematics of the bridge structures, which have a narrow region with a length l = 5 μm and a width w = 0.5–10 μm introduced in the center of the wire. The dots on the schematics denote the fixed positions $\boldsymbol{A}$ (50 μm away from the end of a wide wire) and $\boldsymbol{B}$ (center of the narrow wire) of the laser beam spots. (b) The variation in the switching field (H_c) against the wire width of the narrow region.

wire junction structure are in the range 22–26 Oe, indicating that the magnetization reversal of the complete structure is determined by the wider region (w_2 = 5 μm). This behavior is in contrast to that of fixed width wires [4] in which the switching field is dependent upon the width of ferromagnetic wires due to buckling of the magnetization perpendicular to the wire, leading to the formation of domain walls perpendicular to the wire [4]. Previous MR measurements have shown that H_c of a single wire ($w_1 = w_2$ = 1 μm) is $\sim$100 Oe [11]. From the similar values of the switching fields in the wide and narrow parts we infer that the threshold field required for nucleation in the wire junction structure is much smaller than that of a single wire, while the field for domain wall motion is almost identical to that of the single wire and independent of the variable wire width in the micron range.

Fig. 2 presents local MOKE hysteresis loops obtained near the junction area and an inset showing the calculated and schematic domain patterns of the wire junction in the remanent state. The calculated results exhibit a zigzag domain pattern and "piling up" of domain walls on the wide part, while the narrow part remains single domain. This zigzag pattern is believed to result from the combined influence of the geometrical shape of the junction and a strong demagnetizing field favoring closure domains despite the abrupt transition in the width. A double-jump switching is clearly observed in the junction of the wire: H_{c1} = 12 Oe and H_{c2} = 22 Oe, as in Fig. 2(b). On travelling across the wire from the wide part during magnetization reversal, domain walls are trapped in the junction, and cannot move further until a field of H_{c2} = 22 Oe is reached, which corresponds to the wall motion field (H_w) in the narrow part and which is much smaller than the nucleation field (H_n = $\sim$100 Oe). This implies that H_n is greater than H_w in the narrow part. The double-jump switching disappears as the probing beam spot moves away from the junction by 5 μm and 10 μm as shown in Fig. 2(c) and (d), respectively.

These results show that the junction in the wire junction structure facilitates magnetization reversal in the narrow part, in contrast to symmetrically modified ends such as pointed [1], [2] and rounded [1], [3] ends which suppress the formation of end domains in rectangular elements and increase the switching field. Multidomains form in the wide part in the vicinity of the junction. The junction offers a more favorable site for reversed domain nucleation than the corners of the wide part. In this way, the initiation of magnetization reversal occurs, and hence switching responds to a much smaller applied field than for a fixed width structure. Similar reversal behavior has been very recently demonstrated using a NiFe/Cu/Co submicron wire, where a domain wall nucleates initially in a larger square pad connected to one end of the wire and is injected into the wire by a field, less than the switching field of the wire [12].

To better understand the effect of the junction geometry on magnetization reversal in the permalloy wires, we also investigated bridge wires. In Fig. 3, we present the variation in the switching field (H_c) against the wire width of the narrow region. The dots on the schematics in Fig. 3(a) denote the fixed positions $\boldsymbol{A}$ (50 μm away from the end of a wide wire) and $\boldsymbol{B}$ (center of the narrow wire) of the laser beam spots whose size were controlled according to the wire width. It is clearly seen that H_c does not vary with decreasing wire width but is identical ($H_c \approx$ 10 Oe) in both regions. These results support the view that the magnetization reversal mechanism is dominated by domain wall nucleation rather than domain wall motion in the permalloy wires and, more importantly, that the junction is

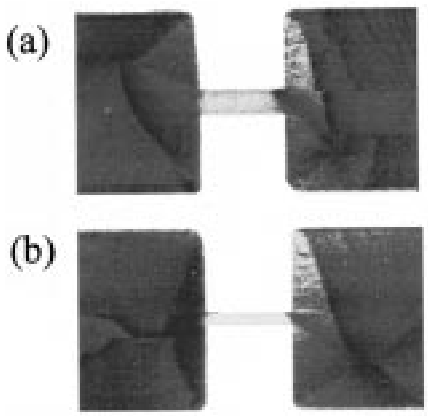

Fig. 4. MFM images of the bridge structure with (a) w = 1 μm and (b) w = 0.5 μm in the demagnetized state. The narrow regions with w = 0.5, 1 μm show a single domain state, while multidomains are seen in the wide wires.

crucial in initiating reversal. This is consistent with the results of MR measurements [13] in a bridge structure with w = 0.5 μm, which shows a single switching.

MFM images indicate that narrow regions with $w \geq 5$ μm accommodate domain walls, whereas narrow regions with $w \leq$ 2 μm show a single domain state [see Fig. 4(a): w = 1 μm, (b): 0.5 (m]. MFM images also show multidomains appearing in the wide wires. The MFM images are in good agreement with the domain patterns obtained by micromangetic simulations [14]. This illustrates that the junction offers a site for reversed domain wall nucleation in the narrow part and hence switching responds to a much smaller applied field than for a fixed width structure. Our results suggest the possibility of designing structures which can be used to "launch" reverse domains in narrow wires within a controlled field range for applications such as spin electronic devices or for fundamental experiments in magnetization reversal dynamics.

IV. Conclusion

We find that the junction in both the wire junction and bridge wire structures offers a site for reversed domain wall nucleation in the narrow part and hence switching occurs for a much smaller applied field than for a fixed width wire. These results illustrate the possibility of lowering the switching field in narrow wires by introducing wider regions that nucleate reverse domains, in contrast to symmetrically modified ends that suppress the formation of end domains in rectangular elements.

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