

Effect of Junction Geometry on Switching Field and Reversal Behavior in Permalloy Wires

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Abstract—We report on the magnetization reversal process and switching field behavior in permalloy ($\text{Ni}_{80}\text{Fe}_{20}$) wire structures investigated by magneto-optic Kerr effect (MOKE) and magnetoresistance (MR) measurements. A combination of electron beam lithography and a lift-off process has been utilized to fabricate three sets of wire structures from a 30 Å Au/300 Å $\text{Ni}_{80}\text{Fe}_{20}/\text{GaAs}(100)$ continuous film: straight wires, elbow wires, and cross wires with width $w=0.5$ –50 μm and length $l=200$ μm . We found that the switching field and reversal behavior in the elbow and the cross wires depend upon the junction geometry, which nucleates or suppresses reverse domains according to the wire width. Consequently the junction determines the magnetization reversal process and switching field in the elbow and cross wires.

Index Terms—Domain configurations, magnetization reversal, mesoscopic structures, switching field.

I. INTRODUCTION

The magnetization reversal behavior of magnetic nanostructures has recently attracted considerable scientific and technological interest from the viewpoint of applications such as high density storage media, miniature read heads, and magnetoelectronic devices [1]–[8]. Numerous studies of finite lateral size effects have been performed using various geometries *e.g.* isolated dots [1], [2], antidots [2], [3] and wire arrays [4]–[11].

Very recently, there have been several efforts to control the magnetization reversal and magnetoresistance (MR) behavior in ferromagnetic wires. As reported in previous studies [4]–[8], the switching field and magnetization reversal process depend strongly on the end shape as well as the width of ferromagnetic wires. The effect of the end shape is attributed to the formation of end domains which are crucial in the reversal mechanism [4]–[8]. Our recent work [7] showed that the magnetization reversal process and MR behavior change significantly in micron-sized permalloy wires with periodically modulated width, due to the modified shape-dependent demagnetizing fields. We also demonstrate the possibility of engineering the switching field by introducing regions that nucleate or suppress reverse domains in $\text{Ni}_{80}\text{Fe}_{20}$ wires according to the wire width [8].

We have investigated the effect of mesoscopic junctions on the switching field associated with the magnetization reversal and domain configurations in $\text{Ni}_{80}\text{Fe}_{20}$ wire structures using scanning Kerr microscopy, magnetic force microscopy (MFM), and MR measurements. We found that

the switching field and reversal behavior in the elbow and the cross wires depend on the junction, which nucleates or suppresses reverse domains according to the wire width. The junction is thus important in determining the magnetization reversal and switching field in the elbow and cross wires. We discuss the effect of the junction on the switching field associated with domain configurations inferred from MFM imaging.

II. EXPERIMENTS

A permalloy film was first deposited at room temperature at a rate of 2 Å/min with a pressure of 6×10^{-9} mbar and then annealed at 120°C for 30 min to remove the uniaxial anisotropy. Such a uniaxial anisotropy is typical for such permalloy films, and can be induced either by strain or by the oblique incidence of the deposition [12]. A combination of electron beam lithography and a lift-off process has been utilized to fabricate three sets of wire structures from a continuous film of 30 Å Au/300 Å $\text{Ni}_{80}\text{Fe}_{20}/\text{GaAs}(100)$. First is a set of straight wires with width $w=0.5$, 1, 2, 10, and 50 μm and length $l=200$ μm . Second is a set of elbow wires which consist of two wires with the same width (w) and length $l=100$ μm , and third a set of cross wires which comprise two wires with the same width (w) and length $l=200$ μm . Fig. 1 displays SEM photographs showing the straight wire (a), the elbow wire (b), and the cross wire (c) with width $w=2$ μm . Contact pads for MR measurements are also shown.

For MR measurements, standard optical lithography, metallization and lift-off of 20 nm Cr/300 nm Au were utilized to fabricate electrical contacts to the wires. A dc current of 50 μA was passed along the wires and the voltage probes were placed very close to the junction for four terminal measurements. Magneto-optic Kerr effect (MOKE) hysteresis loops were obtained by scanning Kerr microscopy [8], [14]. Two objective lenses ($\times 20$, Numerical Aperture: 0.55, $\times 50$, 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 using a low stray field tip so as to observe domain configurations of the wires in the demagnetized state.

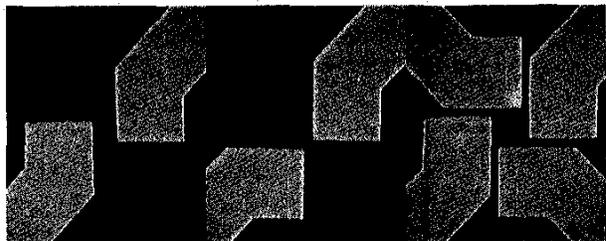


Fig. 1 SEM photographs showing the straight wire (a), elbow wire (b), and cross wire (c) with $w=2$ μm .

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III. RESULTS AND DISCUSSION

Fig. 2 displays microscopic MOKE hysteresis loops for the straight wires (a), elbow wires (b), and cross wires (c) with $w=1, 2, 10,$ and $50 \mu\text{m}$ obtained by scanning Kerr microscopy when magnetic fields applied parallel to the wire axis. The dots on the schematics denote the fixed position ($50 \mu\text{m}$ away from the end of the structure) of the laser beam spot whose size was controlled according to the wire width. It is clearly seen that for each set of wires, the coercive field (H_c) is observed to increase with decreasing wire width. This is assumed to be due to buckling of the magnetization perpendicular to the wire, giving rise to the formation of domain walls perpendicular to the wire [9]. The MOKE results are in qualitative agreement with earlier work [9]. Regardless of the shape of the wire, it is observed that the wire axis is the easy direction throughout the entire size range studied, due to the magnetic shape anisotropy.

On the other hand, although an increase in the coercive force with decreasing wire width is observed for the three sets of wire structures, each set of wires shows quantitatively distinct magnetization reversal and switching field behavior with decreasing wire width. For $w=50 \mu\text{m}$, the coercivities in the straight wire and the elbow wire are $H_c^S=14 \text{ Oe}$ and $H_c^E=11 \text{ Oe}$, respectively, while the coercivity in the cross wire is $H_c^C=4 \text{ Oe}$ ($H_c^S > H_c^E > H_c^C$). The value of the coercivity in the cross wire is comparable with that of the continuous film in spite of the expected shape anisotropy. For $w=10 \mu\text{m}$, the coercivities in all the wire structures are almost identical ($H_c^S=H_c^E=H_c^C \approx 18 \text{ Oe}$). For $w=1 \mu\text{m}$, however, the cross wire shows the highest value of coercivity of $H_c^C=54 \text{ Oe}$ ($H_c^S < H_c^E < H_c^C$).

In Fig. 3, we present the variation in the switching field as a function of the wire width for the three types of wire. As indicated by the arrow in Fig. 3, it is found that a crossover of the switching fields for the straight, elbow, and cross wires occurs at $w=10 \mu\text{m}$. We attribute the observed behavior to the size-dependent effect of the junction on the magnetization reversal process and domain configurations. We have demonstrated that domain nucleation at the junction of the double-width wire initiates magnetization reversal in the narrow half [8]. This illustrates the possibility of engineering the switching field by introducing regions that nucleate or suppress reverse domains according to the wire width.

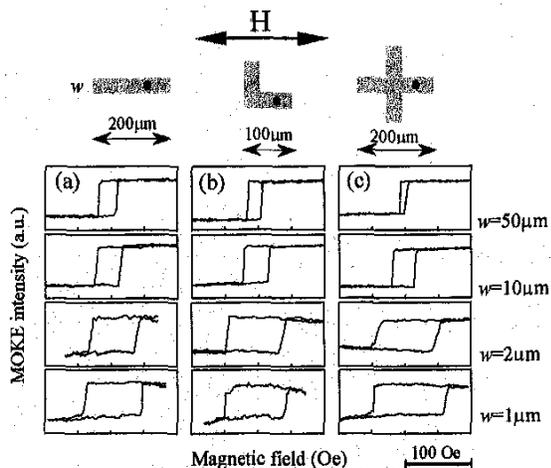


Fig. 2 MOKE hysteresis loops for the straight wires (a), elbow wires (b), and cross wires (c) obtained by scanning Kerr microscopy when magnetic fields applied parallel to the longitudinal wire axis.

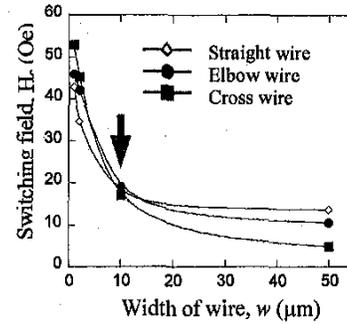


Fig. 3 The variation of the switching field as a function of the wire width for the straight wires, elbow wires, and cross wires. The arrow indicates the crossover of the variation of the switching field.

It is well recognized that magnetotransport measurements such as magnetoresistance provide a sensitive probe of the magnetization reversal behavior in mesoscopic ferromagnetic structures [3], [7]-[11]. In the present work, we have designed the elbow and cross wires in order to confine a limited number of domain walls at the junction with size comparable to the single domain width. Detailed information associated with the domain configurations at the junction could be obtained by MR measurements. Fig. 4 shows the longitudinal (a) and transverse (b) MR response of the $1 \mu\text{m}$ cross wire. The magnetic field and current directions are indicated in the schematic insets of Fig. 4. The maximum applied field is $\sim 600 \text{ Oe}$, and the values of the longitudinal and transverse MR ratio are $\sim 0.04 \%$ and $\sim 1.4 \%$, respectively. In the longitudinal MR response [Fig. 4(a)], the minimum resistance corresponding to the coercive field is $\sim 50 \text{ Oe}$, i.e., smaller than that ($H_c=54 \text{ Oe}$) obtained by MOKE at the position $50 \mu\text{m}$ away from the edge of the structure in Fig. 2(c). However, the value of H_c determined by MR measurements is greater than that ($H_c=43 \text{ Oe}$) of the $1 \mu\text{m}$ width straight wire shown in Fig. 2(a).

On the other hand, in the transverse MR response, the maximum resistance corresponding to the coercive field is $\sim 35 \text{ Oe}$ in Fig. 4(b). 'Barkhausen jumps' clearly occur in the transverse MR curves in the field range $100\text{-}250 \text{ Oe}$. Such 'Barkhausen jumps' are even more pronounced in the transverse MR curves of the $0.5 \mu\text{m}$ cross wire [10]. This transverse MR behavior is quite different from that of the $1 \mu\text{m}$

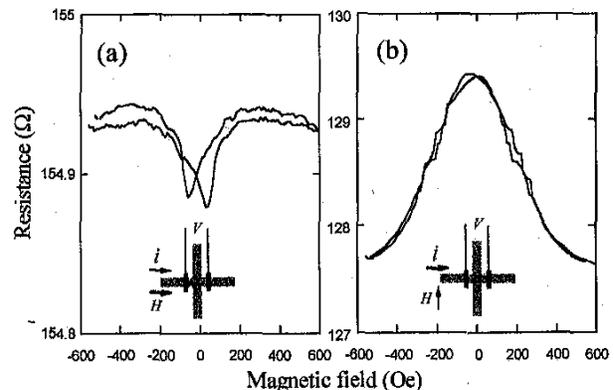


Fig. 4 The longitudinal (a) and transverse (b) MR response of a $1 \mu\text{m}$ cross wire to magnetic fields. The magnetic field and current directions are indicated in the schematic insets.

straight wire, which is smooth and free of jumps due to spin rotation dominating the reversal, suggesting that domains no longer develop across the width of the wire [7]-[9]. Tsang and Decker [11] have correlated the domain process and MR response in small permalloy elements, demonstrating that two domain processes are responsible for the 'Barkhausen jumps' in the MR response, i.e., abrupt reductions of domain population and the nucleation and expansion of walls. Our MR results illustrate the existence of domain walls at the junction, which have a different nature from end domains in rectangular elements [4]-[6]. As reported in previous work [5], due to the end domain configurations, the reversal behavior of a rectangular element differs from the predictions of the Stoner-Wohlfarth model, giving rise to a non-square M - H loop. Modified ends such as pointed [4], [6] and rounded [5], [6] ends suppress the formation of end domains in rectangular elements and increase the switching field.

Fig. 5 presents an MFM image (a) and the corresponding schematic domain pattern (b) of a $1\mu\text{m}$ cross wire, which was separately made without contact pads for MFM measurements in order to observe domain patterns at the ends and junction. The bright and dark regions illustrate magnetic poles of opposite polarity in the MFM image. Four end domains were visible in the cross wire [Fig. 5(a)], as seen in NiFe rectangular elements with higher aspect ratio in previous work [4]-[6]. The MFM image also shows two levels of magnetic contrast (black and white) at the junction, indicating that the two magnetizations in adjacent domains are antiparallel along the junction diagonal. This implies that a 180° wall is trapped at the junction. This wall configuration is in good agreement with our micromagnetic simulation results. A detailed discussion of the simulation results will be presented separately [13]. Similar wall configurations were also observed at the junction of 0.5 - $2\mu\text{m}$ cross and elbow wires.

We attribute the observed magnetic behavior to the size-dependent influence of the junction on the magnetization reversal and domain configurations within the elbow and the cross wires. In contrast to end domains [4]-[6], the junction in the elbow and cross wires nucleates or suppresses reverse domains for magnetization reversal according to the wire width. For $w > 10\mu\text{m}$, the junction facilitates domain wall nucleation in the elbow and cross wires and thus reduces the switching field. However, for $w < 10\mu\text{m}$, the formation of reverse domains is suppressed due to the presence of a dia-

gonal 180° wall at the junction induced by the perpendicular arms in the elbow and cross wires, giving rise to an increase in the switching field. The effect of the junction on the switching field and the reversal behavior in the elbow and the cross wires is of practical significance since it may be used in optimizing miniature magnetic device performance [14].

V. CONCLUSION

Mesoscopic junction effects on the magnetization reversal and switching field in $\text{Ni}_{80}\text{Fe}_{20}$ wire structures have been studied using MOKE, MR measurements and MFM. Distinct reversal behavior has been observed in the elbow and cross wires where domain wall nucleation is facilitated or suppressed by the junction. We attribute the observed magnetic behavior to the size-dependent influence of the junction on the magnetization reversal and domain configurations within the elbow and the cross wires.

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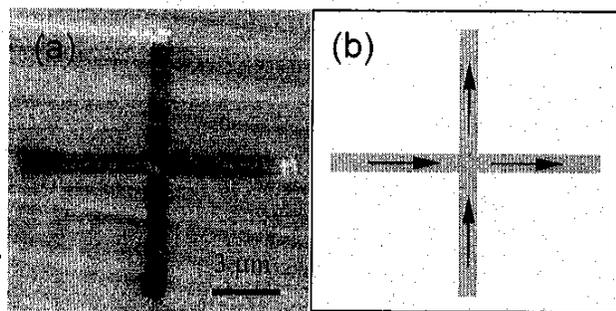


Fig. 5 MFM image (a) and the corresponding schematic domain pattern (b) of a $1\mu\text{m}$ cross wire.