May 2002

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Tsai, J. L.; Lee, S.F.; Yao, Y.D.; Yu, C.; and Liou, Sy_Hwang, "Magnetoresistance study in thin zig zag NiFe wires" (2002). *Si-Hwang Liou Publications*. 76.
https://digitalcommons.unl.edu/physicsliou/76

JOURNAL OF APPLIED PHYSICS VOLUME 91, NUMBER 10 15 MAY 2002

Magnetoresistance study in thin zig zag NiFe wires

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Thickness dependence on the domain wall resistivity of zig zag thin permalloy wires was studied from 10 to 300 K. The maximum domain wall resistivity was obtained in wire with 100-nm-film thickness. The multidomain state resistivity was 14.29 $\mu\Omega$ cm, while single-domain state resistivity was 14.36 $\mu\Omega$ cm at 10 K. The ratio of domain wall magnetoresistance was measured to be 0.034%, 0.112%, and 0.258%, and the magnetic field where the domain wall started to switch was measured as -70, -40, and $+80$ Oe for wires with thicknesses of 20, 40, and 100 nm, respectively, at 250 K. Domain wall resistivity was nearly independent of temperature for wire with 40-nm-film thickness but varied significantly with temperature for 100-nm-thick wire between 10 and 300 K. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1453318]

I. INTRODUCTION

The development of lithography techniques makes it possible to fabricate well-defined nanometer-size dots, chains, and wires. It provides a good way to explore the interplay between electron transport and magnetic properties in mesoscopic magnetic devices. The contribution of domain walls to magnetoresistance (MR) has been studied at low temperature in Ni nanowires.[1] Resistivity due to domain walls was pointed out to be associated with macroscopic quantum tunneling.[2] Negative domain wall MR was reported in Fe and Co nanowires.[3,4] In theory, the negative MR effect was proposed within the linear response theory, where decoherence of weakly localized electrons play an important role.[5] In particular, magnetic domain structure could be well controlled in zig zag Co and $Ni_{80}Fe_{20}$ nanowire by applied magnetic field with different angle orientation in the plane of films.[6–8] Discontinuous jumps in the wire resistivity were observed and proved as the nucleation and movement of domain walls from multidomain to single-domain state.

In this article, we utilize zig zag $Ni_{80}Fe_{20}$ wires with different film thicknesses to explore the temperature dependence of the domain wall contribution to MR. In addition, the thickness dependence of the switching fields and domain wall MR jumps at these switching fields is discussed.

II. EXPERIMENT

Field emission electron-beam lithography (Hitachi 4200) and lift-off process as used to prepare $Ni_{80}Fe_{20}$ zig zag wires on Si (100) with 100 nm SiO_2 buffer layers. PMMA and copolymer were spin coated onto the substrate under a proper speed and baked at 135 °C. After the e-beam writing process methyl isobutyl keyton: IPA isopropylalcohol (MIBK)=1:3 and IPA as used to develop the patterns. $Ni_{80}Fe_{20}$ films were deposited by thermal evaporation with a base pressure of 1×10^{-6} Torr.

Wires with a pitch of 4 μm were zig zagged between two gold pads separated by 50 μm. Samples with the same line-width of 500 nm and different thicknesses of 20, 40, 100, and 150 nm were fabricated. The total length of these wires are nearly the same, $L=73\pm1$ μm. Therefore, the number of corners for each wire is 25.

MR measurements were made by four-point methods in a variable temperature and magnetic field platform (PPMS, Quantum Design Model 6000) in the temperature range 10–300 K. The magnetic field was applied in the plane and the field angle is measured in the transverse direction of the wires. Resistance at 20 kOe was used as the reference when calculating MR percentage, and detailed investigation was performed from -1500 to 1500 Oe. At room temperature, magnetic domain observation was made by magnetic force microscopy (MFM, NT-MDT Slolver P47) and the field was applied in the longitudinal or transverse directions before measurement.

III. RESULTS AND DISCUSSION

The wire consists of 26 straight segments and the length between the neighboring corners, i.e., the pitch, is 4 μm. From the MFM image in Fig. 1, alternating black and white areas were observed at the corners of the zig zag wire in its remanent state after a magnetic field was applied in the transverse direction of the wire. This indicates that a multidomain magnetic structure is induced by the shape anisotropy of each segment. Figure 2 shows the normalized MR curves of

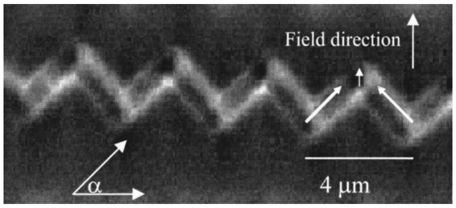

FIG. 1. The magnetic force microscopy image of a $Ni_{80}Fe_{20}$ zig zag wire which consists of 25 corners and with a thickness of 40 nm.

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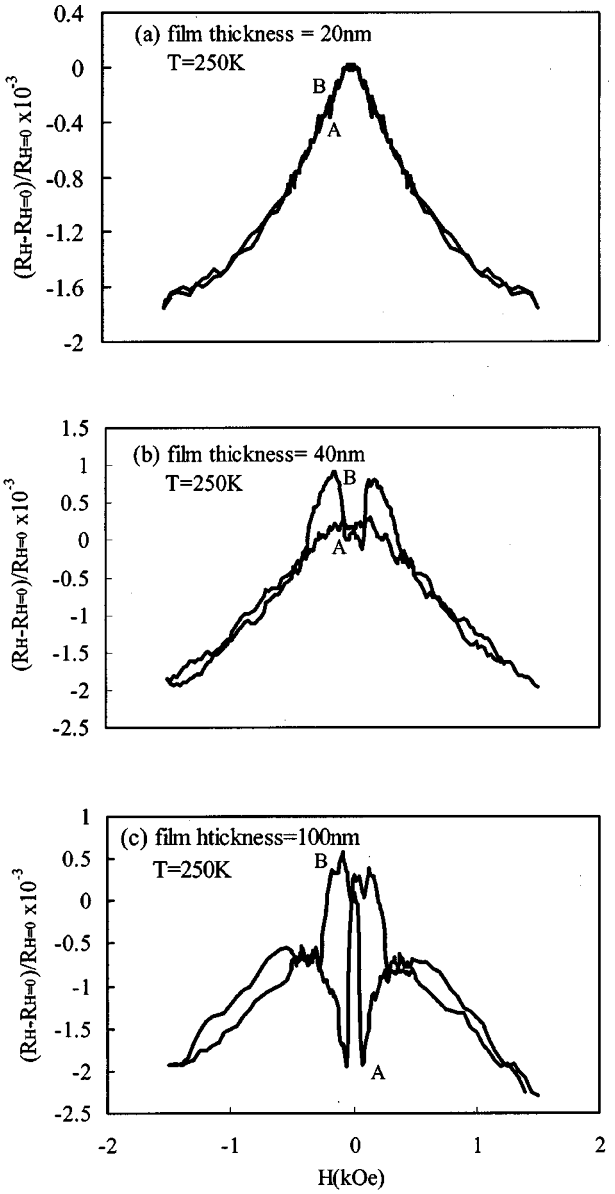

FIG. 2. The normalized MR curves of $Ni_{80}Fe_{20}$ zig zag wires at 250 K with different film thicknesses (a) 20 nm, (b) 40 nm, and (c) 100 nm.

the $Ni_{80}Fe_{20}$ zig zag wires at 250 K with different film thicknesses. The field was applied in the transverse orientation of the wires with the maximum field 20 kOe to eliminate any magnetic history effect. The wires nearly saturate at 3 kOe, therefore, the change of the normalized MR in an applied magnetic field between 3 and 20 kOe was very small. As the field is reduced from 1.5 kOe and then reversed, there is a resistivity minimum (a dip) around $+80\sim-70$ Oe as shown in Figs. 2(a), 2(b), and 2(c). The multidomain-type configuration at corners (point A in Fig. 2) is related to the dips as pointed out by Taniyama *et al.*[6,7] As the reversed field is increased, domain wall switches and the MR jumps to a single-domain-type state (point B) in Fig. 2) that corresponds to the maximum resistivity. The ratio of domain wall MR is measured to be 0.034%, 0.112%, and 0.258% in zig zag wires with thickness of 20, 40, and 100 nm. The magnetic field at which the domain wall initiates to switch was measured as −70, −40, and +80 Oe for wires with thickness of 20, 40, and 100 nm, respectively.

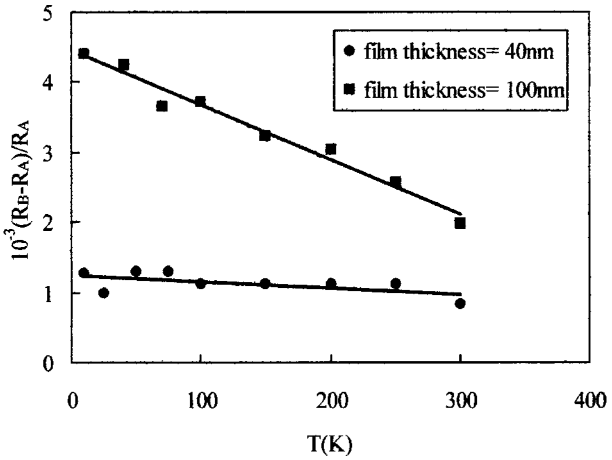

FIG. 3. Temperature dependence of the domain wall MR in zig zag wire with different thicknesses.

Figure 3 shows the temperature dependence on the MR ratio from the multidomain state to the single-domain state. The influence of temperature on domain wall MR with different film thickness was substantially different. In Fig. 3, the wire with 100 nm film thickness has larger dR/R in the temperature range from 10–300 K. This phenomenon can be elucidated by the difference of domain wall type for different film thickness. The Bloch and Néel domain wall width as a function of permalloy film thickness can be calculated by the equation[9] as follows:

$$\gamma_{\mathrm{Block}}=\frac{1}{2}\gamma_0\left(\frac{\delta}{\delta_0}+\frac{\delta_0}{\delta}\right)+\frac{2\pi\delta^2M_s^2}{\delta+t},$$

$$\gamma_{\mathrm{Náel}}=\frac{1}{2}\gamma_0\left(\frac{\delta}{\delta_0}+\frac{\delta_0}{\delta}\right)+\frac{2\pi t\delta M_s^2}{\delta+t},$$

where γ_0 and δ_0 are the bulk wall energy and bulk wall width with the value of 0.1 erg/cm^2 and 2 μm, respectively. M_s is the magnetization of permalloy film. δ and t are the domain wall width and thickness of films. By minimizing the total energy, which takes into account the magnetostatic energy, exchange energy, and anisotropy energy, domain wall width with different film thickness is estimated and listed in Table I. According to the $Ni_{80}Fe_{20}$ domain wall phase diagram, different types of domain walls dominate at different $Ni_{80}Fe_{20}$ film thicknesses. For very thick permalloy films, the domain wall is dominated by Bloch-type in the film center and terminated by Néel caps at the film surface. With reducing film thickness, the domain wall turns into an asymmetric Bloch wall (vortex wall), then into a complex cross-tie wall, and finally for very thin films, into a symmetric Néel wall. For zig zag wires with 100-nm-film thickness, asymmetric Bloch wall dominates and the calculated wall width is 50 nm. The wall width (50 nm) is smaller than the wire width (500 nm) and the film thickness (100 nm). As a result, the domain wall density is high at the corners. Therefore, domain wall scattering is significant in this film. In contrast, for

TABLE I. The characteristic length scale of $Ni_{80}Fe_{20}$ zig zag wires at 250 K.

Film thickness	Bloch wall (Ref. 9)	Néel wall (Ref. 9)	Mean free path	10^{-3} $(R_B-R_A)/R_A$
20 nm	10 nm	17 000 nm	$<$0.2nm	0.34
40 nm	20 nm	9 000 nm	0.85 nm	1.12
100 nm	50 nm	40 nm	20.5 nm	2.58
Bulk	2000 nm	⋯	2.57 nm	20

wires with 40 or 20 nm film thickness, complex cross-tie wall or symmetric Néel wall should dominate and the wall width should be large. Domain wall scattering is not substantial because of low domain wall density. Our MFM currently does not have good enough resolution nor can it work at high magnetic field. Detailed domain structure analysis under field will be carried out in the future.

Our bulk $Ni_{80}Fe_{20}$ (thick, unpatterned film) has an estimated mean free path of ~2.57 nm according to the free electron model with the parameters of free sphere radius, Bohr radius, and resistivity.[10] Estimated mean free paths of the zig zag wires are also listed in Table I. The values of mean free path are much smaller than the domain sizes and domain wall width. For the wire with 100-nm-film thickness, the mean free path is about 2.05 nm. The slope of MR versus temperature curve in Fig. 3 is related to the domain wall width that is correlated to the intrinsic properties of materials such as saturation moment (M_s), anisotropic constant (K), and exchange stiffness constant (A). The wire with 100-nm-film thickness has a much larger slope than that with 40-nm-film thickness $[\delta(R_B-R_A)/R_A/\delta T=7.8\times10^{-3}>0.9\times10^{-3}]$. It implies that the domain wall MR is more sensitive to the variation of temperature in the wire with 100 nm film thickness. As a result, effective anisotropy of zig zag wires is a function a film thickness.

Static domain wall MR was also proved in this experiment by measuring the angular dependence of resistance at remnant state. High resistivity was observed at the angle range from 0°–45° ($\alpha=1°–45°$ in Fig. 1), and the resistivity was slightly lower from 45°–75° that reflected the single domain state. In contrast, as the field was applied in the orientation of 75°–90°, much lower resistivity was obtained. This evidenced static domain wall MR by changing the angle between the applied field and current.

In summary, domain wall resistivity as a function of film thickness was studied by zig zag wire, which can control the domain configuration well, in the article. Different domain wall types dominated in different film thicknesses that significantly influenced the domain wall resistivity.

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