Current-induced domain wall motion in Co/Ni nano-wires with different Co and Ni thicknesses

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Abstract. The authors have investigated magnetic domain wall motion induced by electric currents in ferromagnetic nano-wires made of Co/Ni multilayers. The thicknesses of Co and Ni layers were changed, whereas the numbers of layer stacks of Co and Ni were the same in all samples. The sample with thinner total Co/Ni thickness showed the lower threshold current density for the domain wall motion as an overall trend, which is qualitatively in agreement with the expectation by the theory based on the adiabatic spin-transfer model. The lowest threshold current density was $2.9 \times 10^{11}$ A/m², obtained in the sample with the total Co/Ni thickness of 3.4 nm and the wire width of 110 nm.

1. Introduction

Current-induced domain wall (DW) motion in ferromagnetic nano-wires has been widely investigated [1-17] because of its potential applications for magnetic random access memories [10-11,17] or logic devices [18] as well as novel physics relevant to the interaction between spin current and local magnetic moment [19-26]. NiFe with in-plane magnetization has been actively investigated for this phenomenon [1,3-8,10,11]. The threshold current density $J_{th}$ for the DW displacement in this system, however, is determined by the strength of pinning field of a DW [10]. This is unfavorable for the device application because the reduction of $J_{th}$ and high thermal stability of DW are incompatible. In contrast, Co/Ni nano-wires with perpendicular magnetization [9,13-17], which is of focus here, has much higher DW pinning field than that of in-plane magnetized system, despite the DW can be reproducitively displaced by current. In addition, our recent experiments on our system shows the threshold current density $J_{th}$ for the DW displacement can be controlled by the wire dimension [14], which is reasonably a qualitative agreement with recent theoretical calculations based on the spin transfer model [21,27]. These advantages of high pinning field and reduction of $J_{th}$ in the perpendicularly magnetized system realize the compatibility of high thermal stability and low power consumption for devices. In this paper, we report the dependence of $J_{th}$ on total thicknesses of Co and Ni layers in Co/Ni nano-wires to obtain the guideline for further reduction of it.

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2. Experiment

The film structures and their magnetic properties were summarized in Table 1. Multilayered Co/Ni films with the cap and buffer layers were deposited on silicon substrates by dc magnetron sputtering. The thickness of Co and Ni layers were varied as follows; Co(0.2)/[Ni(0.4)/Co(0.2)]₄ (t = 2.6 nm, sample #1), Co(0.2)/[Ni(0.6)/Co(0.2)]₄ (t = 3.4 nm, sample #2), Co(0.3)/[Ni(0.6)/Co(0.3)]₄ (t = 3.9 nm, sample #3), Co(0.3)/[Ni(0.9)/Co(0.3)]₄ (t = 5.1 nm, sample #4), where t is the total thickness of the multilayer. The magnetic properties of the films were evaluated by magnetization measurements. For each samples, a series of devices with different wire width, w = 110 nm, 220 nm and 330 nm were fabricated by electron-beam lithography and ion-milling. Figure 1 shows the schematic illustration of the device structure. Two Au(100 nm)/Ti(5 nm) electrodes, labelled as A and B were formed at both ends of the wire. A Hall probe made of Ta(50 nm) was placed on the wire to detect the magnetization direction through the anomalous Hall effect. All measurements were performed at room temperature.

Figure 2 shows the typical hysteresis loop obtained by the Hall measurement (w = 110 nm, sample #2), where the vertical axis indicates the offset Hall resistance ΔR_Hall. The square loop was observed, indicating the wire shows perpendicular magnetic anisotropy.

The experiments for the current-induced DW motion were performed as following procedure. First, the large positive magnetic field of +4 kOe was applied along perpendicular direction to make the wire single domain state. Next, the local magnetic field were applied by injection of the current through the electrode A in the orthogonal direction with respect to the wire. From the separate measurements (not shown), the distribution of the pinning-fields for the DW were confirmed to be 105 Oe to 303 Oe in all devices, which is one or two orders magnitude larger than that of NiFe nano-wires. After introducing DW, multiple current pulses with the duration of 10 ns were injected into the wire. At every injection of pulsed currents, Hall resistance was measured to check whether the DW was propagated under the Hall probe. In each device, the same procedures were performed for 20 times to determine the probability of the DW propagation from the initial position to the position under the Hall probe.

| Sample | Co (nm) | Ni (nm) | total thickness t (nm) | M_s (×10⁵ A/m) | K_u (×10⁵ J/m²) |
|--------|---------|---------|----------------------|----------------|-----------------|
| #1     | 0.2     | 0.4     | 2.6                  | 7.58           | 4.1             |
| #2     | 0.2     | 0.6     | 3.4                  | 6.68           | 4.2             |
| #3     | 0.3     | 0.6     | 3.9                  | 7.79           | 6.0             |
| #4     | 0.3     | 0.9     | 5.1                  | 6.84           | 3.9             |

Table 1. Thickness and magnetic properties of four Co/Ni multilayers.

![Figure 1](image1.png)  
**Figure 1.** Schematic illustrations of device structure and measurement configuration.

![Figure 2](image2.png)  
**Figure 2.** Result of Hall measurement in the sample #2 with w = 110 nm.
3. Result and discussion

A typical current density \( J \) dependence of the propagation probability \( P \) of the three devices with different wire width \( w \) (sample #2) is shown in Fig. 3. One can see that \( P \) abruptly increases with \( J \) above threshold values in all devices with various \( w \). With decreasing \( w \), the threshold value was found to be lower, as previously reported by our group\(^{[14]}\). This tendency is in agreement with the theoretical prediction based on the adiabatic spin transfer model in which the threshold current density \( J_{th} \) is dominated by the intrinsic DW pinning mechanism. If we defined \( J_{th} \) as \( J \) where the probability is \( 0.5 \), from which they were determined to be \( 4.5 \times 10^{11} \text{ A/m}^2 \), \( 4.4 \times 10^{11} \text{ A/m}^2 \), and \( 2.9 \times 10^{11} \text{ A/m}^2 \) for \( w = 330, 220, \) and \( 110 \text{ nm} \) in this series of devices, respectively. \( J_{th} \) as a function of \( w \) in all samples is shown in Fig. 4. The same trend was obtained reproducibly in all samples with different Co and Ni thicknesses.

![Figure 3](image1.png)

**Figure 3.** The current density \( J \) dependence of probability \( P \) for DW displacement in devices with various \( w \) made of sample #2.

![Figure 4](image2.png)

**Figure 4.** The wire width \( w \) dependence of the threshold current density \( J_{th} \) of all samples.

Finally, we discuss the thickness dependence. From Fig. 4, overall tendency shows that \( J_{th} \) reduces with decreasing the sample total thickness \( t \). In the theory based on the adiabatic spin transfer model\(^{[21,22,27,28]}\), the current flowing in the wire exerts the torque on the local spins inside the DW and rotates them in the sample plane, resulting in the periodic change of DW structure between Bloch (stable state) and Néel wall (higher energy state). Within this scenario, the threshold current density is proportional to the hard axis anisotropy constant \( K_{h.a.} \), which is the energy density of magnetic anisotropy associated with the rotation of the DW spins in the sample plane. \( K_{h.a.} \) reduces with decreasing \( t \) because the difference between the in-plane demagnetizing factors decreases. Our experimental results are qualitatively in accordance with this scenario, although further comparison between the experiments and theory is needed because \( J_{th} \) also depends on the carrier spin polarization and the width of the DW.

4. Summary

In summary, we have described the DW motion induced by the application of electric current in the perpendicularly magnetized Co/Ni wire, and found that \( J_{th} \) for DW motion is tend to decrease with reducing Co/Ni thickness. The lowest current density of \( 2.9 \times 10^{11} \text{ A/m}^2 \) was obtained in the sample with the Co/Ni thickness of 3.4 nm and the wire width of 110 nm. The small threshold current density as well as high de-pinning field for the DW shows that our system is the favorable candidate for the realization of the memory and logic devices based on the electrical DW motion\(^{[10-11, 17-18]}\).

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