Spin-current-assisted domain-wall depinning in a submicron magnetic wire

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We demonstrate experimentally the domain-wall depinning triggered by injecting the polarized spin current into the domain wall. The domain wall is pinned at the junction of a large pad and a narrow wire prior to the current injection experiment. When the polarized spin current is injected along the direction of the domain-wall propagation, the pinned domain wall is freed and pushed into the wire at the critical current that monotonously decreases by increasing the applied bias magnetic field. These results imply that the injection of the spin-polarized current into the domain wall causes additional magnetic pressure due to the spin-momentum transfer between the spin-polarized current and the localized magnetic moment.

Spin injection into the ferromagnetic materials induces the torque due to the exchange interaction between the conduction electron spin and the localized magnetic moment. This means that the induced torque acts not only on the electron spin but also on the localized magnetic moment. The magnetization may thus be rotated when large spin current is injected into the ferromagnetic layer whose magnetic moment orients differently from the injected electron spin. Recently, such switching mechanism was demonstrated experimentally and is expected to be applied to the magnetization switching method in the magnetic random access memories and other spintronic devices. Moreover, this could significantly lower the energy consumption for the switching in nanoscale magnetic devices because the injecting current necessary for switching the magnetization is decreased as the size of the magnetic element is reduced.

The above idea can be employed to exert magnetic pressure on the domain wall since a ferromagnet separated into two domains by a domain wall resembles a magnetic multilayered structure. Berger and Hung investigated such an effect in Ni–Fe films using pulsed current, and observed the domain-wall drag due to the s–d exchange field acting on the localized magnetic moment. More recently, Grollier et al. observed the current-induced depinning of the trapped domain wall at a constriction patterned in a NiFe/Cu/NiFe/CoO ferromagnetic layered strip. However, in the giant magnetoresistive (MR) structure for detecting the domain-wall displacement, the highly conductive Cu layer carries the most of the current, where the current-induced Oersted field may have an additional contribution to the domain-wall displacement. In a previous study, we thus investigated, using the anisotropic MR (AMR) effect, the pure effect of the injection current on the depinning field of the domain wall in the wire with a large pad. The results suggest that the domain wall trapped at the connection of the pad and the wire is subjected to the additional pressure from the spin polarized current. In this article, we show more experimental results obtained from a viewpoint of depinning the trapped domain wall by the spin current injection under the bias field.

A Ni–Fe narrow wire with four Cu leads for MR measurement was fabricated by a conventional lift-off technique, details of which are explained in our previous work. The Ni–Fe wire consists of a large 1×5 μm² rectangular pad and a 250 nm wide wire, as illustrated in Fig. 1. The thickness of the Ni–Fe structure is 30 nm. The resistivity measurements were performed at 3 K using a low-noise four-terminals dc measurement system in the range of the external magnetic field H from −1000 Oe to 1000 Oe along the wire. The system allows one to detect the change in MR ratio smaller than 1 m% due to a slight change in domain structure.

Figure 2 shows a typical longitudinal MR of the fabricated wire at 3 K. This behavior can be understood as an

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FIG. 1. Schematic illustration of the fabricated magnetic wire with pad. The inset shows the scanning electron microscope image of the fabricated Ni–Fe wire.
AMR effect in association with magnetization reversal. The first small jump at $H\approx 145$ Oe and the second large one at $H\approx 240$ Oe correspond to the magnetization switching of the wide pad and that of the narrow wire, respectively. The first jump is followed by a plateau, indicating that the magnetic state remains between two jumps. The domain wall is therefore considered to be pinned at the connection while the external field $H$ is in between 145 Oe and 240 Oe. Then, the wall propagates into the wire at $H\approx 240$ Oe. A similar two stage demagnetization process has also been observed in our previous study. In the present case, the depinning field of the domain wall is much smaller than that of the previous study. This is due to difference in the dimensions of the Ni–Fe pad and wire, such as thickness, width, and shape.

According to our previous study, the influence of the spin current injection on the trapped domain wall is pronounced when the spin current flows along the direction of the domain-wall propagation. In the present probe configuration, the application of the negative current corresponds to the spin current injection along the wall propagation. In order to examine the depinning process of the domain wall with injecting the spin current, the resistance was measured with increasing the negative injecting dc current through the domain wall at the fixed external magnetic field. As shown in Fig. 2, the resistance with the pinned domain wall is smaller than that without the domain wall. Therefore, when the depinning of the domain wall occurs at the critical current, the resistance is expected to increase abruptly to the value without the wall. Figure 3 shows the observed results of the domain-wall depinning with applying the negative dc current at the bias field $H_B=150$ Oe. In Fig. 3(a), the MR at the current $I=-0.1$ mA exhibits a sharp increase at $H\approx 150$ Oe, corresponding to the domain-wall pinning. The field is then fixed at $H=150$ Oe, and the injection dc current is increased negatively. The change in AMR due to the domain-wall depinning is only 10 m%, much smaller than the background resistance which increases by 1% with the current up to 1 mA because of the Joule heat. Therefore, we have plotted the differential resistance given by $\Delta R = V_n/I_n - V_{n-1}/I_{n-1}$, with the current $I_n$ and the voltage $V_n$ at the $n$th point measured with a current increment of $-1 \mu A$ to find the change in resistance due to the domain-wall depinning. As seen in Fig. 3(b), the variation of $\Delta R$ exhibits a sharp spike at $I=-0.97$ mA ($\approx 1.6 \times 10^7$ A/cm$^2$). The magnitude of the spike amounts to 200 m$\Omega$, corresponding to the change in resistance associated with the depinning of the domain wall. The MR curve in Fig. 3(c) measured subsequently to the depinning in the field range from 150 Oe to

![Figure 2](image2.png)

**FIG. 2.** Typical longitudinal MR of the fabricated wire measured at 3 K. The arrows indicate the resistance jumps due to the magnetization reversals.

![Figure 3](image3.png)

**FIG. 3.** (a) MR change at the dc current of $-0.1$ mA when the magnetic field is swept from $-1000$ Oe to 160 Oe. (b) The differential resistance as a function on the injecting current at the bias field of 160 Oe when the current increases negatively. (c) Reversed MR change at the dc current of $-0.1$ mA after the injecting current increases negatively up to $-1$ mA.

![Figure 4](image4.png)

**FIG. 4.** (a) The differential resistance as a function on the injecting current at the bias field of 160 Oe when the current is increased negatively. (b) Reversed MR change at the dc current of $-0.1$ mA after the injecting current increases up to 1.9 mA.
$1000 \text{ Oe}$ clearly shows the characteristic two stage switching process from the pad to the wire. This proves that the dc current injection induces the magnetization reversal of the wire via the wall propagation under the bias field $H_B = 150 \text{ Oe}$.

On the other hand, when the positive current is applied, the differential resistance $\Delta R$ shows no spike with the injecting current up to $1.9 \text{ mA}$ as in Fig. 4(a). Moreover, the subsequently measured MR curve with the magnetic field swept from 150 Oe to $-1000 \text{ Oe}$ shows single jump corresponding to the switching of the pad. This implies that the positive current injection does not depin the domain wall, because of the asymmetric pinning potential due to the inclined free energy landscape.

The Joule heat does not affect the depinning process of the domain wall. If the Joule heat is responsible for the depinning process, the current should contribute equally to the wall depinning irrespective of polarity. The experimental fact supports that the observed domain-wall depinning originates from the spin transfer effect not the Joule heat.

Figures 5(a) and 5(b), respectively, show the injecting current dependence of the differential resistance $\Delta R$ in different bias fields $H_B$ of 200 Oe and 150 Oe. In the $I-\Delta R$ measurements for both fields, the observed resistance change amounts to 200 m$\Omega$, the value expected for the depinning. Figure 5(c) shows the bias field dependence of the absolute value of the switching current. The switching current monotonically decreases by increasing the bias field. This tendency can be understood as a more inclined free energy landscape facilitates the domain-wall depinning assisted the spin torque effect.

In conclusion, we have investigated the influence of the dc current injection on the trapped domain wall by using the submicron scale magnetic structure consisting of the large pad and the wire. The trapped domain wall is pushed into the wire with an assistance of the spin torque when the spin current is injected from the pad to the wire. On the other hand, when the spin current is reversed, the domain wall is not moved. The absolute value of the critical current gradually decreases by increasing the bias magnetic field. The results demonstrate that the injection of the spin-polarized current into the domain wall causes the spin torque effect that assists the domain-wall depinning.