CoB/Ni-Based Multilayer Nanowire with High-Speed Domain Wall Motion under Low Current Control

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1. Introduction

When a spin-polarized electron current hits a magnetic moment, it exerts a torque on the moment, transfers its angular momentum to the moment, and thereby affects the precession motion and switching of the moment. This phenomenon was theoretically predicted by Berger1) and Slonczewski,2,3) and subsequently was named the spin-transfer torque (STT). The motion of magnetic domain walls (DWs) caused by an electrical current in magnetic nanostructures is also a consequence of the SST in which the spin-polarized current switches the magnetic moments in the wall. This is nowadays widely applied in spintronic semiconductors) has a Curie temperature far below room temperature and therefore is not realistic for room-temperature devices.

Among the researchers, Yamanouchi et al.14) were successful in establishing the motion of magnetic DWs in a perpendicularly magnetized ferromagnetic semiconductor (Ga,Mn)As with a very low current density of about $10^6$ A m$^{-2}$. However, this material (and most ferromagnetic semiconductors) has a Curie temperature far below room temperature and therefore is not realistic for room-temperature devices.

In this article, we present the enhancement of the motion of the magnetic DWs in the CoB/Ni multilayer nanowire at a low current density. The addition of B atoms to the Co layers decreased the density of the pinning sites in the film, enhanced the DW motion, and improved the stability of the multilayer by preventing the diffusion between the Co/Ni interfaces.

2. Experimental Methods

A multilayer film of Pt 5 nm/[CoB 0.6 nm/Ni 1.1 nm]4/CoB 0.6 nm/Pt 1 nm was fabricated by radio-frequency (RF) magnetron sputtering using Ar gas. The base vacuum of the deposition chamber was $3 \times 10^{-3}$ Torr whereas the Ar pressure was maintained at 5 mTorr during the deposition process. The composition of the CoB target was chosen as Co$_{80}$B$_{20}$ (at. %). The film was grown on a naturally oxidized Si substrate. A nanowire with 300 nm width and 150 µm length was subsequently patterned by electron beam lithography and ion beam etching (Fig. 1). The nanowire was modified to have a planar Hall shape for magnetotransport measurements. A square pad was made at one end of the wire as a source for DW nucleation,15) and the shape of the other end of the wire was modified to be triangular to prohibit the propagation of DW.16) A Ti/Au electrode pattern produced by photolithography was mounted to the wire for magnetotransport measurements. The magnetic properties of the film specimen were measured using an alternating gradient magnetometer (AGM).

The magnetic DWs were nucleated in the square pad by an Oersted field generated from the 30 ns width, 6.5 MHz pulse current flowing in the Ti/Au electrode deposited on the perpendicular magnetic anisotropy was one of the keys to reduce the critical current density. Nonetheless, layer thickness in those multilayers was normally ~3–20 Å and might be badly influenced by the heat from electrical current. The perpendicular anisotropy is logically threatened to disappear due to the diffusion of the layers under Joule heating of electrical current.

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The spin-transfer torque motion of magnetic domain walls (DWs) in a CoB/Ni-based nanowire driven by a low current density of $(1.12 \pm 0.8) \times 10^{11}$ A m$^{-2}$ has been observed indirectly by magnetotransport measurements. A high DW velocity of $85 \pm 4$ m s$^{-1}$ at zero field was measured at the threshold current density. Upon increasing the current density to $2.6 \times 10^{11}$ A m$^{-2}$, the DW velocity increases to $197 \pm 16$ m s$^{-1}$ before decreasing quickly in the high-current-density regime attributed to nonadiabatic spin-transfer torque at a low damping factor and weak pinning. The addition of B atoms to the Co layers decreased the magnitude of saturation magnetization, Gilbert damping factor, and density of pinning sites, making the CoB/Ni multilayer nanowire favorable for practical applications. © 2012 The Japan Society of Applied Physics
the pad (Fig. 1, electrodes A–B). The motion of DWs in the nanowire was then driven by a DC current ($J_{DC}$, electrodes G–B in Fig. 1). Anomalous Hall effect measurement (either electrodes C–D or E–F) was carried out to detect the propagation of DW in the wire. Hysteresis loop measurement on the continuous film specimen (data not shown) using the AGM confirmed that the film exhibited a strong perpendicular magnetic anisotropy with a saturation magnetization of $M_s = 5.6 \times 10^5$ A/m (about 15% lower than that of a Co/Ni-based film) and a uniaxial anisotropy constant of $K_u = 3.57 \times 10^5$ J/m$^3$ (∼8% higher than that of a Co/Ni film).

3. Results and Discussion

The time-resolved Hall effect signal observed from the nanowire at a driven current (DC current) of 0.59 mA, corresponding to a current density of $J_{DC} = 1.12 \times 10^{11}$ A m$^{-2}$ and an external field of +5 mT is illustrated in Fig. 2(a) and represents the movement of DW along the wire. Initially, the wire was magnetically saturated, then magnetization reversal was induced by an Oersted field that was the time when the front-edge wall of the domain started coming to the Hall bar (inset of Fig. 2(a)]. Therefore, the influence of the Oersted field on the motion of the wall along the wire (described in Fig. 2) could be minor, whereas the effect of the spin-polarized current is essentially considered.

The current dependence of the variation of normalized Hall resistance, $\Delta R_{Hall}$, is illustrated in Fig. 3. The normalized Hall resistance here was defined as the change in the Hall voltage signal when the domain propagated through the Hall bar [Fig. 2(b)]. Therefore, the normalized Hall resistance became high (1) above a threshold current density of $1.12 \times 10^{11}$ A m$^{-2}$, whereas this value was low (0) below the threshold current density. This indicates that the motion of the magnetic DWs, denoted by a change in Hall resistance, could be induced when the density of the spin-polarized current is above $1.12 \times 10^{11}$ A m$^{-2}$, confirming that it is possible to drive the DW motion in the 300 nm width CoB/Ni nanowire with a threshold current density of $1.12 \times 10^{11}$ A m$^{-2}$ by the STT mechanism. It is important that the threshold current density obtained here was reasonably lower than either $\sim(1-3) \times 10^{12}$ A m$^{-2}$ in the NiFe-based devices or $\sim(2-5) \times 10^{11}$ A m$^{-2}$ in a similar multilayer Co/Ni wire or lower than the current density in a spin-valve nanowire reported recently. Moreover, it is seen in Fig. 2 that the pulse like signal of Hall voltage is periodic and coherent with the nucleation pulse, presuming the continuous propagation of a multidomain similar to a shift register writing process.

From the pulse like Hall signal, the velocity of DW moving in the Hall bar could be derived from Fig. 2(b): $v = \frac{L}{\Delta T}$ where $L = 500$ nm. Therefore, the velocity of the front-edge wall could be referred as $L/\Delta T = (T_4 - T_1)/\Delta T$. The time-resolved Hall effect voltage signal appeared to be a periodic pulse. This was nucleated and driven to the wire periodically and the time when the domain (with the two walls) had passed the Hall bar. The progress of the Hall signal could be interpreted approximately on the basis of a simple schematic shown in Fig. 2(b). Because of a periodic pulse, the domains were nucleated and driven to the wire periodically and the Hall voltage signal appeared to be a periodic pulse. This result looks similar to the DW motion observed previously. A square Hall-voltage hysteresis loop [inset of Fig. 2(a)] exhibits a sharp change in the magnetization, proving a fast propagation of a domain through the Hall bar. The square aspect of the hysteresis loop indicated that a reversal occurred through DW nucleation followed by easy DW propagation. It should be noted that the Oersted field released from the driven current was estimated to be about 30 mT, which was much smaller than the coercive field of the sample (see the Hall effect hysteresis loop in the inset of Fig. 2(b)). Therefore, the influence of the Oersted field on the motion of the wall along the wire (described in Fig. 2) could be minor, whereas the effect of the spin-polarized current is essentially considered.

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On the other hand, the velocity of the rear-edge wall could be attained from the time interval \( \Delta t = t_f - t_i \). Furthermore, from the phase delay between the signals at the C–D and E–F Hall bars that reflected the time of flight of the wall between two Hall bars, the velocity of the wall in the straight wire (from C to E) was determined. Figure 4 shows the wall velocity in the straight wire area as a function of external magnetic field measured at the threshold current density. The field dependence here is consistent with the following expression:20

\[
v(H) = \mu_H(H - H_0) + v(J),
\]

where \( \mu_H(J) \) is the DW mobility, \( J \) is the current density, and \( H_0 \) is the “dynamic coercive force”. The term \( v(J) - \mu_H H_0 \) can be referred as the velocity at zero field.

Using this linear dependence, a zero-field wall velocity of \( 86 \pm 5 \text{ m/s} \) was calculated at the critical current density \( 1.12 \times 10^{11} \text{ A/m}^2 \) with a mobility of \( 2640 \pm 170 \text{ (m s}^{-1} \text{ T}^{-1}) \). This matches well with the velocity measured directly at \( H = 0 \text{ (85 \pm 4 m/s)\). It is interesting to note that the field-free wall velocity here was much higher than that of the Co/Ni wire\(^{12,13} \) or TbFeCo nanowire\(^{18,21} \)). Therefore, this aspect is very promising for high-speed devices. As DW moved in the region of the Hall bars, the wall velocity (as defined above) was found to be slightly lower than that in the straight wire area but only in the error scale of the measurement. The non-zero DW velocity and linear dependence of the wall velocity on the external field can be attributed to the motion driven by the nonadiabatic torque.20

The velocities of the front- and rear-edge walls were perfectly identical to each other and remained invariable at positions of two Hall bars. These suggest that i) the effect of the pinning on the motion of the walls along the wire was predominantly governed by the material rather than the geometry of the Hall bars and ii) no distortion of the domain and the wall geometry as the domain length was conserved when they were located in the Hall bars. Usually, the distortion of the domain in the Hall bar, denoted by the small difference between the velocities of the front-edge wall (faster) and the rear-edge wall (slower), was only observed at a high applied field (over 90 mT), and can be imagined similarly to the distortion of a balloon, as reported elsewhere.22

Regarding other interesting points, the time interval \( T_f - T_i \) [see Fig. 2(b)] expresses the period necessary for the whole domain to reach the rear side of the Hall bar, allowing domain size to be estimated. Using this relationship, the average size of the domain was calculated to be \( 900 \pm 35 \text{ nm} \) at the critical current density of \( 1.12 \times 10^{11} \text{ A/m}^2 \) and zero field. Under an external field, the domain size was slightly reduced to \( 630 \pm 25 \text{ nm} \) at the field of 40 mT, which was similar to theoretical prediction.23

It is supposed that the external field in this case acted oppositely to the nucleated field from the pulse current, and compressed the domain when it was nucleated. It should be noted that the domain length was conserved when the domain was located in two Hall bars.

The dependence of wall velocity at zero field on controlled current density is depicted in Fig. 5. The velocity firstly increased with current density from 85 m/s at the threshold current density to a maximum value of 197 ± 16 m/s at a current density of \( 2.63 \times 10^{11} \text{ A/m}^2 \), then markedly dropped at higher current densities. The variation of wall velocity with current density in this case can be explained qualitatively by referring to the model given in refs. 7 and 24. The model proposed by Tatara et al.\(^{24} \) predicted that the trend of the wall velocity variation (including a linear increase at low current and a decrease with increasing current at high currents) is a consequence of the nonadiabatic torque driving when the damping factor is low and the pinning effect is weak. In the low current regime, DW velocity was linearly dependent on current density, which is in accordance with the zero-field velocity described in eq. (1) and somehow similar to a previous experimental observation.20 At a high current density (above \( 2.63 \times 10^{11} \text{ A/m}^2 \)), wall velocity appeared to decrease, indicating that the nonadiabatic parameter \( \beta \) was not zero and not equal to the Gilbert damping factor. This led to a deformation of the wall structure above the Walker breakdown current density.20 This dependence and linear field-velocity function discussed in previous paragraphs indicated that the motion of the walls in our device was mainly governed by the nonadiabatic term.

In an attempt to explain the decrease in the threshold current density, theoretical models\(^{7,24} \) are employed, in which the threshold (or intrinsic critical) current density could be referred to as follows:7

\[ J_{\text{c}} = \frac{1}{L} \left( \frac{\mu_B M_s}{\gamma} \right)^{1/3} \]
with the nonadiabatic STT mechanism. These advantages were attributed to the presence of CoB layers with a low Gilbert damping factor, a low saturation magnetization, and a low density of pinning sites. The addition of B also helps in preventing the diffusion between Co and Ni layers and enhances the stability of the multilayer structure and the performance of our device. Using a 30 ns pulse as a writing current, the device could perform shift-register writing of a multidomain state in the wire with an average domain size of $900 \pm 35 \text{ nm (without field)}$ and a minimum size of $630 \pm 25 \text{ nm (with field)}$.

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\[ J_c = \frac{\alpha e M_s \Delta}{g \mu_B P} \frac{1}{|\beta - \alpha|}, \]

where $\alpha$ and $\beta$ are the Gilbert damping factor and nonadiabatic spin-transfer torque parameter, respectively; $\Delta$ is the DW width; $M_s$ is the saturation magnetization; $P$ is the spin polarization of the material; $g$ is the gyromagnetic ratio, $e$ is the electron charge, and $\mu_B$ is the Bohr magneton.

**Fig. 5.** (Color online) Variation of wall velocity as a function of driven current density at zero external field.

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