Local domain structure of exchange-coupled NiFe/CoO nanowire probed by nonlocal spin valve measurement

T. Kimuraa and Y. Otanib

Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, Japan and RIKEN FRS, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

(Received 1 September 2007; accepted 3 February 2008; published online 29 April 2008)

We investigate the local magnetization process in a 100-nm-wide Permalloy/CoO exchange-coupled domain structure by means of nonlocal spin valve measurements for a structure with lateral geometry. The domain structure in the exchange-coupled wire is found to change with the direction of the exchange bias. When the exchange bias is parallel to the easy axis of the Permalloy wire, the magnetization-reversal process can be expressed by the single domain model. However, when the exchange bias is perpendicular to the easy axis, the magnetization reversal is accompanied by domain nucleation and annihilation processes even in the lateral dimension of 100 nm. The reason for the dependence of the domain structure on the direction of the exchange bias is discussed.

© 2008 American Institute of Physics. DOI: 10.1063/1.2903509

I. INTRODUCTION

Exchange anisotropy is caused by the magnetic interaction at the interface between a ferromagnetic (F) layer and an antiferromagnetic (AF) layer. A shift of the center of the hysteresis loop away from the zero field (loop shift) is well known as a phenomenon originated from the exchange anisotropy and has been utilized for pinning the soft magnetic layer in spin valve structures.1 This phenomenon is described by the Meiklejohn–Bean model, which is based on a uniform domain structure with a unidirectional anisotropy.2 However, in realistic cases, complex magnetization-reversal processes such as an unsharp switching in the magnetization and coercivity enhancement have been observed.3–5 Experimental observations and theoretical predictions reveal that these processes are related to the formation of multidomain structures during the magnetization reversal.6–10 The size of the F domains in a F/AF bilayer during the magnetization reversal is known to be much smaller than that in a single F layer.11

Exchange anisotropy has been extensively investigated mainly in thin films. However, recent developments in the areal density of magnetic recording technology and other spintronic devices have necessitated the investigation of F/AF systems with reduced lateral dimensions. In such structures, the geometrically induced magnetostatic interaction also becomes important in addition to the exchange interaction from the AF. Moreover, when the lateral element size of a F/AF structure is equivalent to the AF grain size, the domain structure may become relatively simple. Recently, several studies on F/AF structures with reduced lateral dimensions have been reported.12–15 An enhancement of the coercive field and the asymmetric magnetization reversal have been observed.16 In addition, interestingly, the enhancement of the exchange bias field by reduction in the lateral dimensions has been reported in several systems12,14 although other groups observed the opposite tendency.15,17 Thus, exchange-coupled systems with patterned structures are very attractive, both, from a fundamental and a technological point of view. Magnetoresistance measurements such as anisotropic magnetoresistance (AMR) and planar Hall effect (PHE) are suitable techniques for investigating the magnetization processes in patterned structures.14,18,19 However, the information obtained from the AMR measurements corresponds to the entire magnetization between the two voltage probes. The PHE measurement can be used to obtain the local information of the magnetization in the Hall cross. However, the additional F voltage probes may disturb the domain structure. Here, we investigate the magnetization process of an exchange-coupled 100-nm-wide Permalloy wire by using nonlocal spin valve measurement.20 This allows us to probe the local domain structure of the AF/F wire with lateral dimensions as small as 100 nm square without flowing an electric current in the AF/F wire. We found that the domain structure and the magnetization process depend on the direction of the exchange bias.

II. EXPERIMENT

The lateral spin valve used for the present study consists of a single permalloy (Py) wire and an exchange-coupled Py/CoO wire bridged by a Cu wire. Figure 1(a) shows a scanning-electron-microscope image of the prepared device. The single Py wire is 100 nm in width and 30 nm in thickness. The Py/CoO wire is also 100 nm in width. The thicknesses of both, CoO and Py, layers in the exchange-coupled wire are 10 nm. The Py and CoO layers are evaporated by using an electron-beam evaporator with a base pressure of $2 \times 10^{-9}$ Torr. Then, the Cu wire is fabricated by using an electron-beam lithographer followed by resistance heating evaporation with a base pressure of $3 \times 10^{-8}$ Torr. The interface between Py and Cu wires is well cleaned by low-voltage Ar-ion milling prior to the Cu deposition resulting in an Ohmic, a very low resistive and transparent Ohmic contact. The spacing between the wires is 400 nm. The resistivities of Py and Cu at 77 K are 9.7 and 1.1 $\mu\Omega$ cm, respectively. The magnetoresistance measurement is performed by using con-
ventional current-bias lock-in technique with an amplitude of 0.2 mA. An external magnetic field $H$ is applied with an angle $\theta$ with respect to the horizontal axis. Figure 1(b) shows the nonlocal spin valve signal measured at room temperature (RT). The spin signal with a magnitude of 0.15 m$\Omega$ is clearly observed. Here, the negative resistance change at 100 Oe and the positive resistance change at 350 Oe correspond to the magnetization switching of the Py/CoO and Py wires, respectively. The field dependence of the nonlocal spin signal is symmetric with respect to the magnetic field because the Néel temperature for the CoO is lower than RT.

III. RESULTS AND DISCUSSIONS

The direction of the exchange anisotropy from the CoO layer is known to be controlled by changing the direction of the applied magnetic field during the cooling of the sample. First, we cooled the sample from RT to 77 K with applying a longitudinal negative magnetic field (~2000 Oe). This results in the exchange bias becoming parallel to the easy axis of the Py wire, as schematically shown in Fig. 2(a). Figure 2(b) shows the field dependence of the spin signal. The magnitude of the spin signal increases to 0.5 m$\Omega$ because of the enhancement of the spin diffusion length of the Cu wire. An asymmetric field dependence with respect to the magnetic field is also clearly observed because of the exchange bias from the CoO. When the magnetic field is swept from the negative to the positive direction (positive field sweep), the magnetization of the single Py wire is reversed before the switching of the exchange-coupled Py/CoO wire. On the other hand, when the magnetic field is swept from the positive to the negative direction (negative field sweep), the magnetization reversal of the exchange-coupled wire takes place before the switching of the single Py wire. To assure this, the minor loops of the nonlocal spin valve signal were measured. In the minor loop shown in Fig. 2(c), only the magnetization of the single Py wire is reversed. Therefore, the switching fields where the signal shows a sudden change in the negative and positive sweeps are the same. On the other hand, in the minor loop shown in Fig. 2(d), only the magnetization of the exchange-coupled Py wire is reversed. A clear loop shift is observed in Fig. 2(d). Based on this result, the exchange bias from the CoO layer is found to be 360 Oe. The coercive field of the exchange-coupled wire is
270 Oe, which is comparable to that of the single Py wire with the same dimensions. It should be noted that the exchange bias and coercive field do not change on repetition of the field sweep. This implies that there is no training effect.\(^{22}\) Moreover, the switching of the Py/CoO wire is very sharp. These observations support that the domain structure of the probing region in the Py/CoO wire is a single domain.

We have also measured the spin signal as a function of the transverse magnetic field corresponding to the hard axis of the Py wire (\(\theta=90^\circ\)). As shown in Fig. 3, the signal also shows a clear spin valve effect with exhibiting the same overall resistance shown in Figs. 2(b)–2(d). In the positive sweep, the spin signal maintains a constant value, which corresponds to the parallel state at \(H<1200\) Oe. This means that the magnetizations of both the wires rotate in accordance with the parallel state. A sudden negative change in the signal appears at \(H=1200\) Oe. This is due to the switching of the Py wire caused by a small misalignment of the magnetic field from the hard axis of the wire. After the switching of the Py wire, the magnetizations are canted to each other. Therefore, in the negative sweep, the signal gradually decreases and takes the minimum value at the remanent state. Since the minimum value is the same as that shown in the antiparallel (AP) state in Fig. 2(b), it can be concluded that this effect is due to the AP orientation between the single and exchange-coupled Py wires, as schematically shown in Fig. 3. Thus, the magnetization process of the exchange-coupled Py wire under the transverse magnetic field can also be understood by the single domain model.

Following this, the sample was heated to RT and then cooled again to 77 K by applying a negative transverse magnetic field (\(-2000\) Oe). In this case, the exchange anisotropy from the CoO layer is aligned with the hard axis of the Py wire. However, at the remanent state, the magnetization of the exchange-coupled Py wire is not fully aligned in the transverse direction because of the large demagnetizing field. Therefore, the magnetization at the remanent state tilts away from the horizontal axis and toward the negative vertical axis, as shown in Fig. 4(a). In order to survey the magnetization processes for both wires, we calculated the field dependences of the angles of both wires and the spin signal under a transverse magnetic field by using the coherent rotation model. We assumed that the energies \(E_{\text{Py}}\) and \(E_{\text{Py'}}\) for the single Py wire and for the exchange-coupled Py wire, respectively, are given by the following equations:

\[
E_{\text{Py}} = K_{\text{Py}} \sin^2 \phi_{\text{Py}} - M_S H \cos(\phi_{\text{Py}} - \theta),
\]

\[
E_{\text{Py'}} = K_{\text{Py'}} \sin^2 \phi_{\text{Py'}} - K_{\text{AF}} \cos(\phi_{\text{Py'}} - \theta_{\text{AF}}) - M_S H \cos(\phi_{\text{Py'}} - \theta),
\]

Here, \(K_{\text{Py}}\) and \(K_{\text{Py'}}\) are the uniaxial shape anisotropies of the single and exchange-coupled wires, respectively. We assume the relation \(K_{\text{Py}} = 3K_{\text{Py'}}\) because of the relation between their thicknesses. \(\phi_{\text{Py}}\) and \(\phi_{\text{Py'}}\) represent the angles with respect to the positive horizontal axis for the single Py and exchange-coupled Py wires, respectively. \(\theta\) and \(\theta_{\text{AF}}\) are the angles for the external magnetic field and the exchange anisotropy, respectively. In the present situation, \(\theta = \theta_{\text{AF}}\). \(M_S\) is the saturation magnetization for Py. The angles \(\phi\) are calculated by solving the conditions \(\partial E/\partial \phi = 0\) and \(\partial^2 E/\partial \phi^2 > 0\). The spin signal \(\Delta R\) is calculated by using the relation...
by HMS

Therefore, the relative angle between \( /H11021 \) change of the spin signal in the negative field sweep as compared to that in the positive field sweep. This leads to a sudden large switching field in the negative field sweep is larger than that in the positive field sweep. The main difference between the two sweeps is seen in the switching field for the exchange-coupled wire. When the magnetic field decreases from negative saturation to zero, first \( /H20850 \) decreases with the magnetic field. When the magnetic field decreases from negative saturation to zero, first \( /H20850 \) decreases with the magnetic field. \( /H20850 \) becomes zero in the absence of the magnetic field because of the large uniaxial anisotropy. \( /H20850 \) starts to decrease at \( h > -0.25 \). Therefore, the relative angle between \( /H20849 \) and \( /H20850 \), first increases at \( h < -0.25 \) and then decreases at \( -0.25 < h < 0 \). Subsequently, the relative angle increases with the magnetic field and takes the maximum value at the switching field for the exchange-coupled wire. This leads to a sudden large change in the spin signal. The spin signal in the negative sweep shows a field response similar to that in the positive field sweep. The main difference between the two sweeps is seen in the switching field for the exchange-coupled wire because of the unidirectional anisotropy from the CoO. Therefore, the relative angle at the switching field in the negative field sweep is larger than that in the positive field sweep. This leads to a sudden large change of the spin signal in the negative field sweep as compared to that in the positive field sweep.

Figure 5(a) shows the experimental result of the spin signal as a function of the transverse magnetic field. The spin signal shows a field dependence similar to the calculated result before the switching of the exchange-coupled wire. However, when the exchange-coupled wire starts to switch, different signatures appear in the experimental results. As mentioned above, the spin signal depends only on the local magnetization below the junction. Therefore, these resistance jumps can be explained by a multidomain structure even in the lateral dimension of 100 nm. Although the switching processes in both the negative and positive field sweeps are accompanied by multiple irreversible processes, the loop shift due to unidirectional anisotropy is clearly observed. The spin signal shows several discontinuous resistance changes, meaning that the switching of the exchange-coupled wire takes place accompanied with several irreversible processes. The switching field of the Py wire in the negative sweep is smaller than that in the positive sweep, as indicated by the dotted arrows in Fig. 5(a). This can be understood by the influence of the stray field from the exchange-coupled Py/CoO wire. When the magnetization is aligned in the transverse direction, a stray field appears because of the magnetic charges at the side edge of the Py layer. Such a stray field assists the magnetization reversal of the Py wire. In the negative sweep, the exchange-coupled wire is easily aligned with the magnetic field because of the exchange anisotropy. This leads to a large stray field from the exchange-coupled wire. On the other hand, it is not easy to align the magnetization of the exchange-coupled wire along the magnetic field. This leads to a small stray field in the positive sweep and induces the larger switching field of the Py wire in the positive sweep than that in the negative sweep. We also measured the minor loop of the spin signal in the transverse magnetic field, as shown in Fig. 5(b). The field dependence of the signal can be explained by the switching of the exchange-coupled wire and the reversible rotation of the Py wire, as schematically shown in the inset of Fig. 5(b). A fully AP state can be realized around the zero field during the positive field sweep. The multiple irreversible processes in the exchange-coupled wire are also observed in the sweep of the horizontal magnetic field. Figure 6 shows the spin signal as a function of the horizontal magnetic field. A negative resistance change in the low magnetic field \(|H| < 200 \text{ Oe}\) and a positive resistance jump at \(H = 400 \text{ Oe}\) correspond to the switching of the exchange-coupled wire and that of the single Py wire, respectively. As seen in the result, the switching process of the exchange-coupled wire proceeds with several resistance jumps. The multiple irreversible switchings occur due to the distribution of the exchange anisotropy.
The exchange anisotropy induced in a structure with reduced lateral dimensions is found to depend on the direction of the magnetic field during the cooling. Since the AF layer does not have a shape anisotropy, the reason for this anisotropic behavior is not clear at present. One of the possible reasons is the difference in the magnitude of the value of the effective field during the cooling of the sample. When the exchange bias is perpendicular to the easy axis, the multidiomain structures are formed even in the lateral dimension of 100 nm. Thus, the F domain structure in the exchange-coupled wire is found to depend on the direction of the exchange bias.

**ACKNOWLEDGMENTS**

This work is partially supported by the Sumitomo Foundation.