Domain wall propagation in single crystalline iron wires

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Abstract. The characterization of magnetization reversal in a magnetic domain wall (DW) in a single crystalline Fe wire with crystalline anisotropy and shape anisotropy has been investigated by the giant magnetoresistance (GMR) measurement. The DW propagation velocity reached about 1 km/s in 110 Oe field at 77 K. The broad distribution of the propagation velocity versus the switching field in the Fe wire with longitudinal axis parallel to the (110) direction was found. The magnetic anisotropy energy including the crystalline and shape anisotropies play an important role in the nucleation and propagation of DW.

1. Introduction
General interest in the magnetization reversal in nano- and micron-sized magnets has been studied intensively from both fundamental and applied points of views. Since the majority of magnetization reversal in ferromagnets takes place by the propagation of magnetic domain wall (DW), understanding DW dynamics is a vital part of the study on the magnetizing process [1 - 12]. Much attention has been focused on the studies of DW. One of the recent findings is the experimental observation of Walker breakdown [1, 9, 10]. Just above the Walker breakdown field, the DW velocity against the driving field causes negative differential DW mobility.

The characterization of DW dynamics considering the crystalline anisotropy and pinning force is an important issue, owing to their fundamental physics and implementation of high-speed operation of information devices. In this paper, we present an experimental study of a single DW motion in a single crystalline Fe micro-wire via the giant magnetoresistance (GMR) measurement [7, 11, 12]. We also discuss the magnetization reversal process of the DW from the viewpoint of micromagnetics.

2. Experimental Procedure
A high-quality single crystalline film was grown on a polished MgO(001) substrate using molecular beam epitaxy (MBE). Further details are found in Refs. 11 and 12. We prepared a single crystalline wire Fe(50 nm)/Au(10 nm)/Fe₉₀Ni₈₁ (10 nm)/Au(3 nm) by cutting out the film. The crystalline orientation of the longitudinal axis of the wire can be selected as shown in Fig. 1(a). Here, we focus on the magnetization reversal process of Fe(001)[110]pzc/Au/Fe₉₀Ni₈₁ wire, hereafter called the [110]-wire. The structural characterization was performed by using a reflection high-energy electron diffraction

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(RHEED) image and X-ray diffraction (XRD). The RHEED image indicates good crystal orientation and flatness \[11, 12\]. The XRD result is shown in Fig.1(b). Only the (00n) diffraction peaks are observed. This indicates that the film is strongly textured in the (001) planes and that it is epitaxially grown on the MgO substrate. The layers of Au and Fe$_{19}$Ni$_{81}$ were subsequently deposited on 50 nm thick epitaxial Fe layers at room temperature. Then, multi-layer wires of 1 μm width were fabricated by combination of electron beam lithography, Ar ion milling and lift-off methods. One end of the wire is tapered to a sharp point in order to prevent the formation of DW nucleation and to control the DW injection into the wire.

In order to study the magnetization reversal in micron-sized wires, we investigate the giant magnetoresistance (GMR) effect as a probe of the DW position in the wire \[7, 11, 12\]. The change in the GMR serves to probe the magnetization dynamics of a micron-sized Fe wire. A magnetic field $H$ is applied along the longitudinal axis of the wire, and the resistance $R$ at 77 K is determined using a standard four-point dc technique. The time evolution of magnetization reversal in the wire was monitored by a differential preamplifier and real-time storage oscilloscope with a sampling rate of $20 \times 10^3$ per second and bandwidth of 4 GHz. The magnetoresistance ratio and the time variation of the voltage derived from the time variation of the DW’s position in the single-crystalline Fe(001)[110]bcc/Au/Fe$_{19}$Ni$_{81}$ wire is shown in Fig. 2(a). The linear variation in resistance with time indicates that the propagation velocity $v$ of the DW is constant during magnetization reversal in the wire.

![Diagram](image)

**Figure 1.** (a) Crystallographic relationship and interface structure of epitaxial bcc Fe(001). Relationship between orientation of longitudinal axis of wire and crystalline direction. (b) XRD pattern of the epitaxial Fe(001) film.

3. Results and Discussion

As the DW velocity $v$ measurements were repeated while sweeping the external magnetic field $H$, the switching filed of the [110]-wire ranges from 60 to 110 Oe. The $v$-$H$ characteristics in Fig. 2(b) are homogeneously distributed. For the [110]-wire, we can estimate the mobility from $v = \mu (H - H_{SW})$ and evaluate $\mu = 13.3 \text{m/(Oe}\cdot\text{s)}$ and $H_{SW} = 60 \text{Oe}$.

In order to reveal the microscopic magnetization reversal process, a simple model has been developed \[4, 5, 11, 12, 13\]. Figure 3 summarizes the geometry relation between the anisotropy and applied field. It is assumed that the in-plane uniaxial shape anisotropy along the wire axis is assumed to superimpose the cubic magnetocrystalline anisotropy and that DW propagation as opposed to DW
nucleation is carried out in the magnetic switching process. We focus the magnetization at the centre magnetization in the DW. The resistance in the absence of magnetic field has already risen as shown in Fig. 2(a). This indicates that the magnetocrystalline anisotropy forced the magnetization to tilt from the longitudinal axis of the wire [9, 10]. Therefore, according to Cowburn et al. [4], Ebels et al. [5] and Zhan et al. [13], we consider the stable single domain spin states aligned along one of the effective magnetization easy axis determined by the competition between the shape anisotropy and the magnetocrystalline anisotropy [6, 11, 12]. Figure 3(a) shows the present coordinate model. The angle $\gamma$ is the tilt angle of the effective axis from the wire axis in the plane. The energy of magnetocrystalline anisotropy $E_K$ and shape anisotropy $E_D$ is described by

$$E_K = \frac{K_1}{64} \left[ (3 - 4 \cos 2 \theta' + \cos 4 \theta')(1 - \cos 4 \phi') + 8(1 - \cos 4 \theta') \right] + \frac{K_2}{256} \left[ (2 - 2 \cos 2 \theta' - 2 \cos 4 \theta' + \cos 6 \theta')(1 - \cos 4 \phi') \right]$$

(1)

$$E_D = \frac{M_s^2}{2\mu_0} \left[ N_x \sin^2 \theta' \sin^2 \phi' + N_y \left( \sin \theta' \cos \phi' \cos \gamma + \cos \theta' \sin \gamma \right) + N_z \left( \sin \theta' \cos \phi' \cos \gamma + \cos \theta' \sin \gamma \right)^2 \right]$$

(2)

where $K_1$ and $K_2$ are the first- and second-order magnetic anisotropy energy, respectively. $M_s$ and $\mu_0$ denote the saturation magnetization and vacuum permeability. $\theta'$ and $\phi'$ are the angular components of the magnetization in the spherical coordinate. $N_x$, $N_y$ and $N_z$ are the demagnetizing coefficient along $x$-, $y$-, $z$-axis, respectively.

Here, we neglect the second-order magnetocrystalline energy $K_2$ because $K_1 = (5.2 \pm 0.1) \times 10^4$ J/m$^3$ is further larger than $K_2 = (0 \pm 0.5) \times 10^4$ J/m$^3$ [14].

Figure 3(b) shows the whole anisotropy energy $E_{\text{total}}$ given by $E_K + E_D$ as function of $\theta'$ and $\phi'$. The contour map of Fig. 3(b) is drawn in Fig. 3(c). The calculation indicates that the shape magnetic anisotropy is much larger than the magnetocrystalline anisotropy and basically dominates magnetization reversal. Figure 3(c) reveals that there is the region where anisotropy energy is equivalent to zero around $(\theta', \phi') = (0', 0)$ and $(0 \leq \theta' \leq 90', 0)$. As is evident from Fig. 3(c), the
expected magnetization reversal proceeds as the following. When the increase in the applied field, the magnetization within the DW rotates from the initial direction to the hard axis out of the plane. Next, the magnetization rotates from the previous direction to the nearest in-plane easy axis as the angle $\theta'$ does not rotate but $\phi'$ rotates because of the flat energy level along the direction of $\phi$. Thus, the magnetization rotates from the initial direction to the nearest easy axis of the magnetocrystalline anisotropy $\{100\}$ in the plane. The $v$-$H$ characteristics in Fig. 2(b) are attributed to the random DW nucleation due to the flat energy level.

![Figure 3](image)

**Figure 3.** (a) Schematic model geometry and symbol definitions. Image plot and contour plot of magnetic anisotropy energy as a function of polar angle $\theta'$ and $\phi'$.

4. Conclusions
In summary, the magnetization reversal in a micron-sized epitaxial Fe(001)[110]/Au/Fe$_{19}$Ni$_{81}$ wire is investigated and it is shown that the switching process is dominated by not only the shape anisotropy but also magnetocrystalline anisotropy. The result is an important step toward a complete microscopic understanding of DW dynamics. It also raises a possibility of the controlling the magnetization reversal by modifying the anisotropy energy barriers.

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