SCIENCE

Propagation of a Magnetic Domain Wall in a Submicrometer Magnetic Wire

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The motion of a magnetic domain wall in a submicrometer magnetic wire was detected by use of the giant magnetoresistance effect. Magnetization reversal in a submicrometer magnetic wire takes place by the propagation of a magnetic domain wall, which can be treated as a "particle." The propagation velocity of the magnetic domain wall was determined as a function of the applied magnetic field.

Recent developments of nanolithography techniques make it possible to prepare submicrometer dots and wires with well-defined shape, which has helped spur studies of the quantum phenomena in mesoscopic magnetic materials such as macroscopic quantum tunneling (MQT) and macroscopic quantum coherence (MQC) (1). Depinning of a magnetic domain wall from the pinning center in ferromagnetic (FM) narrow wires occurring through MQT has been discussed from both experimental (2) and theoretical (3) viewpoints. Investigation of this problem requires detection of magnetic domain wall motion in the wire. Because of the small particle volume, however, magnetization (M) measurements of mesoscopic magnetic materials were, in general, limited to samples consisting of a huge number of presumably identical particles or wires. As a result, the essential magnetic properties of a single particle or a single wire were masked by the inevitable distribution of size or shape. Experimental studies of an individual magnetic particle or wire in a submicrometer range have become possible with the development of techniques such as magnetic force microscopy (4), electron holography (5), Lorenz microscopy (6), and micro-superconducting quantum interference device magnetometry (7). Up to now, however, quantitative measurements (such as velocity estimation) on dynamical properties of a domain wall in a submicrometer magnetic wire have proved very difficult.

In a very narrow FM wire, the M is restricted to be directed parallel to the wire axis because of the magnetic shape anisotropy. Normally, it is considered that the M reversal takes place by nucleation and propagation of the magnetic domain wall, which lies in a plane perpendicular to the wire axis. The process of M reversal is especially interesting at low temperatures, where the MQT process may dominate. Direct measurement of M in a submicrometer magnetic wire, however, is difficult because the volume is very small.

We studied the M reversal in a single submicrometer magnetic wire based on a non-coupled-type giant magnetoresistance (GMR) effect. The GMR is the electrical resistance change caused by the change of the magnetic structure in multilayers (8). Thus, the magnetic structure of the system can be detected by resistivity (ρ) measurements. Especially in the case of wire composed of FM nonmagnetic FM layers, the GMR change is directly proportional to M in one of the FM layers. As we reported (9), it is possible to detect a very small change in M in a single NiFe/Cu/NiFe trilayer wire (thicknesses of 200, 100, and 50 Å, respectively) with 0.5 μm width by the GMR effect. The time variation of the resistance during the M reversal reveals how the magnetic domain wall propagates in the wire (10).

The magnetic field H was applied along the wire axis, and ρ was determined using a four-point dc technique. An electrical current flowing in a sample was supplied by a battery (1.5 V) to minimize the noise from a current source. The magnitude of the electrical current was adjusted by using a proper resistance

in the circuit. The typical current was 100 μA. The voltage across two voltage probes was monitored by a differential preamplifier (LeCroy DA1855) and an 8-bit digital oscilloscope (LeCroy 9310), with 1 × 10⁵ per second sampling rate and 400-MHz bandwidth. The current passing through the magnet was also monitored by the digital oscilloscope so as to simultaneously obtain resistance and applied magnetic field during the M reversal.

The resistance change of the trilayer system at 77 K is shown as a function of the applied magnetic field (Fig. 1). Before the measurement, a magnetic field of 500 Oe was applied in order to align M in one direction. Then the resistance was measured at 10-ms intervals, while sweeping the field toward the counter direction at a rate of 20 Oe, s. As far as the counter field being smaller than a critical field (70 Oe), both M values in two NiFe layers are aligned in parallel and the resistance takes the smallest value. When the applied magnetic field exceeds 70 Oe, the resistance rises and stays at the largest value until the field reaches 120 Oe, when the resistance abruptly decreases to the smallest value. The result indicates that the antiparallel M alignment is realized in the field range between 80 and 120 Oe, where the resistance shows the largest value. We have evidence from a preliminary study of NiFe wire arrays deposited onto V-groove substrates in the thickness range described here indicating that the thicker NiFe layer has a larger coercive force than the thinner one (11). Therefore, the change in resistance at 80 and 120 Oe is attributed to the M reversals of the 50 Å NiFe and 400 Å NiFe layers, respectively. Because we did not find any measured point during the M reversal of the 400 Å NiFe layer (Fig. 1), we conclude that the M reversal of the 400 Å NiFe layer is completed within 10 ms. However, the M reversal of the 50 Å NiFe layer gradually proceeds with increase of the applied magnetic field. This result indicates that the M reversal of the 50 Å NiFe layer takes place by the pinning and depinning of

Fig. 1. Resistance as a function of the external magnetic field at 77 K determined by a four-point dc technique. The resistance was measured at 10-ms intervals, while sweeping the field at a rate of 20 Oe/s. The magnetic domain structures inferred from the resistance measurement are schematically shown.
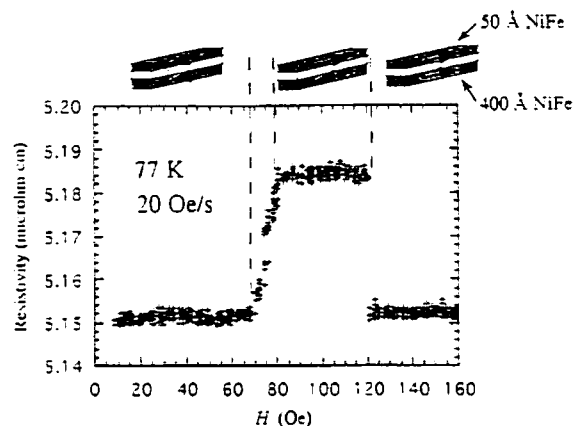
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Fig. 2. Time variation of the resistance during the M reversal of the 400-Å NiFe layer at 77 K, which was collected at 40-ns intervals. The applied magnetic field simultaneously monitored by digital oscilloscope was 121 Oe. Because the sweeping rate of the applied magnetic field was 20 Oe/s, the variation of the applied magnetic field during M reversal was less than 2×10^{-5} Oe. Thus, the applied magnetic field is regarded as constant during the measurements.
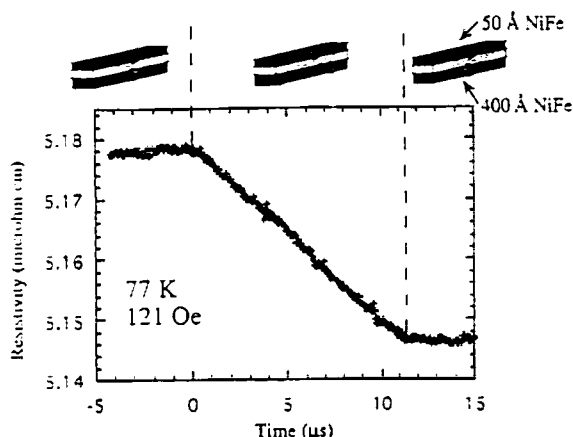
the magnetic domain wall. Hereafter, we focus on the M reversal of the NiFe layer of 400 Å thickness.

An experimental result is shown for the time variation of the resistance during the M reversal in the 400 Å NiFe layer (Fig. 2). The data were collected at 40-ns intervals. The linear variation of resistance with time in Fig. 2 indicates that the propagation velocity of the magnetic domain wall is constant during the M reversal of the 400 Å NiFe layer. This constant velocity suggests that the M reversal takes place by the propagation of a single magnetic domain wall. the propagation velocity of which at the applied field of 121 Oe is estimated to be 182 m/s from the time (11 μs) of the wall traveling across the two voltage probes (2 mm). Because the sweeping rate of the applied magnetic field was 20 Oe/s, the variation of H during M reversal is less than 2×10^{-5} Oe. Thus, H is regarded as constant during the measurements. It should be noted that the time variation of resistance can be converted into the time variation of domain wall position in the wire, because the domain wall comes from one of two voltage probes and runs toward the other voltage probe. Therefore, the domain wall position as a function of time can be obtained by this method.
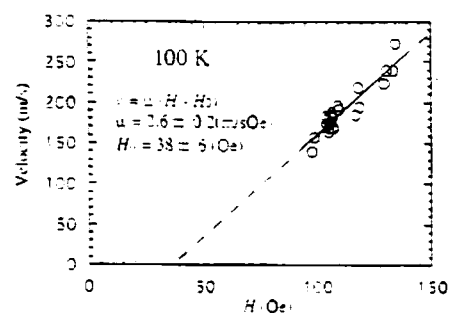
Because the reversal field of the 400 Å NiFe layer fluctuated from run to run in the range of 90 to 140 Oe, the wall velocities at various H's were obtained by repeating the measurements shown in Fig. 2. The result at 100 K is shown in Fig. 3. The wall velocity depends linearly on H and is described as $v = \mu(H - H_0)$, where v is the wall velocity and μ is the so-called wall mobility; it was obtained that $\mu = 2.6 \pm 0.2$ m/sOe and $H_0 = 38 \pm 6$ Oe. This mobility is much less than that obtained for a NiFe film with the same thickness (12). Figure 4 shows the temperature (T) dependence of mobility (μ) and H_0. H_0 is considered to be the field below which the magnetic domain wall cannot propagate because of the pinning by structural defects. Therefore, the decrease of H_0 with increase of T (Fig. 4) can be interpreted as a thermal-assisted effect. In contrast, the wall mobility is almost constant in the range from 100 to 160 K. When the wall mobility is limited by eddy currents, the mobility is described as $\mu = C\rho/M_s d$, where C is constant, M_s is the saturation, and d is the film thickness (13). Therefore, the mobility should increase with increase of temperature, because ρ increases and M_s decreases with an increase of T. Moreover, the rough estimation of the mobility, assuming a rigid wall, gives $\mu = 1.6 \times$
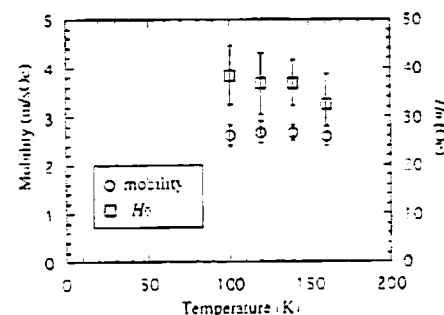
10^4 m/sOe for the 400 Å NiFe film (13). This value is three orders of magnitude larger than the experimentally obtained value. Therefore, the experimentally obtained mobility cannot be explained by the eddy currents loss. The other mechanism which limits the wall mobility is the Gilbert damping. If we assume a flat domain wall with a continuous internal spin structure, the wall mobility expresses theoretically as $\mu = \gamma\Delta/\alpha$ (14), where γ is the gyromagnetic ratio, Δ is the domain wall width, and α is the Gilbert damping parameter. By using the experimentally obtained value of μ and assuming $\Delta = 100$ nm, $\alpha = 0.63$ is obtained. Although this value is greater than that estimated from the width of the FM resonance line (12), such large α values have also been reported in ultrathin Co films (15) and were attributed to the presence of defects at the surface and interface. The edge effect should also be taken into account in the case of magnetic wires. As a consequence, we conclude that the mobility is dominantly limited by Gilbert damping.

Our experiments describe a method to observe the magnetic domain wall propagation in a single submicrometer wire, and this method, as far as the resistance can be measured, can be applied to narrower wires in which the volume of the magnetic domain wall is smaller. Therefore, this method opens the way to addressing other interesting problems, such as one-dimensional propagation of a magnetic domain wall as a soliton and MQT by depinning of a magnetic domain wall from a pinning center.

References and Notes
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10. The samples were prepared by using lift-off techniques as follows: First, a 0.1 μm thickness of ZEP520 resist was spin-coated on a Si(100) substrate. After the pattern of wire was exposed by an electron-beam writer, the resist was developed. The NiFe(400 Å)/Cu(200 Å)/NiFe(50 Å) trilayer film was deposited on the patterned mask by electron-beam evaporation in a vacuum of 1×10^{-8} Torr. The wire with trilayered structure was obtained after the resist mask was removed. Because of the large Cu-layer thickness, the interlayer exchange coupling between the NiFe layers is negligible. The width of the wire is 0.5 μm, and the sample has four current-voltage terminals, where the voltage is probed over a distance of 2 mm.
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Fig. 3. Dependence of domain wall velocity v on amplitude H of the applied magnetic field at 100 K. The wall velocity depends linearly on the applied magnetic field and is described as $v = \mu(H - H_0)$, where $\mu = 2.6 \pm 0.2$ m/sOe and $H_0 = 38 \pm 6$ Oe.

Fig. 4. Temperature dependence of mobility μ and H_0. Whereas H_0 decreases with an increase of temperature, the wall mobility is almost constant in the temperature range from 100 to 160 K.

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