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-superscanning 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 NiFeCuNiFe 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 p 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 × 10^4 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⁻¹. 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. 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/ns, the variation of the applied magnetic field during M reversal was less than $2 \times 10^{-4}$ Oe. Thus, the applied magnetic field is regarded as constant during the measurements.

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 $\mu$ is the so-called wall mobility; it was obtained that $\mu = 2.6 \pm 0.2 \text{ m/s Oe}$ and $H_0 = 38 \pm 6$ Oe. This mobility is much less than that observed for a NiFe film with the same thickness (12). Figure 4 shows the temperature ($T$) dependence of mobility ($\mu$) 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 $\mu = C p / d^2$, where $C$ is constant, $p$ is the saturation, and $d$ is the film thickness (13). Therefore, the mobility should increase with increase of temperature, because $p$ increases and $M_s$ decreases with an increase of $T$. Moreover, the rough estimation of the mobility, assuming a rigid wall, gives $\mu = 1.6 \times 10^6$ m/s Oe 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 current 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 $\mu = g V \alpha \Delta (14)$, where $g$ is the gyromagnetic ratio, $V$ is the domain wall width, and $\alpha$ is the Gilbert damping parameter. By using the experimentally obtained value of $\mu$ 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 $\alpha$ 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
1. For a review of MQT/MQD see, for example, V. M. Chudnovsky and J. Tegada, Macroscopic Quantum Tunneling of the Magnetic Moment (Cambridge Univ. Press, New York, 1998).
10. The samples were prepared by using lift-off techniques as follows: first, 0.1 μm thickness of ZnS 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. A 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 $1 \times 10^{-6}$ Torr. The wire with patterned 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 samples have four current-voltage terminals, where the voltage is probed over a distance of 2 mm.
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Magnetization reversal in submicron magnetic wire studied by using giant magnetoresistance effect

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The magnetization reversal phenomenon in a submicron magnetic wire with a trilayer structure consisting of NiFe(200 Å)/Cu(100 Å)/NiFe(50 Å) was investigated by measuring the electric resistance in an external magnetic field. A giant magnetoresistance (GMR) effect of about 0.8% was observed when the magnetizations in two NiFe layers are oriented antiparallel. It is demonstrated that magnetization reversal phenomena can be very sensitively investigated by utilizing the GMR effect. © 1998 American Institute of Physics. [S0003-6951(98)01509-5]

Recent developments of nanolithography techniques make it possible to prepare well-defined dots and wires. Generally, magnetism in mesoscopic systems has become an updated topic from both the scientific and technological point of view. The process of magnetization reversal in a single-domain ferromagnetic structure is very basic in magnetism and has been of considerable interest to theorists and experimentalists since the pioneering work of Néel.\(^1\) An understanding of this problem is of fundamental importance for the magnetization reversal in complex systems, such as assemblies of fine particles, thin films, bulk materials, etc., and may also be relevant to current problems, such as macroscopic quantum tunneling (MQT) and macroscopic quantum coherence (MQC).\(^2\) The process of magnetization reversal is also very important in recording media applications. As recording densities increase, the understanding of thermal-magnetization switching behavior is necessary. Until recently, however, the experimental studies were in general limited to those samples consisting of a huge number of presumably identical particles because of their small volume. Most of the single-particle or single-wire properties were hidden behind the distribution of size and shape. Experimental studies of individual magnetic particles in the submicron range became possible with the techniques of magnetic force microscopy (MFM),\(^3\) electron holography,\(^4\) and micro-superconducting quantum interference device (SQUID) magnetometry.\(^5\)

In very narrow ferromagnetic wires, due to the magnetic shape anisotropy, the magnetization is restricted to be directed either parallel or antiparallel to the wire axis. Normally, it is considered that magnetization reversal takes place by nucleation and propagation of a magnetic domain wall which lies in a plane perpendicular to the wire axis. The process of magnetization reversal attracts interest especially at low temperatures where a quantum tunneling process may be dominant. The MQT of a domain wall in a ferromagnetic metal wire has been recently investigated both theoretically\(^6\) and experimentally.\(^9\) The magnetization measurement of magnetic wires, however, is difficult in general because the volume is very small.

In this letter, we present magnetoresistance measurements of a single submicron magnetic wire based on a non-coupled type GMR effect. The GMR is the electrical resistance change caused by the change of the magnetic structure in multilayers.\(^10\) This means, in turn, the magnetic structure of the system can be detected by resistivity measurements. Especially in the wire case, where due to the magnetic shape anisotropy the direction of the magnetization is restricted to be parallel or antiparallel along the wire axis, the GMR change is directly proportional to the magnitude of the switching layer magnetization. As we have reported in a previous paper, it is possible to detect very small magnetization changes in a NiFe(100 Å)/Cu(100 Å)/NiFe(10 Å)/Cu(100 Å)/NiFe(50 Å) multilayer wire array by the GMR effect.\(^11\) Here, we applied this method to a single NiFe(200 Å)/Cu(100 Å)/NiFe(50 Å) trilayer wire with 0.5 μm width. The result clearly shows that the artificial neck introduced in the wire works as a pinning center for the magnetic domain wall.

The samples were prepared by lift-off techniques employed to electron-beam evaporated NiFe(200 Å)/Cu(100 Å)/NiFe(50 Å) trilayer films. Due to the large Cu-layer thickness, the interlayer exchange coupling between the thin and thick NiFe layer is negligible. The magnetoresistance measurements were performed at 300 K. The magnetic field was applied along the axis of the wires. Resistivity was determined using a four-point dc technique. As seen in Fig. 1, the samples have four current-voltage terminals where the voltage is probed over a distance of 20 μm. Furthermore, the samples have an artificial neck (0.35 μm width) introduced at 1/3 distance from one voltage probe in order to monitor the magnetic domain wall propagation.

Figure 2 shows the resistance of our trilayer system as a function of the applied external field. Prior to the measurement, a magnetic field of 100 Oe was applied in order to achieve magnetization alignment in one direction. Then the resistance was measured in steps of 1 Oe as the field was swept towards the counter direction. The result of our magnetoresistance measurement essentially displays four very
sharp leaps. The first and second leaps correspond to the magnetization reversal of the thin NiFe layer whereas the third and fourth leap correspond to the magnetization reversal of the thick NiFe layer. There is clear evidence resulting from a preliminary study on NiFe wire arrays deposited onto V-groove substrates that for the thickness range to be considered, the thicker NiFe layer has a larger coercive force than the thinner one. Here we discuss how the magnetization reversal takes place in the sample. As long as the counterfield is smaller than a critical field, the magnetizations of both thin and thick NiFe layers align parallel and the resistance shows the lowest value. As the applied magnetic field exceeds 5 Oe, the resistance abruptly jumps and maintains a constant value up to 10 Oe. Then, exceeding 10 Oe, resistance abruptly jumps again and maintains the largest value up to 22 Oe. The result indicates that the antiparallel magnetization alignment is realized at an external field between 11 and 22 Oe where the resistance shows the largest value. The ratio of the resistance which changes at the first and second leap is 1:2. This means that one-third of the total magnetization of the thin NiFe layer changes its direction at the first leap in Fig. 2, since the GMR change is directly proportional to the switching layer magnetization. The ratio of one-third corresponds to the ratio of length between one voltage probe and the neck to the overall length of the wire between the voltage probes. Therefore, in this case, a magnetic domain wall nucleates in the shorter part of the wire (left-hand side of the scanning electron microscopy (SEM) image in Fig. 1) and propagates to the neck where it is pinned up to 10 Oe. The second leap when exceeding 10 Oe corresponds either to depinning of the magnetic domain wall from the neck or to nucleation and propagation of another magnetic domain wall on the other side of the neck (right-hand side of the SEM image in Fig. 1). These two possibilities cannot be distinguished from the result shown in Fig. 2. Since the ratio of the resistance changes at the third and fourth leap is also 1:2, the magnetization reversal of the thick NiFe layer takes place in the same manner as in the thin NiFe layer described above. As shown in Fig. 2, there appeared small resistance change before the magnetization reversal takes place in the stages (1) and (4). This may be due to the small displacement of the magnetic domain wall pinned at some imperfections of the wire.

So far, we reported on magnetoresistance measurements of submicron magnetic wire based on the GMR effect and found that magnetic domain wall propagation is controlled by the neck artificially introduced into the wire. It should be noted that the method reported in this letter corresponds to a very high sensitive magnetization measurement. For the sample reported above, the sensitivity is as high as $10^{-13}$ emu (100 spins). The method, in principle, can be applied to smaller samples as far as the resistance of the samples can be measured and the relative sensitivity increases with decreasing sample volume.

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