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Propagation of the magnetic domain wall in submicron magnetic wire investigated 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(400 Å)/Cu(200 Å)/NiFe(50 Å) was investigated by measuring the electric resistance in external magnetic fields. It is shown that the magnetization reversal can be very sensitively investigated by utilizing the giant magnetoresistance effect. The time variation of resistance during the magnetization reversal was also measured and the velocity of the magnetic domain wall propagating in the wire was determined at 77 K. [S0021-8979(99)69808-5]

INTRODUCTION

Recent developments of nanolithography techniques make it possible to prepare well-defined dots and wires, and magnetism in mesoscopic systems has become an updated topic both from scientific and technological viewpoints. The process of magnetization reversal in a single-domain ferromagnetic structure is a key issue in magnetism after the pioneering work of Néel.[1] An understanding of this problem is of fundamental importance for the magnetization reversal in complex systems, such as fine particles, wires, and thin films. Furthermore, it may be also relevant to current problems such as macroscopic quantum tunneling (MQT) and macroscopic quantum coherence (MQC).[2] The understanding of magnetization reversal is also very important for recording media applications. As recording densities increase, the thermal agitated magnetization switching dominates in a recording bit. On the other hand, the magnetization measurements were in general limited to samples consisting of a huge number of presumably identical particles because of their small volume. As a result, the magnetic properties of a single particle or single wire were hidden behind the distribution of size or shape. Experimental studies of an individual magnetic particle in a submicron range became possible with the techniques such as magnetic force microscopy,[3] electron holography,[4] and microsuperconducting quantum interference device magnetometry.[5–7]

In very narrow ferromagnetic wires, the magnetization is restricted to direct parallel to the wire axis due to the magnetic shape anisotropy. Normally, it is considered that magnetization 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 magnetization reversal attracts interests especially at low temperatures where the MQT process may be dominant. The MQT of a domain wall in a ferromagnetic metal wire has been recently investigated from both experimental[8] and theoretical viewpoints.[9] The magnetization measurement of magnetic wires, however, is difficult because the volume is very small.

In this article, we present the study of the magnetization reversal in a single submicron magnetic wire based on a noncoupled type giant magnetoresistance (GMR) effect. The velocity of the magnetic domain wall in a bulk wire of NiFe alloy was first measured by Sixtus and Tonks.[10] Here, we report the velocity of the magnetic domain wall in a submicron wire of NiFe alloy. The GMR is the electrical resistance change caused by the change of the magnetic structure in multilayers.[11] This means that the magnetic structure of the system can be detected by resistivity measurements. Especially in the case of wire, the GMR change is directly proportional to the magnitude of the switching layer magnetization. As we have reported in a previous article,[12] it is possible to detect a very small magnetization change in a single NiFe(200 Å)/Cu(100 Å)/NiFe(50 Å) trilayer wire with 0.5 μm width by the GMR effect. Here, we present the time variation of the resistance during the magnetization reversal. This reveals how the magnetic domain wall propagates in the wire.

EXPERIMENT

The samples were prepared by using lift-off techniques as follows. First, 0.1-μm-thick ZEP520 resist was spin coated on a Si(100) substrate. After the pattern of wire exposed by an electron-beam writer, the resist was developed. 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. Due to the large Cu-layer thickness, the interlayer exchange coupling between NiFe layers is negligible. As seen in Fig. 1, 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.

A block diagram for the time variation measurements of the resistance during the magnetization reversal is shown in Fig. 2. The magnetic field was applied along the wire axis.

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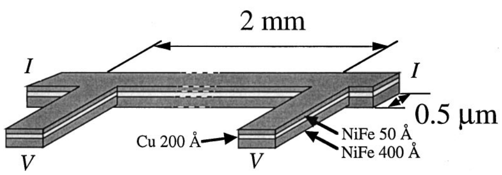

FIG. 1. Schematic illustration of sample structure. The width of the wire is 0.5 μm and the sample has four current–voltage terminals where the voltage is probed over a distance of 2 mm.

The resistivity was determined using a four-point direct current (dc) technique. An electrical current flowing in a sample was supplied by using a battery (1.5 V) to minimize the noise from a current source. The magnitude of the electrical current was adjusted by using proper resistance in the circuit. The typical current was 77 μA with the resistance of 15 kΩ, since the resistance of sample was 4.4 kΩ at 77 K. The voltage across two voltage probes was monitored by a differential preamplifier (LeCroy DA1855) and a digital oscilloscope (LeCroy 9310) which is 8 bits, 1×10^8/s sampling rate and 400 MHz bandwidth. The differential preamplifier is necessary to obtain good resolution, since the resistance change during the magnetization reversal is only 1.5% at 77 K. The magnet power was supplied by a power amplifier which amplifies the triangular wave generated using a low frequency oscillator so as to control both the magnitude and frequency of the applied magnetic field. The current passing through the magnet was also monitored by the digital oscilloscope. To obtain both the resistance and the applied magnetic field during the magnetization reversal simultaneously, the internal trigger level was set the value between the maximum and minimum resistances. All measurements were carried out at 77 K.

RESULTS AND DISCUSSION

Figure 3 shows a resistance change of the trilayer system as a function of the applied field. Prior to the measurement, a magnetic field of 500 Oe was applied in order to align the magnetization in one direction. Then the resistance was measured with sweeping the field towards the counter direction at the sweeping rate of 50 Oe/s. As far as the counterfield is smaller than the critical field, both magnetizations in two NiFe layers are aligned in parallel and the resistance takes the smallest value. When the applied magnetic field exceeds 38 Oe, the resistance abruptly rises and stays at the largest value until the field reaches 84 Oe, and then the resistance abruptly decreases to the smallest value. The result indicates that the antiparallel magnetization alignment is realized in the field range between 38 and 84 Oe where the resistance shows the largest value. Resulting from a preliminary study on NiFe wire arrays deposited onto V-groove substrates, it was clarified that the thicker NiFe layer has a larger coercive force than the thinner one.[13] Therefore, the change in resistance at 38 and 84 Oe is attributed to the magnetization reversals of NiFe(50 Å) and NiFe(400 Å) layers, respectively.

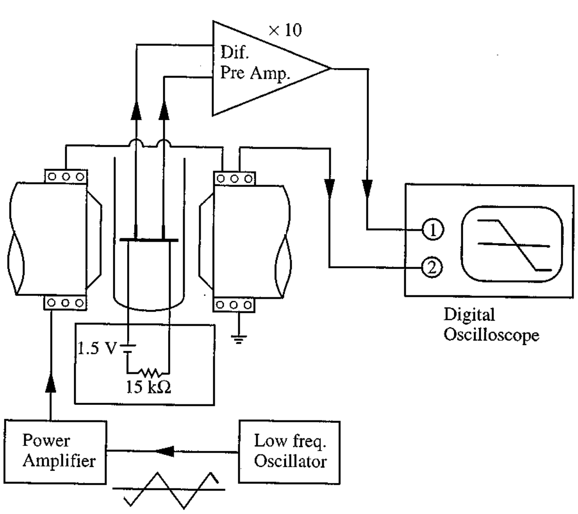

FIG. 2. Block diagram for the time variation measurements of the resistance during the magnetization reversal.

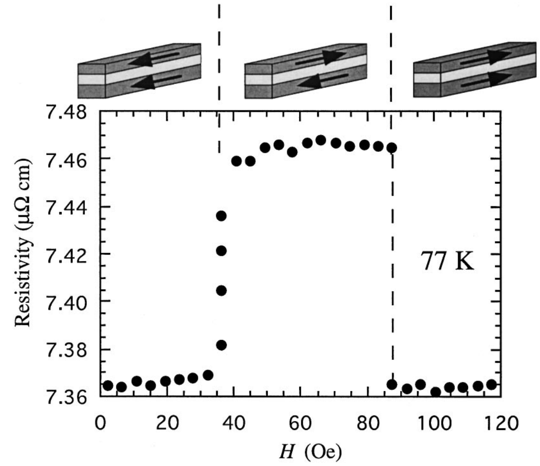

FIG. 3. Resistance as a function of the external magnetic field at 77 K determined by a four-point dc technique. The magnetic domain structures inferred from the resistance measurement are schematically shown.

Figures 4(a) and 4(b) show the experimental results on the time variation of the resistance during the magnetization reversal in the 400-Å-thick and 50-Å-thick NiFe layers, respectively. The resistance linearly decreases with time during the magnetization reversal of the 400-Å-thick NiFe layer, while the resistance change is much slower and has some structures during the magnetization reversal of the 50-Å-thick NiFe layer.

The linear variation of resistance with time in Fig. 4(a) indicates that the propagation velocity of the magnetic domain wall is constant during the magnetization reversal of the 400-Å-thick NiFe layer. This implies that the magnetization reversal takes place by the propagation of a single magnetic domain wall. The propagation velocity of the magnetic domain wall at the applied field of 88 Oe is estimated to be 182 m/s from the time interval (11 μs) of the wall traveling across the two voltage probes (2 mm). As the sweeping rate of the applied magnetic field was 5 Oe/s, the variation of the applied magnetic field during magnetization reversal is less than 5×10^{-5} Oe, namely, the applied field is regarded as constant during the measurements.

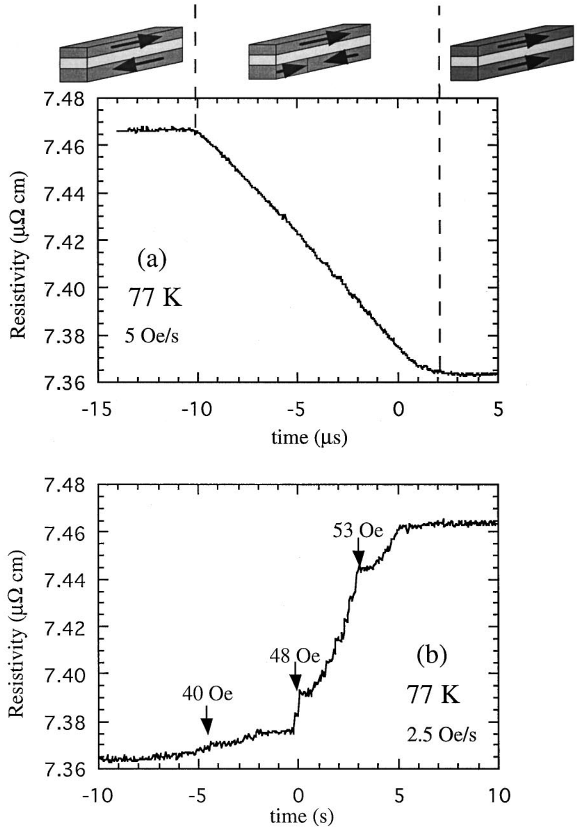

FIG. 4. Time variation of the resistance during the magnetization reversal of the (a) 400-Å-thick NiFe layer and (b) 50-Å-thick NiFe layer at 77 K.

As seen in Fig. 4(b), a linear relationship between the resistance and time was not observed during the magnetization reversal of the 50-Å-thick NiFe layer. It is considered that the magnetization reversal takes place by successive pinning and depinning of the magnetic domain wall. The magnetic domain wall trapped at a pinning center is depinned with further increase of the applied magnetic field. Then, it moves and is trapped again by another pinning center whose pinning potential is larger than that of former. There is a possibility that, while the domain wall is trapped at the first pinning center, new domain wall nucleates at the other end of the wire and it propagates to the direction in reverse. Therefore, the situation is not so simple as that for the reversal of thick NiFe layer. In contrast to the case of Fig. 4(a), the resistivity change is slow and consequently the applied field has changed during the measurements. It is interesting, however, that the profile of resistivity versus time shown in Fig. 4(b) is similar from one measurement to another. Therefore, by analyzing this profile, we may obtain some information about the distribution of pinning centers included in the sample.

Finally, we compare the method described above with the other methods, such as Kerr microscopy[14] and Lorenz microscopy.[15] Lorenz and Kerr microscopy have an advantage to directly observe the magnetic domain structure, but the time resolution is about 10^{-3} s as far as an ordinary video system is used. Comparing with methods described above, the method reported in this article has the following advantage. That is, the method corresponds to a very high sensitive magnetization measurement. For the sample NiFe(200 Å)/Cu(100 Å)/NiFe(50 Å) trilayer wire 0.5 μm in width and 20 μm in length, the sensitivity is as high as 10^{-13} emu (10^7 spins).[12] 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.

In summary, the magnetoresistance measurements of a submicron magnetic wire based on the GMR effect were presented. The magnetic domain wall propagation can be very sensitively observed. The velocity of the magnetic domain wall propagating in the NiFe wire 0.5 μm in width and 400 Å in thickness is 182 m/s at the applied field of 88 Oe at 77 K.

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