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 microsuperconducting quantum interference device (SQUID) magnetometry.[5-7]

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[8] 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(100 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

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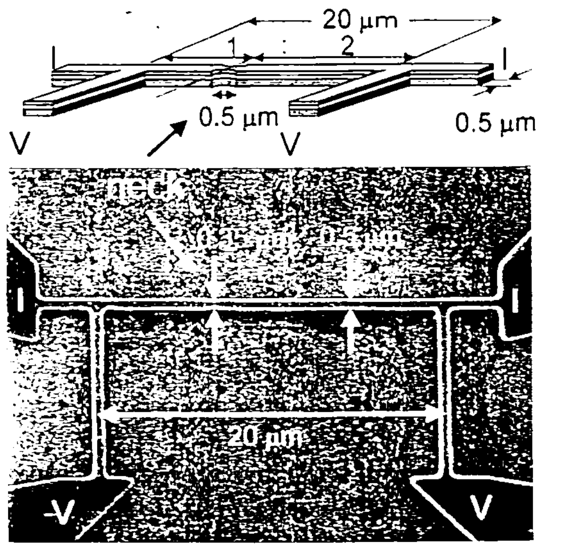

FIG. 1. SEM image and schematic illustration of the sample. The sample consists of a NiFe(200 Å)/Cu(100 Å)/NiFe(50 Å) trilayer.

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.[12] 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

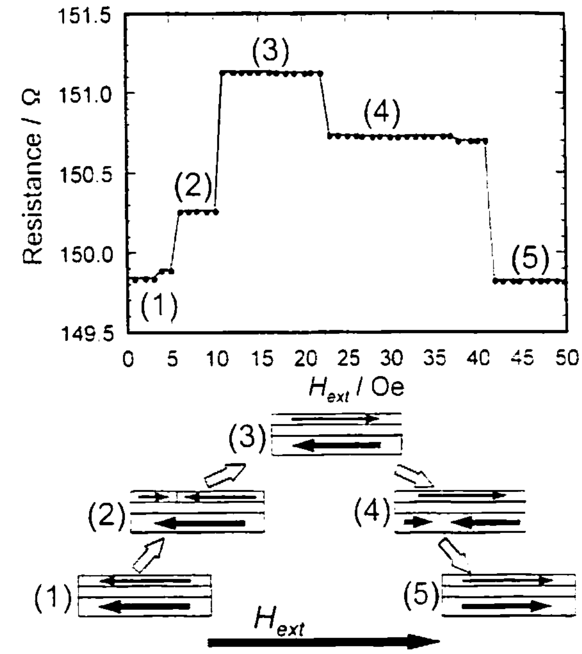

FIG. 2. Resistance as a function of the external magnetic field at 300 K determined by the four-point dc technique as illustrated in Fig. 1. The magnetic domain structures inferred from the resistance measurement and the direction of the external field are schematically shown.

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 (10^7 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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