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Studies on Magnetization Reversal in Submicron Wires and Domain Wall Behaviors

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Several recent experimental studies on microstructured samples of ferromagnetic materials are described. Magnetization reversal phenomena were investigated on submicron wire samples consisting of two magnetic layers with different coercivities utilizing the giant magnetoresistance (GMR) effect. From resistivity measurements, the domain wall movements are sensitively monitored and the velocity of propagation is determined. Experiments to estimate the contribution of domain wall to the resistivity are also introduced.

KEYWORDS: microfabrication, submicron wires, GMR (giant magnetoresistance effect), magnetization reversal, domain wall propagation, domain wall resistance

§1. Introduction

Microfabrication techniques have been utilized routinely in the field of semiconductor physics to prepare mesoscopic systems. It has been well recognized that electronic structures are modified by artificially designed microstructures and eventually novel phenomena are exhibited. For metallic and magnetic systems, on the other hand, the use of microfabrication techniques has not yet been common, although the properties of mesoscopic magnetic systems are of great interest both from basic and technical viewpoints. In the present article, several experimental studies on the magnetic properties of microstructured systems recently carried out by the authors' group are described.

The discovery of giant magnetoresistance (GMR) effect[1,2] has given us a breakthrough, and in the last decade various studies relating to GMR have been promoted intensely.[3] It is still crucial to investigate the condition to realize a large MR ratio at room temperature under weak magnetic fields. A possible method to enhance the MR ratio is to utilize the CPP (with current perpendicular to the plane) geometry.[4] Almost all GMR experiments have been made in the CIP (with current in the plane) geometry and those in CPP geometry have been very limited because of the resistance being extremely small. This inconvenience is avoided if we use microstructured samples. For the authors, the initial purpose to install the microfabrication equipment was CPP-MR studies. As introduced in the next section, GMR studies on multilayers deposited on substrates with V-shaped micro-grooves have been carried out, whose geometry is named CAP (with current at an angle to the plane).[5] Since the CAP geometry lies in between CIP and CPP, an enhancement of MR ratio is expected.

By depositing a ferromagnetic material on a V-groove substrate in a tilted direction, an array of microwires is prepared and magnetization reversal phenomena of ferromagnetic wires have been studied. The concept of domain wall has been established long time ago and extensive studies on domain walls have been made already on various magnetic systems.[6] Recently, magnetic domain walls in mesoscopic scales have attracted renewed attention since the possibility of macroscopic quantum tunneling (MQT) process was predicted.[7] Pioneering studies on MQT in mesoscopic systems have been reported by several groups.[8,9] In ultrathin wires of a ferromagnetic material, the direction of magnetization is limited so that it is parallel to the wire axis because of the shape anisotropy. If there is only one domain wall, the magnetization reversal is regarded as propagation of the domain wall. In case that the cross section of the wire is very small, the domain wall size also should be a mesoscopic scale and the domain wall is expected to behave as a quasiparticle. It is of great interest to observe the properties of single domain wall in a very narrow wire. The authors have prepared single wire systems consisting of two magnetic layers with different coercivities and succeeded in observing the domain wall movements in submicron wires utilizing GMR effect. In the third section, several results on single wire systems are described.

In the region of domain wall generally, spin directions of each atom vary gradually and a non-collinear spin structure is formed. The disordered spin structure may influence the conductivity but the contribution of a domain wall to the resistivity is very small and still an open question. In the last place, this problem will be argued with introducing latest experimental results.

§2. GMR Studies in CAP Geometry and Multiwire Systems

The method to prepare a microstructure with V-shaped grooves on Si substrates has been established in the field of semiconductor technologies. The period of

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artificially prepared grooves in the present experiment was typically 1 μm. For the study of GMR in CAP geometry, multilayers exhibiting non-coupled type GMR effect[10] were deposited on V-groove substrates rather thickly along the normal direction to the initial Si surface (Fig. 1(a)). Then the electric current parallel to the initial Si plane has an angle of 55° to the multilayer interfaces. Enhancement of MR ratio owing to the CAP geometry was confirmed as shown in Fig. 1(b).[11] From the same sample, the MR values in the normal CIP geometry are able to estimate by taking the direction of current to be parallel to the grooves and the CIP-MR value thus observed is also shown in the same figure for comparison.

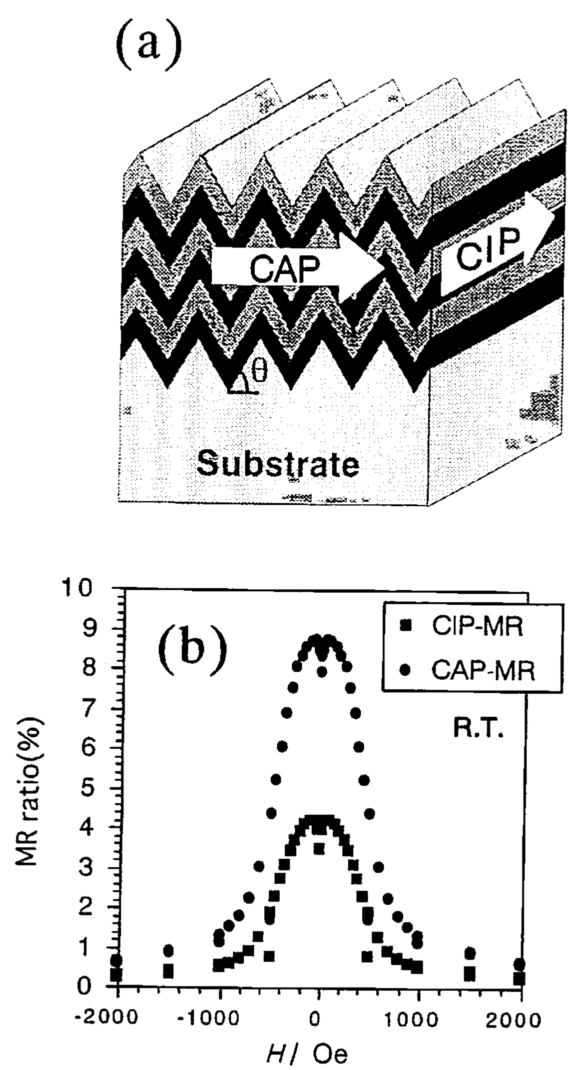

Fig. 1. (a) Structure of multilayers deposited on a V-groove substrate for the study of GMR in CAP geometry. (b) Non-coupled-type GMR curves for CAP and CIP geometries. The composition of the multilayer is [Co 12 Å/Cu 116 Å/NiFe 12 Å/Cu 116 Å]× 91.

An array of wires with a submicron width is prepared by depositing in a tilted angle as shown in Fig. 2(a). The deposited film is divided into a wire shape at each groove and subsequently an array of wires is prepared. Using a V-groove with a pitch of 0.5 μm, wires with 0.3 μm width are obtained. In a sample on a Si substrate with an area of 10 mm × 10 mm, about 2000 pieces are included. Sugita *et al.* have prepared wire samples of permalloy ($Ni_{80}Fe_{20}$) with various thicknesses and from magnetization measurements they found that the coercive force of the permalloy wires increases with increase of thickness in the region up to about 300 Å.[12] In this region, magnetization is almost restricted in the plane even during domain wall nucleation. Accordingly the coercive force depends on a demagnetizing factor perpendicular to the wire axis in the plane. In this case the

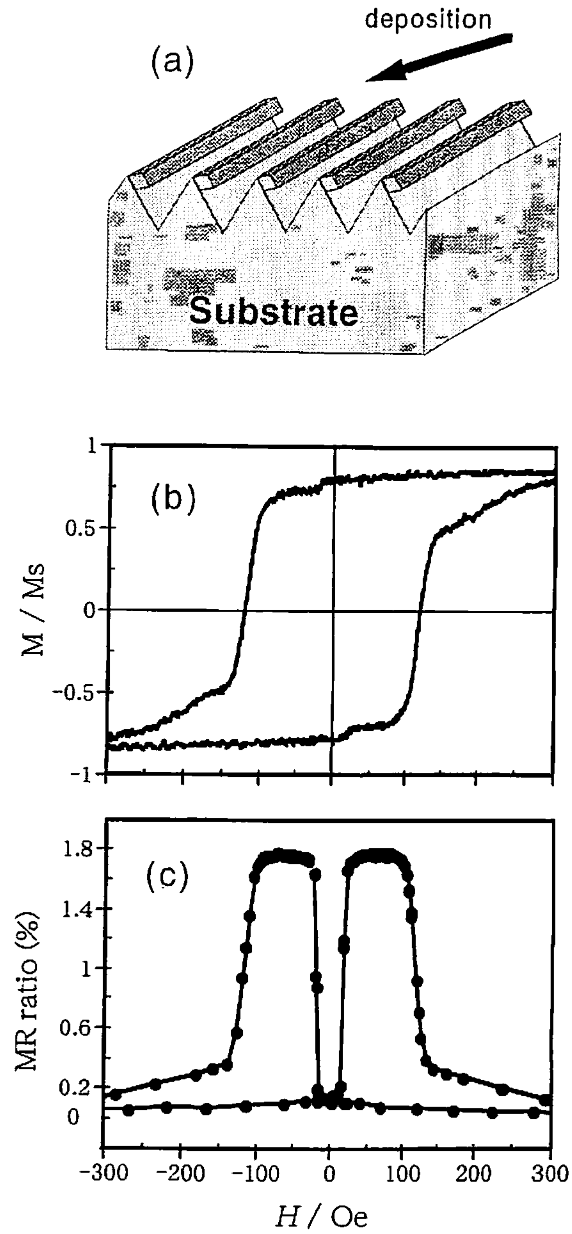

Fig. 2. (a) Structure of wire array deposited on a V-groove substrate. The arrow indicates the directions of deposition. (b) Magnetization and (c) resistivity both at 300 K of wire arrays with a nominal structure of [NiFe 100 Å/Cu 100 Å/NiFe 10 Å/Cu 100 Å/NiFe 100 Å] as a function of external magnetic field.

demagnetizing factor is proportional to the layer thickness. Therefore, in the thickness region below 300 Å, the coercive force of permalloy layer is controlled by varying the thickness. For thickness greater than 300 Å, magnetization direction can be directed out of the plane. This causes to decrease the total energy during domain wall nucleation. Therefore the coercive force decreases gradually with increase of thickness. Using permalloy layers with different thicknesses, a non-coupled-type GMR multilayer system is realized in a wire array sample. For example, the obtained results for a multiwire sample with a nominal structure of [NiFe 100 Å/Cu 100 Å/NiFe 10 Å/Cu 100 Å/NiFe 100 Å] is shown in Figs. 2(b) and (c).[13] The coercive force of thin NiFe layer (10 Å) is fairly small but that of the thicker one is larger than 100 Oe. In the magnetization curve, a small lump is observed at about 20 Oe, corresponding to the reversal in the 10 Å layer. In contrast, the resistivity change at this field is strikingly large, that is the GMR effect, because the magnetizations are antiparallel in the field region from 20 to 100 Oe. Until the reversal of magnetization in the thicker layers, the antiparallel magnetic arrangement is held and the resistivity has little change. If the external field is larger than 100 Oe, all magnetizations gradually saturate and the resistivity returns to the initial zero field value. It is noteworthy that owing to the GMR effect, the resistivity change is much more remarkable than the corresponding change in the magnetization curve. The present results prove that resistivity measurements are a useful method to detect magnetization reversal phenomena sensitively.

Concerning magnetization reversal phenomena, from resistivity measurements on multiwire samples, we obtain a statistical information. It is a merit of multiwire samples that the magnetization is able to measure and compared with a change in the resistivity. Several other experimental techniques may be applicable because of sample including many wires. On the other hand, it is of great interest and significance to detect the behaviors of domain wall in a single wire sample. The present results suggest that the resistivity measurements utilizing the GMR effect have a sufficient sensitivity to observe magnetization reversal phenomena in a single wire sample.

§3. Single Wire Systems

Magnetization in a single wire with submicron width is too small to measure by normal experimental techniques and it is not easy to study magnetization reversal phenomena in single wire samples. The results on multiwire samples described in the preceding section suggest that the resistivity measurements utilizing GMR effect may have a capability to detect magnetization reversal phenomena in single wire samples. Samples for resistivity measurements having a pattern shown in Fig. 3(a) were prepared by electron-beam lithography apparatus (JEOL JBX-5000) using lift-off method. The content is the following trilayer structure, [NiFe 200 Å/Cu 100 Å/NiFe 50 Å] and the wire width is 0.5 μm. The distance between the probes for resistivity measurements is 20 μm. In addition, the sample has a neck point at 1/3 distance from one voltage probe, where the width

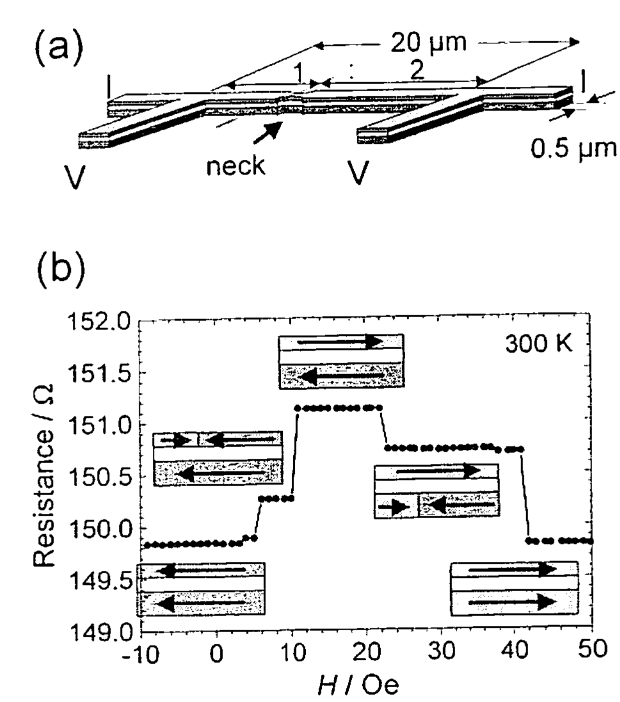

Fig. 3. (a) Structure of single wire sample for the resistivity measurements. The width is 0.5 μm. The distance between two voltage probes is 20 μm and a neck was artificially prepared at 1/3 distance from one probe. (b) Resistivity at 300 K as a function of external magnetic field.

was artificially narrowed (0.35 μm width). Domain wall propagation is expected to be pinned at the neck. The resistivity as a function of the applied field at 300 K is shown in Fig. 3(b). Prior to the measurement, a magnetic field of 100 Oe was applied in order to align all magnetization parallel. Then the resistivity was measured with sweeping the external field. In the figure, the enhancement of resistivity owing to the GMR effect is clearly observed.[14]

Both the increase and the decrease of resistivity have two steps and the jumps between the steps are very fast. The relative height ratio of the two steps is 1:2 at both increasing and decreasing. This result means that 1/3 of the magnetization is reversed first and therefore the magnetic structures at each step should be as illustrated in the figure. As expected, a domain wall is trapped at the neck point and is stopping for a while. If the external field exceeds a certain critical value, the domain wall is depinned or another domain wall comes from the other side and walls are cancelled out. At the situation where magnetizations in two layers are antiparallel, the resistivity is kept to be the maximum. Although we have no other information than the resistivity, it is no doubt that the magnetic structure at each step is as illustrated in the figure because of the sharp two-step changes with the relative heights of 1:2 and therefore all the process is interpreted as a movement of single domain wall.

By a magnetization measurement, it is hard to detect a magnetization change in a microwire with a dimension of 100 Å × 0.5 μm × 20 μm. In addition to the wire part, the terminal parts for resistivity measurements are also made of the same magnetic layers, which have a much larger contribution in the magnetization. The present results indicate that the resistivity measurement utilizing GMR effect has an enough sensitivity to study magnetization reversal phenomena in a single wire while no information is available from magnetization measurements.

The resistivity measurements are useful also to estimate the velocity of domain wall propagation. There are several techniques to observe magnetic domain structures, such as magnetic force microscopy (MFM), spin-polarized LEED and Kerr microscopy. However, it is generally difficult to observe dynamical behaviors of domain walls in extremely small systems. A typical quantity to characterize the dynamical properties of domain wall is the velocity of propagation. Using the resistivity method, the estimation of velocity has been attempted. The result shown in Fig. 3(b) suggests that the velocity of the domain wall propagation in the distance of 20 μm is too fast to measure. For the velocity measurements, therefore a sample with 100 times larger length (2 mm) was prepared. The width is the same 0.5 μm and the constitution is [NiFe 400 Å/Cu 200 Å/NiFe 50 Å] and no neck was prepared. The resistivity change as a function of external field at 77 K is shown in Fig. 4(a).[15] Prior to the field sweeping, 500 Oe was applied to align the magnetizations in one direction. The sweeping rate of the field was 20 Oe/s. It is confirmed that the resistivity is enhanced in the field region of 35 to 85 Oe by the non-coupled type GMR effect. The increase at about 35 Oe corresponds to the reversal of magnetization in the thinner NiFe layer and the decrease at about 85 Oe, in the thicker one. The former one is rather slow because pinning and depinning of domain wall should take place in moderate external fields. In contrast, the decrease of the resistivity caused by the reversal of the thicker layer is very fast. The time dependence of the resistivity was recorded by using a digital oscilloscope. The observed resistivity as a function of time at the applied field of 88 Oe is shown in Fig. 4(b). Because the field sweeping speed is very slow, the external field during the domain wall propagation is actually constant. The resistivity changes almost linearly with time and from the gradient we can derive the velocity of the domain wall propagation. The time length to travel the distance between the terminals (2 mm) is measured to be about 11 μs and therefore the velocity is calculated to be 182 m/s. It is to be noted that the domain wall motion is very fast but the velocity is nearly constant for the propagation in the probing region. This result gives us an evidence that a domain wall in a small wire is regarded to behave as a particle.

The results in Figs. 3 and 4 indicate that the domain wall propagations occur suddenly if the external field exceeds a critical value. The critical field for magnetization reversal corresponds to a potential barrier for a domain wall and therefore it should be a crucial physical quantity for the arguments of domain wall dynamics. However, it has been noticed that the observed critical field values for these samples are not unique but have considerable distributions. If the magnetic field sweeping was repeated, the magnetization reversal (i.e., the change of resistivity) occurred each time at different fields. The reason is thought to exist in the structure of the wire sample. Since the terminal parts also have been composed of the same magnetic materials, the nucleation of magnetization reversal starts at the parts with large areas and domain walls should move from terminal parts to the wire region. The connecting parts between terminal and wire, especially elbow-shape parts may pin the domain wall.

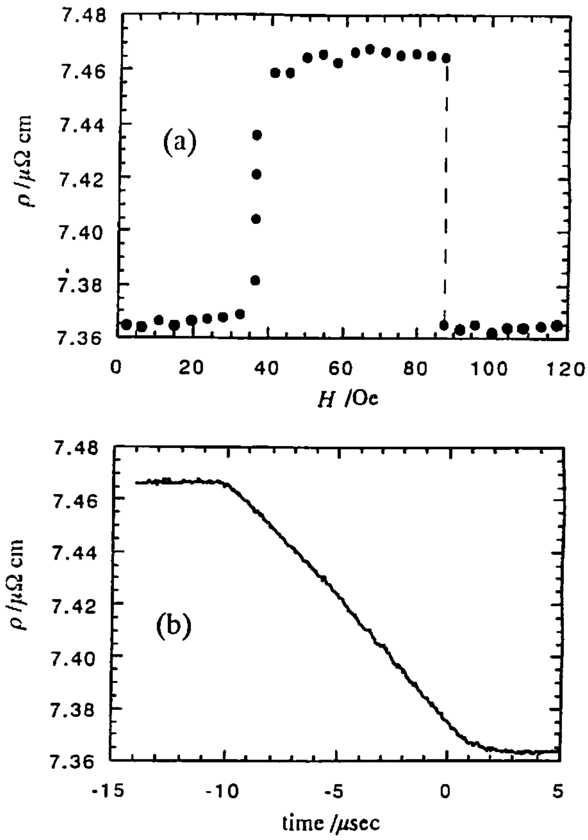

Fig. 4. Resistivity at 77 K of single wire sample, [NiFe 400 Å/Cu 200 Å/NiFe 50 Å] with an extended length, 2 mm. (a) As a function of external field. (b) As a function of time, at an external field of 88 Oe.

Very recently, improvement of the quality of wire sample has been attempted in the following manner. In order to control the nucleation of magnetization reversal and identify the structure of domain wall, only the wire part of the sample was prepared by ferromagnetic materials and the terminal parts were by a non-magnetic metal (Cu). In addition, at one end of the wire, a wide area part was attached (so-called pad) to specify the nucleation site (see Fig. 5(a)) . The results in Figs. 5(b) and (c) were obtained for a sample whose magnetic layers were consisting of permalloy and cobalt.[16]

Similarly to the results in Figs. 3 and 4, abrupt resistivity changes due to the individual reversals of magnetization in permalloy and cobalt layers are observed. For this sample, the values of external field for the re-

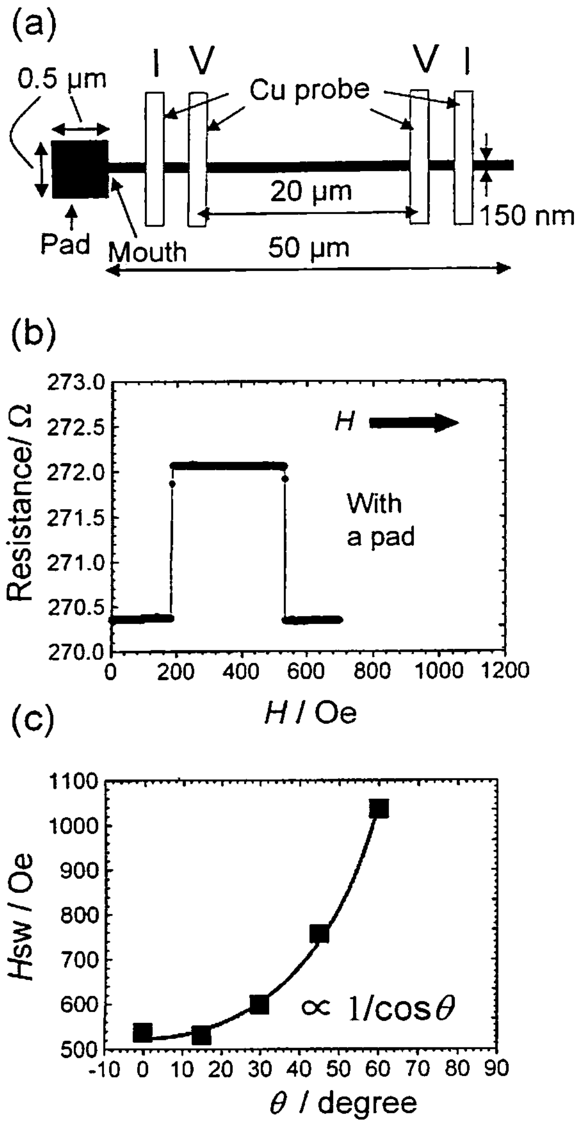

Fig. 5. (a) Schematic illustration of a [NiFe 20 Å/Cu 20 Å/Co 40 Å] nanowire with a pad at the edge. (b) Resistance as a function of external magnetic field H parallel to the wire axis at 300 K. (c) Angular dependence of the switching field H_{sw} of the Co layer at 300 K. The magnetic field was applied in the plane of the substrate at an angle θ with respect to the wire axis.

sistivity change are almost unique, having a reasonably good reproducibility. The reversal process of the present sample is considered to be the following. The nucleation starts in the pad area but a domain wall is trapped at the connecting position between the pad and wire. If the external field attains to a critical value, the domain wall starts to propagate. This model is verified by the measurement with changing the direction of external fields relative to the wire axis. With increase of the angle, θ, from the axis, the critical field, H_{sw}, increases as shown in Fig. 5(c). However, $H_{sw}\cos\theta$ is found to be constant. Namely the component of magnetic field to the direction of the axis is the same. The domain wall starts to propagate when the magnetic field strength to the propagation direction reaches to a certain value, which indicates the existence of a well-defined barrier for the domain wall. A systematic study for refined samples is in progress.

§4. Resistivity of Domain Wall

In the preceding sections, studies on domain walls utilizing GMR effect were introduced. In those resistivity measurements the electric currents have mainly flown in the spacer (non-magnetic) layers and a contribution of domain walls in the magnetic layers was negligible. In domain wall regions, spin directions of each atom are varied gradually and the non-collinear spin structure may influence the conductivity.[17,18] There have been several experiments to study the contribution of domain walls to the conductivity using films and wire samples.[19-22] However because the contribution is small and also anisotropic magnetoresistance (AMR) is predominantly superposed, a conclusive result has not yet been obtained. Whether the existence of domain walls enhances or reduces the conductivity is still an open question.

The authors group has prepared a model system to study the contribution of a domain wall to the conductivity by utilizing an exchange-spring bilayers, which consist of soft magnetic (NiFe) and hard magnetic (CoSm) layers with an exchange coupling at the interface.[23] In this system, the magnetic moments in the soft magnetic layer are pinned by the hard magnetic layer at the interface. When an inverse magnetic field is applied to the saturated state along the easy axis (the x direction), the magnetic moments start to rotate at a certain magnetic field with the directions distributed as a function of the depth from the interface (Fig. 6(a)). The magnetic moments rotate reversibly as the magnetic field increases, until the moments in the hard magnetic layer are reversed abruptly to the saturation by an irreversible magnetization process. The direction of the magnetic moments at each magnetic field during the reversible magnetization process can be calculated from the condition that gives the minimum in the sum of the exchange, Zeeman, and magnetic anisotropy energies. Therefore, the NiFe layer is regarded as a model system which has a well-characterized magnetic structure with gradually rotating magnetic moments. When the magnetoresistance of a NiFe/CoSm bilayer is measured in a current-in-plane geometry, the electric current mostly flows in the NiFe layer, since the resistivity of the CoSm layer is about 100 times larger than that of the NiFe layer. The magnetoresistance measured in this way corresponds to that for an electric current parallel to a Bloch wall.

The magnetoresistance of NiFe(300 Å)/CoSm(1000 Å) measured with the electric current parallel (ρ_{xx}) and perpendicular (ρ_{yy}) to the magnetic field are shown in Fig. 6(b). A reversible change is observed in the magnetic field range where the reversible magnetization process takes place. The curves measured in the two geometries appear to be a mirror image of each other relative to the horizontal axis. This fact implies that the effect due to AMR, i.e., the magnetoresistance dependent on the angle ϕ between the magnetization and the electric current, is dominant in the observed magnetoresistance.

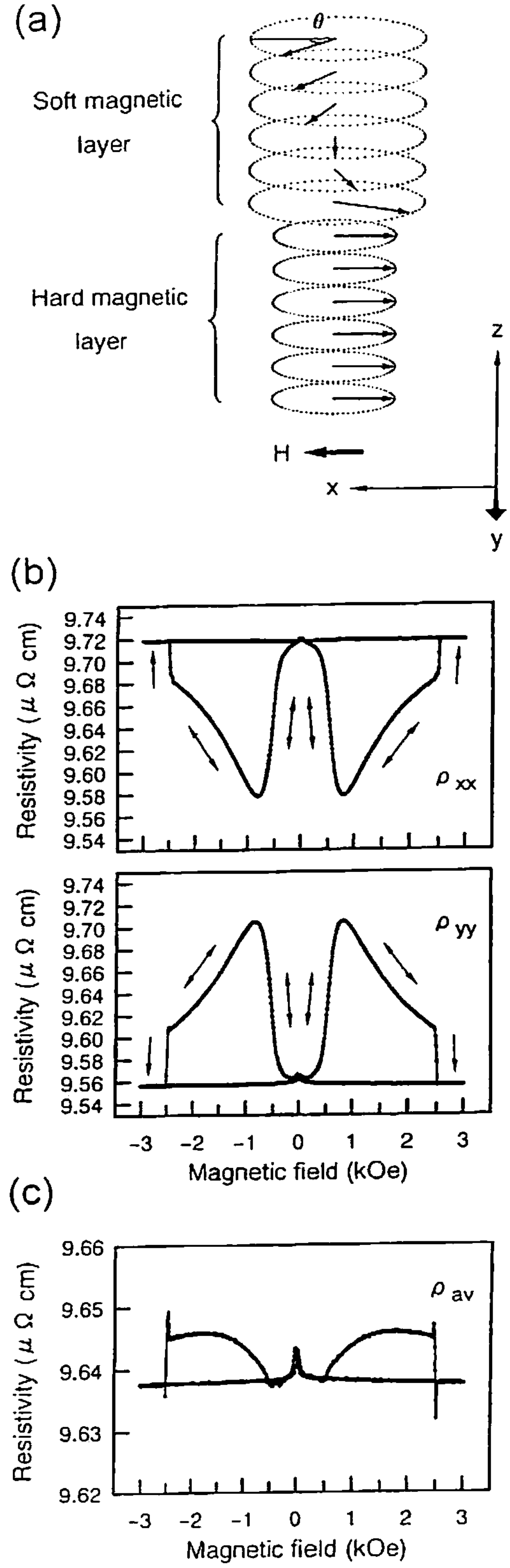

Fig. 6. (a) Illustration of an exchange-spring state in a soft-magnetic/hard-magnetic bilayer. (b) Magnetoresistance curves of NiFe(300 Å)/CoSm(1000 Å) with the electric current parallel (ρ_{xx}) and perpendicular (ρ_{yy}) to the magnetic field at 300 K. Reversible and irreversible processes are shown by double-headed and single-headed arrows, respectively. (c) Average of ρ_{xx} and ρ_{yy}; a positive magnetoresistance effect is obtained after canceling out the AMR effect.

In the present system, the direction of magnetic moment relative to the electric current is different as a function of the depth from the interface. If the phenomenological angular dependent equation for AMR (i.e., AMR $\propto \cos^2\phi$), which is valid for uniformly magnetized films, is applied to such a system, the local resistivity is distributed as a function of the depth from the interface. The AMR of the NiFe as a whole is estimated from the parallel circuit of the distributed local resistivity. The calculated resistivity reproduces the feature of the reversible parts in Fig. 6 (b) well. If the magnetoresistance due to the electric current flowing in the NiFe layer is only from the AMR effect, the average of ρ_{xx} and ρ_{yy} should be almost constant, independent of the rotation angles. The experimental average (ρ_{av}) of ρ_{xx} and ρ_{yy} for NiFe(300 Å)/CoSm(1000 Å) shows a small positive effect as shown in Fig. 6(c). The result indicates that a positive magnetoresistance effect that cannot be explained with the AMR effect exists in the observed ρ_{xx} and ρ_{yy}. The average resistance ρ_{av} increases as the relative angle between the magnetic moments in the NiFe layer increases. Therefore the effect is thought to be due to a GMR-type effect, i.e., magnetoresistance dependent on the relative configuration of magnetic moment. In this way, it was found that the magnetoresistance of a NiFe layer with gradually rotating magnetic moments is composed of an AMR-type effect of several % and a GMR-type effect of less than 0.1%.

A preliminary experiment to control the domain nucleation in a wire has been carried out very recently.[24] As shown in Fig. 7(a), a wire of permalloy with attaching CoSm pads was prepared using the e-beam lithography method. The permalloy wire is 200 Å thick, 1 μm width and 300 μm length and CoSm pad, 400 Å thick and 30 × 30 μm area. After saturation, by applying a moderate field inversely, the major parts of permalloy layer without covered by CoSm pad change the magnetization direction while the covered parts by CoSm pads maintain the initial direction of magnetization and eventually two domain walls per each pad are produced artificially (Fig. 7(b)). The Cu terminal leads have been attached to measure the resistivity of each part. The result of resistivity measurements shows that a domain wall contributes to reduce the resistivity and the contribution is proportional to the number of domain walls (Fig. 7(c)). This result proves that the domain wall nucleation is satisfactorily controlled. The reduction of resistance due to a domain wall in this case is interpreted to be the AMR effect since in the domain wall region the spin directions are deviated from the current direction (parallel to the wire axis). The size of the negative resistance contribution observed here is a reasonable one as an AMR effect, if the wall width in the wire is several times larger than that in bulk permalloy. The temperature dependence of the domain wall resistance shows a similar tendency to that of AMR for bulk permalloy, which also evidences that the negative resistance is from AMR. Because AMR contribution is much dominant, it is not possible to judge the existence of other contribution to the resistivity from domain walls.

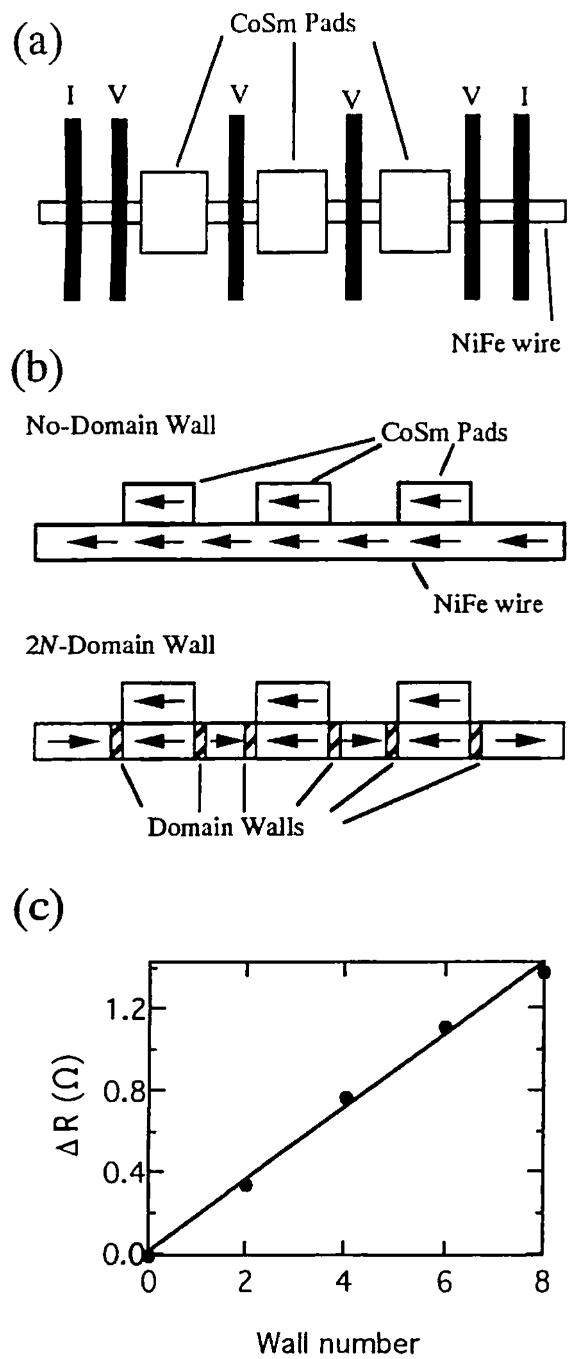

Fig. 7. (a) Schematic image of a NiFe nanowire with CoSm pinning pads. (b) No-wall state (magnetically saturated state) and $2N$-wall state. (c) The size of negative resistance as a function of domain wall number.

§5. Summary

Experimental studies on the following subjects are briefly surveyed and the usefulness of microfabrication techniques for magnetic materials research is introduced.

(1) GMR studies have been made on multilayers prepared on V-groove substrates and an enhancement of MR ratio due to the CAP geometry is observed.

(2) Submicron ferromagnetic wires were prepared by depositing on V-grooves in a tilted direction. From resistivity using GMR effect, magnetization reversal was detected.

(3) Behaviors of a single domain wall in a single wire system prepared by microfabrication technique were also studied from resistivity measurements. The velocity of domain wall propagation is estimated.

(4) The nucleation and propagation of a single domain wall in a single submicron wire were satisfactorily controlled.

(5) A positive magnetoresistance due to a GMR-type effect from a domain wall was observed in an exchange-spring bilayer system.

(6) A wire system with designed number of domain walls was successfully constructed by attaching hard-magnetic pads and the resistivity due to a domain wall was estimated.

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