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The local domain wall position in ferromagnetic thin wires: simultaneous measurement of resistive and transverse voltages at multiple points

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Abstract

We have simultaneously measured the field dependences of voltages at multiple pairs of resistance and transverse voltage probes in ferromagnetic wires (with either magnetic or non-magnetic voltage probes). Both the resistive (through the giant magnetoresistance and anisotropic magnetoresistance) and transverse voltages (through the planar Hall effect) exhibit abrupt jumps, reflecting discrete motion of domain walls or rotations of magnetization. Voltage probes, even if non-magnetic, are found to affect the jump fields depending on the sample conditions. We demonstrate that the specific information on the domain (wall) motion along a thin ferromagnetic wire could be obtained from the jump fields.

1. Introduction

Exotic behaviour in mesoscopic magnetic systems is one of the most intensively investigated topics in solid-state physics. Magnetoresistance (MR) measurement has been utilized as a powerful tool for investigating the magnetization of small ferromagnetic thin wires [1–12], since the change in magnetization is usually too small to be measured directly. Hong and Giordano [1] found sharp steps in the field dependence of the resistance, and ascribed them to a domain wall motion. An additional interesting feature of the resistance steps is an apparent negative resistive contribution from domain walls. Combining MR measurements with electron microscope images, Otani *et al* [3] have ascribed the steps to the process of domain wall pinning and depinning processes. Theoretically, both negative and positive resistances associated with the presence of a domain wall have been reported. Levy and Zhang [13] first reported a positive

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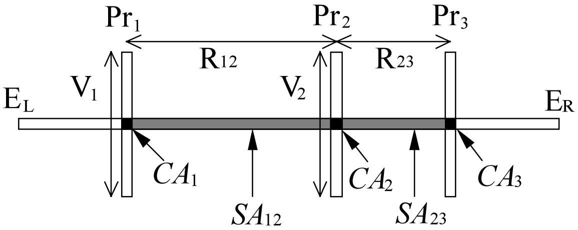

Figure 1. A schematic diagram of the shapes of the samples. E_i, Pr_i, CA_i and SA_{ij} are the names we use for the current leads, voltage leads, crossed areas and sample areas, respectively.

domain wall resistance, as naturally expected from additional conduction electron scattering by domain walls. Tatara and Fukuyama [14] explained the negative domain wall resistance as due to the suppression of the weak localization near domain walls. Gorkom *et al* [15] have found that the domain wall resistance could be either positive or negative, depending on the difference between the spin-dependent scattering times, based on a semi-classical approach. Thus, theoretically, the domain wall resistance can be of either sign, depending on the models and the material parameters. Experimentally, Ebels *et al* [10] found a large positive domain wall resistance in 35 nm diameter Co wires, while the MR for 50 nm diameter wires is negative, which they qualitatively explained on the basis of the anisotropic MR resulting from the magnetization rotation away from the wire axis. The latter behaviour has also been reported for relatively thick wires, which has been qualitatively explained by Wegrowe *et al* [9] on the basis of Aharoni's model [16] of a curling rotational mode. In contrast, Kent *et al* [11] reported a negative domain wall resistance in Fe epitaxial thin-film microstructures, which may result from the reduction of surface scattering of conduction electrons due to the internal magnetic field near the domain walls. To the best of the authors' knowledge, even the sign of the domain wall resistance in ferromagnetic wires is still controversial. In order to further investigate the domain wall resistance contribution, it is desirable to obtain more specific information on the domain motions (pinning of walls and/or rotation of magnetization directions) by measuring the transport property itself.

Ono *et al* [5] have succeeded in detecting the local domain wall motion in a NiFe/Cu/NiFe trilayer wire by determining the area of the thin NiFe layer with its magnetization anti-parallel to the thick NiFe layer utilizing the GMR effect. Shigeto *et al* [17] have proposed a way to define the direction of a domain wall motion by attaching a pad with a size larger than the wire width at one of the edges as an injection source for a domain wall. In recent works, transverse voltage measurements have been utilized to observe a rotation of magnetization related to the wall motion in a local area around the voltage probes in submicron magnetic wires [18–20].

In [18], we reported on a transverse voltage measurement made to obtain the local information on a local area (CA_i; see figure 1) where the voltage probe crosses the main part of sample wire. In this paper, we report a way to obtain more specific information on the domain motion by combining the GMR effect and simultaneous measurements of resistive and transverse voltages at multiple pairs of voltage probes. It could be used to extract further information on the anisotropic MR contribution associated with the domain wall motion in thin ferromagnetic wire. We also report the unexpected effect of non-magnetic electric probes on domain wall motion in ferromagnetic wires.

2. Experimental details

Two types of sample wire, type (1) with magnetic voltage and current probes and type (2) with non-magnetic ones, were prepared. The type (1) samples are simply shaped as shown in figure 1 (with a width of ~ 0.5 μm) from NiFe(40 nm)/Cu(20 nm)/NiFe(5 nm)/Cu(2 nm) films on thermally oxidized Si substrates using electron-beam lithography and lift-off techniques [5, 17]. Thus, the voltage probes are made of the same material as the main sample part. The ratio of the distances between the two pairs of resistance probes (L_{12} and L_{23}) is 2:1 with a total distance of $L_{12} + L_{23} = 50$ μm. The voltage drops (between the multiple pairs of resistive and transverse voltage probes) are simultaneously measured using multiple nanovoltmeters while the magnetic field is swept slowly (0.17–0.038 Oe s^{-1}). The sweep rate has a crucial effect on the fine structure of the MR curve reported in this paper. When a sweep rate over 1 Oe s^{-1} is used, some important fine structures in the present experiment are found to disappear. The type (2) samples are 10–20 nm thick NiFe single-layer wires with three different widths (w_d) of 0.1, 0.3 and 0.5 μm. As voltage probes, three pairs of 80 nm thick Cu wires with width 0.5 μm are placed with the same distance ratio of L_{12}:L_{23} = 2:1 and $L_{12} + L_{23} = 20$ μm. In this work, the magnetic field is always applied parallel to the current direction with an accuracy better than 0.5° unless specifically mentioned, and the data presented are ones taken after a high enough field was applied in the same direction. The current in this work was selected between 5 and 40 μA where not-so-drastic changes of the MR curves were found.

3. Results and discussion

3.1. Type (1) sample with magnetic voltage probes

Type (1) samples have the disadvantage that the magnetic voltage probe itself behaves as a pinning or nucleation site of domain walls. However, this can be considered as an advantage if one intends to study the motion of domain walls in a thin ferromagnetic wire.

Figure 2 shows the field dependences of the resistance (R_{ij}) and transverse voltage (V_{ti}) measured at 4.2 K simultaneously using the multiple pairs of voltage probes for each component. The anti-parallel state (AP state) of two NiFe layers is recognized as a large resistance plateau at around ± 150 Oe in R_{12} and R_{23}; a step-like increase due to the magnetization reversal of the thin NiFe layer at ~ 130 Oe followed by a step-like decrease due to the magnetization reversal of the thick NiFe layer at ~ 170 Oe with increasing field as had already been reported [5]. The change of the jump field with the layer thickness can be ascribed to the dependence of the demagnetization field on the layer thickness. The ratios R_{12}:R_{23} and ΔR_{12}:ΔR_{23} (ΔR_i is the jump in R_i) agree with the designed ratio of 2:1 within the experimental accuracy. The most prominent feature in figure 2 is the growth of V_{ti} with hysteresis starting above 1000 Oe which is far above the jump fields for R_{ij}. The monotonic change of the transverse voltage arises from the planar Hall effect [18] and reflects a continuous magnetization rotation in CA. This result shows that the magnetization near the voltage probe starts to rotate continuously far above the flipping field of the magnetization in the main sample part. Correlated with the higher-field jumps in R_{ij} resulting from the flipping of the magnetization of the thick NiFe layer, clear jumps appear also in V_{t1} and in V_{t2} at around 170 Oe, which reflect a sudden large-angle rotation of the magnetization in the area CA. In contrast, no apparent structure is identified in V_{ti} at the field at which reversal of the magnetization direction occurs in the thin NiFe layer. The insensitivity of V_{ti} to the magnetization rotation of the thin NiFe layer is ascribed to the reduction of the induced planar Hall voltage by the (eight-times) thicker NiFe layer. Another important feature is the coincidence of jumps in the

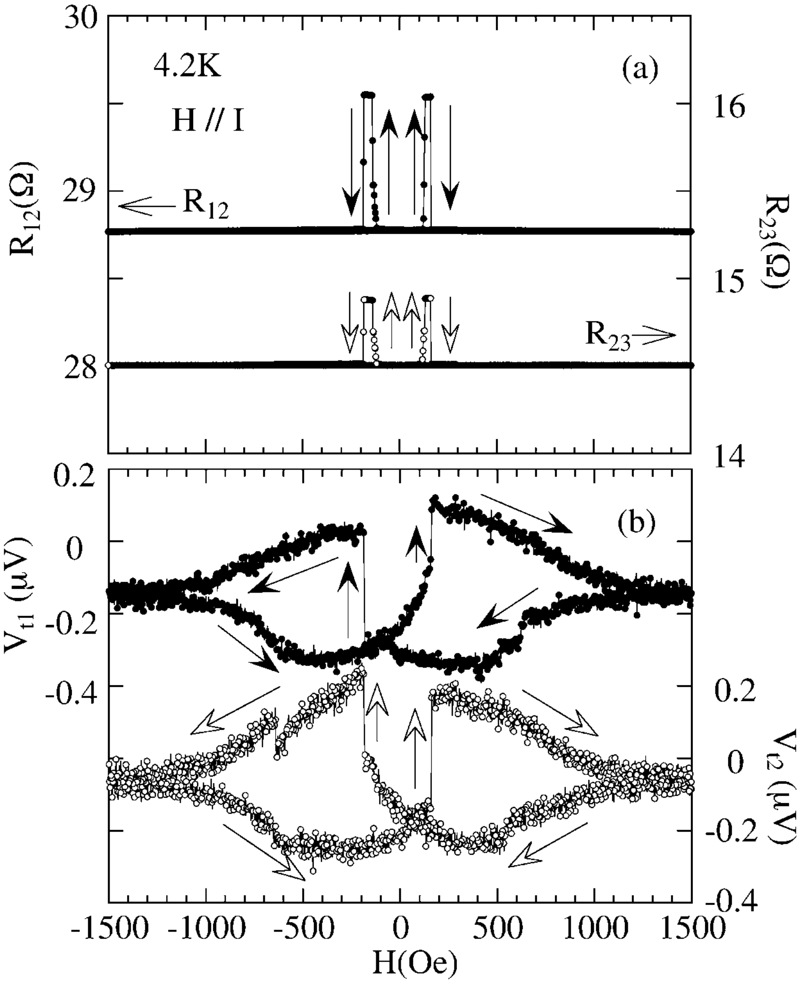

Figure 2. Field dependences of the resistances and transverse voltages at multiple pairs of probes for a type (1) sample.

four traces at 172 Oe for increasing field in figure 2. The fact suggests that a domain wall, associated with the reversal of magnetization in the thick NiFe layer, passes through the three pairs of probes at a same field.

More detailed information is obtainable from a higher-sensitivity measurement with a slower field-sweep mode (0.038 Oe s^{-1}) in a limited field interval near the magnetization reversal as shown in figure 3. The jump on the higher-field side occurs almost instantly, while the complex behaviours at the lower-field jump (related to the thin-NiFe-layer magnetization reversal) suggest multi-step domain wall motion and/or tilting of the domain magnetization. Judging from figure 3, the magnetic configuration in S_{12} and S_{23} changes from the parallel state (PA state) to the AP state in two steps at H_{1A}, H_{1B} and H_{2A}, H_{2B}, respectively, with a finite width ΔH_{iJ} ($i = 1$ or 2, $J = A$ or B) for each step. With increasing field, R_{12} starts to increase at around $H_{1A} \approx 122$ Oe and reaches a metastable state above $H_{1A} + \Delta H_{1A}$ ($\approx$123 Oe) with a resistance change of $\Delta R_{12A}/\Delta R_{12} \approx 15\%$ ($\Delta R_{12} \approx 0.75\ \Omega$ is the total jump), suggesting a domain wall trapped in the region SA_{12} (15% of L_{12} from CA_1). R_{12} increases again above

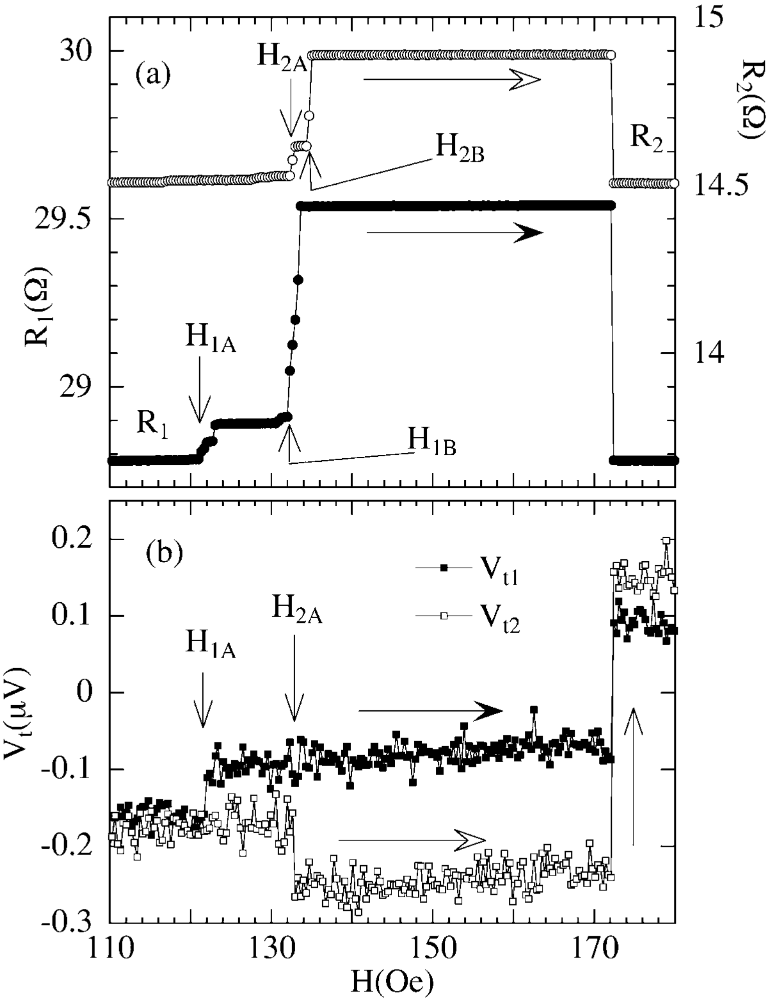

Figure 3. An expanded view of the step-like changes for the negative-field side shown in figure 2 (type (1) sample).

$H_{1B} \approx 132$ Oe and the AP state at around $H_{1B} + \Delta H_{1B}$ ($\approx$133.7 Oe). At H_{2A} slightly above H_{1B}, R_{23} shows an initial increase to a metastable state with $\Delta R_{23A}/\Delta R_{23} \approx 25\%$ above $H_{2A} + \Delta H_{2A}$ ($\approx$133 Oe). With further increasing field, R_{23} shows a final increase to the AP-state value at $H_{2B} \approx 135$ Oe. Also, in the transverse voltages, a clear sign of the domain wall motion appears as an apparent step-like change. For both V_t, a step appears in the first growth of R_{ij}; i.e., between H_{iA} and $H_{iA} + \Delta H_{iA}$, where a sudden large-angle rotation (up to 90°) of the magnetization in CA_1 and CA_2 occurs. It should be noted that the domain wall resistance contribution can be neglected in the analysis, since its magnitude is several orders of magnitude smaller than that of the resistance jumps in figure 3 [5, 18].

Summarizing the above information, the positions of the domain walls along with the direction of the magnetization in the thin NiFe layer are schematically illustrated in figure 4, for typical values of the magnetic field.

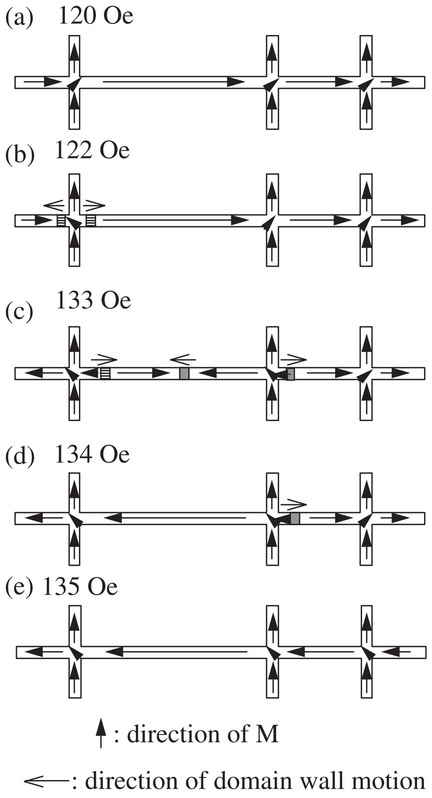

Figure 4. Schematic drawings representing the magnetic configuration at each field.

3.2. Type (2) samples with non-magnetic voltage probes

In order to reduce the effect of the crossed area as a pinning or nucleation site for domain walls, experiments were made on the type (2) samples with non-magnetic voltage probes. Unfortunately, no simultaneous transverse voltage measurements at different pairs of probes have been successful yet at this stage. The small overlap distance, $<0.1\ \mu$m between the sample and voltage probes (see figure 7), required to reduce the reduction effect makes reliable electrical contacts hardly achievable. Even so, simultaneous measurements at the two pairs of adjacent resistance probes give us additional insight into the domain wall resistance.

For the type (2) samples, the field dependence of the MR associated with the rotation (gradual decrease) or the switching (sudden jumps) has not been found on the 0.1 μm width wire in the longitudinal geometry ($\boldsymbol{H} \parallel$ wire axis). The resistance of the 0.1 μm width wires keeps decreasing almost linearly with increasing field (not shown); this observation was common to all the wires and is probably the ordinary forced MR. In the transverse geometry, for the field perpendicular to the film plane, the ordinary anisotropic MR of 3.7, 3.5 and 1.8%, tending to saturate at around 10 kOe, has been observed at 4.2, 77 K and RT, respectively, with a minor dependence on w_d. The only influence of the reduced width on the transverse MR is the decrease of the saturation field at RT. Low-field measurements for $\boldsymbol{H} \parallel$ wire axis have been made intensively on samples with $w_d = 0.5\ \mu$m; these are reported below.

Figure 5 shows two typical examples of the field dependence of the MR for the samples A and B with $w_d = 0.5\ \mu$m at 4.2 K. The main difference between the data for the two samples

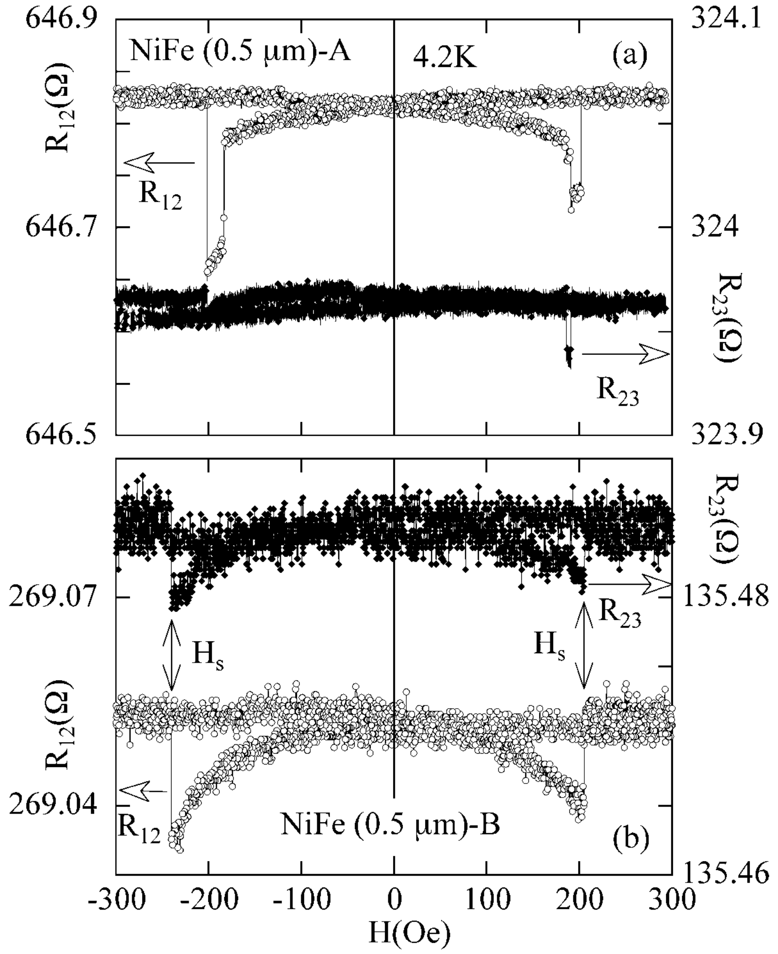

Figure 5. Comparison of the MR on two 0.5 μm NiFe wires, A and B, of type (2).

is as regards fine structures near the sudden jumps in R_{ij}. The difference may be ascribed to some slight difference between the voltage probes or in wire quality. For a same sample under the same conditions, the basic features are reproducible. Most of the MR curves measured for the wide samples ($w_d > 0.3$ μm) are classified into these two types.

Firstly, we discuss the MR curves without the fine structures, namely those for sample B, in figure 5(b). Both R_{12} and R_{23} show a gradual decrease with increasing (decreasing) field starting near $H = 0$, which suggests a gradual rotation of the magnetization over a wide area—extending over the areas SA$_{12}$ and SA$_{23}$. At the switching fields H_S, both R_{12} and R_{23} exhibit sudden jumps to the high-field values, above which the magnetization becomes parallel to $\boldsymbol{H}$. H_S, which is near 200 Oe at 4.2 K, slightly depends on the sample and the field polarity. For the sample B, both R_{12} and R_{23} monotonically decrease up to the switching fields $H_{S+} = 205$ Oe and $H_{S+} = -240$ Oe. Assuming a homogeneous rotation over the area SA$_{12}$, the rotation angle across the jump is estimated from R_{12} to be 1.3° and 0.95° for the negative and positive field directions, respectively. At 77 K, the switching fields decrease to $H_{S+} = 155$ and -165 Oe, respectively, as expected from a decrease in the effective pinning potential caused by the thermal activation. The different changes in R_{12} (ΔR_{12}) and R_{23} (ΔR_{12}) below H_S

imply that the average angles of the magnetization rotation are different for SA_{12} and SA_{23}. In a micromagnetic simulation of ferromagnetic wires neglecting crystal anisotropy, Ferre *et al* [4] found two critical fields in a hysteresis behaviour for large diameters; at the nucleation field H_n the magnetization starts to deviate from saturation and at the switching field H_s an irreversible magnetization jump occurs. In contrast, for very thin bars, the domain nucleation avalanche continues until the entire magnetization of the wire has been reversed. In our 0.5 μm wide NiFe wire, classified as a large-width wire, the nucleation starts from both ends at low fields, and brings about the rotation of the magnetization into the sample areas SA_{12} and SA_{23} from both ends. The nucleation depends sensitively on the conditions of the shapes of the sample ends [4, 17] and the field direction, which leads to the difference in the $\Delta R_{12}(H)$ and $\Delta R_{23}(H)$ at low fields found in figure 5(b). The switching, mainly caused by the depinning of the domain wall nucleated at both edges [4], is possibly related to the misalignment of the field direction, estimated to be $<1°$ in the present experiment. We have tested the angular dependence of the MR curve within 10° around the longitudinal geometry. However, the change in H_s is minor (<5%), while a noticeable feature was found on the appearance of the jump; R_{23} only occasionally exhibits the jump, in contrast to R_{12} exhibiting a jump all the time. The latter feature implies that the nucleation first takes place at the edge of the Pr_1 side, while the magnetization in the central part of the sample remains oriented parallel to the wire axis. On further increasing the field, the magnetization rotation (the nucleated vortex) spreads into the SA_1 area up to H_S, where the magnetization of the wire reverses completely through domain wall nucleation and propagation mechanisms, in qualitative agreement with the simulation reported in [4]. The coincidence of H_S for R_{12} and R_{23} (whenever the jumps are observed in both R_{12} and R_{23}) is regarded as of major importance. It suggests that a domain wall introduced from one of the edges always passes through all the voltage leads simultaneously (in the magnetic field).

For sample A, the resistance change below ~200 Oe in R_{12} is very different from that in R_{23}, although both exhibit multi-step resistance jumps (figure 5(a)). Such multi-step jumps have already been reported [3, 10] and discussed in connection with the macroscopic quantum tunnelling of a domain wall, although the origin is not yet definitively established. In order to allow a more precise comparison, expanded plots near the resistance jumps are shown in figure 6.

For the negative field direction, only R_{12} decreases sharply with decreasing H, while at H'_c both R_{12} and R_{23} increases to the high-field-state values. In the present case, the resistance change may be simply ascribed to the anisotropic MR associated with the tilting of the magnetization, since no GMR effect can be expected in a single-layered NiFe wire. For the transverse voltage measurement, we already know that such tilting can be expected near domain walls. From these facts, such complex resistance steps are explicable on the basis of a domain (wall) introduced between the leads Pr_1 and Pr_2. Once a domain (wall) is introduced, a continuous decrease of R_{12} takes place for $H < H'_a$, and finally at H'_c the domain wall escapes from the pinning potential. As H'_c is approached, the tilted area (effective wall width: δ_w) of the local magnetization reaches the area SA_{23}, which is reflected in the continuous but apparent decrease of R_{23} near H'_c.

For the positive field direction, the simultaneous step-like decrease of R_{12} and that of R_{23} at H_a imply that the width of the area exhibiting discontinuous rotation of the magnetization ($\sim\delta_w$) extends over the areas SA_{12} and SA_{23}. On further increasing the field, R_{12} (R_{23}) shows a step-like decrease (increase) at H_b, which suggests that the domain (the tilted area of magnetization) left the area SA_{23} and was trapped in the area SA_{12}, as shown schematically in figure 7. These facts imply that even a non-magnetic voltage lead can work as a pinning potential for domain walls in the areas CA_i, which could be expected from the magnetostrictive

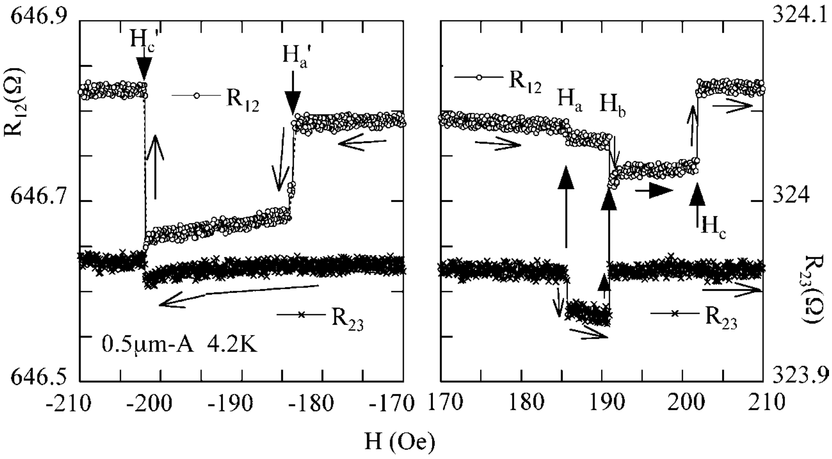

Figure 6. Expanded views of the resistance in figure 5(a) near the jumps (the wire sample A of type (2)).

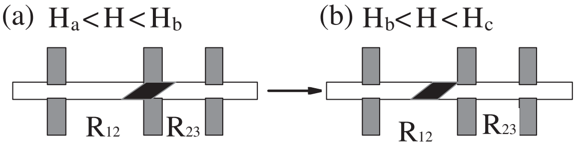

Figure 7. Schematic figures representing the motion of domains (more generally the rotated magnetization area) near the field H_b in figure 6.

effect of Cu leads on NiFe. This may be related to the fact that such multiple-step jumps were observed for sample A with a smaller cross-section in comparison with the Cu leads.

Of course, the field dependence shown in figure 6(b) could be explained in another way—namely, if two domain walls simultaneously nucleated at the two sample edges and became trapped within SA_{12} and SA_{23} independently for $H_a < H < H_b$, and at H_b the one trapped in SA_{23} moved to and disappeared in SA_{12} by combining with the other domain wall trapped in SA_{12}. However, it should be noted that the latter would only occur quite fortuitously.

In summary, the simultaneous measurement of the voltages at multiple pairs of the resistance and transverse voltage probes can be a useful tool for detecting a local magnetization. For ferromagnetic wires with magnetic voltage probes, we obtained clear evidence of the continuous rotation of the magnetization in the local area. This rotation should provide some of the negative domain wall contribution reported in recent papers. Even for the wires with non-magnetic voltage probes, we are unable to disregard the contributions from such rotation of the magnetization in the area where the sample and voltage leads cross.

Acknowledgments

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