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Velocity Measurements of Magnetic Domain Wall by Local Hall Effect

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1. Introduction

One of the most attractive devices that have been proposed or demonstrated in spintronics [1] is a logic device with manipulation of the spin degree of freedom. Logic devices are generally operated utilizing charge in semiconductors. However, logical NOT operations were recently demonstrated with ferromagnetic metals that are used for nonvolatile memory devices [2]. A key to making logic devices using ferromagnetic materials is controlling the magnetic domain wall (MDW), therefore intensive investigations of basic properties such as the velocity, v, [3] or the mass [4] of the MDW have been carried out. In this work, a method to measure v of the MDW using local Hall effect (LHE) are demonstrated. This method has the advantages of (1) millivolt large signal, (2) independency of the shapes of micro-magnets, and (3) flexibility of changing temperature.

2. Sample Fabrication and Experimental Method

By the molecular-organic-chemical-vapor-deposition method, a sample that consists of an 2.5-nm-thick InP layer between a two-dimensional electron gas (2DEG) channel layer of InGaAs and a barrier layer of InAlAs was grown. The InP layer was inserted for the purpose of selective etching, which makes it possible to reduce the distance between the micro-magnet and the 2DEG channel layer of InGaAs. From the Hall effect measurements at 300 K, the carrier concentration and the electron mobility were obtained to be 1.4×10^{12} cm^{-2} and 8600 cm^2/Vs, respectively. By the electron beam lithography (EBL) and the electron cyclotron resonance dry etching, a Hall bar was fabricated. After the removal of the barrier layer of InAlAs using the selective wet etching, a 60-nm-thick rectangular $Ni_{80}Fe_{20}$ micro-magnet was made on the Hall bar and was deposited on the top of InP layer by the EBL and the lift-off technique. The width, w, of the micro-magnet was designed to be 200 nm and the length, L, were varied between 5 and 160 μm. The micro-magnet was covered with a 10-nm-thick Au layer for preventing the oxidation of the $Ni_{80}Fe_{20}$ layer. Figures 2 (a) and (b) show an optical microscope image of the sample with L = 10 μm and a schematic cross view of the sample, respectively. In this study, an external magnetic field was applied parallel to the direction of L. By the LHE, the fringing magnetic fields from the both edges of the micro-magnet were measured with the V_H1 and the V_H2 probes. The local Hall voltage (LHV), V_H#, is defined as the voltages between V_H#+ and V_H#- probes, here # = 1 or 2. The LHV at 77 K was monitored with a sampling rate of 2.5 GS/s, that is a time resolution of 400 ps, using a real-time oscilloscope.

In the case of w < 0.5 μm [5], magnetization reversal processes of $Ni_{80}Fe_{20}$ micro-magnets proceed as follows: (1) nucleation of the only one MDW on one side of the micro-magnet, (2) displacement of the MDW to the other side, and (3) annihilation of the MDW on the other side. Figures 2 (a) and (b) show a schematic cross view of the sample around the coercive force, H_c, and the LHV as a function of time, T, respectively. In Fig. 2, the top two figures at $T = t_0$ represent situations before the nucleation of the MDW. The middle two graphs at $T = t_1$ and the bottom two graphs at $T = t_2$ show situations during the displacement of MDW and those after the annihilation of the MDW, respectively. At $T = t_1$, the MDW is located at the center of the micro-magnet. The fringing magnetic fields from the right and the left sides

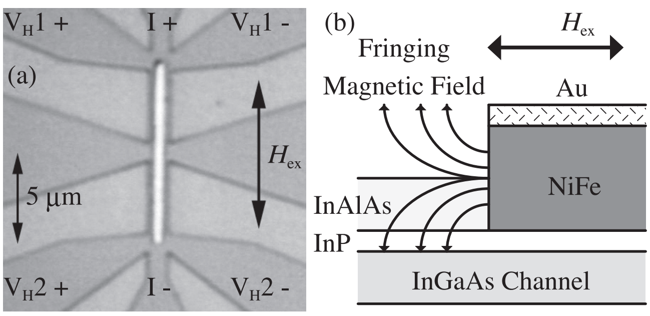

Fig. 1 (a) An optical microscope image of the sample with L = 10 μm. (b) A schematic cross view of the sample. The fringing magnetic field can be detected by the LHE.

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of the micro-magnet are measured with the V_H1 and the V_H2 probes. The nucleation and the annihilation of the MDW on the sides of the micro-magnet change the directions of the fringing magnetic field, which results in the change of the sign of the LHVs. In Fig. 2, the magnetization reversal process in which the MDW displaces from the side of the V_H1 probe to that of the V_H2 probe is represented. When the MDW nucleates on the side of the V_H1 probe of the micro-magnet, V_H1 changes its sign . The MDW annihilates on the side of the V_H2 probe of the micro-magnet after the MDW propagates from the side of the V_H1 probe to that of the V_H2 probe, which results in the change of the sign of V_H2. The

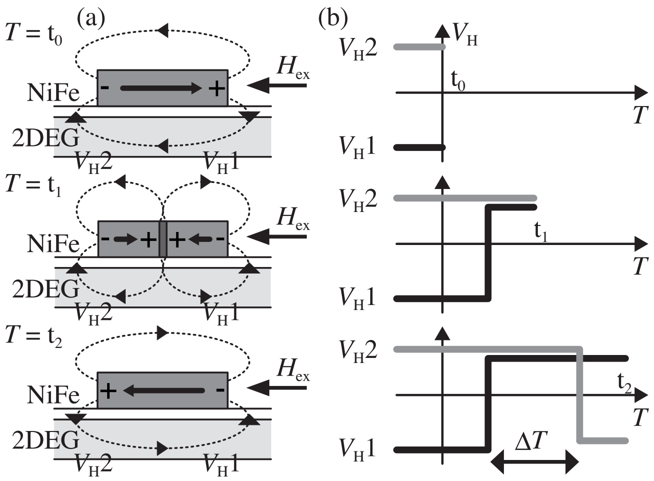

Fig. 2 (a) A schematic cross view of the sample. (b) the time dependence of V_H1 and V_H2. The situations at $T = t_0$, t_1, and t_2 are before the nucleation of the MDW, during the displacement of the MDW, and after the annihilation of the MDW, respectively. At $T = t_1$, the MDW exsists at the center of the micro-magnet.

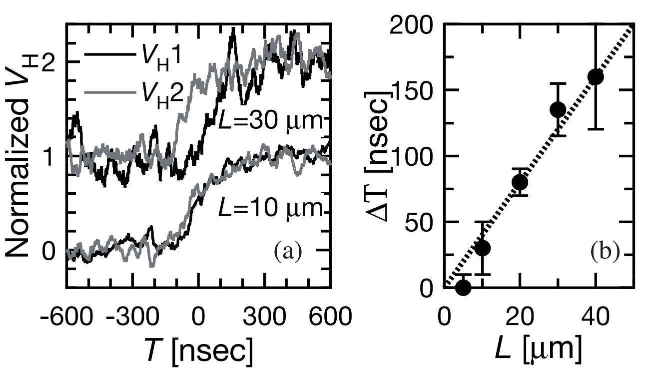

Fig. 3 (a) The time dependence of the normalized and averaged LHVs of the samples with L = 10 and 30 μm at 77 K. The black and the gray curves represent V_H1 and V_H2, respectively. In both cases, ΔT is clearly observed. (b) The length dependence of ΔT of the samples with various L. With increasing L, ΔT increases. The dotted line gives a velocity of 200 m/s of the MDW.

time difference, ΔT, between moments when V_H1 and V_H2 change their signs is considered to be a period in which the MDW displaces through the micro-magnet. From the relation of $v = L/\Delta T$, v of the MDW is obtained.

3. Experimental Results and Discussion

Figure 3(a) shows the time dependence of the normalized and averaged LHVs detected with the V_H1 and the V_H2 probes on the samples with L = 10 and 30 μm at 77 K. The black and the gray curves represent V_H1 and V_H2, respectively. The changes of the LHVs are normalized to be unity and the normalized LHVs of the sample with L = 30 μm are shifted along the y axis for the ease of comparison. Before the normalization, V_H1 increased (or decreased) and V_H2 decreased (or increased) around H_c as explained in Fig 2. The changes of the LHVs of the samples with L = 10 and 30 μm were approximately 0.5 and 0.3 mV, respectively. This is because applied current that flows between I+ and I- probes in Fig. 1(a) was different. Noise voltages were over 1.5 mV peak to peak, therefore the normalized Hall voltages were averaged over a period of 40 nS, that is 101 points. After these procedures, ΔT was clearly observed in several samples with various L. In Fig. 3(a), ΔT of the samples of L = 10 and 30 μm are approximately 30 and 135 ns, respectively. Figure 3(b) shows ΔT of the samples with various L as a function of L. With increasing L, ΔT increases. A period for the MDW displacement through the micro-magnet is considered to be ΔT. The dotted line in Fig. 3(b) gives v = 200 m/s. Therefore, v of the MDW of approximately 200 m/s on the $Ni_{80}Fe_{20}$ micro-magnet can be obtained. This determined v is similar to that in Ref. 3. These results indicates the method of measuring v of the MDW by the LHE is powerful method for investigating the dynamics of the MDW.

4. Conclusion

The velocity of MDW of approximately 200 m/s on the $Ni_{80}Fe_{20}$ micro-magnet has been obtained from measurements of the fringing-field-induced LHV. This method has the advantages of (1) millivolt large signal, (2) independency of the shapes of micro-magnets, and (3) flexibility of changing temperature.

Reference

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