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E-2-3

Characterization of Ferromagnetic Electrodes for Spin Injection into Semiconductor Using Local Hall Effect

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1. Introduction

Ferromagnetic metal (FM) /Semiconductor (SM) hybrid structures combine the field of magnetism and that of semiconductor physics. One of the applications using the FM/SM junctions is a spin-injection into SM. A large number of efforts are still in progress to realize the injection of a spin-polarized current into SM channel. In order to detect a spin-polarized signal in FM/SM/FM junctions, parallel and anti-parallel magnetization configuration between the two FM electrodes is essential. Therefore, it is important to characterize the magnetic properties of the FM electrodes for spin-injection experiment. A recent paper predicts that for FM/SM junctions iron (Fe) electrodes should provide a higher degree of current polarization than NiFe electrodes [1, 2]. We have investigated the width dependence of the coercive field (Hc) for NiFe and Fe micro-magnets, using fringing field induced local Hall effect (LHE) [3, 4].

2. Fabrication of the Samples

The layer structure for the samples is shown in Table I. InAlAs and InGaAs layers were grown by MOCVD on semi-insulating InP substrate on top of 200 nm InAlAs buffer layer. All InAlAs layers are lattice matched to InP, and $In_{0.8}Ga_{0.2}As$ is a channel layer. An AlAs layer is used for a good Schottkey property and an InP layer is inserted in the Schottkey layers for the purpose of selective etching used in the later processes.

The Hall cross was defined by electron beam lithography (EBL) and electron cyclotron resonance (ECR) dry etching. NiFe and Fe FM micro-magnets are made, using EBL in combination with lift-off technique. FM electrodes were deposited on InP after the removal of the i-InAlAs and i-AlAs Schottkey layers using a chemical etching. A scanning electron microscope (SEM) picture of the fabricated micro-magnet is shown in Fig. 1. A typical length of the micro-magnets on the Hall bar is about 5 μm. The widths are designed to be from 0.2 μm to more than 1 μm.

Table I Semiconductor layer structure

Material	Thichness	
i-InAlAs	5 nm	Barrier
i-AlAs	1.5 nm	Barrier
i-InAlAs	20 nm	Barrier
i-InP	5 nm	Etch Stop
i-InAlAs	2.5 nm	Barrier
$i-In_{0.8}Ga_{0.2}As$	15 nm	Channel
i-InAlAs	6 nm	Spacer
n-InAlAs	6 nm	$4x\ 10^{18}\ cm^{-3}$

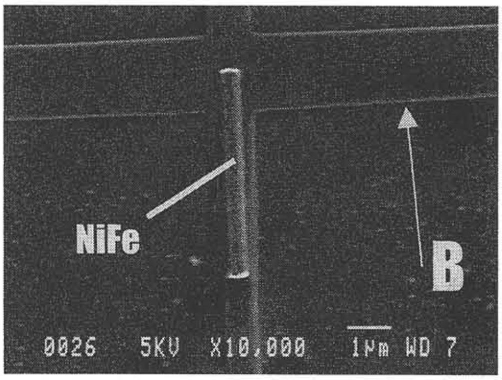


Fig. 1 A SEM picture of NiFe micro-magnet on top of InGaAs channel Hall bar.

3. Results and Discussion

We utilize the LHE produced by fringing fields near the edge of the FM for determining the values of Hc [4]. In this method, the edge of FM electrode has to be placed sufficiently closed to the Hall cross so that the induced fringing field is reflected in the measured Hall voltage. The LHE is suitable for two-dimensional electron gas (2DEG) structures due to the relatively low carrier concentration which enhances Hall effects. However, the information is only from the edge of FM electrodes. A magnetic force microscopy (MFM) opens the possibility for observing domain structures in FM electrodes.

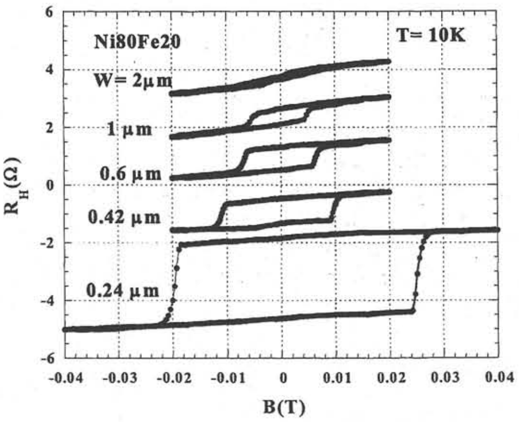


Fig. 2 Hysteresis loops of the local Hall resistance for various sizes of the NiFe micro-magnets. The measured Hall resistances are shifted vertically for clarity.

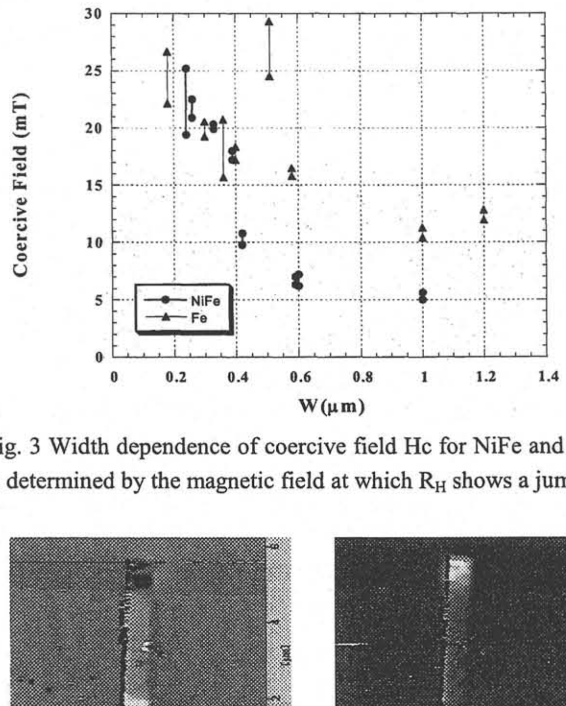
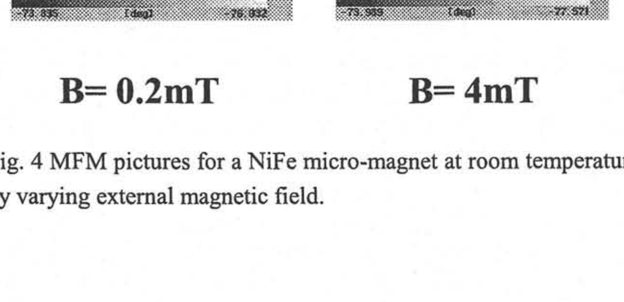


Fig. 3 Width dependence of coercive field Hc for NiFe and Fe. Hc is determined by the magnetic field at which R_H shows a jump.



B= 0.2mT **B= 4mT**

Fig. 4 MFM pictures for a NiFe micro-magnet at room temperature by varying external magnetic field.

Figure 2 shows the hysteresis loops in Hall resistance R_H observed for NiFe micro-magnets. Here the external magnetic field B was applied parallel to both the easy axis of FM micro-magnet and the 2DEG plane as shown in Fig. 1. The jumps in the Hall resistance are due to the rapid change of the fringing field of the magnets, and correspond to the coercive fields Hc. The Hc showed a strong width dependence, which is in good agreement with the earlier results [4]. Similar results were obtained for Fe magnets of width smaller than 0.4 μm as shown in Fig. 3. These results suggest that the coercive field in sub-micron magnetic electrodes are controlled by their shape anisotropies. Micro-magnets with widths smaller than 0.5 μm showed a sharp step in Hall resistance. However, broadened hysteresis loops were obtained for wider micro-magnets.

We also investigated the magnetic domain structures using MFM as a function of a magnetic field. In narrow electrodes (w= 0.6 μm) as shown in Fig. 4, magnetic poles (dark and bright spots) appeared only at the edges except near the coercive field. In most of magnetic field regime, MFM pictures look a single domain. However, a wider electrode (w= 2 μm) shows multi-domain structure. The switching of magnetization seems to be sharper for smaller widths. Although the LHE reflects the information only from the edge of FM micro-magnets, the rapid jump in R_H seems to imply the sharp magnetization switching.

4. Conclusions

We have investigated the width dependence of Hc for NiFe and Fe micro-magnets, using fringing field induced LHE and MFM. For spin-injection experiments, at least one of the FM electrodes in FM/SM/FM junctions should have a width smaller than 0.6 μm in order to get a reasonable field range where the magnetization of FM electrodes is anti-parallel.

Acknowledgments

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