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Magnetic Properties of a Ferromagnet-Semiconductor Hybrid System: Towards Spintronics

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Until very recently, the spin of the electron was ignored in mainstream electronics. Indeed, there are many ways that the spin of the electron can be utilized to add new capabilities and new functionalities [1]. The understanding of this enormous application potentiality has given birth to an emerging research field named as *Spintronics* (also *magnetoelectronics*). The study of the hybrid ferromagnet-semiconductor structure is one of the hottest topics in magnetism today. This offers several unique advantages for spintronic applications, and fringe field devices from promising category, including magnetic sensors, magnetic storage media, and devices based on spin-polarized carriers (spin FET). When Fert's group in France discovered giant magnetoresistance (GMR) in 1988, the first steps on the road to the utilization of the spin degree of freedom of the electron were taken. It took about 10 years for the fruits of this discovery to ripen with the appearance of very high density disk storage, first announced by IBM and quickly followed by many other manufacturers in the US and Japan. Today, thousands of people are working in this promising field for new functionalities, and research on ferromagnetic-semiconductor layered structure is in the center feature of this emerging field.

In order to experimentally study the ferromagnetic thin films, three types of samples, namely, Ni/GaAs(001) and Ni/Si(001) bilayer, Si/Ni/GaAs(001) trilayer, and Ni/Si/Ni/GaAs(001) multilayer were studied. The Ni films deposited onto the commercial GaAs (001) and Si (001) substrates were named as A-type. On the other hand, before depositing the B-type Ni films, 100 nm thick GaAs (001) epilayer was grown onto the commercial GaAs (001) substrate and the Ni was deposited onto this.

The work has been started with the fundamental magnetic study of thin Ni films deposited onto GaAs (001) and Si (001) substrates in connection with an anomalous effect (Fig. 1) observed in the early stage of my work. The magnetic moment of Ni film while deposited on GaAs (001) substrate was largely reduced at low temperature in the vicinity of the hysteresis, which did not happen in Ni film deposited onto Si (001) substrate. The saturation moment in both cases was fairly equal and was approximately 10~13 % less than that of the bulk value. The remanent moment of the Ni/GaAs decreased with the decrease of temperature and at 1.8 K the ratio M_r/M_s became as low as 0.48 comparing the value 0.81 at 300 K. The Ni/GaAs took large (> 0.25 T) field to saturate in parallel field. In addition to this, the coercivity of Ni/GaAs was found to be 37.8 mT, which was five times larger than that of the Ni/Si at 1.8 K. Both the A-type and B-type Ni/GaAs samples exhibited these anomalous behaviors in parallel field and at low temperatures. In order to understand the origin of the anomaly appeared in Ni/GaAs, different experiments were performed. These included rotational magnetization measurement, FMR (ferromagnetic resonance), transport properties, anisotropy study,

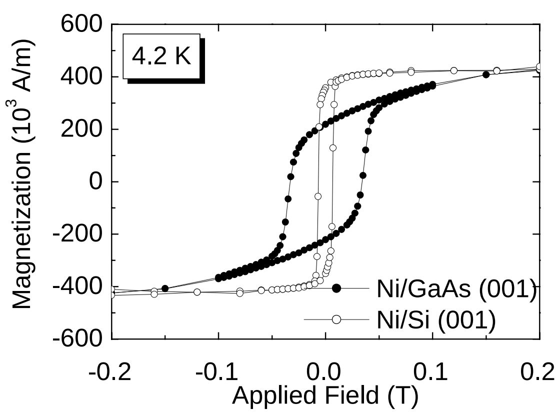

Fig. 1 Hysteresis curves of Ni/GaAs (001) and Ni/Si (001) measured at 4.2 K.

roughness study by AFM (atomic force microscopy) and domain study by MFM (magnetic force microscopy). Firstly, it was speculated that an antiferromagnetic type interaction between Ni and GaAs was playing the key role in connection to this anomaly, which gradually disappeared with the increase of temperature and Ni became magnetically isolated from the GaAs. It was primarily speculated that that an antiferromagnetic like magnetic interaction between the Ni and GaAs (001) was playing key role to reduce the remanent moment.

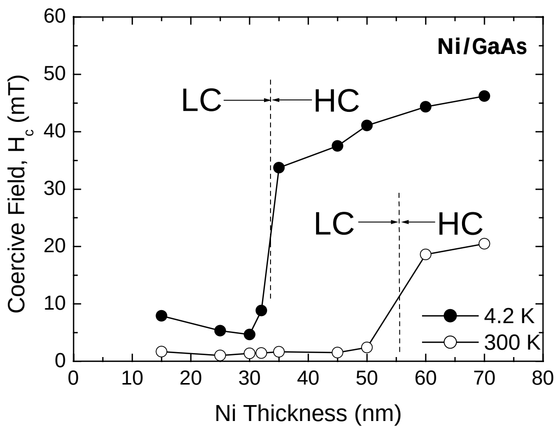

Fig. 2 Variation of coercive field with thicknesses of Ni film deposited onto GaAs (001)

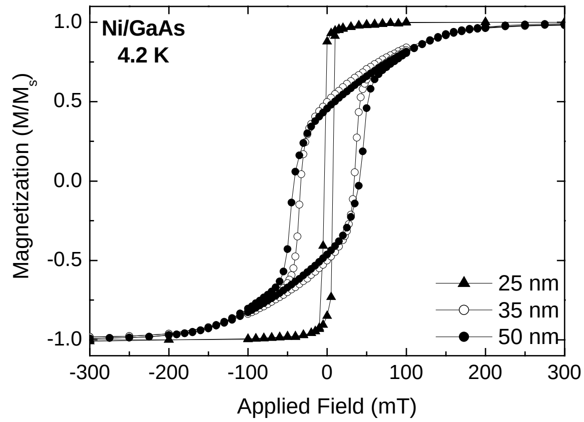

Fig. 3 Field dependent magnetization (M–H) at 4.2 K of 25, 35 and 50 nm Ni film in a normalized scale.

Therefore, identical Ni films having various (15 ~ 70 nm) thicknesses were prepared and the magnetization processes were investigated in similar fashion. Interestingly, the A-type Ni films having thickness below 32 nm did not come up with the anomalous effect but the films having thicknesses greater than that exhibited the anomalous effect. The thickness 32 nm appeared as a threshold thickness giving two distinct regimes (Fig. 2). The hysteresis of each regime was identical. The reduction of the squareness and the enhancement of the coercivity were always occurred together (Fig. 3). Since the thinner films were free from the anomalous effect, the possibility of the speculated interaction was surely rejected. However, the magnetization data and the FMR study revealed that the magnetic anisotropy of this Ni film varied with temperature. This was quite capable to explain the anomalous effect. The roughness studied by the AFM had no major role on this effect although the domain study went in vain because of a technical limitation. Apart from this, thin (≤12nm) B-type Ni films on the GaAs (001) showed perpendicular magnetic anisotropy (Fig. 4). The anisotropy became in-plane with the increase (≥ 15nm) of the Ni thickness.

Changes of thickness of the Ni film dramatically changed the hysteresis properties, particularly, the coercivity. These facts led a possibility of having an antiparallel spin state in a multilayer, which would be essentially a combination of these materials. An achievement of this special ferromagnet-semiconductor hybrid structure having antiparallel spin state would lead the GMR phenomenon. Expecting this phenomenon, I have implemented Ni/Si/Ni/GaAs multilayer. The magnetization measured at 1.8 K (Fig. 5) confirmed the presence of the expected antiparallel spin state in the multilayer. Since the magnetization reversal occurred in two phases, the multilayer allowed achieving an antiparallel spin state in it. The top Ni layer has low coercivity because of the underneath Si layer. On the other hand, the sandwiched Ni layer has high coercivity because of the influence of the underneath GaAs substrate. This special spin state was confirmed by the magnetization measurement as well as transport measurement. The antiparallel spin state disappeared over 250 K. The two Ni layers having antiparallel spin state and separated by a semiconductor (Si) layer was promising for giant magnetoresistance. However, such an effect needed very thin spacer layer. The Si spacer layer thickness of this multilayer was not thin enough.

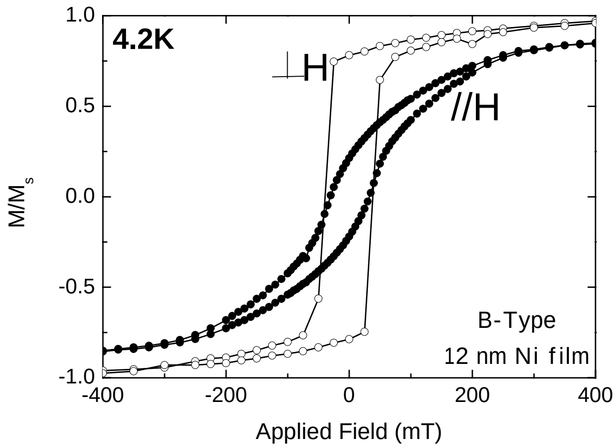

Fig. 4 Magnetization process of the 12 nm B-type Ni/GaAs in parallel and perpendicular magnetic field and at 4.2 .

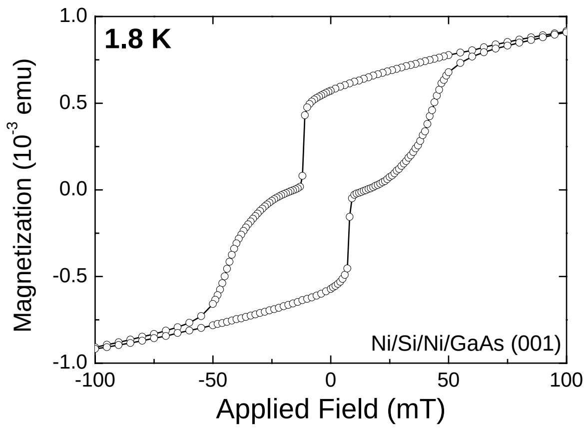

Fig. 5 Hysteresis curve of the Ni(20nm)/Si(25nm)/Ni(50nm)/GaAs multilayer measured at 1.8 K.

Apart from the application potential this study revealed couple of interesting problem, which would be worth to study basic physics in this multilayer. Firstly, the bottom Ni layer had contacts with both GaAs and Si, but it was affected only by the GaAs but the Si had no effect on it. This was confirmed by investigating a trilayer Si/Ni/GaAs. Variation of the Ni thickness exactly followed the Ni/GaAs bilayer characteristics, showing the two coercive field regimes. Secondly, the Schottky barrier height of the Ni/Si/Ni/GaAs multilayer was found to be much less than that of the Ni/GaAs bilayer. Besides the application potential, never the less this multilayer opened several basic problems to be solved. The transport measurement of this multilayer in CPP configuration is not so simple because of the presence of Schottky barrier. However, the challenge is to find a new technique to overcome the problem. The GaAs substrate used here was doped having a carrier concentration of $10^{24}/m^3$. It has been recently reported [2] by a Cambridge group that the change of carrier concentration of GaAs reduced the barrier height of the Ni/GaAs. Thus, the multilayer could be made with highly doped GaAs to perform the transport measurement without much influence of the Schottky barrier. This change of carrier concentration will no longer change the magnetic properties of Ni films, which is already verified in my experiment.

In general, basic research is the most important and initial step in implementing new devices. As it is already mentioned that spintronics devices based on the hybrid ferromagnet-semiconductor structure is an emerging field with huge potentiality, the basic research in this field is equally important. From this point of view, my research is hoped to contribute towards the development of spintronics devices.