F-8-1(Invited)

Extended Abstracts of the 2010 International Conference on Solid State Devices and Materials, Tokyo, 2010, pp1132-1133

Magnetic anisotropy of GaMnAs and its application for multi-valued memory device

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1. Introduction

GaMnAs ferromagnetic semiconductors have received a great deal of attention due to the possibility of spintronic applications, in which both the charge and spin properties of the electron are utilized in a single device.[1] A magnetic memory device, in which information is stored via the direction of magnetization, maybe the most practical application for the ferromagnetic GaMnAs semiconductors and, thus, the control of magnetization in the material is of crucial importance for designing the device structure. In this context, the magnetic anisotropy which determines the direction of easy magnetization must be precisely investigated for a given material system..

We present investigation of interesting magnetic anisotropy properties of GaMnAs film via magneto-transport experiments. We also report the realization of four resistance states by utilizing multi-domain structure of GaMnAs film as well as by growing magnetic films on vicinal GaAs (001) substrate. Furthermore, we demonstrate such achievement based on GaMnAs film can extend to the ferromagnetic metal, such as Fe film, thus bring the idea of a quaternary memory device much closer to practical implementation.

2. Experiments

The GaMnAs films were grown on standard (001) and on vicinal GaAs substrates by molecular Beam epitaxy (MBE). Prior to growth of GaMnAs layer, the GaAs buffer layers was grown at 600°C using the optimized growth condition. The substrate temperature was lowered to 250 °C for the growth of GaMnAs films.

For transport measurements, the magnetic films were patterned into 300 μm×1500 μm Hall bars by photolithography and by chemical wet etching with long dimension along [110]. Measurements of the Hall resistance, R_{xy}, were performed using a sample holder such that a magnetic field could be applied in the plane of the sample at an arbitrary azimuthal angle.

1. Results and discussion

The magnetic anisotropy of ferromagnetic film can be determined by Hall measurements together with magnetic free energy based on the Stoner-Wohlfarth model. [2] In the case of magnetic fielm with in-plane magnetic easy axes, such as GaMnAs grown on GaAs substrate, the planar Hall resistance (PHR) contains information about the direction of magnetization as given by [3]

$$R_{xy} = \frac{k}{t} M^2 \sin 2\varphi \qquad (1)$$

where the k is a constant related to anisotropic magneto-resistance effect; M and t are the magnetization and the thickness of the film, respectively. The magnetic free energy, which determines the direction of magnetization within the plane, is given by [4]

$$F = M[\frac{H_{4\|}}{8}\cos^2 2\varphi - \frac{H_{u\|}}{2}\sin^2\varphi - H_{4\|}/4 - H\cos(\varphi - \varphi_H)] \qquad (2)$$

where $H_{4\|}$ and $H_{u\|}$ are the in-plane four-fold symmetric (cubic) anisotropy and the in-plane two-fold (uniaxial) anisotropy, respectively. φ is angle between magnetization direction in the (001) plane measure from the [110] crystallographic direction .The Eqs. (1) and (2) provides an opportunity for the experimental investigation of in-plane magnetic anisotropy fields of the ferromagnetic system using the angle dependence of the PHR measurements. Since the direction of magnetization will follow the position of magnetic energy minimum, the angle dependence of PHR data can be fitted with the formula obtained from the free energy minimum conditions by treating the magnetic anisotropy fields $H_{4\|}$ and $H_{u\|}$ as fitting parameters.[4]

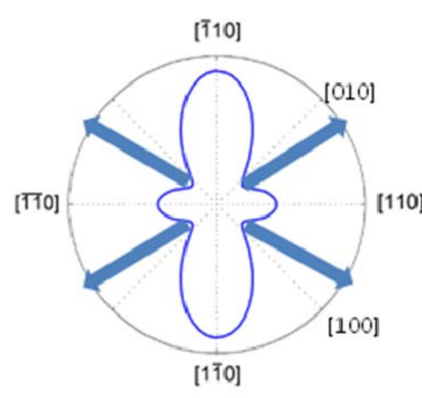

Fig.1 Magnetic free energy density diagram at zero field. The diagram clear shows four minima near the <100> direction indicating presence four magnetic easy axes at the directions marked by arrows. The effect of the uniaxail anisotropy is appear as different energy barrier between the [110] and the [-110] directions.

The magnetic anisotropy fields obtained from the fitting allow one to construct free energy diagram as shown in Fig.1, which clearly shows four energy minima near the <100> directions indicating presence of four in-plane magnetic easy axes in the film.

The presence of four in-plane magnetic easy axes in the GaMnAs film provides very interesting magnetization reversal process, when it is monitored by the planar Hall effect. Figure 2 shows the Hall resistance, R_{xy}, measured on GaMnAs film with applied magnetic field at φ_H = 80° relative to the current I. The upper panel of Fig. 2 shows staggered asymmetric hysteresis, which contains four plateaus in the loop. In the minor scan shown in the lower panel of Fig. 2 clearly shows that the four distinct PHR states are obtained at zero field. This phenomenon is originated from the multi-domain structures that formed during the transition of magnetization. The detail explanation on this phenomenon is well described in the Ref. [3].

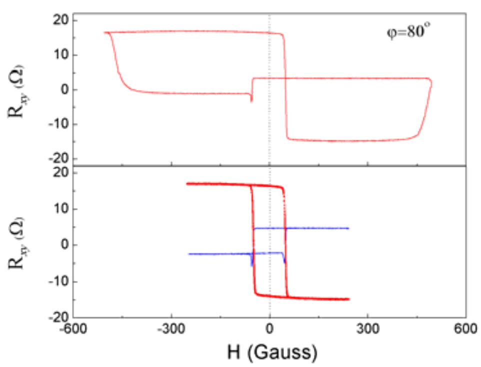

Fig. 2. (upper) A symmetric PHR loop obtained with φ = 80°, showing the four plateaus. (lower) Four distinct PHR values are obtained at zero field.

The similar asymmetric PHR loop can be obtained, when the magnetic film with four in-plane easy axes, such as GaMnAs and Fe, is grown on the vicinal GaAs substrate. Even though the PHR experiment result is almost identical for the two material system, we present results obtained from Fe film since the phenomenon was observed at room temperature for the Fe film, which is more realistic for the practical devices. Figure 3 shows the Hall resistance, R_{xy}, measured on four Fe films, which are grown on different vicinal substrates, with four in-plane magnetic easy axes and with applied magnetic field at φ_H = 70° relative to the current flow.

Interestingly, we have observed an unexpected asymmetry, which increases with tilted angle of substrate, in magnetic field dependence of the Hall resistance, R_{xy}. Specifically, the values of the Hall resistance plateaus, which correspond to the stable magnetization states in the process of magnetization reversal, are conspicuously unequal in the film grown on vicinal substrate. This asymmetric hysteresis displaying four distinct Hall resistance values is originated from the combined contributions of the anomalous Hall effect(AHE) and the planar Hall effect(PHE). This behavior can be understood if magnetization **M** is confined by magnetocrystalline anisotropy to one of the easy axes in the (001) crystal plane instead of layer plane.

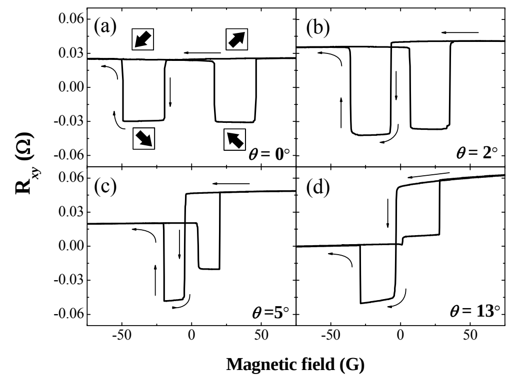

Fig. 3. Hall resistances, R_{xy}, measured in-plane magnetic fields at φ_H = 70° relative to the current I in ferromagnetic Fe films grown on (a) non-vicinal [θ = 0°] and (b, c, and d) vicinal [θ = 2°, 5°, 13°] GaAs substrates at room temperature. PHE hysteresis loops show magnetization reversals.

4. Conclusion

We have investigated magnetic anisotropy properties of GaMnAs film by using magneto-transport measurements. The precise values of anisotropy fields are obtained from the angle dependence measurement of PHE. The presence of four magnetic easy axes results in the asymmetric hysteresis loop of PHR containing four stable states when the returning field is set in the transition region. This was understood in terms of multi-domain formation. The asymmetric hysteresis loop of PHR was also obtained from the GaMnAs and Fe films grown on vicinal GaAs substrates. The phenomenon arises from the combination of anomalous and planar Hall effect because the magnetocrystalline anisotropy of the film confines the magnetization **M** to a preferred crystal plane rather than to the plane of the film. The nonzero component of **M** normal to the sample plane lifts degenerated resistance states, which results in four discrete resistances values. These asymmetric hysteresis loops of PHR obtained by forming the multi-domain structure and by growing on vicinal substrate provide a unique opportunity of realizing practical four-value memory devices.

Acknowledgment

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2009-0071795); by the Seoul R&DB Program (ST090777).

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