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Magnetic anisotropy in a ferromagnetic (Ga,Mn)Sb thin film

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ABSTRACT

We have grown a 5-nm-thick (Ga,Mn)Sb with Mn composition of 0.032, and investigated its magnetic properties and their electric-field dependence. The sample shows ferromagnetism below about 25 K, whose magnetic easy axis is perpendicular to plane. By utilizing a field-effect transistor structure, we show that the Curie temperature and magnetic anisotropy field can be controlled by the application of electric field.

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1. Introduction

III–V based magnetic semiconductors show hole-induced ferromagnetism, in which the exchange interaction among localized magnetic spins is mediated by itinerant holes [1,2]. According to the *p–d* Zener model, their magnetic anisotropy, which is one of the important magnetic properties, is determined by the combination of the *p–d* exchange and the spin–orbit interactions in valence band structure [2,3]. The model shows that the magnetic anisotropy direction can be controlled either in-plane or out-of-plane by changing hole concentration p, which was confirmed experimentally by changing p of (Ga,Mn)As by low-temperature annealing [4]. The control of the magnitude of perpendicular magnetic anisotropy of (Ga,Mn)As was also shown by changing p by the application of electric-field E_G by using field-effect transistor (FET) structure [5]. The control of magnetic anisotropy by electrical means is important not only to understand further the behavior of p-dependent anisotropy but also to demonstrate a new scheme of magnetization switching [5].

In this work, we have fabricated an FET with a (Ga,Mn)Sb channel and investigated their properties under E_G to see the material dependence of the effect of electric fields on (Ga,Mn)Sb. GaSb is a narrow gap semiconductor with a band gap of ~0.8 eV, and a magnetic semiconductor (Ga,Mn)Sb based on GaSb shows ferromagnetism at reduced temperatures below 25 K [6–8]. The observed ferromagnetism is brought about by the *p–d* exchange interaction [1,2,9]. It was shown that (Ga,Mn)Sb under tensile strain with ZnTe buffer layer has perpendicular magnetic easy axis, whereas that under compressive strain with GaSb buffer layer has in-plane easy axis [7,8]. This indicates that the easy axis direction is strain dependent as in the case of (Ga,Mn)As [10]. (Ga,Mn)Sb is always metallic, while (Ga,Mn)As is often insulating at low Mn composition and/or low hole concentration [11]. The difference is most probably due to the difference of Mn acceptor level; 16 meV for GaSb [12] is much shallower than 110 meV in GaAs [13].

2. Sample preparation

A 5-nm-thick $Ga_{0.968}Mn_{0.032}Sb$ layer has been grown through 4 nm GaSb/300 nm $Al_{0.8}Ga_{0.2}Sb$/10 nm AlSb buffer layer (from surface side) on a semi-insulating GaAs (0 0 1) substrate by low-temperature molecular beam epitaxy [6–8]. The growth temperature of (Ga,Mn)Sb is set to 230 °C to avoid the formation of MnSb second phase [6]. Reflection high energy electron diffraction shows a streaky (1 × 3) pattern during growth of (Ga,Mn)Sb. Mn composition x=0.032 is determined from the lattice constant a measured by X-ray diffraction for a thick (Ga,Mn)As layer, which is grown by using the same beam flux ratio of Mn/Ga as (Ga,Mn)Sb. A 300-nm-thick $Al_{0.8}Ga_{0.2}Sb$ (a=0.613 nm) buffer is inserted to relax the lattice strain, originating from the lattice mismatch between GaAs (a=0.565 nm) and GaSb (a=0.610 nm). Full relaxation of the $Al_{0.8}Ga_{0.2}Sb$ lattice constant is confirmed by asymmetric X-ray diffraction measurement. A thin (Ga,Mn)Sb layer on a fully relaxed $Al_{0.8}Ga_{0.2}Sb$ buffer layer is expected to be under ~0.4% of tensile strain, by assuming the Vegard's law and by using theoretically obtained a=0.617 nm for zinc-blende MnSb [14].

Samples were cleaved from the wafer for magnetization and transport measurements. For magnetization measurements, we

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use a sample with a size of $4\times4\ \mathrm{mm}^2$. The sample for transport measurements is processed into an FET with a 150 μm long and 30 μm wide channel along [− 1 1 0] orientation. The channel has a Hall-bar shape to detect its magnetic properties through the anomalous Hall effect [15,16]. In order to apply E_G to the channel, we deposit a 47-nm-thick ZrO_2 gate insulator at 150 °C by atomic layer deposition [17], and then form the topmost gate electrode of Au/Cr by lift-off. The value of dielectric constant κ of ZrO_2 is determined to be 23 by measuring device-size dependence of capacitance of Au/ZrO_2/Au capacitors [5,16,17].

3. Experimental results and discussion

Fig. 1 shows the temperature T dependence of the remanent magnetization M along the crystal orientation of in-plane [1 0 0], [1 1 0], [− 1 1 0], and perpendicular to plane [0 0 1]. The largest M along [0 0 1] indicates that the easy axis for magnetization is perpendicular to the plane, which is consistent with the direction expected from the p–d Zener model for (Ga,Mn)Sb with tensile strain of 0.4% and $p\sim xN_0$ (N_0: cation density). The magnitude of M || [0 0 1] of 30 mT at 5 K agrees well with the calculated spontaneous magnetization of 33 mT by $M=xN_0g\mu_BS$, indicating that the most of incorporated Mn participate in a ferromagnetic order, where $g=2$ is the Landé g factor, μ_B the Bohr magneton, and $S=\frac{5}{2}$ the Mn spin.

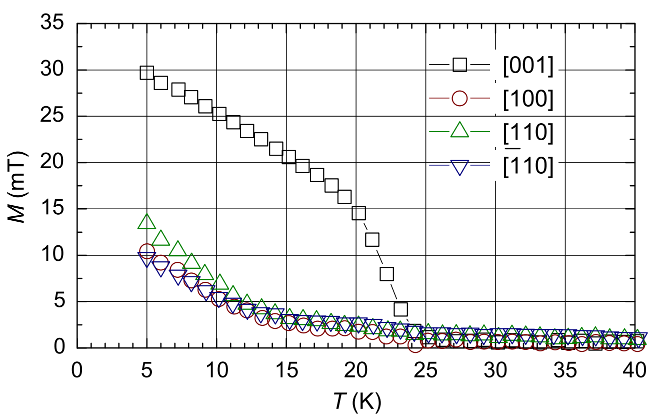

Fig. 1. Temperature T dependence of the remanent magnetization M for crystal orientation along perpendicular [0 0 1], and in-plane [1 0 0], [1 1 0], and [− 1 1 0].

Fig. 2 shows the magnetic field H dependence of the Hall resistance R_{Hall} for the FET; (a) the results at $E_G=0$ as a function of T and (b) at 6 K as a function of E_G. H is applied perpendicular to the device surface. For ferromagnetic materials, R_{Hall} is expressed as,

$$R_{\mathrm{Hall}}=(R_0/t)\mu_0H_\perp+(R_S/t)M_\perp, \tag{1}$$

where the first and second terms correspond to ordinary and anomalous Hall resistance, respectively, and R_0 is ordinary Hall coefficient, R_S anomalous Hall coefficient, and μ_0 permeability of vacuum, $t=5$ nm the thickness of the channel, and $H_\perp$ and $M_\perp$ the perpendicular components of H and M. At low T, a nonlinear dependence of R_{Hall} on H with small hysteresis indicates that the anomalous Hall resistance is dominant and that the channel is in the ferromagnetic state below 25 K. The sign of the anomalous Hall coefficient is negative and is consistent with previous reports [6–8], which is opposite to that of most of (Ga,Mn)As and (In,Mn)As layers [10,11,15,16]. At 300 K, at which the anomalous Hall effect becomes almost negligible, the sign of the Hall coefficient turns to positive, showing that the material is p-type. Thus, the application of negative (positive) E_G results in the increase (decrease) of p. Fig. 2(c) shows the E_G dependence of the sheet conductance G_{sheet} at 15 K, which shows that we can change 17% of G_{sheet} by the application of $|E_G|\leq3.8$ MV/cm. The effect of E_G is clearly seen in the R_{Hall} curves in Fig. 2(b). By making Arrott plots with an approximation of $R_{\mathrm{Hall}}\propto M_\perp$ (not shown), we determined E_G dependence of T_C in Fig. 2(d), which indicates that the increase of p enhances the ferromagnetic interaction in (Ga,Mn)Sb, as same as other ferromagnetic semiconductor materials [15,16].

In order to determine the magnetic anisotropy field quantitatively and to investigate the effect of E_G on it, we measure R_{Hall} as

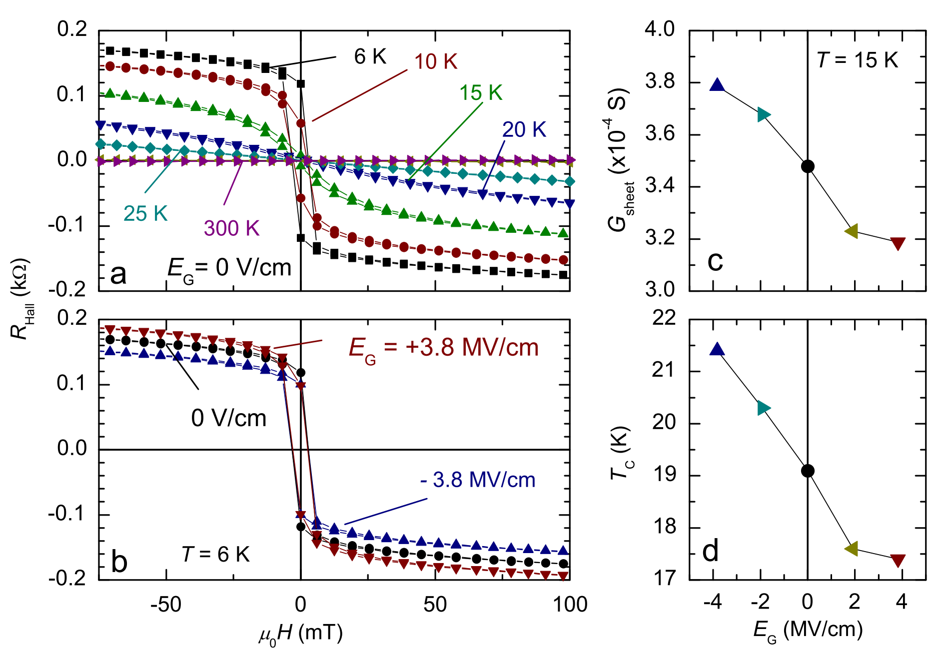

Fig. 2. Magnetic field H dependence of Hall resistance R_{Hall} (a) at gate electric field $E_G=0$ as a function of temperature T and (b) under $E_G=+3.8$, 0, −3.8 MV/cm at 6 K. (c) E_G dependence of sheet conductance G_{sheet} measured at 15 K. (d) E_G dependence of the Curie temperature T_C obtained from the Arrott plots.

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