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Easy axis reorientation and magneto-crystalline anisotropic resistance of tensile strained (Ga,Mn)As films

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A B S T R A C T

We present a study of magnetic anisotropy by using magneto-transport and direct magnetization measurements on tensile strained (Ga,Mn)As films. The magnetic easy axis of the films is in-plane at low temperatures, while the easy axis flips to out-of-plane when temperature is raised or hole concentration is increased. This easy axis reorientation is explained qualitatively in a simple physical picture by Zener's p–d model. In addition, the magneto-crystalline anisotropic resistance was also investigated experimentally and theoretically based on the single magnetic domain model. The dependence of sheet resistance on the angle between the magnetic field and [1 0 0] direction was measured. It is found that the magnetization vector ***M*** in the single-domain state deviates from the external magnetic field ***H*** direction at low magnetic field, while for high magnetic field, ***M*** continuously moves following the field direction, which leads to different resistivity function behaviors.

1. Introduction

The discovery of diluted magnetic semiconductor (DMS) (Ga,Mn)As [1–3] has attracted great attention for both basic and applied research, paving the way for the development of semiconductor spintronics [4,5]. Although this material is still limited to the laboratory use because the Curie temperature (T_C) is still well below room temperature [6–9], it has been proved to be a model material in the family of DMS.

The most widely accepted theoretical method to describe the ferromagnetism of (Ga,Mn)As is the p–d mean field Zener's model of valence band holes mediated ferromagnetism [10], which has been used to explain a number of experiments, including magnetic anisotropy [11–13]. The ability to manipulate anisotropy has great implications for fundamental research and is of vital significance in potential applications in magnetic recording technologies. A lot of experimental results [14–19] and theoretical predictions [11–13] have shown that magnetic anisotropy of (Ga,Mn)As is determined by a combination of hole density, strain, and temperature. Depending on lattice constant of the substrate, (Ga,Mn)As film can be compressively strained if it is grown on a substrate with a smaller lattice constant (e.g., on GaAs buffer), or tensile strained in the opposite case (e.g., on (In,Ga)As buffer). Magnetic anisotropy of compressive biaxial strained (Ga,Mn)As films has been carefully investigated [14–19]. The easy axis is out-of-plane at low temperature when the hole density is low. On the contrary, the easy axis will fall into the plane either when the hole density is high. However, the number of works focusing on tensile strained (Ga,Mn)As films [19–21] is limited. An early study reported that (Ga,Mn)As under tensile strain shows strong out-of-plane easy axis [22]. Later theories of magnetic anisotropy [11–13] predicted that tensile strained (Ga,Mn)As films should show rich physical phenomena. However, to confirm these predictions, particular experimental data are needed.

In this paper, we have studied the magnetic anisotropy of tensile strained (Ga,Mn)As films by measuring magneto-transport behaviors and magnetization characters. Our results show that (Ga,Mn)As films under tensile strain do exhibit an in-plane easy axis at low temperature. But when temperature is raised or hole concentration is increased by low-temperature annealing, the opposite tendency occurs. We explained this easy axis reorientation qualitatively by Zener's model. We have also investigated angle dependence of longitudinal resistivity of the tensile strained (Ga,Mn)As films, where easy axis lies in-plane or out-of-plane. It is found that the magnetization vector ***M*** in the single-domain state deviates from the external magnetic field ***H*** direction at low magnetic field, while for high magnetic field, ***M*** continuously moves following the field direction, which leads to different resistivity function behaviors.

2. Experiment

The (Ga,Mn)As films were grown on semi-insulating GaAs (0 0 1) substrates by molecular-beam epitaxy (MBE). The surface

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Table 1
Relative parameters of the samples are listed below. The Curie temperature, effective Mn concentration, and coercive force are determined by SQUID. The In concentration of (In,Ga)As and lattice mismatch are deduced from double-crystal high resolution X-ray diffraction. The hole density is determined by transport measurement at room temperature.

Sample	In (%)	$\Delta a/a$ (%)	T_C (K)	H_C (Oe)	x_{eff} (%)	Hole density at 300 K (cm^{-3})
A (as-grown)	8.5	−0.31	55	73	3.9	3.8×10^{19}
A (annealed)	8.5	−0.31	101	54	5.9	6.6×10^{19}
B (as-grown)	12.5	−0.45	50	76	3.8	4.8×10^{19}

was monitored *in situ* by a reflection high-energy electron diffraction (RHEED) system. Standard effusion cells supplied fluxes of Ga, Mn, In, and As_4. In the first step, a GaAs buffer of a thickness of 100 nm was grown at 560 °C. Then the substrate temperature was lowered to 500 °C, and a 500 nm strain-relaxed (In,Ga)As buffer layer was grown. At last the substrate was cooled down to 250 °C for the growth of 100 nm (Ga,Mn)As film. During the growth, the V/III beam equivalent pressure ratio and growth rate were set at 15 and 10 nm/min, respectively, and clear streaky (1×2) surface reconstruction pattern was monitored, showing two dimensional growth mode. No evidence of precipitation of the second phase, hexagonal MnAs, was observed. After removal of the samples from the MBE chamber, the wafers were cleaved into smaller pieces and some of these pieces were annealed at 250 °C in air for 1 h. The low-temperature annealing process [23] leads to out-diffusion of interstitial Mn atoms, which were then neutralized and oxidized on the surface. Appropriate low-temperature annealing can improve the quality of (Ga,Mn)As by improving the homogeneity of the material, which increases its Curie temperature, magnetic moment, and hole concentration, and changes the temperature dependence of its magnetization [24]. Related parameters of the samples we focused on in this paper are listed in Table 1.

To understand magneto-transport behaviors, we measured the longitudinal and Hall resistivity in $300\times900\ \mu m^2$ Hall bars patterned using optical lithography and chemical wet etching, with indium contacts and gold wire leads. The current direction was selected along the [1 1 0] direction. Both longitudinal resistivity ρ_{xx} and transverse resistivity (Hall resistivity) ρ_{xy} were measured simultaneously using an ac current of 1 μA. To measure the anomalous Hall effect, the magnetic field was set perpendicular to the sample plane. For the angle dependence of resistivity, the magnetic field was set in the (0 0 1) plane, and it was performed in a superconducting magnet equipped with a rotating sample holder, which makes possible the continuous change of the angle between the magnetic field and the electric current.

3. Results and discussion

3.1. Temperature and carrier induced the easy axis reorientation of tensile strained (Ga,Mn)As

The Hall resistivity [25] of ferromagnetic materials can be expressed as $\rho_{xy}=R_oH+R_sM$, where R_o is the ordinary Hall coefficient, R_s the anomalous Hall coefficient arising from spin–orbit interaction, which breaks the symmetry of the scattering mechanism of spin-up and spin-down carriers and ***H*** and ***M*** are the magnetic field and magnetization perpendicular to the sample surface, respectively. The anomalous Hall effect usually exceeds the ordinary Hall effect by several orders of magnitude; thus the phenomenon can be expressed as $\rho_{xy}\propto \boldsymbol{M}$, which enables us to use the magnetization dependent Hall effect to extract magnetic properties of the film. The curves of ρ_{xy} versus magnetic field of as-grown and annealed Sample A are shown in Fig. 1. In Fig. 1(a), the loop shape of the as-grown sample evolves from elongated shape at low temperature to square shape at high temperature, indicating a temperature induced reorientation behavior of the easy axis from in-plane to out-of-plane. In Fig. 1(b), the loops of the annealed sample appear as square shapes at both low and high temperatures, indicating a consistently out-of-plane easy axis at higher hole concentration. Fig. 2 also shows consistent square loops for Sample B, whose parameters are listed in Table 1, indicating no reorientation of easy axis was observed.

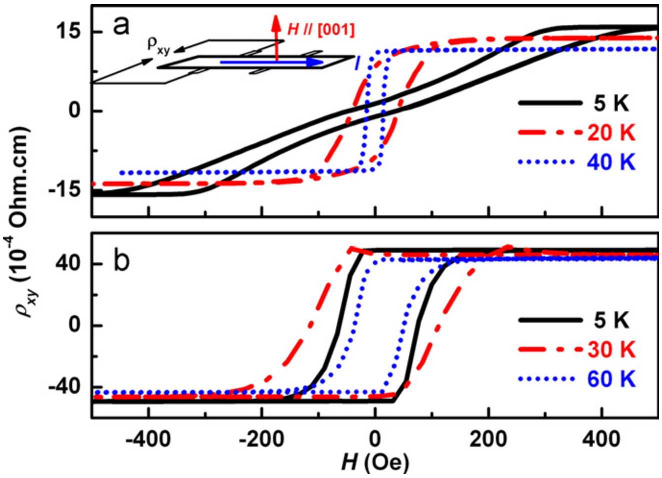

Fig. 1. Anomalous Hall effect of Sample A, as-grown (a) and annealed (b) measured at different temperatures. The inset shows a sketch of the experimental geometry.

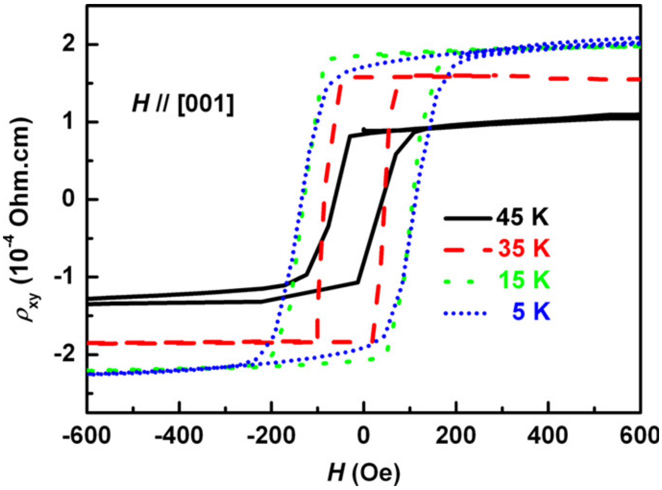

Fig. 2. Anomalous Hall effect of as-grown Sample B, which shows consistent out-of-plane easy axis.

To validate the temperature/hole concentration-induced reorientation of the easy axis obtained from magneto-transport