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Magnetic Properties of Submicron-sized *p*-$In_{0.97}Mn_{0.03}As$ Ferromagnetic Semiconductors

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1. Introduction

Much attention has been recently paid to III-V-based ferromagnetic semiconductors [1, 2] as one of the most promising candidates to realize semiconductor spintronics devices [3]. In the past few years, controls of ferromagnetism by the electric field [4] and by the optical spin injection [5] were demonstrated. Furthermore, electron spin injection was successfully performed [6].

For spintronics devices, basic properties of small-sized ferromagnetic semiconductors should be clarified for the first step. In this paper, we report the magnetic properties of submicron-sized ferromagnetic semiconductor *p*-$In_{0.97}Mn_{0.03}As$, especially we focus on the properties of the coercive force H_c, which are important for switching devices. Previous work showed H_c of $In_{1-x}Mn_xAs$ strongly depends on the magnetic anisotropy, which can be controlled by a buffer layer grown between the layer of $In_{1-x}Mn_xAs$ and a substrate [7]. In general there are two different models to explain the magnetization reversal process [8]. One is the rotation magnetization model in which single domain ferromagnetic particles rotates toward the direction of the applied magnetic field. The other is the domain wall displacement model in which domain walls displace when the magnetic field is applied. The magnetization process of $In_{1-x}Mn_xAs$ is not clear whether the magnetization reversal occurs by the rotation of the single domain ferromagnetic particles or the domain walls displacement. Measurements of the angle dependence of H_c can clarify the magnetization process, because the angle dependence of H_c shows quite different behavior between these two mechanism.

2. Experiment and Discussions

By the molecular beam epitaxy method, a top ferromagnetic layer of a 15-nm-thick *p*-$In_{0.97}Mn_{0.03}As$ was grown after the growth of a 500-nm-thick $Al_{0.3}Ga_{0.7}Sb$ buffer, a 200-nm-thick GaSb buffer and a GaAs buffer on a GaAs(100) semi-insulating substrate.

We carried out the measurements of the Hall resistivity on Hall bars whose widths ranged from 0.5 μm to 250 μm by the four-probe method. The Hall bars were fabricated using the electron beam lithography and were aligned along the [110] direction. Figure 1 (a) shows the scanning electron microscope picture of a 0.7-μm-wide Hall bar. The Hall resistivity ρ_{yx} is expressed by the summation of the ordinary Hall effect term due to the Lorentz force and the anomalous Hall effect term which is proportional to the magnetization M [9]. Then we can extract the value which is proportional to M from the measurements of ρ_{yx}. We measured the angle dependence of ρ_{yx} at various temperatures. Applied magnetic field is in the *yz*-plane in this work.

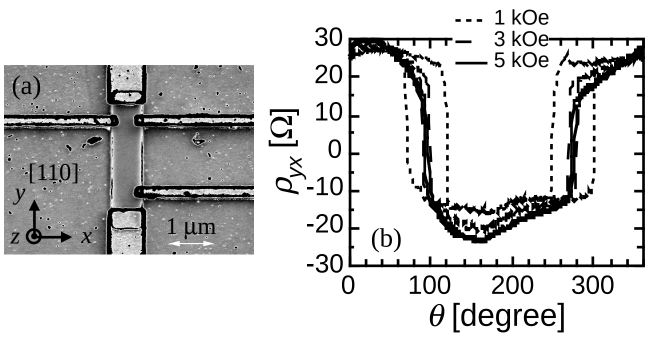

Fig. 1 (a) The SEM picture of the 0.7-μm-wide Hall bar. The Hall bar is alined along the [110] direction. (b) The angle dependence of the Hall resistivity ρ_{yx} with fixed magneitc fields of 1 kOe, 3 kOe and 5 kOe at 10 K. The angle θ was swept from 0 ° to 360 °, then was swept back from 360 ° to 0 °

Figure 1 (b) shows the angle dependence of the Hall resistivity with fixed magnetic fields of 1 kOe, 3 kOe and 5 kOe at 10 K. The angle θ was swept from 0 ˚ to 360 ˚, then was swept back from 360 ˚ to 0 ˚. Large jumps and hysteresis loops of ρ_{yx} are observed only around 90 ˚ and 270 ˚, and the hysteresis loops become larger with decreasing the magnetic field. These results clearly show that this sample has ideal uniaxial magnetic anisotropy whose easy axis is aligned perpendicular to the plane and anisotropy energy of other easy axes could be negligible. These anisotropic properties are distinct from the magnetic anisotropic properties of the similar ferromagnetic semiconductor $Ga_{1-x}Mn_xAs$ which has both the uniaxial easy axis along [110] in plane and the cubic easy axis [10].

Figure 2 shows the angle dependence of the coercive force and the Hall resistivity at H=0 $\rho_{yx}(H=0)$ in the temperature of 10 K. With changing θ toward 90 ˚, H_c increases remarkably. In passing, we note that H_c at the angle θ of 0 ˚ did not depend on the size of the Hall bars whose widths ranged from 0.5 μm to 250 μm. This size-independence of H_c probably suggests that domain size is smaller than 0.5 μm. In Fig. 2, with changing θ, $\rho_{yx}(H=0)$ does not change except in the vicinity of 90 ˚. In the vicinity of 90 ˚, $\rho_{yx}(H=0)$ decreases abruptly to zero toward 90 ˚. The Hall resistivity is proportional to the perpendicular component of magnetization M. The angle dependence of $\rho_{yx}(H=0)$ indicates that M sticks perpendicular to the plane even when the direction of the applied magnetic field is not perpendicular to the plane. The direction of M can not tilt due to the strong perpendicular anisotropy.

These angle dependence of H_c and $\rho_{yx}(H=0)$ can rule out the rotation magnetization process of the uniaxial anisotropic sample. On the other hand, in the magnetization reversal process due to the 180 ˚ magnetic domain wall displacement, H_c increases proportional to 1/cosθ with increasing θ, and M does not tilts but changes to the opposite direction abruptly. The angle independence of $\rho_{yx}(H=0)$ except in the vicinity of 90 ˚, which indicates the magnetization does not tilt toward the direction of the applied magnetic field, can be explained well by the 180 ˚ magnetic domain wall displacement. In Fig. 2, the dotted curve represents $H_c(\theta=0˚)/\cos\theta$. The results of H_c agree qualitatively with the dotted curve. However H_c is lower than the value of $H_c(\theta=0˚)/\cos\theta$. At present this discrepancy is not yet clear. The sample has maybe a small-sized multidomain structure. Probably this small-sized multidomain structure is somehow related to the lower H_c. Therefore the reversal process is more likely governed by the magnetic domain wall displacement in the small-sized multidomain structure.

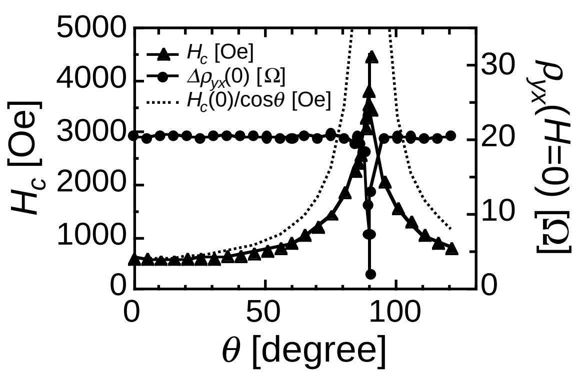

Fig. 2 The angle dependence of the coercive force H_c and the Hall resistivity at H=0 $\rho_{yx}(H=0)$ in the temperature of 10 K. The dotted curve represents $H_c(\theta=0˚)/\cos\theta$.

3. Conclusions

The magnetic properties of submicron-sized p-$In_{0.97}Mn_{0.03}As$ have been investigated by performing angle dependence of the Hall resistivity. The results show that the ideal uniaxial magnetic easy axis perpendicular to the plane is realized, which is distinct from the anisotropic properties of $Ga_{1-x}Mn_xAs$. The magnetization reversal process is more likely due to the magnetic domain wall displacement in the small-sized multidomain structure rather than the rotation magnetization process. These results give useful information for future spintronics devices based on submicron-sized $In_{1-x}Mn_xAs$.

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