Magnetic anisotropy switching from perpendicular to in-plane with temperature in heavily-Fe-doped ferromagnetic semiconductor (Ga,Fe)Sb

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Ferromagnetic semiconductors (FMSs) with high Curie temperature (T_C) are strongly required for spintronics device applications. So far, the mainstream study of FMSs is Mn-doped III-V FMSs; however they are only *p*-type and T_C is much lower than 300 K. Recently, we have grown Fe-doped FMSs, such as (Ga,Fe)Sb and (In,Fe)Sb, with high T_C [> 300 K][1] and good compatibility with III-V semiconductor heterostructures; they are very promising for spintronics applications. In order to use (Ga,Fe)Sb for practical devices, understanding its magnetic anisotropy (MA) is essential.

Recently, we found that MA of ($Ga_{0.8}$,$Fe_{0.2}$)Sb films can be controlled with epitaxial strain where a tensile and compressive strain induces an in-plane magnetic anisotropy (IMA) and a perpendicular magnetic anisotropy (PMA), respectively [2]. Also, we found that in heavily Fe-doped ($Ga_{0.7}$,$Fe_{0.3}$)Sb thin films, the MA properties at room temperature changes from IMA to PMA with increasing the thickness from 15 nm to 55 nm [3]. Here, we report on the temperature dependence of the MA of a 40-nm-thick ($Ga_{0.7}$,$Fe_{0.3}$)Sb film grown on AlSb/semi-insulating GaAs(001) substrates by low-temperature molecular-beam epitaxy (LT-MBE) [Fig. 1(a)]. We estimated the MA constants of the film by measuring the ferromagnetic resonance (FMR) and magnetization using superconducting quantum interference device (SQUID) magnetometry. Figure 1(b) shows the resonance field of the (Ga,Fe)Sb film as a function of θ_H, which is the out-of-plane angle of the applied magnetic field $\boldsymbol{H}$ from [001] to [110], at various temperatures. By fitting to the $\boldsymbol{H}$-angle dependence of the resonance field and combining with the value of the saturation magnetization M_S measured by SQUID, we obtained the values of K_{sh}, $K_{2\perp}$, $K_{4\perp}$, and $K_{2//}$, which are the shape anisotropy constant, perpendicular uniaxial-anisotropy constant, perpendicular cubic-anisotropy field constant, and in-plane uniaxial anisotropy constant, respectively. Figure 1(c) summarizes the obtained perpendicular MA energy $E_\perp(= -K_{2\perp} - K_{sh} - K_{4\perp}/2)$ as a function of temperature. When we decrease the temperature from 300 K to 10 K, $E_\perp$ changes its sign from positive to negative, indicating a switching from IMA to PMA. From microstructure characterizations, we attribute the origin of this temperature dependence to the fluctuation in the local Fe density, which causes nano-columnar-like Fe-rich regions elongating along the growth axis. PMA at low temperature may be due to the dominant magnetization alignment along the perpendicular direction inside these nanocolumns. This study will help to understand the mechanism of ferromagnetism in high-T_C FMS (Ga,Fe)Sb.

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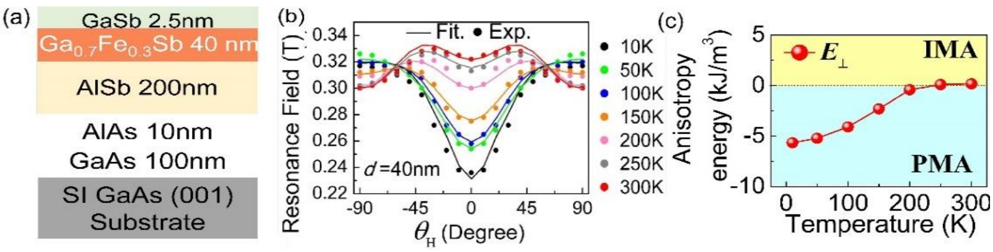

Fig.1 (a) Schematic sample structure. (b) FMR field as a function of the $\boldsymbol{H}$ direction θ_H. (c) the total MAE $E_\perp$ (red circles) of ($Ga_{0.7}$,$Fe_{0.3}$)Sb along [001] as a function of temperature.

Refs: [1] N. T. Tu *et al.*, PRB **92**, 144403 (2015); APL **108**, 192401 (2016); APEX **11**, 063005 (2018). [2] S. Goel et al. PRB **99**, 014431 (2019), [3] S. Goel *et al.*, PRM, submitted.