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Magnetic properties of (Ga,Mn)As (110) epitaxial films

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Abstract

Magnetic properties of (Ga,Mn)As films epitaxied on GaAs (110) substrates have been investigated. Dominant in-plane magnetic anisotropy and spin reorientation transition upon the change of temperature were observed. The uniaxial and cubic magnetic anisotropic fields were quantitatively determined by the planar Hall measurements, based on which the above phenomena were discussed.

1. Introduction

(III,Mn)V dilute magnetic semiconductors have been acting as an ideal playground for the exploration of many novel concepts in spintronic devices [1-2], among which (Ga,Mn)As is the most extensively investigated. However, the Curie temperature (T_C) of (Ga,Mn)As is still lower than the room temperature, with the record sticking at around 200 K [3]. Besides, as one of the most important parameters in magnetic materials, magnetic anisotropy of (Ga,Mn)As, especially the origin of the bulk uniaxial magnetic anisotropy is still to be elucidated by experiments [1, 4].

The GaAs substrate orientation offers the possibility to address the above questions, since both the incorporation of Mn atoms into the lattice sites and the diffusion efficiency of interstitial Mn atoms depend on the specific atom arrangement of the surface. So far, there are only a few reports on (Ga,Mn)As films grown on high-index crystallographic planes of GaAs substrate, such as (111), (311) and (411) faces [5-8]. However, the comprehensive study of (Ga,Mn)As (110) epitaxial films is still lacking. In this work, (Ga,Mn)As (110) epitaxial films were fabricated and investigated systematically.

2. Experiments and Results

The (Ga,Mn)As (110) films were grown by low-temperature molecular-beam epitaxy, with its growth front monitored *in-situ* by reflection high-energy electron diffraction. Figure 1 presents the schematics of the crystal structure and the atom arrangements labeled with characteristic crystal directions. For GaAs (110) substrates, three linear edges with directions parallel with [00-1], [-11-1] and [-111] will naturally appear after cleavage, as specified in Fig. 1(b).

Figures 2(a) and (b) show the temperature dependent remnant magnetization (M_r-T) curves measured in three different directions for the as-grown and annealed (Ga,Mn)As films. For the as-grown samples, the M_r-T curves display a non-monotonic behavior with the peak at around 20 K when measured along the [-110] and [-11-1] directions, implying an easy axis reorientation transition. Conversely, all the M_r-T curves for the annealed samples depend on the temperature monotonically, with the easy axis lying in the [-110] direction. The out-of-plane magnetization component (the magnetization projected on the [110] direction) was almost zero for samples before and after annealing, indicating dominant in-plane magnetic anisotropies.

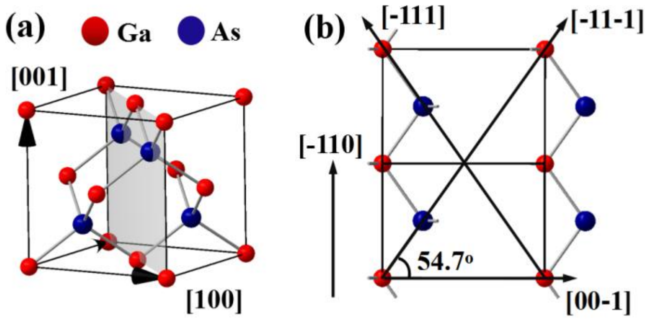

Fig. 1 Schematics of (a) the (110) plane highlighted in a zinc-blende structure, (b) the atomic arrangements on GaAs (110) surface with four special directions (top view).

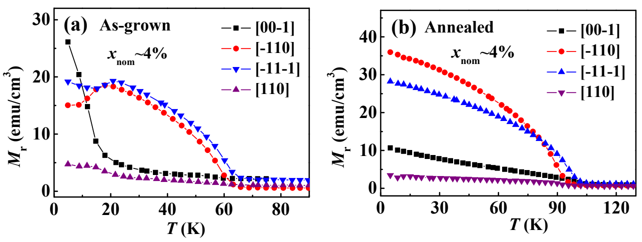

Fig. 2 M_r-T curves measured along different directions for the (a) as-grown and (b) annealed (Ga,Mn)As films.

To obtain an overall and quantitative information of the magnetic anisotropic fields in (Ga,Mn)As (110) films, the angle-dependent spin transport measurements were carried out. A DC electrical current with a fixed amplitude of 10 μA was applied along the [-11-1] direction, while the planar Hall resistance (PHR) were recorded. These curves deviate from the standard sinusoidal function, as a result of the interplay between the external magnetic field and the internal effective anisotropic fields, providing the information of in-plane magnetic anisotropies. A phenomenological coherent rotation model was used to fit the above PHR data, as presented in Fig. 3.

The fitting results indicate that the sign of uniaxial anisotropic filed H_U in the as-grown films becomes opposite and the magnitude becomes larger when the temperature was increased from 5 K to 40 K, which is quite different from the normal behavior of magneto-crystalline anisotropy. This sign reversal of H_U accompanied with the 60° rotation of the magnetic easy axis, implying a totally different mechanism. In addition, H_U changes very slowly for the annealed samples, but H_C decreases rapidly in both the as-grown and annealed samples.

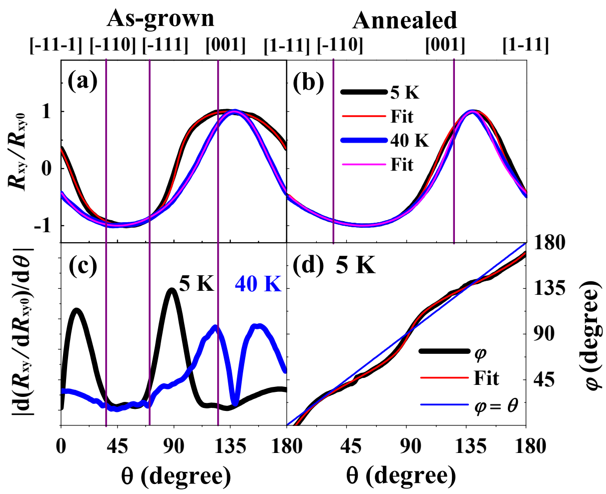

Fig. 3 In-plane magnetic field angle θ dependence of the planar Hall resistance R_{xy} curves for the (a) as-grown and (b) annealed (Ga,Mn)As films. (c) The angle-derivative of normalized Hall resistance versus θ curves for the as-grown samples. (d) Magnetization angle φ as a function of θ for the annealed samples at 5 K, the φ=θ line is shown for comparison.

3. Discussion

It is well known that the magnetic anisotropy of (Ga,Mn)As is very sensitive to hole density and strain, which can be explained by the nature of hole-mediated ferromagnetism reflecting the strain-induced anisotropy of the valence band in (Ga,Mn)As. Since the magnetization and thus the spin-splitting of the valence sub-bands decrease as increasing the temperature, the orientation of magnetization might be changed to meet the minimum-energy requirement. Hence, the reorientation of the uniaxial magnetic easy axis in as-grown samples is consistent with the previous theory. In addition, the annealed samples with larger hole concentration have similar magnetic anisotropy with the as-grown samples at higher temperature, which can also be understood by the *p-d* Zener model: the post-growth annealing shifts the Fermi level due to the increasing of the hole density, therefore the light hole sub-band would possibly be more populated, resulting in a favored [-110] magnetic easy axis.

Moreover, the [110] and [-110] axes is thought to be equivalent for (Ga,Mn)As (001) films according to the symmetry analyses of zinc-blende crystals. However, many experiments have shown that the magnetic easy axis could be one of them, with [-110] the dominant easy axis for heavy Mn-doped samples. Recent first principle calculations ascribed this puzzling bulk uniaxial anisotropy to a nonrandom distribution of substitutional Mn atoms formed during the epitaxial growth [4]. For (Ga,Mn)As [110] films, nearest-neighbor Mn-pairing along the in-plane [-110] direction might also prefer to form due to the layer by layer growth mode, leading to the dominant [-110] magnetic easy axis in (Ga,Mn)As (110) epitaxial films.

4. Conclusions

In conclusion, the magnetic properties of epitaxial (Ga,Mn)As films grown on GaAs (110) substrate have been investigated. Dominant in-plane magnetic anisotropies and obvious spin reorientation transition with the change of temperature have been observed. The above phenomena can be attributed to the competition between the cubic and the uniaxial magnetic anisotropy, which are quantitatively obtained by fitting the planar Hall resistances with a coherent rotation model. The preferred [-110] uniaxial magnetic easy axis is attributed to the nearest-neighbor Mn-pair along the [-110] direction formed during the layer by layer epitaxial growth. Our work provides additional piece of information for the understanding of the origin of magnetic anisotropies in (Ga,Mn)As films.

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