

MAGNETIC PROPERTIES AND ANISOTROPY OF GaMnAs STRUCTURES FOR SPINTRONIC DEVICES

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Introduction

During the last decade, considerable experimental and theoretical efforts have been devoted to the study of GaMnAs semiconductors due to their high ferromagnetic transition; "Curie temperature (T_c)" and their interesting magnetic properties [1].

The potential implementation of structures based on GaMnAs diluted magnetic semiconductors as spintronic devices needs solid understanding of magnetic anisotropy and magnetization reversal processes. Nowadays, it is well established that the ferromagnetic interaction between magnetic ions is mediated by charge carriers, holes in this case. However, defects such as As antisites and Mn interstitials play a crucial role in determining the magnetic properties of GaMnAs. The objective of this study is to investigate the magnetic properties and anisotropy using magnetotransport measurements as well as the dynamics domain wall by high resolution magneto-optical imaging.

Experimental

Materials

$\text{Ga}_{1-x}\text{Mn}_x\text{As}$ sample grown on GaAs substrate or InGaAs buffer by low-temperature molecular beam epitaxy. In the suitable case, manganese atoms are located in substitution of gallium sites preferentially (Mn_{Ga}). In this position, Mn_{Ga} acts as an acceptor (1 hole per Mn) and provides a magnetic moment $S=5/2$ due to its d^5 atomic configuration. However, the low temperature growth technique induces formation of compensating defects such as Mn interstitials (Mn_i) which act as double donor, decreasing thus the concentration of holes provided by Mn_{Ga} acceptors. Original optimal post growth annealing technique [2] allowed us to prove that the highly mobile Mn_i defects out diffuse to and are passivated at the free surface by As capping. Then, the removal Mn_i from the bulk of GaMnAs leads to an increase of the hole concentration (p) and also of the ferromagnetic-paramagnetic transition temperature (T_c) by about 100%.

Results and discussion

The Curie temperature was determined from direct magnetization measurements using sensitive SQUID magnetometer at Neel Institute (Grenoble). Figure 1(a)

presents the temperature dependence of magnetization before and after annealing. We can note that the T_c increases from 75K to 145K after annealing process. Electrical measurements are performed on Hall bars of $150\mu\text{m}$ width prepared using photolithographic patterning and wet chemical etching. At Grenoble High Magnetic Field Laboratory (GHMFL), we carried out the magnetoresistance and Hall resistance measurements up to 23T magnetic field. Analyses of Hall resistance versus magnetic field at 4K give us the hole concentration. For a 20 nm thick $\text{Ga}_{1-x}\text{Mn}_x\text{As}/\text{GaAs}$ layer ($x = 7\%$), the determined hole concentration is $p \sim (4.5 \pm 0.4) 10^{20}\text{cm}^{-3}$ before annealing and increases up to $p \sim (9.3 \pm 0.6) 10^{20}\text{cm}^{-3}$ after annealing. In the same time, we observe a T_c increasing with holes concentrations. These results are in good agreement with theoretical model predicting that, $T_c \sim p^{1/3} \cdot x_{\text{eff}} \cdot N_0$ [3] where x_{eff} is the active manganese concentration. Thus the active manganese concentration deduced reaches 55% and 65% of manganese introduced.

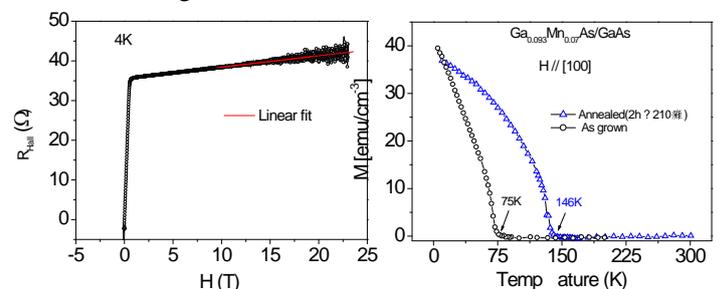


Fig.1 (a): magnetic field dependence of Hall resistance at 4K, (b): temperature dependence of magnetization before and after annealed.

Besides, magnetic anisotropy is a decisive physical quantity in the understanding of magnetization reversal process and determining the easy axes directions of ferromagnetic system. This anisotropy depends on macroscopic anisotropy constants K_i ($i = c$, cubic and u , uniaxial respectively). We have carried out the Planar Hall Effect (PHE) measurements in order to investigate the planar magnetic anisotropy of GaMnAs layers with an in-plane magnetization orientation. Both angular and magnetic field dependences of PHR have been performed in both as grown and annealed samples. Our results show that, annealing induces changes in magnetic anisotropy –Fig. 2a. For $H \sim$

0, the coercive field H_{C2} decreases from 720 Oe to 170 Oe. At the other hand, the PHR [4] can be described by $R_{HP}(\phi_H) = (R_{//} - R_P)\sin(\phi_H)\cos(\phi_H)$ (eq1)

For $H = 200\text{Oe}$, the PHR vs ϕ_H exhibits no sine-shape curves for the as-grown sample. The square signal indicates the existence of strong cubic anisotropy [4]. Then, for the annealed sample at the same field, the curve is sinusoidal (fig 2b). To understand this behaviour, we have determined the cubic, K_c and uniaxial, K_u , constants anisotropy by combining (eq 1) and the free energy density of ferromagnetic system [5] given by the relation

$$E = K_u \sin^2(\phi_H) + 1/4 K_c \cos(2\phi_H) - MH \cos(\phi_H - \theta) \quad (\text{eq2})$$

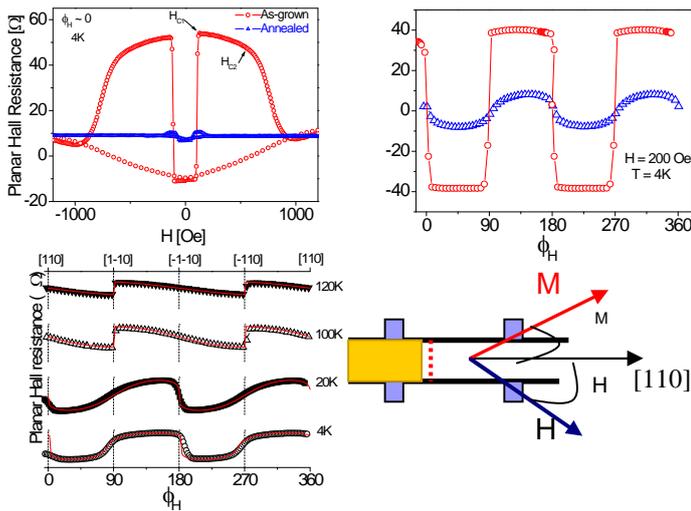


Fig.2: (a) and (b) magnetic field and angle dependence of PHR before and after annealing, (c) angle dependence of PHR for several temperatures and at a fixed field $H = 20$ Oe for the annealed sample (curves have been shifted vertically for clarity) red solid lines are fits. (d) Schematic diagram of Hall device structure with relative orientation of current I , magnetization, M , and magnetic field H .

Magnetization M is determined by sensitive SQUID measurements. An example of angular dependence of PHR for $H = 200\text{Oe}$ on annealed sample is given in Fig; 2c. We can emphasize the good agreement between angle-PHR behaviour and theoretical model (red solid curves) for several temperatures. Figure 3 presents the temperature dependence of anisotropy constants K_u , K_c deduced by fitting experimental PHR vs ϕ_H for both as-grown and annealed samples. We can note that, the post growth annealing seriously altered the cubic anisotropy. At 4K, after annealing, the cubic anisotropy constant K_c decreases by about 90%, whereas the uniaxial anisotropy constant K_u decreases by only 40%. Then the increasing of the ratio K_u/K_c can be explained by increasing of the holes concentration after annealing. These results are in agreement with previous measurements probed by ferromagnetic resonance on similar samples by other groups [6]. In this paper, we present for the first time the evidence of two in-plane uniaxial axis

reorientations. By respect to the crystallographic axes: From $[110]$ ($K_u > 0$) to $[-110]$ ($K_u < 0$) after annealing and: From $[-110]$ to $[110]$ at $T \sim 80\text{K}$ on the annealed sample. This effect corresponds exactly to the distortion change in PHR curves as seen in Fig 2 c in the temperature range from $T = 20$ K to $T = 120$ K.

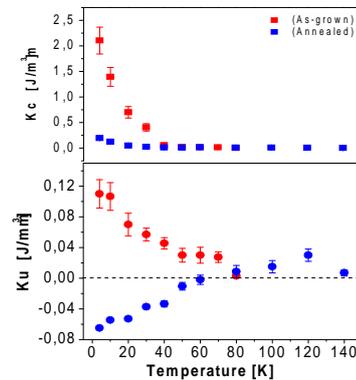


Fig.3: (a) temperature dependence of cubic anisotropy constant K_c and (b) in-plane uniaxial anisotropy constant K_u , before and after annealing.

For complementarily, we have also studied the magnetoresistance anomalies and magnetic domain on GaMnAs/InGaA. These structures have an out of plane magnetization direction. The results have been recently published [7]. The domain wall motion (velocity) study driven by magnetic field has been performed using high-resolution magneto-optical imaging at INSP institute.

Conclusion

In summary, we have investigated magnetic properties of GaMnAs devices. Many experimental techniques have been used to achieve characterization of these structures such as: SQUID measurements for magnetization, Hall Effect for holes concentration, Magnetic Optical Kerr Effect (MOKE) for domain wall imaging and Planar Hall Effect for magnetic anisotropy studies. Predicted theoretical models and developed ones by our team are in good agreement with experimental data. Finally, we emphasize the first evidence by transport measurements of two in-plane uniaxial axis reorientations.

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