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Anisotropic magnetoresistance of GaMnAs:Be

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Abstract. The effect of co-doping with Be on the magnetic anisotropy in $Ga_{0.972}Mn_{0.028}As$ epitaxial layers has been studied by magnetoresistance measurements. Co-doping with Be has been shown to lead to reorientation of both easy and hard magnetic axes in GaMnAs. Measurements of the temperature dependence of the anisotropic magnetoresistance demonstrate no changes in the type of the magnetic anisotropy with the increase in temperature. The results of the study of the anisotropic magnetoresistance indicate that the parameters of the magnetic anisotropy in GaMnAs are significantly influenced by the magnitude of the compressive strain.

Keywords: GaMnAs, epitaxial layers, molecular beam epitaxy, anisotropic magnetoresistance, magnetic anisotropy, easy axis.

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1. Introduction

Since the discovery of ferromagnetism in III-V semiconductors heavily doped by transition ions, GaMnAs has attracted considerable attention because of both fundamental physics aspects and practical viewpoint [1–4]. Even though no remarkable progress in raising the Curie temperature of GaMnAs has been observed in the last 10 years (the highest T_C value of about 200 K has been reported in [5]), due to its perfect compatibility with existing III-V semiconductors technologies, GaMnAs is still considered as a testing material for semiconductor spintronics, where both charge and spin degree of freedom of carriers can be used for information transfer and processing [6–8]. In accordance with conventional approach, ferromagnetic order in III-V semiconductors is a result of interaction between localized spins of magnetic ions and delocalized or slightly localized holes [8, 9]. Mn ions in GaMnAs occupy the sites of Ga atoms and act as both origin of spins and accepters. In general, ferromagnetism in GaMnAs can be successfully described by the Zenner model [1, 8] that predicts anisotropy of the magnetic properties of this material. However, Mn concentration required to obtain ferromagnetism in GaMnAs must significantly exceed the solubility limit of Mn in GaAs. Such concentrations can be obtained only by using non-equilibrium methods such as *e.g.* low-temperature molecular beam epitaxy (LT MBE) [10, 11]. Since LT MBE grown epitaxial layers are characterized by high defect concentrations [12, 13], the anisotropy effects observed in GaMnAs substantially differ from those predicted theoretically. As far as control of the magnetic anisotropy is a critical issue for successful realization of spintronics devices, magnetic anisotropy effects in GaMnAs have been intensively studied in the last years. It has been established by now that magnetic anisotropy in GaMnAs epilayers depends on the stress within the film as well as on the temperature and hole concentration [14–17]. It has been shown recently that the parameters of the magnetic anisotropy can be modified by co-doping with nonmagnetic impurities [18–20]. In this work, we present the results of the investigation of the effects of Be co-doping on the parameters of magnetic anisotropy in GaMnAs epilayers.

2. Samples preparation and experiment

$Ga_{0.972}Mn_{0.028}As$ epitaxial layers co-doped with Be were grown on GaAs (001) semi-insulating substrates by LT MBE technique. Prior to the GaMnAs:Be deposition, a GaAs buffer layer with the thickness of approximately 250 nm was grown at ~580 °C. Then the substrate temperature was reduced to 275 °C to grow the main layers with the thickness of 300 nm. GaMnAs epitaxial layers without Be co-doping to use as the reference samples were grown under the same conditions. Crystalline quality of the GaMnAs epilayers with and without Be co-doping was monitored *in situ* by reflection high-energy electron diffraction (RHEED) and post-growth XRD measurements. The results obtained by these methods indicate that all the GaMnAs epilayers are homogeneous without any inclusions of second phases.

The Be concentration in the Be co-doped samples was controlled by the temperature of the effusion cells, T_{cell}(Be). It was shown previously that the Curie temperature (T_C) in GaMnAs co-doped with Be has a complex dependence on the Be concentration, namely: in semiconducting GaMnAs, co-doping with Be increases the T_C value due to the increase in the hole concentration, as is expected from the Zener model of ferromagnetism. However, further increase of the carrier concentration results in the decrease of the number of Mn atoms in Ga substitutional sites and, hence, the Curie temperature [21, 22]. For the samples studied in this work, T_{cell}(Be) was 1150 °C. This ensured the equality of T_C in the reference and Be co-doped epitaxial layers, which was about 50 K as estimated from the anomalous Hall effect measurements in accordance with [23]. To determine magnetic anisotropy, we used magnetoresistance (MR) measurements along different crystallographic directions at different orientations of magnetic field. MR measurements were performed by 4-point probe method in the Van der Pauw geometry. The MR values were measured for the following orientations of magnetic field with respect to the crystal axis: H is parallel to the axis, H is normal to the axis and parallel to the film plane, and H is normal to the axis and normal to the film plane, labeled as parallel field orientation, normal field orientation and out of plane field orientation, respectively. During the MR measurements, the current flow direction was along the crystal axis under consideration. For convenience, in the data obtained for different samples were compared using the normalized MR values R_H determined as $R_H = (R(H) - R(0))/R(0)$, where $R(H)$ and $R(0)$ are the resistances measured at a given value of H and at zero field, respectively.

3. Results and discussion

Fig. 1 shows the MR data for the reference and Be co-doped samples obtained by measuring along different crystallographic directions at 20 K. It is clearly seen from this figure that the MR curves for both the Be co-doped and reference samples strongly depend on the magnetic field orientation. This dependence is more obvious at low magnetic fields (up to 2500 Oe), when the magnetoresistance is determined by the processes occurring during magnetization reorientation in the external magnetic field [17, 24]. In this region of the magnetic field values, the positive MR or plateau is observed for the normal and out-of-plane field orientation. For parallel field orientation, the MR is negative but nonlinear. When H is strong enough to saturate magnetization, the magnetoresistance becomes negative for all the field orientations. In this region of the magnetic field values, the slope of the MR is linear and independent (or weakly dependent) on the field orientation. According to the earlier studies, the negative MR observed in GaMnAs at high magnetic fields results from the reduction of scattering due to spin alignment in metallic samples in external magnetic fields and suppression of localization in insulating samples [25]. The subject of this study is the magnetoresistance at low fields, which is commonly called anisotropic magnetoresistance (AMR) and is widely used for characterizing magnetic anisotropy in GaMnAs [16, 23].

It is clearly seen from Fig. 1 that in the low magnetic field region, the positive MR in the GaMnAs:Be epitaxial layer is more pronounced in the case of the $\langle 110\rangle$ crystallographic direction for normal field orientation. In this case, significant difference in the MR measured along the equivalent crystallographic axes [110] and $[1\bar{1}0]$

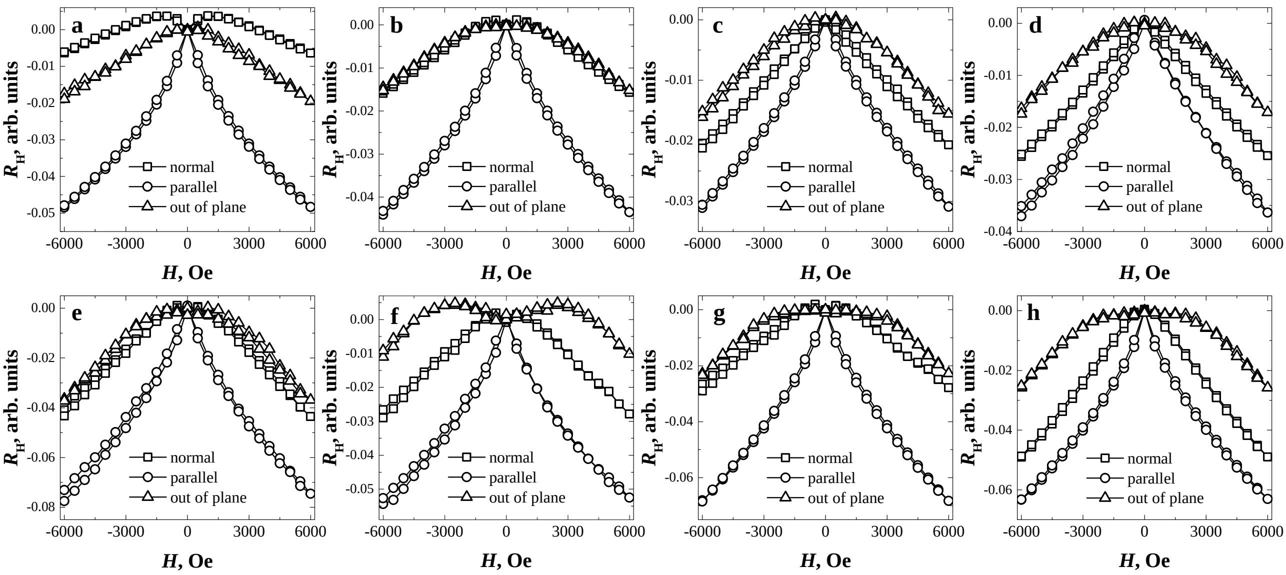

Fig. 1. Magnetoresistance measured at 20 K for different magnetic field orientations: a, b, c, d – GaMnAs:Be; e, f, g, h – reference GaMnAs; a, e – [110]; b, f – $[1\bar{1}0]$; c, g – [100]; d, h – [010].

was observed. On the contrary, AMR measured along the ⟨100⟩ directions is stronger for the out of plane field orientation. Only slight differences in the MR curves obtained for the equivalent axes [100] and [010] are observed. Hence, the AMR data are an evidence of the magnetic anisotropy along the ⟨110⟩ directions in the GaMnAs:Be epitaxial layer. One can also notice that the saturation field for the out-of-plane field orientation is higher as compared to that for the normal orientation, which indicates that the hard axis is oriented normally to the epilayer surface of the sample.

The anisotropy of the MR along the ⟨110⟩ directions is also clearly observed in the reference GaMnAs epitaxial layers. However, the highest saturation field is detected for the MR along the [110] axis at the normal field orientation. Moreover, the saturation field in the reference sample measured along all the crystal axes at the out-of-plane field orientation is stronger than that for the normal field orientation. Such differences in the AMR behavior may indicate that co-doping GaMnAs with Be leads to a change of the orientation of the hard axis from the in-plane to the perpendicular direction.

To study the effects of anisotropy in magnetic semiconductors, it is convenient to describe AMR by the values R_x and R_z, which are defined as follows:

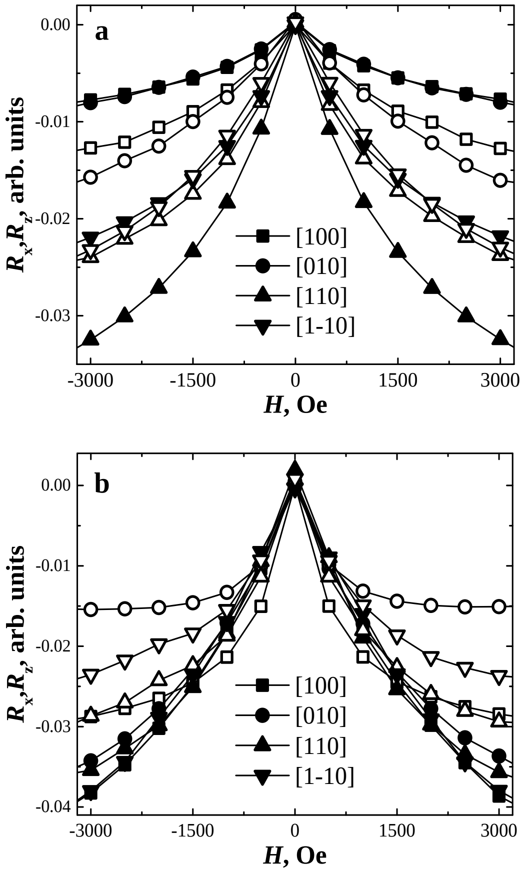

Fig. 2. AMR measured for in-plane (R_x – open symbols) and out-of-plane (R_z – closed symbols) magnetic field orientation: (a) – GaMnAs:Be; (b) – reference GaMnAs.

$$R_x = R_p(H) - R_{n1}(H),$$

$$R_z = R_p(H) - R_{n2}(H),$$

Here, R_p is the value of R_H measured at the parallel field orientation, and R_{n1} and R_{n2} are the values of R_H measured at the normal and out-of-plane field orientation, respectively [16, 24]. Hence, we can use R_x and R_z for characterizing the in-plane and out-of-plane magnetic anisotropy. The R_x and R_z values determined at 20 K are shown in Fig. 2.

The strong discrepancy in the AMR behavior for the Be co-doped and the reference GaMnAs epilayers is clearly observed. For the Be co-doped sample, one can see the strong difference in the AMR values determined for the in-plane and out-of-plane field orientation. In accordance with [17], the lowest AMR value is observed for the easy axis of magnetization. Hence, the data presented in Fig. 2 indicate that in the Be co-doped samples, the easy axis has a dominant component in the direction normal to the epilayer surface. However, as far as for this sample one can see the strong difference in the R_x and R_z values determined for different crystal axes, we can conclude that the easy axis also has an in-plane component oriented along the [100] axis. For the GaMnAs sample, only the difference in the R_x values measured for different crystal axes has been observed, whereas the R_z value is almost the same for all the axes. Since the lowest value of R_x is observed for the [010] crystallographic axis, we may conclude that the easy axis in the reference sample is fixed along this direction. Be co-doping thereby leads to the change in the orientation of the easy axis in GaMnAs from the in-plane (in-plane anisotropy) to the out-of-plane (out-of-plane anisotropy).

Let us now discus the physical origin of the reorientation of the easy axis in the Be co-doped GaMnAs. It is well established that orientation of the easy axis in the GaMnAs epitaxial layers strongly depends on the strain within the film. The easy axis is perpendicular to the GaMnAs layer under tensile strain, while it lies in the film plane for the GaMnAs layer under compressive strain [1, 19]. The GaMnAs epitaxial layers grown on GaAs substrates are compressively strained due to the mismatch between the GaAs and GaMnAs lattice constants. The strain increases with the increase in the Mn concentration. Therefore, the easy axis in the GaMnAs epilayers grown on GaAs substrates should be oriented in the plane of the film. However, as demonstrated in [16, 26], despite compressive strain, the easy axis may be oriented in the direction perpendicular to the GaMnAs epilayer surface for the samples with low hole and Mn concentrations. The orientation becomes the standard in-plane one when the hole concentration is increased by low temperature annealing [27]. The tendency to increase the in-plane anisotropy at the increase of compressive strain and hole concentration was also reported in [16]. On the one side, Be is known as an effective acceptor in GaAs. Hence, co-doping with Be increases the hole concentration. On the other hand, co-doping with Be decreases the lattice mismatch between the GaAs

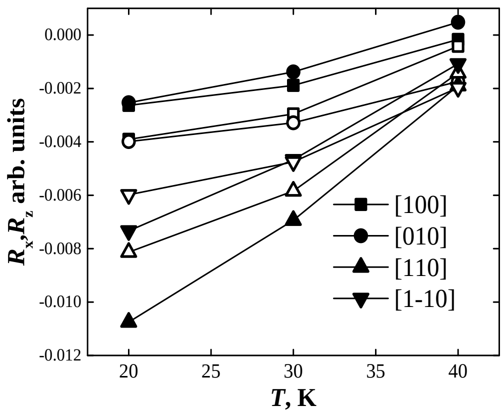

Fig. 3. Temperature dependence of AMR in GaMnAs:Be: open symbols – R_x, closed symbols – R_z.

substrate and the GaMnAs epilayer thus reducing the compressive strain within the film [20]. Since an in-plane anisotropy has been observed in the reference sample, one may expect that co-doping GaMnAs with Be may initiate two opposite effects, namely enhancement of the in-plane anisotropy due to the increase in the hole concentration and producing the out of plane anisotropy due to the reduction of the compressive strain. Since the out-of-plane anisotropy is dominant in the studied GaMnAs:Be epilayers, we may conclude that the sign and magnitude of the strain within the epitaxial layer effects on the magnetic anisotropy in GaMnAs stronger then the carrier concentration.

Fig. 3 presents the temperature dependences of R_x and R_z. It can be seen from this figure that R_x and R_z monotonously increase for all the crystallographic directions. Moreover, the results presented in Fig. 3 show that the out-of-plane anisotropy continues to dominate at the increase in temperature. The in-plane component of the easy axis also remains constant in the investigated temperature range. Such behavior of the in-plane component of the easy axis in GaMnAs:Be is different from the data observed for the GaMnAs LT MBE grown on GaAs substrates. For such samples, rotation of the easy axis from the ⟨100⟩ to the ⟨110⟩ crystallographic direction at the increase in temperature has been detected by magnetoresistance [17], spontaneous photomagnetoelectric effect [28] and direct magnetization measurements [29]. Reorientation of the easy axis in GaMnAs results from the competition between the uniaxial and biaxial contributions to the magnetic anisotropy. At low temperatures, the contribution related to the biaxial anisotropy dominates and determines the orientation of the easy axis along the ⟨100⟩ directions. With the increase in temperature, this term decays more rapidly as compared to those related to the uniaxial anisotropy, which become dominant and determining the orientation of the easy axis along the ⟨110⟩ directions [16]. Hence, our data indicate that in the GaMnAs co-doped with Be, the biaxial anisotropy dominates in the entire investigated temperature range.

4. Conclusions

In this study, we have used magnetoresistance measurements to investigate the behavior of magnetic anisotropy in Be co-doped GaMnAs epitaxial layers. It has been found out that co-doping with Be changes magnetic anisotropy from the in-plane one in the reference GaMnAs sample to the out-of-plane anisotropy in the GaMnAs:Be epitaxial layer. Analysis of the physical mechanisms, which may be responsible for the reorientation of the easy axis in the Be co-doped GaMnAs has shown that the sign and the magnitude of the strain within the GaMnAs epitaxial layer strongly effects on the magnetic anisotropy, whereas the changes in the hole concentration due to the Be doping is less pronounced. Study of the temperature dependence of AMR has shown that the orientation of the in-plane component of the easy axis remains constant in the GaMnAs:Be. This indicates domination of the biaxial anisotropy in the entire investigated temperature range.

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Nasirov A.A.: formal analysis, investigation, project administration.

Yuldashev Sh.U.: methodology, formal analysis, supervision, project administration, funding acquisition, writing – original draft.

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Анізотропний магнітоопір GaMnAs:Be

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Анотація. За допомогою вимірювань магнітоопору досліджено вплив легування Be на магнітну анізотропію в епітаксійних шарах $Ga_{0.972}Mn_{0.028}As$. Показано, що легування Be приводить до зміни орієнтації як легкої, так і жорсткої магнітних осей у GaMnAs. Вимірювання температурної залежності анізотропного магнітоопору демонструють відсутність змін типу магнітної анізотропії з підвищенням температури. Результати дослідження анізотропного магнітоопору свідчать про те, що величина деформації стиску істотно впливає на параметри магнітної анізотропії в GaMnAs.

Ключові слова: GaMnAs, епітаксійні шари, молекулярно-променева епітаксія, анізотропний магнітоопір, магнітна анізотропія, легка вісь.