DOI 10.1007/s11182-023-02823-5

Russian Physics Journal, Vol. 65, No. 10, February, 2023 (Russian Original No. 10, October, 2022)

EFFECT OF Be CO-DOPING ON ANISOTROPY OF MAGNETORESISTANCE IN GaMnAs EPITAXIAL LAYERS

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UDC 537.622.4

The effect of beryllium co-doping on the magnetoresistance anisotropy in the GaMnAs *layer grown via low-temperature molecular beam epitaxy is investigated in this paper. The magnetoresistance anisotropy is observed in the* GaMnAs:Be *epilayer in the range of fields up to 2000 Oe along [110] and* $[1\bar{1}0]$ *crystalligraphic axes. This anisotropy manifests itself in the different behavior of the temperature dependence of magnetoresistance and can result from the formation of spatially oriented structures in the* GaMnAs *epilayer, which emerge in the bulk of this layer during its growth.*

Keywords: anisotropy, negative magnetoresistance, epitaxial layer, ferromagnetic ordering, GaMnAs:Be.

INTRODUCTION

Since the discovery of the ferromagnetic ordering in solid GaMnAs solutions obtained by low-temperature molecular-beam epitaxy (MBE), it has attracted much attention from research groups engaged in semiconductor physics and semiconductor materials science. One of the most interesting effects observed in GaMnAs epilayers, is the anisotropy of their magnetic and magnetotransport properties. This effect manifests itself in different magnetic properties of the GaMnAs epilayer determined along different crystallographic directions, including equivalent ones [1−3].

To date, it is found that the behavior of the magnetic and magnetotransport anisotropy in GaMnAs epilayers, depends on the mechanical stress and its sign in the bulk epilayer, temperature, and concentration of charge carriers [4−8]. Lately, it has been shown that the anisotropy parameters of GaMnAs epilayers can be modified through co-doping with nonmagnetic impurities. According to [9], co-doping with the phosphorus impurity changes the orientation of the easy magnetic axis of GaMnAs epilayers. Chang *et al*. [9] associate this effect with the change in mechanical stresses in the GaMnAs epilayer due to the introduction of the phosphorus impurity in its crystal lattice. In our early research [10], we show that co-doping with the beryllium impurity modifies the temperature dependence of the magnetoresistance anisotropy in GaMnAs epilayers. But the nature of this effect remains essentially unstudied. These results arouse interest in co-doping with nonmagnetic impurities affecting the magnetic and magnetotransport anisotropy of GaMnAs epilayers. In this work, we study the influence of beryllium co-doping on the magnetoresistance anisotropy of ferromagnetic GaMnAs epilayers.

SAMPLE PREPARATION AND EXPERIMENTAL TECHNIQUE

The GaMnAs epilayer co-doped with beryllium (GaMnAs:Be), was obtained by low-temperature molecular-beam epitaxy (MBE) onto a semi insulating GaAs substrate with the (001) crystallographic orientation. During MBE,

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the substrate temperature was 275°C. During the growth, the temperature of Mn and Be effusion cells was 860 and 1100°C, respectively. The thickness of these epitaxial layers was varied between 250 and 300 nm. In general, the epilayer technology was similar to that described in [10, 11]. The structural homogeneity of the epilayer was controlled by the reflection high-energy electron diffraction (during the layer growth) and the X-ray diffraction (XRD) analysis. Both methods demonstrated no phase separation processes in growing GaMnAs:Be epilayers. The Mn impurity concentration in these epilayers was identified as 0.78 at.% using a JEOL JXA-8600 SuperProbe Scanning Electron Microscope Probe X-Ray Microanalyzer. The JXA-8600 SuperProbe did not allow to determine the beryllium concentration in the epilayer. At the same time, since this element is an effective acceptor with 0.03 eV ionization energy [12], the concentration of the electrically active fraction of the Be impurity in the GaAs substrate, can be obtained from measuring the content of the charge carriers. The GaAs epilayer doped with beryllium during the growth, was obtained to determine the concentration of the Be impurity. Since low-temperature MBE synthesized GaAs epilayers differ by the higher content of the donor-type defects, the GaAs:Be epilayer was grown at the substrate temperature of 600°C to eliminate the defect influence on the content of the charge carriers. The latter determined for measuring the Hall effect at room temperature in the GaAs:Be epilayer, was $2.8 \cdot 10^{19}$ cm^{-3}, that matched a 0.05 at.% concentration of electrically active Be atoms. Nevertheless, according to Bak-Misiuk *et al.* [13], not all Be atoms were electrically active in the GaAs:Be epilayer. Thus, at the Be concentration of about $5 \cdot 10^{19}$ cm^{-3}, the content of electrically active Be atoms was ~50% of their total concentration. We therefore, could estimate that in the studied epilayers, the Be content was approximately 0.1 at.%.

The content of the charge carriers in the GaMnAs:Be epilayer determined at room temperature, is $1.6 \cdot 10^{19}$ cm^{-3}, which is almost 2 times lower than in the GaAs:Be epilayer. This decrease can be explained by the above mentioned process of compensation of acceptor Be and Mn impurities by the donor-type defects forming in the bulk epilayer during its low-temperature MBE.

According to the XRD analysis, the constant lattice parameters in the direction normal to the plane of the epitaxial layer, are 5.6669 Å for GaMnAs:Be and 5.6759 Å for GaMnAs epilayers, while the in-plane parameter is 5.6533 Å for both epilayers, which matches the GaAs lattice parameter. Thus, co-doping with beryllium leads to a 60% reduction in the parameter mismatch between the substrate crystal lattice and the growing epilayer.

The Curie point of these epilayers is 45 K, which is determined by the temperature dependence of the anomalous Hall effect [14]. Magnetoresistance is measured by using the four-point probe method in the van der Pauw geometry. During these measurements, the magnetic field is oriented normal to the sample surface.

For comparison of results obtained for different crystallographic axes, magnetoresistance is described by the normalized magnetoresistance R_H, which is determined as

$$R_H = \frac{R(H) - R(0)}{R(0)},$$

where $R(H)$ is the resistance obtained at the specified magnetic field, $R(0)$ is the resistance in the absence of the magnetic field.

In order to identify the effect from the Be impurity on the GaMnAs epilayer magnetoresistance anisotropy, we compared the obtained results with those presented in [15] for the GaMnAs epilayer without the Be impurity and grown under the similar MBE conditions.

RESULTS AND DISCUSSION

Figure 1 presents dependences between R_H value of the GaMnAs:Be epilayer measured along the different crystallographic axes at 20 K. Note that the dependence $R_H(H)$ is not monotonous. At $H = 500$ Oe, a slight positive magnetoresistance is observed for all axes, which disappears with the magnetic field growth. Starting from several values $H > H_t$, the dependence $R_H(H)$ becomes linear. The value H_t is 1500 Oe for the [110] crystallographic axis and 2000 Oe for other axes.

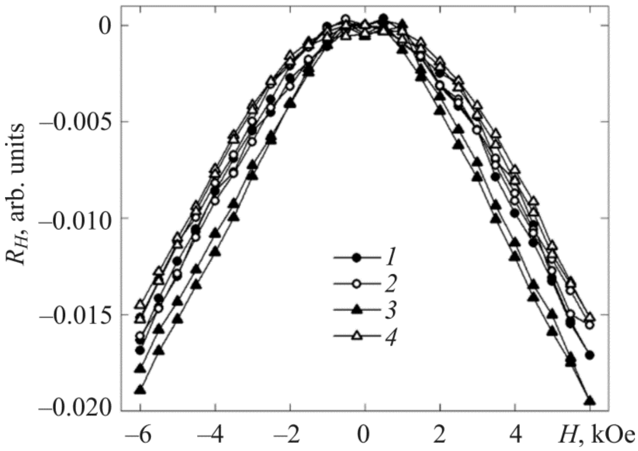

Fig. 1. Magnetoresistance of GaMnAs:Be epilayer measured along different crystallographic axes at 20 K: *1* – [010], *2* – [100], *3* – [110], *4* – [1$\bar{1}$0].

The dependence between the magnetoresistance and external magnetic field observed in Fig. 1, is determined by the fact that in diluted magnetic semiconductors in the ferromagnetic ordering state, the magnetoresistance nature within the high and weak magnetic fields, is determined by different mechanisms. In weak magnetic fields, the processes associated with the reorientation of the epilayer magnetization most of all contribute to the magnetoresistance. In the case of the perpendicular orientation of the magnetic field relative to the current passing through the epilayer, these processes lead to the formation of positive magnetoresistance. In high magnetic fields, where the reorientation of the epilayer magnetization completes, the processes associated with the change in the localization of the charge carriers, predominate. These processes provide the formation of negative magnetoresistance [16]. Positive magnetoresistance observed in the magnetic field lower than 500 Oe, indicates that at the given H values, the contribution of processes associated with the epilayer magnetization reorientation, dominate the contribution of processes associated with the change in the localization of the charge carriers. The linear dependence $R_H(H)$ at the magnetic field higher than H_t, relates to the magnetic ordering in the GaMnAs:Be epilayer. The contribution of processes associated with the magnetization reorientation disappears, and magnetoresistance is determined only by the processes associated with the change in the localization of the charge carriers.

To characterize the slope angle of the linear part of magnetoresistance dependences in magnetic fields higher than H_t, let us use the value R_x:

$$R_x = \frac{R_H(H_{\max}) - R_H(H_t)}{|H_{\max}| - |H_t|},$$

where $H_{\max}$ is the maximum magnetic field obtained during measurements, $|H_{\max}|$ and $|H_t|$ are numerical values of $H_{\max}$ and H_t, $R_H(H_{\max})$ and $R_H(H_t)$ are values of R_H at the magnetic field $H_{\max}$ and H_t, respectively. It should be noted that in our epilayers, R_x value differs for different crystallographic directions. The highest R_x value is $-3.38 \cdot 10^{-6}$ for the [100] crystallographic axis and the lowest is $-3.89 \cdot 10^{-6}$ for the [010] crystallographic axis.

According to the comparison of the GaMnAs:Be epilayer magnetoresistance and the data obtained earlier for the GaMnA epilayer, positive magnetoresistance of the GaMnAs:Be epilayer is weaker and disappears at lower H values in contrast to positive magnetoresistance of the GaMnAs epilayer. Moreover, Be co-doping results in a decrease in the magnetoresistance dependence in magnetic fields higher than H_t. The value R_x determined in [15] for the GaMnAs epilayer, is 2−3 times higher than that determined in this work. It is worth noting that in the GaMnAs:Be epilayer, the difference in the value R_x measured along different crystallographic directions, is not so pronounced as in the epilayer without the Be impurity.

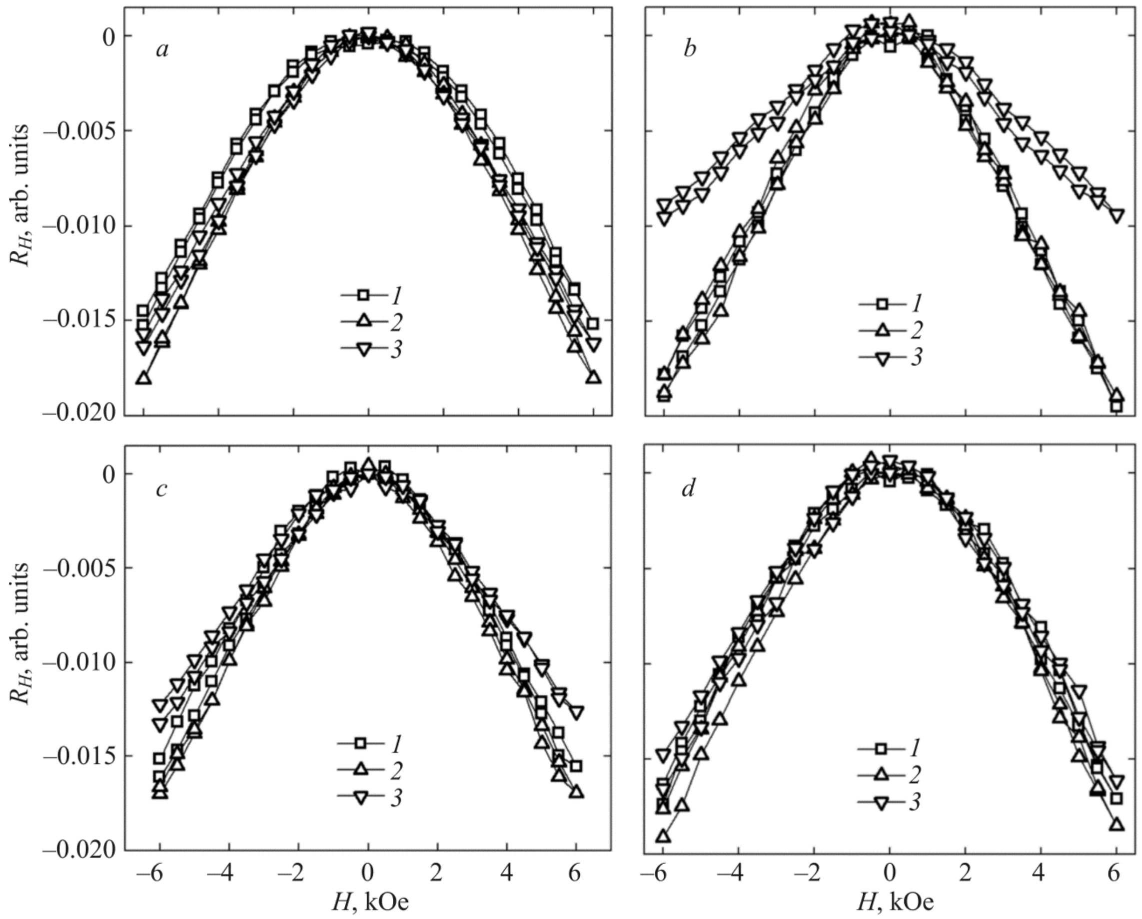

Fig. 2. Magnetoresistance of GaMnAs:Be epilayer measured along different crystallographic directions: *a* – $[1\bar{1}0]$, *b* – [110], *c* – [100], *d* – [010]. Measurement temperature: *1* – 20 K, *2* – 30 K, *3* – 40 K.

Figure 2 contains $R_H(H)$ plots for the GaMnAs:Be epilayer obtained in the temperature range of 20–40 K. Pay attention to the disappearance of positive magnetoresistance with the temperature rise. However, in the magnetic field not exceeding H_t, the dependence $R_H(H)$ weakly depends on temperature. At the magnetic field exceeding H_t, one can see a change in the slope angle of the linear part of the dependence $R_H(H)$, and this change depends on the crystallographic axis.

In Fig. 3, temperature dependences are given for the value R_x determined along different crystallographic directions. The temperature dependence of the value R_x is non-monotonous and shows the minimum at 30 K. Despite the qualitative coincidence of the behavior of these temperature dependences along different crystallographic directions, they differ quantitively. The value R_x identified for the $[1\bar{1}0]$ crystallographic direction, changes by more than 2 times with increasing temperature, while for the [110] crystallographic direction, it is 5%. A change in the value R_x determined along [100] and [010] directions, is 35 and 16%, respectively. It is interesting to note that the greatest difference in the temperature dependence of the value R_x is observed for the equivalent $[1\bar{1}0]$ and [110] directions, while for [100] and [010] directions, this difference is weakly pronounced. The different behavior of the temperature dependence of the value R_x determined along different crystallographic directions, indicates to the anisotropy of magnetotransport properties of the GaMnAs:Be epilayer in the magnetic field higher than H_t. The magnetoresistance anisotropy effect intensifies when approaching to the Curie point.

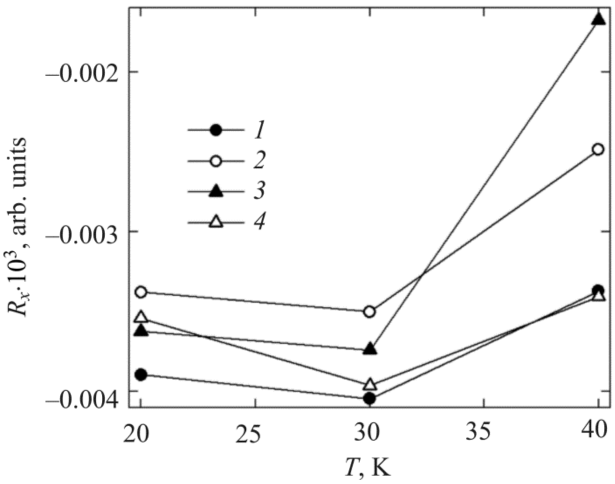

Fig. 3. Temperature dependences of slope angle of $R_x(H)$ dependence along different crystallographic axes at the magnetic field $H > H_t$: *1* – [010], *2* – [100], *3* – [110], *4* – [1$\bar{1}$0].

In general, the analysis of the $R_H(H)$ dependence behavior with the temperature rise shows that the anisotropy in the magnetic field below H_t, is weaker than in the magnetic field higher than H_t.

According to the comparison of the temperature dependence of magnetoresistance of GaMnAs:Be and GaMnAs epilayers, Be co-doping significantly modifies the anisotropy behavior. The most significant changes are observed in the magnetic field lower than H_t. Both in GaMnAs:Be and GaMnAs epilayers, at the magnetic field lower than H_t, we observe the magnetoresistance anisotropy along [110] and [1$\bar{1}$0] crystallographic directions. However, in co-doped epilayers, the anisotropy effects are weakly pronounced and weakly depend on temperature. In the magnetic field higher than H_t, the magnetoresistance anisotropy is observed mostly along [1$\bar{1}$0] and [110] crystallographic directions of both GaMnAs:Be and GaMnAs epilayers.

Let us consider mechanisms, which determine the influence of the Be impurity on the magnetoresistance anisotropy behavior in the GaMnAs epilayer. It is presently found that the anisotropy effects in this layer depend on the mechanical stress and its sign in the bulk epilayer. Thus, in the magnetic field range, where the anisotropy effects are determined by the reorientation of the magnetic moment, they dominate in the plane of epilayers under the compressive strain, whereas under the tensile strain, the anisotropy dominates in the direction normal to the epilayer plane [5]. As is mentioned above, Be co-doping significantly decreases the parameter mismatch between the GaAs substrate crystal lattice and the growing GaMnAs:Be epilayer, thereby reducing the compressive strain in its bulk. Thus, a significant weakening of the in-plane magnetoresistance anisotropy in the GaMnAs:Be epilayer at the magnetic field below H_t, can be associated with the change in the behavior of dominating anisotropy effects caused by the stress decrease in the co-doped GaMnAs epilayer.

At the same time, the magnetoresistance anisotropy is observed in epilayers at the magnetic field higher than H_t, when the reorientation of magnetic moments in the bulk epilayer already completes. To the authors' opinion, this indicates that the nature of the magnetoresistance anisotropy at the magnetic field lower than H_t, differs form that at the magnetic field higher than H_t. According to [15], negative magnetoresistance anisotropy in the GaMnAs epilayer observed at the magnetic field higher than H_t, can be associated with spatially oriented structures forming in the epilayer due to the non-uniform distribution of the Mn impurity. These structures appear during the growth of the epitaxial layer and are oriented along the <110> crystallographic direction. The magnetoresistance anisotropy in the GaMnAs:Be epilayer probably indicates that such spatially oriented structures are present in its bulk also. The fact that the magnetoresistance anisotropy in GaMnAs and GaMnAs:Be epilayers is mostly observed along [110] and [1$\bar{1}$0] axes, indicates to the similar spatial orientation of these structures in both epilayers.

CONCLUSIONS

This research clearly showed the presence of the magnetoresistance anisotropy in the GaMnAs epilayer co-doped with beryllium, along [110] and $[1\bar{1}0]$ crystallographic axes, which were equivalent to each other in the undeformed GaAs structure. It was shown that at the magnetic field over 2000 Oe, the anisotropy was manifested in the difference in the temperature dependence of the slope angle of the linear part of the magnetoresistance measured along different crystallographic directions. At the magnetic field over 2000 Oe, the anisotropy could result from the presence of spatially oriented structures in the bulk epilayer appeared due to the non-uniform distribution of the Mn impurity in the growing epilayer. These structures formed during the MBE growth of GaMnAs and GaMnAs:Be epilayers, were oriented in one direction. That fact indicated that the mechanical stress reduction observed after co-doping the GaMnAs epilayer with the Be impurity, did not affect the orientation of such structures. At the same time, at the magnetic field lower than 2000 Oe, the mechanical stress reduction led to a significant weakening of the magnetoresistance anisotropy in the GaMnAs:Be epilayer as compared to the GaMnAs epilayer without the Be impurity.

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