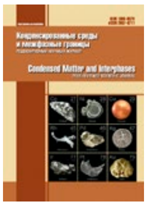

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Spontaneous photomagnetoelectric effect in ferromagnetic GaMnAs epitaxial layers

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Abstract

Spontaneous photomagnetoelectric effect in ferromagnetic GaMnAs epitaxial layers has been investigated. The goal of this work is to study the temperature dependence of the spontaneous PME effect, determined along [110] and $[1\bar{1}0]$ crystal axes. GaMnAs layers with Mn concentration of 2.9 atomic percent studied in this paper were grown by low-temperature molecular beam epitaxy on semi-insulating GaAs (001) substrate. It was shown that below Curie temperature in the illuminated GaMnAs epilayers a transverse voltage (photo-EMF) was observed. This photo-EMF is associated with the photomagnetoelectric effect resulting from the separation the photogenerated carriers by the intrinsic magnetic field of the semiconductor matrix in ferromagnetic state. The temperature dependence of intrinsic photomagnetoelectric effect in GaMnAs epilayer was determined along [110] and $[1\bar{1}0]$ crystallographic axes. It was found that the photo-EMF measured along [110] crystal axis exhibits a maximum at temperatures of 35–40 K, while the photo-EMF measured along $[1\bar{1}0]$ axis increases monotonically with temperature decay. It was shown that the non-monotonous temperature dependence of the photomagnetoelectric effect along [110] axis can arise due to the reorientation of the easy axis of the sample with decreasing temperature.

Keywords: GaMnAs, Photomagnetoelectric effect, Molecular beam epitaxy, Ferromagnetic ordering, Curie temperature, Photoconductivity

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1. Introduction

Nowadays, semiconductor GaMnAs solid solutions obtained by means of low-temperature molecular beam epitaxy (LT-MBE) are of great interest for scientists specializing in semiconductor materials. This is explained by the fact that low-temperature epitaxial growth (250–300 °C) allows obtaining GaMnAs solid solutions with a concentration of Mn which is several times higher than its solubility limit in the semiconductor matrix of gallium arsenide [1–2]. The presence of a large number of Mn magnetic ions enables ferromagnetic ordering in GaMnAs epitaxial layers. As a result, these materials combine semiconductor and magnetic properties, which is impossible for materials obtained by traditional methods [3–5].

It is known that spontaneous magnetization occurring in ferromagnetic materials at temperatures below the Curie temperature (T_C) enables the origin of spontaneous galvanomagnetic effects in such materials, which are observed without an external magnetic field [6-8]. For GaMnAs, the most well-studied are the Hall and Nernst effects, known as the anomalous (spontaneous) Hall effect and the anomalous Nernst effect [9–11]. We should also note that the epitaxial layers of GaMnAs grown on GaAs substrates by means of LT-MBE can also demonstrate the spontaneous photomagnetoelectric (PME) effect that manifests itself as the transverse voltage (photo-EMF) occurring when the materials are illuminated and the external magnetic field is zero [12]. Indeed, in epitaxial GaMnAs grown on GaAs substrates, the easy axis of magnetization and therefore the spontaneous magnetization vector $\boldsymbol{M}_0$ are in the plane of the film [13, 14]. Then, when illuminating the surface of the epitaxial layer, the flow of photogenerated charge carriers from the surface to the depth of the epitaxial layer will be perpendicular to vector $\boldsymbol{M}_0$, which accounts for the formation of transverse photo-EMF. However, up to now, the photomagnetoelectric effects of GaMnAs have not been thoroughly studied. Therefore, the purpose of our study was to investigate a spontaneous PME effect in the epitaxial layers of GaMnAs in the state of ferromagnetic order and determine the dependence of the effect on temperature and crystallographic orientation.

2. Experimental

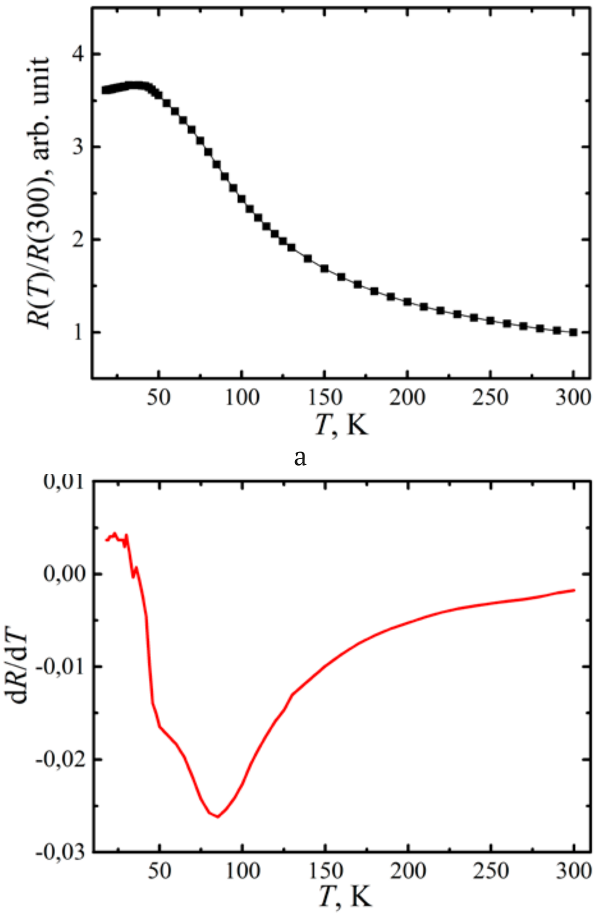
The epitaxial layers of GaMnAs investigated in our study were obtained via LT-MBE on a semi-insulating GaAs (001) substrate. Prior to the growth of the GaMnAs layers, a 200 nm GaAs buffer layer was grown at a temperature T_S = 580–600 °C to heal the surface defects. Then the temperature of the substrate was lowered to 250 °C in order to grow GaMnAs layers. The thickness of the resulting GaMnAs epitaxial layers was 300 nm. The method of obtaining epitaxial layers used in our study is generally similar to the one presented in [15]. The quality of the obtained layers was controlled by means of X-ray diffraction analysis and (during the growth process) reflection high-energy electron diffraction. Both methods demonstrated that the obtained epitaxial films were homogeneous and did not contain any additional crystalline phases. The concentration of Mn in GaMnAs was measured by means of energy dispersive X-ray spectroscopy (EDX) using a JEOL JSM IT 200 electron microscope and was 2.9 at. %. To study the magneto-transport properties and the PME effect, a pattern was formed on the surface of the samples by the photolithography method. The pattern presented two mutually perpendicular Hall bars with side contacts. These bars were oriented along the [110] and [$1\bar{1}0$] crystal axes. The contacts on the GaMnAs surface were created using an indium solder applied to the surface of the epitaxial layer at a temperature of 220–230 °C.

3. Results and discussion

The Curie temperature (T_C) of the studied epitaxial layer was determined based on the temperature dependence of its resistance (R). As it was shown in [16] the temperature dependences $R(T)$ in GaMnAs demonstrated a specific feature in the form of an inflection point near the paramagnetic-ferromagnetic phase transition. This feature is accounted for by the change in the dominating mechanism of charge carrier scattering. The position of the inflection point can be used to determine T_C with high accuracy. Fig. 1 demonstrates the temperature dependences of the resistance $R(T)$ and its first derivative $dR(T)/dT$ for the studied GaMnAs layer. The dependence of $R(T)$ was measured in the dark with no external magnetic field. For the convenience of presentation, $R(T)$ was normalized to the value of $R(300)$, where $R(300)$ is the resistance of the sample at room temperature. $dR(T)/dT$ values were determined by means of numerical differentiation of $R(T)$.

The temperature dependence $dR(T)/dT$ shown in fig. 1b demonstrates a pronounced minimum corresponding to the inflection point on the dependence $R(T)$. The position of the minimum can be used to determine the T_C of the studied epitaxial layer in the range of 80–85 K. We should note that at temperatures higher than T_C the resistance of the sample monotonously increases following a decrease in temperature. This indicates the semiconductor nature of the electrical conductivity of the studied GaMnAs epitaxial layers.

To study the PME effect, the investigated samples were illuminated with a white LED. The illumination intensity was controlled by the current value I_L in the LED. When illuminated, the samples demonstrated lower resistance, which indicates the presence of photoconductivity effects in GaMnAs. Fig. 2 presents the temperature dependence of the photoconductivity of the studied samples determined at I_L = 1–3 mA. The photoconductivity of the samples was characterized by ΔR determined as $\Delta R = (R_I - R_0)/R_0$, where R_0 is the dark resistance of the sample and R_I is the resistance of the sample illuminated with a LED. The dependences show that the photoconductivity of the studied samples is observed at temperatures below 100 K and ΔR monotonously increasing with a decrease in temperature. This kind of behavior of the temperature dependence of photoconductivity appears to be quite predictable, taking into account the fact that the semiconductor nature of electrical conductivity results in a monotonous decay in the concentration of charge carriers with decreasing temperature. Obviously, if the number of photogenerated charge carriers in the semiconductor matrix does not depend on the temperature (or depends only insignificantly), the difference between the light and dark resistance of the sample and hence ΔR will increase with



a

b

Fig. 1. *a* – temperature dependence of the resistance of the GaMnAs epitaxial layer normalized to the value of resistance measured at 300 K ($R(300)$); *b* – temperature dependence of dR/dT of the GaMnAs epitaxial layer

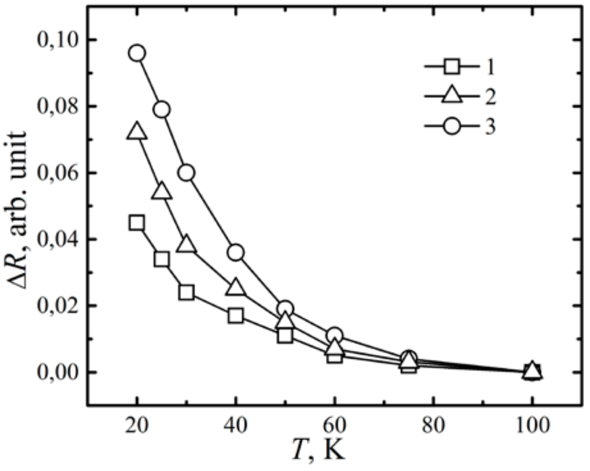


Fig. 2. Temperature dependence of the photoconductivity of GaMnAs measured at various values of the LED current: *1* – I_L = 1 mA; *2* – I_L = 2 mA; *3* – I_L = 3 mA

a decrease in temperature. At the same time, at temperatures above 100 K, the concentration of photogenerated charge carriers is negligibly small as compared to the thermodynamically equilibrium concentration of charge carriers in GaMnAs. Therefore, there is practically no photoconductivity effect at such temperatures.

Fig. 3 shows dependences of the photo-EMF – U_I in the studied epitaxial layer on the temperature measured along the [110] and $[1\bar{1}0]$ crystal axes at I_L = 2 and 3 mA. The dependences demonstrate that U_I increases with greater illumination of the sample. We believe that the fact that photo-EMF in the studied samples is only observed starting with temperatures lower than T_C indicates that this photo-EMF is accounted for by the PME effect, which occurs because the flow of photogenerated charge carriers is divided by the intrinsic magnetic field of the semiconductor matrix in the state of ferromagnetic ordering. It should be noted that U_I, measured along the $[1\bar{1}0]$ crystal axes monotonously increases with lower temperatures, while the temperature dependence of U_I, measured along the [110] crystal axis demonstrates a local maximum at 34–36 K.

The difference in the temperature dependences of U_I measured along different crystal axes can be explained taking into account the fact that the PME effect depends on both the absolute value of vector $\boldsymbol{M}_0$ and its orientation with regard to the direction of measurements. It is obvious that at a set magnetization value of the sample, U_I varies from maximum values (when the measurements are performed perpendicular to vector $\boldsymbol{M}_0$) to zero (when the measurements are performed along the direction of vector $\boldsymbol{M}_0$). Without an external magnetic field, the magnetization vector is oriented towards the easy axis of magnetization of the sample. In GaMnAs, the degree of ferromagnetic ordering and therefore the absolute value of vector $\boldsymbol{M}_0$ monotonously increase with a decrease in the temperature. At the same time, the existing experimental data demonstrates that the orientation of the easy axis of magnetization in the epitaxial layers of GaMnAs in the state of ferromagnetic ordering is not constant. It depends on the dominant type of magnetocrystalline anisotropy and temperature [17,18]. When the concentration of photogenerated charge carriers does not depend on temperature, the temperature dependence of U_I is determined by the temperature dependence of the absolute value of vector $\boldsymbol{M}_0$ and the temperature dependence of its orientation with regard to the [110] and $[1\bar{1}0]$ crystal axes. In this regard, the non-monotonic behavior of the temperature dependence of U_I along the [110] axis can be explained by a decrease in the angle between vector $\boldsymbol{M}_0$ and the crystal axis at a temperature of 35–40 K. At the same time, the angle between the magnetization vector of the sample and the $[1\bar{1}0]$ crystal axis, on the contrary, increases, as evidenced by the increase in the rate of change in U_I observed for this axis in the same temperature range. Particularly, this can be the case, when the easy axis of magnetization in the epitaxial layer is reoriented from <110> to <100> direction with decreasing of temperature, as observed for GaMnAs in [17–19].

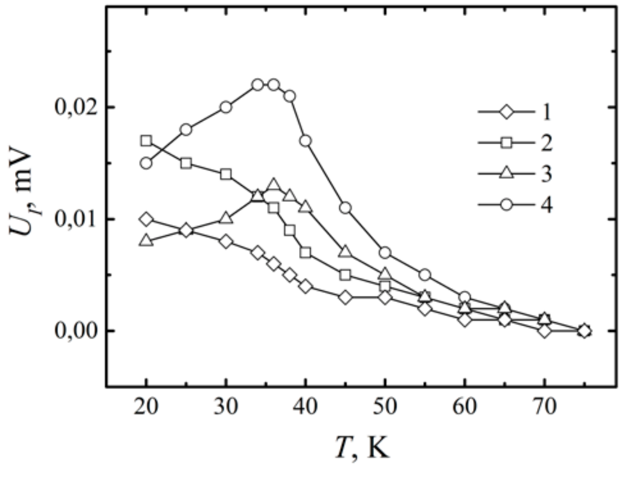


Fig. 3. Temperature dependence of the photo-EMF measured along $[1\bar{1}0]$ (curves 1 and 2) and [110] (curves 3 and 4) crystal axes at I_L = 2 mA (curves 1 and 3) and I_L = 3 mA (curves 2 and 4)

4. Conclusions

Our study demonstrated that at temperatures below T_C illuminated GaMnAs epitaxial layers demonstrate transverse photo-EMF, which can be explained by a spontaneous PME effect in the semiconductor matrix in the state of ferromagnetic ordering. This effect is associated with the interaction of photogenerated charge carriers with the intrinsic magnetic field of the semiconductor matrix. For the first time we studied the temperature dependence of the spontaneous PME effect for the [110] and [$1\bar{1}0$] crystal axes. The study demonstrated that the temperature dependences of the PME effects measured along the [110] and [$1\bar{1}0$] axes of GaMnAs epitaxial layer are significantly different. We believe that the observed difference can be explained by the fact that the value of the spontaneous PME effect is determined by both the absolute magnetization value of the sample and the orientation of the magnetization vector $\boldsymbol{M}_0$ with regard to the crystal axes along which the PME effect was measured. In this case, the non-monotonic behavior of the photo-EMF measured along the [110] axis can be explained by the reorientation of the easy axis of magnetization in the epitaxial layer from <110> to <100> directions, which is observed with decrease of temperature and a corresponding decrease in the angle between the spontaneous magnetization vector and the [110] crystal axis.

Author contributions

Parchinskiy P. B. – scientific leadership, research concept, final conclusions, conducting research, text writing, and editing. Gazizulina A. S. – conducting research, processing the results, text writing, editing, and preparing the article for publication. Nusretov R. A. – conducting research and processing the results and their interpretation.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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