Giant transverse magnetoresistance in an asymmetric system of three GaAs/AlGaAs quantum wells in a strong magnetic field at room temperature

V.I. Tsebro*, O.E. Omel’yanovskii, V.V. Kapaev, Yu.V. Kopaev
P.N. Lebedev Physics Institute, Russian Academy of Science, 117924 Moscow, Russia

V.I. Kadushkin
Scientific-Research Technological Institute, 390011 Ryazan’, Russia
(December 25, 1996)

The giant transverse magnetoresistance is observed in the case of photinduced nonequilibrium carriers in an asymmetric undoped system of three GaAs/AlGaAs quantum wells at room temperature. In a magnetic field of 75 kOe, the resistance of nanostructure being studied increases by a factor of 1.85. The magnetoresistance depends quadratically on the magnetic field in low fields and tends to saturation in high fields. This phenomenon is attributed to the rearrangement of the electron wave function in magnetic field. Using the fact that the incoherent part of the scattering probability for electron scattering on impurities and bulk defects is proportional to the integral of the forth power of the envelope wave function, the calculated field dependence of the magnetoresistance is shown to be similar to that observed experimentally.

In our previous paper [1] we studied for the first time in detail the lateral photogalvanic effect (PGE) in an asymmetric system of three GaAs/AlGaAs wells illuminated with white light of various intensities in a strong magnetic field. The spontaneous PGE current $J_{\text{PGE}}$ was shown to exhibit a maximum as a function of magnetic field $H$, the phenomenon earlier predicted theoretically in [2]. We have also found that, at room temperature, the PGE voltage reaches the value of several tenths of Volt per millimeter of the specimen length in the illuminated region, and exhibits only a weak dependence on the light intensity. The temperature dependence of PGE was found to be rather weak: $J_{\text{PGE}}$ decreases by a factor of two upon cooling from room temperature to $\sim 200$ K.

The conclusion [2] about the maximum of $J_{\text{PGE}}$ vs $H$ follows from an analysis of the expression for the toroidal moment density $T$, to which the spontaneous PGE current is proportional. On the other hand, we have also proposed [1] that such a maximum may be caused by a strong transverse magnetoresistance (TMR) of the nanostructure. Therefore, it was of interest to measure the TMR and its field dependence, particularly at high, room temperature, where the PGE was shown to be the largest.

In the present paper, we report the results of investigation of the TMR in the asymmetric system of three quantum wells, whose structure (see Fig. 1) was exactly the same as in our previous paper [1]. Namely, the samples of the $i$-Al$_x$Ga$_{1-x}$As/$i$-GaAs ($x=0.25$) nanostructures containing three quantum wells with layer of width $L_B = 54, 60$ and 70 Å separated by barrier layers of width $L_B = 20$ and 30 Å were investigated. This asymmetric system of tunneling-coupled quantum wells was sandwiched between two wide (200 Å) $i$-Al$_x$Ga$_{1-x}$As ($x=0.25$) barriers layers adjacent to an $i$-GaAs (1 µm) buffer layer and to an $i$-GaAs (200 Å) layer covering the structure.

The samples were rectangular with dimensions of the order of $8 \times 2$ mm with single pair of in-line contacts (1, 2 in Fig. 1). The contacts were produced by the allowing in of indium. The measurements were carried out at room temperature in a specially designed “warm-field” insert of a superconducting solenoid. Light from a halogen lamp was delivered to the sample along a flexible optical fiber. The maximum power of the radiation delivered to the sample was of the order of 5 mW. The contacts and the adjacent parts of the samples were covered with a special shield (3), so that only the central part of the sample was illuminated. The samples were oriented with the plane of the layers parallel to the magnetic field and with the line of the contacts perpendicular to the magnetic field.

The measurement circuit shown in Fig. 1 was a simple closed one with the sample connected in series with a source of controllable DC bias voltage $E_v$ and a standard measuring resistance $R_n$. The current $J$ in the circuit was determined from the voltage drop across the $R_n$. Note that the measured current was essentially the short-circuit current $J_{sc}$, since the resistance of the samples (of order of 100 MΩ under nominal illumination) was much larger than $R_n$ (10 kΩ). During the experiments, the magnetic field dependencies $J(H)$ were measured at different $E_v$ and nominal fixed illumination. As the magnetic field was scanned bidirectionally from $-75$ kOe to 75 kOe, the measured values of $J$ were stored and averaged over a large number of readings.

Figure 2 shows the magnetic field dependencies $J(H)$ measured at different bias voltages $-6$ V < $E_v$ < 6 V. The odd curve $J(H)$ (at $E_v = 0$) represents the magnetic field dependence of the spontaneous PGE current $J_{\text{PGE}}(H)$, that was investigated in details earlier in paper [1]. As positive or negative bias voltage is applied,
the \( J(H) \) curves are shifted up or down. At the same time, a strong decrease of the absolute values of the current with increasing magnetic field is observed, i.e. a high magnetoresistance becomes apparent.

The \( J(E_v) \) values at given \( H \) enable us to judge to what extent the current–voltage characteristics of the samples are linear and symmetric in so wide range of bias voltage. The data presented in Fig. 2 reveal that the current–voltage characteristics are linear and symmetric with the accuracy to within several percents throughout the studied \( E_v \) and \( H \) ranges. Special tests showed that the degree of nonlinearity and asymmetry primarily depends on the quality (symmetry) of the contacts and show a noticeably tend to reduction with increasing magnetic field.

Since, contrary to PGE, the magnetoresistance is an even function of \( H \), the procedure of obtaining its magnetic field dependence and excluding the contribution of PGE consists in subtracting the \( J(H) \) dependence measured at negative \( E_v \) from that measured at positive \( E_v \): \( R(H) = 2E_v/(J^+(H) - J^-(H)) \). The magnetic field dependencies of the magnetoresistance obtained using this procedure for both low (1 V) and high (6 V) absolute values of \( E_v \) are shown in Fig. 3 as \( \Delta R(H)/R(0) \). A small difference between these two curves can be related to a weak field-dependent nonlinearity of the current–voltage characteristics. In low magnetic fields (\( H < 10 \) kOe), the magnetoresistance is a quadratic function of \( H \). In high fields, a tendency to saturation is seen. In a maximum field of 75 kOe used in present measurements, the resistance of the nanostructure increased by a factor 1.85.

For interpretation of the data obtained, calculation of the energy spectrum and the wave functions for the studied asymmetric nanostructure has been performed by the envelope method in a magnetic field normal to the plane of the sample (\( x \)-axis). Figure 4 (curves 1–3) shows the magnetic field dependencies of the probabilities for an electron to be located in the corresponding (according to the number in Fig. 1) quantum well in the minimum of the first conduction subband of the spatial quantization. Note that the nanostructure studied was specially designed in such a way that, in zero magnetic field, the probabilities for electrons to be located in the ground state in the narrower quantum wells (1 and 2) are rather high. As seen from Fig. 4 (curve 3), the magnetic field induced rearrangement of the wave function leads to the localization of electrons in the widest well that certainly affects the conductivity (resistivity) of the nanostructure in the lateral direction.

The resistivity of the nanostructure in the lateral direction is determined by the electron scattering on the heterojunction imperfections, residual impurities, and bulk defects. The localization of the wave function in the center of the widest well is likely to reduce the scattering on the heterojunction imperfections and, as a consequence, to decrease the resistivity.

As for the scattering on impurities, it can be shown within the strongly localized potential approximation

\[
U(\vec{r}) = U_0 \delta(\vec{p} - \vec{p}_i) \delta(x - x_i)
\]

(here, \( \vec{p}_i \) is the impurity coordinate in the lateral direction, and \( x - \) along the \( x \)-axis), that the incoherent part of the probability for the electron scattering on such a potential is proportional to

\[
\varphi \sim \int N_S(x)|f_i(x)|^4 dx
\]

\( (N_S \) is the surface concentration of impurity) i.e., for a homogeneous distribution of scattering centers, the scattering probability and, hence, the resistivity of the nanostructure, are proportional to the integral of the fourth power of the envelope wave function.

The magnetic field dependence of \( \varphi \) value is shown by curve 4 in Fig. 4. It is seen that in magnetic field of the order of 160 kOe \( \varphi \) is more than doubled. It is also seen, that the calculated curve \( \varphi(H) \) is similar to the experimental \( R(H) \) dependence, showing the same tendency to saturation but in higher magnetic field. (A tendency to saturation of the experimental \( R(H) \) curve is seen even in a field of 50 kOe.) As mentioned above, a decrease in electron scattering on the heterojunction imperfections with increasing magnetic field should result in reduced resistivity. If so, the competition of the two mechanism, when taken into account in the calculations, may give a better agreement between the calculated and experimental values of the magnetic field where the saturation begins.

It should be noted in conclusion that the observed transverse magnetoresistance of this particular asymmetric nanostructure is certain to have a significant effect on the field dependence of spontaneous PGE current \( J^{PGE}(H) \), but does not explain the nonmonotonic behavior of \( J^{PGE}(H) \) observed in paper [1]. This nonmonotonic behavior of \( J^{PGE}(H) \) is likely to be due to the PGE nature.

This work was partly supported by the Russian Foundation for Basic Research, Project No.95-02-04358-a, and partly by Russian Program “Solid State Nanostructure Physics”, Project No.1-083/4.

[1] O. E. Omel’yanovskii, V. I. Tsebro, and V. I. Kadushkin. 
*JETP Lett.*, **63**, 209 (1996).

[2] A. A. Gorbatsevich, V. V. Kapaev, and Yu. V. Kopaev. 
*JETP Lett.*, **57**, 580 (1993).

FIG. 1. TMR measurement circuit and the structure of the asymmetric system of three GaAs/AlGaAs quantum wells.
FIG. 2. $J(H)$ dependencies at different bias voltages $-6 \text{ V} < E_v < 6 \text{ V}$ (labeled by the numbers at the curves).

FIG. 3. Field dependencies of the magnetoresistance at low (1 V) and high (6 V) absolute values of $E_v$.

FIG. 4. Calculated magnetic field dependencies of the probabilities for an electron to be located in the corresponding (according to the number in Fig. 1) quantum well (curves 1 - 3), and $\varphi$ vs $H$ (curve 4).
\[ \Delta R(H)/R(0) \]

- \( E_v = 1.0 \text{ V} \)
- \( E_v = 6.0 \text{ V} \)

H (kOe)
