Photogalvanic effect in an asymmetric system of three quantum wells in a strong magnetic field

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The photogalvanic effect (PGE) in an asymmetric undoped system of three GaAs/AlGaAs quantum wells illuminated with white light of various intensities is investigated in magnetic fields up to 75 kOe at temperatures ranging from 4.2 K up to 300 K. A maximum of the spontaneous photogalvanic current J^{PGE} as a function of the magnetic field predicted by A. A. Gorbatsevich *et al.*, JETP Lett. **57**, 580 (1993), is observed. Analysis of the experimental data shows that the main initial characteristic of the PGE is not the spontaneous current but rather the electromotive force E^{PGE} arising in the direction perpendicular to the applied magnetic field. It is determined that this emf is independent of the intensity of the incident light, increases linearly with the size d of the illuminated region, and decreases slowly with temperature: $E^{\mathrm{PGE}}_{\mathrm{max}} \sim 0.8$ V at 300 K and ~ 0.1 V at 4.2 K for $d \sim 3$ mm. The curve $E^{\mathrm{PGE}}(H)$ at room temperature is determined with allowance for the strong transverse magnetoresistance of the nanostructure. *© 1996 American Institute of Physics.* [S0021-3640(96)01103-4]

In Ref. 1 it was shown that the photoinduced nonequilibrium character of the carrier distribution function in an asymmetric system of quantum wells in a magnetic field oriented parallel to the layers of a nanostructure results in the appearance of a lateral photogalvanic effect (PGE) — the appearance of a spontaneous current directed along the layers of the nanostructure and perpendicular to the magnetic field. This effect was detected experimentally in Ref. 2 from the displacement of the current–voltage characteristic of an asymmetric GaAs/AlGaAs structure with three tunneling-coupled quantum wells. In Ref. 2 the measurements of the PGE were performed in a weak magnetic field $H \sim 5$ kOe at temperatures $T > 77$ K.

In the present paper we report the results of investigations of the PGE for a similar asymmetric nanostructure in strong magnetic fields of up to 75 kOe at temperatures from 4.2 to 300 K. Samples of the nanostructure i-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}/i$-GaAs ($x = 0.25$) with three quantum wells with layers of width $L_W = 54$, 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-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ ($x = 0.25$) barrier 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 8×2 mm, with a single pair of in-line contacts symmetrically located 4 mm apart. The contacts were produced by the alloying in of indium in vacuum or in a nitrogen atmosphere at a temperature of 420°C for several minutes. A special insert, 20 mm in diameter with an optical lead-through placed vertically into the intermediate temperature Dewar insert of a superconducting solenoid, was constructed for the measurements of the PGE. The temperature of the sample was stabilized in the range from 4.2 K up to room temperature to within ~ 0.05 K. Light from a KGM-70 halogen lamp was delivered to the sample along a flexible optical fiber ~ 1 mm in diameter. The maximum power of the radiation delivered to the sample was of the order of 5 mW. Calibrated metal grids were used to decrease the power in a controlled manner. The contacts and the neighboring sections of the sample were covered with a special shield, so that the central region of the sample was illuminated with a light spot whose diameter ranged from 2 to 3 mm. A simple check showed that the electrical resistance of the illuminated section of the sample was approximately 100 times smaller than that of the shielded section. The samples were oriented with the plane of the layers parallel to the magnetic field and could be turned so that the line of the contacts was parallel or perpendicular to the magnetic field.

The measurement scheme consisted of a simple closed series circuit consisting of the sample and a standard measuring resistance. The current circulating in the circuit was determined from the voltage drop across the measuring resistance. We note that the measured current was equal to the short-circuit current J_{sc}^{PGE}, since the resistance of the experimental samples (which, depending on the diameter of the light spot, ranged from 60 to 140 MΩ at room temperature under maximum illumination) was much larger than the measuring resistance (10 kΩ). The magnetic field dependences $J_{sc}^{PGE}(H)$ at different temperatures and levels of illumination were measured. The magnetic field was scanned in two directions: from 0 to 75 kOe and from 0 to -75 kOe. As the field was scanned, the computer data acquisition and processing system stored the measured values of the current and averaged them over a large number of readings, as a result of which the current sensitivity reached ± 0.001 nA.

The basic results of the experiments reduced to the following:

1) In the absence of a magnetic field a very weak current $J_{sc}^{0}(W)$ (tenths of a nanoampere), which depended on the power of the light W (photocurrent at $H=0$) and whose magnitude and sign depended on the temperature, was always observed.

2) When the samples were oriented so that the line of the contacts was perpendicular to the magnetic field, a pronounced photogalvanic effect, with $J_{sc}^{PGE} \gg J_{sc}^{0}(W)$ with an asymmetric, nonmonotonic dependence $J_{sc}^{PGE}(H)$, was observed. The magnitude of the PGE and the form of the magnetic-field dependences $J_{sc}^{PGE}(H)$ depended strongly on the temperature;

3) When the samples were oriented so that the line of the contacts was parallel to the magnetic field, there was no photogalvanic effect to within the sensitivity of the measuring circuit.

The characteristic features of the data are illustrated by the following.

Figure 1 shows the magnetic-field dependences $J_{sc}^{PGE}(H)$ measured for a sample at 283.7 K with different light powers $0.36W_{max}$, $0.49W_{max}$, $0.65W_{max}$ and the maximum

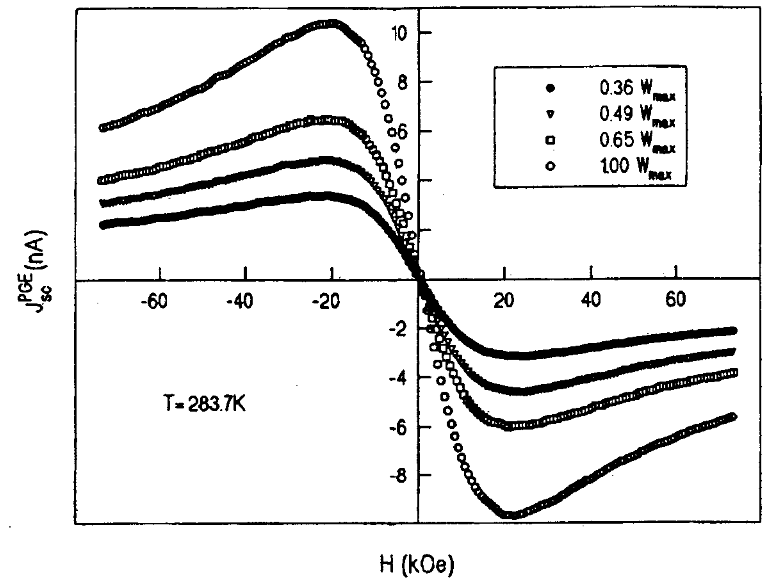

FIG. 1. Field dependences of the photogalvanic current $J_{sc}^{PGE}(H)$ at $T = 283.7$ K under different levels of illumination.

power $W_{max} \approx 5$ mW. One can see that at this temperature the magnetic-field dependences $J_{sc}^{PGE}(H)$ are nearly symmetric, odd functions of H with pronounced extrema near the positive and negative values of J_{sc}^{PGE}. At this temperature the current–voltage characteristics $J(U)$ measured at $H=0$ for different values of W exhibit a very weak nonlinearity in the range of values -10 nA $< J < 10$ nA characteristic for the observed PGE, and their slight asymmetry is due to the presence of a zero photocurrent $J_{sc}^{0}(W)$. In the absence of a magnetic field the conductivity of the nanostructure determined from the slope of the dependences $J(U)$ at this temperature is directly proportional to W. If the experimental curves $J_{sc}^{PGE}(H)$ are converted, using the current–voltage characteristics $J(U)$ measured for different values of W, into the curves $U_{tr}^{PGE}(H)$, then a single, W-independent, odd function $U^{PGE}(H)$, describing the magnetic field dependence of the PGE and reaching the extreme values $U_{max}^{PGE} = \pm 0.63$ for $H_{max} \approx \pm 20$ kOe, is obtained (see curve *1* in Fig. 3).

As the temperature is lowered, the photogalvanic effect measured according to the current becomes much weaker, and the experimental curves $J_{sc}^{PGE}(H)$ become strongly asymmetric. For example, Fig. 2 shows the $J_{sc}^{PGE}(H)$ curves measured at a temperature of 204.1 K for the same power levels W as before. One can see that although the effect measured as the difference between the peak values of $J_{sc}^{PGE}(H)$ is approximately five times weaker, the symmetry of the curves $J_{sc}^{PGE}(H)$ relative to the origin has changed substantially. At this temperature, in the face of an overall decrease in the conductivity of the system the nonlinearity and asymmetry of the current–voltage characteristics are now much stronger (see inset in Fig. 3). As before, if the generalized function $U_{tr}^{PGE}(H)$ is constructed from the current–voltage characteristics measured for $H=0$ and different values of W, then an odd function $U^{PGE}(H)$ that is universal for different values of W is

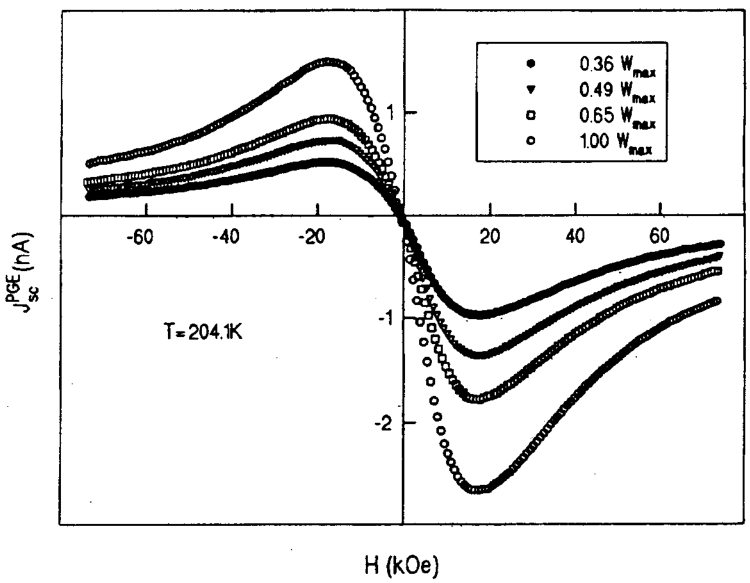

FIG. 2. Field dependences of the photogalvanic current $J_{\rm sc}^{\rm PGE}(H)$ at $T=204.1$K under different levels of illumination.

also obtained, with peak values $U_{\rm max}^{\rm PGE}=\pm 0.3$ V only a factor of two smaller than at $T=283.7$ K (see curve *2* in Fig. 3).

The photogalvanic effect can also be observed at very low (liquid-helium) temperatures. For example, the curves $J_{\rm sc}^{\rm PGE}(H)$ measured at 4.2 K for different values of W are presented in Fig. 4. The magnitude of the effect determined at this temperature from the difference of the amplitudes $J_{\rm sc}^{\rm PGE}$ is exactly 100 times smaller than at room temperature. Unfortunately, the current–voltage characteristics of a nanostructure at 4.2 K at current strengths characteristic for the PGE could not be constructed with the accuracy required for constructing the function $U_{\rm tr}^{\rm PFE}(H)$. The initial sections of the $J(U)$ curves at 4.2 K are nonlinear, and the current–voltage characteristics are on the whole strongly asymmetric in a large range of values of U. The peak values of $U_{\rm tr}^{\rm PGE}(H)$ can nevertheless be estimated using the conductivity of the nanostructure for large positive and negative voltages. Such an estimate gives $U_{\rm max}^{\rm PGE}\sim\pm 0.1$ V.

In Ref. 1 it was predicted that a spontaneous photogalvanic current determined by the simple relation $\mathbf{J}_{\rm PGE}=\beta\mathbf{T}$ (β is a dissipative coefficient arising as a result of the disequilibrium and $\mathbf{T}$ is the toroidal moment density) should pass through a maximum as the magnetic field is scanned. This is because $\mathbf{T}$ decreases with increasing $\mathbf{H}$ as a result of the localization of the wave functions of the electrons. The data obtained in the present work can be regarded as a confirmation of this prediction. However, the very regular antisymmetric form of the curve $U^{\rm PGE}(H)$, which at this temperature does not depend on the light power W, suggests that the initial characteristic of the PGE is not the spontaneous current, but rather the electromotive force $E^{\rm PGE}$ arising perpendicular to the applied

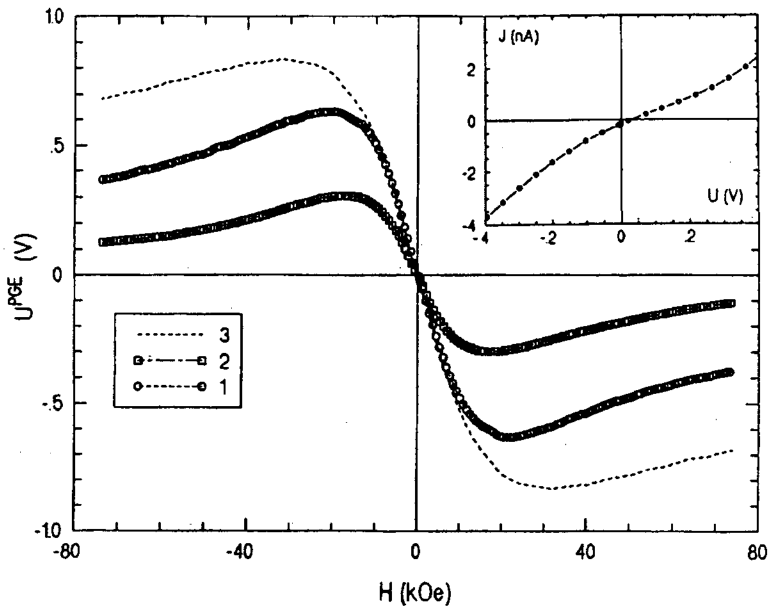

FIG. 3. $U^{PGE}(H)$ reconstructed from the experimental curves of $J_{sc}^{PGE}(H)$ and the current–voltage characteristics $J(U)$ at $T = 283.7$ K (curve *1*) and $T = 204.1$ K (curve *2*). Inset: Initial section of the current–voltage characteristic of the nanostructure at $T = 204.1$ K. Curve *3* shows the field dependence of the photogalvanic emf at $T = 283.7$K, allowance for the transverse magnetoresistance of the nanostructure.

magnetic field. If it is assumed that the function $U_{tr}^{PGE}(H)$ reconstructed from the experimental curves $J_{sc}^{PGE}(H)$ and the characteristics $J(U)$ largely reflects the basic character of the function $E^{PGE}(H)$, then $E^{PGE}(H)$ is independent of the power of the incident light and therefore of the density of nonequilibrium charge carriers and is nearly temperature-independent, decreasing in magnitude by only a factor of six when the nanostructure is cooled from room temperature to the temperature of liquid helium. In this sense the spontaneous photogalvanic current, which, as was shown above, becomes strongly asymmetric as the temperature decreases, appears to be a consequence of the nonlinear and asymmetric current–voltage characteristics of the nanostructure as measured independently with an external dc voltage applied to the structure.

Experiments in which the size of the light spot on the sample was varied support the interpretation of the data in terms of the appearance of a photogalvanic emf. These experiments made it possible to track the dependence of the proposed emf on the length of the illuminated section. For example, when the diameter of the light spot increased from 2 to 3 mm, the slope of the current-voltage characteristics $J(U)$ increased by a factor of 2.2 (since the length of the unilluminated sections decreased by approximately a factor of 2) and the photogalvanic current $J_{sc}^{PGE}(H)$ increased by a factor of 3.3, i.e., the emf $E^{PGE}(H) \propto J_{sc}^{PGE}(H)/J(U)$ increased by a factor of 1.5, exactly the amount by which the length of the illuminated central section of the sample increased.

At the present time, the reasons why the nonlinearity and asymmetry of the charac-

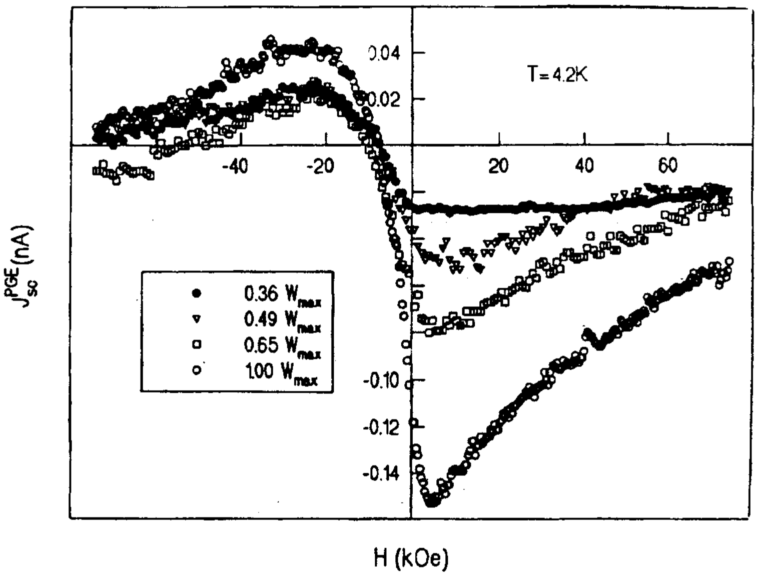

FIG. 4. $J_{sc}^{PGE}(H)$ measured at $T=4.2$ K under different levels of illumination.

teristics $J(U)$ increase as the temperature decreases are not clear. However, if the photogalvanic effect initially involves the appearance of an emf proportional to H, at least in weak fields, then it is very significant that the nonmonotonic dependence of $J^{PGE}(H)$ with extrema could simply be due to the large positive magnetoresistance of the nanostructure. We investigated the transverse magnetoresistance on samples of these nanostructures[3] at $T=283.7$ K, and we showed that the resistance of the nanostructure increases very strongly with the field, following a field-dependence $R(H)$ which is nearly linear in moderate fields and tends to saturate in strong fields. At low voltages (up to 1 V) applied to the structure, $(R(H)-R(0))/R(0)=1.85$ in a magnetic field of 75 kOe. If the dependence $E^{PGE}(H)=J_{sc}^{PGE}(H)\cdot R(H)$ is constructed using the experimental values of the magnetoresistance $R(H)$ and the current $J_{sc}^{PGE}(H)$, then the dependence represented by curve *3* in Fig. 3 is obtained. One can see that the extrema of this dependence are much less pronounced, i.e., the photogalvanic current decreases in fields >20 kOe mainly as a result of the high magnetoresistance. It should be noted that in Ref. 3 the magnetoresistance was investigated at the shortest light-spot diameter (2 mm) used in our experiments, for which the contribution of the unilluminated sections of the sample to the total resistance of the nanostructure remains large. The real magnetoresistance of the illuminated region of the nanostructure can be much larger than the resistance measured in Ref. 3. In this case the function $E^{PGE}(H)$ may not have any extrema at all, but may simply saturate in fields >20 kOe.

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[1] A. A. Gorbatsevich, V. V. Kapaev, and Yu. V. Kopaev, JETP Lett. **57**, 580 (1993).
[2] Yu. A. Aleshchenko, I. D. Voronova, S. P. Grisechkina *et al.*, JETP Lett. **58**, 384 (1993).
[3] V. I. Tsebro, O. E. Omel'yanovskiĭ, and V. I. Kadushkin, in press.

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