# Magnetic-field-induced photovoltaic effect in an asymmetric system of quantum wells

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A magnetic-field-induced photovoltaic effect has been observed in the GaAs/AlGaAs system. The sign and magnitude of the emf $V_{phv}$ depend on the temperature and wavelength of the light. The effect is explained on the basis of an asymmetry which the electron spectrum acquires in a magnetic field for an asymmetric electron wave function.

According to Ref. 1, when a semiconductor system with a quantum well flanked by barriers of equal height or an asymmetric structure of quantum wells is illuminated in a magnetic field, the photovoltaic effect gives rise to an emf $V_{phv}$. This effect occurs if the magnetic field $B$ is oriented along the layers, and if the light is propagating along the axis of the structure. In the present letter we report a study of a GaAs/AlGaAs heterosystem with three *i*-GaAs quantum wells, 70, 60, and 54 Å thick, separated by *i*-$Al_{0.25}Ga_{0.75}As$ barriers 30 and 20 Å thick (Fig. 1a). The quantum-well system is separated from the substrate [GaAs(Cr), 300 $\mu$m] by an *i*-GaAs buffer layer (0.5 $\mu$m), bounded by *i*-$Al_{0.25}Ga_{0.75}As$ barrier layers (300 Å), and it terminates in an *i*-GaAs layer (200 Å). The structure was grown on a Tsna apparatus for molecular beam epitaxy.

The short-circuit current $I_{sc}$ and the current–voltage characteristics of the structure were measured for various magnitudes and directions of the magnetic field ($B^{+,-}=0-0.5$ T) over the temperature range $77\leqslant T\leqslant 30$ K and the spectral range $0.69\leqslant\lambda\leqslant 1.4$ $\mu$m. The emf $V_{phv}$ was found as the product $\Delta I_{sc}^{+,-}(B^{+,-},\lambda)R(B^{+,-},\lambda)$, where

$$\Delta I_{sc}^{+,-}(B^{+,-},\lambda)=\Delta I_{sc}^{+,-}(B^{+,-},\lambda)-I_{sc}(0,\lambda)$$

and $R(B^{+,-},\lambda)$ is the resistance of the structure found from the current–voltage characteristic. The experimental geometry is shown in Fig. 1b. The light sources were various incandescent lamps; the maximum radiant power on the sample was $P\approx 10$ mW. A KGM-150 lamp was used in place of an ordinary globar lamp in the spectral measurements.

At $T=300$ K the current–voltage characteristics of the structure are linear under the conditions $B=0$, $B^{+,-}=$const, with or without illumination. These measurements were carried out with both illuminated and shaded contacts. When the structure was excited by light with a power $P\approx 10$ mW, the resistance decreased by more than an

  

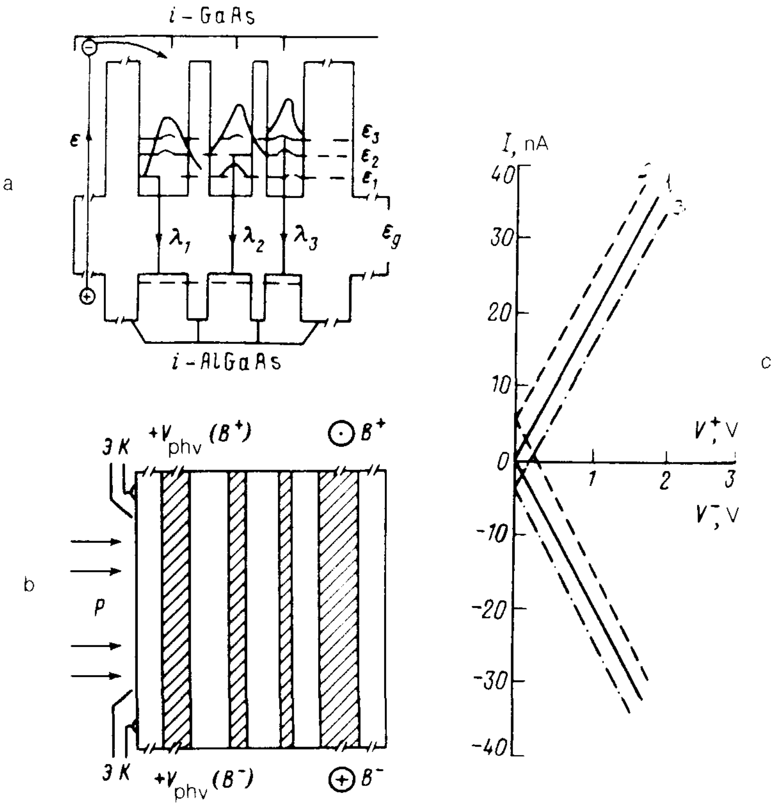


FIG. 1. a: Band diagram of a system of tunneling-coupled quantum wells. $\epsilon$—Energy of the exciting photon; $\epsilon_g$—band gap of GaAs; $\lambda_{1-3}$—spectral lines of photoluminescence from the ground and excited levels. b: Experimental geometry and polarity of $V_{\mathrm{phg}}$ in a magnetic field $B^{+,-}$. *S*—Protective screen; *C*—contacts. c: Current–voltage characteristic of the structure at $P \sim 10$ mW and $T = 300$ K. *1*—$B=0$; *2*—$B^+ = 0.5$ T; *3*—$B^- = 0.5$ T.

order of magnitude. At the maximum illumination power, and also at the maximum magnetic field, we observed a shift of the current–voltage characteristic along the $V$ axis, in a symmetric way with respect to the characteristic for $B=0$ (Fig. 1c). The value of $V_{\mathrm{phv}}$ can be estimated from the intersections of the current–voltage characteristics for various fields $B$. It was found that the $B$ dependence of $V_{\mathrm{phv}}$ is linear for magnetic fields from 0 to $\sim 0.5$ T. At $P \approx 10$ mW and $B \approx 0.5$ T, the value reaches 260 mV.

Figure 2 shows spectral characteristics of the photovoltaic effect. The $I_{\mathrm{sc}}^{+,-}(B^{+,-},\lambda)$ curves recorded in a magnetic field are shifted away from the $I_{\mathrm{sc}}$ curves for $B=0$ (Fig. 2a) along the ordinate. The sign of the shift depends on the direction of the magnetic field; the magnitude of the shift increases linearly with increasing $B$ (this is a linear effect) at photon energies $\epsilon > \epsilon_g$. At $\epsilon < \epsilon_g$, the $I_{\mathrm{sc}}^{+,-}(B^{+,-},\lambda)$ curves shift in the same direction; i.e., the sign of the shift does not depend on the direction

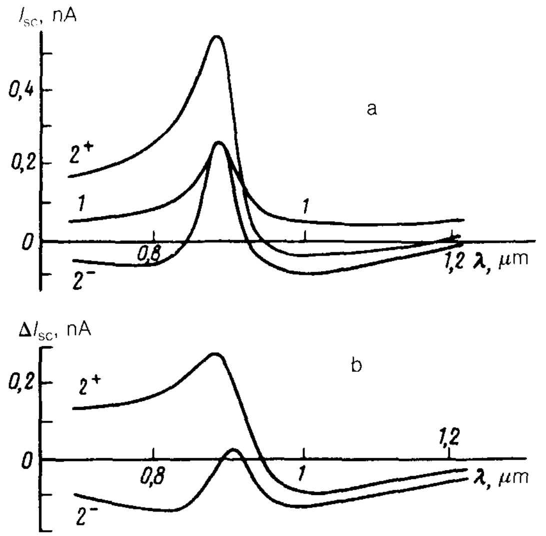


FIG. 2. Spectral characteristics. a: Short-circuit current $I_{sc}$. $1$—$B=0$; $2^{+,-}$—$B^{+,-}=0.5$ T, $P\approx 0.5$ mW, and $T=300$ K. b: The same, for $\Delta I_{sc}$ induced by a magnetic field.

of the magnetic field. We did not make a detailed study of the magnitude of the shift as a function of $B$ at $\epsilon<\epsilon_g$.

Figure 2b shows the value of $\Delta I_{sc}$ induced by a magnetic field. At $\epsilon > \epsilon_g$, $\Delta I_{sc}$ has different signs for different $B$ directions, while at $\epsilon < \epsilon_g$ the signs are the same. From the curves of $\Delta I_{sc}^{+,-}(B^{+,-},\lambda)$ and the resistance $R(B^{+,-},\lambda)$ we found the dependence $V_{phv}^{+,-}(B^{+,-},\lambda)$, which turned out to have essentially the same shape as $I_{sc}^{+,-}(B^{+,-},\lambda)$ at $\epsilon > \epsilon_g$.

The temperature dependence of $I_{sc}$ at $B=0$ (Fig. 3) has a change in sign at $T\approx 120$ K (during illumination with an incandescent lamp). The value of $\Delta I_{sc}(B\neq 0)$ also changes sign as the temperature is lowered from 300 to 77 K. As Fig. 3 shows, the value of $\Delta I_{sc}$ at $T=300$ K is much larger than that at 77 K. However, the absolute value of $V_{phv}$ at 77 K was not determined, because of the pronounced nonlinearity of the current–voltage characteristic of the structure at this temperature.

The temperature dependence of $I_{sc}(B = 0)$ is approximately the same as that which was seen in Ref. 2 for the photovoltaic effect in bulk crystals. In that previous study, the change in the sign of $I_{sc}$ was attributed to a change in the carrier excitation mechanism (from a band-band mechanism to an impurity–band mechanism) as the temperature was lowered. We suggest that in the absence of a magnetic field the temperature dependence of $I_{sc}$ may be due to an effect of this sort in the buffer layer and the substrate. In an effort to identify anomalies introduced in the photovoltaic effect by the substrate, we carried out some control experiments with a substrate into which some structure had been etched. These experiments revealed that the substrate makes no significant contribution to the observed value of $\Delta I_{sc}$.

We believe that the photovoltaic effect which is observed is confirmation of a prediction of Ref. 1. When the electron wave functions have an asymmetric structure in a magnetic field, nonuniform currents arise. These currents induce not only a

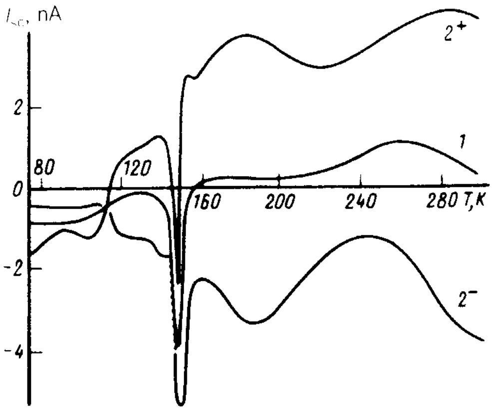


FIG. 3. Temperature dependence of $I_{sc}$. $1—B=0$; $2^{+,-}—B^{+,-}=0.5$ T.

magnetic moment (as in the case of symmetric wave functions) but also a toroidal moment.

As a result, the electron energy becomes an asymmetric function of the quasimomentum component perpendicular to the magnetic field, $k_y$ (in the plane of the layer): $E(k_y)\neq E(-k_y)$. When there is a nonequilibrium distribution function, a uniform current component arises and leads to the photovoltaic effect.[3] A calculation of the electron spectrum of this structure has shown that the distances from the first and second excited states to the ground state are 110 and 450 K, respectively (Fig. 1a). At $T=77$ K the photovoltaic effect is dominated by the lower level ($\epsilon_1$). The shift of the wave functions along the axis of the structure for the first and second excited levels ($\epsilon_2,\epsilon_3$) is directed opposite the shift for the ground level ($\epsilon_1$) and is greater in magnitude. As a result, the shift of the $E(k_y)$ minima for these excited states is in the direction away from the ground state for the same magnetic field direction. An increase in the population of these states ($\epsilon_2,\epsilon_3$) with increasing temperature is apparently responsible for the change in the sign of the photovoltaic effect. Indeed, this change in the population of the ground level and the excited levels is seen in a comparison of the photoluminescence spectra for $T=77$ and 300 K.

Testing this proposed mechanism for the photovoltaic effect which we have observed will require measurements in strong magnetic fields (up to $\sim$10 T). According to Ref. 1, the photovoltaic effect should go through a maximum as a function of $B$ in this field region.

The photovoltaic effect observed in Ref. 4 for one asymmetric quantum well is apparently of the same nature, and it, too, should go through a maximum as a function of $B$. However, the mechanism which we have been discussing here for a change in the sign of the photovoltaic effect as the temperature is varied does not operate in that type of structure.

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