Giant photocurrent in 2D structures in a magnetic field parallel to the 2D layer

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A giant photocurrent has been observed in a GaSb/InAs/GaSb structure with a single quantum well in a magnetic field B directed parallel to the surface of the sample. This current flows in the plane of the 3D layer, in the direction perpendicular to the magnetic field. It does not depend on the direction of the exciting light. Its shape is that of the laser pulse ($\tau_p = 100$ ns). Its magnitude increases with increasing B. The current density reaches 10 kA/cm^2 in a magnetic field as low as $B = 4.5$ T, at a light intensity $I = 2$ kW/cm^2. A model is proposed for this effect on the basis of the existence of a loop of extrema in the energy spectrum of the electrons in the well.

In this letter we are reporting the observation of a giant photocurrent in a GaSb/InAs/GaSb structure with a single quantum well upon the application of a magnetic field along the 2D layer. The light source was an optically pumped pulsed D_2O laser. The wavelength of the light was 385 μm (the photon energy was $\hbar\omega = 3.2$ meV), the pulse length was $\tau_p = 100$ ns, and the light intensity was $I = 2$ kW/cm^2.

The structures were grown by molecular beam epitaxy on a semi-insulating GaAs substrate. The thicknesses of the GaSb buffer layer, the InAs quantum well, and the GaSb upper layer were 1 μm, 20 nm, and 20 nm, respectively. We used structures with $n_s = 1.1 \times 10^{12}$ cm^{-2} and $\mu = 5 \times 10^4$ cm^2/(V·s) at $T = 77$ K. During the measurements, the samples were in the cavity of a superconducting solenoid at $T = 4.2$ K.

The inset in Fig. 1 shows the experimental geometry. The magnetic field was applied along the 2D layer; the light was directed along the normal to the plane of the sample; and the photocurrent j was measured in the plane of the 2D layer, in the direction perpendicular to the magnetic field. We detected a prompt photoresponse which reproduced the shape of the laser pulse. Curves a and b in Fig. 1 show the results measured for two opposite directions of the magnetic field. As the magnetic field is increased, we observed a pronounced increase in the photocurrent. As early as $B = 4.5$ T, the photocurrent reaches the huge value of 10 kA/cm^2 (a simple calculation yields an open-circuit voltage of 7 V for the test sample, with dimensions of 3×5 mm). When the magnetic field was reversed, the sign of the photocurrent changed, but a change in the direction of the exciting light had no noticeable effect on the results. Some photocurrent was also observed in the direction along the magnetic field, but it amounted to 5% of that described above (curves c and d in Fig. 1). We believe that this photocurrent can be explained completely in terms of small deviations from the desired experimental geometry.

To explain the experimental results, we adopt the following model. It has been

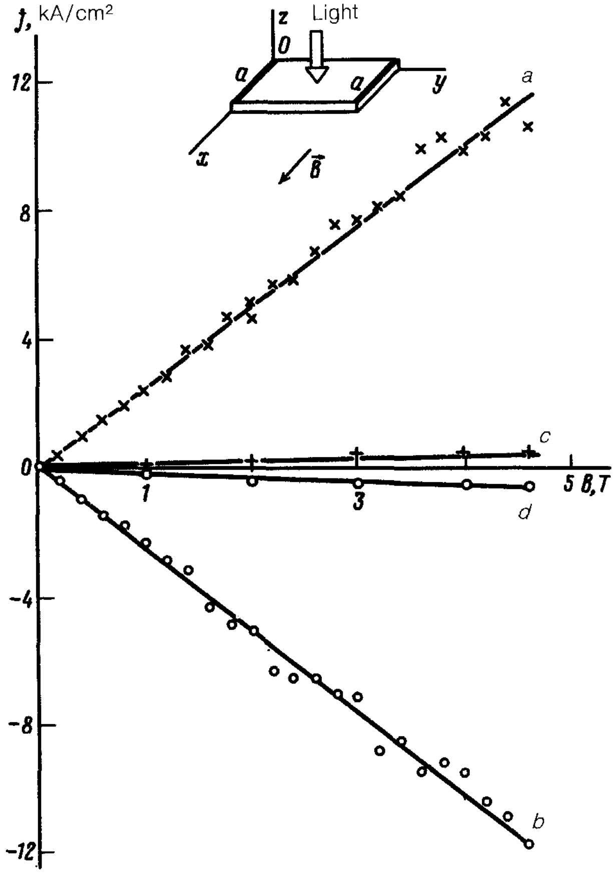

FIG. 1. Photocurrent density versus the strength and direction of the magnetic field. *a*, *b*—Photocurrent density through terminals *a–a* for two opposite directions of the magnetic field; *c*, *d*—photocurrent density through terminals *a–a* after the sample is rotated 90° around the *Z* axis, again for two opposite directions of the magnetic field. The inset shows the experimental geometry.

established elsewhere that the amount of charge at one interface in a GaSb/InAs/GaSb structure will be substantially greater than the amount at the other, unless special measures are taken to prevent this situation. As a result, a strong electric field (up to 10^5 V/cm) arises. Because of this field and the spin-orbit interaction, a loop of extrema appears in the electron energy spectrum according to Ref. 2 (Fig. 2a):

$$\epsilon^{\pm}(k) = \frac{\hbar^2 k^2}{2m^*} \pm \alpha k,$$

where m^* is the effective mass, k is the wave vector of the electron, and the coefficient α is determined by the properties of the given system. The structure we used was grown by the same procedure as was used for the structure studied in Ref. 3, where the existence of a ring of extrema was confirmed experimentally.

If a magnetic field is applied to the structure, along the 2D layer, e.g., along the X direction, the spectrum for the motion of electrons in the XY plane changes, becoming

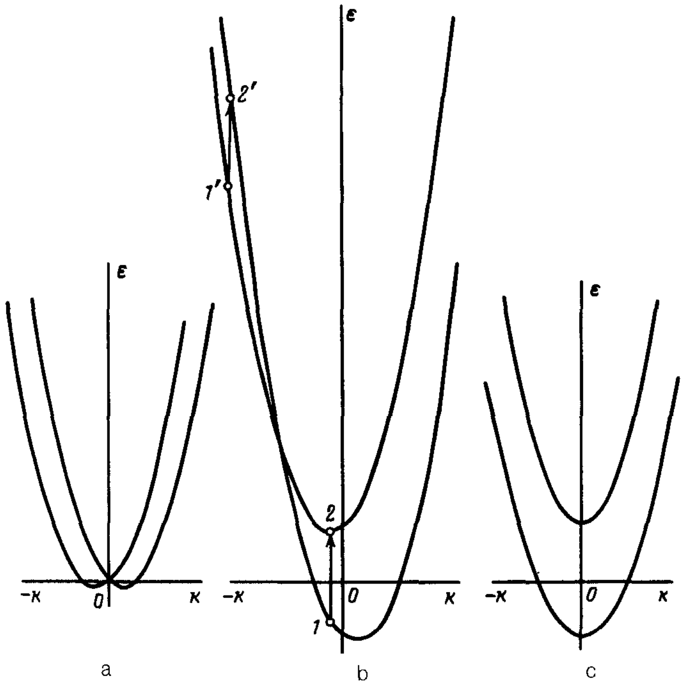

FIG. 2. Electron energy spectrum in the quantum well. *a*—Without an external magnetic field; *b*—along the *Y* direction, when an external magnetic field is applied along the *X* direction; *c*—along the *X* direction when an external magnetic field is applied along the *X* direction. Also shown in part *B* is the scheme of optical transitions caused by light with a photon energy of 3.2 meV in an external magnetic field of 4.5 T.

$$\epsilon^{\pm}(k) = \frac{\hbar^2 k^2}{2m^*} \pm \sqrt{(ak_y + \tfrac{1}{2} g \mu_B B)^2 + a^2 k_x^2}\,,$$

where g is the g-factor of the electron. The electron spectra along the Y and X directions are shown in Fig. 2 (b and c, respectively). Note that the spectrum becomes sharply asymmetric along the Y direction. As a result, the energies and thus the populations of the states with wave vectors k and $-k$ are different. The energy spectrum in velocity space $[v = 1/\hbar(\partial\epsilon/\partial k)]$ is of course symmetric, so the populations of states with opposite velocities remain the same.

The light causes optical transitions between two branches of the spectrum, through virtual states in the InAs valence band[4] (Fig. 2b). In momentum space, the transitions are vertical, while in velocity space they deviate substantially from the vertical. An electric current arises because of the difference between the populations of initial states 1 and 1′ and the difference between the velocities and the initial and final points of the optical transition. As the magnetic field is strengthened, this difference in populations increases, so the current also increases.

A current does not arise in the direction which is longitudinal with respect to the magnetic field, since the spectrum is symmetric in this direction (Fig. 2c).

In our test sample, with a well 20 nm wide, the first quantum-size level lies about 70 meV below the Fermi level, while the second level essentially coincides with the Fermi level. It follows from our estimates incorporating the particular value of the photon energy and the coefficient α for the given well ($\alpha = 3\times 10^{-9}$ eV·cm according to Ref. 3) that transitions cannot occur between the states of the first quantum-size level in the magnetic-field range of interest, since the initial and final pints for such transitions lie far below the Fermi level. For the second quantum-size level, the initial point for the $1\rightarrow 2$ transition (Fig. 2b) shifts down the energy scale with increasing B but remains near the Fermi level. The initial energy for the transition $1'\rightarrow 2'$, on the other hand, increases substantially with increasing B. This transition apparently makes no appreciable contribution to the current. The position of the Fermi level in this system is known within a few millielectron volts. This point is unimportant, however, since under these experimental conditions the intense exciting light heats the electron gas significantly (by an amount on the same order of magnitude).

In addition to the mechanism discussed above, there is another mechanism which might cause a current flow under these conditions: a relaxation of electrons heated in one spin subband as they are scattered into another subband.[5]

Reaching a detailed understanding of this effect will obviously require additional experimental and theoretical research, which we plan to undertake in the near future.

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