Negative photoconductivity of 2D electrons in semiconductor heterostructures

I. M. Grodnenskiĭ, K. V. Starostin, and D. V. Galchenkov
Institute of Radio Engineering and Electronics, Academy of Sciences of the USSR

(Submitted 25 November 1985)
Pis'ma Zh. Eksp. Teor. Fiz. **43**, No. 1, 54–56 (10 January 1986)

A method for arranging a negative photoconductivity in a heterostructure with a two-dimensional (2D) electron gas is proposed. The method involves an optical ejection of carriers from a 2D channel. The method has been demonstrated experimentally. The effect may prove useful for studying the properties of 2D systems in such structures.

The idea of a spatial displacement of charge carriers during heating by a current in a layered semiconductor structure was apparently first predicted in Ref. 1. In heterostructures with a 2D electron gas, a transition of electrons from the high-mobility 2D channel in a narrow-gap semiconductor into a wide-gap semiconductor with a low mobility μ, which leads to a negative differential conductivity, was first observed in Ref. 2.

In the present letter, in contrast with Refs. 1 and 2, we suggest depleting the 2D channel by means of light with a photon energy greater than the difference between the energy of the maximum of the conduction band of the wide-gap semiconductor near the interface, E_S, and the Fermi energy E_F (see the inset in Fig. 1). The light will reduce the density (n_{2D}) of 2D electrons with a high mobility μ_{2D} ($\mu_{2D} > \mu$) because of their displacement into the layer of wide-gap semiconductor, so that a negative photoconductivity should arise.

In the present experiments we use GaAs-AlGaAs heterostructures similar to those used in Ref. 3. The values of n_{2D} in the various samples are $(2–6) \times 10^{11}$ cm^{-2}, and the mobilities are $\mu_{2D}(T = 4.2 \text{ K}) \simeq (3–8) \times 10^4$ cm^{-2}/(V · s). The static measurement electric field is directed along the heterojunction and is no stronger than

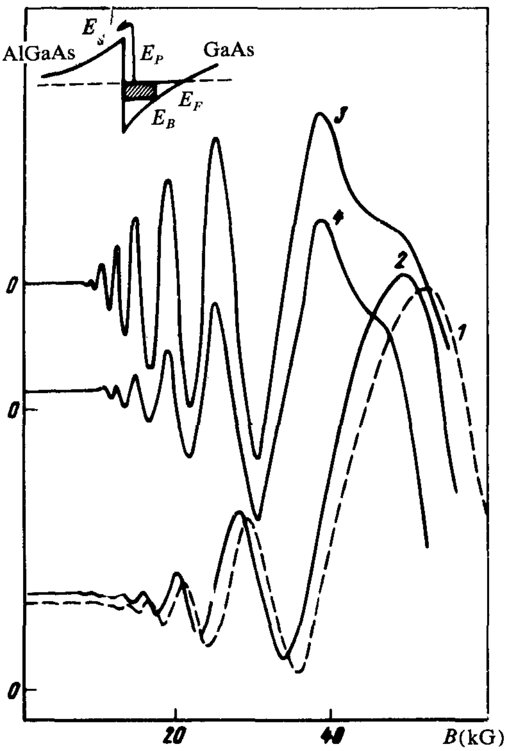

FIG. 1. 1—Longitudinal resistivity ρ_{xx} in darkness versus the magnetic field (dashed line); 2—the same, but with illumination; 3—$\partial\rho_{xx}/\partial B$; 4—$\partial\rho_{xx}/\partial J$. The inset shows the conduction band of a semiconductor heterostructure with a 2D electron gas at the interface.

10^{-2} V/cm. We use a tunable CO laser with a photon energy E_P in the interval 205–240 meV. Estimates indicate that the condition $E_P > E_S - E_F$ holds in this interval; in addition, a frozen photoconductivity is not observed in it.[4] Most of the measurements were carried out at liquid-helium temperatures, for which there is no conductivity along the AlGaAs layer in these samples.

As suggested, the photoconductivity $\Delta\sigma$ of the test samples is negative. Measurements in a magnetic field B show that the magnitude and sign of $\Delta\sigma$ are determined by the change in only the density of 2D electrons. It can be seen from curves 1 and 2 in Fig. 1 that the period and phase of the Shubnikov-de Haas oscillations change upon illumination, reflecting the decrease in n_{2D}. The magnitude of the change in n_{2D} depends on the light intensity, reaching $\sim 5\%$ at an intensity $J \sim 10^{-2}$ W/cm^2. According to measurements of the Hall resistivity ρ_{xy} and estimates of the Dingle temperature, there is no change in μ_{2D} upon illumination. Further evidence that there are no heating effects comes from the results of special experiments in which a coating that absorbed the incident light was placed on the samples. The experiments also showed that the times required to switch the photoconductivity on and off are quite different: The switch-on time is no longer than 0.1 s (the time constant of the measurement system), while the switch off time is $(1\text{–}5) \times 10^2$ s. This difference suggests that the processes which work in the direction opposite the optical flipping and which

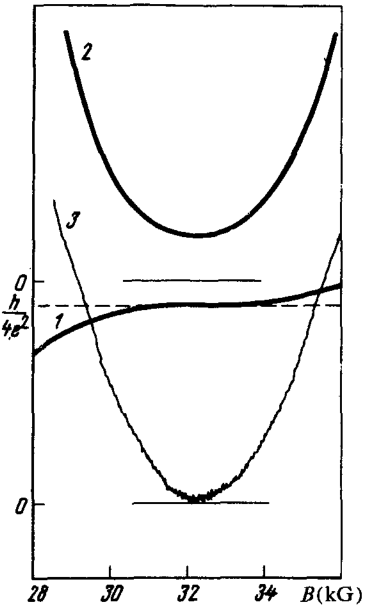

FIG. 2. 1—ρ_{xy}; 2—ρ_{xx}; 3—$\partial\rho_{xy}/\partial n_{2D}$ in the Hall plateau with $\nu = 4$ versus the magnetic field.

restore n_{2D} to its original value after the light is turned off, are of a tunneling or activation nature.

The results found in measurements of the dependence of the derivatives $\partial\rho_{ij}/\partial J$ on the magnetic field at light modulation frequencies up to $\sim 10^3$ Hz also indicate a change in n_{2D} upon illumination. Since we have $\partial\rho_{ij}/\partial n_{2D} = -(\partial\rho_{ij}/\partial B)(B/n_{2D})$ at equilibrium, a change in n_{2D} should lead to a corresponding agreement of $(\partial\rho_{ij}/\partial B)(B)$ and $(\partial\rho_{ij}/\partial J)(B)$, as is found experimentally (curves 3 and 4 in Fig. 1).

Similar results for $\partial\rho_{ij}/\partial J$ were found with light for which E_P is much greater than the difference $E_S - E_F$. For light with $E_P < E_S - E_F$ ($E_P \simeq 117$ meV), on the other hand, we observe no photoconductivity in these samples, even at a high light intensity.

The optical depletion of the 2D channel observed here might be exploited for an effective study of the properties of 2D systems in semiconductor heterostructures. There are two ways to carry out such studies. One would involve studying the relation between $d\rho_{xy}$ [$d\rho_{xy} = (h/e^2\nu) - \rho_{xy}$, where ν is the filling factor] and ρ_{xx} in the Hall plateau. In contrast with silicon inversion layers, the corresponding experiments with semiconductor heterostructures are complicated by difficulties involving the change in n_{2D}. It can be seen from Fig. 2 that this effect is sensitive enough for finding the relationship between $d\rho_{xy}$ and ρ_{xx} at various points in the plateau.

The other approach would be for a spectroscopy of the 2D system: to find the shape of the 2D potential well, the magnitude of the discontinuity in the conduction band at the interface, etc.

We wish to thank V. A. Volkov, T. N. Pinsker, and V. B. Sandomirskiĭ for a discussion of these results; V. I. Masychev for assistance in adjusting the CO laser; and M. I. Elinson for support of this study.

[1] Z. S. Gribnikov, Fiz. Tekh. Poluprovodn. **6**, 1380 (1972) [Sov. Phys. Semicond. **6**, 1204 (1972)].
[2] K. Hess, H. Morkoc, B. Streetman, and H. Shichijo, Appl. Phys. Lett. **35**, 469 (1979).
[3] D. V. Galchenkov, I. M. Grodnenskiĭ, O. P. Matov, T. N. Pinsker, and K. V. Starostin, Piz'ma Zh. Eksp. Teor. Fiz. **40**, 410 (1984) [JETP Lett. **40**, 1228 (1984)].
[4] V. A. Volkov, D. V. Galchenkov, I. M. Grodnenskiĭ, and K. V. Starostin, Pis'ma Zh. Eksp. Teor. Fiz. **36**, 370 (1982) [JETP Lett. **36**, 448 (1982)].

Translated by Dave Parsons