Negative differential conductivity (NDC) in semiconductors with a negative magnetic resistance (NMR)

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The measurements of magnetic resistance and numerical experiments show that, because of inelastic scattering by polar optical phonons, the electrons in the Γ valley of an *n*-GaAs semiconductor are divided into two groups at 77 K in electric and magnetic fields. This gives rise to a possible negative differential conductivity (NDC).

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A system of free electrons in a semiconductor, in which the inelastic scattering by optical phonons $\hbar\omega_0$ in crossed electric $\mathbf{E}_0$ and magnetic $\mathbf{B}_0$ fields is dominant, can be divided into two groups: in one group the electrons gain energy $\epsilon \geqslant \hbar\omega_0$, then lose it in the time τ^+ due to emission of a phonon, and then repeat this "transit" cycle of motion; in the other group they are subjected to a cyclotron rotation with a frequency $\omega_c = eB_0/m$ during the time $\tau^- \gg \tau^+$, while they occupy a spindle-shaped region in the velocity space with the center $\nu_c = E_0/B_0$, where $\nu_c < \nu_0 = \sqrt{2\hbar\omega_0/m}$. The galvanomagnetic effects in such a system, which were analyzed in Ref. 1, were observed in AgCl and AgBr (Ref. 2) under conditions $\omega_c\tau^+ \to 0$ and $\omega_c\tau^- \gg 1$. The analytic model,[1,2] however, does not make it possible to solve the problem concerning the division of electrons in GaAs-type semiconductors in which the coupling constant of electrons with polar optical (PO) phonons α_{PO} is at least an order of magnitude smaller than that in AgCl and AgBr, and only very soft conditions $\omega_c\tau^+ \leqslant 1$ and $\omega_c\tau^- \geqslant 1$ can be satisfied.

An interest in this problem was stimulated by predictions of decreasing regions in the static current-voltage (IV) characteristics[3] and also by the observed generation of harmonics and amplification of microwave oscillations in n-GaAs at $T = 77\,\mathrm{K}$[4] and in $\mathbf{E}_0$ and $\mathbf{B}_0$ fields, which are required for the appearance of two groups of electrons in the Γ valley.

By using n-GaAs at $T = 77$ K in this investigation we obtained results which prove that the electrons are divided into groups under the conditions $\omega_c\tau^+ \leqslant 1$ and $\omega_c\tau^- \geqslant 1$, and we showed that, because of this division, a negative differential conductivity (NDC) is possible in the presence of a small constant field component $E_{0y} \| B_0$ ($E_{0y} \ll E_{0x}$).

1. To prove that electrons can be divided into groups in n-GaAs at 77 K, we have measured the field dependence of the magnetic resistance in the Hall configuration (the sweep in Fig. 1). In such configuration the intense PO scattering under the conditions $\nu_0/2 < \nu_c < \nu_0$ may produce a negative magnetic resistance (NMR) because of bending of the "drift" electron trajectories in the momentum space[1] and because of the presence of highly mobile electrons in the "spindle."[3,5] The latter produce a strong Hall field $E_H \approx \omega_c\tau^- E_{0x}$ and, after shifting at right angles to the total field $\mathbf{E}_t - \mathbf{E}_H + E_{0x}$ at the drift velocity $v_c = E_t/B_0$, they contribute significantly to the current. The results of the measurements of the NMR, which were conducted by using the integral microwave method,[6] are shown in Fig. 1 (open circles). Figure 1 (curve 1) also shows the results of a numerical modeling of the NMR by using the Monte Carlo method, which was conducted using the following parameters of n-

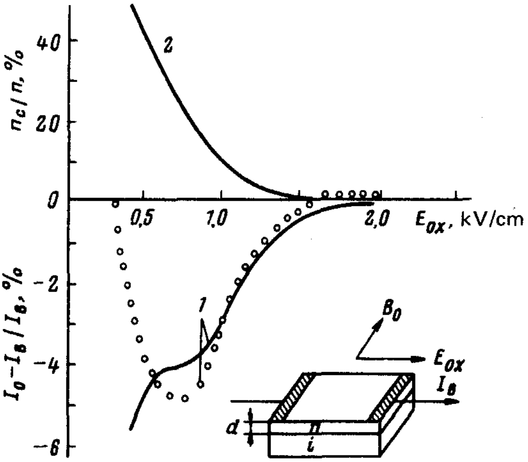

FIG. 1. Field dependence of the transverse reluctance (1) and of the ratio of the number n_c of electrons in the "spindle" to the total number n of electrons per unit volume (2) for n-GaAs in the Hall configuration (inset). The open circles represent the results of measurements and the solid curves denote the results of numerical experiments. $n = 1 \times 10^{15}$ cm^{-3}, $B_0 = 0.5$ Tesla, $T = 77$ K, $d = 10.3$ μm, and i is the insulation substrate.

GaAs: $\hbar\omega_0 = 36.2$ meV, $\alpha_{PO} = 0.067$, effective mass $m = 0.066\ m_0$, and the nonparabolicity coefficient of the Γ valley $\alpha_m = 0.62\ \text{eV}^{-1}$. The scattering by ionized impurities with the concentration $N_I = 1 \times 10^{15}\ \text{cm}^{-3}$ and elastic scattering by acoustic phonons were taken into account. A three-valley model of the conduction band of GaAs was used[7]; this verified that the intervalley transitions to the NMR do not occur in the investigated region of fields. There is a good quantitative agreement between the measurements and the results of the numerical experiment in the region $E_{0x} > 500$ V/cm, in which the condition for elastic acoustic scattering is satisfied and in which the spindle-shaped region no longer covers the bottom of the conduction band. The absolute values of the NMR decrease in a strong electric field; as can be seen in Fig. 1 (curve 2), this is attributable to the departure of electrons from the "spindle" to another group.

2. A separation of electrons into groups leads to the appearance of nondiagonal components of differential conductivity $\sigma^d_{xy} = \partial j_x/\partial E_y$ and $\sigma^d_{yx} = \partial j_y/\partial E_x$, if the field component $E_{0y} \ll E_{0x}$ is present. These components appear because of the variation of n_c and $\tau^-$by the E_{0x} and E_{0y} components. The σ^d_{ij} tensor can be determined from the static IV characteristics in Fig. 2, from which it follows that $|\sigma^d_{xy}| > |\sigma^d_{yx}|$, $\sigma^d_{xy} < 0$, and $\sigma^d_{yx} < 0$. The diagonal σ^d_{xx} and σ^d_{yy} components are positive, since the static IV characteristics $j_{0x}(E_{0x})$ and $j_{0y}(E_{0y})$ do not have decreasing regions. The average power $\delta \mathbf{j} \cdot \delta \mathbf{E}$ per cycle of the small, variable signal can nonetheless be negative. The condition for the NDC $\delta \mathbf{j} \cdot \delta \mathbf{E} < 0$ in the problem under consideration can be reduced to the following form:

$$(\sigma^d_{xy} + \sigma^d_{yx})^2 > 4\sigma^d_{xx}\sigma^d_{yy} .$$

This condition is satisfied in the region of fields in which the current $j_{0x}(E_{0x})$ approaches saturation. The data in Fig. 2 correspond to the regions $650 < E_{ox} < 850$ V/cm

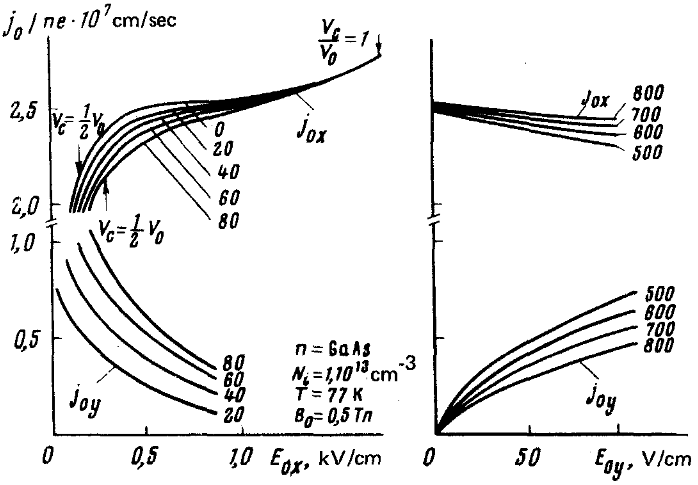

FIG. 2. Static I-V characteristics of a flat n-GaAs layer in the Hall configuration (see inset in Fig. 1) in the presence of the field component E_{0y} in the direction of B_0, obtained by using the Monte Carlo method. The numbers on the curves denote the values of E_{0x} and E_{0y} in V/cm.

and $20 < E_{0y} < 70$ V/cm; the range of ϕ angles between the $\delta\mathbf{E}$ vector and the x axis, in which the NDC for the E_{0x} and E_{0y} data exists, is equal to several degrees. This range can be expanded by increasing the magnetic field intensity.

The division of electrons into groups and NDC can also occur in other semiconductors such as A^3B^5 and in their solid solutions, which give rise to electric instabilities and enhanced generation of noise and harmonics.

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