ON THE POSSIBILITY OF NEGATIVE CONDUCTIVITY WITH NONEQUILIBRIUM ELECTRONS IN A QUANTIZING MAGNETIC FIELD

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1. It has been firmly established recently that when a semiconductor is illuminated with monochromatic light it is possible to produce in it nonequilibrium electrons that are concentrated in a narrow energy interval (see [1]). Such a situation leads to a number of interesting phenomena [1,2].

We show in the present paper that in the case of monoenergetic distribution of the photoelectrons there can occur an effect of absolute negative conductivity in a transverse quantizing magnetic field, i.e., the current perpendicular to the magnetic field flows in a direction opposite to the applied electric field. The effect is connected with peculiarities in the state density of the electron in the magnetic field.

2. Let us consider a semiconductor in which the concentration of the equilibrium carriers is small compared with the concentration of the photoelectrons produced in the conduction band under the influence of an external monochromatic source $Ig(\epsilon - \omega)$ ($\hbar = 1$). We shall assume that the electrons are produced with energy ω smaller than the energy of the optical phonon, and that the lifetime τ_e of the photoelectron is much shorter than the time of relaxation on the acoustic phonons and the time of the electron-electron interactions; the momentum is scattered by the impurities. The expression for the photoelectron current density produced under the influence of the electric field $E = E_x$ directed perpendicular to the strong magnetic field $H = H_z$ ($\Omega \gg kT$, $\Omega\tau \gg 1$, Ω - Larmor frequency) is [3]

$$j_x = \frac{e}{4\pi L_z} \sum_{\kappa, \kappa', q} w_{im}(\kappa, q; \kappa') D(\kappa, q; \kappa') q_y , \tag{1}$$

where $w_{im}(\kappa, \vec{q}; \kappa')$ - probability of elastic scattering of the electron by the impurity; $D(\kappa, \vec{q}; \kappa') = f_{\kappa'} - f_\kappa$; f_κ - distribution function of the photoelectrons, i.e., the number of electrons in the state $\kappa = (N, p_z)$. The function f_κ satisfies the equation

$$\sum_{\kappa', q} w_{im}(\kappa, q; \kappa') D(\kappa, q; \kappa') - f_\kappa / \tau_e = Ig(\epsilon_\kappa - \omega), \tag{2}$$

the solution of which in a weak electric field E ($eE\sqrt{\omega}/\Omega\sqrt{m} \ll \omega - \Omega(N + 1/2)$) is

$$D(\kappa, q, \kappa') = - \frac{E q_y}{H} \frac{\partial f(\epsilon)}{\partial \epsilon}, \tag{3}$$

where

$$f(\epsilon) = I\tau_e g(\epsilon - \omega),\ \epsilon = \epsilon_\kappa = \Omega(N + 1/2) + p_z^2/2m.$$

Substituting (3) in (1) and assuming that the effective radius of the forces between the electron and the impurity atom is small compared with the Larmor radius, we obtain (see [3])

$$\sigma_{xx} = -\left(\frac{3\Omega}{32\omega}\right)\sigma_0 \int_0^\infty dx \frac{df(x)}{dx} \sum_{NN'} \frac{N + N' + 1}{\sqrt{x - N - 1/2}\sqrt{x - N' - 1/2}}, \tag{4}$$

where $\sigma_0 = 4e^2 Jk(\omega)\tau_e(3\Omega^2\tau_{im})^{-1}$ is the "classic" photoconductivity at $\Omega\tau_{im} \gg 1$, $f(x) = \delta(x - \omega/\Omega)$, J is the intensity of the light, and $k(\omega)$ is the coefficient of absorption of light at $H = 0$. Integrating by parts, we get from (4)

$$\sigma_{xx} = \left(\frac{3\Omega}{32\omega}\right)\sigma_0 \left\{\frac{d}{dx}\sum_{NN'} \frac{N + N' + 1}{\sqrt{x - N - 1/2}\sqrt{x - N' - 1/2}}\right\}_{x=\omega/\Omega}. \tag{5}$$

We consider first the case when $\Omega/2 < \omega < 3\Omega/2$. Then only one term with $N = N' = 0$ remains in the double sum, and from (5) we find that the conductivity is negative:

$$\sigma_{xx} = -\sigma_0\left(\frac{3\Omega}{32\omega}\right)\frac{\Omega^2}{(\omega - \Omega/2)^2}. \tag{6}$$

When $\omega \to \Omega/2$, the conductivity increases until the broadening of the Landau levels comes into play as a result of the finite lifetime of the electron τ, so that we obtain in the limit

$$\sigma_{xx} = -\frac{3}{16}\sigma_0(\Omega\tau)^2. \tag{7}$$

With increasing energy ω (H = const) the conductivity becomes periodically negative under the condition $\omega = (N + 1/2)\Omega$. When ω = const, the resonance condition is attained by changing H, the resonances appearing with a period

$$\Delta\left(\frac{1}{H}\right) = \frac{e}{mc\omega}. \tag{8}$$

For larger quantum numbers, the conductivity becomes positive, since the double sum in (5) tends to the value $16x^2/3$ [4].

3. Let us consider the physical interpretation of the effect of negative conductivity. The electric current in a strong transverse magnetic field is due to two processes. First, drift motion of the center of the Larmor circle under the influence of the electric field during the time of the collision. This current is always directed along the field. Second, the rotation of the electron. The electric field, changing the energy of the electron, can influence the instant of collision, since the total number of collisions is proportional to the scattering probability and to the density of the initial and final states and depends thus on the energy. For equilibrium electrons, the instants of collisions are on the average equally probable, and the contribution from the incomplete number of revolutions to the current is equal to zero.

However, if the photoelectrons fill a narrow energy interval $\epsilon = \omega \geq \Omega(N + 1/2)$, where the density of the states depends strongly on the energy, the second process becomes predominant. The collisions then occur more frequently when the electron moves along the field, since its energy decreases and the scattering is more effective. Therefore the current produced as a result of an incomplete Larmor circle flows in a direction opposite to the applied field.

4. It should be noted that the coefficient of transverse diffusion of the photoelectrons is always positive, since it is necessary to substitute $f(\epsilon)$ in (4) in lieu of $-\partial f(\epsilon)/\partial\epsilon$. Physically this is connected with the fact that in the diffusion process the electric field does not influence the collision act [4]. At the same time, the diffusion coefficient, as well as the conductivity, will experience oscillations with a period (8).

5. We emphasize that the negative-resistance model with impurity scattering, which we investigated, is not the only one, since the effect is connected only with the singularity of the state density (a mechanism with scattering by optical phonons is possible). The considered situation can apparently be experimentally realized in pure p-InSb.

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CONCERNING THE TRANSFORMATION OF PHOTON PAIRS INTO HADRONS AT HIGH ENERGIES

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In this letter we consider $\gamma\gamma$ interaction at high energies on the basis of the model of vector dominance, which has recently come into wide use.

This model makes it possible to relate the process $\gamma + \gamma \to \rho^0 + \rho^0$ at high energies with the $\rho^0\rho^0$ scattering process:

$$\frac{d\sigma}{d\Omega}(\gamma\gamma \to \rho^\circ\rho^\circ) = g^4_{\gamma\rho}\frac{d\sigma}{d\Omega}(\rho^\circ\rho^\circ \to \rho^\circ\rho^\circ), \tag{1}$$

where we have for the $\gamma\rho$-transition constant $g^2_{\gamma\rho} \approx 0.5\alpha$ $(\alpha = 1/137)$.

Assuming that the $\rho\rho$ scattering amplitude at high energies is pure imaginary, we obtain

$$\frac{d\sigma}{d\Omega}(\gamma\gamma \to \rho^\circ\rho^\circ)|_0 = \frac{g^4_{\gamma\rho}}{16\pi^2}k^2\sigma^{(t)2}_{\rho\rho}(k), \tag{2}$$

where $\sigma^{(t)}_{\rho\rho}$ is the total cross section of the $\rho\rho$ interaction and k is the three-dimensional momentum in the c.m.s. $(m_\rho/2k \ll 1)$. The quantity $\sigma^{(t)}_{\rho\rho}(k)$ for large k can be obtained with good approximation by assuming that the contribution of the Pomeranchuk pole predominates