

- [5] N.E. Andreev, A.Yu. Kiril, and V.P. Silin, Zh. Eksp. Teor. Fiz. 57, 1024 (1969)[Sov. Phys.-JETP 30, 559 (1970)].

INSTABILITY IN OPTICALLY-PUMPED SEMICONDUCTORS IN STRONG MAGNETIC FIELDS

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The possibility of realizing situations in which the conduction current flows in a direction opposite to that of the electric field has been predicted in a number of papers (e.g., [1, 2]). Such an effect has been named absolute negative conductivity. It is connected as a rule with an appreciable lack of carrier equilibrium. It is known [3] that a homogeneous state in a system with such a conductivity can be unstable. However, the presence of equilibrium carriers, if their density is not low enough, suppresses the absolute negative conductivity and the associated instability (see [4]), since the conductivity produced by these carriers is positive.

We call attention in this paper to the possible existence in such systems of another type of instability. This instability can occur, as will be shown below, even when the total conductivity is positive.

Let us consider, for concreteness, a p-type semiconductor with short electron lifetimes, placed in a strong magnetic field. Assume that photoelectrons are generated in the conduction band under the influence of a monochromatic source of light. Let the magnetic field intensity be large enough ($\omega_c \tau \gg 1$, where ω_c is the cyclotron frequency of the electrons and τ the relaxation time) to satisfy the conditions for quantization of the electron energy. In this case the photoelectrons are concentrated in a narrow-energy interval, and their contribution to the conductivity is negative [2]. We assume also that the conductivity due to the holes (both majority holes and photo-holes) exceeds in absolute magnitude the photoconductivity due to the photoelectrons, i.e., the total conductivity is positive. Such a situation is close to that observed in the experiment [4].

To describe the low-frequency processes in the system under consideration, we can use the Poisson equation and the continuity equations. The latter, if we assume that all the quantities depend only on the coordinates transverse to the magnetic field, is given by

$$\frac{\partial n}{\partial t} - \operatorname{div} [n(\mu_n \mathbf{E} + \mu_n^H [\mathbf{E} \times \mathbf{h}]) + D_n \operatorname{grad} n] = - \frac{\partial N}{\partial t} = gN - \gamma n(N_i - N), \quad (1)$$

$$\frac{\partial p}{\partial t} + \operatorname{div} [p(\mu_p \mathbf{E} + \mu_p^H [\mathbf{E} \times \mathbf{h}]) - D_p \operatorname{grad} p] = 0. \quad (2)$$

Here n , μ_n , μ_n^H , D_n , and p , μ_p , μ_p^H , and D_p are respectively the concentrations, mobilities, and diffusion coefficients of the electrons and holes ($\mu_n < 0$, $\mu_p > 0$), N_i and N are the concentrations of the impurities from which and to which electron pumping is effected, g and γ characterize the generation and recombination of the electrons, and $\mathbf{h} = \mathbf{H}/H$. We have neglected in (1) and (2) the dependence of the mobilities on the electric field, assuming the latter to be small (there is no external electric field). We also assume that the total number of holes remains constant.

By linearizing (1) and (2), taking the Poisson equation into account, and assuming for simplicity that $g > \gamma N_1$, we obtain for perturbations of the type $\exp[i\vec{k} \cdot \vec{r} - \omega t]$, where $\vec{k} \perp \vec{h}$, the following dispersion equation:

$$\alpha \left[\frac{\mu_n}{i\omega - \frac{1}{\tau_R} - D_n k^2} + \frac{\eta \mu_p}{i\omega - D_p k^2} \right] = 1. \quad (3)$$

Here $\alpha = 4\pi en_0/\kappa$, $\eta = p_0/n_0$, κ is the dielectric constant of the lattice, $1/\tau_R = g + 2\gamma n_0 \approx g$, and n_0 and p_0 are the unperturbed densities of the electrons and holes ($n_0 \approx N_1$).

We assume that $|\omega| \ll \alpha |\mu_n|$, $\alpha \mu_p$. We then obtain from (3)

$$\omega \approx -i \frac{\frac{\eta \mu_p}{\tau_R} + (\mu_n D_p + \eta \mu_p D_n) k^2}{\mu_n + \eta \mu_p}. \quad (4)$$

Since $\mu_n + \eta \mu_p > 0$ by assumption, it follows from (4) that instability is possible only if the following condition is satisfied:

$$\frac{\mu_n}{D_n} + \eta \frac{\mu_p}{D_p} < 0. \quad (5)$$

Short-wave perturbation will develop in this case, and the perturbations of the electron and hole densities approximately cancel each other.

Since the holes are thermalized, they satisfy the Einstein relation. On the other hand, calculation of the ratio μ_n/D_n under the assumption of a δ -like photoelectron distribution function in the case of pumping at only the lower Landau subband yields

$$\frac{\mu_n}{D_n} = - \frac{|\epsilon|}{2\bar{\epsilon}}, \quad (6)$$

where $\bar{\epsilon}$ is the energy of the photoelectrons moving along the magnetic field.

Taking into account the Einstein relation for the holes and expression (6), we obtain the following instability criterion:

$$\bar{\epsilon} < \frac{T}{2\eta} \quad (7)$$

where T is the effective hole temperature (in energy units).

The initial equations included expressions for the diffusion currents in the diffusion-coefficient approximation. This is valid in the case of strong magnetic fields only when $kL \ll 1$, where L is the magnetic radius. Let us verify the satisfaction of this condition for the unstable perturbations with the longest wavelength. For such perturbations we have $k^2 \sim \eta \mu_p [\tau_R |\mu_n D_p + \eta \mu_p D_n|]^{-1}$. Let $\eta \sim 1$, $\mu_p \gg \mu_n$, and $T \gg 2\bar{\epsilon}$. Then the indicated condition takes the form $(\omega_c \tau)(\hbar/\tau_R T) \ll 1$. If $\omega_c \tau \sim 10$ and $\tau_R \sim 10^{-10}$ sec, then the employed approximation is valid if $T \gg 1^\circ\text{K}$.

In conclusion, we present a physical interpretation of the instability under consideration. We assume that a fluctuation took place in the photoelectron density (the photoelectron concentration has increased, for example, in some region). Then, owing to the negative conductivity of the photoelectrons, the concentration of the latter will increase. At the same time, the hole density will increase in the same place (owing to the action of the fluctuation field). The diffusion and recombination will wipe out the resultant inhomogeneity. If the ratio $n\mu_p/D_p$ exceeds $|\mu_n|/D_n$, then the hole diffusion will exert a lesser influence, the holes will have time to compensate the fluctuation field, and the growth of the fluctuation will stop. In the opposite case when condition (5) is satisfied, the rate of influx of the photoelectrons into the fluctuation region exceeds the rate of hole influx. In this case the fluctuation will increase. We note that in this instability the concentrations of the photoelectrons and holes approximately cancel each other in the developing fluctuations. The instability has therefore a quasineutral character. This was used by us in fact in the solution of the dispersion equation. One can expect, owing to the aperiodicity of the instability, that the result of the instability development will be a stationary state with an inhomogeneous carrier-density distribution. This can apparently be used for an experimental observation of this instability.

- [1] V.I. Ryzhii, ZhETF Pis. Red. 7, 35 (1968) [JETP Lett. 7, 25 (1968)]; A.D. Gladun and V.I. Ryzhii, Zh. Eksp. Teor. Fiz. 57, 978 (1969) [Sov. Phys.-JETP 30, 534 (1970)].
- [2] V.F. Elesin, ZhETF Pis. Red. 7, 229 (1968) [JETP Lett. 7, 176 (1968)]; Zh. Eksp. Teor. Fiz. 55, 798 (1968) [Sov. Phys.-JETP 28, 413 (1968)].
- [3] A.L. Zakharov, Zh. Eksp. Teor. Fiz. 38, 665 (1960) [Sov. Phys.-JETP 11, 478 (1960)].
- [4] A.S. Aleksandrov, Yu.A. Bykovskii, V.F. Elesin, E.A. Protasov, and A.G. Rodionov, ZhETF Pis. Red. 12, 57 (1970) [JETP Lett. 12, 41 (1970)].