MOTION OF n-InSb ELECTRON-HOLE PLASMA PRODUCED BY LOCAL IMPACT IONIZATION IN A MAGNETIC FIELD

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It is known that current and voltage instabilities, accompanied by microwave radiation, occurs in n-InSb at 77°K in sufficiently strong crossed electric and magnetic fields [1] ($E \sim 200$ V/cm, $\omega_c^e\tau_e >> 1$ and $\omega_c^h\tau_h < 1$, where $\omega_c^{e,h}$ and $\tau_{e,h}$ are the cyclotron frequencies and electron and hole relaxation frequencies, respectively). The nature of these instabilities and the radiation mechanism have not yet been explained. We attempt in this communication to relate the threshold of the instability with the onset and motion of plasma perturbations formed as a result of local impact ionization in the strong-field region at one of the contacts. The existence of such a region is connected with the boundary conditions for the electric field on the end contacts and the Hall faces of the sample [2].

The non-equilibrium carriers resulting from impact ionization in the strong-field region at the cathode produce a density perturbation that can move in an external electric field with ambipolar velocity. The absolute value and the direction of motion of the perturbation depends strongly on the magnitude of the magnetic field. This dependence can be easily obtained in the region of the homogeneous electric field, determining by the standard procedure [3], the values of the Hall field H_x, and the ambipolar mobility in the longitudinal direction μ_a^*:

$$E_x = \frac{E_y H_z(\mu_e\mu_e^* n_o - \mu_h\mu_h^* p_o)}{n_o\mu_e^* + p_o\mu_h^*}, \tag{1}$$

$$\mu_a^* = \frac{\mu_e^*\mu_h^*(n_o - p_o)}{n_o\mu_e^* + p_o\mu_h^*} - \frac{H_z\mu_e^*\mu_h^*(\mu_h n_o + \mu_e p_o)(\mu_e\mu_e^* n_o - \mu_h\mu_h^* p_o)}{(n_o\mu_e^* + p_o\mu_h^*)^2}, \tag{2}$$

where

$$\mu_{e h}^* = \frac{\mu_{e,h}}{1 + \mu_{e,h}^2 H_z^2} .$$

It is seen from (2) that μ_a^* depends strongly on H_z and can reverse sign at certain values $H_z > H_z^{cr}$. For n-InSb with negligibly small concentration of the equilibrium holes the critical Hall and magnetic fields H_x^{cr} and H_z^{cr} at which $\mu_a^* < 0$ are determined by the condition

$$\mathrm{tg}\,\phi^{cr} = -\sqrt{\left|\frac{\mu_e}{\mu_h}\right|} = \frac{E_x^{cr}}{E_y} . \tag{3}$$

In our case the distributions of E_x and of the longitudinal electric field E_y are not homogeneous, and can be represented, in accord with [2], in the form

$$E_x \cong \left(\frac{2}{\pi}\right)^{\ell}\left(\frac{h}{r}\right)^{\ell}|E_\infty|[\theta(1-\ell)\cos\theta + \sin\theta], \tag{4}$$

$$E_y \cong \left(\frac{2}{\pi}\right)^{\ell}\left(\frac{h}{r}\right)^{\ell}|E_\infty|[\theta(1-\ell)\sin\theta - \cos\theta], \tag{5}$$

where $|E_\infty| = +[E'^2_x + E'^2_y]^{1/2}$, $\ell = 2\pi/\phi$, E'_y and E'_x are the longitudinal and Hall fields at the center of the sample, and r and θ are the polar coordinates of the point at which the field is calculated, with the center of the polar coordinate system located at the vertex of the strong-field corner. As seen from (4) and (5), E_x and E_y have strong opposite gradients in the longitudinal direction, and this leads at $H_z > H_z^{cr}$, in accordance with (3), to the appearance of a "discontinuity surface" in the form of a cylinder with axis z and genetratrix r^{cr}, $\theta^{cr} = f(H_z)$. This surface separates all the plasma perturbations in accordance with their displacement directions. All the non-equilibrium carriers in the internal region bounded by the discontinuity surface and the sample faces move with $\mu_a^* > 0$, and those outside this region with $\mu_a^* < 0$.

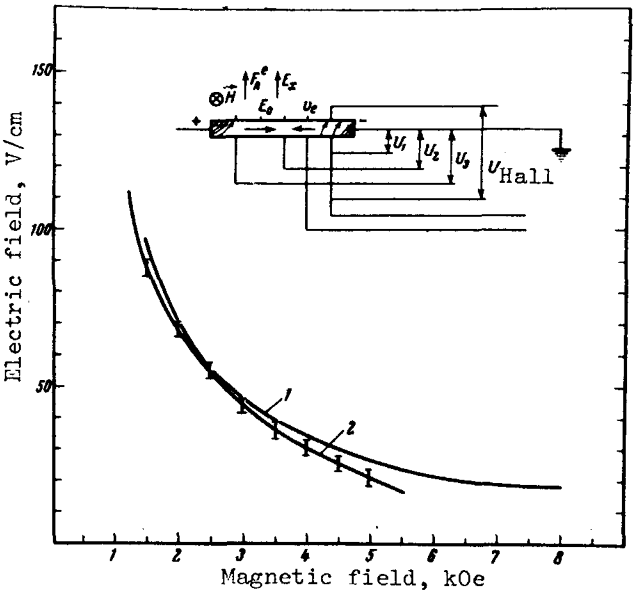
If it is assumed that the mechanism of formation of the non-equilibrium carriers in connected only with impact ionization, then the threshold electric field for the process of filling the sample with plasma from the cathode direction should coincide with the threshold field for the impact ionization on the "discontinuity surface." The latter can be determined by using the results of the theory [4] and taking into consideration the solutions of (4) and (5) with respect to r^{cr}, $\theta^{cr} = f(H_z)$ under the condition (3):

$$E'_y = \pi^{\ell}(\hbar\omega_{opt})^{1/2}/2^{\ell-1/2}m_e^{*1/2}\left(\frac{h}{r}\right)^{\ell}\mu_e[\theta^{cr\,2}(1-\ell)^2 + 1]^{1/2}, \tag{6}$$

where $\hbar\omega_{opt}$ is the energy of the polar optical phonons, m_e^* is the effective mass of the electron, and h is the thickness of the sample in the Hall direction. In the derivation of (6), just as in [4], it was assumed that the excess carriers are generated by the "runaway electrons" by impact ionization if $W_e > \hbar\omega_{opt}$, where W_e is the energy of the electrons, the number of which is large as a result of the strong anisotropy of the polar scattering. The electron energy W_e was determined from the solutions of the equations of motion at the points on the "discontinuity surface," a procedure legitimate when the inhomogeneity scale is much larger than the electron mean free path.

If the necessary conditions for impact ionization are satisfied, the conditions for intense excitation of different plasma instabilities that may be responsible for the microwave radiation are simultaneously satisfied with a large margin. In particular, according to the estimates of [5], the most probable is the excitation of strong oscillations of the hole-sound type. It is therefore possible for the influence of the intense hole-sound waves on the above-described mechanism of non-equilibrium carrier transport to cause the instabilities observed in [6, 7].

To verify the foregoing reasoning, an experiment was set up on the determination of the threshold fields $E'_y = f(H_z)$ of the instability observed in [6]. The results and the experimental setup are shown in the figure. An n-InSb sample measuring 0.4 × 0.8 × 9 mm was cut from a crystal with donor concentration $n \sim 10^{14}$ cm^{-3} and mobility $\mu_e = (6 - 9) \times 10^5$ cm^2/V-sec. Five contacts



Threshold fields $E'_y = f(H_z)$ for the instability observed in [6, 7], and setup for the measurement of E'_y. Curves: 1) calculated threshold characteristic for $\mu_e = 7 \times 10^5$ cm^2/V-sec, $\mu_h = 10^4$ cm^2/V-sec; 2) experimental threshold characteristic.

spaced 1.5 mm apart were soldered to the Hall faces along the sample. The sample at 77°K was placed in a transverse magnetic field. The electric field at the center of the sample was determined by measuring the voltages across successive sections of the sample, as shown in the figure. The instability thresholds relative to the electric and magnetic fields were determined from the characteristic "break" of the voltage at the Hall contacts closest to the cathode. The presence of a "break" is evidence of the start of impact ionization in the region next to the contact. Under such conditions, a weak rise of the voltage, lasting 10 nsec, was observed across the second pair of contacts on the strong-field face of the sample. Further increase of the voltage on the sample led to development of an instability in the form of a drifting strong-field domain [6]. As seen from a comparison of curves 1 and 2, the results of a numerical calculation of $E'_y = f(H_z)$ (curve 1) in accord with formula (6) agree well with the experiment (curve 2) for $\mu_e = (6.5 - 7) \times 10^5$ and $\mu_h = 10^4$ cm^2/V-sec. When plotting curve 2, the experimental values of the electric field were averaged over three voltages across different sections of the sample. The velocity of the perturbation in an average electric field $E_{av} \sim 200$ V/cm calculated from (2) is also in satisfactory agreement with the experiment described in [6]. Thus, the n-InSb instabilities observed in [6, 7] can apparently be attributed to motion of the plasma produced by local impact ionization in the region near the cathode.

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