CONTRIBUTION OF BAND NONPARABOLICITY TO NONLINEAR SUSCEPTIBILITY OF *n-TYPE* InSb *IN THE MILLIMETER RANGE*

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The self-action and tripling of frequency of electromagnetic radiation in an InSb single crystal of the n-type is investigated experimentally in the 4 mm range and at 77°K. It is shown on the basis of the experimental data that nonparabolicity of the conduction band plays the main role in tripling in InSb in the millimeter and submillimeter wavelength ranges.

It is well known that most of the nonlinear electromagnetic effects connected with free carriers in homogeneous semiconductors result from heating up of the carriers (change of the collision frequency), "breakdown" (change of the electron and hole concentrations n and p), peculiarities in the dynamics of the carriers in the bands or the dependence of their effective mass m* on the field. It is still far from obvious, however, which of the mechanisms plays the dominant role in the processes of nonlinear transformation of electromagnetic radiation in the millimeter and submillimeter bands, and it is far from obvious[1)] even for a semiconductor as fully investigated as the n-type InSb. The dependence of collision and plasma frequencies ν and $\omega_p^2 = 4\pi e^2 n/\epsilon_0 m^*$ in homogeneous semiconductors on the power of incident electromagnetic radiation, in the millimeter wavelength range, can easily be determined by an experimental investigation of the self-action effects. Thus, for example, it is possible to determine the law of variation of the real (k') and the imaginary (k'') parts of the propagation constant from the measured coefficients of reflection (R) and transmission (T) of the power of an electromagnetic wave of frequency ω passing through a semiconductor plate, and consequently the dependence of ν and ω on the incident power, provided that the thickness of the plate d is much smaller than $1/k''$ ($d \ll k''$).

Measurements were carried out on n-type InSb sample, at 77°K, with concentration $n_0 = 8.7 \times 10^{13}$ cm^{-3} and collision frequency $\nu_0 = 1.65 \times 10^{11}$ sec^{-1}. The semiconductor plate of thickness d = 0.07 mm was placed, in a rectangular waveguide designed for the fundamental mode and cooled to liquid nitrogen temperature. Figure 1 shows the dependence of R and T, at the frequency $\omega = 4.37 \times 10^{11}$ sec^{-1}, on the incident power P. The quantities k' and k'', calculated with an electronic computer on the basis of the measured R and T, and the square of the electric field intensity E^2 averaged over the volume of the interior of the semiconductor are also shown in Fig. 1 as functions of the power P. The collision and plasma frequencies ν and

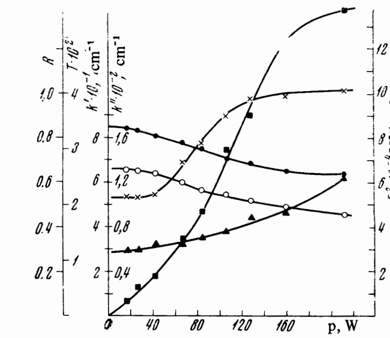

FIG. 1. Dependence of R (●), T (×), k′ (▲), k″ (○), and E² (■) on the power incident on a semiconductor plate.

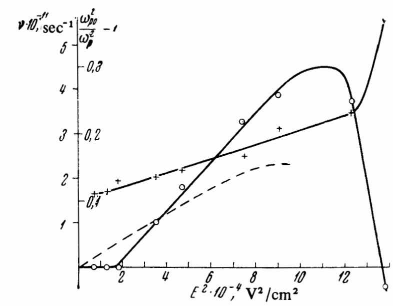

FIG. 2. Dependence of $\nu(+)$ and $\omega_{p0}^2/\omega_p^2 - 1$(○) on the squared average field intensity in a semiconductor. The dotted curve shows the relative change in the effective mass $\Delta m^*/m^*$.

ω_p were determined in terms of k' and k'' by means of the relations characteristic of a homogeneous plasma (homogeneous semiconductor), and therefore the quantities ν and ω_p presented in Fig. 2 should be regarded, generally speaking, as some average parameters of the semiconductor in the presence of a high-frequency electric field E. The dotted curve in Fig. 2 corresponds to the relative change of the effective mass

$$\Delta m^* / m_0^* = \omega_{p_0}^2 / \omega_p^2 - 1,$$

computed in the single-electron approximation. The collision frequency ν and $1/\omega_p^2$ depends linearly on E^2 in the field range $E < 300$ v/cm. The decrease in the plasma frequency with increasing field intensity is due to the increase in the effective mass-averaged over the

[2)]Most often nonlinear effects in the ultra high frequency range (UHF) are associated with heating of carriers, although the contribution of nonparabolicity may be significant.

velocities. The local relative change in the average effective mass $\Delta m^*/m_0^*$, in the region linear in the square of the electric field, equals approximately to 0.3, when $\Delta\nu/\nu_0 \approx 1$. The abrupt increase in the plasma frequency in fields $E^2 > 10^5 V^2/cm^2$ results from a rapid increase in the free-carrier density as a consequence of breakdown. The electron temperature in the breakdown range ($E \sim 400$ V/cm) can be estimated from the change of the electron density[1], and corresponds approximately to about 150°K. During the pulse (which lasts approximately 50 nsec) the lattice temperature is practically constant. We note that in the temperature range from 77°K to 150°K and in the absence of a UHF field, the relative change in the average mass of the electrons is about 0.007.[2] Therefore the mass change shown in Fig. 2 should primarily be connected with the oscillatory motion of the electron in the field.

Besides the radiation of frequency ω, the signal transmitted through the plate contained another component of frequency 3ω and power 30 mW while the absorbed radiation power of frequency ω was of the order of 30 W ($P \approx 130$ W). To identify the tripling mechanism (carrier heating vs. band nonparabolicity), it is possible to employ in principle the temperature dependence of the effect. A definite answer to this question, however, can be obtained by taking into account the different contributions of these mechanisms to the self-action and tripling. It can easily be shown that in case of carrier heating the ratio of the extraneous current at frequency 3ω to that at the signal frequency equals

$$\frac{j_{3\omega}}{j_\omega} = \frac{1}{2}\frac{\nu_e}{\sqrt{4\omega^2+\nu_e^2}}\frac{\nu}{\sqrt{9\omega^2+\nu^2}}\frac{\Delta\nu}{\nu_0} \tag{1}$$

where ν_e^{-1} is the energy relaxation time, whereas in case of band nonparabolicity this relation is

$$\frac{j_{3\omega}}{j_\omega} = \frac{1}{3}\frac{\Delta m^*}{m_0^*}. \tag{2}$$

Estimates yield $\nu_e^{-1} \sim 10^{-11}$ sec at the respective temperatures $T_0 = 77$°K and $T_e = 155$°K of the lattice and of the electron gas, provided this quantity is governed by the interaction of electrons with the optical phonons.[3] Taking account of the experimentally obtained values of $\Delta\nu/\nu_0$ and $\Delta m^*/m_0^*$ it follows from (1) and (2) that the third harmonic of the radiation, under the conditions of the described experiment, basically results from band nonparabolicity. Obviously this mechanism is the dominating one in frequency tripling in the submillimeter band.

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