ON FREQUENCY MULTIPLICATION IN THE MILLIMETER RANGE IN n-InSb

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An experimental investigation was made of the generation of the third harmonic in n-InSb at a temperature 77°K in the millimeter range of wavelengths. The results are compared with a theoretical calculation on the assumption that the nonlinear susceptibility is caused by the nonparabolicity of the conduction bands.

At present great attention is being devoted to problems of the frequency conversion of electromagnetic radiation in bulk semiconductors. Specifically, in a number of papers [1-5] a description has been given of frequency multiplication using "hot" electrons in the centimeter range of wavelengths. The frequency multiplication may be associated not only with the heating but also with the singularities of the dispersion law of the carriers in the band. With increasing frequency the role of heating in multiplication must naturally fall off, while for sufficiently high frequencies the principal contribution to nonlinearity may be made by mechanisms associated with nonparabolicity of the band. Thus, in [6] it was shown that frequency multiplication in pure n-InSb at liquid-nitrogen temperature in the millimeter range of wavelengths takes place principally due to nonparabolicity of the conduction bands. The authors of [6] arrived at this conclusion indirectly by analyzing the results of an experiment on the self-action of an electromagnetic wave in semiconductor plasma. In the present paper the effect of tripling the frequency of an electromagnetic field in the n-InSb semiconductor in the millimeter range of wavelengths is investigated in greater detail. A comparison is made between the experimental results and calculations carried out on the assumption that the nonlinear susceptibility for tripling is caused by the nonparabolicity of the conduction band; under these conditions the effect of a strong pumping field on the conditions governing the radiation of the third harmonic was taken into account. The variation of the radiation conditions occurs because in strong fields the parameters of the semiconductor (the effective electron mass \( m^* \) and the collision frequency \( \nu \)) and consequently the complex permittivity also, vary noticeably with a variation of the pumping field \( E \) (see, for example, [6]). A rigorous calculation of the third-harmonic power assumes the solution of the Maxwell equation jointly with the nonlinear material equations and represents a very complex problem. It may be simplified substantially if one makes use of the condition requiring a small field of the \( 3\omega \) frequency in comparison with the pumping field and replaces \( \nu(E) \) and \( m^*(E) \) in the material equations by the values averaged over the volume which depends solely on the pumping power. These values averaged over the volume may be found from experiments on self-action.

In order to clarify the assumptions made in the calculation we shall consider the behavior of conduction electrons in the drift approximation [7]. The equation of motion of an electron in the field \( E \) has the form

\[
\frac{dp}{dt} = -eE + g. \tag{1}
\]

Here \( p \) is the quasimomentum of an electron; \( e \) is the electron charge; \( g \) is the friction force exerted on an electron by other particles. The friction force \( g \) of the electrons may be described approximately by the expressions \( g = -\nu(p^2, T)p \), where \( \nu \) is the collision frequency, while \( T \) is the electron temperature which may differ from the latter temperature \( T_0 \). In order to take account of the nonparabolicity of the conduction band of InSb we make use of the Kane dispersion law which provides a good description of the conduction band of InSb [8]:

Here $\varepsilon(p)$ is the energy of an electron having the quasimomentum $p$; $\varepsilon_g$ is the width of the forbidden band; $m^*$ is the effective mass on the bottom of the conduction band. Representing the right side of (2) in the form of a series in the small parameter $p^2/m^*\varepsilon_g$ and limiting the analysis to the first terms of the expansion, we find that the density of the conduction-electron current has the form

$$j=-en\frac{\partial\varepsilon}{\partial p}=-\frac{en}{m^*}p\left(1-\frac{p^2}{m^*\varepsilon_g}\right),$$

where $n$ is the electron concentration.

Let us write the quantity $E$, $p$, $j$, $T$ in the form

$$E = E_1 e^{i\omega t} + E_2 e^{i(\omega - \Delta) t} + E_3 e^{i(\omega + \Delta) t} + E_4 e^{-i2\omega t},$$

$$p = p_1 e^{i\omega t} + p_2 e^{i(\omega - \Delta) t} + p_3 e^{i(\omega + \Delta) t} + p_4 e^{-i2\omega t},$$

$$j = j_1 e^{i\omega t} + j_2 e^{i(\omega - \Delta) t} + j_3 e^{i(\omega + \Delta) t} + j_4 e^{-i2\omega t},$$

$$T = T_1 + T_2 e^{i2\omega t} + T_3 e^{-i2\omega t},$$

on the assumption that in the considered range of fields

$$|E_1| \ll |E_2|, \quad |p_1| \ll |p_2|, \quad |j_1| \ll |j_2|, \quad |T_1| \ll |T_2|.$$ 

It should be noted that the constant component of the electron temperature $T_1$ depends on the pumping field and differs substantially from the lattice temperature $T_L$ in strong fields. Let us substitute Eqs. (4) into Eq. (3), and let us isolate the terms of zero and first order smallness in $|E_3/E_1|^2$ which vary at frequencies $\omega$ and $3\omega$. Assuming the field $E$ to be linearly polarized, we obtain

$$j_1 = -\frac{en}{m^*}p_1 + \frac{en}{m^*}^3|p_1|^\frac{p_1}{\varepsilon_g};$$

$$j_3 = -\frac{en}{m^*}p_3 + \frac{en}{m^*}^5|p_3|^\frac{p_3}{\varepsilon_g}.$$ 

In order to complete an analogous transition from Eq. (1) to the equations for the complex amplitudes it is necessary to have a detailed knowledge of the function $\nu(p^2, T)$. However, without making the form of the function $\nu(p^2, T)$ specific, we assume $\dagger$ that the heating does not make a contribution to the nonlinear susceptibility but merely changes the radiation conditions of the third harmonic; this is manifested via the dependence $\nu(T_1)$. Then for isolation of the terms that vary at the frequencies $\omega$ and $3\omega$ from Eq. (1), one may discard terms which yield a contribution to the variation of $\nu$ via the variable component of the temperature $T_2$ and the square of the momentum. Thus, subsequently we shall take into account self-action and the influence of pumping on the conductivity at the frequency $3\omega$ only via the constant component of the electron temperature and the nonparabolicity of the conduction band. For this assumption we obtain the following results from Eq. (1):

$\dagger$ The complex amplitudes depend on the coordinates in these expressions.

$\dagger$ From the results of [9] it follows that such an assumption is fully justified.

$$i\omega p_1 + \nu(T_1)p_1 = -eE_1;$$

$$i3\omega p_3 + \nu(T_1)p_3 = -eE_3.$$