DYNAMIC MECHANISM OF NONLINEARITY AND FREQUENCY CONVERSION OF MILLIMETER ELECTROMAGNETIC RADIATION IN n-TYPE InSb

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The frequency mixing of millimeter electromagnetic radiation in n-type InSb was investigated at 77 °K. It is shown that the mixing of near-multiple frequencies can be explained completely by a nonlinearity mechanism associated with the nonparabolicity of the conduction band.

1. Single crystals of n-type indium antimonide cooled to a temperature of the order of 4 °K are widely used as nonlinear elements in detectors[1] and heterodyne mixers[2] of millimeter and submillimeter radiation. Such frequency converters have good conversion coefficients but a slow response (of the order of 10^{-6}–10^{-7} sec), which is due to the fact that the nonlinear weak-field susceptibility of n-type InSb at 4 °K is mainly due to the heating of electrons.[3] When the electron temperature and the high-frequency field intensity are increased, the electron dynamics determined by the characteristic features of the energy band structure begins to play an increasingly important role in frequency conversion. At temperatures of the order of 77 °K, a fast-response dynamic nonlinearity mechanism associated with the nonparabolicity of the conduction band of InSb dominates frequency conversion in the submillimeter range.[4]

The present paper describes an experimental investigation of the frequency conversion of millimeter radiation in n-type InSb at 77 °K. The role of the dynamic nonlinearity mechanism in the mixing of near-multiple frequencies is determined. The physical factors governing the conversion coefficient of the mixer suggested in [5] are determined more fully.[1)]

2. In n-type InSb, the current density is an odd function of the field and we can have the usual heterodyne effect (mixing of similar frequencies) in the presence of a static bias,[2] as well as the mixing of near-multiple frequencies.[5] When the nonlinearity is due to the dynamic mechanism, the coefficient of conversion of a high-frequency signal (ω_S) into a low-frequency wave (Ω) in the presence of a pumping field of frequency $\omega_p = \frac{1}{2}\omega_S \pm \Omega$, defined as the ratio of the powers P_Ω/P_S, is of the form[5]

$$\eta_{2\omega_S-\omega_c}=\frac{P_\Omega}{P_c}=\frac{P_S^2}{4P_*^2}\frac{4RZ_b}{(R+Z_b)^2}, \qquad (1)$$

where P_Ω is the power of the low-frequency signal delivered to a load Z_b; P_S and P_p are the high-frequency signal and pumping powers absorbed in n-type InSb; R is the dc resistance of indium antimonide; P_* is the power which is a quantitative measure of the contribution of the dynamic nonlinearity mechanism to the frequency conversion:

$$P_* = {}^2/_3 g^{-1}\mathscr{E}_g n\nu V. \qquad (2)$$

Here, $\mathscr{E}_g$ is the forbidden band width; ν is the collision frequency; n is the electron density; V is the volume of the sample; g^2 is a factor which is a measure of the ratio of the conversion coefficients for a real electron distribution and for a delta-like distribution. As long as the width of the distribution function in the momentum space is small compared with $(\mathscr{E}_g m^*)^{1/2}$, the value of g is close to unity. If the distribution function is of the form $\exp[E(|p-p_0|)/kT_e]$, where $p_0(t)$ is the average momentum, T_e is the electron density, the factor g is

$$g(\mu)=\left[\frac{\sqrt{\pi}\,\mu}{4\Gamma(3/2)\,K_2(\mu)}\right]^{-1}\left[\int_0^\infty \frac{e^{-\mu(1+x)^{1/2}}x^{1/2}}{(1+x)^{3/2}}\left(1+\frac{2}{3}x\right)dx\right]\int_0^{-2\infty}\frac{e^{-\mu(1+x)^{1/2}}x^{1/2}}{(1+x)^{1/2}}dx.$$

Here, $\mu = \mathscr{E}_g/2kT_e$; $K_2(\mu)$ is a modified Bessel function of the second kind; Γ is the gamma function. The dependences of g and T_e on the pumping power density are plotted in Fig. 1. The electron temperature is found from the laws of conservation making allowance for the scattering by optical phonons.[6]

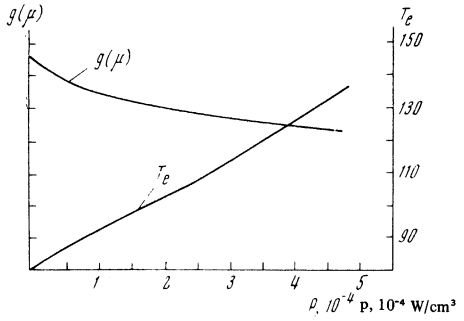

FIG. 1. Theoretical dependences of $g(\mu)$ and T_e on the power absorbed per unit volume. The value of $g(\mu)$ decreases from 0.75 to 0.7 when the temperature T_e increases from 77 to 140 °K.

3. A block diagram of the apparatus used is shown in Fig. 2a. The mixing unit is shown in Fig. 2b. A plate of n-type InSb (0.25 × 0.21 × 0.07 mm) was used as the mixing element (14). This element was placed between the plates of a strip line 13. Ohmic contacts between the semiconductor and the strip line were made by soldering with pure indium. The resistance of these contacts did not exceed a few percent of the resistance of

[1)] Such a mixer is interesting because the static component and the associated shot noise are absent from the converted signal. Moreover, the large difference between the pumping and the signal frequencies ($\omega_p \approx \omega_s/2$) reduces considerably the stringency of the requirements which the heterodyne pumping oscillator must satisfy.

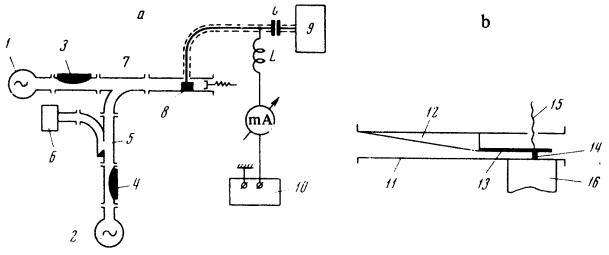

FIG. 2. Block diagram of the apparatus (a): 1) pumping oscillator, generating frequency ω_p; 2) signal oscillator, generating frequency ω_s; 3) decoupling attenuator; 4) calibrated attenuator; 5) directional coupler; 6) calorimetric power meter; 7) hybrid waveguide junction; 8) intermediate-frequency power meter; 9) P5-16 meter; 10– dc bridge; L and C are decoupling elements. Construction of mixer unit (b): 11) standard waveguide (3.6 X 1.8 mm); 12) taper junction with strip line 13; 14) InSb sample; 15) silver wire (30μ diameter lead to standard microwave joint; 16) cooled radiator.

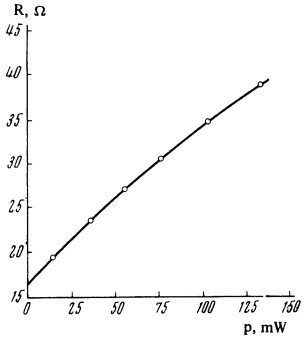

FIG. 3. Dependence of the resistance of the sample on the dc power absorbed in it.

the mixing element itself. This construction ensured homogeneity of the high-frequency field inside the thin semiconductor plate. The strip line had a dc discontinunity. The mixer assembly was cooled to liquid nitrogen temperature.

The pumping and the signal waves were fed to the mixer by means of a hybrid junction 7. The absorptions of the high-frequency pumping and signal waves in the semiconductor plate were deduced from its dc resistance. The calibration curve was the dependence of the resistance on the dc power absorbed in the semiconductor[2] (Fig. 3).

The absorption coefficient of the signal wave in the semiconductor was measured in the presence of the pumping field or a static bias, using a relatively strong signal but still within the range $P_S \ll P_p, P_0$. The signal power was regulated by means of a calibrated attenuator 4. The intermediate-frequency signal Ω was fed to the input of a calibrated P5-16 meter along a 50-Ω coaxial cable. The transfer coefficient of the intermediate-frequency channel increased from 0.16 to 0.24 when the pumping power was raised from zero to 0.2 W.

4. The coefficient of conversion of a high-frequency signal ($\lambda_S \sim 2$ mm) into a low-frequency wave ($\lambda_\Omega \sim 10$ cm) in a mixer consisting of an indium antimonide single crystal ($n \sim 11 \times 10^{13}$ cm^{-3}, $\mu \sim 6.5 \times 10^5$ cm$^2 \cdot$ V$^{-1} \cdot$ sec^{-1}, lattice temperature $T_L = 77$°K) was investigated in the presence of pumping in the 4-mm or 2-mm range (ordinary heterodyne effect). In the first

[2] In prebreakdown fields, the resistance of a semiconductor is determined mainly by the absorbed power and is not greatly affected by the frequency.

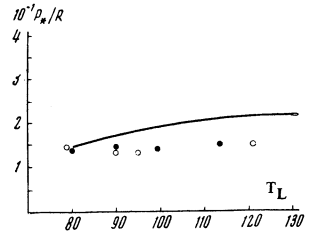

FIG. 4. Dependence of P_*/R on the lattice temperature: O and ● are experimental values obtained at pumping levels of 25 and 40 mW, respectively.

case, the condition $|2\omega_p - \omega_s| = \Omega \pm \Delta\Omega/2$ ($\Delta\Omega$ is the low-frequency pass band of the detector) was satisfied and the conversion coefficient $\eta_{2\omega_p - \omega_s}$ was practically independent of the quality of the low-resistance contacts, whereas in the second case, $|\omega_h - \omega_s| = \Omega \pm \Delta\Omega/2$, the conversion coefficient $\eta_{\omega_h - \omega_s}$ changed greatly when the technique used in the preparation of the low-resistance contacts was altered slightly. When the power outputs of the pumping ($\omega_p \approx \omega_s/2$) and the heterodyne ($\omega_h \approx \omega_s$) oscillators were identical, the conversion coefficient $\eta_{2\omega_p - \omega_s}$ was 3–4 orders of magnitude higher than $\eta_{\omega_h - \omega_s}$.[3] Thus, it became evident that the overall characteristic of the mixer had a quadratic and a cubic term but that the coefficient in front of the quadratic term was small compared with that in front of the cubic term.[4] The quadratic term was due to the contacts and the cubic one to the bulk of the indium antimonide single crystal.

The origin of the cubic term in the characteristic of the InSb mixer, i.e., whether this term was due to the heating of electrons or the conduction band nonparabolicity, was determined by recording experimentally the dependence of P_*/R on the lattice temperature T_L at a low pumping level (Fig. 4). The dependence obtained in the case of electron heating should be quite different from that corresponding to the dynamic nonlinearity mechanism. In the first case,[5] we should have $P_*/R \propto T_L^\gamma$ ($\gamma \geq 1$), whereas in the second case, P_*/R should be practically independent of T_L. Measurements showed that the ratio P_*/R was approximately constant in the range of temperatures in which n = const (Fig. 4). Consequently, we concluded that frequency conversion was dominated by the dynamic nonlinearity mechanism. The experimental values of the conversion coefficient $\eta_{2\omega_p - \omega_s} = \eta$ are plotted in Fig. 5 for different values of the pumping power absorbed in the semiconductor sample.

It is worth drawing attention to the fact that the con-

[3] In this case, the heterodyning took place in the absence of a static field and with a uniform distribution of the temperature across the semiconductor sample. If the temperature distribution across the sample was not uniform, the thermoelectric power in the semiconductor generated a static field, which could give rise to heterodyning in accordance with a cubic characteristic.

[4] The presence of a quadratic term in the mixer characteristic made it possible to generate the second harmonic of the pumping field, but in the case when $\eta_{2\omega_p - \omega_s} \gg \eta_{\omega_h - \omega_s}$ the mixing of the second harmonic of the pumping wave with the signal had practically no effect on the conversion coefficient $\eta_{2\omega_p - \omega_s}$.

[5] In particular, a dependence of P_*/R on the lattice temperature ($\gamma \approx 1$) occurs if the distribution function is close to a biased Maxwellian one [4].

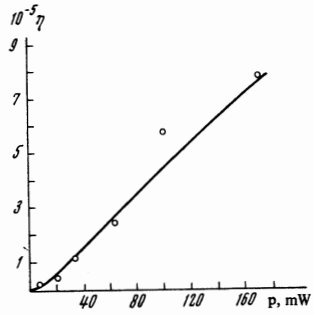

FIG. 5. Dependence of conversion coefficient η on the pumping power absorbed in the sample: the continuous curve is theoretical and the experimental points are denoted by O.

version coefficient was independent of the signal power if $P_S \ll P_p$. In fact, when the signal power was varied from 10^{-11} W to 10^{-2} W, the conversion coefficient η remained constant. The continuous curve in Fig. 5 shows the theoretical dependence of the conversion coefficient η on the pumping power P_p calculated on the assumption that the nonlinearity of the mixer characteristic is due to the conduction band nonparabolicity. We can see that the experimental points fit satisfactorily this theoretical dependence. Thus, it is clear that the dynamic nonlinearity mechanism dominates frequency conversion not only in the qualitative sense (as indicated by the temperature dependence of η) but also in the quantitative sense. The dependence of η on P_p is not quadratic (Fig. 5). This is due to the fact that P_* and R are both proportional to the collision frequency ν and this frequency increases with increasing P_p.

It is evident from Eq. (1) and Fig. 5 that the conversion coefficient increases as the pumping power P_p increases but Eq. (1) is valid only if $P_p < P_*$ and n = const. Consequently, this equation is unsuitable for the accurate determination of the maximum conversion coefficient. A rapid increase in the electron density (breakdown), associated with Auger type processes, was observed experimentally in the measurements of the dependence of R on P_p when the pumping power reached $P_p \approx 0.15P_*$ (see also [7]). Therefore, Eq. (1) could be used only to estimate the maximum value of the conversion coefficient in fields close to the breakdown value. This maximum value was $\eta_{max} \sim 5 \times 10^{-3}$. In our measurements of η, the pumping power absorbed in this semiconductor did not exceed $4 \times 10^{-2} P_*$ and the conversion coefficient was $\eta \approx 10^{-4}$.

We also investigated experimentally the mixing of two similar frequencies ($\lambda_S \sim 2$ mm, $\lambda_h \sim 2$ mm) in pure indium antimonide ($n \sim 11 \times 10^{13}$ cm^{-3}, $\mu \sim 6.5 \times 10^5$ cm$^2 \cdot$V$^{-1} \cdot$sec^{-1} at 77°K) in the presence of a static field.[6)] In this case, the conversion coefficient $\eta\omega_h - \omega_S + 0 = \eta_0$ was of the same order as $\eta 2\omega_p - \omega_S$ provided that $P_0P_h \approx P_p^2/2$. Here, P_h denotes the heterodyne power absorbed in a sample at a frequency close to the signal frequency, P_0 is the dc power absorbed in a sample, and P_p is the pumping power for $\omega_p \approx \omega_S/2$. The conversion coefficient increased linearly with increasing P_0 when P_h = const > P_0 and with increasing P_h if P_0 = const > P_h. In particular, in the case of an InSb plate mearuing 0.22 × 0.2 × 0.16 mm, the the linear dependence of η_0 on P_0 was observed, for $P_h \approx 250$ mW, right up to P_0 = 100 mW and the slope of this dependence was $\eta_0/P_0 \approx 2.2 \times 10^{-3}$ W^{-1}. Further increase in P_0 resulted in a deviation from the linear law because the resistance of the sample and, consequently, the characteristic power P_* were functions of the total field $|E_0 + E_h|$. We assumed that in this case the nonlinear characteristic of the mixer was again due to the nonparabolicity of the conduction band of indium antimonide and we then found that the conversion coefficient η_0 was given by

$$\eta_0 = \frac{P_h P_0}{2P_*^2} \frac{4RZ_b}{(R+Z_b)^2}.$$

In the particular case considered above ($P_h \approx 250$ mW, $R \approx 15.5\Omega$, $Z_b = 50\Omega$, $\nu = 4.1 \times 10^{11}$ sec^{-1}), the theoretical value $\eta_0/P_0 = 2.25 \times 10^{-3}$ W^{-1} was equal to the experimental value.

The conversion coefficients $\eta_0 = \eta\omega_h - \omega_S + 0$ and $\eta = \eta 2\omega_p - \omega_S$ were practically unaffected when the intermediate frequency $\Omega = |\omega_h - \omega_S| = |2\omega_p \approx \omega_S|$ was varied from 0.25 to 4 GHz. Consequently, the characteristic response time of the dynamic nonlinearity mechanism of pure indium antimonide was less than 5×10^{-11} sec at 77°K.

5. The reported investigation showed that the frequency mixing in pure indium antimonide at 77° K can be fully explained by the dynamic nonlinearity mechanism which is due to the conduction band nonparabolicity. The heating of electrons is manifested primarily in the self-interaction effects, i.e., in the change in the collision frequency and the electron density (at breakdown) with the field amplitude. The coefficient of conversion of millimeter and submillimeter signals into centimeter waves is limited by the high-frequency breakdown. The maximum value of the conversion coefficient of InSb subjected to breakdown fields is 5×10^{-3} at lattice temperatures of the order of 80° K. The value of the conversion coefficient can be increased by lowering the lattice temperature.

[6)] The mixing of frequencies (the heterodyne effect) in indium antimonide at 4°K in the presence of a static field was investigated by Putley et al. [2] The frequency conversion effect in InSB at 4°K was primarily due to the heating of electrons. The characteristic response time of the heating of electrons at $T_L \sim 4$°K was of the order of $\tau_e \sim 10^{-6}$–10^{-7} sec. Consequently, efficient conversion was achieved provided the frequency $\Omega = |\omega_S - \omega_h|$ was less than 10^7 Hz.

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