MICROWAVE EMISSION FROM THE BULK OF n-TYPE INDIUM ANTIMONIDE*

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(Received 8 April 1970)

We have observed microwave (3 and 9 GHz) emission from round loop samples of n-type InSb at 77°K subjected to dc magnetic and induced 20-MHz electric fields. A theoretical model, which identifies the emission as shot noise produced in localized regions of high electric field where the ionization by electrons is enhanced by the transverse magnetic field, is shown to fit the experimental data.

Since the first discovery of microwave emission from n-InSb at 77°K in moderate applied electric and magnetic fields,[1,2] considerable interest has been attached to distinguishing between contact effects and bulk effects that may be responsible for the observed emission. Recent experiments have identified some types of emission as originating from the contacts.[3] In order to determine whether emission occurs also from the bulk, we have used round loops of n-InSb in which the electric field was induced circumferentially by a time-variant magnetic field. Contact effects were thus completely eliminated.

All samples were cut from (111) plane wafers of single-crystal n-type InSb, having electron densities in the range $(1\text{-}2)\times10^{14}$ cm^{-3} and mobilities in the range $(5\text{-}7)\times10^{5}$ cm^2/V sec at 77°K. The loops were of 8.7-mm outside diameter with a 1-mm square cross section. These samples were placed in the transverse plane of an eccentric transmission line as shown in Fig. 1. Each sample could be rotated about an axis through its center C. A static magnetic field B_0 was applied perpendicular to the plane of the loop sample. The electric field E_0 was induced in the sample by passing pulses of 20-MHz current (100 pulses/sec, 25 μsec width) through a coil wound on the slotted outer conductor of the transmission line.[4] Emission form the samples was synchronously detected by conventional microwave receivers operating at frequencies of 2.6-3.2 and 8.5-10.0 GHz.

Twelve different loop samples were tested. Five of these samples produced no observable emission when the maximum available electric and magnetic fields (60 V/cm peak and 5 kG) were applied. The other samples produced broadband emission which increased monotonically with either E_0 or B_0 once certain threshold field values were exceeded, as is usually observed with rod samples.[1] The emission from a given loop sample was essentially the same for frequencies in either the 3- or 9-GHz range. The threshold electric and magnetic fields observed were typically 20-50 V/cm and 2-4 kG, significantly larger than those usually reported for "low-field" emission from rod samples with contacts.[1,3] The experimental points in Fig. 2 show a typical threshold characteristic. For samples that showed emission, 360° rotation of the sample around its center, with E_0 and B_0 held constant, generally produced two broad peaks in emission approximately 180° apart (Fig. 3), with the total variation of emission level ranging from 3 to 10 dB. No obvious correlation between these variations with sample rotation and the known crystal axes in the samples could be found. From all of these results, three general features, namely the higher thresholds compared with samples having contacts, the variety of behavior for identically prepared samples, and the change in observed emission level with sample rotation, force the conclusion that the microwave emission is produced in localized regions and is related to inhomogeneities in the sample material.

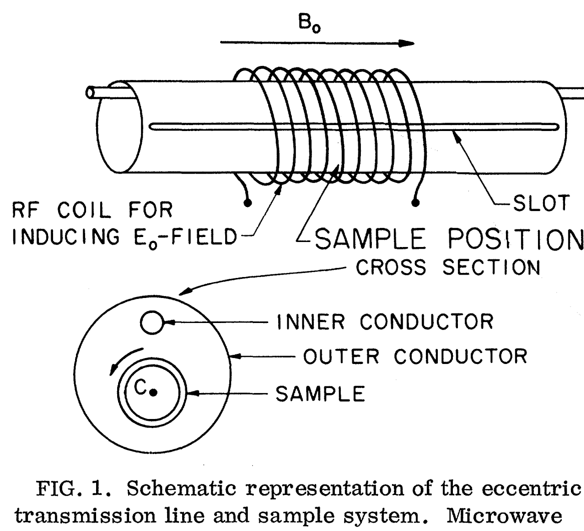

FIG. 1. Schematic representation of the eccentric transmission line and sample system. Microwave tuning is adjusted with a sliding short at one end of the line. A static magnetic field B_0 is applied as shown. The structure is immersed in liquid nitrogen.

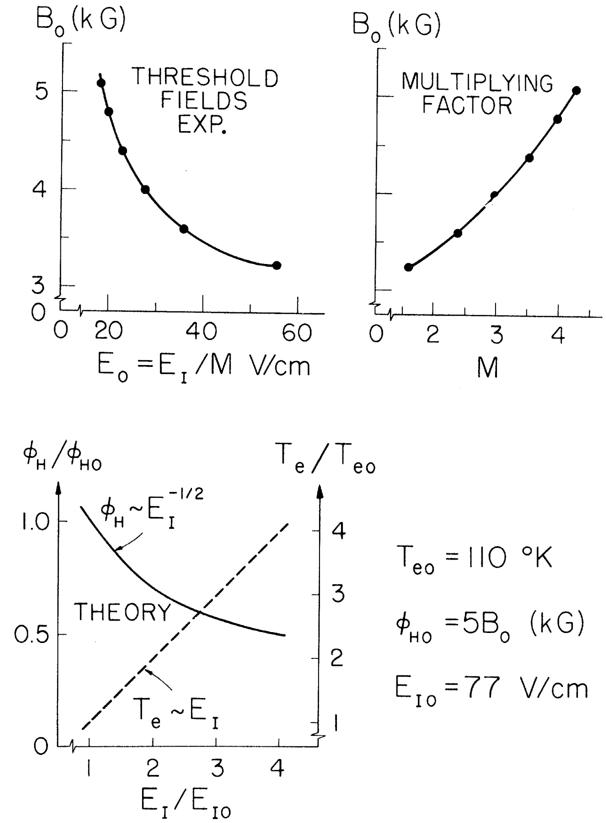

FIG. 2. Experimental values of electric and magnetic field required to maintain a constant threshold (minimum detectable) emission level equivalent to that of a thermal source of $(0.5\text{-}1.0)\times10^3$°K at 9.0 GHz. The theoretical model for which $T_e \sim E_I$ and $\varphi_{\rm H} \sim E_I^{-1/2}$ requires that the multiplying factor M vary with B_0 as shown in order to obtain an exact fit to the experimental threshold fields and emission level.

We now turn to the devolopment of a theoretical model for the emission process. Metallurgical studies[5] of InSb show that inhomogeneities in the impurity density occur in 1-10 μm regions where the electric field (for regions of lower electron density) could be higher by 2-4 times than the applied average field. Also, enhancement of the ionization rate by a transverse magnetic field has been demonstrated experimentally and theoretically.[6] Using these facts, we describe the emission as coming from shot noise produced by the magnetic-field-enhanced ionization process in localized high electric field regions.

In a uniform material, the power input to an electron of a particular energy ϵ is given by $P_I \equiv e\vec{v}(\epsilon)\cdot\vec{E}_t$, where e is the electron charge, $\vec{v}(\epsilon)$ is the "drift" velocity of an electron, and $\vec{E}_t$ is the total electric field (applied field and

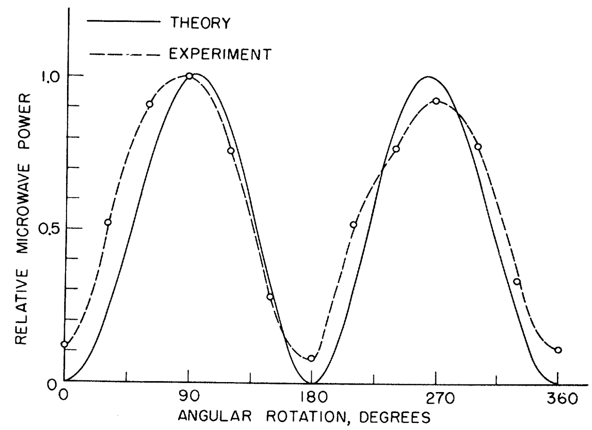

FIG. 3. Relative microwave power measured as a function of sample rotation compared with computations which assumed that the microwave current distribution around the loop sample was produced by a localized source. Experimental conditions: $E_0 = 54$ V/cm, $B_0 = 5.1$ kG, and frequency = 9.0 GHz.

Hall field). We find $\vec{v}(\epsilon)$ by solving the time-independent Boltzmann equation in the relaxation-time approximation, assuming an energy-dependent relaxation time $\tau(\epsilon)$ and effective mass $m^*(\epsilon)$.[7,8] With the boundary condition of zero Hall current, which is appropriate for our experiments, we then have

$$P_I = \frac{e^2\tau(1+\varphi_{\rm H}^2)}{m^*(1+\omega_c^2\tau^2)}E^2, \qquad (1)$$

where $\omega_c = eB_0/m^*$ is the electron-cyclotron frequency, E is the applied electric field, and $\varphi_{\rm H}$ is the ratio of the Hall electric field to the applied electric field. The quantity $\varphi_{\rm H}$ is given by[7]

$$\varphi_{\rm H} = -\left\langle \frac{\omega_c\tau^2/m^*}{1+\omega_c^2\tau^2}\right\rangle \left\langle \frac{\tau/m^*}{1+\omega_c^2\tau^2}\right\rangle^{-1}, \qquad (2)$$

where the brackets indicate an average over the energy distribution function.[9]

In order to determine the conditions for the onset of local breakdown, we must compare the energy gain rate of Eq. (1) with the energy loss rate. The higher-energy electrons which will be of interest here lose energy chiefly to optical phonons at a rate given by $\hbar\omega_o/\tau_e$, where ω_o is the optical phonon frequency and τ_e is the electron-energy scattering time. An electron starting from an energy ϵ may gain energy and produce an ionizing collision provided P_I exceeds $\hbar\omega_o/\tau_e$ for energies from ϵ to above the energy gap ϵ_g. Figure 4 shows a plot of the normalized energy gain and loss rates, P_I/E^2 and $\hbar\omega_o/\tau_e E^2$, as a function of electron energy.[10] We note that

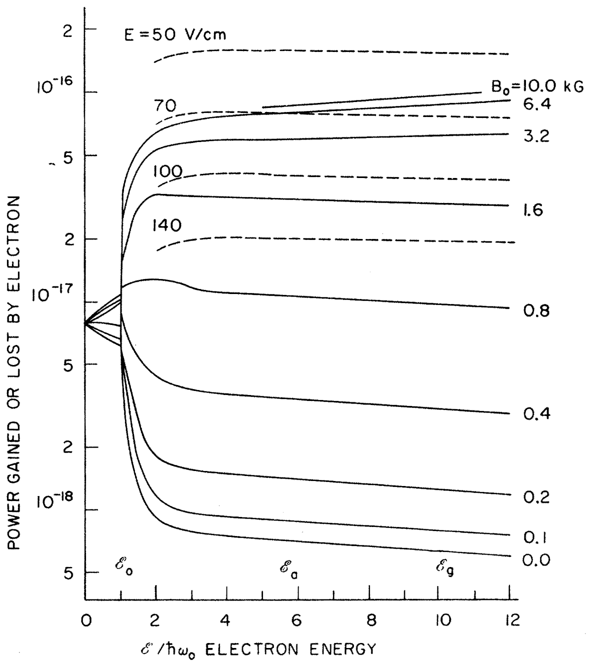

FIG. 4. Power gain P_I/E^2 (solid lines) or loss $\hbar\omega_o/\tau_e E^2$ (dashed lines) per electron divided by the square of the applied electric field (W m^2/V^2) as a function of electron energy in optical-phonon units for various electric and magnetic field values. The energy ϵ_a that enters into calculating the ionizing fraction F is obtained from the intersection above which $P_I > \hbar\omega_o/\tau_e$.

for sufficiently small values of E and B_0 no electrons satisfy the condition $P_I > \hbar\omega_o/\tau_e$. As E and B_0 are increased, P_I eventually exceeds $\hbar\omega_o/\tau_e$ for energies from some value $\epsilon_a < \epsilon_g$ through energies above ϵ_g. The fraction of the electrons having energy greater than ϵ_a can gain energy from the total electric field to produce ionizing collisions. The "ionizing fraction" F of the electron population can be calculated by assuming an appropriate electron distribution, as will be done below, i.e., $F = \int_{\epsilon_a}^{\infty} f(\epsilon)d\epsilon$.

These results can be specialized to describe the conditions in an inhomogeneity region of the InSb crystal.[11] The length of the inhomogeneity region (1-10 μm) is such that each electron in the ionizing fraction that passes through the region creates, on the average, one additional electron-hole pair. These generated carriers give rise to a shot-noise current which is approximately FI_0, where I_0 is the drift current in the sample.[12] The inhomogeneity region can then be thought of as a localized microwave current source of rms value $[2eFI_0(\Delta f)]^{1/2}$, where Δf is the receiver bandwidth. The localized current source establishes a microwave current-density distribution $\vec{J}_a$ around the loop sample which excites the eccentric transmission line. From this known excitation of the transmission line, the microwave power delivered to the receiver can be computed directly. An immediate comparison of this model with our experiments can be made for the variation in output power with sample rotation (Fig. 3). The power delivered to the receiver is proportional to $|\int \vec{e}_T \cdot \vec{J}_a dA|^2$, where $\vec{e}_T$ is the electric field mode function for the eccentric transmission line, A is the cross section of the line, and $\vec{J}_a$ is defined above. From this, we can calculate the output power as a function of sample rotation. The results of this calculation are shown in Fig. 3 where they are compared with experimental data for a sample which showed a marked variation in output with sample rotation. The model of a localized source is indeed supported by the experiments.[13]

We next turn to a more detailed test of our model in which we seek to predict the observed E_0-B_0 threshold curve and the output power at threshold (Fig. 2). The two principal unknowns in our model are the electric field in the inhomogeneity region E_I and the electron-energy distribution function. The first affects the electric field amplitude [Eq. (1)] and the second enters into φ_H, both then determining ϵ_a (Fig. 4) and thus the B_0 vs E_0 dependence on the ionizing fraction F. Since we have no detailed knowledge of the inhomogeneity in the material, we shall initially make the simplest assumption that $E_I = ME_0$, where M may be a function of B_0.[14] In the case where acoustic phonon scattering determines the main body of the distribution function, it can be shown[7,8] that in moderately high electric and magnetic fields ($\mu E/v_a \gg \omega_c\tau_a \gg 1$, where v_a and τ_a are the acoustic velocity and scattering time, respectively) the isotropic part of this distribution, f_i, is approximately Maxwellian with an electron temperature T_e that increases as E_I, and which when used in Eq. (2) leads to $\varphi_H \sim E_I^{-1/2}$.

Using these results we find that both the observed variation of the threshold fields and the microwave output power can be matched with an M that varies approximately linearly with B_0 (Fig. 2),[15] which also implies that the electric field E_I remains approximately constant. Since for our experiments $\varphi_H^2 \gg 1$, and hence by Eq. (1) $P_I \sim \varphi_H^2 M^2 E_0^2$, the energy gained by an electron is a strong function of B_0 only. Alternatively, the threshold fields and microwave power can be fitted fairly well by assuming that M is constant (in the range 2-4), $T_e \sim E_0$, and $\varphi_H \sim E_0^{-1}$. However, in contrast to the forms assumed in Fig. 2, these dependences of T_e and φ_H upon E_0 are not consistent with the theory of acoustic phonon scattering.[16] Both sets of assumptions about the variation of φ_H and T_e predict that the microwave emission increases as either E_0 or B_0 is increased above threshold conditions. The predicted rates of increase with field are larger than those generally observed experimentally, however. Further knowledge of the electron distribution function with applied electric and magnetic fields would provide additional means for testing our model.

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*Work supported by the National Science Foundation under Grant No. GK-10472.

[1]S. J. Buchsbaum, A. G. Chynoweth, and W. L. Feldmann, Appl. Phys. Lett. 6, 67 (1965); see also a comprehensive review of other work since then in M. Glicksman, IBM J. Res. Develop. 13, 626 (1969).

[2]The "moderate" or "low-field" regimes are 2-20 V/cm and 1-3 kG.

[3]T. Musha, J. Ohnishi, and M. Hirakawa, Phys. Rev. Lett. 22, 1254 (1969); E. V. George and G. Bekefi, Appl. Phys. Lett. 15, 33 (1969); B. Ancker-Johnson and C. L. Dick, Jr., Appl. Phys. Lett. 15, 141 (1969); A. H. Thompson and G. S. Kino, IBM J. Res. Develop. 13, 616 (1969). Our attention has been directed to the theoretical work of J. E. King, J. Appl. Phys. 40, 5350 (1969); this work differs from ours in that shot noise is generated by holes that are heated sufficiently to ionize; the predicted frequency spectrum and power level of emission from this theory are inconsistent with our experimental results.

[4]When applied through contacts to rod samples, 20-MHz voltage pulses produced the same microwave emission as dc voltage pulses.

[5]A. F. Witt and H. C. Gatos, J. Electrochem. Soc. 113, 808 (1966); A. F. Witt, *ibid.*, 114, 298 (1967).

[6]M. Toda and M. Glicksman, Phys. Rev. 140, A1317 (1965); H. Schmidt and D. J. Nelson, Phys. Rev. 184, 760 (1969). In these works the emphasis is on total current breakdown; for our experiment, where only a small fraction of the electrons is able to ionize, we develop a more detailed model of energy gain by these electrons.

[7]A. Bers and R. N. Wallace, Massachusetts Institute of Technology Research Laboratory of Electronics Quarterly Progress Reports No. 97 and No. 99, 1970 (unpublished).

[8]H. F. Budd, Phys. Rev. 131, 1520 (1963).

[9]$\langle X \rangle \equiv \sum_\epsilon [X(-\frac{2}{3})\epsilon(df_i/d\epsilon)]/\sum_\epsilon f_i$, where f_i is the isotropic part of the electron distribution function.

[10]In making this plot, we have used known data for the variation of the effective mass with energy [F. R. Kessler and E. Sutter, Z. Naturforsch. 16a, 1173 (1961)] and theoretical formulas for the electron momentum and energy scattering times in interactions with optical phonons [E. M. Conwell, *High Field Transport in Semiconductors* (Academic, New York, 1967), pp. 157-158]. An average momentum scattering time of 4×10^{-12} sec, deduced from the low-field electron mobility, was used for electron energies less than $\hbar\omega_0$.

[11]For the applied electric and magnetic fields in our experiment, the ionizing fraction F is essentially zero outside the inhomogeneity region (e.g., at 30 V/cm and 3 kG, $F \sim 10^{-10}$).

[12]The transit time of the electrons through these short regions is small enough to insure a flat shot-noise spectrum throughout the range of observed microwave frequencies, consistent with our experimental observations.

[13]It should be noted that the imperfect nulls observed in Fig. 3, and for all other samples that emitted, indicate the presence of multiple sources. However, the fact that two peaks were generally observed indicates that at threshold one of the sources dominates the emission. As a further confirmation of our model of a localized source, a single-crystal loop sample which showed no emission was broken and resoldered with indium; it then produced strong emission.

[14]The distortion of the electric field near an inhomogeneity is expected to be a function of B_0.

[15]Both the amplitude of M and its variation with B_0 are relatively insensitive to the assumed value of T_{e0} over the range 77 to 145°K.

[16]It should be remarked that a two-temperature distribution function with different temperatures above and below the optical phonon energy may be possible in InSb. See, for example, G. Persky and D. J. Bartelink, IBM J. Res. Develop. 13, 607 (1969).