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The Role of Acoustic Wave Amplification in the Emission of Microwave Noise from InSb*

Abstract: The experimental evidence for the generation of microwave emission from InSb by acoustic amplification of thermal noise is reviewed. The conditions in which the electron-phonon interaction is likely to dominate over other possible physical mechanisms are discussed, with particular reference to crystallographic orientation and crystal geometry. The application of the small signal acoustic amplification theory is shown to lead to qualitative agreement between constant gain loci and emission threshold curves.

Introduction

The observations of microwave emission from InSb have occurred under such a wide variety of experimental conditions that it is unlikely that any single physical mechanism is responsible. However, there is strong experimental evidence that amplification of acoustic noise flux provides the primary source of the emission in particular circumstances, namely in long [110] oriented n-type crystals at 77°K, below the impact ionization region.

The purpose of this paper is to examine those factors which must be satisfactorily explained in order to reconcile experimental observations of microwave emission with our present knowledge of the acoustoelectric effect in the presence of a magnetic field. We do not exclude the possibility that the same mechanism might produce microwave emission at high electric fields, even in the impact-ionization region; however, it would be much more difficult to isolate the acoustoelectric effect as the major source of the emission.

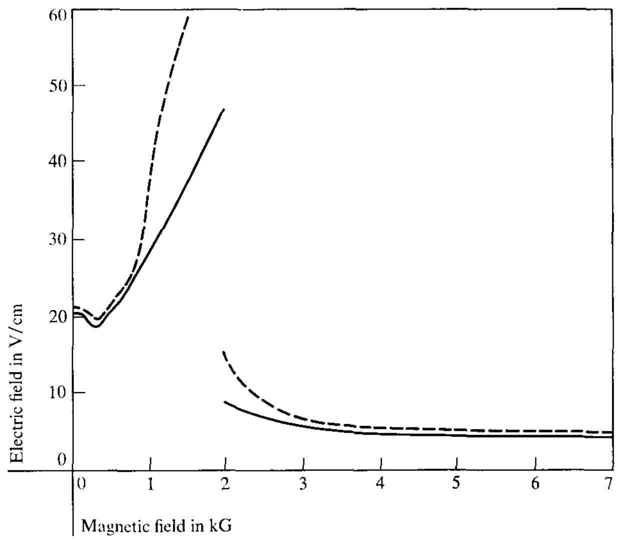

Figure 1 Typical threshold curves for acoustoelectric current oscillations (———) and 4 GHz microwave emission (– – –). (Refs. 2 and 4.)

Experimental evidence

The experimental observations that have linked the microwave emission most closely with the acoustoelectric effect are those of Arizumi[1] and the author.[2] Although there are a number of differences in the experimental observations and the interpretation of the results, there is fairly broad agreement between the two groups. The principal results obtained are summarized in Figs. 1–3. The threshold curves for microwave emission are found to lie close to those measured for acoustoelectric current oscillations, for crystals greater than 1 cm in length, with electron concentrations around 10^{14} cm^{-3}. The magnetic-field dependence with respect to magnitude and orientation is very similar for the two phenomena. The strongest emission for the low-electric-field region is obtained from [110] oriented crystals, which also exhibit the largest acoustoelectric effect. The acoustic shear waves are piezoelectrically active along this direction with growth rates of 50 to 100 dB/cm being characteristic of phonon frequencies around 1 GHz.

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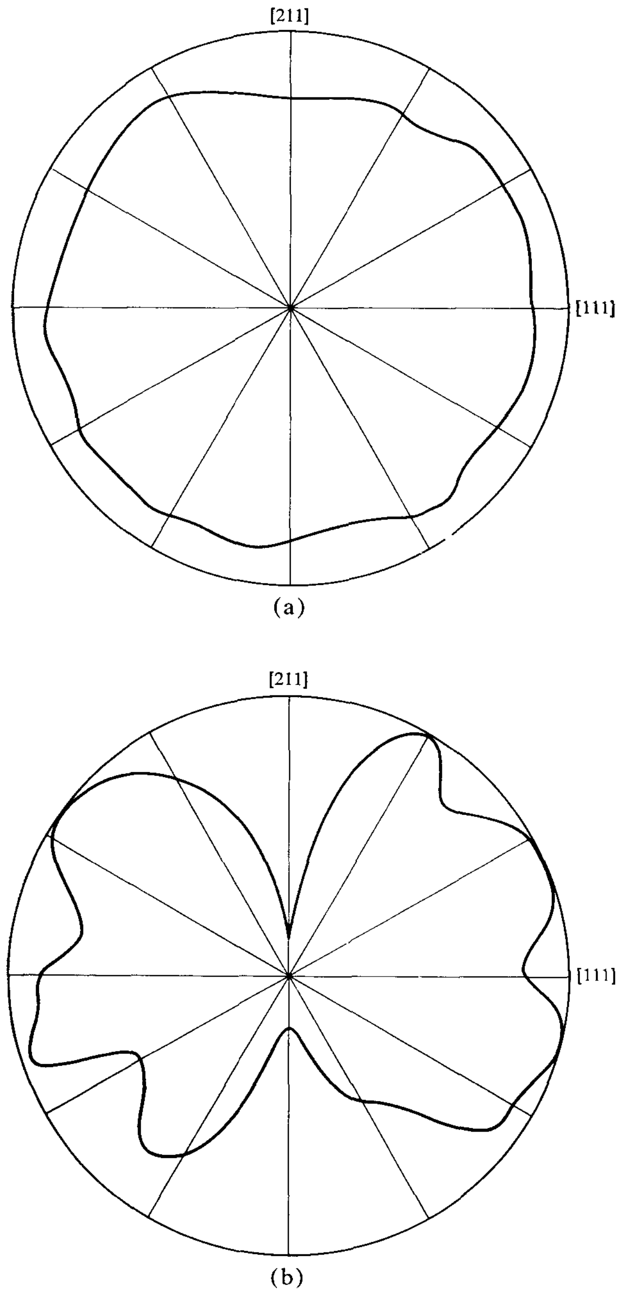

Figure 2 Dependence of 4 GHz microwave emission on rotation of the magnetic field in the azimuthal plane. (a) $E = 45$ V/cm, $B = 1.1$ kG; (b) $E = 15$ V/cm, $B = 4$ kG. (Data from Ref. 4.)

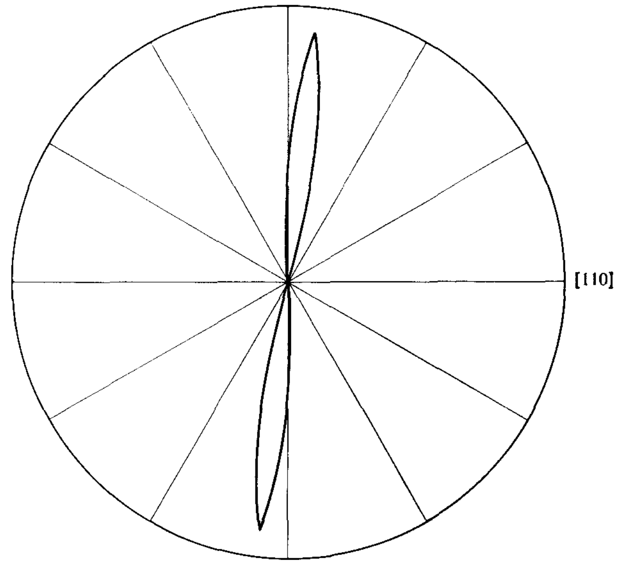

Figure 3 Dependence of 10 GHz microwave emission on rotation of the magnetic field in the sagittal plane. $E = 5$ V/cm, $B = 4.5$ kG. (Data from Ref. 2.)

Discussion

The similarity of the threshold curves for the acoustoelectric current oscillations and the microwave emission is suggestive of a common physical mechanism but, of course, by itself does not constitute sufficient evidence for identifying acoustic wave amplification as the principal source of microwave emission. In the discussion that follows we will examine various aspects of the experimental results with the aim of reaching as complete a conclusion about the origin of low-field emission as is possible at the present.

- *Threshold observations*

The identification of the threshold electrical field for microwave emission at a given frequency is a function of the sensitivity and bandwidth of the receiver used. Our results appear to give the lowest threshold fields so far observed, about 1 V/cm, probably because of the −105 dBm sensitivity in a 2 MHz bandwidth of the receiver used, in the frequency range 500 MHz to 10 GHz. Since the emission rises to a maximum level of at least −50 dBm it is clearly important to define the power level at which the threshold is observed. Further, it is common practice to use the appearance of a time dependence in the sample current to define the threshold of acoustoelectric current oscillations. However, helicon wave transmission measurements by Potzl[3] have indicated that domains are present in the InSb before non-ohmic effects show up in the current. As a result, the relative positions of the two threshold curves may simply reflect the sensitivity of the detection apparatus for each phenomenon.

There is no a priori reason to expect the threshold curves to be identical since the acoustoelectric effect is the result of the integrated influence on the conduction current of a very wide phonon spectrum, whereas the microwave emission is observed within the i.f. bandwidth of the receiver under virtually monochromatic conditions, although it, too, is intrinsically a broadband phenomenon. Of greater significance is the close correlation exhibited between loci of constant small-signal gain (for fixed frequencies) and the respective threshold curves. Recent work[4] has extended the range of magnetic fields for which good agreement exists, to the region where the Larmor radius of the drifting carriers exceeds the wavelengths of microwave phonons.

• *Crystal geometry and orientation*

The drift velocity in rectangular bars of InSb, with a transverse magnetic field applied, is essentially uniform except for short square-shaped regions near the end contacts. Uniform amplification of acoustic noise flux is therefore favored by crystals with large length-to-width ratios, since the gain is a strong function of the local drift velocity, in general. The minimum length required for mature acoustoelectric domains to form in InSb is found to be somewhat greater than 10 mm.[4] It follows that the most favorable geometry for promoting the amplification of acoustic flux is that of long thin specimens (e.g. $20 \times 1 \times 1$ mm.[3] The very short specimens (less than 5 mm) used by many workers, even if cut along the [110] direction, would produce very weak emission from acoustic sources because of the nonuniform current flow and the resultant low level of acoustic flux. The absence of acoustoelectric effects in these samples is indicative of the low gain present. The uniform-region drift velocity will be reduced below the zero magnetic field value by the geometrical magnetoresistance factor, which can become appreciable. For example, in a square specimen the required externally applied electric field to reach a given velocity increases by an order of magnitude as B goes from zero to 2kG, for a mobility $\mu = 500{,}000\ \text{cm}^2/\text{V-sec}$, so that acoustic amplification effects are no longer significant at low electric fields in such a crystal.

The crystallographic orientation of the specimen plays a critical role in determining whether acoustic amplification will be significant in the production of emission. The [110] directions are noticeably more active piezoelectrically than other orientations. For example, the cubic axes are inactive while the longitudinal waves along the [111] direction have approximately one-third the growth rate of [001] polarized shear waves along [110]. Off-axis amplification will become important for crystals cut along weak coupling directions. Insufficient experimental data have been obtained so far to give a comprehensive account of the orientation dependence of the emission, but the results obtained from [110] and [111] crystals provide strong correlation between the piezoelectric activity and the efficiency of the emission process.

• *Contact considerations*

It is not possible at this time to exclude the contacts (assumed here to be at the ends of the specimen) as a source of microwave emission. However, the experimental evidence suggests that their contribution is small compared to that of the bulk. For example, the emission obtained in experiments where the contact regions were well outside the rf coupling circuit, together with the geometrical and orientation dependence noted above, cannot be explained unless the bulk contribution was significant. We believe that the most likely influence of the contacts is in promoting the nucleation of acoustoelectric domains at the cathode and in influencing the reflection and quenching of the domains at the anode. This will affect the magnitude of the emission measured in a particular experiment but it is not considered to be a fundamental emission process.

The dc flow solution in a transverse magnetic field reveals the presence of very high electric fields at two diagonally opposite corners of a rectangular crystal. Local breakdown can occur over very small regions, even for modest electric fields applied to the crystal contacts (≈ 5 V/cm), when the product $\mu B \gg 1$. Any emission originating from impact ionization at these points can be treated as a contact phenomenon and can be discriminated against by a suitable design of microwave coupling circuit.

• *The effect of the magnetic field orientation*

A transverse magnetic field affects the emission at a given electric field in a manner completely consistent with an acoustoelectric explanation of the phenomenon. Rotation of the field in the azimuthal plane produces similar variations in the intensities of the microwave emission and the current oscillations. The origin of these variations, which are significant only at magnetic fields above 2 kG, appears to be crystal inhomogeneities rather than inherent crystalline anisotropy, and can be traced to the dependence of the electronic gain on the field direction. At lower magnetic fields the emission becomes independent of the orientation, and as B approaches zero the threshold electric fields rise to the values measured for longitudinal magnetic fields. In this region ($B < 500$ G) the magnetic field is no longer important in determining the threshold field or the intensity of the emission.

• *The small signal theory of acoustic wave amplification*

It is convenient to divide the E–B plane into two regions for the application of a small-signal theory of acoustic amplification. The threshold curves shown in Fig. 1 essentially span the E–B diagram over (low B-high E) and (high B-low E) values. In the (low B-high E) region, the collision-dominated theory is no longer valid since typical microwave phonon wavelengths are small compared to the Larmor radius of the carriers. In addition, inertial effects cannot be neglected because the Doppler-shifted phonon frequency is comparable to the collision frequency. The theory[5] predicts that the constant gain loci, shown in Fig. 4, rise to larger electric fields as B increases above 1 kG and the frequency of maximum gain increases beyond the value obtained from the modified theory of White.[2]

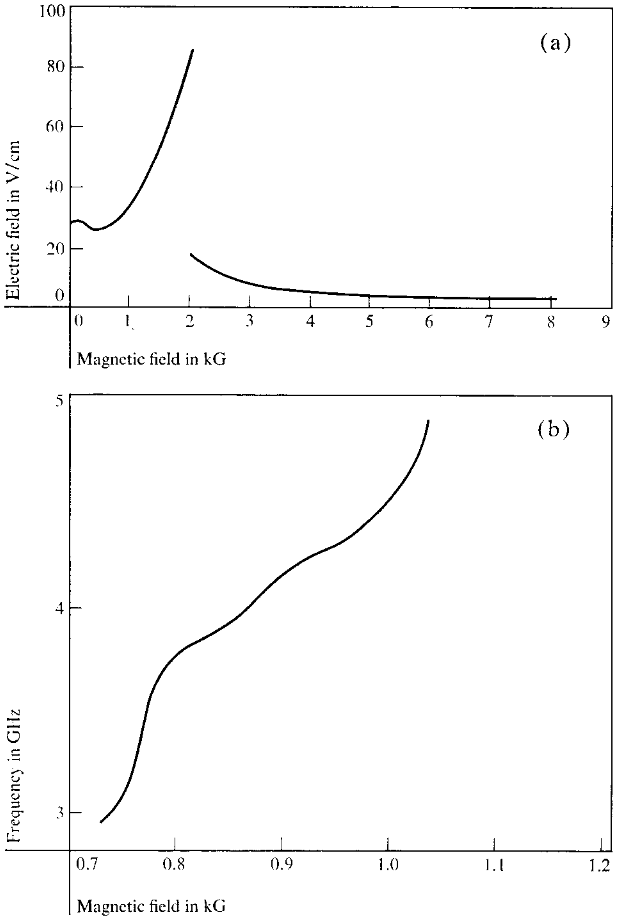

Figure 4 (a) General form of 4 GHz constant gain loci in the *E–B* plane; (b) variation of frequency of maximum emission with magnetic field intensity.

These features are in agreement with the experimental observations of microwave emission and current oscillations. The measured shift in the frequency of maximum emission is also shown in Fig. 4.

For magnetic fields above 2 kG, the collision-dominated theory may be used to describe the amplification for frequencies around 1 GHz. Crystals with carrier concentrations of 10^{14} cm^{-3} have a frequency of maximum gain of about 1.5 GHz, with a growth rate of 50 dB/cm. The threshold curves for emission at these frequencies follow closely the constant gain loci for $B > 2$kG.[2]

- *Emission spectrum and power level*

It has been noted above that the emission spectrum near 1 GHz showed good agreement with the general behavior of the acoustoelectric effect. Broadband emission is observed, however, over the frequency range from a few MHz to 12 GHz in acoustoelectric experiments. The small acoustic gain expected at frequencies below 100 MHz suggests that emission in this region results from mixing or down-conversion from higher frequencies. Similarly, the frequency at which the lattice attenuation exceeds the electronic gain is well below 12 GHz, so that mixing products are required to explain the production of X-band emission by acoustic amplification. The nonlinearities involved may be lattice anharmonicity or acoustoelectric. Using Haydl's[6] estimate for the thermal acoustic noise power in a 1 MHz bandwidth, which is approximately −110 dBm here, small-signal gains of the order of those measured in InSb (typically 50 dB/cm) are sufficient to produce emission at the power levels commonly observed, allowing for a generous loss factor arising from the poor coupling efficiency of the waveguide-crystal arrangement.

- *Acoustoelectric domains*

It is difficult to avoid the simultaneous excitation of current oscillations when observing microwave emission under the experimental conditions considered here. This results in two interesting phenomena which help to identify further the source of the emission. Firstly, before the acoustic flux builds up in the crystal, the current is approximately at the ohmic value; the threshold field required for emission is an order of magnitude above that when non-ohmic conditions take over several microseconds later. This initial emission has also been observed in samples too short to exhibit acoustoelectric effects,[7] and is easily distinguishable from the noise emitted during acoustoelectric instabilities. It also occurs in crystals oriented in directions other then [110] and is therefore unlikely to arise from acoustic amplification. Secondly, the acoustic flux is distributed nonuniformly in the crystal during current oscillations because of domain formation. The emission has been observed to conform to the spatial distribution of acoustic flux for the case where a stationary domain forms adjacent to the anode contact. This appears to exclude contact and local breakdown phenomena as first-order sources. However the noise originating in these regions can clearly supplement the acoustic flux of thermal origin and so play an indirect role in the emission process.

Conclusions

We have examined the experimental conditions under which microwave emission may be produced by amplification of acoustic noise flux. It has been shown that there is considerable evidence to support the view that the piezoelectric interaction between drifting carriers and thermal phonons is the dominant mechanism in long [110] oriented crystals immersed in a transverse magnetic field. Other sources of noise such as the contacts and local breakdown regions remain plausible, and may well contribute significantly in other circumstances (particularly in short crystals) but these effects almost certainly play a subordinate role in the experiments discussed here.

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