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Acoustoelectric Amplification in InSb*

Abstract: It was demonstrated by Kikuchi that two modes of acoustoelectric domain oscillation occur in InSb in a transverse magnetic field. Using lithium niobate transducers on an acoustic amplifier, we have measured linear acoustic gain as a function of electric and magnetic field and frequency. At high magnetic fields ($B \geq 3000$ gauss) the results are in good agreement with White's theory. However, at low magnetic fields, the wavelength of the sound waves is less than the mean free path of the electrons, and the macroscopic theories break down. We have extended a microscopic theory of magnetacoustic interactions, due to Spector, to include electron drift. We find excellent agreement between theory and experiment over the whole range of magnetic field. Moreover, the results account very clearly for the two modes of acoustic domain formation.

Introduction

Acoustic amplification and acoustic domain formation occur in n-InSb at 77°K because of electrons drifting through the medium in the presence of a transverse magnetic field and interacting with sound waves through piezoelectric coupling. We shall describe in this paper direct measurements of microwave acoustic amplification in the 0.5 to 2.0 GHz range for shear wave propagation in the [110] direction, the orientation giving the strongest piezoelectric coupling. In this frequency range, the acoustic wavelength is of the same order of magnitude as the mean free path, making it necessary to consider the detailed motion of the drifting carriers in the theory for this effect. Like others[1,2] who have used the same general approach, we have modified a zero-drift theory, due originally to Spector,[3] to take into account a drifting-carrier distribution. In our case, however, we have placed particular emphasis on evaluating the theory for the experimentally important low drift-velocity range, and we find quite good agreement with our measurements of linear acoustic gain. We have also used this theory to predict, for the first time, the threshold of acoustic domain formation, again with good agreement. This demonstrates very clearly why the two-mode behavior reported previously by Kikuchi et al.,[4] and by Kino and Route,[5] occurs.

Linear amplification

The theory for this effect is complicated by the fact that the carrier mean-free-path is of the same order of magnitude as the acoustic wavelength at 1 to 2 GHz. Hence the medium is not strictly collision dominated, and one must use microsopic theory when solving the transport problem. Spector[3] has used the path integral method of Chambers[6] to find the rf conductivity in a transverse magnetic field assuming a nondrifting, Maxwellian carrier distribution. We include the effect of a drifting-carrier distribution by simply shifting to a moving reference frame, producing a Doppler-shifted frequency at the electron velocity. The modified expression for the rf conductivity is then, assuming $e^{i(\omega t - qz)}$ dependence,

$$\frac{\sigma'}{\sigma_0} = -\frac{2(1 - i\eta\omega\tau)f(x)}{\eta(ql)^2}\left[1 + i\frac{f(x)}{\eta\omega\tau}\right]^{-1}, \qquad (1)$$

where

$$f(x) \equiv 1 - e^{-x}\sum_{m=-\infty}^{\infty}\frac{(1 - i\eta\omega\tau)I_m(x)}{(1 - i\eta\omega\tau - im\omega_B\tau)};$$

also, $\eta = [(u/v_s) - 1]$, u = carrier drift velocity, v_s = sound wave velocity, τ = relaxation time, $q = \omega/v_s$, $l = v_{Th}\tau$ = carrier mean free path, $v_{Th} = \sqrt{2kT/m^*}$, $\omega_B = eB/m^*$, $x = (ql)^2/2(\omega_B\tau)^2$, and $I_m(x)$ is the modified Bessel function. This result is expected to be valid for drift velocities small compared to the thermal velocity. One can see immediately from this expression that resonances will occur whenever the Doppler-shifted frequency becomes equal to the cyclotron frequency, i.e., $\eta\omega = m\omega_B$. In fact, if the dispersion equation were solved in the absence of a sound wave, one would obtain a series of slow, attenuated plasma waves with dispersion relations $\omega - qu \approx m\omega_B$. These waves would interact strongly with a sound wave whenever their phase velocities were equal

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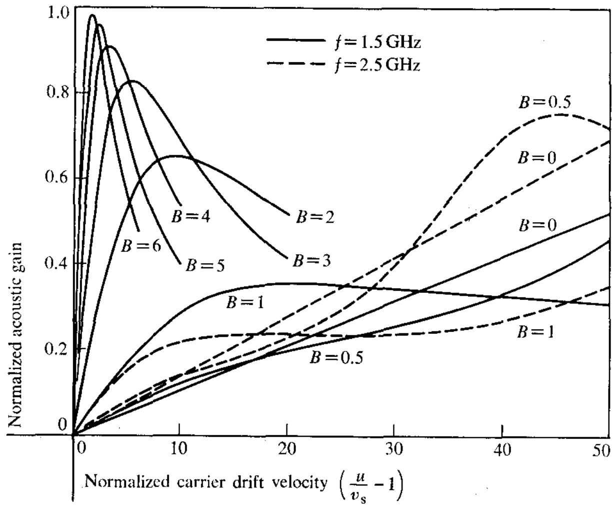

Figure 1 Microscopic theory of gain vs. carrier drift velocity showing both the high magnetic field region near the frequency of strongest interaction, and the low magnetic field region where resonance phenomena occur and where the strongest interaction occurs for significantly higher frequencies; $\omega_m(B=0)=\sqrt{3}\omega_m(B \gg 1)$.

to the sound velocity. This would occur when

$$\omega(u/v_s - 1) \cong m\omega_B,$$

or

$$u \cong (1 + m\omega_B/\omega)v_s.$$

For such interactions to occur below 3 GHz, excessively high drift velocities are required unless ω_B is very small. If ω_B is small, however, collisions broaden and weaken the resonance. Thus in practice the resonance phenomenon may not always be of great importance.

When σ' is known, the attenuation constant is obtained by considering the power transferred to the acoustic wave via the piezoelectric interaction, yielding

$$\alpha = \frac{K^2\omega_c}{2v_s}\,\mathrm{Re}\left\{\frac{-\sigma'/\sigma_0}{1 - i(\omega_c/\omega)(\sigma'/\sigma_0)}\right\}, \qquad (2)$$

where K = electromechanical coupling coefficient and $\omega_c = \sigma_0/\epsilon$. In the high magnetic field limit $ql/\omega_B\tau \ll 1$, which means that the Larmor radius is small compared with the rf wavelength. Here, the expression for α reduces to the classical result of White[7] obtained from macroscopic theory

$$\alpha = \frac{K^2\omega_c}{2v_s(\omega_B\tau)^2}\cdot\frac{\eta}{\eta^2 + [1/(\omega_B\tau)^4][(\omega_c/\omega) + (\omega/\omega_D)]^2}. \qquad (3)$$

This theory predicts a frequency of maximum gain $\omega_m = \sqrt{\omega_c\omega_D}$ where $\omega_D = v_s^2/D_e$ and $D_e = kT\mu/q$. In the opposite zero magnetic field limit, the conductivity becomes

$$\frac{\sigma'}{\sigma_0} = -\frac{2(1 - i\eta\omega\tau)}{\eta(ql)^2} \cdot \frac{1 - (\sqrt{\pi}/ql)(1 - i\eta\omega\tau)F(Y)}{1 + [i/\eta\omega\tau)(1 - (\sqrt{\pi}/ql)(1 - i\eta\omega\tau)F(Y)]}, \qquad (4)$$

and we obtain the result

$$\alpha = \frac{K^2\omega_c}{2v_s}\cdot\frac{\eta\sqrt{\pi}\,[(\omega/\omega_D)(v_s/v_{Th})]}{[(\omega_c/\omega) + (\omega/\omega_D)]^2} \qquad (5)$$

when $ql > 1$. Here, $\omega_m = \sqrt{3\omega_c\omega_D}$, where $Y = (1 - i\eta\omega\tau)/ql$ and $F(Y) = \exp(Y^2)\,\mathrm{erfc}\,(Y)$. For intermediate values of magnetic field, numerical techniques are required. Figure 1 shows an entire family of acoustic gain curves for the frequency $\omega = \sqrt{\omega_c\omega_D}$ taken over a large range of magnetic fields. Strong interaction occurs for high magnetic fields and fairly low values of carrier drift velocity, while for high values of drift velocity and low magnetic fields the resonance effect can be seen. However, in the region where resonances occur, the drift velocity is becoming comparable to the thermal velocity and one does not expect the simple Doppler-shifted theory to be correct here.

The material used in our experiments was high mobility InSb, and the configuration was very similar to that used by Kikuchi et al.,[4] namely a bar of InSb, 1 mm^2 in cross section, and roughly 1 cm long in the [110] direction. Opposite ends of the samples were polished optically flat and parallel. Bulk $LiNbO_3$ shear-wave transducers and ohmic contacts to apply the drift field were then attached at each end. The acoustic interaction was determined by placing the samples in an rf circuit and measuring the change in insertion loss vs. carrier drift velocity and magnetic field. The drift current with the electrons drifting at the sound wave velocity, defined as the synchronous current I_{syn}, was then determined experimentally and this condition was used to define zero acoustic gain.

In Fig. 2 we present a comparison between theory and the actual measurements obtained in the physically important low drift velocity range. The agreement is excellent except for the high magnetic field region $10 > B > 6$ kG, where the maxima of acoustic gain do not fall quite where predicted. This may be due to the Hall saturation effect in a finite sample.

Acoustic domain formation

It has been observed experimentally by Kikuchi et al.,[4] and by Kino and Route,[5] that there are two modes of acoustic domain formation in long bars of InSb, mode I occurring for high drift velocities and low magnetic fields, and mode II occurring for low drift velocities and higher magnetic fields. While the macroscopic theory of White[7] accounts quite well for mode II, it does not account for mode I, predicting much too high a carrier drift velocity. We have applied the small-signal microscopic theory shown

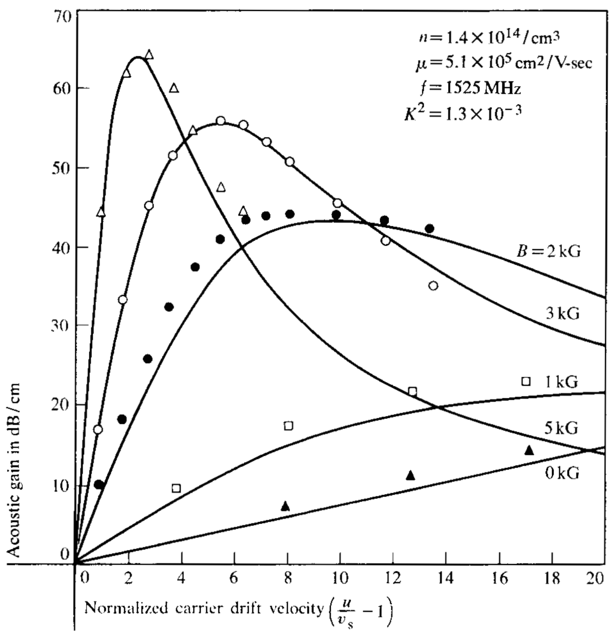

Figure 2 Comparison between microscopic theory and experiment using $K^2 = 1.3 \times 10^{-3}$, $\mu = 5.1 \times 10^5$ cm²/V-sec, and $n = 1.4 \times 10^{14}$/cm³.

in Fig. 1 to the problem of acoustic domain formation. It provides a clear explanation of why the two modes occur and gives reasonable numerical agreement with experiment, depending on the assumptions used to define the threshold of acoustic domain formation.

To obtain a relationship between electron drift velocity and transverse magnetic field at the threshold of acoustic domain formation, we assume it requires some fixed value of net acoustic gain within a sample, such as 75 dB at an unspecified frequency, to form an acoustic domain. We also assume the net acoustic gain, G_{net}, can be expressed as

$$G_{\text{net}} = G - C\omega^2, \tag{6}$$

where G is the acoustic gain due to electronic interaction and $C\omega^2$ is a frequency-dependent lattice attenuation. Setting $G_{\text{net}} = 75$ dB gives a threshold condition for domain formation. Using a series of curves like those in Fig. 1, only for a wider range of frequencies, one can obtain a graphical solution to the threshold condition, obtaining for each value of magnetic field the lowest value of electron drift velocity that satisfies the threshold condition. This, one defines as the threshold value of electron drift velocity. This technique neglects the broadband contribution to domain formation since acoustic domains are produced from thermal noise originating at the cathode, and it assumes the background noise power there is independent of any high-field effects which may occur in mode I operation. Nevertheless, it does yield reasonably good agreement with experiment, shown in Fig. 3. The two-mode behavior is definitely explained, and numerical agreement is reasonable although not always this good for mode I operation, depending on the sample. The generally good agreement throughout suggests that we now have a fairly complete understanding of the sound-wave amplification effect in n-InSb.

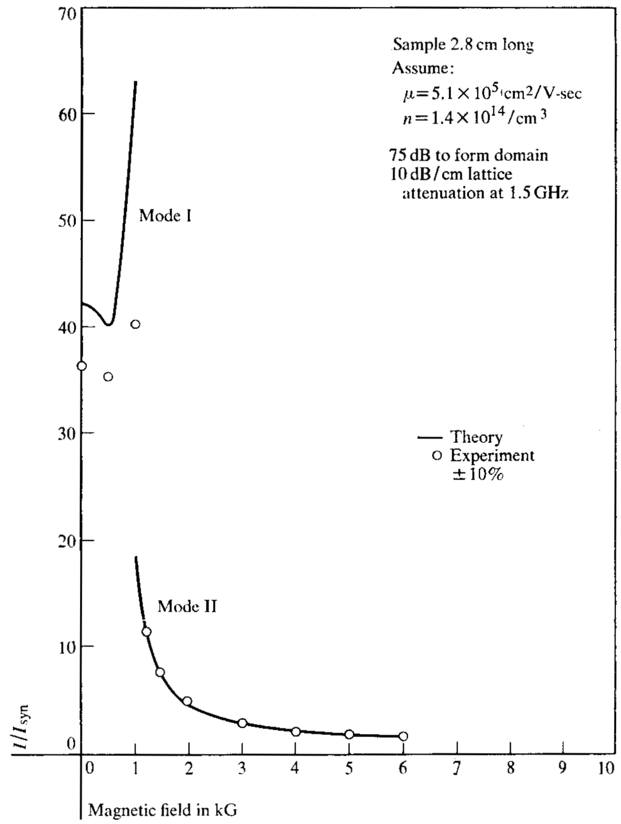

Figure 3 Qualitative comparison between simple theory of acoustic domain formation and experiment. Values of I/I_{syn} were obtained from Fig. 1 by a graphical solution of $G_{\text{threshold}} = G - C\omega^2$, which is a simple threshold condition assuming a frequency-dependent lattice attenuation; $I_{\text{syn}} = Nev_s$ is the drift current when the electrons are drifting at the sound wave velocity.

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