[3]T. C. Simonen, T. K. Chu, and H. W. Hendel, Phys. Rev. Letters 23, 568 (1969).

[4]B. Van der Pol, Phil. Mag. 43, 700 (1922).

[5]H. Lashinsky, in Proceedings of the Seventh International Conference on Phenomena in Ionized Gases, Belgrade, 1965 (Gradjevinska Knjiga Publishing House, Belgrade, Yugoslavia, 1966), p. 710.

[6]H. Lashinsky, in Proceedings of a Conference on Plasma Physics and Controlled Nuclear Fusion Research, Culham, England, 1965 (International Atomic Energy Agency, Vienna, Austria, 1966), p. 499.

[7]R. H. Abrams, E. J. Yadlowsky, and H. Lashinsky, Phys. Rev. Letters 22, 275 (1969).

[8]B. E. Keen and W. H. W. Fletcher, Phys. Rev. Letters 23, 760 (1969).

[9]B. E. Keen and W. H. W. Fletcher, to be published.

[10]T. H. Stix, Phys. Fluids 12, 617 (1969).

[11]See for example N. Nimorsky, Non-Linear Oscillations (Van Nostrand, Princeton, N. J., 1962).

[12]R. V. Aldridge and B. E. Keen, to be published.

MAGNETOPHONON RESONANCES IN ACOUSTOELECTRIC GAIN IN n-InSb *

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Novel resonances in the acoustoelectric gain have been observed in pure n-InSb at longitudinal magnetic fields corresponding to the well-known Gurevich-Firsov magnetophonon resonances. The magnetoacoustoelectric resonances were obtained at 77 and at 4.2°K, with acoustic phonons internally amplified from the thermal background. The resonant peaks in the gain are attributed to resonant cooling of hot carriers by the resonant enhancement of optical-phonon induced transitions between Landau levels.

We report here a new magnetoacoustoelectric (MAE) resonant phenomenon, consisting of the introduction of the magnetophonon resonances into the acoustoelectric interaction in n-InSb. Magnetophonon resonances, first proposed by Gurevich and Firsov,[1] are well known in the magnetoresistance.[2] They correspond to the resonant inelastic scattering of electrons between Landau levels which are separated by just the longitudinal-optical-phonon energy $\hbar\omega_0$. In the parabolic-band approximation, the resonances occur at values of magnetic field B determined by the condition

$$nBe/m^* = \omega_0, \qquad (1)$$

where n is an integer and m^* is the electron effective mass. The novel[3] MAE resonances consist of strong positive peaks in the acoustoelectric gain at the resonant values of B. A comparison with the magnetoresistance (MR) variation shows that the MAE resonances are not merely a secondary manifestation of the MR resonances.

The present work was restricted to the longitudinal magnetic field configuration with B along the [110] length of the sample, parallel to both the electron-drift velocity v_d, and the phonon-propagation direction. The acoustic flux is produced internally, by acoustoelectric amplification of phonons from the thermal equilibrium background.[4-6] For sufficient net gain in pure n-InSb, this requires application of current pulses making v_d much greater than the piezoelectrically active shear-wave velocity $v_s = 2.3\times10^5$ cm/sec. The amplification is selective,[5,6] producing a beam of phonons in a narrow cone along the [110] direction, with a narrow band of frequencies centered around 1.7 GHz. The latter is the theoretical[7] frequency of maximum gain ($\omega_{\max}$), at 77°K, for n-InSb with carrier concentration $N \sim 4\times10^{13}/\mathrm{cm}^3$ and electron mobility $\mu \sim 6\times10^5$ cm^2/V sec. The important parameter ql (phonon wave vector × electron mean free path) is ~9.

Both measurement and analysis of the MAE are greatly simplified when the gain is achieved with very constant current pulses,[4-6] which maintain the current-dependent gain factor $v_d/v_s - 1$ constant. The amplified acoustic flux is detected through the delayed increase in the voltage across the sample, as illustrated by the recorded pulses in Fig. 1(a). During the delay of ~4 μsec, the acoustic flux propagating towards the anode grows exponentially by many orders of magnitude. Eventually it becomes detectable in the electrical resistance, producing the voltage rise ΔV_{ae}, which is determined by the rate of loss of electron drift momentum to the amplified phonon beam. The acoustoelectric signal ΔV_{ae}, is given by $\alpha\Phi/Nev_s$, where Φ is the amplified acoustic energy density integrated over the length of the sample, $\alpha = \alpha_0(v_d/v_s - 1)$ is the acoustoelectric power gain, and α_0 is a material and magnetic-field-dependent interaction coef-

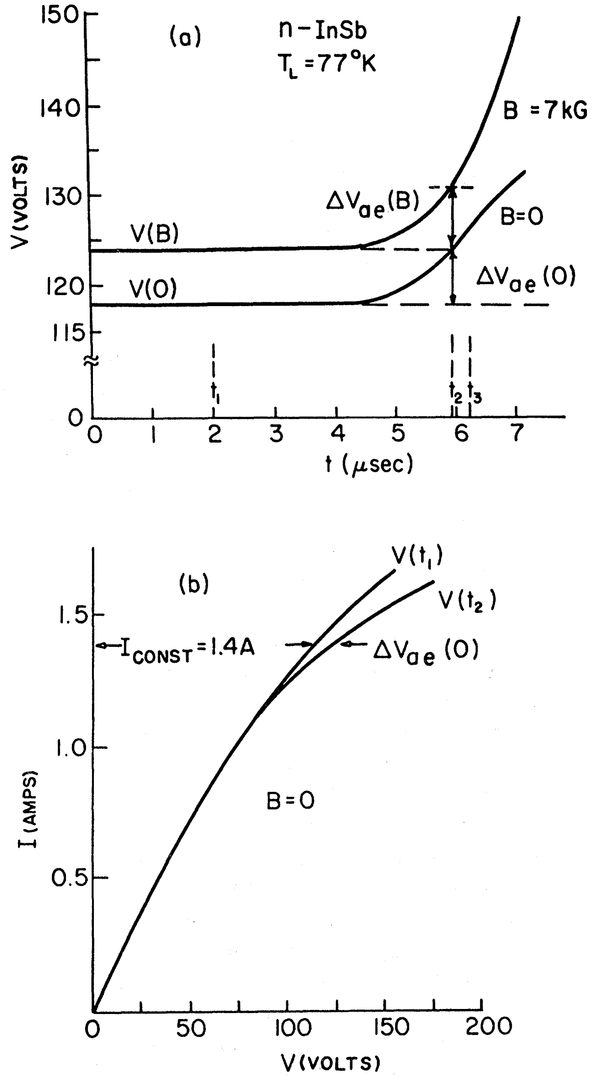

FIG. 1. (a) The delayed increase in voltage across the sample during growth of acoustic flux, for constant current pulses. Measurements of V or ΔV_{ae} as a function of magnetic field B were made at the indicated times. (b) Current-voltage characteristics at t_1 and t_2, before and during detectable acoustic flux growth.

ficient. Finally, after a transit time L/v_s (where $L = 1.9$ cm is the sample length), ΔV_{ae} attains a steady-state value, and the flux attains a steady-state spatial distribution in the form of an intense, narrow domain at the anode. However, the high electric field developed in such a domain can produce minority carrier injection and intrinsic breakdown[5] in n-InSb. We avoided these complications by making all our measurements earlier, at t_2 and t_3 in Fig. 1(a), where the amplified flux is much less intense, and is uniformly distributed in approximately the last $\frac{1}{3}$ of the sample near the anode. As a further safeguard, we restricted ΔV_{ae} to $\lesssim 10\,\%$ of the applied voltage.

Figure 1(b) shows the I-V characteristic measured by sampling techniques at t_1 and t_2, before and after detectable flux buildup. At the lowest currents required to observe the acoustoelectric effect, the I-V trace at t_1 is already well into the non-Ohmic, hot-carrier regime. The deviation of the characteristic at t_2 from that at t_1 comes from the acoustoelectric amplification.

The signal ΔV_{ae} was measured by a differential-sampling technique. The total voltage across the crystal was sampled at t_1 and t_2, respectively, in alternate pulses. These signals were stretched in the sampling scope, and their difference produced a square wave of amplitude ΔV_{ae}. The latter was fed to a PAR lock-in amplifier, whose dc output was displayed on an X-Y recorder. The magnetic field was supplied by a superconducting solenoid which was swept at a slow rate compatible with a 1-sec integrating time of the amplifier. A signal proportional to the magnet current supplied the X deflection of the recorder. Pulse repetition rates were held to 20/sec, and pulse durations to 8μsec, to avoid heating. Examples of the recorded ΔV_{ae} data at 77 and 4.2°K are shown in Fig. 2. For comparison, the longitudinal mangetoresistance[8] at 77°K, also measured at 1.4 A in the hot-carried regime, is shown. The latter is the fractional change with B, in the initial voltage plateau at t_1, $[V(B)-V(0)]/V(0)$.

In curves (a) and (b) of Fig. 2, at least four resonances in ΔV_{ae} (labeled $n = 1$ to 4) are clearly visible at 77°K, superimposed on a weakly increasing background. The facts that these resonances occur very close to the values of B expected from Eq. (1), and that no further strong structure is apparent at fields above the $n = 1$ peak, clearly identify the resonances with the magnetophonon effect. The structure at low fields, $B \leqslant 5$ kG, is probably not related to the magnetophonon effect, and will not be considered here. The resonances are also visible at 4.2°K, where they are relatively much weaker against the continuum background as well as slightly displaced down in magnetic field.

The fact that the resonances in ΔV_{ae} are relatively large and sharp (the $n = 1$ peak being about double the adjacent continuum value), does not mean that there are correspondingly large increases in the acoustoelectric gain. Since ΔV_{ae} grows nearly exponentially with αt, only a small

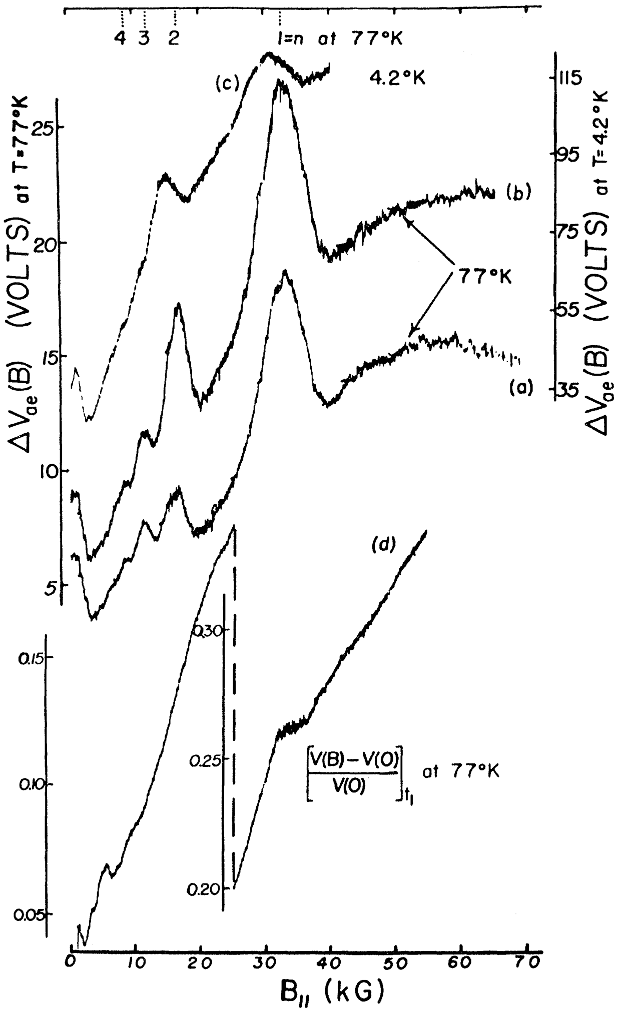

FIG. 2. The magnetic field dependence of the acoustoelectric voltage ΔV_{ae}. Curves (a) and (b) were obtained at sampling times t_2 and t_3, respectively [see Fig. 1(a)], at 77°K; curve (c) at 4.2°K. Curve (d) represents the magnetoresistance of the sample, measured at t_1 for $I = 1.4$ A.

fractional increase in α, or in t in Fig. 1(a), can double ΔV_{ae}. This sensitivity of ΔV_{ae} provides a built-in mechanism for sharpening the resonances, and promises to be useful for detecting more subtle effects from, e.g., nonparabolicity, spin splitting of Landau levels, and two-phonon transitions.

In considering the origin of the MAE resonances, it is necessary first to dispose of the possibility that they are merely a secondary manifestation of the MR effect, as would be the case if the magnetoresistance itself affected the gain.[8] However, a comparison of the MAE and MR data in Fig. 2 clearly demonstrates that the continuum and the resonant variations with magnetic field occur in completely different strengths in the two cases. For the MAE effect, the resonances are strong in comparison with the continuum changes, while the reverse is true for the MR effect. Thus, we can conclude that there is no trivial connection between the two phenomena.

A more exotic explanation, that the resonant optical-phonon interaction contributes directly to the strength of the acoustic-phonon beam, or to the formation of an optical-phonon beam, appears very unlikely. We present a more indirect mechanism based on the fact that the MAE effects, in n-InSb at least, take place within a hot-carrier regime, where (for resonant processes or not) the rate of emission of optical phonons must exceed that of absorption, thereby restricting the heating of the electron gas. Therefore, corresponding to the resonant enhancement of the optical-phonon interaction there must be a resonant cooling of electrons.[9] We shall examine the nature of this cooling and attempt to relate it to the observed resonant enhancement of the acoustoelectric gain.

The inter-Landau-level transitions of the electrons, induced by the resonant optical-phonon interactions, are restricted[1,2] to those near $k_z = 0$, for B along the z direction. The cooling then takes the immediate form of a downshift in electron population near $k_z = 0$, to lower Landau levels. Through other processes, such as carrier-carrier scattering and nonresonant interband transitions, this downshift may be transformed into a decrease in the thermal spread of the carriers in each Landau level. The effect on the gain is best visualized from the Pippard[10] model (valid for $ql \gg 1$), wherein the gain takes place through the stimulated emission of phonons by an inverted population of electrons; the "inversion" is applicable only to the interactions with the phonon beam, and is a consequence of a sufficient drift displacement ($v_d/v_s > 1$) of the carrier-distribution function. From this model, it can be expected that a decrease in the thermal spread of the carriers could increase the degree of inversion and hence the gain, thus qualitatively explaining the observed resonances in the gain. Implicit in this argument is the assumption that there is no bizarre, local perturbation in the electron distribution, particularly near $k_z = 0$, affecting the inversion of the electrons most involved in the acoustoelectric interaction. Any more detailed insight requires solving for the electron-distribution function under rather complex circumstances. A simple solution exists only for the special case of strong carrier-carrier scattering which, though not strictly applicable for our rather pure material, does help to make our argument more plausible. In this case, the carrier distribution is a displaced Maxwellian, characterized by an electron temperature T_e. From acoustoelectric theory,[7,11] it can be shown that the gain at ω_{max} should vary as $1/T_e$, thus providing a specific relationship between electron cooling and the gain.

The observation of MAE resonances at 4.2°K further emphasizes the importance here of the hot carriers. Magnetophonon effects cannot be obtained at low lattice tempreature unless the carriers are hot enough to populate upper Landau levels and emit optical phonons. Of additional interest here is the down shift of the resonant peaks at the lower temperature. The temperature dependence of m^* or ω_0, as tabulated[2] for various investigations, appears insufficient and even in the wrong direction to explain the observed shift. We consider, therefore, that the resonance lines may be broadened by various contributions, e.g., (1) from transitions between high Landau levels for a nonparabolic band, (2) from spin splitting of the levels, and (3) from transitions from Landau levels to impurity levels[9] which are depressed[12] by the high magnetic field. The center of gravity of the resonance line may then shift depending on how the distribution of electrons in the various levels, and the respective transition probabilities, vary with temperature and possibly even with field strength.

Note that we have invoked Landau-level quantization only to provide the resonant cooling process. The effect of the quantization on the continuum variation of the gain is also of interest. The only relevant theoretical calculation[13] for longitudinal B is limited to the extreme quantum limit; it predicts an enhancement of the acoustoelectric attenuation (or gain) in agreement with attenuation measurements (at $v_d = 0$) by Nill and McWhorter[14] for injected 9-GHz ultrasonic waves. This is consistent with our observation of enhanced gain in the continuum.

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[1] V. L. Gurevich and Y. A. Firsov, Zh. Eksperim. i Teor. Fiz. 40, 196 (1961) [Soviet Phys. JETP 13, 137 (1961)].

[2] For a comprehensive summary and list of early references, see R. A. Stradling and R. A. Wood, J. Phys. C: Phys. Soc. (London) Proc. 1, 1711 (1968).

[3] The magnetoacoustoelectric resonances, based on magnetophonon resonances, predicted by S. V. Gantsevich and V. L. Gurevich, Fiz. Tverd. Tela 6, 2871 (1964) [Soviet Phys. Solid State 6, 2286 (1965)], are quite distinct from the ones reported here and have not yet been observed.

[4] V. Dolat, J. B. Ross, and R. Bray, Appl. Phys. Letters 13, 60 (1968).

[5] R. Bray, IBM J. Res. Develop. 13, 487 (1969).

[6] C. Hamaguchi, J. B. Ross, and R. Bray, Bull. Am. Phys. Soc. 14, 353 (1969).

[7] For $ql \gg 1$, $\omega_{\text{max}} = (3\omega_\sigma \omega_D)^{1/2}$, where $\omega_\sigma = Ne\mu/\epsilon$ and $\omega_D = ev_S^2/\mu kT$ are dielectric relaxation and diffusion frequencies, respectively. H. N. Spector, Phys. Rev. 127, 1084 (1962); C. Jacoboni and E. W. Prohofsky, J. Appl. Phys. 40, 454 (1969).

[8] The differential techniques used here prevent the magnetoresistance from being carried along in the measurement of ΔV_{ae}. The maintenance of constant current is very useful for preventing the magnetoresistance—as it changes with B—from grossly varying the gain and hence ΔV_{ae} simply through varying the gain factor $(v_d/v_S - 1)$.

[9] Resonant-cooling arguments were advanced to explain MR resonances in n-GaAs in a hot-carrier regime at low temperature. R. A. Stradling and R. A. Wood, Solid State Commun. 6 701 (1968).

[10] A. B. Pippard, Phil. Mag. 8, 161 (1963).

[11] The acoustoelectric theory in Ref. 7 is formulated for electrons at the same temperature as the lattice, but can be expected to apply also to electrons at an elevated temperature. This can be justified from the equivalence of the formal theory to the Pippard model for $ql \gg 1$. The equivalence is shown by J. H. McFee, in *Physical Acoustics*, edited by W. P. Mason (Academic, New York, 1966), Vol. 4A, p. 24.

[12] L. J. Neuringer, in *Proceedings of the Ninth International Conference on the Physics of Semiconductors, Moscow, U. S. S. R., 1968* (Nauka, Leningrad, U.S.S.R., 1968), Vol. 2, p. 715; R. Kaplan, Phys. Rev. 181, 1154 (1969).

[13] C. Jacoboni and E. W. Prohofsky, Phys. Letters 28A, 765 (1968).

[14] K. W. Nill and A. L. McWhorter, J. Phys. Soc. Japan Suppl. 21, 755 (1966); K. W. Nill, thesis, Massachusetts Institute of Technology, 1966 (unpublished).