elastic-constant data,[5] is very similar.

We can make an estimate for the distance in energy that the second band lies below E_F at absolute zero from Schirber and Switendick's volume-dependent band calculation.[7] This gave a difference between the increase in energy of the second band at Γ and the energy of the other bands at L of 0.067 V with ~30 kbar. Assuming this difference is a measure of the rate at which the second band moves relative to E_F, this equates ~0.002 V to 1 kbar and puts the band ~0.012 V below the Fermi energy at absolute zero. This value is roughly consistent with the thermal behavior of the Knight shift and elastic-constant data which change in a temperature region centered around 80 K or ~0.007 V. This reasoning also indicates that the peak in the density of states is quite sharp (width at half-height of perhaps 0.005 V) since T_c drops appreciably between 6 and 8 kbar.

In conclusion, we feel that the combination of the unusual pressure dependence of the third-zone Fermi-surface cross sections and the almost discontinuous pressure dependence of the superconducting transition temperature argue very strongly for a pressure-induced electron transition in $AuGa_2$. Such a transition supports both the experimental inference from the studies of $AuGa_2$, $AuAl_2$, and $AuIn_2$ series and the theoretical predictions of Schirber and Switendick's volume-dependent band model. We further propose that the anomalous temperature dependence of magnetic properties of $AuGa_2$ stems from a purely thermal depopulation of the second band, thus requiring no explicit phonon effects such as suggested earlier.[7]

The technical assistance of R. L. White is gratefully acknowledged, as are helpful discussions with A. C. Switendick, J. P. Van Dyke, and A. Narath.

[1]V. Jaccarino, M. Weger, J. H. Wernick, and A. Menth, Phys. Rev. Lett. 21, 1811 (1968), and references therein.

[2]A. C. Switendick and A. Narath, Phys. Rev. Lett. 22, 1423 (1969).

[3]J. H. Wernick, A. Menth, T. H. Geballe, G. Hull, and J. P. Maita, J. Phys. Chem. Solids 30, 1949 (1969).

[4]G. C. Carter, I. D. Weisman, and L. H. Bennett, Phys. Rev. B (to be published).

[5]L. R. Testardi, Phys. Rev. B 1, 4851 (1970).

[6]S. Hüfner, G. K. Wertheim, R. L. Cohen, and J. H. Wernick, Bull. Amer. Phys. Soc. 17, 92 (1972).

[7]J. E. Schirber and A. C. Switendick, Solid State Commun. 8, 1383 (1970).

[8]J. E. Schirber, Phys. Rev. B (to be published).

[9]I. M. Lifshitz, Zh. Eksp. Teor. Fiz. 38, 1569 (1960) [Sov. Phys. JETP 11, 1130 (1960)].

[10]L. D. Jennings and C. A. Swenson, Phys. Rev. 112, 31 (1958).

[11]V. I. Makarov and I. Ya. Volynskii, Zh. Eksp. Teor. Fiz., Pis'ma Red. 4, 369 (1966) [JETP Lett. 4, 249 (1966)].

[12]C. W. Chu, T. F. Smith, and W. E. Gardner, Phys. Rev. B 1, 214 (1970).

[13]E. S. Itskevich and L. M. Fisher, Zh. Eksp. Teor. Fiz., Pis'ma Red. 6, 748 (1967) [JETP Lett. 6, 219 (1967)].

[14]J. E. Schirber and J. P. Van Dyke, Phys. Rev. Lett. 26, 246 (1971), and references therein.

[15]J. E. Schirber, Cryogenics 10, 418 (1970).

[16]J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. 108, 1175 (1957).

Magnetophonon Resonance of Hot Electrons in n-InSb at 77°K

Chihiro Hamaguchi, Tsuguru Shirakawa, Tatsuo Yamashita, and Junkichi Nakai
Department of Electronics, Osaka University, Suita City, Osaka, Japan
(Received 29 February 1972)

Magnetophonon resonances in the hot-electron mobility have been observed in pure n-InSb at 77°K in transverse magnetic fields with the application of sufficiently small voltage to produce a slight change in the mobility. The minima in the quantity β in the formula $\mu = \mu_0(1-\beta E^2)$ are attributed to resonant cooling of hot electrons due to optical-phonon–induced transitions between Landau levels.

We report here a new type of resonance experiment consisting of the observation of magnetophonon resonances in the hot-electron mobility in n-InSb at 77°K. Magnetophonon resonances were first predicted by Gurevich and Firsov,[1] and subsequently confirmed experimentally by many workers.[2] Magnetophonon phenomena in the electrical resistance reflect the resonant inelastic scattering of electrons between the high densities of states in Landau levels close to k_z

$=0$, which are separated by just the longitudinal-optical-phonon energy $\hbar\omega_1$. Oscillatory magnetoresistance will occur whenever the scattering of conduction electrons is dominated by optical-phonon scattering and when $\omega_c\tau \gg 1$, where ω_c is the cyclotron frequency and τ is the collision time. In the simple parabolic-band approximation, the resonances occur at values of magnetic field B determined by the condition

$$\omega_1 = N\omega_c = NeB/m_0^*, \tag{1}$$

where N is an integer, and m_0^* is the electron effective mass at the band edge.

The oscillatory components of the magnetoresistance are always very small, and therefore it is necessary to employ differential techniques to deduce the second derivative of the resistance with respect to magnetic field.[3] Another improvement in the measurements was achieved by the observation of magnetophonon structure in the acoustoelectric gain made by Dolat and Bray.[4] In this Letter we report a very sensitive method for observing such a weak magnetophonon resonance. Our experimental method is based upon the measurement of the small deviation of the hot-electron mobility from the Ohmic mobility μ_0. The present work was restricted to the warm-electron condition under which the field-dependent mobility can be represented by an expansion in powers of the electric field E,

$$\mu = \mu_0(1-\beta E^2), \tag{2}$$

where β is independent of the field and is called the warm-electron coefficient. As it is well known, the electron temperature is also approximated by

$$T_e - T_L = \alpha E^2, \tag{3}$$

where T_L is the lattice temperature and α is a constant which is proportional to β.[5] When resonant cooling of the electrons occurs by the emission of optical phonons, the electron temperature T_e, and hence the coefficient α, will decrease. Therefore the warm-electron coefficient β decreases. From these considerations we find that magnetophonon resonances are clearly observed if we can measure the quantity β explicitly. For this purpose we developed an extremely sensitive technique which is based upon the method of Guldbrandsen, Meyer, and Schjaer-Jakobsen.[6] A simplified diagram of the bridge curcuit is shown in Fig. 1. A sinusoidal voltage of 2 kHz is applied across the sample, and the fundamental and the higher harmonics from the generator and the transformer are balanced out by the bridge circuit, so that only the third harmonic generated in the sample due to the nonlinear mobility is detected by a lock-in amplifier (PAR, HR-8). Under this condition the warm-electron coefficient is given by

$$\beta = 4d^2V_3/V_1^3, \tag{4}$$

where d, V_1, and V_3 are the sample length, the fundamental voltage, and the third-harmonic voltage, respectively. A detailed description of our measuring circuit and of the experimental errors will be published elsewhere soon. By employing the lock-in amplifier for detection of the third-harmonic voltage, the sensitivity is improved and in a typical case is about $\Delta\mu/\mu_0 \simeq 10^{-6}$ for the low-impedance materials used in the present work. The samples used in the present experiment are n-InSb with carrier concentration $n = 2.6\times10^{14}$ cm^{-3} and electron mobility $\mu_0 = 3.8\times10^5$ cm^2/V sec, and with $n = 1.8\times10^{14}$ cm^{-3} and $\mu_0 = 5.8\times10^5$ cm^2/V sec, at 77°K. We report here only the result for the sample with $n = 1.8\times10^{14}$ cm^{-3} and $\mu_0 = 5.8\times10^5$ cm^2/V sec. The measurements were made in a transverse magnetic field configuration with electric field E along the [110] direction, whose amplitude was restricted to less than 1 V/cm to avoid Joule heating. A typical result at 77°K is shown in Fig. 2, where we find at least five resonance extrema in β (labeled $N=2$ to 6 for the curve $\Delta\beta$, which will be mentioned later) superimposed on a weakly increasing background. The minima in β are found to correspond to magnetophonon resonance maxima. The following procedure was adopted to provide a consistent determination of the extremal positions and amplitudes of the magnetophonon resonances. A smooth curve was drawn to touch all maxima.

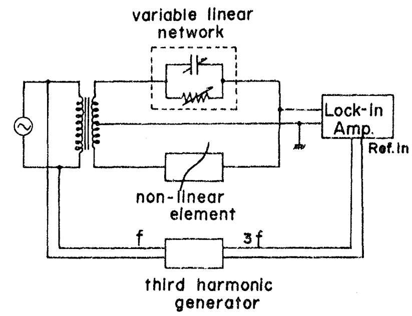

FIG. 1. Schematic diagram of bridge circuit for measuring harmonic components generated by a nonlinear element. The third-harmonic voltage is proportional to the warm-electron coefficient $\beta = (\mu_0 - \mu)/\mu_0 E^2$.

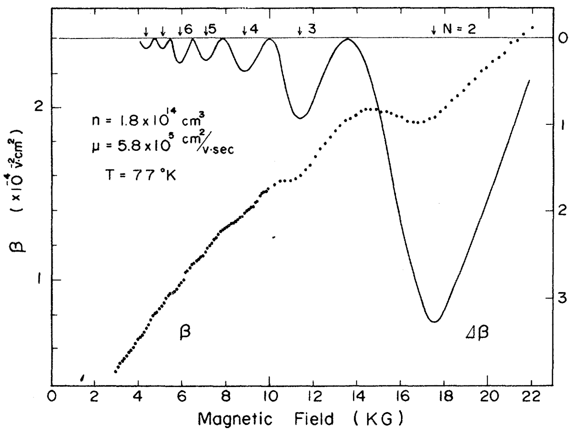

FIG. 2. Magnetic field dependence of the warm-electron coefficient β. The magnetophonon resonance peaks correspond to minima in β. The change $\Delta\beta$ obtained by subtracting the data points from the envelope is shown by the solid curve (see discussions in text).

Subtracting the experimental values from the envelope, we have the change $\Delta\beta$, which is shown by a solid curve in Fig. 2. By this means we obtain accurate peak positions, which are $B=17.5 \pm 0.2$, 11.4 ± 0.2, 8.9 ± 0.2, 7.0 ± 0.2, 5.8 ± 0.2, and 5.0 ± 0.2 kG for the $N=2, 3, \cdots, 7$ transitions, respectively.

The behavior of the warm-electron mobility predicted by Eq. (2) has been verified by many experiments in Ge and Si.[7] Kanai[8] and Sladek[9] have carried out similar experiments in n-InSb on the variation of the quantity β with magnetic field and lattice temperature. However, they were unsuccessful in explaining the magnetic field dependence of the quantity β. It should be mentioned here that their experimental accuracy is poor with the sensitivity $\Delta\mu/\mu_0 \sim 10^{-3}$ which is much less than that of the present work ($\sim 10^{-6}$). Kinch[10] has also measured the coefficient β at low temperatures ($T_L < 20$°K) and the result is less accurate. Recently Kotera, Komatsubara, and Yamada[11] investigated the magnetic field dependence of the coefficient β in order to study the effect of polar optical-phonon scattering at 4.2°K. However, it should be noted that their result is again less accurate and that the deduced quantity β includes the change in carrier density in the conduction band due to magnetic freezeout, as pointed out by Miyazawa and Ikoma.[12] Furthermore we have to note that they applied high electric fields to excite electrons in the higher Landau levels. Therefore we cannot estimate the electron temperature, and a comparison of their results with theory is impossible because of the lack of knowledge of the electron temperature. One of the most important points is that the resonance amplitude decreases at low temperatures because of the weak excitation of the optical modes. Our measurements were carried out at 77°K, and therefore we can neglect the effect of magnetic freezeout. The scattering of conduction electrons is predominated by polar optical-phonon scattering, and hence megnetophonon resonances are clearly seen. At the present stage, however, no theory exists on the variation of the coefficient β with magnetic field. We shall present here calculations for the magnetophonon resonance peaks only. We take the nonparabolicity of the conduction band into account. The present analysis has been performed with the following formula which has been shown to describe accurately the nonparabolicity of the conduction band of InSb:

$$\epsilon_L = -\tfrac{1}{2}\epsilon_G + \tfrac{1}{2}\epsilon_G\left[1 + 4\left(L + \tfrac{1}{2} \pm \tfrac{1}{4}g_0 \frac{m_0^*}{m}\right)\frac{\hbar\omega_c}{\epsilon_G}\right]^{1/2}, \quad (5)$$

where ϵ_G, g_0, and L are the energy gap, the electron g factor at the bottom of the band ($g_0 = -52$), and the integer corresponding to the Lth Landau level, respectively. Using the parameters $\epsilon_G = 0.225$ eV,[13] $m_0^* = 0.0145m$,[14] and $\omega_1 = 195$ cm^{-1},[2] we obtain $B = 38.9$ (35.9), 18.1 (17.4), 11.8 (11.5), 8.7 (8.6), 7.0 (6.8), 5.8 (5.7), and 4.9 (4.9) kG for transitions from higher Landau levels to the $L=0$ level, corresponding to $N=1, 2, \cdots, 7$, with spin-conserved transitions $M_s = -\frac{1}{2}$ to $M_s = -\frac{1}{2}$ ($M_s = +\frac{1}{2}$ to $M_s = +\frac{1}{2}$). Spin-flip transitions ($\Delta M_s = \pm 1$) are negligible in InSb.[2] These values are in good agreement with the present experimental data. Stradling and Wood[2] have found that the amplitudes of the magnetophonon extrema observed in the transverse magnetoresistance decrease exponentially with the harmonic number N like $\exp(-\gamma N)$, where γ is a constant which depends on the electron mobility. Such an exponential behavior was not observed in the present experiment, but instead a strong increase in the amplitudes for $N=3$ and $N=2$ transitions was found (those for $N \geq 4$ varied slowly). This result seems to indicate a resonant cooling of hot electrons as proposed by Dolat and Bray[4] in the case of magnetoacoustoelectric resonance. For these values of electric fields, the energy loss from the electron system to the lattice is predominated by the emission of polar optical phonons through the transition from the high-energy tail of the electron distribution near $k_z = 0$ at higher Landau levels to lower Landau levels, and the magnetophonon resonance is therefore attributed to the effect of the magnetic field on the rate of phonon emission and hence on the decrease in the mean energy of the electrons. Such a resonant cooling must have a stronger effect on the hot-electron mobility when the harmonic number N is smaller.

Recently, Stradling and Wood,[15] investigated magnetophonon extrema in the hot-electron magnetoresistance at 11 and 20°K and found that the magnetophonon extrema shifted to a lower magnetic field than predicted by Eq. (5). This shift was explained by a mechanism associated with the transition of electrons from the high-energy tail of the distribution at higher Landau levels to donor sites accompanied by optical-phonon emission. In the present experiment, however, we have not found such a shift of the extrema. Therefore, such a transition seems to be negligible at 77°K. The magnetoresistance peaks observed by Stradling and Wood,[15] 33.7, 16.4, 10.8, 8.15, 6.51, 5.42, 4.63, 4.05, and 3.60 kG at 77°K, are slightly lower than those obtained in the present work. These differences are not clear at the present stage. It should be mentioned here that our experimental method has another capability: The magnetoresistance can be obtained at the same time from the reading of the variable resistor. We found that there exists good agreement between the extrema of the quantity β and of the magnetoresistance for $N = 2$, 3, and 4, where the extrema in the magnetoresistance for $N \geqslant 5$ were not large enough to be compared quantitatively with good accuracy.

One of the authors (C.H.) is pleased to acknowledge discussions with Professor R. Bray during his stay at Purdue University which stimulated the present investigation. We are thankful to Dr. Yōichi Ueda, Fujitsu Laboratories, for the supply of the InSb samples, and to Dr. Yasuji Sawada for a careful reading of the manuscript.

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

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

[3]R. A. Stradling and R. A. Wood, J. Phys. C: Proc. Phys. Soc., London 3, L94 (1970); R. A. Stradling *et al.*, in *Proceedings of the Tenth International Conference on the Physics of Semiconductors,* edited by S. P. Keller, J. C. Hensel, and F. Stern (U.S. AEC, Oak Ridge, Tenn., 1970), p. 369.

[4]V. Dolat and R. Bray, Phys. Rev. Lett. 24, 262 (1970).

[5]I. Licea, Phys. Status Solidi 25, 461 (1968), and 26, 115 (1968).

[6]T. Guldbrandsen, N. I. Meyer, and J. Schjaer-Jakobsen, Rev. Sci. Instrum. 36, 743 (1965).

[7]C. Hamaguchi and Y. Inuishi, J. Phys. Soc. Jap. 18, 1755 (1963); and for a review see E. M. Conwell, *High Field Transport in Semiconductors,* Suppl. No. 9 to *Solid State Physics* (Academic, New York, 1967).

[8]Y. Kanai, J. Phys. Soc. Jap. 15, 830 (1960).

[9]R. J. Sladek, Phys. Rev. 120, 1589 (1960).

[10]M. A. Kinch, Brit. J. Appl. Phys. 17, 1257 (1966).

[11]N. Kotera, K. F. Komatsubara, and E. Yamada, J. Phys. Soc. Jap. Suppl. 21, 411 (1966).

[12]H. Miyazawa and H. Ikoma, J. Phys. Soc. Jap. 23, 290 (1967).

[13]D. Long, in *Semiconductors and Semimetals,* edited by R. K. Willardson and A. C. Beer (Academic, New York, 1966), Vol. 1, p. 143.

[14]E. D. Palik, G. S. Picus, S. Teitler, and R. F. Wallis, Phys. Rev. 122, 475 (1961).

[15]R. A. Stradling and R. A. Wood, J. Phys. C: Proc. Phys. Soc., London 3, 2425 (1970).