Magnetoacoustic effects in *n*-type InSb: Magnetic freezeout and hopping conductivity at low temperatures

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Magnetotransport measurements on lightly doped *n*-type InSb were performed using ultrasonic spectroscopy. We report attenuation measurements at temperatures between 0.25 and 4.2 K and in magnetic fields B up to 80 kG. For the sample with a doping of 6.3×10^{13} cm^{-3}, the experimental results are consistent with the magnetic freezeout effect. For the sample with a higher doping of 1.8×10^{15} cm^{-3}, the data show a clear signature of a magnetic-field-induced metal-insulator transition, as seen in conventional magnetotransport measurements. These observations provide good evidence for the usefulness of ultrasonic spectroscopy, which is insensitive to surface-layer contributions.

I. INTRODUCTION

There is a great deal of interest in studying the acoustoelectric effect in large magnetic fields. This is important in III-V semiconductors due to the strong piezoelectric potential. The study and the understanding of the mutual interaction between ultrasonic and electrical properties in three-dimensional bulk crystals are primordial if acoustoelectric devices are to emerge in new two-dimensional materials (heterojunctions, multiple quantum wells).

In our previous work on *p*-type InSb,[1-3] we showed that acoustic data (attenuation change and velocity shift) on the piezoelectrically active modes of this semiconductor could give valuable information on the electrical properties under various conditions. Activation energy, magnetoresistance, and scaling behavior in the ac conductivity were derived from the experimental data.

Having established that this acoustic spectroscopy could give reliable results on the conductivity behavior at low temperatures, we started a similar study of *n*-type InSb. Even at low temperatures, *n*-type InSb exhibits metallic behavior. However, with the application of a moderate magnetic field, freezeout of the carriers occurs.[4] Under certain conditions, a magnetic-field-induced metal-insulator (MI) transition is also observed.[5]

In this paper, we present the results of our study of the behavior of *n*-type InSb in a magnetic field using acoustic attenuation measurements. This paper is organized as follows. Section II gives a brief account of the theory required to discuss acoustic waves in piezoelectric semiconductors. Section III describes experimental methods, further details of which are given elsewhere.[6] Section IV contains the results and analysis. Finally, Sec. V summarizes the main features of this paper. Brief preliminary accounts of this work were given elsewhere.[7-9]

II. HUTSON-WHITE MODEL OF ACOUSTIC WAVES IN PEIZOELECTRIC SEMICONDUCTORS

In the present work, magnetoacoustic studies have been performed at sufficiently low temperatures so that the acoustic attenuation in zero magnetic field is due to two contributions: the residual attenuation and the electronic attenuation. In piezoelectric semiconductors, the electronic contribution can easily be studied by measuring the acoustic properties of the piezoelectrically active acoustic mode. For these modes, the piezoelelectric interaction enhances the coupling between the acoustic wave and the carriers in the semiconductor. The piezoelectric interaction is well described by the Hutson-White model as our previous studies in *p*-type InSb (Refs. 1–3) have demonstrated. Most generally, in the Hutson-White model, the acoustic attenuation is given by[10]

$$\alpha=\frac{K^2\omega}{2V_S}\frac{\omega_C/\omega}{1+(\omega_C/\omega)^2(1+\omega^2/\omega_C\omega_D)^2}\ , \tag{1}$$

where K^2 is the electromechanical coupling coefficient and V_S the sound velocity. This attenuation is characterized by two frequencies, the dielectric frequency $\omega_C=\sigma/\varepsilon$ and the diffusion frequency $\omega_D=(q/f\mu k_BT)V_S^2$ where μ and σ are the mobility and the conductivity, respectively. The fraction f accounts for the acoustically produced space charge which is mobile. For complete ionization of donors, for example, $f=1$ while when the carrier concentration in the conduction band drops as in thermal freezeout, $f\ll1$. The dielectric frequency represents the dynamic screening by the charge carriers of the electric field produced by the acoustic wave whereas the diffusion frequency describes the static screening by the carriers which is always present due to their thermal velocity.

In *p*-type InSb,[3] the diffusion effect could be neglected

in all experimental conditions so that the familiar relaxation type equation is obtained:

$$\alpha=\frac{K^2\omega}{2V_S}\frac{(\omega_C/\omega)}{1+(\omega_C/\omega)^2}\ . \tag{2}$$

The behavior of this equation has been extensively investigated in our work in p-type InSb (Refs. 1–3) by varying the conductivity, the temperature, or the magnetic field. Moreover, sound velocity measurements[2] have also shown good agreement with the Hutson-White prediction for the velocity shift in the absence of the diffusion effect.

In the present work, we will make extensive use of Eq. (1) to describe the experimental data since, as we will show, Eq. (2) cannot describe the experimental results.

III. EXPERIMENTAL METHODS

The magnetoacoustic experiments on n-type InSb samples were performed under similar conditions as our previously reported results on p-type InSb.[3] Briefly, attenuation measurements were made on InSb single crystals using either $LiNbO_3$ or ZnO transducers.[11] For experiments above 2 K, a double calorimeter cryostat with a 70-kG magnet was used while a dilution refrigerator with a 50-kG magnet was necessary to extend the experiments to lower temperatures (0.1–2.2 K). At high magnetic field, temperature was measured by either a capacitive thermometer or a calibrated Speer resistor installed in a reduced magnetic field region where the temperature correction due to the magnetoresistance effect is negligible for our purposes.[12] Sample mounting has been described in detail elsewhere.[6,13] Pulsed acoustic-attenuation measurements were performed using standard equipment. High total attenuation and small attenuation differences were measured by using a suitable choice of the two echoes used in attenuation measurements. Echoes separated by small time differences were used for high-attenuation data while echoes widely separated in time were used for low-attenuation data to improve sensitivity.

For these experiments, compensated n-type InSb single crystals were obtained from Cominco, Ltd. Most experiments were made with the longitudinal piezoelectrically active mode along [111]. Unless indicated, all ultrasonic experiments in a magnetic field were performed in the longitudinal geometry ($\mathbf{q}\|\mathbf{H}$). A few measurements were done on the transverse mode along [110]. The electrical and acoustic properties relevant to this work are summarized in Table I.

IV. RESULTS AND DISCUSSION

A. Acoustic attenuation in $B=0$

The results of the acoustic attenuation in zero magnetic field are shown in Figs. 1 and 2 for the two samples of lowest excess concentrations. In both cases, it is observed that the attenuation is independent of temperature within the scatter of the data. With either Eqs. (1) or (2), we suggest that because the zero-field conductivity is high and its temperature variation is small, the associated attenuation changes are too small to measure. More specifically, using the dc magnetoresistance data[7] obtained for sample 1 at 4.2 and 2.1 K, we estimate that using Eq. (2), since $(\omega^2/\omega_C\omega_D)$ is negligible in this case, the absolute attenuation at 160 MHz due to the piezoelectric interaction should be 0.06 and 0.17 dB/cm, respectively. This small change is comparable to the scatter in our data at 153 MHz in Fig. 1. At higher frequency, the large scatter in the data about 0.4 dB/cm at 292 MHz, is also of the same order of magnitude as the calculated change in the attenuation expected between 2.1 and 10 K. For sample 2 which had a slightly higher concentration, the smaller scatter is also comparable to the reduced attenuation that we should expect for a sample of higher conductivity. The smaller scatter and low total attenuation measured for this sample as seen in Fig. 2 were the results of a higher quality ZnO thin-film transducer for this particular sample. The high conductivity and the weak temperature dependence of the conductivity, not measurable with our acoustic measurements, has been observed for similar samples by Ishida and Otsuka.[5] Based on their work, we estimate that the compensation ratio N_A/N_D of our samples lies in the range 0.5–0.7.

With the absence of any measurable change in zero magnetic field, we conclude that our samples of low concentration are in a regime of quasimetallic conductivity. This conclusion is in agreement with the study by Ishida and Otsuka[5] where they concluded that, based on galvanometric properties, their n-type InSb samples of similar characteristics were in a regime of metallic impurity conduction.

B. Acoustic attenuation in a magnetic field

1. Low concentration results: samples 1 and 2

In Figs. 3–6, our magnetoacoustic attenuation data are presented at various frequencies for the sample of lowest

TABLE I. Properties of n-type InSb samples.

Sample No.	N_D-N_A[a] (cm^{-3})	Acoustic mode	Direction	Coupling constant K^2	Sound velocity (10^5 cm/s)
1	6.3×10^{13}	Long.	[111]	6.4×10^{-4}	3.89
2	8.5×10^{13}	Long.	[111]	6.4×10^{-4}	3.89
3	1.8×10^{15}	Long.	[111]	6.4×10^{-4}	3.89
4	6.8×10^{13}	Transv.	[110]	11.0×10^{-4}	2.29

[a]The excess concentration was deduced from the Hall effect at 77 K.

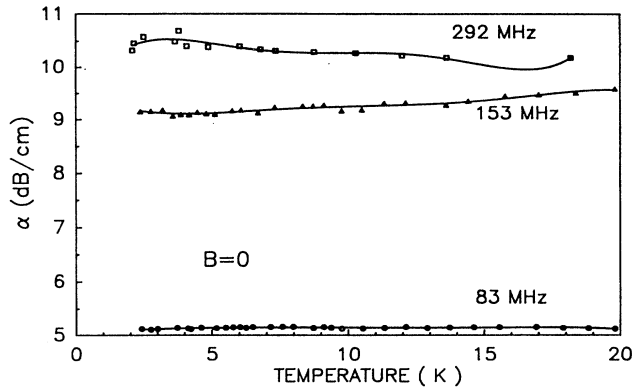

FIG. 1. Acoustic attenuation along [111] vs temperature for sample 1 with the lowest excess concentration of 6.3×10^{13} cm^{-3}.

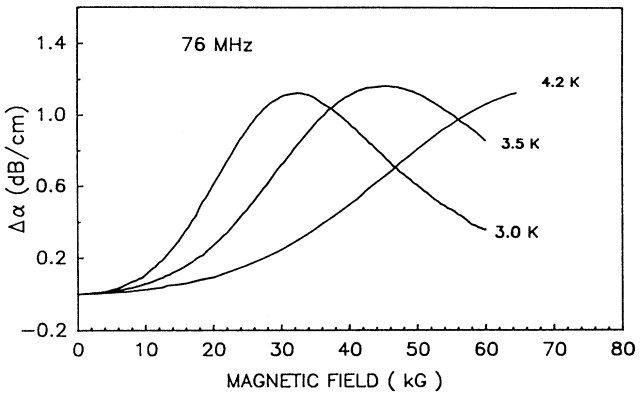

FIG. 3. Acoustic attenuation along [111] vs magnetic field at 76 MHz for the sample with an excess concentration of 6.3×10^{13} cm^{-3}.

excess concentration while data for a slightly higher nominal concentration are shown in Figs. 7 and 8. Some work on n-type InSb (Ref. 14) has demonstrated the importance of amplitude-dependent acoustic attenuation in a magnetic field. On some samples, we performed measurements of the power dependence of the acoustic attenuation in order to make sure that all data are, as much as possible, independent of the acoustic power used in the various experiments. In Fig. 9, data taken on sample 2 show clearly the effect of acoustic power on the attenuation peak. A shift in both the amplitude and its magnetic field position is observed. These measurements were under the conditions that the sample temperature (lattice temperature) was constant within the accuracy of our temperature measurement (at best 5%). While our data on the power dependence are limited, they confirm that the lowest acoustic power consistent with a reasonable signal-to-noise ratio should be used. Because of our restricted attenuation dynamic range of about 35–40 dB, a compromise had to be reached in order to obtain reliable data. In most cases, an attenuation in the line of 25 to 30 dB was used to minimize the acoustic power to the sample. With this attenuation in the line, we had enough sensitivity to measure the full attenuation curve which always passes through a maximum.

From all the data on samples 1 and 2, several important features should be pointed out. First, the curves always go through a maximum at some critical magnetic field $B_{max} < 80$ kG provided the temperature is low or the frequency is high. Secondly, the attenuation peak amplitude and the critical magnetic field decrease as the temperature is lowered. This is in contradiction with the expected behavior if we try to use Eq. (2) to explain the magnetoacoustic data. This expression predicts that the peak amplitude occurs at $\omega_C/\omega=1$ and is given by

$$\alpha_P=\frac{K^2\omega}{4V_S} . \tag{3}$$

For a given frequency, the peak amplitude depends on two constants K^2 and V_S; therefore, we should expect a constant peak in the attenuation curve as the temperature is lowered, which is contrary to what is observed. Ac-

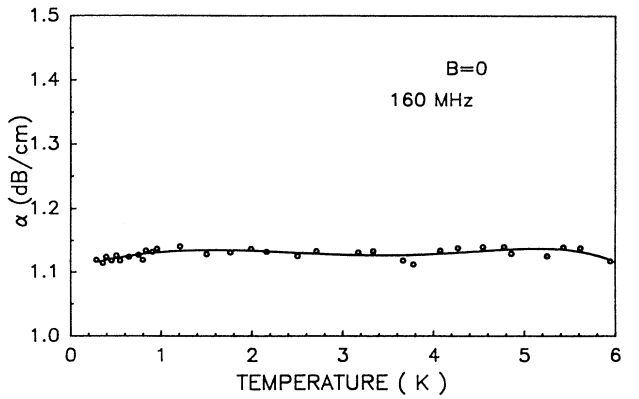

FIG. 2. Acoustic attenuation along [111] vs temperature for sample 2 with an excess concentration of 8.5×10^{13} cm^{-3}.

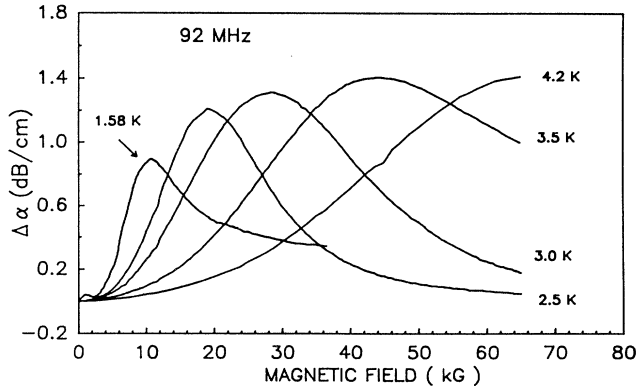

FIG. 4. Acoustic attenuation along [111] vs magnetic field at 92 MHz for the sample with an excess concentration of 6.3×10^{13} cm^{-3}.

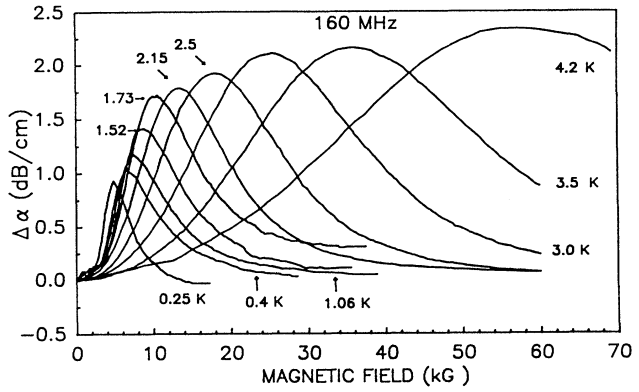

FIG. 5. Acoustic attenuation along [111] vs magnetic field at 160 MHz for the sample with an excess concentration of 6.3×10^{13} cm^{-3}.

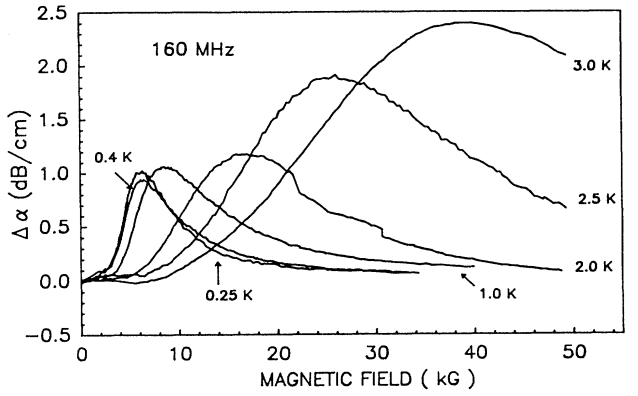

FIG. 7. Acoustic attenuation along [111] vs magnetic field at 160 MHz for the sample with an excess concentration of 8.5×10^{13} cm^{-3}.

cording to expression (3), at any given temperature the peak amplitude should be linearly proportional to ω. In earlier work on p-type InSb,[1] with a measured value of the sound velocity, we could determine the correct value of K^2 by the linear relationship between α_P and ω which was obeyed at 4.2 K and $B=0$. A more precise determination of K^2 using sound velocity changes[2] in p-type InSb agrees with the value obtained by the attenuation measurement. A detailed analysis of our data shows that the peak amplitude is smaller than predicted by Eq. (3) and is not linear in frequency.

With this discrepancy regarding the peak amplitude and the frequency dependence, we can conclude that the simple Hutson-White model [Eq. (2)] without the diffusion term, which has been very successful in explaining all our data in p-type InSb, is inadequate for n-type InSb.

In the more general expression (1), which includes a diffusion term ω_D, the correction factor $(1+\omega^2/\omega_C\omega_D)^2$ is in the denominator if we compare with expression (2). Being in the denominator, a non-negligible contribution of that correction term leads to a reduced attenuation. The term $\omega^2/\omega_C\omega_D$ can be expressed in a more simple suitable form in terms of transport parameters:

$$\frac{\omega^2}{\omega_C\omega_D}=\frac{\omega^2\varepsilon f\mu k_B T}{\sigma q V_S^2}\ . \tag{4}$$

Using the equation which defines the electron density in the conduction band $\sigma=nq\mu$, we obtain the following simple equation:

$$\frac{\omega^2}{\omega_C\omega_D}=\frac{f\Gamma_\omega T}{nq}\ , \tag{5}$$

where $\Gamma_\omega=\omega^2\varepsilon k_B/qV_S^2$ is a constant for a given frequency. Alternatively, this term can be expressed simply in terms of the Hall coefficient assuming one type of carrier, $R_H=1/nq$:

$$\frac{\omega^2}{\omega_C\omega_D}=f\Gamma_\omega R_H T\ . \tag{6}$$

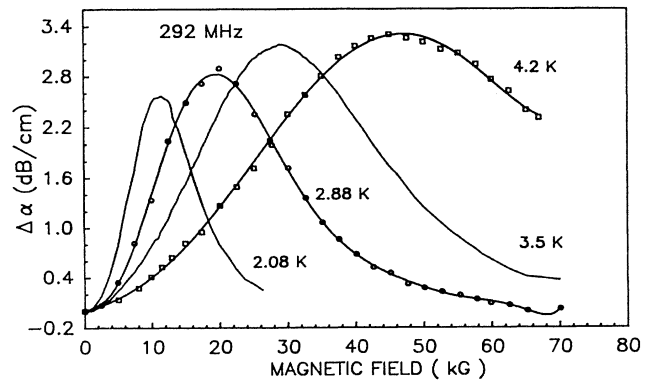

FIG. 6. Acoustic attenuation along [111] vs magnetic field at 292 MHz for the sample with an excess concentration of 6.3×10^{13} cm^{-3}.

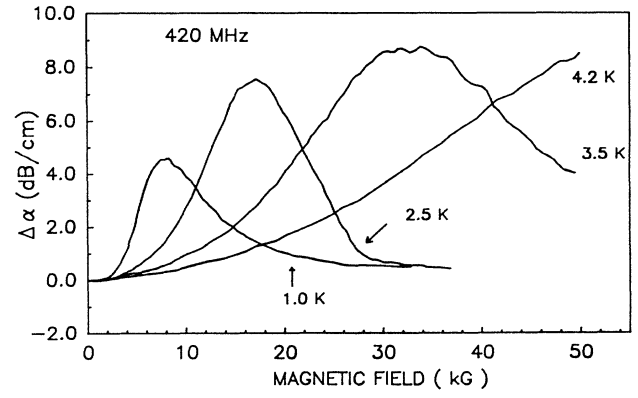

FIG. 8. Acoustic attenuation along [111] vs magnetic field at 420 MHz for the sample with an excess concentration of 8.5×10^{13} cm^{-3}.

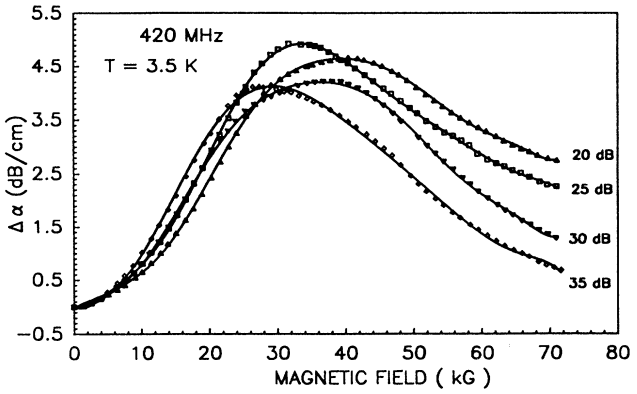

FIG. 9. Power dependence of the magnetoacoustic attenuation at 420 MHz for the sample with an excess concentration of 8.5×10^{13} cm^{-3}. Each curve is characterized by an attenuation value which represents the value of an attenuator placed between the transmitter and the sample. All data were obtained under isothermal conditions ($T=3.5$ K).

Mansfield and Kusztelan[4] have shown that in n-type InSb, the Hall coefficient increases rapidly with magnetic field when $T<4.2$ K. This behavior has been largely explained in terms of the magnetic freezeout of the carriers. As the magnetic field increases, the carriers in the conduction band drop down to the impurity levels hence the density of carriers in the conduction band decreases sharply. Defining $F=\Gamma_\omega T/nq$, we can rewrite the attenuation Eq. (1) in the more condensed form:

$$\alpha=2\alpha_P\frac{x}{1+x^2(1+fF)^2}\ , \tag{7}$$

where $\alpha_P=K^2\omega/4V_S$ and $x=\omega_C/\omega$. Since F is proportional to R_H, the rapid increase of F due to the magnetic freezeout will lead to a reduced acoustic attenuation. Qualitatively, our shrinking acoustic-attenuation peak with lower temperature is certainly compatible with the magnetic freezeout effect which is growing with decreasing temperature. To be more quantitative, we will assume that the important effect lies in the change of the carrier density in the conduction band when the magnetic field is swept at low temperatures.

In these conditions, the carrier density n in the conduction band is given by the well-known formula

$$\frac{n(N_A+n)}{N_D-N_A-n}=2N_Ce^{-\varepsilon_b/k_BT}\hbar\omega_b/k_BT\ , \tag{8}$$

where $2N_C=2N_{C0}T^{3/2}$ (measured in cm^{-3} and $2N_{C0}=7.1\times10^{12}$) is the density of states in the conduction band for $B=0$, ε_b the binding energy of the donors, and ω_b the cyclotron frequency. In a finite magnetic field, $n\ll N_A$, Eq. (8) can be written as

$$\frac{n_0}{n}=1+\frac{k_BT}{\hbar\omega_b}\frac{N_Ae^{\varepsilon_b/k_BT}}{2N_{C0}T^{3/2}}\ , \tag{9}$$

where $n_0=N_D-N_A$ is the excess concentration as deduced from the Hall effect at 77 K. The correction term defined in (5) can then be expressed as

$$\frac{f\Gamma_\omega T}{nq}=f\Gamma_\omega\left[\frac{T}{n_0q}+\frac{k_BT}{\hbar\omega_b}\frac{T^{-1/2}Ke^{\varepsilon_b/k_BT}}{2N_{C0}q(1-K)}\right]\ , \tag{10}$$

where the acceptor concentration N_A is related to the compensation ratio $K=N_A/N_D$ by the following relation:

$$N_A=\frac{K}{(1-K)}(N_D-N_A)\ . \tag{11}$$

The behavior of the correction term (10) in the attenuation equation (7) can be seen qualitatively by using a simple model for the donor binding energy. Within the Yafet, Keyes, and Adams (YKA) model this binding energy (in meV) is simply related to the magnetic field by[15,16]

$$\varepsilon_b(\mathrm{YKA})=1.96B^{1/3}\ , \tag{12}$$

where B is the magnetic field in tesla. Using $K=0.58$ for our sample as determined from the work of Ishida and Otsuka,[5] we can use this expression (12) to calculate exactly the contribution of the correction term to the acoustic attenuation. For simplicity, we will assume that $f=1$ even if the model of Hutson-White[10] predicts a decrease of f when freezeout occurs.

Numerical calculations for the concentration corresponding to sample 1 show that the first term in (10) which is independent of the magnetic field gives a negligible zero-field correction. At 4.2 K, the second term is never larger than 0.1 up to 80 kG. However, as the temperature is reduced, this second term in F increases rapidly largely because of the factor e^{ε_b/k_BT}. In Fig. 10, we show the field dependence of F at 160 MHz and 2.15 K. As can be seen in this figure, F has a non-negligible contribution near the magnetic field at which a maximum in the attenuation is observed in Fig. 5. Using Eq. (7), it can easily be shown that given a value of F at a magnetic field

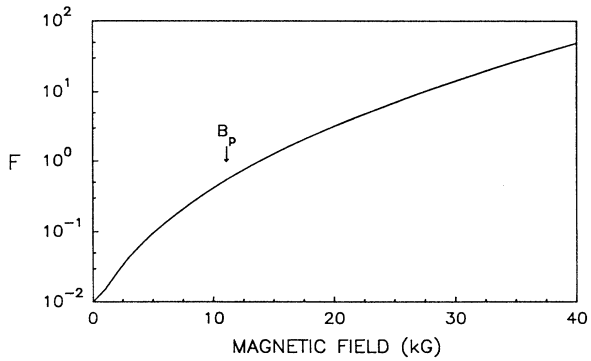

FIG. 10. Correction factor F at 160 MHz and 2.15 K as a function of the magnetic field. The curve was calculated using Eq. (10) and the YKA binding energy. The arrow indicates the position of the value of F corresponding to the magnetic field at which a peak attenuation occurs.

B, the maximum of the attenuation occurs at a value $x=1/(1+F)$ and its magnitude is smaller:

$$\alpha=\frac{2\alpha_P}{2(1+F)} . \tag{13}$$

This simple result demonstrates that our model for the correction factor fF (with $f=1$) based on the variation of the carrier density out of the conduction band, predicts the reduction of the attenuation peak and the increasing shift of the peak magnetic field at a lower value irrespective of a detailed knowledge of the magnetoresistance [value of $x(B)=1/\varepsilon\omega\rho(B)$].

With this model based on the carrier density variation in a magnetic field, which has also been called "magnetic freezeout," we have used Eqs. (7), (10), (11), and (13) to analyze our data shown in Figs. 3–8 in order to obtain the donor binding energy corresponding to these two excess concentrations. The YKA binding energy, in Eq. (12), should be valid for a very low excess concentration since it has been shown by transport measurements[17] that the behavior of the binding energy is concentration dependent. The attenuation peaks in Figs. 3–8 were used to fit the data assuming that $f=1$ and $K=0.58$. The magnetic field dependence of the donor binding energy corresponding to our data is shown in Fig. 11. As expected from previous measurements on higher excess concentration (10^{14} cm^{-3} in the work of Robert *et al.*[17]), our acoustically derived binding energy is larger and lies closer to the YKA binding energy since theoretical[18] and experimental[17] work has shown that the binding energy is reduced as the excess concentration increases. Considering the approximations that have been used for this analysis (in particular of K and f), the qualitative agreement with the expected behavior should be considered satisfactory. In particular, our data show the correct qualitative behavior since the binding energy curve for the sample of higher excess concentration (sample 2 in Fig. 11) is lower than the curve corresponding to the lower excess concentration (sample 1).

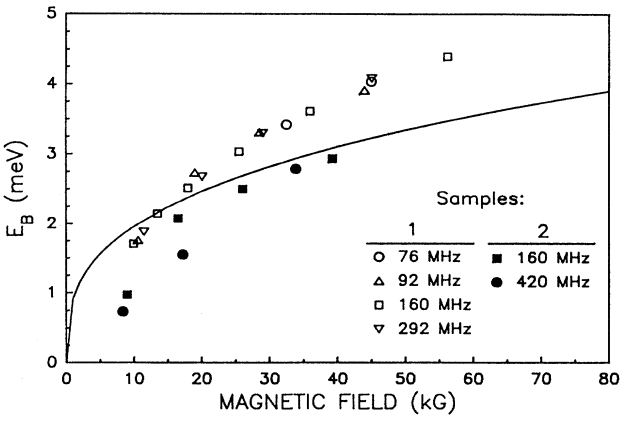

FIG. 11. Magnetic field dependence of the donor binding energy derived from the magnetoacoustic data of Figs. 3–8. The solid line represents the binding energy of the YKA model according to Eq. (12).

2. Hopping magnetoresistance in the high field limit

Our previous results showed that for a low excess concentration sample, a magnetic freezeout effect can describe qualitatively the behavior of the attenuation peak occuring in a wide range of magnetic fields. Beyond this attenuation peak, all our curves (Figs. 3–8) show an attenuation decreasing towards the zero-magnetic-field attenuation.

Tokumoto and Mansfield[19] measured the attenuation of the piezoelectric active transverse mode along [110] in a transverse magnetic field at 48 MHz. Their results for a sample similar to our sample 1 but with a compensation of 0.7 show qualitatively a similar behavior as regards the shrinking attenuation peak with lower temperatures. While they argued that magnetic freezeout should be present based on their transport data,[20] they did not analyze their data in detail to demonstrate its presence. More important, beyond the magnetic field corresponding to the attenuation peak, the attenuation relative to the zero-field value [$\alpha(B)-\alpha(0)=\Delta\alpha$] decreased towards a negative value [$\alpha(B)<\alpha(0)$]. In order to investigate this behavior, we performed experiments on this transverse mode with a sample (4 in Table I) of similar concentration as the sample 1. At 160 MHz in two magnetic field configuration (q parallel and perpendicular to B), our data revealed as previously a shrinking attenuation peak with decreasing temperature at low field and always a positive relative attenuation [$\alpha(B)>\alpha(0)$] at high field.

More recently, Galperin *et al.*[21] measured the attenuation of the longitudinal mode along [111] of n-type InSb samples of similar excess concentration as ours. According to transport data on their samples, they concluded that their samples which were strongly compensated were in the hopping conductivity regime. A smaller peak compared to ours was always seen to shrink with lower temperatures but the peaks were located at lower fields also. Moreover, as was the case for the work of Tokumoto and Manfield, their high fields ($B>10$–20 kG) relative attenuation became negative. A comparison[9] of some of their data with ours showed that at $f=200$ MHz and $T=3$ K, the apparent contradictory behavior could well be explained by the fact that while the excess concentration was similar, $N_{ex}=N_D-N_A=6\times10^{13}$ cm^{-3}, the compensation was quite different, $K=N_A/N_D=0.58$ for us compared to higher values of 0.84–0.94 for three samples in the work of Galperin *et al.*[21]

Extreme care should be taken when trying to interpret and compare such relative attenuation data, since for each set of data the behavior of the relative attenuation depends strongly on the initial value $\alpha(B=0)$. Our samples, as we showed in Sec. IV A, did not show any change in the attenuation as a function of temperature confirming that our samples with a compensation of about 0.58 remained in a metallic regime with a temperature-independent conductivity. Consequently, our starting value for the relative attenuation $\alpha(B=0)$ was always the same for a given frequency irrespective of the temperature. On the other hand, in the work of Galperin *et al.* their conductivity data in $B=0$ showed a temperature dependence confirming a hopping behavior

for their highly compensated samples. We would expect on the basis of all our experimental work[1–3] on the interpretation of the Hutson-White model that in zero field, their starting value $\alpha(B=0)$ should obey Eq. (2) and should depend on temperature. Unfortunately, these authors did not show any data on the expected temperature-dependent attenuation in zero field. While a precise and complete comparison of their data with ours cannot be made in view of this uncertainty about their value of $\alpha(B=0)$, some general remarks can still be made. In their work, Galperin *et al.* argued that since hopping conductivity definitely dominates the conductivity at high magnetic fields, the acoustic attenuation cannot be compared to the Hutson-White model, valid only for free electrons according to them. They showed that a microscopic calculation of the contribution of the hopping electron between two donors gave the following expression for the acoustic attenuation:

$$\alpha_h = \Gamma_0 F(B) \ . \tag{14}$$

where Γ_0 (in dB/cm)$=4.34K^2(\omega/V_S)$ and the function $F(B)$ is independent of frequency up to logarithmic terms. In the high-field limit with the donor binding energy ε_b of the form $B^{1/3}$, $F(B)$ behaves as $B^{-4/3}$. The acoustic attenuation follows a similar field dependence in this hopping regime at a high magnetic field:

$$\Delta\alpha = \alpha_h(B) - \alpha_h(0) = A_h B^{-4/3} \ . \tag{15}$$

Galperin *et al.*'s high-field data confirm this field dependence at various frequencies (150–750 MHz) at 4.2 K for magnetic field above about 24 kG. So far, we have fitted our attenuation peak using a model of the magnetic freezeout effect to understand the attenuation peak. As we said earlier[9] the compensation plays an important role in the shape of the field dependence of the relative attenuation so it is not unreasonable to try to analyze our data and check whether they are consistent with a hopping attenuation suggested by Eq. (15).

In Fig. 12, we have displayed our data on sample 1 near $T=2.5$ K since at this temperature there is a large number of data points in the high-field regime (B higher than 20 kG in most cases) over a wide frequency range. For a comparison, we show also some of the data from the work of Galperin *et al.*[21] As can be seen in this figure, our data are qualitatively consistent with the $B^{-4/3}$ dependence even if our relative attenuations $\Delta\alpha$ are positive. This qualitative agreement suggests that over a range of compensation, the absorption of acoustic waves at high field in n-type InSb samples are due to the hopping contribution. For our samples, these results might lead us to conclude that the samples underwent a metal to insulator transition as a function of magnetic field. However, this remark should be taken with caution since we do not see any sharp feature in the acoustic absorption suggesting directly this transition.

Galperin *et al.* stated that the hopping absorption is incompatible with a contribution arising from the Hutson-White formula while we claim based on our p-type InSb results that it is quite adequate to retain the Hutson-White formalism[1,3] despite the fact that the carriers are hopping between donor sites. It is of interest here to show that similar behavior as Eq. (15) can be obtained from the Hutson-White formalism. In zero magnetic field, Eq. (2) gives the following result (in dB/cm) in the limit $\omega_C/\omega \gg 1$:

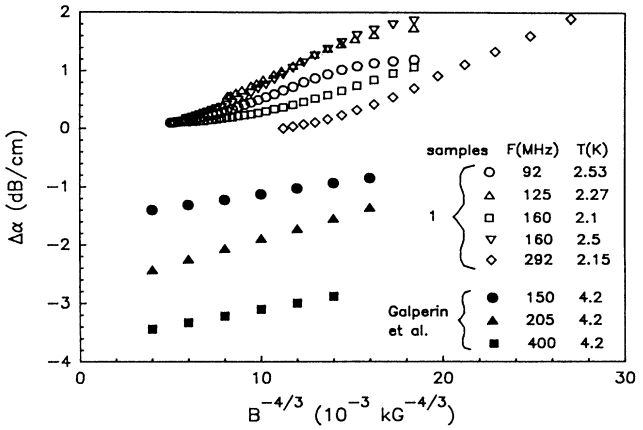

FIG. 12. Acoustic attenuation in the hopping regime. We compare some of our data on sample 1 in the high-field limit with results obtained by Galperin *et al.* (Ref. 21).

$$\alpha_{\mathrm{HW}}(0) = 4.34 \frac{K^2\omega}{V_S} \frac{(\varepsilon\omega 10^{-2})}{\sigma(B=0)} \ , \tag{16}$$

a result almost independent of temperature in our metallic regime in zero field. We will make the assumption that beyond the magnetic freezeout where Eq. (1) must be used and seems to describe well the data, the results might be described by Eq. (2) as was the case for our p-type samples[1–3] in the hopping regime. With this formula, we get the following results for the attenuation at high magnetic field:

$$\alpha_{\mathrm{HW}}(B) = \frac{\Gamma_0}{100}\sigma_0(B)\frac{\omega^{s-1}}{\varepsilon} = \Gamma_0 G(B) \ . \tag{17}$$

In the hopping regime, we assumed the power law for the frequency-dependent conductivity $\sigma(B)=\sigma_0(B)\omega^s$. Since s usually takes a value around 0.8, it is easily seen that the function $G(B)$ is a weak function of frequency. Our results seen in Fig. 12 for the field dependence of the relative attenuation [the difference of Eqs. (17) and (16)] do seem to confirm the features predicted by the Hutson-White formalism. First, the $B^{-4/3}$ field dependence can be assigned to the conductivity term $\sigma_0(B)$ while the apparent difference in the slope of our curves might be explained by the weak frequency dependence of the ω^{s-1} term in $G(B)$. Secondly, we notice that the negative intercepts of the straight lines have a much smaller magnitude for our data since these intercepts are proportional to the term $1/\sigma\ (B=0)$ being smaller for our metalliclike conducting samples in zero field. Equation (16) does indeed predict the larger negative values of intercept seen in the data of Galperin *et al.* since the conductivity of their samples is lower in zero field.

In summary, while our data at high field show a

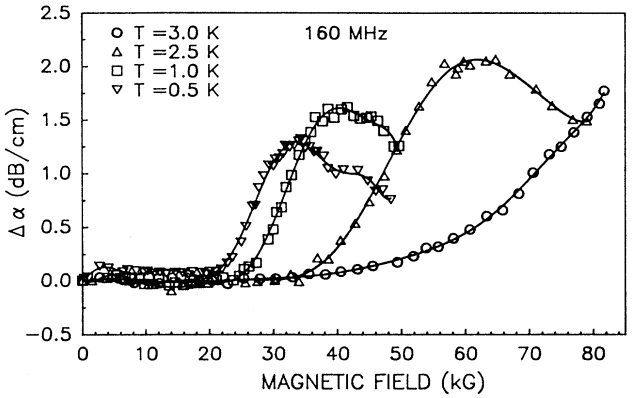

FIG. 13. Acoustic attenuation along [111] vs magnetic field at 160 MHz for sample 3 with an excess concentration of 1.8×10^{15} cm^{-3}.

different relative attenuation as compared with the work of Galperin *et al.*, both sets of data suggest the same conduction mechanism for the electron motion, a hopping process between donor sites. This work underlies the importance of getting a reasonably good control and knowledge of the compensation of doped semiconductors.

3. *Metal-insulator (MI) transition at high doping level*

We also performed experiments with a sample (3 in Table I) of much higher excess carrier concentration. Again qualitatively, as seen in Fig. 13, the results of the acoustic-attenuation behavior in a magnetic field is quite similar to previous results on lower doping (attenuation peak decreases with T). However, two new features are worth emphasizing. First, the attenuation peak occurs at much higher magnetic field for a given temperature and frequency (62 kG in Fig. 13 in comparison with 25 kG at 3.0 K in Fig. 5). Secondly, in all our data, we see very little change in acoustic attenuation up to 20 kG; moreover, the higher the temperature, the higher the magnetic field at which we observe a rising acoustic attenuation. Using the full equation (1) in the Hutson-White model, we interpret the absence of change at low field as meaning that ω_C and ω_D do not change with magnetic field for this high doping level. Using the definition of these frequencies, this result is therefore interpreted as the absence of any variation in the conductivity, excess carrier density and mobility with magnetic field. It is worth noting that the sudden increase in acoustic attenuation for all curves (Fig. 13) at some critical magnetic field B_C is sharper as the temperature is lowered. The sharp increase in these transport parameters has been observed previously[5] and more recently[22] by direct electrical properties measurement in a magnetic field. This rapid increase near a critical magnetic field has been interpreted as a magnetic-field-induced metal-insulator transition.[5,22] A comparison of the electrical resistivity derived from our magnetoacoustic attenuation with direct measurement is useful since the recent study of Shayegan *et al.*[22] underlined the difficulty in transport measurements with some semiconductors like Hg-Cd-Te and InSb due to the surface layer contribution shorting out the bulk conductivity.

Some time ago, Mansfield and Kusztelan[4] mentioned that a proper evaluation of the effect of chemical etching on resistivity measurement was an important step in order to obtain reliable data, particularly in the magnetic freezeout regime in n-type InSb where the resistivity increases very quickly by several orders of magnitude. In our work so far on the acoustic properties of p-type and n-type InSb, we have already emphasized that our derived electrical resistivity data do not suffer from these experimental problems encountered in the conventional methods.

Several points should be explained before we discuss our resistivity curves. First, the apparent wide magnetic field range where there is essentially no change in ω_C and ω_D is misleading. We recall that Eq. (2) represents the change in the acoustic attenuation without the diffusion term as a function of conductivity. It should be noted that in most conventional pulse methods of measuring attenuation, it is difficult to measure changes below the range 10^{-1}–10^{-3} dB. In practice, for our case, the minimum change we could measure was of order 0.02 dB/cm corresponding to a sensitivity of about 2 $\mu\Omega$ cm. It is known that in zero field, the residual resistivity of our samples similar to the samples measured by Shayegan *et al.* (both samples came from Cominco, Ltd.) should be less than this value of 2 $\mu\Omega$ cm. However, unless our attenuation change is greater than 0.02 dB/cm, we cannot resolve the gradual resistivity change expected at low field below the metal-insulator transition. Consequently, our low-field resistivity data appears flat and overestimated because of our experimental attenuation resolution. As the resistivity gradually increases beyond the MI transition, we expect that the magnetic freezeout effect will dominate. Using the donor binding energy measured by Robert *et al.*,[17] we estimate that, again, at high field, the diffusion term starts to become important in agreement with the fact that we observe a shrinking attenuation peak. However, we do not have a precise value of the compensation that we can reliably use. In the literature, the cited compensation of samples with similar excess concentration varies enormously, 0.1–0.2 in Shayegan *et al.*,[22] compared to 0.5 for Ishida *et al.*[5] For this sample, we are not interested in the behavior of the magnetic freezeout effect and binding energy since a careful study has already been made by Robert *et al.*[17] However, our measurements identify a critical magnetic field at which the resistivity starts to rise quickly in the vicinity of the MI transition. Since at low field below the attenuation peak the correction factor due to ω_D is negligible for this sample, we have calculated the resistivity obtained from our data for magnetic field ranging from zero to the maximum field at which the correction factor starts to increase. In Fig. 14, we plot our resistivity data at 160 MHz and compare it with the work of Shayegan *et al.*[22] and Ishida *et al.*[5]

As can be seen, our ac resistivity is systematically higher than the dc measurements. In this field range, there is no hopping contribution, consequently we expect that our higher ac resistivity is a real effect. Moreover,

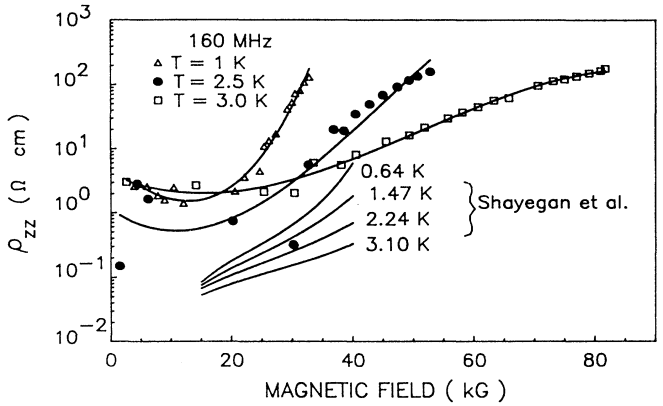

FIG. 14. Magnetoresistance of n-type InSb of high doping level at field below the MI transition. We compared our data of Fig. 13 with those of Shayegan *et al.* (Ref. 22) on a similar sample. The solid lines going through our data are intended to be a guide to the eye. In view of the large scatter in the data at a low magnetic field, the minimum seen in all curves should not be taken as a real effect.

any hopping contribution will decrease the ac resistivity, contrary to what is observed. Our higher observed resistivity might be an indication that the results of the work of Shayegan *et al.*[22] and Ishida *et al.*[5] were not totally free of surface-layer contributions. On the other hand, the major problem in our acoustic measurements which limit strongly the range of conductivity measurement is the low resolution of pulse methods and the need of low power to avoid power dependence well below any detectable heating effect. Despite these limitations, these acoustic results on the high-concentration samples demonstrate the usefulness of this method of conductivity measurements in magnetic fields for samples like Hg-Cd-Te where surface treatment of the sample can affect dramatically the results and their interpretation.[22] As far as the magnetic field dependence of the conductivity σ_{ZZ} or of the acoustic attenuation is concerned, the critical magnetic field B_C apparently temperature dependent in our experiment lies between the field B_0 (8.1 kG) at which the last Shubnikov–de Haas maximum in ρ_{XX} is observed and the field B_{MI} (33 kG) above which ρ_{XY} abruptly rises at low temperatures. Certainly more work is needed to fully exploit our techniques to the study of the metal-insulator transition induced by magnetic field where spurious effects can be eliminated as the acoustic attenuation is a true bulk effect.

V. SUMMARY AND CONCLUSIONS

In this paper, we have presented the results of a study of the magnetic field dependence of the acoustic attenuation for two types of n-InSb samples, a low and a high doping level. From a detailed analysis, the following points emerge.

(1) In zero magnetic field, the samples do not show any large temperature-dependent conductivity in agreement with the expected quasimetallic behavior observed in conventional measurements.

(2) The reduction of the magnetoacoustic attenuation peak upon decreasing temperature is consistent with the magnetic freezeout effect in both samples. This acoustic result is an attractive alternate method compared to the usual Hall-effect experiment to measure the electron density change.

(3) At high magnetic field, the data for the low doping level suggest a hopping conductivity contribution. It was also shown that compensation of the samples plays a dramatic role in the behavior of the relative attenuation change. More work is necessary to verify this conductivity regime by looking more closely at the frequency dependence (exponent s in the conductivity law).

(4) At the highest doping level, our attenuation data give evidence for a metal-insulator transition induced by a magnetic field. We report also a larger ac magnetoresistance with our acoustic measurement in comparison with published direct magnetoresistance data in agreement with our belief that acoustic method is relatively free of surface conducting layer problems.

We have shown that meaningful results on magnetotransport data in semiconductors can be obtained at low temperatures using acoustic measurements. Improvement on our data could be made in various ways. Velocity shift measurements will give complementary information. A more detailed study of power dependence effect at temperature below 1 K should be made to check whether electron heating effects are serious problems. Finally, a more complete analysis would be possible if samples of known and controlled compensation could be used.

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