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Metallic impurity band in the narrow-band-gap semiconductor *n*-type InSb

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Magnetotransport and far-infrared laser spectroscopy have been combined to probe the nature of the impurity band in the vicinity of the magnetic-field-induced metal-insulator transition. The spectroscopic results obtained in *n*-type InSb show the persistence of the impurity cyclotron resonance, (000)→(110), through the metal-insulator critical field which is determined by the transport measurement. This first observation in the narrow-band-gap semiconductor together with the earlier results of *n*-type GaAs reported by Romero *et al.* provides strong evidence for the existence of a metallic impurity band, split off from the conduction band, and this may be a universal feature of the metal-insulator transition occurring in doped semiconductors regardless of their gap properties.

In doped semiconductors, a metal-insulator transition can be induced by variation of the donor concentration or by application of a stress or a magnetic field. In a magnetic field the donor effective Bohr radius shrinks. If a sample is metallic in zero field a metal-insulator transition will take place at a critical magnetic field. However, the basic question of whether the metal-insulator transition takes place in the conduction band or in the impurity band has been debated for many years. The Knight-shift data in Ge:As by Tunstall and Deshmukh[1] suggest that, as donor concentration increases to a critical value, the impurity band merges progressively with the conduction band in such a way that above the critical donor concentration all impurity band structure disappears. On the other hand, many features of NMR measurements,[2,3] Raman measurements,[4-6] and magnetotransport[7,8] seem to indicate the presence of localized electrons above the critical concentrations. In particular, Raman spectra by Doehler, Colwell, and Solin[4] on Ge:As show that a substantial amount of the valley-orbit impurity transition $[1s(A_1)\rightarrow 1S(T_2)]$ appears to remain above the critical donor concentration. This certainly implies the existence of impurity level structure above the critical concentration. They interpreted this striking result in terms of the local-density fluctuations which lead to an inhomogeneous mixture of submacroscopic metallic and semiconducting regions near the critical concentration. In magnetic-field-induced metal-insulator transition, the subject still remains unsolved. Mott[9] suggested that in Si:P the metal-insulator transition takes place in the conduction band, and this can only occur in many-valley semiconductors. On the other hand, for direct-band-gap InP doped near the transition, Biskupski *et al.*[10] argued that the metallic low-temperature conduction should be attributed to an impurity band rather than to a tail of the conduction band. Recent magneto-optical studies in *n*-type GaAs by Romero *et al.*,[11] using Fourier-transform spectroscopy, show that the $1s\rightarrow 2p$ donor transition persists through the metal-insulator transition field. This observation certainly confirms the Raman result of Doeher, Colwell, and Solin. However, Romero *et al.*, noting that the oscillator strength of impurity absorption remains almost unchanged through the critical magnetic field, interpreted the data in terms of the homogeneous Mott transition where the coexistence of both insulating and metallic regions is ruled out, and claimed that the metal-insulator transition takes place in an impurity band split off from the conduction band. However, the observation of a donorlike transition below the metal-insulator critical field is hardly understood within the basic concept of the Mott transition. The Mott transition takes place when two Hubbard bands merge at a critical field. It is then doubtful that any well-defined donor impurity bands exist in a metallic state.

In this work, using the narrow-band-gap semiconductor *n*-type InSb, we address the above controversy by laser spectroscopy technique. InSb is particularly attractive because its small effective mass leads to the high-field-limit condition, $\gamma \gg 1$ ($\gamma = \hbar\omega_c/2\mathcal{R}^*$ where $\hbar\omega_c$ and $\mathcal{R}^*$ are the cyclotron energy and effective Rydberg constant), which can be achieved at modest magnetic fields. In the high-field-limit condition the hydrogenic donor wave function can be exactly expressed as an adiabatic form,[12] so that a quantitative analysis is possible throughout the metal-insulator transition.

We confirm the striking results obtained in the *n*-type GaAs by Romero *et al.*[11] The impurity cyclotron resonance, (000)→(110) (corresponding to the $1s\rightarrow 2p^+$ donor transition in the wide-band-gap semiconductors), is indeed observed to persist through metal-insulator critical field which is determined by transport measurement. The oscillator strength of the impurity transition seems to be almost constant both below and above the critical field. This new result obtained in the *n*-type InSb together with the earlier result of *n*-type GaAs provides strong evidence for the existence of a metallic impurity band, split off from the conduction band, and this may be a universal feature of the metal-insulator transition occurring in doped semiconductors regardless of their gap properties.

The high mobility and low compensated n-type InSb used in this study was grown at Cominco. The sample carrier density of 4.5×10^{14} cm^{-3} (at 77 K) was selected for convenience for the laser spectroscopic study of the metal-insulator transition. It is desired that the resonant magnetic fields corresponding to the convenient far-infrared (FIR) photon energies should occur around the critical magnetic field. The metal-insulator critical field B_{MI} for our sample is estimated to be $\simeq 9-10$ kG from the Mott criterion which is given by $n^{1/3}a(B)\simeq 0.25$, where the effective Bohr radius $a(B)$ is $a(B)=(a_{\perp}^{2}a_{\parallel})^{1/3}$. The parameters $a_{\perp}$ and $a_{\parallel}$ as a function of magnetic field are given by the work of Yafet, Keys, and Adams.[12] For $\hbar\omega=6.74$ meV, the impurity cyclotron resonance (ICR), $(000)\rightarrow(110)$, would occur at a resonant field around 7.5 kG, so that our FIR laser lines provide a good chance to probe the electronic states in the vicinity of the metal-insulator transition. An increase of the critical field by higher doping concentration may be possible, but it is limited in transmission experiments since the sample with high carrier density $\geq 10^{15}$ cm^{-3} requires extremely small thickness (below 10 μm) for a reasonable amount of transmission. From the carrier density and the Hall mobility of 5×10^{5} cm^{2}/V sec at 77 K a low compensation of $k\simeq 0.18$ was deduced from the Brooks-Herring analysis[13] where a correction arising from the polar-optical phonon scattering was taken into account. For transport study the sample was cut to a Hall bar with size of $3.2\times0.8\times0.64$ mm^{3}. It was etched in CP$_4$ solution and immediately followed by In-Sn electric contacts. The transport measurements were done in a ^{3}He cryostat for temperatures down to 0.45 K and for magnetic fields up to 10 T. The four-terminal dc technique was used to obtain the longitudinal conductivity (**B**$\parallel$**I**). In the FIR transmission measurement, the sample was cleaved from a wafer, and polished to the thickness of 25 μm. It was etched in CP$_4$ solution minutes before mounting on an undoped Ge substrate and placing in the helium cryostat. An optically pumped cw molecular gas laser provides FIR photon energies ranging from $\lambda=96$ to 888.9 μm. The radiation was circularly polarized using a polarizer consisting of a linear polarizer followed by a set of quartz-crystal $\lambda/4$ plates. The detector was a composite bolometer operating at 4.2 K.

Figure 1 shows the temperature-dependent longitudinal resistance below the metal-insulator transition field. The enhanced temperature effect even in metallic regime has been interpreted as the manifestation of the weak localization and the interaction effect.[14] In the extremely low-field range, as seen in the inset of Fig. 1, the data show a negative magnetoresistance followed by a single Shubnikov–de Hass (SdH) oscillation around 1.5 kG. As magnetic field increases the resistance becomes strongly temperature dependent and, above 10 kG, increases by several orders of magnitude relative to the low-field values. This behavior is characterized as a phase transition from the metallic to the insulating state. Since the critical field B_{MI} for the metal-insulator transition is defined at zero temperature, the best estimate for the B_{MI}

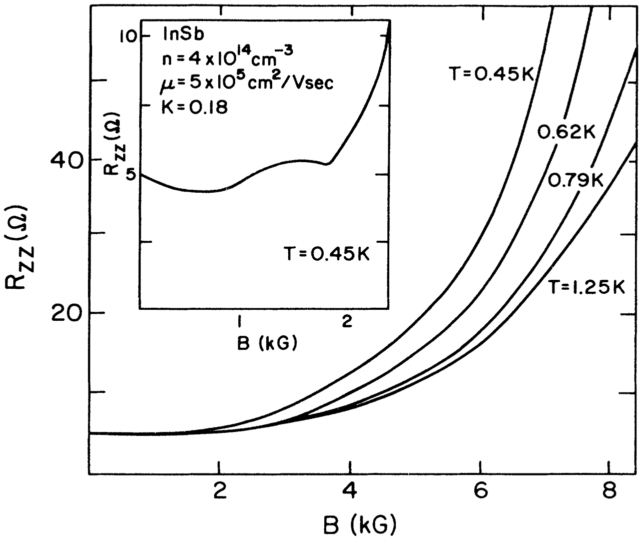

FIG. 1. Temperature dependence of longitudinal resistance below the metal-insulator transition magnetic field.

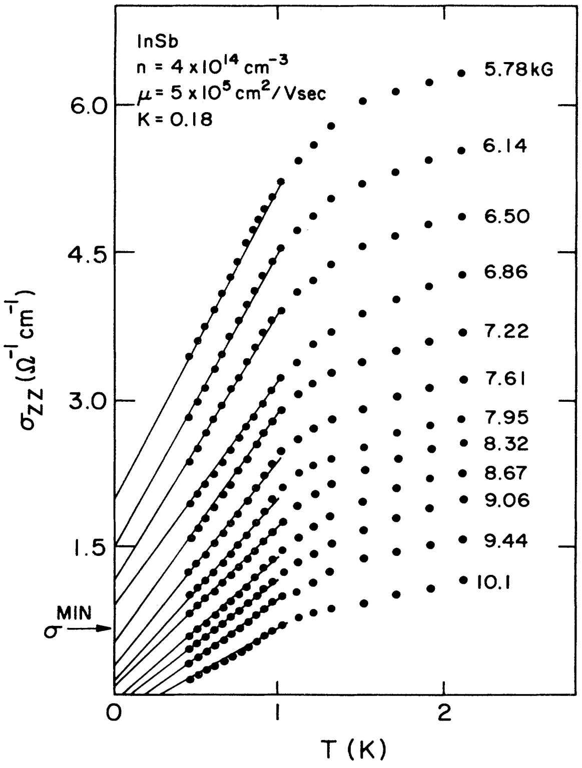

FIG. 2. Temperature dependence of the conductivity for a succession of fixed magnetic fields close to the metal-insulator transition. A value of $\simeq 0.75$ Ω^{-1} cm^{-1} indicated by an arrow is the Mott minimum metallic conductivity ($\simeq 0.25e^{2}/\hbar a$).

can be obtained by extrapolating the temperature-dependent conductivity $\sigma(T)$ to zero temperature. The magnetic field corresponding to zero conductivity then gives B_{MI}. Figure 2 shows the temperature dependence of the longitudinal conductivity for a succession of fixed magnetic fields close to the metal-insulator transition. It is clear that, for $T \leq 1$ K, the $\sigma(T)$ shows a linear dependence on the temperature, indicating dominant localization correction over the *e-e* interaction effect. However, we may expect a crossover from T to $T^{1/2}$ with decreasing temperature. We are most probably not at low enough temperature to see this crossover and pick up (what could be) a sizeable *e-e* interaction term. Unlike this expectation the linear behavior was indeed observed down to 40 mK by Mansfield, Abdul-Gader, and Fozochi.[15] A linear extrapolation of the $\sigma(T)$ for $T \leq 1$ K to zero temperature, which is predicted by the localization theory, is displayed as a solid line for each magnetic field in Fig. 2. This gives the critical field $B_{\mathrm{MI}} \simeq 8.5 \pm 0.2$ kG. This value, however, should be taken as a lower bound since the temperature dependence of the conductivity near 0.45 K is seen to deviate slightly upwards from the linear behavior, which is reasonable because otherwise the extrapolated $\sigma(0)$ would be negative for $B \geq 9$ kG. The uncertainty in the value of B_{MI} is largely because we cannot extrapolate data to zero temperature with great precision with measurement only down to 0.45 K. However, the value of $B_{\mathrm{MI}} \geq 8.5$ kG is in good agreement with the theoretical estimate from the Mott metal-insulator criterion.

Typical magnetotransmission in the Faraday geometry is shown in Fig. 3 for a photon energy $\hbar\omega = 6.74$ meV. The temperature dependence of the spectra identifies the $(000) \rightarrow (110)$ impurity cyclotron resonance (ICR) which occurs at a resonant field of $\simeq 7.5$ kG which is lower than that of the conduction-band cyclotron resonance (CCR). At $B = 7.5$ kG the donor binding energy is estimated to be about 1.8 meV, which is sufficient to freeze out most electrons onto the (000) ground state at 1.5 K. This leads to the dominance of the ICR absorption over the CCR, as seen in Fig. 3. The oscillator strength of the ICR at 1.5 K is found to be nearly the same as that of the CCR at 32 K. The observation of the residual CCR at 1.5 K is just due to the finite temperature effect, i.e., thermal excitation of the electrons from the (000) ground state to the conduction band. The critical magnetic field B_{MI} for the metal-insulator transition was found to be ≥ 8.5 kG from the low-temperature transport measurement. It is then evident that the metallic transition behavior, i.e., the finite value of the zero-temperature conductivity, $\sigma(0)$, occurring at $B = 7.5$ kG (below B_{MI}) should be attributed to the electrons in an impurity band, because, at $T = 0$ K, there are no electrons in the conduction band whose energy is higher than the donor ground state by $\simeq 1.8$ meV. But, at finite temperatures we can hardly tell whether the measured $\sigma(T)$ is attributed to the conduction band or the impurity band. A careful analysis of the temperature dependence of the conductivity combined with Hall measurements may be used for clarifying this problem. The fact that resistance and Hall coefficient are almost independent of temperature has been used as evidence indicating that the carriers are in rather mobile bandlike states, i.e., an impurity band.[16] However, clearer conclusions can be deduced from our spectroscopic results.

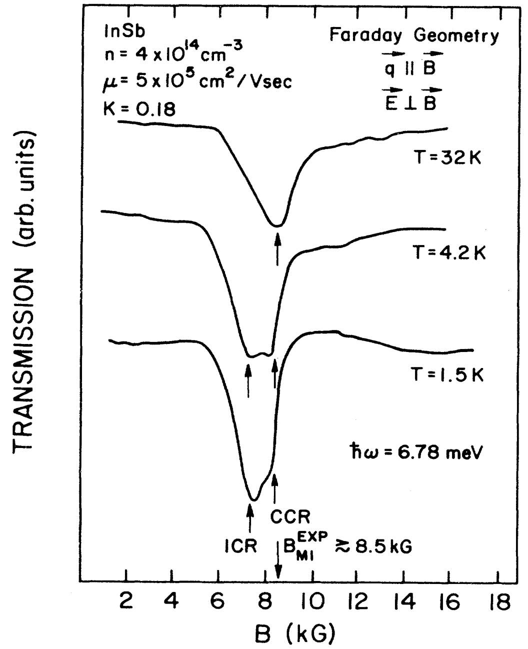

FIG. 3. Temperature dependence of ICR and CCR in the Faraday-geometry magnetotransmission.

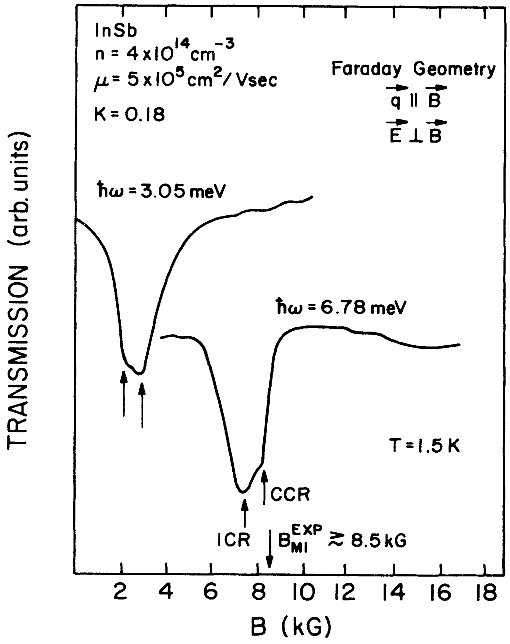

FIG. 4. Faraday-geometry magnetotransmissions spectra at $T = 1.5$ K below the metal-insulator critical field.

That is, the observation of the ICR below the critical field (i.e., in metallic regime) provides conclusive evidence for the existence of a metallic impurity band. Figure 4 provides further evidence for the persistence of the ICR on the metallic side far below B_{MI}. The relatively weak ICR observed for $\hbar\omega=3.05$ meV is due to the small donor binding energy at $B\simeq 2.5$ kG, i.e., about 1 meV which is not sufficient to freeze out electrons onto the ground state at even 1.5 K.

Therefore, these spectroscopic results and the transport measurements are combined to demonstrate that the magnetic-field-induced metal-insulator transition in the n-type InSb takes place within a donor impurity band which is well split off from the conduction band.

The observation of a donor transition below the critical field can be hardly understood in terms of the basic concept of Mott transition. The Mott transition takes place when the lower and the upper Hubbard bands merge at a critical field. In the tight-binding approach, an increase in bohr radius with decreasing magnetic field (same effect as increasing donor concentration at zero field) leads to broadening of bands, and also shifting the lower Hubbard band toward the conduction-band edge. This broadening and shifting effect arises from the increasing nondiagonal hopping energy integral in the tight-binding Hamiltonian.[17] Furthermore, as the critical field is approached, the screening effect reduces the intra-Coulomb interaction (Hubbard U) and this results in the merging of two Hubbard bands. We can clarify this point by roughly estimating the bandwidth and the density-of-states peak of an impurity band arising from the (000) donor ground states at the Mott critical field, and by comparing them with the isolated donor binding energy. A randomly distributed impurity system in a doped semiconductor may be modeled by a crystalline lattice with a mean distance of $\bar{r}\simeq(3/4\pi n)^{1/3}$ and with an effective coordination number z. Following the tight-binding approach the bandwidth W of the 1s impurity states $\simeq 2zI_{ij}$ where I_{ij} is the Coulomb energy overlap integral between two nearest-neighbor sites. For hydrogenic 1s wave function, $I_{ij}=2/3(r_{ij}/a_0)\exp(-v_{ij}/a_0)\mathcal{R}^*$, where $\mathcal{R}^*$ is $e^2/\epsilon_0 a_0$, i.e., the ground-state binding energy of an isolated donor and a_0 is the effective Bohr radius. In the magnetic-field-induced metal-insulator transition, the carrier density n is fixed, whereas Bohr radius changes its size with increasing field. Replacing r_{ij} by the mean distance between the randomly distributed donor sites $\bar{r}$, and a_0 by the field dependent a_B, then $I_{ij}\simeq 2/3(\bar{r}/a_B)\exp(-\bar{r}/a_B)\mathcal{R}^*$. On the other hand, the peak position of the density of states of the impurity band is shifted approximately by an amount of I_{ij} because the tight-binding Hamiltonian with N-identical off-diagonal integral elements of I_{ij} gives rise to an energy eigenvalue of $-\mathcal{R}^*+I_{ij}$ with $N-1$ degeneracy (peak) and a nondegenerate $-\mathcal{R}^*-(N-1)I_{ij}$ (tail). Taking $\bar{r}\simeq(3/4\pi n)^{1/3}$ and $z=6$ (simple cubic), the Mott criterion can be rewritten as $(\bar{r}/a_B)\simeq 2.5$. Then, at the critical field, the shift of the peak with respect to that of the isolated donor, ΔE is $\simeq 0.137\mathcal{R}^*$ and the bandwidth $W\simeq 1.64\mathcal{R}^*$. Therefore, this rough estimate, based on a single electron tight-binding picture neglecting e-e interaction, shows that the (000) impurity band should overlap with the conduction-band tail at the critical field. A numerical Hartree-Fock calculation[18] which considers both the e-e interactions and the disorder of the impurity sites in finite cluster ensembles, confirms the above simple prediction, i.e., shows that the impurity band merges with the conduction band for donor densities somewhat below the critical density.

Contrary to these theoretical considerations, our observation of ICR, whose oscillator strength remains unchanged through the critical field, requires the persistence of the (000) impurity band which is well split off from the edge of the zeroth Landau continuum.

In summary, we have studied the magnetic-field-induced metal-insulator transition in the n-type InSb. The impurity cyclotron resonance has been observed to persist through metal-insulator critical field to the metallic regime. This is direct evidence for the existence of a metallic impurity band, split off from the conduction band, in this narrow-band-gap semiconductor. This conclusion is only marginally affected by the transport studies which are used mostly to determine a lower bound of the critical field. The observation of a donorlike transition between metallic impurity bands in the n-type InSb together with the earlier results on n-type GaAs,[11] which seems to be a material-independent feature of the metal-insulator transition, needs a quantitative theoretical justification.

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