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LETTER TO THE EDITOR

The electronic heat capacity of n-InSb close to the metal–insulator transition

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Abstract. In this Letter we present direct measurements of the electronic heat capacity in samples of metallic n-doped indium antimonide (n-InSb) with electron concentrations close to that at the metal–insulator transition (MIT). We find that far from the transition there is good agreement with the value expected from free-electron theory, but that it decreases to about a sixth of the expected value close to the transition. The heat capacity in insulating samples has been deduced from previously published work and we find the same reduction on both sides of the transition. We show that electron–electron interactions are not sufficient to account for this change and consider the role of the impurity band in n-InSb.

Continuing interest in measurements of the electronic heat capacity arises from the information they can give about the density of states at the Fermi level, $\mathcal{D}(\epsilon_F)$. One widely used technique is to apply a steady electric field to the sample and measure the resulting change in temperature of a small bolometer—this gives the electronic heat capacity, albeit in an indirect way. Here we extend an earlier technique [1], first used by Long and Pepper [2], and by measuring the change in electron energy that occurs in the 500 ns after the start of an electric pulse, we determine the electronic heat capacity directly.

We first consider the effect of an electric field, E , on a crystal. If the electrons are heated from the lattice temperature T_L to a higher temperature T_e , then the total rate of change of electron energy may be expressed as

$$\partial\langle\epsilon\rangle/\partial t = \mu e E^2 - (\langle\epsilon(T_e)\rangle - \langle\epsilon(T_L)\rangle)/\tau_\epsilon. \quad (1)$$

The first term on the right-hand side describes the rate at which the electrons gain energy from the field and the second the rate at which they lose energy through collisions. $\epsilon(T_e)$, $\epsilon(T_L)$ are the energies of the electron at the higher and lattice temperatures and τ_ϵ is defined to be the electron energy relaxation time. The mobility μ and τ_ϵ depend on the electron energy and generally only numerical solutions can be obtained [3, 4]. However if μ and τ_ϵ are independent of energy then the average energy is

$$\langle\epsilon\rangle = \epsilon(T_L) + \tau_\epsilon e \mu E^2 (1 - e^{-t/\tau_\epsilon}). \quad (2)$$

The increase of $\langle\epsilon\rangle$ with time is thus not straightforward when the mobility is a function of energy.

The energy loss mechanisms in n-InSb have been extensively studied [5–8]. Kahlert and Bauer [8] have used the Kane expression for the conduction band and have shown

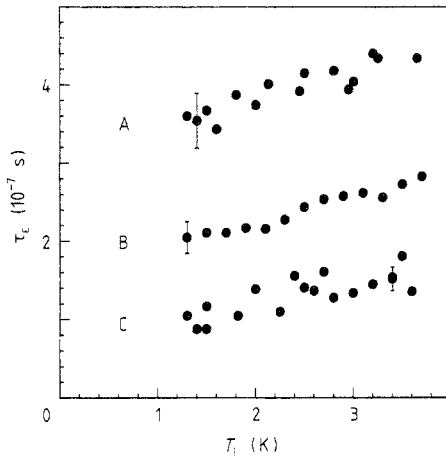


Figure 1. The energy relaxation time versus lattice temperature for the three metallic samples. The error in each measurement is about 10% and this is shown by the bars. (For A, B, C, see the text.)

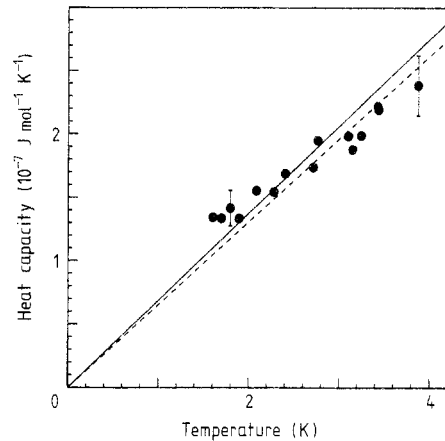


Figure 2. The results for the most metallic sample. The dotted line is a best fit to the data that vanishes at zero Kelvin and the full line is the heat capacity predicted by free-electron theory. There is good agreement between this theory and the experimental points. $n = 4.32 \times 10^{20} \text{ m}^{-3}$.

that for concentrations close to the transition, the main loss mechanism is via the piezoelectric potential. Kogan [6] expressed τ_ϵ as

$$\tau_\epsilon = d\epsilon/dP = nc_{el}/(dP/dT) \quad (3)$$

where c_{el} is the heat capacity per electron and dP/dT , the rate at which the power loss to the lattice varies with temperature, is the thermal conductivity of the electron system. For samples with these concentrations, in the range 1–7 K, τ_ϵ is anomalous in that it increases with an increase in lattice temperature. Early measurements of the power loss [8, 9] have assumed that the heat capacity is free-electron-like in order to calculate that τ_ϵ is of order 300 ns. $\langle \epsilon \rangle$ will increase to within 1% of its final value after a few microseconds and the direct measurement of these times is described below.

The experiments were performed on three samples prepared from n-type bulk InSb. The samples all showed metallic conduction and had electron concentrations of 4.32×10^{20} , 3.03×10^{20} and $2.23 \times 10^{20} \text{ m}^{-3}$, referred to as A, B and C respectively. (On the basis of the Mott criterion [10] the critical concentration for the metal-insulator transition, n_c , in InSb is $\approx 1.4 \times 10^{20} \text{ m}^{-3}$.) Sample dimensions after etching with CP4 were $\approx 1 \times 1 \times 10 \text{ mm}^3$ and Ohmic contacts were ensured by using In:Sn solder. A square voltage pulse with a rise time of $\sim 1 \text{ ns}$ was applied to the sample and a boxcar averager measured the change in voltage seen across a resistor in series. Good high-frequency signal propagation was achieved by using semi-rigid coaxial cables and matching the circuit to 50Ω . The applied electric field was sufficiently small that μ and τ_ϵ could be considered constant and the output signal showed clean exponential behaviour in agreement with (2). The measured relaxation times are shown in figure 1 and the variation of τ_ϵ with T_L agrees with the form derived by Long [2]. As the electron concentration is reduced, the screening is reduced and the scattering rate is expected to increase. The effect of this increase is seen by the clear reduction in the relaxation times with carrier concentration.

Table 1.

Sample	n (10^{20} m^{-3})	γ_{freee} ($10^{-8} \text{ J k}^{-2} \text{ mol}^{-1}$)	γ_{exptl} ($10^{-8} \text{ J k}^{-2} \text{ mol}^{-1}$)	$\frac{\gamma_{\text{exptl}}}{\gamma_{\text{freee}}}$	Conductivity ($(\Omega \text{ m})^{-1}$)
A	4.32	7.54	7.1 ± 0.4	0.94	$489 - 138 T^{1/2} + 80 T$
B	3.03	6.68	6.0 ± 0.2	0.90	$509 - 80 T^{1/2} + 63 T$
C	2.23	6.07	1.0 ± 0.1	0.17	$136 - 69 T^{1/2} + 42 T$
D	≈ 1.2	4.92	≈ 0.8	0.17	—
E	0.77	4.22	≈ 0.6	0.17	—

Once the relaxation times have been measured, energy conservation means that the electronic heat capacity may be directly calculated from

$$\sigma E^2 \tau_{\epsilon} = \int_{T_l}^{T_c} c_{\text{el}} dT. \quad (4)$$

The electron temperature is obtained from the sample resistance, this having been previously measured as a function of temperature in the Ohmic regime.

The results from these samples are shown in the first three rows of the table and figures 2 and 3. The heat capacity behaves as a degenerate electron gas in all three samples in that it varies with temperature and vanishes only at $T = 0 \text{ K}$. The values are close to those calculated for a free-electron gas for the two most metallic samples (that for A is shown in figure 2), but for the sample closest to the MIT (figure 3) the measured value is reduced to about a sixth of the free-electron value. This reduction as the MIT is approached was investigated further, by calculating the heat capacities in two insulating samples.

The data for sample D are obtained by analysis of two early papers [1, 11] which considered energy loss mechanisms in samples of n-InSb with an electron concentration of $1.2 \times 10^{20} \text{ m}^{-3}$. In the first the lattice temperature is fixed at 4.2 K and a pulse technique used to measure the electron energy relaxation time for a wide range of electron temperatures. In the second the energy-loss rate to the lattice at 4.2 K was calculated from the variation of conductivity with applied field. The heat capacity is calculated from (3) using the value of τ_{ϵ} when the electron temperature is close to that of the lattice and the result is about a sixth of the free-electron heat capacity. The most insulating sample (E) was investigated by Long [2] and had an electron concentration of $0.77 \times 10^{20} \text{ m}^{-3}$. Careful re-examination of the original data finds that the measured heat capacity is also about a sixth of the free-electron value as shown in the last row.

Figure 4 shows the combined result of measurements and analysis. For the three samples of n-InSb (C, D, E) close to the MIT, the heat capacity is reduced from that expected using free-electron values. This reduction is seen on both sides of the transition and clearly the density of states does not go to zero at the transition. (This has also been seen in samples of uncompensated Si:P [12].)

It should be stressed that the approach used here is significantly different from that published by Nimtz and Stadler. These authors suggested that the early results on InSb showed a transition from degenerate to non-degenerate behaviour [13], and they suggested that in n-Hg_{0.8}Cd_{0.2}Te the heat capacity reduces with temperature due to the onset of Wigner crystallisation [14]. However, their conclusions are invalid because they

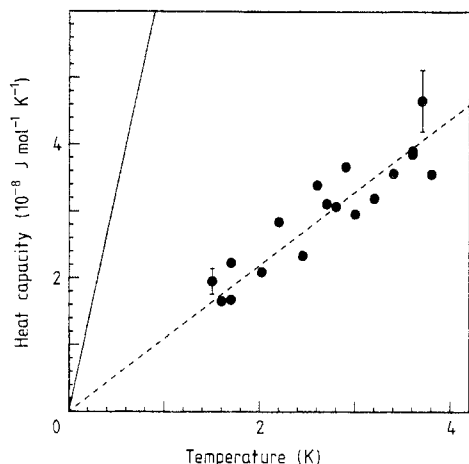


Figure 3. The results for the sample closest to the metal–insulator transition. The lines are as defined in figure 2 and show the clear difference between the free-electron theory and experiment. $n = 2.23 \times 10^{20} \text{ m}^{-3}$.

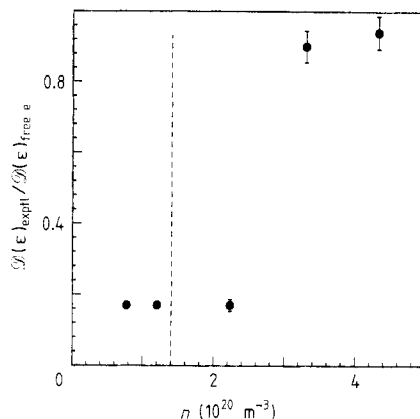


Figure 4. The ratio of the measured density of states to the free-electron density of states, plotted against carrier concentration. The vertical broken line indicates the position of n_c .

neglect the fact that the electron–phonon scattering rates will depend on the temperature of the lattice as well as that of the electrons.

It is well known that the presence of electron–electron interactions will affect the transport properties in disordered semiconductors. Altshuler and Aronov [15] found that the change in the conductivity varies as $T^{1/2}$, but our measurements over the range 1.4–4.2 K (in the fifth column of the table) find the conductivity also includes a term linear in temperature. The magnitude of the changes are five times the theoretical values and the measured reduction in the heat capacities are also found to be much greater than predicted. Further analysis is complicated as these samples have a high level of disorder present— $k_F l$ is close to unity for even the most metallic sample and this situation is not modelled well by interaction theories.

We suggest that a more complete explanation must consider the position of the impurity band in n-InSb. This is very close (0.7 meV) to the bottom of the conduction band and Mansfield [15] has suggested that there are no localised states between the bands. The effect of the impurity band on $\mathcal{D}(\epsilon_F)$ will vary with the electronic concentration and will become more pronounced as the concentration is reduced. The band structure will no longer be free-electron-like but the heat capacity will remain linear in temperature provided the density of states is constant in an energy spread of $k_B T$ around ϵ_F . The reduction in $\mathcal{D}(\epsilon_F)$ for samples close to the MIT is then due to the movement of the Fermi level into the impurity band.

In summary, we have demonstrated that the direct observation of the energy relaxation time is a successful method of directly measuring the heat capacity thus $\mathcal{D}(\epsilon_F)$. In n-InSb the density of states approximates well to the free-electron model for metallic samples but as $n \rightarrow n_c$ the density of states falls to about a sixth of that predicted using free-electron theory. Calculation of the heat capacity in two insulating samples finds a similar reduction and suggests that the density of states does not drop to zero at the transition. The reduction is greater than predicted by electron–electron interaction

theory, and may be affected by the presence of an impurity band joined to the bottom of the conduction band.

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