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NON-EXTRINSIC CONDUCTION IN SEMI-INSULATING GALLIUM ARSENIDE

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The electrical properties of semi-insulating n-type gallium arsenide single crystals are reported. Two independent pieces of evidence show that conduction is non-extrinsic over most of the temperature range studied. One dominant level is situated approximately 0.40 eV from the conduction band. A deeper level at 0.98 eV is attributed to the chromium impurity in the crystals.

IN PHYSICAL TERMS one of the requirements for a simple activation energy to be manifest in electronic conduction is that specific energy levels must contribute overwhelmingly to partition functions for the electrons and holes. At each temperature there must be only one such dominant level for each carrier. For an n-type material, if the excess donor concentration is small in comparison with the concentration of electrons excited from the dominant hole level (density of states N_q situated at energy E_q) to the dominant electron level (density of states N_m situated at energy E_m) then the Fermi level is located between the two dominant levels in such a way as to make the concentration of electrons in N_m equal to the concentration of holes in N_q. This is what is termed the *non-extrinsic* situation.[1] It may be distinguished experimentally from the familiar *extrinsic* condition by simply comparing the activation energies for the Ohmic and space charge limited (SCL) currents. The appropriate theorem as introduced by Roberts and Schmidlin is as follows.

Theorem 1. The existence of different activation energies for Ohmic and SCL conduction is both a necessary and sufficient condition for Ohmic conduction to be non-extrinsic.

This theorem has been used to interpret results on many wide band gap semiconductors including GaP, CdS, HgS, CdTe and organic solids. Because the various investigators observed SCL conduction in these crystals, the locations and concentrations of all the dominant levels involved were established unequivocally.

Many commercially important semiconductors contain relatively high thermal densities of free carriers at reasonable temperatures with the result that SCL currents cannot be easily observed in these materials. To assist in cases of this kind, where only an Ohmic activation energy can be measured, Schmidlin and Roberts[2] extended their theory to account for situations in which there were temperature-induced changes in the activation energies for electrical conduction. They formulated various rules and applied them to other workers' data on Ge, Si and GaAs. Their analysis showed conclusively that many authors had misinterpreted their conductivity data and had incorrectly assigned energy levels to various impurities in these materials. One theorem which was found to be particularly useful in this context was the following.

Theorem 2. A decrease in slope of an activation energy plot as the temperature increases implies that the initial condition is non-extrinsic; that is, the lower temperature activation energy cannot be an ionization energy.

The purpose of this letter is to report the first set of activation energy curves for a single sample that exemplifies *both* the theorems mentioned above. Our results have been obtained for single crystal n-type chromium-doped GaAs, an important device material for which there has been no generally acceptable scheme of energy levels. One report commonly quoted in the literature[3] places the Cr level at a distance 0.70 eV below the conduction band edge.

Epitaxial layers were grown on opposite faces of the liquid encapsulated Czochralski crystals[4] used in our investigations to facilitate electron injection. Contact was made to these layers with evaporated indium. The conductivity measurements were made in a helium exchange gas cryostat. The current–voltage curves obtained with these structures consistently showed Ohmic behaviour up to electric fields $\sim 50\,V\,cm^{-1}$

followed by a region in which the current J was approximately proportional to the square of the applied voltage. The characteristics were in fact very similar to those previously reported by Haisty and Hoyt.[5]

Figure 1 shows the variation of the Ohmic and SCL currents with reciprocal temperature for a typical specimen. One must assume from the good straight line segments, a relatively weak temperature dependent contribution from the product of mobility and effective state density and therefore slopes which identify well defined activation energies in different temperature regions. In the low temperature region it may be seen that the thermal activation energies for the Ohmic and SCL regions are identical. The value obtained, 0.40 eV, suggests a trap located at this energy distance from the conduction band. It is interesting to note that Lang[6] has recently reported a level at this approximate position in n-type undoped GaAs.

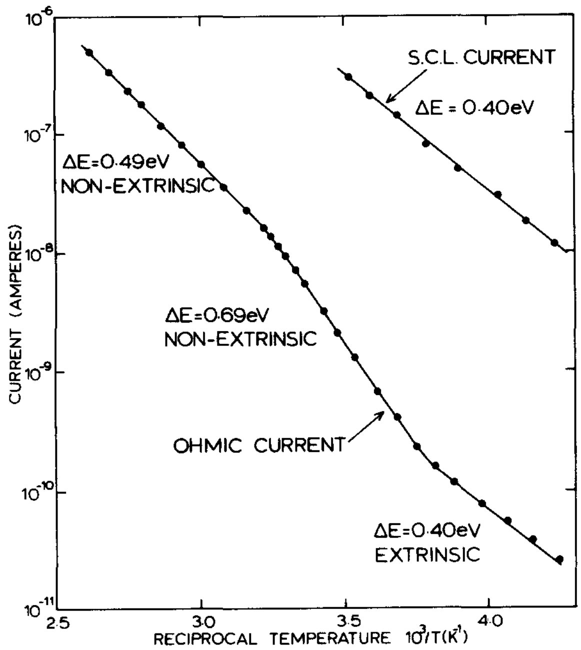

Fig. 1. Variation of current with temperature for $V = 0.04$ V (Ohmic region) and $V = 1$ V (SCL region) for single crystal n-type GaAs: $L = 0.43$ mm; electrode area = 3.0 cm^2.

An important feature in Fig. 1 is the transition that occurs in the conduction behaviour at approximately 264 K. Below this temperature the material is extrinsic. However, above this temperature, since the two currents have different activation energies (0.69 and 0.40 eV) the conduction is evidently non-extrinsic (Theorem 1). A simple calculation shows that the Fermi level in this temperature region is controlled by two dominant levels situated at 0.40 eV ($E_c - E_m$) and 0.98 eV ($E_c - E_q$) from the conduction band edge. Using an electron effective mass value $m^* = 0.068m$,[7] we find that the concentrations of the dominant electron and hole states are $N_m \triangleq 5 \times 10^{12}$ cm^{-3} and $N_q \triangleq 1.5 \times 10^{15}$ cm^{-3}, respectively.

Another distinctive feature in Fig. 1 is the transition that occurs in the Ohmic activation energy curve at approximately 308 K. Theorem 2 can be used at this stage to confirm that the activation energy 0.69 eV cannot be an ionization energy since the straight line observed in the temperature region immediately below 308 K is followed by one of lower slope as the temperature increases. A detailed analysis of the high temperature transition region yields the following explanation for the 0.49 eV activation energy; at temperatures above 308 K, the partition function for electrons is controlled by the conduction band rather than the level at E_m. The hole partition function, however, continues to be controlled by the level at E_q, with the result that the expected activation energy is $\frac{1}{2}(E_c - E_q) = 0.49$ eV, the value observed experimentally.

Thus, we have obtained two quite independent pieces of evidence to show that Cr-doped GaAs is non-extrinsic in the important temperature range around room temperature. Recent data we have obtained for semi-insulating InP show a similar pattern of transitions to those reported here for GaAs.

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Sont rapporteés les propriétés électriques des cristaux uniques demi-isolants de l'arséniure de gallium du type 'n' Deux morceaux d'évidence indépendants montrent que la conduction est non-extrinsèque pour la plupart de la gamme de température étudieé. Un niveau dominant se situe à 0.40 eV approximativement de la bande de conduction. On attribue un niveau plus bas à 0.98 eV à l'impureté causeé par du chrome dans les cristaux.