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Impurity-band conduction in heavily doped n-type GaAs

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dc conductivity measurements in the liquid-helium to room-temperature range and Hall mobility and magnetoresistance measurements in the liquid-nitrogen to room-temperature range have been made on a degenerate n-type GaAs sample. The measurements suggest that the contribution of impurity-band conduction is quite significant even at temperatures as high as 140 K. The conduction mechanism in the low-temperature region is discussed.

I. INTRODUCTION

The emphasis on semiconductor technology has shifted during the last few years from pure materials to heavily doped materials. This has happened because modern semiconductor electronics is based more on the use of heavily doped semiconductors than on pure semiconductors. The understanding of the electronic and atomic aspects of the properties of heavily doped semiconductors has therefore become a subject of current interest. The phenomenon of nonmetal-to-metal transitions[1] which occur in heavily doped semiconductors owing to the overlapping of impurity-electron wave functions[2,3] is very significant for semiconductors having low-effective-mass charge carriers, e.g., n-type GaAs and InSb. The critical concentration for the Motts transition[4] in these semiconductors is therefore far lower compared to that in semiconductors with high-effective-mass carriers, e.g., Ge, Si, and CdS.

Owing to its small magnitude, the conductivity due to impurity-band conduction can normally be observed only at cryogenic temperatures when the free charge carriers more or less completely freeze out and free-electron conduction in the extended states becomes relatively insignificant. However, depending on the degree of compensation and impurity concentration, impurity-band conduction may affect the electrical properties of the material even at higher temperatures. In fact, in semiconductors having a high energy gap (so that the contribution of intrinsic free carriers is negligible) in which compensation is nearly full, impurity-band conduction may become significant[5,6] even at room temperature and above. The nature of the impurity is also[7,8] known to affect the electrical properties of the semiconductor. It is therefore essential that studies of the phenomenon of impurity-band conduction should be made under widely different conditions of the material.

In the present paper results of investigations of the electrical properties (conductivity, Hall mobility, and magnetoresistance) have been reported for a highly degenerate sample of n-type GaAs from room temperature to liquid-He temperature. It has been found that the effect of impurity-band conduction is quite significant up to about 100 K and this contribution has been separated from the normal free-electron conduction.

II. EXPERIMENTAL DETAILS

The conductivity, Hall-mobility, and magnetoresistance measurements were performed on $6 \times 3 \times 0.5\text{-mm}^3$ rectangular slices cut from a boule of a tellurium-doped single crystal of n-type GaAs, oriented along the [100] axis. The samples were cleaned ultrasonically in benzene trichloroethylene and phenol followed by soxhelete cleaning in propanol. The samples were then etched in a hot mixture of 1 : 1 : 3 H_2O, H_2O_2, and H_2SO_4 and then washed with deionized water. Ohmic contacts were made on the sample by evaporating under vacuum a Ag–In–Ge alloy at a substrate temperature of 200°C. Partial alloying of the contacts was then made at 650°C under the flowing-forming-gas atmosphere. The current contacts were spread over the entire cross section area of the sample, while the voltage and Hall contacts were ~0.25 mm in diameter. The conductivity measurements were made by keeping the sample in a conventional-type liquid-helium cryostat. An electronic temperature controller was used to obtain and maintain the temperature in the liquid-helium to liquid-nitrogen range. The potential difference across the sample was measured using a potentiometer (model 2783) with a Leeds-Northrop null detector. The current through the sample was measured via the potential drop across a standard resistance. The temperature measurements were made using a gold-Chromel thermocouple. Since there was no arrangement for the application of a magnetic field in the above-mentioned setup, the Hall-coefficient and the magnetoresistance measurements on the sample were made only in the room-temperature to liquid-nitrogen temperature range by mounting the sample on a copper block (with electrical insulation) and keeping it in a Dewar flask containing liquid nitrogen. The Hall voltage was measured by reversing the current through the sample as well as reversing the direction of the magnetic field. To make the magnetoresistance measurements a variable high resistance was kept in series with the sample so as to keep the current constant. The change in voltage across the sample upon application of the magnetic field was measured by offsetting the voltage developed across the sample before application of the magnetic field. Only the measurements made on the best slice are reported in the present analysis.

III. RESULTS AND DISCUSSION

The temperature variation of the measured conductivity ($\log\sigma$ vs $1/T$) for the sample is shown in Fig. 1. It is observed that between room temperature and 140 K normal free-electron lattice scattering is predominant, while between 140 and 40 K the ionized impurity scattering is more important for the conduction process. Below 40 K the conductivity temperature variation is found to be approximately linear, (activated type) showing the predominance of impurity-band conduction. Taking the conductivity temperature variation in this low-temperature region to be given by the equation[9]

$$\sigma = \sigma_0 \exp(-\Delta W/kT)\,, \tag{1}$$

where σ_0 is the conductivity at $T\rightarrow\infty$, the activation energy ΔW is found to be 0.01 meV. However, as is shown in Fig. 2, the low-temperature conductivity that fits the variable-range hopping process better[10,11] is described by the relation

$$\sigma = A\exp[-(T_0/T)^{1/4}]\,, \tag{2}$$

where T_0 is a constant which depends on the density of states $N(E)$ at the Fermi level, given by the expression[12]

$$N(E) = 16\alpha^3/kT_0\,, \tag{3}$$

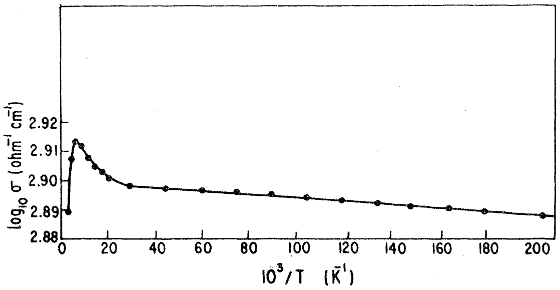

FIG. 1. Variation of the conductivity with temperature ($\log\sigma$ vs $1/T$) for the degenerate n-type GaAs sample.

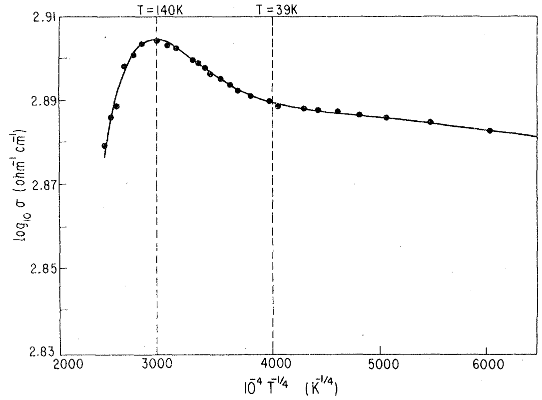

FIG. 2. Log σ vs $T^{-1/4}$ plot in the low-temperature region (4–40 K) for the n-type GaAs sample.

where α is the coefficient of exponential decay of the localized wave functions, of value[13] 10^7 cm^{-1}. The value of $N(E)$ is found to be 8.55×10^{21} eV^{-1} cm^{-3}. A dependence of the type given by Eq. (2) has been found experimentally for many amorphous semiconductors[14-17] and also for few crystalline semiconductors[18,19] at very low temperatures (4 to 10 K). Considering the low value of ΔW obtained from Eq. (1) and considering the fact that the low-temperature data fit Eq. (2) better than Eq. (1), we conclude that the conduction process is not due to phonon-assisted thermally activated tunneling in the localized-gap state near the mobility edge, but rather is due to variable-range hopping conduction in the localized states near the Fermi level. This is contrary to the normally observed behavior in amorphous and heavily doped compensated semiconductors in which the density of the localized states near the Fermi level is very much smaller compared to that near the mobility edges, as a result of which (except at very low temperatures where the number and energy of the phonons available for the absorption decrease) the conductivity due to phonon-assisted activated tunneling is very much greater than the conductivity due to the variable-range hopping process.[21] This shows that the semiconductors is well above the nonmetal-to-metal transition and that compensation in the semiconductor is not enough to shift the Fermi level outside the impurity band near the mobility edge. The observed variation of the Hall coefficient with temperature ($\log R_H$ vs $1/T$) is shown in Fig. 3. The observed Hall coefficient is characteristic of a typical degenerate semiconductor. Assuming the Hall scattering factor to be unity at such a degenerate level, the carrier concentration of the free electrons is estimated to be 2.5 $\times\,10^{18}$ cm^{-3}. The donor ionization energy of shallow donors in GaAs is known[20] to tend to zero for

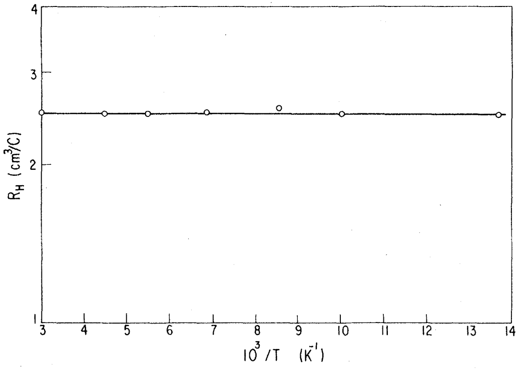

FIG. 3. Variation of Hall coefficient with temperature. (log R_H vs $1/T$) for the n-type GaAs sample.

donor concentrations $>2\times10^{16}$ cm^{-3}. The variation of the Hall mobility ($R_H\sigma$) with temperature in the temperature range 300–70 K is shown in Fig. 4. The mobility value at 140 K, where there is a mobility maximum, has been used to estimate the total impurity concentration N_I ($n+2N_A$, where N_A is the concentration of acceptors) in the sample in the following manner.

The relevant scattering mechanisms at this temperature have been considered to be the deformation-potential (DPS), polar-optical-phonon (OPS), and ionized-impurity scatterings (IIS). The mobility values for these scattering mechanisms have been calculated using the relaxation-time technique,[22-24] and the relevant scattering parameters have been taken from Aspens[25] and Adams.[26] Using Matthiessen's rule,

$$\frac{1}{\mu_{\text{eff}}}=\frac{1}{\mu_{\text{OPS}}}+\frac{1}{\mu_{\text{DPS}}}+\frac{1}{\mu_{\text{IIS}}}\,, \qquad (4)$$

where μ_{eff} is the observed mobility at 140 K, the value of μ_{IIS} is obtained from Eq. (4), and the value of N_I has been estimated using the Brooks-Herring formula.[24] The concentration of acceptors in the sample is estimated in this manner to be 3.9×10^{18} cm^{-3} and that of donors to be 6.4×10^{18} cm^{-3}. Using these values, the ionized scattering mobility, and hence the total mobility μ_{eff} (using Eq. 4), have been estimated in the entire temperature range and these have been shown in Fig. 4 by solid curves. It is observed from the figure that the observed mobility and the calculated values of total mobility μ_{eff} are in agreement from room temperature to 125 K. However, below 125 K the calculated mobility values start increasing, as compared to the observed mobility, as the temperature is lowered. This shows the existence of impurity-band conduction below 125 K, the contribution of which increases as the temperature is lowered.

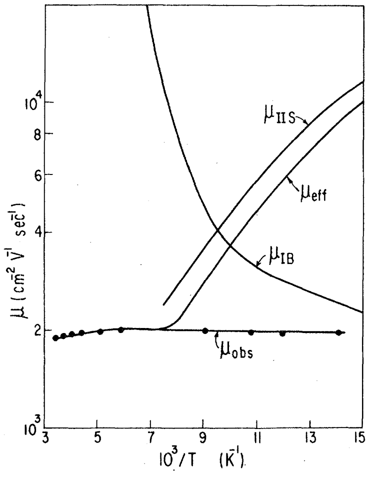

FIG. 4. Temperature variation of the observed Hall mobility ($\mu_{\text{obs}}=R_H\sigma$) for the n-type GaAs sample. The curve μ_{IIS} represents the temperature variation of ionized-impurity-scattering limited mobility calculated from the Brooks-Herring formula. The curve μ_{eff} represents the temperature variation of the total free-electron mobility (lattice + ionized). μ_{IB} is the mobility due to impurity-band conduction.

It may be mentioned that the assumption of the absence of impurity-band conduction at 140 K appears to be justified because the observed mobility values and the calculated μ_{eff} values are coinciding even below 140 K (up to 125 K). Had impurity-band conduction existed at 140 K, the curves μ_{obs} and μ_{eff} would not have overlapped between 140 and 125 K. The calculated values of the mobility μ_{IB} in the impurity band have been estimated from the observed mobility value and the calculated μ_{eff} values by applying Mathiessen's rule, and these values also are shown in Fig. 4. It is found that in the low-temperature region (70–120 K) the mobility μ_{IB} is of the activated type following the

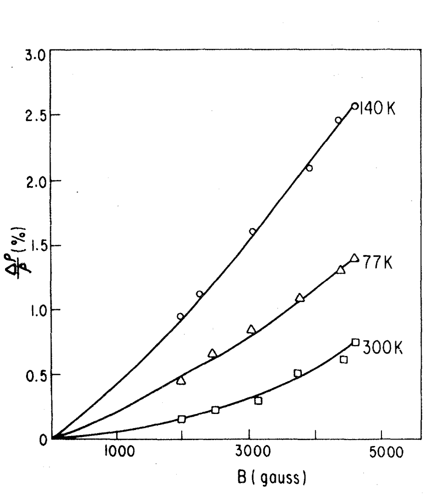

FIG. 5. Variation of magnetoresistance with magnetic field at different temperatures.

relation.

$$\mu = \mu_0 \exp(-\Delta W/kT)$$

and the mobility activation energy ΔW is found to be 6.4 meV. This value of the activation energy is very much higher than the conductivity activation energy observed at temperatures below 40 K. The probable cause of this difference in the two activation-energy values is the existence of thermally assisted tunneling conduction in the localized-state tails rather than of variable-range hopping conduction in the higher-temperature range (70–120 K).

The magnetoresistance (MR) measurements as a function of magnetic field, made on the sample at 300, 140, and 77 K are shown in Fig. 5. The observed MR at 300 K is consistent with the square-law behavior expected for free electrons. However the MR measurements show significant deviations from the square-law behavior at 140 and 77 K, suggesting the existence of impurity-band conduction. The MR at 140 K is in fact higher than that at 77 K. This is due to the fact that there is a higher contribution of impurity-band conduction at 77 K and owing to this reason there is a higher negative component of the MR at 77 K.

Assuming the variation of the MR $\Delta\rho/\rho$ to be proportional to B^n, the value of n at 140 and 77 K is found to be 1.27 and 1.03, respectively. This also indicates the existence of a higher contribution[27] of impurity-band conduction at 77 K compared to that at 140 K.

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