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# Electron transport in heavily doped and compensated n-type InSb in the temperature range 4.2–300 K

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Measurements of dc conductivity at various field strengths in the liquid-helium to room-temperature range and Hall mobility measurements in the liquid-nitrogen to room-temperature range have been made on a heavily doped and compensated n-type InSb sample. The measurements suggest that the contribution of impurity-band conduction is quite significant even at temperatures as high as 140 K.

## I. INTRODUCTION

The low-temperature electrical properties of semiconductors are very sensitive to doping concentration and to degree of compensation of the material. In an $n$-type semiconductor, if the doping is below the Mott's transition limit,[1] the low-temperature conduction is characterized by an activation energy $\epsilon_2$ which is co-related to the energy difference between the ground state of the donor impurity and an impurity band which comes into existence in the forbidden energy gap near the impurity level. The impurity band is formed due to a small overlap of the wave functions of two neighboring impurity states.[2] The low-temperature conduction in this case takes place by the thermally activated tunneling of electrons from neutral donor atoms to ionized ones, and the conductivity is given by[3]

$$\sigma=\sigma_{02}\exp(-\epsilon_2/kT)\,, \tag{1}$$

where $\sigma_{02}$ is the conductivity in the limit $1/T\rightarrow 0$. On the other hand, if the doping concentration is above the Mott's transition limit (i.e., $Na^3\gg 1$, where $N$ is the impurity concentration and $a$ the radius of the first Bohr orbit of the impurity atom) the impurity band merges[4] with the conduction band. In this case, if the compensation is absent or is very low, the Fermi level lies in the extended-state region and the heavily doped semiconductor forms almost a perfect Fermi gas. The conduction under this condition is of a metallic nature, i.e., the conductivity is high and does not vary strongly with temperature. If the compensation is appreciable, the metallic conduction in the semiconductor is destroyed and the material is said to undergo a metal-to-nonmetal transition.[5] The Fermi level in this case is located in the impurity band and the low-temperature conduction is due to thermally assisted hopping with a very small activation energy $\epsilon_3$ in accordance with the relation

$$\sigma=\sigma_{03}\exp(-\epsilon_3/kT)\,. \tag{2}$$

The activation energy $\epsilon_3$ is co-related to the potential barrier between the adjacent electron droplets which are formed[6] when the metal-to-nonmetal transition takes place. At very low temperatures (near the cryogenic temperature range), or under the condition of a weak localization of the electron states in the impurity band, the conduction may not be due to the thermally activated hopping to the nearest-neighbor site but may be due to the variable range hopping to impurity sites having equal energy in accordance with the Mott's relation[7]

$$\sigma=A\exp(-T_0/T)^{1/4}\,. \tag{3}$$

The parameter $T_0$ is co-related to the density of states $N(E_F)$ near the Fermi level, given by the relation[8]

$$N(E_F)=16\alpha^3/kT_0\,, \tag{4}$$

$\alpha$ being the coefficient of exponential decay of the localized wave function.

The basic difference between the hopping conduction in a lightly doped semiconductor and a heavily doped semiconductor is that in the latter case the electron states before and after the hop do not belong to the same impurity (as is the case in lightly doped semiconductors) but are due to fluctuations in the concentration of the impurities, and the electron states therefore involve many impurities simultaneously.

At higher temperatures the conduction is mainly by the transition of electrons from the ground state of the impurity to the extended states of the conduction band with an activation energy $\epsilon_1$ which corresponds to the donor ionization level of the impurity in the semiconductor. The conductivity in this case is given by

$$\sigma=\sigma_{01}\exp(-\epsilon_1/kT)\,. \tag{5}$$

While the impurity-band conduction is, in general, significant only at temperatures low enough for the free electrons to return from the extended states to the donor impurity atoms, the relative importance of the various conduction processes in a given material depends on the degree of compensation. In a heavily compensated semiconductor, in which the concentration of free electrons is negligible, the impurity-band conduction, described by Eqs. (1)–(3), may be quite significant even at room temperature.[9,10] It is easy to distinguish between the various conduction mechanisms because $\epsilon_1 \gg \epsilon_2 \gg \epsilon_3$ and $\sigma_{01} \ll \sigma_{02} \ll \sigma_{03}$.

The impurity-band conduction is very important for semiconductors having low effective mass of the charge carriers, e.g., $n$-type InSb and GaAs. In this case the critical impurity concentration required for the impurity-band formation is quite low.[1] The present paper reports the dc-conductivity measurements as a function of bias electric field and temperature (in the range 4–300 K) on a degenerate and compensated $n$-type InSb sample. The Hall mobility measurements have also been made in the temperature range 77–300 K. From the analysis of the data it is concluded that there is significant contribution of impurity-band conduction in the temperature range 4.2–140 K. The non-Ohmic behavior of the dc conductivity in the low-temperature range (4.2–77 K) is found to fit with the Poole effect[11] while at intermediate temperatures (77–140 K), the non-Ohmic behavior is attributed to the loss of energy of the charge carriers due to ionized impurity scattering. The average hopping distance and the density of localized states near the Fermi level are estimated from the conductivity measurements in the cryogenic temperature region.

## II. EXPERIMENTAL DETAILS

The conductivity and Hall mobility measurements were made on rectangular slices of dimensions $2.4\times2\times0.6$ mm$^3$, cut from a tellurium-doped single crystal of $n$-type InSb, oriented along the $\langle 100\rangle$ axis, grown by the Czochralski technique. The samples were first properly cleaned by ultrasonic cleaning in propanol. The samples were lapped using a fine mesh of carborundum powder and thereafter were etched in a solution of concentrated $HNO_3$ and 40% HF in equal parts by volume. After etching, the samples were washed with deionized water, and Ohmic contacts were then made by placing small In dots on the periphery of the sample and heating it in a furnace with continuously flowing argon gas to provide an inert atmosphere. The alloying temperature was maintained at 250 °C with the help of a Variac. The current contacts were spread over the entire area of the cross section of the sample while the voltage and Hall contacts were ~0.5 mm in diameter. The conductivity measurements were performed by mounting the sample in a conventional type of liquid-helium cryostat. An electronic temperature controller was used to regulate and maintain the temperature from the liquid-helium to liquid-nitrogen temperature range. For measuring the potential difference across the sample, a potentiometer (model 2743) with a Leeds-Northrup null detector was used. Current through the sample was passed from a constant-current source. A gold-iron (99.03 at.% Au + 0.97 at.% Fe) versus chromel thermocouple was used to measure the temperature in the entire range. To study the field effect, the voltage across the sample was measured for different values of current in the temperature range 4.2–77 K. Since there was no arrangement for the application of a magnetic field at liquid-helium temperatures, the Hall coefficient measurements on the sample could be made only in the liquid-nitrogen to room-temperature range. This was done on a different setup by mounting the sample on a copper block (with electrical insulation) and keeping it in a Dewar flask containing liquid nitrogen. The Hall measurements were made for both the directions of the current and the magnetic field. Only the measurements made on the best sample are reported in the present analysis.

## III. RESULTS AND DISCUSSION

The variation of the measured low-field dc conductivity with temperature ($\sigma$ vs $1/T$) for the sample is shown in Fig. 1. It is observed that in the low-temperature region (4–15 K), the conduction process is thermally activated and the conductivity varies in accordance with the equation

$$\sigma = \sigma_0 \exp(-\Delta W/kT)\,. \tag{6}$$

The activation energy $\Delta W$ is found to be 1.0 meV and the preexponential factor $\sigma_0$ is found to be 94 ohm$^{-1}$ cm$^{-1}$. The low values of $\Delta W$ and $\sigma_0$ suggest that the activated type of conduction in this temperature range is due to hopping conduction in the impurity band near the conduction-band edge. The low value of the activation energy shows that while the compensation in the materials is enough to transform the material to nonmetallic state, it is not sufficient to shift the Fermi level outside the localized state region near the conduction-band edge, in which case the activation energy would have been much higher. In the absence of sufficient compensation, the material would have been in metallic state (degenerate) and the conductivity would not have been activated. In several

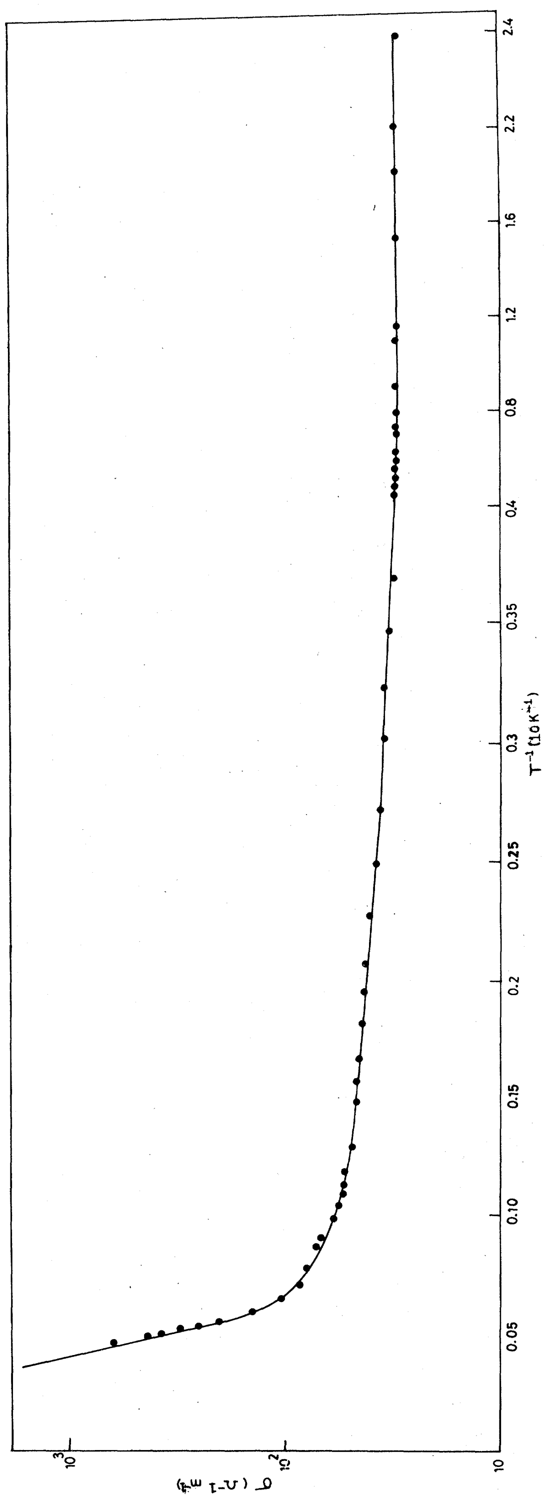

FIG. 1. Variation of the low-field dc conductivity with temperature ($\sigma$ vs $10/T$) in the heavily doped and compensated $n$-type InSb.

amorphous[12-14] and crystalline semiconductors,[15-17] variable range-hopping conduction has been observed at cryogenic temperatures in accordance with Eq. (3). In the variable range-hopping conduction mechanism, $(T_0/T)$ represents the ratio of disorder to thermal energy and this conduction mechanism occurs in the temperature region in which $(T_0/T)^{1/4} \gg 1$. In the present case the value of $(T_0/T)^{1/4}$ is ~$10^{-3}$ and it appears that the localization of electron states in the impurity band is quite strong (i.e., $\alpha R \gg 1$ where $R$ is the average hopping distance), so that the probability for thermally activated hopping to the nearest-neighbor site is much greater as compared to the probability for variable range hopping to distant equi-energy impurity sites. When the Fermi level just coincides with the mobility edge, the value of the preexponential factor $\sigma_0$ represents the metallic conductivity. It has been shown by Mott and Davis[18] that the minimum metallic conductivity of a degenerate semiconductor is given by

$$\sigma_m = (6/z^2)(0.06e^2/\hbar a), \qquad (7)$$

where $z$ is the coordination number and $a$ is the distance between the adjacent potential wells. The value of $z$ for InSb is 4, and taking $a$ as 6.4789 Å, which is the lattice constant of InSb (Ref. 19) (actually $a$ = lattice constant minus width of potential well), the value of $\sigma_m$ is found to be ~348 $\text{ohm}^{-1}\,\text{cm}^{-1}$. On the other hand, the observed value of $\sigma_0$ in the present case is found to be 94 $\text{ohm}^{-1}\,\text{cm}^{-1}$ which shows that the material is in the nonmetallic state, i.e., the Fermi level is well inside the impurity band.

It follows from Fig. 1 that in the temperature range 15–140 K the increase of conductivity with temperature is quite fast, which is due to the predominance of the ionized impurity scattering (IIS). At about 140 K, the conductivity rises exponentially, showing intrinsic behavior in the sample.

In the low-temperature range (4–77 K), the dc conductivity was also measured as a function of bias electric field $E$ in the range 50–500 V/m and the results are shown in Fig. 2 on a $\log_{10}\sigma$ vs $E$ plot. It has been observed that in the cryogenic temperature range the conductivity-field variation is in accordance with the following relation derived by Hill[20]:

$$\sigma(E) = \sigma_0 \exp(eER/kT). \qquad (8)$$

The value of $R$ from our data is found to be 7200 Å. Although this value of $R$ is about two orders of magnitude higher than that in typical amorphous semiconductors, it is in agreement with the results of Ryvkin and Shilmak[21] in heavily doped and compensated Ge. In the temperature range 15 K and

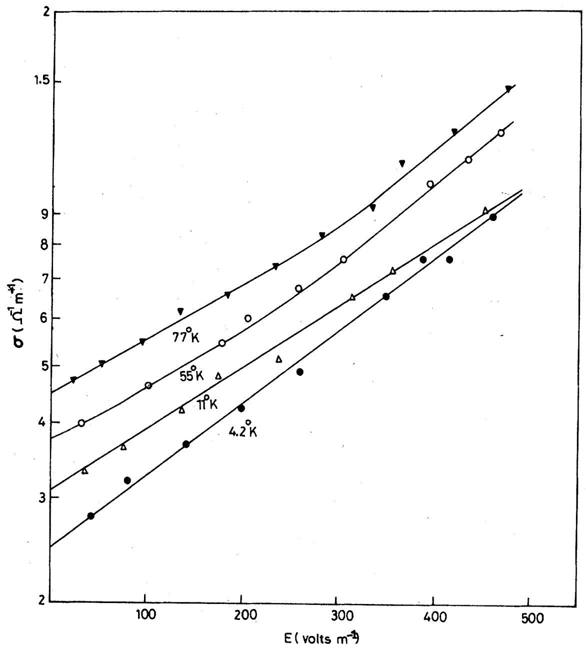


FIG. 2. Variation of the dc conductivity with bias electric field ($\log_{10}\sigma$ vs $E$) in the heavily doped and compensated $n$-type InSb at various temperatures.

above, the conductivity-field variation is faster than that expected from Eq. (8). It was shown by Saldek[22] that in $n$-type InSb, in the temperature region in which IIS is predominant, the low-field mobility deviates quadratically from Ohm's law in accordance with the relation

$$\mu = \mu_0(1+\beta E^2), \tag{9}$$

where $\beta$ is a quantity which depends on the energy gain and loss rates of the carriers. Since the material is degenerate, the conductivity is also expected to follow Eq. (9). The observed variation of conductivity with field between 15 and 77 K is found approximately in accordance with Eq. (9), which shows the dominance of IIS in this temperature range.

The variation of Hall coefficient $R_H$ with temperature ($R_H$ vs $1/T$) for the sample is shown in Fig. 3 in the temperature range 77 to 300 K. It is observed that in the temperature range 77–140 K, the Hall coefficient decreases very slowly with the increase of temperature which is characteristic of a degenerate semiconductor. Above 140 K, the Hall coefficient temperature variation is characteristic of the intrinsic state of the semiconductor. The temperature variation of low-field Hall mobility ($\mu_H = R_H\sigma$) is shown in Fig. 4 by the curve marked $\mu_{\text{OBS}}$. It is observed that in the low-temperature region, the mobility increases with the increase of temperature and reaches a maximum at 215 K. With a further increase of temperature, the mobility decreases rapidly with the increase of temperature. The maximum mobility value at 215 K has been used to estimate the total impurity concentration $N_I$ ($= n + 2N_A$, where $N_A$ is the total concentration of acceptors in the sample) in the following manner.

The relevant scattering mechanisms at about 215 K in InSb are known to be optical phonon scattering (OPS), deformation potential scattering (DPS), and ionized impurity scattering (IIS). The values of $\mu_{\text{OPS}}$ and $\mu_{\text{DPS}}$ have been calculated using relaxation-time techniques,[23-25] and the relevant scattering parameters have been taken from Ref. 26. The value of $\mu_{\text{IIS}}$ has been calculated using

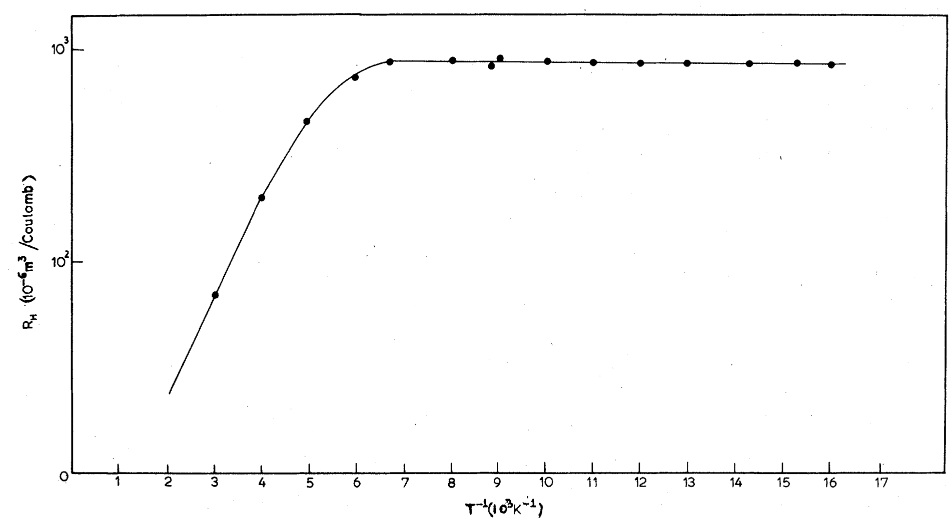


FIG. 3. Variation of the Hall coefficient with temperature $R_H$ vs $10^3/T$ in the heavily doped and compensated $n$-type InSb.

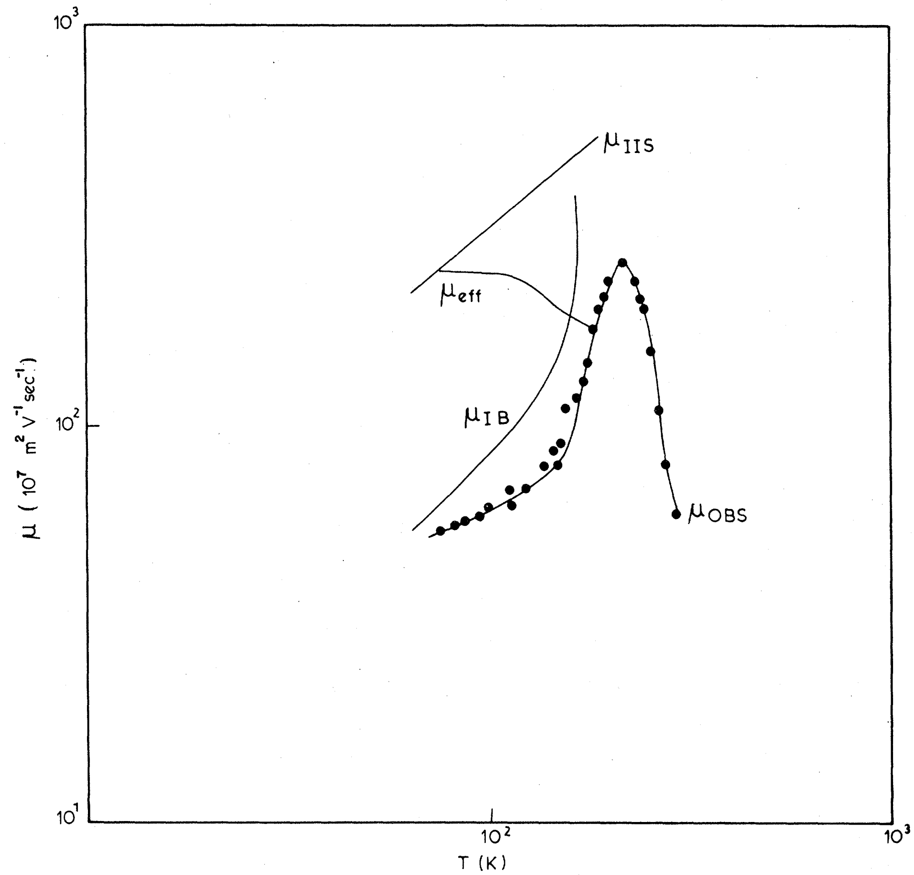


FIG. 4. Temperature variation of the observed Hall mobility ($\mu_H = R_H\sigma$) for the $n$-type InSb sample. The line $\mu_{IIS}$ represents the temperature variation of ionized-impurity-scattering-limited mobility calculated from the Brooks-Herring formula. The curve $\mu_{eff}$ represents the temperature variation of the total free-electron mobility (lattice plus ionized). The curve $\mu_{IB}$ represents the variation of impurity-band mobility with temperature.

Matthiessen's rule

$$\frac{1}{\mu_{eff}} = \frac{1}{\mu_{OPS}} + \frac{1}{\mu_{DPS}} + \frac{1}{\mu_{IIS}}, \tag{10}$$

where $\mu_{eff}$ is the observed mobility at 215 K. From the value of $\mu_{IIS}$ so calculated, the value of $N_I$ has been estimated using the Brooks-Herring formula[25] taking the value of the free-carrier concentration to be $n = 1/R_H e$. The concentrations of the donors $N_D$ and acceptors $N_A$ calculated in this manner are found to be $15.7\times10^{15}$ and $7.1\times10^{15}$ $cm^{-3}$, respectively. The values of $\mu_{IIS}$ at other various temperatures are calculated using these values of $N_D$ and $N_A$ and using the Brooks-Herring formula; these mobility values are shown in Fig. 4 by the line labeled $\mu_{IIS}$. The effective mobility calculated using Eq. (10) is shown in this figure by the curve labeled $\mu_{eff}$. It is found that in the low-temperature region, the $\mu_{eff}$ curve showing the contribution of some other scattering mechanisms—other than OPS, DPS, and IIS, which is due to impurity-band conduction. The contribution of the impurity-band conduction is found to decrease with the increase in temperature. The values of $\mu_{IB}$, the mobility due to impurity-band conduction at various temperatures, have been

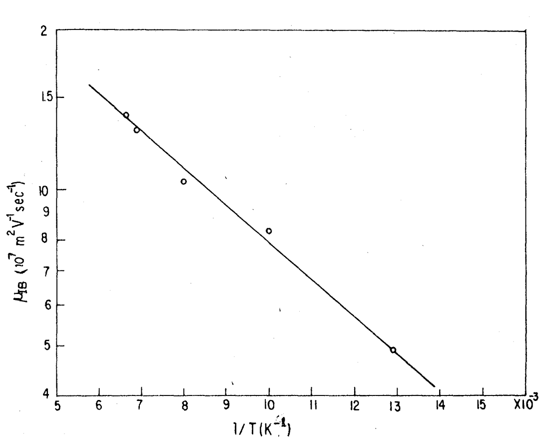


FIG. 5. Temperature variation of mobility in the impurity band ($\log_{10}\mu_{IB}$ vs $1/T$).

estimated from the values of $\mu_{eff}$ applying Matthiesen's rule and are shown in Fig. 4 by the curve labeled $\mu_{IB}$. It is found that there is a significant contribution of the impurity-band conduction in the low-temperature range, but above 140 K its contribution to the electron transport is negligible.

The mobility due to the impurity-band conduction is of the activated type in accordance with the relation

$$\mu_{IB} = \mu_0 \exp(-\Delta\epsilon/kT), \quad (11)$$

where $\Delta\epsilon$ is the activation energy for the mobility in the impurity band and $\mu_0$ is the mobility in the limit $1/T \to 0$. As shown in Fig. 5, the calculated $\mu_{IB}$ values are in agreement with the exponential relation of Eq. (11). The value of $\Delta\epsilon$ is found to be 14 meV. This value of activation energy is very much higher than the conductivity activation energy observed at lower temperatures. A probable cause for this difference is that the drifting carriers are repeatedly trapped and thermally released from shallow traps during their transit.

We therefore conclude that there is significant contribution of impurity-band conduction in the temperature range 4–140 K in the heavily doped and compensated $n$-type InSb.

[1]N. F. Mott and Z. Zinamon, Rep. Prog. Phys. 33, 881 (1970).
[2]W. Baltensperger, Philos. Mag. 44, 1355 (1953).
[3]E. A. Davis and N. F. Mott, Philos. Mag. 22, 903 (1970).
[4]R. S. Knox, Solid State Phys. Suppl. 5, 5 (1963).
[5]N. F. Mott and E. A. Davis, Philos. Mag. 17, 1269 (1968).
[6]B. I. Shklovskii, Fiz. Tekh. Poluprovod. 6, 1197 (1972) [Sov. Phys. Semicond. 6, 1053 (1973)].
[7]N. F. Mott, Philos. Mag. 19, 835 (1969).
[8]V. Ambegaokar, B. I. Halperin, and J. S. Langer, Phys. Rev. B 4, 2612 (1971).
[9]B. R. Sethi, P. C. Mathur, and J. Woods, J. Appl. Phys. 49, 3618 (1978).
[10]B. R. Sethi, P. C. Mathur, and J. Woods, J. Appl. Phys. 50, 352 (1979).
[11]J. Frenkel, Phys. Rev. 54, 647 (1938).
[12]P. Blood, Acta Electron. 15, 33 (1972).
[13]M. Pollak, J. Non-Cryst. Solids 8–10, 486 (1972).
[14]N. F. Mott, Philos. Mag. 19, 835 (1969).
[15]M. Morgan and P. A. Walley, Philos. Mag. 23, 661 (1973).
[16]I. S. Shilimak and E. I. Nikulin, Zh. Eksp. Teor. Fiz. Pis'ma Red. 15, 30 (1972) [JETP Lett. 15, 20 (1972)].
[17]O. V. Emel'yaneko, D. N. Nasledov, E. I. Nikulin, and I. N. Temohenko, Fiz. Tekh. Poluprovod. 6, 2283 (1972) [Sov. Phys. Semicond. 6, 1926 (1973)].
[18]N. F. Mott and E. A. Davis, *Electronic Progress in Non-Crystalline Materials* (Oxford University Press, New York, 1971), p. 26.
[19]O. Madelung, *Physics of III-V Compounds* (Wiley, New York, 1964), p. 11.
[20]R. M. Hill, Philos. Mag. 24, 1307 (1972).
[21]S. M. Ryvkin and I. S. Shilimak, *Amorphous and Liquid Semiconductors*, edited by J. Stuke and W. Breniz (Taylor and Francis, London, 1974), p. 1155.
[22]R. J. Sladek, Phys. Rev. 120, 1589 (1960).
[23]K. Seeger, *Semiconductor Physics* (Springer, New York, 1973), p. 175.
[24]D. J. Howarth and E. H. Sondheimer, Proc. R. Soc. London A219, 53 (1953).
[25]H. Brooks, Adv. Electron. Electron. Phys. 1, 85 (1955).
[26]*Semiconductors and Semimetals*, edited by A. C. Beer and R. K. Willardson (Academic, New York, 1975), Vol. 10.