# Conductivity of $n$-type GaAs near the Mott transition

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(Received 4 December 1986; revised manuscript received 30 March 1987)

Low-$T$ transport data on $n$-type GaAs in several regimes from insulating to metallic is presented. On the insulating side of the Mott transition, it is shown that the power $s$ in the variable-range-hopping law, $\sigma_v=\sigma_0\exp[-(T_0/T)^s]$, which is found to be $\frac{1}{4}$ for pure enough samples, can reach $\frac{1}{2}$ for a narrow range of higher impurity concentrations. A small metal-like contribution to the conductivity can explain the observed shift in $s$ and is supported by Hall-mobility data. Consequently, the corresponding behavior can hardly be interpreted as due to a Coulomb gap in the density of impurity states. Evidence is presented for weak localization and then normal metallic behavior for higher impurity concentrations.

Precise and extensive low-temperature ($T$) conductivity measurements on crystalline epitactic $n$-type GaAs, $n$-type InP, and $n$-type Si:As have recently shown[1-3] that the Mott law for variable-range hopping,[4]

$$\sigma_v=\sigma_0\exp[-(T_0/T)^s] \quad \text{with } s=\tfrac{1}{4}\ , \tag{1}$$

is a better description of the observed data than the corresponding Efros and Shklovskii[5] law [Eq. (1) with $s=\frac{1}{2}$], derived by assuming the presence of a Coulomb gap in the one-electron density of localized states. All the previous measurements were performed on samples whose impurity concentrations fell below the metal-insulator ($M$-$I$) transition in order to ensure the existence of an impurity band of totally localized donor states. They were also specifically aimed at the determination of the exact value of the power $s$.

Nevertheless, two other recent reports[6,7] on similar precise conductivity measurements still support $s=\frac{1}{2}$ in Eq. (1), and thus the importance of the Coulomb gap for conductivity arises. One $n$-type Si:P sample[6] and one $n$-type InP sample[7] were considered. Both were again on the insulating side of the $M$-$I$ transition as given by the Mott criterion:[8]

$$n_c^{1/3}a_0=0.25\ , \tag{2}$$

where $n_c$ is the critical electron concentration and $a_0$ the effective Bohr radius of the corresponding material. Fritszche[9] suggested a similar criterion, where $n_c$ in Eq. (2) is replaced by the critical donor impurity concentration $N_{Dc}$, pointing out that compensation should increase the corresponding critical value. As the previous experiments are precise and reliable, an apparent contradiction exists between the results. Nevertheless, we can point out, by comparing the results for $n$-type InP, that in our samples giving $s=\frac{1}{4}$,[2] $N_D$ ranges from $2\times10^{15}$ cm$^{-3}$ to $8\times10^{15}$ cm$^{-3}$. On the other hand, Finlayson and Mason[7] find $s=\frac{1}{2}$ for a sample with $N_D=2\times10^{16}$ cm$^{-3}$. Based on the simple atomic model, $N_{Dc}=3.1\times10^{16}$ cm$^{-3}$ in InP, and we see that their sample,[7] for which $s=\frac{1}{2}$, falls closer to the $M$-$I$ transition than ours. The results for Si:As and Si:P are not directly comparable, the two distinct dopants giving different values of the critical concentration $n_c$, due to different binding energies. Nevertheless, for the Si:P sample,[6] the electron concentration $n$ is found by Hall effect to be $2.5\times10^{18}$ cm$^{-3}$, a value again relatively close to the corresponding critical value ($n_c=3.7\times10^{18}$ cm$^{-3}$). The resistivity measurements performed on Si:As,[3] giving $s=\frac{1}{4}$ in Eq. (1) for a set of seven samples, appear very precise. Nevertheless, the electron concentrations quoted, which fall very close to the $M$-$I$ transition ($n_c=8.5\times10^{18}$ cm$^{-3}$ for Si:As), were determined by a rather indirect technique, involving neutron activation calibration tables due to Newman, Hirsh, and Holcomb,[10] and might need some clarification.

On the basis of the previous remarks, we extend here a previous work[1] on relatively pure $n$-type GaAs to more doped samples close to the $M$-$I$ transition ($n_c=1.6\times10^{16}$ cm$^{-3}$ for GaAs, on the basis of the simple atomic model), looking for a possible effect of the impurity concentrations on the power $s$ of Eq. (1). In addition, Hall-mobility results are presented both in the variable-range-hopping regime, and for a range of higher impurity concentrations.

Nine epitactic $n$-type GaAs samples with donor concentrations $N_D$ ranging from $6\times10^{15}$ cm$^{-3}$ to $3.5\times10^{16}$ cm$^{-3}$ are studied in this paper. They were grown by metalorganic vapor-phase epitaxy (MOVPE) on semi-insulating GaAs with a thickness of more than 5 $\mu$m to reduce both their resistance at the lowest $T$ and possible interface effects. Such a thickness, for the impurity concentrations considered, proved, by a detailed Hall-mobility and free-electron analysis, to be sufficient to avoid a depletion-effect correction. The samples were selected to assure both good uniformity and linearity in the $I$-$V$ characteristics of all Au-Ge contacts. Uniformity was checked by using a multiple-contact Hall bridge configuration, with three electrodes on each side of the 1-cm-long by 0.2-cm-wide epilayer. Impurity concentrations were achieved by varying the ratio of trimethylgallium to arsine in the reactor, and no particular dopant

 

was introduced. The measurements were performed under low-field conditions. The results were thus independent of the applied electric field, which was kept below 50 mV/cm in the hopping regime. The Hall mobility $\mu_H$ and the electronic concentration $n$ were obtained with a 4 kG magnetic field. $T$ was read through a precision Carbon-Glass sensor, embedded in the copper sample holder, with a precision better than 0.01 K. To minimize $T$-gradient effects between the sample and the holder, $T$ was not heat stabilized, and was let to recover naturally at a very slow rate from its lowest value. The data was collected by a conventional manual technique for all samples except sample 3. In this case, a high-input-impedance precision data-acquisition system was used, allowing an experimental point every 0.05 K.

For the samples studied, the donor concentration $N_D$, the acceptor concentration $N_A$, the compensation ratio $K$, the electronic concentration at room $T$, denoted $n^{300}$, and the corresponding values for $n^{1/3}a_0$ and $N_D^{1/3}a_0$, are presented in Table I. $N_D$ and $N_A$ were extracted from the Falicov-Cuevas[11] drift-mobility formula for ionized impurity scattering below 60 K, keeping consistency with the observed $n^{300}$. The variations of the Hall factor were neglected, but a correction was introduced to account for the fact that all electrons are not excited to the conduction band at 300 K, particularly when the doping level is high. This convenient approach gives results surprisingly close to the ones obtained with much more sophisticated techniques recently reported by us,[12] that account for the Hall factor. We point out that sample 3 shows a very high compensation. According to the Mott criterion, samples 1–7 fall below the $M$-$I$ transition. This is not so according to the Fritzsche criterion, for which only samples 1–4 fall below the $M$-$I$ transition.

Figure 1 shows the behavior of $\mu_H$ as a function of $T$ between 1.4 and 6 K for samples 1, 2, and 4. In the particular case of sample 3, the data showed excessive scatter between 1.4 and 5 K due to high resistivity and is not presented. For sample 1, a linear behavior as a function of $T$ is observed below 3.5 K. Sample 2 shows the same behavior below 4.5 K, the two previous samples being the purest of the set. Moreover, the extrapolation of the results seems to indicate that $\mu_H \to 0$ as $T \to 0$. For sample 4, which is more heavily doped, the corresponding $\mu_H$ is clearly different. The Hall mobility is higher and shows a small but definite negative curvature, particularly noticeable below 3 K. Lower-$T$ data is desirable to draw a conclusion on the behavior of $\mu_H$ at $T=0$, but is very difficult to obtain due to both the high resistivities involved, the weakness of the Hall voltage, and the low values of the excitation current needed to maintain low-field conditions.

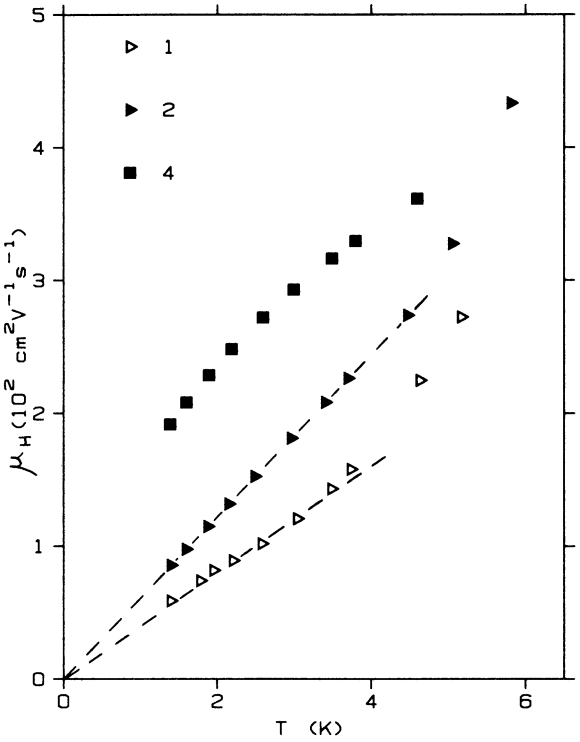


FIG. 1. $\mu_H$ vs $T$ from 1.4 to 6 K for samples 1, 2, and 4. The behavior is linear at the lowest $T$ for the two purest samples. As doping increases (sample 4), $\mu_H$ is higher but shows a curvature in its decrease with $T$.

Figure 2 presents $\mu_H$ versus $T$ between 1.4 and 6 K for samples 5–9. The general trend is an increase in $\mu_H$ with increasing $n^{300}$, which applies for all samples. The

TABLE I. Impurity concentrations $N_D$ and $N_A$, compensation, room-$T$ electronic concentration, and corresponding results for the Mott and Fritzsche criteria.

| Sample | $N_D$ (cm$^{-3}$) | $N_A$ (cm$^{-3}$) | $K$ | $n^{300}$ (cm$^{-3}$) | $n^{1/3}a_0$ | $N_D^{1/3}a_0$ |
|---|---|---|---|---|---|---|
| 1 | $5.8\times10^{15}$ | $3.9\times10^{15}$ | 0.68 | $1.8\times10^{15}$ | 0.12 | 0.19 |
| 2 | $7.1\times10^{15}$ | $3.2\times10^{15}$ | 0.45 | $3.7\times10^{15}$ | 0.16 | 0.19 |
| 3 | $1.1\times10^{16}$ | $1.0\times10^{16}$ | 0.92 | $8.4\times10^{14}$ | 0.09 | 0.22 |
| 4 | $1.4\times10^{16}$ | $9.8\times10^{15}$ | 0.70 | $3.8\times10^{15}$ | 0.16 | 0.24 |
| 5 | $1.8\times10^{16}$ | $9.0\times10^{15}$ | 0.50 | $8.2\times10^{15}$ | 0.20 | 0.26 |
| 6 | $2.3\times10^{16}$ | $1.0\times10^{16}$ | 0.45 | $1.1\times10^{16}$ | 0.22 | 0.29 |
| 7 | $2.5\times10^{16}$ | $1.4\times10^{16}$ | 0.57 | $9.2\times10^{15}$ | 0.21 | 0.29 |
| 8 | $3.4\times10^{16}$ | $1.2\times10^{16}$ | 0.35 | $1.9\times10^{16}$ | 0.27 | 0.33 |
| 9 | $3.5\times10^{16}$ | $1.3\times10^{16}$ | 0.37 | $1.8\times10^{16}$ | 0.26 | 0.33 |

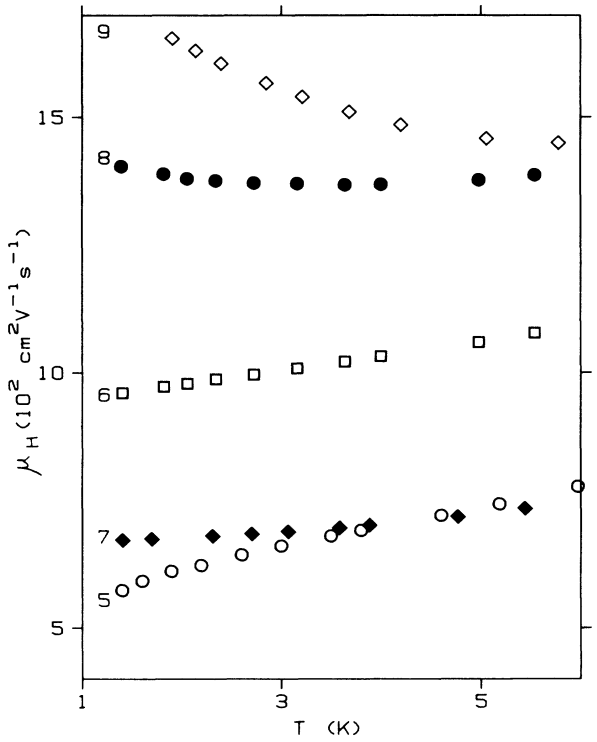


FIG. 2. $\mu_H$ vs $T$ from 1.4 to 6 K for samples 5–9. As doping is higher, the behavior of $\mu_H$ with decreasing $T$ varies from a nonlinear decrease (sample 5) to an increase (samples 8 and 9). Samples 6 and 7 show the intermediate situation where $\mu_H$ is almost constant with $T$.

shape of the curves is also dependent on $n$. For sample 5, $\mu_H$ decreases nonlinearly with $T$, as for sample 4 in Fig. 1. When $N_D$ increases, $\mu_H$ is almost constant when $T$ varies (samples 6 and 7), and then increases with decreasing $T$ for the highest impurity concentrations presented (samples 8 and 9). At higher $T$, a fast increase in $\mu_H$ develops for all nine samples, followed by an approximate $T^{3/2}$ behavior, corresponding to impurity scattering in the conduction band. We point out that for samples with $N_D \sim 10^{17}$ cm$^{-3}$, falling well above the $M$-$I$ transition for the considered compensation levels, low-energy excitation to the conduction band (lower than 2 meV) is still observed,[13] indicating either some separation of the metallic impurity band from the conduction band or more likely localization at the impurity band edge. Furthermore, a rough $T^{3/2}$ behavior is still evident for $\mu_H$.

Samples 1 and 2 correspond to concentrations (see Table I) for which variable-range hopping is expected. Figure 3 presents $\ln(\sigma)$ versus $T^{-1/4}$ for sample 3 between 1.4 and 11 K, where $\sigma$ is the conductivity. The corresponding data for samples 1 and 2 is similar, but only between 1.4 and 6 K. It has already been published,[1] and is not shown here. This clearly corresponds to the Mott variable-range hopping regime, as the power $s$ obtained will show later. The $T$ range where it is ob-

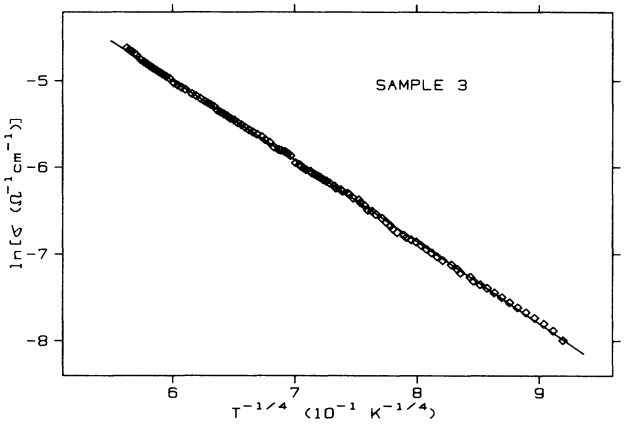


FIG. 3. $\ln(\sigma)$ vs $T^{-1/4}$ for sample 3 between 1.4 and 11 K. Mott's law is observed in a relatively broad $T$ range due to the heavy compensation of this sample, where excitation to the conduction band appears at higher $T$. The continuous line is the best fit giving $s = 0.276 \pm 1\%$.

served for sample 3 is large compared to available results for shallow impurity bands in crystalline semiconductors, and was expected for the following reason. As this sample is very heavily compensated, its relatively large average binding energy only allows excitation to the conduction band at relatively high $T$. As this contribution vanishes earlier with decreasing $T$, the underlying hopping regime appears in a broader $T$ range. Figure 4 presents $\ln(\sigma)$ versus $T^{-1/2}$ for samples 4 and 5, showing that $s$ of Eq. (1) is close to $\frac{1}{2}$ in these two cases. The continuous lines of Figs. 3 and 4 represent the best fit to the experimental data obtained by using Eq. (1), where $\sigma_0$, $T_0$, and $s$ were let free to vary. The numerical least-squares fitting technique was a classical iterative procedure suited for nonlinear functions. Table II gives $\sigma_0$,

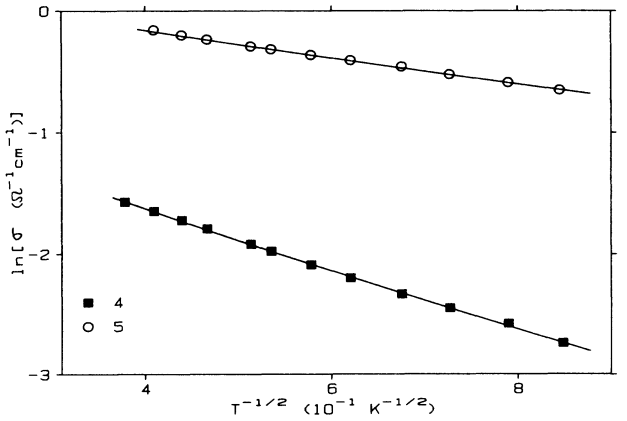


FIG. 4. $\ln(\sigma)$ vs $T^{-1/2}$ for samples 4 and 5 between 1.4 and 6 K. The powers obtained are, respectively, $0.414 \pm 2\%$ and $0.398 \pm 2\%$, as given by the best fits represented by the continuous lines. Both samples show a relatively high $\mu_H$ in this $T$ range, attributed to some metallic contribution.

TABLE II. Parameters of $\sigma_v=\sigma_0\exp[-(T_0/T)^s]$ and of $\sigma'_v=\sigma'_0\exp[-(T'_0/T)^{1/4}]+\sigma_m$ along with the relative errors on $\sigma_v$, on $s$ and on $\sigma'_v$.

| Sample | $\sigma_0$ ($\Omega^{-1}$cm$^{-1}$) | $T_0$ (K) | $s$ | $\delta\sigma$ | $\delta_s$ | $\sigma'_0$ ($\Omega^{-1}$cm$^{-1}$) | $T'_0$ (K) | $\sigma_m$ ($\Omega^{-1}$cm$^{-1}$) | $\delta'\sigma$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.77 | 870 | 0.253 | $8.5\times10^{-3}$ | $8.9\times10^{-3}$ | 1.81 | 1070 | 0.000 | $8.7\times10^{-3}$ |
| 2 | 3.35 | 560 | 0.269 | $1.2\times10^{-2}$ | $1.1\times10^{-2}$ | 4.27 | 1040 | 0.000 | $1.2\times10^{-2}$ |
| 3 | 0.961 | 2510 | 0.277 | $1.3\times10^{-2}$ | $7.3\times10^{-3}$ | 1.60 | 6860 | 0.000 | $1.5\times10^{-2}$ |
| 4 | 0.72 | 11.5 | 0.414 | $6.4\times10^{-3}$ | $1.0\times10^{-2}$ | 3.58 | 487 | 0.021 | $1.9\times10^{-2}$ |
| 5 | 1.56 | 1.70 | 0.398 | $3.6\times10^{-3}$ | $1.2\times10^{-2}$ | 2.53 | 11.0 | 0.063 | $6.0\times10^{-3}$ |

$T_0$, and $s$ as obtained for samples 1–5. For the other samples, showing a different behavior, this fit could not be obtained, the trend being values of $s$ close to zero. The values of $\delta\sigma$ and $\delta s$ quoted in Table II are the average relative errors for the conductivity $\sigma$ and for the power $s$, respectively. They were defined as

$$\delta\sigma=\frac{1}{N}\sum_{i=1}^{N}\left|\frac{\sigma(\sigma_0,T_0,s,T_i)-\sigma_i}{\sigma_i}\right|, \tag{3}$$

$$\delta s=\frac{1}{Ns}\sum_{i=1}^{N}\left|\left[\frac{\partial\sigma}{\partial s}\right]^{-1}_{\sigma_0,T_0,s,T_i}[\sigma(\sigma_0,T_0,s,T_i)-\sigma_i]\right|, \tag{4}$$

where $N$ is the number of experimental points in the range shown on the corresponding figure. Each point is defined by the conductivity $\sigma_i$ at the temperature $T_i$.

Table II shows that Eq. (1) holds for the purest samples presented. It is particularly clear for sample 3, where Mott's law is observed in a 10-kT range with a precision better than 0.01 K. Nevertheless, samples 4 and 5 show values of $s$ close to $\frac{1}{2}$. Although this result could be seen as due to the presence of a Coulomb gap in the density of localized impurity states, such an interpretation is hardly understandable for large values of $n$ that should, if anything, screen Coulomb interactions. On the other hand, those samples correspond to an intermediate situation, where $\mu_H$ is relatively high and nonlinear with $T$. Their impurity concentrations fall between situations corresponding, on the one side, to the Mott's variable-range hopping regime, and in the other side to extended-states conduction, as will be seen for samples 8 and 9. It is then reasonable to speculate that these two samples are showing an admixture of two effects, namely, Mott's variable-range hopping and some kind of metal-like contribution. Such kind of conduction could be described by an expression of the form

$$\sigma'_v=\sigma'_0\exp[-(T'_0/T)^{1/4}]+\sigma_m, \tag{5}$$

where $\sigma_m$ represents a metallike contribution to the conductivity. Equation (5) was fitted to the data corresponding to samples 1–5, with $\sigma'_0$, $T'_0$, and $\sigma_m$ as adjustable parameters. The results obtained are quoted in Table II with the corresponding fitting error. For samples 1–3, $\sigma_m$ appears negligible compared to the exponential term , indicating pure variable-range hopping in such cases. For samples 4 and 5, $\sigma_m$ is more than 1 or 2 orders of magnitude larger, depending on the sample, and increases very significantly with $N_D$. We note however that $\sigma_m$ is still small, except at the lowest $T$ for sample 4, compared to the exponential term of Eq. (5), but not negligible. The error on $\sigma_m$, as extracted from the least-squares fit, is between 1% and 2% depending on the sample. As the corresponding fits could not be distinguished from the ones in Fig. 4, they were not drawn. Consequently, the above results show that when the power $s$ of Eq. (1) is found to be close to $\frac{1}{2}$ instead of $\frac{1}{4}$, a small metal-like contribution to the conductivity can explain the observed shift in $s$. This is also consistent with both the higher impurity concentrations and the relatively high Hall mobility observed for the corresponding samples (see Figs. 1 and 2). Moreover, it appears, from a detailed higher-$T$ (5–300 K) Hall-mobility analysis, that GaAs and InP data corresponding to impurity concentrations similar to those of samples 5 and 6 cannot be explained unless a two-band model, including a metal-like contribution to conduction, is accounted for.[12] Such an effect vanishes for purer samples.

For slightly higher impurity concentrations, that is, for barely metallic samples, a weak localization regime is expected for the conductivity, with characteristic $T$-dependent corrections to normal metallic conductivity. Such effects have been observed in several other materials,[14–16] the corresponding behavior for the conductivity being of the form[17]

$$\sigma_w=\sigma_1+\sigma_2T^p, \tag{6}$$

where $\sigma_1$ is the $T=0$ K conductivity. The $\sigma_2T^p$ term either represents weak localization corrections due to quantum interference or Coulomb interaction effects.[17,18] The prefactor $\sigma_2$ and the power $p$ are then dependent on the nature of the dominant mechanism.

Figure 5 shows $\sigma$ versus $T$ between 1.4 and 7 K for samples 6 and 7. The continuous curves are the fits of Eq. (6) to the corresponding data. The parameters obtained are quoted in Table III along with the relative error on the conductivity introduced by the fit [Eq. (3)], and the corresponding error for the power $p$ [Eq. (4)]. Equation (6) appears to be a good description of the observed conductivity versus $T$, and indicates that samples 6 and 7 fall slightly above the $M$-$I$ transition. Above 7 K, a change of curvature is observed in the behavior of $\sigma_w$ versus $T$, and is attributed to excitation to the conduction band. The values obtained for $p$ are close to $\frac{1}{2}$ and are consistent with the predictions of Altshuler and

TABLE III. Parameters of $\sigma_w=\sigma_1+\sigma_2 T^p$ for two samples in the weak localization regime, with the relative errors on $\sigma_w$ and $p$.

| Sample | $\sigma_1$ ($\Omega^{-1}$cm$^{-1}$) | $\sigma_2$ ($\Omega^{-1}$cm$^{-1}$) | $p$ | $\delta\sigma$ | $\delta p$ |
|---|---|---|---|---|---|
| 6 | 0.953 | 0.368 | 0.410 | $9.9\times10^{-4}$ | $1.1\times10^{-2}$ |
| 7 | 0.628 | 0.129 | 0.531 | $1.7\times10^{-4}$ | $1.3\times10^{-3}$ |

Aronov[19,20] and Lee and Ramakrishnan[21] when electron-electron interactions are accounted for in the presence of a random distribution of impurities. As in a previous work in Si:P,[22] the interaction effect is sizeable, the conductivity increasing by approximately 20% for both samples between 1.4 and 6 K.

Finally, the impurity concentrations quoted in Table I for samples 8 and 9 show that they fall well above the $M$-$I$ transition. A true metallic behavior can then be expected, due to the merging of the impurity band with the conduction band. This is supported on the one hand by the fact that attempts to fit Eq. (6) to the corresponding low-$T$ conductivity failed completely. On the other hand, $\sigma$ appeared to be constant at the lowest $T$. Moreover, low-energy excitation to the conduction band from band tails is likely to be present, and should be effective at low $T$. This suggests the behavior

$$\sigma_3=\sigma_E\exp[-(E_E/kT)]+\sigma'_m\ , \tag{7}$$

where $E_E$ is the excitation energy to the conduction band and $k$ is the Boltzmann constant. $\sigma'_m$ is the metallic conductivity. Figure 6 shows $\sigma$ as a function of $T$ between 1.4 and 15 K for samples 8 and 9. $\sigma$ is flat at the lowest $T$ and increases exponentially with $T$. The continuous curves are the fits of Eq. (7) to the experimental data, the corresponding parameters being quoted in Table IV along with the corresponding least-squares errors. As expected, the constant term $\sigma'_m$ increases with increasing impurity concentrations (with similar compensation) as the small excitation energy $E_E$ decreases.

In conclusion, we provided low-$T$ Hall and conductivity data for a set of compensated $n$-GaAs samples with impurity concentrations corresponding to distinct regimes near the $M$-$I$ transition. For pure enough samples, corresponding to the strong localization regime, electron transport clearly follows Mott's variable-range, hopping law, with a power $s$ very close to $\frac{1}{4}$. This has been in particular confirmed in a comparatively broad (10-K) temperature range with a heavily compensated sample. It supports recent theoretical work showing that the low values observed for $T_0$ in Mott's variable-range-hopping expression can be obtained with an appropriate shape of the density of states,[23] and also that the Coulomb gap is either reduced or nonexistent in three-dimensional systems, depending on the hopping

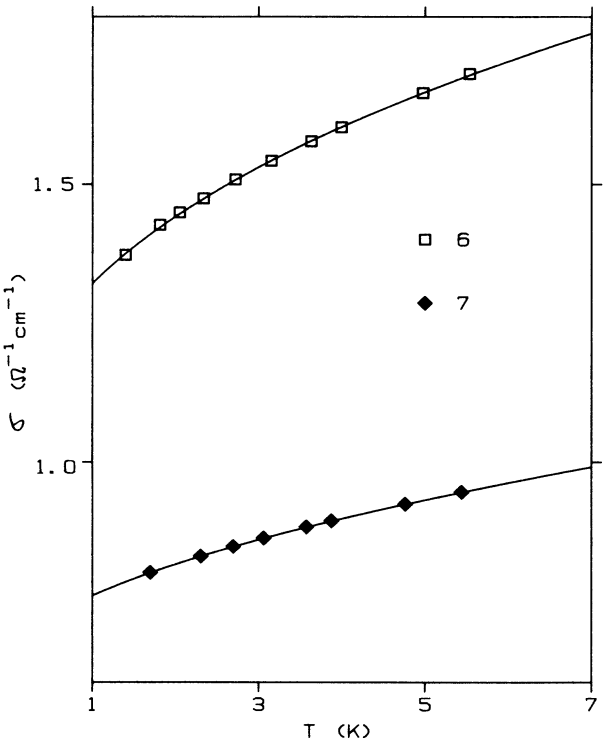


FIG. 5. $\sigma$ vs $T$ for samples 6 and 7 between 1 and 7 K. The continuous curves are the fits of $\sigma_w\equiv\sigma_1+\sigma_2T^p$ to the data, showing evidence for the weak localization regime.

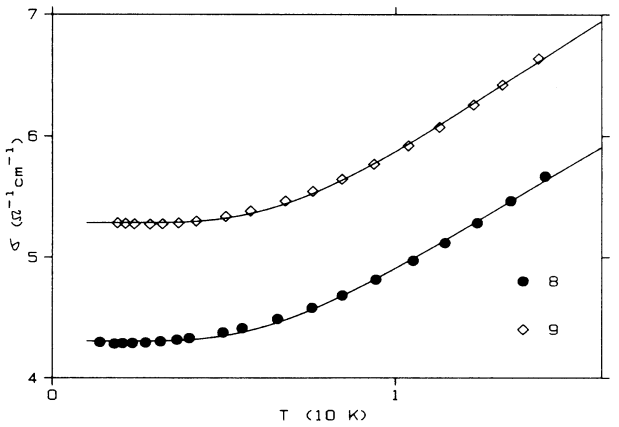


FIG. 6. $\sigma$ vs $T$ for samples 8 and 9 between 1 and 16 K. The continuous curves are the fits of $\sigma_3=\exp[-(E_E/kT)]+\sigma'_m$ to the experimental points, indicating normal metallic behavior with low energy excitation to the conduction band.

TABLE IV. Parameters of $\sigma_3=\sigma_E\exp[-(E_E/T)]+\sigma'_m$ for two samples showing a normal metallic behavior. $\delta\sigma$ is the relative error on $\sigma_3$.

| Sample | $\sigma_E$ ($\Omega^{-1}$ cm$^{-1}$) | $E_E$ (meV) | $\sigma'_m$ ($\Omega^{-1}$ cm$^{-1}$) | $\delta\sigma$ |
|---|---|---|---|---|
| 8 | 8.15 | 2.25 | 4.31 | $3.5\times10^{-3}$ |
| 9 | 9.37 | 2.40 | 5.29 | $2.0\times10^{-3}$ |

rate.[24] The Hall mobility, although not interpreted, shows in such cases a linear behavior with $T$, with $\mu_H\rightarrow0$ as $T\rightarrow0$.

For two samples falling in a small range of higher impurity concentrations, the power $s$ obtained is close to $\frac{1}{2}$. Such a value has been reported in other studies, and has been attributed to the presence of a Coulomb gap in the density of states of the corresponding material. This is hardly understandable on the view of purer samples giving $s=\frac{1}{4}$, higher electron concentrations being expected to screen Coulomb effects. According to Mott's criterion, our samples giving $s=\frac{1}{2}$ fall well below the $M$-$I$ transition. On the other hand, if one uses the Fritzsche criterion, where the electron concentration of the Mott criterion is replaced by $N_D$, these samples appear to be extremely close to the $M$-$I$ transition. Moreover, the corresponding $\mu_H$ is relatively high and decreases nonlinearly with $T$, this being a distinctive feature of these two samples. In addition, the higher-$T$ $\mu_H$ has been shown, in similar samples,[12] to be very sizeably reduced by metal-like conduction. The above considerations indicated some kind of intermediate behavior, corresponding to the admixture of Mott's variable-range hopping and some small metal-like contribution to the conductivity. The addition of such a small constant term to the Mott expression could explain the observed shift in $s$. It is still unclear, in this particular regime, whether or not $\mu_H\rightarrow0$ as $T\rightarrow0$. In the affirmative, we can speculate on two possibilities. The first is the existence in the impurity band of a transition from partially metallic to fully localized states with decreasing $T$. A shift of the Fermi level from extended to localized states could be another explanation. On the other hand, if $\mu_H$ is finite at $T=0$, extended states exist at all $T$ in the impurity band. At this point, it appears then that experiments aimed at an exact determination of the power $s$ should only be performed on pure enough samples, for which $\mu_H$ tends linearly to 0 as $T\rightarrow0$.

At slightly higher impurity concentrations, two samples showed evidence for a weak localization regime between 1.4 and 6 K. Positive interaction effects appeared dominant over quantum interference. A small decrease of $\mu_H$ with decreasing $T$, eventually stabilizing for one sample, was observed in this regime.

Finally, for two samples with similar compensation falling clearly above the $M$-$I$ transition, a constant conductivity, increasing with $N_D$, was observed at the lowest $T$, indicating a true metallic regime. Low-energy excitation to the conduction band was observed at higher $T$, the corresponding energy decreasing with increasing $N_D$. $\mu_H$ showed in both cases a definite increase with decreasing $T$, more noticeable at higher $N_D$.

We wish to thank the Quebec Ministry of Science and Technology for financial support.

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