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# Electrical conduction properties of Si δ-doped GaAs grown by MBE

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ABSTRACT

The temperature dependent Hall effect and resistivity measurements of Si δ-doped GaAs are performed in a temperature range of 25–300 K. The temperature dependence of carrier concentration shows a characteristic minimum at about 200 K, which indicates a transition from the conduction band conduction to the impurity band conduction. The temperature dependence of the conductivity results are in agreement with terms due to conduction band conduction and localized state hopping conduction in the impurity band. It is found that the transport properties of Si δ-doped GaAs are mainly governed by the dislocation scattering mechanism at high temperatures. On the other hand, the conductivity follows the Mott variable range hopping conduction (VRH) at low temperatures in the studied structures.



## 1. Introduction

Si δ-doped GaAs has been received much attention because of its potential applications such as field-effect transistor [1] and electronic memory circuit [2]. In GaAs with δ layer, the electrons form a two-dimensional (2D) electron gas in the plane of the δ layer. Some researchers has been undertaken to understand the electrical transport mechanisms in Si δ-doped GaAs [3–5]. Since the lattice constant of Si (5.43 Å) is smaller than the lattice constant of GaAs (5.65 Å), the Si δ layers have tensile strain about 4%. This leads to dislocation formations in the structure [6]. When the δ-layer becomes thicker than three monolayers, the numbers of defects increase [7]. These defects and dislocations form localized levels in the impurity band. With the decreasing temperature, these localized levels trap some of the carriers. In this case, the conduction changes from the conduction band conduction to the impurity band conduction. If carrier concentration ($n$) is below metal–insulator transition concentration ($n_c$), the conduction is mainly described by hopping conduction in the impurity band, while it is of called "metallic" conduction for $n > n_c$.

The compensation ratio is another important quantity in impurity band conduction. Both acceptor and donor levels are necessary to form the hopping conduction in the system. According to Look et al. [8], the hopping conduction in GaAs is applicable when compensation ratio ($k = N_A/N_D$ for n-type GaAs) becomes high. If a system is very heavily compensated, its relatively large average binding energy only allows excitation to the conduction band at relatively high temperatures [9]. Then, it is possible that the hopping regime can be observed in a wide temperature range. In Si δ-doped GaAs, presence of residual acceptors can create vacant positions in the impurity band and this results in a 2D variable-range hopping (VRH) conduction in the δ-plane [10]. The vacancy defect is identified as the Ga vacancy in the Si δ-doped GaAs. When the concentrations of these defects increased strongly, the free carrier concentration is reduced at the δ-plane [11].

Past studies for the transport properties of δ-doped layer indicates that the conductivity in the δ-doped layer is of "hopping" type like when $n \cong 10^9$–$10^{12}\,cm^{-2}$, it is "metallic" type like when $n \cong 10^{14}\,cm^{-2}$ [5,10,12,13]. However, several works show that it is possible to observe 2D VRH in δ-doped layer even if it is degenerate [10]. Although, the Si δ-doped GaAs samples having 4 and 6 monolayers of Si δ-doped layer ($n \cong 10^{11}$–$10^{13} cm^{-2}$) were degenerate, 2D VRH conduction was observed [10]. Khondaker et al. [13] reported that the 2D VRH conduction appears in a disordered 2D electron gas in δ-doped GaAs/AlGaAs

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heterostructure with values of $n = 0.91–1.85 \times 10^{11}\,\mathrm{cm}^{-2}$. Levin et al. [5] found that the 2D VRH conduction dominates at low temperatures in Si δ-doped GaAs with the carrier concentration and mobility, $n = 1.6 \times 10^{12}\mathrm{cm}^{-2}$ and $\mu = 2000\ \mathrm{cm}^2/\mathrm{V\,s}$, respectively.

In this work, we investigated the transport properties of high-compensated Si δ-doped GaAs with a thick δ-layer. In the case of thick δ-layer usage, the number of defects and dislocations are expected to increase due to introduced strain relaxation at the δ-doped region [6,7]. However, using a thick δ-layer is essential for this study to observe the impurity band conduction and to determine the effect of dislocation scattering on the electron transport properties. The temperature dependent carrier density and conductivity data of the investigated samples have been explained in terms of the conduction band and impurity band conductions.

## 2. Experimental

The structures were grown by a VG80-H solid source molecular beam epitaxy (MBE) system on epi-ready semi-insulating GaAs (1 0 0) substrates, and with Si deposited from a dopant source. The exposure time of Si, with the cell at 1150 °C, was 44 s. Both the Si layer and the 100 nm GaAs cap layer were grown at 550 °C. The thickness of δ-doped layer depends on the growth suspension time. This time was calculated according to $\tau = N^{2D}/Nv_g$. In this equation [14], $N^{2D}$ is the targeted two-dimensional density of dopants, $N$ is the three-dimensional dopant concentration obtained at a specific effusion cell temperature, and $v_g$ is the growth rate. Therefore, all parameters were adjusted for targeted thicknesses of the δ layer. The thickness of δ-doped layer was calculated as 80 Å.

In this work, the obtained carrier density and mobility are the same magnitude as reported earlier for this system [10,15,16]. Hai et al. [16,17] calculated the dependence of mobility on the thickness of δ-doped layer for Si δ-doped GaAs at different values of donor concentration ($N_D$). The calculated mobility is in good agreement with our experimental results. Therefore, we can consider that our system has two-dimensional properties with a δ-layer.

For resistivity and Hall effect measurements by the van der Pauw method, square shaped ($5 \times 5\,\mathrm{mm}^2$) samples were prepared with four contacts in the corners. Using annealed indium dots, ohmic contacts to the sample were prepared and their ohmic behavior was confirmed by the current–voltage characteristics. Measurements were performed at temperature steps over a temperature range 25–300 K using a Lake Shore Hall effect measurement system (HMS). At each temperature step, the Hall coefficient (with maximum 5% error in the studied range) and resistivity (with maximum 0.2% error in the studied range) were measured for both current directions, both magnetic field directions that were perpendicular to the surface and all the possible contact configurations at 0.4 T (with 0.1% uniformity).

## 3. Results and discussion

To understand the presence of different conduction mechanisms in Si δ-doped GaAs, we consider the variation of the sheet Hall carrier concentration ($n_s$) with temperature. Fig. 1 shows the measured sheet Hall carrier concentration ($n_s$) as a function of inverse temperature for the investigated samples. Temperature dependence of $n_s$ exhibits a minimum about 200 K. This behavior may arise due to presence of both the conduction band and the impurity band conductions in Si δ-doped GaAs. In the impurity

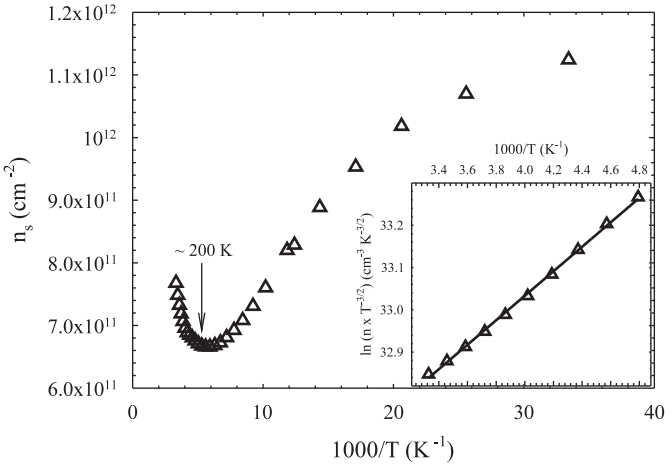


**Fig. 1.** Variation of the sheet carrier concentration with inverse temperature for Si δ-doped GaAs in a temperature range 25–300 K. Solid lines in the inset of the Fig. 1 are the best-fit lines with Eq. (3).

band of semiconductors, when the Fermi level ($E_F$) is lower than the mobility edge ($E_C$), it is well known that the conduction has an insulating feature. From Fig. 1, one can expect that the major conduction may be via the conduction band conduction at the high temperatures, and the most of the donor levels are empty in Si δ-doped GaAs. However, it is possible that the impurity band conduction starts to appear as the temperature decreases. At low temperatures, the electrons have not enough energy to jump from donor levels to conduction band. Therefore, the dominant conduction may change from conduction band conduction to the impurity band conduction, as the temperature decreases in Si δ-doped GaAs structures.

From temperature dependent Hall carrier concentration data, we can determine thermal activation energy, $E_D$, at high temperatures. To determine $E_D$, we can utilize semiconductor charge-balance equations. In a doped semiconductor, charge neutrality is provided when the total positive charge (holes and ionized donors) equals the total negative charge (electrons and ionized acceptors). Then one can get the well-known relation [18]

$$\frac{n(n+N_A)}{N_D - N_A - n} = \frac{N_C}{g_d}\exp\left(-\frac{E_D}{k_B T}\right) \tag{1}$$

where $k_B$ is the Boltzmann constant, donor degeneracy factor $g_d$ is 2 and $N_C$ is the effective density of states in the conduction band which is given by

$$N_C = 2\left(\frac{2\pi m^* k_B T}{h^2}\right)^{3/2} \tag{2}$$

In the case $n \ll N_A < N_D$, namely a small number $n$ of the electrons are excited to the conduction band, and Eq. (1) simplifies to

$$n = \left(\frac{N_D - N_A}{2N_A}\right) N_C \exp\left(-\frac{E_D}{k_B T}\right) \tag{3}$$

Since above equations, $n$ is unit of $\mathrm{cm}^{-3}$, we used $n_s/t$ ($t$ is δ layer thickness) instead of sheet carrier concentration ($n_s$). Eq. (3) perfectly fitted to experimental data. Using Eq. (3), the activation energy value is deduced from the fitted curves of $\ln(nT^{-3/2})$ versus $1000/T$ at high temperatures, and it is found as $E_D = 22$ meV for the investigated samples (see inset of Fig. 1). Using $m^* = 0.067 \cdot m_0$ in Eq. (2), the value of $N_C$ is obtained as $8.63 \times 10^{13} T^{3/2}\,\mathrm{cm}^{-3}$ for GaAs. Then the compensation ratio ($k = N_A/N_D$) is determined as $k = 0.91$ from the extrapolation of

the linear part of the same curve in inset of Fig. 1. Since the investigated samples are very highly compensated, it is possible that the impurity band conduction appears in a wide temperature range.

Temperature dependence of mobility and carrier concentration of a 150 Å δ-doped layer with the changing Si dope concentrations from $2\times10^{12}$ to $6\times10^{12}\,cm^{-2}$ were investigated by Young et al. [15]. They obtained that both mobility and carrier concentration is temperature independent, for the all Si dope concentration from $2\times10^{12}$ to $6\times10^{12}\,cm^{-2}$. In the same study, mobility and carrier concentration of the studied structure are reported as $2000\,cm^2/Vs$ and $8.5\times10^{12}\,cm^{-2}$, respectively. Our observations are also consistent with these mobility and carrier concentration values. However, these two quantities are not temperature independent in our case. This may be due to highly compensated situation and the presence of an important number of dislocations in our samples. As the temperature decreases, the temperature dependence of carrier concentration increases for $T<200$ K. An increment in the carrier concentration with decreasing temperature has been explained previously as a result of the simultaneous contribution to conduction of hopping and conduction band conductions [8,10].

Fig. 2 shows the temperature dependence of the sheet conductivity plotted as $\ln(\sigma)$ vs. $1000/T$ (Arrhenius plot) in a temperature range of 25–300 K for the investigated samples. The sheet conductivity decreases with the decrease in temperature. This represents a semiconducting behavior in the whole temperature range. Fig. 2 also represents a mixed conductivity situation, i.e. there are different contributions to conduction in Si δ-doped GaAs. It can be seen from Fig. 2, the slope changes with a deviation from linearity, as the temperature decreases, and the activation energy is temperature dependent. This indicates that the activation type of conduction can be only dominating in the higher temperatures. On the other hand, the contribution to conduction may be predominantly from the impurity band that is formed by shallow donor levels at low temperatures. However, it is difficult to distinguish two regimes from the linear fitting results. In a δ-doped system, high donor concentration leads to an impurity band just below the conduction band. The random distribution of the impurities could create localization states. The fluctuations in the thickness of the δ-doped layer may also cause the impurity band conduction that governs the conduction even at high temperatures [17].

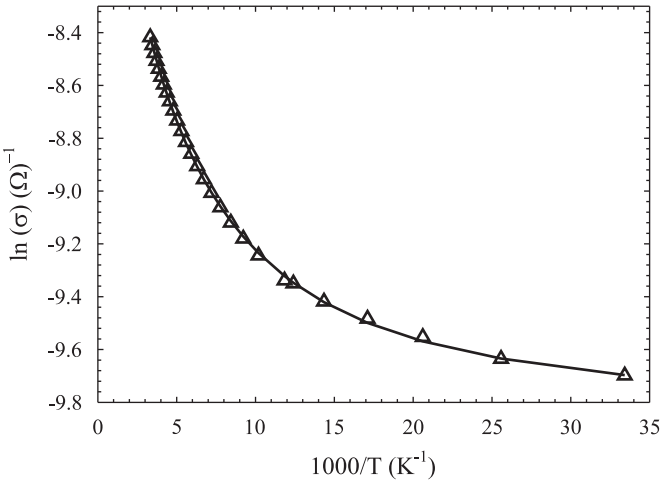


**Fig. 2.** Temperature dependence of the sheet conductivity of the investigated samples plotted as $\ln(\sigma)$ vs. $10^3/T$ in a temperature range of 25–300 K. Solid lines are the best-fit lines of Eq. (4) at whole temperature range.

Also in Fig. 1, the temperature dependence of carrier concentration exhibits a characteristic minimum associated with carrier transfer in two-band conduction. Therefore, one can expect that the total conductivity can be determined as the sum of the contribution from conduction band and impurity band. The conductivity can be then expressed as

$$\sigma(T)=\sigma_c\exp[-E_D/k_BT]+\sigma_0\exp[-(T_0/T)^s] \quad (4)$$

where the first term describes the conduction band conductivity, and the second term corresponds to the hopping-type conductivity in the impurity band. The latter term has its origin from the scatter of impurity energy levels: the transition of an electron from one impurity atom to another is possible with phonon absorption and emission processes. Here $\sigma_c$ is a parameter depending on the semiconductor nature, $T_0$ is the characteristic temperature coefficient and $\sigma_0$ is the pre-exponential factor. The value of the exponent $s$ depends critically on the nature of hopping process. We fitted Eq. (4) to the experimental conductivity data of Si δ-doped GaAs using $\sigma_c$, $E_D$, $\sigma_0$, $T_0$ and $s$ as adjustable parameters. The open triangles in Fig. 2 are the experimental data and the solid line is the best fitted values. The $r^2=0.999$ ($r=$ correlation coefficient) is obtained, which indicates a satisfactory fit. The values of parameters in Eq. (4) are obtained as $\sigma_c=(6.04\times10^{-5}\pm2.49\times10^{-6})\Omega^{-1}$, $E_D=(19\pm0.15)$ meV, $\sigma_0=(4.52\times10^{-3}\pm2.57\times10^{-4})\Omega^{-1}$, $T_0=(1.3\times10^4\pm8.3\times10^2)K$ and $s=(0.32\pm0.018)$. The deduced value of $E_D$ from the fitting is close to the value of 22 meV which is obtained from temperature dependent carrier concentration data.

The value of $s=0.32\cong1/3$ in Eq. (4) indicates that the conduction in Si δ-doped GaAs is due to 2D Mott VRH conduction at low temperatures. Then we can calculate Mott VRH parameters which are given by following equations [19]:

$$T_0=\frac{3.5\alpha^2}{k_Bg(\varepsilon_F)} \quad (5)$$

$$R_{hop}=\alpha^{-1}(T_0/T)^{1/3} \quad (6)$$

$$W_{hop}=k_BT(T_0/T)^{1/3} \quad (7)$$

where $T_0$ is the characteristic temperature coefficient, $g(\varepsilon_F)$ is the density of the localized states at the Fermi level, $\alpha^{-1}$ is the localization length, $R_{hop}$ is the hopping distance and $W_{hop}$ is the average hopping energy. Assuming $g(\varepsilon_F)$ is to be energy independent [20], we can obtain the localization length, $\alpha^{-1}$, as 33.4 Å from Eq. (5). $\alpha^{-1}$ is of the order 10 Å, which is consistent with the expected magnitude in VRH regime [21]. The value of localization length of $\alpha^{-1}=150$ Å was reported by Buyanov et al. [10]. Since their hopping temperature value of $T_0=780$ K, according to Eq. (5), $\alpha^{-1}$ becomes high. In our case, due to $T_0=1.3\times10^4$ K, $\alpha^{-1}$ decreases. Therefore, it can be regarded as realistic. Similar values of $\alpha^{-1}$ were reported for various two-dimensional systems [22,23]. In a reported GaAs/AlGaAs based 2D electron gas system, the localization length is obtained as $\alpha^{-1}=50$ Å [22]. This value is in a good agreement with the value estimation from the classical Drude conductance. On the other hand, a similar localization length value of $\alpha^{-1}=80$ Å was also reported for a 2D Si inversion layer [23].

Using the above equations, values of $R_{hop}=213$ Å and $W_{hop}=19.6$ meV are obtained at 30 K, respectively. Although the Si δ-doped GaAs are partial degeneracy, the observation of VRH in this system is quite remarkable. Similarly, Buyanov et al. [10] proposed 2D VRH transport in Si δ-doped GaAs structures with Si doping levels that are several orders of magnitude higher than the degenerate limit ($\sim10^{11}\,cm^{-2}$ for this system). This was attributed to the effects of disorders or dislocations in Si δ-doped GaAs [10].

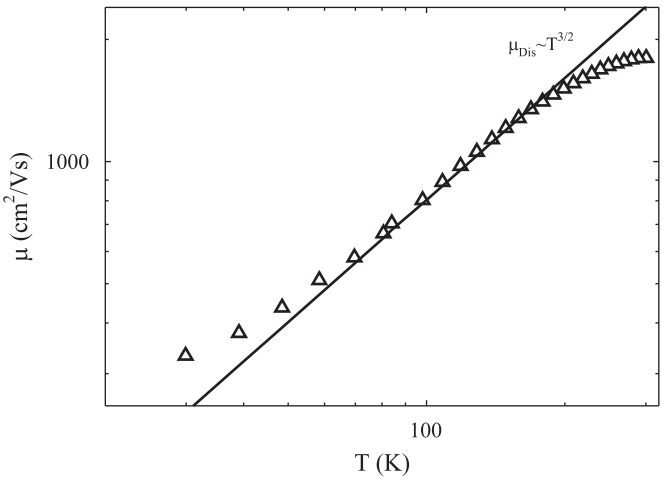


**Fig. 3.** Temperature dependent Hall mobility of the investigated samples. Solid lines are the best-fit lines of Eq. (10) with a dislocation density of $7.8 \times 10^8\,\mathrm{cm}^{-2}$.

In addition to this, the obtained hopping parameters should satisfy the 2D VRH criterions [19]:

$$W_{hop} > k_B T \tag{8}$$

and

$$R_{hop} > t \tag{9}$$

The average hopping energy ($W_{hop}$) and the hopping distance ($R_{hop}$) are considerably $> k_B T$ and the δ-layer thickness ($t$), respectively. Also, the deduced value of exponent $s$ is very close to 1/3, which confirms the presence of 2D VRH in the investigated samples. Obtained values of hopping parameters can be compared with values reported [10,24]. It has been pointed out that VRH can be dominant on electron transport at even high temperatures depending on the strength of Coulomb interaction [19]. Therefore, the magnitudes of $T_0$ and then other hopping parameters can be different depending on temperature interval. Raikh et al. [24] reported 2D VRH at very low temperatures in Si δ-doped GaAs with a compensation ratio $k = 0.05$ and they found the value of $T_0$ and $R_{hop}$ as $0.84 \times 10^3$ K and 600 Å, respectively. As mentioned earlier, when the value of $k$ increases, hopping regime can be observed at even high temperatures. The value of $T_0$, which is a measure of disorder in the material, significantly increases with increasing $k$. Since our case $k = 0.91$, the hopping regime is observed at high temperatures and a high value of $T_0$ is obtained. Similar observations were reported for GaAs [9,25].

Fig. 3 shows the temperature dependence of the Hall mobility of the investigated samples in a temperature range of 25–300 K. Generally for high mobility GaAs structures, temperature dependent mobility at high temperatures is limited by the optical phonon scattering. However, the observed temperature dependent mobility of Si δ-doped GaAs decreases with decreasing temperature in the overall studied temperature range with the temperature dependence $T^r$. This behavior indicates that the dominant scattering mechanisms are the defect related mechanisms such as ionized impurity scattering and dislocation scattering even at high temperatures. The Hall mobility decreases with decreasing temperature and obeys a temperature dependence of $T^{3/2}$, which is the typical temperature dependence for ionized impurity scattering mobility [26]. However, when we tried to fit to our data using this mechanism, we did not obtain any acceptable fit for Si δ-doped GaAs. It may be due to partial degeneracy of the investigated samples. After utilizing Brooks–Herring analysis [26], unrealistic $N_D$ and $N_A$ values are obtained. As mentioned above, because of the lattice mismatch and thicker δ-layer in studied structures, both dislocations and defects can be effective on electron transport. In this case, a candidate scattering mechanism may give a major contribution to scattering. This scattering mechanism may be the dislocation scattering since this mechanism also limits the mobility with a temperature dependence of $T^{3/2}$ as in ionized impurity scattering. The 2D VRH observation in Si δ-doped GaAs may confirm the presence of disorders in structure. Therefore, we are motivated to fit dislocation scattering to the mobility data of Si δ-doped GaAs at low temperatures. The degradation of mobility is expected due to the presence of dislocations. This mechanism is particularly significant for carriers with low effective mass [27]. We can assume that, in the temperature range where scattering by dislocations dominates the conduction, the mobility can be described by [28]

$$\mu_{Dis} = \frac{30\sqrt{2\pi}\varepsilon_s^2\varepsilon_0^2 d^2 (k_B T)^{3/2}}{e^3 N_{Dis} f^2 \lambda_D m^{*1/2}} \tag{10}$$

where $d$ (~5.65 Å) is the distance between adjacent broken bonds, taken to be of the order of the lattice parameter, and $f$ is the fraction of the acceptor centers occupied, taken to be unity. $N_{Dis}$ is the density of dislocation lines per unit area, $\lambda_D$ is the Debye screening length, $\lambda_D = \sqrt{\varepsilon_s \varepsilon_0 k_B T / e^2 n}$ [29] and $\varepsilon_0$ ($= 8.854 \times 10^{14}$ F/cm) is the permittivity of vacuum. Here, $N_{Dis}$ is used as a fitting parameter. Actually, a good fit is observed with a dislocation density $N_{Dis} \sim 7.8 \times 10^8\,\mathrm{cm}^{-2}$ for the studied samples. As mentioned early, the lattice constant of Si is smaller than that of GaAs, which leads to a high density of dislocations. The density of dislocations in the Si δ-doped systems is within the range from $10^8$ to $10^{10}\,\mathrm{cm}^{-2}$ [30–34]. The dislocation density of $7.8 \times 10^8\,\mathrm{cm}^{-2}$ obtained for our sample is within this range. It is assumed that these dislocations may act as acceptor-like centers. A space charge region is formed along the dislocation line, resulting in a reduction of carrier mobility. The fit exhibits a deviation from experimental data about 80 and 200 K. These observations indicate that phonon scattering affects the mobility at $T > 200$ K. At temperatures below 80 K, the hopping-type impurity band conduction, which is discussed previously, starts to control the conduction.

## 4. Conclusion

The Hall effect and electrical resistivity measurements of Si δ-doped GaAs are carried out in a temperature range of 25–300 K. The thermal activation energy and compensation ratio values are found as 22 meV and 0.91, respectively. It is found that the temperature dependent conductivity can be well described as the sum of the contribution from conduction band and impurity band. Hall mobility data show that the dislocation scattering has a strong effect on electron transport in the investigated samples with a dislocation concentration of $7.8 \times 10^8\,\mathrm{cm}^{-2}$ even at high temperatures. Phonon scattering has a little influence at high temperatures. At low temperatures, the conduction properties can be well explained in the terms of Mott VRH model. Both dislocation concentration and various hopping parameters of the present samples are found to be appropriate for 2D VRH regime.

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