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# Electron Transport in Ga-Rich $In_xGa_{1-x}N$ Alloys *

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*Resistivity and Hall effect measurements on n-type undoped Ga-rich $In_xGa_{1-x}N$ ($0.06 \leq x \leq 0.135$) alloys grown by metal-organic vapour phase epitaxy (MOVPE) technique are carried out as a function of temperature (15–350 K). Within the experimental error, the electron concentration in $In_xGa_{1-x}N$ alloys is independent of temperature while the resistivity decreases as the temperature increases. Therefore, $In_xGa_{1-x}N$ ($0.06 \leq x \leq 0.135$) alloys are considered in the metallic phase near the Mott transition. It has been shown that the temperature-dependent metallic conductivity can be well explained by the Mott model that takes into account electron–electron interactions and weak localization effects.*

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Recently, Ⅲ-nitride wide band gap alloy semiconductors have received significant attention due to their potential applications in many fields. For example, $In_xGa_{1-x}N$ and $Al_xGa_{1-x}N$ alloys enter into different fields of applications such as optoelectronic, high power and high temperature microwave and electronic devices.[1–4] In contrast to the importance of $In_xGa_{1-x}N$ alloys, only a few studies exist which deal electronic transport properties of $In_xGa_{1-x}N$ alloys.[5–9] The most of these studies are related with In-rich $In_xGa_{1-x}N$ alloys. In this study, an electronic transport characterization of Ga-rich $In_xGa_{1-x}N$ alloys has been carried out.

The growth temperature of $In_xGa_{1-x}N$ is generally lower than that of GaN.[5] The decomposition rate of ammonia ($NH_3$) becomes low at low-growth temperatures. Thus the background carrier concentration of undoped $In_xGa_{1-x}N$ is high due to the increase of nitrogen vacancies.[5] On the other hand, in Ga-rich $In_xGa_{1-x}N$ alloys having a high energy-gap ($> 3$ eV) in which compensation is nearly full. In this case, the impurity conduction may become significant even at high temperatures. Although there have been many reports on the optical properties in InGaN-based materials, there have been few reports on their electrical properties due to the above reasons.[5–9]

In this study, the temperature-dependent resistivity and Hall effect measurements in undoped Ga-rich $In_xGa_{1-x}N$ alloys ($0.06 \leq x \leq 0.135$) grown by MOVPE are reported. The temperature-dependent conductivity are analysed in the terms of the Mott model.

$In_xGa_{1-x}N$ epilayers studied in this work were grown in an atmospheric pressure vertical MOVPE reactor with a 'shower head' configuration.[10] For determination of the In mole fraction in $In_xGa_{1-x}N$ layers, a Bruker AXS D8-Discover x-ray diffractometer was used. For resistivity, and Hall effect measurements by the van der Pauw method, square shaped ($5 \times 5$ mm$^2$) samples were prepared with four contacts in the corners. Measurements were made at temperature steps over temperature range 15–350 K using a Lake Shore Hall effect measurement system (HMS).

Figures 1(a), 1(b) and 1(c) show the temperature dependence of resistivity, Hall carrier concentration and Hall mobility, respectively, for undoped Ga-rich $In_xGa_{1-x}N$ alloys in the temperature range 15–350 K. Their room-temperature values, Fermi levels and the critical concentrations, which are estimated from Mott criterion, are also given in Table 1. All $In_xGa_{1-x}N$ layers show n-type behaviour with a carrier concentration higher than the critical carrier concentration $n_c$, which is due to a large number of nitrogen vacancies. It can be seen from Fig. 1(a) that the resistivity decreases as the temperature increases. On the other hand, the resistivity and its temperature dependence increase with the increasing In composition $x$. At the minimum In composition ($x = 0.06$), the resistivity is nearly independent of temperature. In addition, as shown in Fig. 1(b), Hall carrier concentration slightly decreases with increasing In composition $x$. However, it is clear that Hall carrier concentration is nearly temperature independent, reminiscent of those for a metal, within the experimental error. Mobilities of the studied $In_xGa_{1-x}N$ samples are also nearly temperature independent as can be seen from Fig. 1(c). Mobilities are lower than that in GaN, which is usually more than 400 cm$^2$/Vs at room temperature.

It is known that the free-carrier concentration in a metal is temperature independent while the free-

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carrier concentration in a semiconductor is thermally activated over a wide range of temperature and thus may increase exponentially with temperature. However, on the other hand, the measured resistivity increases with decreasing temperature in contrast to metals. For the samples which have carrier concentrations well above the critical concentration $n_c$, the resistivity decreases with decreasing temperature, which typical for a good metal. For concentrations near the metal-insulator transition, however the resistivity increases instead as the temperature is lowered.[11] On the other hand, for each sample, the Fermi level determined from the measured carrier concentration lies slightly above the bottom of conduction band in the whole studied temperature range. Therefore, Ga-rich $In_xGa_{1-x}N$ alloys must be considered in the metallic site of Mott transition although the measured resistivity increases with decreasing temperature. When $n > n_c$ or near the transition, the temperature variation of the conductivity is given by Mott,[12]

$$\sigma(T) = \sigma(0) + mT^{1/2} + BT, \qquad (1)$$

where the first term on the right-hand side is the zero temperature conductivity, the second term results from electron-electron interactions, and the third term is the correction to $\sigma(0)$ resulting from localization effects. This model predicts that electron-electron interactions play an important role in the low-temperature transport, whereas weak localization effects are dominant at higher temperatures.

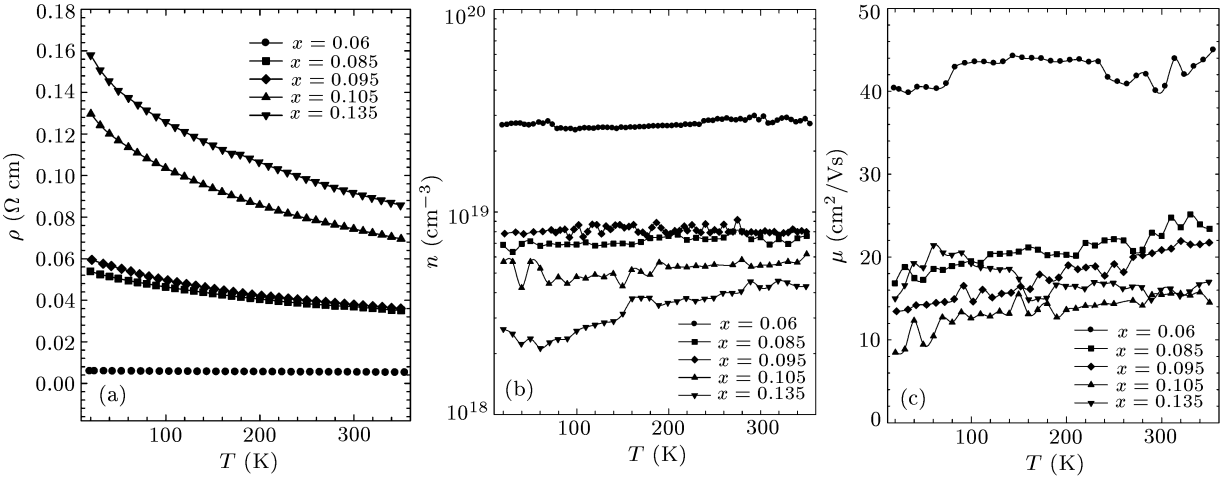


**Fig. 1.** Measured resistivity (a), Hall carrier concentration (b) and Hall mobility (c) for the studied $In_xGa_{1-x}N$ samples.

Table 1. Properties of $In_xGa_{1-x}N$ alloys; room-temperature values of conductivity, Hall carrier concentration and mobility, the critic carrier concentration $n_c$ and Fermi level (with respect to conduction band) at 25 K.

| $x$ | $\sigma$ $(\Omega\text{cm})^{-1}$ | $n_H$ $(\text{cm}^{-3})$ | $\mu_H$ $(\text{cm}^2/\text{Vs})$ | $n_c$ $(\text{cm}^{-3})$ | $E_F$(eV) |
|---|---|---|---|---|---|
| 0.060 | 191.9 | $2.85 \times 10^{19}$ | 40.6 | $8.38 \times 10^{17}$ | 0.153 |
| 0.085 | 27.1 | $7.51 \times 10^{18}$ | 22.5 | $7.79 \times 10^{17}$ | 0.067 |
| 0.095 | 26.3 | $7.91 \times 10^{18}$ | 20.8 | $7.58 \times 10^{17}$ | 0.069 |
| 0.105 | 13.4 | $5.44 \times 10^{18}$ | 15.5 | $7.37 \times 10^{17}$ | 0.048 |
| 0.135 | 10.9 | $4.25 \times 10^{18}$ | 16.0 | $6.76 \times 10^{17}$ | 0.030 |

A determination of the critical behaviour of the zero temperature conductivity $\sigma(0)$ requires a reliable extrapolation of the conductivity to its zero temperature limit. Therefore, Eq. (1) is fitted to the measured conductivity with the localization term and without localization term. For both the cases the fitting results are given in Fig. 2 and Table 2. Omitting the localization term in Eq. (1), the acceptable fits can be obtained in the studied temperature range as can be seen from Fig. 2. Although the fits of Eq. (1) (with localization term) are more satisfying than that of omitting the localization term, the obtained zero temperature conductivity ($\sigma(0)$) values are close to each other for both cases. This leads to the localization term having a small contribution to the zero temperature conductivity and the temperature-dependent conductivity. The obtained values of coefficients $m$ from the fits of Eq. (1) are of the same order of magnitude as found in a variety of systems,[11,13,14] while the coefficient $B$ is close to zero and it is approximately $10^2$ times smaller than the reported ones for metallic systems.[11,13,14] However, the coefficients $m$ and $B$ can be determined theoretically.

Firstly, deal with $m$, which is given by[13]

$$m = \alpha\left[\frac{4}{3} - \left(\frac{3}{2}\right)\gamma F\sigma\right], \qquad (2)$$

where

$$\alpha = \frac{e^2}{\hbar}\Big(\frac{1.3}{4\pi^2}\Big)\Big(\frac{k_B}{2\hbar D}\Big)^{1/2}. \quad (3)$$

In these expressions, $D$ is the diffusion coefficient. To determine $D$, the relation $\sigma(0) = 2S_0\eta e^2 DN(0)$ is used, where $N$ is the density of states ($N(0) = m^* k_F/2\pi^2\hbar^2$). For $In_xGa_{1-x}N$, $S_0\eta = 1$ since anisotropy of effective mass can be neglected. Here $\gamma F\sigma$ is the Coulomb interaction parameter, $\gamma$ is a constant and it can be calculated from the band structure. For $In_xGa_{1-x}N$ the value of $\gamma$ is taken as 1.95.[15] The quantity $F\sigma$ is related to the Fermi-liquid parameter $F$ by[11]

$$F\sigma = \Big(-\frac{32}{3}\Big)\Big[1 - \frac{3F}{4} - \Big(1 - \frac{F}{2}\Big)^{3/2}\Big]F^{-1}. \quad (4)$$

The Fermi-liquid parameter $F$ can be calculated from the Thomas–Fermi approximation. $F$ values generally range between 0 and 1.[11,16] The calculated $F$ values change between 0.29 and 0.40 for Ga-rich $In_xGa_{1-x}N$. They are far closer to 0 than 1. The screening length becomes large near the transition, and it is expected that $F$ will therefore decrease toward zero as the transition is approached.[11]

The $m$ parameters determined from the fits of Eq. (1) are positive. This implies that $\gamma F\sigma < 8/9$. The calculated interaction parameters ($\gamma F\sigma$) and the values of coefficient $m$ are given in Table 2. The calculated $\gamma F\sigma$ values range from 0.598 to 0.875, which are smaller than 8/9. A reliable agreement is obtained between the experimental and the theoretical $m$ values as it can be seen from Table 2. Again, it should be noted that the obtained experimental and theoretical values of coefficients $m$ are of the same order of magnitude as found in a variety of systems.[11,13,14]

Secondly, considering the weak localization term in Eq. (1), $B$ is given by[13]

$$B = \frac{e^2}{\hbar\pi^2}\Big[\frac{S_0\eta}{2}\Big(\frac{c}{D}\Big)^{1/2}\Big], \quad (5)$$

where $c$ is a constant and it is related to the energy relaxation time $\tau$ via $1/\tau = cT^2$. Following Thomas *et al.*,[14] the coefficient $B$ of the linear term in Eq. (1) can be calculated theoretically. These values are given in Table 2, along with the values deduced from the fits to the experimental data. An agreement between theory and experiment is obtained since both the theoretical and experimental values of $B$ are of the same order of magnitude. The obtained values of $B$ are in fact $10^2$ times smaller than that found in good metallic systems.[11,13,14] On the other hand, Thomas *et al.* showed that $B$ suddenly drops to zero at the critic concentration as the carrier concentration is decreased.[14] This suggests that the weak localization effect is very small in Ga-rich $In_xGa_{1-x}N$ alloys with a carrier concentration of about $5 \times 10^{18}\,cm^{-3}$.

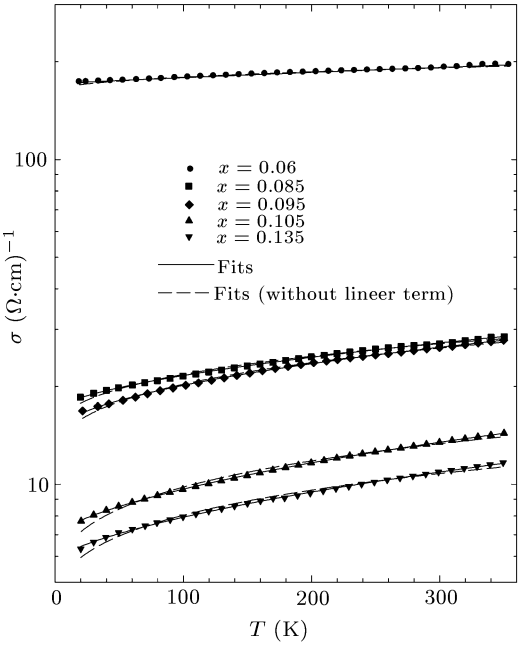


**Fig. 2.** Conductivity versus temperature. Symbols represent the measured conductivity and lines are fits to Eq. (1).

Table 2. Values of zero-temperature conductivity $\sigma(0)$, coefficients $m$ and $B$ obtained from fitting of Eq. (1) to the data with $B = 0$ and $B \neq 0$.

| | $B \neq 0$ | | | | | | $B = 0$ | |
|---|---|---|---|---|---|---|---|---|
| | $\sigma(0)$ | $m$ ($\Omega$ cm)$^{-1}$/K$^{1/2}$ | | $\gamma F\sigma$ | $B$ ($10^2\Omega$ cm K)$^{-1}$ | | $\sigma(0)$ | $m$ |
| $x$ | ($\Omega$ cm)$^{-1}$ | Expt. | Theor. | | Expt. | Theor. | ($\Omega$ cm)$^{-1}$ | ($\Omega$ cm)$^{-1}$/K$^{1/2}$ |
| 0.06 | 170.7 | 0.194 | 0.482 | 0.574 | 6.009 | 1.16 | 163.1 | 1.638 |
| 0.085 | 16.65 | 0.341 | 0.851 | 0.671 | 1.566 | 3.42 | 14.2 | 0.721 |
| 0.095 | 14.21 | 0.449 | 0.560 | 0.758 | 1.479 | 3.64 | 12.2 | 0.810 |
| 0.105 | 6.793 | 0.153 | 0.582 | 0.787 | 1.346 | 5.07 | 5.0 | 0.479 |
| 0.135 | 5.739 | 0.108 | 0.795 | 0.875 | 1.100 | 5.19 | 4.3 | 0.374 |

It is also noted that when the fitting is restricted in low temperatures ($T < 60\,K$), any considerable changes of values of coefficients $m$ and $B$ are not obtained than those in the whole studied temperature range. Therefore, it can be suggested that this model (Eq. (1)) is applicable to high-temperature data, and the temperature-dependent conductivity of $In_xGa_{1-x}N$ alloys can be explained well with this model.

In conclusions, the Hall effect and resistivity measurements on undoped Ga-rich $In_xGa_{1-x}N$ alloys ($0.06 \leq x \leq 0.135$) grown by MOVPE have been car-

ried out in the temperature range 15–350 K. The results show that the carrier concentrations are, in the experimental error, temperature independent, similar to those in metal while the resistivity increases with decreasing temperature as in semiconductors. Therefore, the studied undoped Ga-rich $In_xGa_{1-x}N$ alloys can be considered in the metallic phase near the Mott transition in which the Fermi level is slightly higher than the conduction band bottom over the whole measurement range.

In the studied temperature range, the temperature dependence of metallic conductivity near the Mott transition has been satisfactorily explained by the Mott model, which takes into account electron-electron interactions and weak localization effects, with parameters that are reasonable agreement with theoretical predictions. It has also been found that the weak localization has a negligible effect on the temperature-dependent conductivity in Ga-rich $In_xGa_{1-x}N$ alloys with a carrier concentration of about $5 \times 10^{18}\,cm^{-3}$.

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