HTML ABSTRACT + LINKS

Electron transport in In-rich $In_xGa_{1-x}N$ films

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We have performed electrical transport measurements on metal-organic vapor phase epitaxy grown In-rich $In_xGa_{1-x}N$ ($x=1$, 0.98, and 0.92) films. Within the experimental error, the electron density in InGaN films is temperature independent over a wide temperature range ($4\ K \leqslant T \leqslant 285\ K$). Therefore, $In_xGa_{1-x}N$ ($0.92 \leqslant x \leqslant 1$) films can be regarded as degenerate semiconductor systems. The experimental results demonstrate that electron transport in In-rich $In_xGa_{1-x}N$ ($x=1$, 0.98, and 0.92) films is metalliclike. This is supported by the temperature dependence of the density, resistivity, and mobility which is similar to that of a metal. We suggest that over the whole measuring temperature range residue imperfection scattering limits the electron mobility in In-rich $In_xGa_{1-x}N$ ($x=1$, 0.98, and 0.92) films. © *2005 American Institute of Physics*.
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The InGaN system has been attracting a great deal of attention in recent years. There has been much interest in the Ga-rich InGaN alloys which can act as the active layer in blue and green lasers. In such an InGaN system the fundamental band-gap energy can be varied over a very wide range. For instance, it has been shown that[1–3] the band gap can be increased from the $In_{0.4}Ga_{0.6}N$ value (≈ 2.3 eV) to the GaN value (~ 3.4 eV). It was also found that the measured band gap of the InGaN alloys shows a strong dependence on the alloy composition. Previously, the fundamental band gap of InN was determined to be ≈ 1.9 eV.[4] Recent progress in epitaxial growth techniques has made it possible to prepare higher-quality InN samples,[4–6] leading to the revision of the fundamental band-gap energy from 1.8–2.1 to 0.7–0.8 eV.[7] This important result has stimulated worldwide interest in both InN and InGaN systems. It has been shown that there is a much smaller bowing parameter of ≈ 1.4 eV in InGaN alloys,[8] in sharp contrast with that (≈ 2.5 eV) determined from previous studies.[1]

The temperature dependence of the electrical conductivity of a material is determined by the temperature T dependence of the free-carrier mobility and the temperature dependence of the free-carrier density. It is known that metals and semiconductors have very different temperature dependence of electrical conductivity. The free-carrier density in a metal is temperature independent and therefore the temperature dependence of the conductivity for a metal arises solely from the temperature dependence of the mobility. The free-carrier density in a semiconductor could be thermally activated over a wide range of temperature and thus may increase exponentially with temperature. The temperature dependence of the mobility depends on the specific scattering process. For example, in a semiconductor, acoustic-phonon scattering could cause the mobility to show a $T^{-3/2}$ dependence.[9]

In order to fully realize the potential of the InGaN as a wide range of optoelectronic devices, a fundamental understanding of its basic properties is required. Despite intensive research interest in this material, there has not been a study on the transport properties of In-rich $In_xGa_{1-x}N$ films. Such a study would determine what limits the electron transport in an InGaN system and yield important information on the electron transport in it. In this letter, we report electrical transport measurements in In-rich $In_xGa_{1-x}N$ ($x=1$, 0.98, and 0.92) films over a wide range of temperature T. We show that, within the experimental error, the carrier density in $In_xGa_{1-x}N$ ($x=1$, 0.98, and 0.92) is temperature independent over a wide temperature range ($4\ K \leqslant T \leqslant 285\ K$). Therefore, the electron transport in In-rich $In_xGa_{1-x}N$ ($0.92 \leqslant x \leqslant 1$) films is metalliclike. The temperature dependence of the measured resistivity shows that the residue imperfection scattering is the dominant scattering mechanism over the whole temperature range. The experimental results suggest that in order to obtain better quality $In_xGa_{1-x}N$ thin films, the residue imperfection must be greatly reduced.

The In-rich $In_xGa_{1-x}N$ ($0.92 \leqslant x \leqslant 1$) samples used in this study were grown with unintentional n-type doping by an Aixtron 200/4RF-S metal-organic vapor phase epitaxy

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(MOVPE) system. It is known that the large lattice mismatch between InN and α-Al_2O_3 (0001) substrate (25%) can result in an extremely high density of structure defects which lowers the electron mobility in an $In_xGa_{1-x}N$ system. A 30-nm-thick GaN nucleation layer was deposited at 500 °C followed by the growth of an approximately 1.5-μm-thick GaN at 1070 °C. Trimethylindium (TMIn) and ammonia (NH3) were used as groups, III and V source materials. The growth temperature for InN is in the range of 500–600 °C and the V/III ratio was 18 000. Triethylgallium (TEGa) was used as Ga source. The Ga content in solid phase $In_xGa_{1-x}N$ was modulated by controlling the TEGa/(TEGa+TMIn) ratio in vapor phase. The Ga atomic fraction was determined by x-ray diffraction (XRD). The XRD analysis shows that high-quality wurtzite-structured $In_xGa_{1-x}N$ epitaxial layers formed with their c spacing of 0.568 nm, which is perpendicular to the substrate surface. The rocking curve of InN (0002) is 650 arc sec. The $\theta-2\theta$ XRD measurements of the full width at half maximum (FWHM) around $In_xGa_{1-x}N$ (0002) symmetric planes are 483, 361, and 598 arc sec for $x=1$, 0.98, and 0.92, respectively, and demonstrated a high-quality single-crystalline structure. The details of the growth process are described elsewhere.[10]

All the electrical transport measurements were performed on cleaved squares (2–3 mm) on a side. Al or Au electrodes on the samples were connected to the outer electrodes by conductive silver paste. It has been shown that metal contacts such as Ti, Al, and Ni can always form an ohmic contact on $In_xGa_{1-x}N$ without any annealing.[11] Four-terminal transport measurements were performed in a continuous-flow He4 system. The low-field electron densities were determined by Hall measurements whereas the resistance and the resistivity of our samples were determined by van der Pauw measurements. Data were taken in rapid succession (≈ 1 s) while the samples were slowly drifted in temperature over the course of several hours. Measurements performed on three different x compositions are presented in this paper. Sample A ($x=1$) has a carrier density of 2.45×10^{25} m^{-3} with a mobility of 1050 cm^2/V s, sample B ($x=0.98$) has a carrier density of 1.95×10^{25} m^{-3} with a mobility of 1000 cm^2/V s, and sample C ($x=0.92$) has a carrier density of 1.55×10^{25} m^{-3} with a mobility of 670 cm^2/V s at room temperature, respectively.

Figure 1 shows the measured carrier density n as a function of temperature for three different samples A, B, and C. The carrier concentrations decrease with decreasing In composition x. We can see that within the experimental errors, the carrier concentrations are approximately temperature independent, reminiscent of those for a metal. This is in line with the data obtained by Mahboob *et al.*[12] in which the Fermi level is well above the conduction-band bottom. Therefore, $In_xGa_{1-x}N$ $(0.92\leqslant x\leqslant 1)$ films could be considered as "metallic" semiconductor systems[13,14] over the whole measuring temperature range.

Having demonstrated that n is temperature independent, the $In_xGa_{1-x}N$ thin films can be regarded as degenerate electron systems.[15] Figure 2 shows the measured resistivity as a function of temperature for the three different samples A, B, and C. We can see that at low temperatures, the measured resistivity tends to saturate. The reason for this is that at low enough temperatures, electron-phonon scattering is negligible.[9] In this regime, residue impurity and dislocation scattering are temperature independent for a truly degenerate electron system, causing the resistivity to saturate. With increasing temperature, electron-acoustic-phonon scattering increases, decreasing the electron mobility in our system. We can see that the ratio $\rho_{RT}/\rho_{4\ K}$ is ≈ 1.1. This is in sharp contrast with, for example, that $(>10^3)$ for an ultrahigh-quality degenerate two-dimensional electron gas at the interface of the modulation-doped GaAs/AlGaAs heterostructure.[16] Our results suggest that over the whole temperature range the dominant scattering mechanism is the residue imperfection scattering since $\rho_{4\ K}$ is only $\approx 10\%$ smaller than ρ_{RT} for $In_xGa_{1-x}N$ $(0.92\leqslant x\leqslant 1)$ thin films.

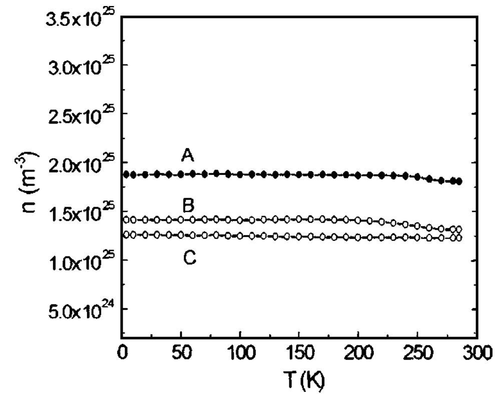

FIG. 1. The measured carrier densities n as a function of temperature T for three different samples A, B, and C.

In order to provide further understanding of the transport properties of $In_xGa_{1-x}N$ $(0.92\leqslant x\leqslant 1)$ films, we have measured their mobility. We calculated the mobility using the averaged carrier concentration through the relation $\mu = 1/n\rho e$. This is the quantity which is generally referred to in charge transport in semiconductors. Figure 3 shows the measured mobility as a function of temperature for the three different samples A, B, and C. At low temperatures, the measured mobility tended to saturate. We can also see that in all the samples the mobility decreases with increasing temperature at $(T>100$ K). The measured $\mu(T)$ shows similar be-

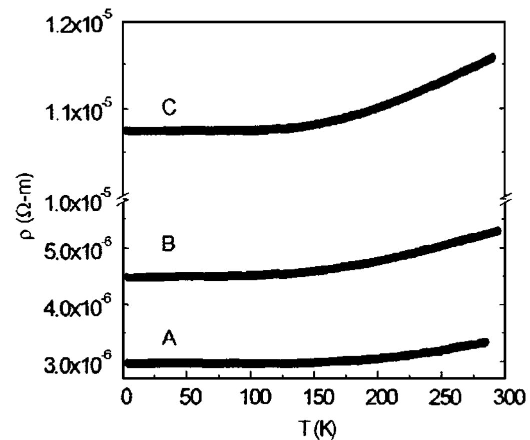

FIG. 2. The measured electrical resistivies ρ_{xx} as a function of temperature T for three different samples A, B, and C.

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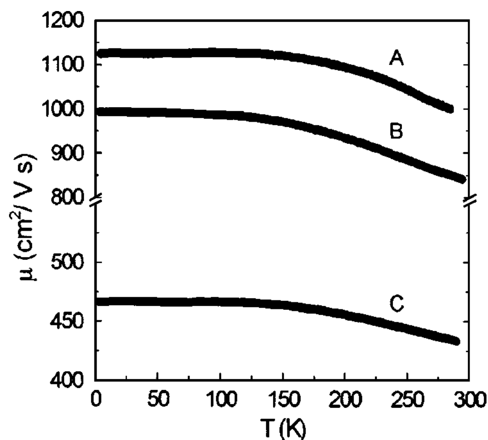

FIG. 3. The measured mobilities μ as a function of temperature T for three different samples A, B, and C.

havior as that of $1/\rho(T)$. This is expected as n is temperature independent over the whole temperature range, μ and $1/\rho$ should show the same temperature dependence in our system. We can see that the mobility of $In_xGa_{1-x}N$ ($x=1$, 0.98, and 0.92) films decreases with decreasing In composition x. It is known that InN possesses superior transport properties to those of GaN over a wide temperature range.[17] Therefore, the mobility of $In_xGa_{1-x}N$ is expected to decrease with decreasing In composition x.

In conclusion, we have performed transport measurements on $In_xGa_{1-x}N$ $(0.92 \leqslant x \leqslant 1)$ thin films over a wide temperature range. Our results show that the carrier densities are, within the experimental error, temperature independent, similar to those in a metal. Therefore, our $In_xGa_{1-x}N$ thin films can be considered as degenerate electron systems in which the Fermi level is much higher than the conduction-band bottom over the whole measurement range. Our results suggest that the dominant scattering mechanism is the residue imperfection scattering over the whole temperature range $(4\ \text{K} \leqslant T \leqslant 285\ \text{K})$ since μ_{RT} is only $\approx 10\%$ smaller than $\mu_{4\ \text{K}}$. We suggest that in order to obtain high-mobility In-rich $In_xGa_{1-x}N$ systems, one needs to substantially reduce the number of background impurities and defects during the growth. Moreover, our experimental data clearly demonstrate that $In_xGa_{1-x}N$ $(0.92 \leqslant x \leqslant 1)$ films, though made from semiconductor materials, exhibit metalliclike behavior as supported by the temperature dependence of the carrier density, resistivity, and electron mobility which is similar to that of a metal.

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