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Temperature dependent electrical transport behavior of InN/GaN heterostructure based Schottky diodes

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InN/GaN heterostructure based Schottky diodes were fabricated by plasma-assisted molecular beam epitaxy. The temperature dependent electrical transport properties were carried out for InN/GaN heterostructure. The barrier height and the ideality factor of the Schottky diodes were found to be temperature dependent. The temperature dependence of the barrier height indicates that the Schottky barrier height is inhomogeneous in nature at the heterostructure interface. The higher value of the ideality factor and its temperature dependence suggest that the current transport is primarily dominated by thermionic field emission (TFE) other than thermionic emission (TE). The room temperature barrier height obtained by using TE and TFE models were 1.08 and 1.43 eV, respectively. © *2011 American Institute of Physics*. [doi:10.1063/1.3549685]

I. INTRODUCTION

In the last few years, InN and GaN have attracted considerable attention because of their applications such as high efficient solar-cells, light emitting diodes, field effect transistors, high speed, and high frequency electronics devices, etc.[1–5] However, it is very difficult to grow high quality epitaxial films of InN due to low dissociation temperature of InN and extremely high equilibrium vapor pressure of nitrogen over the indium.[6] In addition, the lack of availability of suitable substrates compatible with InN in terms of thermal expansion coefficient and lattice parameters[7] poses additional complexity. The above constraints lead to the formation of dislocations and strain in the grown epitaxial layers resulting in the degradation of the device performance.

The interfaces of the semiconductor heterostructures are important part of semiconductor electronic and optoelectronic devices. One of the most interesting properties of a semiconductor heterostructure interface is its Schottky barrier height (SBH), which is a measure of the mismatch of the energy levels for the majority carriers across the interface. The SBH controls the electronic transport across the interface. Apart from semiconductor heterostructure interfaces, the metal-semiconductor interfaces are also very important in the operation of semiconductor devices. GaN based Schottky diodes with different metal contacts have been studied by several groups.[8–12] However, there are few reports on InN/GaN based Schottky diodes.[13–15] Chen *et al.*[14] studied the current-voltage characteristics of InN/GaN Schottky diodes in the temperature range 300–400 K, and reported nearly temperature independent barrier height (1.25 eV) and ideality factor (1.25). Wang *et al.*[13] investigated the capacitance-voltage measurements on the InN/GaN heterostructure and they have reported the Schottky barrier height as 0.94 eV. In this work, we fabricated InN/GaN Schottky junctions and extensively studied the temperature dependent electrical transport properties. We have found out in the present work, that the barrier height as well as the ideality factor are temperature dependent. The room temperature barrier height and the ideality factor obtained in the present work, by using thermionic emission (thermionic field emission) [TE (TFE)] models, were 1.08 (1.43) eV and 1.30 (1.21), respectively.

II. EXPERIMENTAL PROCEDURE

InN thin films of thickness around 300 nm were grown on 4 μm-GaN/Al_2O_3 (0001) templates by Omicron PAMBE system. An n-GaN template was used to ensure the compatibility with InN in terms of lattice constant in order to minimize the dislocation density and strain in the overgrown InN epilayer. During growth, the nitrogen pressure was at 2.8×10^{-5} mbar with a flow rate of 0.5 sccm and the forward RF-power of the plasma source was fixed at 350 W. Oxford scientific nitrogen plasma source was used which gives the atomic nitrogen and the beam equivalent pressure (BEP) of the atomic nitrogen was found to be 2.25×10^{-6} mbar. The ultra high pure indium was evaporated from the standard effusion cell and the BEP of indium was kept 1.53×10^{-7} mbar. The film was grown by using a two step process; (a) growth of low temperature (400 °C) InN buffer layer followed by, (b) the growth of InN epilayer at high temperature (500 °C). The low temperature InN buffer layer was used to ensure a continuous InN nucleation layer.[16,17] After the growth of low temperature InN buffer layer at 400 °C, the growth was stopped. The substrate temperature was increased to 500 °C under the nitrogen plasma atmosphere and then growth of high temperature InN epilayer at 500 °C was resumed. Reactive ion etching (RIE, Anelva) was carried out on InN film until the GaN layer was exposed for ohmic contact. Then the circular ohmic contacts of diameter 600 μm were made on InN as well as on GaN layers by

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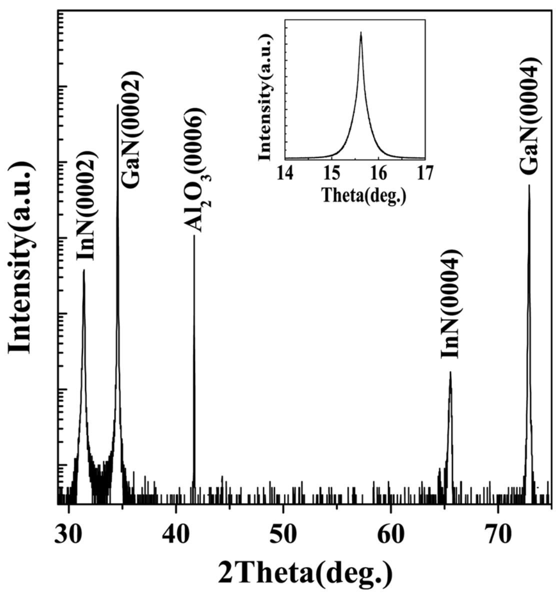

FIG. 1. 2θ-ω HRXRD scanning curve of InN film grown on GaN/sapphire template. Inset shows the XRC of the (0002) InN reflection.

thermally depositing Al (thickness ~200 nm) metal followed by a thermal annealing at 200 °C for 20 mins. The structural analysis of the film was carried out by high resolution x-ray diffraction (HRXRD) measurements using a Bruker-D8 discover four circle diffractometer. The *I-V* measurements were performed by taking contacts from two Al metals deposited on InN and GaN layers. The *I-V* measurements were carried out by using computer interfaced Keithley-236 source meter system in the temperature range of 200–500 K by steps of 50 K in the dark condition.

III. RESULTS AND DISCUSSION

Figure 1 shows a typical 2θ-ω HRXRD scan. The peaks at $2\theta = 31.3°$ and 65.5° are assigned to the (0002) and (0004) planes of the InN film. The peaks at $2\theta = 34.56°$ and 72.81° correspond to (0002) and (0004) planes of the GaN film along with sapphire peak at $2\theta = 41.69°$. The X-ray rocking curve (XRC) of the (0002) InN reflection is shown in the inset of Fig. 1. The XRC full width at half maximum of the (0002) InN reflection was found to be 450 arcsec, which is comparable to the reported value of InN grown by molecular beam epitaxy.[16]

Figure 2(a) shows room temperature *J-V* measurements for the device. The schematic of the device structure has been shown in the inset of the Fig. 2(a). The highly linear nature of the Al/InN/Al and Al/GaN/Al *J-V* plots in Fig. 2(a) is a good indication that the Al contacts to both the InN and GaN layers are ohmic. The rectifying behavior of *J-V* characteristic measurement suggests that the junction between InN and GaN exhibits a Schottky behavior. The Schottky barrier has been shown in the equivalent schematic band diagram of the InN/GaN heterostructure in Fig. 2(b). To investigate, in detail, the electrical transport through the InN/GaN junction, we have carried out temperature dependent *J-V* (*J-V-T*) measurements ranging from 200 to 500 K by steps of 50 K. Figure 3 shows the forward *J-V* characteristics as a function of temperature for the InN/GaN Schottky diode. It is very clear from the *J-V-T* curve that at fixed bias the forward current increases with increasing temperature. This indicates that the current is induced by the TE. The values of SBH (φ_b) and the ideality factor (η) for the junction were calculated as a function of measuring temperature by fitting a line in the linear region of the forward *J-V* curves using the TE model. From the TE theory, where $qV > 3kT$ and ignoring the SBH lowering due to image force (because the long range interaction between the image charges is very less as compared to the electric field at the interface), the forward *J-V* characteristic of a Schottky diode is given by[18–20]

$$J = J_s \exp\left(\frac{qV}{nkT}\right), \tag{1}$$

where
$$J_s = A^* T^2 \exp\left(-\frac{\varphi_b}{kT}\right). \tag{2}$$

Here, J_s is the saturation current density, T is the measurement temperature, A^* is the Richardson's constant, k is the Boltzmann constant, q is the electron charge, φ_b is the Schottky barrier height, and η is the ideality factor. The theoretical value of A^* was taken as 24 A cm^{-2} K^{-2},[18] for our calculations. The values of φ_b and η at different temperatures were obtained from the linear region of the forward *J-V* characteristics by fitting Eq. (1) as shown in Fig. 3. The value of φ_b and η obtained from *J-V-T* measurements based on TE model are given in Table I. We have observed that there is a temperature dependent variation of both φ_b and η (i.e., φ_b increases and η decreases with increasing temperature). This

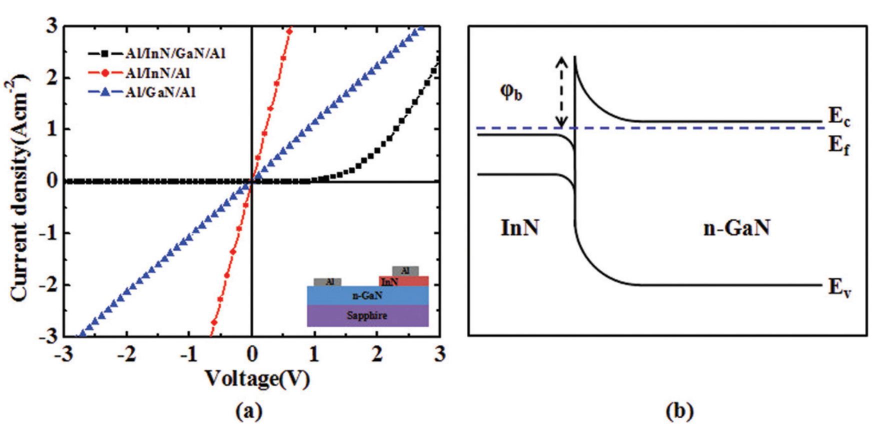

FIG. 2. (Color online) (a) Room temperature *J-V* measurement of the device. Inset shows the schematic of the device structure. (b) The equivalent schematic band diagram of the InN/GaN heterostructures.

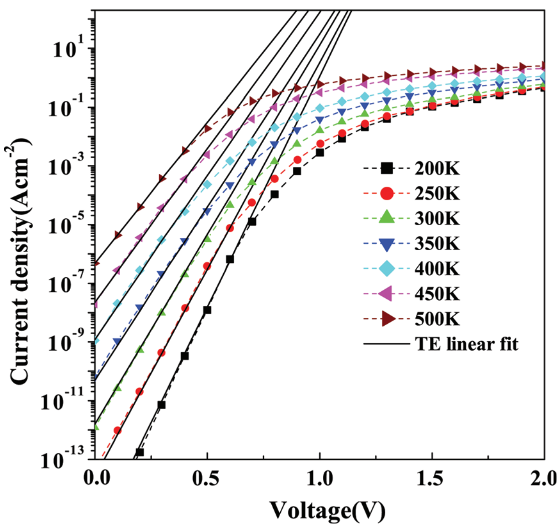

FIG. 3. (Color online) The forward J-V characteristics as a function temperature for the InN/GaN Schottky diode and the TE fitting to the J-V characteristics.

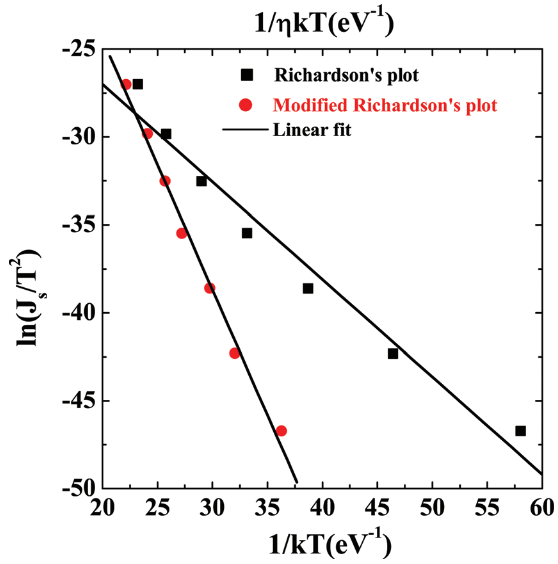

FIG. 4. (Color online) The conventional Richardson's plot of $\ln(J_s/T^2)$ versus $1/kT$ and the modified Richardson's plot of $\ln(J_s/T^2)$ vs $1/nkT$.

is different from what has been observed by Chen *et al.*[14] where they found an average value of φ_b and η to be 1.25 eV and 1.25, respectively, in the temperature range of 300–400 K. Thus, the results of our present investigation on temperature dependence of φ_b truly indicate that the SBH is inhomogeneous in nature. The inhomogeneous SBH may be due to various types of defects that could be present at the InN/GaN interface.[13,21,22]

The values of the saturation current density (J_s) were obtained at each temperature from the J-V data. The conventional Richardson's plot of $\ln(J_s/T^2)$ versus $1/kT$ was obtained and is shown in Fig. 4. From the linear fit to the plot, the Richardson's constant and barrier height were calculated to be 1.23×10^{-7} A cm^{-2} K^{-2} and 0.55 eV, respectively. The value of Richardson constant obtained from the conventional Richardson plot is much lower than the theoretical value. Also, the value of barrier height is less than the experimental values, suggesting the formation of an inhomogeneous SBH at the interface. In order to take into account of temperature dependent ideality factor and SBH, the modified Richardson's plot of $\ln(J_s/T^2)$ versus $1/\eta kT$ as proposed by Hackam and Harrow[23] is shown in Fig. 4. From the linear fit of the modified plot, the Richardson's constant and the barrier height were calculated to be 49 A cm^{-2} K^{-2} and 1.42 eV, respectively. The value of Richardson constant obtained from the modified Richardson plot was found to be closer to the theoretical value.

TABLE I. The values of barrier height and ideality factor of the InN/GaN Schottky diode obtained by using TE and TFE models.

	TE		TEF	
Temp. (K)	η	φ_b (eV)	η	φ_{btfe} (eV)
200	1.60	0.86	1.50	1.40
250	1.45	0.98	1.35	1.42
300	1.30	1.08	1.21	1.43
350	1.22	1.16	1.14	1.44
400	1.13	1.23	1.10	1.47
450	1.07	1.28	1.07	1.49
500	1.05	1.30	1.04	1.50

The high value of ideality factor (greater than unity) and its temperature dependence suggest that the current transport is primarily dominated by TFE.[24,25]

In TFE, the carriers will tunnel through the potential barrier from GaN to InN at the interface. If the current transport obeys the TFE theory, the J-V characteristic of a Schottky diode can be given by[26–29]

$$J = J_0 \exp\left(\frac{qV}{E_0}\right), \tag{3}$$

where

$$E_0 = E_{00} \coth\left(\frac{E_{00}}{kT}\right) = nkT, \tag{4}$$

and J_0 is the saturation current density for the TFE process and is given by

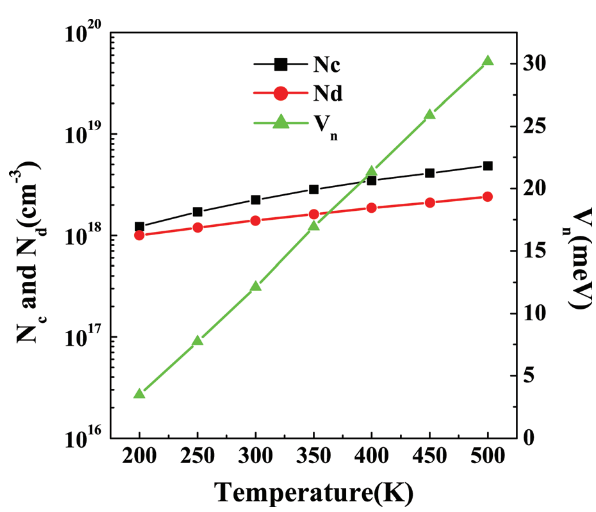

FIG. 5. (Color online) The variation of N_C, N_D, and V_n of n-GaN with temperatures.

TABLE II. Calculated and experimental electrical parameters of InN/GaN Schottky diode.

	E_{00} (meV)		E_{00}/kT		E_0 (meV)		E_0/kT	
Temp. (K)	Calculated values	Experimental values	Calculated values	Experimental values	Calculated values	Experimental values	Calculated values	Experimental values
200	13.83	24.12	0.80	1.39	20.79	26.00	1.20	1.50
250	16.94	25.85	0.78	1.19	25.81	29.20	1.15	1.35
300	19.57	28.17	0.77	1.08	30.61	31.50	1.13	1.21
350	23.56	30.16	0.76	0.99	36.06	34.50	1.11	1.14
400	26.25	34.00	0.74	0.98	40.89	38.00	1.09	1.10
450	28.01	37.00	0.72	0.95	45.30	41.50	1.08	1.07
500	30.94	40.00	0.71	0.92	50.25	45.00	1.08	1.04

$$J_0 = \frac{A^*T\sqrt{\pi E_{00}(\varphi_{\mathrm{btfe}} - qV - V_n)}}{k\cosh\left(\frac{E_{00}}{kT}\right)} \times \exp\left[-\frac{V_n}{kT} - \frac{(\varphi_{\mathrm{btfe}} - V_n)}{E_0}\right]. \tag{5}$$

Here, V_n is the energy difference between the conduction band minimum (E_c) and Fermi level (E_f) of n-GaN and is given by $V_n = kT/q\ \ln(N_C/N_D)$, where N_C is the effective density of states in the conduction band and N_D is the carrier concentration of n-GaN. The variation of N_C, N_D and V_n of n-GaN with temperature is shown in Fig. 5. The energy difference between the conduction band minimum and the Fermi level of InN has been taken care by the effective Schottky barrier height (φ_{btfe}). From Fig. 5, it is evident that V_n increases with increasing temperature. The increase in V_n with temperature might be the reason for tunneling transport at the InN/GaN interfaces, which resulting the higher value of ideality factor.[10] The parameter E_{00} is the characteristic tunneling energy that is related to the tunnel transmission probability and is given by[9]

$$E_{00} = \frac{h}{4\pi}\left(\frac{N_D}{m^*\varepsilon_s}\right)^{1/2}, \tag{6}$$

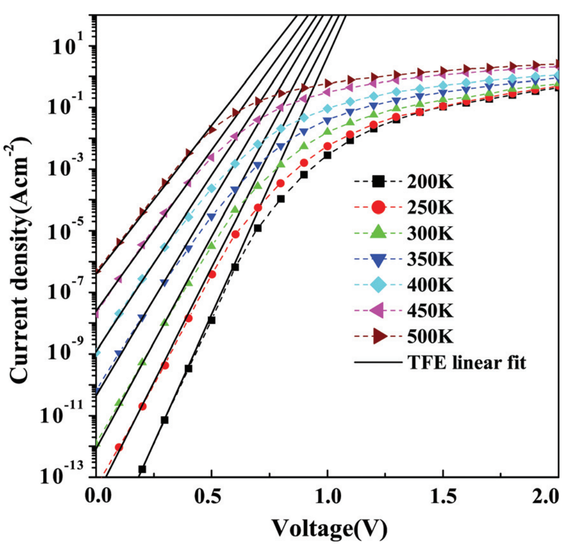

FIG. 6. (Color online) The forward J-V characteristics as a function temperature for the InN/GaN Schottky diode and the TFE fitting to the J-V characteristics.

where m^* is the effective mass of the electron and ε_s is the dielectric constant of GaN. Taking the values of $m^* = 0.2\ m_0$ and $\varepsilon_s = 9.5\ \varepsilon_0$, the value of E_{00}/kT at room temperature was found to be 0.77. However, the experimental value for the E_{00}/kT was found to be 1.08 at room temperature. The thermionic field emission is effective whenever $E_{00}/kT \approx 1$, because the Boltzmann distribution tail of thermionic emission drops off by a factor of $\exp(-1)$, which is much faster than the decrease rate of the tunneling probability. On the other hand, thermionic emission is predominant when $E_{00}/kT \ll 1$ because the tunneling probability drops off faster than TE.[30] Since $E_{00}/kT \approx 1$, the current transport in the present case is dominated by TFE. The experimental as well as calculated values of E_{00}/kT and E_0/kT are given in Table II. The TFE model has been applied to the experimental J-V characteristics in order to calculate φ_{btfe} and η. The values of φ_{btfe} and η at different temperatures were obtained from the linear region of the forward J-V characteristics by fitting Eq. (3) and are shown in Fig. 6. The value of φ_{btfe} and η obtained from J-V-T measurements based on TFE model are given in Table I. The temperature dependence of φ_{btfe} and η obtained from TFE model are shown in Fig. 7 and compared with the values obtained from TE model. As shown in Fig. 7, the ideality factors obtained from the TE and TFE models are almost the same. However, there is a difference in the SBHs

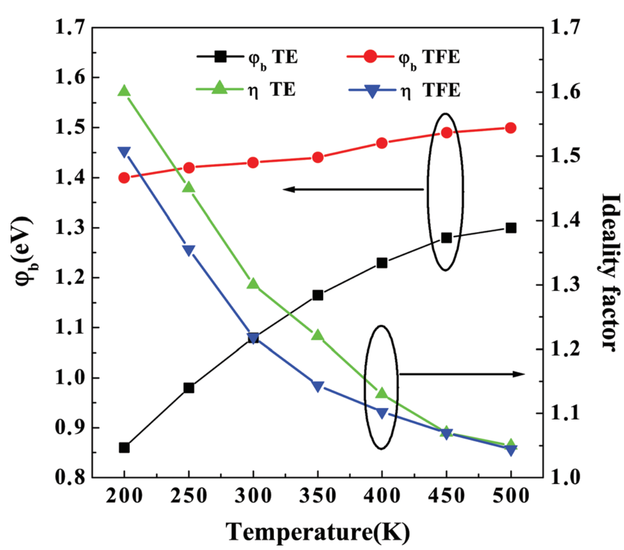

FIG. 7. (Color online) The temperature dependence of SBH and ideality factor obtained from TE and TFE models.

obtained from TE and TFE models. Since $E_{00}/kT \approx 1$, it suggests that TFE can be considered to be a more realistic model for the analysis of the electronic transport in InN/GaN heterostructure.

IV. CONCLUSION

In conclusion, we have fabricated InN/GaN heterostructure based Schottky diodes. The rectifying behavior of J-V characteristic measurement suggests that the junction between InN and GaN exhibits a Schottky type behavior. The barrier height and ideality factor of the Schottky diode were found to be temperature dependent. The room temperature barrier height and ideality factor obtained by using TE (TFE) models were 1.08 (1.43) eV and 1.30 (1.21), respectively. The higher value of the ideality factor compared to the ideal value, and its temperature dependence suggest that the current transport is mainly dominated by TFE.

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