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Barrier characteristics of Pt/Ru Schottky contacts on *n*-type GaN based on *I–V–T* and *C–V–T* measurements

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Abstract. We have investigated the current–voltage (I–V) and capacitance–voltage (C–V) characteristics of Ru/Pt/n-GaN Schottky diodes in the temperature range 100–420 K. The calculated values of barrier height and ideality factor for the Ru/Pt/n-GaN Schottky diode are 0·73 eV and 1·4 at 420 K, 0·18 eV and 4·2 at 100 K, respectively. The zero-bias barrier height (Φ_{b0}) calculated from I–V characteristics is found to be increased and the ideality factor (n) decreased with increasing temperature. Such a behaviour of Φ_{b0} and n is attributed to Schottky barrier (SB) inhomogeneities by assuming a Gaussian distribution (GD) of barrier heights (BHs) at the metal/semiconductor interface. The current–voltage–temperature (I–V–T) characteristics of the Ru/Pt/n-GaN Schottky diode have shown a double Gaussian distribution having mean barrier heights ($\bar{\Phi}_{b0}$) of 1·001 eV and 0·4701 eV and standard deviations (σ_0) of 0·1491 V and 0·0708 V, respectively. The modified $\ln(J_0/T^2) - (q^2\sigma_0^2/2k^2T^2)$ vs $10^3/T$ plot gives $\bar{\Phi}_{b0}$ and Richardson constant values as 0·99 eV and 0·47 eV, and 27·83 and 10·29 A/cm^{2}K^2, respectively without using the temperature coefficient of the barrier height. The difference between the apparent barrier heights (BHs) evaluated from the I–V and C–V methods has been attributed to the existence of Schottky barrier height inhomogeneities.

Keywords. Pt/Ru Schottky rectifiers; n-type GaN; temperature–dependent electrical properties; inhomogeneous barrier heights; double Gaussian distribution.

1. Introduction

In recent years, GaN and related materials have been extensively investigated due to their exciting applications in visible/ultraviolet laser and light emitting diodes (LEDs), field effect transistors (FETs) for high temperature and high power electronics. These exciting applications present numerous challenges in making high performance metal contacts to GaN-based materials, which is crucial for device performance (Liu and Lau 1998). One of the important issues in GaN-based electronics is still the formation of reproducible and reliable rectifying contacts, with a high barrier height and low leakage current.

In most of the previous studies, Schottky diodes formed on n-GaN are limited to the determination of the Schottky barrier height (SBHs) at room temperature (RT) by measuring either the current–voltage (I–V) or capacitance–voltage (C–V) characteristics of the diodes (Hacke *et al* 1993; Guo *et al* 1995; Liu *et al* 1998; Wang *et al* 2005; Diale and Auret 2009). Analysis of the current–voltage (I–V) characteristics of the Schottky barrier diode at room temperature alone does not give detailed information about their conduction process or the nature of barrier formation at the metal–semiconductor (MS) interface (Song *et al* 1986; Chand and Kumar 1995; Tung 2001; Chand and Bala 2005). The current transport across a Schottky junction is of interest in material science and device physics. The determination of Schottky barrier diode (SBD) parameters in a wide temperature range allows us to understand different aspects of the barrier formation and the current transport mechanisms. Although the thermionic emission (TE) theory is normally used to extract SBD parameters, there are reports of certain anomalies at lower temperatures causing deviations from the theory. For example, the ideality factor and the barrier height determined from the forward-bias current–voltage (I–V) characteristics are found to be a strong function of temperature. It was reported that the ideality factor increases and barrier height decreases with decreasing temperatures from experimental I–V–T characteristic studies of SBDs (Sawada *et al* 2003; Osvald *et al* 2005). These findings have been satisfactorily explained recently by incorporating the concept of barrier inhomogeneities and introducing a Gaussian distribution function with a mean and a standard deviation for the description (Werner and Guttler 1991; Chand and Kumar 1996).

Several groups have studied temperature-dependent electrical characteristics of Schottky contacts on n-type GaN (Zhou *et al* 2007; Ravinandan *et al* 2008, 2009; Dogan *et al* 2009; Lin 2009; Momar 2009; Horvath *et al* 2010; Phark *et al* 2010). Zhou *et al* (2007) studied the electrical characteristics of Schottky rectifiers with a SiO_2 field plate on a free standing n-GaN in the temperature range 298–473 K. They reported that the barrier height Φ_b^{I-V} increases while the barrier height Φ_b^{C-V} slightly decreases

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with temperature. Ravinandan *et al* (2008) studied current–voltage characteristics of Pt/Au Schottky contacts on n-GaN in the temperature range of 85–405 K and found that the barrier parameters vary significantly with temperature. Dogan *et al* (2009) investigated the temperature-dependent electrical characteristics of Au/Ni/n-GaN Schottky diode over a wide temperature range (40–320 K). They successfully explained their findings on the basis of the thermionic emission mechanism by assuming the presence of multiple Gaussian distributions of barrier heights. Mamor (2009) fabricated Pd, Ni, Pt Schottky contacts on n-GaN and studied the electrical properties in the temperature range 80–400 K. They have explained the temperature dependence of barrier height and ideality factor by assuming the existence of double Gaussian distributions of the barrier heights. Lin (2009) investigated the electrical properties of Pt/GaN Schottky diode in the temperature range of 100–300 K. They reported on the basis of TE model that changes in the effective density of states in the conduction band and the probability of tunneling at low temperature were responsible for the decrease of the barrier height and increase in the ideality factor. Ravinandan *et al* (2009) investigated the temperature-dependent electrical properties of the Au/Pd/n-GaN Schottky diode in the temperature range of 90–410 K. They reported that the decrease in the ideality factor and increase in the barrier height with increasing temperature could be attributed to spatial variations of the barrier heights. Recently, Phark *et al* (2010) successfully explained the temperature-dependent electrical properties of Pt Schottky contacts to a-plane n-type GaN by TE and TFE models. Very recently, Horvath *et al* (2010) studied the electrical behaviour of Al/n-GaN/Al structures and reported that the temperature dependence of ideality factor and apparent barrier height in the Al/n-GaN/Al structures can be due to the increasing contribution of space charge limited current with decreasing temperature.

In the present work, the current–voltage (I–V) and capacitance–voltage (C–V) characteristics of Pt/Ru Schottky contacts on n-GaN are measured in the temperature range of 100–420 K in steps of 40 K. The forward current–voltage (I–V) characteristics are used to establish the current transport mechanism in Ru/Pt/n-GaN diodes as well as to estimate the variation of ideality factor (n) and the zero-bias barrier height (Φ_{b0}) at different temperatures. The temperature-dependent barrier characteristics of the Ru/Pt/n-GaN Schottky diodes have been interpreted on the basis of a TE mechanism with Gaussian spatial distribution of the barrier heights (BHs) around a mean value due to barrier height inhomogeneities prevailing at the metal/semiconductor (MS) interface.

2. Experimental

In the present work, Schottky contacts were fabricated on a 2 μm thick Si-doped GaN films which were grown by metalorganic chemical vapour deposition (MOCVD) on c-plane Al_2O_3 substrate. Trimethylgallium and ammonia were used as source materials of Ga and N, respectively. Silane was used as the n-type dopant. The optimized growth temperature, pressure, and time were 1160°C, 20 mbar, and 60 min, respectively. The carrier concentration of the GaN wafers obtained from Hall measurement at room temperature was about $\sim 4{\cdot}07 \times 10^{17}$ cm^{-3}. The n-GaN layer was first ultrasonically degreased with warm trichloroethylene followed by acetone and methanol for 5 min each. This degreased layer was then dipped into boiling aqua regia [HNO_3:HCl=1:3] for 10 min to remove the surface oxides and rinsed in deionized (DI) water. The samples were immediately loaded into the electron beam evaporation system. Ti(20 nm)/Al(100 nm) ohmic contacts were deposited on a portion of the sample. Then the samples were annealed at 650°C in nitrogen ambient for 3 min. The Schottky contacts were formed by evaporation of Pt (20 nm)/Ru (30 nm) (Pt, 99·999%; Ru, 99·999%) with a diameter of 0·7 mm through a stainless steel mask. All evaporation processes were carried out in a vacuum coating unit at about 7×10^{-6} mbar. The current–voltage (I–V) and capacitance–voltage (C–V) characteristics were measured in the temperature range 100–420 K in steps of 40 K in dark using temperature controlled cryostat with an accuracy of ± 1 K. The current–voltage (I–V) measurements were carried out by use of Keithley Source Measure unit (model no. 2400). The capacitance–voltage (C–V) measurements were performed by automated deep level spectrometer (SEMILAB, DLS – 83D).

3. Results and discussion

3.1 *Current–voltage (I–V) characteristics of Schottky barrier diode as a function of temperature*

The forward and reverse current density–voltage (J–V) characteristics of Pt/Ru Schottky contacts to n-GaN in the temperature range 100–420 K are shown in figure 1. The current density (J) through a Schottky barrier diode (SBD) at a forward bias (V) according to thermionic emission (TE) theory is given by (Sze 1981; Rhoderick and Williams 1988)

$$J = J_0 \exp\left(\frac{qV}{nkT}\right)\left[1 - \exp\left(\frac{-qV}{kT}\right)\right], \tag{1}$$

where J_0 is the saturation current density derived from the forward-bias semi-logarithmic $\ln J$ vs V plots and can be written as

$$J_0 = A^* T^2 \exp\left(\frac{-q\Phi_{b0}}{kT}\right), \tag{2}$$

where V is the applied voltage, q the electronic charge, k the Boltzmann's constant, T the absolute temperature in Kelvin, n the ideality factor and A^* the effective Richardson's constant (26·4 A/cm^{2}K^2 for n-type GaN (Hacke *et al* 1993)). The value of 'n' is calculated from the slope of the linear region of the forward-bias $\ln J$ vs V plots and can be written from (1) as

$$n = \frac{q}{kT}\left(\frac{dV}{d\ln(J)}\right). \tag{3}$$

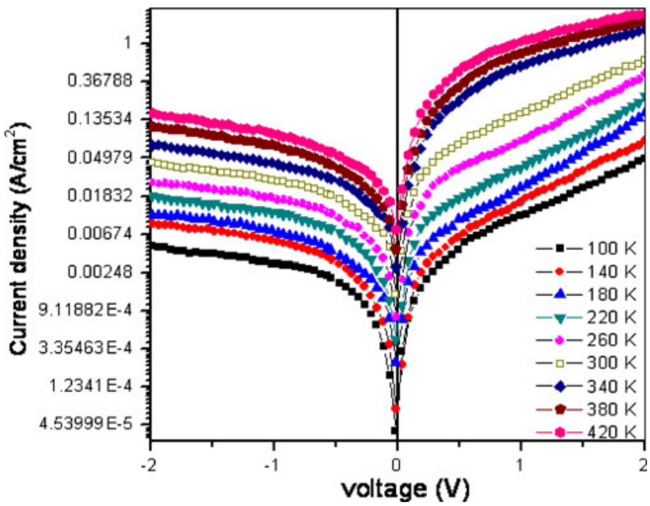

Figure 1. Experimental reverse and forward-bias current density–voltage (J–V) characteristics of Ru/Pt/n-GaN Schottky diode in temperature range of 100–420 K.

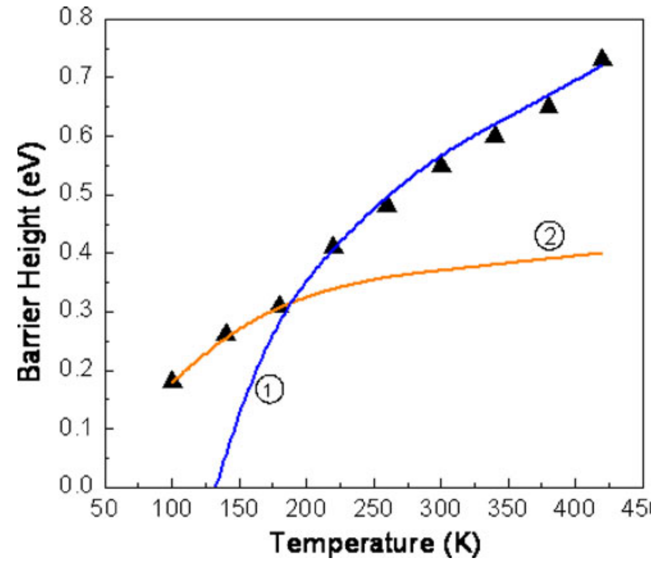

Figure 2. Zero-bias barrier height as a function of temperature (filled triangles) for Ru/Pt/n-GaN Schottky diode investigated. Continuous curve related to filled triangles represents estimated values of Φ_{ap} using (9) for two Gaussian distributions of barrier height with $\bar{\Phi}_{b0} = 1{\cdot}001$ eV and $\sigma_0 = 0{\cdot}14919$ V at 180–420 K (curve 1) and $\bar{\Phi}_{b0} = 0{\cdot}4701$ eV and $\sigma_0 = 0{\cdot}07085$ V at 100–180 K (curve 2).

The ideality factor (n) is introduced to take into account the deviation of the experimental J–V data from the ideal thermionic emission model and should be $n = 1$ for an ideal contact. The zero-bias barrier height is determined from the extrapolation of J_0 in the semi-log forward-bias $\ln J$ vs V characteristics, Φ_{b0} is given by

$$\Phi_{b0} = \frac{kT}{q} \ln\left(\frac{A^* T^2}{J_0}\right). \tag{4}$$

The experimental values of the barrier height, Φ_{b0} and the ideality factor, n, for the device are determined from intercepts and slope of the forward-bias $\ln J$ vs V plot at each temperature. As can be seen from figure 1, the leakage current density at a reverse bias of -1V is $3{\cdot}14 \times 10^{-3}$ A/cm^2 at 100 K and $9{\cdot}4 \times 10^{-2}$ A/cm^2 at 420 K. It is also noted that the leakage current density increases with increase in temperature. The n and Φ_{b0} values are calculated using (3) and (4) at different temperatures. The estimated values of n and Φ_{b0} for the Ru/Pt/n-GaN Schottky diode ranges from 4·2 and 0·18 eV (at 100 K) and 1·4 and 0·73 eV (at 420 K), respectively. It can be seen from figures 2 and 3 that the experimental values of Φ_{b0} decreases while n increases with decreasing temperature.

An apparent increase in the ideality factor and decrease in the Schottky barrier height at low temperatures are possibly caused by structural defects in the semiconductor, inhomogeneous doping, interface roughness, interfacial reactions and diffusion/interdiffusion of the contamination of applied material on semiconductor surface. Other possible effects are due to inhomogeneities of thickness and composition of the layer, and non-uniformity of interfacial charges or the presence of a thin insulating layer between metal and semiconductor (Song *et al* 1986; Werner and Guttler 1991; Sullivan *et al* 1991; Chen *et al* 2003; Zhu *et al* 2004). Since current transport across the metal/semiconductor (MS) interface is a

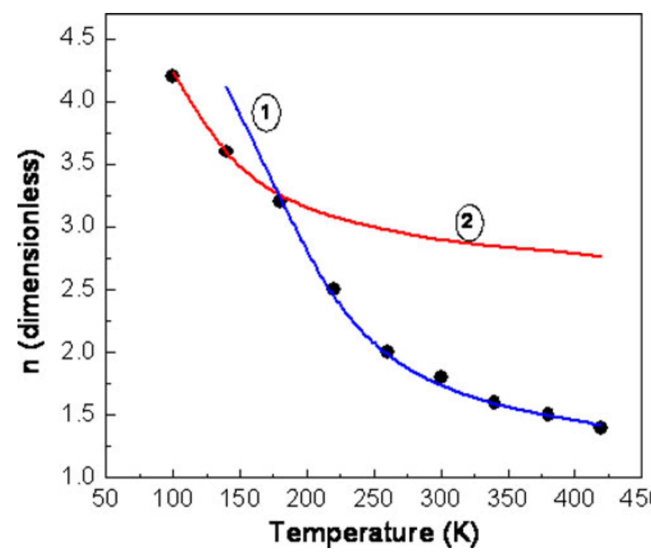

Figure 3. Temperature dependence of ideality factor for Ru/Pt/n-GaN Schottky contact (filled circles). Continuous curves show estimated values of ideality factor (n_{ap}) using (10) for two Gaussian distributions of barrier heights with $\rho_2 = -0{\cdot}01397$ V, $\rho_3 = -0{\cdot}02254$ V at 180–420 K (curve 1) and $\rho_2 = 0{\cdot}59983$, $\rho_3 = -0{\cdot}00283$ V at 100–180 K (curve 2).

temperature activated process, electrons at low temperatures can surmount the lower Schottky barrier height (SBH) and the dominant current flow is through the regions of lower Schottky barrier height (SBH). As the temperature increases, more electrons have sufficient energy to surmount higher

SBH. Therefore, the dominant barrier height increases with temperature.

According to Schmitsdorf *et al* (1995), a linear relationship between the experimental SBH and ideality factor (n) values is an indication of the barrier irregularity and can be explained by lateral inhomogeneities of BHs. The value of homogeneous barrier height is obtained from the extrapolation of the experimental Schottky barrier heights vs ideality factors plot to $n = 1$ (Schmitsdorf *et al* 1995; Mamor 2009; Phark *et al* 2010). Because of the double Gaussian distributions of the barrier heights in the present work, two sets of homogeneous barrier height values are obtained by extrapolation of the experimental Schottky barrier height values vs ideality factor plot to $n = 1$ (plot not shown here). For Ru/Pt/n-GaN Schottky diode, the homogeneous barrier height values of 0·59 eV and 0·74 eV are obtained in the temperature range 100–180 K (distribution 1) and 180–420 K (distribution 2), respectively.

Another way to determine the Schottky barrier height and the Richardson constant is to use an activation energy plot. Using the values of the saturation current density, J_0, at each temperature from the J–V data as shown in figure 1, the conventional Richardson plot of $\ln(J_0/T^2)$ vs $1000/T$ is obtained in the temperature range 100–420 K. From the linear fit of the plot in figure 4, the Schottky barrier height and Richardson constant are calculated to be 0·101 eV and $1{\cdot}016 \times 10^{-6}$ A/cm^{2}K^2, respectively. The estimated value of the Richardson constant is much lower than the theoretical value of n-GaN (26·4 A/cm^{2}K^2). The deviation in the conventional Richardson plot may be due to the spatially inhomogeneous barrier heights and potential fluctuations at the interface that consists of low and high barrier areas (Song *et al* 1986; Werner and Guttler 1991; Dogan *et al* 2009). Horvath (1996) reported that the A^* value obtained from the temperature-dependent I–V characteristics may be affected by lateral inhomogeneity of the barrier.

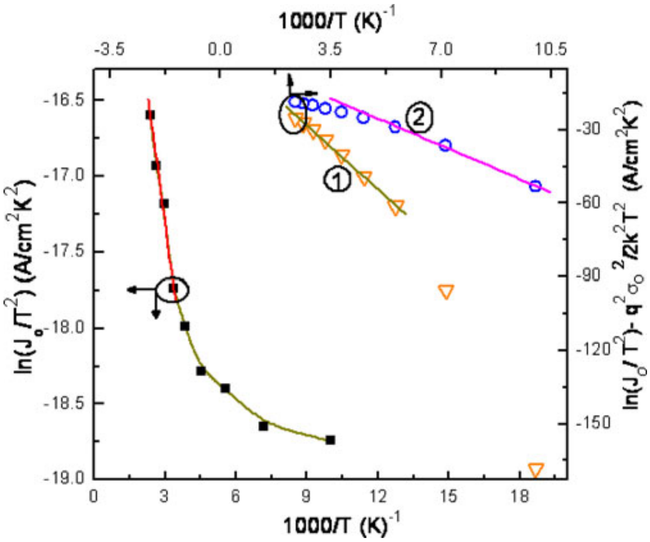

Figure 4. Conventional Richardson plot of $\ln(I_0/T^2)$ vs $1000/T$ (filled squares) and modified Richardson $\ln(J_0/T^2)$–$(q^2\sigma_0^2/2k^2T^2)$ vs $1000/T$ plots for Ru/Pt/n-GaN Schottky contact according to two Gaussian distributions of barrier heights. Open triangles represent plot calculated for $\sigma_0 = 0{\cdot}14919$ V and open circles represent plot calculated for $\sigma_0 = 0{\cdot}07085$ V. Straight lines 1 and 2 indicate best fittings of data in temperature ranges 180–420 K and 100–180 K.

3.2 *Effect of thermionic field emission (TFE)*

Until now, the current–voltage (I–V) characteristics of Pt/Ru/n-GaN Schottky diode are analyzed based on TE model. The observed ideality factors are greater than unity for our samples, implying that the pure TE model is inappropriate to explain the current–voltage (I–V) characteristics. The recombination current resulting from the minority carrier injection in the Schottky barrier region could also contribute to the carrier transport. If the current transport is controlled by the thermionic field emission (TFE) theory, the relation between current density and voltage can be expressed as (Rhoderick and Williams 1988)

$$J = J_0 \exp\left[\frac{V}{E_0}\right], \tag{5}$$

where

$$E_0 = E_{00} \coth\left[\frac{qE_{00}}{kT}\right] = \frac{n_{\mathrm{tun}} kT}{q}, \tag{6}$$

where E_{00} is the characteristic energy, which is related to the transmission probability of the carrier through the barrier given by

$$E_{00} = \frac{h}{4\pi}\left(\frac{N_{\mathrm{d}}}{m_{\mathrm{e}}^* \varepsilon_{\mathrm{s}}}\right)^{\frac{1}{2}}, \tag{7}$$

where h is the Planck constant ($h = 6{\cdot}626 \times 10^{-34}$ J.s), N_{d} the donor concentration, ε_{s} the semiconductor dielectric constant and m_{e}^* the electron effective mass.

In the case of our Ru/Pt/n-GaN Schottky diode, with $N_{\mathrm{d}} = 4{\cdot}07 \times 10^{17}$ cm^{-3}, $m_{\mathrm{e}}^* = 0{\cdot}22m_0$ and $\varepsilon_{\mathrm{s}} = 9{\cdot}5\varepsilon_0$ (Hacke *et al* 1993), the value of E_{00} is found to be about 8·2 meV. When considering the bias coefficient of the barrier height, β, (6) can be written as (Horvath 1996; Ayyildiz *et al* 2005)

$$n_{\mathrm{tun}} = \frac{E_0}{kT(1-\beta)}. \tag{8}$$

The temperature dependence of theoretical ideality factor for the case when the current through Schottky junction is dominated by the TFE as shown in figure 5. The solid lines in figure 5 are obtained by fitting (6) to the experimental temperature dependence values of ideality factor presented for different values of the characteristic energy, E_{00}, without considering the bias coefficient of the barrier height, β = 0, for the Ru/Pt/n-GaN Schottky diode. The filled circles in figure 5 show the temperature dependence values of ideality

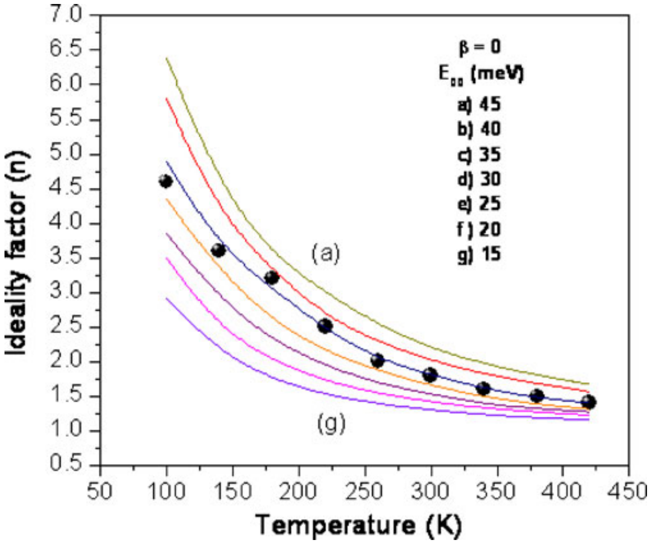

Figure 5. Theoretical temperature dependence of ideality factor for case when current through junctions is dominated by TFE with characteristic energy values, E_{00}, according to (6) (solid lines) for Ru/Pt/n-GaN Schottky diode. The filled circles show experimental temperature dependence values of ideality factor obtained from J–V characteristics as shown in figure 1.

factor obtained from the experimental current–voltage (I–V) characteristics. From figure 5, it is observed that the experimental temperature dependence of ideality factor is in agreement with the curve (C) obtained with $E_{00} = 35$ meV for the Ru/Pt/n-GaN diode studied in the temperature range 100–420 K. As can be seen from figure 5 there is a significant consistency between theoretical and experimental characteristics over the whole temperature range.

The characteristic energy, E_{00} value, is about 4·2 times larger than the value of 8·2 meV calculated for n-GaN. To understand the possible origin of the high characteristic energy values of E_{00}, it should be underlined that E_{00} is connected with the transmission probability (Ayyildiz *et al* 2005). The characteristic energy has been related to several effects such as the electric field present on the surface of the semiconductor, the existence of interfacial insulating layer between the deposited metal and semiconductor and the density of states (Hudait *et al* 2001; Ayyildiz *et al* 2005; Benamara *et al* 2006). Therefore, any mechanism which enhances the electric field or the density of states at the semiconductor surface will increase TFE, and so the apparent E_{00} (Horvath 1996; Ayyildiz *et al* 2005). However, one cannot distinguish between the two possible models (TE and TFE) on the basis of the I–V characteristics only, i.e. the domination of TFE can be connected with the lateral distribution of BH. Since the enhancement of the transmission probability can be due to local enhancement of electric field, it can also yield a local reduction of BH (Horvath *et al* 2003; Ayyildiz *et al* 2005). In this study, we suggest that the dominance of TFE may be connected to the Gaussian distribution of the barrier height.

3.3 *Analysis of barrier inhomogeneities*

To explain the decrease in the barrier height with a decrease in temperature, we adopted a lateral distribution of BH with a Gaussian distribution of the barrier height values over the Schottky contact area with the mean barrier height, $\bar{\Phi}_{b0}$ and standard deviation, σ_0. The standard deviation is a measure of the barrier homogeneity. The Gaussian distribution of the BHs yields the following expression for the BH (Song *et al* 1986; Werner and Guttler 1991; Chand and Bala 2005)

$$\Phi_{ap} = \bar{\Phi}_{b0}\,(T = 0) - \frac{q\sigma_0^2}{2kT}, \tag{9}$$

where Φ_{ap} is apparent barrier height measured experimentally. The temperature dependence of σ_0 is usually small and can be neglected. The variation of observed ideality factor with temperature in the model is given by (Werner and Guttler 1991; Chand and Kumar 1995)

$$\left(\frac{1}{n_{ap}} - 1\right) = -\rho_2 + \frac{q\rho_3}{2kT}, \tag{10}$$

where n_{ap} is the apparent ideality factor and ρ_2 the voltage coefficient of the mean barrier height, and ρ_3 the voltage coefficient of the standard deviation. By assuming a linear bias dependence of both the mean barrier height, $\bar{\Phi}_{b0}$ and square of the standard deviation, σ_0^2, with coefficient, ρ_2 and ρ_3, (i.e. $\bar{\Phi}_b(V) = \bar{\Phi}_{b0} + \rho_2 V$ and $\sigma_0^2(V) = \sigma_0^2 + \rho_3 V$), respectively.

The linearity of the apparent barrier height or ideality factor vs $1/2kT$ curves in figure 6, and the continuous curves in figures 2 and 3 show that the temperature-dependent experimental data of the Ru/Pt/n-GaN Schottky contact are

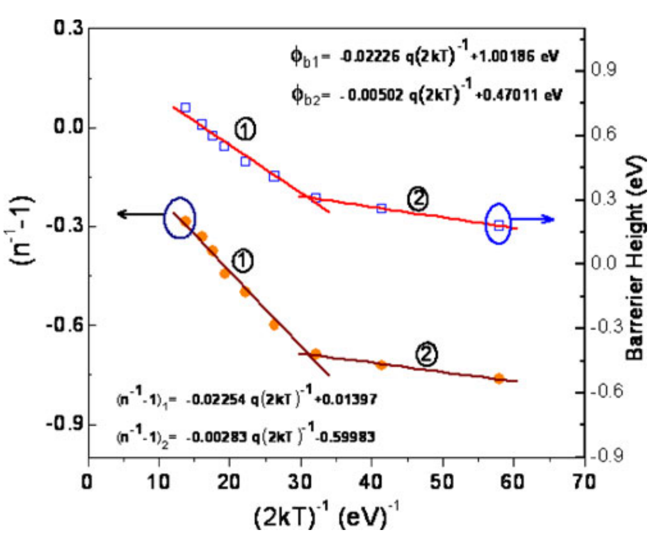

Figure 6. Zero-bias apparent barrier height (open squares) and ideality factor (filled circles) vs $1/(2kT)$ curves of Ru/Pt/n-GaN Schottky contact according to two Gaussian distributions of BHs. Data show linear variation in two temperature ranges with a transition around 180 K.

in agreement with the recent model which is related to thermionic emission over a Gaussian BH distribution (Song *et al* 1986; Werner and Guttler 1991; Chand and Kumar 1995; Chand and Bala 2005). Figure 6 shows the experimental Φ_{ap} vs 1/2kT and n vs 1/2kT plots obtained by means of the data obtained from figure 1, respond to two lines instead of a single straight line with transition occurring at 180 K. These two different slopes at the lower and higher temperatures indicate two activated processes with different mean barrier heights. The above observations indicate the existence of two Gaussian distributions of barrier heights in the contact area. Two sets of values of σ_0 and $\bar{\Phi}_{b0}$ are obtained from the slopes and intercepts of these straight lines as 0·149 V and 1·0018 eV in the temperature range of 180–420 K (distribution 1), and 0·0708 V and 0·4701 eV in the temperature range 100–180 K (distribution 2). Furthermore, Φ_{ap} values can be estimated from (9) over the entire temperature range 100–420 K for each set of σ_0 and $\bar{\Phi}_{b0}$ values and are shown by the continuous curves 1 and 2 in figure 2. That is, the continuous solid lines related to the filled triangles in figure 2 represents the data estimated using (9). As can be seen from the figure, the computed values exactly coincide with the experimental results in the respective temperature ranges for two different distributions. Vanalme *et al* (1997, 1999) already experimentally observed the existence of a double Gaussian distribution in Schottky diodes by ballistic electron emission microscopy (BEEM). Chand and Kumar (1996) also indicated the existence of a double Gaussian in the metal/semiconductor contacts which can be attributed to the nature of the inhomogeneities themselves. This may involve variation in the interface composition/phase, interface quality, electrical charges, non-stoichiometry etc. They are important enough to electrically influence the I–V characteristics of the Schottky diodes, at particularly low temperatures. Thus, I–V measurements at very low temperatures are capable of revealing the nature of barrier inhomogeneities that exist in the contact area. Furthermore, the temperature range covered by each straight line suggests the regime where the corresponding distribution is effective (Chand and Kumar 1996).

Figure 6 shows the plot of n_{ap} vs 1/2kT which is a straight line that gives voltage coefficients, ρ_2 and ρ_3, from the intercept and slope, respectively. The values of ρ_2 obtained from the intercepts of the experimental n_{ap} vs 1/2kT plot are −0·01397 V in 180–420 K range (distribution 1) and 0·5998 V in 100–180 K range (distribution 2), whereas the values of ρ_3 from the slopes are −0·02254 V in 180–420 K range (distribution 1) and −0·00283 V in 100–180 K range (distribution 2). The linear behaviour of this plot demonstrates that the ideality factor indeed expresses the voltage deformation of the Gaussian distribution of the Schottky barrier height. The continuous solid lines 1 and 2 in figure 3 represent the data estimated with the above values of ρ_2 and ρ_3 using (10). It is observed that the computed values exactly coincide with the experimental results in the respective temperature ranges for two different distributions. As can be seen from the n_{ap} vs 1/2kT plot, ρ_3 value or the slope of the distribution 1 is larger than that of distribution 2, therefore, it may point out that the distribution 1 has wider and relatively higher BH. This is actually clear from the determined values of the mean BH and the standard deviation of distributions 1 and 2 which are given above. Thus, it can be stated that distribution 2 at very low temperatures may possibly arise due to some phase change taking place on cooling below a certain temperature.

Considering the barrier inhomogeneity, the modified Richardson plot can be obtained by combining (2) and (9) as follows

$$\ln\left(\frac{J_0}{T^2}\right) - \left(\frac{q^2\sigma_0^2}{2k^2T^2}\right) = \ln(A^*) - \frac{q\bar{\Phi}_{b0}}{kT}. \tag{11}$$

A modified Richardson plot $\ln(I_0/T^2) - \left(q^2\sigma_0^2/2k^2T^2\right)$ vs 1000/T plot (figure 4) according to (11) should also be a straight line with the slope and the intercept at the ordinate directly yielding the zero-bias mean barrier height $\left(\bar{\Phi}_{b0}\right)$ and A^*, respectively. The $\ln(J_0/T^2) - \left(q^2\sigma_0^2/2k^2T^2\right)$ values are estimated for two values of σ_0 obtained for the temperature ranges 100–180 K and 180–420 K. The open triangles and closed circles in figure 4 have given the modified $\ln(J_0/T^2) - \left(q^2\sigma_0^2/2k^2T^2\right)$ vs 1000/T plots for both values of σ_0. The best linear fitting to these modified experimental data are shown by solid lines in figure 4 which represent the true activation energy plots in respective temperature ranges. The calculations yielded zero-bias mean barrier height $\left(\bar{\Phi}_{b0}\right)$ of 0·47 eV (in the range of 100–180 K) and 0·993 eV (in the range of 180–420 K). These values match exactly with the mean barrier heights obtained from the Φ_{ap} vs 1/2kT plot in figure 6. The intercepts at the ordinate give the Richardson constant A^* as 10·29 A/cm^{2}K^2 in 100–180 K range and 27·83 A/cm^{2}K^2 in 180–420 K range without using the temperature coefficient of the barrier heights. The Richardson constant value of 27·83 A/cm^{2}K^2 for the range of 180–420 K is nearly equal to theoretical value of 26·4 A/cm^{2}K^2 for n-type GaN (Hacke *et al* 1993).

3.4 *Capacitance–voltage (C–V) characteristics of Schottky barrier diode as a function of temperature*

The experimental reverse bias C^{-2}–V characteristics of the Ru/Pt/n-GaN SBD in the temperature range of 100–420 K in steps of 40 K are shown in figure 7. Figure 8 shows the Φ_{C-V} (indicated by open triangles) values obtained from the reverse bias C^{-2}–V characteristics depending on temperature. C–V measurements are also performed at a frequency of 1 MHz. The C–V relationship for Schottky diode can be expressed as (Sze 1981; Rhoderick and Williams 1988)

$$\frac{1}{C^2} = \left(\frac{2}{\varepsilon_s q N_d A^2}\right)\left(V_{bi} - \frac{kT}{q} - V\right), \tag{12}$$

where ε_s is the permittivity of the semiconductor ($\varepsilon_s = 9{\cdot}5\varepsilon_0$), V the applied voltage, A the area of the contact, N_d the donor concentration and k the Boltzmann's constant. The

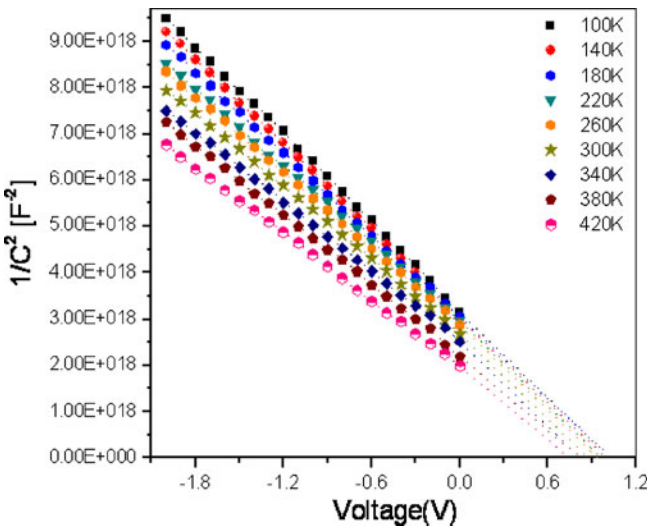

Figure 7. Experimental reverse-bias C^{-2}–V characteristics of Ru/Pt/n-GaN Schottky diode in temperature range 100–420 K.

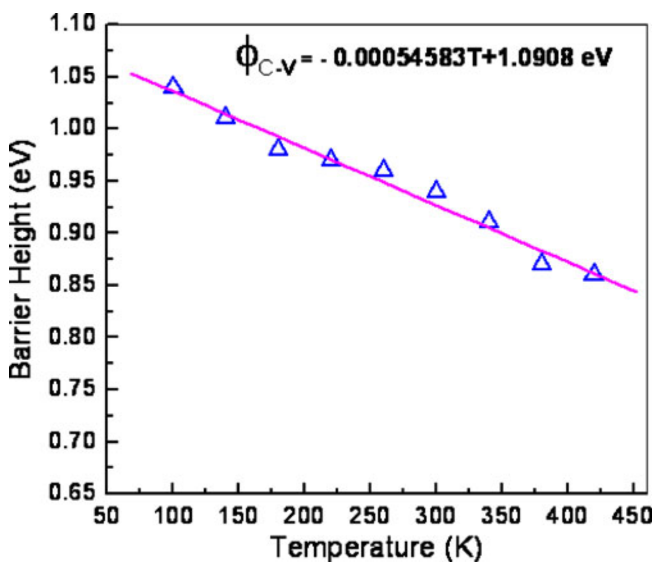

Figure 8. Plot of barrier height (from C–V characteristics) vs temperature for Ru/Pt/n-GaN Schottky diode.

x-intercept of the plot of $(1/C^2)$ vs V gives V_0 and it is related to the built-in potential, V_{bi}, by the equation

$$V_{bi} = V_0 + kT/q,$$

where T is the absolute temperature. The barrier height is given by the equation

$$\Phi_{C-V} = V_0 + V_n + kT/q,$$

here $V_n = (kT/q)\ln(N_c/N_d)$. The density of states in the conduction band edge is given by $N_c = 2(2\pi m^* kT/h^2)^{3/2}$, where $m^* = 0{\cdot}22 m_0$ and its value is $2{\cdot}53 \times 10^{18}$ cm^{-3} for n-GaN at room temperature (Hacke *et al* 1993).

Moreover, the temperature dependence of the experimental donor concentration (N_d) has been calculated from the slope of reverse bias C^{-2}–V characteristics from figure 7. The values of N_d varied from $3{\cdot}77 \times 10^{17}$ to $4{\cdot}22 \times 10^{17}$ cm^{-3} for the n-type GaN wafer over the temperature range of 100 K–420 K. It is observed that carrier concentration for n-GaN increased with increase in temperature. The temperature dependent N_d values are used in calculating Φ_{C-V} values. Due to the square dependence of Φ_{C-V} on $1/C$, compared to the logarithmic dependence of Φ_{b0} on current, Φ_{C-V} is more sensitive to the experimental errors of the measured data than Φ_{b0} (Zhu *et al* 2000). The barrier height, Φ_{C-V}, determined from the C–V measurements was 1·04 eV at 100 K and decreases to 0·86 eV at 420 K, and the values are given in table 1. The temperature dependence of Φ_{C-V} is expressed as

$$\Phi_{C-V} = \Phi_{C-V}(T = 0K) + \alpha T, \tag{13}$$

where Φ_{C-V} ($T = 0$ K) is the barrier height extrapolated to zero temperature and α the temperature coefficient ($\alpha = dE_g/dT$, where E_g is the energy gap and T the temperature) of the barrier height. As shown in figure 8, the experimental Φ_{C-V} vs T plot yields Φ_{C-V} ($T = 0$) = 1·0908 eV and $\alpha = -0{\cdot}545833$ meV/K. From figure 8, it is also observed that the barrier height obtained from the C–V method decreases as the temperature increases. Generally, the temperature dependence of the Schottky barrier height should follow the temperature dependence of the bandgap with a coefficient almost identical to that of the bandgap (Aboelfotoh 1989; Chen *et al* 1993; Lu and Mohammad 2006; Soylu and Abay 2009). The bandgap shrinks at higher temperature. If it is assumed that the conduction band edge shifts downward, the valence band edge shifts upwards during this shrinkage, and that these two shifts are equal and opposite (Sze 1981; Lu and Mohammad 2006). Thus, it can be said that the variation of the bandgap with temperature is hardly effected by the Fermi level temperature dependence for GaN.

Table 1. Temperature dependent values of electrical parameters of Ru/Pt/n-GaN Schottky diode determined from I–V and C–V measurements in the temperature range, 100–420 K.

Temperature (K)	Φ_{b0} (eV)	Φ_{C-V} (eV)	n
100	0·18	1·04	4·2
140	0·26	1·01	3·6
180	0·31	0·98	3·2
220	0·41	0·97	2·5
260	0·48	0·96	2·0
300	0·55	0·94	1·8
340	0·60	0·91	1·6
380	0·65	0·87	1·5
420	0·73	0·86	1·4

The barrier height values measured by the I–V method are lower than those obtained by the C–V method in our measurements. Similar trends have already been reported for metal/semiconductor Schottky diodes by Ozdemir *et al* (2006) and Cimilli *et al* (2009). The differences in barrier height values obtained from the I–V and C–V may be due to the presence of an insulating layer or charges existing at the metal–semiconductor interface, deep impurity levels, image force barrier lowering, and edge leakage currents (Tung *et al* 1971; Crowel 1977; Tyagi 1984; Rhoderick and Williams 1988; Hacke *et al* 1993). The existence of Schottky barrier height inhomogeneity offers another explanation for the discrepancy between measured I–V and C–V barrier heights. The current in the I–V measurement is dominated by the current which flows through the regions of low SBH. Hence, the measured I–V barrier height is significantly lower than the weighted arithmetic average of SBHs. In contrast, the C–V measured barrier height is influenced by the distribution of charge at the depletion region boundary and this charge distribution follows the weighted arithmetic average of the SBH inhomogeneity; hence the barrier height measured by C–V is close to the weighted arithmetic average of the SBHs. Therefore, SBH determined from the zero-bias intercept assuming thermionic emission as current transport mechanism is well below the C–V measured BH and the weighted arithmetic average of the SBHs (Tung *et al* 1971; Sullivan *et al* 1991; Werner and Guttler 1991).

4. Conclusions

The current–voltage–temperature (I–V–T) and capacitance–voltage–temperature (C–V–T) characteristics of Ru/Pt/n-GaN Schottky barrier diodes (SBDs) have been investigated. When measurement temperature is lowered, the barrier height decreased, the ideality factor increased and the Richardson plot deviated from linearity. These observations have been ascribed to barrier height inhomogeneities at the metal/semiconductor interface. In order to obtain evidence of single or double/multiple Gaussian distribution of the BHs, we have drawn Φ_{b0} vs $1/2kT$ plot. From this plot we obtained two straight lines with negative slope for double Gaussian distribution of BHs. While the slope of each straight line gives the standard deviation, the intercept at the ordinate yields the mean of the Gaussian distribution. The same has also been observed for $n^{-1} - 1$ vs $1/2kT$ plot in the present case. Moreover, experimental values of the ideality factor are in agreement with curve (C) in figure 5, obtained using a characteristic energy value, E_{00}, of 35 meV in tunneling mechanism. Then, the values of Richardson constant, A^*, were obtained from a modified $\ln(J_0/T^2) - \left(q^2\sigma_0^2/2k^2T^2\right)$ vs $1000/T$ plot as 10·29 A/cm^{2}K^2 in the temperature range 100–180 K and 27·83 A/cm^{2}K^2 in the temperature range 180–420 K. The Richardson constant value obtained in the temperature range 180–420 K is nearly equal to the theoretical value of 26·4 A/cm^{2}K^2 for n-GaN. It has been concluded that the I–V characteristics of Ru/Pt/n-GaN SBDs can be successfully explained on the basis of TE mechanism with two Gaussian distributions of the Schottky barrier heights in the temperature range of 100–420 K.

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