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Investigations on the nonidealities in Pd/n-GaN Schottky diodes grown by MOCVD

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ABSTRACT

The effect of ammonia flow rate on the device characteristics of Pd/n-GaN Schottky diodes is discussed. The carrier concentration and hall mobility of the as grown epilayers were found to decrease with an increase in the V/III ratio. Current–Voltage (*I–V*) barrier height initially decreases and then increases with an increase in V/III ratio. The ideality factor and leakage current decreases with an increase in the V/III ratio. The Capacitance–Voltage (*C–V*) measurements of small area contacts showed a large variation in the slope of the lines of A^2/C^2 vs. V plot. *I–V–T* measurements revealed that the ideality factor and the reverse leakage current increases with temperature confirming that the conduction mechanism is through trap-assisted tunneling process or deep center hopping conduction. Device parameters of GaN Schottky diodes were found to be strongly affected by the variation in localized structural changes induced by V/III ratio.

1. Introduction

Gallium nitride (GaN) III-N semiconductor material is known for its light emitting characteristics in spite of having a large density of dislocations [1]. The metal organic chemical vapor deposition (MOCVD) grown GaN has been commercially used for fabricating various opto-electronic and micro-electronic components. Recently there is considerable interest in developing GaN nanocrystals, subsequent sublimation of which enables realization of free standing GaN which can be used for obtaining better device characteristics [2]. The advantages of GaN based electronic devices lie in the domain of high electric fields where the saturation velocities and breakdown voltages are superior to Si and GaAs and even the main competitor, SiC. However, the real life nitride devices at present cannot, as a rule, go to such high electric fields because of the problems with excessive leakage and early breakdown.

Several groups have suggested that defects in particular dislocations might play an important role in the device characteristics [3–6]. The presence of bulk non-uniformities of shallow and deep centers as revealed by various techniques is the primary reason for the nonideal performance in high electric fields. The nature of these non-uniformities and the ways they affect the device performance should be understood and technological approaches minimizing electrical non-uniformity of the materials have to be found. Even though many electronic devices have been fabricated on the GaN and related alloy systems, degradation of electrical characteristics of the Schottky devices due to the variation in the density of threading dislocations have not been studied in detail. Deeper understandings of the compensation mechanism in GaN and interface properties are critical for developing reliable high power high electron mobility transistors (HEMTs) and solar-blind detectors.

Detailed Schottky diode studies were reported for various metal contacts on n-GaN [7–12]. Recently, the dependence of device parameters on threading dislocations in GaN based light emitting diodes (LEDs) and Schottky diodes fabricated on different substrates or templates were reported [13–15]. In this paper, we present results of Pd/n-GaN Schottky diodes of 100 nm thick and 50, 100, 150, 200, 400 μm in diameters fabricated on 3 μm thick GaN grown by MOCVD with different V/III ratios. Using Hall effect measurement, *I–V*, *C–V* and *I–V–T* measurements, the dependence of the device parameters such as barrier height, ideality factor and leakage current on the quality of GaN were correlated and a suitable mechanism responsible for the nonideal behavior was discussed.

2. Materials and methods

Nominally identical, unintentionally doped n-type GaN epilayers were grown on sapphire (0 0 0 1) substrates using MOCVD system. Trimethylgallium (TMG) and ammonia (NH_3) were used as precursors. Initially the sapphire substrate was heated up to 1100 °C for about 10 min in a stream of hydrogen. 30 nm thick GaN layer was deposited as buffer at 550 °C. After buffer layer growth, substrate was heated up to 1075 °C to grow 3 μm thick unintentionally doped GaN epilayers. The optimization was carried out by keeping the gallium flow rate for all the samples at 80 μmol/s and changing the ammonia flow in the reactor from 4 to 7 SLM. The V/III ratio was changed, keeping all other growth parameters constant.

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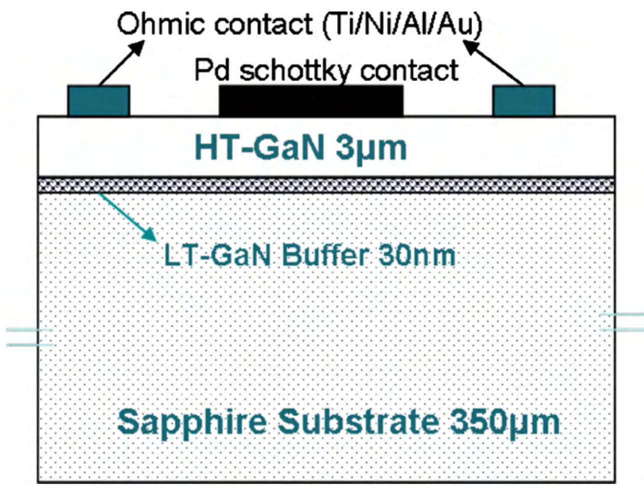

Fig. 1. The cross-sectional view of the fabricated Schottky devices.

Fig. 1 shows the device structure of the Pd Schottky diodes fabricated on GaN. Before depositing 100 nm thick palladium Schottky of varying diameters, multilayer guard ring type ohmic contacts made up of Ti/Al/Ni/Au (15/75/12/40 nm) were deposited and annealed at 950 °C for 90 s in rapid thermal annealing. All the metals were deposited using the e-beam evaporation system whereas Al was deposited by vacuum thermal evaporation after using a standard surface treatment. The pattern was realized using the photolithography technique. The diameter of the Pd Schottky contacts was varied from 50 to 400 µm. Current–Voltage (*I*–*V*) and Capacitance–Voltage (*C*–*V*) characteristics of the Schottky diodes were measured; parameters like barrier height, ideality factor and reverse leakage current were calculated from the forward and reverse *I*–*V* measurements. The capacitance was measured at 1 MHz and the *C*–*V* barrier height was also calculated. The Current–Voltage–Temperature (*I*–*V*–*T*) measurements were carried out in the temperature range of 298–390 K.

3. Results and discussion

3.1. Hall effect measurements

Fig. 2 shows the variation of the carrier concentration and Hall mobility with respect to the V/III ratio. The hall mobility for most of the samples was greater than 500 $cm^2/V s$ indicating fairly good quality of GaN layers. The electron concentration of the sample varies from 5×10^{16} to 3.4×10^{16} cm^{-3}. Hall mobility and the electron concentration of the samples decrease while increasing the V/III ratio from 1258 to 2200.

Intrinsic defects increase due to an increase in the V/III ratio [16]. It is expected that as the ammonia flow rate increases, the concentration of the electron donating N-vacancy site decreases. A decreasing trend in electron concentration as shown in Fig. 2 can also be accounted for the increase of compensating centers caused by the high ammonia flow rates. The mobility reduction with increasing ammonia flow rate also confirms the above argument. The variation of hall mobility from 610 to 490 $cm^2/V s$ may be attributed to the ionized impurity scattering in GaN. Ionized impurity scattering is due to the presence of intrinsic defects [17,18].

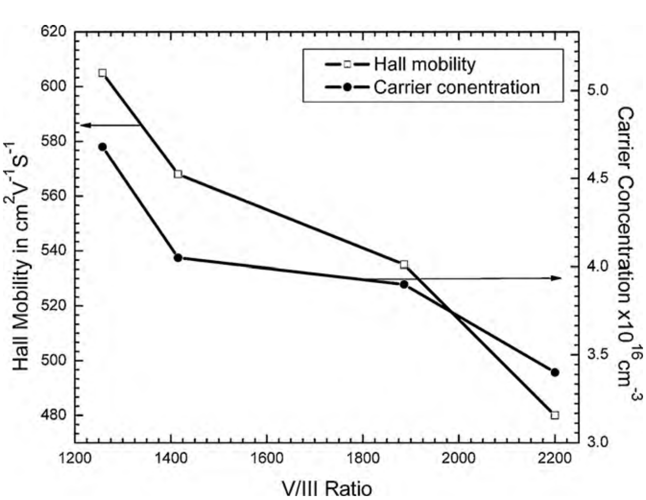

Fig. 2. The variation of Hall mobility and donor concentration with V/III ratio.

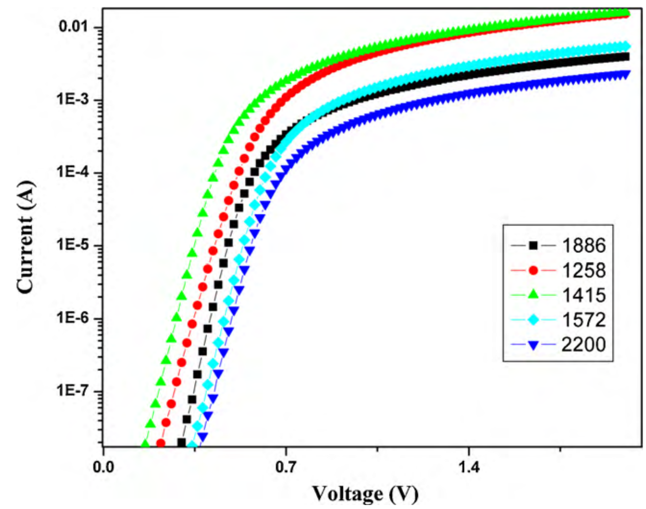

Fig. 3. Forward-bias log(*I*)–*V* characteristics of 400 µm diameter Pd Schottky contacts on GaN grown with different V/III ratio.

3.2. I–V measurements

Fig. 3 shows the typical log(*I*)–*V* characteristics of Pd Schottky contacts on GaN grown with different V/III ratio. The series resistances of all the metal contacts were found to increase from 250 to 300 Ω on increasing the V/III ratio. The barrier height ($q\phi_b$) and the ideality factor (n) were extracted using the equation below:

$$I = AA^*T^2 \exp\left(\frac{-q\phi_b}{K_BT}\right) \exp\left(\frac{qv}{nK_BT} - 1\right)$$

where A is the diode area, A^* is the Richardson constant (26.4 A cm^{-2} K^{-2}).

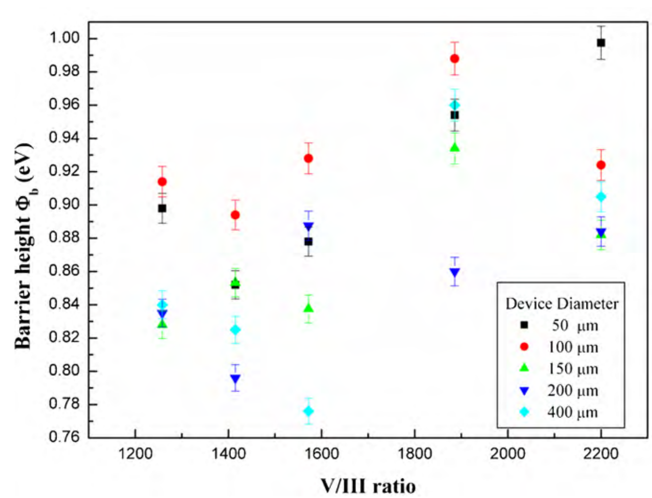

Fig. 4. The variation of barrier height extracted from the *I*–*V* characteristics of various diameter diodes with respect to the V/III ratio growth parameter.

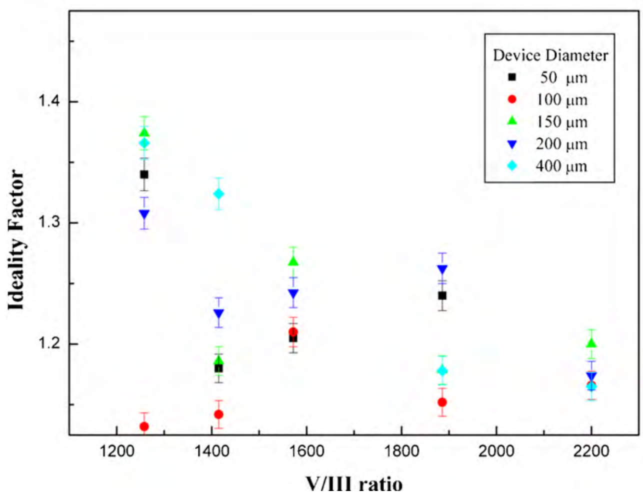

Fig. 5. The variation of ideality factor extracted from the *I–V* characteristics of various diameter diodes with respect to the V/III ratio growth parameter.

Fig. 4 shows the dependence of barrier height values on V/III ratio extracted from *I–V* characteristics of Pd/n-GaN Schottky diodes. All the data in the plot were average values of 4–5 diodes. The standard deviation was less than 0.05. Variation in barrier height was measured with respect to the V/III ratio which has no systematic dependence on contact diameter. The estimated barrier height varies from 0.75 to 0.98 eV on varying the V/III ratio, which agreed well with the theoretical prediction and earlier reported value for Pd/n-GaN Schottky diodes of 0.93 eV [19]. Previous experiments by Arehart et al. with Ni/n-GaN Schottky diodes made on different GaN templates with varying concentration of threading dislocations have showed no variation in the barrier height obtained from *I–V–T* results [15]. In the present investigation, barrier height of the Schottky diodes decreases as the V/III ratio is increased from 1258 to 1582, a further increase in V/III ratio results in the increase of barrier height value. This barrier height and similar variation of the series resistance may be explained based on the microscopic inhomogeneities within the diodes which induce localized current blocking high potential barrier regions. This current blocking leads to less than ideal *I–V* behavior due to the variations in the concentration of threading dislocations induced by the ammonia flow rate, which may have acted as compensating centers as supported by the Hall Effect measurements.

The dependence of the ideality factor on the V/III ratio is shown in Fig. 5. The ideality factor greater than 1 indicates that the conduction process inside the diode has both thermionic emission and field emission component. Both the thermionic and field emissions dominate the conduction for samples grown at low V/III ratio. As the V/III ratio increases the ideality factor of the diodes decreases. This suggests that higher V/III ratios generate more and more electron traps at the dislocation sites and could not participate in the quantum tunneling and other transport processes making the thermionic emission transport process dominant.

The reverse leakage current of 400 μm device at 5 V is around 90 nA which is three orders higher than the saturation current and has a dependence on reverse voltage, which implies that the leakage is through threading dislocations [20]. As shown in Fig. 6 on increasing the V/III ratio, leakage current decreases by almost two orders in magnitude from 1.07×10^{-6} to 8.332×10^{-8} A for a 150 μm sized diodes. Edge dislocations in GaN (deposited by MOCVD) have been identified as charge compensating acceptor levels [21], and first principles calculations and experimental studies with scanning current voltage microscope have shown that screw dislocations act as high electrical conductivity leakage paths

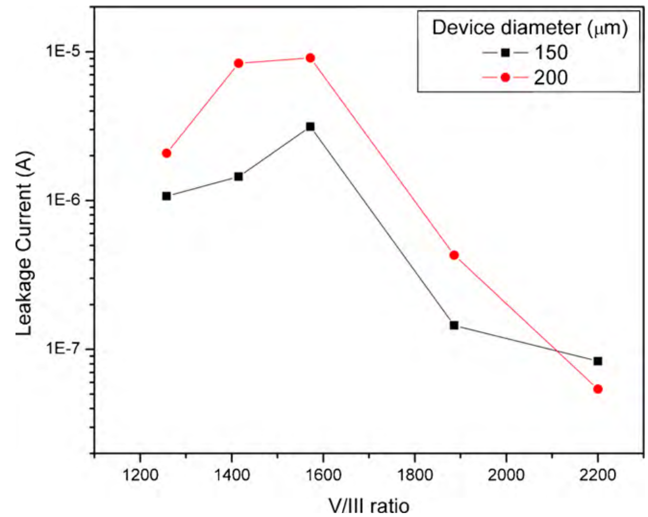

Fig. 6. The variation of reverse leakage current extracted from the *I–V* characteristics of 150 and 200 μm diameter diodes with respect to the V/III ratio growth parameter.

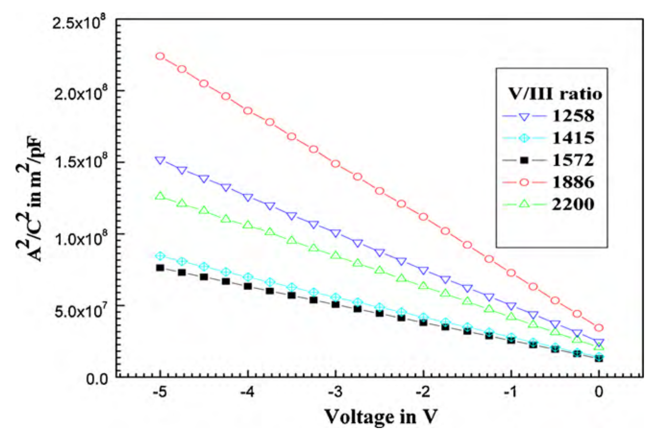

Fig. 7. A^2/C^2 vs. *V* plot of 400 μm diameter Schottky diodes.

[22,23]. It is known that the broadening of the FWHM of the X-ray rocking curve in the (1 0 2) asymmetric orientation is associated with edge type threading dislocations and it increases from 425 to 580 arcsec on increasing the V/III ratio and (0 0 2) symmet-

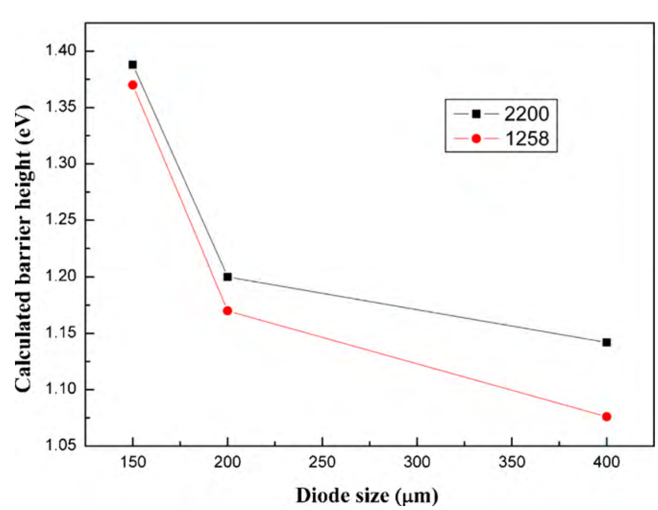

Fig. 8. The variation of barrier height extracted from the *C–V* measurements with respect to the diode size.

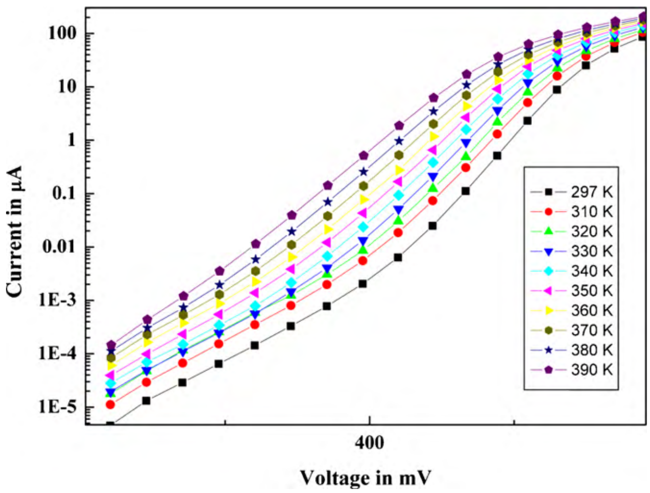

Fig. 9. The Current–Voltage characteristics for a 400 μm diameter contact between 298 and 390 K.

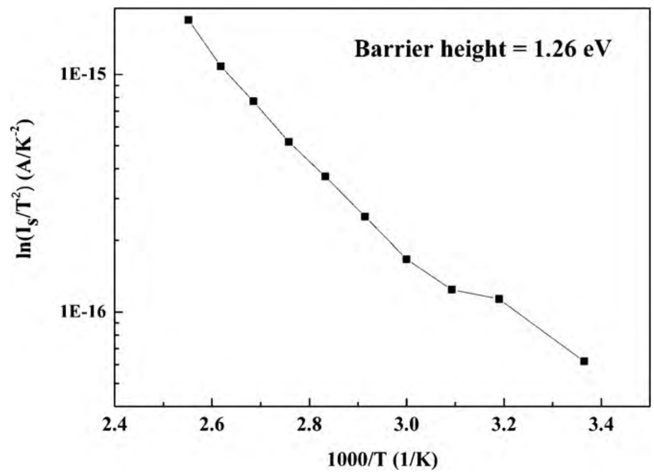

Fig. 10. The Richardson plot $\ln(I_s/T^2)$ vs. $1/T$ plot showing a linear variation and barrier height value is 1.26 eV.

ric orientation, associated with screw type threading dislocation decreases from 400 to 350 arcsec. *S*-parameter values from low energy positron beam annihilation analysis of the GaN samples, which is associated with the density of point defects that can trap positrons [16] increases on increasing the V/III ratio from 0.553 to 0.556. From the little variation in FWHM of the X-ray rocking curves, and *S*-parameter with increasing the ammonia flow rate, it is clear that the concentration of the point defects and edge type threading dislocation increases as screw type threading dislocation decreases. The edge type threading dislocation and point defect density increases whereas screw type threading dislocations decreases on increasing the V/III ratio effecting a decrease in the leakage currents.

3.3. *C–V* measurements

Fig. 7 shows the A^2/C^2 vs. *V* plot for the same Schottky diodes. In general, the plot of A^2/C^2 vs. reverse bias voltage for a Schottky barrier diode fabricated on a uniformly doped sample should be linear, with a gradient proportional to N_d^{-1}. Barrier height was extracted from the *C–V* measurements using the equation below:

$$\left(\frac{A}{C}\right)^2 = \frac{2(V_{bi} - V - K_B T/q)}{q\varepsilon_o K_s N_d}$$

where N_d is the donor density, the barrier height is defined by: $q\phi_b = q(V_{bi} + V_o)$. $V_o = K_B T/q \ln(N_c/N_d)$, $V_{bi} = V_i + K_B T/q$, V_i is the intercept voltage extracted from the A^2/C^2 vs. *V* plot, N_c is (2.55×10^{18} cm^{-3}) the effective density of states in the conduction band.

The barrier height trend observed with *C–V* measurements was found to be similar to that of *I–V* measurements with respect to the V/III ratio. The variation in barrier height with respect to the size of the diode is shown in Fig. 8. It shows a drastic increase in the *C–V* barrier height on decreasing the diode size from 400 to 150 μm. Device parameters extracted from *C–V* measurements are sensitive to several factors like deep traps within the barrier layer and varia-

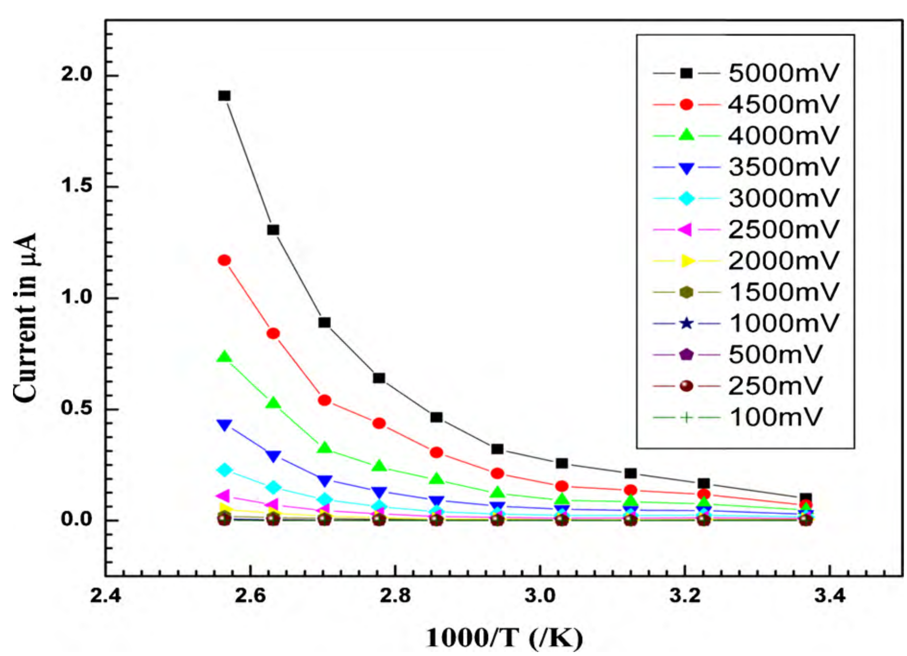

Fig. 11. Measured Current–Temperature characteristics for a Schottky diode at different reverse bias voltages.

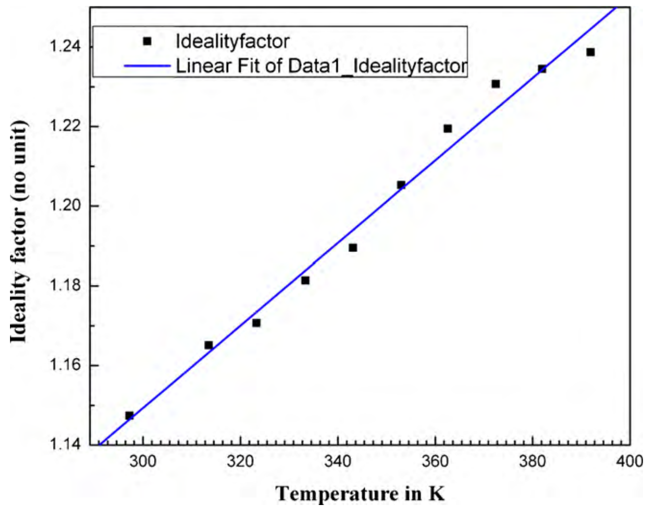

Fig. 12. The variation of ideality factor with temperature.

tion of effective area of the contacts [24]. For a diode diameter less than 150 μm we observed large variation in the slope of the line in A^2/C^2 vs. V plot. A detailed calculation with differential capacitance method shows that the interface of the small area diodes was not uniform due to presence of shallow and deep centers induced during device processing.

3.4. *I–V–T measurements*

Fig. 9 shows the forward *I–V–T* measurements of the 400 μm Schottky diode. The Richardson plot $\ln(I_s/T^2)$ vs. $1000/T$ in the case of a homogeneous diode is a straight line as shown in Fig. 10 in which the slope gives the barrier height. The barrier height calculated by fitting the I_s/T^2 vs. $1000/T$ is 1.26 eV which is comparable with the *I–V–T* barrier heights of Schottky diodes reported previously [15,25].

The reverse bias characteristic of the diode with respect to the temperature is shown in Fig. 11. Leakage current in GaN has been explained by a conduction mechanism associated with the threading dislocation in the material [23,26]. For temperatures of approximately 298 to 390 K, a thermally activated mechanism with exponential temperature dependence is clearly identifiable from Fig. 10. This mechanism was associated with either a two-step trap-assisted tunneling process or a one-dimensional variable-range hopping conduction along the threading dislocations in the material. It shows that the trapped electrons at the compensating centers were activated at high reverse voltages and high temperatures and thus contributes to the transport of the carriers.

Fig. 12 shows calculated ideality factor variation with temperature. As the temperature increases from 298 to 390 K, the ideality factor increases from 1.14 to 1.24. The deviation of ideality factor from unity is probably due to the increase of thermionic field emission or recombination current at the depletion region or interface [26]. This implies that there is recombination and trapping of carriers in the depletion region which may be due to the activation of the trapped electrons at the compensating centers especially at the edge dislocations.

4. Conclusions

Rectifying contacts of palladium were fabricated on n-GaN. Influences of V/III ratio on the defects generation and its effects on device parameters in Pd/n-GaN Schottky diodes were investigated using *I–V*, *C–V*, *I–V–T* measurements. Carrier concentration and Hall mobility of the as grown epilayers decreases with an increase in the V/III ratio due to the increase of compensating centers which was confirmed with conduction mechanism studies. *I–V–T* measurements showed that the ideality factor and reverse leakage current increases with temperature confirming the trap-assisted tunneling or deep center hopping type conduction. Nonideal *I–V* and *C–V* behavior and changes in parameters like barrier, ideality factor and leakage current of devices with V/III ratio are mainly due to the variation in concentration of point defects like Ga vacancy, edge and screw dislocations density.

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