INVESTIGATION OF CURRENT TRANSPORT PROPERTIES OF Ni SCHOTTKY DIODES FABRICATED ON MBE GROWN GaN ON SILICON SUBSTRATE

M. AJAZ-UN-NABI[a,*], K. MAHMOOD[a], M. I. ARSHAD[a,] A. ALI[a], N. AMIN[a], M. S. SHIFA[a], F. IQBAL[b], M. ASGHAR[b]
[a]*Department of Physics, Govt College University Faisalabad, Pakistan*
[b]*Department of Physics, The Islamia University of Bahawalpur, Pakistan*

The temperature dependent electrical properties of Ni Schottky diodes fabricated on GaN grown on silicon(111) substrate have been investigated in the wide temperature range of 165-420 K. The electrical parameters such as ideality factor and zero-bias barrier height were calculated from semi-logarithmic current-voltage (I-V) characteristics and found to be strongly temperature dependent. Such behavior is attributed to the barrier inhomogenities by assuming a Gaussian distribution (GD) of barrier heights at the Ni-GaN interface. It is evident that the diode parameters such as ideality factor decreases and zero-bias barrier height increases with increasing temperature. The temperature dependent behavior of these parameters is explained by considering two sets of Gaussian distribution (region I and II) in temperature range of 165-220 K and 220-420 K, respectively. The values for barrier height and Richardson constant also have been calculated as 0.63 eV, 25.6 $AK^{-2}cm^{-2}$ and 0.68 eV, 11.6 $AK^{-2}cm^{-2}$ from the modified Richardson plot for the respective temperature region. The calculated A^* value is close agreement with the standard value (26 $AK^{-2}cm^{-2}$) for n-GaN.

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1. Introduction

GaN is very promising material for electronic, high power and high frequency device applications [1-3] due to its amazing properties like wide band gap, high break down field and high electron saturation velocity [4,5]. Due to these remarkable properties, GaN emerges as potential candidate for light emitting diodes, laser diodes, high electron mobility transisters and filed effect transistors [6-8]. GaN has been conventionaly grown on foreign substrates i.e. sapphire, silicon carbide etc. These substrates have large lattice and thermal mismatch that induces large dislocation density in GaN layers. Furthermore, sapphire is insulating in nature that confronts many issues in the fabrication of GaN based devices [9-11]. In the recent years, silicon got great attention of researchers to be used as an alternative substrate for the growth of GaN. The Si has many remarkable advantages on other conventionally used substrates like its good thermal conductivity, significantly low cost, availabity in large diameter and obviously the possible its integration with well established Si based technology [12-15].However, all these applications of GaN are linked with the successful fabrication of Schottky and ohmic contacts. Due to technological importance of Schottky barrier diodes, the investigation of transport mechanism and contact behavior is of great interest. It is reported that room temperature current-volatge characteristics of Schottky barrier diodes usually deviate from the ideal thermionic model due to the strong dependence of both barrier height and ideality factor on temperature and nonlinearity of the Richardson plots [16-18]. This observed non-ideal behavior of Schottky barriers has been

[*]Corresponding author: majazunnabi@gcuf.edu.pk

attributed to the inhomogenity at the interface of metal and GaN. The temperature dependent characteristics of GaN based Schottky devices have been studied by many authors in different temperature ranges. Reddy et al. [19] investigated the temperature dependent electrical characteristics of Se/n-GaN Schootky barrier diodes in the temperature range of 130-400K. They observed the double Gaussian distribution of inhomoggeneous barrier heights in Se/n-GaN Schottky diodes. M. Siva et al.[20] suggested that Ni/Pd/n-GaN Schottky diode can be explained by assuming the existence of double Gaussian distribution of the Schottky barrier heights in the wide temperature range. Huang et al. [21] demonstrated the current transport mechanism in Au/Ni/n-GaN Schottky diodes using I-V in the temperature range 27-350 ^{0}C. They reported that thermionic emission model with a Gaussian distribution of Schottky barrier diode (SBD) is thought to be responsible for the electrical behavior at lower temperature, while the generation recombination process takes place at temperature above 230 ^{0}C. Lakshmi et al. [22] studied the current-voltage characteristics of Au/n-GaN (MIS) schottky contacts in the temperature range 120-390 K temperature range. Peta et al. [23] studied the I-V characteristics of (Pt/Au)/Ga polarity GaN/Si(111) Schottky diodes in the temperature range of 200-375 K. They reported the strong dependence of barrier height, ideality factor and series resistance on temperature. Dogan et al. [24] investigated the temperature dependent characteristics of Au/Ni /n-GaN Schottky diodes in the wide temperature range of 40-400 K. They explained the temperature dependence of SBHs in three different regions on the basis of Gaussian distributions successfully. However, there is no report available on the double Gaussian distribution inhomogenity of Ni schottky diode fabricated on GaN/Si(111) by MBE in literature, according to best of our knowledge. Therefore , a detailed study to explore the characteristics of Ni contact on GaN/ Si(111) is still needed.

In this paper, we have investigated the I-V characteristics of Ni Schottky contact on GaN grown on Si(111) substrate in the temperature range of 165-420K. The measured values of temperature dependent ideality factor and barrier height suggested that ideality factor decreases and barrier height increases as temperature increases. Furthermore, we observed a linear relationship between ideality factor and barrier height. The temperature dependence of SBH characteristics of Ni/GaN/Si(111) was interpreted on the basis of the existance of double Gaussian distributions of the barrier heights due to inhomogenites at the M/S interface.

2. Experimental procedure

MBE chamber was prepared for the growth of GaN on Si(1 1 1) substrate. The resisdent oxide on the polished surface of the Si (111) substrate was removed by pirhana procedure: i. 20 minutes dipping into a solution of H_2SO_4 (96%) and H_2O_2 (150:100 ml), ii. 10 minutes dipping into a flowing DI water, iii. Dipping into HF (49%) for 10s, iv. Imersion into flowing DI for 20 minutes followed by drying by nitrogen. As-cleaned substrate was loaded into the MBE chamber. During the 4 hours growth procedure, the chamber pressure, substrate temperature and gallium cell temperature were set as 1.4×10^{-9} Torr, 1050^{o}C and 930^{o}C, respectively. The nitrogin plasma was generated by RF powere supply maintained at 250W. It is pertinent to mention here that an amorphous layer of AlN to act as buffer layer was deposited for about 10 minutes while maintaining the substrate temperature 600^{o}C. For electrical characteracterization, circular dots of diameter (1mm, 2mm and 3 mm) of Ni were deposited on GaN, while Al layer of thickness 2000A was deposited on the Si (back) surface followed by heat treatment for 10 minutes at 450^{o}C. Various diagonastic techniques i.e. X-ray diffraction, FTIR spectroscopy, photoluminiscence (PL) spectroscopy and scanning electron microscopy (SEM) were performed to confirm the presence and quality of GaN on the Si substrate and repoted elsewhere (12). The temperature dependent I-V measurements of the Ni/GaN Schottky diodes were performed by automated deep level transient spectrometer (SEMILAB DLS-83). The device temperature was controlled with accuracy of ±1 K by temperature controller DLS-83D cryostat

3. Results and discussion

The current flow through the Schottky barrier diode can be explained by the thermionic emission theory. The I-V relationship of diode, neglecting series resistance is given as [19],

$$I = I_S\left[\exp\left(\frac{qv}{nkT}\right) - 1\right] \tag{1}$$

Where n is the ideality factor and I_S is the reverse saturation current given by the relation,

$$I_S = AA^*T^2\exp\left[\frac{-q\phi_B}{kT}\right] \tag{2}$$

Where A is the contact area, A^* is the Richardson constant and its value is 26 AK^{-2} cm^{-2} for n-GaN [25]. T is temperature in Kelvin, k is the Boltzmanns constant (k= 8.617×10^{-5}eV/K), q is the electric charge and φ_B is the barrier height.

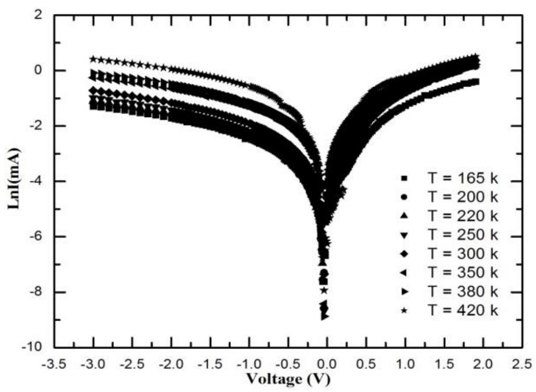

Fig. 1. Semi log I–V characteristics of Ni/GaN/Si(111)Schottky barrier diode in the temperature range of 165

The ideality factor n at different temperatures was calculated by the slope q/nkt of semi-log plot of the forward bias I–V curve (Fig. 1) by using the relation,

$$n = \frac{q}{kT\times slope} \tag{3}$$

The semi-log plot of the (I–V) curve (Fig.1) was used to calculate the barrier height ϕ_B(I-V) by using the following relation [26],

$$\phi_{B(I-v)} = \frac{kT}{q}\ln\left(\frac{AA^*T^2}{I_S}\right) \tag{4}$$

Where k =8.617×10^{-5}eV/K, T is the temperature in Kelvin, A is the contact area =0.78mm^2 and A^* is the Richardson constant having value 26 AK^{-2} cm^{-2} for n-GaN[25].

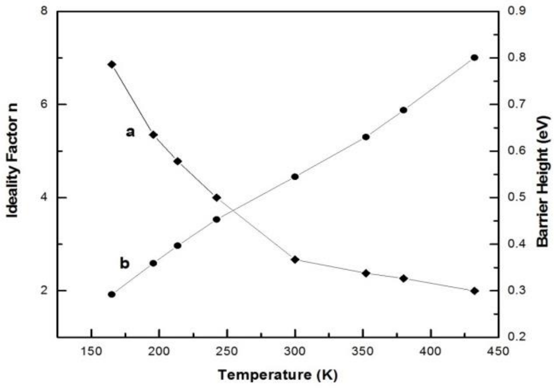

Fig. 2: Plot of ideality factor and barrier height versus temperature for Ni/GaN/Si(111)Schottky diode

The calculated room temperature values of n and BH for Ni/GaNSchottky diode are 2.6±0.01 and 0.55±0.01 eV, respectively. The variation of ideality factor and barrier heights with temperature are demonstrated in Fig.2. It is observed that ideality factor decreases and barrier height increases with increasing temperature. The temperature dependence behavior of ideality factor and barrier height indicates the inhomogeneous nature of Schottky barrier height [27,28].

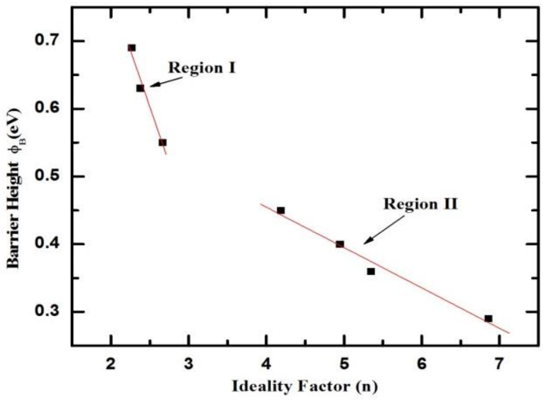

Fig. 3.Schottky barrier heights versus ideality factor of the Ni/GaN/Si(111)Schottky barrier diode in the temperature range of 165–420 K

Figure 3 shows a plot of ideality factor and barrier height for Ni/GaN Schottky diode. This straight line plot indicates a linear relationship between experimental effective barrier height and ideality factor of Schottky diodes. Again, the decrease of ideality factor and increase of barrier height with increasing temperature shows a discontinuity at the Ni/GaN interface. Similar results have been reported in the literature [19]. The graph in Fig. 3 demonstrated that there are two linear regions between experimental zero-biased BH and ideality factor, which can be explained by lateral inhomogenities of BH. The extrapolation of experimental barrier height and ideality factor plot for n=1 gives mean values of barrier heights 0.63 and 0.68 eV for region I and II respectively.
This barrier height inhomogeneity can be explained by using Gaussian distribution model of barrier height. According to this model, the barrier height can be written as [29]

$$\varphi_{ap} = \varphi_{bo} - \frac{q\sigma_s^2}{2kT} \quad (5)$$

where φ_{ap} is the apparent BH which can be measured experimentally, φ_{bo} is the mean BH and σ_s is the standard deviation of the BH distribution. The standard deviation is the measure of barrier homogeneity. The temperature dependence of σ_s is usually small and can be neglected.
In this model the observed variation of ideality factor with temperature is given by [30]

$$\frac{1}{n_{ap}} = -\rho_2 + \frac{q\rho_3}{2kT} \qquad (6)$$

where n_{ap} is the apparent ideality factor and ρ_2 and $\rho_3$are voltage coefficients which may depend on temperature and they quantify the voltage deformation of the BH distribution.

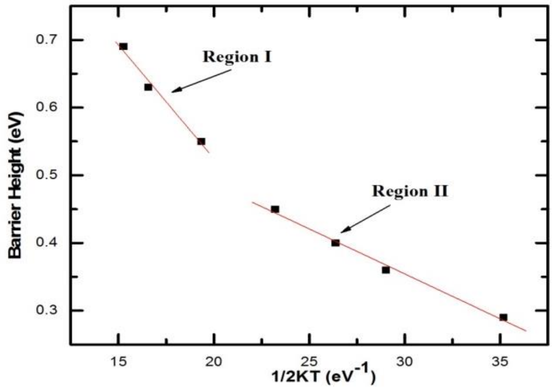

Fig. 4: Zero-bias apparent barrier height versus 1/(2kT) curves of the Ni/GaN/Si(111) Schottky diode according to double Gaussian distributions of BHs. The data show linear variation in the two temperature ranges with a transition around 220 K.

Fig. 4 shows a plot between φ_{ap} and 1/2kT for Ni/GaN Schottky diode. The Fig. 4 demonstrated that there are two straight lines instead of single line which indicates the presence of double Gaussian distribution at the interface [31]. Furthermore, the linear relationship between barrier height and 1/2kT shows that temperature dependent I-V data is in agreement with Gaussian distribution model [32,33]. The intercept and slope of this plot gives the mean barrier height and the zero-bais standard deviation with values 0.63 ±0.01, 0.68 ±0.01 eV and 0.034 ±0.001, 0.013±0.001 eV for distribution I and II respectively. The inhomogenity of the interface depends upon the value of standard deviation i.e. lower value of standard deviation corresponds to more homogeneous barrier heights.

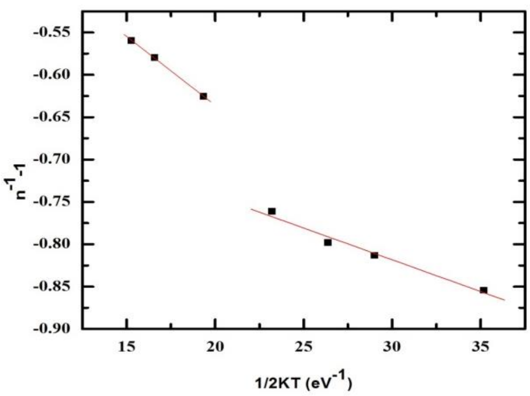

Fig. 5: Ideality factor versus 1/(2kT) curves of the Ni/GaN/Si(111)Schottky diode according to twoGaussian distributions of BHs. The data show linear variation in the two temperature ranges with a transition around 220 K.

The plot of ($1/n_{ap}$-1) verses 1/2kT is again has linear relationship with two distributions shown in Fig. 5. The values of voltage coefficients ρ_2 and ρ_3 can be calculated from the intercept and slope of this graph. The values of ρ_2 obtained from the intercept of experimental n_{ap} verses 1/2kT curve are 0.31 ±0.01 eV for region I and 0.59 ±0.01eV for region II while the values of ρ_3 obtained from the slope are -0.016 ±0.01 eV and -0.0075 eV for region I and II respectively.

It is reported fact that conventional Richardson plot (1000/T verses $\ln AA^*$) plot normally deviate from linearity at low temperature. Therefore according to Gaussian distribution of barrier height, we can write equation for modified Richardson constant as [34],

$$\ln\left(\frac{I_o}{T^2}\right) - \left(\frac{q^2\delta^2}{2k^2\,T^2}\right) = \ln(AA^*) - \frac{q\varphi_b}{kT} \quad (7)$$

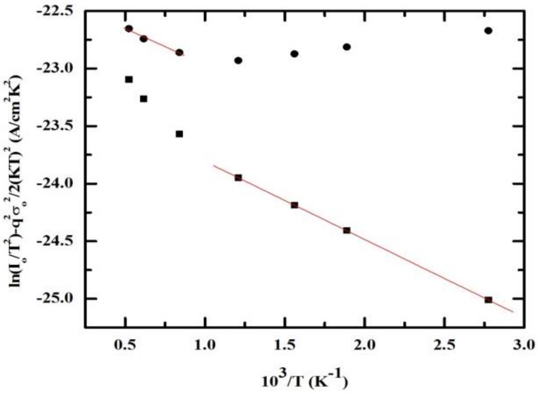

Fig. 6: Modified Richardson $\ln(Io/T^2)-(q^2\sigma^2/2k^2T^2)$ versus 1000/T plot of theNi/GaN/Si(111)Schottky barrier diode according to the double GD of BHs for distribution I and II.

The plot of a modified ln (Io/T^2)–$q^2\sigma^2/2k^2T^2$ versus 1000/T, according to Eq. (7) should give a straight line with the slope directly yielding the mean barrier height and the intercept (ln AA^*) at the ordinate determining A^* for the given diode area A [35]. The ln (Io/T^2)–$q^2\sigma^2/2k^2T^2$ versus 1000/T values are calculated for both values of σ obtained for the temperature range of 165–220 K (Region I) and 220-420K (Region II) as shown in Fig.6. The calculated values of barrier heights and Richardson constants for Region I and II are 0.63 ±0.01 eV, 0.68 ±0.01 eV and 25.6, 11..5 $AK^{-2}cm^{-2}$ respectively. The Richardson constant value of 25.6 $AK^{-2}cm^{-2}$ for temperature range 220–420 K is very closer to the theoretical value (26.4 $AK^{-2}cm^{-2}$) in case of n-type GaN.

4. Conclusions

we have investigated the transport characteristics of Ni-GaN Schottky diodes using double Gaussian distribution model of Schottky barrier heights in the temperature range 165-420 K. The decrease of ideality factor and increase of barrier height demonstrated inhomogenous nature of Ni-GaN Schottky diodes. The temperature-dependent current–voltage characteristics of the Schottky barrier heights have shown a double Gaussian distribution giving mean BHs of 0.63 ±0.01, 0.68 ±0.01 eV and standard deviations of 0.034 ±0.001 and 0.013±0.001 eV, respectively. The modified Richardson plot was also drawn to calculate the value of Richardson constant with value 25.6 $AK^{-2}cm^{-2}$. These results suggest that the experimental data of the Ni-GaN Schottky diodes can be explained by assuming the existence of double Gaussian distribution of the Schottky barrier heights in the wide temperature range.

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