Temperature-Dependent Barrier Characteristics of Inhomogeneous Pd/n-GaN Schottky Barrier Diodes Surface

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Abstract—The current-voltage ($I-V$) characteristics of Pd/n-GaN Schottky barrier were studied at temperatures over room temperature (300-470K). The values of ideality factor ($n$), zero-bias barrier height ($\Phi_B$), flat barrier height ($\Phi_{FB}$) and series resistance ($R_s$) obtained from $I-V-T$ measurements were found to be strongly temperature dependent while ($\Phi_B$) increase, ($n$), ($\Phi_{FB}$) and ($R_s$) decrease with increasing temperature. The apparent Richardson constant was found to be $2.1 \times 10^9$ Acm$^{-2}$K$^{-2}$ and mean barrier height of 0.19 eV. After barrier height inhomogeneities correction, by assuming a Gaussian distribution (GD) of the barrier heights, the Richardson constant and the mean barrier height were obtained as 23 Acm$^{-2}$K$^{-2}$ and 1.78eV, respectively. The corrected Richardson constant was very close to the theoretical value of $26$ Acm$^{-2}$K$^{-2}$.

Keywords—Electrical properties, Gaussian distribution, Pd-GaN Schottky diodes, thermionic emission.

I. INTRODUCTION

GALLIUM NITRIDE (GaN) has a direct band gap of 3.4 eV, which has a broad range of electrical applications, especially in high temperature electronic devices, optoelectronic and high-electron devices. Intensive activities on high-power devices, short-wavelength light (blue, violet) emitting diodes (LEDs), and laser diodes (LDs) have been conducted [1].

To construct such devices, it is necessary first to clarify the physics of metal/GaN interface and its influence on electrical characteristics of metal/GaN Schottky diodes. Many researchers using high work function metals as Schottky contacts like Ni, Pt and Pd report Schottky contacts on GaN [2]-[9]. It is well known that the electrical characteristics of a Schottky contact are controlled mainly by its interface properties. Thus, the study of interface states is important for the understanding of the electrical properties of Schottky contacts.

The analysis of the $I-V$ characteristics of metal/semiconductor diodes at wide temperature range allows us to understand different aspects of barrier formation and current-transport mechanisms and gives information about the quality of the contacts especially at temperatures higher than room temperature. A lot of work has already been reported on electrical characterization but there are few works studied the temperature dependence of electrical characteristics of GaN Schottky diodes [10]-[14]. Akkal et al. [10] investigated the current-voltage characteristics of Au/n-GaN Schottky diodes below room temperature in the range 80-300 K. Osvald et al. [11] investigated the temperature dependence of the electrical characteristics of GaN Schottky diodes with two crystal polarities (Ga- and N-face). They reported a decrease in the barrier height with a decrease in temperature and an increase in ideality factor for both polarities. Arehart et al. [12] studied the impact of threading dislocation density on the Ni/n-GaN Schottky diode using forward measurements. Tekeli et al. [13] investigated the behavior of the forward bias ($I-V-T$) characteristics of inhomogeneous (Ni/Au)-Al$_{0.3}$Ga$_{0.7}$N/AlN/GaN heterostructures in the temperature range of 295–415 K using double layers of metal and multi layers of GaN and AlN. Recently, Ravinandan et al. [14] reported on the temperature-dependent electrical characteristics of the Au/Pd/n-GaN Schottky diode in the temperature range of 90–410 K.

This study aims to gain insight about the current-transport mechanism through a single metal contact of palladium on GaN (Pd/GaN) by measuring their electrical properties from room temperature to well above it (300-470 K). This is very important in order to get more accurate results on single metal Schottky contact on single GaN layer operating at higher temperature. The values of ideality factor ($n$), zero-bias barrier height ($\Phi_B$), flat barrier height ($\Phi_{FB}$) and series resistance ($R_s$) were extracted from the forward bias $I-V$ measurements. The temperature dependence of the Schottky barrier height of Pd/GaN are interpreted based on the existence of the Gaussian distribution (GD) of the barrier heights around a mean value due to the barrier height inhomogeneities prevailing at the metal-semiconductor interface.

II. EXPERIMENTAL PROCEDURES

The samples used in this study were commercial n-GaN grown by metalorganic chemical vapor deposition (MOCVD) on Al$_2$O$_3$ substrates. The electron concentration (Si doped) obtained by Hall measurements was n = $1 \times 10^{17}$ cm$^{-3}$. The samples were cleaned first with acetone and methanol, then secondly in 1:20 NH$_4$OH:H$_2$O for 10 min, followed by a third cleaning in 1:50 HF: H$_2$O solution to remove the surface oxides. This was followed by a fourth cleaning in 3:1 HCl: HNO$_3$ at 80 °C for 10 min. Between the cleaning steps, the samples were rinsed in deionized water. After cleaning the diode was completed by deposition of Pd on a portion of the sample of n-GaN using the A500 Edwards RF magnetron.
sputtering unit. The ultimate pressure was $1 \times 10^{-6}$ mbar, which was raised to $2 \times 10^{-2}$ mbar by purging the chamber with high purity argon (Ar 99.99%); the power of sputtering was 150 W. The (I-V) measurement of the sample was carried out using the Keithley model 2400 on different temperature in the range of 300-470 K and in the dark. The operation temperature of the diode was measured by a calibrated K-type thermocouple mounted on the device.

III. RESULTS AND DISCUSSION

Typical current-voltage (I-V) characteristics of the Pd/GaN Schottky diode measured in atmospheric conditions, in the temperature range of 300-470 K are shown in Fig. 1. From the figure, one can observe that the contact of Pd with an n-type GaN acts as rectifying junction for forward and reverse currents. The figure also shows an increment of the linear region as the temperature increases. Meanwhile the non-linear region shows a decrease of series resistance as temperature increases (Fig. 1 (b)).

Current transports in a diode are governed by two regimes. At low voltage, it is governed by thermionic emission and at higher voltage it is governed by other mechanisms than thermionic emission [10].

$$I = I_0 \exp\left(\frac{q(V - I R_s)}{n kT}\right)$$

where $V$ is the voltage across the diode, $n$ the ideality factor, $k$ is the Boltzmann constant, $R_s$ is the series resistance and $I_0$ is the saturation current given by

$$I_0 = A A'^2 T^2 \exp\left(-\frac{q \phi_{Bat}}{kT}\right)$$

where $q$ is the electron charge, $T$ is the temperature in Kelvin, $A$ is the contact area, $A'$ is the Richardson constant and $\phi_{Bat}$ is the Schottky barrier height. By plotting $ln(I)$ vs. $V$ for each temperature in the range (300-470 K) for the Pd/GaN Schottky diode we get a straight line with the slope $= q/ nkT$ and y-intercept ($V=0$) at $I_n$. From the value of $I_n$, Schottky barrier height $\phi_{Bat}$ (zero-bias barrier height) was calculated using (2) [18]. In addition, from the slope the ideality factor $n$ was calculated, which is a measure of the thermionic emission current transport ideality.

$$\phi_{Bat} = (n-1)(E_C - E_F)$$

$$E_C - E_F = \frac{KT \ln(N_C)}{q}$$

Fig. 2 shows the barrier height and ideality factor as a function of temperature in the temperature range (300–470 K) for the Pd/GaN Schottky diode.

From this figure, one can observe that the ideality factor $n$ decreases with increasing temperature while the zero-bias barrier height increased with increasing temperature, which agrees with the thermionic emission theory. These indicate that the contact between Pd and GaN enhanced with increasing temperature.

When ideality factor is larger than unity thermionic emission is not the only mechanism that contributes to the transfer of current. The barrier height obtained under the flat band condition is called the flat band barrier height and is considered as the real fundamental quantity. The flat band barrier height, $\phi_{BF}$ can be derived from $\phi_{Bat}$ using the following equation [11]:

$$\phi_{BF} = n\phi_{Bat} - (n-1)(E_C - E_F)$$

where $E_F$ is the Fermi energy and $E_C$ is the conduction band energy, the energy difference between the conduction band and the Fermi level is given by

$$E_C - E_F = \frac{KT \ln(N_C)}{q}$$

where $N_C$ is the effective density of states in the conduction band and $N_D$ is the donor concentration. Assuming that the electron effective mass and $N_D$ do not change with the
Temperature, but the effective density of states in the conduction band \( N_C \) will change with the temperature according to the relation \( N_C (\text{cm}^{-3}) = 2.6 \times 10^{18} \left( \frac{T}{300} \right)^{3/2} \) [10], [19]-[21]. Based on these equations the flat band barrier height \( \phi_{BF} \) can be obtained. The results are shown in Fig. 3. One can observe that the flat barrier height slightly decreased with temperature, while the zero-bias barrier height increases with temperature. The difference between the zero-bias and the flat barrier height values may come from the fact that, the thermionic emission is not the only mechanism by which electrons can cross the Schottky barrier.

\[
N_C (\text{cm}^{-3}) = 2.6 \times 10^{18} \left( \frac{T}{300} \right)^{3/2}
\]

Fig. 3 The barrier height for Pd/n-GaN Schottky diodes vs. temperature

Equation (2) can also be used to construct a Richardson plot of \( \ln (I_0/AT^2) \) versus \( 1/kT \), with the slope giving \( \phi_{BB} \) and \( A^{**} \) is determined by the intercept. This plot is shown in Fig. 4.

\[
I_0 = A A^{**} T^2 \exp \left( \frac{q \phi_{BB}}{kT} \right)
\]

where \( I_0 \) is the current at a bias \( V \) for a barrier of height \( \phi_{BB} \) based on the ideal thermionic emission diffusion (TED) theory and \( P (\phi_B) \) is the normalized distribution function giving the probability of accuracy for barrier height. Performing this integration, one can obtained the current \( I(V) \) through a Schottky barrier at a forward bias but with a modified barrier as

\[
I(V) = I_0 \exp \left( \frac{q V}{n_{ap} kT} \right) \left[ 1 - \exp \left( -\frac{q V}{kT} \right) \right]
\]

with

\[
I_0 = A A^{**} T^2 \exp \left( \frac{q \phi_{BB}}{kT} \right)
\]

where \( \phi_{BB} \) and \( n_{ap} \) are the apparent barrier height at zero bias and apparent ideality factor, respectively given by [25], [28]

\[
\phi_{ap} = \phi_B (T = 0) - \frac{q \sigma_0^2}{2 kT}
\]

\[
\frac{1}{n_{ap}} - 1 = \rho_2 = \frac{q \rho_1}{2 kT}
\]

We need to assume that the mean Schottky barrier height \( \phi_B \) and \( \sigma_0 \) are linearly bias-dependent on Gaussian parameters, such that \( \phi_B = \phi_B (T = 0) + \rho_1 V \) and standard deviation \( \sigma_0 = \rho_2 V \), where \( \rho_1 \) and \( \rho_2 \) are voltage coefficients which may depend on temperature [29]. The temperature dependence of \( \sigma_0 \) is small and therefore can be neglected [30].
We attempted to draw a $\varphi_0$ versus $q/2kT$ plot (Fig. 5) to obtain the value of the GD of the barrier heights and from the intercept and the slope the values of $\varphi_0$ and $\sigma_0$ are 1.753 eV and 0.225 respectively. The structure with the best rectifying performance presents the best barrier homogeneity with the lower value of the standard deviation. It was seen that the value of $\sigma_0$ is not small compared to the mean value values of $\varphi_0$, and it indicates the presence of interface inhomogeneities. Therefore, the plot of $[1/(n-1)]$ versus $q/2kT$ should be a straight line that gives the voltage coefficients $\rho_2 = 0.161$ V and $\rho_2 = 0.038$ V from the intercept and slope, respectively (as shown in Fig. 5). Now, by combining (8) and (9), the Richardson plot can be modified to

$$\ln\left(\frac{I_0}{T^2}\right) - \frac{q^2 \sigma_0^2}{2kT^2} = \ln(AA^{**}) - \frac{q\varphi_{00}}{kT} \tag{11}$$

The plot of the modified $\ln\left(\frac{I_0}{T^2}\right) - \frac{q^2 \sigma_0^2}{2kT^2}$ versus $q/kT$, should give a straight line with the slope yielding the mean $\varphi_{00}$ as 1.78 eV and the intercept (ln $AA^{**}$) at the ordinate determining $A^{**}$ for a given diode area $A$ as 23 A/cm$^2$ K$^{-2}$ (as seen in Fig. 6), respectively, without using the temperature coefficient of the SBHs. As can be seen, $\varphi_{00}$ = 1.78 eV from this plot according to (11), in good agreement with the value of $\varphi_{00}$ = 1.75 eV from $\varphi_0$ versus $q/kT$ (Fig. 5). Therefore, it can be concluded that the temperature dependence of the forward $I-V$ characteristics of the Pd/GaN can be successfully explained based on the thermionic emission mechanism with a Gaussian distribution of barrier heights.

**REFERENCES**


