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EFFECT OF SERIES RESISTANCE AND INTERFACE STATE DENSITY ON ELECTRICAL CHARACTERISTICS OF Au/SiO$_2$/n-GaN SCHOTTKY DIODES

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We have investigated the current-voltage (I – V) *characteristics of (Au/SiO$_2$/n-GaN) metal-insulator-semiconductor (MIS) Schottky diodes and compared with (Au/n-GaN) metal-semiconductor (MS) Schottky diode. The effect of SiO$_2$ on the surface preparation of n-GaN (MIS) Schottky diode is analyzed. The extracted Schottky barrier height and ideality factor of the MS Schottky diode is found to be* 0.79 *eV and* 1.45 *respectively. It is observed that the Schottky barrier height increases to* 0.86 *eV and ideality factor decreases to* 1.3 *for MIS diode. The interface state density as determined by Terman's method is found to be* 3.79×10^{12} *and* 3.41×10^{10} cm^{-2} eV^{-1} *for the MS and MIS Schottky diodes, respectively. In addition, the values of series resistance* (R_s) *are determined using Cheung's method. The* I – V *characteristics confirmed that the distribution of* N_{ss}, R_s *and interfacial layer are important parameters that influence the electrical characteristics of MIS Schottky diodes.*

Keywords: *METAL-INSULATOR-SEMICONDUCTOR CONTACTS, SCHOTTKY BARRIER HIEGHT, IDEALITY FACTOR, INTERFACE DENSITIES.*

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1. INTRODUCTION

Gallium nitride (GaN) has been widely used in optoelectronic devices such as light emitting diodes [1], laser diodes [2] and UV detector. On the other hand, excellent physical and electronic properties of GaN have also attracted much attention for electronic device development. Metal-insulator-semiconductor (MIS) structure is important for device application. MIS technology is desirable since it provide a high dc input impedance, large gate voltage swings, normally off operation with high source-drain blocking voltage and high temperature operation as a result of reduced gate leakage.

Surface and interface properties play an important role in the electrical performance of metal-semiconductor (MS) Schottky diodes and metal-insulator-semiconductor (MIS) structures with small dimensions. The performance of these devices especially depends on the formation of interfacial insulator layer between metal and semiconductor, the interface states located at the semiconductor/insulator interface, series resistance and an inhomogeneous Schottky barrier contacts. There are currently a vast number of reports of experimental studies on Schottky barrier heights in a great variety of MS and MIS Schottky diodes [3-6].

2. EXPERIMENTAL DETAILS

Si-doped GaN samples used in this study were grown by metal-organic chemical vapor deposition (MOCVD) on a c-plane Al_2O_3 substrate. The carrier concentration obtained by means of Hall measurements was $\sim 4.07 \times 10^{17}$ cm $^{-3}$. The n-GaN was first ultrasonically cleaned with warm trichloroethylene followed by acetone and methanol for 5 min each. This layer was then dipped into boiling aqua-regia [HNO_3: HCl = 1:3] for 10 min to remove the surface oxides and then rinsed in deionized (DI) water. Ti (25 nm)/Al (100 nm) were deposited on a portion of the sample as ohmic contacts using an electron beam evaporation system under a vacuum pressure of 4×10^{-6} mbar. The samples were annealed at 650 °C in N_2 ambient for 3 min. First Au (50 nm) Schottky contact with a diameter of 0.7 mm were deposited through stainless steel mask using e-beam evaporation on one of the piece of GaN film. A 20 nm thick SiO_2 layer was deposited on the other piece of GaN sample followed by 50 nm thick Au by electron beam evaporation system. Au evaporation processes were carried out in a vacuum coating unit at a pressure of about 5-6 $\times 10^{-6}$ mbar. The current-voltage (I-V), capacitance-voltage (C-V) characteristics of Au/n-GaN (MS) and Au/SiO_2/n-GaN (MIS) Schottky contacts were measured using Keithley source measuring unit 2400 and automated DLTS (DLS-83D) system at room temperature.

3. RESULTS AND DISCUSSION

3.1 Current-voltage (I – V) characteristics

The current-voltage characteristics are used widely to study the performance of the Schottky contacts since they offer many important device parameters. Fig. 1 shows the forward and reverse biased curves of Au/n-GaN (MS) and Au/SiO_2/n-GaN (MIS) Schottky diodes at room temperature. For forward bias and $V > 3kT/q$, the following equation describe the I-V characteristics of the Schottky diode according to the thermionic emission theory [7],

$$I = I_s \exp\left(\frac{q(V - R_s I)}{nKT}\right) \tag{1}$$

where saturation current I_s is expressed by,

$$I_s = AA^{**}T^2 \exp\left(-\frac{q}{kT}\varphi_b\right) \tag{2}$$

where q is the electronic charge, T the measurement temperature in Kelvin, n the ideality factor, A^{**} the effective Richardson constant (by using an effective mass of 0.22 m_e for n-GaN, the value of A^{**} is calculated to be 26.4 Acm $^{-2}$K $^{-2}$), k the Boltzmann constant, R_s the series resistance, φ_b the zero-bias barrier height and A the contact area. Measurements show that the value of the barrier height for MS and MIS Schottky diodes are 0.79 eV and 0.86 eV respectively. The increase in barrier height of the Au/n-GaN Schottky diode with insulating layer could be explained by an increase in negative charges at the interface. These negative charges probably arise due to electron traps localized at the GaN interface and associated with Ga vacancies created near the surface during the formation of insulating layer. Consequently it is clear that the different barrier heights could be due to modified-interface chemistry.

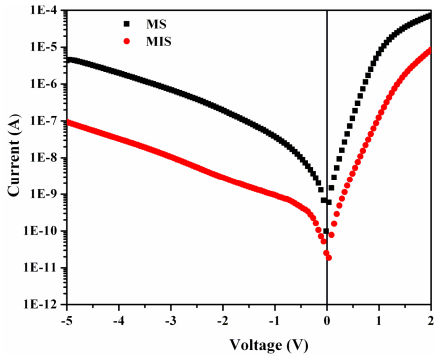


Fig. 1 *– Typical current-voltage characteristics of the Au/n-GaN (MS) and Au/SiO_2/n-GaN (MIS) diodes at room temperature*

The values of series resistance R_s were estimated using the method developed by Cheung [8] at higher current range (over which the I-V characteristics is not linear). The Cheung's functions are given as,

$$\frac{dV}{d(\ln I)} = IR_s + \left(\frac{kT}{q}\right) \tag{3}$$

$$H(I) = V - \frac{nkT}{q}\ln\left(\frac{I}{AA^{**}T^2}\right) \tag{4}$$

$$H(I) = IR_s + n\varphi_b \tag{5}$$

should give a straight line for the data of downward curvature region in the forward bias I-V characteristics. The term IR_s is the current drop across the series resistance of Schottky diodes.

Fig. 2 (a) shows the experimental dV/dlnI versus I plot for the MS and MIS Schottky diodes respectively. Thus the values of R_s and nkT/q have been obtained from the slope and y-axis intercepts of the dV/dlnI versus I plot respectively. From Fig. 2(b), it is evident that the plot of H(I) versus I gives a straight line with the y-axis intercept equal to n φ_b and the slope parameter can be used to check the consistency of cheung's method. However, it can be clearly seen that there is relatively difference between the values of ideality factor obtained from the downward curvature regions of forward bias I-V plots and from the linear regions of the same characteristics. The reason of this difference can be attributed to the existence of effects such as series resistance and the bias dependence of Schottky barrier height according to the voltage drop across the interfacial layer and change of the interface states with the bias in the low voltage region of the I-V plot. Table 1 shows the series resistance values determined from the Cheung's equations, ideality factor and barrier height.

3.2 Determination of interface state density (N_{ss})

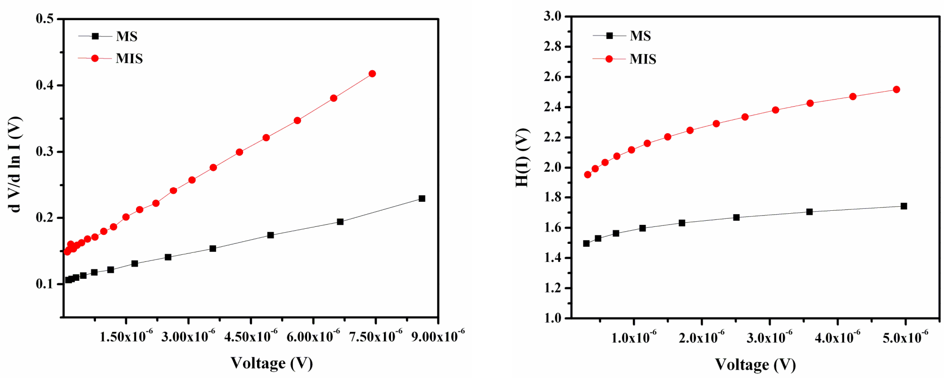
The interface state density for electrons or holes is always affected by the interfaces must not necessarily introduce energy levels in the band gap. At high forward bias voltages, the nonlinearity of the I-V characteristics of the MIS Schottky diode indicate the presence of continuum of interface states in equilibrium with the semiconductor [9]. The expression for the interface state density can be given as,

$$Nss(V) = \frac{1}{q}\left[\frac{\varepsilon_i}{\delta}(n(V)-1) - \frac{\varepsilon_s}{W_D}\right] \quad (6)$$

where W_D is the space charge region width, $n(V) = V/(kT/q)\ \ln(I/I_s)$, ε_s and ε_i are the permitivities of the semiconductor and the insulator layer (SiO_2), respectively. In an n-type semiconductor, the energy of the interface states E_{ss} with respect to the bottom of the conduction band at the surface of the semiconductor is given by,

$$E_c - E_{ss} = q(\varphi_b - V) \quad (7)$$

Equations (6)-(7), along with the I-V characteristics can be used for the determination of the interface state density as a function of interface states energy E_{ss} with respect to the bottom of the conduction band. The resulting dependence of N_{ss} was converted to a function of E_{ss} using equation 7. N_{ss} versus $E_c - E_{ss}$ is also shown in Fig. 3. Increase in effective barrier height φ_b of both the diodes forward bias is observed. This may be due to the increase in quasi-Fermi energy level of the majority carriers on the semiconductor side. This causes most of the electrons will be injected directly into the metal forming a thermionic emission current, while some of them are trapped by the interface states. This charge capture process results in an increase in effective barrier height thereby reducing the diode current [10, 11].



a b

Fig. 2 – *Plot of series resistance (a) dV/dlnI versus I of Au/n-GaN (MS) and Au/*SiO_2*/n-GaN (MIS) diodes (b) H(I) versus I of Au/n-GaN (MS) and Au/*SiO_2*/n-GaN (MIS) diodes*

Table 1 – *Various parameters determined from* I-V *characteristics of MS and MIS n-GaN Schottky diodes*

Sample	Ideality factor (n)	Barrier height (eV)	Series resistance R_s (Ω)		Interface density (from Terman's method)
			$dV/d\ln I$ versus I	$H(I)$ versus I	
MS	1.45	0.79	123.99	130.25	3.79×10^{12}
MIS	1.30	0.86	682.79	788.17	3.41×10^{10}

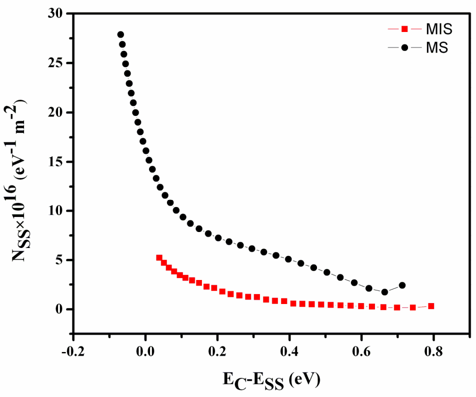


Fig. 3 – *Interface state density distribution profiles as a function of* $E_c - E_{ss}$ *for MS and MIS diodes*

The interface state density as determined by Terman's method is found to be 3.79×10^{12} and 3.41×10^{10} cm^{-2} eV^{-1} for the MS and MIS Schottky diodes respectively [12]. From Fig. 3, it can be seen that an exponential increase in interface states density exists from mid gap towards the bottom of the conduction band. This rise is less significant for the MIS diode compared to that of the MS diode. At any specific energy, the interface state density of the MIS diode is less compared to that of the MS diode, which may be due to the fact that MIS diode has a thick oxide layer than that of the MS diode [10-11 and 13] because of the saturation of dangling bonds.

4. CONCLUSIONS

In this study, the interface properties of Au/n-GaN and Au/SiO_2/n-GaN Schottky diodes have been investigated by current-voltage (I-V) measurement. The calculated value of the barrier height for MS and MIS Schottky diodes are found to be 0.79 eV and 0.86 eV respectively. The downward curvature at sufficiently large voltages is caused by the effect of series resistance R_s, apart from the presence of the interface states, which are in equilibrium with the semiconductor. The value of the R_s has been calculated from high voltage region of the structure by using Cheung's functions. It is seen that there is a good agreement between the values of the series resistance obtained from two Cheung's plots. We conclude that the non-ideal behaviour of I-V characteristics MIS Schottky diodes have been controlled by the interfacial insulator layer and interface states.

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