CHAPTER 5

STUDY OF ELECTRICAL CONDUCTION IN
Ni/Au –GaN SCHOTTKY DIODES

GaN and its heterostructures have become the promising materials for the light emitting diodes, photodetectors, and high temperature/high power electronic devices. GaN-based electronic and optoelectronic devices, including blue lasers (Miyajima et al. 2001), visible light emitting diodes (LEDs) (Nakamura et al. 1994), metal semiconductor field-effect transistor (Asif Khan et al. 1993a), high electron mobility transistors (HEMT) (Asif Khan et al. 1993), UV photodetectors (Asif Khan et al. 1992) have been demonstrated. High quality ohmic and Schottky contacts are demanded for these devices.

5.1 METAL CONTACT

If the n-type and p-type semiconductors are in a very close contact a p-n junction is formed, which is commonly used as a diode. Like the way when a metal surface is brought in contact with a semiconductor surface – it forms two types of contacts. Contact to semiconductor basically consists of region of semiconductor surface just below first metal layer, metal semiconductor interface and few layers of metallization above it. Invariably the as deposited contact does not give the desired properties (either low resistance or high Schottky barrier). So the contacts are annealed which results in the formation of different complex intermetallic compounds by way
of solid state reaction among metal layers and semiconductor surface. Thus a contact simply is referred to as the region of metal semiconductor interface that leads to desirable electrical characteristic. The current transport in metal-semiconductor contact occurs by majority carriers. There are two different types of contacts namely Ohmic and Schottky. In ohmic contact the current-voltage relation follows Ohms law that is it should be linear. The contact resistance should be very low so that there is negligible voltage drop across it and hence negligible power drop. This is very important for devices and more so in power application where minimum loss and maximum efficiency is required. Another critical requirement for high temperature application is the need to have contact which does not degrade or rather have a high resistance to degradation. Smooth surface morphology, sharp edge acuity and reliability and reproducibility are other features that are desired in an ideal contact. Another type of contact is schottky contact, or rectifying contact in which large current can flow in one direction at small voltage and almost no current in reverse direction. High barrier height is essential for producing rectifying effects.

Whether a metal-semiconductor interface forms an ohmic or schottky contact depends upon the metal work function, $\phi_m$, and semiconductor work function, $\phi_s$. Work function is the amount of energy required to excite an electron from Fermi energy level to the vacuum level. The semiconductor work function ($\phi_s$) is sum of the electron affinity ($\chi$) and energy difference between Fermi energy ($E_F$) and the bottom of the conduction band ($E_c$).
Theoretically, on n-type semiconductor, ohmic contact is formed when $\phi_m < \phi_s$, and schottky contact is formed when $\phi_m > \phi_s$. Conversely, in p-type material, $\phi_m > \phi_s$ and $\phi_m < \phi_s$ produces ohmic and rectifying contact, respectively.

5.1.1 Schottky Contact

When an intimate contact is formed between metal and a semiconductor, the Fermi levels in the two materials should be equal at thermal equilibrium. This can be achieved through a charge flow from semiconductor to metal. Thus a barrier forms at their interface and an equal and opposite space charge is distributed over the barrier region near the semiconductor surface as shown in the Figure 5.2.
The Schottky barrier heights of metal–semiconductor systems with intimate contact are, in general, determined by both the metal work function and the surface states. The current transport in metal-semiconductor contacts is mainly due to majority carrier, in contrast to p-n junctions. Two major processes under forward bias are (a) transport of electrons from the semiconductor over the potential barrier into the metal; (b) quantum-mechanical tunneling of electrons through the barrier. In addition, we may have (c) recombination current in the space-charge region and (d) in neutral region and leakage current at the contact periphery.

Figure 5.3 Current Transport Mechanisms
The transport of electrons over the potential barrier is often the dominant process for Schottky diodes on moderately doped semiconductors. It can be adequately described by thermionic emission theory for high mobility semiconductor and the electric current density over the barrier has the following expression

$$J = J_s \left[ \exp \left( \frac{q(V - JR_s)}{nk_B T} \right) - 1 \right]$$

(5.1)

We have taken the account of series resistance $R_s$, which is usually represented by the combination of a Schottky diode and a resistor through which the current flows. Hence the voltage $V_d$ across the diode is expressed as a function of the total voltage drop $V$ across the device, with $V_d = V - JR_s$ and $J_s$ is the saturation current density given by

$$J_s = A^{**} T^2 \exp \left[ - \frac{q \Phi_B}{k_B T} \right]$$

(5.2)

where $\Phi_B$ and $n$ are the effective barrier height and the diode ideality factor, $A^{**}$ is the Richardson constant ($26.4 \text{Acm}^{-2}\text{K}^{-2}$) and $k_B$ is the Boltzmann constant.

A number of metals such as Au, Ni, Ti, Pd, Pt, PtSi, Ni/Au, Pt/Au, and indium tin oxide (ITO) (Zhu et al 2000, Bandic et al 1999, Liu et al 1997, Yu et al 1998, Sheu et al 1998, Liu et al 1998, Schmitz et al 1996, Hacke et al 1993, Schmitz et al 1996, Noh et al 2001) have been deposited for the rectifying behaviour on nitride materials. In these the barrier height is found to be varied from 0.8 to 1.4 eV. It is known that the Schottky diode behaviour depends on the metal used, the morphology of the semiconductor, the processing used for diode formation and an interfacial states and defects.
5.1.2 Ohmic Contact

A semiconductor device should be connected to the outside world with no adverse change to its current-voltage characteristics. This can be accomplished through ideal ohmic contacts to the semiconductor. An ohmic contact is defined as a metal/semiconductor contact that has negligible contact resistance relative to the bulk or spreading resistance of the semiconductor. A satisfactory ohmic contact can supply the required current with a voltage drop that is sufficiently small compared with the drop across the active region of the devices. One important figure of merit for ohmic contact is specific contact resistance $r_c$, which is defined as

$$r_c = \left( \frac{\partial j}{\partial V} \right)_{V=0}$$

(5.3)

Typically in ohmic contact the tunnelling mechanism occurs in the current transport. It is difficult to make ohmic contacts on wide-bandgap semiconductors, such as GaN ($E_g = 3.4$ eV, $c = 4.1$ eV) and SiC. Generally the doping concentration is relatively low due to the high ionization level of typical dopants.

A wide variety of metallization schemes have been attempted for ohmic contact for n- GaN. Some of the earliest report of ohmic contact to n-GaN had Al as the ohmic contact metal with specific contact resistivity of $\sim 10^{-7}$ $\Omega \cdot cm^2$ (Foresi and Moustakus 1993). Specific contact resistivity of $8 \times 10^{-6}$ $\Omega \cdot cm^2$ using Ti/Al was achieved after 900$^\circ$C anneal for 30sec in N$_2$ ambient (Lin et al 1994, Luther et al 2000) and also Ti/Al (Guo et al 1995), Ni/Al (Lee et al 1998), Ti/Al/Ti/Au (Fan et al 1996) were reported. Among many such contact metallization schemes, Ti/Al/Ni/Au (Qin et al 2004, Ruvimov et al 1996) contacts are a kind of the most widely used ones for ohmic contact formation to n-GaN and this metal combination is used in this
study. The minimum specific contact resistance of $8.9 \times 10^{-8} \ \Omega \ cm^2$ has been achieved by Ti/Al/Ni/Au when the contact was annealed at 900°C in N$_2$ ambience (Fan et al 1996).

Different new phases are often formed at the metal semiconductor interface, as a result the electrical properties of the contact formed will change drastically. These phases are often thin and patchy, and may be formed in close proximity at interface. Ruvimov et al (1998) have studied the formation of a thin polycrystalline cubic TiN layer at the metal composite-GaN interface. The formation of epitaxial interface nitride phases is thought to induce nitrogen vacancies in the GaN surface, which act as n-type doping centers and thus improve the tunneling mechanism of electron across the interface, which reduces the contact resistance (Sawada et al 2002).

5.2 FABRICATION OF THE DIODE

Three random samples of size 1cm x 1 cm are taken for the diode fabrication. Following the surface cleaning of the grown epilayers, the Ohmic and Schottky contacts are formed by electron beam evaporation through a metal shadow mask. For Ohmic contact the metal combination of Ti/Al/Ni/Au with thickness in the order of 200Å/1500Å/600Å/1000 Å has been made and annealed at 775°C under nitrogen atmosphere for 5 minutes by rapid thermal annealing (RTA). The most common contact scheme used is Ti/Al bilayer with Ni/Au, Au is used for reducing sheet resistance of the layers and to prevent oxidation during high temperature annealing. RTA allows uniform heating and cooling that reduces thermal gradients that can lead to warping and stress-induced defects, enabling more dense design and fewer failures due to dislocations. Circular Ni/Au Schottky dots are formed with the deposition of Ni and Au films of approximate thickness 300Å and 1200Å.
5.3 CAPACITANCE – VOLTAGE BEHAVIOR

To study the behavior of the schottky diode, the electrical measurements are carried out. The primary interest of the C-V measurement is to understand the nature of the depletion region created in the diode. The capacitance in the thin insulating layer between the metal and semiconductor can be expressed as

\[
C^{-2} = 2 \frac{V_{bi} - \frac{k_B T}{q} - V}{A^2 q^2 N_d \epsilon_s \epsilon_0}
\]

(5.4)

where \(V_{bi}\) is the built-in potential, \(N_d\) is the donor concentration, \(A\) is the area of the diode, \(V\) is the applied gate voltage and \(\epsilon_s\) is the relative dielectric constant of the semiconductor. The C - V curve at various frequencies of the diode A is shown in the Figure 5.5.

When a small ac voltage is applied to a Schottky diode, various defect energy levels sweep through the quasi-Fermi level, which produce an oscillation in the charge density. If the frequency is higher than the level response time, it cannot respond. The \(C^{-2} - V\) plot of the diodes at the frequency 10 KHz is shown in the Figure 5.6.
From the non-linearity of the $C^{-2} - V$ plot in the samples C, it is apparent that this schottky diode has the presence of bulk traps and surface states. The Value of the built-in potential is extracted from the voltage axis intersection and the doping concentrations of the samples are determined from the slope.
5.4 CURRENT – VOLTAGE BEHAVIOUR

Figure 5.7 shows the measured current density vs voltage (J-V) curve. For analysing the diode characteristics the diode equation based on thermionic emission theory is used. A method to extract the series resistance $R_s$ of an ideal Schottky diode i.e., with $n = 1$ was first proposed by Norde (1979). Later Sato et al (1985) modified Norde’s approach for the cases $n > 1$, to extract the values of the ideality factor, the barrier height, and the series resistance from the forward I-V data. In this approach two experimental I-V measurements conducted at two different temperatures were required. Cheung and Cheung (1985) gave an alternative approach for determining the values for the diode parameters using a single I-V measurement. This method was very efficient for extracting the series resistance $R_s$, the barrier height $\phi_B$, and the ideality factor $n$ of a Schottky diode and it was applied in the present study.

![Figure 5.7 Current vs applied voltage plot](image)

According to them the equation (5.2) can be modified as

$$v = R_s AJ + n\phi_B + \frac{nK_BT}{q} \ln \left( \frac{J}{A^eT^2} \right)$$  \hspace{1cm} (5.5)
Differentiation of equation (5.5) with respect to J and rearrangement lead to the following function

\[ \frac{dv}{d(ln J)} = R_s A J + \frac{nK_B T}{q} \quad (5.6) \]

A plot of \( \frac{dV}{d(ln J)} \) vs J yields \( R_s A \) as the slope (in figure 5.8) and \( nK_B T/q \) as the intercept on the y axis. A function \( H(J) \) was defined to evaluate \( \phi_B \)

\[ H(J) = V - \frac{nK_B T}{q} \ln \left( \frac{J}{A^{\phi_B} T^2} \right) \quad (5.7) \]

From equation (5.6), one can deduce the equation,

\[ H(J) = n \phi_B + R_s A J \quad (5.8) \]

**Figure 5.8 Plot of \( \frac{dV}{d(ln J)} \) vs J**

One can determine the \( n \) value from equation (5.6), using that a plot \( H(J) \) vs J (in Figure 5.9) also yields a straight line with a y-axis intercept \( n\phi_B \).
The slope of this plot allows a second determination of $R_s$ that can be used to check the consistency of this approximation. Thus, by plotting two different graphs using the results obtained from a single I-V measurement, all three parameters of the diode, $n$, $\varphi_B$ and $R_s$ can be determined. The obtained values are tabulated in table (5.1). The sample C shows soft diode like behaviour. From Figure 5.10, it is evident that the surface defects decreased the diode properties and it much favours the tunneling. And there is also large leakage current in the reverse bias.

Guo et al (1996) have shown the thermal stability of Ni – n GaN (grown by LP- MOCVD) schottky diode. They observed the formation of nickel gallium and nickel nitrate alloys as the diode is annealed and also the variation in the barrier height with the annealing. Schmitz et al (1996) have characterized the Schottky barriers of Ti, Cr, Au, Pd, Ni and Pt on n-type GaN epitaxial layers grown by low-pressure metal-organic chemical vapour deposition on sapphire. For Ni contact they reported the barrier height of 0.99 eV using the Norde calculation. Noha and Bhattacharya (2001) have reported the effect of carrier concentration (doping) in the diode parameters of Au metal contact to n-GaN grown by MOCVD. In our samples the effect of
variation in carrier concentration (defects occurred during the growth) in the diode parameters is shown in table 5.1. Sun et al (2002) have calculated the ideality factor of 1.47 and barrier height of 0.689 eV in Ni/Au/n-GaN contact to n-type unintentionally doped GaN epilayers grown by MOCVD.

Figure 5.10  SEM image of the sample C the white line are the scratches made during the measurement. Encircled area shows the presence of defects

In the Thin Surface Barrier (TSB) model (Oyama et al 2002) in Figure 5.11, the surface defects are taken into account. (Hashizume et al 2004) have shown that the barrier thinning caused by unintentional surface defects enhances the tunneling process in leading to large leakage currents through GaN and AlGaN Schottky interfaces. So the enhancement of the tunneling by the surface defects may likely be the reason for the observed large leakage current.
Figure 5.11 Thin Surface Barrier model

Table 5.1 Determined Diode parameters

<table>
<thead>
<tr>
<th>Sample</th>
<th>Donor concentration (cm$^3$)</th>
<th>n (I-V)</th>
<th>n (dV/dlnJ)</th>
<th>$R_s$ (dV/dlnJ)</th>
<th>$R_s$ (H(J))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>6.87 x 10$^{16}$</td>
<td>1.5</td>
<td>1.7</td>
<td>1972</td>
<td>1751</td>
</tr>
<tr>
<td>B</td>
<td>8.22 x 10$^{16}$</td>
<td>1.6</td>
<td>1.9</td>
<td>1051</td>
<td>908</td>
</tr>
<tr>
<td>C</td>
<td>2.12 x 10$^{17}$</td>
<td>2.4</td>
<td>2.9</td>
<td>115</td>
<td>97</td>
</tr>
</tbody>
</table>

5.5 BARRIER HEIGHT DETERMINATION

The Schottky barrier height can be obtained from C-V measurement by knowing the built in voltage using the expression,

$$\phi_B = V_{bi} + \xi + \frac{k_B T}{q}$$  \hspace{1cm} (5.9)

where $\xi$ is the position of the Fermi level relative to the bottom of the conduction band. The calculated barrier height is given in Table (5.2). There is some difference in the values determined comparing to the I-V measurements. Werner and Guttler (1991) demonstrated that spatial inhomogenieties rather
than a thin interfacial layer at the metal semiconductor may actually be responsible for a possible anomaly in the \( I - V \) characteristics, leading to a difference between the barrier height determined by C-V and I-V methods. The difference in the values thus obtained is due to the response of capacitance to deep level traps. The capacitance–voltage method yields the flatband barrier height, whereas the current–voltage method yields the zero-bias barrier height. In general, the flatband barrier height is a better measure of the barrier height than the zero-bias barrier height (Suzue et al 1996).

![Diagram of Image Force Lowering Barrier](image.png)

**Figure 5.12 Image – force lowering barrier**

As is apparent that the barrier height obtained from the thermionic emission model is affected by the image force barrier lowering given by (Rhoderick et al 1996),

\[
\Delta \phi_B = \left[ \frac{q^2 N_d}{8 \pi^2 \phi_s^2} \left( \phi_B - V - \xi - \frac{k_B T}{q} \right) \right] ^{\frac{1}{2}}
\]  

(5.10)

From the figure 5.12 it can be seen that the presence of the surface defects mainly develops the image potential. It is evident that image-force lowering becomes more effective with increasing doping concentration or the defects. The intrinsic barrier height, \( \phi = \phi_B + \Delta \phi_B \) is calculated and given in
Table 5.2. Possible effects of unoccupied states of a thin insulating layer, or of charges existing at the semiconductor -metal interface may cause the zero-bias barrier height to be lower than the flatband barrier height. The zero bias barrier height of the sample C is higher indicating that the thermionic emission model alone cannot explain the current transport in this.

**Table 5.2 Effective Barrier height of the samples**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Barrier lowering $\Delta\phi_B$ (eV)</th>
<th>Intrinsic Barrier height $\phi = \phi_B + \Delta\phi_B$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\phi_B$ (I-V) $\phi_B$ (C-V)</td>
</tr>
<tr>
<td>A</td>
<td>0.04608</td>
<td>0.84 0.91</td>
</tr>
<tr>
<td>B</td>
<td>0.04822</td>
<td>0.86 0.92</td>
</tr>
<tr>
<td>C</td>
<td>0.05084</td>
<td>0.68 0.50</td>
</tr>
</tbody>
</table>

5.6 CONCLUSION

The experimental investigation of the Ni/Au-GaN Schottky diodes has been carried out. Both current–voltage and capacitance–voltage measurements have shown interesting characteristics. An analysis has been carried out to understand the physical mechanisms underlying the anomalous current–voltage characteristics. The diode parameters of the samples are calculated based on Cheung and Cheung model. The effect of image-force lowering has been taken into account. Out of three diodes studied, two of the sample diodes (A and B) show the reasonable barrier height and the other parameters. The other one (sample C) shows soft diode behaviour due to the presence of the surface defects, which is expected to immensely modify its surface charge density and enhance the tunneling property. Its current leakage also indicates the presence of traps at the interface or the defects at the surface.