Chapter 2

Physics of Metal-Semiconductor Contact and Circular Transmission Line Model (CTLM)

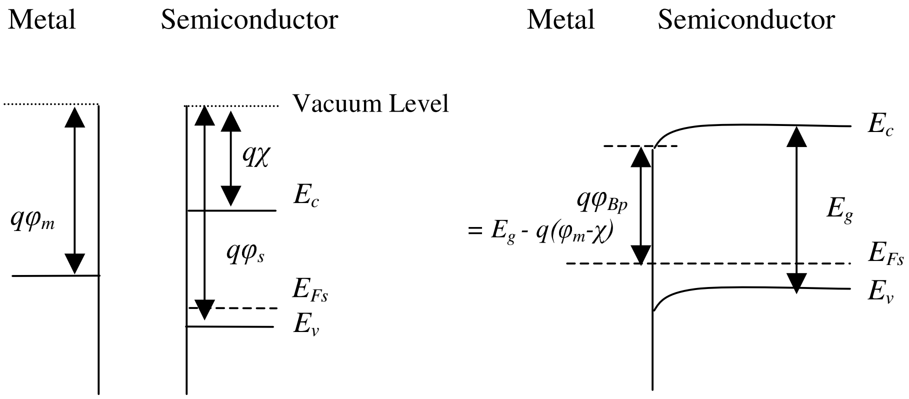
2.1 Introduction

It is imperative that a semiconductor device can be connected to the outside world with no adverse change to its current-voltage characteristics and no additional voltage drop. It can be accomplished only through low-resistance ohmic contact on the semiconductor. An ideal ohmic contact is one where, when combined with the semiconductor, no barriers to the carrier flow are encountered in either the positive and negative direction. Ideally, this occurs when the work functions of the semiconductor and the metal are about the same, and there are no appreciable interface states which tend to pin the Fermi Level. However, it is not possible as the work function of the semiconductor varies with doping concentration and for wide bandgap semiconductor such as p-GaN, there is an added difficulty because it is impossible to find a metal that has a large enough workfunction. Hence, it is not an easy task to achieve a good ohmic contact between p-GaN and metal.

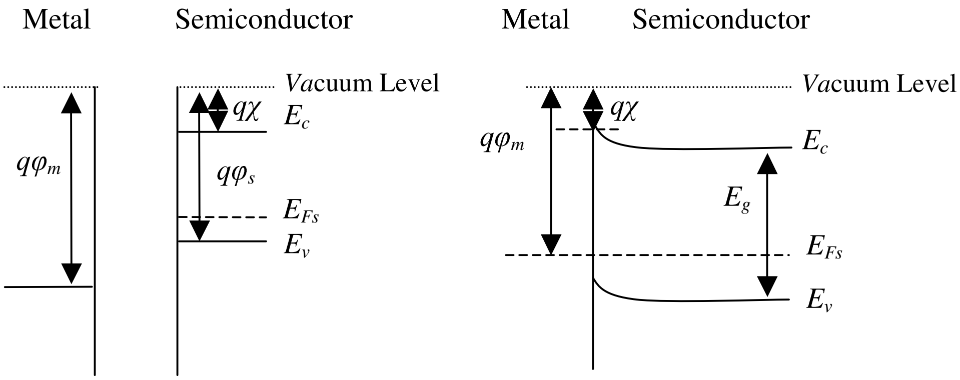
In order to provide some understanding on ohmic contacts, basic physics of metal-semiconductor contact is briefly discussed in this chapter. In addition, the basic principles of the circular transmission line model (CTLM), which is used to measure the specific contact resistance ρ_c, are introduced.

2.2 Metal to p-type Semiconductor Contact

When a metal and a semiconductor with different workfunctions are brought into contact at thermal equilibrium, their Fermi levels are forced to align [6, 47-48]. The energy band diagrams for the metal to p-type semiconductor interface [47-48] are depicted in Figure 2.1.



(a) p-type, $q\varphi_m < q\varphi_s$ (rectifying)



(b) p-type, $q\varphi_m > q\varphi_s$ (ohmic)

Figure 2.1 Energy band diagrams of metal to p-type semiconductor contacts.

The ohmic or rectifying characteristics of the contact depends upon the work function of the metal ($q\varphi_m$) and that of the semiconductor ($q\varphi_s$). With reference to Figure 2.1, it is seen clearly that a depletion region is formed near the surface of GaN in Figure 2.1(a) while an accumulation layer is formed in Figure 2.1(b). This indicates that for p-type semiconductors, the contact is ohmic if $q\varphi_m > q\varphi_s$, and rectifying if $q\varphi_m < q\varphi_s$. The latter forms a Schottky barrier according to the Schottky-Mott model [47-48]. The height of the Schottky barrier for p-type semiconductor ($q\varphi_{Bp}$), measured relative to the Fermi level, as indicated in Figure 2.1 (a), is given by [48]:

$$q\varphi_{Bp}= E_g- q(\varphi_m-\chi) \tag{2.1}$$

where $q\varphi_m$ = Workfunction of the metal;

$q\varphi_s$ = Workfunction of the semiconductor;

$q\chi$ = Electron affinity of the semiconductor; and

$q\varphi_{Bp}$ = Schottky barrier height of p-type semiconductor

Several other interfacial phenomena also affect contact resistance including surface states present at the semiconductor surface, causing the barrier height to be less sensitive of the metal work function ($q\varphi_m$). An explanation of this weak dependence on $q\varphi_m$ was put forward by Bardeen [49]. According to the Bardeen model [49], the Fermi level at the interface between a metal and a semiconductor is pinned by interface states originating from the surface states or interfacial reactions and this is known as Bardeen limit.

As shown in Figure 2.2, the barrier height ($q\varphi_{Bp}$) is 'pinned' by the high density of surface states, and is given by:

$$q\varphi_{Bp} = q\varphi_o \qquad \text{(p-type semiconductor)} \qquad (2.2)$$

where $q\varphi_o$ = Neutral energy level.

The meaning of $q\varphi_o$ is explained as follows with reference to Figure 2.2. Assuming a continuous distribution of surface states at the interface between the semiconductor and the native oxide, a series of energy levels are formed on the surface. Among these, the neutral energy, $q\varphi_o$, will nearly coincide with the Fermi level when the metal-semiconductor contact is formed. It specifies the energy level below which all surface states are filled for charge neutrality at the surface [49].

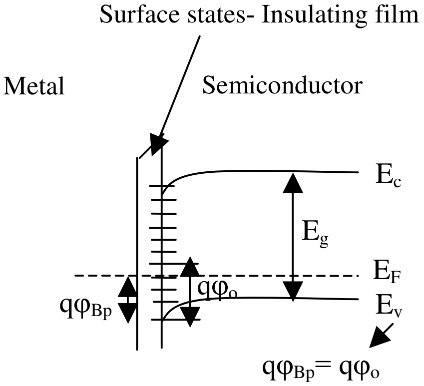


Figure 2.2 Metal to p-type semiconductor contacts with surface states.

The higher the density of surface states is, the lesser is the deviation of $q\varphi_o$ from E_F. As a result, the barrier height, $q\varphi_{Bp}$, is given by equation (2.2). It is seen that it is determined by the property of the semiconductor surface and is independent on the workfunction of the metal.

From the above mentioned two models, the Schottky-Mott model and the Bardeen model, the Schottky-Mott model is more appropriate for metal/GaN contact as it has been reported in recent papers [50-51] that GaN does not suffer from Fermi level pinning. Nevertheless, they provide some guide on the choice of the metal system for the p-type semiconductor. The following can be concluded from Figure 2.1 and equation (2.1): metals with higher work function are more likely to yield ohmic contacts; hence Pd is a good candidate as it has a comparable high workfunction (5.11eV). This forms the basis to the author's study of the Pd-based contacts on p-type GaN.

It is important to note that the current conduction across a metal/semiconductor contact can be due to thermionic emission and tunneling (field emission), depending on the doping concentration of semiconductor. In general, the tunneling or field emission makes the present-day ohmic contact possible. For metal/ semiconductor contact, a useful characteristic energy E_{00} is defined as [48]:

$$E_{00} = 0.5(q\hbar)\sqrt{(N_D/m^*\varepsilon)} \qquad (2.3)$$

where q = Electronic charge;

$\hbar$ = Planck's constant;

N_D = Doping level of the semiconductor;

m^* = Electron tunneling effective mass; and

ε = Permittivity of semiconductor.

For $E_{00} >> kT$, field emission is the dominant current transportation mechanism through the metal/ semiconductor interface. Therefore, one can infer from equation (2.3) that, for a constant temperature, a highly doped semiconductor material is essential to form an ohmic contact.

The doping levels of all samples used in the current project are moderate, i.e. ~10^{17}cm^{-3}. According to equation (2.3), the characteristic energy, E_{00} has been calculated to be less than kT. Hence, the thermionic emission should be considered.

2.3 Specific Contact Resistance

For a contact between two dissimilar materials, such as metal and semiconductor, there exists a contact resistance, R_c, which is a metal- and geometry-dependent parameter as its magnitude is determined by the sheet resistance of the conducting semiconductor, the contact area, and etc. Consequently, contact resistance is not a useful parameter to characterize contacts.

Another parameter that is independent on the measurement and geometry of the contact, known as the specific contact resistance, ρ_c, is often used to parameterize the interface. It is defined as the resistance of a unit area of the thin interfacial layer between the bulk metal and semiconductor substrate, as given by [52]:

$$\rho_c = \left[\frac{\partial J}{\partial V} \right]_{V=0}^{-1} [\Omega . cm^2] \qquad (2.3)$$

where J = Current density through the interface; and V = Potential drop across the interface.

Physically, ρ_c is the finite resistance seen by the infinitesimal current crossing the metal-semiconductor interface that has an infinitesimally small potential difference, as seen in Figure 2.3.

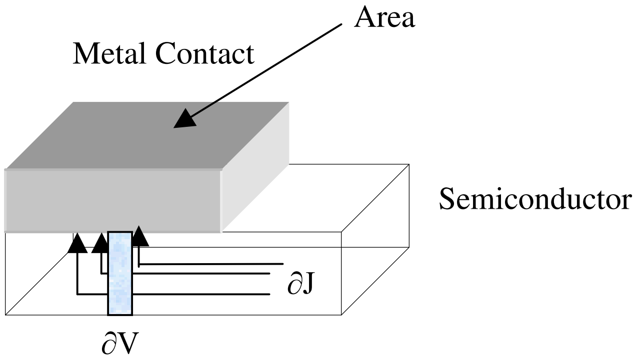


Figure 2.3 Physical layout of a metal/ semiconductor contact.

As the specific contact resistance ρ_c cannot be measured directly but must be inferred from a measurement on a real contact, hence several approaches [52-53] have been used to model the current-voltage behavior of the contact and to extract ρ_c from the equations from the measured quantities of current (*I*) and voltage (*V*). One of the approaches is circular transmission line method (CTLM) which will be discussed in detail in **Section 2.4**.

2.4 Circular Transmission Line Method (CTLM) [51]

In the following section, the basic concepts and principles of CTLM are presented.

2.4.1 Contact Geometry

Test pattern of either circular or rectangular geometry is commonly used to determine the specific contact resistance of ohmic contact systems in semiconductor devices [52], as depicted in Figure 2.4 and Figure 2.5. However, a mesa structure needs to be fabricated if the rectangular test pattern is used [53], unlike circular test patterns where such complication can be totally avoided. The definition of mesa is required to confine the current flow between two contacts. As a result, circular pattern has been chosen in this work.

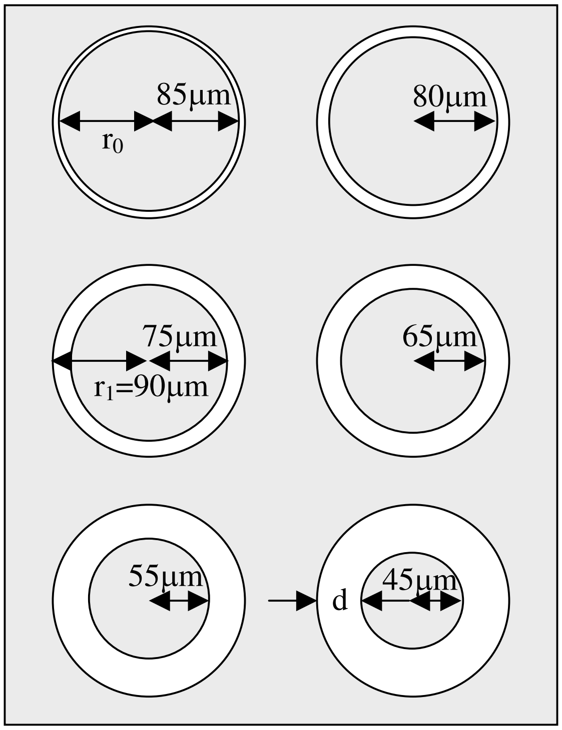


Figure 2.4 Test pattern for ohmic contact characterization: Circular pattern, where r_o is the radii of the inner circular contact; r_1 is the radii of the outer region; and d is the difference between r_o and r_1.

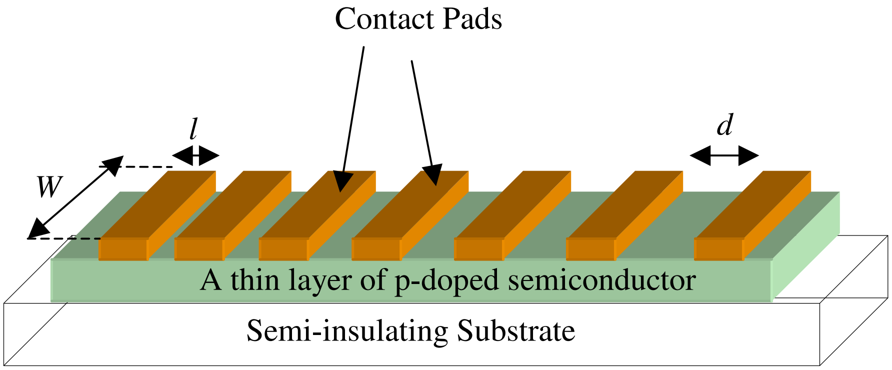


Figure 2.5 Test pattern for ohmic contact characterization: Rectangular pattern where *W* is the width of the pads, *l* is the length of the pads and *d* is the contact pad separation.

2.4.2 Derivation of Specific Contact Resistance

By having a constant current (i_o) through the inner circular and outer contact pads using a Precision Parameter Analyzer, as indicated in Figure 2.6, there will be a voltage drop, ΔV, across the separation (d) between two points.

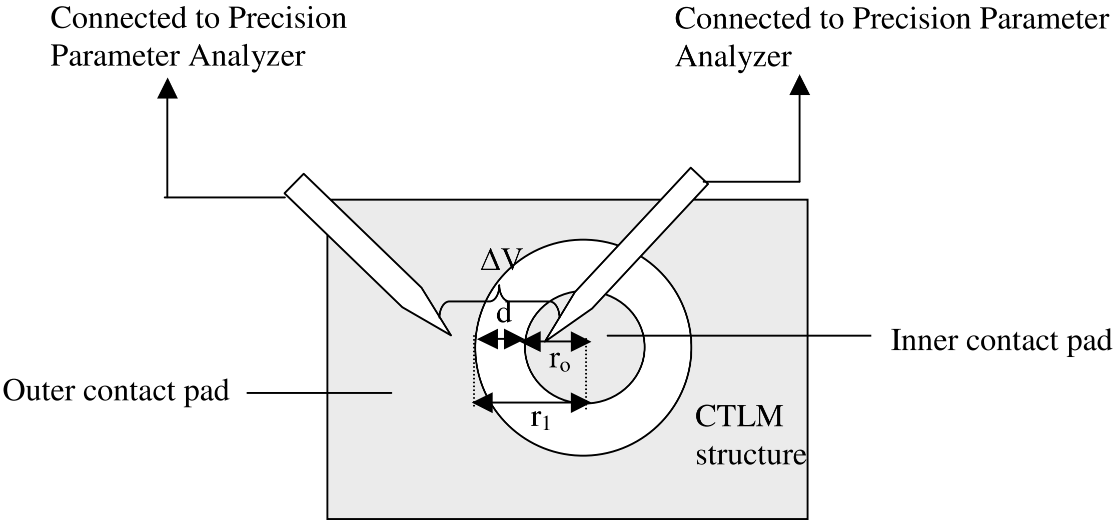


Figure 2.6 Experimental setup for deviation of specific contact resistance.

The voltage drop across the separation *d*, is given by [53-54]:

$$\Delta V = \frac{i_o R_s}{2\pi}[\ln\left(\frac{r_1}{r_o}\right) + \frac{L_T}{r_o}\frac{I_o(r_o / L_T)}{I_1(r_o / L_T)} + \frac{L_T K_o \ (r_1/L_T)}{r_1 K_1(r_1 / L_T)} \ ] \tag{2.4}$$

where i_o = Current across the separation, *d*;

R_s = Semiconductor sheet resistance;

L_T = Transfer length;

I_o, I_1, K_o, K_1 = Modified Bessel Functions; and

r_o , r_1 = Radii of the inner circular contact and the outer region that define the separation *d* (See Figure 2.4).

The transfer length, L_T, is related to the specific contact resistance, ρ_c, of the metal/semiconductor contact and the sheet resistance, R_s, of the semiconductor, as given by

$$L_T = \sqrt{\left(\frac{\rho_c}{R_s}\right)} \tag{2.5}$$

In cases where r_o and r_1 are greater than L_T by at least a factor of 4, both I_o/I_1 and K_o/K_1 approximate to unity [8]. Thus, equation (2.4) becomes

$$\Delta V = \frac{i_o R_S}{2\pi}\left[\ln\left(\frac{r_1}{r_1 - d}\right) + L_T\left(\frac{1}{r_1} + \frac{1}{r_1 - d}\right)\right] \quad . \tag{2.6}$$

Since the total resistance (R_T) between the contacts is defined as the ratio of the voltage across the separation (ΔV) and the current (i_o) or the inverse gradient of the I-V curve, hence

$$R_T = \Delta V / i_o$$

$$R_T = \frac{R_S}{2\pi}\left[\ln\left(\frac{r_1}{r_1 - d}\right) + L_T\left(\frac{1}{r_1} + \frac{1}{r_1 - d}\right)\right] \tag{2.7}$$

Since $2\pi(r_1 - d) \gg d$, equation (2.7) can be simplified to

$$R_T = \frac{R_S}{2\pi r_1}\left[d + 2L_T\right] \tag{2.8}$$

where R_T includes the probe resistance. However, the probe resistance is normally very small (i.e., 1Ω) and hence it has been ignored.

It can be seen from equation (2.8) that there is a linear relationship between R_T and the circular contact pad spacing, d. Thus, a graph of R_T versus d can be plotted, where the slope of the graph gives the value of $\frac{R_S}{2\pi r_1}$ and the interception with the vertical R_T-axis gives the value of $\frac{R_S}{\pi r_1}\left[L_T\right]$, as shown in Figure 2.7.

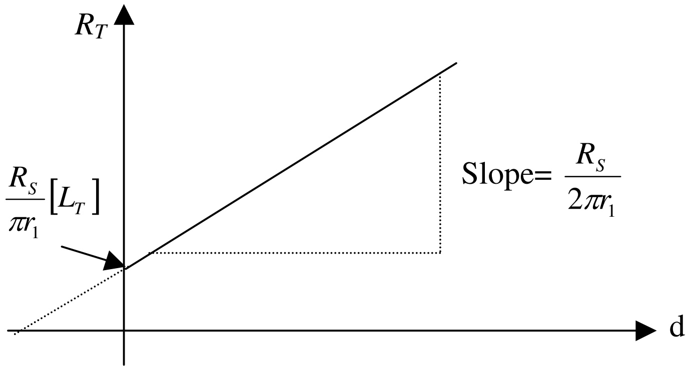


Figure 2.7 Graph of R_T versus *d* can be used to deduce specific contact resistance ρ_c.

Thus, the values of the transfer length, L_T, and sheet resistance, R_S, can be obtained as shown below:

$$L_T = (\text{y-interception /slope}) \times 2 \tag{2.9}$$

$$R_s = (\text{Slope}) \times 2\pi r_1 \tag{2.10}$$

Using equation (2.5), equation (2.9) and equation (2.10), the value of specific contact resistance, ρ_c, can then be obtained:

$$\rho_{c,} = (L_T)^2 \times R_s \tag{2.11}$$

2.5 Summary

In this chapter, the physics of metal semiconductor contacts and Circular Transmission Line Model (CTLM) have been presented. According to the Schottky-Mott model, in achieving the formation of an ohmic contact on p-GaN, the metal with a high workfunction is a good candidate, hence Pd that has a high workfunction of 5.11 eV is chosen in this work. It has been seen that the CTLM structure is a common and useful technique to determine the specific contact resistance, ρ_c, as it is simple and easy to use.