

MASTER

Fabrication and characterization of metal-semiconductor contacts for application in Al_xGa_{1-x}N/GaN HEMTs

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Fabrication and Characterization of
Metal – Semiconductor Contacts for
Application in $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ HEMTs

Masters Thesis

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Summary

The subject of my masters thesis research project was the fabrication and characterization of metal – semiconductor contacts for application in Aluminum Gallium Nitride ($\text{Al}_x\text{Ga}_{1-x}\text{N}$) / Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs). The HEMTs are implemented on a GaN – based materials system because these materials systems are suitable for high frequency, high power applications. In particular, these HEMTs have to be able to yield output powers of 4 W/mm at 10 GHz (X – band) at room temperature [1]. In order to achieve this, metal – semiconductor contacts and in particular Ohmic and Schottky contacts are required that enable this performance.

Ohmic contacts serve as the drain and source contacts of the HEMTs. Therefore, their contact resistance (R_c) is required to be as low as possible in order to achieve among others a high saturation current (I_{sat}), a high transconductance (g_m) and a high current gain cut – off frequency (f_t). First, a theoretical introduction to this type of metal – semiconductor contacts is provided. Next, our optimization procedure of the Ohmic contact fabrication process on n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructures from ATMI/Epitronics is described. The goal of this optimization scheme was to develop an Ohmic contact with an as low as possible contact resistance and corresponding specific contact resistance (ρ_c) for the used $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material. In addition, the Ohmic contact fabrication process should be reproducible, which is very important for a reliable implementation in the HEMT fabrication process. Furthermore, the optimized Ohmic contacts should allow for a high current density passing through them and they should also have a good line definition and a nice surface morphology. Our optimized Ohmic contact fabrication process consists of a $\text{Ti}/\text{Al}/\text{Ni}/\text{Au} = 30/180/40/150$ nm metallization scheme which is e – beam evaporated. After rapid thermal annealing (RTA) at 900 °C for 30 seconds in an N_2 ambient, values for R_c and ρ_c of 0.2 Ωmm and $7.3 \times 10^{-7} \Omega\text{cm}^2$ respectively are obtained. These values are determined using a circular implementation of the transfer length method (TLM). Comparing our values for R_c and ρ_c with those reported in literature [27, 29], it can be concluded that our optimized Ohmic contact on n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructures is among the best in the world.

Schottky contacts serve as the gate contacts of the HEMTs. Therefore, they should among others yield a low reverse current (I_s) and a high breakdown voltage (V_{break}), which is generally defined as the voltage at which the reverse current equals 1 mA taking into account the geometrical dimensions of the device. Similar to the Ohmic contacts, first a theoretical introduction to the Schottky contacts is provided followed by a discussion of our preliminary experiments and results. With respect to our experiments it has to be noted that due to the

used heterostructure material it is principally not possible to determine values for among others the effective barrier height (Φ_e) and the ideality factor (n) using the conventional current – voltage ($I - V$) and capacitance – voltage ($C - V$) characterization methods. To circumvent this problem we have decided to focus on the reverse current and the breakdown voltage in order to compare our Ni/Au = 20/200 nm Schottky contacts and to indicate their quality.

It was shown that the reverse current and the breakdown voltage of practical Schottky contacts are among others affected by the presence of an interfacial layer and surface states. As a result, pre – metallization treatments such as plasma enhanced cleaning and wet chemical etching are applied in order to render the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ surface stable and reproducible. Hence, we have decided to focus our preliminary experiments first on the determination of the optimal pre – metallization treatments in the case of the used Ni/Au = 20/200 nm Schottky contacts. For the moment, we have obtained the best electrical Schottky characteristics after application of an O_2 plasma at 20 W (dc bias = - 60 V) for 2 minutes which is followed by a dip in diluted NH_4OH ($\text{NH}_4\text{OH} : \text{DI} = 1:10$) for 15 seconds. However, this process has to be refined in future investigations. Also the effect of a post – metallization heat treatment on the reverse current – voltage characteristics has been investigated. We found that rapid thermal annealing (RTA) at 300 °C for 30 seconds in an N_2 ambient improved the reverse current – voltage characteristics. For future investigations we are convinced of the fact that with respect to the optimization of the Schottky contact fabrication process on n –type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material, the optimization of the pre – metallization treatments have the highest priority. Furthermore, it is very important to do both DC and radio frequency (RF) capacitance – voltage measurements in order to determine the Schottky contact behavior as a function of frequency and to extract an RF equivalent circuit that describes this behavior.

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CHAPTER 1

Introduction

This report describes the subject and the obtained results of my masters thesis research project: *“The fabrication and characterization of metal – semiconductor contacts for application in Aluminum Gallium Nitride ($\text{Al}_x\text{Ga}_{1-x}\text{N}$)/Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs)”*.

The work has been carried out with the chair Opto Electronic Devices (OED), which is part of the Telecommunication Technology and Electromagnetics Group (TTE) at the department of Electrical Engineering of the Eindhoven University of Technology (TU/e). The activities of OED include simulating, modeling and realizing III-V semiconductor devices for both optical and electronic applications.

My investigations comprise a small part of the PhD – research project of my daily supervisor Ir. B. Jacobs. His project is concerned with the design, fabrication and characterization of high frequency, high power HEMTs based on an n – type $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructure. Furthermore a high frequency, high power amplifier based on these HEMTs has to be designed. In literature [1, 2] it has been stated that $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ HEMTs should be able to provide typical high frequency output powers in the order of 4 W/mm at 10 GHz [1] and maximum drain-source currents larger than 1200 mA/mm [2] at room temperature. These devices are likely to find application in power amplifiers for base station transmitters for cellular telephone systems, high definition television (HDTV) transmitters, power modules for phased-array radars and other applications in the X-band (8 GHz - 12 GHz) [1]. In order to accomplish such device performance it is among others very important to develop high quality Ohmic and Schottky contacts. The former serve as the drain and source contacts and the latter serve as the gate contacts in the HEMTs.

High quality Ohmic and Schottky contacts means that they should not, or as little as possible, form the limiting factors for the performance of the HEMTs. The contact resistance of the Ohmic contacts should be as small as possible to achieve a:

- high saturation current ($I_{sat} \approx 1200$ mA/mm [1, 2]);
- high transconductance ($g_m \approx 200$ mS/mm [1, 2]);
- high current gain cut-off frequency ($f_i \approx 60$ GHz [1, 2]); and
- high power added efficiency (PAE $\approx 40 - 50$ % [1] within X – band).

The Schottky contacts should yield a:

- low reverse current density ($J_s \approx 10^{-5}$ A/cm² at breakdown [1, 2]);
- high breakdown voltage ($V_{break} > 100$ V [1, 2]); and
- unity approaching ideality factor (n).

The status of the Ohmic and Schottky contacts for application to n – type $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructures before my thesis work was as follows:

The used Ohmic metallization scheme consisted of Titanium (Ti)/Aluminum (Al) with layer thicknesses of 35/115 nm, respectively. Application of this metallization scheme to n – type $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ material yielded values for the contact resistance (R_c) and the corresponding specific contact resistance (ρ_c) of $R_c > 4$ Ωmm and $\rho_c > 10^{-3}$ Ωcm^2 , respectively after rapid thermal annealing (RTA) at 600 °C for 30 seconds in an argon (Ar) ambient. Compared to the values for R_c and ρ_c reported in literature [27, 29] these values are very high and not suitable for application in the high frequency, high power HEMTs.

For the Schottky contacts several different metallization schemes were in use such as Platinum (Pt), Ni, Au and Ni/Au. In the case of the single layer metallization schemes a layer thickness of 100 nm was commonly used. The layer thicknesses of the Ni/Au metallization scheme were commonly 20/200 nm, respectively. Application of these metallization schemes to n – type $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ material yielded Schottky contacts with, compared to literature [1, 2], very low breakdown voltages ($V_{break} \approx - 10$ V) and very large reverse current densities ($J_s \approx 10$ A/cm² at breakdown). Furthermore, the Pt and Au Schottky contacts suffered from a very bad adhesion to the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material. This resulted in a very poor mechanical stability of these contacts i.e. they were very easily scratched away by the measurement probes. The Ni and Ni/Au Schottky contacts showed a much better mechanical stability and were not easily scratched away by the measurement probes.

The objective of my work with respect to the Ohmic contacts was to develop a metallization scheme for application to n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructures in such a way that the obtained values for R_c and ρ_c are as low as possible and that these contacts are suitable for application in the high frequency, high power HEMTs. Furthermore, these contacts should have a good line definition, a nice surface morphology and be mechanically stable. For the application in high power devices it is also important that a high current density can pass through these contacts without destroying them.

The objective of my work with respect to the Schottky contacts was also to develop a metallization scheme for application to n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructures. The goal was to obtain high breakdown voltages and low reverse current densities because this is most important for the application in high power devices. These contacts should also have a nice surface morphology and a good mechanical stability.

The layout of this report is as follows:

Chapter 2 provides a brief and general introduction to GaN – based materials systems. First the growth of these materials systems will be briefly considered. Next the most commonly used substrates are discussed followed by the chemical inertness of the GaN – based materials systems and its consequences. Furthermore, the crystal structure of these materials systems is briefly described. After that, an overview is provided of both the optoelectronic and microelectronic applications of the GaN – based materials systems. Finally, the material properties of these materials systems are compared with those of several other semiconductors.

Chapter 3 provides an overview of the basic theory of metal – semiconductor contacts. First the energy band diagrams of both ideal and practical metal – semiconductor contacts will be considered. Furthermore, the current transport processes, which govern the conduction properties of these contacts, will be discussed. Finally, conclusions and some recommendations for practical metal – semiconductor contacts are provided.

Chapter 4 provides a theoretical introduction to Ohmic contacts. The chapter starts with an overview of the basic principles of Ohmic contact formation. Next, the specific contact resistance (ρ_c), which is the most important property of Ohmic contacts, will be discussed. Furthermore, the transfer length method (TLM), which is the most commonly used analysis technique to determine ρ_c , will be considered. Finally, the most important conclusions are briefly summarized.

Chapter 5 is concerned with Ohmic contacts on n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructures. The first part of this chapter (sections 5.2 – 5.4) is concerned with the technology of the Ohmic contacts. First, the most commonly reported metallization schemes and the proposed formation mechanisms for Ohmic contacts on this materials system will be considered. Furthermore, an overview is given of the pre – metallization and post – metallization treatments respectively, which according to literature [33, 34] are applied in order to decrease the contact resistance (R_c) and the corresponding specific contact resistance (ρ_c).

The remainder of this chapter (sections 5.5 – 5.7) deals with both the experiments that have been carried out in order to develop an Ohmic contact with an as low as possible (R_c) and (ρ_c) and the obtained results. First the used $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure and the basic operation of a High Electron Mobility Transistor (HEMT), which is based on this layer structure, will be described. Next, the circular TLM mask design that is used to fabricate the Ohmic test structures will be considered. Furthermore, the optimization scheme, which has been developed to arrive at the Ohmic contact with an as low as possible contact resistance for the used $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N} / \text{GaN}$ layer structure, will be described. After this, the experimental results of the Ohmic contact fabrication will be presented, followed by a discussion. Finally, the most important conclusions and recommendations for the fabrication of Ohmic contacts on $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N} / \text{GaN}$ material will be provided.

Chapter 6 provides a theoretical introduction to Schottky contacts. The chapter provides a brief overview of the Schottky contact parameters such as the barrier height (Φ_{Bn}), the ideality factor (n), the reverse current (I_s), the breakdown voltage (V_{break}) and the capacitance (C), which can be used to indicate their quality. Furthermore, the different characterization methods that can be used to determine these Schottky parameters will be briefly discussed.

Chapter 7 is concerned with the preliminary technology and experimental results of the fabricated Schottky contacts on the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT epitaxial structure that has been described in section 5.5.1. First, the most commonly used metallization schemes for Schottky contacts on n – type $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ material will be described. Furthermore, an overview is given of the pre – metallization and post – metallization treatments described in literature, which are applied in order to decrease the reverse current (I_s) and to increase the breakdown voltage (V_{break}). After this, the experiments with respect to the Schottky contact fabrication and the preliminary results will be presented. First, the limitations with respect to the characterization of the Schottky contacts will be discussed. Next, the circular mask design that is used to fabricate the Schottky test structures will be considered.

Furthermore, the Ni/Au and Ir/Au metallization schemes will be discussed. After that, we tried to determine the influence of both the pre – metallization treatments and the post – metallization heat treatment on the preliminary experimental results obtained from the

current – voltage ($I - V$) measurements. This is followed by a brief discussion of the capacitance – voltage ($C - V$) measurements. Finally, the conclusions and recommendations for the fabrication of Schottky contacts on our n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ / GaN material will be provided.

Chapter 8 presents the most important conclusions that can be drawn from this work. Furthermore, recommendations are provided for future investigations.

CHAPTER 2

General Introduction to GaN – based Materials Systems

2.1 Introduction

This chapter provides a brief and general introduction to GaN – based materials systems. First the growth of these materials systems will be briefly considered. Next the most commonly used substrates are discussed followed by the chemical inertness of the GaN – based materials systems and its consequences. Furthermore, the crystal structure of these materials systems is briefly described. After that, an overview is provided of both the optoelectronic and microelectronic applications of the GaN – based materials systems. Finally, the material properties of these materials systems are compared with those of several other semiconductors.

2.2 Growth

GaN and GaN – based materials systems such as $\text{In}_x\text{Ga}_{1-x}\text{N}$ and $\text{Al}_x\text{Ga}_{1-x}\text{N}$ are wide direct bandgap semiconductors in the III-V nitride family. Due to the high melting point of GaN at about 1700 °C it is extremely difficult to grow GaN and its derivative compounds from a liquid melt. Nevertheless, the existence of very small GaN substrates (0.25 cm² or less) grown at extremely high pressures (typically 25 kbar) has been reported [3]. Because of their small size these GaN substrates are not suitable for commercial applications. Generally, GaN-based materials systems are hetero-epitaxially grown on either silicon carbide (SiC) or sapphire ($\alpha\text{-Al}_2\text{O}_3$) substrates using molecular beam epitaxy (MBE) or metal organic vapor phase epitaxy (MOVPE).

2.3 Type of substrate

The lattice mismatch of epitaxial GaN layers grown on SiC substrates is much smaller (3 - 4 % [4]) than that of GaN epilayers grown on sapphire substrates (13 % [5]). The thermal conductivity (κ) of silicon carbide is considerably larger than that of sapphire, which results in a smaller thermal impedance of the epitaxially grown layers [4]. However, despite these advantages of SiC over sapphire, from an economical point of view sapphire substrates are still the most commonly used.

2.4 Chemical inertness

Depending on the applied buffer layer and growth temperature, MBE grown GaN epilayers are either nitrogen (N) faced or gallium (Ga) faced. The Ga – faced epilayers are chemically inert and have a much smoother surface than the N – faced epilayers. MOVPE grown GaN-based materials on SiC or sapphire are most commonly Ga – faced. The chemical inertness of the Ga – face is both an advantage and a disadvantage. The advantage of this characteristic is that it allows for the application of these materials systems in chemically highly aggressive environments. Therefore among others the contacts of such devices have to be able to withstand these conditions as well. The disadvantage of the chemical inertness is that structures (e.g. mesas) can only be made using dry etching techniques like reactive ion etching (RIE) or chemically assisted ion beam etching (CAIBE).

2.5 Crystal structure

Depending among others on the applied substrate, its orientation and the used growth technique, the GaN-based materials systems appear in two configurations. These are the hexagonal (wurtzite) and cubic (zinc-blende) crystal structures. The former is the thermodynamically stable phase at ambient conditions and the latter is the metastable structure [6]. Like its cubic counterpart, each atom in the wurtzite crystal forms a tetrahedral bond with its nearest neighbor. The GaN-based materials systems having either the wurtzite or the cubic crystal structure both belong to the “direct semiconductors”. This implies that they can be used for both electrical and optical applications.

2.6 Applications

2.6.1 Optoelectronic applications

At present the $\text{In}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ materials system is the most commonly used *optoelectronic* materials system for the fabrication of blue and green light emitting diodes (LEDs) and blue laser diodes (LDs). The fabrication of the first high brightness blue LED by Shuji Nakamura in 1993 [7] and the fabrication of the first blue LD also by Shuji Nakamura in 1996 [7] enabled a large variety of commercial applications. High brightness LEDs are applied in areas where strong, energy sufficient and reliable green, blue and UV light sources are needed (e.g. automotive/aircraft lighting and traffic lights). In addition, as the three primary colors (red, green and blue) have become available in LED technology, the production of full color LED displays has become possible (e.g. outdoor television screens, indoor flat panel display screens, full color scanners etc.). Green/blue, blue and UV GaN-based LDs can be used in the field of optical reading and writing of data in compact disk memories and optomagnetic memories. Since the storage density in these memories is largely determined by the wavelength of the applied LD, it is expected that blue LDs will increase the storage density by about a factor of four compared to presently employed LDs at $\lambda = 780 \text{ nm}$ (red/infrared) [7]. By altering the Indium (In) content of the $\text{In}_x\text{Ga}_{1-x}\text{N}$ material, the bandgap energy (E_g) can be varied from 1.9 eV ($\lambda = 654 \text{ nm} \equiv \text{orange-red}$) for InN up to 3.4 eV ($\lambda = 366 \text{ nm} \equiv \text{ultra violet (UV)}$) for GaN at room temperature.

2.6.2 Microelectronic applications

By adjusting the Aluminum (Al) content of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material, E_g can be varied from 3.4 eV ($\lambda = 366 \text{ nm} \equiv \text{UV}$) for GaN up to 6.2 eV ($\lambda = 200 \text{ nm} \equiv \text{deep UV}$) for AlN at room temperature. Despite the major difficulties at present, the $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ materials system could eventually be used to fabricate UV / deep UV LDs for high density data storage applications. However, the $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ materials system is most commonly used for *microelectronic* applications such as high frequency, high power HEMTs which can be applied in power amplifiers for base station transmitters for cellular telephone systems, high definition television (HDTV) transmitters, power modules for phased-array radars and other applications in the X-band (8 GHz - 12 GHz) [1].

2.7 Material properties

Due to the large bandgap discontinuity (ΔE_g) at the $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterojunction a two dimensional electron gas (2DEG) is formed in the GaN layer which serves as the channel in the HEMTs. The electron mobility μ_n in this 2DEG has typical values of 1000-1500 cm^2/Vs [8], which are much larger than the electron mobilities that can be reached in GaN. Compared to the values for the saturation velocity (v_{sat}) of Si and GaAs, v_{sat} of GaN is considerably higher [8]. Table 1 presents some material properties of silicon (Si), gallium arsenide (GaAs), 4H-silicon carbide (4H-SiC), 6H-silicon carbide (6H-SiC) and GaN for comparison purposes. The large bandgap energy (E_g) of the GaN-based materials results in a high breakdown electric field ($E_{break} = 3 \times 10^6 \text{ V/cm}$ [9]) which is one order of magnitude larger than the breakdown electric fields of Si and GaAs. High breakdown voltages allow for high supply voltages which are necessary to obtain large high frequency output powers. Also due to their large E_g the GaN-based materials have the potential to operate at elevated temperatures, largely exceeding the maximum operating temperatures for GaAs devices [10]. All these properties make the GaN-based materials superior over e.g. GaAs-based materials for high frequency, high power and high temperature electronic applications.

Table 1: Material properties of several semiconductors.

Materials $\Rightarrow$ Properties $\Downarrow$	Si	GaAs	4H-SiC	6H-SiC	GaN (wurtzite)
E_g [eV] (T=300K)	1.12	1.42	3.2	2.86	3.4
ϵ_r [-]	11.9	12.5	10	10	9.5
μ_n [$\text{cm}^2/(\text{V}\cdot\text{s})$]	1350	8500	1400	1400	400-500 1000-1500 (2DEG)
v_{sat} [$10^7 \times \text{cm/s}$]	1	0.8	1.5	1.5	2-2.5
E_{break} [MV/cm]	0.3	0.4	1-5	1-5	3
κ [W/(cm K)]	1.5	0.54	4	4	1.3

2.8 Conclusions

From this chapter it can be concluded that the GaN – based materials systems are very promising and that they have a large variety of both optoelectronic and microelectronic applications.

CHAPTER 3

Metal – Semiconductor Contacts

3.1 Introduction

The objective of this chapter is to provide an overview of the basic theory of metal – semiconductor contacts. First the energy band diagrams of both ideal and practical metal – semiconductor contacts will be considered. Furthermore, the current transport processes, which govern the conduction properties of these contacts, will be discussed.

3.2 Energy band diagrams

In this section we will consider the energy band diagrams of two limiting cases of the metal – semiconductor contact. The first limiting case is that of an *ideal* contact between a metal and an n – type semiconductor in the absence of surface states. The second limiting case is that of a *practical* contact between a metal and an n – type semiconductor, where a thin interfacial layer with an infinitely large density of surface states is present on the semiconductor surface. Figures 3.1 and 3.2 show the energy band diagrams for the first and the second limiting case respectively.

Figure 3.1a shows the flat band situation for a semiconductor without a surface layer and surface states. When a metal is placed in intimate contact with such a semiconductor, the conduction (E_c) and valence (E_v) energy bands have to bend in order to reach thermal equilibrium. In the case of thermal equilibrium (i.g. no external voltages are applied, no currents are induced, no temperature gradients are present) the Fermi levels in the metal and the semiconductor are at an equal level ($E_{Fm} = E_{Fs}$). Figure 3.1b shows the barrier that has been formed at the metal – semiconductor interface after establishing thermal equilibrium.

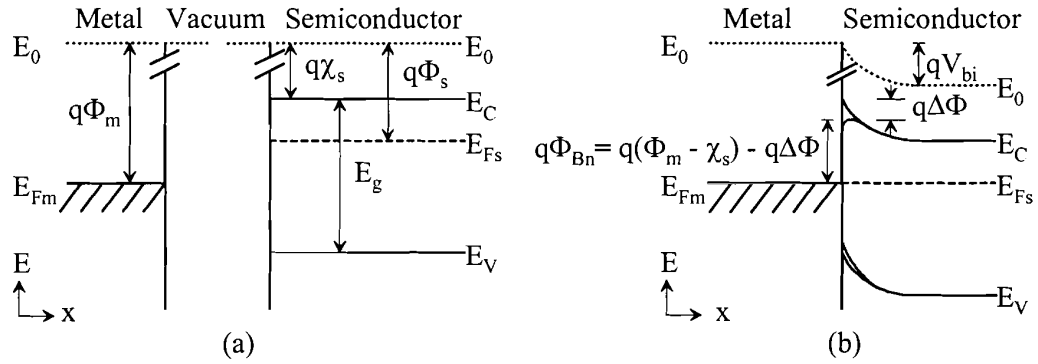


Figure 3.1: Energy band diagrams of a metal – semiconductor contact without an interfacial layer and surface states before (a) and after (b) intimate contact under thermal equilibrium.

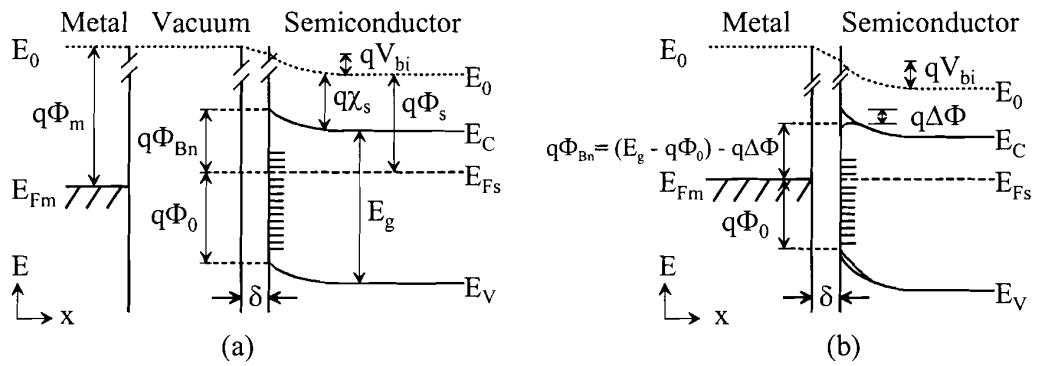


Figure 3.2: Energy band diagrams of a metal – semiconductor contact with a thin interfacial layer (δ) and an infinitely large density of surface states before (a) and after (b) intimate contact under thermal equilibrium.

Figure 3.2a shows the energy band diagram of a semiconductor with a thin surface layer e.g. a native oxide and a large density of surface states. If a metal is placed into contact with such a semiconductor, the physics of the junction are not governed by the bulk properties of the metal and semiconductor material but by the properties of the surface boundaries and primarily those of the semiconductor surface [16]. The strong influence of the semiconductor surface is due to the surface states that are present inside the bandgap. In this case it is possible to define a neutral level Φ_0 that represents the position of the Fermi level in the case that the semiconductor surface is electrically neutral. If surface states below Φ_0 are empty the semiconductor surface will be positively charged and if surface states above Φ_0 are filled the semiconductor surface will be negatively charged. If the Fermi level at the surface does not

coincide with the neutral level Φ_0 there will be a net charge at the surface. This charge produces an electric field ($\vec{\mathcal{E}}$) in the semiconductor which causes the energy bands to bend. If the surface charge is negative, as is the case for practical n – type $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layers [39], the energy bands will bend upwards towards the surface. As a consequence, the semiconductor material near the surface is already depleted before it has been brought into contact with the metal as can be observed in figure 3.2a. This figure also shows that the energy levels of the surface states are occupied with electrons up to E_{Fs} , which in the case of an infinitely large density of surface states equals Φ_0 , in order to establish thermal equilibrium between the surface states and the bulk of the semiconductor material. Figure 3.2b shows the energy band diagram of such a practical metal – semiconductor contact.

In the case that no surface states are present, the height of the potential barrier, which the electrons have to overcome if they flow from the metal into the semiconductor, is ideally equal to the difference between the metal work function (Φ_m) and the semiconductor electron affinity (χ_s). Actually, the image – force – induced lowering of the barrier height in the case of an applied electric field ($\vec{\mathcal{E}}$), which is known as the Schottky effect, should also be taken into account. The value of the resulting barrier height (Φ_{Bn}) is then given by:

$$q\Phi_{Bn} = q(\Phi_m - \chi_s) - q\Delta\Phi \quad [\text{eV}] \quad (3.1)$$

where $\Delta\Phi$ represents the Schottky barrier lowering. In the case of a metal – semiconductor system $\Delta\Phi$ is given by [15]:

$$\Delta\Phi = \sqrt{\frac{q\mathcal{E}}{4\pi\epsilon_0\epsilon_{r,s}}} \quad (3.2)$$

where $\mathcal{E}$ is the maximum electric field at the interface, ϵ_0 the permittivity of free space and $\epsilon_{r,s}$ is the relative permittivity of the semiconductor material. The observed change of the bandgap of the semiconductor material at the metal – semiconductor interface compared to that in the bulk of the semiconductor could be explained by the distortion of the periodicity of the potential function of the atoms near this interface. As a result, the potential energy of the electrons that follows from the solution of the Schrödinger equation is distorted. This leads to a distorted (E, k) diagram i.e. with different allowed and forbidden energy bands compared to that of the bulk semiconductor material.

If the density of the surface states is infinitely large, the barrier height (Φ_{Bn}) and as a consequence the energy band diagram change only very little after placing the metal into intimate contact with the semiconductor. Thermal equilibrium between the two materials will be established by a small drop of the semiconductor Fermi level relative to that of the metal.

The drop of E_{Fs} is small because the electrons, which are required for this process, are provided by the occupied surface states below E_{Fs} . In this case the Fermi level at the interface is “pinned” by the surface states at a value $q\Phi_0$ above the valence band (E_V). The barrier height (Φ_{Bn}) is independent of the metal work function (Φ_m) and is entirely determined by the doping and surface properties of the semiconductor. If again the Schottky effect is taken into account, the resulting barrier height is given by [15]:

$$q\Phi_{Bn} = (E_g - q\Phi_0) - q\Delta\Phi \quad (3.3)$$

The formation of surface states has shown to be dependent on the bonding type (covalent or ionic) of the semiconductor material [15, 16, 17]. Unsaturated bonds at the surface of covalent semiconductors (e.g. Si, Ge, GaAs) give rise to a (very) large density of surface states. If these surface states are formed inside the bandgap, Fermi level pinning at the interface occurs. This Fermi level pinning can explain the fact that the barrier height is essentially independent of the metal work function. As a rule of thumb, the barrier heights in these semiconductors equal $q\Phi_{Bn} = 2/3 E_g$ in case of n – type doping and $q\Phi_{Bp} = 1/3 E_g$ in case of p – type doping [17].

Ionic semiconductors (e.g. AlN, GaN, $\text{Al}_x\text{Ga}_{1-x}\text{N}$) with strongly polarized crystal lattices stabilize their surfaces by shifting the atomic layers near the surface [17]. As a result, no surface states inside the bandgap are formed and Fermi level pinning at the interface does not occur. For ionic semiconductors the barrier height generally depends strongly on the metal and a correlation has been found between interface behavior and the electronegativity (X) [15]. The electronegativity is defined as the power of an atom in a molecule to attract electrons to itself. The “index of interface behavior” (S) is a quantitative indication of how strongly the barrier height of a metal – semiconductor contact depends on the electronegativity of the applied metal and is given by:

$$S \equiv \frac{d\Phi_{Bn}}{dX_m} \quad (3.4)$$

where X_m is the electronegativity of the applied metal. Figure 3.3 (from [15]) shows a plot of S as a function of the electronegativity difference of different semiconductors. A sharp transition can be observed from the covalent semiconductors (such as GaAs with $\Delta X = 0.4$) to the ionic semiconductors (such as AlN with $\Delta X = 1.5$). For semiconductors with $\Delta X < 1$ the index S is small indicating that the barrier height depends only weakly on the metal electronegativity (or the work function). For $\Delta X > 1$ the index S approaches 1 and the barrier height depends on the metal electronegativity (or again the work function).

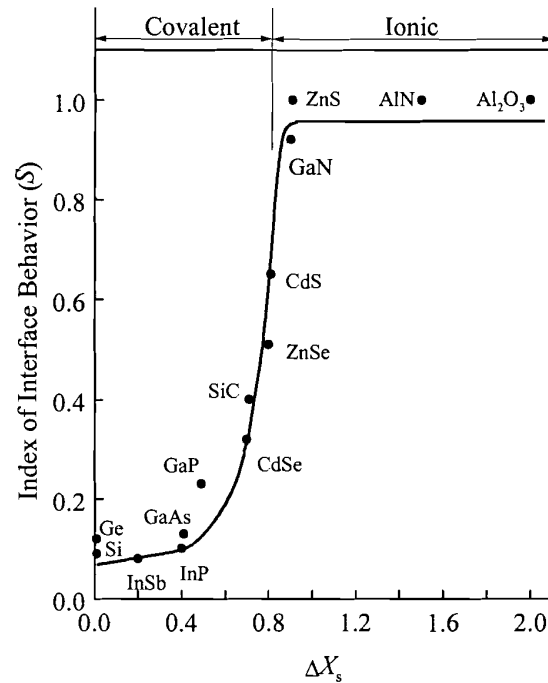


Figure 3.3: The index of interface behavior S as a function of the electronegativity difference of different semiconductors [15].

According to figure 3.3, the values for ΔX of GaN and AlN are approximately equal to 0.9 and 1, respectively. Hence, GaN (and $\text{Al}_x\text{Ga}_{1-x}\text{N}$) will hardly suffer from Fermi level pinning and the barrier height is determined by the work function of the applied metal.

3.3 Current transport mechanisms

The current transport in metal – semiconductor contacts is mainly due to majority carriers, in contrast to $p - n$ junctions where the minority carriers are responsible. Figure 3.4 shows the four basic transport processes under forward bias for a metal – n - type semiconductor contact. The inverse processes occur under reverse bias. The mechanisms are [16]:

- 1) emission of electrons from the semiconductor over the top of the barrier into the metal;
- 2) quantum mechanical tunneling of electrons from the semiconductor through the barrier into the metal;
- 3) recombination of electrons and holes in the depletion region; and
- 4) recombination of electrons and holes in the neutral region (“hole injection”).

Schottky barriers in which the process described under 1) is the most important current transport mechanism are generally referred to as “nearly ideal” because the electrons can only pass the potential barrier at the interface by surmounting it completely. Due to the high barrier height encountered in the reverse direction the reverse current (I_s) will be very low, which is one of the characteristics of a nearly ideal Schottky contact. The processes under 2), 3) and 4) cause departures from this ideal behavior because the electrons also have the opportunity to pass the potential barrier at the interface using alternative paths. All four processes will be discussed briefly in the following subsections.

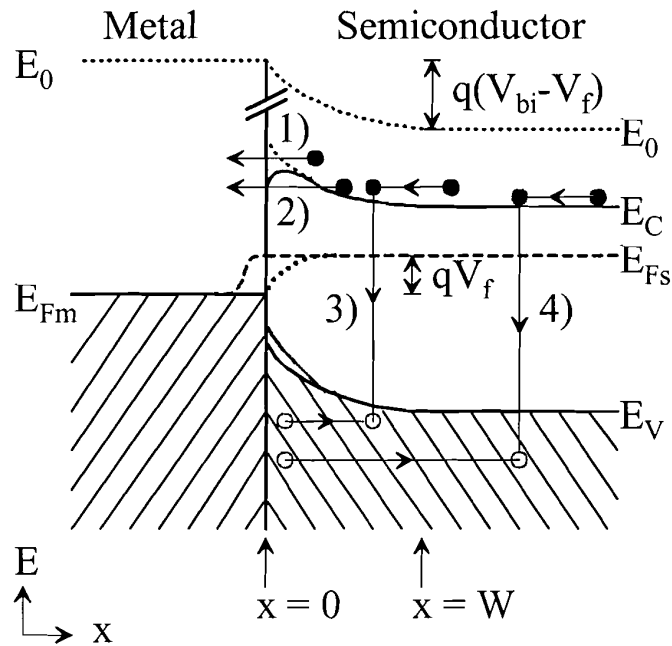


Figure 3.4: Four basic transport processes under forward bias.

3.3.1 Emission over the barrier

The emission of electrons from the semiconductor over the top of the potential barrier into the metal can be described by two basic mechanisms, which in fact are two limiting cases. For high mobility semiconductors the transport can be adequately described by the *thermionic emission theory*. The transport in low mobility semiconductor material can be understood using the *diffusion theory*. In practice, the true behavior of the transport process will lie somewhere between these two extremes of the thermionic emission theory and the diffusion theory. This consideration has led to the development of the *combined thermionic emission / diffusion theory*. The assumptions that provide the basis for the development of these three theories and their final results will be described in the following subsections.

3.3.1.1 The thermionic emission theory

The thermionic emission theory by Bethe (1942) is derived from the assumptions [15, 41] that:

- 1) the barrier height ($q\Phi_{Bn}$) is much larger than kT , where k is the Boltzmann factor and T is the absolute temperature;
- 2) thermal equilibrium is established at the plane that determines emission;
- 3) the existence of a net current flow does not effect this equilibrium, so that the two current fluxes, one from the semiconductor to the metal and one from the metal to the semiconductor, can be superimposed;
- 4) the current – limiting process is the actual transfer of electrons across the interface between the semiconductor and the metal; and
- 5) the width of the region over which a kT drop in potential energy occurs at the barrier should be smaller than the electron mean free path.

According to these assumptions the shape of the barrier profile is immaterial and the current flow depends only on the barrier height. Hence, if the thermal energy of an electron is sufficiently high to surmount the potential barrier, this transport process is called thermionic emission. In the case of thermal equilibrium the electron flow from the semiconductor into the metal is equal to that from the metal into the semiconductor. As a consequence, the total current density ($\vec{J}$) across the interface is equal to zero because the current densities in reverse and forward direction cancel each other out. If a forward bias voltage ($V_f > 0$) is applied, the Fermi level in the semiconductor shifts to a higher energetic level with respect to the Fermi level in the metal by an amount of qV_f . As a result, the barrier height for electron flow from the semiconductor into the metal, which is determined by the built – in voltage (V_{bi}), has been lowered. The current density in forward direction is now larger than that in reverse direction because electrons with smaller thermal energies can also surmount the potential barrier. If a reverse bias voltage ($V_r < 0$) is applied, the Fermi level in the semiconductor shifts to a lower energetic level with respect to the Fermi level in the metal by an amount of qV_r . The barrier qV_{bi} in the semiconductor is enlarged and the current density in forward direction falls below that in reverse direction. It has to be noted that the current density in reverse direction is independent of the polarity of the applied bias and remains constant because the barrier for electrons flowing from the metal into the semiconductor ($q\Phi_{Bn}$) remains unchanged. The total current density according to the thermionic emission theory is given by [15, 16, 17]:

$$J = \left[A^* T^2 \exp\left(\frac{-q\Phi_{Bn}}{kT}\right) \right] \left[\exp\left(\frac{qV}{kT}\right) - 1 \right]$$

$$J = J_{ST} \left[\exp\left(\frac{qV}{kT}\right) - 1 \right] \quad (3.5)$$

where

$$J_{ST} = A^* T^2 \exp\left(\frac{-q\Phi_{Bn}}{kT}\right) \quad (3.6)$$

and

$$A^* = \frac{4\pi q m_n^* k^2}{h^3}. \quad (3.7)$$

In equations (3.5) – (3.7), A^* is the Richardson constant, T the absolute temperature, q the electron charge, k Boltzmann's constant, Φ_{Bn} the barrier height to electron flow from the metal into the semiconductor, V the applied voltage across the barrier, m_n^* the electron effective mass, h Planck's constant and J_{ST} is the saturation current density according to the thermionic emission theory.

3.3.1.2 The diffusion theory

The diffusion theory by Schottky (1939) is derived from the assumptions that [15]:

- 1) the barrier height ($q\Phi_{Bn}$) is much larger than kT ;
- 2) the effect of electron collisions within the depletion region is included;
- 3) the carrier concentrations at $x = 0$ and $x = W$ are unaffected by the current flow (i.e. they have their equilibrium values); and
- 4) the impurity concentration of the semiconductor is nondegenerate.

To derive the current – voltage characteristic according to the diffusion theory, the current density in the depletion region in the x – direction is written in the usual way as:

$$J = J_x = q\mu_n n(x)E(x) + qD_n \frac{\partial n}{\partial x} \quad (3.8)$$

where q is the electron charge, μ_n the electron mobility, $n(x)$ the electron concentration in the x – direction, $E(x)$ the electric field in the barrier in the x – direction and D_n the diffusion coefficient for electrons. It is important to note that it is only possible to write the expression for the current density in the simple form of equation (3.8) if it is legitimate to use the concepts of a mobility and a diffusion coefficient which are independent of the electric field

[16]. However, if such a simplification is not made the analysis becomes extremely tedious and therefore equation (3.8) is usually assumed to be valid. But it should always be borne in mind that the accuracy of the analysis ultimately rests on the truth of this assumption [16]. Using the Einstein relationship $D_n/\mu_n = kT/q$, it is possible to write equation (3.8) in the form:

$$J = qD_n \left[-\frac{qn(x)}{kT} \frac{\partial V(x)}{\partial x} + \frac{\partial n}{\partial x} \right] \quad (3.9)$$

where $V(x)$ is the voltage across the barrier. Under the steady state condition and neglecting the Schottky effect, the total current density according to the diffusion theory is given by [15, 16, 17]:

$$J \cong \left\{ \frac{q^2 D_n N_C}{kT} \left[\frac{q(V_{bi} - V) 2N_D}{\epsilon_0 \epsilon_{r,s}} \right]^{\frac{1}{2}} \exp\left(-\frac{q\Phi_{Bn}}{kT}\right) \right\} \left[\exp\left(\frac{qV}{kT}\right) - 1 \right]$$

$$J = J_{SD} \left[\exp\left(\frac{qV}{kT}\right) - 1 \right] \quad (3.10)$$

where

$$J_{SD} \equiv \left\{ \frac{q^2 D_n N_C}{kT} \left[\frac{q(V_{bi} - V) 2N_D}{\epsilon_0 \epsilon_{r,s}} \right]^{\frac{1}{2}} \exp\left(-\frac{q\Phi_{Bn}}{kT}\right) \right\} \quad (3.11)$$

In equations (3.10) and (3.11), N_C is the effective density of states function in the conduction band, V_{bi} the built – in voltage, N_D the donor impurity concentration, ϵ_0 the permittivity of free space, $\epsilon_{r,s}$ the relative permittivity of the semiconductor material and J_{SD} is the saturation current density according to the diffusion theory. The expressions for the current densities of the thermionic emission and diffusion theories, equations (3.5) and (3.10) respectively, are basically very similar. However, the saturation current density J_{SD} for the diffusion theory (equation (3.11)) varies more rapidly with the voltage but is less sensitive to the temperature compared with the saturation current density J_{ST} for the thermionic emission theory (equation (3.6)) [15].

3.3.1.3 The combined thermionic emission / diffusion theory

The difference between the thermionic emission theory and the diffusion theory is well illustrated by the behavior of the quasi – Fermi level for electrons in the conduction band of the semiconductor as already has been shown in figure 3.4 (section 3.3). According to the diffusion theory the concentration of conduction electrons in the semiconductor immediately adjacent to the interface is not altered by the applied bias. This is equivalent to assuming that at the interface the quasi – Fermi level in the semiconductor coincides with the Fermi level in the metal. In this case, the quasi – Fermi level falls through the depletion region as shown in figure 3.4 by the dotted line. This behavior is in sharp contrast with the situation in a $p - n$ junction under bias, where the quasi – Fermi levels for both types of carriers are generally assumed to be flat throughout the depletion region [16].

The electrons emitted from the semiconductor into the metal are not in thermal equilibrium with the conduction electrons in the metal but have an energy that exceeds the metal Fermi energy by the barrier height. Hence, these electrons can approximately be regarded as “hot” electrons. In literature [16] it has been suggested that the hot electrons in the metal can be thought of as a species of electron different from the “ordinary” conduction electrons and they can be described by their own quasi – Fermi level. As the hot electrons penetrate into the metal, they lose energy by collisions with the conduction electrons and the lattice atoms. Finally, they reach equilibrium with the conduction electrons in the metal. Their quasi – Fermi level falls until it coincides with the metal Fermi level [16]. This process is rather like recombination in a semiconductor. This point of view implies that the electron quasi – Fermi level at the interface does not have to coincide with the metal Fermi level. It is now possible to imagine that the quasi – Fermi level remains flat throughout the depletion region as in a $p - n$ junction [16]. This is the assumption made in the thermionic emission theory and is shown in figure 3.4 (section 3.3) by the dashed line. Bearing in mind that the gradient of the quasi – Fermi level provides the driving force for electrons, the main obstacle to current flow in case of the diffusion theory is provided by the combined effects of drift and diffusion in the depletion region. According to the thermionic emission theory the bottleneck lies in the process of emission of electrons into the metal [16]. In practice, the true behavior of the transport process will lie somewhere between these two extremes of the thermionic emission theory and the diffusion theory. This consideration has led to the development of the combined thermionic emission / diffusion theory.

The most fully developed theory is that of Crowell and Sze, who introduce the concept of a recombination velocity (v_r) at the top of the barrier [16]. This recombination velocity is defined by equating the net electron current into the metal to $v_r(n - n_0)$, where n is the electron density at the top of the barrier and n_0 its value at zero bias. The terms $v_r n$ and $v_r n_0$ represent

the electron fluxes from semiconductor to metal and from metal to semiconductor respectively [16]. Without taking into account the effect of backscattering of electrons at the Schottky barrier by electron optical – phonon scattering when they try to pass it and without considering quantum mechanical tunneling and reflection, the total current density according to the combined thermionic emission / diffusion theory is given by [15, 16, 17]:

$$J = \frac{qN_C v_r}{1 + \frac{v_r}{v_d}} \exp\left(-\frac{q\Phi_{Bn}}{kT}\right) \left[\exp\left(\frac{qV}{kT}\right) - 1 \right] \quad (3.12)$$

with

$$v_d \equiv \left[\int_{x_m}^W \frac{q}{\mu kT} \exp\left[-\frac{q(\Phi_{Bn} + \psi)}{kT}\right] dx \right]^{-1}. \quad (3.13)$$

In equations (3.12) and (3.13), N_C is the effective density of states function in the conduction band, v_r the recombination velocity at the top of the barrier, Φ_{Bn} the barrier height, k Boltzmann's constant, T the absolute temperature, V the applied voltage across the barrier and $q\psi$ is the electron potential energy. The term v_d in these equations, is an effective diffusion velocity associated with the transport of electrons from the edge of the depletion layer at $x = W$ from the interface (at $x = 0$) to the potential energy maximum at $x = x_m$ ($0 < x_m < W$) and not at $x = 0$ because of the Schottky effect.

If $v_d \gg v_r$, the pre-exponential term in equation (3.12) is dominated by v_r and the thermionic emission theory most nearly applies. However, if $v_d \ll v_r$, v_d is dominant and the diffusion theory is in charge. If the image force effects are neglected and if the electron mobility is assumed to be independent of the electric field, v_d would be equal to $\mu_n \mathcal{E}$ where $\mathcal{E}$ is the electric field in the semiconductor near the boundary [15]. The standard diffusion result as given by equation (3.10) would then be obtained.

To conclude this subsection, the complete $J - V$ characteristics, which take into account the earlier mentioned and at that time neglected backscattering, quantum mechanical tunneling and reflection processes, are given by [15]:

$$J = J_{sc} \left[\exp\left(\frac{qV}{kT}\right) - 1 \right]$$

$$J_{sc} = A^{**} T^2 \exp\left(-\frac{q\Phi_{Bn}}{kT}\right) \quad (3.14)$$

where

$$A^{**} = \frac{f_p f_Q A^*}{1 + \frac{f_p f_Q v_r}{v_d}} \quad (3.15)$$

In equations (3.14) and (3.15), J_{SC} is the saturation current density in case of the combined thermionic emission / diffusion theory, A^{**} the effective Richardson constant in that case, v_r the recombination velocity at the top of the barrier and v_d is the effective diffusion velocity. The term f_p represents the probability of electron emission over the potential maximum and can be given by [15] $f_p = \exp(-x_m/\lambda)$, where x_m is the position of the potential maximum from the interface and λ is the carrier mean free path at this location. The term f_Q represents the ratio of the total current flow, considering quantum mechanical tunneling and reflection, to the current flow neglecting these effects. This ratio depends strongly on the electric field and the electron energy measured from the potential maximum [15].

3.3.1.4 The effect of the image force on the current – voltage relationship

The current – voltage relationship predicted by the thermionic emission theory (equation (3.5)) is of the form of the ideal rectifier characteristic $J = J_0 [\exp(qV/kT) - 1]$, with $J_0 = A^{**}T^2 \exp(-q\Phi_{Bn}/kT)$, provided that the barrier height is independent of bias. However, there are several reasons why the barrier height depends on the electric field in the depletion region and hence on the applied bias. In particular, even in an ideal contact with no interfacial layer, the barrier height is reduced as a result of the image force by an amount $\Delta\Phi$ which depends on the bias voltage [16]. If a forward bias voltage ($V_f > 0$) is applied, the barrier height is larger than at zero bias. However, if a reverse bias voltage ($V_r < 0$) is applied the barrier height is smaller than at zero bias [15]. The effective barrier that electrons have to surmount before they can reach the metal is therefore given by $\Phi_e = \Phi_{Bn} - \Delta\Phi$. Moreover, in the presence of an interfacial layer the barrier height (Φ_{Bn}) depends on the bias voltage. Besides the bias dependence of Φ_e for the just mentioned two reasons, the penetration of the wave functions of the metal electrons into the semiconductor has a possible effect on Φ_e . After penetration of these wave functions of electrons in the metal with energies corresponding to the forbidden gap in the semiconductor, they damp out exponentially. This represents a transfer of charge from the metal to the semiconductor and the states are often referred to as metal – induced gap states (MIGS) [16]. The bias dependence of Φ_e is very important with respect to the reverse current – voltage characteristics of a Schottky diode and it will consequently modify these current – voltage characteristics. This dependence, using a Taylor expansion of Φ_e which is terminated after the linear term, is given by:

$$\Phi_e = (\Phi_e)_0 + \frac{\partial \Phi_e}{\partial V} V \quad (3.16)$$

with

$$(\Phi_e)_0 = (\Phi_{Bn})_0 - (\Delta\Phi)_0 \quad (3.17)$$

where $(\Phi_e)_0$, $(\Phi_{Bn})_0$ and $(\Delta\Phi)_0$ refer to the effective barrier height, the (uncorrected) barrier height and the image – force – induced barrier lowering at zero bias respectively. Assuming that Φ_e/V is constant, the effective barrier height is given by [16]:

$$\Phi_e = (\Phi_{Bn})_0 - (\Delta\Phi)_0 + \beta V \quad (3.18)$$

where the coefficient β is positive because Φ_e always increases with increasing forward bias [16]. Inserting equation (3.18) in the current – voltage relationship of the ideal rectifier now gives:

$$J = A^* T^2 \exp\left(-\frac{q((\Phi_{Bn})_0 - (\Delta\Phi)_0 + \beta V)}{kT}\right) \left[\exp\left(\frac{qV}{kT}\right) - 1 \right]$$

$$J = J_s \exp\left(-\frac{q\beta V}{kT}\right) \left[\exp\left(\frac{qV}{kT}\right) - 1 \right] \quad (3.19)$$

where

$$J_s \equiv A^* T^2 \exp\left(-\frac{q((\Phi_{Bn})_0 - (\Delta\Phi)_0)}{kT}\right) \quad (3.20)$$

Equation (3.19) can be written in the form:

$$J = J_s \exp\left(\frac{qV}{nkT}\right) \left[1 - \exp\left(-\frac{qV}{kT}\right) \right] \quad (3.21)$$

where

$$\frac{1}{n} = 1 - \beta = 1 - \frac{\partial \Phi_e}{\partial V} \quad (3.22)$$

and n is called the ideality factor. If Φ_e/V is constant, n is constant too [16]. For values of V larger than $3kT/q$, equation (3.21) can be written as:

$$J = J_s \exp\left(\frac{qV}{nkT}\right) \quad \text{for } V > 3kT/q \quad (3.23)$$

As will be shown in the following subsections, there are other mechanisms besides the bias dependence of Φ_e , in particular thermionic field emission (section 3.3.2) and recombination in the depletion region (section 3.3.3), which yield a current – voltage relationship like equation (3.21). In literature [15, 16, 17], equation (3.21) is often given in the form:

$$J = J_s \left[\exp\left(\frac{qV}{nkT}\right) - 1 \right] \quad (3.24)$$

In fact, this form is incorrect because the barrier lowering affects the flow of electrons from the metal to the semiconductor as well as the flow from the semiconductor to the metal.

Hence, the second term in the square brackets of equation (3.24) should obtain the ideality factor n . The difference between equations (3.21) and (3.24) is negligible for $V > 3kT/q$, but the correct form given by equation (3.21) has the advantage that n can be determined experimentally by plotting $\ln[J/\{1 - \exp(-qV/kT)\}]$ versus V . This graph should be a straight line with a slope of q/nkT if the ideality factor n is constant, even for $V < 3kT/q$ and for reverse bias [16]. In practice however, Φ_{ϕ}/V is not constant and the plot of $\ln[J/\{1 - \exp(-qV/kT)\}]$ versus V is not linear. The ideality factor defined by equation (3.22) is in that case a function of bias. However, it is still a useful concept which can be determined from the experimentally obtained current – voltage characteristic through the relationship [16]:

$$\frac{1}{n} = \frac{kT}{q} \frac{d}{dV} \ln \left[\frac{J}{1 - \exp\left(-\frac{qV}{kT}\right)} \right] \quad (3.25)$$

or, for $V > 3kT/q$,

$$\frac{1}{n} = \frac{kT}{q} \frac{d}{dV} \ln(J) \quad (3.26)$$

The parameter n is generally a function of V and can only be specified for a particular operating point on the characteristic. Equation (3.26) is more commonly found in literature, but equation (3.25) has the advantage that it can be used for $V < 3kT/q$ and for reverse bias [16].

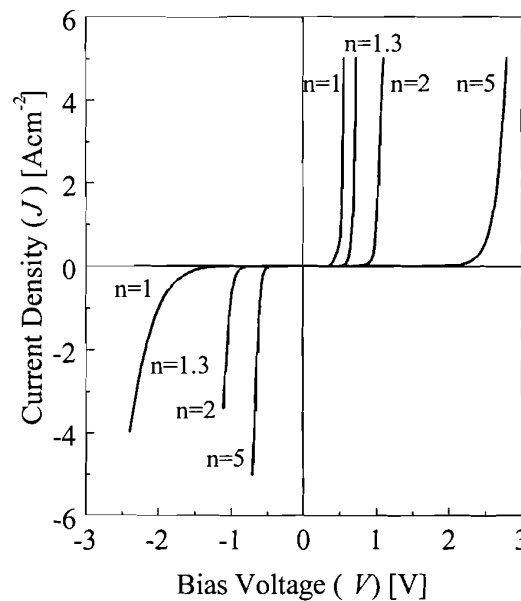


Figure 3.5: (J - V) characteristics of a Schottky diode and the dependence on n .

Figure 3.5 shows the current – voltage (J - V) characteristics of a Schottky diode under reverse and forward bias according to equation (3.21). Furthermore, it shows the dependence of the (J - V) characteristics on the ideality factor (n). It can be observed that as n increases, the Schottky diode becomes increasingly leaky and in the end shows better conduction in the reverse than in the forward direction.

3.3.2 Tunneling through the barrier

This subsection will describe the second basic transport process under forward bias for a metal – n - type semiconductor contact as was mentioned at the beginning of section 3.3. Depending on the circumstances it may be possible for electrons with energies below the top of the potential barrier to penetrate the barrier by quantum mechanical tunneling. This tunneling process modifies the ordinary thermionic emission process in one of the two ways which are shown in figure 3.6. Figures 3.6a and 3.6b show the energy band diagrams in the case of *field emission (FE)* and *thermionic field emission (TFE)* respectively.

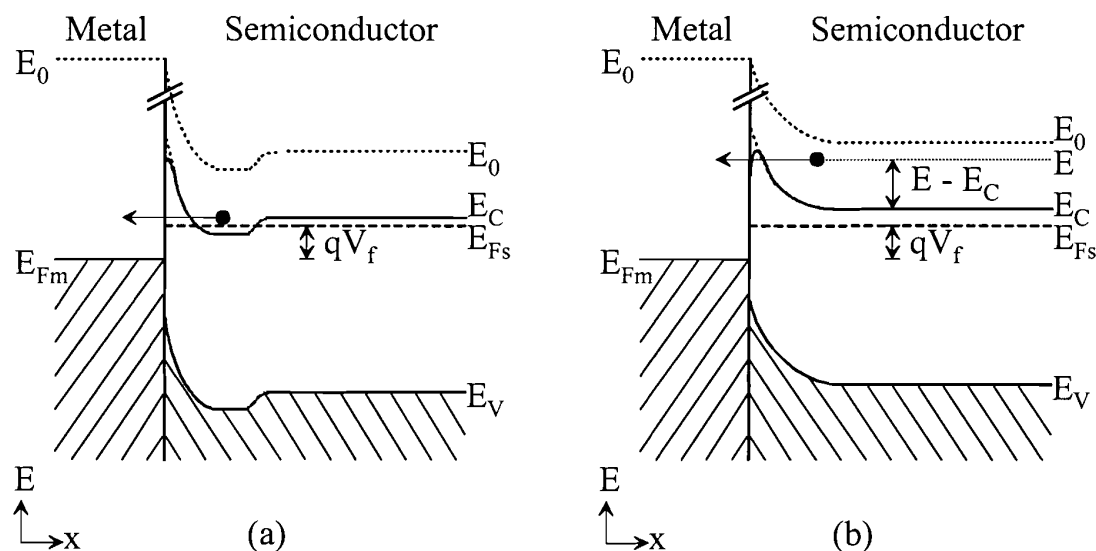


Figure 3.6: Energy band diagrams in the case of field emission (FE) (a) and thermionic field emission (TFE) (b) under forward bias for a metal – n - type semiconductor contact.

In the case of a very highly doped (degenerate) region of the semiconductor material near the surface (figure 3.6a), at low temperature the current in the forward direction is due to the tunneling of electrons with energies close to the Fermi energy in the semiconductor. This is known as field emission (FE). Field emission is of considerable importance with respect to Ohmic contacts which usually consist of Schottky barriers on very highly doped semiconductor material. If the temperature is raised, electrons are excited to higher energies and the tunneling probability increases very rapidly because the electrons encounter a thinner and lower potential barrier. In this case, electrons can tunnel through the barrier at a height $E - E_C$ above the bottom of the conduction band. This is known as thermally assisted tunneling or thermionic field emission (TFE). If the temperature is raised still further, a point is eventually reached in which virtually all of the electrons have enough energy to go over the top of the barrier. The effect of tunneling is then negligible and pure thermionic emission (TE) remains [15, 16].

To arrive at a universal expression for the current densities in the different current transport mechanisms (TE, TFE and FE, respectively) we can use the ideality factor n introduced in section 3.3.1.4. This universal equation is given by:

$$J = J_s \exp\left(\frac{qV}{nkT}\right) \left[1 - \exp\left(-\frac{qV}{kT}\right)\right], \quad \begin{cases} n = 1 \text{ (TE)} & (3.27-a) \\ 1 < n < 2 \text{ (TFE)} & (3.27-b) \\ n \geq 2 \text{ (FE)} & (3.27-c) \end{cases}$$

where the saturation current density (J_s) is again given by equation (3.20). In the case of equation (3.27-a – c), the ideality factor is more or less used as a fitting parameter in order to fit the universal equation to the practical current – voltage characteristics rather than a parameter indicating the bias dependence of Φ_e . For practical matters it is generally assumed that if n is equal to unity, equation (3.27-a) describes pure thermionic emission (TE). In the case of $1 < n < 2$, equation (3.27-b) is assumed to describe thermionic field emission (TFE) [17]. Finally, in the case of $n \geq 2$, equation (3.27-c) is assumed to describe field emission (FE) [17]. Hence, it can be concluded that if the thermionic field emission and field emission become increasingly dominant, the “ideality factor” will consequently increase.

3.3.3 Recombination in the depletion region

At the beginning of section 3.3, recombination of electrons and holes in the depletion region was mentioned as the third basic transport process in a forward biased metal – n - type semiconductor contact. Recombination current is a common cause of departure from ideal behavior in Schottky diodes.

The recombination in the depletion region normally takes place via localized energy states. According to the theory of Shockley, Read and Hall (1952) the most effective centers are those with energies lying near the center of the forbidden energy zone or band gap (E_g) [16]. The theory of the current due to such recombination centers in Schottky diodes is similar to that for $p - n$ junctions and the current density for low forward bias is approximately given by [15, 16]:

$$J_r = J_{r0} \exp\left(\frac{qV}{2kT}\right) \left[1 - \exp\left(-\frac{qV}{kT}\right)\right] \quad (3.28)$$

where

$$J_{r0} = \frac{qn_i W}{2\tau_r} \quad (3.29)$$

In equation (3.29), q is the electron charge, n_i the intrinsic electron concentration which is proportional to $\exp(-qE_g / 2kT)$, W the thickness of the depletion region and τ_r is the life time within the depletion region. To arrive at this simple form for the current density due to recombination in the depletion region (J_r) given by equation (3.28), three rather drastic assumptions have to be made [16]:

- 1) the energy levels of the centers coincide with the intrinsic Fermi level;
- 2) the capture cross sections for electrons and holes are equal; and
- 3) the centers are distributed in a spatially uniform manner.

None of these assumptions is likely to be true in practice, especially the equality of the electron and hole capture cross sections which may differ by as much as three orders of magnitude. Depending on the ratio of the capture cross sections for electrons and holes respectively, the n value for the recombination current is between 1 and 2 [16]. If equation (3.28) is assumed to be valid, the total current density is given by [16]:

$$J = J_{ie} + J_r$$

$$J = J_{st} \left[\exp\left(\frac{qV}{kT}\right) - 1 \right] + J_{r0} \exp\left(\frac{qV}{2kT}\right) \left[1 - \exp\left(-\frac{qV}{kT}\right) \right]$$

$$J = \left[J_{ST} \exp\left(\frac{qV}{kT}\right) + J_{r0} \exp\left(\frac{qV}{2kT}\right) \right] \left[1 - \exp\left(-\frac{qV}{kT}\right) \right] \quad (3.30)$$

where J_{ie} is the current density according to the thermionic emission theory given by equation (3.5) and J_{ST} is the saturation current density in the case of thermionic emission given by equation (3.6). The ratio of the thermionic emission current to the recombination current is proportional to:

$$T^2 \tau_r \exp\left(\frac{q(E_g + V - 2\Phi_{Bn})}{2kT}\right) \quad (3.31)$$

This ratio increases with τ_r , V and E_g , and decreases with Φ_{Bn} . In addition, for small forward bias voltages (V) this ratio also increases with T . Thus the recombination component of equation (3.30) is likely to be relatively more important in high barriers, in material of low life time, at low temperatures and at low forward bias voltage. When recombination current is important, the temperature variation of the forward current shows two activation energies [16] [17]. In general, any process which shows a temperature dependence of the form $\exp(-E_a / kT)$ is said to have an activation energy E_a . At high temperatures the activation energy tends to the value $\Phi_{Bn} - V$, characteristic of the thermionic emission component. At low temperatures it approaches the value $(E_g - V)/2$, characteristic of the recombination component [16].

3.3.4 Hole injection

Recombination of electrons and holes in the neutral region or “hole injection” will be briefly described in this subsection. At the beginning of section 3.3, this was mentioned as the fourth basic transport process in metal n - type semiconductor contacts under forward bias. If the height of a Schottky barrier on n - type material is greater than half the band gap, the region of the semiconductor adjacent to the metal becomes p - type and contains a high density of holes. Under forward bias, some of these holes might be expected to diffuse into the neutral region of the semiconductor, thus giving rise to the injection of holes.

The transport of holes through the depletion region of a Schottky barrier and their subsequent diffusion in the neutral region of the semiconductor is identical to the mechanism of hole transport in a $p - n$ junction. Hence, the hole current density is given by [16]:

$$J_h = J_{oh} \left[\exp\left(\frac{qV}{kT}\right) - 1 \right] \quad (3.32)$$

where

$$J_{0h} = \left[\frac{qN_v\bar{v}}{(3r_h)^{\frac{1}{2}}} \right] \exp\left(-\frac{q\Phi_h}{kT}\right) \quad (3.33)$$

In equation (3.33), N_v is the effective density of states function in the valence band, $\bar{v}$ the mean thermal velocity of the holes and Φ_h is the barrier for holes shown in figure 3.7. The term r_h is defined as $r_h = \tau_{rh} / \tau_{ch}$ where τ_{rh} is the recombination time for holes and τ_{ch} is the mean time between collisions for holes [16, 17]. The hole injection ratio γ_h is therefore given by [16]:

$$\gamma_h = \frac{J_h}{J_e + J_h} \approx \frac{J_h}{J_e} = \frac{4N_v}{(3r_h)^{\frac{1}{2}} N_c} \exp\left(-\frac{q(\Phi_h - \Phi_{Bn})}{kT}\right) \quad (3.34)$$

where the current density due to electrons (J_e) is in the case of thermionic emission equal to J_{te} and is given by equation (3.5). Equation (3.34) shows that γ_h increases with increasing Φ_{Bn} because of the reduction in J_e and decreases with increasing Φ_h because of the reduction in J_h . The hole injection ratio (γ_h) is generally negligible in practically useful diodes. It is for this reason that Schottky diodes are often described as “majority carrier” devices [15, 16]. However, the hole injection ratio of a Schottky diode can be increased by the presence of a thin interfacial layer [16]. In this case, hole injection can become appreciable at high forward current densities. It can be expected that the additional electrons, which have to enter the neutral region to maintain charge neutrality, would increase the conductivity and reduce the series resistance. Conductivity modulation arising from this cause has been reported in literature [15, 16, 17]. This effect is noticeable only with large barrier heights and in weakly doped material [16].

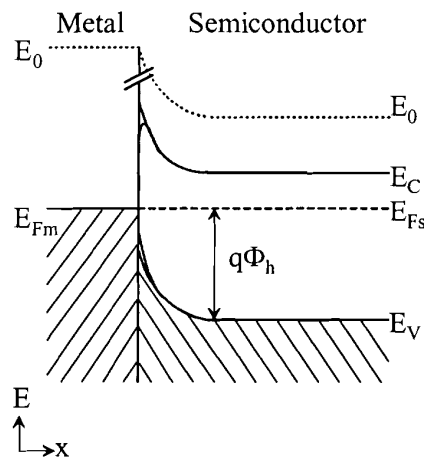


Figure 3.7: Energy band diagram of a Schottky barrier under thermal equilibrium showing the barrier for holes Φ_h .

3.4 Conclusions and recommendations for practical metal – semiconductor contacts

In this chapter it has been shown that the presence of an interfacial layer and an infinitely large density of surface states can cause pinning of the Fermi level in the semiconductor. As a result, the barrier height is essentially independent of the metal work function. In section 3.2 it has been discussed that Fermi level pinning in the case of the GaN – based materials systems is of minor importance and that the major contribution to the Schottky barrier height is due to the difference in the metal and semiconductor work functions. Hence, metals with a low work function e.g. Titanium (Ti) and Aluminum (Al) are used for Ohmic contacts on n – type GaN – based materials systems. To obtain Schottky contacts on n – type GaN – based materials systems metals with a high work function e.g. Platinum (Pt), Nickel (Ni), Gold (Au), Iridium (Ir) and Palladium (Pd) are used.

Furthermore, it has been shown that an interfacial layer and surface states render the Schottky barrier bias dependent. As a result the ideality factor will significantly deviate from unity. It is obvious that for the fabrication of high quality metal – semiconductor contacts the influence of an interfacial layer and an infinitely large density of surface states should be minimized. The most effective way to do this is of course the complete removal of a surface layer and surface states from the semiconductor material prior to metallization. However, this will almost be impossible due to practical matters such as the impossibility to work in an oxygen – free environment. However, it should be tried to fabricate Schottky contacts with an ideality factor (n) that approaches unity as nearly as possible because in that case the reverse current (I_s) will be minimized and the breakdown voltage (V_{break}) will be maximized and the Schottky contacts can be applied in high power devices.

CHAPTER 4

Theoretical Introduction to Ohmic Contacts

4.1 Introduction

This chapter deals with the first of the two limiting cases of metal – semiconductor contacts: the Ohmic contacts. The term “Ohmic contact” is generally used to refer to contacts for which the current – voltage characteristics are determined by the resistivity of the semiconductor material or by the behavior of the device to which they belong, rather than by the characteristics of the contacts themselves. The ideal contact would have an impedance which is negligible compared to that of the semiconductor material. This trivial statement puts a rather stringent requirement on the metal – semiconductor contacts in modern very large scale integrated (VLSI) circuits. In addition, the contact should not inject minority carriers and should be stable both electrically and mechanically. Ohmic contacts with very low contact resistances are needed to establish the connections between any semiconductor device or integrated circuit and the outside world. Furthermore, high quality Ohmic contacts are essential for performing very accurate Van der Pauw / Hall measurements.

This chapter starts with an overview of the basic principles of Ohmic contact formation. Next, the specific contact resistance (ρ_c), which is the most important property of Ohmic contacts, will be discussed. Finally, the transfer length method (TLM), which is the most commonly used analysis technique to determine ρ_c , will be considered.

4.2 Basic principles of Ohmic contact formation

The fabrication of Ohmic contacts is still more an art than a science. Every laboratory tends to have its own favorite recipes which involve particular metal or alloy systems, particular deposition methods and particular forms of heat treatment. However, all these recipes appear to depend on one of the following three basic principles [16]:

- 1) If the semiconductor is one which conforms approximately to the simple Schottky – Mott theory ($\Phi_{Bn} = \Phi_m - \chi_s$), it should in principle be possible to obtain a contact with a negative barrier height (which should behave as an Ohmic contact) by finding a metal with a work function less than the work function of an n - type semiconductor or greater than the work function of a p - type semiconductor. Alternatively, if the barrier height is determined by Fermi level pinning, it occasionally happens that the pinning position is within the conduction band or valence band. In this case negative barrier heights should be obtainable on n - type or p - type semiconductors respectively. Unfortunately, there are very few metal – semiconductor combinations with this property. However, if the barrier height is positive, but very small, the contact should have a low enough resistance to be effectively Ohmic.
- 2) The vast majority of Ohmic contacts depend on the principle of having a thin layer of very highly doped semiconductor material immediately adjacent to the metal – semiconductor interface. In that case, the depletion region is so thin that field emission (FE) takes place and the contact has a very low resistance at zero bias. This mechanism has already been discussed in subsection 3.3.2. The heavily doped layer may be formed by diffusion techniques or by ion implantation. Alternatively, the heavily doped region may result from the deposition and subsequent heat treatment of an alloy containing an element which acts as a donor or acceptor in the semiconductor. The heat treatment can be carried out in an ordinary furnace or by rapid thermal annealing (RTA). When heated, some of the semiconductor dissolves in the metal and on subsequent cooling it recrystallizes with a high concentration of the electrically active element in solid solution. One of the most important properties of a suitable alloy for Ohmic contacts is that it should “wet” the surface of the semiconductor material when it melts.
- 3) If the surface of the semiconductor material is damaged (e.g. by etching), crystal defects may be formed near the surface which act as efficient recombination centers. If the density of these centers is high enough, recombination in the depletion region will become the dominant conduction mechanism and will cause a significant decrease in the contact resistance. This mechanism has already been considered in subsection 3.3.3. This method is mainly of historical interest. It was widely used during the early days of semiconductor research for making contacts to silicon (Si) and germanium (Ge), the actual contacts being obtained either by soldering or by the application of pressure [17].

4.3 Specific contact resistance

The specific contact resistance (ρ_c) is the most important property of Ohmic contacts. It provides the most systematic way to compare different metallization schemes with respect to the contact resistance. The specific contact resistance is due to the potential barrier at the metal – semiconductor interface and is defined by [15, 18]:

$$\rho_c \equiv \left(\frac{\partial J}{\partial V} \right)_{V=0}^{-1} \quad (4.1)$$

where V is the voltage across the barrier and J is the current density through the barrier. The expression for the current density depends on the ruling current transport mechanism. The second basic principle of Ohmic contact formation that has been described in section 4.2 is the most widely occurring. Hence the current transport mechanisms that are of interest in Ohmic contacts are thermionic emission (TE), thermionic field emission (TFE) and field emission (FE) respectively. Using the definition of ρ_c and equations (3.27-a – c) that give the expressions for the current densities in the case of TE, TFE and FE respectively, the expressions for the specific contact resistance in each of these cases can be determined [18]:

$$(TE) \quad \rho_c \propto \exp\left(\frac{q\Phi_{Bn}}{kT}\right) \quad (4.2)$$

$$(TFE) \quad \rho_c \propto \exp\left\{ \frac{4\pi\sqrt{m^*\epsilon_0\epsilon_{r,s}}}{h} \left(\frac{\Phi_{Bn}}{\sqrt{N_d}} \right) \tanh\left[\frac{qh}{4\pi kT} \sqrt{\frac{N_d}{m^*\epsilon_0\epsilon_{r,s}}} \right] \right\} \quad (4.3)$$

$$(FE) \quad \rho_c \propto \exp\left[\frac{4\pi\sqrt{m^*\epsilon_0\epsilon_{r,s}}}{h} \left(\frac{\Phi_{Bn}}{\sqrt{N_d}} \right) \right] \quad (4.4)$$

The value of ρ_c in a given metal – semiconductor system is determined by the combination of the following three parameters [18]:

- 1) the potential barrier height (Φ_{Bn});
- 2) the dopant concentration (N_d , in the case of an n - type semiconductor); and
- 3) the temperature (T).

The relative effect of these parameters in the various current transport mechanisms can be deduced from the exponential terms that contribute to ρ_c . Equation (4.2) shows that in the thermionic emission process the specific contact resistance is independent of the dopant concentration (N_d). In the case of a thermionic field emission tunneling mechanism (equation (4.3)), $\ln(\rho_c)$ varies nonlinearly with $N_d^{-1/2}$. It does vary linearly with $N_d^{-1/2}$, however, when a

low – temperature tunneling process, known as field emission (equation (4.4)), is the mechanism for current transport across the barrier.

In order to determine the specific contact resistance, the actual contact resistance (R_c) has to be measured. In the highly hypothetical case of a uniform current distribution over the contact area, the resistance of the metal – semiconductor contact (R_c) can be written as:

$$R_c = \frac{\rho_c}{A} \quad (4.5)$$

where A is the area of the metal – semiconductor contact. In reality however, the current density is seldom uniformly distributed across the contact area due to the voltage drop in the semiconductor. This phenomenon is referred to as the current crowding effect. In practice, it is generally sufficient to mention that the current density is negligible beyond a certain distance from the front edge of the contact. This distance, which is also an important property of Ohmic contacts, is the so – called transfer length (L_t). This quantity is related to the lateral distance required for current to flow into or out of the contact. The total current density passes through an imaginary plane at the edge of the contact, as shown in figure 4.1. A portion of this current density flows into the metal very near the edge of the contact while other portions enter the metal further from the edge.

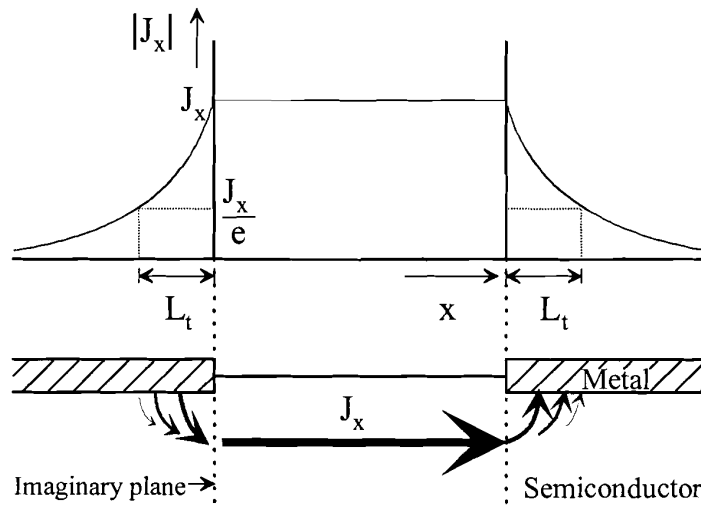


Figure 4.1: Flow of the current density in a planar Ohmic contact.

In the case of a rectangular metal contact and if the contact length $d \gg L_t$ (electrically long), the effective contact area (A_{eff}) becomes $L_t \cdot W_c$ where W_c is the contact width in the direction perpendicular to the current flow. For such a contact, the contact resistance is given by:

$$R_c = \frac{\rho_c}{A_{eff}} = \frac{\rho_c}{L_t \cdot W_c} \quad (4.6)$$

Unlike the contact resistance (R_c), the specific contact resistance (ρ_c) is unaffected by the current crowding effect and as mentioned before, ρ_c is determined by the barrier height, the doping concentration and the temperature [18]. In other words, unlike the contact resistance (R_c), the specific contact resistance (ρ_c) is a unique, geometry independent characteristic of the metal – semiconductor interface. To allow for an accurate extraction of the specific contact resistance, a major problem has to be solved. In the case of low - resistive Ohmic contacts, the voltage drop across the metal – semiconductor interface is a small fraction of the total voltage. In order to circumvent this problem, a number of sophisticated test structures and procedures have been developed. However, the current flow pattern in these test structures is usually rather complicated. In particular, the current density is nonuniformly distributed across the contact area in the test structures as well as in the actual semiconductor devices. This requires the use of a theoretical model to enable the extraction of the specific contact resistance from experimental data. To simplify the analysis, test structures are designed in such a way that the current flow pattern is approximately one – dimensional or at least symmetrical [16, 18].

4.4 Transfer length method

The transfer length method (TLM), three-terminal resistor or transmission line model (also abbreviated as TLM) was developed by Shockley [18] and is known as a technique to extract the specific contact resistance from experimental data. This method has attracted much attention as it has been used and modified in many contact resistance studies. These modifications include the approximate modeling of the two – dimensional current flow pattern in the conductive layer beneath the contact area as well as the attempts to account for the finite thickness of this conductive layer. A useful definition with regard to the latter modification is that of a quantity called the sheet resistance (R_{sh}), which is given by [19]:

$$R_{sh} = \frac{\rho}{t} \quad (4.7)$$

where ρ is the specific resistance of the conductive semiconductor layer and t is the thickness of this layer. In the strict sense, R_{sh} has the dimensions of ohms, but it is universally given the

units “ohms per square” (Ω/sq). A “square” of material ($L = W$) has an end – to – end resistance of R_{sh} . Three “squares” of material placed in series and assuming that the current flows along $L = 3W$, have of course an end – to – end resistance of $3R_{sh}$, and so on. The sheet resistance can be usefully employed in calculations without any knowledge of the exact thickness of the conductive layer (which may be hard to measure accurately). More importantly, the concept of the sheet resistance is valid even when the resistivity of the conductive layer is not uniform, but is some unknown function of depth, and also when there is no sharp boundary between conductive and insulating material [19].

Besides considering the finite thickness of the conductive layer, alloying and sintering effects were included in the model by taking into account the difference in sheet resistances of the conductive layer beneath ($R_{sh,c}$) and outside the contact area (R_{sh}). Finally, circular TLM (CTLM) has been developed [20] in order to simplify the fabrication procedure and achieve a more symmetrical current flow pattern by eliminating the edge effects that exist in the linear TLM (LTLM).

4.4.1 Linear TLM

The simplest and most used configuration of the transfer length method is a linear array of Ohmic contacts, all of the same size but placed at increasing distances l_i ($l_1 < l_2 < \dots < l_i$), on the semiconductor surface. Because of the linear arrangement of the Ohmic contacts, this configuration is often referred to as the linear transfer length method (LTLM). Figure 4.2 shows a schematic impression of the LTLM configuration. The figure also shows that the contacts have been isolated in order to restrict the current to flow only across the distances l_i and to prevent current spreading. This isolation can be obtained by etching away areas of the electrically active semiconductor material down to the semi – insulating (s.i.) substrate. Usually photolithography techniques are used to define the areas that should be etched away. As a result, so – called “mesas” of the active semiconductor material are created.

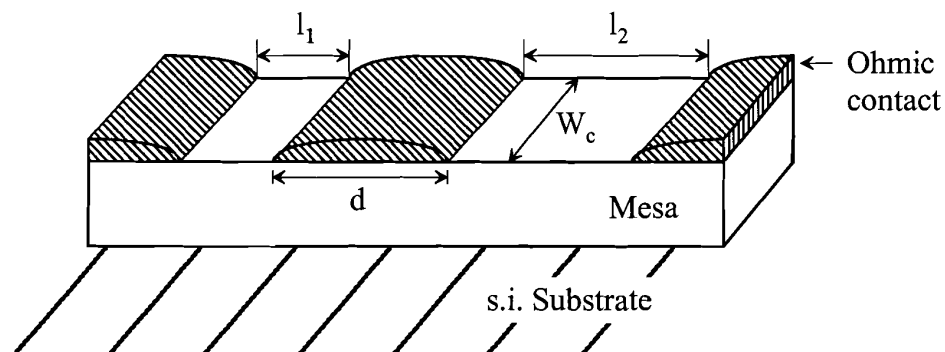


Figure 4.2: Schematic impression of the LTLM configuration.

Looking at figure 4.2, the following equations describe the total resistances R_1 and R_2 that correspond to the contact separations l_1 and l_2 respectively:

$$R_1 = 2R_c + R_{sh} \left(\frac{l_1}{W_c} \right) \quad (4.8)$$

$$R_2 = 2R_c + R_{sh} \left(\frac{l_2}{W_c} \right) \quad (4.9)$$

where R_{sh} is the sheet resistance of the semiconductor material outside the contact area. In principle, the contact resistance (R_c) can be obtained by measuring the total resistances R_1 and R_2 . Solving for R_c gives:

$$R_c = \frac{(R_2 l_1 - R_1 l_2)}{2(l_1 - l_2)} \quad (4.10)$$

However, the disadvantage of this procedure is that usually the contact resistance is small compared with that of the semiconductor material between the contacts ($2R_c \ll R_{sh} \cdot l_1 / W_c$). In this case, R_c is determined from equation (4.10) as a small difference of large quantities and thus is extremely sensitive to experimental errors in the values of R_1 , R_2 , l_1 and l_2 .

A somewhat better result can be obtained when the total resistance $R_T = 2R_c + R_{sh}(l/W_c)$ is plotted as a function of the distance l between several pairs of the planar contacts. In this case, R_c is determined by a linear extrapolation of the experimental data to $l = 0$, which is shown in figure 4.3. Note that the external resistance of the measurement system, the probe resistance, is assumed to be negligible. This assumption is valid if a four – point probe measurement technique is used. This technique makes use of two outer probes to pass the current (I) and two inner probes to measure the potential difference (V). In addition, a high impedance voltmeter is used to avoid affecting the current.

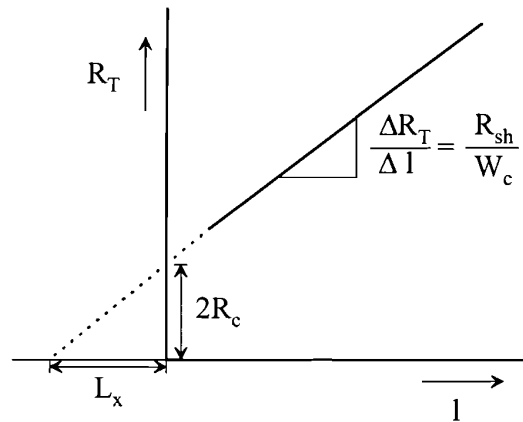


Figure 4.3: Plot of the total resistance (R_T) versus the distance (l) between the planar contacts.

Furthermore, it has to be noted that R_c is obviously a function of device size. Hence, R_c is generally spoken of in terms of a normalized size (usually 1 mm) and is given the dimension of Ωmm , which can be obtained by multiplying the measured contact resistance in Ohms with the length (d) of the contact pad in millimeters; $R_c [\Omega\text{mm}] = R_c [\Omega] \cdot d [\text{mm}]$.

Extraction of the specific contact resistance (ρ_c) from the contact resistance determined by the method described above requires that a certain model of the planar metal – semiconductor contact is adopted. A transmission line model (also abbreviated by TLM) is almost exclusively used for this purpose [18]. Its validity is based on the fulfillment of the following conditions [18]:

- 1) The current lines are normal to the metal – semiconductor interface.
- 2) The thickness of the metal and diffusion layers can be neglected.
- 3) The current – voltage characteristic of the contact is linear.

Of these three assumptions, only the third one can be verified directly by measuring the current – voltage characteristic of the metal – semiconductor contact. Figure 4.4 shows an equivalent circuit of the rectangular metal – semiconductor contact with approximately one – dimensional current flow pattern.

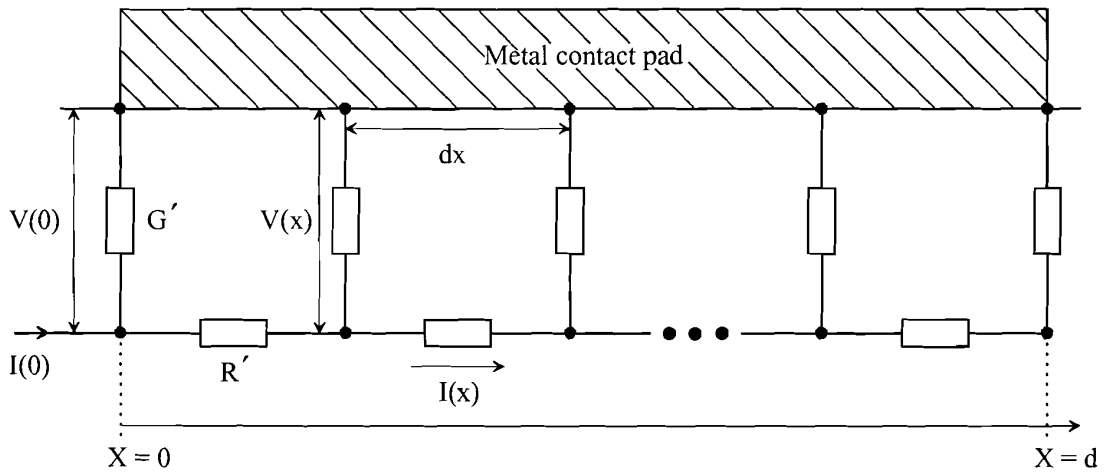


Figure 4.4: Equivalent circuit of the rectangular metal – semiconductor contact.

The resistance R' and the conductance G' per unit length of the contact, shown in figure 4.4, can be written as:

$$R' = \frac{R_{sh,c}}{W_c} \quad (4.11)$$

and

$$G' = \frac{W_c}{\rho_c} \quad (4.12)$$

Next, the metal layer is considered to be equipotential, which strictly speaking is correct only when the metal sheet resistance $R_m \ll R_{sh,c}$. Then, the voltage drop in the semiconductor material between the contacts can be written as:

$$dV(x) = -R' I(x) dx \quad (4.13)$$

while according to Kirchhoff's law:

$$dI(x) = -V(x) G' dx \quad (4.14)$$

where $I(x)$ denotes the current in the semiconductor material between the contacts at a distance x from the front edge of the contact. A differential equation of the one - dimensional TLM follows from equations (4.13) and (4.14):

$$\frac{d^2 V}{dx^2} - \frac{V}{L_t^2} = 0 \quad (4.15)$$

or

$$\frac{d^2 I}{dx^2} - \frac{I}{L_t^2} = 0 \quad (4.16)$$

where the transfer length is defined as [18]:

$$L_t = \frac{1}{\sqrt{R' G'}} = \sqrt{\frac{\rho_c}{R_{sh,c}}} \quad (4.17)$$

By introducing the current I_0 and the voltage V_0 at the input of the transmission line, the boundary conditions can be formulated as:

$$V(0) = V_0 \quad (4.18)$$

and

$$I(0) = I_0 \quad \text{or} \quad \left[-\frac{1}{R'} \frac{dV(x)}{dx} \right]_{x=0} = I_0 \quad (4.19)$$

The solution of equation (4.15) subject to these boundary conditions yields [18, 19]:

$$V(x) = V_0 \cosh\left(\frac{x}{L_t}\right) - Z I_0 \sinh\left(\frac{x}{L_t}\right) \quad (4.20)$$

where

$$Z = R' L_t = \frac{R_{sh,c} L_t}{W_c} = \frac{\sqrt{\rho_c R_{sh,c}}}{W_c} \quad (4.21)$$

which denotes the characteristic resistance of the transmission line. The expression for the current $I(x)$ follows now from equations (4.13) and (4.20):

$$\begin{aligned} I(x) &= -\frac{1}{R'} \frac{dV(x)}{dx} \\ &= I_0 \cosh\left(\frac{x}{L_t}\right) - \left(\frac{V_0}{Z}\right) \sinh\left(\frac{x}{L_t}\right) \end{aligned} \quad (4.22)$$

Returning to the equivalent circuit shown in figure 4.4, it has to be noted that $I(x) = 0$ for $x > d$. Hence, the current continuity requires that $I(d) = 0$ and according to equation (4.22):

$$\frac{V_0}{I_0} = Z \coth\left(\frac{d}{L_t}\right) \quad (4.23)$$

Since the imaginary separation between the semiconductor material between the contacts and the metal – semiconductor area is made at the contact edge ($x = 0$), the contact resistance R_c appearing in equation (4.8) corresponds to the input resistance of the transmission line given by equation (4.23). Using equation (4.21), R_c can be given by:

$$R_c = \frac{R_{sh,c} L_t}{W_c} \coth\left(\frac{d}{L_t}\right) \quad (4.24)$$

In the case that the sheet resistance beneath the contacts, as a practical matter, is assumed to be equal to the sheet resistance between the contacts, $R_{sh,c} = R_{sh}$, equation (4.24) can be solved numerically with respect to L_t by using the value of R_c as determined by the extrapolation technique mentioned earlier. The determination of the transfer length can be further simplified in the case of electrically long contacts, that means if $d \gg L_t$. In that case equation (4.24) can be reduced to $R_c \approx R_{sh} L_t / W_c$. The total resistance (R_T) between a pair of identical contacts separated by a distance l then becomes:

$$R_T \approx \left(\frac{R_{sh}}{W_c}\right) (2L_t + l) \quad (4.25)$$

The transfer length is then determined by a linear extrapolation of the experimental data to the point $R_T = 0$ as shown in figure 4.3. According to equation (4.25), the negative x – axis

intercept (L_x) equals two times the transfer length, hence, $L_t = L_x / 2$. Once L_t is determined, the specific contact resistance can be calculated using equation (4.17):

$$\rho_c = R_{sh,c} L_t^2 \quad (4.26)$$

where $R_{sh,c} = R_{sh}$. When the alloying (sintering) effect cannot be neglected, the extrapolation procedure developed earlier is not sufficient to determine the transfer length $L_t \neq L_x / 2 = L_t' (R_{sh,c} / R_{sh})$ even for electrically long contacts. In this case ($R_{sh,c} \neq R_{sh}$), the measurement of the end contact resistance (R_E) is needed to extract ρ_c from the experimental data [18, 19]. One version of the measurement procedure that can be used in this case is schematically shown in figure 4.5a. Figure 4.5b shows the corresponding equivalent circuit [18, 19]. The resistances R_1 and R_2 in figure 4.5b are those given by equations (4.8) and (4.9).

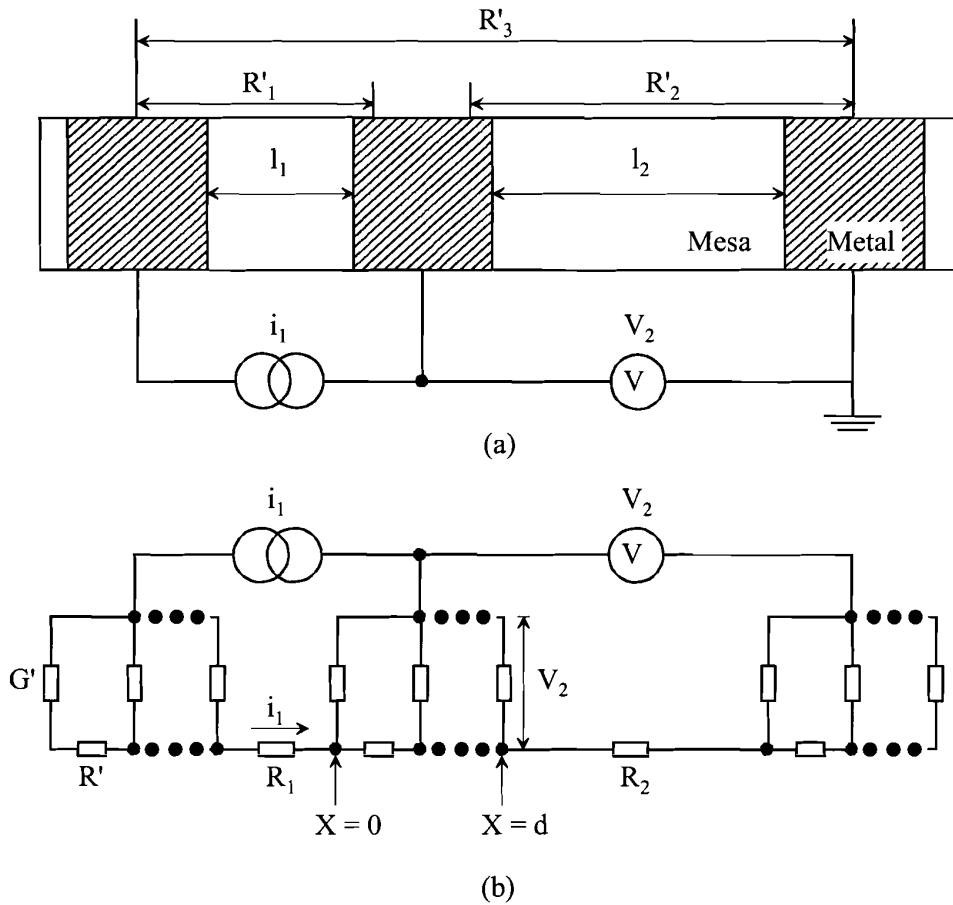


Figure 4.5: Schematic representation of a possible procedure to measure the end resistance (R_E) of a metal – semiconductor contact (a) and the corresponding equivalent circuit (b).

From the equivalent circuit shown in figure 4.5b, it can be seen that the resistance defined as $R_E = V_2 / i_1$ is the end resistance $V(d) / I(0)$ of the transmission line, modeling the central contact. Then, according to equations (4.20), (4.22) and (4.23) the end resistance is given by [18, 19]:

$$R_E = Z \cosh\left(\frac{d}{L_t}\right) \coth\left(\frac{d}{L_t}\right) - Z \sinh\left(\frac{d}{L_t}\right)$$

$$R_E = \frac{R_{sh,c} L_t}{W_c \sinh\left(\frac{d}{L_t}\right)} \quad (4.27)$$

where equation (4.21) has been used for the characteristic impedance of the transmission line. The last equation makes it possible to find the transfer length using the experimentally determined values of R_c and R_E . Elimination of $R_{sh,c}$ from equations (4.24) and (4.27) gives [18]:

$$\frac{R_c}{R_E} = \cosh\left(\frac{d}{L_t}\right) \quad (4.28)$$

or

$$L_t = \frac{d}{\ln\left[\left(\frac{R_c}{R_E}\right) + \sqrt{\left(\frac{R_c}{R_E}\right)^2 - 1}\right]} \quad (4.29)$$

After L_t is calculated, ρ_c can be determined by the exclusion of $R_{sh,c}$ from equations (4.17) and (4.24). The specific contact resistance is then given by:

$$\rho_c = R_c W_c L_t \tanh\left(\frac{d}{L_t}\right) \quad (4.30)$$

or

$$\rho_c = R_E W_c L_t \sinh\left(\frac{d}{L_t}\right) \quad (4.31)$$

Finally, the modified sheet resistance (due to the alloying effect) of the semiconductor material beneath the contact area can be calculated using the expression:

$$R_{sh,c} = \frac{\rho_c}{L_t^2} \quad (4.32)$$

that follows from definition (4.17) of the transfer length.

Reeves and Harrison [18] have shown that the end resistance R_E can also be determined from a series of two – point measurements, which are also illustrated in figure 4.5. Hence, R_E is given by [18]:

$$R_E = \frac{1}{2} (R'_1 + R'_2 - R'_3) \quad (4.33)$$

Independent of the measurement technique, the specific contact resistance is calculated using equations (4.29) and (4.30) or equations (4.29) and (4.31).

The boxes below present a summary of the equations in the different cases of the LTLM.

General equations / definitions for the LTLM:

$$\rho_c = R_c \cdot L_t \cdot W_c \quad (4.34)$$

$$R_c [\Omega mm] = R_c [\Omega] \cdot d [mm] \quad (4.35)$$

$$R_c = \frac{R_{sh,c} L_t}{W_c} \coth \left(\frac{d}{L_t} \right) \quad (4.36)$$

$$L_t = \sqrt{\frac{\rho_c}{R_{sh,c}}} \quad (4.37)$$

$$R_{sh,c} = \frac{\rho_c}{L_t^2} \quad (4.38)$$

$$R_{sh} = W_c \cdot \frac{\Delta R_T}{\Delta l} \quad (4.39)$$

In the case that $R_{sh,c} = R_{sh}$:

$$L_t = \frac{L_x}{2} \quad (4.40)$$

$$R_c \approx \frac{R_{sh} \cdot L_t}{W_c} \quad (4.41)$$

$$\rho_c = R_{sh} \cdot L_t^2 \quad (4.42)$$

Finally, in the case that $R_{sh,c} \neq R_{sh}$:

$$L_t \neq \frac{L_x}{2} = L_t \cdot \frac{R_{sh,c}}{R_{sh}} \quad (4.43)$$

$$R_E = \frac{R_{sh,c} \cdot L_t}{W_c \sinh\left(\frac{d}{L_t}\right)} \quad (4.44)$$

$$R_c = R_E \cosh\left(\frac{d}{L_t}\right) \quad (4.45)$$

$$L_t = \frac{d}{\ln\left[\left(\frac{R_c}{R_E}\right) + \sqrt{\left(\frac{R_c}{R_E}\right)^2 - 1}\right]} \quad (4.46)$$

$$\rho_c = R_c \cdot W_c \cdot L_t \tanh\left(\frac{d}{L_t}\right) \quad (4.47)$$

$$\rho_c = R_E \cdot W_c \cdot L_t \sinh\left(\frac{d}{L_t}\right) \quad (4.48)$$

4.4.2 Circular TLM

In investigations of Ohmic contacts, linear TLM (LTLM) measurements are often performed by using a mesa etching of the epitaxial layer to achieve an one – dimensional current flow pattern and omit current spreading. As this mesa etching step requires additional steps in the fabrication process, it has been tried to exclude them and hence simplify the fabrication process. This can be done by choosing a different geometry of the test structures. The use of a circular contact geometry eliminates the need for the mesa etch of the epitaxial layer. Furthermore it can be noted that the use of circular TLM (CTLM) structures eliminates the errors that are introduced by the lateral current crowding and gap effect, which are always present in the linear TLM structures.

In the past, many different configurations for circular test patterns were developed. In 1979, Reeves [20] proposed a test pattern consisting of a central disc contact and two concentric ring contacts to determine the specific contact resistance. In 1981, Marlow and Das [21] used a configuration where the inner disc contact is defined by removing circular rings with varying diameter from a metal plate. In 1999, Rechid and Heime [22] refined Reeves' configuration by increasing the number of concentric ring contacts from two up to seven. This expansion is needed for the case that the resistivity of the metal contacts cannot be neglected. Since Reeves used only three contacts (one disc and two rings), he was not able to see the influence of the metal layer resistivity [22]. Figures 4.6a – c give a schematic representation of the described circular test patterns.

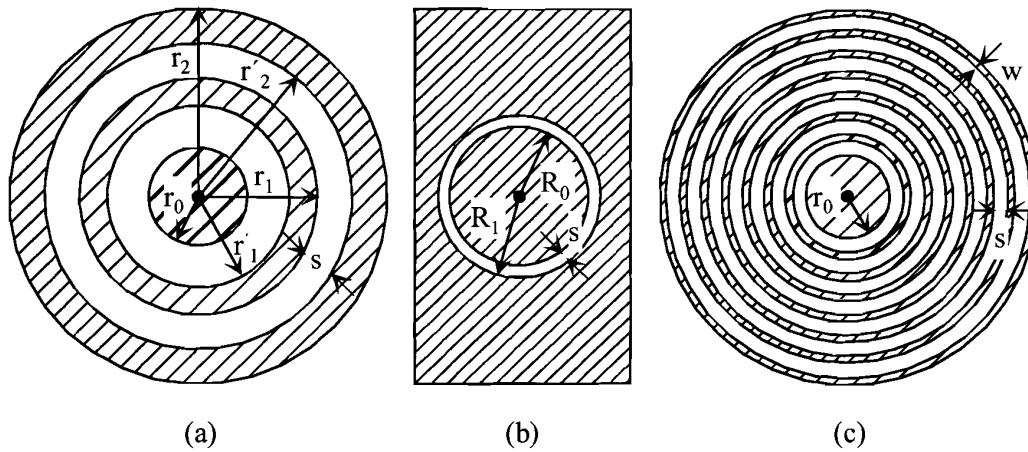


Figure 4.6: Schematic representation of the circular test patterns according to (a) Reeves [20], (b) Marlow and Das [21] and (c) Rechid and Heime [22].

In order to calculate the total resistance ($R_{T,circ}$) of any circular contact configuration, first the resistance of the annular contact, which is shown in figure 4.7 [18], will be calculated. According to Reeves [20] this can be done using the nonuniform transmission line model of the planar circular metal – semiconductor contact. In this case, the usual resistances and conductances which describe the transmission line model for a rectangular contact (equations (4.11) and (4.12)) have to be modified to account for the circular contact geometry. However, according to Cohen [18], it is also possible to arrive at the same expression for $R_{T,circ}$ using a two – dimensional current continuity equation. At this point, only the results of this calculation will be presented. The derivation of the equations is given in appendix A.

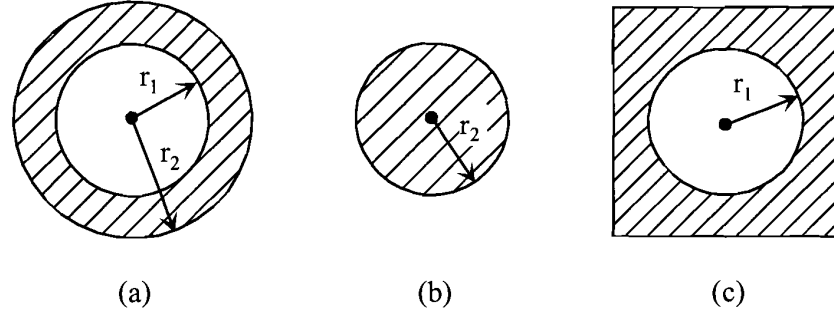


Figure 4.7: Annular metal – semiconductor contacts. (a) General case, (b) $r_1 = 0$, and (c) $r_2 \rightarrow \infty$ [18].

For the general case of an annular contact as is shown in figure 4.7a, the contact resistance of the inner ($2\pi r_1$) and outer ($2\pi r_2$) circumferences respectively, is given by:

$$R_c^{inner}(r_1, r_2) = \frac{R_{sh,c}}{2\pi k r_1} \left[\frac{K_1(kr_2)I_0(kr_1) + I_1(kr_2)K_0(kr_1)}{K_1(kr_1)I_1(kr_2) - K_1(kr_2)I_1(kr_1)} \right] \quad (4.49)$$

and

$$R_c^{outer}(r_1, r_2) = \frac{R_{sh,c}}{2\pi k r_2} \left[\frac{I_0(kr_2)K_1(kr_1) + I_1(kr_1)K_0(kr_2)}{I_1(kr_2)K_1(kr_1) - I_1(kr_1)K_1(kr_2)} \right] \quad (4.50)$$

For the extreme cases of $r_1 = 0$ (circular contact shown in figure 4.7b) and $r_2 \rightarrow \infty$ (figure 4.7c) the contact resistances are respectively given by:

$$R_c^{outer}(0, r_2) = \frac{R_{sh,c}}{2\pi k r_2} \frac{I_0(kr_2)}{I_1(kr_2)} \quad (4.51)$$

$$R_c^{inner}(r_1, \infty) = \frac{R_{sh,c}}{2\pi k r_1} \frac{K_0(kr_1)}{K_1(kr_1)} \quad (4.52)$$

If we for example consider the circular test structure proposed by Marlow and Das [21], shown in figure 4.6b, the total resistance ($R_{T,circ}$) can be written as:

$$R_{T,circ} = R_{gap} + R_c^{outer}(0, R_0) + R_c^{inner}(R_1, \infty) \quad (4.53)$$

where R_{gap} denotes the resistance of the gap between the inner and outer contacts and the last two terms are given by equations (4.51) and (4.52), respectively. If further is assumed that $R_{sh} = R_{sh,c}$, we find:

$$R_{T,circ} = \frac{R_{sh}}{2\pi} \left[\ln\left(\frac{R_1}{R_0}\right) + \frac{L_t}{R_0} \frac{I_0\left(\frac{R_0}{L_t}\right)}{I_1\left(\frac{R_0}{L_t}\right)} + \frac{L_t}{R_1} \frac{K_0\left(\frac{R_1}{L_t}\right)}{K_1\left(\frac{R_1}{L_t}\right)} \right] \quad (4.54)$$

When $R_0 \gg L_t$ (in practice it is enough to require that $R_0 > 4L_t$) we can use the approximate expression for the modified Bessel functions given in appendix B to show that $I_0(x) / I_1(x)$ and $K_0(x) / K_1(x)$ approximate to unity for $x \gg 1$. Equation (4.54) with $s = R_1 - R_0$ then becomes:

$$R_{T,circ} \approx \frac{R_{sh}}{2\pi} \left[\ln\left(\frac{R_1}{R_1 - s}\right) + L_t \left(\frac{1}{R_1 - s} + \frac{1}{R_1} \right) \right] \quad (4.55)$$

The transfer length (L_t) can now be determined by a least squares fit of experimental data to equation (4.54) or (4.55). This fit also yields a value for R_{sh} . The specific contact resistance (ρ_c) can then be calculated using equation (4.26). In addition, it can be observed that for $2\pi R_1 \gg s$ equation (4.55) can be further simplified to obtain the same form as equation (4.25) with $W_c = 2\pi R_1$ and $l = s$.

4.5 Conclusions

It has become clear that almost all practical Ohmic contacts are tunnel contacts that depend on the presence of a thin layer of highly doped (degenerate) semiconductor material near the metal – semiconductor interface. This highly doped (degenerate) region may be formed by diffusion techniques, ion implantation or a heat treatment of the deposited metallization scheme which renders the semiconductor material to be highly doped. In this case, the depletion region is so thin that field emission (FE) takes place and the contact has a very low resistance at zero bias. Furthermore, it has been shown that the most important Ohmic contact parameter is the specific contact resistance (ρ_c). It provides the most systematic way to compare different metallization schemes with respect to contact resistance. This parameter can however not be measured but has to be calculated from the measured Ohmic contact parameters such as the contact resistance (R_c), the transfer length (L_t) and the sheet resistance (R_{sh}). In order to determine these Ohmic contact parameters from experiments, several sophisticated test structures have been developed of which the transfer length method (TLM) is the most commonly used. We have considered the two configurations (LTLM and CTLM, respectively) that are commonly used to implement the transfer length method. It has been discussed that the CTLM configuration has considerable advantages over the LTLM configuration with respect to fabrication issues (no need to etch mesas) and with respect to the

accuracy of the obtained measurement results (no induced errors due to the current crowding effect). For both an LTLM and CTLM configuration, the Ohmic contact parameters can be calculated using the derived equations.

CHAPTER 5

Ohmic Contacts on n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ Heterostructures

5.1 Introduction

The first part of this chapter (sections 5.2 – 5.4) is concerned with the technology of Ohmic contacts on n - type $\text{Al}_x\text{Ga}_{1-x}\text{N}$ / GaN heterostructures. First, the most commonly reported metallization schemes and the proposed formation mechanisms for Ohmic contacts on this materials system will be considered. Furthermore, an overview is given of the pre – metallization and post – metallization treatments respectively, which according to literature [33, 34] are applied in order to decrease the contact resistance (R_c) and the corresponding specific contact resistance (ρ_c).

The remainder of this chapter (sections 5.5 – 5.7) deals with both the experiments that have been carried out in order to develop an Ohmic contact with an as low as possible (R_c) and (ρ_c) and the obtained results. First the used $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure and the basic operation of a High Electron Mobility Transistor (HEMT), which is based on this layer structure, will be described. Next, the circular TLM mask design that is used to fabricate the Ohmic test structures will be considered. Furthermore, the optimization scheme, which has been developed to arrive at the Ohmic contact with an as low as possible contact resistance for the used $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ layer structure, will be described. After this, the experimental results of the Ohmic contact fabrication will be presented, followed by a discussion. Finally, the most important conclusions and recommendations for the fabrication of Ohmic contacts on $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material will be provided.

5.2 Ohmic metallization schemes

According to literature, Ohmic contacts to $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructures are most commonly formed using Titanium/Aluminum (Ti/Al) based metallization schemes. The most frequently reported metallization schemes are [25, 26, 27]:

- Ti/Al/Ti/Au;
- Ti/Al/Ni/Au; and
- Ti/Al/Pt/Au.

These metallization schemes have shown the lowest contact resistances ($0.04 \text{ } \Omega\text{mm}$ [27] $< R_c < 0.6 \text{ } \Omega\text{mm}$ [29]) and corresponding specific contact resistances ($5 \times 10^{-8} \text{ } \Omega\text{cm}^2$ [27] $< \rho_c < 3 \times 10^{-6} \text{ } \Omega\text{cm}^2$ [29]) for Ohmic contacts to $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ HEMT structures depending among others on:

- the doping and composition of the layers of the epitaxial HEMT structures;
- the Al content within the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layers;
- the applied pre – metallization treatments;
- the actual composition of the metal layer stack; and
- the applied post – metallization treatments.

The various metal layers in the metallization schemes proposed above, have their specific role in the formation of an Ohmic contact to the $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ HEMT structures. Titanium (Ti) is the first metal layer that is deposited on the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material and is believed to:

- serve as an adhesion layer in order to provide a good mechanical stability [25];
- dissolve the native oxide on the surface of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material [26, 37]; and
- create nitrogen vacancies (V_N) by reacting with nitrogen atoms from the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material at the interface and hence rendering this $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer to be highly n – type doped [25, 26].

Next, Aluminum (Al) is applied in order to:

- react with Ti and form an Al_3Ti layer which is assumed to reduce the oxidation of the contacting Ti layer at the bottom [25, 26]; and
- serve as a diffusion barrier for Nickel (Ni) or Platinum (Pt) because these metals form high Schottky barriers to n – type $\text{Al}_x\text{Ga}_{1-x}\text{N}$ [37].

Nickel (Ni) and Platinum (Pt) are used to form a diffusion barrier for the Gold (Au) top layer. If Au and Al react they form an alloy called “purple plague” which is highly resistive. In addition, due to its surface tension, the Au top layer has a tendency to contract into balls during post – metallization annealing at high temperatures. The Ni is added as a wetting agent to prevent this. Furthermore, the Ni/Au or Pt/Au layers on top of the Ti/Al layers prohibit the Al to form drops or to smear out during high temperature post – metallization annealing. Hence it is possible to apply annealing temperatures above the melting point of Al (660 °C at atmospheric pressure). Finally, the Au top layer has to form the highly conductive contact layer.

Literature shows that the actual mechanism of Ohmic contact formation is still subject of discussion and yet to be understood. Two models, a low barrier Schottky or a tunneling contact, are generally proposed to explain the Ohmic behavior of the above mentioned metallization schemes on $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ HEMT structures. The principles of the proposed models have already been discussed in section 4.2.

The model of a low barrier Schottky contact can be understood considering the work functions of Ti ($\Phi_m = 4.33$ eV) and Al ($\Phi_m = 4.28$ eV), which according to the simple Schottky – Mott theory (section 4.2) yield relatively low Schottky barrier heights to $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ with an electron affinity $\chi_s = 3.21$ eV [28]. The electrons can pass these low barrier heights in either direction by thermionic emission (TE) or thermionic field emission (TFE).

The model of a tunneling contact involves the outdiffusion of nitrogen towards the metal layers. The nitrogen vacancies (V_N) resulting from this outdiffusion of nitrogen render the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material near the metal – semiconductor interface to be highly n – type doped. As a result, the possibility of carrier tunneling governed by field emission (FE) is enhanced. In literature [25] the following mechanism is suggested for the formation of the Ti/Al based tunnel contacts during post – metallization annealing. The reactions first start between Ti and Al at rather low temperatures (in the range of 250 – 300 °C) with the formation presumably of the Al_3Ti phase as expected according to the binary Al – Ti phase diagram. Formation of an Al_3Ti layer from individual Al and Ti layers requires the Al/Ti thickness ratio to be equal to 2.82 taking into account the densities of Ti and Al. If the Al/Ti thickness ratio is smaller than 2.82, excess Ti can react with the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material at the interface. The reaction between Ti and $\text{Al}_x\text{Ga}_{1-x}\text{N}$, which starts probably above 400 °C, results first in the dissolution of the native oxide from the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ surface and after that in the outdiffusion of nitrogen and the formation of a Ti–Al–N interfacial phase. Decomposition of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material that probably happens at higher temperatures (above 850 °C) leads to the formation of a Ti_2AlN

phase at the interface. Partial decomposition of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ results also in the outdiffusion of Ga and sometimes in the formation of small pockets at the interface (especially at higher temperatures and longer annealing times). Those pockets and the resulting interface roughness might be responsible for the increase of the contact resistance at high temperatures. This mechanism is, to some extent, independent of the particular metallization scheme.

5.3 Pre – metallization treatments of the undoped $\text{Al}_x\text{Ga}_{1-x}\text{N}$ cap layer

In literature [26, 27, 30], it is frequently stated that the quality of Ohmic contacts is influenced by the condition of the semiconductor surface prior to metallization as well as the post – metallization heat treatment, which will be discussed in the next section. In order to influence the condition of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ surface several pre – metallization treatments can be carried out, such as:

- a high temperature pre – processing anneal;
- dry etching of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ surface; and
- wet chemical etching of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ surface.

These pre – metallization treatments will be briefly discussed in the following subsections.

5.3.1 Pre – processing anneal at high temperature

It has been reported [26] that pre – annealing of $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ HEMT structures at 850 °C for 60 minutes in an N_2 ambient appears to improve the Ohmic contacts. This improvement is pointed out by a decrease in the contact resistance (R_c) and the corresponding specific contact resistance (ρ_c). It is believed that the decrease in R_c and ρ_c can be attributed to the release of compensating hydrogen and the creation of nitrogen vacancies during the high temperature pre – processing anneal. Both these effects render the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material at the interface to be highly n – type doped and hence support the formation of a tunnel contact. However, this improvement in Ohmic contact behavior is not always observed. This can probably be explained by the earlier described formation of small pockets at the interface and the corresponding interface roughness due to the outdiffusion of Ga which is not unlikely during these high temperature processes and long annealing times.

5.3.2 Dry etching

In literature [33, 34] it has been stated that pre – metallization etching of the semiconductor surface could reduce the contact resistance of Ohmic contacts by:

- removing the native oxide on the semiconductor surface; and
- forming a donor – like layer in the ion – damaged region.

Due to the chemical stability of the III – V nitrides and $\text{Al}_x\text{Ga}_{1-x}\text{N}$ in particular to wet etchant solutions, dry etching is a necessity for reliable pattern transfer in these materials. Reactive ion etching (RIE) and chemically assisted ion beam etching (CAIBE) have proven to be valuable techniques in order to dry etch GaN based materials systems. It has to be noted that the applied dry etching process should not induce too much damage to the semiconductor surface because the contact resistance in that case increases instead of decreases. In order not to induce too much damage the plasma chemistry should consist of both a physical and a chemical etch mechanism. In the case that RIE is used as the dry etching technique, the physical etch mechanism can be realized using argon (Ar). The chemical etch mechanism consists among others of silicon tetrachloride (SiCl_4). This chemical mechanism induces less damage due to:

- the higher etch rate that partially removes damage as it is being created; and
- the adsorption of the reactive species on the surface which acts as a protective layer that reduces or passivates the damage [34].

Although the appropriate RIE etching process could improve the quality of the Ohmic contacts, literature [32] shows that it can also deteriorate the quality of the Schottky contacts because the RIE induced damage enhances parasitic leakage currents such as the surface leakage current.

5.3.3 Wet chemical etching

Wet chemical etching could remove the native oxide that has to be present on the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ surface due to the oxidation of the Al from the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material [24, 27, 29]. This can be done by dipping the samples in various wet chemical etching solutions such as hydrochloric acid (HCl), sulfuric acid (H_2SO_4), hydrofluoric acid (HF) or diluted ammonia (NH_4OH). As the surface will oxidize again very rapidly, immediately after wet chemical etching the samples should be loaded into the evaporator for the deposition of the metal layers. As a consequence, the choice of wet chemical etching solution depends among others on the type

of the used photoresist, i.e. the photoresist that is used to pattern the Ohmic contacts should not be removed after wet chemical etching.

5.4 Post – metallization heat treatment

The post-metallization heat treatment is traditionally done in a furnace under an inert gas flow such as argon (Ar) or nitrogen (N_2) for a time of 10 – 30 minutes. This produces an alloying of the metal with the upper layer of the semiconductor material. The interface of the alloyed layer can be quite irregular and it is difficult to control the alloy depth. Therefore, considering the thin device layers used nowadays, this method is more and more being replaced by rapid thermal annealing (RTA) where the material is brought very quickly to the desired temperature, kept there for 10 – 90 seconds, and then cooled down rapidly again. In this way the alloy depth can be kept very shallow while still producing a good contact [36]. The most commonly used post – metallization annealing temperatures for the Ti/Al/Ti/Au, Ti/Al/Ni/Au and Ti/Al/Pt/Au metallization schemes respectively, vary between 700 °C and 950 °C [27, 29].

5.5 Experiments and results

This section is concerned with both the experiments that have been carried out in order to develop an ohmic contact with an as low as possible (R_c) and (ρ_c) and the obtained results. First the used $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure and the basic operation of a High Electron Mobility Transistor (HEMT), which is based on this layer structure, will be described. Next, the circular TLM mask design that is used to fabricate the ohmic test structures will be considered. Furthermore, the development of the optimal metal layer stack for the used semiconductor layer structure will be described. After that, the influence of the different pre – metallization treatments, which have been proposed in section 5.3, on the contact resistance will be discussed. Finally, the optimal fabrication process for Ohmic contacts with the lowest contact resistance and corresponding specific contact resistance (ρ_c) on the used $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT structures will be presented.

5.5.1 HEMT epitaxial structure

It has to be noted that we have chosen to do the experiments to minimize R_c and ρ_c and the fabrication of the HEMTs on identical epitaxial structures. The used HEMT epitaxial structures were obtained from ATMI / Epitronics. These structures were grown by metal organic vapor phase epitaxy (MOVPE) on C – plane (0001) orientated sapphire ($\alpha\text{-Al}_2\text{O}_3$)

substrates. The MOVPE epilayers on top of these sapphire substrates successively comprised a 40 nm AlN nucleation layer, a 2 μm non intentionally doped (n.i.d.) GaN buffer layer, a 3 nm $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ n.i.d. spacer layer, a 10 nm $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ silicon (Si) doped ($n = 1 \times 10^{19} \text{ cm}^{-3}$) supply layer and finally a 5 nm n.i.d. $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ cap layer. Figure 5.1 shows a schematic representation of the composition of the used HEMT structure.

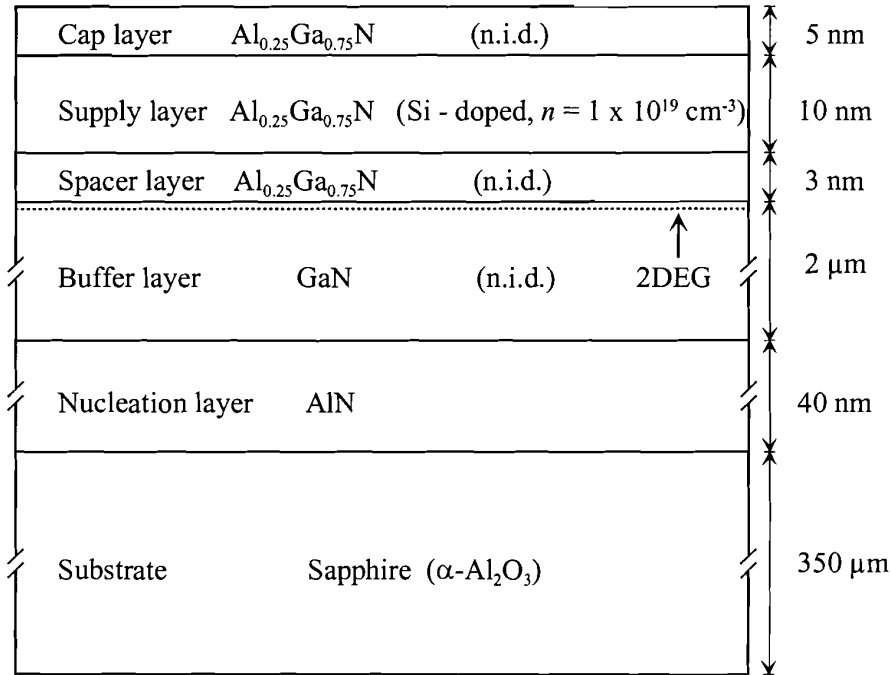


Figure 5.1: Schematic representation of the composition of the used $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ HEMT structure.

The main characteristic of a HEMT epitaxial structure is that it is based on a heterojunction. A heterojunction is a junction between two different materials. For the structure that is shown in figure 5.1, the heterojunction is formed by the n.i.d. $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ spacer layer and the n.i.d. GaN buffer layer. The continuity of the vacuum level (E_0) and the difference in bandgap energies at this heterojunction cause a discontinuity in the energy levels of both the conduction and valence bands. The larger bandgap of the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ material ($E_g(T = 300 \text{ K}) = 3.9 \text{ eV}$) compared to that of the GaN material ($E_g(T = 300 \text{ K}) = 3.4 \text{ eV}$) causes a quantum well like structure in the conduction band. Quantum mechanics dictates that electrons which are confined to this quantum well have quantized energy levels. However, the energy levels are only quantized in one spatial direction (perpendicular to the heterojunction) and the electrons are free to move in the other two spatial directions. The Si – doped $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ supply layer provides the electrons that after tunneling the potential barrier in

the conduction band at the heterojunction are contained in the quantum well. Due to the fact that their movement in this quantum well is restricted to two spatial directions only, these electrons are usually referred to as a two – dimensional electron gas (2DEG). This 2DEG forms the channel of the HEMT. As the 2DEG is situated in the n.i.d. GaN buffer layer, this buffer layer should be semi – insulating otherwise the HEMT can never be pinched off completely due to an always existing parallel conducting path. The electrons in the 2DEG obtain high mobilities of typically $\mu_n = 1000 - 1500 \text{ cm}^2/\text{Vs}$ depending on the dislocation density and the temperature [24]. The n.i.d. $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ spacer layer is applied to further enhance the mobility. A high sheet carrier density (n_s) in the 2DEG (typically $n_s = 5 \times 10^{12} - 5 \times 10^{13} \text{ cm}^{-2}$ [24]) is achieved by a large conduction band discontinuity (ΔE_c) and the piezoelectric effect. The piezoelectric effect is due to the lattice mismatch between the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ and GaN layers and their hexagonal (wurtzite) structure. The piezoelectric field induces charge in the 2DEG at the heterojunction. Figure 5.2 shows a schematic representation of the energy band diagram of the used epitaxial $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT structure with a Schottky gate contact under thermal equilibrium omitting the piezoelectric effect. The Schottky contact is placed on top of the n.i.d. $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ cap layer which has been applied in order to reduce the leakage current.

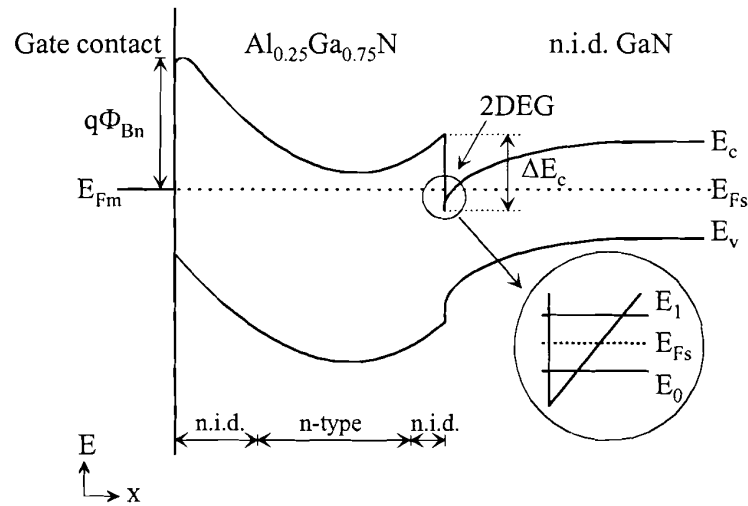


Figure 5.2: Schematic representation of the energy band diagram of the used epitaxial $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT structure with a Schottky gate contact under thermal equilibrium omitting the piezoelectric effect.

5.5.2 Circular TLM mask design

In section 4.4.2 the circular TLM (CTLTM) test structures proposed by Reeves [20], Marlow and Das [21] and Rechid and Heime [22], respectively have been described. In order to fabricate these structures a mask had to be designed. Figure 5.3 illustrates the layout of the mask and indicates the corresponding dimensions.

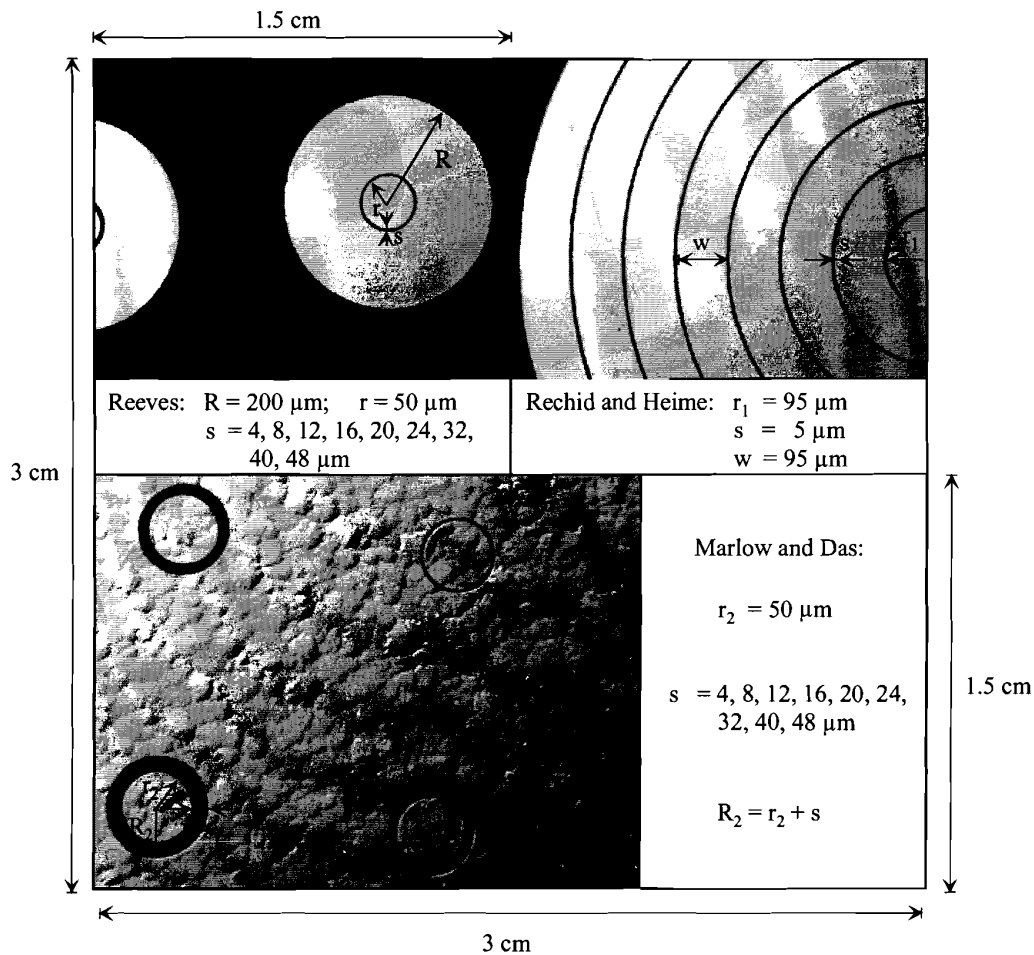


Figure 5.3: Layout and dimensions of the circular TLM mask design.

Comparing figures 4.6 and 5.3 learns that we have slightly modified the CTLTM structures proposed by Reeves and by Marlow and Das, respectively. In our implementation of the test structure proposed by Reeves we have omitted the outer ring contact. If in the original test structure the resistance is measured between the outer ring contact and the disc contact, the current will also pass through the inner ring contact. To avoid the influence of this inner ring contact we have chosen to implement the disc contact and one ring contact only. Furthermore

it has to be remarked that the thickness of the outer ring contact diminishes as the gap spacing (s) increases. However, it has been borne in mind that the thickness of the outer ring contact is always much larger than the transfer length (L_t). Hence, the concept of the electrically long contact remains valid.

In our implementation of the CTLM test structure proposed by Marlow and Das we have chosen to keep the radius of the disc contact (r_2) constant and the outer radius (R_2) results from adding the desired gap spacing (s) to the constant disc radius (r_2). This has been done in order to avoid problems with the positioning of the probes on the disc contact using a four – point probe measurement technique. Principally, this choice does not affect the validity or the accuracy of the original test structure because in the original configuration the outer radius is kept constant and the disc radius results from subtracting the desired gap spacing from the constant outer radius. Hence, the total resistance ($R_{T,circ}$) that is measured using our implementation of the CTLM test structure proposed by Marlow and Das is given by:

$$R_{T,circ} = \frac{R_{sh}}{2\pi} \left[\ln \left(\frac{R_2}{r_2} \right) + \frac{L_t}{r_2} \frac{I_0 \left(\frac{r_2}{L_t} \right)}{I_1 \left(\frac{r_2}{L_t} \right)} + \frac{L_t}{R_2} \frac{K_0 \left(\frac{R_2}{L_t} \right)}{K_1 \left(\frac{R_2}{L_t} \right)} \right] \quad (5.1)$$

Assuming that the condition $r_2 \gg L_t$ is valid and with $R_2 = r_2 + s$ equation (5.1), analogous to equation (4.54), becomes:

$$R_{T,circ} \approx \frac{R_{sh}}{2\pi} \left[\ln \left(\frac{r_2 + s}{r_2} \right) + L_t \left(\frac{1}{r_2 + s} + \frac{1}{r_2} \right) \right] \quad (5.2)$$

5.5.3 Optimization of the metal layer stack

In order to fabricate an Ohmic contact with the lowest possible contact resistance (R_c) and corresponding specific contact resistance (ρ_c) to the used $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ HEMT structures we started with the optimization of the applied metal layer stack. The starting point for this optimization was the metal layer stack $\text{Ti}/\text{Al}/\text{Ni}/\text{Au}$ (20/80/40/150 nm) that according to literature [27] yielded the best results on comparable HEMT structures as our ATMI/Epitronics structures. It was reported to yield a contact resistance $R_c = 0.04 \, \Omega\text{mm}$ and a specific contact resistance $\rho_c = 5.4 \times 10^{-8} \, \Omega\text{cm}^2$ after rapid thermal annealing (RTA) at 900 °C for 35 seconds in a nitrogen (N_2) ambient. This metallization scheme was applied to our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT structures using the same technological recipe as described in

literature [27]. The metal layers were e-beam evaporated in an AIRCO system at a base pressure of 10^{-7} mbar. An RTA sweep from 700 °C to 1000 °C indeed showed that at 900 °C for 30 seconds in N_2 the lowest values for R_c and ρ_c ($1.3 \text{ } \Omega\text{mm}$ and $2.7 \times 10^{-5} \text{ } \Omega\text{cm}^2$, respectively) using this metal layer stack were obtained. The sheet resistance of the sample was $R_{sh} = 615 \text{ } \Omega/\text{sq}$. Bearing in mind that according to literature [25] an Al/Ti thickness ratio of 2.82 is critical for the formation of a tunneling Ohmic contact and after comparison of our best results and the best results reported in literature using the proposed metallization scheme, it is obvious that the composition of the metal layer stack needs to be optimized for our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT structures.

5.5.3.1 Aluminum to Titanium thickness ratio

We started the optimization of the metal layer stack by determining the optimal Al/Ti thickness ratio as literature [25] suggested that this thickness ratio should be smaller than 2.82 for the formation of a tunneling Ohmic contact (section 5.2). In order to investigate the validity of the proposed Ohmic contact formation mechanism in the case of our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT structures we tried Al/Ti thickness ratios of 2.37, 4, 6 and 8 respectively. It has to be remarked that for comparison reasons the Ni and Au thicknesses in all these cases were 40 nm and 150 nm respectively. The metal layers were e-beam evaporated in an AIRCO system at a base pressure of 10^{-7} mbar without applying any pre – metallization treatment such as a high temperature pre – processing anneal, dry etching of the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ surface or wet chemical etching of this surface. After metallization an RTA sweep between 700 °C and 1000 °C showed that for each Al/Ti thickness ratio the lowest values for R_c and ρ_c were obtained at 900 °C for 30 seconds in a N_2 ambient. Figure 5.4 shows these lowest values for R_c and ρ_c as a function of the Al/Ti thickness ratio. The sheet resistances (R_{sh}) of the different samples varied between 500 Ω/sq and 700 Ω/sq .

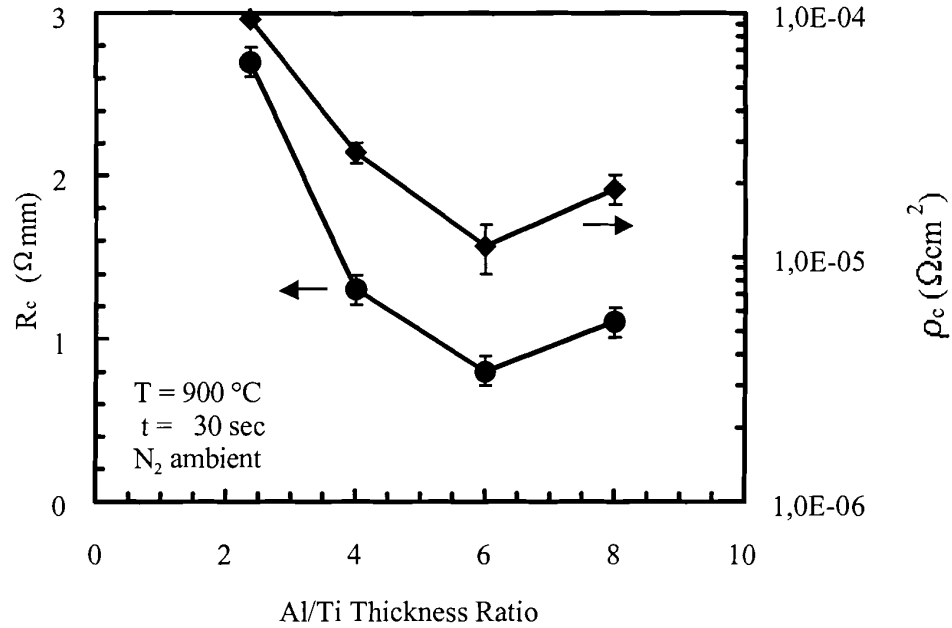


Figure 5.4: R_c and ρ_c as a function of the Al/Ti thickness ratio.

Figure 5.4 shows that for our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT structures an Al/Ti thickness ratio of 6 yields the lowest values for R_c and ρ_c of $0.8 \Omega\text{mm}$ and $1.1 \times 10^{-5} \Omega\text{cm}^2$, respectively. However, in order to try to approach the reported values $R_c = 0.04 \Omega\text{mm}$ and $\rho_c = 5.4 \times 10^{-8} \Omega\text{cm}^2$ [25], still a lot of work has to be done.

5.5.3.2 Aluminum and Titanium layer thicknesses

The next step in the optimization procedure of the metal layer stack is the determination of the optimal layer thicknesses of the Ti and Al layers at an Al/Ti thickness ratio of 6. We have fabricated Ti layer thicknesses of 10 nm, 20 nm, 30 nm, 35 nm and 40 nm. It has to be remarked that for comparison reasons the Ni and Au thicknesses in all these cases again were 40 nm and 150 nm respectively. The metal layers were also e-beam evaporated in an AIRCO system at a base pressure of 10^{-7} mbar again without applying any pre – metallization treatment. The post – metallization RTA sweep between 700 °C and 1000 °C again showed that for each pair of Al and Ti layer thicknesses the lowest values for R_c and ρ_c were obtained at 900 °C for 30 seconds in a N_2 ambient. Figure 5.5 shows these lowest values for R_c and ρ_c as a function of the thickness of the Ti layer. The sheet resistances (R_{sh}) of the used samples varied between 500 Ω/sq and 800 Ω/sq .

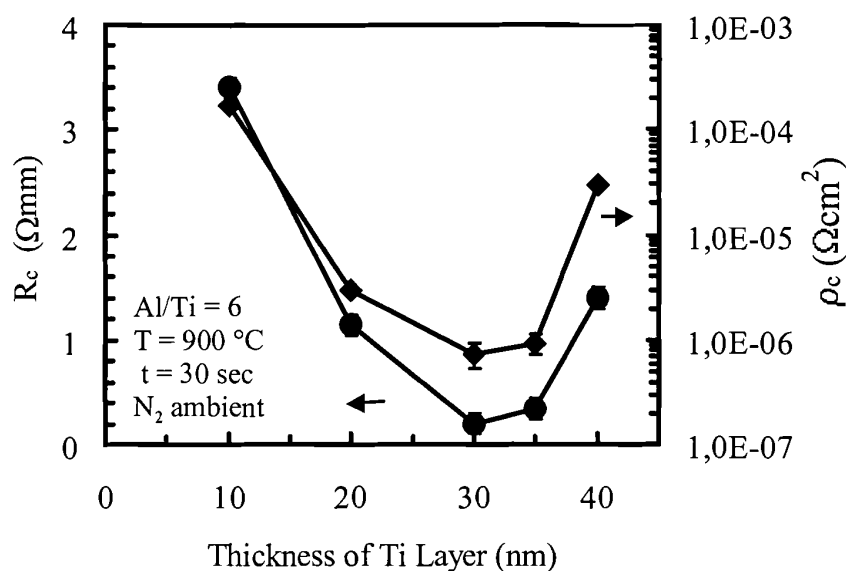


Figure 5.5: R_c and ρ_c as a function of the thickness of the Ti layer.

Figure 5.5 shows that for our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT structures a Ti layer thickness of 30 nm and a corresponding Al layer thickness of 180 nm yields the lowest values for R_c and ρ_c of 0.2 Ωmm and $7.3 \times 10^{-7} \Omega\text{cm}^2$, respectively.

5.5.3.3 Nickel and Gold layer thicknesses

After optimizing the Al/Ti thickness ratio and the thickness of the Ti and Al layers we have tried to lower the values of R_c and ρ_c even further by determining the optimal layer thicknesses of the Ni and Au layers. As starting point we used of course the optimized layer thicknesses for Ti and Al of 30 nm and 180 nm respectively. Furthermore, the sum of the Ni and Au layer thicknesses has been kept constant at 190 nm. We have fabricated Ni layer thicknesses of 30 nm, 40 nm and 50 nm. Also in these cases pre – metallization treatments have been omitted and the metal layers were e-beam evaporated in an AIRCO system at a base pressure of 10^{-7} mbar. The post – metallization RTA sweep between 700 °C and 1000 °C again showed that for each pair of Ni and Au layer thicknesses the lowest values for R_c and ρ_c were obtained at 900 °C for 30 seconds in a N_2 ambient. Figure 5.6 shows these lowest values for R_c and ρ_c as a function of the thickness of the Ni layer. The sheet resistances (R_{sh}) of the used samples varied between 500 Ω/sq and 800 Ω/sq .

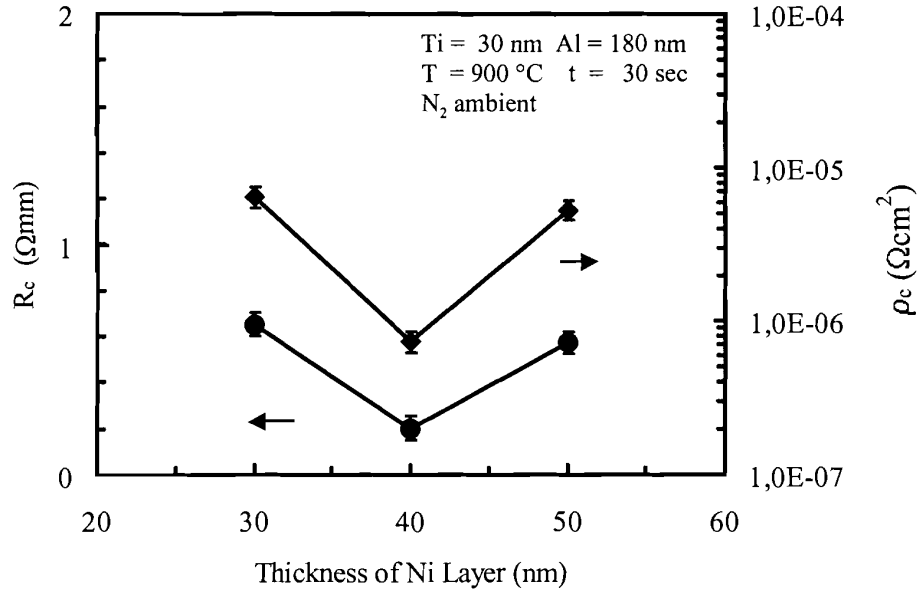


Figure 5.6: R_c and ρ_c as a function of the thickness of the Ni layer.

Figure 5.6 shows that the lowest values for R_c and ρ_c are obtained with a thickness of the Ni layer of 40 nm and a corresponding thickness of the Au layer of 150 nm. These lowest values for R_c and ρ_c are again $0.2 \Omega\text{mm}$ and $7.3 \times 10^{-7} \Omega\text{cm}^2$, respectively.

It can be concluded that the optimization of the proposed Ti/Al/Ni/Au metallization scheme for the fabrication of Ohmic contacts to our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT structures has resulted in the following composition of the metal layer stack:

- Ti = 30 nm;
- Al = 180 nm;
- Ni = 40 nm; and
- Au = 150 nm.

The lowest values for R_c and ρ_c were $0.2 \Omega\text{mm}$ and $7.3 \times 10^{-7} \Omega\text{cm}^2$, respectively with a sheet resistance of $564 \Omega/\text{sq}$. These values were obtained without any pre – metallization treatment and after an RTA at 900°C for 30 seconds in a N_2 ambient.

5.5.3.4 Influence of the annealing temperature and time

After optimization of the composition of the metal layer stack we have investigated the influence of both the annealing temperature and the annealing time on the values of the contact resistance and the specific contact resistance of this optimized contact. Therefore, we fabricated the optimized Ohmic contacts on samples of our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT structures with comparable sheet resistances that varied between $500 \, \Omega/\text{sq}$ and $800 \, \Omega/\text{sq}$. Again, any pre – metallization treatments have been omitted and the metal layers were e-beam evaporated in an AIRCO system at a base pressure of 10^{-7} mbar. All the processes of the post – metallization RTA sweep were done in a N_2 ambient at the temperatures and during the times that are listed in table 2.

Table 2: Temperatures and times used for the RTA sweep.

Time [s] $\Rightarrow$ Temperature [°C] $\Downarrow$	15	30	60	120
800	-			
900				-
950				-
1000				-

Figure 5.7 shows the contact resistance as a function of both the annealing temperature and the annealing time. It can be observed that the lowest value for the contact resistance is obtained at an annealing temperature of $900 \, ^\circ\text{C}$ and for a time of 30 seconds. By chance we have always done the RTA processes at $900 \, ^\circ\text{C}$ for 30 seconds in a N_2 ambient. The results of the temperature and time sweep show that this combination of temperature and time yields the lowest value for the contact resistance in the case of our optimized metallization scheme applied to our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT structures.

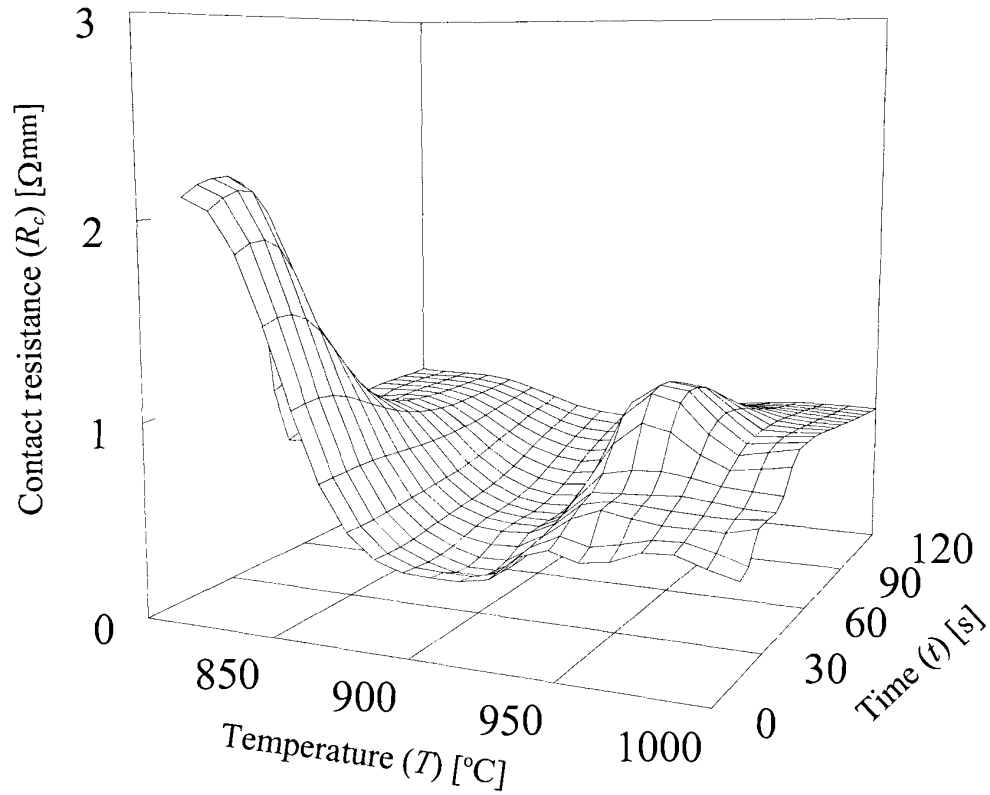


Figure 5.7: R_c as a function of both annealing temperature and annealing time.

5.5.4 Influence of the pre – metallization treatments

In section 5.3 we have described the possible effects of several pre – metallization treatments on the contact resistance of Ohmic contacts. In the following subsections we will discuss the need for the application or omission of these pre – treatments in our experiments.

5.5.4.1 Pre – processing anneal at high temperature

Although literature [31, 32] showed that a high temperature pre – processing anneal could improve the behavior of Ohmic contacts, it also showed that this would severely deteriorate the quality of the Schottky contacts which of course have to be processed on the same $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ HEMT material as the Ohmic contacts. In particular the leakage currents of the Schottky contacts were shown to increase very much after applying a high temperature pre – processing anneal. This is due to the reduction of the Schottky barrier height when high

pre – annealing temperatures are applied. Furthermore this could be caused by the increased interface roughness and the creation of nitrogen vacancies (V_N) in the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ contact layer. Therefore, we did not apply a high temperature pre – processing anneal in our investigations.

5.5.4.2 Dry etching

According to literature [33, 34] dry etching of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ surface without introducing too much damage could reduce the Ohmic contact resistance. In order not to introduce too much damage to the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ surface a highly chemical reactive ion etching (RIE) process is required. From preliminary work on Ohmic contacts to n – type GaN we know that even a highly chemical thus relatively smooth RIE process considerably deteriorates the quality of Ohmic contacts. Because of the fact that dry etching of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ surface not necessarily leads to a reduction of the contact resistance, we have decided to omit a dry etching process.

5.5.4.3 Wet chemical etching

As mentioned in section 5.3.3 the native oxide on the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ surface could be removed by wet chemical etching. Hydrofluoric acid (HF) diluted in water free acetic acid (HAc) is considered to be the most effective wet chemical solution to remove this native surface oxide. HF is diluted in water free HAc in order to prevent the HF as much as possible from ionizing. This is very important because only HF in molecular form is capable of dissolving the native oxide on the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ surface. Therefore, we used a wet chemical etching solution that consisted of one part of HF and five parts of water free HAc ¹⁾. A major problem with respect to this wet chemically etching solution is that the photoresist (AZ5214), which is used to fabricate the Ohmic CTLM pattern, is completely removed after the wet chemically etching process and consequently no metallization can be done anymore. Hence, this wet chemically etching process cannot be done just before the metallization but has to be done before the optical lithography of the Ohmic CTLM pattern. However, no reduction of the contact resistances of samples that have been wet chemically etched using the HF : 5 HAc solution has been observed compared to the contact resistances of samples that have not been wet chemically etched. It has to be noted that the very low values of R_c and ρ_c of $0.2 \Omega\text{mm}$ and $7.3 \times 10^{-7} \Omega\text{cm}^2$, respectively are already approaching the maximum resolution of the transfer length method (TLM) which is about $1 \times 10^{-7} \Omega\text{cm}^2$ [19]. Hence, any possible further reduction of the values of R_c and ρ_c cannot be detected with TLM measurements because it falls in the margins of error of the TLM.

¹⁾ The author wishes to thank Dr. R. Tijburg for the fruitful discussions with respect to this subject.

Although we did not measure any reduction of the values of R_c and ρ_c applying the wet chemical etching process, we were very interested in determining the presence and the thickness of the native oxide on the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ surface. This can be done by elastic recoil detection (ERD) measurements, which have been carried out within the Physics Department of the TU/e. These measurements have established the presence of the native oxide layer on the as grown $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ surface. However, due to the high background noise that results from the nitrogen originating from the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ layer it was not possible to quantitatively determine the thickness of this oxide layer accurately from the ERD measurements. A rough estimate of the total amount of oxygen in our sample ($1 \text{ cm} \times 1 \text{ cm}$) is $5 \times 10^{14} \text{ at/cm}^2$ and the oxygen pollution of the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ layer (assuming that only the Al from the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ layer oxidizes) is roughly estimated to be equal to $3 \times 10^{20} \text{ at/cm}^3$. Despite the lack of a quantitatively determined thickness of the native oxide layer it was qualitatively concluded that the native oxide layer is relatively thin considering the relatively high Aluminum content (25%) of the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ cap layer. Because of all the above mentioned reasons we have decided to omit a pre – metallization wet chemical etching process.

5.5.5 Optimal Ohmic contact fabrication process

In this section we have discussed the optimization procedure of the Ti/Al/Ni/Au metallization scheme. The goal of this optimization was to obtain an Ohmic contact with the lowest possible values for the contact resistance R_c and the corresponding specific contact resistance ρ_c on our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT structures. As shown, our optimal Ohmic contact fabrication process consists of a Ti/Al/Ni/Au = 30/180/40/150 nm metallization scheme, which is e-beam evaporated using an AIRCO system at a base pressure of 10^{-7} mbar without any pre – metallization treatments of the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ cap layer. After the metallization the contacts were exposed to an RTA process at 900 °C for 30 seconds in a N_2 ambient. The resulting values for R_c and ρ_c are 0.2 Ωmm and $7.3 \times 10^{-7} \Omega\text{cm}^2$, respectively with a sheet resistance (R_{sh}) of 500 – 600 Ω/sq . The technological recipe for our optimized Ohmic contact on n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ is described in appendix C.

5.6 Discussion of the experiments and their results

5.6.1 Experimental setup

As mentioned in section 5.5.1, we have chosen to do the minimization of the contact resistance R_c and the corresponding specific contact resistance ρ_c and the fabrication of the HEMTs on identical epitaxial structures from ATMI / Epitronics. The starting point of our experiments in order to fabricate Ohmic contacts with the lowest possible values for R_c and ρ_c on this material was the in literature [27] proposed Ti/Al/Ni/Au (20/80/40/150 nm) metal layer stack. The results of section 5.5.3 showed this metal layer stack had to be optimized for our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT structures. Because of the limited amount of material and the limited time we have chosen to carry out this optimization procedure by first determining the optimal Al/Ti thickness ratio (section 5.5.3.1) followed by the optimal Al and Ti layer thicknesses for this optimal Al/Ti thickness ratio (section 5.5.3.2). The next step was the optimization of the Ni and Au layer thicknesses under the condition that the sum of the Ni and Au layer thicknesses is kept constant at 190 nm (section 5.5.3.3). After the optimization of the metal layer stack we have investigated the influence of the annealing temperature and time (section 5.5.3.4). Because of the results reported in literature [31 – 34] and our experience with the possible effects of pre – metallization treatments on the values of R_c and ρ_c and on the quality of the Schottky contacts we have decided to omit them from our technological fabrication process (section 5.5.4). Our optimal Ohmic contact fabrication process has been described in section 5.5.5. Despite the fact that it was not possible to carry out a full matrix of experiments, we are convinced that our systematic approach has resulted in the lowest values for R_c and ρ_c on the used $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT structures.

5.6.2 Measurement setup

The setup for measuring the total resistance of the Ohmic contacts consisted of a HP4141B and a probe station with four tungsten (W) probes. The measurements were automated using ICCAP software running on a HP UNIX computer. The influence of the resistances of the external circuitry (e.g. probes, wiring and switches), which are usually lumped under the term probe resistance, can be eliminated using a four – point probe measurement technique. Figure 5.8 shows a schematic representation of this technique in which two probes are placed near each other on each side of the resistance (usually placing both probes on the same probe pad).

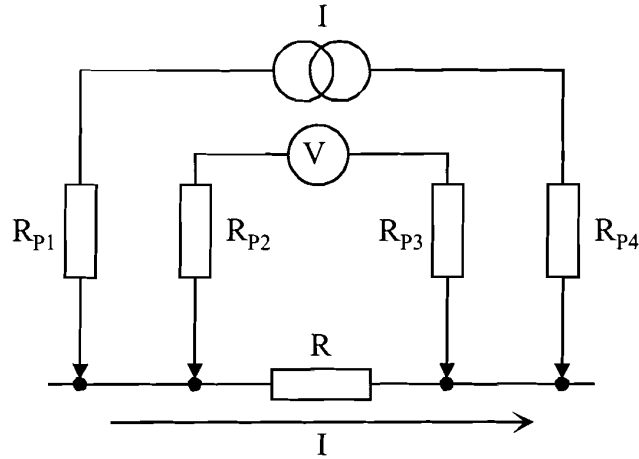


Figure 5.8: Schematic representation of the four – point probe measurement technique.

One pair of probes is used to pass the current I and the other pair is used to measure the voltage V . Assuming a high – impedance voltage measurement the current passing through the voltage sensing probes can be regarded negligible to the main current I . Therefore, there will be essentially no voltage drop across the two probe resistances R_{P2} and R_{P3} and the voltage V will be equal to V_R to exceedingly high accuracy. The current passing through the resistance R , of course, is equal to the externally measured or imposed current. Hence, this procedure allows V_R and I to be determined independently of the values of the probe resistances. This measurement setup can be calibrated using standard resistors with a known value. The used four point – probe measurement setup has been calibrated and the measured values for the total resistance $R_{T,circ}$ are accurate within 1 %.

5.6.3 Calculation of R_c and ρ_c using CTLM

The three different CTLM test structures proposed by Reeves [20], Marlow and Das [21] and Rechid and Heime [22], respectively (section 4.4.2) can be used to measure the total resistance ($R_{T,circ}$) of the Ohmic contacts as a function of the gap spacing (s). A typical plot of $R_{T,circ}$ versus s for the three different CTLM test structures using the four – point probe measurement technique is shown in figure 5.9.

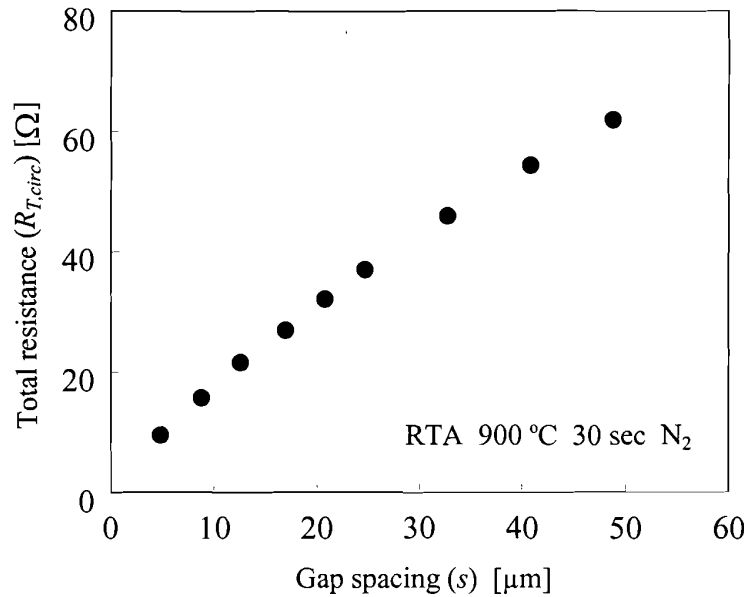


Figure 5.9: Total resistance ($R_{T,circ}$) versus gap spacing (s).

This nonlinear relationship between the total resistance $R_{T,circ}$ and the gap spacing (s) is due to the changing circular geometry of the contacts. The contact resistance R_c and the corresponding specific contact resistance ρ_c can be calculated from these CTLM measurement results by:

- applying a linear approximation; and / or
- fitting the exact expression for $R_{T,circ}$.

5.6.3.1 Linear approximation of the experimental CTLM results

We will first consider the case that a linear approximation is used in order to calculate R_c and ρ_c from the experimental CTLM results. Using this linear approximation enables a more straightforward extraction of the Ohmic contact parameters as in the case of the linear TLM (LTLM) described in section 4.4.1. In order to arrive at the linear approximation of the experimental CTLM results the introduction of correction factors (c_i) is required. They account for the changing circular geometry of the contacts depending on the type of the used CTLM test structure. The correction factors in the case of the CTLM test structures proposed by Reeves and by Marlow and Das are the same because in both cases the circular geometry of the outer ring contacts changes in a similar way due to the variation of the gap spacing. The

correction factors in the case of the CTLM test structure proposed by Rechid and Heime are somewhat more difficult to calculate because the circular geometry of both the inner and the outer ring contacts change when measuring successive pairs of contacts. In addition, the measurement of $R_{T,circ}$ of a pair of ring contacts using the test structure by Rechid and Heime requires that the voltage is measured at two different angles ϕ . Angles of 90° and 180° are convenient because they can be adjusted by eye. As a consequence, the measurement of $R_{T,circ}$ using this CTLM test structure involves 3 pairs of probes. In other words, it is a six – point probe measurement technique. If this test structure cannot be measured with six probes it is not possible to determine the resistivity of the metal layers. Hence, using a four – point probe measurement technique this CTLM test structure loses its additional value compared to the original test structure by Reeves of which the structure by Rechid and Heime is an expansion as described in section 4.4.2. We did not use the CTLM test structure by Rechid and Heime because we could not measure $R_{T,circ}$ with six probes. The test structure has however been included in our CTLM mask for the sake of completeness as it might be possible to realize such a six – point probe measurement setup in the future.

The CTLM test structures proposed by Reeves and Marlow and Das have shown to yield the same values for R_c and ρ_c . From a technological point of view the test structure by Marlow and Das is somewhat easier to process and hence we have chosen to use this CTLM test structure for the optimization of the Ti/Al/Ni/Au Ohmic contacts. The derivation of the correction factors using this test structure will be given in appendix D. The result of this derivation is that the experimental CTLM data should be divided by the correction factors in order to arrive at the values that can be used for the linear fit. Table 3 shows the calculated correction factors for the used gap spacings and a nominally radius of the inner disc contact (r_2) of $50\text{ }\mu\text{m}$.

Table 3: Gap spacings and their corresponding correction factors.

Gap spacings (s) [μm]	Correction factors (c_i) [-]
4	0.962
8	0.928
12	0.896
16	0.868
20	0.841
24	0.817
32	0.773
40	0.735
48	0.701

Using the correction factors of table 3 the nonlinear relationship between the original values of the total resistance $R_{T,circ}$ and the gap spacing s has been transformed into a linear relationship. Hence, two times the contact resistance ($2R_c$) is found at the R_T – axis intercept and, assuming that the sheet resistances beneath ($R_{sh,c}$) and outside (R_{sh}) the contact area are equal, the modulus value of two times the transfer length ($|2L_t|$) is found at the negative s – axis intercept. In this case the sheet resistance R_{sh} , the contact resistance R_c and the corresponding specific contact resistance ρ_c can be calculated very easily using equations (4.39), (4.41) and (4.42) respectively, which are known from the LTLM (section 4.4.1). It is obvious that using equations (4.39) and (4.41) the contact width W_c has to be replaced by $2\pi r_2$ where r_2 again is the radius of the inner disc contact in the test structure of Marlow and Das. Figure 5.10 shows both the original CTLM measurement results and the linear approximation of our best $\text{Ti}/\text{Al}/\text{Ni}/\text{Au} = 30/180/40/150$ nm Ohmic contact. It also shows the calculated values for R_{sh} , L_t , R_c , ρ_c and the value of the Pearson product (R^2), which is a measure for the quality of the linear curve fit. In the ideal situation the Pearson product equals unity ($R^2 = 1$).

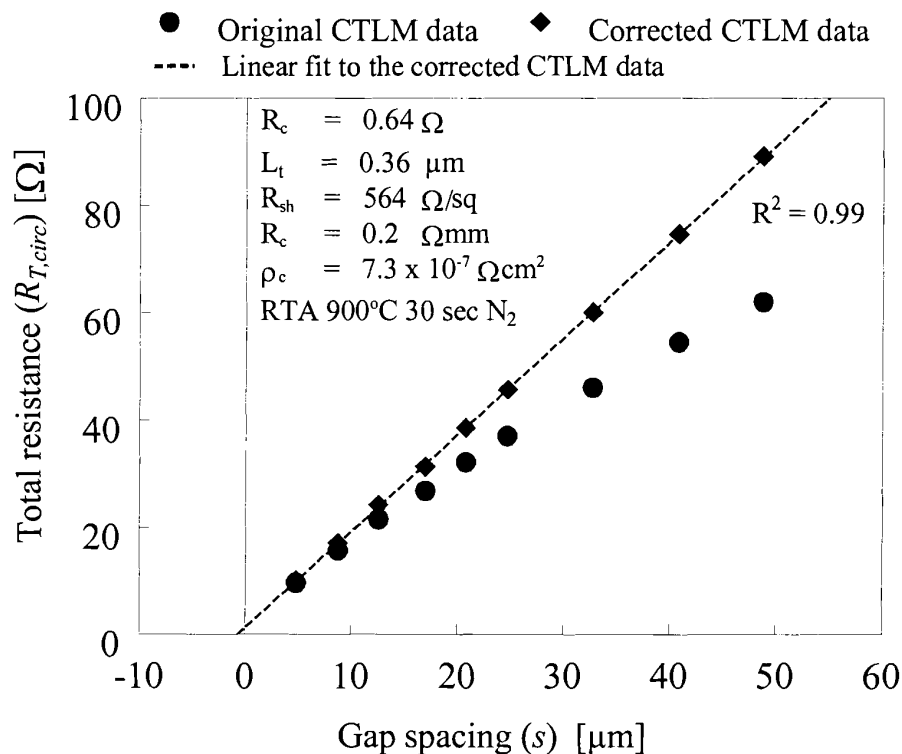


Figure 5.10: Original CTLM measurement results and the linear approximation.

5.6.3.2 Fitting of the exact expression for $R_{T,circ}$ to the experimental CTLM results

Another approach to calculate R_c and ρ_c from the original nonlinear CTLM results is to perform a fit of the exact expression for $R_{T,circ}$ to these data. Again we only consider our implementation of the test structure proposed by Marlow and Das in which case the total resistance according to equation (A.39) is given by:

$$\begin{aligned}
 R_{T,circ} &= \frac{R_{sh}}{2\pi} \ln\left(\frac{R_2}{r_2}\right) + \frac{R_{sh,c} \cdot L_t}{2\pi r_2} \frac{I_0\left(\frac{r_2}{L_t}\right)}{I_1\left(\frac{r_2}{L_t}\right)} + \frac{R_{sh,c} \cdot L_t}{2\pi R_2} \frac{K_0\left(\frac{R_2}{L_t}\right)}{K_1\left(\frac{R_2}{L_t}\right)} \\
 &= \frac{R_{sh} \cdot R_{sh,c}}{2\pi} \left[\frac{1}{R_{sh,c}} \ln\left(\frac{R_2}{r_2}\right) + \frac{L_t}{R_{sh} \cdot r_2} \frac{I_0\left(\frac{r_2}{L_t}\right)}{I_1\left(\frac{r_2}{L_t}\right)} + \frac{L_t}{R_{sh} \cdot R_2} \frac{K_0\left(\frac{R_2}{L_t}\right)}{K_1\left(\frac{R_2}{L_t}\right)} \right] \\
 &= \frac{R_{sh} \cdot R_{sh,c}}{2\pi} \left[\frac{1}{R_{sh,c}} \ln\left(\frac{r_2 + s}{r_2}\right) + \frac{L_t}{R_{sh} \cdot r_2} \frac{I_0\left(\frac{r_2}{L_t}\right)}{I_1\left(\frac{r_2}{L_t}\right)} + \frac{L_t}{R_{sh} \cdot (r_2 + s)} \frac{K_0\left(\frac{r_2 + s}{L_t}\right)}{K_1\left(\frac{r_2 + s}{L_t}\right)} \right] \quad (5.4)
 \end{aligned}$$

We have implemented equation (5.4) in a MATLAB routine that besides the value of the radius of the inner disc contact (r_2) and the values of the used gap spacings (s) requests starting values for the sheet resistance beneath ($R_{sh,c}$) and outside (R_{sh}) the contact area and for the transfer length (L_t). The stop criterion for this fitting procedure is that the error between the experimental CTLM data and the fit results should be minimized to a certain degree. The resulting values for $R_{sh,c}$, R_{sh} and L_t are then assumed to be a very accurate representation of the actual values for $R_{sh,c}$, R_{sh} and L_t of the Ohmic contact under test. The values for R_c and ρ_c can now be calculated using equations (4.34) and (4.38). In the case of equation (4.34) W_c is equal to $2\pi r_2$ where r_2 is the radius of the inner disc contact. Figure 5.11 shows a plot of the experimental CTLM data and the fit results using equation (5.4). It also shows the calculated values for R_{sh} , $R_{sh,c}$, L_t , R_c and ρ_c .

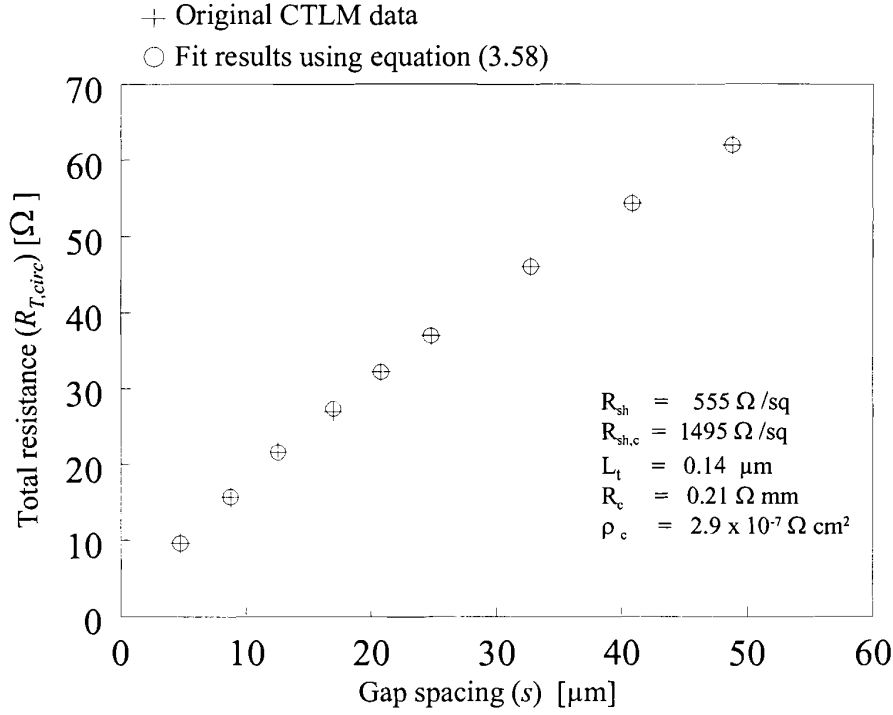


Figure 5.11: Experimental CTLM data and fit results using equation (5.4).

If we assume that $R_{sh} = R_{sh,c}$, equation (5.4) reduces to:

$$R_{T,circ} = \frac{R_{sh}}{2\pi} \left[\ln\left(\frac{r_2 + s}{r_2}\right) + \frac{L_t}{r_2} \frac{I_0\left(\frac{r_2}{L_t}\right)}{I_1\left(\frac{r_2}{L_t}\right)} + \frac{L_t}{r_2 + s} \frac{K_0\left(\frac{r_2 + s}{L_t}\right)}{K_1\left(\frac{r_2 + s}{L_t}\right)} \right] \quad (5.5)$$

We have implemented equation (5.5) in a different MATLAB routine that also besides the value of the radius of the inner disc contact (r_2) and the values of the used gap spacings (s) requests starting values for the sheet resistance outside (R_{sh}) the contact area and for the transfer length (L_t). The stop criterion for this fitting procedure is also that the error between the experimental CTLM data and the fit results should be minimized to a certain degree. The values for R_c and ρ_c can now be calculated using equations (4.41) and (4.42). In the case of equation (4.41) W_c is equal to $2\pi r_2$ where r_2 is the radius of the inner disc contact. Figure 5.12 shows a plot of the experimental CTLM data and the fit results using equation (5.5). This figure also shows the calculated values for R_{sh} , $R_{sh,c}$, L_t , R_c and ρ_c .

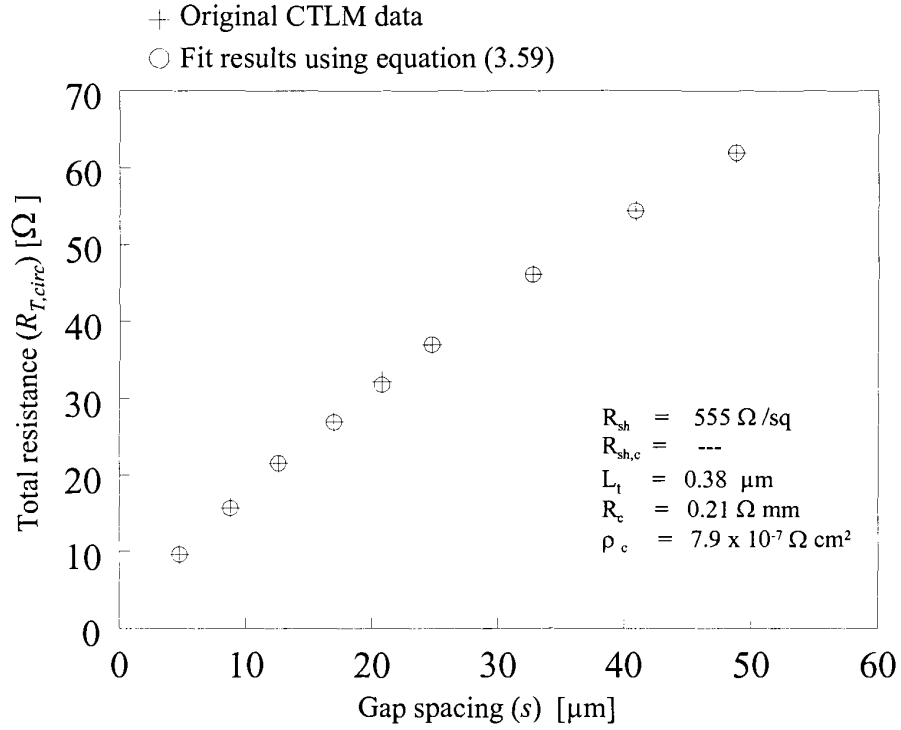


Figure 5.12: Experimental CTLM data and fit results using equation (5.5).

Comparing the results of the three different calculation procedures leads to several conclusions. The large margin of error (148 %) for the value of the specific contact resistance (ρ_c) is mainly due to the large discrepancy in the calculated values of the transfer length (L_t) in the case of the linear approximation and the fit based on equation (5.5) on the one hand and the fit based on equation (5.4) on the other hand. The accuracy of the calculation of ρ_c would be improved considerably if the actual value of L_t could be determined accurately. In section 4.4.1, where the LTLM has been discussed, an end resistance (R_E) measurement has been proposed to accomplish this. In section 5.6.4.2, we will discuss this approach into further detail.

With respect to the calculated values of the contact resistances (R_c) in Ohm – mm (Ωmm), however, it can be concluded that they can be determined with a margin of error of only 5 % using the three different calculation procedures. Also the values of the sheet resistances outside (R_{sh}) the contact area can be calculated very accurately within 2 %. Furthermore, it should be noted that the choice of the starting values for $R_{sh,c}$, R_{sh} and L_t does not influence the fit results. Even if we use very different starting values, exactly the same fit results are obtained using our MATLAB routines.

Finally, it can be concluded that both approaches (the linear approximation and the fitting procedures, respectively) are suitable to calculate values for R_c and the corresponding ρ_c .

5.6.4 Accuracy of the calculation of R_c and ρ_c

It is important to note that the accuracy with which the values of the contact resistance (R_c) and the specific contact resistance (ρ_c) can be calculated from the linear approximation of the experimental CTLM results and the fitting procedure of the exact expression for the total resistance ($R_{T,circ}$) depends very heavily on the accuracy with which the values of the gap spacings (s), the transfer length (L_t) and $R_{T,circ}$ can be determined. The latter depends among others on the used measurement technique and the calibration of the measurement setup. These topics have been discussed in section 5.6.2.

5.6.4.1 Measurement of the gap spacings

In general, it is very important that after the fabrication process of any TLM structure, the gap spacings (s) are measured very accurately because due to the inaccuracy induced by the fabrication process these values can differ from the values for the gap spacings specified on the mask. In order to determine the gap spacing as accurately as possible we have tried different measurement techniques. First, we have measured the gap spacings using a Reichert – Jung optical microscope in combination with a Varimet distance analyzer. After calibration of this setup, the measured gap spacings were typically $0.3 - 0.8 \mu\text{m}$ larger than the nominal gap spacings on the CTLM mask ($s = 4, 8, 12, 16, 20, 24, 32, 40, 48 \mu\text{m}$). It is specified that the measured values are obtained with an accuracy of $\pm 0.1 \mu\text{m}$. This is validated by the measurements which show that if a deviation of e.g. $0.3 \mu\text{m}$ compared to the nominal values for the gap spacings is measured, this deviation occurs within the accuracy of $\pm 0.1 \mu\text{m}$ for all gap spacings. Despite the uniformity in the obtained results we were and still are not able to give a plausible explanation for the fact that the measured gap spacings are larger than the nominally values. From the photolithographically fabrication process it is more likely to expect that the gap spacings are smaller than the nominal values instead of larger. Because of this observation we have tried to obtain more certainty about the correctness of the measured values using the Varimet.

Therefore, we have also measured the gap spacings with a scanning electron microscope (SEM). The measured values of the smaller gap spacings ($s < 16 \mu\text{m}$) were in good agreement with the measured values using the Varimet. The measured values of the larger gap spacings ($s \geq 16 \mu\text{m}$) were however smaller than the nominal gap spacings. These results were totally

contrary to the results obtained with the Varimet. We believe that the measurements of the largest gap spacings using the SEM are not correct given the fact that the earlier observed uniformity of the measurement results is totally absent in the SEM measurements. A possible explanation could be the fact that it is necessary to change the magnification of the SEM in order to measure the largest gap spacings. The magnification can be changed by switching from one electrical circuit inside the SEM to another. We have investigated the influence of this change in magnification and we found that it introduced an inaccuracy of approximately 5 – 10 % in the measurement results. So, the measurement of the gap spacings using the SEM did not solve our initial problem of the measurement results which were larger than expected.

Finally, we have measured the gap spacings using atomic force microscopy (AFM) at the Physics Department of the TU/e. Also in this case, the smaller gap spacings ($s < 16 \mu\text{m}$) were in reasonable agreement with the results obtained using the Varimet and the SEM. For the largest gap spacings ($s \geq 16 \mu\text{m}$), however, the measurements were very irreproducible and showed a very large spreading. This is more or less obvious if it is borne in mind that the AFM measurement setup is calibrated to measure in the nanometer (nm) range and when measuring the larger gap spacings it is operating at the edge of its detection limit.

In conclusion, we have decided to rely on the values of the gap spacings measured with the Varimet. These measurement results have been used in both the linear approximation and the fitting procedure of the exact expression for $R_{T,circ}$ in order to calculate the values of R_c and ρ_c .

5.6.4.2 Measurement of the end resistance

Using the linear approximation of the corrected CTLM results and the fit of equation (5.5) to the original CTLM measurement results, it is assumed that the sheet resistances beneath ($R_{sh,c}$) and outside (R_{sh}) the contact area are equal. As a practical matter this assumption is often very useful, however, due to the alloying of the metal and the semiconductor material during our RTA processes at 900 °C this cannot be the case. Hence, the measurement of the end resistance (R_E) as described in section 4.4.1 should be carried out in order to determine the transfer length (L_t) and calculate the value of the specific contact resistance (ρ_c) that most accurately represents the actual value of ρ_c in our contacts. However, due to the used circular contact geometry it is principally not possible to carry out such an end resistance measurement because the contacts do not have the same geometry. As a result, the distance where the current equals zero cannot be defined as in the case of the LTLM configuration. However, if the CTLM test structure proposed by Rechid and Heime [22] is used, it is possible to perform a measurement of R_E . Considering the problems with respect to an accurate determination of L_t and as a consequence an accurate calculation of ρ_c , we rather use

the value of the contact resistance (R_c) in Ωmm than the value of ρ_c in Ωcm^2 to indicate the quality of an Ohmic contact as far as the contact resistance is concerned because the calculation of R_c in Ωmm does not involve L_t .

5.6.5 Reproducibility of the Ohmic contacts

It is obvious that the reproducibility of the Ohmic contact fabrication process and its results is very important for a reliable implementation in the HEMT fabrication process. We have investigated the influence of the used $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material and the choice of the used e – beam evaporator on this reproducibility.

5.6.5.1 Influence of the used $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material

In order to enhance the reproducibility of the Ohmic contacts we have used identical (i.e. same layers structure, comparable sheet resistance (R_{sh}) and Al content) $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ wafers from ATMI/Epitronics, as mentioned in section 5.5.1. During the course of our investigations, however, we found that the Ohmic behavior varied over a particular wafer and from one wafer to another even though these wafers were nominally the same. Literature [38] showed that the variations in the values of the contact resistance (R_c) and the corresponding specific contact resistance (ρ_c) can be explained by variations in the values of R_{sh} . These variations in R_{sh} are due to both a varying Al mole fraction within the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer of one particular wafer and in those of nominally identical wafers and a varying thickness of these $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layers. Therefore, we have only compared the values of R_c and ρ_c obtained from samples with comparable values for R_{sh} . In that case, the values of R_c and ρ_c showed a very good reproducibility as they were within 10 %.

5.6.5.2 Influence of the choice of evaporator

In our cleanroom we have two e – beam evaporators of different manufactures (Leybold and AIRCO, respectively) at our disposal. Hence, we were interested in the influence of the choice of the e – beam evaporator on the obtained contact resistance and specific contact resistance. Therefore, we have identically processed two samples of comparable sheet resistances applying a Ti/Al/Ni/Au (20/120/40/150 nm) Ohmic contact as we already investigated this influence before the layer stack had completely been optimized. Figure 5.13 shows R_c and ρ_c as a function of the annealing temperature of the sample that has been metallized using the Leybold e – beam evaporator and the AIRCO e – beam evaporator respectively.

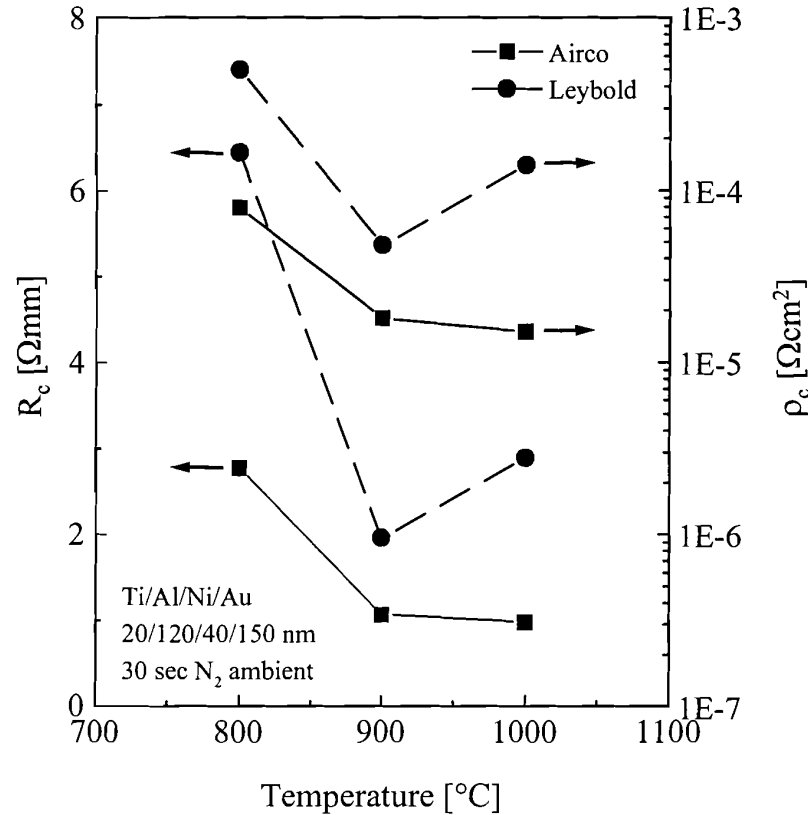


Figure 5.13: R_c and ρ_c as a function of annealing temperature obtained using the Leybold and AIRCO e – beam evaporators, respectively.

Figure 5.13 shows that the obtained values for R_c and ρ_c using the AIRCO e – beam evaporator are considerably lower than those obtained using the Leybold e – beam evaporator. This result is, however, contrary to what we would have expected because the base pressure at which the metal layers are evaporated in the Leybold (typically 10^{-8} mbar) is considerably lower than that in the AIRCO (typically 10^{-7} mbar). The lower base pressures in the Leybold are obtained because it is equipped with a loadlock and hence the chamber can remain at high vacuum while the samples are loaded or unloaded. The AIRCO does not have such a loadlock and as a consequence the chamber has to be brought to atmospheric pressure before it can be opened to load or unload the samples. An explanation for this rather unexpected result could be a difference in the quality of the metals in the Leybold and the AIRCO respectively. A contamination of the metals in the Leybold or of the system as a whole could probably be the cause of the inferior results compared to those obtained with the AIRCO. Recently, the Leybold has been cleaned and we have again compared two samples but now applying the optimized Ohmic contact fabrication process as described in appendix C. In this case, the values for R_c and ρ_c that were obtained using the Leybold e – beam evaporator were equal to

those obtained using the AIRCO e – beam evaporator ($0.21 \text{ } \Omega\text{mm}$ and $8.5 \times 10^{-7} \text{ } \Omega\text{cm}^2$, respectively). This result implies that contamination of the metals in the Leybold or of the system as a whole caused the discrepancy between the earlier obtained results.

5.6.6 Comparison of the theoretical and experimental values for ρ_c

In section 4.3, three different equations ((4.2) – (4.4)) were given in order to calculate the specific contact resistance ρ_c depending on the prevailing current transport mechanism, i.e. thermionic emission (TE), thermionic field emission (TFE) or field emission (FE), respectively. Comparison of the obtained theoretical values for ρ_c using these equations and the experimentally determined values for ρ_c shows that they differ over many orders of magnitude. This discrepancy, however, is largely due to the used value for the Richardson constant (A^*), which in literature [37] is reported to have a theoretical value of approximately $26.4 \text{ Acm}^{-2}\text{K}^{-2}$, but in practice can vary over many orders of magnitude. In order to fairly compare the theoretical and experimental values for ρ_c it is necessary to experimentally determine the value of A^* for the used $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ material. This can be done by a temperature dependent current – voltage (I - V - T) measurement using e.g. a Norde plot. Unfortunately, we do not have a measurement setup to perform such measurements and hence we can only use the theoretical value for A^* .

5.6.7 Correctness of the in literature proposed model for Ohmic contact formation

In section 5.2 a model for the formation of a tunneling Ohmic contact, which was proposed in literature [25], has been described. The main issue of this model is that the Al/Ti thickness ratio should be less than 2.82 in order that excess Ti can react with the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material at the interface and thus initiating the formation of a tunneling Ohmic contact.

If we examine the results of our experiments with respect to the Al/Ti thickness ratio, we have to conclude that in our case the proposed model fails completely because contrary to what the model predicts we have found the lowest values for R_c and ρ_c at an Al/Ti thickness ratio of 6. At the Chemistry Department of the TU/e we had our contacts examined using secondary ion mass spectroscopy (SIMS) and X – ray photo – electron spectroscopy (XPS) in order to determine the composition of the layers that have been formed at the metal – semiconductor interface after annealing. However, due to calibration and detection problems the obtained results from these analysis methods could not provide an unambiguous composition of the layers at the metal – semiconductor interface in our annealed contacts. Hence, at this moment it is not possible to provide a plausible explanation for the discrepancy between the results

according to the proposed theoretical model [25] and those obtained from our experiments. In the future it should be tried to physically analyze the annealed Ohmic contacts using transmission electron microscopy (TEM) or high resolution electron microscopy (HREM) in order to find a model that can describe the formation mechanism of our Ohmic contacts.

5.6.8 Maximum current density

With regard to the application of the optimized Ohmic contacts in a high power HEMT, we were interested in the maximum current that could pass through the Ohmic contacts before they would be destroyed. This maximum current has been measured using the contacts with the smallest gap spacing (nominally $s = 4 \mu\text{m}$) because as the gap spacing increases, the maximum current decreases due to the increasing influence of the series resistance of the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ material. A two – point probe measurement technique using a Tektronix 577 curve tracer was carried out in order to determine the maximum current. The maximum current that has been measured for the Ti/Al/Ni/Au (30/180/40/150 nm) Ohmic contacts on our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT structures just before they turned black indicating that the contacts have completely been destroyed was 200 mA at 20 V. It has to be noted that this result is independent of the used e – beam evaporator. For comparison reasons this maximum current is generally spoken of in terms of a maximum current density with the dimensions of milliamps per millimeter (mA/mm). Calculating the periphery of the inner disc contact to be equal to ($2\pi r_2 = 2\pi \cdot 50 \times 10^{-3} \text{ mm}$) 0.314 mm, the maximum current density is equal to 637 mA/mm.

According to literature [27], the maximum current density can be predicted if the $n_s \mu$ product of the used $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ material is known. Unfortunately, we do not know the $n_s \mu$ product for our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT structures. Hence, we do not have any reference point to which we can compare our value of the maximum current density. If we compare our value of 637 mA/mm to the values reported in literature [27, 40] for similar structures, our value is rather low. However, we do not think that the Ohmic contacts severely limit the maximum current density considering the low values of their R_c and ρ_c .

5.6.9 Line definition and morphology of the Ohmic contacts

Considering the high post – metallization rapid thermal annealing (RTA) temperature of 900 °C we were interested in both the line definition and the morphology of our Ohmic contacts. The Ohmic contacts are applied as the source and drain contacts in the high electron mobility transistors (HEMTs) and the Schottky contact, which forms the gate contact, has to be fabricated between them. In order to minimize parasitic resistances and to increase the

transconductance (g_m) and hence to increase both the current gain cut – off frequency (f_t) and the maximum frequency of oscillation (f_{max}), it is very important that the source and drain contacts in the HEMT design are placed in as close a proximity as possible to the gate contact. If the drain and source contacts show a bad line definition it is almost impossible to position the gate contact between them without creating a short circuit. Figure 5.14 shows a scanning electron microscope (SEM) image of the very good line definition of our optimized Ohmic contact.

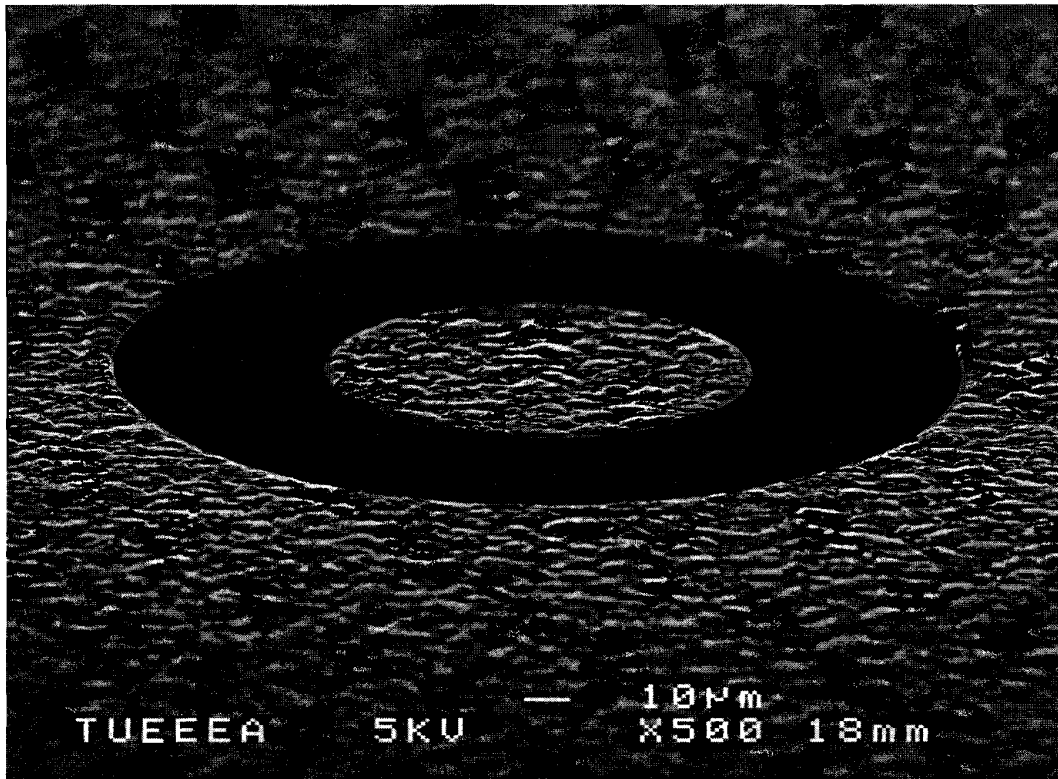


Figure 5.14: SEM image of our optimized Ohmic contact showing the good line definition.

A good line definition of the Ohmic contacts after annealing at 900 °C is also important with respect to the alignment marks that are needed for the alignment of the Schottky contacts. If the line definition of these marks is very bad, it is impossible to use them for an accurate alignment of the Schottky contacts. Figure 5.14 and the obtained image using atomic force microscopy (AFM) shown in figure 5.15 show the nice surface morphology of our annealed Ohmic contacts. In addition it can be remarked that the mechanical stability of our Ohmic contacts is very good. The measurement probes do not inflict any damage that is worth mentioning.

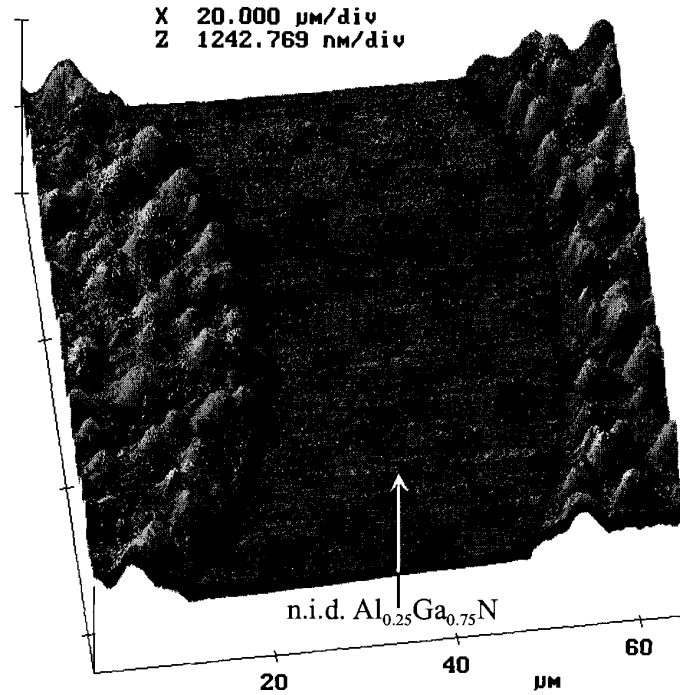


Figure 5.15: AFM image of our optimized Ohmic contact showing the nice surface morphology.

5.7 Conclusions and recommendations

This section presents the most important conclusions that can be drawn from the experimental results that have been described in the former section. Furthermore, recommendations are provided for future investigations.

5.7.1 Conclusions

Our optimized fabrication process for Ohmic contacts on the n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure that has been described in section 5.5.1, consists of a $\text{Ti}/\text{Al}/\text{Ni}/\text{Au} = 30/180/40/150$ nm metallization scheme, which is e-beam evaporated at a base pressure of typically $10^{-7} - 10^{-8}$ mbar without any pre – metallization treatments. After an RTA process at 900°C for 30 seconds in a N_2 ambient, the resulting values for the contact resistance R_c and the corresponding specific contact resistance ρ_c are $0.2 \Omega\text{mm}$ and $7.3 \times 10^{-7} \Omega\text{cm}^2$, respectively with a sheet resistance R_{sh} of $500 - 600 \Omega/\text{sq}$. Comparing our values for R_c and ρ_c

with those reported in literature [27, 29], it can be concluded that our optimized Ohmic contact on n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructures is among the best in the world. The technological recipe is described in appendix C. Furthermore, we are convinced that our systematic approach of the optimization procedure has resulted in an Ohmic contact with as low as possible values for R_c and ρ_c . The Al/Ti thickness ratio of 6 that we use in the optimized metal layer stack, is however in contrast with the theoretical model [25] proposed in literature for Ohmic contact formation of Ti/Al – based metallization schemes on $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material. It is obvious that in our case the proposed theoretical model does not apply.

The calculation of the values for R_c and ρ_c from the experimental results for the total resistance as a function of the gap spacing using a CTLM configuration can be done in two ways. The first way is to apply a linear approximation to the experimental CTLM results, which requires the use of correction factors that account for the changing circular contact geometry. After this linear approximation the calculations can be carried out using the equations known from the LTLM configuration. The second way is to fit the exact expression for the total resistance $R_{T,circ}$ (equation (5.4)) to the experimental CTLM results. From our experiments it can be concluded that the values for R_c and ρ_c can be determined with a margin of error of only 5 %. It should be noted that the choice of the starting values in the case of our fitting procedure using MATLAB routines does not influence the fit results. Furthermore, from our experiments it can be concluded that both calculation methods are suitable to determine the values for R_c and ρ_c .

It can be concluded that the accuracy with which the values for R_c and ρ_c can be calculated from the linear approximation of the experimental CTLM results and the fitting procedure of the exact expression for $R_{T,circ}$ depends very heavily on the accuracy with which the values of the gap spacings s , the transfer length L_t and $R_{T,circ}$ can be determined. The latter depends among others on the used measurement technique and the calibration of the measurement setup. Using a four – point probe measurement technique, the probe resistance can be neglected and reliable values for $R_{T,circ}$ can be obtained. In order to accurately determine the value for L_t and hence to accurately calculate the value for ρ_c , the end resistance R_E of the transmission line that is used to model the metal contact can be measured. However, due to the used CTLM configuration used in our experiments (Marlow and Das [21]) it was not possible to perform an end resistance measurement.

Reproducibility of the Ohmic contact fabrication process and its results is extremely important for a reliable implementation in the HEMT fabrication process. Literature [38] showed that the variations in the values for R_c and ρ_c can be explained by variations in the values of the sheet resistance R_{sh} . These variations in R_{sh} are due to both a varying Al mole fraction within the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer and a varying thickness of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer. Therefore, only values for R_c and ρ_c that are obtained from samples with comparable values for R_{sh} should be compared. In that case, the values for R_c and ρ_c of our optimized Ohmic contacts showed a very good reproducibility as they were within 10 %. Furthermore, from our experiments it can be concluded that contamination of the metals of an e-beam evaporator or of the system as a whole can seriously affect the reproducibility of the obtained results.

It can be concluded that comparison of the theoretical values for ρ_c and the experimentally determined values for ρ_c differ over many orders of magnitude. This discrepancy is largely due to the used value for the Richardson constant (A^*), which in literature [37] is reported to have a theoretical value of approximately $26.4 \text{ Acm}^{-2}\text{K}^{-2}$. In practice however, it can vary over many orders of magnitude. In order to fairly compare the theoretical and experimental values for ρ_c it is necessary to experimentally determine the value of A^* for the used $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ material. This can be done by a temperature dependent current – voltage (I - V - T) measurement using e.g. a Norde plot. We do not have a measurement setup to perform such measurements and hence we can only use the theoretical value for A^* .

The maximum current density of our optimized Ohmic contacts is of importance for the application in high power devices. If we compare our value of 637 mA/mm to the values reported in literature [27, 40] for similar structures, our value is rather low. However, we do not think that the Ohmic contacts severely limit the maximum current density considering the low values of their R_c and ρ_c .

Finally, our Ohmic contacts have shown a very good line definition and a nice surface morphology despite the high post – metallization rapid thermal annealing (RTA) temperature of 900 °C. As the Ohmic contacts are used as the drain and source contacts in the HEMT a good line definition and surface morphology are required among others for the positioning of the gate contact between the drain and source contacts. Furthermore, this is also important with respect to the alignment marks that are needed for the alignment of the Schottky contacts. If the line definition of these marks is very bad, it is impossible to use them for an accurate alignment of the Schottky contacts.

5.7.2 Recommendations

In order to accurately calculate the contact resistance R_c and the specific contact resistance ρ_c , it is very important to accurately measure the gap spacings of the fabricated TLM test structures. Due to the inaccuracy induced by the fabrication process these values can differ from the values for the gap spacings specified on the mask.

Due to limited time we have not done an end resistance measurement on the CTLM test structure proposed by Rechid and Heime [22] in order to accurately determine the value for L_t from experiments. In future investigations this should be tried as the required CTLM test structures are available on our CTLM mask.

The high background noise that results from the nitrogen originating from the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ layer renders secondary ion mass spectroscopy (SIMS) and X – ray photo – electron spectroscopy (XPS) not suitable to provide an unambiguous composition of the layers at the metal – semiconductor interface of our optimized Ti/Al/Ni/Au Ohmic contact and the used $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material. In the future, transmission electron microscopy (TEM) or high resolution electron microscopy (HREM) could be tried to perform such a physical characterization in order to propose a model for the Ohmic contact formation because in our case the theoretical model [25] proposed in literature does not apply.

The e-beam evaporators should be regularly cleaned in order to prevent contamination of the metals and of the system as a whole. From our experiments it can be concluded that such a contamination can seriously affect the reproducibility of the obtained results.

Finally, a measurement setup should be created that enables the measurement of temperature dependent current – voltage characteristics (I - V - T) on wafer. Then it would be possible to determine a practical value for the Richardson constant A^* of the used $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material.

CHAPTER 6

Theoretical Introduction to Schottky Contacts

6.1 Introduction

This chapter is concerned with the second of the two limiting cases of metal – semiconductor contacts: the Schottky contacts. Their excellent rectifying properties are used to form Schottky diodes, which are majority carrier devices and hence have very short switching times typically in the picoseconds range. It is this property that makes Schottky diodes very suitable for high frequency applications. In the high power $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMTs, the Schottky contacts are applied as the gate contacts. Therefore, the Schottky contacts should have a high breakdown voltage (V_{break}) and a low reverse current (I_s). Due to the large bandgap of the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ material high values for the breakdown voltage can be expected theoretically.

This chapter provides a brief overview of the Schottky contact parameters that can be used to indicate their quality. Furthermore, the different characterization methods that can be used to determine them will be briefly discussed.

6.2 Schottky contact parameters

Two very important parameters for the characterization of Schottky contacts, the barrier height (Φ_{Bn}) and the ideality factor (n), respectively, have already extensively been discussed in chapter 3, which presents the basic theory of metal – semiconductor contacts. It has been shown that in the case of an ideal Schottky contact the barrier height is bias independent and the current is only determined by thermionic emission (TE). In that case, the forward current – voltage characteristics are linear and the ideality factor equals unity. In practice, however, the Schottky contact will generally be far from ideal. This could among others be due to the bias dependency of the barrier height, the presence of an interfacial layer or due to other current transport mechanisms being more dominant than thermionic emission. As a result, the forward current – voltage characteristics will show noticeable deviations from linearity. In that case, it can be described by equation (3.27) where the ideality factor exceeds

unity. Literature [42] showed that there is a linear relationship between Φ_{Bn} and n , which is schematically shown in figure 6.1.

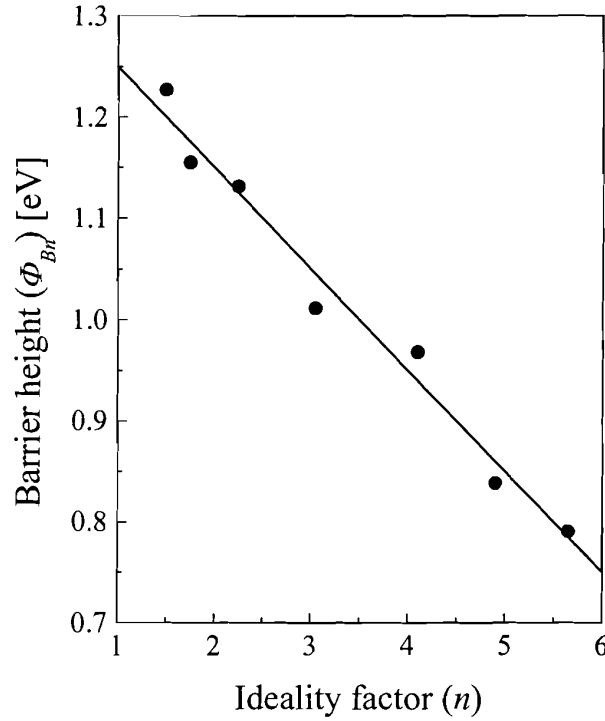


Figure 6.1: Linear relationship between the barrier height (Φ_{Bn}) and the ideality factor (n).

The reverse current (I_s) and the breakdown voltage (V_{break}), which generally is defined as the voltage at which the reverse current is 1 mA taking into account the geometrical dimensions of the device, are other very important Schottky parameters with respect to the application of Schottky contacts as gate contacts in high power devices in general and in our high power $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMTs in particular. For this application a low I_s and a high V_{break} are required. The most important mechanism in junction breakdown is avalanche multiplication or impact ionization. In literature [19] it has been shown that the breakdown voltage is inversely proportional to the product of the doping concentration (N_d in the case of an n -type semiconductor) and the thickness of the semiconductor contact layer. Therefore, the 5 nm non intentionally doped (n.i.d.) $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ cap layer has been included in the epitaxial structure of the Epitronics $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT wafers. Furthermore, the breakdown voltage of practical contacts is among others affected by the presence of an interfacial layer and surface states. This makes the breakdown voltage of practical contacts sensitive to process details. In addition, a very irregular line definition of the Ohmic and Schottky contacts could modify the

electric field configuration in such a way that the breakdown voltage is considerably diminished.

Finally, the capacitance (C) of the Schottky contacts is a very important parameter that enables the determination of the doping concentration of the semiconductor contact layer and the value of the built – in voltage (V_{bi}). Figure 6.2 shows the energy band diagram of an ideal Schottky diode (without any interfacial layer and surface states) on an n – type semiconductor under reverse bias (V_r).

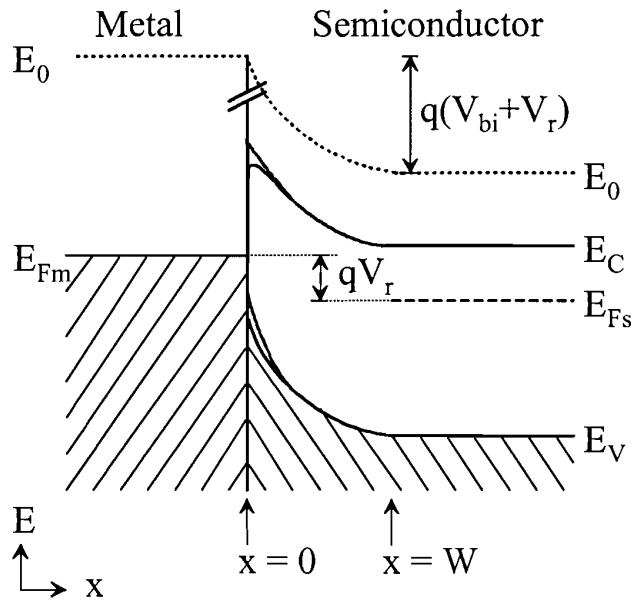


Figure 6.2: Energy band diagram of an ideal Schottky diode (without any interfacial layer and surface states) on an n – type semiconductor under reverse bias (V_r).

The semiconductor material next to the metal – semiconductor interface is depleted of electrons. What remains is a region containing the ionized donor atoms (N_d^+). This region is called the depletion region of a Schottky barrier. Depending on the concentration of the donor atoms (N_d), the applied bias (V) controls the depth (W) to which the depletion region extends into the semiconductor material. In some respects, the depletion region behaves like a parallel plate capacitor [16, 19], which capacitance (C) generally is given by:

$$C = \frac{\epsilon_0 \cdot \epsilon_r \cdot A}{W} \quad (6.1)$$

where ϵ_0 is the permittivity of free space, $\epsilon_{r,s}$ the relative permittivity of the semiconductor material, W the width between the parallel plates and A the area of the Schottky contact. The

same result can also be obtained more formally [16, 19] using the fundamental definition of capacitance $C = dQ/dV$. The potential difference in the depletion region is equal to [16]:

$$V = V_{bi} - \frac{kT}{q} - \frac{qN_d W^2}{2 \cdot \epsilon_0 \cdot \epsilon_r} \quad (6.2)$$

where N_d is the density of the donor atoms that are assumed to be uniformly distributed, V_{bi} the built – in voltage and kT/q the thermal voltage. Combining equation (6.2) with the current – voltage relationship given by equation (3.21) (section 3.3.1.4) yields:

$$\frac{1}{C^2} = \frac{2 \cdot \left(V_{bi} - V - \frac{kT}{q} \right)}{q \cdot \epsilon_0 \cdot \epsilon_r \cdot N_d \cdot A^2} \quad (6.3)$$

This expression describes the dependency of the Schottky contact capacitance (C) on the applied bias (V). A plot of $1/C^2$ versus the applied voltage (V) would then yield a straight line with a slope determined by N_d . After a derivation of equation (6.3) with respect to V , N_d is given by:

$$N_d = \frac{2}{q \cdot \epsilon_0 \cdot \epsilon_r \cdot A^2} \cdot \frac{-1}{dC^{-2}/dV} \quad (6.4)$$

Equation (6.4) shows that the doping profile of the semiconductor material can be determined from a measurement of the capacitance – voltage (C - V) profile of a Schottky diode.

6.3 Measurement of Schottky contact parameters

In literature [16, 18, 19] several measurement techniques are described in order to experimentally determine the Schottky contact parameters described in the former section. These measurement techniques are:

- 1) the current – voltage (I - V) method;
- 2) the capacitance – voltage (C - V) method;
- 3) the activation energy method; and
- 4) the internal photo – emission method.

6.3.1 Current – voltage (I - V) method

The current – voltage relationship of a Schottky diode has already extensively been discussed in chapter 3. The universal expression that describes this current – voltage relationship is given by equation (3.27) in section 3.3.2.1. For convenience this equation is repeated here:

$$J = J_s \exp\left(\frac{qV}{nkT}\right) \left[1 - \exp\left(-\frac{qV}{kT}\right) \right] \quad (6.5)$$

where

$$J_s \equiv A^* T^2 \exp\left(-\frac{q((\Phi_{Bn})_0 - (\Delta\Phi)_0)}{kT}\right) \quad (6.6)$$

if the Schottky effect has also been taken into account. For values of V larger than $3kT/q$, equation (6.5) can be written as:

$$J = J_s \exp\left(\frac{qV}{nkT}\right) \quad \text{for } V > 3kT/q \quad (6.7)$$

Equation (6.7) can be written as:

$$\ln(J) = \ln(J_s) + \frac{qV}{nkT} \quad \text{for } V > 3kT/q \quad (6.8)$$

A plot of $\ln(J)$ versus the applied forward bias (V) ideally yields a straight line with a slope that is equal to q/nkT and an $\ln(J)$ – axis intercept that is equal to $\ln(J_s)$. In practice however, the Schottky diode will not be ideal and the plot will show noticeable deviations from linearity due to among others the presence of an interfacial layer and surface states and the series resistance of the semiconductor material. Figure 6.3 gives a schematic representation of an ideal (dashed line) and a practical (solid line) $\ln(J)$ versus V plot.

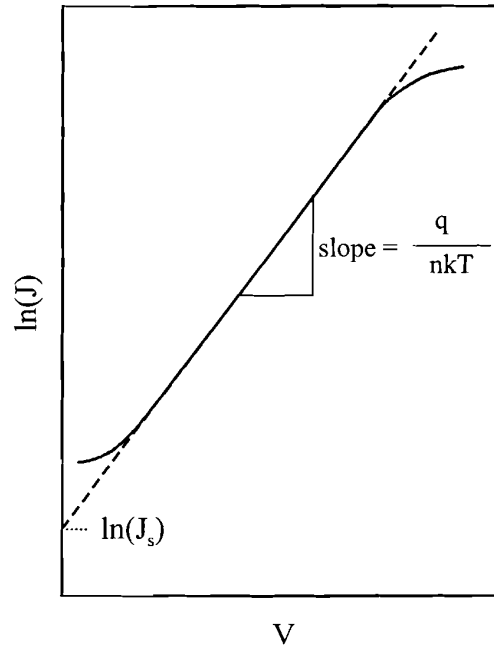


Figure 6.3: Schematic representation of an ideal (dashed line) and a practical (solid line) $\ln(J)$ versus V plot.

After determination of the slope of the forward (I - V) plot, the ideality factor n can be calculated using:

$$n = \frac{q}{k \cdot T \cdot \text{slope}} \quad (6.9)$$

After determination of the value for J_s from the $\ln(J)$ – axis intercept, the effective barrier height $\Phi_e = \Phi_{Bn} - \Delta\Phi$ can be calculated using:

$$\Phi_e = \left(\frac{kT}{q} \right) \cdot \ln \left(\frac{A^* T^2}{J_s} \right) \quad (6.10)$$

A remark has to be made with respect to the Richardson constant (A^*). For an accurate calculation of the effective barrier height (Φ_e) the value of A^* should be determined experimentally for the semiconductor material at hand because literature [37] showed that the value for A^* can vary over many orders of magnitude and hardly ever equals the theoretical value of approximately $26.4 \text{ Acm}^{-2}\text{K}^{-2}$.

6.3.2 Capacitance – voltage (C - V) method

The basic procedure to obtain a capacitance – voltage (C - V) profile of a Schottky contact is to apply a reverse DC bias to the contact, which results in the formation of a depletion region with a certain depth and corresponding capacitance. This capacitance can be measured using an AC capacitance bridge. The amplitude of the AC test signal should be much less than the applied DC bias in order that it does not significantly alter the depletion depth and the capacitance. A difficulty in obtaining the (C - V) profile could be caused by the presence of electron traps in the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material [19]. These electron traps may be filled or depleted in response to the AC test signal, which could influence the measurement results. To eliminate this effect as good as possible, the (C - V) measurements are generally performed at a frequency of 1 MHz [19, 43, 44]. At this frequency the traps fail to follow the AC test signal and reliable measurement results can be obtained.

The capacitance – voltage method can be used to determine the effective barrier height (Φ_e) if the doping concentration (N_d) is uniform. The effective barrier height under thermal equilibrium can be given by:

$$\Phi_e = q(V_{bi} + V_0) \quad (6.11)$$

where

$$V_0 = \frac{kT}{q} \cdot \ln\left(\frac{N_c}{N_d}\right) \quad (6.12)$$

and

$$N_c = 2 \cdot \left(\frac{2 \cdot \pi \cdot m_n^* \cdot k \cdot T}{h^2} \right)^{\frac{3}{2}} \quad (6.13)$$

In equations (6.11) – (6.13), V_{bi} is the built – in voltage, V_0 the potential difference between the bottom of the conduction band and the Fermi level in the semiconductor, N_c the effective density of states function in the conduction band, N_d the donor concentration, h Planck's constant and m_n^* is the electron effective mass. According to equation (6.3) a plot of $1/C^2$ versus the applied reverse bias (V) will yield a straight line as shown in figure 6.4. After determination of the slope of the (C - V) plot, the donor concentration N_d can be calculated using:

$$N_d = \frac{2}{q \cdot \epsilon_0 \cdot \epsilon_r \cdot \text{slope}} \quad (6.14)$$

The modulus value of the built – in voltage ($|V_{bi}|$) can be determined from the negative V – axis intercept.

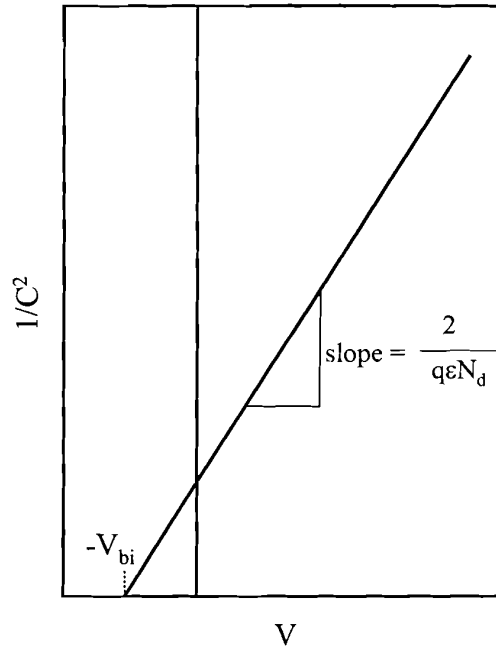


Figure 6.4: Schematic representation of a plot of $1/C^2$ versus the applied reverse bias (V).

In literature [37, 43, 45] it has been observed that the values for the effective barrier height (Φ_e) derived by the (C - V) method are generally higher than those derived by the (I - V) method. This discrepancy of the experimental results between the different methods may among others result from the Schottky effect, the presence of a thin interfacial layer and surface states, contamination in the interface and deep impurity levels acting as electron traps [15, 16, 43].

6.3.3 Activation energy method

The principle advantage of the determination of the effective barrier height (Φ_e) using the activation energy method is that no assumption of the electrically active area is required [15]. This feature is particularly important in the investigation of new or unusual metal – semiconductor contacts, because often the actual value of the contacting area is not known. In order to determine (Φ_e) and the effective Richardson constant (A^{**}) it is required to measure the forward current – voltage characteristics of the Schottky contacts at different temperatures, (I - V - T) measurements. Another approach involving these (I - V - T) measurements in order to determine Φ_e and A^{**} is the modified Norde plot. We do not have a measurement setup to perform (I - V - T) measurements at our disposal and hence we have to use the theoretical value for A^{**} of approximately $26.4 \text{ A cm}^{-2} \text{ K}^{-2}$ in the calculations of the Schottky contact parameters. For more detailed information on the activation energy method and the modified Norde plot we refer to literature [15, 19, 43].

6.3.4 Internal photo – emission method

An alternative way to determine the effective barrier height (Φ_e) of a metal – $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructure is to use the internal photo – emission method. The principle of this method is that monochromatic light is illuminated on the metal contact of a Schottky barrier thus generating hot electrons in the metal. When these electrons by diffusion arrive at the depletion region, they are attracted by the built – in electric field in the barrier. This causes a photocurrent across the Schottky diode. In principal, all the electrons located in the depletion region should contribute to the total photocurrent irrespective if they were generated and diffused from the metal side or generated within the depletion region of the semiconductor by the incident photons. The two components of the photocurrent need to be separated for the measurement of the effective barrier height since only the contribution of the hot electrons from the metal side relates to the determination of the effective barrier height. In order to distinguish the two different components of the photocurrent the following could be done [46]: electrons located in the depletion region under a built – in electric field would be driven toward the semiconductor and provide a photocurrent. However, when a forward bias voltage is applied to the Schottky barrier the electric field in the depletion region decreases causing the photocurrent to decrease. When the applied voltage becomes larger than the built – in voltage the depletion region disappears and the applied voltage should drop across the bulk semiconductor. Electrons in the semiconductor generated by the band – to – band absorption and the absorption from the deep levels inside the bandgap, if any, would move toward the metal and provide the photocurrent. Under this condition the system behaves as that in a photoconductivity measurement of the semiconductor [46]. The sign of the photocurrent in this situation is opposite to that of the photocurrent without bias. According to Fowler's theory [46] the relationship between the photocurrent per photon (R) and the incident photon energy ($h\nu$) is given by:

$$R \propto (h\nu - q\Phi_e)^2 \quad \text{for } h\nu - q\Phi_e > 3kT \quad (6.15)$$

where h is Planck's constant and ν is the frequency of the monochromatic light. This relationship is valid when $h\nu - q\Phi_e > 3kT$ and is in the range of several tenths of an electron volt in magnitude [46]. The effective barrier height of the Schottky contact can be obtained from the straight line relationship of the square root of the photocurrent per photon versus the incident photon energy. For more detailed information on the internal photo – emission method we refer to literature [15, 46].

6.4 Conclusions

In this chapter it has been pointed out that for the application of the Schottky contacts in high power devices, high breakdown voltages (V_{break}) and low reverse currents (I_s) are required. Furthermore, it has been discussed that the breakdown voltage and the reverse current of practical Schottky contacts are affected among others by the presence of an interfacial layer and surface states. In addition, it has been reported in literature [37, 43, 45] that the values for the effective barrier height (Φ_e) derived by the (C - V) method are generally higher than those derived by the (I - V) method. This discrepancy of the experimental results between the different methods may among others result from the Schottky effect, the presence of a thin interfacial layer and surface states, contamination in the interface and deep impurity levels acting as electron traps [15, 16, 43]. Hence, it can be concluded that the surface preparation of the semiconductor material prior to metallization is very critical for the obtained results. Therefore, great care should be taken with respect to the conditioning of the semiconductor surface in order to render it stable and reproducible. In the previous section we have discussed four measurement techniques that can be used to determine the Schottky contact parameters. Table 4 provides a summary of the Schottky contact parameters and the measurement techniques by which they can be determined.

Table 4: Schottky contact parameters and measurement techniques.

Measurement techniques ↓		Schottky contact parameters		
(I-V)	Forward	Φ_e equation (6.10)	J_s ln(J) - axis intercept	n equation (6.9)
	Reverse		V_{break} reverse current 1 mA	
(C-V)		Φ_e eqns (6.11) – (6.13)	N_d equation (6.14)	V_{bi} V – axis intercept
Activation energy		Φ_e	A^{**}	
Internal photo-emission		Φ_e		

CHAPTER 7

Schottky Contacts on n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ Heterostructures

7.1 Introduction

Chapter 7 is concerned with the preliminary technology and experimental results of the fabricated Schottky contacts on the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT epitaxial structure that has been described in section 5.5.1. First, the most commonly used metallization schemes for Schottky contacts on n – type $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ material will be described. Furthermore, an overview is given of the pre – metallization and post – metallization treatments described in literature, which are applied in order to decrease the reverse current (I_s) and to increase the breakdown voltage (V_{break}). After this, the experiments with respect to the Schottky contact fabrication and the preliminary results will be presented. First, the limitations with respect to the characterization of the Schottky contacts will be discussed. Next, the circular mask design that is used to fabricate the Schottky test structures will be considered.

Furthermore, the Ni/Au and Ir/Au metallization schemes will be discussed. After that, we tried to determine the influence of both the pre – metallization treatments and the post – metallization heat treatment on the preliminary experimental results obtained from the current – voltage measurements. This is followed by a brief discussion of the capacitance – voltage measurements. Finally, the conclusions and recommendations for the fabrication of Schottky contacts on our n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N} / \text{GaN}$ material will be provided.

7.2 Schottky metallization schemes

According to literature, the most commonly used metallization schemes for Schottky contacts on n – type $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ material are [27, 29, 45]:

- Nickel/Gold (Ni/Au);
- Platinum/Titanium/Gold (Pt/Ti/Au); and
- Palladium/Gold (Pd/Au).

In literature [27, 29, 45] these metallization schemes were reported to show the lowest values for the reverse current (I_s) and the highest values for the breakdown voltage (V_{break}). The reported values for V_{break} however vary considerably from values as low as 40 Volts up to very high values of 450 Volts depending on the layout and the dimensions of the test structures. The effective barrier heights (Φ_e) for the different metallization schemes are reported [45] to depend on the Al mole fraction of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer. It has been shown that Φ_e increases with increasing Al mole fraction. According to literature [45, 48] for our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ material we can expect values for Φ_e between 0.7 eV and 1.1 for the Ni/Au, Pt/Au and Pd/Au metallization schemes. However, we cannot determine them experimentally because of reasons to be discussed in section 7.5.1. It has to be noted that the thermal stability of the generally used Schottky metallization schemes is reported to be rather poor [48]. Aging tests at 400 °C have shown that the values for their effective barrier heights decrease drastically, e.g. the effective barrier height of the Pt/Ti/Au scheme decreases from approximately 0.75 eV to approximately 0.45 eV within the first hours of annealing. As a consequence, the reverse current (I_s) increases considerably and the breakdown voltage (V_{break}) decreases significantly. Recently, a new metallization scheme has attracted a lot of attention with respect to the improvement of the thermal stability of the Schottky contacts. This new Schottky metallization scheme consists of sputtered Iridium/Gold (Ir/Au) layers and is reported [48] to have a superior thermal stability. The effective barrier height of Ir/Au contacts to $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ layers is reported to be approximately 0.9 eV [48]. Aging tests at 400 °C have shown that the effective barrier height for these contacts actually increases to approximately 1.1 eV upon annealing instead of decreases. These Schottky contacts should then be able to establish high values for V_{break} and low values for I_s . Furthermore, the mechanical stability of the Schottky contacts is an important issue. The Ni/Au contacts showed to have a superior mechanical stability over Pt/Ti/Au and Pd/Au contacts because Ni has a better adhesion to the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material than Pt and Pd.

7.3 Pre – metallization treatments of the undoped $\text{Al}_x\text{Ga}_{1-x}\text{N}$ cap layer

In literature [32, 45, 50] it has been reported that pre – metallization treatments of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ surface are crucial to obtain good electrical characteristics of the Schottky contacts. In section 3.2 it has been discussed that Fermi level pinning in the case of the GaN – based materials systems is of minor importance and that the major contribution to the Schottky barrier height is due to the difference in the metal and semiconductor work functions. Nevertheless, it has also been reported [35] that nonoptimized surface preparation conditions can lead to considerable Fermi level pinning and other nonidealities. The most commonly

reported [32, 35, 45, 50] pre – metallization treatments of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ surface in order to render it stable and reproducible are:

- plasma enhanced cleaning; and
- wet chemical etching.

These pre – metallization treatments will be briefly discussed in the following subsections.

7.3.1 Plasma enhanced cleaning

In literature relatively little work has been reported with respect to the effects of plasma processes on the electrical characteristics of Schottky contacts on n – type $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ material. Exposure to pure argon (Ar) discharges in order to remove e.g. native oxides just before metallization has been reported [50] to cause higher reverse currents and lower breakdown voltages. The increase in reverse current can among others be explained by the increased surface roughness due to the distorted stoichiometry of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material. As a result, this gives rise to parasitic leakage currents such as the surface leakage current [50]. From preliminary work on Schottky contacts to n – type GaN and from literature [32] we know that even highly chemical thus relatively smooth RIE processes severely deteriorate the quality of the Schottky contacts. However, literature [48] also reported that the application of “soft” (i.e. at a low DC bias) O_2 plasmas for several minutes resulted in an improvement of the electrical characteristics of the Schottky contacts. It is suggested [48] that the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ surface is rendered more stable and reproducible by this plasma enhanced removal of surface contaminants.

7.3.2 Wet chemical etching

Contrary to the subject of the former subsection, a lot of work has been reported in literature [35, 45, 50] with respect to wet chemical etching of the surface of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ structures in order to render it stable and reproducible. The most commonly applied pre – metallization surface treatments involving wet chemical etching solutions are [35, 45, 48, 50]:

- 1) cleaning in organic solvents (e.g. acetone, isopropanol) only;
- 2) cleaning in organic solvents followed by a dip in:
 - a. $\text{HF} : \text{HCl} : \text{H}_2\text{O} = 1:5:5$; or
 - b. undiluted HCl; or
 - c. $\text{HCl} : \text{H}_2\text{O} = 1:5$; or
 - d. aqua regia ($\text{HNO}_3 : \text{HCl} = 1:2$) followed by HF rinse; or
 - e. cold or warm (50 °C) $\text{NH}_4\text{OH} : \text{H}_2\text{O} = 1:10$.

It has been reported [50] that for the e – beam evaporated Schottky contacts, which were formed after a treatment only in organic solvents, (regardless of the used metallization scheme) high reverse currents (10^{-1} A/cm^2) and low breakdown voltages ($V_{break} < 40 \text{ V}$) were obtained. For the contacts that were formed after HF, HCl, combined HF/HCl and aqua regia/HF treatments, also very poor current – voltage characteristics were reported [35, 50]. The contacts formed after a warm NH_4OH treatment were reported [50] to show very good electrical Schottky properties i.e. low reverse currents (10^{-4} A/cm^2) and high breakdown voltages ($V_{break} > 100 \text{ V}$). As a result, it was concluded [50] that there exists a strong correlation between the chemical and electronic properties of metal/ $\text{Al}_x\text{Ga}_{1-x}\text{N}$ interfaces formed by e – beam evaporation. Namely, the almost oxide – free and near stoichiometric surfaces obtained after the NH_4OH treatment have been reported [50] to remain stable during metal contact formation. This gave rise to the excellent Schottky contact characteristics. On the other hand, oxide containing and non – stoichiometric surfaces obtained after application of the wet chemical etching treatments mentioned under 2a – d, have been reported [50] to become unstable during contact formation. As these metal – semiconductor junctions suffered from the presence of an interfacial layer, they exhibited poor Schottky contact characteristics. Immediately after the wet chemical etching treatment the samples should be loaded into the e – beam evaporator, as the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ surfaces will oxidize again very rapidly. As a consequence, the choice of wet chemical etching solution depends among others on the type of the used photoresist, i.e. the photoresist that is used to pattern the Schottky contacts should not be removed during wet chemical etching.

7.4 Post – metallization heat treatment

In literature it has been reported [18, 37] that newly formed Schottky contacts are known to exhibit aging effects on their interface barrier properties. Post – metallization heating of the contacts in a traditional furnace usually at 100°C for one hour can accelerate these aging effects. It is therefore important to make sure that the metal – semiconductor system has been properly aged before attempting to determine reliable values for the Schottky contact parameters. It is believed that the aging phenomena are due to ionic activity within the interfacial layer [18]. Positively charged ions would be attracted towards the metal by the built – in field. The modifications to the Schottky contact parameters observed during the period that these charges migrate come as a result of a changing dipole moment. The interfacial dipole moment exists because of the positive ionic charge distribution near the surface of the semiconductor and the compensating negative charges on the surface of the metal. The dipole moment vanishes when all the positive ions reach the metal and their charges are neutralized. The fast diffusing positively charged ions may be present in the semiconductor material prior to the metal deposition but most likely they are introduced

during the metal deposition. This is particularly the case when use is made of sputter deposition. From preliminary work on e – beam evaporated Nickel (Ni) Schottky contacts to n – type GaN and from literature [35] it is known that rapid thermal annealing (RTA) of these contacts in the range of $100\text{ }^{\circ}\text{C} - 300\text{ }^{\circ}\text{C}$ for 30 seconds leads to a reduction of the reverse current (I_s).

7.5 Experiments and results

This section describes the experiments with respect to the Schottky contact fabrication and the preliminary results. First, the limitations with respect to the Schottky contact characterization will be discussed. Next, the circular mask design that is used to fabricate the Schottky test structures will be considered. Furthermore, the Ni/Au and Ir/Au metallization schemes will be discussed. After that, it is tried to determine the influence of both the pre – metallization treatments and the post – metallization heat treatment (sections 7.3 and 7.4, respectively) on the preliminary experimental results obtained from the current – voltage measurements. Finally, a brief discussion of the capacitance – voltage measurements will be given.

7.5.1 Limitations to Schottky contact characterization

Similarly to the optimization procedure of the Ohmic contacts, we have chosen to do the optimization of the Schottky contacts on identical $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material as is used for the fabrication of the HEMTs (section 5.5.1). However, it has to be noted that this is the most unfortunate choice one can make with respect to the characterization of the Schottky contacts because the characterization methods described in sections 6.3.1 – 6.3.3 are the conventional techniques used to determine the Schottky parameters on “bulk” semiconductor layers. However, for a heterojunction such as our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMT structure these conventional techniques may not yield an accurate determination of the Schottky parameters because a structure of a metal on a heterojunction can be considered as two diodes connected in series back to back. The first diode is a metal – $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ Schottky diode and the second diode is an equivalent Schottky diode due to the heterojunction between the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ and GaN layers [46, 47]. Under such conditions the (I – V) characteristics of Schottky contacts on our HEMT structures cannot be analyzed by the universal Schottky equation given by equation (3.27). In addition, a plot of $1/C^2$ versus the applied reverse bias V would not yield a straight line. Consequently, it is not possible to determine a reliable value for the built – in voltage (V_{bi}) of such a structure. As a result, the internal photo – emission method has to be used to determine the Schottky contact parameters. However, we do not have an internal photo – emission measurement setup at our disposal and hence we are not able to determine

the effective barrier height, the ideality factor, the built – in voltage and the donor concentration for our Schottky contacts. Therefore, we cannot compare our Schottky contacts to Schottky contacts reported in literature because those contacts are fabricated on relaxed $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material and the literature which is concerned with $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ devices only mention the metal layer stacks of the used contacts and do not report on the Schottky contact parameters. However, in order to compare our different Schottky contacts to each other we have decided to use the reverse current and the breakdown voltage as the parameters that give an indication of their quality. The forward and the reverse current – voltage measurements have been carried out using a four – and a two – point probe technique respectively. The measurements were automated using ICCAP software running on a HP UNIX computer. The reverse capacitance – voltage measurements were done using a HP4275A multi – frequency LCR meter at a frequency of 1 MHz.

7.5.2 Circular Schottky mask design

It has been reported [52] that the reverse current in Schottky diodes is generally much larger than expected from the thermionic emission theory most likely due to defect states around the contact periphery. To reduce this leakage current and to prevent early breakdown, edge termination techniques such as guard rings and field plates are necessary. Taking this into consideration, we have decided to fabricate circular Schottky contacts. Therefore, we have used a circular Schottky mask design that is shown in figure 7.1. It can be observed that the mask consists of four parts which are called: “mesa” part, “Ohmic” part, “open” part and “Schottky” part, respectively. Each of these parts has a width and a height of 1.5 cm and consists of nine unit cels. One of these unit cels of each part is shown in figure 7.1. The objective of each of these parts and the dimensions of the structures of each unit cel will be described in the following subsections.

7.5.2.1 Mesa part

It is obvious that the objective of the mesa part is the formation of circular mesas. The diameter of the mesas is $150\text{ }\mu\text{m}$. These mesas are located in the top right and the bottom left corners of the unit cel. In the dark areas surrounding the “white” mesas the chromium (Cr) has been removed from the mask plate and the semiconductor surface will be etched. In the top left and bottom right corners CTLM test structures proposed by Marlow and Das [21] (section 5.5.2) will be fabricated using the “Ohmic” part of the mask. However, the top left corner of the unit cel is totally covered with chromium. This has been done to determine the influence

of the etching of the semiconductor material on the quality of the Ohmic contacts that will be placed on this etched material around the circular mesas.

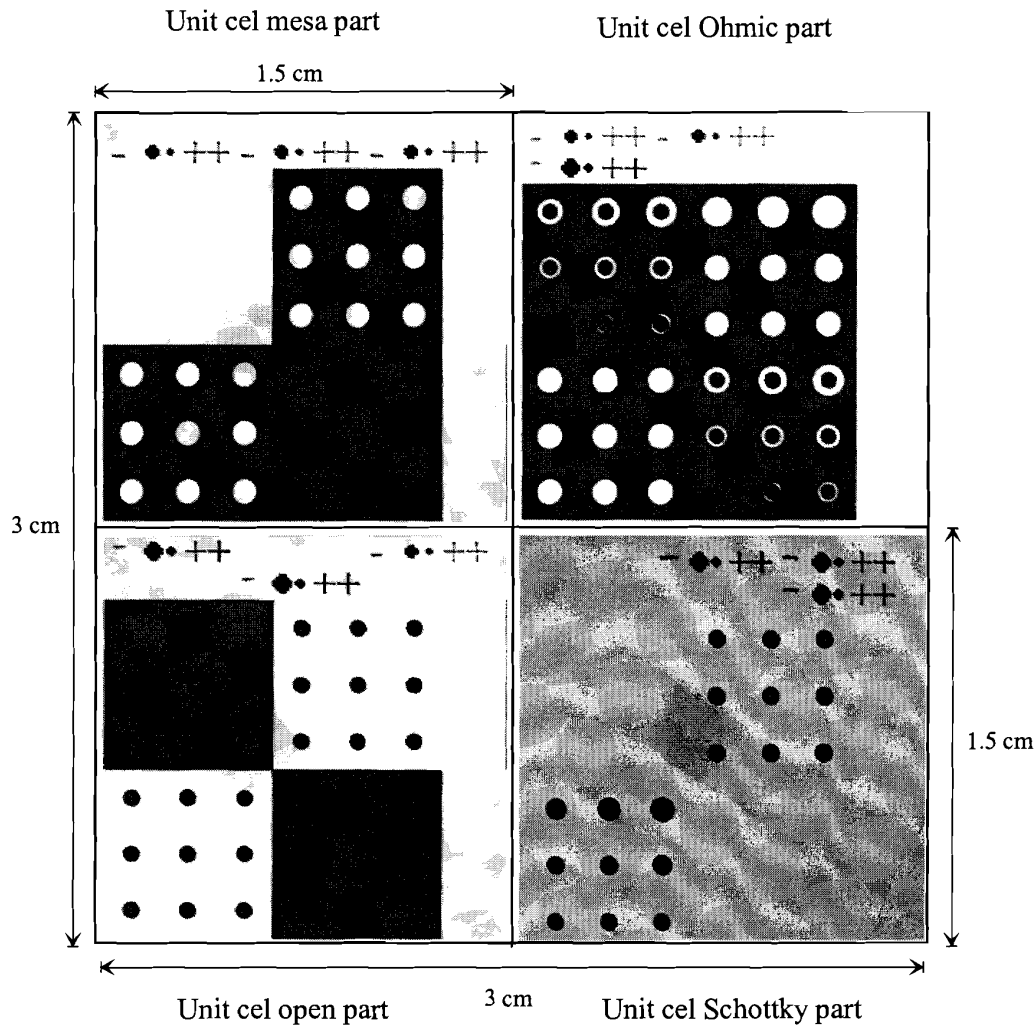


Figure 7.1: Layout of the circular Schottky mask design.

7.5.2.2 Ohmic part

The “Ohmic” part is used to fabricate both the Ohmic contacts around the etched mesas and the CTLM test structures mentioned in the former subsection. These Ohmic contacts surrounding the etched mesas are situated in the top right and bottom left corners of the unit cel. The “white” circles indicate the areas where the mesas will be positioned. The Ohmic contacts in the top right corner have increasing diameters of 154, 156, 158, 160, 170, 180, 190, 200 and 210 μm respectively. The gap between them and the mesa is then 2, 3, 4, 5, 10,

15, 20, 25 and 30 μm respectively. The Ohmic contacts in the bottom left corner have a constant diameter of 160 μm and the gap between them and the mesa is 5 μm . The CTLM test structures are fabricated to monitor the quality of the Ohmic contacts.

7.5.2.3 Open part

The “Open” part can be used to open the areas in the deposited silicon nitride (SiN_x) layer where the pedestals (which of course are Schottky contacts) of the mushroom Schottky contacts can be fabricated. These areas are situated in the top right and the bottom left corners of the unit cel. The chromium in the top left and the bottom right corners of the unit cel has completely been removed in order to seal the CTLM test structures with the SiN_x layer. The pedestals have a constant diameter of 100 μm and hence are 25 μm separated from the edge of the mesa. After the evaporation of the pedestals the SiN_x layer can be removed by dipping it in a buffered HF solution. However, if the SiN_x layer is not removed it can be used to do dispersion experiments.

7.5.2.4 Schottky part

The “Schottky” part can be used to define the areas for the cap of the Schottky mushroom contact. These areas are situated in the top right and the bottom left corners of the unit cel. The top left and the bottom right corners of the unit cel are completely covered with chromium in order to seal the CTLM test structures with photoresist. The Schottky contacts in the top right corner have a constant diameter of 108 μm and a constant separation between them and the edge of the mesa of 21 μm . They hang over the pedestals by 4 μm . The schottky contacts in the bottom left corner have increasing diameters of 102, 104, 106, 108, 114, 120, 130, 140 and 150 μm respectively. The gap between them and the edge of the mesa correspondingly are 24, 23, 22, 21, 18, 15, 10, 5 and 0 μm , respectively. In this case they hang over the pedestals by 1, 2, 3, 4, 7, 10, 15, 20 and 25 μm , respectively.

7.5.2.5 Use of the mask

The alignment marks in the four parts and in each unit cel have been designed and positioned in such a way that each reasonable combination of the four parts is possible and can be aligned. As a result, this circular Schottky mask has a very great functionality. In this research we have only used the “Ohmic” part and the “Schottky” part to fabricate our Schottky contacts. Figure 7.2 shows the result of this fabrication process. The Schottky contacts in the top right corner have a constant diameter of 108 μm and due to the increasing diameter of the

surrounding Ohmic contacts the gap spacing increases and has values of 23, 24, 25, 26, 31, 36, 41, 46 and 51 μm , respectively. The diameter of the Ohmic contacts in the bottom left corner is constant (160 μm) but due to the increasing diameter of the Schottky contacts in this case (102, 104, 106, 108, 114, 120, 130, 140 and 150 μm , respectively) the gap spacing consequently decreases and has values of 29, 28, 27, 26, 23, 20, 15, 10 and 5 μm , respectively.

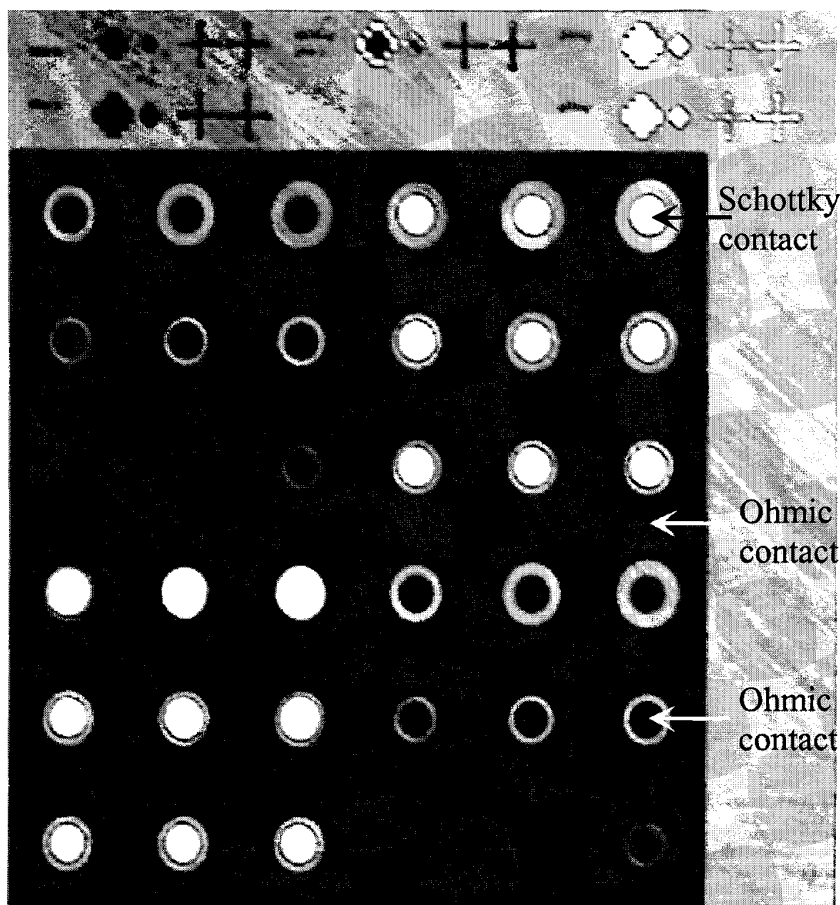


Figure 7.2: Result of circular Schottky fabrication process.

The contacts in the top right corner of this configuration enable the determination of the influence of the gap spacing on the breakdown voltage and the reverse current. Unfortunately, due to the simultaneously changing diameter and gap spacing in the case of the contacts in the bottom left corner it is not possible to determine whether the reverse current is proportional to the contact perimeter or to the contact area. In order to investigate this in future work we need to design a new mask that contains Schottky contacts with varying diameters but constant gap

spacings. Table 5 gives an overview of the dimensions of both the Schottky contacts in the top right corner and the bottom left corner.

Table 5: Overview of the dimensions of the Schottky contacts in the top right corner and the bottom left corner.

Bottom left corner			Top right corner		
Diameter (μm)	Gap spacing (μm)	Diode area (cm^2)	Diameter (μm)	Gap spacing (μm)	Diode area (cm^2)
150	5	1.8×10^{-4}	108	23	9.2×10^{-5}
140	10	1.5×10^{-4}	108	24	9.2×10^{-5}
130	15	1.3×10^{-4}	108	25	9.2×10^{-5}
120	20	1.1×10^{-4}	108	26	9.2×10^{-5}
114	23	1×10^{-4}	108	31	9.2×10^{-5}
108	26	9.2×10^{-5}	108	36	9.2×10^{-5}
106	27	8.8×10^{-5}	108	41	9.2×10^{-5}
104	28	8.5×10^{-5}	108	46	9.2×10^{-5}
102	29	8.2×10^{-5}	108	51	9.2×10^{-5}

7.5.3 Ni/Au and Ir/Au Schottky contacts

With respect to the optimization of the Schottky contacts we used a different approach as in the case of the Ohmic contacts. Instead of optimizing the metal layer stack we have chosen to focuss on the influence of the pre – metallization treatments of the already used Ni/Au = 20/200 nm Schottky contacts. From previous discussions in this thesis it has become clear that this is a very important issue to Schottky contact technology and hence it can be concluded that we have made a legitimate decision. However, we had the fortunate opportunity to obtain a sputtered Ir/Au deposition from the author ²⁾ of the article [48] in which their excellent Schottky characteristics have been reported (section 7.2). These sputtered Schottky contacts consisted of Ir/Au = 50/200 nm. Prior to the sputter deposition an O_2 plasma for 60 seconds, a diluted HCl dip (HCl : DI = 1 : 10) for 60 seconds and a rinse in DI water for 2×30 seconds have been applied to the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ surface.

²⁾ The author wishes to thank Dr. J. Würfl from the Ferdinand Braun Institut für Höchstfrequenztechnik in Berlin Germany for his very willing cooperation.

In order to investigate the influence of the pre – metallization treatments (discussed in section 7.3) on the reverse current and the breakdown voltage of the Ni/Au Schottky contacts we have processed six identical samples of our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material. The Ohmic contacts on these six samples consisted of our optimized $\text{Ti}/\text{Al}/\text{Ni}/\text{Au} = 30/180/40/150$ nm metallization scheme, which has been rapid thermal annealed at 900 °C for 30 seconds in a N_2 ambient. After that, prior to the e – beam evaporation of the $\text{Ni}/\text{Au} = 20/200$ nm metallization scheme, the following pre – metallization treatments have been applied:

- 1) no pre – metallization treatment;
- 2) undiluted HCl dip for 90 seconds;
- 3) diluted NH_4OH ($\text{NH}_4\text{OH} : \text{DI} = 1:10$) for 15 seconds;
- 4) O_2 plasma at 20 W (DC bias = - 60V) for 120 seconds;
- 5) O_2 plasma at 20 W (DC bias = - 60V) for 120 seconds followed by a dip in undiluted HCl for 90 seconds; and
- 6) O_2 plasma at 20 W (DC bias = - 60V) for 120 seconds followed by a dip in diluted NH_4OH ($\text{NH}_4\text{OH} : \text{DI} = 1:10$) for 15 seconds.

In the following subsections, the results obtained from the current – voltage ($I - V$) and the capacitance – voltage ($C - V$) measurements for both the Ni/Au and Ir/Au Schottky contacts will be described.

7.5.3.1 Current – voltage measurements

From the discussion in section 7.5.1 about the limitations with respect to the characterization of the Schottky contacts it has become clear that the forward current – voltage measurements do not yield any reliable information. Therefore, we focussed on the reverse current – voltage characteristics in order to determine the best Schottky contact metallization scheme (i.e. Ni/Au or Ir/Au) and to determine the best pre – metallization treatment for the Ni/Au Schottky contacts. Figure 7.3 shows the reverse current voltage characteristics of the Ni/Au Schottky contact to which an O_2 plasma at 20 W (DC bias = - 60V) for 120 seconds followed by a dip in undiluted HCl for 90 seconds has been applied and the Ir/Au Schottky contact with a comparable pre – metallization treatment (section 7.5.3). It has to be noted that the Ni/Au and the Ir/Au contacts have the same contact areas ($1 \times 10^{-4} \text{ cm}^2$) and the same gap spacings (23 μm).

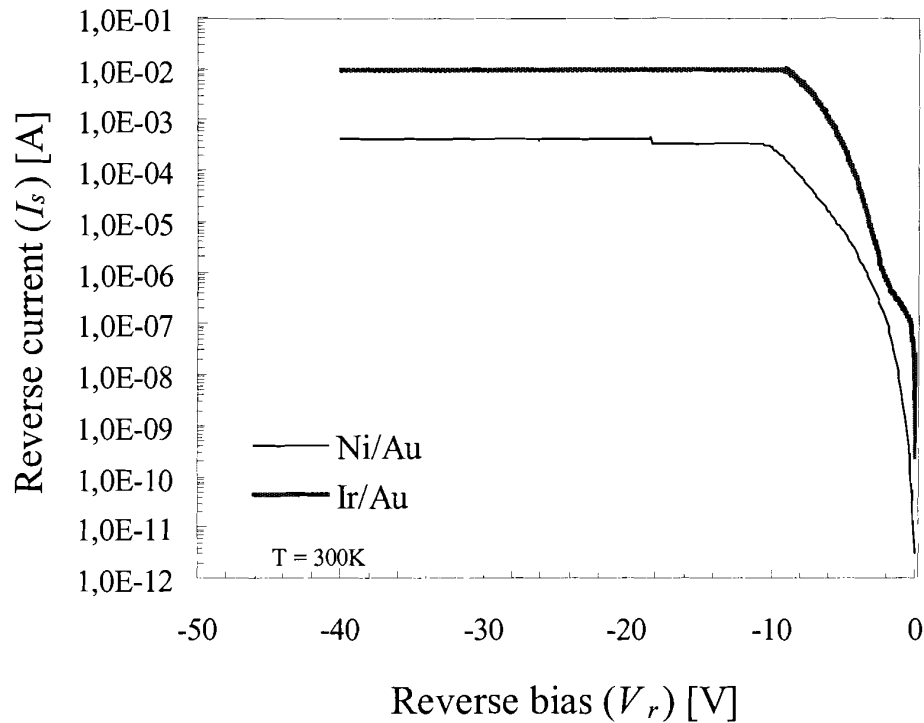


Figure 7.3: Reverse ($I - V$) characteristics of a Ni/Au Schottky contact (O_2 plasma at 20 W (DC bias = - 60V) for 120 seconds and dip in undiluted HCl for 90 seconds) and an Ir/Au Schottky contact with a comparable pre – metallization treatment. Both Schottky contacts have the same area and gap spacing.

The results shown in figure 7.3 are very surprising because of the extremely poor reverse current – voltage characteristics of the Ir/Au Schottky contacts. The breakdown voltage of these contacts is approximately - 7 V, which was completely unexpected considering the reported [48] excellent Schottky contact behavior. Unfortunately this result was reproducible over the entire sample. At this point it is difficult to provide a plausible explanation for these surprising results, but according to literature [50] the observed “bump” in the reverse characteristics of the Ir/Au contacts in the low reverse bias region could indicate the presence of thin insulator – transition layers at the interface and/or the formation of inhomogeneous metal – semiconductor contacts. Figure 7.3 also shows that the Ni/Au Schottky contacts to which an O_2 plasma at 20 W (DC bias = - 60V) for 120 seconds followed by a dip in undiluted HCl for 90 seconds has been applied, yields a reverse current of approximately 5×10^{-4} A at - 40 V. From breakdown measurements carried out using a Tektronix 577 curve tracer, the breakdown voltage has been measured to be larger than 100 V for the smallest gap spacings (5 μm).

Figure 7.4 shows the reverse current – voltage characteristics of the Ni/Au Schottky contacts to which the pre – metallization treatments as mentioned in section 7.5.3 have been applied. Again, all these contacts have the same contact areas ($1 \times 10^{-4} \text{ cm}^2$) and the same gap spacings ($23 \mu\text{m}$).

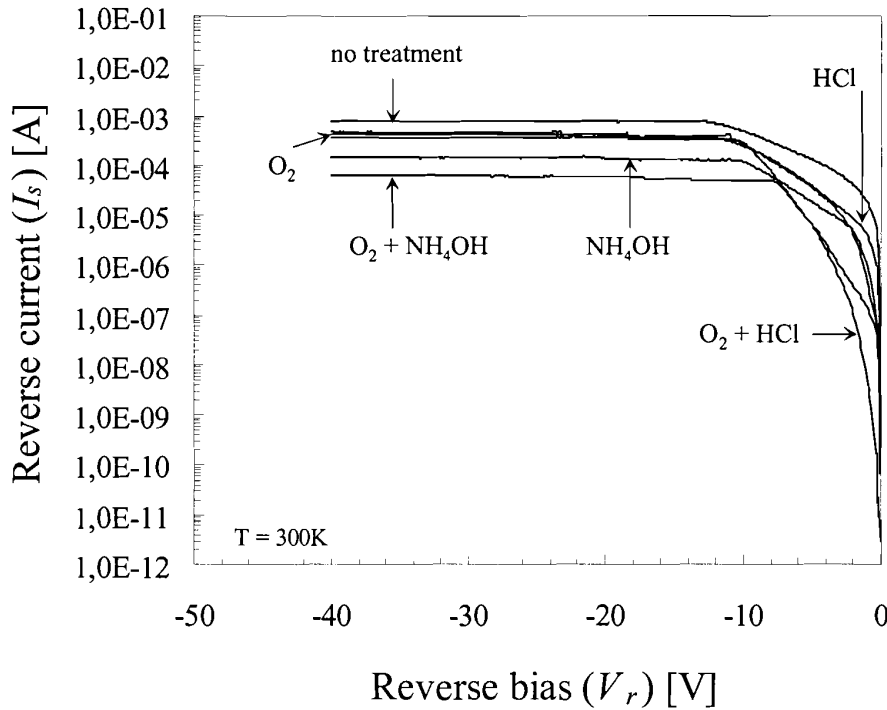


Figure 7.4: Reverse ($I - V$) characteristics of the Ni/Au Schottky contacts with the pre – metallization treatments as mentioned in section 7.5.3. All contacts have the same contact areas and same gap spacings.

From figure 7.4 it can be concluded that all the pre – metallization treatments give rise to an improvement of the reverse current of the Ni/Au Schottky contacts. The most significant improvement however is shown by those pre – metallization treatments that comprise a NH_4OH dip. The best result is obtained from the pre – metallization treatment that involves an O_2 plasma at 20 W (DC bias = - 60V) for 120 seconds followed by a dip in diluted NH_4OH ($\text{NH}_4\text{OH} : \text{DI} = 1:10$) for 15 seconds. In that case, the reverse current is approximately $6 \times 10^{-5} \text{ A}$ at - 40 V. The breakdown voltage has been measured to be larger than 100 V for the smallest gap spacing ($5 \mu\text{m}$). In order to test the reproducibility of the pre – metallization treatment that has been found to yield the best Schottky contact behavior for the used Ni/Au = 20/200 nm metallization scheme, we processed another sample using the same technological recipe. The obtained results however were very disappointing because the earlier obtained fairly good results were not obtained anymore. The Ni/Au Schottky contacts

now showed very large reverse currents and reached breakdown at approximately - 8 V already. A possible explanation for these results could be the contamination of the plasma etch system (Oxford 100), which is used to apply the O_2 plasma, as a result of etching experiments with respect to Indium Phosphide (InP). However, we have not had the opportunity to process another sample in order to verify this assumption. Hence, at this moment no statement can be made with respect to the reproducibility of the $\text{NH}_4\text{OH}/\text{O}_2$ pre – metallization treatment. It is therefore obvious that in future great emphasis should be laid on the development of an optimal pre – metallization treatment for our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructures.

In order to determine the influence of the post – metallization heat treatment on the reverse current – voltage characteristics, we have rapid thermal annealed (RTA) the Ni/Au contacts that have been treated with an diluted NH_4OH dip at 300, 400, 500 and 600 °C, respectively for 30 seconds in a N_2 ambient. The resulting reverse current – voltage characteristics are shown in figure 7.5. Note that all contacts have the same contact areas ($1 \times 10^{-4} \text{ cm}^2$) and the same gap spacings (23 μm).

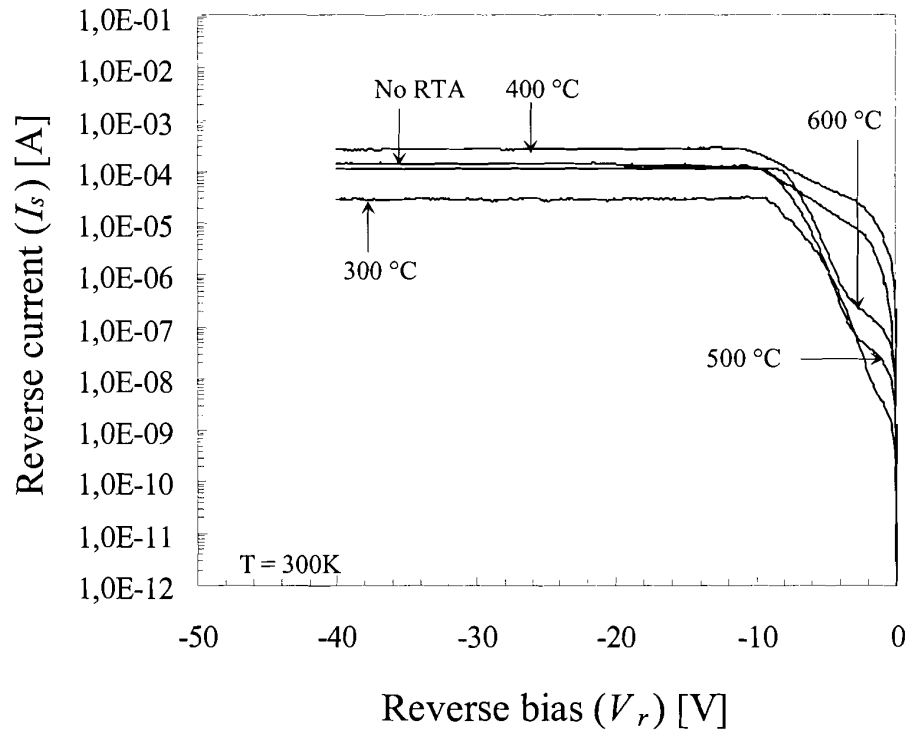


Figure 7.5: Reverse current – voltage characteristics for Ni/Au schottky contacts after RTA at 300, 400, 500 and 600 °C for 30 seconds in a N_2 ambient.

From figure 7.5 it can be concluded that the reverse current – voltage characteristics have only considerably improved for rapid thermal annealing at 300 °C for 30 seconds in a N_2 ambient. This is in good agreement with earlier reported results (section 7.4). The preliminary technological recipe for Schottky contacts on n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ is described in appendix E.

Figure 7.6 shows the reverse current – voltage characteristics of the Ni/Au Schottky contacts to which the $\text{NH}_4\text{OH}/\text{O}_2$ pre – metallization treatment has been applied. These Schottky contacts have equal contact areas of $9.2 \times 10^{-5} \text{ cm}^2$ but increasing gap spacings of 23, 24, 25, 26, 31, 36, 41, 46 and 51 μm respectively (table 5 in section 7.5.2.5). The smallest gap spacing is indicated by 1 and the largest is indicated by 9.

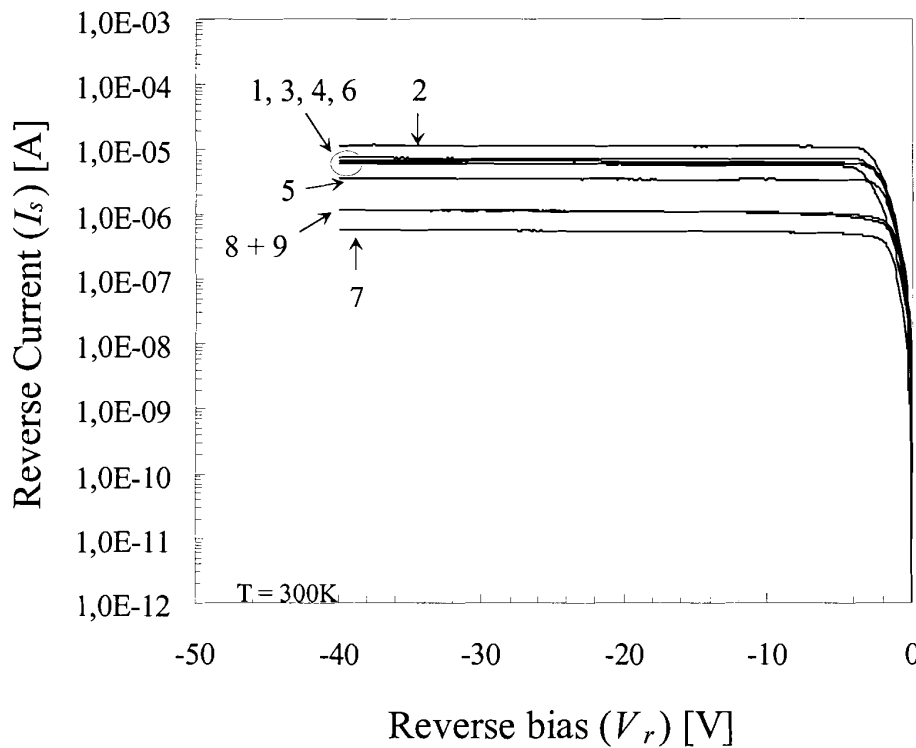


Figure 7.6: Reverse ($I - V$) characteristics of Ni/Au Schottky contacts with equal contact areas of $9.2 \times 10^{-5} \text{ cm}^2$ but with increasing gap spacings.

It is expected that the reverse current decreases with increasing gap spacing due to the larger series resistance of the semiconductor material. Figure 7.6 more or less shows this behavior but the obtained results are rather ambiguous. A possible explanation for this ambiguity could be the combination of too large uncertainties in the measurements for the smallest gap spacings and too small differences in the successive gap spacings. In order to investigate this

influence more accurately, the difference in the gap spacing on the new Schottky mask has to be much larger.

7.5.3.2 Capacitance – voltage measurements

This subsection deals with the capacitance – voltage ($C - V$) characteristics of the $\text{Ni}/\text{Au} = 20/200$ nm Schottky contacts to which the $\text{NH}_4\text{OH}/\text{O}_2$ treatment has been applied and that at this moment have shown the best results. The measurement of these characteristics has been carried out using a HP4275A multi – frequency LCR meter at a frequency of 1 MHz and the amplitude of the AC test signal was 250 mV. Figure 7.7 shows a schematical representation of the theoretical ($C - V$) characteristic for both forward and reverse bias conditions of a Schottky contact with an area of $1 \times 10^{-4} \text{ cm}^2$ and a gap spacing of $23 \mu\text{m}$. This figure also shows the measured ($C - V$) characteristic for such a Schottky contact.

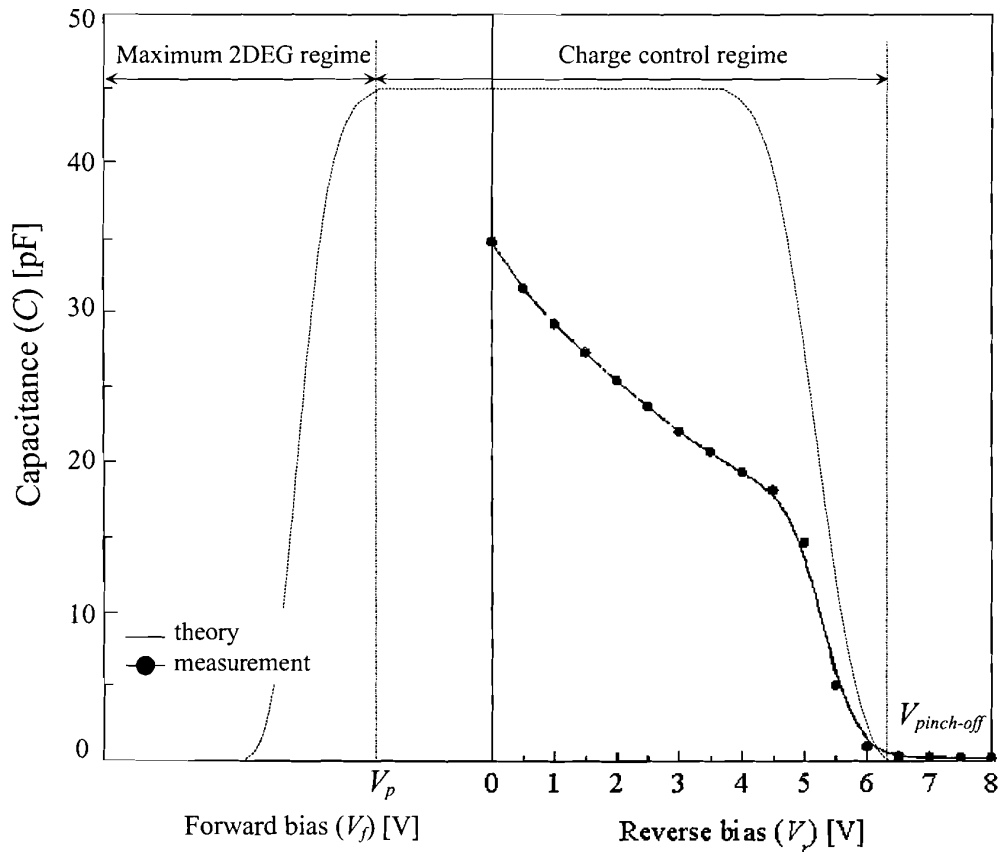


Figure 7.7: ($C - V$) characteristic of a Ni/Au Schottky contact with an area of $1 \times 10^{-4} \text{ cm}^2$ and a gap spacing of $23 \mu\text{m}$.

The forward bias voltage indicated by V_p is the voltage at which the depletion regions of the Schottky contact and the heterojunction just touch. If the forward bias is increased above V_p the two depletion regions do not overlap and the maximum 2DEG model is applicable [53]. In this case the capacitance decreases very rapidly. For bias conditions ranging from the reverse direction up to V_p the two depletion regions overlap and the charge control model applies [53]. In this case the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material is completely depleted and the thickness of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material can be calculated using the simple expression for a parallel plate capacitor using equation (6.1). Theoretically, the value of the capacitance required for this calculation is at a constant level until the 2DEG is pinched off [53, 54]. This can be seen by the sharp decrease of the capacitance for increasing reverse bias. The value of the constant capacitance can approximately be calculated using equation (6.1) and the specified thickness of the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ material which equals 18 nm (section 5.5.1). The value for the relative permittivity of the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ material can be calculated using:

$$\varepsilon_{r,\text{AlxGa}(1-x)\text{N}} = x \cdot \varepsilon_{r,\text{AlN}} + (1-x) \cdot \varepsilon_{r,\text{GaN}} \quad (7.1)$$

The values for $\varepsilon_{r,\text{AlN}}$ and $\varepsilon_{r,\text{GaN}}$ are 8.5 [28] and 9.5 [28] respectively. Hence the value for $\varepsilon_{r,\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}}$ is 9.25. Inserting these values in equation (6.1) we obtain a capacitance of 45 pF. Figure 7.7 shows that the measured ($C - V$) characteristic deviates very much from the theoretical ($C - V$) characteristic. This deviation could be due to edge effects. In literature [54] Schottky contacts have been reported that approach the theoretical ($C - V$) characteristic very well. However, these contacts have an area that is 50 times larger than our contacts. In that case these edge effects are of negligible importance. From our measurement results it is not possible to accurately calculate the thickness of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material and the sheet carrier density (n_s) of the 2DEG. However, the expression that can be used to calculate the sheet carrier density in the charge control regime is given by [53]:

$$n_s = \frac{\varepsilon_0 \cdot \varepsilon_{r,s}}{q \cdot d} \cdot (V_{gs} - V_{pinch-off}) \quad (7.2)$$

where V_{gs} is the applied voltage and d is the total thickness of the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ material. The pinch – off voltage is given by [53]:

$$V_{pinch-off} = \Phi_e - \Delta E_C - V_p \quad (7.3)$$

where

$$\Delta E_C = \chi_{\text{GaN}} - \chi_{\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}} \quad (7.4)$$

and

$$V_p = \frac{q \cdot N_d}{2 \cdot \varepsilon_0 \cdot \varepsilon_{r,s}} \cdot (d - d_s)^2 \quad (7.5)$$

The pinch – off voltage can easily be determined from figure 7.7. At this voltage no carriers are present in the channel (2DEG). In our case, the value for the pinch – off voltage is - 6.5 V. In equation (7.3), Φ_e is the effective Schottky barrier height, ΔE_C the discontinuity in the conduction bands of the GaN and $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ material and V_p is the voltage at which the both depletion regions just touch. In equation (7.4), χ_{GaN} and $\chi_{\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}}$ are the electron affinities of the GaN and $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ material respectively. In equation (7.5), N_d is the donor concentration, d the total thickness of the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ material and d_s the thickness of the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ spacer layer.

Furthermore, in literature [54] it has been reported that normalization of the $(C - V)$ characteristics allows an immediate qualitative assessment of the material. The normalized $(C - V)$ characteristics of good quality material overlay. Figure 7.8 shows the $(C - V)$ characteristics after normalization for the contact area of two Ni/Au Schottky contacts with gap spacings of 23 μm and contact areas of $1 \times 10^{-4} \text{ cm}^2$ and $9.2 \times 10^{-5} \text{ cm}^2$, respectively.

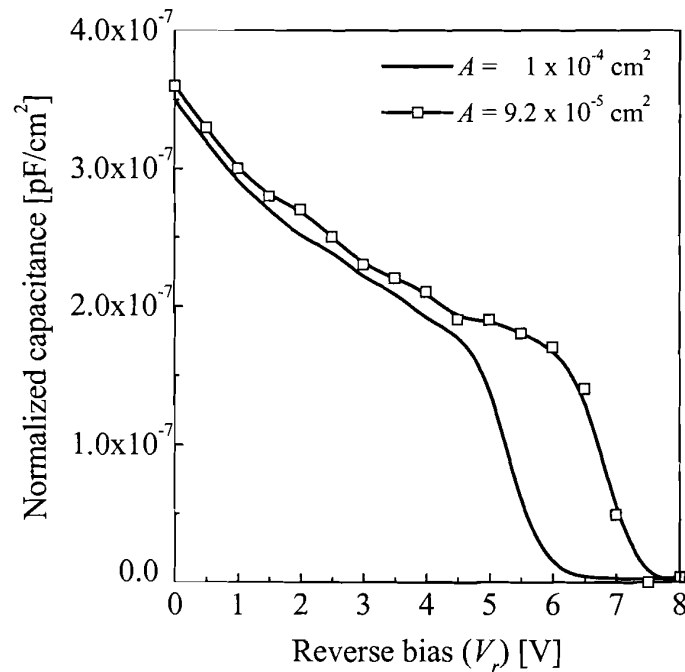


Figure 7.8: Normalized $(C - V)$ characteristics of two Schottky contacts with gap spacings of 23 μm and contact areas of $1 \times 10^{-4} \text{ cm}^2$ and $9.2 \times 10^{-5} \text{ cm}^2$, respectively.

Figure 7.8 shows that in the first part of the characteristic the normalized $(C - V)$ curves overlay reasonably well. In the second part however, there is a great disparity between them. The cause of this disparity is not very obvious yet, but it could perhaps be found if also forward $(C - V)$ measurements are carried out. In that case it would be possible to calculate

the amount of charge in the channel (2DEG). The observed disparity could indicate a difference in these amounts of charge, but at this moment this is only speculative.

7.6 Conclusions and recommendations

This section provides the preliminary conclusions for the fabrication of Schottky contacts on $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material and some recommendations for future investigations.

7.6.1 Conclusions

It has been discussed that Ir/Au Schottky contacts are reported [48] to show superior electrical Schottky behavior compared to Ni/Au Schottky contacts on n – type $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructures. However, preliminary experiments with respect to these Ir/Au contacts on our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material have not confirmed this reported behavior. At this moment, the reasons for these disappointing results have not been clarified yet.

It has been discussed that pre – metallization treatments of the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ material are extremely important in order to obtain reliable electrical characteristics of the Schottky contacts. The influences of plasma enhanced cleaning and wet chemical etching of the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ surface, in order to render it stable and reproducible, have been discussed. From this discussion it can be concluded that induced damage to the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ surface has to be avoided as much as possible. Furthermore, the influence of a post – metallization heat treatment of the Schottky contacts has been considered. In literature [18] it is stated that Schottky contacts should first be properly aged before reliable values for the Schottky contact parameters can be obtained.

The limitations that arise from our choice to do the optimization of the Schottky contacts on identical $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material as is used for the fabrication of the HEMTs have been discussed. We have tried to circumvent these problems by focussing on the reverse current (I_s) and the breakdown voltage (V_{break}) in order to indicate the quality of our Ni/Au Schottky contacts.

Despite the great functionality of the designed circular Schottky mask, it unfortunately does not allow to determine whether the reverse current is proportional to the contact perimeter or to the contact area.

Our preliminary experiments towards the determination of the optimal pre – metallization treatments, have at this moment resulted in the application of an O_2 plasma at 20 W (DC bias of - 60 V) for 2 minutes which is followed by a dip in diluted NH_4OH ($\text{NH}_4\text{OH} : \text{DI} = 1 : 10$) for 15 seconds. The effect of the post – metallization heat treatment on the reverse current – voltage characteristics has been observed most clearly after rapid thermal annealing (RTA) at 300 °C for 30 seconds in a N_2 ambient. Our preliminary technological recipe for Ni/Au Schottky contacts on $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ is described in appendix E.

From the capacitance – voltage measurements it has become clear that in the case of small area Schottky contacts most probably edge effects are responsible for the large disparity between the theoretical and measured ($C - V$) characteristics. In addition, forward capacitance – voltage measurements are required to calculate the amount of charge in the channel (2DEG). Knowledge of this amount of charge could possibly explain the observed disparity between the normalized capacitance – voltage characteristics.

7.6.2 Recommendations

We are convinced that future investigations with respect to the optimization of the Schottky contact fabrication process on n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material should first focus on the optimization of the pre – metallization treatments. In particular, the “warm” (50 °C) NH_4OH treatment should be investigated. It is important to investigate first if the used photoresist (AZ5214) can withstand “warm” NH_4OH and for how long. After the optimization of the pre – metallization treatments we can focus on the optimization of the metallization scheme.

The causes of the unexpected very poor results of the sputtered Ir/Au Schottky contacts to our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material have to be found. Therefore, we will contact the group of Dr. Joachim Würfl at the Ferdinand Braun Institut für Höchstfrequenztechnik in Berlin (Germany) where these Ir/Au contacts have been fabricated.

We have to design a new Schottky mask that contains contacts with varying areas but constant gap spacings. Then we are able to determine whether the reverse current is proportional to the contact perimeter or the contact area. In addition, this mask should contain contacts with the same contact areas but with increasing gap spacings that differ considerably (e.g. multiple of 25 μm). This is required for a more accurate determination of the influence of the gap spacing on the reverse current – voltage characteristics.

Finally, with respect to the capacitance – voltage measurements it has to be noted that in future investigations forward ($C - V$) measurements have to be carried out in order to determine the amount of charge in the channel. Furthermore, radio frequency (RF) capacitance measurements up to 40 GHz have to be done in order to determine the behavior of the Schottky contacts at these frequencies. In addition, it is possible to extract an RF equivalent model for the Schottky contacts from these measurements.

CHAPTER 8

Conclusions and Recommendations

This chapter presents the most important conclusions that can be drawn from our work. Furthermore, recommendations are provided for future investigations.

8.1 Conclusions

In chapter 3 it has been shown that the presence of an interfacial layer and an infinitely large density of surface states can cause pinning of the Fermi level in the semiconductor. As a result, the barrier height is essentially independent of the metal work function. Furthermore, it has been discussed that Fermi level pinning in the case of the GaN – based materials systems is of minor importance and that the major contribution to the Schottky barrier height is due to the difference in the metal and semiconductor work functions. Hence, metals with a low work function e.g. Titanium (Ti) and Aluminum (Al) are used for Ohmic contacts on n – type GaN – based materials systems. To obtain Schottky contacts on n – type GaN – based materials systems metals with a high work function e.g. Platinum (Pt), Nickel (Ni), Gold (Au), Iridium (Ir) and Palladium (Pd) are used.

It has also been shown that an interfacial layer and surface states render the Schottky barrier bias dependent. As a result the ideality factor will significantly deviate from unity. It is obvious that for the fabrication of high quality metal – semiconductor contacts the influence of an interfacial layer and an infinitely large density of surface states should be minimized. The most effective way to do this is of course the complete removal of a surface layer and surface states from the semiconductor material prior to metallization. However, this will almost be impossible due to practical matters such as the impossibility to work in an oxygen – free environment. However, it should be tried to fabricate Schottky contacts with an ideality factor (n) that approaches unity as nearly as possible because in that case the reverse current (I_s) will be minimized and the breakdown voltage (V_{break}) will be maximized and the Schottky contacts can be applied in high power devices.

Chapter 4 showed that almost all practical Ohmic contacts are tunnel contacts that depend on the presence of a thin layer of highly doped (degenerate) semiconductor material near the metal – semiconductor interface. This highly doped (degenerate) region may be formed by diffusion techniques, ion implantation or a heat treatment of the deposited metallization scheme which renders the semiconductor material to be highly doped. In this case, the depletion region is so thin that field emission (FE) takes place and the contact has a very low resistance at zero bias. Furthermore, it has been shown that the most important Ohmic contact parameter is the specific contact resistance (ρ_c). It provides the most systematic way to compare different metallization schemes with respect to contact resistance. This parameter can however not be measured but has to be calculated from the measured Ohmic contact parameters such as the contact resistance (R_c), the transfer length (L_t) and the sheet resistance (R_{sh}). In order to determine these Ohmic contact parameters from experiments, several sophisticated test structures have been developed of which the transfer length method (TLM) is the most commonly used. We have considered the two configurations (LTLM and CTLM, respectively) that are commonly used to implement the transfer length method. It has been discussed that the CTLM configuration has considerable advantages over the LTLM configuration with respect to fabrication issues (no need to etch mesas) and with respect to the accuracy of the obtained measurement results (no induced errors due to the current crowding effect). For both an LTLM and CTLM configuration, the Ohmic contact parameters can be calculated using the derived equations.

Chapter 5 was concerned with the optimization of the Ohmic contact fabrication process on the n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure that has been described in section 5.5.1. Our optimized fabrication process consists of a $\text{Ti}/\text{Al}/\text{Ni}/\text{Au} = 30/180/40/150$ nm metallization scheme, which is e-beam evaporated at a base pressure of typically $10^{-7} - 10^{-8}$ mbar without any pre – metallization treatments. After an RTA process at 900 °C for 30 seconds in a N_2 ambient, the resulting values for the contact resistance R_c and the corresponding specific contact resistance ρ_c are 0.2 Ωmm and $7.3 \times 10^{-7} \Omega\text{cm}^2$, respectively with a sheet resistance R_{sh} of 500 – 600 Ω/sq . Comparing our values for R_c and ρ_c with those reported in literature [27, 29], it can be concluded that our optimized Ohmic contact on n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructures is among the best in the world. The technological recipe is described in appendix C. Furthermore, we are convinced that our systematic approach of the optimization procedure has resulted in an Ohmic contact with as low as possible values for R_c and ρ_c . The Al/Ti thickness ratio of 6 that we use in the optimized metal layer stack, is however in contrast with the in literature proposed theoretical model [25] for Ohmic contact formation of Ti/Al – based metallization schemes on $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material. It is obvious that in our case the proposed theoretical model does not apply.

The calculation of the values for R_c and ρ_c from the experimental results for the total resistance as a function of the gap spacing using a CTLM configuration can be done in two ways. The first way is to apply a linear approximation to the experimental CTLM results, which requires the use of correction factors that account for the changing circular contact geometry. After this linear approximation the calculations can be carried out using the equations known from the LTLM configuration. The second way is to fit the exact expression for the total resistance $R_{T,circ}$ (equation (5.4)) to the experimental CTLM results. From our experiments it can be concluded that the values for R_c and ρ_c can be determined with a margin of error of only 5 %. It should be noted that the choice of the starting values in the case of our fitting procedure using MATLAB routines does not influence the fit results. Furthermore, from our experiments it can be concluded that both calculation methods are suitable to determine the values for R_c and ρ_c .

It can be concluded that the accuracy with which the values for R_c and ρ_c can be calculated from the linear approximation of the experimental CTLM results and the fitting procedure of the exact expression for $R_{T,circ}$ depends very heavily on the accuracy with which the values of the gap spacings s , the transfer length L_t and $R_{T,circ}$ can be determined. The latter depends among others on the used measurement technique and the calibration of the measurement setup. Using a four – point probe measurement technique, the probe resistance can be neglected and reliable values for $R_{T,circ}$ can be obtained. In order to accurately determine the value for L_t and hence to accurately calculate the value for ρ_c , the end resistance R_E of the transmission line that is used to model the metal contact can be measured. However, due to the used CTLM configuration used in our experiments (Marlow and Das [21]) it was not possible to perform an end resistance measurement.

Reproducibility of the Ohmic contact fabrication process and its results is extremely important for a reliable implementation in the HEMT fabrication process. Literature [38] showed that the variations in the values for R_c and ρ_c can be explained by variations in the values of the sheet resistance R_{sh} . These variations in R_{sh} are due to both a varying Al mole fraction within the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer and a varying thickness of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer. Therefore, only values for R_c and ρ_c that are obtained from samples with comparable values for R_{sh} should be compared. In that case, the values for R_c and ρ_c of our optimized Ohmic contacts showed a very good reproducibility as they were within 10 %. Furthermore, from our experiments it can be concluded that contamination of the metals of an e-beam evaporator or of the system as a whole can seriously affect the reproducibility of the obtained results.

Chapter 5 also shows that comparison of the theoretical values for ρ_c and the experimentally determined values for ρ_c differ over many orders of magnitude. This discrepancy is largely due to the used value for the Richardson constant (A^*), which in literature [37] is reported to have a theoretical value of approximately $26.4 \text{ Acm}^{-2}\text{K}^{-2}$. In practice however, it can vary over many orders of magnitude. In order to fairly compare the theoretical and experimental values for ρ_c it is necessary to experimentally determine the value of A^* for the used $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ material. This can be done by a temperature dependent current – voltage (I - V - T) measurement using e.g. a Norde plot. We do not have a measurement setup to perform such measurements and hence we can only use the theoretical value for A^* .

The maximum current density of our optimized Ohmic contacts is of importance for the application in high power devices. If we compare our value of 637 mA/mm to the values reported in literature [27, 40] for similar structures, our value is rather low. However, we do not think that the Ohmic contacts severely limit the maximum current density considering the low values of their R_c and ρ_c .

In addition, our Ohmic contacts have shown a very good line definition and a nice surface morphology despite the high post – metallization rapid thermal annealing (RTA) temperature of 900 °C. As the Ohmic contacts are used as the drain and source contacts in the HEMT a good line definition and surface morphology are required among others for the positioning of the gate contact between the drain and source contacts. Furthermore, this is also important with respect to the alignment marks that are needed for the alignment of the Schottky contacts. If the line definition of these marks is very bad, it is impossible to use them for an accurate alignment of the Schottky contacts.

In chapter 6 it has been pointed out that for the application of the Schottky contacts in high power devices high breakdown voltages (V_{break}) and low reverse currents (I_s) are required. Furthermore, it has been discussed that the breakdown voltage and the reverse current of practical Schottky contacts are affected among others by the presence of an interfacial layer and surface states. In addition, it has been reported in literature [37, 43, 45] that the values for the effective barrier height (Φ_e) derived by the (C - V) method are generally higher than those derived by the (I - V) method. This discrepancy of the experimental results between the different methods may among others result from the Schottky effect, the presence of a thin interfacial layer and surface states, contamination in the interface and deep impurity levels acting as electron traps [15, 16, 43].

In chapter 7 it has been discussed that pre – metallization treatments of the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ material are extremely important in order to obtain reliable electrical characteristics of the Schottky contacts. The influences of plasma enhanced cleaning and wet chemical etching of the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ surface, in order to render it stable and reproducible, have been discussed. From this discussion it can be concluded that induced damage to the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ surface has to be avoided as much as possible. Furthermore, the influence of a post – metallization heat treatment of the Schottky contacts has been considered. In literature [18] it is stated that Schottky contacts should first be properly aged before reliable values for the Schottky contact parameters can be obtained.

Our preliminary experiments towards the determination of the optimal pre – metallization treatments, have at this moment resulted in the application of an O_2 plasma at 20 W (DC bias of - 60 V) for 2 minutes which is followed by a dip in diluted NH_4OH ($\text{NH}_4\text{OH} : \text{DI} = 1 : 10$) for 15 seconds. The effect of the post – metallization heat treatment on the reverse current – voltage characteristics has been observed most clearly after rapid thermal annealing (RTA) at 300 °C for 30 seconds in a N_2 ambient. Our preliminary technological recipe for Ni/Au Schottky contacts on $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ is described in appendix E.

It has been discussed that Ir/Au Schottky contacts are reported [48] to show superior electrical Schottky behavior compared to Ni/Au Schottky contacts on n – type $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructures. However, preliminary experiments with respect to these Ir/Au contacts on our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material have not confirmed this reported behavior. At this moment, the reasons for these disappointing results have not been clarified yet.

The limitations that arise from our choice to do the optimization of the Schottky contacts on identical $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material as is used for the fabrication of the HEMTs have been discussed. We have tried to circumvent these problems by focussing on the reverse current (I_s) and the breakdown voltage (V_{break}) in order to indicate the quality of our Ni/Au Schottky contacts.

Despite the great functionality of the designed circular Schottky mask, it unfortunately does not allow to determine whether the reverse current is proportional to the contact perimeter or to the contact area.

From the capacitance – voltage measurements it has become clear that in the case of small area Schottky contacts most probably edge effects are responsible for the large disparity between the theoretical and measured ($C - V$) characteristics. In addition, forward capacitance – voltage measurements are required to calculate the amount of charge in the

channel (2DEG). Knowledge of this amount of charge could possibly explain the observed disparity between the normalized capacitance – voltage characteristics.

8.2 Recommendations

With respect to the accuracy of the calculations of the Ohmic contact parameters and in particular of the contact resistance R_c and the specific contact resistance ρ_c , it is very important to accurately measure the gap spacings of the fabricated TLM test structures. Due to the inaccuracy induced by the fabrication process these values can differ from the values for the gap spacings specified on the mask.

Due to limited time we have not done an end resistance measurement on the CTLM test structure proposed by Rechid and Heime [22] in order to accurately determine the value for L_t from experiments. In future investigations this should be tried as the required CTLM test structures are available on our CTLM mask.

The high background noise that results from the nitrogen originating from the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ layer renders secondary ion mass spectroscopy (SIMS) and X – ray photo – electron spectroscopy (XPS) not suitable to provide an unambiguous composition of the layers at the metal – semiconductor interface of our optimized Ti/Al/Ni/Au Ohmic contact and the used $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material. In the future, transmission electron microscopy (TEM) or high resolution electron microscopy (HREM) could be tried to perform such a physical characterization in order to propose a model for the Ohmic contact formation because in our case the theoretical model [25] proposed in literature does not apply.

The e-beam evaporators should be regularly cleaned in order to prevent contamination of the metals and of the system as a whole. From our experiments it can be concluded that such a contamination can seriously affect the reproducibility of the obtained results.

A measurement setup should be created that enables the measurement of temperature dependent current – voltage characteristics (I - V - T) on wafer. Then it would be possible to determine a practical value for the Richardson constant A^* of the used $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material.

We are convinced that future investigations with respect to the optimization of the Schottky contact fabrication process on n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material should first focus on the optimization of the pre – metallization treatments. In particular, the “warm” (50 °C) NH_4OH treatment should be investigated. It is important to investigate first if the used photoresist

(AZ5214) can withstand “warm” NH_4OH and for how long. After the optimization of the pre – metallization treatments we can focus on the optimization of the metallization scheme.

The causes of the unexpected very poor results of the sputtered Ir/Au Schottky contacts to our $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ material have to be found. Therefore, we will contact the group of Dr. Joachim Würfl at the Ferdinand Braun Institut für Höchstfrequenztechnik in Berlin (Germany) where these Ir/Au contacts have been fabricated.

We have to design a new Schottky mask that contains contacts with varying areas but constant gap spacings. Then we are able to determine whether the reverse current is proportional to the contact perimeter or the contact area. In addition, this mask should contain contacts with the same contact areas but with increasing gap spacings that differ considerably (e.g. multiple of $25\text{ }\mu\text{m}$). This is required for a more accurate determination of the influence of the gap spacing on the reverse current – voltage characteristics.

Finally, with respect to the capacitance – voltage measurements it has to be noted that in future investigations forward ($C - V$) measurements have to be carried out in order to determine the amount of charge in the channel. Furthermore, radio frequency (RF) capacitance measurements up to 40 GHz have to be done in order to determine the behavior of the Schottky contacts at these frequencies. In addition, it is possible to extract an RF equivalent circuit for the Schottky contacts from these measurements.

Appendices

Appendix A

Derivation of the resistance of an annular contact

This appendix is concerned with the derivation of the resistance of an annular contact as shown in figure 4.7. For convenience this figure is repeated in figure A.1. The results of this derivation enable us to calculate the total resistance ($R_{T,circ}$) of any circular contact configuration. As mentioned in section 4.3.2, this derivation will not be based on the nonuniform transmission line model of the planar circular metal – semiconductor contact according to Reeves [20]. Instead, the starting point will be a two – dimensional current continuity equation according to Cohen [18].

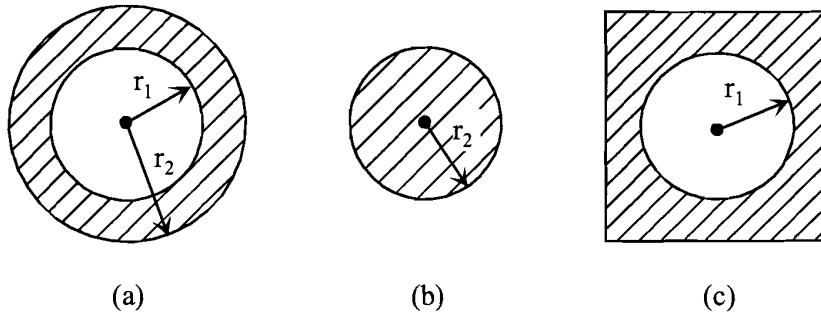


Figure A.1: Annular metal – semiconductor contacts. (a) General case, (b) $r_1 = 0$, and (c) $r_2 \rightarrow \infty$ [18].

Figure A.2 shows a schematic representation of a piece of semiconductor material beneath a metal contact. A resistance R characterizes the metal – semiconductor transition and is given by:

$$R = \frac{\rho \cdot l}{A} = \frac{\rho \cdot l}{dx \cdot dy} \quad (\text{A.1})$$

where ρ is the specific resistivity of this transition region, l its thickness and $dx \cdot dy$ its area. If we define $\rho_c = \rho \cdot l$ to be the specific contact resistance, equation (A.1) can be written like:

$$R = \frac{\rho_c}{dx \cdot dy} \quad (\text{A.2})$$

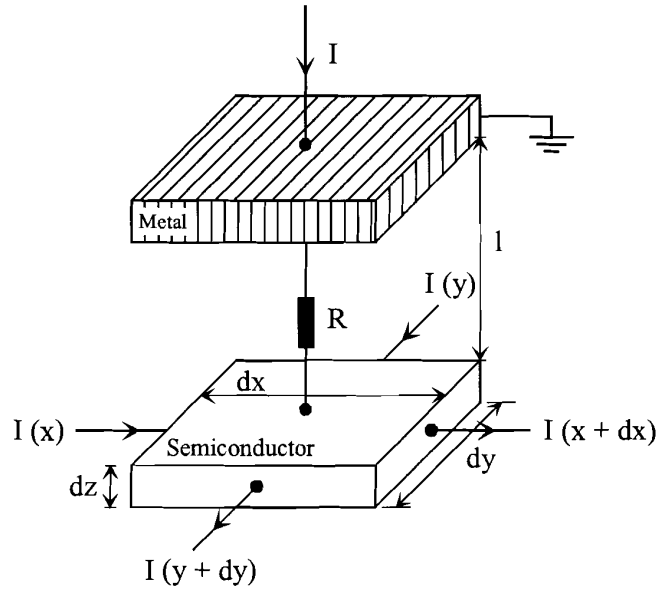


Figure A.2: Schematic representation of a piece of semiconductor material beneath a metal contact.

The metal contact is assumed to be grounded and the potential in the semiconductor material is considered to be two – dimensional, i.e. $V = V(x,y)$. In that case, the current I shown in figure A.2 is given by:

$$I = \frac{-V(x,y)}{R} = \frac{-V(x,y) \cdot dx \cdot dy}{\rho_c} \quad (\text{A.3})$$

Applying Kirchhoff's two – dimensional current continuity equation to the piece of semiconductor material gives:

$$\nabla_2 \vec{I}_2 = I \quad (\text{A.4})$$

or

$$I(x+dx) - I(x) + I(y+dy) - I(y) = I \quad (\text{A.5})$$

where $\vec{I}_2$ in equation (A.4) denotes the two – dimensional current in the semiconductor material beneath the metal contact and $\nabla_2 = \hat{x}(\partial/\partial x) + \hat{y}(\partial/\partial y)$. In terms of current densities equations (A.3) and (A.5) can be written like:

$$J = \frac{I}{dx \cdot dy} = \frac{-V(x,y)}{\rho_c} \quad (\text{A.6})$$

respectively,

$$\{J(x+dx) - J(x)\} \cdot dy \cdot dz + \{J(y+dy) - J(y)\} \cdot dx \cdot dz = J \cdot dx \cdot dy \quad (\text{A.7})$$

Using the relationship $J_2 = \sigma \cdot E(x, y) = -1/\rho \cdot \nabla_2 V(x, y)$, the combination of the equations (A.6) and (A.7) after elimination of $dx \cdot dy$ yields:

$$dz \cdot \nabla_2 \left(-\frac{1}{\rho} \nabla_2 V(x, y) \right) = \frac{-V(x, y)}{\rho_c} \quad (\text{A.8})$$

The two – dimensional differential equation that results from equation (A.8) is given by:

$$\frac{dz}{\rho} \nabla_2^2 V(x, y) - \frac{V(x, y)}{\rho_c} = 0 \quad (\text{A.9})$$

According to the definition for the sheet resistance given by equation (4.7), $R_{sh,c}$ in the configuration of figure A.2 is given by:

$$R_{sh,c} = \frac{\rho}{dz} \quad (\text{A.10})$$

Hence, the two – dimensional differential equation can be written as:

$$\nabla_2^2 V(x, y) - \frac{R_{sh,c}}{\rho_c} V(x, y) = 0 \quad (\text{A.11})$$

Using the definition for the transfer length given by equation (4.17), equation (A.11) becomes:

$$\nabla_2^2 V(x, y) - k^2 V(x, y) = 0$$

where

$$k = \frac{1}{L_t} \quad (\text{A.12})$$

Equation (A.12) is valid regardless of the shape of the contact area. For a one – dimensional current flow in the rectangular contact of width W_c it coincides with the differential equation for the linear TLM given by equation (4.15). For an annular contact as shown in figure A.1a with a radial current flow, it is more convenient to rewrite equation (A.12) in polar coordinates:

$$\frac{d^2 V(r)}{dr^2} + \frac{1}{r} \frac{dV(r)}{dr} - k^2 V(r) = 0 \quad (\text{A.13})$$

A general solution of equation (A.13) is expressed in terms of the zero – order modified Bessel functions of the first (I_0) and second (K_0) kind described in appendix B:

$$V(r) = C_1 I_0(kr) + C_2 K_0(kr) \quad (\text{A.14})$$

According to the relationship $J_2 = -1/R_{sh,c} \cdot \nabla_2 V(x, y) \hat{=} -1/R_{sh,c} \cdot dV(r)/dr$ (in polar coordinates), the corresponding two – dimensional current density is given by:

$$J_2 = -\left(\frac{k}{R_{sh,c}}\right) [C_1 I_1(kr) - C_2 K_1(kr)] \quad (A.15)$$

where I_1 and K_1 denote the modified Bessel functions of the first order.

First the current flow into the inner circumference of the contact area is considered. In this case, the current continuity at the outer edge of the contact region requires:

$$J_2(r_2) = 0$$

or

$$C_2 = C_1 \left[\frac{I_1(kr_2)}{K_1(kr_2)} \right] \quad (A.16)$$

Then, the contact resistance defined as:

$$R_c^{inner}(r_1, r_2) = \frac{V(r_1)}{2\pi r_1 J_2(r_1)} \quad (A.17)$$

can be obtained by combining equations (A.14), (A.15) and (A.16):

$$R_c^{inner}(r_1, r_2) = \frac{R_{sh,c}}{2\pi k r_1} \left[\frac{K_1(kr_2)I_0(kr_1) + I_1(kr_2)K_0(kr_1)}{K_1(kr_1)I_1(kr_2) - K_1(kr_2)I_1(kr_1)} \right] \quad (A.18)$$

When the current is directed into the outer circumference of the contact, the current continuity at the inner radius of the contact region requires:

$$J_2(r_1) = 0$$

or

$$C_2 = C_1 \left[\frac{I_1(kr_1)}{K_1(kr_2)} \right] \quad (A.19)$$

The contact resistance defined as:

$$R_c^{outer}(r_1, r_2) = \frac{V(r_2)}{2\pi r_2 J_2(r_2)} \quad (A.20)$$

can be determined by combining equations (A.14), (A.15) and (A.19):

$$R_c^{outer}(r_1, r_2) = \frac{R_{sh,c}}{2\pi k r_2} \left[\frac{I_0(kr_2)K_1(kr_1) + I_1(kr_1)K_0(kr_2)}{I_1(kr_2)K_1(kr_1) - I_1(kr_1)K_1(kr_2)} \right] \quad (A.21)$$

In the case of the circular contact ($r_1 = 0$) shown in figure A.1b, $C_2 = 0$ (otherwise $V(r) \rightarrow \infty$ for $r \rightarrow 0$) and:

$$R_c^{outer}(0, r_2) = \frac{R_{sh,c}}{2\pi k r_2} \frac{I_0(kr_2)}{I_1(kr_2)} \quad (A.22)$$

Similarly, in the case of $r_2 \rightarrow \infty$ shown in figure A.1c, $C_1 = 0$ (otherwise $V(r) \rightarrow \infty$ for $r \rightarrow \infty$) and:

$$R_c^{inner}(r_1, \infty) = \frac{R_{sh,c}}{2\pi k r_1} \frac{K_0(kr_1)}{K_1(kr_1)} \quad (A.23)$$

It has to be noted that the equations (A.22) and (A.23) can be obtained as limiting cases of equations (A.18) and (A.21). If we for example consider the circular test structure proposed by Marlow and Das [21], shown in figure 4.6b, the total resistance ($R_{T,circ}$) can be written as:

$$R_{T,circ} = R_{gap} + R_c^{outer}(0, R_0) + R_c^{inner}(R_1, \infty) \quad (A.24)$$

where R_{gap} denotes the resistance of the semiconductor material in the gap between the inner and outer contacts and the last two terms are given by equations (A.22) and (A.23), respectively. The expression for R_{gap} can be derived as follows: consider the configuration of figure A.1a and now assume that the dashed region represents the semiconductor material in the gap and that the white regions represent the metal. Applying Kirchhoff's current continuity equation to the semiconductor material in the gap yields:

$$J(r = r_1) \cdot 2 \cdot \pi \cdot r_1 \cdot dz = I_{gap} = J(r = r_2) \cdot 2 \cdot \pi \cdot r_2 \cdot dz \quad (A.25)$$

where $J(r = r_1)$ and $J(r = r_2)$ are the current densities that leave and enter the metal at $r = r_1$ and $r = r_2$ respectively. The terms $2\pi r_1 dz$ and $2\pi r_2 dz$ represent the areas through which the current densities leave and enter respectively. Using the relationships $\vec{J} = \sigma \cdot \vec{E} = -\sigma \cdot \vec{\nabla} V$ and $\vec{\nabla} \cdot \vec{J} = 0$, this yields $-\sigma \cdot \vec{\nabla}^2 V = 0$. In polar coordinates this results in the following differential equation:

$$\frac{d^2 V(r)}{dr^2} + \frac{1}{r} \frac{dV(r)}{dr} = 0 \quad (A.26)$$

$$\frac{d^2V(r)}{dr^2} = -\frac{1}{r} \frac{dV(r)}{dr} \quad (\text{A.27})$$

After substitution of $y = \frac{dV(r)}{dr}$ equation (A.27) becomes:

$$\frac{dy}{dr} = -\frac{1}{r} \cdot y \quad (\text{A.28})$$

$$\frac{1}{y} \cdot dy = -\frac{1}{r} \cdot dr \quad (\text{A.29})$$

$$\ln(y) = -\ln(r) \quad (\text{A.30})$$

$$y = \frac{1}{r} \quad (\text{A.31})$$

Substitution of equation (A.31) in $y = \frac{dV(r)}{dr}$ gives:

$$\frac{1}{r} = \frac{dV(r)}{dr} \quad (\text{A.32})$$

The general solution of this simple differential equation is given by:

$$V(r) = C_0 \cdot \ln(r) \quad (\text{A.33})$$

The constant C_0 can be determined using the boundary condition given by equation (A.25) and the relationship $\vec{J} = -\sigma \cdot \vec{\nabla} V = -\frac{\sigma \cdot C_0}{r}$. Hence, C_0 is equal to:

$$\begin{aligned} -\frac{\sigma \cdot C_0}{r_1} \cdot 2 \cdot \pi \cdot r_1 \cdot dz &= I_{gap} \\ C_0 &= \frac{-I_{gap}}{2 \cdot \pi \cdot \sigma \cdot dz} \end{aligned} \quad (\text{A.34})$$

Using equation (A.10), equation (A.34) can be written as follows:

$$C_0 = \frac{-I_{gap} \cdot R_{sh,c}}{2\pi} \quad (\text{A.35})$$

The potential difference across the gap is given by:

$$\begin{aligned}
 V_{gap} &= V(r = r_1) - V(r = r_2) \\
 &= \frac{-I_{gap} \cdot R_{sh,c}}{2\pi} \ln(r_1) - \frac{-I_{gap} \cdot R_{sh,c}}{2\pi} \ln(r_2) \\
 &= \frac{-I_{gap} \cdot R_{sh,c}}{2\pi} \ln\left(\frac{r_1}{r_2}\right) \\
 &= \frac{I_{gap} \cdot R_{sh,c}}{2\pi} \ln\left(\frac{r_2}{r_1}\right)
 \end{aligned} \tag{A.36}$$

Hence, R_{gap} is given by:

$$R_{gap} = \frac{V_{gap}}{I_{gap}} = \frac{R_{sh,c}}{2\pi} \ln\left(\frac{r_2}{r_1}\right) \tag{A.37}$$

In the case of the test structure proposed by Marlow and Das [21], equation (A.37) can be written as:

$$R_{gap} = \frac{R_{sh,c}}{2\pi} \ln\left(\frac{R_1}{R_0}\right) \tag{A.38}$$

The exact expression for $R_{T,circ}$ is then given by:

$$\begin{aligned}
 R_{T,circ} &= \frac{R_{sh}}{2\pi} \ln\left(\frac{R_1}{R_0}\right) + \frac{R_{sh,c} \cdot L_t}{2\pi R_0} \frac{I_0\left(\frac{R_0}{L_t}\right)}{I_1\left(\frac{R_0}{L_t}\right)} + \frac{R_{sh,c} \cdot L_t}{2\pi R_1} \frac{K_0\left(\frac{R_1}{L_t}\right)}{K_1\left(\frac{R_1}{L_t}\right)} \\
 &= \frac{R_{sh} \cdot R_{sh,c}}{2\pi} \left[\frac{1}{R_{sh,c}} \ln\left(\frac{R_1}{R_0}\right) + \frac{L_t}{R_{sh} \cdot R_0} \frac{I_0\left(\frac{R_0}{L_t}\right)}{I_1\left(\frac{R_0}{L_t}\right)} + \frac{L_t}{R_{sh} \cdot R_1} \frac{K_0\left(\frac{R_1}{L_t}\right)}{K_1\left(\frac{R_1}{L_t}\right)} \right]
 \end{aligned} \tag{A.39}$$

If further is assumed that $R_{sh} = R_{sh,c}$, we find:

$$R_{T,circ} = \frac{R_{sh}}{2\pi} \left[\ln\left(\frac{R_1}{R_0}\right) + \frac{L_t}{R_0} \frac{I_0\left(\frac{R_0}{L_t}\right)}{I_1\left(\frac{R_0}{L_t}\right)} + \frac{L_t}{R_1} \frac{K_0\left(\frac{R_1}{L_t}\right)}{K_1\left(\frac{R_1}{L_t}\right)} \right] \quad (\text{A.40})$$

When $R_0 \gg L_t$ (in practice it is enough to require that $R_0 > 4L_t$) we can use the approximate expression for the modified Bessel functions given in appendix B to show that $I_0(x) / I_1(x)$ and $K_0(x) / K_1(x)$ approximate to unity for $x \gg 1$. Equation (A.40) with $s = R_1 - R_0$ then becomes:

$$R_{T,circ} \approx \frac{R_{sh}}{2\pi} \left[\ln\left(\frac{R_1}{R_1 - s}\right) + L_t \left(\frac{1}{R_1 - s} + \frac{1}{R_1} \right) \right] \quad (\text{A.41})$$

The transfer length L_t can now be determined by a least squares fit of experimental data to equation (A.39), (A.40) or (A.41). This fit also yields values for $R_{sh,c}$ and R_{sh} in the case of equation (A.39) and it yields a value for R_{sh} in the case of equations (A.40) and (A.41). The specific contact resistance ρ_c can then be calculated using equations (4.38) or (4.42) respectively. In addition, it can be observed that for $2\pi R_1 \gg s$ equation (A.41) can be further simplified to obtain the same form as equation (4.25) with $W_c = 2\pi R_1$ and $l = s$.

Appendix B

Modified Bessel functions

This appendix briefly provides the basic properties of the functions $I_n(x)$ and $K_n(x)$ used in the calculation of the resistance of an annular contact. A comprehensive theory of these functions can be found in any of the standard textbooks about Bessel functions [23].

The modified Bessel functions of the first and second kind are defined as:

$$I_n(x) = i^{-n} J_n(ix) \quad (\text{B1})$$

respectively,

$$K_n(x) = \frac{\pi}{2} \frac{I_{-n}(x) - I_n(x)}{\sin(n\pi)} \quad (\text{B2})$$

where J_n denotes the Bessel function of order n , and for an integer n the definition (B2) is treated as the limit:

$$K_n(x) = \frac{\pi}{2} \lim_{\varepsilon \rightarrow n} \frac{I_{-\varepsilon}(x) - I_{\varepsilon}(x)}{\sin(\varepsilon\pi)}. \quad (\text{B3})$$

The functions $I_n(x)$ and $K_n(x)$ satisfy the differential equation:

$$x^2 \frac{d^2 y}{dx^2} + x \frac{dy}{dx} - (x^2 + n^2)y = 0 \quad (\text{B4})$$

and the recurrence relations following from those for $J_n(x)$. In particular:

$$\frac{dI_0}{dx} = I_1 \quad (\text{B5})$$

and

$$\frac{dK_0}{dx} = -K_1. \quad (\text{B6})$$

For $x = 0$ the modified Bessel function of the first kind of an integer order remains regular while $K_n(x)$ has a logarithmic singularity:

$$I_n(x) = \sum_{r=0}^{\infty} \frac{(x/2)^{n+2r}}{r! \Gamma(n+r+1)} \quad (\text{B7})$$

$$K_0(x) = -[I_0(x) + \gamma] \log\left(\frac{x}{2}\right) + \sum_{r=0}^{\infty} \frac{(x/2)^{2r}}{(r!)^2} \Phi(r) \quad (\text{B8})$$

$$K_n(x) = (-1)^{n+1} \sum_{r=0}^{\infty} \frac{(x/2)^{n+2r}}{r!(n+r)!} \left\{ \log\left(\frac{x}{2}\right) - \frac{1}{2} \Phi(r) - \frac{1}{2} \Phi(n+r) + \gamma \right\} \\ + \frac{1}{2} \sum_{r=0}^{n-1} \frac{(-1)^r (n-r-1)!}{r! (x/2)^{n-2r}} \quad n = 1, 2, 3 \dots \quad (\text{B9})$$

where $\gamma \approx 0.5772157$ is Euler's constant, $\Phi(0) = 0$, and for $r \geq 1$:

$$\Phi(r) = \sum_{k=1}^r \frac{1}{k} \quad (\text{B10})$$

For $x \rightarrow \infty$, the asymptotic forms of the modified Bessel functions are:

$$I_n(x) \sim \frac{\exp(x)}{\sqrt{2\pi x}} \left(1 - \frac{4n^2 - 1}{8x} + \dots \right) \quad (\text{B11})$$

$$K_n(x) \sim \sqrt{\frac{\pi}{2x}} \exp(-x) \left(1 + \frac{4n^2 - 1}{8x} + \dots \right) \quad (\text{B12})$$

Appendix C

Technological recipe for Ohmic contacts on n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$

1. Surface cleaning:

- Acetone (ultrasonic)
- Acetone + iso-propanol spray
- N_2 dry

2. Optical lithography of the CTLM pattern:

- Resist AZ5214 5000 rpm 30 seconds
- Soft bake 95 °C 5 minutes
- Flood exposure UV 300 2 seconds (NO MASK)
- Hard bake 105 °C 5 minutes
- Exposure UV 300 45 seconds (CTLM mask)
- AZ developer DI water : AZ = 1 : 1 1 minute 20 seconds
- RO + DI water rinse (5 MΩ)
- N_2 dry
- Visual inspection

3. Metallization:

- AIRCO e-beam evaporator Ti/Al/Ni/Au 30/180/40/150 nm

4. Lift off:

- Acetone (ultrasonic)
- Acetone + iso-propanol spray
- N_2 dry
- Visual inspection

5. Post-metallization treatment:

- RTA 900 °C 30 seconds N_2

Appendix D

Derivation of correction factors for linear approximation

The starting point of the derivation of the correction factors that are needed to arrive at a linear approximation of the CTLM measurement results depends on the used CTLM test structure. In our case we used the test structure proposed by Marlow and Das [21] and hence the starting point of the derivation is equation (5.2), which gives the total resistance ($R_{T,circ}$) assuming that $r_2 \gg L_t$ and with $R_2 = r_2 + s$. For convenience this equation is again given by equation (D1):

$$R_{T,circ} \approx \frac{R_{sh}}{2\pi} \left[\ln \left(\frac{r_2 + s}{r_2} \right) + L_t \left(\frac{1}{r_2 + s} + \frac{1}{r_2} \right) \right] \quad (D1)$$

If the condition $r_2 \gg s$ is valid the $\ln$ term of equation (D1) can be evaluated using a Taylor expansion. Terminating this Taylor expansion after the linear term yields:

$$\ln \left(\frac{r_2 + s}{r_2} \right) = \ln \left(1 + \frac{s}{r_2} \right) \approx \frac{s}{r_2} + O \left(\left(\frac{s}{r_2} \right)^2 \right) \quad (D2)$$

Inserting the linearization of the $\ln$ term in equation (D1) requires the introduction of a correction factor c . Equation (D1) then becomes:

$$\begin{aligned} R_{T,circ} &\approx \frac{R_{sh}}{2\pi} \left[\frac{s}{r_2} + L_t \left(\frac{1}{r_2 + s} + \frac{1}{r_2} \right) \right] \cdot c \\ &\approx \frac{R_{sh}}{2\pi r_2} \left[s + L_t \left(\frac{r_2}{r_2 + s} + 1 \right) \right] \cdot c \\ &\approx \frac{R_{sh}}{2\pi r_2} [s + 2L_t] \cdot c \end{aligned} \quad (D3)$$

According to equation (4.25) where W_c in this case is equal to $2\pi r_2$, equation (D3) can be written as:

$$R_{T,circ} \approx R_{T,lin} \cdot c \quad (D4)$$

The calculation of the correction factors c_i , which depend on the used gap spacing (s), is according to equation (D4) rather straightforward.

$$\frac{R_{sh}}{2\pi} \left[\ln \left(\frac{r_2 + s}{r_2} \right) + L_t \left(\frac{1}{r_2 + s} + \frac{1}{r_2} \right) \right] \approx \frac{R_{sh}}{2\pi r_2} [s + 2L_t] \cdot c \quad (D5)$$

If the condition $s \gg L_t$ is valid the L_t – dependent terms at both sides cancels out with respect to the L_t – independent terms. This yields:

$$\ln \left(\frac{r_2 + s}{r_2} \right) = \frac{s}{r_2} \cdot c$$

and hence

$$c = \frac{r_2}{s} \cdot \ln \left(\frac{r_2 + s}{r_2} \right) \quad (D6)$$

Table D1 shows the correction factors that have been calculated using equation (D6) for the used gap spacings and a nominally radius of the inner disc contact (r_2) of 50 μm .

Table D1: Gap spacings and their corresponding correction factors.

Gap spacings (s) [μm]	Correction factors (c_i) [-]
4	0.962
8	0.928
12	0.896
16	0.868
20	0.841
24	0.817
32	0.773
40	0.735
48	0.701

Appendix E

Preliminary technological recipe for Schottky contacts on n – type $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$

1. Surface cleaning:

- Acetone (ultrasonic)
- Acetone + iso-propanol spray
- N_2 dry

2. Optical lithography for the Ohmic contacts using the “Ohmic” part of the circular Schottky mask:

- | | | | |
|-----------------------|-----------------------|---------------------|---------------------------------------|
| • Resist AZ5214 | 5000 rpm | 30 seconds | |
| • Soft bake | 95 °C | 5 minutes | |
| • Flood exposure | UV 300 | 2 seconds | (NO MASK) |
| • Hard bake | 105 °C | 5 minutes | |
| • Exposure | UV 300 | 45 seconds | (“Ohmic” part circular Schottky mask) |
| • AZ developer | DI water : AZ = 1 : 1 | 1 minute 20 seconds | |
| • RO + DI water rinse | (5 MΩ) | | |
| • N_2 dry | | | |
| • Visual inspection | | | |

3. Ohmic metallization:

- | | | |
|-----------------------------|-------------|------------------|
| • Leybold e-beam evaporator | Ti/Al/Ni/Au | 30/180/40/150 nm |
|-----------------------------|-------------|------------------|

4. Lift off:

- Acetone (ultrasonic)
- Acetone + iso-propanol spray
- N_2 dry
- Visual inspection

- RTA 900 °C 30 seconds N₂

- Acetone + iso-propanol spray
- N₂ dry

• Resist AZ5214	5000 rpm	30 seconds
• Soft bake	95 °C	5 minutes
• Flood exposure	UV 300	2 seconds (NO MASK)
• Hard bake	105 °C	5 minutes
• Exposure	UV 300	45 seconds (“Schottky” part circular Schottky mask)
• AZ developer	DI water : AZ = 1 : 1	1 minute 20 seconds
• RO + DI water rinse	(5 MΩ)	
• N ₂ dry		
• Visual inspection		

- Oxford 100 (RIE) O₂ plasma 50 sccm 20 W 200 mTorr
DC bias = - 60 V T = 20 °C t = 2 minutes
- Wet chemical etch NH₄OH : DI = 1 : 1 t = 15 seconds
- RO + DI water rinse (5 MΩ)
- N₂ dry

- Leybold e-beam evaporator Ni/Au 20/200 nm

- Acetone (ultrasonic)
- Acetone + iso-propanol spray
- N₂ dry
- Visual inspection

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