Gold free contacts to AlGaIn/GaN heterostructures

Marcin Hajłasz

GOLD FREE CONTACTS TO AlGaN/GaN HETEROSTRUCTURES

Members of the graduation committee:

prof. dr.	J. N. Kok	University of Twente (chairman and secretary)
prof. dr.	D. J. Gravesteijn	University of Twente (promoter)
prof. dr. ir.	R. A. M. Wolters	University of Twente
prof. dr. ir.	G. Koster	University of Twente
prof. dr.	L. Nanver	University of Delft
prof. dr.	R. Jos	Chalmers University of Technology
dr. ir.	J. H. Klootwijk	Philips Research
dr.	A. Y. Kovalgin	University of Twente

This research was carried out under project number M62.3.11449 in the framework of the Research Program of the Materials innovation institute (M2i) in the Netherlands (www.M2i.nl).

This research work was carried out at NXP Semiconductors, Eindhoven, The Netherlands.

Copyright © 2018 by Marcin Hajłasz, Wrocław, Poland.

Cover design: Weronika Lechowska

Cover image: (front and back) an artistic impression of Nitrogen mapping in the contact region cross section; (back) SEM image of Garfield made from the Ohmic contact metal.

This work is licensed under the Creative Commons Attribution-Non-Commercial 3.0 Netherlands License. To view a copy of this license, visit <http://creativecommons.org/licenses/by-nc/3.0/nl/> or send a letter to Creative Commons, 171 Second Street, Suite 300, San Francisco, California 94105, USA.

Typeset with $\text{\LaTeX}$. Printed by Gildeprint, Enschede, The Netherlands.

ISBN 978-90-365-4538-9

DOI 10.3990/1.9789036545389

<https://doi.org/10.3990/1.9789036545389>

GOLD FREE CONTACTS TO ALGAN/GAN HETEROSTRUCTURES

DISSERTATION

to obtain
the degree of doctor at the University of Twente,
on the authority of the rector magnificus,
prof. dr. T. T. M. Palstra,
on account of the decision of the graduation committee,
to be publicly defended
on Friday the 25th of May 2018 at 12:45

by

Marcin Hajłasz

born on 22nd of August 1986
in Wrocław, Poland

This dissertation is approved by the promoter:

prof. dr. D. J. Gravesteijn University of Twente (promoter)

"Fall in love with some activity, and do it! Nobody ever figures out what life is all about, and it doesn't matter. Explore the world. Nearly everything is really interesting if you go into it deeply enough."

Richard Feynman

ABSTRACT

Transistors and diodes based on AlGaN/GaN are suitable candidates for high-voltage and high-speed electronics due to the GaN material properties such as wide bandgap, large breakdown field, high electron saturation velocity and good thermal conductivity.

When thin AlGaN layer is grown epitaxially on GaN, it is typically under tensile stress. Consequently, we observe piezoelectric polarization, which is additional to the spontaneous polarization in these materials. The polarization induced sheet charge density forces free electrons to try to compensate for it. These charges accumulate at the heterojunction of AlGaN and GaN layers to create a Two-Dimensional Electron Gas. The electrons are confined to the interface due to band bending in the GaN, and in order to make a contact to them, it is necessary to pass through the AlGaN layer.

Due to the complexity of AlGaN/GaN devices, they are not yet fully understood. This is especially true for the electrical contacts, where the relatively well characterized and described Au-containing metal stacks have to be replaced by Au-free stacks to allow production at scale. The mass production of GaN devices, required for consumer applications of GaN, makes it necessary to use existing Si fabrication facilities, where it is not allowed to use gold, as very low concentrations lead to strong performance degradation of Si devices. Therefore, it is crucial to investigate alternative metal stacks, such as for example TiW, as a replacement for gold. The aim of this thesis is to broaden the understanding of Ohmic and Schottky contact to AlGaN/GaN by means of material characterization techniques and novel electrical test structures.

Chapter 1 introduces the AlGaN/GaN material system and High Electron Mobility Transistor. It is described in detail how the Two-Dimensional Electron Gas is formed and how the AlGaN/GaN transistor works.

In Chapter 2 a review of current technology to form Ohmic and Schottky contacts to GaN and AlGaN/GaN heterostructures is presented. Different metals and metal multilayers are discussed and Au-free alternatives are analyzed. It is shown that there are different ways to minimize the contact resistance.

Chapter 3 reports on method of accurate extraction of Ohmic contact parameters such as specific contact resistance and transfer length. It is the first work investigating sheet resistance under Ohmic contacts to AlGaN/GaN.

Research highlights how reactions at metal-semiconductor interface affect the material under the contact and how the extracted contact parameters change when the resistance under the contact is accounted for properly.

Chapter 4 presents a specific case of Ohmic contacts - so called recessed contacts where (part of) the AlGa_N is removed resulting in either a thinner barrier to the 2DEG or even a side contact, in which case AlGa_N layer and part of Ga_N is completely removed, with the aim to reduce the contact resistance. The control of the etching process requires nanometer accuracy, as the AlGa_N layer is typically less than 30 nm thick. In this chapter, reactions under the contact are investigated and consequences of neglecting of the actual value of sheet resistance under the contact are discussed.

In Chapter 5 results of metal-stack-induced stress, on Schottky diode behaviour are presented. Two hundred diodes are investigated in a de-processing experiment, where we removed, in 50 nm steps, the TiW(N) top layer of the Schottky metal stack. Schottky barrier height was extracted before and after each etch step, on exactly the same devices to avoid variability over the wafer. The observed change in Schottky barrier height of a Ni and Ni/TiW/TiWN/TiW contact is explained by stress effects induced by the TiW/TiWN/TiW capping layer, rather than by chemical reactions at the metal-semiconductor interface.

Chapter 6 summarizes the investigation of the barrier height inhomogeneity of the Schottky contacts to AlGa_N/Ga_N. The ideal diode behavior is often not observed in AlGa_N/Ga_N based diodes. In this chapter we present electrical measurements of gold-free Schottky contacts, such as TiN and TiW(N). The devices exhibit temperature dependence of the Schottky barrier height and ideality factor as typically observed in AlGa_N/Ga_N, which indicates barrier inhomogeneity. From the modified Richardson plots it is concluded that the Schottky barrier height inhomogeneity is caused by wafer properties, such as dislocations, and not by the metal stacks themselves.

In Chapter 7 the main results of this thesis are summarized and recommendations for further research are provided.

SAMENVATTING

Transistors en diodes gebaseerd op AlGa_N/Ga_N zijn geschikte kandidaten voor hoogspanning en hoge snelheid elektronica vanwege de materiaal eigenschappen van Ga_N, zoals een grote band gap, hoog doorslag veldsterkte, een hoge elektronen verzadigingssnelheid en een goede thermische geleidbaarheid.

Als dunne lagen AlGa_N epitaxiaal op Ga_N worden gegroeid, bevinden ze zich onder trekbelasting. Bijgevolg wordt er piezoelektrische polarisatie waargenomen, die nog eens komt bij de spontane polarisatie die in de materialen optreedt. De positieve polarisatie geïnduceerde lading dwingt vrije elektronen om de lading te compenseren. Deze ladingen accumuleren op het grensvlak van de Ga_N en AlGa_N lagen en creëert en zogenaamd tweedimensionaal elektronen gas. De elektronen bevinden zich op de heterojunctie ten gevolge van band buiging in het Ga_N, en om er een contact vanaf het oppervlak naar te maken moeten de elektronen door de AlGa_N laag.

Door de complexiteit van AlGa_N/Ga_N devices zijn ze nog steeds niet volledig begrepen. Dit geldt in het bijzonder voor de elektrische contacten, waar de relatief goed gekarakteriseerde Au-bevattende metaal lagen vervangen moeten worden door Au vrije lagen om massa productie mogelijk te maken. Voor de massa productie van Ga_N devices, die nodig is voor consumenten toepassing van Ga_N, moeten bestaande Si fabricage fabrieken gebruikt worden, waarin geen goud toegestaan is, aangezien zeer lage concentratie goud leiden tot een sterke afname van de prestatie van Si devices. Het is daarom cruciaal om alternatieve metaal stacks, zoals bijv. TiW, als vervanging voor goud te ontwikkelen. Het doel van dit proefschrift is verbreding van het begrip van Ohmse en Schottky contacten naar AlGa_N/Ga_N door middel van materiaal karakterisatie technieken en nieuwe elektrische test structuren.

Hoofdstuk 1 geeft een inleiding voor het AlGa_N/Ga_N materiaal systeem en hoge elektron mobiliteit transistors. In detail wordt de vorming van het tweedimensionale elektronen gas en de werking van de AlGa_N/Ga_N transistor beschreven.

In hoofdstuk 2 wordt een overzicht gegeven van de huidige technologie om Ohmse en Schottky contacten te maken naar Ga_N en AlGa_N/Ga_N heterostructuren. Verschillende metalen en metaal multilagen worden besproken en Au-vrije alternatieven worden geanalyseerd. Er blijken ver-

schillende routes te zijn om de contact weerstand te verminderen.

Hoofdstuk 3 behandelt een methode om nauwkeurig de Ohmse contact parameters, zoals de specifieke contact weerstand, en transfer lengte, te bepalen. Het is het eerste werk dat de sheet weerstand onder Ohmse contacten naar AlGa_N/Ga_N bestudeerd. Het onderzoek toont aan dat reacties op het metaal-halfgeleider interface het materiaal onder het contact aantasten en dat de geëxtraheerde contact parameters veranderen als rekening wordt gehouden met de weerstand onder het contact.

In hoofdstuk 4 wordt een speciaal geval van Ohmse contacten, de zogenaamde 'verzonken' contacten waar (een gedeelte) van het AlGa_N wordt verwijderd wat resulteert in een dunnere barrière naar het tweedimensionale elektronengas, of een zogenaamd zijcontact, in welk geval ook een gedeelte van het Ga_N wordt verwijderd. Doel is de vermindering van de contact weerstand. De accuratesse van het ets proces vereist nauwkeurigheden op de nanometer schaal, aangezien de AlGa_N typisch minder dan 30 nm dik is. Praktisch is deze nauwkeurigheid niet te bereiken. In dit hoofdstuk worden reacties onder de contacten bestudeerd, en worden de consequenties van het verwaarlozen van de werkelijke waarde van de sheet weerstand onder het contact besproken.

In hoofdstuk 5 worden de resultaten gepresenteerd van stress, geïnduceerd door de metaal lagen, op het gedrag van Schottky diodes. Twee honderd diodes zijn onderzocht in een experiment waar in stappen van 50 nm de TiW(N) top laag verwijderd is. De hoogte van de Schottky barrière werd bepaald voor en na elke ets stap, op dezelfde devices om variabiliteit over de plak te vermijden. De verandering in de Schottky barrière hoogte van Ni en Ni/TiW/TiWN/TiW contacten, als functie van het aantal etsstappen, wordt uitgelegd in termen van de stress geïnduceerd door de TiW/TiWN/TiW capping laag, en niet door chemische reacties op het metaal-halfgeleider grensvlak.

Hoofdstuk 6 bevat de resultaten van de studie van de inhomogeniteit van de barrière hoogte van Schottky contacten naar AlGa_N/Ga_N. Het ideale diode gedrag wordt vaak niet waargenomen in AlGa_N/Ga_N devices. In dit hoofdstuk presenteren we elektrische metingen aan goud-vrije Schottky contacten, zoals TiN en TiW(N). De devices vertonen een temperatuur afhankelijkheid van de Schottky barrière hoogte en de idealiteitsfactor, zoals typisch is voor AlGa_N/Ga_N, wat wijst op inhomogeniteiten van de barrières. Uit de gemodificeerde Richardson plots wordt geconcludeerd dat de Schottky barrière hoogte inhomogeniteit wordt veroorzaakt door eigenschappen van de plakken, zoals dislocaties, en niet door de metaal lagen zelf.

In hoofdstuk 7 worden de belangrijkste resultaten van dit proefschrift samengevat en aanbevelingen gedaan voor verder onderzoek.

CONTENTS

ABSTRACT	· vii
SAMENVATTING	· ix
1 INTRODUCTION	· 1
1.1 Gallium nitride	· 2
1.2 Material properties	· 5
1.3 Device schematic and principle of operations	· 8
1.4 Project description; why contacts need to be Au-free	· 10
1.5 Outline of the thesis	· 11
2 STATUS OF OHMIC AND SCHOTTKY CONTACTS	· 13
2.1 Introduction	· 14
2.2 Ohmic contacts	· 14
2.3 Schottky contacts	· 21
2.4 Summary	· 25
3 SURFACE OHMIC CONTACTS	· 27
3.1 Introduction	· 28
3.2 Test structures	· 28
3.3 Device description	· 34
3.4 Material analysis	· 35
3.5 Electrical measurements	· 39
3.6 TCAD simulations	· 41
3.7 Conclusions	· 42
4 RECESSED OHMIC CONTACTS	· 45
4.1 Introduction	· 46
4.2 Materials	· 47
4.3 Analysis and methods	· 47
4.4 Material characterization	· 50
4.5 Electrical results	· 54
4.6 Discussion	· 56
4.7 Conclusions	· 59
5 STRESS IN SCHOTTKY METAL STACK	· 63
5.1 Introduction	· 64

5.2	<i>Methodology</i>	· 65
5.3	<i>Material analysis</i>	· 67
5.4	<i>Electrical characterization</i>	· 69
5.5	<i>Discussion</i>	· 72
6	SCHOTTKY BARRIER INHOMOGENEITY	· 75
6.1	<i>Introduction</i>	· 76
6.2	<i>Methods</i>	· 78
6.3	<i>Electrical measurements</i>	· 80
6.4	<i>Discussion</i>	· 84
6.5	<i>Conductive Atomic Force Microscopy</i>	· 87
6.6	<i>Conclusions</i>	· 89
7	SUMMARY AND RECOMMENDATIONS	· 91
7.1	<i>Introduction</i>	· 92
7.2	<i>Recommendations and further research</i>	· 94
	BIBLIOGRAPHY	· 97
	PUBLICATIONS	· 105
	ACKNOWLEDGEMENTS	· 107

CHAPTER 1

INTRODUCTION

Abstract

In this chapter, an overview of gallium nitride and its applications are discussed. An explanation about material properties, especially piezoelectric polarization, is given. Furthermore, basic principles of operations of AlGaN/GaN High Electron Mobility Transistor are introduced. Finally, motivation for the research on gold-free electrical contacts to AlGaN/GaN is presented.

1.1 Gallium nitride

The power semiconductor manufacturing started with germanium and selenium devices and subsequently switched to silicon around the 1950s. However, silicon power MOSFETs are reaching their theoretical limits and new semiconductor materials have to be used to provide performance required in new systems. A material that can potentially replace Si is gallium nitride (GaN) - it can outperform silicon in power handling, thermal stability, and speed.

While there is a growing number of areas where GaN devices are needed, their impact will be highest in two application areas, namely light generation and control of electrical power. In both areas, large commercial markets exist and the need for even better and more efficient devices will stimulate development of the technology. The most important advantage of GaN devices is the ability to do more (more light, more power) with less (higher efficiency) [1].

One of the unique properties of GaN is related to its wide bandgap. The light color emitted by the diode is indicative of the magnitude of energy needed for an electron to cross the band gap. After an electron is excited (by heat or electricity) into the conduction band, its return to the lower energy valence band causes a release of a photon whose energy is expressed as:

$$E = \frac{hc}{\lambda} \quad (1.1)$$

where h is Planck's constant, c is speed of light and λ is wavelength of light.

GaN is a direct band gap semiconductor material with a 3.4 eV band gap which corresponds to near ultraviolet light (364 nm). Accessing this wavelength made it possible to fabricate highly efficient semiconductor-based white light sources. Solid-state lighting based on light-emitting diodes (LEDs) allows consumers to replace less efficient and less reliable lighting technologies, such as incandescent, fluorescent and metal halide light sources [1]. Different applications of GaN devices are summarized in Table 1.1 [1].

While GaN LED market is already mature, a new application area of electrical systems and power electronics is still under development. For example, energy efficiency in power conversion for industrial and consumer electronics, electric vehicles and power generation can all benefit from new GaN devices. Gallium nitride has several properties that distinguish it from silicon and enable better performance. It is a wide bandgap semiconductor (3.4 eV), it has a large critical breakdown electric field ($\sim 3\text{MV/cm}$) and high electron mobility ($\sim 1500 - 2000\text{cm}^2/\text{V} \cdot \text{s}$ at room temperature). These properties result in low on-resistance, low switching losses, high power conversion efficiencies and good performance at elevated temperatures. GaN allows us to go beyond limits of both silicon and silicon carbide, as

Table 1.1: Applications for GaN-based devices.

LED	Power electronics	Laser diodes
Backlighting	RF power amplifiers for communications and radars	Optical data storage
Full-color, large format video screens	Switch mode power supplies	Projectors
Automotive lighting	Motor controls	Displays
General lighting	Satelite power systems	Commercial printing
	High-temperature electronics	Testing and measurement

for example presented by device-specific on-resistance for a given reverse voltage, as can be seen in Fig. 1.1

Figure 1.1: Comparison of R_{ON} for Si, SiC and GaN [2]

One disadvantage of GaN is the cost of bulk material. Commercially available GaN substrates are very expensive in comparison to Si and not available in large size. However, affordable GaN wafers became possible after development of GaN-on-Si technology, where few- μm -thick epitaxial active GaN layers are deposited by means of CVD on silicon (111) wafers by using transition layers that mitigate differences in lattice constants and coefficients of thermal expansion [3]. An example of a GaN-on-Si with a transition layer can be seen in the Fig. 1.2. AlN and AlGaIn layers are used to allow growth of a relaxed GaN layer.

Crack-free GaN films can be grown on 6- and 8-in (111) Si substrates to manufacture GaN power devices [5]. The epitaxial growth typically starts

Figure 1.2: Cross-sectional SEM image of GaN on Si with an AlGaIn/AlN intermediate layer ©The Japan Society of Applied Physics. Reprinted with permission. All rights reserved [4].

with an AlN nucleation layer [5] that also plays the role of preventing Si from diffusing into the GaN, followed by a transition layer (1 – 3 μm) for stress balance and crystallinity, a GaN buffer (1 – 2 μm), and a barrier [6]. Because GaN layers grown on Si are under tensile stress, the transition layer should provide compressive stress to the GaN epitaxial layer for stress compensation. Exemplary transition layers may include AlGaIn layer [7], AlN/GaN super lattices [8], or multiple AlN stress-release insertion layers [9].

Research on GaN-on-Si has already led to a significant price reduction and further price decrease is expected [10]. This makes GaN an interesting candidate for consumer products. However, cost effective large-scale production of these devices is only possible in standard Si wafer fabs [11]. Another factor is that as Si ICs production migrates to larger substrates, older facilities become available for GaN production.

While using Si facilities seems to solve problems with cost-effective production, it creates issues too. Conventionally, the electrical contacts to GaN are made of metal stacks with gold capping for both Ohmic [12–14] and Schottky contacts [15–17]. However, gold is not allowed into Si fabs, as it easily contaminates silicon, and hence, alternative metal stacks have to be developed to enable cost effective mass production of GaN devices.

So far, most of the research on Ohmic and Schottky contacts has been focused on Au-containing stacks. Ti/Al/x/Au metal multilayers (where

x was a blocking metal chosen among different options) were most often investigated as candidates for Ohmic contacts [12, 18, 19]. For the Schottky contacts, Ni/Au bilayer was most extensively investigated [16, 20]. These contacts, even though thoroughly analyzed [20, 21], are still not fully understood. Many different phenomena such as the dependencies of ideality factor and Schottky barrier height on temperature [22, 23] are still to be explained. Some work has been done on Schottky barrier height inhomogeneity [24, 25], however there is still not much inhomogeneity research experiments on AlGaIn/GaN heterostructures. This is especially significant for Au-free metal stacks which have not received enough attention and many aspects of contacts formation and their behavior are not described in detail.

1.2 Material properties

GaN is one of the of III-V semiconductors as it is composed of elements from group III and group V of the periodic table. It is a direct bandgap semiconductor [26] with a bandgap of 3.4 eV (in comparison 1.1 eV for Si). The gallium and nitrogen atoms in GaN are arranged in a wurtzite (hexagonal) crystal structure [26], as presented in Fig. 1.3.

Figure 1.3: GaN wurtzite crystal structure [27].

It is grown most commonly by metal organic chemical vapor deposition (MOCVD) [28, 29] or alternatively by molecular beam epitaxy (MBE) [30, 31]. As a noncentrosymmetric compound, GaN has two different sequences of the atomic layers in the two opposing directions parallel to certain crystallographic axes [32]. Ga and N layers order is reversed along the [0001] and [000-1] directions. Since the material consists of bilayers of two closely spaced hexagonal layers of which one is formed by cations and the other by anions, this leads to polar faces and spontaneous polarization in

Table 1.2: Properties of different semiconductor materials

Quantity	GaN	Al _{0.2} Ga _{0.8} N	AlN	6H-SiC	Si	Units
Band gap	3.43	3.77	6.20	3.03	1.12	eV
Breakdown field	3.3	4.32	8.4	3.2	0.3	MV/cm
Relative permittivity	9.5	9.3	8.5	9.66	11.9	
Lattice constant a	3.189	3.174	3.112	3.073	5.431	Å

the material. In GaN we can have a basal surface that would be either Ga- or N-faced as schematically shown in Fig. 1.4

Figure 1.4: Ga-face and N-face crystal structures of GaN. Reprinted from O. Ambacher, J. Smart, J. R. Shealy, N. G. Weimann, K. Chu, M. Murphy, W. J. Schaff, L. F. Eastman, R. Dimitrov, L. Wittmer, M. Stutzmann, W. Rieger, and J. Hilsenbeck, "Two-dimensional electron gases induced by spontaneous and piezoelectric polarization charges in N- and Ga-face AlGa_xN/GaN heterostructures," *Journal of Applied Physics*, vol. 85, no. 6, p. 3222, 1999, with the permission of AIP Publishing.

By convention, the z or [0001] direction is given by a vector pointing from a Ga to a nearest-neighbor N atom. We can now consider Al_xGa_{1-x}N material, where x (the mole fraction) of Ga atoms is replaced Al atoms. Such material will have intermediate properties between GaN and AlN, as shown in Table 1.2.

When an Al_xGa_{1-x}N layer is grown epitaxially on top of the relaxed GaN it will be under tensile mechanical stress, due to the smaller lattice constant. AlGa_xN will be strained only if remaining below a critical thickness, above which dislocations would appear and relax the layer. In the absence of external electric fields, the total polarization (P) of a GaN or AlGa_xN layer is the sum of spontaneous polarization P_{SP} and piezoelectric polarization

P_{PE} , due to the stress. Spontaneous polarization arises from the lack of inversion symmetry of the wurtzite crystal, whereas piezoelectric polarization, is a result of the stress and strain created due to the lattice mismatch of the GaN and $Al_xGa_{1-x}N$ layers. The spontaneous polarization along the c-axis of the wurtzite crystal is $P_{SP} = P_{SP} * z$ and the piezoelectric polarization can be calculated from [32]:

$$P_{PE} = e_{33}\epsilon_z + e_{31}(\epsilon_x + \epsilon_y) \quad (1.2)$$

Where e_{33} and e_{31} are piezoelectric coefficients, a_0 and c_0 are the equilibrium values of the lattice parameters, $\epsilon_z = (c - c_0)/c_0$ is the strain along the c-axis, and the in-plane strain $\epsilon_x = \epsilon_y = (a - a_0)/a_0$ is assumed to be isotropic. The relationship between the lattice constant of the hexagonal GaN is given by [32]:

$$\frac{c - c_0}{c_0} = 2 \frac{C_{13}}{C_{33}} \frac{a - a_0}{a} \quad (1.3)$$

Where C_{13} and C_{33} are elastic constants. Using equations x and y we can calculate the piezoelectric polarization in the direction of the c-axis using [32]:

$$P_{PE} = 2 \frac{a - a_0}{a} \left(e_{31} - e_{33} \frac{C_{13}}{C_{33}} \right) \quad (1.4)$$

Based on the above equation we can say that for AlGaN, the piezoelectric polarization is negative for tensile and positive for compressive strain respectively. The spontaneous polarization for GaN and AlN is negative [32], meaning that for Ga(Al)-face heterostructure the spontaneous polarization is pointing towards the substrate [32]. Hence the resultant total polarization (piezoelectric and spontaneous) will depend on AlGaN strain (tensile or compressive) and structure of GaN being Ga-faced or N-faced. All these combinations are presented schematically in Fig. 1.5

If the polarization induced sheet charge density is positive ($+\sigma$), as in the case of strained AlGaN on Ga-face GaN, free electrons will try to compensate for the charges induced by polarization and vice versa. These charges will accumulate at the heterojunction of the barrier and the buffer layer to create a Two-Dimensional Electron Gas (2DEG). The electrons are confined to the interface due to band bending in the GaN and the conduction-band offset between the two materials (resulting from the larger band gap of AlGaN). The band diagram is schematically shown in Fig 1.6.

The electron concentration of 2DEG can be in the range of 10^{13} cm^{-2} , well in excess of those observed in other III-V materials [33]. Since this material system does not include any doping, hence there is no impurity scattering and consequently very high mobility (around $1500\text{-}2000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ [32, 34] at room temperature) can be achieved. Therefore, such heterostruc-

Figure 1.5: Polarization induced sheet charge density and directions of the spontaneous and piezoelectric polarization in Ga- and N-face strained and relaxed AlGaIn/GaN heterostructures [32]. Note that dimensions are not to scale to improve readability.

tures are a basis of so called High Electron Mobility Transistors (HEMT), the subject of this thesis.

1.3 Device schematic and principle of operations

AlGaIn/GaN HEMT comprises of AlGaIn/GaN heterostructure on a substrate layer, with typically Ti/Al based source and drain [35] and Ni gate metal [17]. Device schematic is presented in Fig. 1.7. Source and drain contacts are Ohmic contacts, i.e. low resistance junction (non-rectifying) which provide current conduction from metal to semiconductor and vice versa with the current-voltage relationship being linear. Fabrication of good Ohmic contacts to GaN is difficult, due to the wide band gap (3.4 eV for GaN) which leads to Schottky barrier height values in the order of 1 eV on n-type and even of 2 eV on p-type material [36]. It is even more difficult in $Al_xGa_{1-x}N$ alloys, where the band gap increases with increasing the Al content (3.4 eV at $x = 0$ to 6.2 eV at $x = 1$). Additionally, fabrication of

Figure 1.6: Band diagram of AlGaN/GaN heterostructure.

such contacts is complex, as use doping like in Si technology, neither by ion implantation nor by diffusion.

Figure 1.7: AlGaN/GaN HEMT schematic. Note that dimensions are not to scale to improve readability.

The gate contact is a Schottky (rectifying) contact and refers to a metal-semiconductor contact having a large barrier height. The main transport mechanism is thermionic emission, which allows electrons to move over the Schottky barrier. The gate, i.e. the Schottky contact in HEMTs, allow to switch the transistor on and off by depleting the 2DEG directly under the gate.

Since the 2DEG is present in the heterostructure without applying any external voltage, HEMT is a 'normally on' transistor. However, this is an unwanted behavior and attempts are made to design 'normally off' HEMTs.

With no voltage applied, the 2DEG is present between source and drain but no current is flowing. Applying voltage between drain and source ($V_{DS} > 0$) forces electrons to flow from source to drain. Applying a negative bias to the gate, such that V_{GS} drops below the threshold voltage of the device (typically around -2 V) can deplete the 2DEG of electrons in the region immediately below the gate. Consequently, the source-drain connection is no longer present and the device is turned off.

1.4 Project description; why contacts need to be Au-free

Traditionally, GaN devices have been processed in dedicated III-V fabs. The capping metal layer for electrical contacts was almost exclusively gold [12, 18, 19], as it has low resistance and protects Ti/Al from oxidation. Since III-V facilities are most often producing devices for specialized high-margin markets like RF power or lasers, they are unsuited for inexpensive high voltage devices. Additionally, traditional III-V fabs do not have the necessary throughput to provide the number of devices required in the consumer market. A potential solution is introduction of GaN processing in a standard silicon fab and use existing production lines. However, gold is not allowed in these facilities, as it diffuses rapidly in Si at relatively low temperatures and forms mid gap states that have a negative effect on the performance of the silicon devices [37]. Therefore, a gold free metallization has to be found that is compatible with an Si fab.

Over the past years there have been multiple attempts to develop Au-free metal multilayers for both Ohmic and Schottky contacts. While the results are already very promising, when one looks at the contact parameters, there is still no full understanding of contact formation and current transport mechanism.

Scientific aim of the thesis

The research on the Ohmic contacts in this thesis aims at providing insight about the electrical transport mechanism from the metal to the 2DEG in the AlGaIn/GaN heterostructures. An in-depth study of the nature of these contacts, with emphasis on the nature of the charge transport into the 2DEG, the reactions occurring at the interfaces between the metals and the GaN would be presented. For this purpose, accurate measurement structures were designed and new characterization methods have been used.

For the Schottky gate structures, metals and alloys with the required high work function were investigated. An in-depth study of the nature of the contact was made. Phenomena specific to the AlGaIn/GaN, such as metal stack strain influence on the Schottky barrier and barrier height inhomogeneity was investigated.

Research has been performed in close collaboration with NXP Semiconductors. Measurements have been performed at NXP Eindhoven, NXP

Nijmegen and partly at University of Twente where complementary facilities and expertise exist. All samples came from NXP processing fabs.

1.5 Outline of the thesis

The thesis is organized as follows:

In *Chapter 2* a review of current technology for Ohmic and Schottky contacts to GaN and AlGaN/GaN heterostructures is presented. Different metals and metal multilayers are discussed and Au-free alternatives are analyzed.

Chapter 3 reports on method of accurate extraction of Ohmic contact parameters such as specific contact resistance and transfer length. It is the first work investigating sheet resistance under Ohmic contacts to AlGaN/GaN. Research highlights how reactions at metal-semiconductor interface affect the material under the contact and how contact parameters change when the resistance under the contact is accounted properly.

Chapter 4 presents a specific case of Ohmic contacts - so called recessed contacts where (part of) AlGaN is removed resulting in either thinner barrier to the 2DEG or even a side contact with the aim to reduce the contact resistance. Reactions under the contact are investigated and consequences of neglecting of actual value of sheet resistance under the contact are discussed.

In *Chapter 5* results of metal-stack-induced stress, on the Schottky diode behaviour are presented. The observed change in Schottky barrier height of a Ni and Ni/TiW/TiWN/TiW contact is explained by stress effects induced by the TiW/TiWN/TiW capping layer, rather than by chemical reactions at the metal-semiconductor interface.

Chapter 6 summarizes investigation on the barrier height inhomogeneity of the Schottky contacts to AlGaN/GaN. Results of material analysis together with extensive electrical measurements show characteristic inhomogeneity phenomena. Analysis of multiple wafers allows to conclude that the source of the inhomogeneity is inherent to the wafers themselves and not to the device processing nor the contact metals.

In *Chapter 7* the main results of this thesis are summarized and recommendations for further research are provided.

CHAPTER 2

STATUS OF OHMIC AND SCHOTTKY CONTACTS

Abstract

Ohmic and Schottky electrical contacts to AlGa_N/Ga_N heterostructures have been intensively investigated over the past 20 years. Most of the researchers' efforts have been focused on the gold-containing metal stacks. In this chapter an extensive literature review is presented. It is discussed what metal stacks are used for each type of contact and what are their properties. Finally, work on gold-free contacts is presented and different metal stack compositions are analyzed.

2.1 Introduction

AlGaIn/GaN High Electron Mobility Transistors (HEMTs) are promising for a variety of applications for high voltage and high-power devices. Their value stems from high breakdown voltage, high power density, stability at elevated temperatures and resistance to harsh environment conditions. Fabrication of high quality devices demands well developed contact structures, both Ohmic and Schottky. Electrical contacts used for HEMTs are mostly adapted from solutions used for GaN epilayers. Generally, gold is used as a topmost layer of the metal multilayer. Au is known as an electronic trap, it diffuses easily into silicon and due to this contamination issue, it is not allowed in silicon fabrication facilities. However for the mass production of AlGaIn/GaN devices in standard silicon fabs, this material has to be replaced with another that can be brought into the facility [38]. In this chapter Ohmic and Schottky contacts to AlGaIn/GaN heterostructures will be discussed. An overview of current technology will be presented. Materials to be used as a replacement for gold will be analyzed and a current understanding of contact formation mechanism will be discussed.

2.2 Ohmic contacts

Intensive research on GaN started after the successful growth of high quality GaN film by Hiroshi Amano in 1986 [39]. Thanks to his discovery, the world of science took up gallium nitride research and started exploring its vast application possibilities. One of the first publications which addresses the low resistance of multilayer Ti/Al¹ based contacts to GaN is the work by Lin et al. [40]. The work of Jenkins and Dow [41] is mentioned as, to the author's knowledge, the primary work in which the theoretical investigation of N vacancies in GaN acting like n-type donors was conducted. The Ohmic contact multilayer structures which are most often met in the literature are based on Ti/Al layers [40] with gold capping layer [42–44]. Gold prevents the oxidation and improves overall contact resistance [45]. However, if one wants to introduce the III-V device fabrication alongside the standard silicon devices in the same facility, gold is a material which has to be avoided.

2.2.1 Materials for Ohmic contacts

Reliable and low resistance contacts are necessary for the functioning of all electronic devices. For power transistors like AlGaIn/GaN HEMTs it is demanded to obtain the specific contact resistance as low as possible. Depending on the application ρ_c in a range of $10^{-5} - 10^{-7} \Omega \text{cm}^2$ is required [46]. As mentioned in the introduction, the majority of the contacts stacks

¹Materials from left to right correspond to the metal stack from the bottom (contact with semiconductor) to the top. Such notation will be used throughout the thesis.

contain Ti. Widely present structures are Ti/Al/Ti/Au [47], Ti/Al/Pd/Au [48] and Ti/Al/Mo/Au [49]. In this section role of each metal in such a stack will be explained.

Titanium

Titanium is the most popular metal used to make Ohmic contacts to GaN. If Ti is not oxidized, it provides a good adhesion to GaN [47]. Literature review shows that Ti/Al layer based structures are most often used material stacks for Ohmic contacts both for AlGaIn/GaN HEMTs [42–44] and GaN [50], [51]. Motayed et al. claim that Ti has the important role of reducing the GaN native surface oxide upon alloying [47]. The GaN surface has a high chemisorption for oxygen and as a result, thin insulating oxides are formed on it. The most typical is Ga_2O_3 , about 5–10 nm thick. Individual metals, such as Ti, may reduce the native oxide. Titanium has the ability to reduce Ga_2O_3 during annealing and retain a stable α – Ti phase with oxygen in solid solution. It was experimentally shown by Kowalczyk et al. that titanium reduces the Ga_2O_3 oxide [52]. There are also many procedures of chemical pretreatment to remove the oxide layer, such as HCl [53], aqua regia [48] or $\text{HF}:\text{HCl}:\text{H}_2\text{O}$ [35]. Major problem of the Ti-only and also Ti/Al contacts (i.e. contacts without capping layer) is their propensity towards oxidation. Motayed et al. [16] state that it was observed that Ti-Al based metal films suffer from oxygen contamination during alloying. They assumed that the Al_2O_3 contact formed on Al during annealing may be one of the reasons of increase in the contact resistance. The Al also tends to ball up in temperatures over 600 °C resulting in a very rough surface [52]. This fact is the reason of adding another metal to the stack, most often Ni and Au.

Aluminum

The main function of aluminum is the reduction of reactivity of Ti towards GaN as evidenced by Van Daele et al. in low-temperature annealed samples [19]. This prevents severe GaN decomposition while still forming TiN.

The N extraction by Ti is triggered by the higher enthalpy of formation of TiN with respect to GaN [54]. Van Daele et al. observed that the reaction is so aggressive that it results in voids below the TiN, as is visible in Fig. 2.1. Higher annealing temperatures enhanced the reaction resulting in larger voids and thicker TiN and TiGa on top (Fig. 2.1). This indicates that Ti can decompose GaN.

Van Daele et al. [19] claim that Al should be present to reduce the aggressive Ti-GaN reaction. However, there should be enough Ti left to form a titanium nitride layer at the interface. On the other hand, too much Ti leads to the formation of voids below TiN. A high Ti/Al relative thickness is required to penetrate through AlGaIn and a low Ti/Al relative thickness is needed for a reduced interface reaction.

Figure 2.1: HAADF image of a Ti/GaN contact annealed at 805 °C. The black region at the TiN/GaN interface is a void. The arrow indicates the scan trace of the EELS profile shown on the right-hand side. The EELS profile shows the normalized intensity for each element. Ga can be found in the Ti layer above the TiN. Reprinted from B. Van Daele, G. Van Tendeloo, W. Ruythooren, J. Derluyn, M. R. Leys, and M. Germain, "The role of Al on Ohmic contact formation on n-type GaN and AlGaIn/GaN," *Applied Physics Letters*, vol. 87, p. 061905, aug 2005, with the permission of AIP Publishing.

Nickel, Molybdenum and other blocking layer metals

Most metal stacks to III-V include a blocking layer between Ti/Al and the capping layer. Most often used materials are Ni, Mo, Pd, Pt or Ti [45]. Nickel prevents the Ti and Al oxidation during alloying and also is believed to be inter diffusion barrier for Au and Al [47]. It is deposited to avoid the creation of highly resistive 'purple plague' [55]. Xin et al. claim that Ni thickness is the dominant factor which affects the contact resistance of Ti/Al/Ni/Au ohmic metal stack [56]. They also provide the optimum Ni:Au ratio 1.8:1 which yields flat surface morphology and low resistance ohmic contact.

Gold and alternative metals

Au coating is most often employed to improve oxidation resistance of Ti and Al [46] and also its thickness dominantly affects surface morphology [56]. The gold layer should also prevent the oxidation during high temperature annealing [46]. It also improves the contact resistance by formation of conductive phases inside the entire metal stack [57] and at the interface [58]. Gold free contact to AlGaIn/GaN received some attention recently [59–61] and scientists try to provide solutions which can be employed at

Figure 2.2: Bright-field TEM image taken in GaN 0002 two-beam diffraction condition. The Ti/GaN contact annealed at high temperature shows large voids at the metal/nitride interface. Reprinted from B. Van Daele, G. Van Tendeloo, W. Ruythooren, J. Derluyn, M. R. Leys, and M. Germain, "The role of Al on Ohmic contact formation on n-type GaN and AlGaIn/GaN," *Applied Physics Letters*, vol. 87, p. 061905, aug 2005, with the permission of AIP Publishing.

silicon fabs.

For example Lee et al. [59] investigated contacts to AlGaIn/GaN heterostructure on Si substrate and chose a Ti/Al layer as a base of the metal stack and decided for tungsten cap layer. The tungsten layer prevents the oxidation of Al layer.

What was important in Lee's et al. approach is the recessed contact. It provides a tenfold reduction in contact resistance comparing to planar structures. The authors evaluated different etch depths and received lowest resistance after complete removal of the AlGaIn layer. This however, puts in question the legitimacy of using the concept of specific contact resistance ($\text{Ohm}\cdot\text{mm}^2$) as the sidewall contact of metal to the two-dimensional electron gas is created ($\text{Ohm}\cdot\text{mm}$). The calculated value of specific contact resistance is $6.5 \cdot 10^{-6} \Omega\text{cm}^2$

It was shown, that recessed contacts showed ohmic behavior after annealing at 800°C in contrast to anneals above 900°C that were needed for samples without recess etch. Malmros et al. [62] were investigating other material systems - Ta/Al/Ni(Ta)/Au and Ta/Al/Ta. The latter proved to have lower contact resistance. One of the major advantages of using Ta-based stack is lower annealing temperature, below 600°C . This results in better surface morphology and also good edge acuity.

Figure 2.3: Schematic cross section of AlGaIn/GaN HEMT with ohmic recess (a) and SEM image of the cross section of a Ti/Al/W contact after annealing. The contact region was recessed about 30 nm (b) [59]. ©2011 IEEE.

The contacts were prepared without any plasma pre-treatment on two different AlGaIn/GaN epilayers, one with 3 nm cap and the other without it. Authors found the optimal RTA temperature to be 550 °C for which they obtained best R_c of 0.06 Ω mm on the sample with GaN cap layer. The optimal Ta/Al ratio was also calculated. The best contact performance was achieved at 1:28 ratio. Malmros et al. claim that Ta extracts nitrogen from GaN leaving N vacancies responsible for conduction mechanism in such structure.

2.2.2 Formation of Ohmic contact to AlGaIn/GaN

III-V semiconductors, especially nitrides, attract attention of many researchers. So far most of the work on contacts to AlGaIn/GaN has been devoted to Au-containing contacts, without a lot of attention paid to alternative metal stacks.

Most often addressed problems are:

- RTA temperature and time
- Metal stack composition and ratios
- Temperature performance and reliability
- Formation of TiN
- Alloying of metals in the stack

While different groups have obtained high-quality Au-free contacts [59–61], the topic is still not fully explored.

Table 2.1: Work function of different metals.

Metal	Work function (eV)
Ga	3.96
Al	4.28
Ti	4.33
Ni	5.15
Au	5.10
Ta	4.25

When analyzing the contact formation mechanism, it is very important to distinguish the contact to bulk GaN and contact to AlGaIn/GaN HEMT. The latter is more complicated as it is needed to have transition from three to two-dimensional system and vice versa. Because the contacts to bulk GaN were investigated intensively it is widely popular to adapt successful solutions to the GaN heterostructures.

Formation of Ohmic contacts to GaN is generally very difficult unless some metal-semiconductor interaction takes place and/or the semiconductor is altered (for example by an RIE process) in a way that the electron concentration is increased [63]. In Table 2.1 different metal work functions are presented. As one can see, there is no metal with work function low enough to form ohmic contact to GaN. This excludes the possibility of thermionic emission to be a mechanism for carrier transport through the contact [63].

Titanium, most popular metal for ohmic contacts, with a work function of 4.33 eV forms a Schottky contact to GaN with the electron affinity 4.1 eV [47]. Despite that, it is possible to fabricate ohmic contacts to GaN using titanium. After RTA (at different temperatures, ranging from 600 °C to even 900 °C) the contact characteristics change from non Ohmic into Ohmic. The RTA step induces complicated changes in the GaN [64]:

- formation of TiN through extraction of nitrogen from GaN
- in- and outdiffusion of metals in the stack and alloying
- GaN and AlGaIn penetration by TiN along threading dislocations

The low barrier mechanism requires compounds having intermediate work function and nitride compounds, such as TiN, are possible candidates [44]. TiN which is a semi metal with a work function of 3.74 eV can provide ohmic contacts to GaN [44]. It was also shown that TiN penetrates the GaN and AlGaIn layer along threading dislocations and provides a direct contact to the 2DEG [44], [64]. At the annealing temperature of 850 °C for Ti/Al/Mo/Au Wang et al. showed that TiN islands formed along the threading dislocations penetrate past the 2DEG plane. These discrete TiN

islands are preferentially formed along dislocations due to either rapid diffusion of atoms along dislocations or preferred TiN nucleation at these low energy sites. Electrons can flow from the 2DEG to the metal layer through these TiN islands, and this could be a more efficient carrier transport means than tunneling through the insulating AlGaIn [64].

The main disadvantage of the TiN protrusions is the possibility of 2DEG degeneration. TiN spikes may increase the electron scattering, what would result in 2DEG mobility reduction. Therefore the contact resistance could become dependent mainly on this mechanism, and possibly the carrier density change [49]. Moreover, the quality of the contact becomes very dependent on the quality of the AlGaIn/GaN in a way that a high quality with low dislocation density will have less of these protrusions and consequently have poorer contacts.

Yow-Jon et al. showed that the formation of TiN on n-GaN occurs above 600 °C [65]. They also claim, basing on their XPS measurements, that the Ohmic behavior of the contacts can be attributed to the presence of a large number of nitrogen-vacancy-related defects and not to the formation of lower barriers at the annealed Ti/n-GaN interface.

Tunneling of electrons is thought to be possible thanks to the out diffusion of nitrogen and the formation of a TiN layer, due to the formation of N vacancies heavily n-doped layer in the semiconductor is formed [44].

While analyzing the currently available literature a few conclusions can be drawn:

- It is commonly believed that Ti forms TiN on GaN and creates N vacancies in GaN but there is no direct experimental confirmation of the existence of those vacancies. The N vacancies lead to n-type doping of the GaN
- Manipulation of metal layer thickness ratios highly influences the contact resistance
- Above mentioned layer composition is affected by RTA temperature and also by the temperature gradient [42]

Temperature performance

Iucolano et al. decided to study the influence of annealing temperature on the temperature dependence of the specific contact resistance [46]. They have shown that Ti/Al/Ni/Au contacts are rectifying up to the annealing temperature of 650 °C. Only after increasing the RTA temperature to 700 °C the contacts became ohmic. They carried out Transfer Length Method (TLM) measurements of samples annealed at two different temperature regimes, 600 °C and 800 °C in a measurement range of 25 °C to 175 °C. The specific contact resistance values are presented in Fig. 2.4.

The experimental data in Fig. 2.4 were fitted using the theoretical expressions of ρ_c based on the different models of current transport through

Figure 2.4: Specific contact resistance to n-type GaN as a function of the sample temperature during measurements. The fit was obtained using the TFE model for the sample annealed at 600 °C and the FE model for the sample annealed at 800 °C. Reprinted from F. Iucolano, F. Roccaforte, A. Alberti, C. Bongiorno, S. Di Franco, and V. Raineri, “Temperature dependence of the specific resistance in Ti/Al/Ni/Au contacts on n-type GaN,” *Journal of Applied Physics*, vol. 100, no. 12, pp. 123701–123706, 2006, with the permission of AIP Publishing.

metal/semiconductor contacts, i.e., thermionic emission (TE), thermionic field emission (TFE), and field emission (FE).

Samples annealed at 800 °C were described by the FE model. Iucolano’s group, basing on their results, the linear I-V characteristics and the reduction of ρ_c observed by increasing the annealing temperature from 600 to 800 °C, claimed that the conduction mechanism is based on the tunneling of the carriers through a lower Schottky barrier [46].

Iucolano et al. presented also the TEM cross section micrographs of the samples annealed at 600 and 800 °C (Fig. 2.5). These two annealing temperatures are reported since they illustrate the distinct contact morphology observed before and after the transition from Schottky to Ohmic behavior.

2.3 Schottky contacts

Schottky contacts are crucial elements in diodes and transistors. Despite intensive research on those contacts to AlGaIn/GaN heterostructures, obtaining high barrier and near-ideal behaviour remains challenging. There are several issues, such as for example adhesion [66], thermal stability [67] or metal diffusion during the annealing [68]. In recent years, substantial effort has been focused on the electrical properties of various Au-free Schottky metal stacks [69–71]. In this section properties of those metals will be discussed.

Figure 2.5: Cross section TEM micrographs of sample annealed at 600 °C (left) and 800 °C (right). Reprinted from F. Iucolano, F. Roccaforte, A. Alberti, C. Bongiorno, S. Di Franco, and V. Raineri, “Temperature dependence of the specific resistance in Ti/Al/Ni/Au contacts on n-type GaN,” *Journal of Applied Physics*, vol. 100, no. 12, pp. 123701–123706, 2006, with the permission of AIP Publishing.

2.3.1 Materials for Schottky contacts

Typically metals with high work function are used for Schottky contacts [72] as based on the Schottky-Mott relationship [73] they should result in the high barrier. Those materials could be for example nickel, platinum or palladium. So far, the most often used in AlGaIn/GaN technology is nickel [17, 74, 75]. Similarly to Ohmic contacts, also in Schottky stacks gold is used as a capping layer [14, 15]. The alternatives considered are for example WN [70], Ti [76], TiN [69] or TiWN [77]. The choice of contact material will influence various parameters such as barrier height but also adhesion, chemical stability or interfacial compositions.

Nickel

Nickel is a material of choice for Schottky contact to AlGaIn/GaN as it has low electrical resistivity and does not form compounds at low temperatures. It also has high barrier height. On the other hand, Ni etching using standard Si production tools is difficult and alternative process flow using an ion beam etch tool has to be used. Ofuonye et al. reported a comprehensive electrical and microstructural characterization of Ni/Au and Ni/Pt/Au Schottky contacts [15]. Contacts underwent thermal anneal temperatures up to 575 °C. The Pt-including metallization improved the performance of the as-deposited Schottky behavior. However, annealing at temperatures above 500 °C degraded the performance due to the formation of Ni-Pt phases causing the Ni to diffuse upward into the Pt and creating mixed

interfaces, which resulted in the lowering of the Schottky barrier heights. For Ni/Au metallization, the uniform accumulation of Au at the interface (Fig. 2.6) contributed to the increase of Schottky barrier heights and also the stability of the contacts.

Figure 2.6: High resolution STEM images of Ni/Au on AlGaIn/GaN after 500 °C annealing for 1 h, (a) and (b), showing accumulation of Au at the metal-AlGaIn interface. ©IOP Publishing. Reproduced with permission. All rights reserved [15]

Qiao et al. studied the dependence of the Schottky barrier height of Ni/ $\text{Al}_x\text{Ga}_{1-x}\text{N}$ contact on the Al mole fraction up to $x = 0.23$ [74]. For low aluminum content ($x < 0.2$), a positive linear relationship between the barrier height and the Al mole fraction was observed. The barrier height for the sample with $x = 0.23$ was smaller than the value predicted by Schottky rule. Authors believe it has been caused by a high density of interface defects.

Titanium

Titanium is rarely used for Schottky contacts, as it typically is used for Ohmic stacks. Nevertheless, it has been investigated in few publications. For example, Yu et al. studied Ni and Ti Schottky barriers on n-AlGaIn [78]. The obtained barrier height for Ti was 20% lower than for Ni reference devices, as expected. Another work investigating Ti Schottky on n-GaN was the work by Binari et al. [76]. The group has found that Ti has considerably lower barrier height than Au. According to authors that indicates that the Fermi level is not pinned at the surface. Arulkumaran et al. [79] investigated annealing effects on Ti Schottky diodes on n-AlGaIn. For all annealing times and temperatures (in the range of 100 °C - 550 °C), the Ti contact showed almost 50% lower barrier height than the reference Ni.

Given that the Ti yields low barrier height and is generally not comparable to alternatives such as Pd or Ni, it has not been investigated more. Most of the work on Ti Schottky contact has been done for GaN or AlGaIn contacts but not for AlGaIn/GaN heterostructures. Titanium contacts generally exhibited poor rectification in all cases or even n-type (Ohmic) contact to n-GaN.

Titanium nitride

Li et al. [80] report results of applying TiN gate for AlGaIn/GaN HEMT. The sputtered TiN exhibits an improved Schottky barrier height (SBH) of 1.1 eV. Authors claim that the improvement of SBH is due to the increase of metal work function either by the incorporation of oxygen in sputtered TiN or by using a high N₂/Ar ratio during the sputtering process. With reference to the device with conventional Ni/Au gate, slight increase in the dynamic- R_{on} was observed. Ao et al. investigated thermal stability of the TiN Schottky contact on AlGaIn/GaN heterostructure [81]. The TiN film was formed by reactive sputtering in Ar and N₂ ambient by DC magnetron sputtering. No obvious degradation was found in the Schottky contact when the device was thermally treated at 600 °C for 1 h or 850 °C for several minutes. Authors observed an increase in TiN sheet resistance after the annealing what might be attributed to oxidation of the material.

Tungsten nitride and titanium tungsten nitride

Tungsten nitride has been explored as a viable alternative for forming Schottky contact to n-GaN [77]. WN_x has been observed to form $\beta - W_2N$ phase. The WN_x Schottky contact to n-GaN was thermally stable up to 850 °C, and the ideality factor and the barrier height remained at 1.10 and 0.80 eV, respectively after 850 °C annealing. Lu explored enhancement of the Schottky barrier height using a nitrogen-rich tungsten nitride thin film [82]. They have investigated tungsten, stoichiometric W_2N , and nitrogen-rich W_2N films as contacts on AlGaIn/GaN. The diode with the nitrogen-rich film exhibited a higher Schottky barrier height and the leakage current was comparable to that of the Ni/Au Schottky contact. Lu concludes that this was due to the increase of the tungsten nitride work function as the result of higher nitrogen incorporation. It is noteworthy that although good contact parameters have been obtained, they were still worse than the reference Ni/Au stack (see Fig. 2.2).

Lu et al. [82] obtained WN_x films by reactive DC sputtering, on AlGaIn/GaN heterostructures. The nitrogen content in the film was controlled by varying the nitrogen-to-argon gas flow ratio during the reactive sputtering deposition. The obtained leakage current of $10^{-6} A/cm^2$ value was lower than that of a Ni/Au reference diode. Lu shows that tungsten nitride can not only improve the leakage current, but also improves the thermal stability of Schottky contacts on AlGaIn/GaN. Hsieh et al. [83] look

Table 2.2: Contact parameters of WN_x Schottky metals on AlGaIn/GaN [82].

Conditions	Barrier height (eV)	Ideality factor	N content (%)
Tungsten	0.89	1.15	
WN_x gas flow ratio 0.2	1.07	1.42	34
WN_x gas flow ratio 0.5	1.21	1.24	48
Ni/Au	1.37	1.16	

specifically for WN_x as a replacement for the standard Ni/Au metals stack. The Schottky barrier heights of the WN_x gate metal on AlGaIn were 0.84 eV, 0.82 eV, and 0.78 eV for the device before, and after thermal annealing at 400 °C and 600 °C respectively. The refractory metal nitrides exhibit excellent thermal stability and are suitable materials to be used as Schottky contact to AlGaIn/GaN. Lee et al. [77] analyzed Schottky characteristics of the $TiWN_x/n - GaN$. In their work contact remained stable up to 650 °C annealing with the ideality factor and the barrier height remaining constant at 1.14 and 0.76 eV, respectively. The contact degraded after 750 °C annealing and Ohmic-like behavior is observed after 850 °C annealing. This is due to mixing of materials at M-S interface as shown in Fig. 2.7.

2.4 Summary

In conclusion, during the last two decades the Ohmic and Schottky contacts technology to GaN and AlGaIn/GaN were researched intensively, yet there are still many unanswered questions. There is still discussion about formation of N vacancies in GaN due to Ti in the Ohmic stack. Similarly, there is no agreement about current transport mechanism. Lee's and Malmros' research on Au-free Ohmic contacts look promising for the application in real devices. The contact resistance achieved by them is sufficient to produce high-quality structures. The further investigation should be devoted to recess contacts based on both Ti and Ta. Schottky contacts on the other hand suffer from other problems. There are not many alternatives to the commonly used Ni/Au stack. Most of the research on Schottky contacts has been conducted on Au-containing stacks, hence the gold free alternatives may exhibit new unexpected behaviors.

Figure 2.7: SIMS depth profiles of the $\text{TiWN}_x/\text{n-GaN}$ contacts after thermal treatments (a) As-deposited; (b) After 650 °C RTA; (c) After 850 °C RTA and of the $\text{WN}_x/\text{n-GaN}$ contacts after thermal treatments, (d) As-deposited; (e) After annealing at 650 °C; (f) After annealing at 850 °C. ©IOP Publishing. Reproduced with permission. All rights reserved [77]

SURFACE OHMIC CONTACTS

Abstract

For the determination of specific contact resistance between metal and semiconductor the sheet resistance under the contact is usually assumed either to be identical to that between the contacts or known from some other measurements. This generally does not hold for contacts to AlGaIn/GaN structures where an effective doping under the contact is thought to come from reactions between the contact metals and the AlGaIn/GaN. As a consequence, one can not assume identical resistances and extraction of the resistance under the contact from other test structures is not straightforward without removing the metal. In this chapter, the sheet resistance under gold-free Ti/Al-based Ohmic contacts to AlGaIn/GaN heterostructures on Si substrates have been investigated by means of electrical measurements, transmission electron microscopy (TEM) and technology computer-aided design (TCAD) simulations. It was found to be significantly lower than that outside of the contact area; temperature-dependent electrical characterization showed that it exhibits semiconductor-like behavior. The increase in conduction is attributed to n-type activity of nitrogen vacancies in the AlGaIn. They are thought to form during rapid thermal annealing of the metal stack when Ti extracts nitrogen from the underlying semiconductor. The high n-type doping in the region between the metal and the 2-dimensional electron gas (2DEG) pulls the conduction band towards the Fermi level and enhances electron transport through the AlGaIn. Using this improved understanding of the properties of the material underneath the contact, accurate values of transfer length and specific contact resistance have been extracted.

This Chapter is based on the following publication: *Sheet resistance under Ohmic contacts to AlGaIn/GaN heterostructures* Hajlasz, M. and Donkers, J. J. T. M. and Sque, S. J. and Heil, S. B. S. and Gravesteijn, D. J. and Rietveld, F. J. R. and Schmitz, J., Applied Physics Letters, 104, 242109 (2014), DOI:<http://dx.doi.org/10.1063/1.4884416>

3.1 Introduction

Ohmic contacts to AlGaIn/GaN have been studied for many years already [55, 62, 63, 84, 85], yet there is no consensus on either the optimum contact structure or on the current transport mechanism. When evaluating the parameters of the Ohmic contacts, two of the frequently used methods are the linear transfer length method (LTLM) and the circular transfer length method (CTLM) [12–14, 49]. LTLM test structures, originally proposed by Shockley [86] and further developed simultaneously by Berger [87] and Murrmann and Widmann [88] are easy to design and fabricate and convenient to characterize. They are however prone to errors coming from simplifying assumptions. One key assumption in this method is that the sheet resistance outside of the contact area (R_{sh}) and the sheet resistance under the contact (R_{sk}) are identical. Since the 2-dimensional electron gas (2DEG) is sensitive to surface conditions [89] and stress, and also because during the rapid thermal annealing there are reactions occurring at the interface between metal and semiconductor [55, 64], this assumption is most likely invalid. In this chapter different test structures used for extracting Ohmic contacts' parameters are presented and compared based on their suitability for the AlGaIn/GaN material system. With the use of proper test structure the extraction of the sheet resistance is done. We show why neglecting the changes in the semiconductor under the Ohmic stack leads to large errors in the extracted parameters. At last, possible current transport mechanisms in the Ohmic contacts to AlGaIn/GaN are discussed.

3.2 Test structures

3.2.1 Types of test structures

Measuring the contact resistance is a procedure which is simple in principle but requires a lot of attention when analysing non-silicon semiconductors. The often-occurring problem with the standard test structures is that they were developed for silicon devices and some simplifying assumptions which hold for Si, are no longer valid for materials such as III–V semiconductors for example. What is more, due to the advancements in technology we are able to reduce the contact resistance significantly but that makes the accurate characterization even more difficult. Therefore, non-standard test structures have to be used and the complete extraction process becomes more elaborate. Nevertheless the standard structures [90] are still used for various reasons. One of the most often used test structure, CTLM, owes its popularity due to simple design and simplicity of use. Due to the circular design there is no need to provide electrical isolation by means of mesa etch or by ion implantation. LTLM structures, on the other hand, require isolation but represents real-life devices better (as they are rectangular) and are more convenient in the industrial setting as it allows automatic characterization thanks to the possibility to make large bondpads. Cross-Bridge

Kelvin Resistors (CBKR) are also often used to characterize contacts, but its accuracy (in its simplest form) is also limited. In this section parameters of Ohmic contacts are described and application of different test structures to characterize Ohmic contacts to AlGaIn/GaN devices is discussed.

Circular Transfer Length Method

The Circular Transfer Length Method is popular for measuring Ohmic contact parameters. The test structure consists of pairs of two metallic contact regions: an inner circle and an outer ring with a gap between them. Complete test structure has set of such pairs of contacts with different gap length, varying between few μm and tens of μm .

This structure is often used mainly because of two reasons. Firstly, thanks to the circular design the current has only one path to flow between inner circle and outer ring metal contacts (see Fig. 3.1). Secondly, since there is no need for isolation the problem with the isolation size being different than contact size can be avoided.

Figure 3.1: Schematic of a CTLM test structure.

When assuming identical sheet resistance under the contact and between the contacts, the total resistance between the two contacts is [90]:

$$R_T = \frac{R_{sh}}{2\pi} \left[\frac{L_T}{L} \frac{I_0(L/L_T)}{I_1(L/L_T)} + \frac{L_T}{L+d} \frac{K_0(L/L_T)}{K_1(L/L_T)} + \ln \left(1 + \frac{d}{L} \right) \right] \quad (3.1)$$

where I and K denote the modified Bessel functions of the first order. R_{sh} is the sheet resistance, L is the inner contact radius, d is the gap width and L_T is the transfer length. For $L \gg 4L_T$, the Bessel function ratios I_0/I_1 and K_0/K_1 tend to unity and R_T becomes:

$$R_T = \frac{R_{sh}}{2\pi} \left[\frac{L_T}{L} + \frac{L_T}{L+d} + \ln \left(1 + \frac{d}{L} \right) \right] \quad (3.2)$$

For $L \gg d$, Eq. (3.2) simplifies to:

$$R_T = \frac{R_{sh}}{2\pi} (d + 2L_T) C \quad (3.3)$$

where C is the correction factor

$$C = \frac{L}{d} \ln \left(1 + \frac{d}{L} \right) \quad (3.4)$$

For $d \ll L$, Eq. (3.3) simplifies to

$$R_T = \frac{R_{sh}}{2\pi L}(d + 2L_T) \quad (3.5)$$

Application of the correction factor is needed to be able to obtain linear fit to the experimental data [90]. Without doing this, the specific contact resistance is underestimated.

When we know the total resistance between two contacts we can apply the correction factor (Eq. 3.4, for $L \gg d$) and plot it as a function of distance between them like in Fig. 3.2. After linear interpolation of the measurement data $2R_c$ can be obtained from the cross section with y-axis and $-2L_T$ can be obtained from the cross section with the x-axis. Sheet resistance is obtained from the slope of the curve.

Figure 3.2: R_T vs d for a CTLM test structure [90]. ©2006 John Wiley & Sons, Inc.

In this way, calculating the specific contact resistance is straightforward but limited to some extent by the simplifying assumptions. Main limitation of CTLM for AlGaIn/GaN devices is the assumption of the identical semiconductor sheet resistance under the metallic contact and in the region between the contacts. While this holds for silicon devices, it is not so obvious for AlGaIn/GaN where contacts receive thermal treatment at elevated temperature, usually above 700 °C [91].

Cross-Bridge Kelvin Resistor

Having in mind limitations of a CTLM structure one could think of a method in which knowing the resistance of the semiconductor is not needed to determine the contact resistance. One structure which allows such measurements is the Cross-Bridge Kelvin Resistor (CBKR) which was used for evaluating metal-semiconductors contacts in 1972 for the first time [92]. This structure has been evaluated seriously later on in the 1980s [93–95]. CBKR is often used as a convenient structure for the Process Control Module (PCM) to characterize the specific contact resistance. In

the simplest form it requires only one structure with conveniently located bond pads. An example of such test structure is presented in Fig. 3.3.

Figure 3.3: Schematic of Cross-Bridge Kelvin Resistor structure [90].©2006 John Wiley & Sons, Inc.

To make the measurement current is forced between contacts 1 and 2 (I_{12}) and voltage is measured between contacts 3 and 4 (V_{34}). Kelvin resistance can be then expressed as:

$$R_k = \frac{V_{34}}{I_{12}} \quad (3.6)$$

Assuming the simple 1D-Model approach [96] the specific contact resistance can be then calculated:

$$\rho_c = R_c A = R_k A \quad (3.7)$$

Severe limitation of this otherwise good model lies in the ignoring current flowing in the overlap region (δ) between the contact edge and the underlying layer sidewall [90]. In the ideal case with $\delta = 0$ (Fig. 3.4), the voltage drop is $V_{34} = IR_c$. For $\delta > 0$ (Fig. 3.4 (b)), the lateral current flow gives an additional voltage drop that is included in V_{34} , leading to higher R_k .

In that case the 2D-Model proposed by Schreyer and Saraswat should be applied to correct for current crowding effects [96]. The measured R_k is then a sum of the R_c and the resistance R_{geom} , due to the current flow around the contact in the overlap region (Eq. (3.8)). The ρ_c can further be extracted from Eq. (3.9), where R_{sh} is the sheet resistance of the underlying layer.

$$R_k = R_c + R_{geom} \quad (3.8)$$

Figure 3.4: Four-terminal contact resistance test structures. (a) Ideal with only lateral current flow, (b) showing current flowing into and around the contact. The black area is the contact area [90]. ©2006 John Wiley & Sons, Inc.

$$R_k = \frac{\rho_c}{A} + \frac{4R_{sh}\delta^2}{3W_xW_y} \left[1 + \frac{\delta}{2(W_x - \delta)} \right] \quad (3.9)$$

CBKR structures have some tradeoffs related to the size of δ but also the contact size. The most accurate measurement using CBKR can be done when both δ and A are varied. The reason to do this is to obtain true R_k from the interpolation of $R(\delta)$ at $\delta = 0$. Variation in contact size needs to be done to avoid underestimating the resistance as not whole contact area may be involved in current transport, especially in case of the very large contacts. Consequently the number of structures to be put on a die and characterize, proliferates extremely fast. With the always-smaller space devoted to test structures and high price of GaN wafers this makes CBKR nor preferred for an accurate specific contact resistance analysis. One needs to notice that for the CBKR 2D-Model the semiconductor sheet resistance has to be known. This requires yet another structure and in the end renders the method, though accurate, even less effective.

Linear Transfer Length Method

LTLM is probably most often used structure to characterize Ohmic contacts. The parameter extraction method is in principle similar to the one of CTLM structure. In the standard LTLM contact-front resistance (R_{cf}) measurement (Fig. 3.5. (a)) a current I_{12} is forced between contacts 1 and 2 and the resulting voltage V_{12} between them is measured. We assume identical sheet resistances in the whole sample ($R_{sh} = R_{sk}$). The measured resistance for a given contact separation d is then described with the following equations

[90]:

$$R_T = \frac{V_{12}}{I_{12}} = \frac{R_{sh}d}{Z} + 2R_{cf} \quad (3.10)$$

$$R_{cf} = \frac{\sqrt{R_{sk}\rho_c}}{Z} \coth\left(\frac{L}{L_{Tk}}\right) = \frac{\rho_c}{L_{Tk}Z} \coth\left(\frac{L}{L_{Tk}}\right) \quad (3.11)$$

where R_T is the total resistance between the two contacts, R_{cf} is the contact-front resistance, ρ_c is the specific contact resistance, R_{sh} is the sheet resistance between the contacts, R_{sk} is the sheet resistance under the contact, Z and L are contact width and length, respectively, and L_{Tk} is the transfer length (extracted from the extrapolated R_T vs. d plot at $R_T = 0$).

However, to get reliable values for the transfer length and specific contact resistance in the AlGaIn/GaN material system, the sheet resistance under the contact must be known. To measure it we use the contact-end resistance (R_{ce}) method (Fig. 3.5(a)), which was first proposed by Reeves and Harrison [97]. In this method the current is forced between contacts 1 and 2 but the voltage is measured between contacts 2 and 3 (Fig. 3.5(b)). Since there is no current flow between them, the potential at $V_{3'}$ is equal to the measured potential V_2 so the voltage drop across the 2DEG/AlGaIn/metal is effectively measured. We assume that the metal is equipotential and that its resistance is negligible compared to that of the semiconductor. R_{ce} is equal to:

$$R_{ce} = \frac{V_{22}}{I_{12}} = \frac{\sqrt{R_{sk}\rho_c}}{Z} \frac{1}{\sinh\frac{L}{L_{Tk}}} = \frac{\rho_c}{L_{Tk}Z} \frac{1}{\sinh\frac{L}{L_{Tk}}} \quad (3.12)$$

Since the transfer length value extracted from the R_T (d) plot is correct only when $R_{sk} = R_{sh}$, we instead have to calculate it from the R_{ce}/R_{cf} ratio:

$$\frac{R_{ce}}{R_{cf}} = \frac{1}{\cosh\frac{L}{L_{Tk}}} \quad (3.13)$$

Knowing that:

$$L_{Tk} = \sqrt{\rho_c/R_{sk}} \quad (3.14)$$

we can extract L_{Tk} , ρ_c and R_{sk} from equations (3.12), (3.13) and (3.14)

To extract accurate contact parameters with the R_{cf} method, the length (L) of the contact has to be at least 1.5 times longer than the transfer length (L_{Tk}) [90]. Since L_{Tk} is not known upfront, the designed L is often up to 50 – 100 times longer. Consequently the voltage drop between contacts 2 and 3 is very low and hence difficult or even impossible to measure. Hence, these structures with appropriate length need to be used.

Figure 3.5: (a) Schematic of R_{cf} and R_{ce} measurements, where V_{12} is measured for the R_{cf} and V_{23} for the R_{ce} , (b) Cross-section of the structure from (a).

3.3 Device description

The investigated samples come from NXP Semiconductors' GaN-on-Si process technology, with Ti/Al-based gold-free Ohmic contacts made in a silicon nitride passivation-first integration scheme [98]. The aluminium layer is a few times thicker than the titanium and the Ti/Al ratio was optimized in order to obtain lowest contact resistance. This ratio is comparable to those used by different research groups [99–101]. Test structures are patterned by dry etching and isolation is obtained using argon ion implantation. Ohmic contacts receive rapid thermal annealing (RTA) treatment at an optimized temperature within a 800 – 900 °C range, which is typical for contacts to AlGaIn/GaN [99, 100]. The top layers of the wafers used in this experiment consist of 1.5 μm of GaN with 20 nm of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}$ and a 3 nm GaN cap, prepared by metalorganic chemical vapor deposition (MOCVD). A schematic of the structure with the Ohmic contact is shown in Fig. 3.6. An SEM cross section of the actual Ohmic contact is shown in Fig. 3.7.

An HP 4155C semiconductor parameter analyzer has been used for

Figure 3.6: Schematic of device structure with a surface Ohmic contact.

Figure 3.7: Cross section of a surface Ohmic contact.

electrical characterization and a FEI Tecnai F30 transmission electron microscope (TEM), equipped with an energy-dispersive X-ray (EDX) spectrometer, for material composition investigation. Technology computer-aided design (TCAD) simulations were conducted with Taurus Medici from Synopsys.

3.4 Material analysis

Ohmic contact properties are determined by the interface between metal and the semiconductor. Any changes in this interface would have profound influence on the contact resistance. Source of the interface changes can be of different origin, e.g. metal stack alloying, chemical reactions of metal

and semiconductor or metal protruding via the semiconductor threading dislocations. Those effects do not require special attention with respect to the test structure choice as long as the sheet resistance of the semiconductor remains unaffected. As discussed in 3.2, standard test structures are capable of correctly extracting the device parameters under the assumption of unchanged sheet resistance. If however, any change in R_{sh} is expected, then the appropriate test method has to be applied.

Figure 3.8: Edge of an unannealed Ohmic contact.

In the investigated devices Ti is the metal of choice to form an Ohmic contact to GaN. One important feature of Ti is the N extraction from GaN, triggered by a higher enthalpy of formation of TiN with respect to GaN [102]. This means that if the TiN formation occurs we have to take into account possible changes in the semiconductor and use of standard contact resistance test structures would no longer be possible. To analyse the devices structure multiple TEM investigations have been conducted, using a transmission electron microscope, equipped with an energy-dispersive X-ray. At first we looked at the as-deposited structure to be able to distinguish later on between deposition and RTA related effects. In Fig. 3.8 an edge of an unannealed Ti/Al Ohmic contact is shown. Such structure needs to be analysed to determine if there are any reasons to expect change in the R_{sh} . This change can be related to processing in steps prior to metal deposition as well as to contact deposition itself. To distinguish between the different mechanisms, we first look at the cross section of a structure which has not received the annealing.

The interface between Ti and GaN visible in Fig. 3.8 is not smooth but is quite uniform, with very good edge coverage. Comparing to the interface between SiN and GaN it can be observed that the metal is located below the region where the top of the semiconductor should be located. This can mean that either part of the GaN was removed during opening the passivation layer or that there were some reactions between Ti and GaN and the interface moved slightly towards the semiconductor side. Etch of

Figure 3.9: Brightfield HRTEM image of the center of an unannealed Ti/Al Ohmic contact to AlGaIn/GaN.

the opening in the SiN passivation layer could be one of the reasons that GaN is affected. The dielectric is removed in dry etching process using SF_6 , so some overetch might be present [103]. Alternatively, the position of the interface could be related to the GaN native oxide formation, as GaN readily oxidizes at the room temperatures and forms Ga_2O_3 [104]. This means that after removal of the passivation layer, GaN would be covered with the oxide. This oxide is then removed during cleaning process before Ohmic metal deposition. This cleaning procedure may result in the small shift of the position of top of the GaN, because part of the material would be removed.

Looking further in the center of the device (Fig. 3.9) one can see that the metal / semiconductor interface is uniform there. Knowing the device structure before annealing we will be able to observe influence of the RTA treatment on the contact.

As-deposited Ti/Al metal stacks require high-temperature annealing to become Ohmic. During the annealing, processes occur at the metal / semiconductor interface. Depending on the annealing temperature, reaction within the metal stack as well as between metal and semiconductor can occur. Therefore material analysis of the annealed contact has to be conducted for each annealing conditions. In order to understand mechanisms governing the investigated Ohmic contacts formation, several TEM micrographs of the contacts annealed at 875 °C have been made. In Fig. 3.10 (a) and edge of the device (identical as in Fig. 3.8) is shown. Two main observations can be made from this micrograph. Firstly, the interface between metal and GaN is now located about 7 nm below the original interface. Secondly, the device edge is no longer perfectly uniform and there is a dark area at the edge. This region is most likely a titanium silicide which is formed during annealing due to a reaction between the SiN and Ti, as silicides can be formed at relatively low temperatures as low as 300

°C. Lastly, the SiN layer on GaN remains unchanged, proving to be a good passivation material.

Figure 3.10: Bright field TEM cross-section of the Ohmic contact edge: (a) TEM cross-section showing the reaction layer going from the metal downwards into the AlGaN; (b) Scanning transmission microscopy (STEM) overview of the area sampled in the EDX scan. Red lines indicate regions investigated with EDX and presented in (c) and (d); (c) EDX profile of the line scan from (b) indicating TiN presence; (d) EDX profile of an interface region where TiN has not formed.

The 7 nm thick layer which can be distinguished at the metal/AlGaN interface is not present in the unannealed samples as visible in Fig. 3.8 and 3.9. To verify the composition of this additional layer, EDX scan has been taken across the affected regions. We know from Chapter 2 that one of the expected alloys in such structure could be TiN. Unfortunately, EDX is not sensitive enough to detect light elements such as nitrogen. Therefore we need to look for some indirect evidence for its formation. The indication of TiN presence can be seen in Fig. 3.10 (c) as a Ti peak in an EDX scan taken next to the AlGaN interface. Such additional Ti indicates some other than Ti-Al alloy (as for example TiN has much higher density than TiAl_3). The observed layer is not continuous, as visible in Fig. 3.10 (b), which was confirmed by EDX scans in another region Fig. 3.10 (d). Looking at data from the EDX measurement from the thermodynamical point of view supports the theory of TiN being formed at the regions where the Ti-rich regions. Since the formation enthalpy for GaN, AlN and TiN are

equal to -110.9, -317.9 and -337.65 kJ/mol respectively [102], the layer at the interface (c) is most likely TiN, as it is energetically the most favorable. It is also possible that some AlN or a ternary Al-Ti-N alloy is formed, but these all cause the same thing: nitrogen extraction and as a consequence effective n-type doping [41] of the region underneath the contact.

3.5 Electrical measurements

The sheet resistance was measured on three different samples. We obtained an average $R_{cf} = 0.35 \text{ } \Omega \cdot \text{mm}$ and $R_{ce} = 0.1 \text{ } \Omega \cdot \text{mm}$. The average value of R_{sh} was $505.8 \text{ } \Omega/\square$ with a standard deviation of $9.6 \text{ } \Omega/\square$, showing very good uniformity. For R_{sk} we obtained an average value of $236.9 \text{ } \Omega/\square$ with a standard deviation of $77.4 \text{ } \Omega/\square$. The high value of the standard deviation in the sheet resistance under the contact can be caused by local depletion/enrichment of the 2DEG and/or non-uniform n-type doping. Nonetheless, R_{sk} is in all cases much lower than R_{sh} . These results indicate that there is a phenomenon causing a conductivity increase in the region underneath the contact. To investigate this, we have done temperature characterization of the sheet resistance, which we present in Fig. 3.11. The increase of the 2DEG sheet resistance between the contacts as a function of temperature is attributed to optical phonon scattering and has been reported in different publications [14, 105]. The temperature dependence of R_{sh} can be approximated using a power law relation, i.e.

$$R_{sh} = R_{sh0} \left(\frac{T_0}{T} \right)^\gamma = \frac{1}{q\mu n_s} \left(\frac{T_0}{T} \right)^\gamma \quad (3.15)$$

where μ is carrier mobility, n_s is carrier concentration, R_{sh0} and μ_0 are the values of R_{sh} and μ at $T_0 = 300 \text{ K}$ and γ is the power index. The fitted value of $\gamma = -2.29$ is consistent with those reported in the literature [105]. The temperature dependence of R_{sk} is the opposite, i.e. the resistance decreases with increasing temperature. This leads to the conclusion that the 2DEG is not the only medium of current transport under the contact. The increase in conductivity may be caused by an increase in carrier concentration or mobility in the 2DEG, but this is highly unlikely because of possible processing damage (dielectric etch, RTA). Furthermore, the carrier density in the 2DEG has a very weak temperature dependence [105]. Alternatively, some additional conductive volume may be formed in parallel to the 2DEG. The low value of R_{sk} led us to a hypothesis of increased carrier concentration underneath the contact. The formation of TiN via extraction of nitrogen from GaN and AlGaN may induce a high concentration of N-vacancies, which act as n-type doping [41]. The effective doping concentration may be even as high as 10^{19} - 10^{20} cm^{-3} for few-nm-thick TiN layers [54]. Since the observed temperature dependence is weak, it is likely that the potential barriers for electrons are low.

Figure 3.11: Temperature characteristics of sheet resistance between (R_{sh}) and underneath (R_{sk}) the contacts.

In Fig. 3.12 the specific contact resistance and transfer length characteristics of the contact at different temperatures are presented. Within the measurement accuracy, the corrected values of specific contact resistance (ρ_{ck}) are almost temperature-independent, while the influence of R_{sk} on the transfer length is significant, especially at higher temperatures. Fig. 3.11(a) presents the specific contact resistance extracted with and without correcting the sheet resistance value. Therefore, the observed ρ_c characteristic reflects the temperature behavior of the sheet resistance in the drift region. This can be understood from the equations defining ρ_c and ρ_{ck} :

$$\rho_c = L_{Tk}^2 \frac{R_{sk}^2}{R_{sh}} \quad (3.16)$$

$$\rho_{ck} = L_{Tk}^2 R_{sk} \quad (3.17)$$

$$\frac{\rho_{ck}}{\rho_c} = \frac{R_{sk}}{R_{sh}} \quad (3.18)$$

As can be seen from Eq. (3.16), ρ_c is inversely proportional to R_{sh} . If the $R_{sk}=R_{sh}$ then equation simplifies to Eq. (3.17). However if the resistances are different, the apparent specific contact resistance ρ_c seems to decrease with the increase of the temperature and appears to be lower than in reality. Since AlGaIn/GaN devices are used as power devices, they normally operate at elevated temperatures, where the actual transfer length is seen to be an order of magnitude greater. This has to be taken into consideration during device design.

Figure 3.12: (a) Specific contact resistance as a function of temperature with and without correcting for the R_{sk} values, (b) Transfer length as a function of temperature with and without adjustment for the R_{sk} values; inset: R_{sh} to R_{sk} ratio.

3.6 TCAD simulations

Since the temperature dependencies of the 2DEG sheet resistivity and R_{sk} have opposite signs and R_{sk} is much smaller at higher temperatures, different conduction mechanisms could be responsible. From these observations we conclude that there must be additional charge carriers under the contact. To estimate their concentration and analyze their influence on current transport, TCAD simulations have been conducted. In the simulation, the 10 nm thick region under the contact has been defined as highly n-type

doped. Different doping regions and concentrations have been studied to best match the experimental data. The complete simulated structure consists of two Ohmic contacts 10 μm apart, biased at zero and 10 V. In Fig. 3.13 we present the carrier concentration and current flow lines at the contact area of the modeled structure. After entering the AlGaIn, current flows horizontally within it before finally entering the metal. This effect is manifested in the electrical measurements as a decrease of the sheet resistance under the contact which leads to an increase of the transfer length. From the band diagram it can be seen that the horizontal current flow corresponds to a region where the high n-type doping pulls the conduction band towards the local quasi-Fermi level. Electrons coming there from the 2DEG move horizontally in the AlGaIn before transferring over to the metal. This effect is reflected in the electrical measurements and in the extracted transfer length. The average transfer length before correcting for the R_{sk} value was 589 nm (standard deviation 166 nm); after making the adjustments it increased to 1.54 μm (standard deviation 174 nm, which corresponds to values extracted from the simulations for a doping level of $3 \cdot 10^{19} \text{ cm}^{-3}$).

Figure 3.13: Carrier concentration and current flow lines in the area under the Ohmic contact to the AlGaIn/GaN heterostructure with the corresponding band diagram (at 10 V); E_c - conduction band, $E_{F,n}$ - quasi-Fermi level for electrons. Note that the vertical dimensions in the cross-section have been exaggerated for clarity.

3.7 Conclusions

Standard Ohmic contact characterization methods, like LTLM, in their simplest form are not directly applicable for AlGaIn/GaN as they are for standard silicon devices. Main reason for this is that while in silicon technology implanted contacts are used almost exclusively [106] in compound semiconductors such as GaN, alloyed contacts are needed. During the for-

mation of alloyed contacts, reactions between the metal and semiconductor occur, and it is no longer reasonable to assume that resistance under the contact has not changed. Since the change in resistance is caused by the contact metal it is not straightforward to extract this resistance. We have shown that in order to properly evaluate Ohmic contacts to AlGaIn/GaN the resistance under the contact has to be known. It can be obtained by employing the contact-end resistance measurement method applied to LTLM test structure.

One important application conclusion from this work is that the apparently low specific contact resistance (calculated with the assumption of $R_{sk} = R_{sh}$) leads to the misconception that the transfer length is short. However, when correcting for the actual resistance value it turns out that already at the room temperature the transfer length is much longer (2.6 times longer in case of this work). This difference becomes even bigger at higher temperatures. Since AlGaIn/GaN is aimed to be utilized for high-power electronics and is intended to operate at elevated temperatures, one can immediately see that not knowing the actual transfer length may cause incorrect contact design, i.e. too short contacts. Consequently, one would observe current crowding in the contact which would result in decrease of the device reliability and a premature failure.

The observations discussed in this chapter should be present not just in Au-free but in any Ti/Al based contacts to AlGaIn/GaN in which TiN formation is observed [55, 99–101]. Furthermore, the magnitude of the sheet resistance change would be even more pronounced in a recessed contact as the 2DEG concentration will decrease with decreasing AlGaIn thickness [32]. Moreover, the etching process probably has some other influence on the structure; for example, it may change the strain condition, which would change the piezoelectric polarization and as a consequence the 2DEG concentration. This would mean that even if N-vacancy doping is not present, the resistance underneath the contact is nevertheless going to be affected.

In conclusion, the sheet resistance under the Ohmic contacts to AlGaIn/GaN on Si substrates has been investigated, and was shown to be much lower than the sheet resistance of the 2DEG. The temperature-dependent measurements imply the presence of additional charge carriers in the AlGaIn under the contact and TCAD simulations have shown this hypothesis to be feasible. The influence of the sheet resistance under the contact on the transfer length and specific contact resistance has been shown to be considerable. It has been demonstrated that this can't be neglected when calculating contact parameters and designing devices.

RECESSED OHMIC CONTACTS

Abstract

Recessed Ohmic contacts to AlGa_N/Ga_N are investigated because they can serve different purpose. Firstly by reducing the AlGa_N thickness locally, the contact resistance may be decreased. Secondly, making recessed contacts allows to reduce the rapid thermal annealing temperature and decrease overall thermal budget. While a lot of attention is paid to the fabrication of recessed Ohmic contacts, the changes of the electrical properties due to thinning of the AlGa_N layer under the contact are not properly acknowledged. In this chapter the physical effects of the local reduction of the AlGa_N thickness on contact resistance are discussed. The characterization methods for recessed Ohmic contacts to AlGa_N/Ga_N are treated in detail. It is shown that, in the worst-case scenario, the prevailing assumption of identical sheet resistance between and under the contacts can lead to errors of up to 3000 % in the extracted specific contact resistivity.

This Chapter was published as Hajlasz, M.; Donkers, J.J.T.M.; Sque, S.J.; Heil, S.B.S.; Gravesteijn, D.J.; Rietveld, F.J.R.; Schmitz, J., "Characterization of recessed Ohmic contacts to AlGa_N/Ga_N," in International Conference on Microelectronic Test Structures (ICMTS) 2015, pp.158-162, 23-26 March 2015 doi: 10.1109/ICMTS.2015.7106133

4.1 Introduction

Ohmic contacts to AlGaIn/GaN devices are not yet optimized and attempts are being taken to improve them for example by partially removing the top layers of the heterostructure and forming so-called recessed contact [35, 60, 107]. The approach to improve Ohmic contacts is focused on two aspects: lowering the contact resistance and decreasing the thermal budget. While the former simply aims to reduce the total on-resistance of the device, the latter is motivated by processing requirements. Since for the surface Ohmic contacts the required RTA temperature is around $700^{\circ} - 900^{\circ}\text{C}$, it is not possible to use a gate-first process flow, because the optimal gate stack anneal is around $400^{\circ} - 600^{\circ}\text{C}$ and some of the gate metals may even melt. Employing recessed contacts can reduce the necessary RTA temperature to 700° and below [108]. Although frequently investigated, the recessed contacts are usually characterized without acknowledging the possible changes in the AlGaIn/GaN under the contact, which leads to the extraction of incorrect parameters. In this chapter, it is discussed which test structures and methodology are necessary for correctly characterizing contacts to AlGaIn/GaN devices. We show that depending on different annealing conditions of the Schottky metal stack, the contact parameters extraction error becomes huge.

Figure 4.1: Processed GaN-on-Si wafer with reference surface contact (Q1) and three different recess etch depths of 7, 15 and 30 nm (Q2, Q3 and Q4 respectively).

4.2 Materials

In the experiments presented in this chapter, 4" GaN-on-Si wafers were used. The top layers comprise 1.5 μm of GaN with 20 nm of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}$ and a 3-nm GaN cap, prepared by metalorganic chemical vapor deposition (MOCVD). A Ti/Al-based metal stack has been used for the Ohmic contacts. LPCVD silicon nitride has been used as a passivation layer. The wafer used in the experiment was divided into four quarters of similar size as shown in Fig. 4.1. Each quarter contains between 27 and 31 dies. Large metal areas were present to enable material analyses such as XRD. For the recessed contacts, three different recess etch depths have been chosen: 7 nm, 15 nm and 30 nm for quarters Q2, Q3 and Q4 respectively. We have performed the dry etching using BCl_3/Cl_2 inductively coupled plasma. After the etch, the depth of the deepest etch has been measured and the obtained etch depth was 30 nm $\pm$ 2 nm. The contacts can be classified as surface contact (Fig. 4.2), shallow recessed contact (7 nm and 15 nm, Fig. 4.3a - GaN cap and part of the AlGaN removed) and deep recess (Fig. 4.4b - GaN cap and AlGaN completely removed). All samples have received a rapid thermal annealing (RTA) treatment at different temperatures within the 700 – 925 $^{\circ}\text{C}$ range.

More information on the processing details can be found elsewhere [98]. An Agilent B1505 semiconductor parameter analyzer has been used for electrical characterization and a FEI Tecnai F30 transmission electron microscope (TEM) for material investigation.

Figure 4.2: Schematic of a device structure with a surface Ohmic contact.

4.3 Analysis and methods

During evaluation of Ohmic contacts, the specific contact resistance is usually the parameter of interest. In order to perform the necessary calculations, the sheet resistance under the contact has to be known. In silicon technology it is assumed to be equal to that in the drift region of the device

Figure 4.3: Schematic of a device with: (a) shallow; and (b) deep recessed contacts. Note that dimensions are not in scale.

[90]. Following that, in AlGaN/GaN it is also typically assumed to be equal to the resistance of a region outside of the contact, but as discussed in Chapter 3, this assumption is only valid for structures that are not modified during processing. When the Ti- (or other appropriate metal) based stack is deposited on AlGaN/GaN, it has to be annealed to form an Ohmic contact. The reactions occurring between the Ti and the underlying GaN affect the contact region and therefore its resistance. What is more, when the top AlGaN/GaN layers are partially etched to form a recessed contact, it is no longer reasonable to assume that the two-dimensional electron gas (2DEG) sheet resistance remains unchanged at the position of the etch. First of all, the 2DEG concentration depends on the AlGaN thickness. This dependence, as calculated based on work of Ambacher et al. [32], is presented in Fig. 4.4. Since in the etching process the GaN cap is removed, the presented calculations are performed for a structure without it. The 2DEG concentration is shown in the figure as a function of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ thickness for different aluminum mole fractions x . One should notice that change of thickness by a few nanometers already has significant influence on the 2DEG concentration. Moreover, it is important to realize that there is certain minimum thickness of AlGaN necessary for formation of the 2DEG [66], which in the case presented here should be around 5 nm. Literature data suggest that this critical thickness could be lower, around 3 nm [109]. In any of those cases, if the AlGaN becomes thinner, the 2DEG will have lower charge carrier concentration.

When looking at the contact types investigated in this chapter, we can already make some assumptions. Looking at Fig. 4.5 we can see that a few nanometers recess etch should not reduce the 2DEG by more than 10 – 15%. Combined with the expected N-vacancy doping (as discussed in Chapter 3) we could expect small increase in the sheet resistance under the contact R_{sk} , and in the case of very high N-vacancy doping it could even decrease. On the other hand, the 15 nm recess etch will most likely result

Figure 4.4: 2DEG sheet carrier concentration N_s as a function of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ thickness calculated for different Al concentrations (x).

Figure 4.5: 2DEG sheet carrier concentration N_s as a function of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ thickness calculated for Al concentration (x) used in this experiment. Dashed lines indicate different recess etch depths.

in poor contact properties as there will be almost no more charge carriers left under the contact. Given the fact that the sheet carrier concentration changes as a function of AlGaIn thickness, we expect that R_{sk} is different from the sheet resistance of the 2DEG elsewhere in the device (R_{sh}). Unfortunately, R_{sk} cannot be measured directly since metal removal, after the RTA, without affecting the 2DEG is most likely impossible. Furthermore, only some of the test structures facilitate extracting R_{sk} in the presence of a metal on top. One of the most often used, the circular transfer length method (CTLM) structure can be applied only when assuming identical sheet resistance across the sample [90], and can't be used to measure R_{sk} . The four-terminal Kelvin structure and its modified version [110] require separate measurement of R_{sk} to determine contact parameters. The six-terminal Kelvin structure enables R_{sk} extraction, but in order to correctly extract the contact parameters, structures with varying overlap and contact

size have to be investigated [111]. Therefore, the most practical solution is the standard Linear Transfer Length Method (LTLM) [90]. Using the contact-end resistance method (R_{ce}) described in Chapter 3 it is possible to extract R_{sk} with this structure.

4.4 Material characterization

Since the properties of the AlGaIn/GaN heterostructure are expected to be strongly dependent on the AlGaIn thickness, the accurate recess etch depths should be known to properly evaluate electrical measurements data. The initial depth measurements provided a good estimate but did not give any information about the metal interface quality (as the measurements were done before the metal deposition). What is more, it is necessary to investigate if the recessed contacts react differently with the underlying semiconductor than in the surface contact case. One reason to investigate this is that in case of the surface contacts analyzed in this work, there is a 3-nm thick GaN cap present on the AlGaIn. Therefore, samples with different recess etch depths were investigated using a Helium Ion Microscope (HeIM) and TEM to evaluate the interface uniformity and the position of the metal/semiconductor (MS) interface. HeIM investigation has been conducted first, because in this technique there is no need for an elaborate sample preparation as for the TEM. Samples were manually cleaved and mounted on the sample holder as presented in Fig. 4.6.

Figure 4.6: HeIM sample holder with three different samples mounted. Samples are located on the left, top and right side and can be switched inside the microscope without breaking the vacuum.

Since surface contacts have been thoroughly investigated with TEM in Chapter 3, they were not analyzed with HeIM anymore. Fig. 4.7 shows a cross section image of the 7 nm recessed contact edge. Even though the HeIM images have much higher resolution than a typical SEM image, it is difficult to accurately measure the depth of the recess etch. The reason for this is that the reference point (interface between GaN cap and LPCVD silicon nitride) is not properly visible due to charging of the silicon nitride layer. Despite that we can see that the metal/AlGaIn interface is smooth and there are no adhesion problems visible.

Figure 4.7: HeIM image of 7 nm recess sample.

If we look further at Fig. 4.8 showing the 15 nm recess etch case, we can see that again it is impossible to exactly assess the depth of the contact etch. One can get an estimate looking at the dark region to the right of the contact, which corresponds to the LPCVD SiN. Having deeper etch than in the previous case does not seem to have impact on the uniformity of the metal semiconductor interface. However it is now more clearly visible that there is some reaction occurring at the Ti/SiN interface. Most likely titanium silicide is formed, but since it only appears at the contact edge, it should not have influence on the contact performance. TEM analysis will be used later in this chapter to study this in more detail.

Figure 4.8: HeIM image of 15 nm recess sample.

Similarly to 7 and 15 nm deep recess, the 30 nm etch presented in Fig. 4.9 exhibits very uniform metal-semiconductor interface.

Since HeIM resolution is not high enough for assessing the recess etch depth, we have conducted TEM analysis on the shallow and deep recess contacts. Firstly, we remind the investigation results from Chapter 3 of the surface contact TEM micrograph presented in Fig. 4.10. The structure visible here is the edge of a contact window, showing the contact metal, part of

Figure 4.9: HeIM image of 30 nm recess sample.

the silicon nitride passivation and the underlying AlGaIn and GaN layers. First feature of this structure that is immediately distinguishable is the dark region between metal and silicon nitride. Similar regions were visible in the HeIM scans and most likely these are titanium silicide. When trying to assess the bottom of the contact (i.e. metal/semiconductor interface) we need to find a reference point. In this case, we will use the SiN/GaN interface as the reference for the initial semiconductor position as no reactions between silicon nitride and GaN are expected. One should note that the micrograph of this resolution does not clearly show the presence of the 3 nm thick cap on top of the AlGaIn. While we have confirmed presence of this layer on the wafer in other experiments, it is likely that it is absent underneath the Ohmic contact (due to etch damage during the processing of LPCVD SiN or chemical reactions with contact metal).

Knowing the reference point it is visible that the contact metal is located below the original position of the top of the semiconductor layer. There may be several reasons for this. Firstly, chemical reactions between Ti and GaN during the RTA may move the interface downwards, to the semiconductor side [84]. Secondly some of the GaN/AlGaIn stack might be removed or damaged during overetching of the LPCVD silicon nitride [112]. One should notice that in the case of what we think to be a surface contact we are also dealing with a pseudo-recessed contact, but with a very shallow recess depth (about 5 nm in this work).

In Fig. 4.11 a cross-section of the shallow contact is presented. Similarly to the surface contact from Fig. 4.10 we see a dark region corresponding to the titanium silicide. The AlGaIn layer is distinguishable in the image and the recess etch depth is about 10 nm.

(a)

(b)

Figure 4.10: TEM cross-sections for the surface contact: (a) Schematic of the contact with the investigated area marked; (b) analysis results.

We have seen in Fig. 4.10a that in case of the surface contact there is a few nanometers shift of the metal-semiconductor interface towards the semiconductor. Since in the shallow recess contact we intended to etch 7 nm of semiconductor, it is likely that here we observe a combination of the recess etch of the designed depth and additionally effect present in the surface contact. Since the etch stopped in the middle of the AlGaIn layer, the 2DEG concentration is expected to remain relatively high (Fig. 4.5) and the contact properties are expected to be good, if no etch damage is present.

The most interesting case occurs in the deep variant (Fig. 4.12), where the metal-semiconductor interface extends 26 nm below the surface - beyond the AlGaIn/GaN interface. The interface non-uniformities suggest reactions of Ti with GaN. Since formation of TiN and other compounds with nitrogen are expected based on their enthalpy of formation (and as observed in Chapter 3), there will be N extraction occurring and effectively causing n-type doping under the contact. While looking at the electrical behavior of this contact it would be important to remember that in this structure we effectively make contact to GaN instead of AlGaIn what would cause different reactions and will result in different properties of the semiconductor layer under the contact. Since already in case of this sample

Figure 4.11: TEM cross-sections for shallow recessed contact.

(with the intentional etch of 15 nm) we are dealing with the deep recess, the 30 nm recess etch sample has not been investigated.

Figure 4.12: TEM cross-sections for the deep recessed contact.

4.5 Electrical results

Each investigated contact was annealed at four different temperatures in order to evaluate the possibility of reducing the processing thermal budget while maintaining low contact resistance. Fig. 4.13 shows I-V characteristics of the surface, shallow-recess, and deep-recess contacts annealed at different temperatures. One could notice several important facts. First of all after annealing at 700 °C, the I-V characteristics of all contacts are nonlinear, which probably means that TiN has not been formed and there is no N-vacancy doping present. These samples are therefore excluded from further analysis. However, if we analyze the non-linearity versus the etch depth we can see that it becomes worse as the recess etch

becomes deeper. This indicates that it should be possible to balance etch depth and annealing temperature to obtain low-resistance contact.

(a)

(b)

(c)

Figure 4.13: I-V characteristics of contacts annealed at different temperatures: (a) surface contact; (b) shallow recess; and, (c) deep recess.

When comparing I-V curves from Fig. 4.13 it is noteworthy that the main factor determining the contact resistance is the recess depth, not

the annealing temperature. This suggests that it may still be possible to decrease the RTA temperature without increasing the contact resistance significantly.

The sheet resistance between and under the contacts was extracted using a LTLM structure and the contact-end resistance method. The R_{sk} changes significantly (Fig. 4.14a), depending on the annealing temperature. This is expected, as different temperatures are leading to formation of different alloys and phases. The transition from rectifying to Ohmic contact after the RTA is ascribed to the formation of metal-nitrogen alloys, which effectively cause N extraction from the AlGaIn/GaN [113]. The density of N vacancies acting as n-type doping would depend on the magnitude of the interface reactions and the amount of metal-N alloys formed.

One could expect that the R_{sk} values for the surface contact should be lower than in shallow recess contacts, due to the decrease of electron concentration in the 2DEG, which is proportional to AlGaIn thickness. However for 825 °C and 875 °C we observe opposite behavior in Fig. 4.14a. While there would be an R_{sk} increase due to the AlGaIn thickness change, simultaneously the thinner AlGaIn will contribute nitrogen for TiN from the whole layer and hence make the whole layer more conductive.

The most profound change is observed, as expected, for the deep recess in which there is no 2DEG under the contact anymore. In that situation it is believed that there are still some N-vacancies formed that serve as the conducting channel making the applied parameter extraction method still valid (note that the standard Ohmic contact parameters extraction methods are not applicable for side contacts as they account for area dependent parameters and not the perimeter dependent ones).

R_{sh} (Fig. 4.14b) stays approximately constant and the observed variation of less than 10 % (about 50 $\Omega/\square$) is consistent with the typical variation across a wafer [114]. From Fig. 4.15a and 4.15b we see that contacts with the lowest resistance are obtained with the shallow recess etch. This may mean that, in this case, a close-to-optimum condition is reached, where the barrier for the electrons is low and simultaneously the conductivity of the 2DEG remains high. Since the R_{sk} may be even 30 times higher than the R_{sh} (deep recess), the error in ρ_c characterized with a standard LTLM method amounts to almost 3000 % in that case. The magnitude of that error is that large because ρ_c depends on the R_{sk}/R_{sh} ratio ($\rho_c = R_{sk}L_{TK}^2$).

4.6 Discussion

In the AlGaIn/GaN devices removing part of the AlGaIn layer under the contact has three main effects which affect the contact resistance:

- 2DEG resistance increases due to AlGaIn thickness reduction
- n-type doping due to nitrogen vacancies formation

Figure 4.14: A set of different contact parameters: (a) Sheet resistance under the contact for samples annealed at different temperatures; (b) Sheet resistance between the contacts for samples annealed at different temperatures.

- Thickness of the n-type doped layer

While the 2DEG resistance is a straightforward relationship discussed earlier in the chapter, the n-doping is not directly quantifiable, since there is no direct experimental method for detecting nitrogen vacancies in AlGaIn. There will be also tradeoffs in the recessed contact structure, when increasing 2DEG resistance would be compensated by doping from N vacancies. This might happen when in the shallow recess the thinner AlGaIn layer would contribute N from the whole layer (of reduced thickness) and effectively become more conducting than in the surface contact. The N-vacancy doping by itself enhances conduction and in the deep recess, it facilitates usage of LTLM method by forming conductive region under the contact.

Material analysis results combined with electrical characterization revealed that neglecting the influence of semiconductor modification in the region underneath the contact will lead to errors in the values of extracted

Figure 4.15: A set of different contact parameters: (a) Contact resistance for different samples as a function of annealing temperature; and, (b) Specific contact resistance for different samples as a function of annealing temperature.

specific contact resistivity. Moreover, without the proper analysis by the contact-end resistance method it would be impossible to optimize the contact. This is because the metal-semiconductor interface resistance (ρ_c) would be mistakenly taken as the driving force for the contact resistance value, whereas in reality it is the resistance under the contact that is the influencing factor.

What happens in all recessed contact structures is that the semiconductor resistance under the contact changes. The deeper the recess etch, the larger the difference between R_{sk} and R_{sh} as the 2DEG resistance depends on AlGaIn thickness. Furthermore different amount of n-type doping, arising from N vacancy formation, may vary for different recess etches because of differences in etch damage induced during processing. This means that if the R_{sk} is high, but in the calculations for standard LTM structure

the R_{sh} is used, then the ρ_c is highly overestimated. Consequently when one tries to optimize the contact resistance, he would look at improving metal-semiconductor resistance instead of trying to lower (or not increase) the R_{sh} .

Recessed contact formation influence on R_{sk} was most notable in the deep recess structure, where the intention was to completely remove the 2DEG from underneath the contact. As confirmed by TEM micrograph, in this structure the 2DEG is no longer present under the contact (as is schematically shown in Fig. 4.3a). In the deep recess structure AlGaIn is completely etched and even a part of underlying GaN is no longer there. Surprisingly, the contact still exhibits Ohmic behavior. In this case two things might be happening: (I) there is only a side-contact to the 2DEG, or (II) new pseudo-channel is formed under the contact due to the N-vacancy formation. If (II) is the case then the resistance of such channel is expected to be high compared to that of the 2DEG in a non-recessed contact. In either case, one could expect poor electrical behavior, i.e. large contact resistance and specific contact resistivity. In case of the analyzed devices it is likely that (II) occurs, as nitrogen vacancy n-type doping is expected, based on results from Chapter 3. Because the 2DEG is no longer there, it is expected that the resistance due to the N-vacancy doping is rather high, which is exactly as extracted with the contact-end resistance method. However if the resistance under the contact is assumed to be as in between the contacts (i.e. lower than the real one), the error appears in the extracted specific contact resistivity as those parameters are directly related. Therefore any attempts to optimize the contact may be misdirected at, for example, optimizing the metal stack while the resistance under the contact is the parameter that should be taken care of. This can of course result in lowering the resistance by trial and error, but the whole process would not be time and resources consuming.

4.7 Conclusions

In this chapter we have shown that for a correct analysis of recessed contacts to AlGaIn/GaN devices it is crucial to extract the values of sheet resistance under the contact. Neglecting the change in R_{sk} leads not only to errors in the extracted specific contact resistivity but what is more important it may falsify the conclusions in the process of contact optimization. In Fig. 4.16 the ρ_c values before and after correction for the R_{sk} are shown. Since in the surface contacts, R_{sk} is not affected that much as in the recessed contacts (AlGaIn is not removed), the difference between parameters before and after correction are not that large. This is however not the case anymore for the shallow recessed contact (Fig. 4.17). The specific contact resistance decreases due to usage of accurate R_{sk} was fivefold for higher annealing temperatures.

What we can conclude from Fig. 4.14a and Fig. 4.17 that the low overall

Figure 4.16: Comparison of specific contact resistivity of surface contact before and after correction for the value of sheet resistance under the contact.

contact resistance is not due to the significant improvement of the specific contact resistivity but rather due to the lowering of resistance under the contact.

Figure 4.17: Comparison of specific contact resistivity of shallow recessed contact before and after correction for the value of sheet resistance under the contact.

Most importantly when looking at the data for deep recessed contact (Fig. 4.18) in which we obtained high contact resistance the typical conclusion would be that the specific contact resistivity for these construction is very large. However in reality the ρ is not high and the effectively large contact resistance is caused by removal of the 2DEG from underneath the contact.

Figure 4.18: Comparison of specific contact resistivity of deep recessed contact before and after correction for the value of sheet resistance under the contact.

Applying the contact-end resistance method on a LTLM structure, we have separated the sheet resistance under the contact from the resistance outside of the contact region in AlGaIn/GaN heterostructures. The ratios of those resistances, and therefore extracted contact parameters, change significantly depending on the recess depths and annealing temperatures. Using correct resistance values for specific contact resistance extraction significantly improves the accuracy of the obtained parameters.

CHAPTER 5

STRESS IN SCHOTTKY METAL STACK

Abstract

In this chapter Ni-based AlGaN/GaN Schottky diodes comprising capping layers with silicon-technology-compatible metals such as TiN, TiW, TiWN and combinations thereof are investigated. The observed change in Schottky barrier height of a Ni and Ni/TiW/TiWN/TiW contact can be explained by stress effects induced by the TiW/TiWN/TiW capping layer, rather than by chemical reactions at the metal-semiconductor interface. Secondary Ion Mass Spectroscopy and Transmission Electron Microscopy techniques, for samples with and without a TiW/TiWN/TiW cap, have been used to show that no chemical reactions take place. In addition, electrical characterization of dedicated samples revealed that the barrier height of Ni/ TiW/TiWN/TiW contacts increases after stepwise selective removal of the TiW/TiWN/TiW cap, thus demonstrating the impact of strain.

This Chapter was published as M. Hajlasz, J. J. T. M. Donkers, S. Pandey, F. Hurkx, R. J. E. Hueting and D. J. Gravesteijn, "Barrier Height Variation in Ni-Based AlGaN/GaN Schottky Diodes," in IEEE Transactions on Electron Devices, vol. 64, no. 10, pp. 4050-4056, Oct. 2017. doi: 10.1109/TED.2017.2742991

5.1 Introduction

Devices based on AlGaIn/GaN are suitable candidates for high-voltage and high-speed electronics due to the GaN material properties such as wide bandgap, large breakdown field, high electron saturation velocity and good thermal conductivity [115]. The interest in this material system really took off after development of GaN-on-Si technology, where few- μm -thick epitaxial active GaN layers are deposited on silicon (111) wafers by using transition layers that mitigate differences in lattice constants and coefficients of thermal expansion [4, 116]. However, GaN device technology has by far not reached the same maturity level as Si, and many aspects of the device behavior are still not fully understood. One example is the formation of the Schottky barrier, especially in terms of defining the barrier height [15]. In AlGaIn/GaN technology the commonly used Schottky metal is nickel (Ni) [17, 78, 117] due to its high barrier on GaN and low resistivity. However, Ni by itself suffers from different problems related to the complete device processing flow. For example, when aluminum (Al) is used in the backend processing to make contacts, it can readily diffuse into Ni and adversely affect the Schottky contact properties [118]. In addition, Ni often suffers from delamination caused by different processing steps and to prevent that, different metal capping layers may be used. In III - V technology, the metal of choice for that protective layer is typically gold [17], [119]. Unfortunately, gold is strictly forbidden in industrial silicon (Si) fabs and it has to be replaced with another Si compatible metal or alloy to allow cost effective production. These requirements prompted investigation of different metals used in Si fabs, such as titanium-nitride (TiN), titanium-tungsten (TiW), TiW(N) and combinations thereof for the capping layer on Ni.

We have observed that Ni contacts with a TiW/TiWN/TiW capping layer, from here referred to as the TiW(N) layer, often have a lower Schottky barrier height (SBH) than Ni only contacts. This is visible in the exemplary set of devices in Fig. 5.1 where the I-V characteristic for Ni Schottky contact shows lower saturation hence leakage currents.

The thermionic current-voltage relationship of a Schottky barrier diode, neglecting series and shunt resistance, is given by [10]:

$$I = AA^*T^2 e^{-\frac{q\Phi_B}{kT}} \left(e^{-\frac{qV}{nkT}} - 1 \right) = I_s \left(e^{-\frac{qV}{nkT}} - 1 \right) \quad (5.1)$$

where I_s is the saturation current, A the diode area, A^* Richardson's constant, Φ_B the SBH, and n the ideality factor. The SBH is calculated from the saturation current which is determined by extrapolating the thermionic emission (exponential part) of the forward-biased current-voltage I-V curve to $V = 0$ (as described by Eq. 5.1). The ideality factor is determined from the slope of the same plot. According to the Schottky-Mott rule [120], the SBH of a contact is solely dependent on the metal work function and semiconductor electron affinity in vacuum, therefore it should be determined

Figure 5.1: I-V characteristics of two sets of diodes, with and without the TiW(N) cap.

by bulk properties of Ni and GaN only. In case of multilayer Schottky metal stacks, ideally the SBH depends on the metal in contact with the semiconductor at the metal-semiconductor (MS) interface. If the metals above the first metal (Ni) do not react in close vicinity to the interface, the SBH should not be influenced by them. MS interface properties, such as the SBH, can also be affected by stress-dependent parameters, for example via polarization-induced charges [121]. One could then expect that the deposition of the metallization layers will affect the stress and therefore the electrical properties of the contacts. Earlier it was shown that stress induced by the SiN passivation influences the sheet charge density [122]. Some initial work shows the dependence of the sheet carrier concentration of the two-dimensional electron gas (2DEG) on Ni thickness [123]. Moreover, strain may affect trap energy levels [124] or the metal work function [125]. However, to our best knowledge the influence of stress from metal layers in Schottky contacts to AlGaIn/GaN has not been studied so far. In this work we show that there are no chemical reactions at the MS interface of different Schottky metal stacks and consequently that the SBH change observed in the experiments can be explained by the stress inside the stack. Subsequently we conduct an experiment in which we remove the stress source, namely the TiW(N) layer, and show the extent of SBH change caused by stress.

5.2 Methodology

For this work we adopted a GaN-on-Si process technology, in a silicon nitride passivation-first integration scheme [98]. The top layers of the wafers used in this experiment consist of $1.5\mu\text{m}$ of GaN with 20 nm of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}$ and a 3 nm GaN cap, prepared by metal-organic chemical

vapor deposition (MOCVD). The as-grown wafers 2DEG carrier density obtained from Hall measurements is $5.8 \cdot 10^{12} \text{cm}^{-2}$ and the electron mobility is equal to $1700 \text{cm}^2/\text{V} \cdot \text{s}$. Devices were patterned by dry etching and isolation was obtained by using argon ion implantation with the energy of 160 keV and dose of $1 \cdot 10^{14} \text{cm}^{-2}$. A Ti/Al-based gold-free metal stack was used for the Ohmic contacts. The Al layer is a few times thicker than the Ti layer and the Ti/Al ratio and anneal conditions were optimized for a specific contact resistivity (ρ_c) stable at/below $10^{-5} \Omega \text{cm}^2$. More details can be found in [98]. The Ohmic contacts received a rapid thermal annealing (RTA) treatment at an optimized temperature within a 800 - 900 °C range, which is typical for contacts to AlGaIn/GaN [99], [100]. We investigated two different Schottky contacts, namely Ni and Ni/TiW(N). In these contacts the 100 nm thick Ni layer was evaporated in both contact schemes. TiW(N) layers were sputter-deposited and their thickness is 10/80/10 nm of respectively TiW, TiWN and again TiW. After the Schottky anode deposition the wafer was annealed at an optimized temperature between 400 - 600 °C. A schematic cross-section of the diode is presented in Fig. 5.2.

Figure 5.2: Schematic cross-section of the AlGaIn/GaN diode. The red rectangle indicates the area investigated with SIMS.

Material analysis has been conducted by using Secondary Ion Mass Spectroscopy (SIMS) and Transmission Electron Microscopy (TEM) with energy dispersive X-ray (EDX) spectrometer. SIMS depth profiles have been measured using a CAMECA IMS 6f. Scanning TEM measurements have been performed with an FEI Titan TEM. EDX spectra have been acquired simultaneously with the EELS spectra. EELS has been performed with a Gatan Tridiem HR detector.

The extensive material characterization is aimed to show if there are any differences at the MS interface between the two different Schottky metal stacks (i.e. Ni and Ni/TiW(N)). In case no differences are found, then the difference in SBH between the two contacts cannot be caused by the chemical reactions at the MS interface. Then the SBH stress-dependence could be an explanation. One way to study this is by conducting a deprocessing experiment of Ni/TiW(N) Schottky diodes to remove the possible stress source - the TiW(N) layer.

In the experiment, metal layers were removed in three steps and electrical measurements were conducted in between each process step to obtain the SBH. In the procedure 30% H_2O_2 at 20 °C was used to remove TiW(N) in two steps in which each time 50 nm (+/- 10 nm) of the material was removed. Subsequently 50 nm of Ni was removed with 1% HNO_3 at 20 °C. The experiment was conducted on one wafer and each time exactly the same devices were measured to avoid wafer-to-wafer and device-to-device variability.

5.3 Material analysis

Since the annealing of the Schottky stack was done after the TiW(N) deposition, some interdiffusion and alloying could occur, especially within the metal stack itself, but also at the MS interface. Consequently the interface properties may change, which would affect the SBH. Diffusion of Ni into GaN and outdiffusion of Ga and N from GaN could also affect the barrier [126]. Therefore, SIMS was applied to two different samples, namely sample A with the Ni metal only, and B with the Ni/TiW(N) stack (Fig. 5.3).

Figure 5.3: Cross section of the samples investigated with SIMS: sample A without the TiW(N) cap and sample B with the TiW(N) cap.

To avoid artifacts in different areas of the sample caused by roughness or possible differences in metal sputter rate (that can result in an incorrect detection of MS interface position and composition), we have conducted backside SIMS, by carefully polishing back the substrate up to an appropriate depth below the device region. Results of those measurements are presented in Figs. 5.4 and 5.5, indicating that there are no differences between the samples at the interface between Ni and the semiconductor below. The Ni signal is steep in both samples (beyond the instrumental resolution) and the Ga signal is also similar for both. While we see signs of reaction at the AlGaIn/GaN interface, the Ni/GaN interface is equally steep in both cases. The W is not present in the close vicinity to the MS interface, hence it was left out from the figures. In other words, based on the SIMS analysis, there is no sign of any reaction at the Ni/GaN interface both in the capped and uncapped version of the anode metal stack.

Figure 5.4: SIMS profiling from the backside of the wafer for sample A, without the TiW(N) capping layer.

In order to confirm the SIMS results, we have also analyzed samples using TEM. In Fig. 5.6 the TEM cross section and the chemical profile of a contact without TiW(N) cap are shown using EELS and EDX. The amount of Ni in the GaN is below the detection limit, as indicated by the tail shape of the Ni profile in the GaN and the Ga profile in the Ni. EELS and EDX give similar results.

The situation for a contact with the TiW(N) cap (Fig. 5.7) is similar and the diffusion, if present, is below the detection limit.

Comparing data for the capped and uncapped contact suggests that

Figure 5.5: SIMS profiling from the backside of the wafer for sample B, with the TiW(N) capping layer.

Figure 5.6: Contact without TiW(N) cap: (a) TEM cross-section of the contact area; (b) chemical profile along the red line indicated in (a).

there is no detectable difference between them at the MS interface. Some diffusion of Ni into GaN cannot be excluded, but it would be very limited. Furthermore, the Ni diffusion should be similar for both metal stacks so it wouldn't explain the observed SBH difference between Ni and Ni/TiW(N) metal stacks.

5.4 Electrical characterization

5.4.1 De-processing to release stress

Since it appears that there are no chemical reactions at the MS interface which could cause the SBH shift, we conducted a deprocessing experiment in order to show whether or not a partial removal of the cap would result in a change in SBH possibly caused by a partial removal of the stress. We removed the TiW(N) capping layer in steps that is expected to be the source of stress affecting the SBH [123–125, 127]. The Ni/TiW(N) anode metal stack was etched in steps on a wafer which was removed from processing after opening the contact windows in the second insulating layer (PECVD silicon nitride). As illustrated in Fig. 5.8, due to a partial covering of the anode area with PECVD nitride, only half of the area could be etched away.

The etchants used to remove TiW(N) and Ni (H_2O_2 and HNO_3 respec-

Figure 5.7: Contact with TiW(N) cap: (a) TEM cross-section of the contact area; (b) chemical profile along the red line indicated in (a).

tively) have a high selectivity to silicon nitride and have some influence on the Ohmic contact parameters. On average the contact resistance, extracted using Transfer Length Method (TLM) test structures, increases from $0.35\Omega\cdot\text{mm}$ to $0.60\Omega\cdot\text{mm}$, but is of minor importance to this work as it does not influence SBH extraction. Moreover, the H_2O_2 etch is highly selective towards Ni, therefore we were able to completely remove TiW(N) without any detrimental effects to other materials. The etching had only a small influence on the Schottky contact surface roughness as observed in the AFM topography 3D scans presented in Fig. 5.9. After the first etch step, the arithmetic average of the roughness profile (R_a) increased from 7.35 nm to 8.10 nm and the root mean square average of the profile height

Figure 5.8: Schematic cross-section of the de-processed diode design.

deviations (R_{rms}) increased from 9.20 nm to 11.02 nm.

Figure 5.9: 3D AFM topography image of the contacts before the etch (a) and after the first etch (b). The central contact is the Ohmic contact and the outer ones are Schottky contacts.

The diodes were probed directly on the contacts, as there were no bond pads yet present at this processing stage. At each step the same devices were measured to assure one-to-one comparison and to avoid effects due to variability over the wafer. Forward I-V characteristics of 200 diodes were measured at each stage and the shift in SBH was determined. A Keysight B1505A semiconductor parameter analyzer has been used for the electrical characterization. Automated measurements were conducted using a Tesla System from Cascade Microtech.

5.4.2 Results

In Fig. 5.10 the I-V characteristic of an exemplary device is shown at different de-processing stages. It can be seen that the removal of the TiW(N) layer leads to a shift in the I-V towards higher voltages (i.e. lower saturation current) and hence to an increase in the effective SBH.

The SBH after the first, second and third etch step as well as the initial values were acquired on over 200 Schottky diodes and compared 1 to 1, meaning that the observed shifts are not a result of the variability over the wafer.

In Fig. 5.11 we present the statistical distribution of the SBH shift for all etch steps. For each TiW(N) etch step of the same depth (about 50 nm

Figure 5.10: I-V characteristics of an example diode at different de-processing stages.

for each step) the change in SBH is similar. In total an SBH reduction of around 50 mV is observed because of the metal stack. The SBH 10 mV shift due to Ni removal is relatively low compared to the total 50 mV shift. Consequently, we can say the effect of Ni exposure to H_2O_2 after TiW(N) removal, and subsequent etching in HNO_3 is of less importance. As can be seen in Fig. 5.12, there is no significant change in the devices' ideality factors between the processing steps.

5.5 Discussion

Both SIMS and TEM results have shown that there are no significant differences at the MS interface of the Ni and Ni/TiW(N) contacts. Neither Ti

Figure 5.11: Measured Schottky barrier heights of devices before and after each etch step.

Figure 5.12: Measured ideality factor at each processing stage.

nor W appear to diffuse towards the interface and there is also no Ni diffusion into the semiconductor. The electrical measurements clearly indicate that the TiW(N) capping layer is responsible for SBH differences between diodes with Ni and Ni/TiW(N) metal stacks.

So far our experimental analysis points out that the nature of SBH change is physical (stress), rather than chemical (reactions at MS interface). The presence of stress may influence the Schottky contact to AlGaIn/GaN in several ways.

First of all, the piezoelectric polarization is expected to change in both (piezoelectric) materials. This would result in change of the electron concentration in the 2DEG [32]. Since the spontaneous polarization is an intrinsic material property, stress can only affect the piezoelectric polarization. We could further assume that the amount of additional stress in both AlGaIn and GaN layers caused by the anode metal is similar. Subsequently, since the piezoelectric coefficients of AlGaIn and GaN are within the same range [26] (parameters for AlGaIn are taken from linear interpolation between GaN and AlN), the difference in the strain-induced piezoelectric polarization is negligible, therefore the 2DEG sheet carrier density should not be affected much [128]. However small changes in the effective SBH would appear because of the presence of additional piezoelectric polarization induced charge.

Secondly, another parameter that directly defines the SBH is the position of the conduction band in AlGaIn and GaN. In the experiments we observed an increase in the Schottky barrier height of +50 mV. Hence there is a $\Delta E_c = -50 \text{ meV}$ induced by the metal stack. According to the work of Fonoberov and Balandin [20] for the Wurtzite GaN conduction band shift holds:

$$\Delta E_c = a_c^{\parallel} \cdot \epsilon_{zz} + a_c^{\perp} \cdot (\epsilon_{xx} + \epsilon_{yy}) \quad (5.2)$$

where $\alpha_c^{\parallel} = -9.5\text{eV}$, $\alpha_c^{\perp} = -8.2\text{eV}$ ($\alpha_c^{\parallel} - 12.0\text{eV}$, $\alpha_c^{\perp} = -5.4\text{eV}$), and the strain tensor ϵ_{ij} with x, y is the in-plane GaN (AlN) surface and z is out-of-plane (c -axis).

Also here, for obtaining values for AlGaN as a first estimate linearly interpolated values from AlN and GaN can be taken. So, for $\text{Al}_{0.20}\text{Ga}_{0.80}\text{N}$, present at the surface of our contacts $\alpha_c^{\parallel} = 10.0\text{eV}$, $\alpha_c^{\perp} = -7.9\text{eV}$,

This implies that for the electron affinity of (Al)GaN holds:

$$\chi = \chi_0 - \Delta E_c = \chi_0 - \alpha_c^{\parallel} \cdot \epsilon_{zz} - \alpha_c^{\perp} \cdot (\epsilon_{xx} + \epsilon_{yy}) \quad (5.3)$$

Since the strain is attributed to differences in the lattice constant and thermal expansion coefficients between different materials (i.e. Ni, TiW(N), (Al)GaN), it is expected that the strain in the layers is a biaxial (in-plane) strain. In this case we can say that $\epsilon_{xx} = \epsilon_{yy}$ and for the out-of plane component [24]:

$$\epsilon_{zz} = \frac{-\nu}{1 - \nu} \cdot \epsilon_{xx} \quad (5.4)$$

with ν is the Poisson ratio (≈ 0.23). Hence, $\epsilon_{zz} \approx -0.3 \cdot \epsilon_{xx}$.

Based on the Poisson ratio and Eq. 5.2 for a reduction in the SBH (or increase in work function) of 50 mV, as observed in our experiments, we estimate a biaxial tensile strain of around 0.27% in our $\text{Al}_{0.20}\text{Ga}_{0.80}\text{N}$ layer induced by the metal stack.

CHAPTER 6

SCHOTTKY BARRIER INHOMOGENEITY

Abstract

The ideal diode behavior is often not observed in AlGa_N/Ga_N based diodes. It is therefore expected that measured current-voltage characteristics would deviate from the idealized curve. In AlGa_N/Ga_N diodes temperature dependence of ideality factor and Schottky barrier height are often observed. These devices are expected to have inhomogeneous Schottky barrier. In this chapter we present electrical measurements of gold-free Schottky contacts, such as TiN and TiW(N). It is shown that the devices exhibit Schottky barrier height and ideality factor temperature behavior as typically observed in AlGa_N/Ga_N, what indicates barrier inhomogeneity. From the modified Richardson plots it is concluded that the Schottky barrier height inhomogeneity is caused by wafer properties, such as dislocations, and not by the metal stacks themselves. Subsequently, Ga_N substrates are analyzed using Conductive Atomic Force Microscopy. The measurements of the wafer topography revealed the donut-like patches with increased conductivity, which could be responsible for Schottky barrier inhomogeneity.

6.1 Introduction

In the derivation of the ideal diode equation a long list of assumptions is made. It may be therefore expected that measured I-V characteristics would deviate from the idealized curve. Therefore, an understanding of the phenomena occurring in the contact is necessary to correctly extract and interpret data from those characteristics. Some of the deviations can be present in regular silicon devices [129] and some are specific to GaN diodes (as for example discussed in [22]). To extract Schottky contact parameters from the diode forward I-V characteristics, one must know the Richardson constant. It can be obtained from the I-V-T measurements, from the Richardson plot [90]. According to the diode theory, the characteristic should be linear and both barrier height and Richardson constant could be extracted from the plot. However, this extraction is only possible and accurate if following conditions are met [90]:

- Barrier height is temperature-independent
- Thermionic emission (TE) current is the only current
- Ideality factor is temperature-independent (what reflects the condition of TE current)

Figure 6.1: Typical data showing deviation of Richardson plot from linearity in a Pt/GaN schottky diode. Reprinted from F. Iucolano, F. Roccaforte, F. Giannazzo, and V. Raineri, "Barrier inhomogeneity and electrical properties of Pt/GaN Schottky contacts," *Journal of Applied Physics*, vol. 102, p. 113701, dec 2007, with the permission of AIP Publishing.

In the wide bandgap semiconductors, such as GaN, Schottky interface properties typically deviate from the theoretical diode behavior and it is not possible to extract data from the Richardson plot. The most commonly observed feature of Richardson plot of Schottky contacts to AlGaIn/GaN is the nonlinearity at lower temperatures, as visible in a typical Richardson plot in Fig. 6.1.

The deviations in diode characteristics are typically interpreted in the literature to be due to the Schottky barrier height inhomogeneity. Tung has discussed that such behavior is related to the spatial variation of the interface dipole [131]. The interface dipole magnitude depends on the contact metal, semiconductor and interface properties. Consequently, the barrier height is not uniform across the whole contact area. The Schottky barrier height variation (due to the dipole variation) is complex and depends on atomic and electronic structure of the interface. Often the contact is described by a model of patches with different, homogeneous barriers

The interaction between the low and high barrier regions is not analytically solvable and a numerical solution had to be found. Tung [131] derived an analytical expression for the effects of barrier height inhomogeneity on the current-voltage-temperature characteristics based on the assumption that the interface dipoles can be approximated as point dipoles. The low barrier regions (patches) surrounded by high barrier can create a saddle point potential which defines carrier emission for the low barrier regions. The saddle point potential is also bias and temperature dependent and can result in various I-V characteristics.

Tung describes the model as low barrier patches mixed within uniform high barrier region. Those patches are defined by the local barrier height and the size of the patch (radius - R_0). The model is further described by the density of low barrier patches (C_1) and difference between high and low barrier (Δ). Tung has proposed a reduced patch parameter γ which couples effects of Δ and R_0 on the I-V characteristics using a single parameter. Tung's parameters are bias and temperature independent. γ quantifies the effect of inhomogeneity on I-V characteristics:

$$\gamma = 3\left(\frac{\Delta R_0^2}{4}\right)^{\frac{1}{3}} \quad (6.1)$$

The contribution from low barrier patches to the total current is expressed as:

$$I_L = \left(\frac{4\pi C_1 \gamma}{9\beta \beta_1}\right) \exp(\beta \beta_1 \gamma) I_{L0}, \quad (6.2)$$

where:

$$I_{L0} = A * T^2 \exp(-\beta \Phi_B) (\exp(\beta (V_a - I_L R_{sp})) - 1) \quad (6.3)$$

$B_1 = (V_{bb}/\eta)^{\frac{1}{3}}$, with $\eta = v_s/qN_d$ is defined as the doping parameter. η captures the barrier height inhomogeneity sensitivity of the substrate

depending on the doping density. C_1 is the total density of patches, β - inverse thermal voltage q/kT . In the case of higher doping density the low barrier regions are harder to pinch off and can dominate the total current. The total current is a sum of the low barrier regions' current and the homogeneous high barrier region current.

Several authors [130, 132, 133] have observed signs of barrier height inhomogeneity, which usually exhibits in temperature dependences of both ideality factor and the barrier height and consequently in distorted Richardson plots. In this chapter we have investigated barrier heights of different Schottky metal stacks on AlGaN/GaN. We study the differences in the temperature dependencies of different diodes to verify if the inhomogeneity is present and related to the applied Au-free Schottky metal stack.

6.2 Methods

We have studied four different wafers with different Au-free Schottky metal stacks. The investigated samples come from NXP Semiconductors' GaN-on-Si process technology, in a silicon nitride passivation-first integration scheme [98]. The top layers of the wafers used in this experiment consist of $1.5\mu\text{m}$ of GaN with 20 nm of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}$ and a 3 nm GaN cap, prepared by metal-organic chemical vapor deposition (MOCVD). A Ti/Al-based gold-free metal stack, same as analyzed in Chapter 3, has been used for Ohmic contacts. The aluminum layer in the Ohmic stack is a few times thicker than the titanium and the Ti/Al ratio was optimized in order to obtain lowest contact resistance. This ratio is comparable to those used by different research groups [99–101]. Test structures are patterned by dry etching and isolation is obtained using argon ion implantation. Ohmic contacts receive rapid thermal annealing (RTA) treatment at an optimized temperature within a 800 – 900 °C range, which is typical for contacts to AlGaN/GaN [99, 100]. Devices were patterned by dry etching and isolation was obtained by using argon ion implantation with the energy of 160 keV and dose of $1 \cdot 10^{14}\text{cm}^{-2}$. We decided to study Au-free Schottky contact schemes which have been already studied in the literature, such as most popular Ni [17, 74, 75], as well as alternative ones like TiN [69] and TiWN [77]. Our aim was to observe if there are any differences, other than ideality factor and barrier height magnitude coming from using different materials. Different Schottky metal stacks have been prepared on four wafers:

- 250 nm TiN
- 250 nm TiN+ (increased nitrogen content)
- 250 nm TiW(N)+
- 250 nm Ni

In these contacts the Ni layer was evaporated whereas TiN and TiW(N) layers were sputter-deposited. The TiW(N) consists of TiW, TiWN and again TiW and their thickness is 10/230/10 nm respectively. After the Schottky anode deposition the wafer was annealed at an optimized temperature between 400 - 600 °C.

I-V characteristics of diodes on all wafers have been measured at room temperature as well as at elevated temperatures up to 200 °C, to allow for making Richardson plot and observing signs of any non-typical behavior.

(a)

(b)

Figure 6.2: Distribution of the I-V characteristics over the wafers of Schottky diodes: (a) TiN; (b) TiN+

Additionally to the electrical measurements, we have conducted Conductive Atomic Force Microscopy (CAFM) measurements to observe changes in the wafer conductivity in the vertical direction (from active layers towards the substrate). In order to make the measurement, a bias voltage is applied between an extremely sharp conductive cantilever tip and sample. During the imaging, the cantilever scans the sample surface in contact

Figure 6.3: Distribution of the I-V characteristics over the wafers of Schottky diodes: (a) TiW(N)+; (b) Ni.

mode to give a topography image and the electric current is measured simultaneously. This allows to determine non-uniformity in current flow if there are any regions (patches) where the current flow would be preferential. The CAFM measurements of the wafers were performed with a Bruker Nano Dimension FastScan scanning probe microscope, in the tapping mode using Si probes (DDESP-FM) Electrical characterization of diodes has been conducted with an Agilent B1505 semiconductor parameter analyzer.

6.3 Electrical measurements

In order to understand differences between diodes with different metal stacks, we have started with electrical measurements of I-V characteristics, and extraction of Schottky barrier height and ideality factor. Such analysis allows to quickly identify any unexpected behavior of the device. On

one hand we look at the differences between different wafers and on the other we also evaluate device parameters uniformity within one wafer by measuring multiple devices.

(a)

(b)

Figure 6.4: Parameters of four different metal stacks: (a) Schottky barrier height; and (b) ideality factor.

The results of I-V characterization, presented in Figs. 6.2 and 6.3, show that for both TiN diodes (with varying nitrogen content), the characteristics are almost identical. Both sets of diodes exhibit similar spread of parameters with average Schottky barrier height of $\sim 0.9\text{V}$ and ideality factor of ~ 1.7 . Subsequently, TiW(N) and Ni diodes prove to be different both in terms parameters as well as in terms of uniformity of the characteristics. The latter cannot be attributed to the metal stack or the wafer at this stage and hence will be relevant to observe in the inhomogeneity analyses. For the TiW(N) contact, the larger uniformity of devices across the wafer comes at a cost of a lower Schottky barrier height. On the other hand, wafer with Ni contact has the highest barrier among all stacks.

Data on Schottky barrier height and ideality factor is presented in the Fig. 6.4. All four wafers exhibit rather large ideality factor, between 1.5 - 1.7 on average. The TiW(N) stack is most uniform and also shows lowest ideality factor.

Further analysis of the wafers required I-V-T measurements which would expose signs of barrier height inhomogeneity. It is expected that if a device inhomogeneous barrier, there will be regions of different barrier height within the device area. Those regions would behave differently as a function of temperature and eventually would cause Schottky barrier height temperature dependence.

We have made I-V-T measurements of all four wafers in the temperature range of 25 °C - 200 °C. The Schottky barrier height box plots for all analyzed devices are presented in Figs. 6.5 and 6.6.

(a)

(b)

Figure 6.5: Schottky barrier height as a function of temperature: (a) TiN; (b) TiN+

The ideality factor characteristic as a function of temperature is similar

(a)

(b)

Figure 6.6: Schottky barrier height as a function of temperature: (a) TiW(N)+; (b) Ni.

to those observed in literature for different contacts to AlGaIn/GaN [117, 134]. There is a decrease of the ideality factor observed up to $\sim 140^\circ\text{C}$ (varies for different Schottky stacks) after which the parameter stabilizes. The same holds for Schottky barrier behavior. Both could be related to the low barrier patches being pinched off after crossing certain temperature threshold.

Knowing that the barrier height and ideality factor are temperature dependent we already know that a correct Richardson plot cannot be constructed [133]. However, plotting one still gives insight into the properties of the Schottky junction. Therefore, we present the Richardson plot in Fig. 6.9.

The plot shows that the characteristic deviates from linearity at lower temperatures. The magnitude of this deviation is different for all wafers, and it is largest for wafer with Ni metal stack. This deviation from the

(a)

(b)

Figure 6.7: Ideality factor as a function of temperature: (a) TiN; (b) TiN+

linearity was initially attributed to the conduction mechanisms other than thermionic emission playing a role in the junction [135, 136]. The device behavior observed in Richardson plot could be described well by the barrier height nonuniformity in AlGaIn/GaN devices.

6.4 Discussion

In Schottky contacts to AlGaIn/GaN the most commonly observed behavior of the Richardson plot is the deviation of the characteristic from linearity at lower temperatures [133, 137], as presented in the results section. Different transport mechanisms result in varying I-V-T characteristics. Although various anomaly equations are a good approximation of the voltage and temperature dependence of the ideality factor in the low barrier dominated regime, i.e. at lower temperatures, the approximation is not valid in the high barrier dominated region. Depending on the extent of the inhomogeneity

(a)

(b)

Figure 6.8: Ideality factor as a function of temperature: (a) TiW(N)+; (b) Ni.

geneity, the determined Richardson constant can deviate from the actual value and a more accurate method is needed to filter the effects of barrier height inhomogeneity on the extracted Richardson constant. Sarpatwari proposed a new approach to analyzing Richardson plot based on Tung's barrier height inhomogeneity model [131]. In this model, the current flowing through an inhomogeneous Schottky diode is characterized by the inhomogeneity parameters C_1 and σ and is given by [133]:

$$\frac{I}{1 - \exp(-(q/kT)V)} = AA * T^2 \exp(-(q/kT)\Phi_B) \left(1 + \frac{8C_1\pi\sigma^2}{9(\beta_1)} \exp\left(\frac{\beta^2\beta_1^2\sigma^2}{2}\right) \exp((q/KT)V)\right) \quad (6.4)$$

where β_1 equals $(V_{bb}/n)^{(1/3)}$. V_{bb} is the band bending at the measurement bias and $\eta = \epsilon_s/qN_d$ is a doping density related parameter.

Figure 6.9: Richardson plot for all four metal stacks.

Rewriting the Eq. (6.4) recognizing that the effective barrier height is the slope of the Richardson plot, the effective Richardson constant (A_{eff}^*) can be expressed as:

$$\ln(A_{eff}^*) = \ln(A^*) + \left(\beta - \frac{1}{\beta \beta_1^2 \sigma^2} \right) (\Phi_{B_{eff}} - \Phi_B) \quad (6.5)$$

Equation (6.5) shows that the extracted Richardson constant (A_{eff}^*) can be related to the effective barrier height $\Phi_{B_{eff}}$, homogeneous Richardson constant (A^*) and homogeneous barrier height (Φ_B). A linear relationship between $\ln(A_{eff}^*)$ and $\Phi_{B_{eff}}$ exists, and as $\Phi_{B_{eff}}$ approaches Φ_B , A_{eff}^* approaches A^* .

Figure 6.10: Adjusted Richardson plot for all four metal stacks.

It is worth noting that the effective Richardson constant actually depends on the patch distribution parameter (σ). Hence, the slope of the adjusted Richardson plot would reveal additional information about the Schottky barrier height inhomogeneity.

In the Fig. 6.10, we present the adjusted Richardson plot made for all four investigated wafers. The effective Richardson constant is plotted as a function of the barrier height. While the effective Richardson constant varies significantly, the slope of the plots remains almost identical. According to Eq. 6.5, the slope depends, among others, from the patch distribution parameter σ . Therefore, data indicate that the barrier height inhomogeneity is due to the same factor in all wafers, regardless of the metal stack being used. One should note that the plotted Richardson constant is an effective constant as described in Sarpatwari's model and it will have a wide range, in most cases distant from the actual values.

6.5 Conductive Atomic Force Microscopy

The analysis of adjusted Richardson plot revealed that it is likely that the source of Schottky barrier inhomogeneity comes from the wafer, i.e. it might be due to the dislocations for example. Hence, in order to better understand the results of electrical characterization, we have investigated the substrate - GaN-on-Si wafer. The topmost layers of the wafer included $1.5\mu\text{m}$ of GaN with 20 nm of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}$ and a 3 nm GaN cap. Below the layers there was a transition layer which served to relieve the stress due to the different lattice constants of GaN and Si. The TEM image of the wafer can be seen in Fig. 6.11.

Due to the structure of the wafer (presence of transition layers) defects in the structure might be present. One of the commonly observed are threading dislocations [138]. Various authors have also observed regions of higher conductivity, what indicates possible source of Schottky barrier height inhomogeneity [134, 139]

We investigated bare GaN-on-Si wafer with the Atomic Force Microscope (AFM). Subsequently, we assessed the conductivity of the wafer using Conductive AFM (CAFM) technique. In the Fig. 6.12 we present topography scan (a) and corresponding phase image (b) of $1 \times 1 \mu\text{m}$ area of the bare wafer. Changes in current are indicative of material changes.

Figure 6.11: STEM bright field image of wafer cross section with dislocations visible in the semiconductor layers.

From the Fig. 6.12 we can observe three things:

- Clear steps from the GaN growth are observed,
- Many pits (probably dislocations) end at the steps, density of these dislocations is about 10^9 cm^{-2} ,
- Donut-like structures are clearly visible in the phase measurement.

The same kind of measurement has been conducted on larger area ($10 \times 10 \mu\text{m}$) of the same wafer (Fig. 6.13).

Figure 6.12: AFM image of $1 \times 1 \mu\text{m}$ GaN-on-Si wafer sample: (a) height (nm); and (b) phase (mV).

Figure 6.13: AFM image of $10 \times 10 \mu\text{m}$ GaN-on-Si wafer sample: (a) height (nm); and (b) phase (mV).

After initial investigation of the wafer topography and phase measurement, it was necessary to look at electrical properties, i.e. conductivity. Hence, a CAFM analysis has been done and is presented in Fig. 6.14. Subfigure (a) shows the tapping mode AFM signal with the donuts. No evidence of the pits at step edges is seen (probably due to the lower lateral

resolution). In (b) the friction AFM picture is presented. Step edges are in this case not seen anymore. The donuts are present, suggesting that this is different material than the rest of the surface. CAFM image in in Fig. 6.14 (c) shows that there is a higher current flowing via the donuts structures, what indicates possible barrier inhomogeneity source.

Figure 6.14: AFM analysis of GaN wafer: (a) tapping mode AFM signal with the donuts; (b) friction AFM picture; and, (c) CAFM.

6.6 Conclusions

We have studied Schottky diodes with four different Au-free metal stacks. They included standard Ni metal stack as well as alternatives of TiW and TiW(N). During the electrical characterization we have observed, as expected, that the investigated devices exhibit differences in their parameters, namely Schottky barrier height and ideality factor. The Ni contact had the highest Schottky barrier height while the TiWN was the most uniform across the wafer. All four schemes exhibited large ideality factor.

The Richardson plots obtained from the I-V-T characteristics resulted in the commonly observed deviation of the plot for low temperatures. Those

deviations, typically attributed to the Schottky barrier height inhomogeneity, led us to analyzing the adjusted Richardson plot model developed by Sarpatwari. In the model, the effective Richardson constant is plotted versus barrier height. The observed characteristics indicated that the patch distribution parameter σ , which determines the slope of the plot, should be similar for all wafers. This indicates a common origin of the device behavior, namely the wafer used.

Wafer have been investigated using CAFM, in order to observe potential sources of the inhomogeneity, such as dislocations. The measurements of the wafer topography revealed the donut-like patches with increased current measured in CAFM. Those regions are likely to be the source of the observed device behavior and consequently the origin of Schottky barrier height inhomogeneity.

CHAPTER 7

SUMMARY AND RECOMMENDATIONS

Abstract

In this chapter, the main conclusions discussed in this thesis are presented. Furthermore, recommendations and further research suggestions are listed for both Ohmic and Schottky contacts.

7.1 Introduction

7.1.1 Summary

The purpose of this thesis is to provide better understanding of gold-free electrical contacts to AlGaIn/GaN heterostructures. This is especially important for mass production of AlGaIn/GaN power devices in industrial context, where certain limitations exist. For example, while GaN devices fabrication would be most cost-effective in standard Si fabs, the metal of choice for electrical contacts - gold - is not allowed there, as it contaminates standard Si devices. Hence, in this work, we investigated Au-free Ohmic and Schottky contacts that are Si-processing compatible, such as TiW and TiWN. We have studied mechanisms of contact formation and phenomena affecting contact parameters.

Ohmic contacts

Both planar and recessed Ohmic contacts have been studied. We have shown that interface reactions occur at the metal-semiconductor interface after deposition and annealing of Ti/Al based Ohmic contacts. Since those interface changes can affect 2DEG concentration, they effectively influence the sheet resistance under the contact. Typically, this resistance is assumed to be identical to the resistance outside the contact area.

In the investigated devices TEM micrographs showed the formation of a few-nm-thick layer at the metal-semiconductor interface. As indicated in the literature review, this layer was most likely TiN and in order to confirm that, we have made EDX analysis of the samples and observed an increased Ti concentration close to the interface. From the EDX measurement and also from thermodynamical point of view (the formation enthalpy of TiN is higher than that of GaN and AlN), the layer at the interface is most likely TiN. It is also possible that some AlN or a ternary Al-Ti-N alloy are formed, but these all cause the same thing: nitrogen extraction and as a consequence effective n-type doping of the region underneath the contact. Such reactions should lead to a decrease of sheet resistance under the contact what has been investigated with new test structures.

We have used contact-end resistance structures to characterize Ohmic contacts and have shown for the first time, that the sheet resistance under the contact to AlGaIn/GaN can change significantly and therefore, if not accounted for, leads to significant errors in contact resistance extraction. Based on results of sheet resistance under the contact at elevated temperatures (which will occur under typical operating conditions of these power devices) it was concluded that at higher temperatures contacts need to be longer than suggested by traditional TLM test structures.

Secondly, experiments with recessed Ohmic contacts showed a way to improve the contact resistance while reducing the processing thermal budget. Different recess etches, where the AlGaIn was either partially or fully

removed, have been investigated. We have shown that the optimization problem with the resistance of recessed contacts is related to the reduction of 2DEG conductivity and not the deterioration of the metal-semiconductor interface. The best results were obtained for the shallow recess etch of 7 nm, where the 2DEG electron concentration under the contact remains high (i.e. sheet resistance is low). For the deep recess etch, the resistance increase caused the contact parameters to deteriorate. In the case of complete Al-GaN removal, the contact resistance was the highest, due to the nature of the contact changing from a planar contact to a side contact.

7.1.2 Schottky contacts

Stress in Schottky metal stacks

Research on Schottky contacts in this thesis was focused on investigation of alternative Au-free metals such as TiW and TiWN. Since we have observed differences in Schottky barrier height between different Ni-based metal multilayers, we have compared MS interfaces of Ni and Ni with Au-free capping stacks. Using different techniques such as TEM, EDX, EELS and SIMS, we have shown there are no indications of reactions at the MS interface. That means there is no observable diffusion of capping metals into either Ni or GaN in the close vicinity of the MS interface. There was also no outdiffusion of elements from semiconductor to the metal.

Therefore, it is proposed that differences in Schottky barrier height between different metal stacks (all with Ni in contact with the semiconductor) are caused by physical factors rather than chemical. In AlGaN/GaN devices, where stress in the AlGaN layer is an important contributor to the formation of the 2DEG (as 2DEG is partly formed due to piezoelectric polarization), it is most likely, that stress induced by the metal layers is also influencing the device. We have conducted de-processing experiments to remove the topmost metal layers in the contact in order to release the stress. Measurements before and after on exactly the same devices, have indicated increase in barrier height of about 50 mV.

Schottky barrier height inhomogeneity

During I-V-T characterization of Au-free Schottky contacts, typical signs of barrier inhomogeneity have been observed. They can especially be observed in the temperature dependence of the ideality factor and the Schottky barrier height. The former decreases with temperature whereas the latter increases. For both parameters levelling off was observed at temperatures above 140 °C. This means that firstly, the Schottky barrier in those devices is inhomogeneous. Secondly, the stabilization of parameters might be due to pinching-off the low barrier patches as described by Tung [131], leading to only high barrier homogeneous regions contributing to current transport. In order to establish if the source of inhomogeneity comes from the metal stack or is due to inhomogeneities in the wafer itself,

we have made analyses based on the adjusted Richardson model [133], where the patch distribution in the contact is taken into the analysis. We have observed that the modified plots for different metal stack exhibit the same slope. This slope is directly related to the patch distribution parameter. Since this is the case, the source of the inhomogeneity should be attributed to the wafer rather than to the metal stack used. To confirm that, we have conducted atomic force microscopy analyses of the wafers. The measurements of the wafer topography revealed the donut-like patches with increased current measured in CAFM. Those regions are likely to be the source of the observed device behavior and consequently the origin of Schottky barrier height inhomogeneity.

7.2 Recommendations and further research

Based on the research results of this thesis, few recommendations and further research suggestions can be made regarding both Ohmic and Schottky contact.

Ohmic contacts

- When extracting contact parameters, the resistance under the contact can not be assumed to be identical as outside contact area, as it has been done for standard Si devices. It is especially relevant for contact size design, where the transfer length in the contact has to be taken into account. Since in case of contacts to AlGaIn/GaN, the resistance under the contact can be lowered due to N-vacancy doping, effectively that would require larger contacts. If not accounted for that, devices are prone to premature failure.
- Additional research should be devoted to engineering of recessed Ohmic contacts. The benefits would be twofold: firstly, the contact resistance can be decreased, and secondly, it is possible to lower the thermal budget of device processing as recessed contacts may require lower annealing temperatures when designed correctly.
- Since recessed contacts are potential solution for AlGaIn/GaN devices, devices with completely removed AlGaIn layer should be investigated and current transport in such side contacts should be analyzed.

Schottky contacts

- Investigation of the stress in Schottky metal stack influencing the barrier height showed that the stress can be exploited to tweak the barrier height in a desired way by engineering the built-in stress in the TiW layer as well as controlling that layer's thickness. Research results suggest that special attention should be paid to the additional passivation layers on top of the contacts as those can also affect the device performance via stress.

- Future work should include computer simulations of stress distribution in the device structure due to stress from metal layers. Theoretical investigation of change of such parameters as conduction band position, trap activation energy or metal work function with stress should be made. While conducting the experimental work a lot of attention should be devoted to prepare devices with identical metal-semiconductor interfaces (i.e. no different chemical reactions) yet different stress due to the additional metal (or other material) layers.
- In order to be able to reduce Schottky barrier height inhomogeneity, further research has to be done on epitaxy of GaN on Si, as defects, such as dislocations, can be the cause of inhomogeneity.

BIBLIOGRAPHY

- [1] D. Ehrentraut, M. Elke, and M. Bockowski, *Technology of Gallium Nitride Crystal Growth*, vol. 133. 2010.
- [2] M. A. Briere, "GaN-based power devices offer game-changing potential in power-conversion electronics," *EE Times Europe*, p. 3, 2008.
- [3] C. W. Hsu, Y. F. Chen, and Y. K. Su, "Quality improvement of GaN on Si substrate for ultraviolet photodetector application," *IEEE Journal of Quantum Electronics*, vol. 50, no. 1, pp. 35–41, 2014.
- [4] H. Ishikawa, G.-Y. Zhao, N. Nakada, T. Egawa, T. Jimbo, and M. Umeno, "GaN on Si Substrate with AlGaIn / AlN Intermediate Layer," *Japanese Journal of Applied Physics*, vol. 492, no. 5, pp. 492–494, 1999.
- [5] M. Ishida, T. Ueda, T. Tanaka, and D. Ueda, "GaN on Si technologies for power dwtching fevices," *IEEE Transactions on Electron Devices*, vol. 60, no. 10, pp. 3053–3059, 2013.
- [6] M. Seon, T. Prokofyeva, M. Holtz, S. A. Nikishin, N. N. Faleev, and H. Temkin, "Selective growth of high quality GaN on Si(111) substrates," *Applied Physics Letters*, vol. 76, pp. 1842–1844, apr 2000.
- [7] L. Pan, X. Dong, J. Ni, Z. Li, Q. Yang, D. Peng, and C. Li, "Growth of compressively-strained GaN films on Si(111) substrates with thick AlGaIn transition and AlGaIn superlattice buffer layers," *Physica Status Solidi (C) Current Topics in Solid State Physics*, vol. 13, no. 5-6, pp. 181–185, 2016.
- [8] Y.-K. Noh, H.-C. Kwon, J.-E. Oh, S.-T. Lee, and M.-D. Kim, "Influence of an embedded low-temperature AlN strain relaxation layer on the strain states and the buffer characteristics of GaN films grown on (110) Si substrates by using ammonia molecular beam epitaxy," *Journal of the Korean Physical Society*, vol. 66, no. 11, 2015.
- [9] P.-J. Lin, C.-H. Tien, T.-Y. Wang, C.-L. Chen, S.-L. Ou, B.-C. Chung, and D.-S. Wu, "On the Role of AlN Insertion Layer in Stress Control of GaN on 150-mm Si (111) Substrate," *Crystals*, vol. 7, no. 5, p. 134, 2017.
- [10] IHS, "Market for GaN and SiC Power Semiconductors to Top \$1 Billion in 2020 | IHS Online Newsroom," 2016.
- [11] D. Marcon, B. De Jaeger, S. Halder, N. Vranckx, G. Mannaert, M. Van Hove, and S. Decoutere, "Manufacturing challenges of GaN-on-Si HEMTs in a 200 mm CMOS fab," *IEEE Transactions on Semiconductor Manufacturing*, vol. 26, no. 3, pp. 361–367, 2013.
- [12] M. W. Fay, Y. Han, P. D. Brown, I. Harrison, K. P. Hilton, a. Munday, D. Wallis, R. S. Balmer, M. J. Uren, and T. Martin, "Structural and electrical characterization of AuPtAlTi Ohmic contacts to AlGaIn/GaN with varying annealing temperature and Al content," *Journal of Applied Physics*, vol. 103, no. 7, p. 074501, 2008.
- [13] D.-F. Wang, F. Shiwei, C. Lu, A. Motayed, M. Jah, S. N. Mohammad, K. a. Jones, and L. Salamanca-Riba, "Low-resistance Ti/Al/Ti/Au multilayer ohmic contact to n-GaN," *Journal of Applied Physics*, vol. 89, no. 11, p. 6214, 2001.
- [14] F. Iucolano, G. Greco, and F. Roccaforte, "Correlation between microstructure and temperature dependent electrical behavior of annealed Ti/Al/Ni/Au Ohmic contacts to AlGaIn/GaN heterostructures," *Applied Physics Letters*, vol. 103, no. 20, p. 201604, 2013.
- [15] B. Ofuonye, J. Lee, M. Yan, C. Sun, J.-M. Zuo, and I. Adesida, "Electrical and microstructural properties of thermally annealed Ni/Au and Ni/Pt/Au Schottky contacts on AlGaIn/GaN heterostructures," *Semiconductor Science and Technology*, vol. 29, no. 9, p. 095005, 2014.
- [16] D. Yan, J. Jiao, J. Ren, G. Yang, and X. Gu, "Forward current transport mechanisms in Ni/Au-AlGaIn/GaN Schottky diodes," *Journal of Applied Physics*, vol. 114, no. 14, 2013.
- [17] N. Miura, T. Nanjo, M. Suita, T. Oishi, Y. Abe, T. Ozeki, H. Ishikawa, T. Egawa, and T. Jimbo, "Thermal annealing effects on Ni/Au based Schottky contacts on n-GaN and AlGaIn/GaN with insertion of high work function metal," *Solid-State Electronics*, vol. 48, pp. 689–695, may 2004.
- [18] A. Vertiatichikh, E. Kaminsky, J. Teetsov, and K. Robinson, "Structural properties of alloyed Ti / Al / Ti / Au and Ti / Al / Mo / Au ohmic contacts to AlGaIn / GaN," vol. 50, pp. 1425–1429, 2006.
- [19] B. Van Daele, G. Van Tendeloo, W. Ruythooren, J. Derluyn, M. R. Leys, and M. Germain, "The role of Al on Ohmic contact formation on n-type GaN and AlGaIn/GaN," *Applied Physics Letters*, vol. 87,

p. 061905, aug 2005.

- [20] Z. Lin, W. Lu, J. Lee, D. Liu, J. S. Flynn, and G. R. Brandes, "Barrier heights of Schottky contacts on strained AlGa_N/Ga_N heterostructures: Determination and effect of metal work functions," *Applied Physics Letters*, vol. 82, no. 24, pp. 4364–4366, 2003.
- [21] C. T. Lee, Y. J. Lin, and D. S. Liu, "Schottky barrier height and surface state density of Ni/Au contacts to (NH₄)₂Sx-treated n-type Ga_N," *Applied Physics Letters*, vol. 79, no. 16, pp. 2573–2575, 2001.
- [22] G. Greco, F. Giannazzo, F. Roccaforte, G. Greco, F. Giannazzo, and F. Roccaforte, "Temperature dependent forward current-voltage characteristics of Ni / Au Schottky contacts on AlGa_N / Ga_N heterostructures described by a two diodes model Temperature dependent forward current-voltage characteristics of Ni / Au Schottky contacts on AlGa_N," vol. 045701, 2017.
- [23] W. Lim, J. H. Jeong, J. H. Lee, S. B. Hur, J. K. Ryu, K. S. Kim, T. H. Kim, S. Y. Song, J. I. Yang, and S. J. Pearton, "Temperature dependence of current-voltage characteristics of Ni-AlGa_N/Ga_N Schottky diodes," *Applied Physics Letters*, vol. 97, no. 24, 2010.
- [24] S. Karboyan, J. Tartarin, and B. Lambert, "Microwave Integrated Circuits Conference (EuMIC), 2013 European," *Microwave Integrated Circuits Conference (EuMIC), 2013 European*, pp. 240–243, 2013.
- [25] J.-h. Shin, J. Park, S. Jang, T. Jang, K. S. Kim, J.-h. Shin, J. Park, S. Jang, T. Jang, and K. S. Kim, "Metal induced inhomogeneous Schottky barrier height in AlGa_N / Ga_N Schottky diode Metal induced inhomogeneous Schottky barrier height in AlGa_N / Ga_N Schottky diode," vol. 243505, no. 2013, pp. 2011–2015, 2016.
- [26] M. E. Levinshstein, S. L. Rumyantsev, M. Shur, V. Bougrov, and A. Zubrilov, *Properties of Advanced Semiconductor Materials: GaN, AlN, InN, BN, SiC, SiGe*. 2001.
- [27] W. contributors, "Ga_N Wurtzite crystal structure," 2018. [Online; accessed 31-January-2018].
- [28] B. L. Liu, M. Lachab, A. Jia, A. Yoshikawa, and K. Takahashi, "MOCVD growth of device-quality Ga_N on sapphire using a three-step approach," *Journal of Crystal Growth*, vol. 234, no. 4, pp. 637–645, 2002.
- [29] V. V. Lundin, E. E. Zavarin, A. I. Besulkin, and A. G. Gladyshev, "MOCVD-Grown AlGa_N / Ga_N Heterostructures with High Electron Mobility," vol. 38, no. 11, pp. 1323–1325, 2004.
- [30] M. A. L. Johnson, "Molecular beam epitaxy growth and properties of Ga_N, Al_xGa_{1-x}N, and AlN on Ga_N/SiC substrates," *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures*, vol. 14, p. 2349, may 1996.
- [31] M. Sánchez-García, E. Calleja, F. Naranjo, F. Sánchez, F. Calle, E. Muñoz, A. Sánchez, F. Pacheco, and S. Molina, "MBE growth of Ga_N and AlGa_N layers on Si(111) substrates: doping effects," *Journal of Crystal Growth*, vol. 201-202, pp. 415–418, may 1999.
- [32] O. Ambacher, J. Smart, J. R. Shealy, N. G. Weimann, K. Chu, M. Murphy, W. J. Schaff, L. F. Eastman, R. Dimitrov, L. Wittmer, M. Stutzmann, W. Rieger, and J. Hilsenbeck, "Two-dimensional electron gases induced by spontaneous and piezoelectric polarization charges in N- and Ga-face AlGa_N/Ga_N heterostructures," *Journal of Applied Physics*, vol. 85, no. 6, p. 3222, 1999.
- [33] H. W. Jang, C. M. Jeon, K. H. Kim, J. K. Kim, S. B. Bae, J. H. Lee, J. W. Choi, and J. L. Lee, "Mechanism of two-dimensional electron gas formation in Al_xGa_{1-x}N/Ga_N heterostructures," *Applied Physics Letters*, vol. 81, no. 7, pp. 1249–1251, 2002.
- [34] M. Shur, B. Gelmont, and M. A. Khan, "Electron Mobility in Two-Dimensional Electron Gas in AlGa_N/Ga_N Heterostructures and in Bulk Ga_N," vol. 25, no. 5, 1996.
- [35] W. S. Lau, J. B. H. Tan, and B. P. Singh, "Microelectronics Reliability Formation of Ohmic contacts in AlGa_N / Ga_N HEMT structures at 500 °C by Ohmic contact recess etching," *Microelectronics Reliability*, vol. 49, no. 5, pp. 558–561, 2009.
- [36] G. Greco, F. Iucolano, and F. Roccaforte, "Ohmic contacts to Gallium Nitride materials," *Applied Surface Science*, vol. 383, pp. 324–345, 2016.
- [37] W. R. Wilcox and T. J. LaChapelle, "Mechanism of gold diffusion into silicon," *Journal of Applied Physics*, vol. 35, no. 1, pp. 240–246, 1964.
- [38] L. Pavesi and D. J. Lockwood, *Silicon Photonics, Volume 1*. 2004.
- [39] H. Amano, N. Sawaki, I. Akasaki, and Y. Toyoda, "Metalorganic vapor phase epitaxial growth of a high quality Ga_N film using an AlN buffer layer," *Applied Physics Letters*, vol. 48, pp. 353–355, feb 1986.
- [40] M. E. Lin, Z. Ma, F. Y. Huang, Z. F. Fan, L. H. Allen, and H. Morkoç, "Low resistance ohmic contacts on wide band-gap Ga_N," *Applied Physics Letters*, vol. 64, no. 8, pp. 1003–1005, 1994.
- [41] D. W. Jenkins and J. D. Dow, "Electronic structures and doping of In_N, In_xGa_{1-x}N, and In_xAl_{1-x}N," *Physical Review B*, vol. 39, no. 5, pp. 3317–3329, 1989.
- [42] Q. Feng, L. M. Li, Y. Hao, J. Y. Ni, and J. C. Zhang, "The improvement of ohmic contact of Ti/Al/Ni/Au to AlGa_N/Ga_N HEMT by multi-step annealing method," *Solid-State Electronics*, vol. 53, no. 9, pp. 955–958, 2009.
- [43] S. Kaciulis, L. Pandolfi, S. Viticoli, M. Peroni, and A. Passaseo, "Characterization of Ohmic contacts on Ga_N/AlGa_N heterostructures," *Applied Surface Science*, vol. 253, no. 3, pp. 1055–1064, 2006.

- [44] L. Wang, F. M. Mohammed, and I. Adesida, "Dislocation-induced nonuniform interfacial reactions of Ti/Al/Mo/Au ohmic contacts on AlGaIn/GaN heterostructure," *Applied Physics Letters*, vol. 87, no. 14, pp. 1–3, 2005.
- [45] R. Gong, J. Wang, Z. Dong, S. Liu, M. Yu, C. P. Wen, Y. Hao, B. Shen, Y. Cai, B. Zhang, and J. Zhang, "Analysis on the new mechanisms of low resistance stacked Ti/Al Ohmic contact structure on Al-GaN/GaN HEMTs," *Journal of Physics D: Applied Physics*, vol. 43, no. 39, 2010.
- [46] F. Iucolano, F. Roccaforte, A. Alberti, C. Bongiorno, S. Di Franco, and V. Raineri, "Temperature dependence of the specific resistance in Ti/Al/Ni/Au contacts on n-type GaN," *Journal of Applied Physics*, vol. 100, no. 12, pp. 123701–123706, 2006.
- [47] A. Motayed, R. Bathe, M. C. Wood, O. S. Diouf, R. D. Vispute, and S. N. Mohammad, "Electrical, thermal, and microstructural characteristics of Ti/Al/Ti/Au multilayer Ohmic contacts to n-type GaN," *Journal of Applied Physics*, vol. 93, no. 2, pp. 1087–1094, 2003.
- [48] E. F. Chor, D. Zhang, H. Gong, G. L. Chen, and T. Y. F. Liew, "Electrical characterization and metallurgical analysis of Pd-containing multilayer contacts on GaN," *Journal of Applied Physics*, vol. 90, no. 3, pp. 1242–1249, 2001.
- [49] L. Wang, F. M. Mohammed, B. Ofuonye, and I. Adesida, "Ohmic contacts to n+-GaN capped Al-GaN/AlN/GaN high electron mobility transistors," *Applied Physics Letters*, vol. 91, p. 012113, jul 2007.
- [50] S. Ruvimov, Z. Liliental-Weber, J. Washburn, K. J. Duxstad, E. E. Haller, Z. F. Fan, S. N. Mohammad, W. Kim, A. E. Botchkarev, and H. Morkoç, "Microstructure of Ti/Al and Ti/Al/Ni/Au Ohmic contacts for n-GaN," *Applied Physics Letters*, vol. 69, no. 11, pp. 1556–1558, 1996.
- [51] M. Placidi, A. Pérez-Tomás, A. Constant, G. Rius, N. Mestres, J. Millán, and P. Godignon, "Effects of cap layer on ohmic Ti/Al contacts to Si+ implanted GaN," *Applied Surface Science*, vol. 255, no. 12, pp. 6057–6060, 2009.
- [52] S. P. Kowalczyk, J. R. Waldrop, and R. W. Grant, "Reactivity and interface chemistry during Schottky-barrier formations: Metals on thin native oxides of GaAs investigated by x-ray photoelectron spectroscopy," *Applied Physics Letters*, vol. 38, no. 3, pp. 167–169, 1981.
- [53] B. Boudart, S. Trassart, X. Wallart, J. C. Pesant, O. Yaradou, D. Théron, Y. Crosnier, H. Lahreche, and F. Omnes, "Comparison between TiAl and TiAlNiAu ohmic contacts to n-type GaN," *Journal of Electronic Materials*, vol. 29, no. 5, pp. 603–606, 2000.
- [54] S. N. Mohammad, "Contact mechanisms and design principles for nonalloyed ohmic contacts to n-GaN," *Journal of Applied Physics*, vol. 95, no. 9, p. 4856, 2004.
- [55] A. N. Bright, P. J. Thomas, M. Weyland, D. M. Tricker, C. J. Humphreys, and R. Davies, "Correlation of contact resistance with microstructure for Au/Ni/Al/Ti/AlGaIn/GaN ohmic contacts using transmission electron microscopy," *Journal of Applied Physics*, vol. 89, no. 6, p. 3143, 2001.
- [56] H. Xin, S. Poust, W. Sutton, and D. Li, "Optimization of AlGaIn/GaN HEMT Ohmic Contacts for Improved Surface Morphology with Low Contact Resistance," *Proc. CS MANTECH Conference, May 17th-20th*, pp. 149–152, 2010.
- [57] X. Kong, K. Wei, G. Liu, and X. Liu, "Role of Ti/Al relative thickness in the formation mechanism of Ti/Al/Ni/Au Ohmic contacts to AlGaIn/GaN heterostructures," *Journal of Physics D: Applied Physics*, vol. 45, no. 26, 2012.
- [58] F. Roccaforte, F. Iucolano, F. Giannazzo, A. Alberti, and V. Raineri, "Nanoscale carrier transport in Ti/Al/Ni/Au Ohmic contacts on AlGaIn epilayers grown on Si(111)," *Applied Physics Letters*, vol. 89, no. 2, 2006.
- [59] H. S. Lee, D. S. Lee, and T. Palacios, "AlGaIn/GaN high-electron-mobility transistors fabricated through a au-free technology," *IEEE Electron Device Letters*, vol. 32, no. 5, pp. 623–625, 2011.
- [60] J. Zhang, S. Huang, Q. Bao, X. Wang, K. Wei, Y. Zheng, Y. Li, C. Zhao, X. Liu, Q. Zhou, W. Chen, and B. Zhang, "Mechanism of Ti/Al/Ti/W Au-free ohmic contacts to AlGaIn/GaN heterostructures via pre-ohmic recess etching and low temperature annealing," *Applied Physics Letters*, vol. 107, no. 26, 2015.
- [61] H. Sun, M. Liu, P. Liu, X. Lin, J. Chen, M. Wang, and D. Chen, "Optimization of Au-Free Ohmic Contact Based on the Gate-First Double-Metal AlGaIn/GaN MIS-HEMTs and SBDs Process," *IEEE Transactions on Electron Devices*, 2017.
- [62] A. Malmros, H. Blanck, and N. Rorsman, "Electrical properties, microstructure, and thermal stability of Ta-based ohmic contacts annealed at low temperature for GaN HEMTs," *Semiconductor Science and Technology*, vol. 26, p. 075006, July 2011.
- [63] Z. Fan, S. N. Mohammad, W. Kim, O. Aktas, A. E. Botchkarev, and H. Morkoç, "Very low resistance multilayer Ohmic contact to n-GaN," *Applied Physics Letters*, vol. 68, no. 12, p. 1672, 1996.
- [64] L. Wang, F. M. Mohammed, and I. Adesida, "Formation mechanism of Ohmic contacts on AlGaIn/GaN heterostructure: Electrical and microstructural characterizations," *Journal of Applied Physics*, vol. 103, no. 9, p. 093516, 2008.

- [65] Y. J. Lin, Y. M. Chen, T. J. Cheng, and Q. Ker, "Schottky barrier height and nitrogen-vacancy-related defects in Ti alloyed Ohmic contacts to n-GaN," *Journal of Applied Physics*, vol. 95, no. 2, pp. 571–575, 2004.
- [66] Y. Hao, J. Zhang, and J. Zhang, "Nitride wide bandgap semiconductor material and electronic devices," p. 372, 2016.
- [67] E. Monroy, F. Calle, R. Ranchal, T. Palacios, M. Verdú, F. J. Sánchez, M. T. Montojo, M. Eickhoff, F. Omnès, Z. Bougrioua, and I. Moerman, "Thermal stability of Pt- and Ni-based Schottky contacts on GaN and Al_{0.31}Ga_{0.69}N," *Semiconductor Science and Technology*, vol. 17, no. 9, 2002.
- [68] E. Sleptsov, A. Chernykh, S. Chernykh, A. Dorofeev, N. Gladysheva, M. Kondakov, A. Sleptsova, A. Panichkin, M. Kononov, and S. Didenko, "Investigation of the thermal annealing effect on electrical properties of Ni/Au, Ni/Mo/Au and Mo/Au Schottky barriers on AlGaIn/GaN heterostructures," *Journal of Physics: Conference Series*, vol. 816, no. 1, 2017.
- [69] T. Kawanago, K. Kakushima, Y. Kataoka, A. Nishiyama, N. Sugii, H. Wakabayashi, K. Tsutsui, K. Natori, and H. Iwai, "Advantage of TiN Schottky gate over conventional Ni for improved electrical characteristics in AlGaIn/GaN HEMT," *European Solid-State Device Research Conference*, pp. 107–110, 2013.
- [70] F. Liu, Z. X. Qin, F. J. Xu, S. Zhao, X. N. Kang, B. Shen, and G. Y. Zhang, "Thermal stability of tungsten and tungsten nitride Schottky contacts to AlGaIn/GaN," *Chinese Physics B*, vol. 20, no. 6, 2011.
- [71] C. Y. Lu, E. Y. Chang, J. C. Huang, C. T. Chang, and C. T. Lee, "Stable AlGaIn/GaN high electron mobility transistors with tungsten nitride gate metallisation," *Electronics Letters*, vol. 45, no. 25, pp. 1348–U104, 2009.
- [72] A. C. Schmitz, A. T. Ping, M. A. Khan, Q. Chen, and J. W. Yang, "Schottky barrier properties of various metals on n-type GaN," vol. 1464, 1996.
- [73] Dieter K. Schroder, "Semiconductor Material and Device Characterization," p. 800, 2006.
- [74] D. Qiao, L. S. Yu, S. S. Lau, J. M. Redwing, J. Y. Lin, and H. X. Jiang, "Dependence of Ni/AlGaIn Schottky barrier height on Al mole fraction," *Journal of Applied Physics*, vol. 87, no. 2, pp. 801–804, 2000.
- [75] J. S. Flynn and G. R. Brandes, "Barrier heights of Schottky contacts on strained AlGaIn_{0.5}GaN heterostructures: Determination and effect of metal work functions," *Applied Physics Letters*, vol. 82, no. 24, pp. 4364–4366, 2003.
- [76] S. Binari, H. Dietrich, G. Kelner, L. Rowland, K. Doverspike, and D. Gaskill, "Electrical characterisation of Ti Schottky barriers on n-type GaN," *Electronics Letters*, vol. 30, no. 11, p. 909, 1994.
- [77] C. S. Lee, E. Y. Chang, L. Chang, C. Y. Fang, Y. L. Huang, and J. S. Huang, "Study of titanium tungsten nitride and tungsten nitride Schottky contacts on n-GaN," *Japanese Journal of Applied Physics, Part 1: Regular Papers and Short Notes and Review Papers*, vol. 42, no. 7 A, pp. 4193–4196, 2003.
- [78] L. S. Yu, D. J. Qiao, Q. J. Xing, and S. S. Lau, "Ni and Ti Schottky barriers on n-AlGaIn grown on SiC substrates," *Applied Physics Letters*, vol. 73, no. 2, pp. 238–240, 1998.
- [79] S. Arulkumaran, T. Egawa, H. Ishikawa, M. Umeno, and T. Jimbo, "Effects of annealing on Ti, Pd, and Ni/n-Al 0.11 Ga 0.89 N Schottky diodes," *IEEE Transactions on Electron Devices*, vol. 48, no. 3, pp. 573–580, 2001.
- [80] Y. Li, G. I. Ng, S. Arulkumaran, Z. H. Liu, K. Ranjan, W. C. Xing, K. S. Ang, P. P. Murmu, and J. Kennedy, "AlGaIn/GaN high electron mobility transistors on Si with sputtered TiN gate," *Physica Status Solidi (A) Applications and Materials Science*, vol. 214, no. 3, 2017.
- [81] J. P. Ao, Y. Naoi, and Y. Ohno, "Thermally stable TiN Schottky contact on AlGaIn/GaN heterostructure," *Vacuum*, vol. 87, pp. 150–154, 2013.
- [82] C. Y. Lu, E. Y. Chang, J. C. Huang, C. T. Chang, M. H. Lin, and C. T. Lee, "Enhancement of the Schottky barrier height using a nitrogen-rich tungsten nitride thin film for the Schottky contacts on AlGaIn/GaN heterostructures," *Journal of Electronic Materials*, vol. 37, no. 5, pp. 624–627, 2008.
- [83] T. E. Hsieh, Y. C. Lin, C. M. Chu, Y. L. Chuang, Y. X. Huang, W. C. Shi, C. F. Dee, B. Y. Majlis, W. I. Lee, and E. Y. Chang, "Au-Free GaN High-Electron-Mobility Transistor with Ti/Al/W Ohmic and WNXSchottky Metal Structures for High-Power Applications," *Journal of Electronic Materials*, vol. 45, no. 7, pp. 3285–3289, 2016.
- [84] S.-H. Lim, J. Washburn, Z. Liliental-Weber, and D. Qiao, "Microstructural evidence on electrical properties of Ta/Ti/Al and Ti/Ta/Al ohmic contacts to n-AlGaIn/GaN," *Applied Physics Letters*, vol. 78, pp. 3797–3799, jun 2001.
- [85] L. Wang, F. M. Mohammed, and I. Adesida, "Differences in the reaction kinetics and contact formation mechanisms of annealed Ti/Al/Mo/Au Ohmic contacts on n-GaN and AlGaIn/GaN epilayers," *Journal of Applied Physics*, vol. 101, no. 1, p. 013702, 2007.
- [86] W. Shockley, "Research and Investigation of Inverse Epitaxial UHF Power Transistors," tech. rep., Air Force Atomic Laboratory, Wright-Patterson Air Force Base, 1964.
- [87] H. Berger, "Contact resistance on diffused resistors," *IEEE International Solid-State Circuits Conference*, pp. 160–161, 1969.

- [88] H. Murrmann and D. Widmann, "Current Crowding on Metal Contacts to Planar Devices," *IEEE Transactions on Electron Devices*, vol. ED-16, no. 12, 1969.
- [89] E. Cho, *GaN BASED HETEROSTRUCTURE GROWTH AND APPLICATION TO ELECTRONIC*. PhD thesis, The University of Michigan, 2009.
- [90] D. Schroder, *Semiconductor Material and Device Characterization*. Hoboken, NJ, USA: John Wiley & Sons, Inc., 3 ed., oct 2005.
- [91] Y. Zhu, W. Cao, Y. Fan, Y. Deng, and C. Xu, "Effects of rapid thermal annealing on ohmic contact of AlGaIn/GaN HEMTs," *Journal of Semiconductors*, vol. 35, no. 2, 2014.
- [92] K. Shih and J. Blum, "Contact resistances of Au-Ge-Ni, Au-Zn and Al to III-V compounds," *Solid-State Electronics*, vol. 15, pp. 1177–1180, nov 1972.
- [93] S. S. Cohen, "Al-0.9% Si/Si Ohmic Contacts to Shallow Junctions," *Journal of The Electrochemical Society*, vol. 129, no. 6, p. 1335, 1982.
- [94] S. Proctor and L. Linholm, "A direct measurement of interfacial contact resistance," *IEEE Electron Device Letters*, vol. 3, no. 1, pp. 294–296, 1982.
- [95] J. A. Mazer, L. W. Linholm, and A. N. Saxena, "An Improved Test Structure and Kelvin-Measurement Method for the Determination of Integrated Circuit Front Contact Resistance," *Journal of The Electrochemical Society*, vol. 132, pp. 440–443, feb 1985.
- [96] T. Schreyer and K. Saraswat, "A two-dimensional analytical model of the cross-bridge Kelvin resistor," *IEEE Electron Device Letters*, vol. 7, no. 12, pp. 661–663, 1986.
- [97] G. K. Reeves and H. B. Harrison, "Obtaining the specific contact resistance from transmission line model measurements," *IEEE Electron Device Letters*, vol. EDL-3, no. 5, pp. 111–113, 1982.
- [98] J. J. T. M. Donkers, S. B. S. Heil, G. A. M. Hurkx, H. Broekman, R. Delhougne, J. A. Croon, D. J. Gravesteijn, and J. Šonský, "600V-900V GaN-on-Si Process Technology for Schottky Barrier Diodes and Power Switches Fabricated in a Standard Si-Production Fab," *CS MANTECH Conference*, pp. 259–262, 2013.
- [99] Q. Z. Liu, L. S. Yu, F. Deng, S. S. Lau, Q. Chen, J. W. Yang, and M. a. Khan, "Study of contact formation in AlGaIn/GaN heterostructures," *Applied Physics Letters*, vol. 71, no. 12, p. 1658, 1997.
- [100] L. Wang, D.-H. Kim, and I. Adesida, "Direct contact mechanism of Ohmic metallization to Al-GaN/GaN heterostructures via Ohmic area recess etching," *Applied Physics Letters*, vol. 95, no. 17, p. 172107, 2009.
- [101] M. W. Fay, G. Moldovan, P. D. Brown, I. Harrison, J. C. Birbeck, B. T. Hughes, M. J. Uren, and T. Martin, "Structural and electrical characterization of AuTiAlTi/AlGaIn/GaN ohmic contacts," *Journal of Applied Physics*, vol. 92, no. 1, p. 94, 2002.
- [102] M. W. J. Chase, "NIST-JANAF Thermochemical Tables, Fourth Edition," *J. Phys. Chem. Ref. Data*, vol. 9, pp. 1–1951, 1998.
- [103] T. Sreenidhi, K. Baskar, A. DasGupta, and N. DasGupta, "Reactive ion etching of GaN in SF₆ + Ar and SF₆ + N₂ plasma," *Semiconductor Science and Technology*, vol. 23, p. 125019, dec 2008.
- [104] K. Prabhakaran, T. G. Andersson, and K. Nozawa, "Nature of native oxide on GaN surface and its reaction with Al," *Applied Physics Letters*, vol. 69, no. 21, p. 3212, 1996.
- [105] Z. H. Liu, S. Arulkumaran, and G. I. Ng, "Temperature dependence of Ohmic contact characteristics in AlGaIn/GaN high electron mobility transistors from -50 to 200ÅL°C," *Applied Physics Letters*, vol. 94, no. 14, p. 142105, 2009.
- [106] S. A. Campbell, *The Science and Engineering of Microelectronic Fabrication*, vol. 476. 2001.
- [107] M. Fagerlind and N. Rorsman, "Optimization of recessed ohmic contacts for AlGaIn/AlN/GaN heterostructures using C(V) characterization of MSHM structures," *Physica Status Solidi (C) Current Topics in Solid State Physics*, vol. 8, no. 7–8, pp. 2204–2206, 2011.
- [108] J. Liu, J. Wang, H. Wang, L. Zhu, and W. Wu, "Improved Ohmic-contact to AlGaIn/GaN using Ohmic region recesses by self-terminating thermal oxidation assisted wet etching technique," *Journal of Physics: Conference Series*, vol. 864, no. 1, 2017.
- [109] R. Brown, D. MacFarlane, A. Al-Khalidi, X. Li, G. Ternent, H. Zhou, I. Thayne, and E. Wasige, "A sub-critical barrier thickness normally-Off AlGaIn/GaN MOS-HEMT," *IEEE Electron Device Letters*, vol. 35, no. 9, pp. 906–908, 2014.
- [110] M. Ono, A. Nishiyama, and A. Toriumi, "A simple approach to understanding measurement errors in the cross-bridge Kelvin resistor and a new pattern for measurements of specific contact resistivity," *Solid-State Electronics*, vol. 46, pp. 1325–1331, September 2002.
- [111] N. Stavitski, J. H. Klootwijk, H. W. van Zeijl, A. Y. Kovalgin, and R. A. M. Wolters, "Cross-Bridge Kelvin Resistor Structures for Reliable Measurement of Low Contact Resistances and Contact Interface Characterization," *IEEE Transactions on Semiconductor Manufacturing*, vol. 22, pp. 146–152, feb 2009.
- [112] A. Thies, N. Kemf, S. A. Chevtchenko, and O. Krüger, "Formation of slanted gates for gan-based hemts by combined plasma and wet chemical etching of silicon nitride," *2013 International Conference on Com-*

pound Semiconductor Manufacturing Technology, CS MANTECH 2013, pp. 395–398, 2013.

- [113] H. Tokuda, T. Kojima, and M. Kuzuhara, "Role of Al and Ti for ohmic contact formation in Al-GaN/GaN heterostructures," *Applied Physics Letters*, vol. 101, no. 26, 2012.
- [114] S. Arulkumaran, G. I. Ng, S. Vicknesh, C. M. Manojkumar, M. J. Anand, H. Wang, K. S. Ang, S. L. Selvaraj, W. Z. Wang, G. Lo, and S. Tripathy, "Uniformity Studies of AlGaIn / GaN HEMTs on 200-mm Diameter Si (111) Substrate," *CS Mantech*, no. 111, pp. 289–292, 2013.
- [115] L. F. Eastman and U. K. Mishra, "The toughest transistor yet," *IEEE Spectrum*, vol. 39, no. 5, pp. 28–33, 2002.
- [116] A. Dadgar, J. Bläsing, A. Diez, A. Alam, M. Heuken, and A. Krost, "Metalorganic Chemical Vapor Phase Epitaxy of Crack-Free GaN on Si (111) Exceeding 1 μm in Thickness," *Japanese Journal of Applied Physics*, vol. 39, no. 11, pp. L1183–L1185, 2000.
- [117] S. Saadaoui, M. Mongi Ben Salem, M. Gassoumi, H. Maaref, and C. Gaquière, "Electrical characterization of (Ni/Au)/Al_{0.25}Ga_{0.75}N/GaN/SiC Schottky barrier diode," *Journal of Applied Physics*, vol. 110, no. 1, 2011.
- [118] M. Finetti, I. Suni, and M. A. Nicolet, "Titanium nitride as a diffusion barrier between nickel silicide and aluminum," *Journal of Electronic Materials*, vol. 13, no. 2, pp. 327–340, 1984.
- [119] H. L. Xing, Y. Dora, a. Chini, S. Heikman, S. Keller, and U. K. Mishra, "High breakdown voltage AlGaIn-GaN HEMTs achieved by multiple field plates," *IEEE Electron Device Letters*, vol. 25, no. 4, pp. 161–163, 2004.
- [120] E. H. Rhoderick and R. H. Williams, *Metal Semiconductor Contacts*. Oxford University Press, second ed ed., 1988.
- [121] Y. R. Wu, M. Singh, and J. Singh, "Lateral and vertical charge transport in polar nitride heterostructures," *Polarization Effects in Semiconductors: From Ab Initio Theory to Device Applications*, vol. 8, pp. 111–159, 2007.
- [122] C. M. Jeon and J.-I. Lee, "Effects of tensile stress induced by silicon nitride passivation on electrical characteristics of AlGaIn / GaN heterostructure field-effect transistors," vol. 172101, pp. 23–26, 2005.
- [123] Z. Jianzhi, L. Zhaojun, L. Yuanjie, C. Timothy D, M. Lingguo, Z. Yu, W. Zhanguo, and C. Hong, "Influence of Ni Schottky contact thickness on two-dimensional electron-gas sheet carrier concentration of strained Al_{0.3}Ga_{0.7}N/GaN heterostructures," *Journal of Semiconductors*, vol. 31, no. 8, 2010.
- [124] S. Y. Son, Y. S. Choi, P. Kumar, H. W. Park, T. Nishida, R. K. Singh, and S. E. Thompson, "Strain induced changes in gate leakage current and dielectric constant of nitrided Hf-silicate metal oxide semiconductor capacitors," *Applied Physics Letters*, vol. 93, p. 153505, oct 2008.
- [125] A. Kiejna and V. Pogosov, "Simple theory of elastically deformed metals: Surface energy, stress, and work function," *Physical Review B*, vol. 62, no. 15, pp. 10445–10450, 2000.
- [126] I. Jyothi, V. Rajagopal Reddy, and C. J. Choi, "Microstructural and electrical characteristics of rapidly annealed Ni/Mo Schottky rectifiers on cleaned n-type GaN (0001) surface," *Journal of Materials Science: Materials in Electronics*, vol. 22, no. 3, pp. 286–291, 2011.
- [127] V. A. Fonoberov and A. A. Balandin, "Excitonic properties of strained wurtzite and zinc-blende GaN/Al_{1-x}Ga_xN quantum dots," *Journal of Applied Physics*, vol. 94, no. 11, pp. 7178–7186, 2003.
- [128] O. Ueda and S. J. Pearton, "Materials and reliability handbook for semiconductor optical and electron devices," *Materials and Reliability Handbook for Semiconductor Optical and Electron Devices*, pp. 1–616, 2013.
- [129] R. F. Pierret, "Semiconductor Device Fundamentals," *New York*, p. 792, 1996.
- [130] F. Iucolano, F. Roccaforte, F. Giannazzo, and V. Raineri, "Barrier inhomogeneity and electrical properties of Pt/GaN Schottky contacts," *Journal of Applied Physics*, vol. 102, p. 113701, dec 2007.
- [131] R. T. Tung, "Electron transport of inhomogeneous Schottky barriers," *Applied Physics Letters*, vol. 58, no. 24, pp. 2821–2823, 1991.
- [132] R. F. Schmitsdorf, "Explanation of the linear correlation between barrier heights and ideality factors of real metal-semiconductor contacts by laterally nonuniform Schottky barriers," *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures*, vol. 15, no. 4, p. 1221, 1997.
- [133] K. Sarpatwari, S. E. Mohny, and O. O. Awadelkarim, "Effects of barrier height inhomogeneities on the determination of the Richardson constant," *Journal of Applied Physics*, vol. 109, no. 1, 2011.
- [134] A. Kumar, R. Kapoor, M. Garg, V. Kumar, and R. Singh, "Direct evidence of barrier inhomogeneities at metal/AlGaIn/GaN interfaces using nanoscopic electrical characterizations," *Nanotechnology*, vol. 28, no. 26, 2017.
- [135] Y. Yao, J. Zhong, Y. Zheng, F. Yang, Y. Ni, Z. He, Z. Shen, G. Zhou, S. Wang, J. Zhang, J. Li, D. Zhou, Z. Wu, B. Zhang, and Y. Liu, "Current transport mechanism of AlGaIn/GaN Schottky barrier diode with fully recessed Schottky anode," *Japanese Journal of Applied Physics*, vol. 54, no. 1, p. 011001, 2015.
- [136] T. C. Nam, J. S. Jang, and T. Y. Seong, "Carrier transport mechanism of strained AlGaIn/GaN Schottky contacts," *Current Applied Physics*, vol. 12, no. 4, pp. 1081–1083, 2012.

- [137] Z. Tekeli, S. Altindal, M. Çakmak, S. Özçelik, D. Çaliskan, and E. Özbay, "The behavior of the I-V-T characteristics of inhomogeneous (Ni/Au)-Al_{0.3}Ga_{0.7}N/AlN/GaN heterostructures at high temperatures," *Journal of Applied Physics*, vol. 102, p. 054510, sep 2007.
- [138] G. Y. Lee, H. H. Liu, and J. I. Chyi, "High-performance AlGaIn/GaN schottky diodes with an Al-GaN/AlN buffer layer," *IEEE Electron Device Letters*, vol. 32, no. 11, pp. 1519–1521, 2011.
- [139] A. Fontserè, A. Pérez-Tomás, M. Placidi, J. Llobet, N. Baron, S. Chenot, Y. Cordier, J. C. Moreno, M. R. Jennings, P. M. Gammon, C. A. Fisher, V. Iglesias, M. Porti, A. Bayerl, M. Lanza, and M. Nafria, "Nanoscale investigation of AlGaIn/GaN-on-Si high electron mobility transistors," *Nanotechnology*, vol. 23, no. 39, 2012.
- [140] M. Hajlasz, J. J. T. M. Donkers, S. J. Sque, S. B. S. Heil, D. J. Gravesteijn, F. J. R. Rietveld, and J. Schmitz, "Sheet resistance under Ohmic contacts to AlGaIn/GaN heterostructures," *Applied Physics Letters*, vol. 104, p. 242109, jun 2014.
- [141] M. Hajlasz, J. J. T. M. Donkers, S. Pandey, F. Hurkx, R. J. E. Hueting, and D. J. Gravesteijn, "Barrier Height Variation in Ni-Based AlGaIn/GaN Schottky Diodes," *IEEE Transactions on Electron Devices*, vol. 64, pp. 4050–4056, oct 2017.
- [142] M. Hajlasz, J. J. T. M. Donkers, S. J. Sque, S. B. S. Heil, D. J. Gravesteijn, F. J. R. Rietveld, and J. Schmitz, "Characterization of recessed Ohmic contacts to AlGaIn/GaN," in *Proceedings of the 2015 International Conference on Microelectronic Test Structures*, pp. 158–162, IEEE, mar 2015.

PUBLICATIONS

Journal Articles

- [1] M. Hajłasz, J. J. T. M. Donkers, S. J. Sque, S. B. S. Heil, D. J. Gravesteijn, F. J. R. Rietveld, and J. Schmitz, "Sheet resistance under Ohmic contacts to AlGa_N/Ga_N heterostructures," *Applied Physics Letters*, vol. 104, p. 242109, jun 2014
- [2] M. Hajłasz, J. J. T. M. Donkers, S. Pandey, F. Hurkx, R. J. E. Huetting, and D. J. Gravesteijn, "Barrier Height Variation in Ni-Based Al-GaN/GaN Schottky Diodes," *IEEE Transactions on Electron Devices*, vol. 64, pp. 4050–4056, oct 2017

Conference proceedings

- [3] M. Hajłasz, J. J. T. M. Donkers, S. J. Sque, S. B. S. Heil, D. J. Gravesteijn, F. J. R. Rietveld, and J. Schmitz, "Characterization of recessed Ohmic contacts to AlGa_N/Ga_N," in *Proceedings of the 2015 International Conference on Microelectronic Test Structures*, pp. 158–162, IEEE, mar 2015

ACKNOWLEDGEMENTS

Finally, I am writing this part of my thesis as a very last thing before sending it to print. It has been almost exactly six years since the start of my PhD and it seems almost unreal how quickly the time has passed. It is thanks to many people that I am where I am, and here is a place to say thank you! It is also time for me to reflect on the past, bring back memories and think about how I was shaped both as a scientist and a person by all of you.

First and foremost, I would like to thank Dirk Gravesteijn, my promoter. Thank you for your unwavering support, advice and motivation! You guided me through my PhD with your extensive knowledge and invaluable experience, offering help whenever I needed. Each time I got lost in research, looking to solve a dozen problems at once, you were always there to help me get back on track. Thank you for giving me confidence when I was doubting my work and for challenging me to do better. Above all, thank you for your great sense of humor and constant enthusiasm about discovering things - it was the most motivating thing to see your excitement as I was slowly understanding all the weird effects in GaN. It was a great privilege to have you as a mentor!

It goes without question that I am also grateful to Jurriaan Schmitz. Jurriaan, thank you for accepting me into the group. Even though we did not interact often, you have taught me a lot about being a good scientist and I have always valued our discussions and your advice!

I am also grateful to all other Semiconductor Components group members who were there for me in many different ways: Alexey, Annemiek, Cora, Lis, Ray, Sander, Remke, Rob and Tom. You all create a wonderful environment. I knew I could always get your invaluable help and I enjoyed every minute spent with you at the University of Twente.

Semiconductor Components is not only great staff, but also great colleagues. I still remember the evening when I came for interviews for the position and went out for dinner with Annemiek, Balaji and Tom. From the very first moment I felt that this is a great place to be and it was thanks to you. Being at NXP was fantastic, however at the same time I missed out on many things at the university. I think that this made me appreciate the time I spent with you even more. I would like to thank my paranymphs, Balaji and Sourish for support. Alessandro, Boni, Buket, Frank, Giulia, Hao, Jiahui, Satadal, Svetlana, Tom and also all the others who I did not

had a chance to get to know well - thank you making this group something special!

This thesis wouldn't be possible without all the people from NXP Semiconductors with whom I had the privilege of working with. You guys are all brilliant scientists and fantastic colleagues! You helped me grow as a scientist and I am thankful for all the knowledge you passed on to me. You inspired me by showing how to be a great researcher day in, day out. You know the feeling that you sometimes do not want to go to work? I have never ever had that, and it is because of you! Thank you for all the tennis games, all chats and for making me feel like a true member of the team.

Johan, your extensive expertise and your willingness to share it is amazing. You helped me out with any GaN processing questions and all those difficult material analyses. Jeroen, you are a master of all kinds of electrical measurements, but the most important thing you were showing me, was your enthusiasm for discovering and understanding things. Steve, thank you for all your invaluable help in TCAD and answering my never-ending questions about different aspects of GaN. Fred, it was inspiring to learn from you and really understand how GaN devices work. Thank you for all the chats and fun times in the office!

I am also grateful to other colleagues who I met at NXP: Martijn Goossens, Stephan Heil, Rob Lander, Twan van Lippen, Giorgia Longobardi, Klaus Reimann, Peter Steeneken, Olaf Wunnicke, Micha in 't Zandt and all the others NXP people who created a great work atmosphere.

M2i team - thanks for bringing me on board and allowing to work in the mix of industry and academia!

A special thank you goes to my house mates, Sebastien and Lindsey, for all the great time, board games and making fun of my cooking (frozen pizzas!). I truly enjoyed the time in Eindhoven, our discussions, squash games, playing Wii and all the other fun things we did together!

Life wouldn't be the same without my friends - Kornelia Indykiewicz, Marcin Jankowski, Michał Czeszek and Michał Kucharski. Thank you for being there for me during the good and bad times!

I am thankful to my graduation committee for their time and valuable comments about my thesis.

I would like to also thank prof. Regina Paszkiewicz, dr Bogdan Paszkiewicz and all colleagues from WZMIN PWr for introducing me to the fascinating world of GaN.

Andrzej Sikora - thank you for all the conversations we had. They always made me enthusiastic about research and doing cool stuff!

It is super difficult to write a thesis when you also have a full-time job. I had a lot of luck in ending up with such a great team. I would like to thank my manager Rob Haasnoot and all my colleagues for support and encouragement when I was finalizing the thesis (for almost two years!).

I am truly thankful to my mum and dad, who shaped me as a person in many different ways. Thank you for pushing me to learn things, for

showing me the value of high quality work and raising me to be the person I am today.

Marysia, Zuzia - my dear sisters, thank you for all the fun time we had (making pierogi with a garlic press, yay! :)) and bringing a bit of home with you when you visited me in the Netherlands.

Weronika, you are my inspiration and the reason that everything is possible. Without you, this thesis would never happen and I wouldn't be the person I am now. You constantly impress me with your curiosity, eagerness to discover the world and learn. You motivate me to do things that matter and to ask questions. There is still so much to do in life and I know we will do it together!