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Schottky and ohmic contacts on non-polar cubic GaN epilayers

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ABSTRACT

In this work we focus on the fabrication of ohmic contacts and of Schottky barrier devices (SBD) on non-polar cubic GaN epilayers grown by molecular beam epitaxy (MBE). A Ti/Al/Ni/Au metallization was used for ohmic contacts and the contact resistance was measured by transmission line measurements (TLM). Ni, Pd, Ag and NiSi Schottky barrier devices 300 μm in diameter were fabricated by thermal evaporation using contact lithography on cubic GaN epilayers. The current-voltage (I-V) and the capacity-voltage (C-V) characteristics were studied at room temperature in detail. A clear rectifying behavior was measured in all SBDs. In the Ni and Ag SBDs an abnormal large leakage current under reverse bias was observed. Isochronal thermal annealing of these Ni and Ag based SBDs at 200°C in air improved the reverse characteristics by up to three orders of magnitude. This is in contrast to the Pd contacts, where the as grown contact showed already good performance and thermal annealing had nearly no influence on the I-V characteristics. For all SBDs the magnitude of the reverse current is generally larger than that expected due to thermionic emission and an exponential increase of the reverse current is observed with increasing reverse voltage. In-depth analysis of the I-V characteristic showed that a thin surface barrier is formed at the metal semiconductor interface and that crystal defects like dislocations may be the reasons for the discrepancy between experimental data and thermionic emission theory.

INTRODUCTION

Schottky and ohmic contacts are key elements for the realization of any GaN based electronic devices such as high-power high electron mobility transistors (HEMTs), high-power metal semiconductor field effect transistors (MESFETs) or UV-photodetectors [1]. Group III-nitrides crystallize in the stable wurtzite structure or in the metastable zincblende structure. An important difference between these material modifications is the presence of strong internal electric fields in hexagonal (wurtzite) III-nitrides grown along the polar c-axis, while these "build-in" fields are absent in cubic (zincblende) III-nitrides. In addition, nonpolar cubic GaN, although more difficult to grow, allows a 50% gain in FET performance in comparison to wurtzite GaN as proposed by 2D Monte Carlo device simulations of nitride field effect transistors [2].

If the cubic group-III nitrides are grown in (001) direction spontaneous and piezoelectric polarization effects can be avoided at the interfaces and surfaces and the density of the two-dimensional electron gas (2-DEG) in cubic $Al_xGa_{1-x}N$/GaN heterostructures is independent on the thickness and Al mole fraction of the $Al_xGa_{1-x}N$ barrier layer and can be controlled by doping with silicon. The combination of these effects may be used to realize cubic AlGaN/GaN HEMTs with both *normally on* and *normally off* operation as it is strongly required for logic devices [3].

In addition, the electronic structure of the cubic GaN (001) surface is different to that of the c-plane in hexagonal GaN and therefore may alters the electronic properties of the Schottky diodes and ohmic contacts [4].

In this work, we investigate the electrical characteristic of metallization contacts to thin non-polar cubic n-type GaN. The I-V characteristics are studied at room temperature and the influence of thermal and rapid thermal annealing in air is explored. It is shown that isochronal thermal annealing of Ni and Ag based contacts at 200°C and subsequent isotermal anealing up to 350°C in air improved the reverse characteristics by up to three orders of magnitude, whereas for Pd contacts the as grown contact showed already good performance and thermal annealing had nearly no influence on the I-V characteristics. A Ti/Al/Ni/Au metallization was used for ohmic contacts and contact resistance was measured by transmission line measurements (TLM).

EXPERIMENT

All cubic GaN layers were nominally undoped, about 600 nm thick and were grown in a Riber 32 system by plasma assisted MBE under Ga rich growth conditions leading to a Ga coverage of 1 monolayer during growth. Details of the growth procedure are given in [5]. The properties and the quality of the cubic epilayers were checked by high resolution X-ray diffractometry, atomic force microscopy and photoluminescence. Metallization contacts were produced by thermal evaporation using contact lithography. Prior to vacuum deposition, the GaN surfaces were cleaned by organic solvents and a buffered oxid etch (BOE).

For the Schottky barrier devices (SBD) a 200 μm thick free standing 3C-SiC (001) substrates with a nominal specific resistance of 6.6×10^{-3} Ωcm is used. Ni, Pd, Ag and NiSi Schottky barriers 300 μm in diameter were fabricated using contact lithography on cubic GaN epilayers. The backside of the 3C-SiC substrates were contacted using Indium. A clear rectifying behavior was measured in all our SBDs and the current voltage (I-V) behavior was studied in detail in the dark at room temperature. Capacitance-voltage (C-V) measurements were used to determine the net donor concentration in our cubic GaN which varied between $3\text{x}10^{16}\text{cm}^{-3}$ to $8\text{x}10^{16}\text{cm}^{-3}$. Different annealing steps were used to improve the reverse bias characteristics of the SBDs and the I-V behavior was measured after each step. The first step was an isothermal annealing in air at 200°C up to a total annealing time of 10 min, 20 min and 80 min, respectively. In the second step isochronal annealing for 10 min at subsequently rising temperatures of 250°C, 300°C, 350°C and 400°C was performed and as a final step a rapid thermal annealing at 825°C for 4 min in vacuum was carried out.

The investigation of Ti/Al/Ni/Au (15/50/15/50 nm) ohmic contacts were performed by TLM on two cubic GaN epilayers, which were grown on a highly insulating 3C-SiC(100)/Si(100) pseudosubstrate. The substrate consists of a 3 nm thick 3C-SiC (001) layer on highly isolating Si with a specific resistance of 2×10^{4} Ωcm which were fabricated using carbonization in a rapid thermal chemical vapour deposition reactor (RTP) [6]. Details of the quality of the cubic GaN epilayers are given in reference [7]. Room temperature Hall effect measurements in Van der Pauw geometry showed a carrier concentration of the two epilayers of $1\text{x}10^{16}\text{cm}^{-3}$ and $5\text{x}10^{17}\text{cm}^{-3}$, respectively. After deposition of the Ti/Al/Ni/Au metall layers the contact was rapid thermal annealed at 800°C for 4 minutes in vacuum. Contact pads 200μm x 1000μm in dimensions are linearly arranged with different separation distances of 25μm, 50μm, 100μm, 200μm and 400μm, and the resistance between different pads is measured. No lateral isolation was done.

RESULTS AND DISCUSSION

Schottky barrier diodes

Figure 1 shows the room temperature (RT) I-V curves for a typical Ni-Schottky contact on our cubic GaN epilayer. The full red circles correspond to the as grown sample, whereas the blue squares, green diamonds and black triangles correspond to samples isothermally annealed at 200°C at air for 10, 20 and 80 min, respectively. In all cases a clearly rectifying I-V characteristic is measured and the blocking characteristic is improved with annealing time. In the inset the reverse current at -5 V is plotted versus the annealing time indicating a saturation in the improvement of the reverse characteristics. This observation is similar to earlier observations, which reported a reduction in leakage current by thermal annealing in air at 200°C [8]. However, as shown in Fig. 2 isochronal annealing for 10 min at subsequently rising temperatures further reduces the leakage characteristics. The inset shows the reverse current at -5 V versus annealing temperature. A minimum reverse current is measured at a temperature of 350°C. At higher temperatures the I-V curves deteriorate again. In a final step we apply a rapid thermal process at 800°C for 4 minutes in vacuum. This step again improves the I-V characteristics. This dramatic improvement in the reverse current by about three orders of magnitude is emphasized in figure 3 in which the current bias dependence is plotted in a semi-logarithmic scale. Similar observations with identical chronological sequence in annealing are also measured for Ag and NiSi contacts (not shown here).

A distinct different annealing behavior however is measured for Pd Schottky contacts (see Fig.4). For this metallization the as grown contact is nearly as good as the thermally annealed Ni, or Ag contacts and both isothermal annealing in air at 200°C and isochronal annealing up to

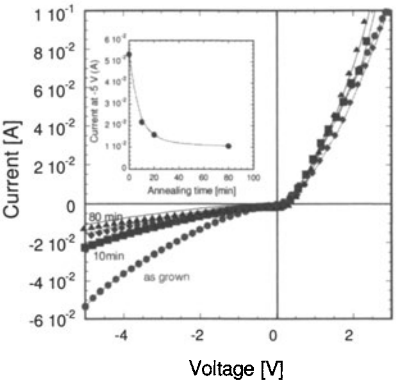

Figure 1. Room temperature current voltage (I-V) characteristics of a Ni-Schottky contact on cubic GaN before annealing (full circles) and after isothermal annealing at 200°C in air at 10 min, 20 min and 80 min (full circles). The inset shows the reverse current at -5V versus annealing time.

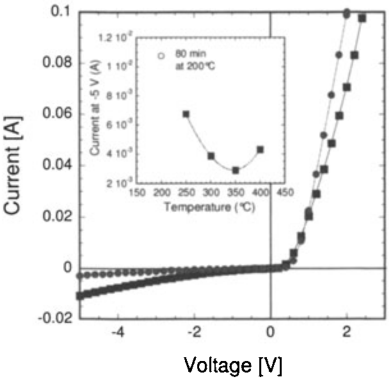

Figure 2. Room temperature current voltage (I-V) characteristics of a Ni-Schottky contact on cubic GaN before isochronal annealing (full squares) and after annealing in air at 350°C (full circles). The inset shows the reverse current at -5V versus the annealing temperature (each step 10 min).

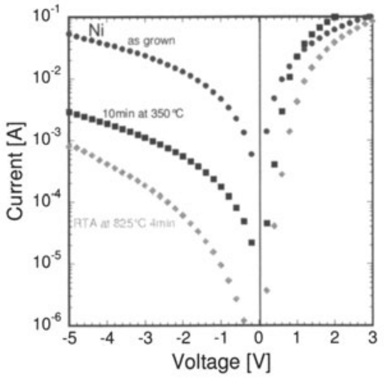

Figure 3. Room temperature current voltage (I-V) characteristics of a Ni-Schottky contact on cubic GaN before annealing (full circles), after annealing in air at 350°C (full squares and after RTA at 25°C (full diamonds).

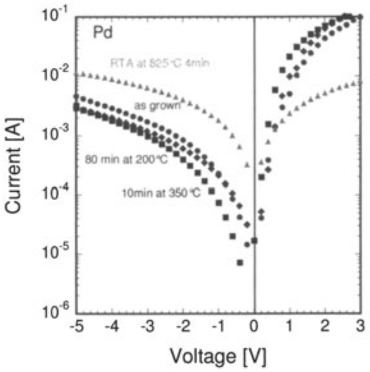

Figure 4. Room temperature current voltage (I-V) characteristics of a Pd-Schottky contact on cubic GaN before annealing (full circles), after annealing in air at 350°C (full squares and after RTA at 25°C (full diamonds).

temperature of 350°C did not severely improve the rectifying characteristics. In addition, RTA annealing at 825°C resulted in nearly ohmic I-V characteristics however with a higher series resistance. This indicates that different chemical interface reactions occur for Pd contacts in comparison to Ni, Ag or NiSi contacts. For Ni contacts Guo et al. [9] reported the formation of Ga_4Ni_3, Ni_3N and Ni_4N at the Ni GaN interface during annealing at temperatures above 200°C. These clusters may form defects, which compensate the donor impurities.

A detailed analysis of both the forwards I-V characteristic as well as the reverse bias characteristic shows strong deviations from the standard thermionic emission (TE) model [10]. Whereas at RT the forward characteristic follows a thermionic emission model, the reverse bias dependence shows strong deviations, which are characterized by the following two salient features. First the magnitude of reverse current is generally larger (by orders of magnitude) than the reverse saturation current given by the TE model, and second a nearly exponential increase of the reverse current is observed at high reverse voltage. This behavior is observed for the as grown, the thermally annealed, and the RTA Schottky diodes. Recently, Hasegawa et al. [11] observed similar features with Ni, Pt and Au Schottky contacts on hexagonal GaN, which they explained by introducing a thin surface barrier (TSB) model. This model proposes the formation of a highly conductive layer due to the presence of defect donors at the interface between the Ni metal and GaN epilayer. Another possibility is discussed by Zhang et al. [12], who suggest that the room temperature leakage current is dominated by the presence of highly conductive dislocations. The key process in leakage current flow is emission of electrons from a trap state near the metal-semiconductor interface into a continuum of states associated with each conductive dislocation.

The value of the barrier height Φ_B was determined by two ways. Since the I-V forward characteristic of our Schottky contacts follows a thermionic emission (TE) model, the value of Φ_B was determined from a fit of the linear region of the forward I-V curves, where $qV > 3kT$, to

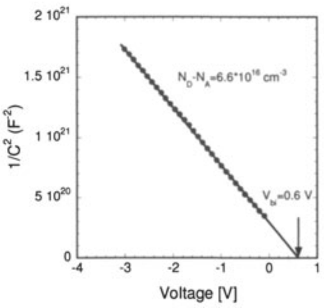

Figure 5. *Room temperature 1/C² vs V characteristics of a Pd-Schottky contact on cubic GaN before annealing (full circles).*

$$I = A\,A^{*}\,T^{2} \exp(-\Phi_B/kT)\,.\,\exp(qV/nkT),$$

where A is the contact area, A^* is the Richardson constant, T is the absolute temperature, q is the electron charge, k is the Boltzmann constant, n the ideality factor. The values of $q.\Phi_B$ are listed in table I.

A second way to determine Φ_B is by measuring the capacity C of the Schottky diode as a function of reverse bias. According to Schottky´s theory [10] for a homogeneously doped semiconductor a linear behavior is expected if $1/C^2$ is plotted versus the applied voltage. In Fig.5 $1/C^2$ vs. voltage is depicted for a Pd Schottky contact on an as grown cubic GaN epilayer. From the slope of the linear regression line and the intersection point with the abscissa a net carrier concentration of N_D-N_A=6.6x10^{16}cm^{-3} and a build-in voltage V_{bi}=0.6 V are evaluated. With $V_{bi} \cong \Phi_B$ a barrier height of 0.6 eV is estimated. Using an electron affinity of cubic GaN χ_{GaN}=4.31 eV and different work functions $q\Phi_m$ for the metals Ni, Pd and Ag the theoretical barrier height is calculated by $q.\Phi_B = q.\Phi_m - q.\,\chi_{GaN}$. In Table I the work functions, the theoretically calculated barrier heights and the experimentally determined barrier heights by I-V and C-V measurements of the different metals are summarized. For Ni and Pd the measured barrier heights agree well with theoretically calculated ones, whereas for Ag a strong deviation is observed. This behavior indicates that at least for Ag contacts surface states may pin the Fermi level [10].

Table I: Sample number, metal, work functions, barrier heights calculated by theory and determined by I-V and C-V measurements and ideality factor n.

#	Metal	Work function $q\Phi_m$ (eV)	Theory $q\Phi_B$ (eV)	I-V $q\Phi_B$ (eV)	n	C-V $q\Phi_B$ (eV)
1687	Ni	5.15	0.84	0.6 (400°C)	1.19	-
1687	Pd	5.12	0.81	0.8 (200°C)	1.20	0.8
1701	Ag	4.26	-0.05	0.9 (400°C)	1.12	-
1701	Pd	5.12	0.81	0.8 (200°C)	1.18	0.9

Ohmic contacts

A Ti/Al/Ni/Au metallization was used for ohmic contacts and the contact resistance was measure by transmission line methode [13, 14]. After deposition of the Ti/Al/Ni/Au metal layers the contact was rapid thermal annealed at 800°C for 4 minutes in vacuum. Contact pads 200µm x 1000µm in dimensions are linearly arranged with different separation distances of 25µm, 50µm, 100µm, 200µm and 400µm. I-V curves and the resistance between different pads are measured. Figure 6 shows the I-V characteristics of the annealed contacts for differently wide separated contacts. All curves have a linear ohmic behavior. In the inset the resistance is plotted versus contact separation. Using the method proposed in Reference 13 the contact resistance, sheet resistance and specific contact resistance ρ_c is estimated from this plot. The data for two

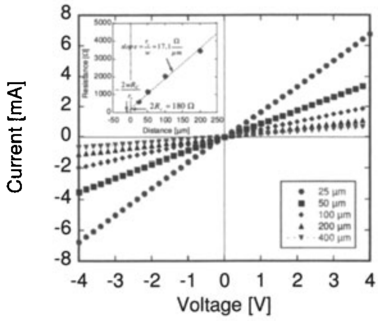

__Figure 6.__ Room temperature current voltage (I-V) characteristics of a Ti/Al/Ti/Au contact after RTA annealing at 800°C for 4 min (contact separation 25µm, 50µm, 100µm, 200µm and 400µm).

differently doped cubic GaN are summarized in Table II. For the higher doped sample a ρ_c of $1x10^{-4}\Omega cm^2$ is determined.

CONCLUSIONS

The electrical characteristic of Ni, Pd and Ag contacts to thin non-polar cubic n-type GaN are studied. The I-V measurements shown that isochronal thermal annealing of Ni and Ag based contacts at 200°C and subsequent isotermal anealing up to 350°C in air improved the reverse characteristics by up to three orders of magnitude. For Pd contacts the as grown contact showed already good performance and thermal annealing had nearly no influence on the I-V characteristics. Ti/Al/Ni/Au forms an ohmic contacts with a contact resistance ρ_c of $1x10^{-4}\Omega cm^2$.

Table II: Carrier concentration and TLM data from two different cubic GaN samples

#	Carrier concentration	Contact resistance	Sheet resistance	Specific contact resistance
1707	$5x10^{17}$ cm^{-3}	90 Ω	18 kΩ	$1x10^{-4}$ Ωcm^2
1645	$1x10^{16}$ cm^{-3}	3 000 Ω	2017 kΩ	9.8 Ωcm^2

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High Temperature Stable Contacts for GaN HEMTs and LEDs

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ABSTRACT

There is continued interest in developing more stable contacts to a variety of GaN-based devices. In this paper we give two examples of devices that show improved thermal stability when boride, nitride or Ir diffusion barriers are employed in Ohmic contact stacks. AlGaN/GaN High Electron Mobility Transistors (HEMTs) were fabricated with Ti/Al/X /Ti/Au source/drain Ohmic (where X is TiB_2, ZrN, TiN, TaN or Ir) contacts and subjected to long-term annealing at 350°C. For GaN layers with an electron concentration of ~3×10^{17} cm^{-3}, the minimum specific contact resistance achieved is 6×10^{-5} Ω cm^2 for Ti/Al/TiN/Ti/Au after annealing at 800°C. The specific contact resistance was found to strongly depend on the doping level, suggesting that tunneling is the dominant mechanism of current flow. By comparison with companion devices with conventional Ti/Al/Ni/Au Ohmic contacts, the HEMTs with boride-based Ohmic metal showed superior stability of both source-drain current and transconductance after 25 days aging at 350°C. The gate current for standard HEMTs increases during aging and the standard Ohmic contacts eventually fail by shorting to the gate contact. Similarly, InGaN/GaN multiple quantum well light-emitting diodes (MQW-LEDs) were fabricated with either Ni/Au/TiB_2/Ti/Au or Ni/Au/Ir/Au p-Ohmic contacts. Both of these contacts showed superior long-term thermal stability compared to LEDs with conventional Ni/Au contacts.

INTRODUCTION

At present there is great interest in wide-bandgap GaN and related materials because of their exciting applications in visible and ultraviolet (UV) lasers and light-emitting diodes (LEDs) for display and data storage, high electron mobility transistors (HEMTs) for high-temperature and high-power electronics, and solar-blind UV detectors. One of the remaining obstacles for commercialization of GaN HEMTs power amplifiers is the development of more reliable and thermally stable Ohmic contacts. GaN high electron mobility transistor (HEMT) power amplifiers have now entered the commercialization stage for use in wireless communications and military applications. There are also possible applications in improved automotive radar and power electronics for hybrid electric vehicles and in advanced satellite communication systems. GaN HEMTs can provide the high-power, high-efficiency, high-linearity RF power transistors required in base stations for mobile data network services. One of the major issues with some applications for these power amplifiers is the need for very stable Ohmic and Schottky contacts, capable of extended operation at elevated temperatures (typically 200°C or higher). Currently, the most common Ohmic metallizations for AlGaN/GaN HEMTs is Ti/Al with overlayers of Ni, Pt, or Ti followed by Au to reduce sheet resistance and decrease oxidation during the annealing needed to achieve the lowest specific contact resistivity [1-9]. The formation mechanism for the Ti/Al-based Ohmic contact can be attributed to the creation of nitrogen vacancies which act as electron donors due to the formation of TiN from Ti and n-GaN. This causes the subsurface below the TiN to be heavily n-type doped, thereby forming a tunneling junction [1,9-11]. The role of Al is to control the aggressive reaction between Ti and the n-GaN. In addition, the formation of $TiAl_x$ intermetallics following annealing stabilizes the contact preventing the structure from balling up [12-14]. Finally, Ni, Pt, and Ti act as a diffusion barrier to avoid the formation of the low melting temperature viscous $AlAu_4$ phase. For the gate contacts, Ni/Au and Pt/Au metallurgies are generally used. However, there is some concern about the thermal stability of these contacts during device packaging and operation. For example, Ni/Au metallization schemes have problems for annealing >500°C due to out-diffusion and oxidation of the Ni and roughening of the contact morphology [15, 17]. Over the last few years, a variety of approaches have been examined for producing thermally stable and reliable Ohmic and Schottky contacts to GaN, including the use of high temperature metals such as W, WSi_x, Mo, Ir, W_2B_5, CrB_2, ZrB_2 and TiB_2 [16-21]. For the gate contact, an alternative approach is the use of metal-oxide-semiconductor gates, though of much of that work is still in its infancy and the metal gate is still the dominant technology. Due to their low electrical resistivity, chemical inertness, metallurgical stability and reliability when subjected to high temperatures, both metallic nitrides such as TiN, TaN and ZrN and their boride counterparts appear very promising for reliable and thermally stable contacts to GaN. However, while these films have been proved successful as diffusion barriers in Si- and GaAs-based electronics, their potential for GaN HEMTs remains to be examined.

Similarly for LEDS, the conventional metallization schemes used for making Ohmic contacts to p-GaN are based on Ni, Pd, Cr or Pt with an overlayer of Au to reduce the sheet resistance. Specific contact resistances of ~10^{-2}-10^{-4} $\Omega.cm^2$ are obtained after annealing at 450-650 °C (17-19). These contacts have stability problems at high temperature as the initial Au/Ni/GaN structure transforms to Ni/Au/GaN with a rough Ni surface with annealing at 600 °C. Once again, to prevent excessive intermixing and contact morphology degradation a good approach is to use a high-melting-point diffusion barrier in the contact stack

In this paper we report on the use of boride, nitride or Ir diffusion barriers in Ohmic contacts for HEMTs or LEDs to improve the stability of these devices during extended aging at elevated temperatures

EXPERIMENT

For HEMT fabrication, the layer structures were grown on sapphire substrates by Molecular Beam Epitaxy and employed a low temperature AlN (300Å thick) buffer, 2μm of undoped GaN grown at 750°C under Ga-rich conditions, 250Å of undoped $Al_{0.2}Ga_{0.8}N$ and a 30 Å undoped GaN cap. Mesas were formed by Cl_2/Ar Inductively Coupled Plasma Etching to provide electrical isolation of the contact pads. A Ti/Al/X/Ti/Au metallization scheme annealed