

## 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  $\mu\text{m}$  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  $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  heterostructures is independent on the thickness and Al mole fraction of the  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  barrier layer and can be controlled by doping with silicon. The combination of these effects may be used to realize cubic  $\text{AlGaN}/\text{GaN}$  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 alter the electronic properties of the Schottky diodes and ohmic contacts [4].

In this work, we investigate the electrical characteristics 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 isothermal annealing 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  $\mu\text{m}$  thick free standing 3C-SiC (001) substrates with a nominal specific resistance of  $6.6 \times 10^{-3} \Omega\text{cm}$  is used. Ni, Pd, Ag and NiSi Schottky barriers 300  $\mu\text{m}$  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  $3 \times 10^{16} \text{cm}^{-3}$  to  $8 \times 10^{16} \text{cm}^{-3}$ . 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.

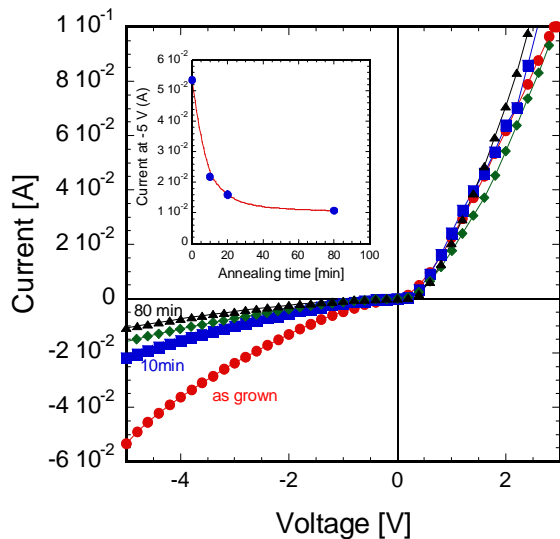
The investigation of Ti/Al/Ni/Au (15/50/15/50 nm) ohmic contacts were performed by TLM on two cubic GaN epilayers, which were grown on a highly insulating 3C-SiC(100)/Si(100) pseudosubstrate. The substrate consists of a 3 nm thick 3C-SiC (001) layer on highly insulating Si with a specific resistance of  $2 \times 10^4 \Omega\text{cm}$  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  $1 \times 10^{16} \text{cm}^{-3}$  and  $5 \times 10^{17} \text{cm}^{-3}$ , respectively. 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 200  $\mu\text{m}$  x 1000  $\mu\text{m}$  in dimensions are linearly arranged with different separation distances of 25  $\mu\text{m}$ , 50  $\mu\text{m}$ , 100  $\mu\text{m}$ , 200  $\mu\text{m}$  and 400  $\mu\text{m}$ , and the resistance between different pads is measured. No lateral isolation was done.

## RESULTS AND DISCUSSION

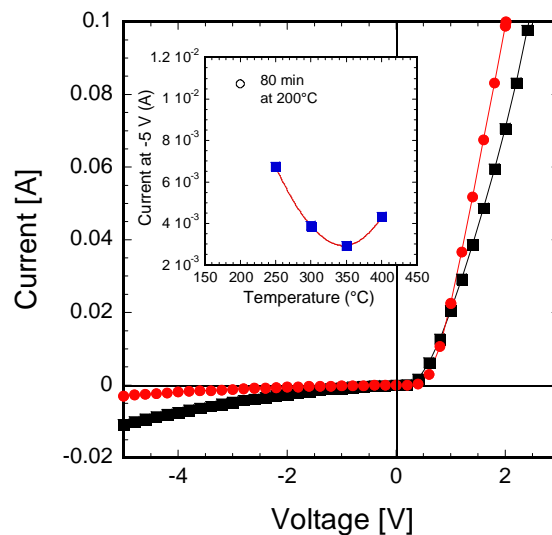
### Schottky barrier diodes

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).

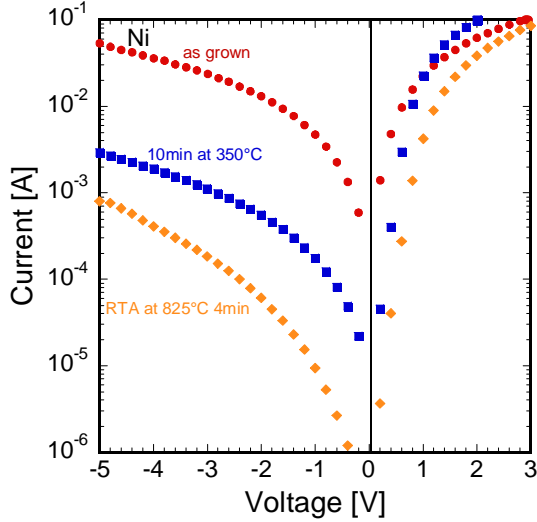
A distinct different annealing behavior however is measured for Pd Schottky contacts (see Fig.4). For this metallization the as grown contact is nearly as good as the thermally annealed Ni, or Ag contacts and both isothermal annealing in air at 200°C and isochronal annealing up to



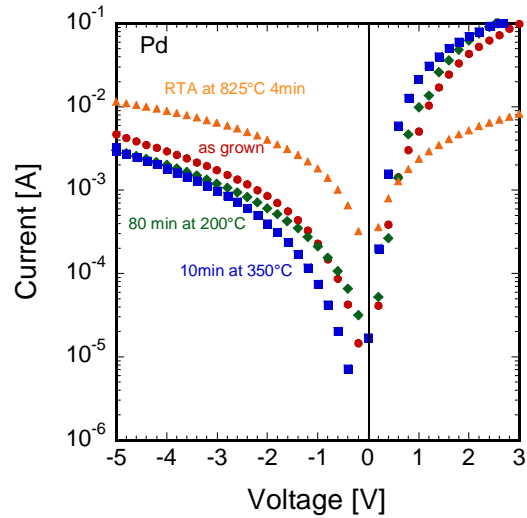
**Figure 1.** Room temperature current voltage (I-V) characteristics of a Ni-Schottky contact on cubic GaN before annealing (full circles) and after isothermal annealing at 200°C in air at 10 min, 20 min and 80 min (full circles). The inset shows the reverse current at -5V versus annealing time.



**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).

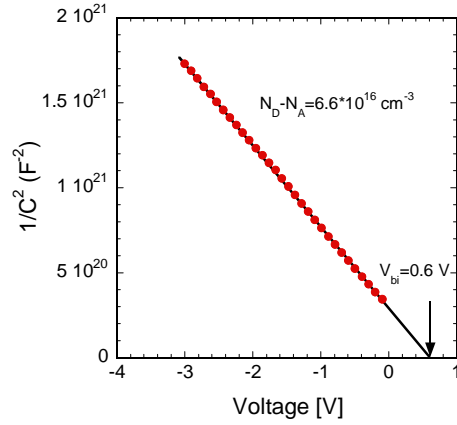


**Figure 4.** Room temperature current voltage (I-V) characteristics of a Pd-Schottky contact on cubic GaN before annealing (full circles), after annealing in air at 350°C (full squares and after RTA at 25°C (full diamonds).

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  $\text{Ga}_4\text{Ni}_3$ ,  $\text{Ni}_3\text{N}$  and  $\text{Ni}_4\text{N}$  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  $\Phi_B$  was determined by two ways. Since the I-V forward characteristic of our Schottky contacts follows a thermionic emission (TE) model, the value of  $\Phi_B$  was determined from a fit of the linear region of the forward I-V curves, where  $qV > 3kT$ , to



**Figure 5.** Room temperature  $1/C^2$  vs  $V$  characteristics of a Pd-Schottky contact on cubic GaN before annealing (full circles).

From the slope of the linear regression line and the intersection point with the abscissa a net carrier concentration of  $N_D - N_A = 6.6 \times 10^{16} \text{ cm}^{-3}$  and a built-in voltage  $V_{bi} = 0.6 \text{ V}$  are evaluated. With  $V_{bi} \cong \Phi_B$  a barrier height of 0.6 eV is estimated. Using an electron affinity of cubic GaN  $\chi_{\text{GaN}} = 4.31 \text{ eV}$  and different work functions  $q\Phi_m$  for the metals Ni, Pd and Ag the theoretical barrier height is calculated by  $q\Phi_B = q\Phi_m - q\chi_{\text{GaN}}$ . 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

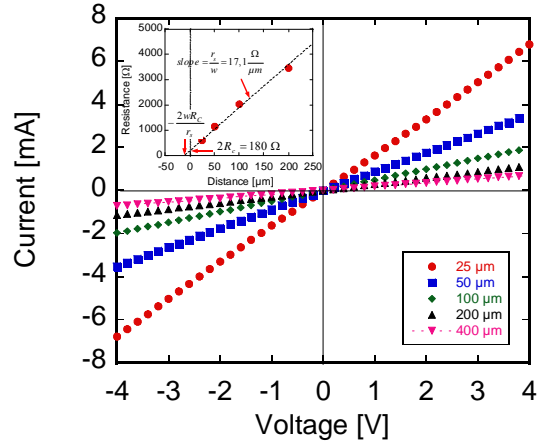
## Ohmic contacts

A Ti/Al/Ni/Au metallization was used for ohmic contacts and the contact resistance was measured by transmission line method [13, 14]. After deposition of the Ti/Al/Ni/Au metal layers the contact was rapidly thermal annealed at 800°C for 4 minutes in vacuum. Contact pads 200  $\mu\text{m}$  x 1000  $\mu\text{m}$  in dimensions are linearly arranged with different separation distances of 25  $\mu\text{m}$ , 50  $\mu\text{m}$ , 100  $\mu\text{m}$ , 200  $\mu\text{m}$  and 400  $\mu\text{m}$ . 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  $\rho_c$  is estimated from this plot. The data for two

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

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  $\Phi_B$  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



**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).

characteristics. Ti/Al/Ni/Au forms an ohmic contacts with a contact resistance  $\rho_c$  of  $1 \times 10^{-4} \Omega \text{cm}^2$ .

differently doped cubic GaN are summarized in Table II. For the higher doped sample a  $\rho_c$  of  $1 \times 10^{-4} \Omega \text{cm}^2$  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 isothermal annealing 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*

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

#	Carrier concentration	Contact resistance	Sheet resistance	Specific contact resistance
1707	$5 \times 10^{17} \text{ cm}^{-3}$	90 $\Omega$	18 k $\Omega$	$1 \times 10^{-4} \Omega \text{cm}^2$
1645	$1 \times 10^{16} \text{ cm}^{-3}$	3 000 $\Omega$	2017 k $\Omega$	9.8 $\Omega \text{cm}^2$

## ACKNOWLEDGMENTS

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## REFERENCES

1. H. Morkoc and L. Liu, in "GaN-based modulation-doped FETs and heterojunction bipolar transistors", ed by P. Ruterana, M. Albrecht and J. Neugebauer, (WILEY-VCH Verlag GmbH, 2003) pp.547.
2. F. Dessenne, D. Cichocka, P. Desplanques and R. Fauquembergue, *Mat. Sci. and Eng. B* **50**, 315 (1997).
3. M. Abe, H. Nagasawa, S. Potthast, J. Fernandez, J. Schörmann, D.J. As and K. Lischka, *IEICE Transaction on Electronics*, **E89-C (7)**, 1057 (2006).
4. T. Maxisch and A. Baldereschi, *phys. stat. sol. (c)*, **2 (7)**, 2540 (2005).
5. D.J. As, D. Schikora and K. Lischka, *phys. stat. sol. (c)*, **0 (6)**, 1607 (2003).
6. V. Cimalla, K.V.Karagodna, J. Pezoldt and G. Eichhorn, *Mater. Sci. Eng. B*, **29**, 170 (1995).
7. E. Tschumak, K. Tonisch, J. Pezoldt and D.J. As, *Proc. of ECSCRM 2008*, paper WeLN-11 (Spain 2008)
8. D.J. As, S. Potthast, J. Fernandez, J. Schörmann, K. Lischka, H. Nagasawa and M. Abe, *Appl. Phys. Lett.* **88**, 152112 (2006)
9. J.D. Guo, F.M. Pan, M.S. Feng, R.J. Guo, P.F. Chou and C.Y. Chang, *J. Appl. Phys.* **80** (3), 1623 (1996).
10. D.K. Schroder, in "*Semiconductor Material and Device Characterization*", Wiley and Sons, New York (1990)
11. E.H. Roderick and R.H. Williams, in "*Metal-Semiconductor Contacts*", Clarendon, Oxford (1988)
12. H. Hasegawa and S. Oyama, *J. Vac. Sci. Technol. B* **20** (4), 1647 (2002).
13. H.H. Berger, *Solid State Electronics* **15**, 145 (1972)
14. D.C. Look, in "*Electrical characterization of GaAs materials and devices*", John Wiley & Sons, New York (1988)