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Cubic GaN/AlGaN Schottky-barrier devices on 3C-SiC substrates

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Abstract

In this work, we focus on the fabrication of cubic GaN based Schottky-barrier devices (SBDs) and measured current voltage (I–V) characteristics and the critical field for electronic breakdown. Phase-pure cubic GaN and c-$Al_xGa_{1-x}N$/GaN structures were grown by plasma assisted molecular beam epitaxy (MBE) on 200 μm thick free-standing 3C-SiC (1 0 0) substrates, which were produced by HOYA Advanced Semiconductor Technologies Co., Ltd. The thickness of the c-GaN and c-$Al_{0.3}Ga_{0.7}N$ epilayers were about 600 and 30 nm, respectively. Ni/In Schottky contacts 300 μm in diameter were produced on c-GaN and c-$Al_{0.3}Ga_{0.7}N$/GaN structures by thermal evaporation using contact lithography. A clear rectifying behavior was measured in our SBDs and the I–V behavior was analyzed in detail, indicating the formation of a thin surface barrier at the Ni–GaN interface. Annealing of the Ni Schottky contacts in air at 200 °C reduces the leakage current by three orders of magnitude. The doping density dependence of breakdown voltages derived from the reverse breakdown voltage characteristics of c-GaN SBDs is investigated. The experimental values of breakdown voltage in c-GaN are in good agreement with theoretical values and show the same dependence on doping level as in hexagonal GaN. From our experimental data, we extrapolate a blocking voltage of 600 V in c-GaN films with a doping level $N_D = 5 \times 10^{15}$ cm^{-3}.

Keywords: Cubic GaN; Schottky barrier; MBE; 3C-SiC substrates

1. Introduction

Schottky contacts are used as key elements in GaN-based electronic devices, such as high-power high electron mobility transistors (HEMTs), high-power metal semiconductor field effect transistors (MESFETs) and UV-photodetectors [1]. For these devices, the width of the Schottky contact depletion layer thickness has to be controlled precisely for optimum device operation. However, GaN based Schottky contacts suffer from anormaleous large leakage currents under reverse bias [2], which strongly degrade gate control characteristics and increase power consumption.

In this work, we focus on the fabrication of cubic GaN based Schottky-barrier devices (SBDs) and measured the critical field for electronic breakdown. From the experimental data we extrapolate a blocking voltage of 600 V in cubic GaN films with a doping level of $N_D = 5 \times 10^{15}$ cm^{-3}.

2. Experimental details

Phase-pure cubic GaN and $Al_{0.3}Ga_{0.7}N$/GaN structures were grown by plasma assisted molecular beam epitaxy (MBE) [3] on 200 μm thick free-standing 3C-SiC (1 0 0) substrates, which were produced by HOYA Advanced Semiconductor Technologies Co., Ltd. (HAST) [4]. The thickness of the c-GaN and c-$Al_{0.3}Ga_{0.7}N$ epilayers were about 600 and 30 nm, respectively. The quality of the cubic epilayers was checked by high resolution X-ray diffractometry, atomic force microscopy and photoluminescence. Details of the MBE growth of cubic GaN and on the properties of c-GaN on free-standing 3C-SiC substrates will be given elsewhere [5]. Ni/In (50/150 nm) Schottky contacts 300 μm in diameter were produced on c-GaN and c-$Al_{0.3}Ga_{0.7}N$/GaN structures by thermal evaporation using

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contact lithography. Prior to vacuum deposition, the GaN and $Al_{0.3}Ga_{0.7}N$ surfaces were cleaned by organic solvents and a buffered oxide etch (BOE). Pure In contacts were used for the ohmic contact to GaN or $Al_{0.3}Ga_{0.7}N$ epilayers. A clear rectifying behavior was measured in our SBDs and the current voltage (*I–V*) behavior was studied in detail in the dark. Capacitance–voltage (*C–V*) measurements and electrochemical CV profiling (ECV) [6] were used to determine the net donor concentration in our cubic GaN and $Al_{0.3}Ga_{0.7}N$ layers which varied between 9×10^{16} and $2 \times 10^{19}\ cm^{-3}$. The doping density dependence of breakdown voltages derived from the reverse breakdown voltage characteristics of c-GaN SBDs is investigated.

3. Results and discussion

The *I–V* curve (full circles) at room temperature (RT) of a typical Ni-Schottky contact on as grown cubic GaN is depicted in Fig. 1, clearly demonstrating a rectifying characteristic. The inset shows a schematic drawing of the device structure. *C–V* measurements performed on the same sample gave a net carrier concentration $N_D - N_A = 1.8 \times 10^{17}\ cm^{-3}$. From the linear increase of current with forward bias a series resistance of $R_S = 230\ \Omega$ is obtained for the as grown sample. By thermal annealing of the Ni contact at 200 °C in ambient air the *I–V* characteristics improved to the one shown by the blue squares. Two effects can be observed, first an increase of the series resistance to $R_S = 310\ \Omega$ is measured and second a severe reduction of the current at reverse biases by about three orders of magnitude is seen. This dramatic effect is emphasized in Fig. 2, in which the current bias dependence is plotted in a semi-logarithmic scale. Whereas the forwards *I–V* characteristics at RT can well be fitted by a standard thermionic emission (TE) model, the reverse bias dependence shows strong deviations [7]. The reverse bias behavior is characterized by the following 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 (see Fig. 2). Furthermore, as temperature was decreased, deviation from the TE behavior became more and more apparent in both forwards and reverse *I–V* characteristics and occasionally a forward current plateau was measured at temperatures below 100 K (not shown here). Recently, the same features have also been observed with Ni, Pt and Au Schottky contacts in hexagonal GaN (h-GaN), which were explained by Hasegawa et al. [8] by introducing a thin surface barrier (TSB) model. This TSB model proposes the formation of a highly conductive layer due to the presence of defect donors at the interface between Ni metal and GaN epilayer. This TSB reduces the barrier thickness and allows severe tunneling of free carriers (field emission). For GaN and $Al_xGa_{1-x}N$ nitrogen vacancies (V_N) are proposed to be the reason for this donor defects [9]. Thermal annealing in air may reduce the density of these defects and improve the *I–V* characteristics, which is in agreement with our experimental results. Another possibility may be the formation of Ga_4Ni_3, Ni_3N and Ni_4N at the Ni GaN interface during annealing at temperatures above 200 °C as it has been observed by Guo et al. [10]. These clusters may form defects, which compensate the donor defects.

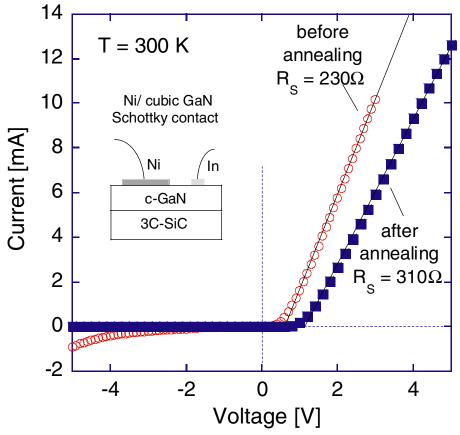

Fig. 1. Room temperature current voltage (*I–V*) characteristics of a Ni-Schottky contact on cubic GaN before annealing (open circles) and after annealing in air at 200 °C (full squares).

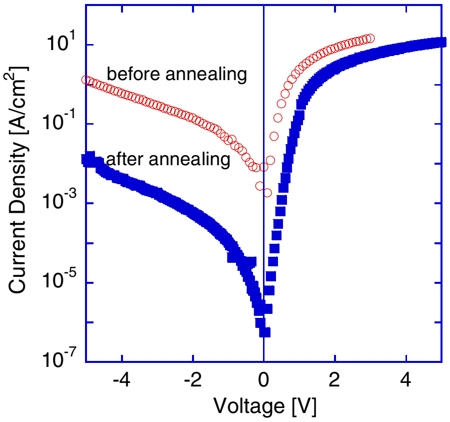

Fig. 2. Semi-logarithmic plot of the *I–V* characteristics of a Ni-Schottky contact on cubic GaN before annealing (open circles) and after annealing in air at 200 °C (full squares).

In Fig. 3 the reverse breakdown voltages (V_{Br}) of c-GaN (full circles) and c-$Al_{0.3}Ga_{0.7}N$ (full squares) Ni–SBDs are plotted versus the doping density ($N_D - N_A$) measured by *C–V* or ECV. The full lines show the doping dependence of V_{Br} calculated by Matocha [11] for c- and h-GaN, respectively. Included in Fig. 3 are also experimental data obtained on h-GaN (open squares [12] and open triangles [13]). The experimental values of V_{Br} in c-GaN are one-third smaller than the theoretical values and show the same dependence on doping level as in h-GaN (dashed lines). Crystal defects like dislocations or point defects may be the reason for the deviation between experimental data and theoretical calculations. This interpretation is supported by the experimental data obtained on the annealed

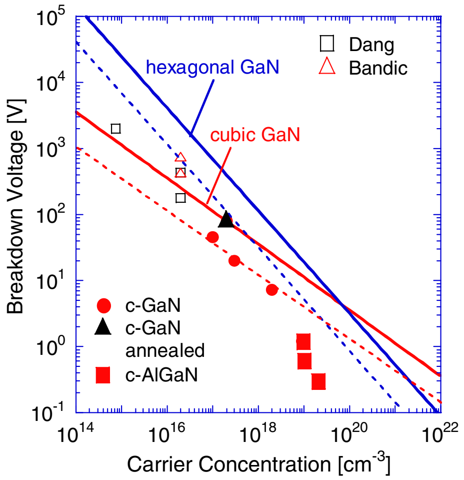

Fig. 3. Reverse breakdown voltage versus carrier concentration.

sample (full triangle), where the measured V_{Br} of 80 V at a carrier concentration of 1.8×10^{17} cm^{-3} is in excellent agreement with the theoretical curve. For c-Al$_{0.3}$Ga$_{0.7}$N epilayers (full squares) the larger deviation to the theoretical curve may be a hint for the existence of a more pronounced TSB. From these experimental data we extrapolate a blocking voltage of higher than 600 V in c-GaN films at a doping level below $N_D = 5 \times 10^{15}$ cm^{-3}.

4. Conclusion

Ni Schottky-barrier devices were fabricated by thermal evaporation using contact lithography on cubic GaN and Al$_x$Ga$_{1-x}$N epilayers. Phase-pure cubic GaN and c-Al$_{0.3}$Ga$_{0.7}$N/GaN structures were grown by plasma assisted MBE on 200 μm thick free-standing 3C-SiC substrates, which were produced by HAST. Analysis of the I–V characteristics of these SBDs at 300 K and at low temperature showed that a thin surface barrier is formed at the Ni GaN interface. Thermal annealing in air at 200 °C alters this thin surface barrier and reduces the leakage current by three orders of magnitude. The doping density dependence of V_{Br} is in good agreement with calculated values and follows the expected trend. From these experimental data a blocking voltage of higher than 600 V is extrapolated for c-GaN films with a doping level of $N_D = 5 \times 10^{15}$ cm^{-3}.

References

[1] H. Morkoc, L. Liu, in: P. Ruterana, M. Albrecht, J. Neugebauer (Eds.), Nitride Semiconductors, Wiley-VCH, Weinheim, 2003, p. 547.
[2] V. Adivarahan, G. Simin, J.W. Yang, A. Lunev, M. Asif Khan, N. Pala, M. Shur, R. Gaska, Appl. Phys. Lett. 77 (2000) 863.
[3] D.J. As, in: Optoelectronic Properties of Semiconductors and Superlattices, vol. 19, 2003, p. 323.
[4] H. Nagasawa, K. Yagi, T. Kawahara, N. Hatta, G. Pensl, W.J. Choyke, T. Yamada, in: W.J. Choyke, H. Matsunami, G. Pensl (Eds.), Silicon Carbide, Springer, Berlin, 2003, p. 207.
[5] D.J. As, S. Potthast, J. Schörmann, S.F. Li, K. Lischka, H. Nagasawa, M. Abe, in: Proceedings of ICSCRM-2005, Pittsburgh USA, paper FA2.EPI.
[6] T. Wolff, M. Rapp, T. Rotter, Phys. Stat. Sol. C 1 (2004) 2491.
[7] D.K. Schroder, in: Semiconductor Material and Device Characterization, Wiley & Sons, New York, 1990, p. 130.
[8] H. Hasegawa, S. Oyama, J. Vac. Sci. Technol. B 20 (2002) 1647.
[9] T. Hashizume, H. Hasegawa, Appl. Surf. Sci. 234 (2004) 387.
[10] J.D. Guo, F.M. Pan, M.S. Feng, R.J. Guo, P.F. Chou, C.Y. Chang, J. Appl. Phys. 80 (1996) 1623.
[11] K. Matocha, T.P. Chow, R.J. Gutmann, Mat. Sci. Forum 389–393 (2002) 1531.
[12] G.T. Dang, A.P. Zhang, M.M. Mshewa, F. Ren, J.I. Chyl, C.M. Lee, C.C. Chuo, G.C. Chi, J. Han, S.N.G. Chu, R.G. Wilson, X.A. Cao, S.J. Pearton, J. Vac. Sci. Technol. A 18 (2000) 1135.
[13] Z.Z. Bandic, P.M. Bridger, E.C. Piquette, T.C. McGill, Appl. Phys. Lett. 74 (1999) 1266.