Available online at www.sciencedirect.com
ScienceDirect
Solid-State Electronics 52 (2008) 171–174
SOLID-STATE ELECTRONICS
www.elsevier.com/locate/sse

Letter

Localised defect-induced Schottky barrier lowering in n-GaN Schottky diodes

G. Parish *, R.A. Kennedy, G.A. Umana-Membreno, B.D. Nener

School of Electrical, Electronic and Computer Engineering, The University of Western Australia, M018, 35 Stirling Hwy, Crawley, WA 6009, Australia

Received 24 January 2007; received in revised form 13 September 2007; accepted 13 September 2007
Available online 10 October 2007

The review of this paper was arranged by Prof. E. Calleja

Abstract

The forward bias current–voltage (*I–V*) characteristics of n-GaN Schottky diodes on sapphire substrate were investigated over a wide temperature range of 70–500 K. For models based on localised regions of lowered Schottky barrier height, a distributed barrier height should be expected when these localised regions are comparable to or smaller in size than the depletion width. However, a suitable fit for the *I–V* curves, which exhibited anomalous two-step (kink) forward bias behaviour, was only obtained when modelling the leakier regions with a single reduced barrier height, by using a model of two discrete diodes in parallel.

Keywords: Gallium nitride; Schottky barrier; *I–V*; Defects; Leakage; Barrier lowering

Despite great advances in the past decade, it has long been evident that the electrical characteristics of GaN-based devices vary significantly from conventional semiconductor device behaviour. Despite the many positive attributes of GaN and its alloys, such as the optically useful bandgap and the excellent transport and breakdown properties, a myriad of defects and defect mechanisms hamper device behaviour. This includes bulk and surface effects, due to both extended (threading dislocation) and point defects. Although the nature and extent of the electrical activity of threading dislocations in GaN is still disputed [1–4], it is increasingly apparent that at least some types of dislocations do significantly affect electrical transport. In particular, there is greater consensus that at least pure screw (and possibly mixed) dislocations are a path for electrical conductivity [3,4].

The various defects affecting GaN bulk and/or surface properties can have significant consequences for Schottky contacts to GaN. For example, a slight saturation of the current at low forward bias is frequently observed for GaN Schottky diodes, corresponding to an ideality factor that increases with bias [5–8]. Consequently, conventional current–voltage (*I–V*) analysis, using only thermionic emission mechanisms, with a single, homogenous Schottky barrier height (SBH), is often inadequate. The subsequently extracted single SBH is not physically meaningful, and usually the result of a somewhat arbitrary fit. Therefore, alternative models must be sought to describe device behaviour. Several authors have published *I–V* characteristics for GaN-based devices modelled with various tunnelling and/or hopping mechanisms [5,6,9,10]. However, in many cases the models require different mechanisms at different temperatures to satisfactorily fit the *I–V* data [9,10], or have only been published for a limited temperature range or limited forward bias range [5,6].

In this work Schottky diodes were fabricated on GaN:Si grown on sapphire substrate by metal–organic semiconductor vapour deposition. The fabricated devices consisted of circular diodes with annealed Al/Cr/Au ohmic contacts and Ni/Au Schottky contacts. *I–V* and *C–V* (capacitance–voltage) measurements were carried out at temperatures

* Corresponding author. Tel.: +61 8 6488 3390; fax: +61 8 6488 1095.
E-mail address: gia@ieee.org (G. Parish).

0038-1101/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.sse.2007.09.005

ranging from 70 to 500 K. From C–V the free carrier concentration was determined to be 4.2–$4.5 \times 10^{17}\ \mathrm{cm}^{-3}$. Over 70–500 K the extracted SBH ϕ_b was found to vary from 1.25 down to 1.1 eV, and the depletion width from 163 to 51 nm.

All diodes exhibited anomalous I–V behaviour, with a plateau section, followed by a second step – giving a kinked curve – that was more evident at lower temperatures (Fig. 1). Most previously reported studies of forward bias GaN diode characteristics have not gone to high enough forward bias to observe the kink, rather just the plateau [5,6]. No meaningful fit was obtainable via application of conventional thermionic emission models, with only segments of the curve between kinks able to be fitted. Doing so, the calculated flatband barrier height was 1–1.2 eV over the measured temperature range. The conventionally extracted ideality factor was very large (above 5) for temperatures below 100 K, decreasing to a constant value of approximately 1.4 for temperatures above 400 K.

Since reported experimental evidence indicates that an oxide-like intervening layer between Ni and GaN is not present even when conventional surface preparation methods are employed [11–13] (an assumption often necessary to justify interface-state based models), the obvious alternative analysis technique is to assume that the SBH is not unique but rather distributed, with regions of lower SBH causing the observed behaviour of the ideality factor and Richardson constant [8,14,15]. Neighbouring regions can then be considered as either interacting (Gaussian distribution) or non-interacting (independent diodes of discrete barrier height). However, in previous models the system is only regarded as interacting when the size of the inhomogeneities is significantly on the order of or smaller than the depletion width, based on pinch-off of the potential for the lower SBH regions [8,15,16]. The electrical width of threading dislocations, for example, has been estimated at 50 nm [3], which is indeed comparable to or smaller than the depletion width of these diodes at all temperatures. However, application of distributed SBH models did not provide a good fit to the data in this case.

As an alternative to conventional analysis, Norde analysis was undertaken [17]. Determination of the minimum (at voltage $V_{\min}$) of the Norde function $F(V)$ given by

$$F(V) = \frac{V}{2} - \left(\frac{kT}{q}\right) \ln\left(\frac{I}{AA^{**}T^2}\right)$$

allows extraction of the zero-bias SBH by

$$\Phi_{B0} = F(V_{\min}) + \frac{V_{\min}}{2} - \frac{kT}{q}$$

where A is the Richardson's constant, A^{**} the modified Richardson's constant, T the temperature (in K), q the electron charge, and k is the Boltzmann's constant.

Two distinct minima were observed in the Norde function for our data, as seen in Fig. 2. As a result, two distinct pairs of SBH, ϕ_b, and series resistance, R_s, were extracted. One of the ϕ_b–R_s pairs was consistent with the expected diode behaviour (matching the SBH extracted from C–V), whilst the other resembled a much leakier diode (reduced SBH (RSBH)), with much higher series resistance. Note that for temperatures below approximately 250 K the second minimum in the Norde function, corresponding to the expected diode behaviour, became too shallow for the analysis program to resolve.

Following Norde analysis, the devices were modelled as two diodes in parallel, one with ideality factor set to one and the other with a variable ideality factor. Such a model has been successfully used by Huang et al. [7] to model reverse leakage in n-GaN Schottky diodes, attributed to the presence of screw dislocations. After applying the model it was evident that the characteristics of one diode (with ideality factor $n = 1$) corresponded to the expected diode and the other had a reduced SBH (and higher ideality factor). This is consistent with the observation of the current plateau, as current flow through RSBH regions will

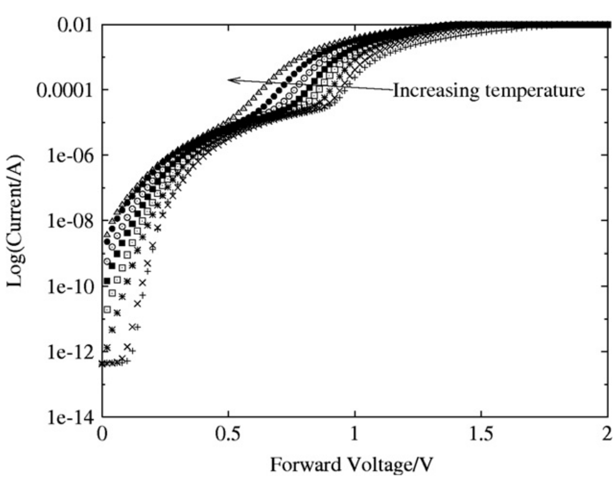

Fig. 1. Typical n-GaN Schottky diode measured current–voltage characteristics for temperatures of 70, 100, 150, 200, 250, 300, 350 and 400 K.

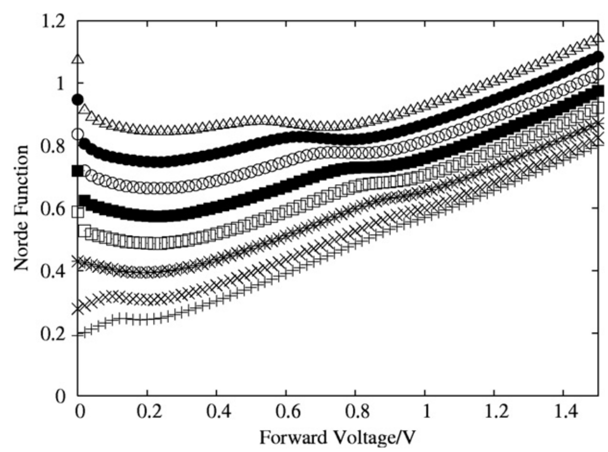

Fig. 2. Norde functions [17] obtained from current–voltage characteristics shown in Fig. 1. Two distinct barrier heights were extracted from the two minima observed.

saturate as forward bias increases and the inhomogeneity disappears. This model closely fitted the data, as can be seen in Fig. 3 for measurement temperatures of 72.2 K (a) and 486 K (b). This excellent fit was achieved for the *I–V* curves for all devices. In contrast to many other models, this single model fit was achieved over the entire temperature range from 70 to 500 K.

The various values of SBH obtained from each of the techniques (*C–V*, conventional *I–V*, Norde analysis, and parallel diode model) are shown together in Fig. 4. As can be seen, the non-reduced SBH obtained from the parallel diode ("2diode") model approximately matches that extracted from *C–V* measurements and from Norde analysis. Conversely, the temperature dependence of the RSBH parallel diode matches that of the SBH obtained from conventional *I–V* analysis and the RSBH obtained from Norde analysis.

An important point to note is that for the different diodes measured, consistent properties were extracted for the expected diode SBH, but the extracted RSBH varied.

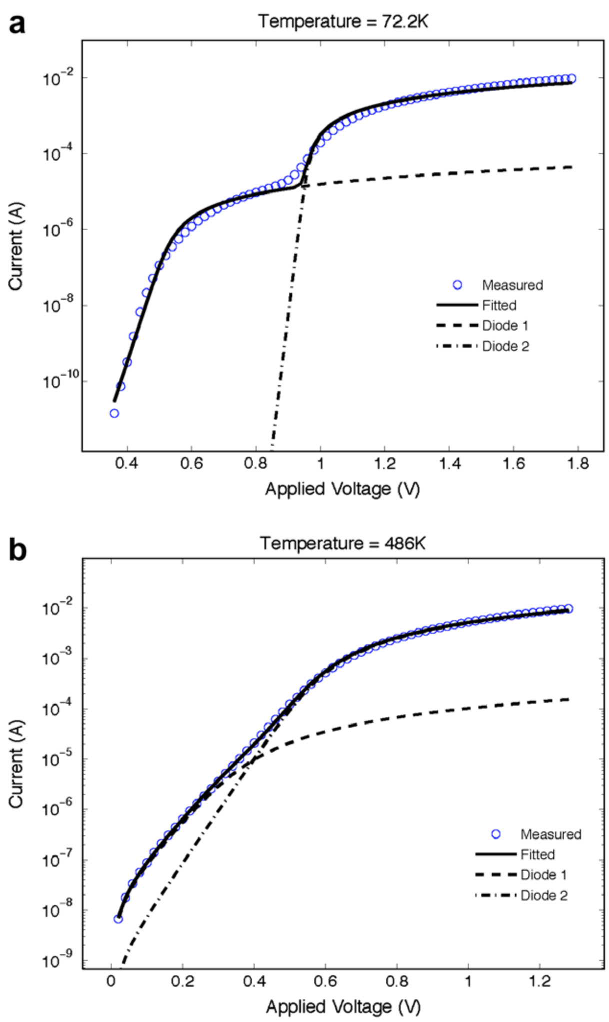

Fig. 3. Fit of the parallel diode model to data measured at (a) 72.2 K and (b) 486 K. Ideality factor was forced to unity for one diode whilst the other was adjusted to find the best fit.

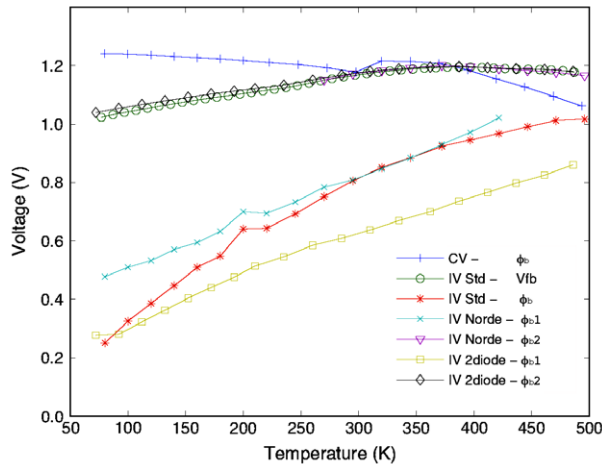

Fig. 4. Comparison of the Schottky barrier heights ϕ_b extracted from *C–V*, conventional *I–V* analysis ("std"), Norde analysis of *I–V*, and parallel diode model of *I–V* ("2diode"). Flatband voltage V_{fb} obtained from conventional *I–V* analysis is also given.

One physical realisation of this model could be a standard Schottky diode (with ideality factor $n = 1$), degraded by threading dislocations with temperature-dependant leakage. Clustering of threading dislocations, resulting in a non-uniform distribution of leakage paths, could then explain the variation in extracted RSBH. Note that Bradley et al. [18] also observed two distinct SBH through measurement of internal photoemission; however, as they were AlGaN diodes they attributed the effect to spatial variation in x_{Al} rather than defects.

The forward bias characteristics of n-GaN Schottky barrier diodes have successfully been fitted using a model with two independent diodes in parallel. Of the two extracted barrier heights, one (for the diode with $n = 1$) matched results from *C–V* and flatband (*I–V*) whilst the other corresponded to reduced Schottky barrier height (RSBH) regions, with temperature dependent barrier height. One physical realisation of this model could be a standard Schottky diode (with a temperature-invariant ideality factor), degraded locally by threading dislocations with temperature-dependant leakage. This would mean that, in contradiction to other published models, RSBH regions with dimensions smaller than the order of the depletion width may still be non-interacting and non-distributed.

Acknowledgements

We wish to acknowledge the Australian Research Council for financial assistance and the University of California, Santa Barbara, for the GaN wafer growth.

References

[1] Elsner J, Jones R, Sitch PK, Porezag VD, Elstner M, Frauenheim Th, et al. Theory of threading edge and screw dislocations in GaN. Phys Rev Lett 1997;79(19):3672–5.

[2] Kozodoy P, Ibbetson JP, Marchand H, Fini P, Keller S, Speck JS, et al. Electrical characterization of GaN p–n junctions with and without threading dislocations. Appl Phys Lett 1998;73(7):975–7.
[3] Brazel EG, Chin MA, Narayanamurti V. Direct observation of localized high current densities in GaN films. Appl Phys Lett 1999;74(16):2367–9.
[4] Simpkins BS, Yu ET, Waltereit P, Speck JS. Correlated scanning Kelvin probe and conductive atomic force microscopy studies of dislocations in gallium nitride. J Appl Phys 2003;94(3):1448–53.
[5] Yu LS, Liu QZ, Xing J, Qiao DJ, Lau SS. The role of the tunneling component in the current–voltage characteristics of metal–GaN Schottky diodes. J Appl Phys 1998;84(4):2099–104.
[6] Hashizume T, Kotani J, Hasegawa H. Leakage mechanism in GaN and AlGaN Schottky interfaces. Appl Phys Lett 2004;84(24): 4884–6.
[7] Huang Y, Chen XD, Fung S, Beling CD, Ling CC. Experimental study and modeling of the influence of screw dislocations on the performance of Au/n-GaN Schottky diodes. J Appl Phys 2003;94(9):5771–5.
[8] Sawada T, Ito Y, Kimura N, Imai K, Suzuki K, Sakai S. Characterization of metal/GaN Schottky interfaces based on *I–V–T* characteristics. Appl Surf Sci 2002;190:326–9.
[9] Miller EJ, Yu ET, Waltereit P, Speck JS. Analysis of reverse-bias leakage current mechanisms in GaN grown by molecular-beam epitaxy. Appl Phys Lett 2004;84(4):535–7.
[10] Kamelkar S, Sathaiya DM, Shur MS. Mechanism of the reverse gate leakage in AlGaN/GaN high electron mobility transistors. Appl Phys Lett 2003;82(22):3976–8.
[11] Liu QZ, Lau SS. A review of the metal–GaN contact technology. Solid State Electron 1998;42(5):677–91.
[12] Rickert KA, Ellis AB, Kim JY, Lee J-L, Himpsel FJ, Dwikusuma F, et al. X-ray photoemission determination of the Schottky-barrier height of metal contacts to n-GaN and p-GaN. J Appl Phys 2002;92(11):6671–8.
[13] Venugopalan HS, Mohney SE, Luther BP, DeLucca JM, Wolter SD, Redwing JM, et al. Phase formation and morphology in nickel and nickel/gold contacts to gallium nitride. In: Mater. Res. Soc. Symp. Proc., vol. 468; 1997. p. 431–42.
[14] Osvald J. Numerical study of electrical transport in inhomogeneous Schottky diodes. J Appl Phys 1999;85(3):1935–42.
[15] Tung RT. Electron transport at metal–semiconductor interfaces: general theory. Phys Rev B 1992;45(23):13509–23.
[16] Sawada T, Ito Y, Imai K, Suzuki K, Sakai S. Influence of inhomogeneous barrier on *I–V* characteristics of metal/GaN Schottky diodes. IPAP Conf Ser 2001(1):801–4.
[17] Norde H. A modified forward *I–V* plot for Schottky diodes with high series resistance. J Appl Phys 1979;50(7):5052–3.
[18] Bradley ST, Goss SH, Hwang J, Schaff W, Brillson LJ. Premetallization processing effects on Schottky contacts to AlGaN/GaN heterostructures. J Appl Phys 2005;97:084502-1-9.