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Correlation of current–voltage–temperature analysis with deep level defects in epitaxial GaN films

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The effect of temperature on the nature of metal-semiconductor system in a Au contact deposited on c-plane and a-plane GaN film was investigated by current–voltage (I–V) measurements. The I–V measurements have been obtained systematically at different temperatures ranging from room temperature (300 K) to low temperature (78 K). Photoluminescence measurements were obtained to investigate correlation between the growth conditions, the substrate used for the growth of GaN film, and the presence of deep level defects therein by equating with the yellow band luminescence. The resistance–voltage–temperature analysis indicates that a gradual shift of the nature of contact towards Schottky behavior takes place while moving from room temperature to low temperature. Additionally, memory effect like aberration is present at low temperature, which can be attributed to the presence of deep-level defects and carrier recombination therein. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4922250]

In recent years, much research interest has been drawn towards III-Nitride solar cells as they exhibit many favorable photovoltaic properties. Perhaps, the most attractive among these characteristics is that, while employing smart designs like multi quantum well (MQW) structures, the complete span of band gaps from that corresponding to UV region ($E_{g\_GaN} = 3.4$ eV) to that of IR ($E_{g\_InN} = 0.7$ eV) region can be, in theory, tuned to absorb almost full solar spectrum.[1] The Solar cells so designed are expected to perform in a wide range of operating temperature. In such a case, an understanding of the current conduction mechanism at different temperatures and relative changes thereof in the device behavior specially in terms of current–voltage (I–V) measurements with respect to change in the temperature need to be understood. A basic III-Nitride based solar cell structure consists of a p-type GaN, an absorption layer of InGaN, and an n-type GaN. Recently, Dahal *et al.* have shown that InGaN/GaN MQW structures can be used as the absorption region for higher efficiency solar cells.[2] As-grown GaN normally shows n-type conductivity due to preferential loss of nitrogen.[3] To develop a better insight into the electrical transport mechanism of such devices, it is imperative to understand the same in the unintentionally doped (UID) GaN film.

Electrical transport in UID semiconductor is influenced by many parameters like defects, defects related traps, and charge balance due to unintentional residual doping, and thus is complicated. The understanding of the contribution of each mechanism, i.e., thermionic emission, field emission, and thermionic field emission, at different temperature range and their correlation with the presence of defects[4] would contribute significantly in the designing of devices operating in conditions with large variation of temperatures.

The current–voltage characteristics deviate substantially, depending on the plane of the GaN, and the ambient temperature. The Au/GaN Schottky contact shows hysteresis at low temperature, indicating influence of deep level defects.[5] This takes on a special meaning in Schottky detectors where the device operates in a variable temperature range.

There is plenty of literature on standard schemes of contacts developed for Ohmic and Schottky contact on GaN; however, only few studies have been carried out to understand the temperature dependant behavior of the metal contacts on GaN. In this report, the current–voltage measurements have been obtained systematically at different temperature varying from room temperature (300 K) to low temperature (78 K). This approach allowed us to analyze the effect of temperature on the I–V measurements and the relative Schottky behavior. Correlation between deep level defects and I–V measurements at various temperatures has been analyzed.

The heteroepitaxial GaN films were grown by Riber Compact 21 PAMBE system equipped with a radio frequency (rf)-plasma source (Addon) to supply active nitrogen species and standard Knudsen cells for evaporating gallium on the substrates. The sapphire substrates used were precleaned by degreasing in acetone for 2–3 min followed by dipping in 1:1 (HCl: DI H_2O) solution for 5 min and further by immersing in 2M NaOH solution for few minutes. *In-situ* thermal annealing was carried out in buffer chamber to remove the residual contaminants from the substrate. The reported samples were grown with a Ga beam equivalent pressure of 1.01×10^{-6} Torr at a constant rf power of

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TABLE I. Growth condition and substrate details of the sample.

Sample No.	Plane of sapphire substrate	Growth temperature
(a)	c-plane	730 °C
(b)	c-plane	745 °C
(c)	c-plane	760 °C
(d)	r-plane	730 °C
(e)	a-plane	730 °C

500 W. The details of the sample are given in Table I. The growth details are reported elsewhere.[6] The growth was monitored *in-situ* by Reflection High Energy Electron Diffraction (RHEED) using STAIB electron gun operating at 12 keV to ensure high quality 2-dimensional (2D) growth. PL measurements were carried out using a He–Cd laser operating at 325 nm as an excitation source.

Prior to loading the samples in an evaporation chamber, each sample was cleaned using a sequence of three solvents to remove organic, inorganic, and physical impurities such as dust or excessive moisture. Acetone, methanol, and isopropanol were used in that order. The wafers were then dried using pressurized nitrogen. The contacts were formed by Au deposition by Physical Vapor Deposition (PVD).

I–V measurements were performed at varying temperature on the sample, and a plot was obtained between the sample resistance (R) v/s the applied bias (V). Figs. 1(a)–1(c), indicate that as the temperature is lowered, the sample exhibits a dramatic increase in tendency of Schottky behavior. The conformal analysis can be obtained from Fig. 3, in which there is a relative change in the rectifying behavior. Samples (a), (c), and (e) follow similar pattern of change in their resistance–voltage (R–V) characteristics, whereas sample (b) shows a sharper shift in R–V plot (Figs. 1(a)–1(c)) with varying applied bias. This relative shift in the Schottky behavior observed in samples (a), (c), and (e) can be better understood in terms of contribution from different current conduction mechanisms. At lower temperatures, the electrons loose considerable thermal energy, and hence, an additional voltage bias is required, for them to gain sufficient energy to overcome the barrier. This implies that even though at room temperature, thermionic emission may contribute significantly towards the current flow, at lower temperature, the contribution from the thermionic emission mode is not dominant. The samples (d) and (e) show similar behavior, but at temperatures 78 K to 100 K, the R–V plot shows a deviation from the aforementioned behavior. This oddity in the R–V plot (Figs. 1(b) and (c)) of samples (d) and (e) could be explained by the presence of trap states. These trap states are participatory in contribution to tunneling current, i.e., field emission mode, thus effectively reducing the resistance and hence a sharper R–V plot.

Another interesting phenomenon is observed in c-plane GaN grown on a-plane sapphire substrate, i.e., Fig. 1(c), in terms of significant decrease in sample resistance on consecutive voltage sweep from −7.5 volt to +7.5 volt and from

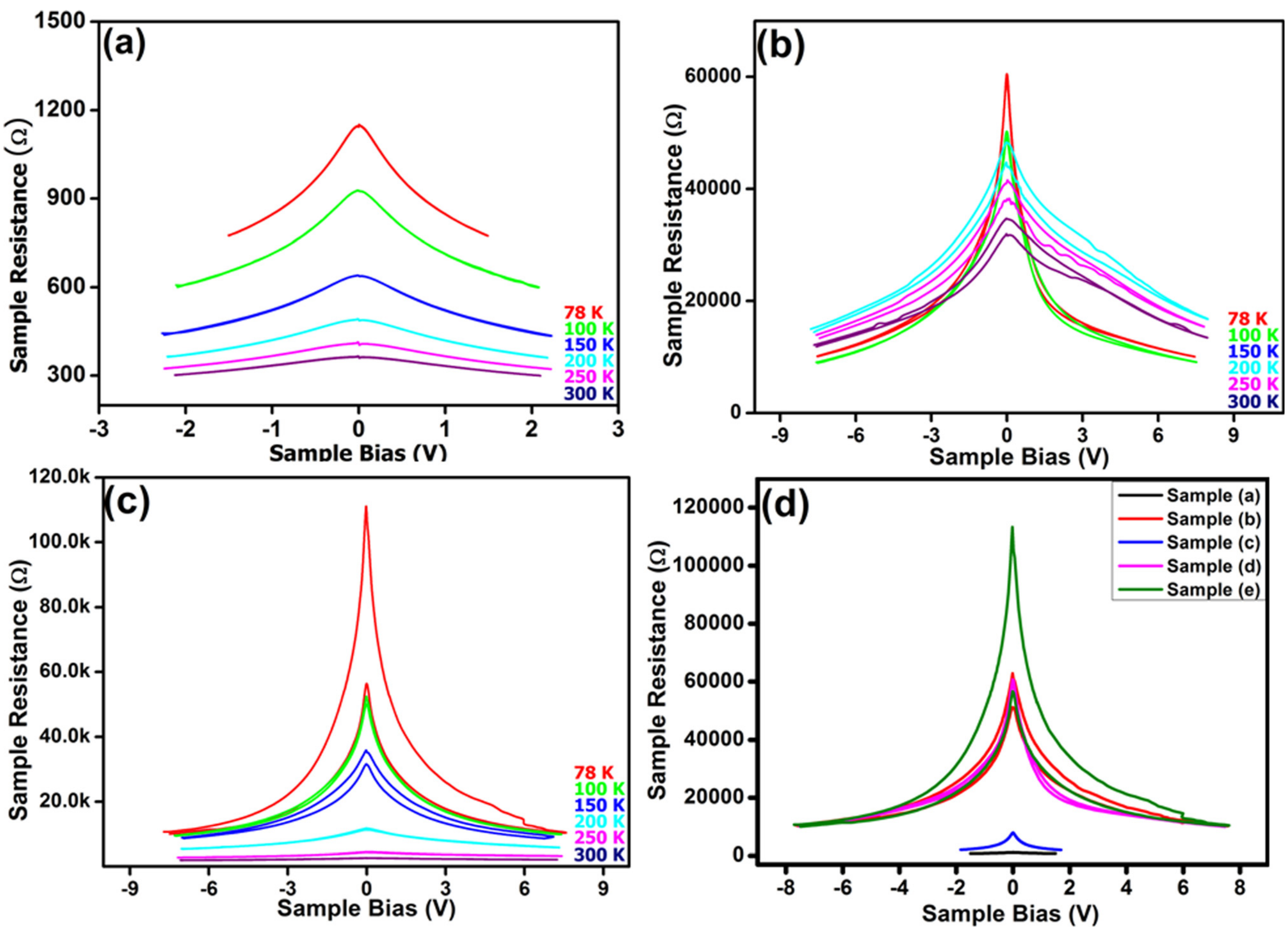

FIG. 1. R–V plot obtained at varying temperature for sample grown at 730 °C with (a) grown on c-plane sapphire substrate, (b) grown on r-plane sapphire and (c) grown on a-plane sapphire, and (d) R–V plot of all the samples (a)–(e) at 78 K.

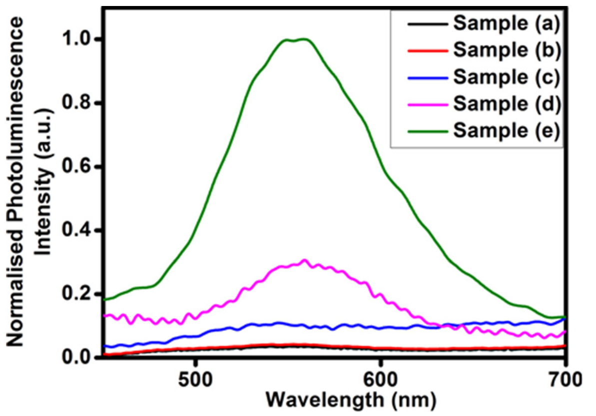

FIG. 2. Photoluminescence spectra showing only the yellow band luminescence obtained for the sample grown at (a) 730 °C, (b) 745 °C, (c) 760 °C, (d) 730 °C, (e) 730 °C, with (a), (b), and (c) grown on c-plane sapphire substrate, (d) grown on r-plane sapphire, and (e) grown on a-plane sapphire substrate. The absorption peak of all the samples was found at around 364 nm.

+7.5 volt to −7.5 volt. The magnitude of this phenomenon is found to be maximum at 0 Volt bias. The sample resistance during first voltage sweep at 0 Volt is approximately 110 kΩ, whereas the sample resistance during second voltage sweep at 0 Volt reduces to almost half its original value to approximately 56 kΩ. This aberration can be partially explained by the role played by defects in the current conduction mechanism. As external bias is applied, electrons tunnel from the Schottky barrier to an interfacial state.[7] Participation by defects introduces memory effects owing to time constants involved in that trap filling and ionization with their characteristic time constant. With the completion of the first voltage sweep, most of the available defect states are expected to be filled. This leaves just a few empty states available for deep-level assisted tunneling. Therefore, during the second voltage sweep, it is also plausible to release trapped electrons. This would give rise to comparatively excess leakage current at low bias voltages, thus resulting in lower value of sample resistance due to larger value of current flowing through the sample at same voltage bias.

The presence of defect states can be confirmed thorough the corresponding PL spectra of the c-plane GaN film grown on a-plane sapphire substrate. The PL spectrum of the samples shows a broad yellow band photoluminescence (as shown in Fig. 2(e)) at around 2.2 eV to 2.3 eV (540 nm to 563 nm). This broad PL band can be attributed to recombination of carriers at deep-level defects.[8,9]

For all practical purposes, ignoring the series resistance, the current–voltage characteristics can be represented by the following equation when dominated by thermionic emission:

$$\mathrm{I} = \mathrm{I_o}\left[\exp\left(\frac{\mathrm{qV}}{\mathrm{nkT}}\right) - 1\right], \tag{1}$$

with n being the ideality factor and lumping deviations from the ideal thermionic emission,[4] where

$$\mathrm{I_o} = \mathrm{AA^*T^2}\exp\left(\frac{-\phi}{kT}\right). \tag{2}$$

Here, V, q, k, ϕ, and T are the total applied voltage, the electron charge, the Boltzmann constant, barrier height, and the absolute temperature, respectively. The contact area is A, and A^* is the Richardson constant. However, the plots of the I–V measurements cannot be simply fitted by the above mentioned equation for modeling ideal thermionic emission, owing to bulk and surface defects. Thus, the current–voltage measurement plots deviate substantially from the aforementioned analysis, and the impact of surface morphology and defects must be taken into consideration.

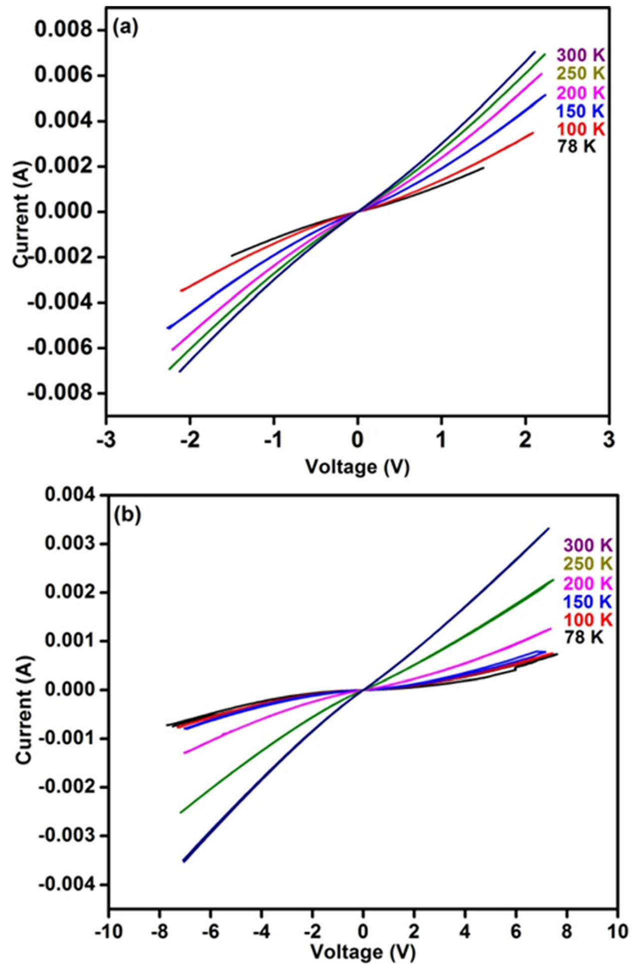

FIG. 3. I–V plot obtained at varying temperature for sample grown at 730 °C, with (a) grown on c-plane sapphire substrate and (b) grown on a-plane sapphire substrate.

Consider GaN samples (a), (d), and (e) grown on c-plane, r-plane, and a-plane sapphire substrates, respectively, which have different substrates but similar growth conditions. The surface morphology of c-plane GaN grown on c-plane sapphire substrate (Fig. 4(a)) shows presence of lot of pits (extended defects), whereas a-plane GaN grown on r-plane sapphire substrate (Fig. 4(d)) shows two faceted islands and that of c-plane GaN grown on a-plane sapphire substrate (Fig. 4(e)) shows a comparatively smoother surface with their root mean square surface roughness obtained with the help of AFM being 2.5 nm, 5.3 nm, and 2.1 nm, respectively. When comparing GaN grown on different planes of sapphire substrate, we find that even though the surface morphology is seen to be improving from c-plane GaN grown on c-plane sapphire to c-plane GaN grown on a-plane sapphire, the presence of deep level defects, gauged with the help of the photoluminescence spectra of respective samples

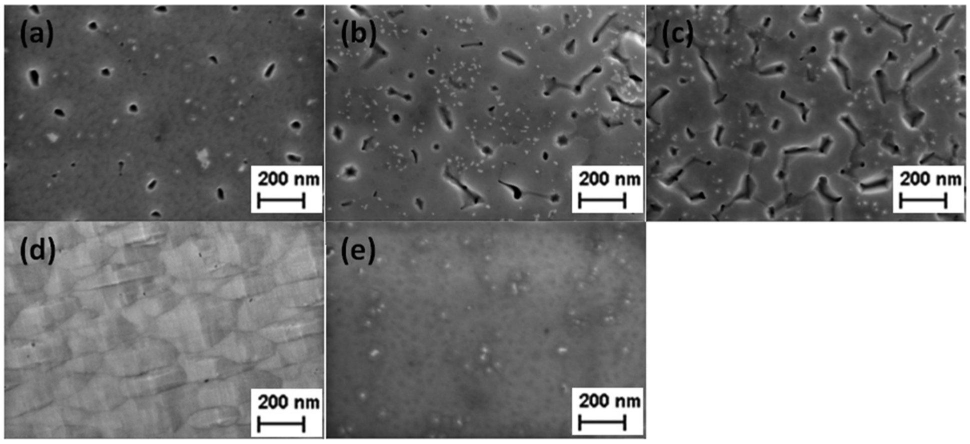

FIG. 4. SEM Images obtained at 50k× Magnification for sample grown at (a) 730 °C, (b) 745 °C, (c) 760 °C, (d) 730 °C, and (e) 730 °C, with (a), (b), and (c) grown on c-plane sapphire substrate, (d) grown on r-plane sapphire, and (e) grown on a-plane sapphire substrate.

provided in Figs. 2(a), 2(d), and 2(e), indicates an opposite trend. Correlating the extent of broadening of the yellow band photoluminescence with the density of deep level defects present, it can be concluded that sample (e) has highest density of deep level defects while sample (b) has the minimum level of deep level defects.

On a comparative note, one can see that the resistance at 0 voltage bias (say R_0) is different for samples with similar substrate but different growth temperature as well as in the case when the samples have different substrate but similar growth temperature. An interesting phenomenon can be observed from Fig. 1(d) that the R_0 for all the samples are different at each temperature. The R_0 at 78 K (as well as at 300 K) is highest for c-plane GaN grown on a-plane sapphire (Fig. 1(c)) and is lowest for c-plane GaN grown on c-plane sapphire (Fig. 1(a)). Higher value of R_0 implies that the current conduction at 0 voltage bias is low, i.e., it will show comparatively higher degree of Schottky behavior. This is evident from Fig. 3, in which a I–V plots of the samples (a) and (e) are given. The I–V plot clearly indicates that c-plane GaN grown on c-plane sapphire shows a quasi-Ohmic nature at 300 K.

A different comparative study of c-plane GaN grown on c-plane sapphire substrate grown with different growth conditions (samples (a), (b), and (c)) was carried out. It is noted from Fig. 1 that the R_0 at 300 K as well as at 78 K for sample (b) is highest and for sample (a) is lowest. This shows that current conduction is maximum in sample (a).

It can also be seen from Fig. 4 that the surface of sample (a) is very smooth. The rms surface roughness measured using AFM was found to be 2.5 nm while that of sample (b) and (c) were 4.4 nm and 4.8 nm. From both the above discussion, it is clear that sample (a) which was grown on c-plane sapphire is best among all the samples grown showing minimum R_0 and showing very smooth surface morphology. Hence, it could be concluded that c-plane GaN grown on c-plane sapphire substrate is best suitable for III-Nitride based solar cell application.

In summary, a gradual shift towards Schottky behavior was observed while moving towards low temperature. At low temperature of 78 K, there was a memory effect in the sample, possibly due to the deep level defect states present in the sample, which result in defect assisted tunneling. It should also be mentioned that the surface of GaN is not completely inert,[5] and any trap whose energy lies between the conduction band of the n-type semiconductor and the Fermi level in the metal would participate in this process. The presence of memory effect at low temperature only is definitely an interesting topic to be further investigated upon. Better understanding of the current conduction mechanism at varying temperature would add to the knowledge bank and would assist in designing better solar cell devices, capable of operating efficiently in a large temperature range.

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[1] J. Wu, W. Walukiewicz, K. M. Yu, W. Shan, J. W. Ager III, E. E. Haller, H. Lu, W. J. Schaff, W. K. Metzger, and S. Kurtz, J. Appl. Phys. **94**, 6477 (2003).
[2] R. Dahal, B. Pantha, J. Li, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **94**, 063505 (2009).
[3] H. Tang, Z. Q. Fang, S. Rolfe, J. A. Bardwell, and S. Raymond, J. Appl. Phys. **107**, 103701 (2010).
[4] K. Shiojima and T. Suemitsu, J. Vac. Sci. Technol., B **21**(2), 698 (2003).
[5] H. Markoc, *Handbook of Nitride Semiconductors and Devices* (Wiley-VCH, 2008), Vol. 2, Chap. I.
[6] S. Krishna T.C., N. Aggarwal, M. Mishra, L. Goswami, G. Gupta, S. Singh, and K. K. Maurya, "Epitaxial growth of single crystalline GaN film on A-plane (11-20) sapphire substrate" (unpublished).
[7] J. C. Carrano, T. Li, P. A Grudowski, C. J. Eiting, R. D. Dupuis, and J. C. Campbell, J. Appl. Phys. **83**(11), 6148 (1998).
[8] D. G. Thomas, J. J. Hopfield, and W. M. Augustyniak, Phys. Rev. **140**, A202 (1965).
[9] A. P. Levanyuk, V. V. Osipov, and F. Nauk, Sov. Phys.: Usp. **427**(24), 187 (1981).