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Experimental analysis and theoretical model for anomalously high ideality factors ($n \gg 2.0$) in AlGaN/GaN *p-n* junction diodes

Jay M. Shah, Y.-L. Li, Th. Gessmann, and E. F. Schubert[a)]
Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, New York 12180

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Diode ideality factors much higher than the expected values of 1.0 to 2.0 have been reported in GaN-based *p-n* junctions. It is shown that moderately doped unipolar heterojunctions as well as metal-semiconductor junctions, in particular the metal contact to *p*-type GaN, can increase the ideality factor to values greater than 2.0. A relation is derived for the effective ideality factor by taking into account all junctions of the diode structure. Diodes fabricated from a bulk GaN *p-n* junction and a *p-n* junction structure with a *p*-type AlGaN/GaN superlattice display ideality factors of 6.9 and 4.0, respectively. These results are consistent with the theoretical model and the fact that *p*-type AlGaN/GaN superlattices facilitate the formation of low-resistance ohmic contacts. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1593218]

INTRODUCTION

GaN-based devices offer several advantages over conventional III-V materials such as high thermal stability, high breakdown electric field, high chemical inertness, great mechanical strength, and the ability to produce light in the blue and ultraviolet (UV) region.[1] Research in this field has resulted in substantial progress towards the solution of material- and device-related problems. One area not fully understood is the high ideality factor in GaN *p-n* junction diodes that has been reported to range between 2.0 and 7.0.[2–5]

As per the Sah–Noyce–Shockley theory,[6] the forward current in a *p-n* junction is dominated by recombination of minority carriers injected into the neutral regions of the junction. This type of current gives an ideality factor of 1.0. Recombination of carriers in the space charge region, mediated by recombination centers located near the intrinsic Fermi level, results in an ideality factor of 2.0. Both currents are schematically shown in Fig. 1. However, the Sah–Noyce–Shockley model cannot account for ideality factors greater than 2.0 found in AlGaN/GaN *p-n* junctions and AlGaInN UV light-emitting diodes (LEDs).

Esaki[7] first discovered an anomalous excess current in Ge *p-n* junctions. The excess current was found in the forward voltage range in which direct interband tunneling of electrons from conduction band to valence band is not possible. At these voltages, only the diffusion current due to minority carrier injection should flow. However, a current considerably in excess of the diffusion current was observed. The excess current was found to be temperature independent and was attributed to tunneling via deep levels in the forbidden gap by Chynoweth, Feldmann, and Logan.[8]

Excess currents in GaAs diodes were attributed to tunneling as well by Dumin and Pearson.[9] However, the authors did not state the exact tunneling mechanism and suggested that the excess current could be due to band–to–band tunneling, band-impurity tunneling, or a cascade process. Note that excess currents attributed to tunneling in GaAs diodes were found only at low temperatures of approximately 100 °K and lower, while the currents at room temperature were consistent with Sah–Noyce–Shockley theory.

The high ideality factors ($n \gg 2.0$) in GaN-based LEDs[2–4] were attributed to deep-level-assisted tunneling, due to temperature-independent slopes of ($\log I$)-versus-V plots. Ideality factors close to 2.0 were attributed to space charge region recombination,[5] consistent with the Sah–Noyce–Shockley theory, due to temperature-dependent slopes of ($\log I$)-versus-V plots. However, a comprehensive theory for the high ideality factors found experimentally in GaN *p-n* junctions has not been presented.

In this article, we propose an alternative explanation for the high ideality factor in GaN-based diodes. This alternative explanation is based on the influence of additional rectifying heterojunctions and metal-semiconductor junctions of the *p-n* junction diode. A theoretical model on the effective ideality factor of a system of junctions is developed. In addition, we report experimental results on *p-n* junction diodes fabricated from two different structures, one bulk GaN *p-n* junction and one incorporating a *p*-type AlGaN/GaN superlattice structure to facilitate ohmic contact formation. The ideality factors of these structures are compared and discussed.

THEORY

Moderately doped unipolar heterojunctions with large band-discontinuities are generally rectifying and their current-voltage (I-V) characteristic is given by[10]

$$I_1 = I_{S1}\left[\exp\left(\frac{qV_1}{n_1 kT}\right) - 1\right], \tag{1}$$

where I_{S1} is the reverse saturation current, q is the elementary charge, k is the Boltzmann constant, T is the absolute temperature, and n_1 is the ideality factor. Chandra and

a)Electronic mail: efschubert@rpi.edu

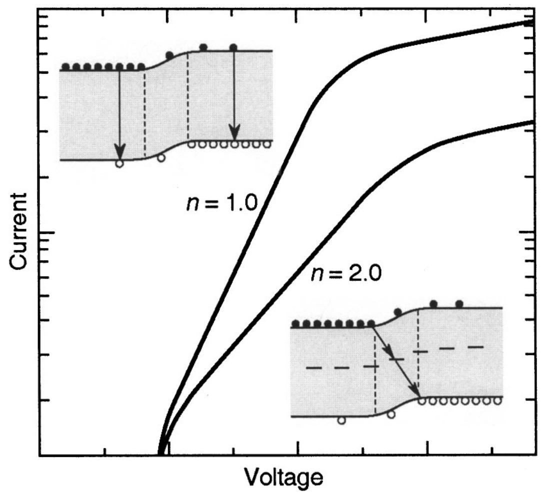

FIG. 1. Schematic representation of I-V characteristics and carrier transport mechanism for diode ideality factors of $n=1.0$ and $n=2.0$.

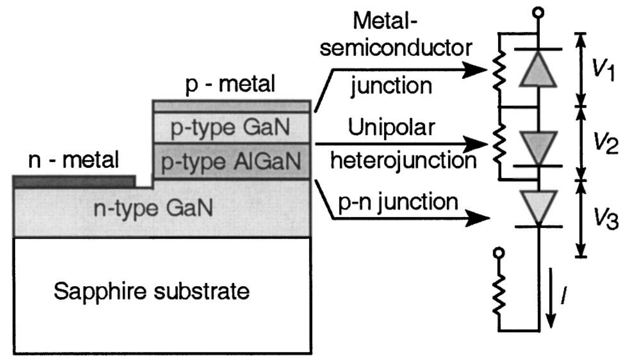

FIG. 2. Schematic structure of *p*-*n* junction diode and equivalent circuit consisting of three diodes.

Eastman[11] showed that unipolar lightly doped n-AlGaAs/n-GaAs heterojunctions exhibit rectifying behavior. Forrest and Kim[12] showed that n-InGaAs/n-InP heterojunctions exhibit a rectifying behavior. Both results are consistent with heterojunction theory.[10] In the III-V nitride material system, rectification is expected in unipolar heterojunctions as well. In fact, the high barriers inherent to the III-V nitride material system and polarization effects that can further increase heterojunction barrier heights make such rectification likely.

The two metal-semiconductor junctions of a diode ideally have ohmic characteristics. However, contacts can exhibit nonlinear characteristics. In the limit of high contact resistance, the metal-semiconductor contact can be considered as a reverse-biased Schottky contact. In the thermionic field-emission regime, the reverse current is given by[13]

$$I_2 = I_{S2} \exp\left(\frac{qV_2}{n_2' kT}\right), \quad (\text{valid for } V_2 > 3kT/q), \tag{2}$$

where I_2 is the reverse current and[13]

$$n_2' = (1 - n^{-1})^{-1} \tag{3}$$

is the ideality factor for reverse bias, where n is the ideality factor for forward bias. Note that the diode bias V_2 is positive in reverse direction.

Finally, the *p*-*n* junction has an I-V characteristic given by

$$I_3 = I_{S3}\left[\exp\left(\frac{qV_1}{n_3 kT}\right) - 1\right]. \tag{4}$$

A GaN-based *p*-*n* junction diode can then be modeled by a series of diodes, the actual GaN *p*-*n* junction diode, unipolar heterojunction diodes, and a Schottky diode at the metal/*p*-type GaN junction. Such a structure and the corresponding equivalent circuit are schematically shown in Fig. 2. The circuit also shows resistors indicating the leaky nature of the diodes. Assuming that these resistors are large, we can derive the current-voltage characteristic of this system of junctions.

As the external current and voltage are given by I and $V = \Sigma V_i$, respectively, the I-V characteristic of the structure is given by

$$V = \Sigma_i V_i = \Sigma_i [n_i (kT/q) \ln I - n_i (kT/q) \ln I_{Si}], \tag{5}$$

where we assumed that the diode voltages are $V_i \gg kT/q$, so that $\exp(qV/nkT) \gg 1$. Rearrangement of the terms in the above equation yields

$$\ln I = \frac{(q/kT)}{\Sigma_i n_i} V + \frac{\Sigma_i n_i \ln I_{Si}}{\Sigma_i n_i}. \tag{6}$$

In Eq. (6), the second summand is a constant because we consider only the linear region of the ($\ln I$)-versus-V characteristic, where n_i are constants. Inspection of Eq. (6) yields that the apparent, i.e., externally measured, ideality factor is the sum of the ideality factors of the individual rectifying junctions. This result can be generalized as

$$n = \Sigma_i n_i, \tag{7}$$

where n_i represent the ideality factors of the *p*-*n* junction, the unipolar heterojunctions, and the metal-semiconductor junctions. Taking into account the result of Eq. (7), it is apparent that ideality factors $\gg 2.0$ can be measured.

EXPERIMENT

The two *p*-*n* junction structures used in the experimental study are schematically shown in Fig. 3. The samples were grown by molecular beam expitaxy on sapphire substrate. The *n*-type GaN layer in both samples consists of a 1.8 μm

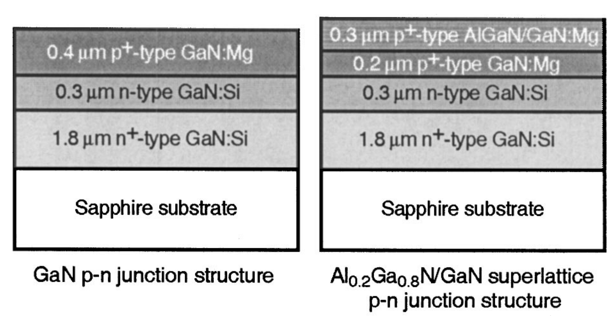

FIG. 3. Schematic structures of two *p*-*n* junction diodes used in the experiment.

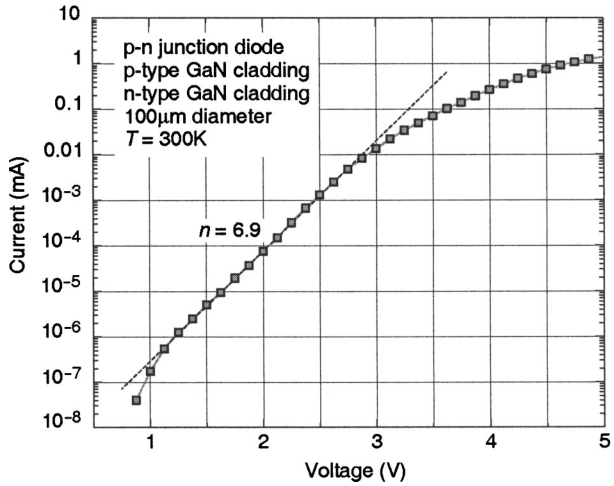

FIG. 4. *I-V* characteristics of *p-n* junction with *p*-type GaN and *n*-type GaN cladding layers.

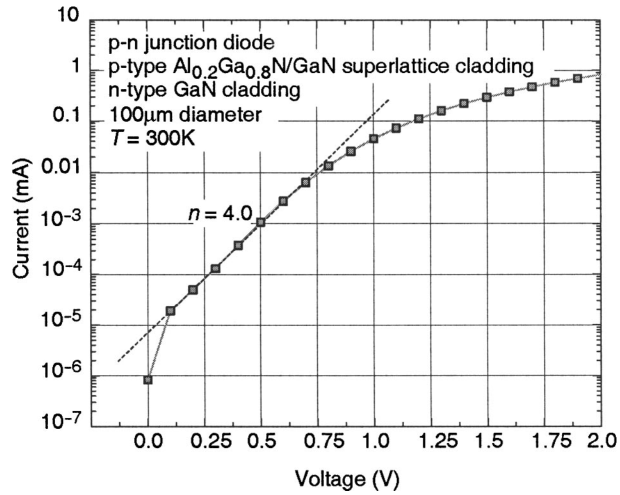

FIG. 5. *I-V* characteristics of *p-n* junction with *p*-type $Al_{0.2}Ga_{0.8}N$/GaN superlattice and *n*-type GaN cladding layer.

n^+-type GaN buffer layer with a Si concentration of $\sim 10^{19}$ /cm^3. This is followed by a 0.3 μm *n*-type GaN layer with Si doping concentration of $\sim 10^{17}$/cm^3. The *p*-type region in the bulk *p-n* junction consists of a 0.4 μm p^+-type GaN layer with a Mg concentration of $\sim 10^{19}$/cm^3. In the superlattice *p-n* junction, the *p*-type region consists of a uniformly doped 0.3 μm p^+-type $Al_{0.2}Ga_{0.8}N$/GaN superlattice structure on top of a 0.2 μm p^+-type GaN layer with Mg doping concentration of $\sim 10^{19}$/cm^3. The superlattice structure is made up of 15 periods and is included to facilitate ohmic contact formation. The widths of the wells and the barriers of the superlattice are 100 Å.

Processing includes treatment of the *p*-type GaN surface in buffered oxide etchant for 5 min to remove native oxides and obtain improved adhesion to metal contacts. Ni/Au (200 Å/200 Å) is deposited as the *p*-type contact metal using electron-beam evaporation. Mesa patterns are etched by chemically assisted ion beam etching using Shipley 1813 photoresist as an etch mask. After the removal of photoresist using acetone and oxygen plasma, *p*-type contacts are subject to rapid thermal annealing in air ambient at 500 °C for 5 min. Subsequently, patterns for *n*-type contacts are transferred by photolithography using Futurrex negative photoresist. Ti/Au (200 Å/200 Å) is deposited as *n*-type contact metal with electron-beam evaporation. The *I-V* characteristics of the diodes are measured using a Karl Suss probe station and a HP 4145B parameter analyzer.

RESULTS AND DISCUSSION

I-V characteristics of the *p-n* junctions measured at room temperature are shown in Figs. 4 and 5. The *I-V* characteristics display a linear dependence of $\ln I$ on V over several orders of magnitude of the injection current. The ideality factors observed are 6.9 for bulk GaN *p-n* junction and 4.0 for GaN *p-n* junction with superlattice structure. The ideality factors for both the diodes are higher than 2.0, thus exceeding the values expected from the Sah–Noyce–Shockley model. The high ideality factors are consistent with results reported by, for example, Dmitriev,[2] Casey *et al.*,[3] and Perlin *et al.*,[4] who, for GaN-based heterojunction diodes, reported $n \sim 2.5$, 6.8, and 5.0, respectively. In addition, we measured ideality factors of commercially available GaN-based blue LEDs, manufactured by reputed companies. Typical values of the ideality factors for three different types of LEDs were 3.2, 4.7, and 7.4.

The ideality factor of a reverse-biased Schottky junction can be inferred from Eq. (3) to be $n_2' = (1-n^{-1})^{-1}$. This relation suggests reverse-bias ideality factors of 2–3 for forward-bias ideality factors of 1.5–2. These values are fully consistent with our experimental results measured on back–to–back *p*-type GaN metal-semiconductor contacts, where we measured reverse-bias ideality factors as high as 5. Moderately doped unipolar heterojunctions biased in forward direction should have ideality factors of approximately 2 (Refs. 14, 15) due to the fact that the barrier lowering caused by the applied voltage is approximately $(eV/2)$, where V is the voltage drop across the heterojunction. This is in contrast to metal-semiconductor junctions, where the barrier lowering caused by the applied forward-bias voltage is equal to eV. However, such heterojunctions may be very leaky, particularly at high temperatures and doping, so that ohmic rather than rectifying characteristics are exhibited. This is especially the case in highly doped superlattice structures, which as a result of high doping enable ohmic contact formation.[16] The *p-n* junction itself should have an ideality factor between 1 and 2 as per the Sah–Noyce–Shockley theory. The sum of the ideality factors of individual components stated above is consistent with our experimentally found high ideality factors.

Conduction–to–valence band (interband) tunneling is highly unlikely in our devices due to the nondegenerate doping concentration. Multistep tunneling at the *p-n* junction would result in an excess current. However, the *I-V* characteristics obtained in Figs. 4 and 5 do not show any excess current. On the contrary, the opposite is observed especially in bulk *p-n* junction, namely, a current that is lower than the theoretically expected current. This would not be expected based on the theory developed by Chynoweth, Feldmann, and Logan[8] and Dumin and Pearson.[9] Tunneling through the

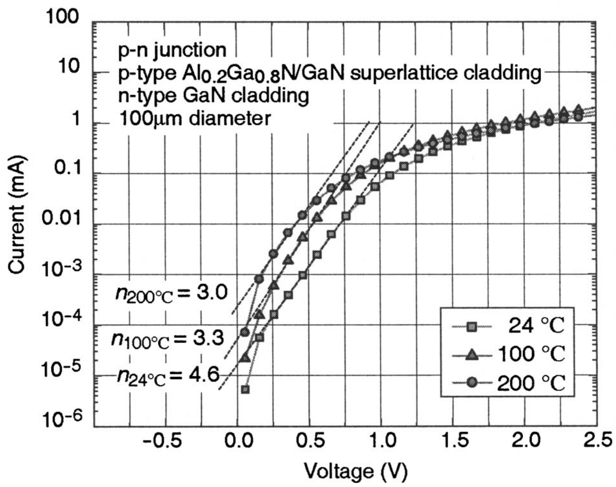

FIG. 6. *I-V* characteristics of *p-n* junction with *p*-type $Al_{0.2}Ga_{0.8}N$/GaN superlattice and *n*-type GaN cladding layer for three different temperatures.

barriers into a quantum well has also been proposed.[5] However such a mechanism is not applicable to our devices due to the absence of quantum wells at the *p-n* junction.

Inspection of the data in Figs. 4 and 5 shows that the ideality factor of the *p-n* junction with *p*-type AlGaN/GaN superlattice structure is significantly lower than that of the GaN bulk *p-n* junction. We attribute the lower ideality factor to the improved transport characteristics of *p*-type AlGaN/GaN superlattices. The lower ideality factor in the superlattice structure is in excellent agreement with the observation that GaN/AlGaN superlattice structure forms better ohmic contacts than bulk GaN, in terms of specific contact resistance, due to higher carrier concentration and polarization effects.[16,17] *P*-type AlGaN/GaN superlattices are well known to enable high conductivity, high hole concentration, and high drift mobilities. The fact that a lower ideality factor is found for the diode that includes the superlattice, indicates the benefit of reduced contact resistance.

The effect of temperature on the ideality factor is shown in Fig. 6. *I-V* characteristics of the GaN *p-n* junction with the superlattice structure are measured at three different temperatures. Close inspection of Fig. 6 reveals that the slope of ($\ln I$)-versus-V plot increases as the temperature is raised from 24 to 100 °C, while the slope decreases when the temperature is further raised from 100 to 200 °C. However, the ideality factor is temperature dependent and decreases consistently with increasing temperature. The change in slope is small and should not be over-interpreted. The ideality factors obtained are 4.6, 3.3, and 3.0 at 24, 100, and 200 °C, respectively. We attribute this behavior to the fact that *p*-type transport properties generally improve with increasing temperature due to the higher activation of acceptors at elevated temperatures. In addition, contacts become less rectifying at higher temperatures and hence result in more ohmic behavior. This decreases the ideality factor contributed by the metal–semiconductor junction, which in turn reduces the overall ideality factor. This interpretation is in agreement with the theoretical model and the experimental results.

CONCLUSION

In conclusion, we have experimentally analyzed and derived a theoretical model for anomalously high ideality factors ($n \gg 2.0$) in AlGaN/GaN *p-n* junction diodes. It is shown that rectification in unipolar heterojunctions as well as metal-semiconductor junctions can increase the ideality factor to values greater than 2.0. The externally measured ideality factor of a *p-n* junction diode is the sum of the ideality factors of the individual rectifying junctions. Experimental results on GaN-based *p-n* junction diodes reveal that bulk GaN *p-n* junction and *p-n* junction with a *p*-type AlGaN/GaN superlattice structure have ideality factors of 6.9 and 4.0, respectively. These results are consistent with the theoretical model and the fact that *p*-type AlGaN/GaN superlattices enable the formation of low-resistance ohmic contacts.

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