N-polar GaN $p$-$n$ junction diodes with low ideality factors

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High-quality N-polar GaN $p$-$n$ diodes are realized on single-crystal N-polar GaN bulk substrate by plasma-assisted molecular beam epitaxy. The room-temperature current–voltage characteristics reveal a high on/off current ratio of $>10^{11}$ at ±4 V and an ideality factor of 1.6. As the temperature increases to 200 °C, the apparent ideality factor gradually approaches 2. At such high temperatures, Shockley–Read–Hall recombination times of 0.32–0.46 ns are estimated. The measured electroluminescence spectrum is dominated by a strong near-band edge emission, while deep level and acceptor-related luminescence is greatly suppressed. © 2022 The Japan Society of Applied Physics

In noncentrosymmetric wurtzite III-nitride heterostructures, spontaneous and piezoelectric polarization fields on the order of MV cm$^{-1}$ (Ref. 1) along the polar c-axis can generate 2D electron and hole gases, which is enabled by combining high-quality N-polar GaN crystal N-polar GaN voltage characteristics, electroluminescence, and the diodes with an ideality factor less than 2 have not been formed on the rear surface of the GaN substrate. A Ti-based cathode ohmic electrode was alloyed at 650 °C under Ga-rich conditions in order to guarantee smooth surface morphology and minimal O impurity incorporation. The Si and Mg dopant densities used in the doped layers have been estimated from separate secondary ion mass spectrometry (SIMS) stack samples. In situ reflection high energy electron diffraction (RHEED) revealed that the MBE-grown layers showed a clear (3 $\times$ 3) surface reconstruction below 200 °C after growth, confirming the N-polarity of the diode structure. The excess Ga droplets after the growth were removed in HCl before any ex situ characterization and device fabrication. Atomic force microscopy exhibits smooth surface morphology with a root-mean-square roughness of 0.6 nm on a 2 $\times$ 2 μm$^2$ [Fig. 1(b)].

The devices were fabricated using a general mesa-design by a plasma etching without applying any edge termination. In order to fabricate the $p$-$n$ junction diodes, the epitaxially grown sample was first cleaned by solvents, HF, and HCl. The mesa structure was fabricated by inductively-coupled plasma (ICP) dry-etching, after which, circular alloyed Pt/Ru anode ohmic electrodes and Ti/Al/Pt thick metal pads were formed by a lift-off process on the surface of the $p^{++}$-GaN cap layer. The Pt/Ru ohmic contacts were alloyed at 650 °C in O$\_2$ ambient. A Ti-based cathode ohmic electrode was formed on the rear surface of the GaN substrate.

In order to estimate the doping concentrations in the $p^+$-GaN region, a capacitance versus voltage (C–V) measurement was performed on the N-polar GaN $p$-$n$ diode at a frequency of 1 MHz. Loss tangent angles >89° indicate very low leakage and high reliability of the measurement. The N-polar GaN $p$-$n$ diode structures were grown on single-crystal N-polar $n^+$-type GaN (0001) bulk substrate (Ref. 29) with a dislocation density of $5 \times 10^2$ cm$^{-2}$ and a mobile electron density of $\sim$10$^{19}$ cm$^{-3}$ in a Veeco GENxplor MBE reactor equipped with standard effusion cells for elemental Ga, Si, Mg, and a radio-frequency plasma source for the active N species. Si and Mg were used as the $n$-type and $p$-type dopant, respectively. The base pressure of the growth chamber was in the range of 10$^{-10}$ Torr under idle conditions, and 1.5 × 10$^{-5}$ Torr during growth. Starting from the nucleation substrate surface, the N-polar GaN $p$-$n$ diode structure consists of 100 nm of GaN:Si followed by 420 nm unintentionally doped (u) GaN, 110 nm GaN:Mg, then 20 nm GaN:Mg. The details of the layer structures are shown in Fig. 1(a). The top heavily doped GaN:Mg layer is intended for a low resistance p-contact. All of the layers were grown under Ga-rich conditions in order to guarantee smooth morphology and minimal O impurity incorporation. The Si and Mg dopant densities used in the doped layers have been estimated from separate secondary ion mass spectrometry (SIMS) stack samples. In situ reflection high energy electron diffraction (RHEED) revealed that the MBE-grown layers showed a clear (3 $\times$ 3) surface reconstruction below 200 °C after growth, confirming the N-polarity of the diode structure. The excess Ga droplets after the growth were removed in HCl before any ex situ characterization and device fabrication. Atomic force microscopy exhibits smooth surface morphology with a root-mean-square roughness of 0.6 nm on a 2 $\times$ 2 μm$^2$ [Fig. 1(b)].

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corresponding $C^2$-$V$ plot in Fig. 1(c) exhibits two distinct slopes. For one-side abrupt junctions, as in the case of the $p$-$n$ diodes in this study, $dC^2/dV \propto N^2$, where $N$ is the dopant density of the lightly doped side.\(^{31}\) Thus, the observed two different slopes correspond to the net donor densities in the u-d-GaN and the Si-doped GaN nucleation layer [Fig. 1(c)]. This net donor density of $3 \times 10^{16}$ cm$^{-3}$ in the u-d-GaN layer is remarkably low for N-polar GaN in that O impurity levels are typically an order of magnitude greater in epitaxially grown N-polar GaN than Ga-polar counterpart.\(^{21,22}\)

We now turn to the transport properties of the fabricated N-polar GaN $p$-$n$ diode devices. Figure 2(a) shows the room-temperature current density–voltage ($J$–$V$) characteristics of a N-polar GaN diode with a diameter of 32 $\mu$m under forward bias. The leakage current density of the diodes remains lower than a noise floor of $10^{-6}$ A cm$^{-2}$ for biases from 0 to $\sim$2 V and the on/off current ratio at $\pm$4 V is $>10^{14}$, which is limited by the experimental setup. The diode turns on at $\sim$3.5 V and has a differential on-resistance of $\sim$0.2 m$\Omega$ cm$^2$ at $\sim$4 V [Fig. 2(a) and the inset]. From the semilog scale of the $J$–$V$ [the inset of Fig. 2(a)], one can see that the current starts to deviate from an exponential function form at $\sim$2.8 V, indicating that the series resistance starts to play an unignorable role in the $J$–$V$ curve above these voltages.\(^{31}\) This effect of the series resistance makes it difficult to extract the true ideality factor at high voltages.\(^{32}\)

As temperature increases, the forward current density increases and turn-on voltage decreases, and the slope of the current, which is directly related to the diode ideality factor, is seen to decrease [Fig. 2(b)]. For high-quality diodes with negligible structural defects causing leakage current, the total current can be expressed as a sum of diffusion, SRH recombination and radiative current, where the diffusion and the radiative current terms have an ideality factor of 1, whereas the SRH recombination current term has an ideality factor of 2.\(^{28,31}\) Among these, the radiative current term has the lowest contribution to the total current for typical GaN $p$-$n$ diodes.\(^{28}\) The experimental diode current can be expressed by the empirical form $J \propto \exp(qV_i/k_B T)$, where $q$ is the magnitude of the electronic charge, $V_i$ is the diode voltage, $k_B$ is the Boltzmann constant, $T$ is temperature and the ideality factor $\eta = (q/k_B T)(dV_i/d \ln J)$ has a value between 1 and 2.\(^{28,31}\) Figure 2(c) shows the temperature dependent $\eta$ calculated from the $J$–$V$ curves in Fig. 2(b). It is seen that the apparent $\eta$ shows a temperature dependent minimal value between 1.6 and 2 in the low bias region. As the bias increases, the apparent ideality factor increases steeply due to the series resistance at high current which shadows the true ideality factor in the high current region.\(^{28,32}\) Thus, an ideality factor close to 1 is likely to be observed, if the effects of the series resistance is removed.\(^{32}\) For high temperatures ($>100 \, ^\circ\text{C}$), the apparent $\eta$ values are seen to close to 2, as the diffusion current terms are overwhelmed by the impacts of the series resistance, indicating that the currents in these low bias regions are dominated by the SRH recombination currents. The recombination current can be written as

$$J_r = \frac{\pi k_B T n_i}{\tau_{\text{SRH}}} \sinh \left( \frac{qV_i}{2k_B T} \right),$$

where $n_i$ is the intrinsic electron density, $\tau_{\text{SRH}}$ is the SRH recombination time and $E_0$ is the electric field at the plane with the highest recombination rate which can be approximated as\(^{28,33}\)

$$E_0 \approx \left[ \frac{N_d k_B T (2 \ln N_d - 2 \ln n_i - qV_i/k_B T)}{\epsilon} \right]^{1/2}.$$

Here, $N_d$ is the donor density in the u-d-GaN region and $\epsilon$ is the dielectric constant. With the temperature dependent $n_i$ and an assumption of negligible series resistance in the low biases, Eqs. (1) and (2) are used to fit the $J$–$V$s for $>100 \, ^\circ\text{C}$ [the dashed lines in Fig. 2(b)], so that $\tau_{\text{SRH}}$ of 0.46, 0.44 and 0.32 ns are extracted at 100 °C, 150 °C, and 200 °C, respectively. These $\tau_{\text{SRH}}$ values are shorter by almost one order of magnitude than those of state-of-the-art Ga-polar GaN $p$-$n$ diodes,\(^{34}\) which indicates that the density of SRH non-radiative centers is higher and/or the capture cross-section is larger for N-polar GaN diodes. However, these $\tau_{\text{SRH}}$ values are still longer by a factor of several than those of state-of-the-art Ga-polar GaN $p$-$n$ diodes.\(^{35}\) It is interesting to note that the $\tau_{\text{SRH}}$ values decreases with increasing temperature within the temperature range, contrary to state-of-the-art Ga-polar GaN $p$-$n$ diodes, for which $\tau_{\text{SRH}}$ increases with a temperature dependence of $T^{1.4}$.\(^{35}\) $\tau_{\text{SRH}}$ is given by $1/N_d v_i \sigma$, where $N_d$ is the density of midgap recombination centers, $v_i (\propto T^{1/2})$ is the thermal velocity of the carriers and $\sigma$ is the capture cross-section. $\sigma$ varies as $T^m$ ($m < 0$) as at higher temperature the energetic carriers have to approach more closely to the centres in order to be captured.\(^{36}\) The decreasing $\tau_{\text{SRH}}$ with increasing temperature, therefore, indicates that $\sigma \propto T^m$ with $-0.5 < m < 0$, i.e. much weaker temperature dependence than those of the Ga-polar diodes, for which $m = -1.9$ (Ref. 28) and $-2.75$ (Ref. 33). It has been reported that $\sigma$ highly depends on the complexities of the recombination centers,\(^{36}\) therefore different temperature dependence of $\tau_{\text{SRH}}$ is likely to be due to different structures of the mid-
gap recombination centers, the formation of which could be affected by the polarity and the growth method and conditions. Especially, the impact of the polarity on the formation of different vacancy defects has been recently reported.\textsuperscript{37} However, more studies will be necessary to understand this phenomenon.

Figure 2(d) shows the room-temperature electroluminescence spectrum measured at a forward bias of 5 V, where near band edge (NBE), conduction band to acceptor (CBA), and deep level (DL) emissions are indicated.
than the result of a previous report.\textsuperscript{27} The true breakdown behaviors can be unveiled with the use of field-plates in the future, as was done with Ga-polar diodes.\textsuperscript{28}

In summary, single-crystal N-polar GaN $p$-$n$ diodes with ideality factors less than 2 have been demonstrated by plasma-assisted MBE. The temperature dependent $J$–$V$ characteristics are well explained with the combination of SRH recombination current and diffusion current. At high enough temperatures, where ideality factors are close to 2, SRH recombination times of 0.32–0.46 ns are estimated by experimental data to model fittings. The measured electroluminescence spectrum is dominated by strong near-band edge emission, while deep level and acceptor-related luminescence are greatly suppressed. A relatively high reverse breakdown field of 2.4 MV cm$^{-1}$ without field-plates has been achieved. This work indicates that the quality of N-polar GaN diodes can soon be comparable to the state-of-the-art GaN diodes, opening up possibilities for new high-quality N-polar devices.

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