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Deep level defects in *n*-type GaN grown by molecular beam epitaxy

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Deep-level transient spectroscopy has been used to characterize electronic defects in *n*-type GaN grown by reactive molecular-beam epitaxy. Five deep-level electronic defects were observed, with activation energies $E_1 = 0.234 \pm 0.006$, $E_2 = 0.578 \pm 0.006$, $E_3 = 0.657 \pm 0.031$, $E_4 = 0.961 \pm 0.026$, and $E_5 = 0.240 \pm 0.012$ eV. Among these, the levels labeled E_1, E_2, and E_3 are interpreted as corresponding to deep levels previously reported in *n*-GaN grown by both hydride vapor-phase epitaxy and metal organic chemical vapor deposition. Levels E_4 and E_5 do not correspond to any previously reported defect levels, and are characterized for the first time in our studies. © *1998 American Institute of Physics.* [S0003-6951(98)02910-6]

III–V nitrides have been a subject of intense investigation recently for blue and ultraviolet light emission,[1] high-temperature, high-power electronic devices,[2,3] and solar-blind ultraviolet detectors.[4,5] An understanding of defects in these materials is essential for improving material quality and, consequently, device performance in this material system. Deep-level transient spectroscopy (DLTS) has been used by a number of investigators to characterize electronic trap states in GaN grown by hydride vapor-phase epitaxy (HVPE)[6] and metal organic chemical vapor deposition (MOCVD).[7–9] Although the activation energies reported for a particular deep level can, in some cases, vary somewhat, three distinct deep levels are consistently observed for *n*-type GaN, with activation energies ranging between 0.18 and 0.27 eV,[6,7,9] 0.49 and 0.598 eV,[6–9] and 0.665 and 0.67 eV,[6,9] respectively. Two additional deep levels with activation energies of 0.14 eV and 1.63 ± 0.3 eV were observed in *n*-type GaN grown by MOCVD.[6] Relatively little has been reported concerning defect levels in GaN grown by molecular-beam epitaxy (MBE). However, such studies are expected to provide information essential for development of devices using MBE-grown material, and comparisons of material grown by a variety of techniques may provide insight into the origin of various electronic defects in GaN.

In this letter, we report detailed characterization of deep-level defects in *n*-type GaN grown by reactive MBE using current–voltage ($I-V$), capacitance–voltage ($C-V$), and DLTS measurements. A total of five donorlike deep levels are observed. Three of these correspond to deep levels previously observed in GaN grown by HVPE or MOCVD.[6–9] However, because we have taken particular care to fabricate Schottky diodes with low leakage and low series resistance, our measurements provide considerably more accurate values for the activation energies of these levels. The remaining two do not correspond to any previously reported levels. Our measurements provide the first observation and characterization of these levels.

GaN samples for these studies were grown by reactive MBE on (0001) sapphire substrates with the epitaxial layers consisting of 3.3 μm n^+-GaN ($n \sim 5 \times 10^{18}$ cm^{-3}) grown on an AlN buffer layer, followed by an 0.5 μm *n*-type GaN layer doped with Si to a concentration of $\sim 6 \times 10^{16}$ cm^{-3}. Details of the growth system and growth procedures have been reported elsewhere.[10] The Schottky diode structures fabricated for these studies are shown schematically in Fig. 1. For fabrication of Ohmic contacts, 5.0×1.0 mm^2 stripes separated by 3.0 mm were formed by reactive ion etching (RIE) to expose the n^+-GaN contact layer. Ohmic contacts were formed by deposition of 300 Å Ti followed by 710 Å Al; without annealing, the total resistance between contact stripes was 40 Ω. Following formation of ohmic contacts, Schottky barriers were fabricated by deposition of 1000 Å Ni followed by 1500 Å Au on *n*-GaN, followed by liftoff to form dots 320 μm in diameter. Care was taken to ensure that the Schottky diodes used in our measurements exhibited low leakage current and low series resistance, typically less than

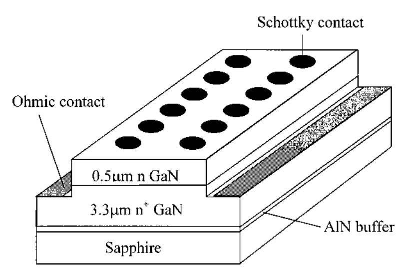

FIG. 1. Schematic diagram of Schottky diode structure fabricated from GaN grown on sapphire. The n^+-GaN layer is necessary to reduce series resistance, an essential consideration for accurate DLTS measurements.

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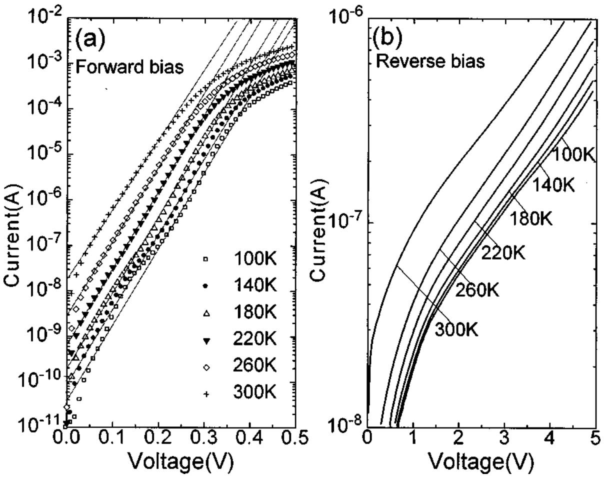

FIG. 2. (a) Forward- and (b) reverse-bias current–voltage characteristics for the n-GaN Schottky diode structure for temperatures ranging from 100 to 300 K.

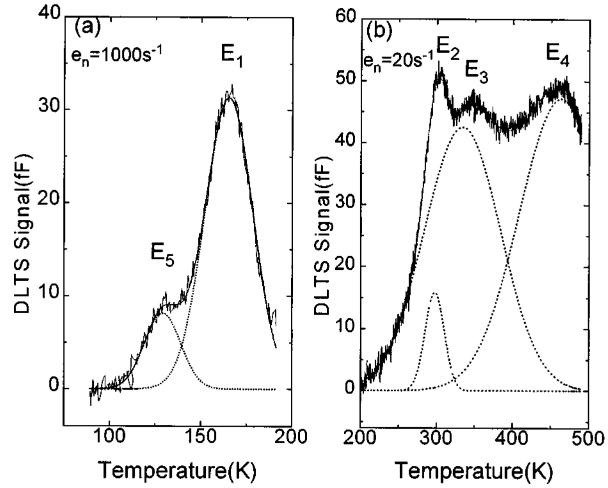

FIG. 3. (a) DLTS spectrum measured with an emission rate window of 1000 s^{-1}, a bias voltage of -2 V, fill pulse voltage of $+2.0$ V, and pulse width of 10 ms. (b) DLTS spectrum measured with an emission rate window of 20 s^{-1}, a bias voltage of -2 V, fill pulse voltage of $+1.5$ V, and pulse width of 10 ms.

100 Ω. This is of considerable importance for accurate DLTS measurements, as previous studies have shown that the DLTS peak measured using a diode with higher series resistance is shifted toward higher temperature than the peak measured in a diode with lower series resistance for the same deep level.[11]

$C-V$ characteristics were measured at frequencies of 10 kHz–1 MHz at temperatures ranging from 90 to 480 K. Little variation with either temperature or frequency was observed, and the carrier concentration derived from these measurements confirmed the dopant concentration of $\sim 6 \times 10^{16}$ cm^{-3}. Figure 2 shows the forward and reverse $I-V$ characteristics of a Schottky diode for temperatures ranging from 100 to 300 K. For large forward bias voltages, the $I-V$ characteristics are dominated by the series resistance of the Schottky diode. For small bias voltages, the $I-V$ characteristics are exponential; a detailed analysis of the $I-V$ characteristics in this regime indicates that transport across the Schottky barrier is heavily influenced by tunneling. Combined with the carrier concentration derived from $C-V$ measurements, this suggests that defects may play a significant role in transport across the Schottky barrier.

DLTS measurements were performed over a temperature range of 85–515 K. Typically, a quiescent reverse bias voltage of -2 V was employed, with fill-pulse voltages ranging from $+1.5$ to $+2$ V. For measurements of deep-level concentrations, a 10 ms pulse was used to insure more complete filling of the traps. Rate windows ranging from 4 to 5000 s^{-1} were used in these measurements. Figure 3 shows DLTS spectra measured with rate windows of 1000 and 20 s^{-1}. A total of five donorlike deep levels are observed. In Fig. 3(a), two overlapping deep-level peaks are visible, while in Fig. 3(b), peaks corresponding to three deep levels are observed. The peaks labeled E_1, E_2, and E_3 correspond to previously reported deep levels in n-GaN,[6] while E_4 and E_5 are previously unreported levels. When the bias voltage, fill-pulse amplitude, and fill-pulse width are varied, the magnitudes of the DLTS signal peaks and the peak-height ratios vary, but the temperatures at which peaks are observed remain constant. These observations indicate that the observed levels correspond to bulk defects: previous DLTS studies have shown that bulk defects are typically characterized by discrete, well-defined energies while spatially localized levels should exhibit a continuous distribution in energy.[12]

Figure 4 shows an Arrhenius plot for all five deep levels, from which we obtain the following activation energies: $E_1=0.234\pm0.006$, $E_2=0.578\pm0.006$, $E_3=0.657\pm0.031$, $E_4=0.961\pm0.026$, and $E_5=0.240\pm0.012$ eV. We interpret the level E_1 as corresponding to the defect level with activation energy of 0.264 eV reported by Hacke *et al.*[6] and 0.18 eV reported by Götz *et al.*;[7] the very close correspondence between the Arrhenius plots for these levels and the similar activation energies derived from these plots suggest that they correspond to the same defect level. Similarly, we interpret our level E_2 as corresponding to the 0.58 eV level reported by Hacke *et al.*,[6] the 0.49 eV level reported by Götz *et al.*[7] and Lee *et al.*,[8] and the 0.598 eV level measured by Haase *et al.*[9] Finally, our observed level E_3 is interpreted as corre-

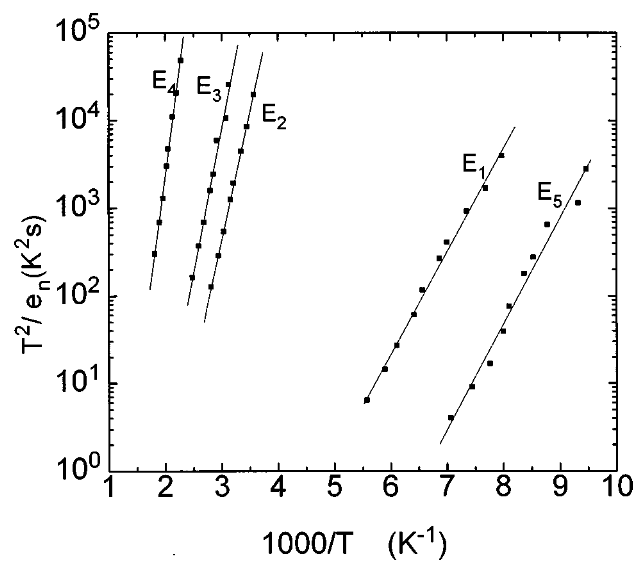

FIG. 4. Arrhenius plot of emission rate and temperature for the five defect levels detected by DLTS. Activation energies are obtained from the slopes of the lines corresponding to each level.

sponding to the 0.665 eV level measured by Hacke *et al.*[6] and the 0.670 eV level measured by Haase *et al.*[9] The Arrhenius plots for the levels E_4 and E_5 observed in our measurements differ substantially from those for defect levels reported in the literature, indicating that these correspond to previously unreported defect levels. Our measurements did not reveal the presence of the 0.14 and 1.63 ± 0.3 eV levels observed by Lee *et al.*[8] in n-type GaN grown by MOCVD; the latter, however, would be beyond the range of activation energies measurable in our experiments.

Following the procedure of Lang,[13] we can calculate the concentration of each deep level. Assuming that the defect levels are uniformly distributed within the n-GaN layer, we obtain the following trap concentrations: $N_1 = 7.7 \times 10^{14}\ \mathrm{cm}^{-3}$ for E_1; $N_2 = 1.2 \times 10^{15}\ \mathrm{cm}^{-3}$ for E_2; $N_3 = 4.2 \times 10^{15}\ \mathrm{cm}^{-3}$ for E_3; $N_4 = 8.3 \times 10^{15}\ \mathrm{cm}^{-3}$ for E_4; and $N_5 = 2.2 \times 10^{14}\ \mathrm{cm}^{-3}$ for E_5.

The exact origin of these deep levels remains an open question. Haase *et al.*[9] have suggested that the E_3 level may be associated with a native defect in GaN: their experiments demonstrated that this level can be generated in GaN by N implantation and subsequently removed by annealing. In studies of n-GaN grown by MOCVD, a level with activation energy 0.14 eV and the E_2 level were observed in GaN grown using trimethylgallium (TMGa); when TMGa was replaced by triethylgallium (TEGa), the 0.14 eV and E_2 levels were no longer detectable by DLTS. This was interpreted as suggesting that the 0.14 eV and E_2 levels may be related to carbon or hydrogen atoms that may be incorporated from the methyl radicals during growth.[8] In comparing DLTS measurements from samples grown by different techniques, it would not be unexpected for electronic levels arising from native defects to be observed in GaN growth by a variety of techniques; conversely, the presence and concentration of defect levels associated with impurities might be expected to vary in material grown by different techniques.

In summary, we have performed I–V, C–V, and DLTS characterization of Schottky diodes fabricated from n-GaN grown by reactive MBE. Particular care was taken to obtain diodes with low series resistance, allowing activation energies of the electronic defect levels observed to be measured to a high degree of accuracy. DLTS measurements revealed the presence five electronic deep-level defects with activation energies $E_1 = 0.234 \pm 0.006$, $E_2 = 0.578 \pm 0.006$, $E_3 = 0.657 \pm 0.031$, $E_4 = 0.961 \pm 0.026$, and $E_5 = 0.240 \pm 0.012$ eV. Levels E_1, E_2, and E_3 are interpreted as corresponding to electronic states previously observed in GaN grown by HVPE and MOCVD; our measurements represent the first observation of these levels in MBE-grown GaN, and provide the most accurate measurements to date of the activation energies for these levels. Our measurements have also provided the first observation and characterization of two additional levels, which we label E_4 and E_5, in GaN.

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