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C. D. Wang  
University of California - San Diego

L. S. Yu  
University of California - San Diego

S. S. Lau  
University of California - San Diego

See next page for additional authors

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

C. D. Wang, a) L. S. Yu, S. S. Lau, and E. T. Yu b)  
Department of Electrical and Computer Engineering, University of California at San Diego, La Jolla, California 92093-0407

W. Kim  
Department of Materials Science and Engineering, University of Illinois, Urbana, Illinois 61801

A. E. Botchkarev and H. Morköç  
Department of Electrical Engineering, Virginia Commonwealth University, P.O. Box 843072, Richmond, Virginia 23284-3072

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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 $E_1=0.234\pm0.006$, $E_2=0.578\pm0.006$, $E_3=0.657\pm0.031$, $E_4=0.961\pm0.026$, and $E_5=0.240\pm0.012$ eV. 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.
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DLTS spectra measured with rate windows of 1000 and 20 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.\(^1\)

\(C-V\) 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 \(\approx 6 \times 10^{16}\) 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: \(E_1=0.234 \pm 0.006\), \(E_2=0.578 \pm 0.006\), \(E_3=0.657 \pm 0.031\), \(E_4=0.961 \pm 0.026\), and \(E_5=0.240 \pm 0.012\) eV. 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 Goetz et al.\(^7\) 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-
sponding to the 0.665 eV level measured by Hacke et al. and the 0.670 eV level measured by Haase et al. 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 eV levels observed by Lee et al. 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, 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: \( N_1 = 7.7 \times 10^{14} \) cm\(^{-3} \) for \( E_1 \); \( N_2 = 1.2 \times 10^{15} \) cm\(^{-3} \) for \( E_2 \); \( N_3 = 4.2 \times 10^{15} \) cm\(^{-3} \) for \( E_3 \); \( N_4 = 8.3 \times 10^{15} \) cm\(^{-3} \) for \( E_4 \); and \( N_5 = 2.2 \times 10^{14} \) cm\(^{-3} \) for \( E_5 \).

The exact origin of these deep levels remains an open question. Haase et al. have suggested that the \( E_2 \) 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. 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 \( E_5 = 2.40 \pm 0.012 \) eV. Levels \( E_1 \), \( E_2 \), and \( E_4 \) 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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