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## Electron-Irradiation-Induced Deep Level in *n*-Type GaN

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Citation: *Appl. Phys. Lett.* **72**, 448 (1998); doi: 10.1063/1.120783

View online: <http://dx.doi.org/10.1063/1.120783>

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# Electron-irradiation-induced deep level in *n*-type GaN

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(Received 6 October 1997; accepted for publication 25 November 1997)

Deep-level transient spectroscopy measurements of *n*-type GaN epitaxial layers irradiated with 1-MeV electrons reveal an irradiation-induced electron trap at  $E_C - 0.18$  eV. The production rate is approximately  $0.2 \text{ cm}^{-1}$ , lower than the rate of  $1 \text{ cm}^{-1}$  found for the N vacancy by Hall-effect studies. The defect trap cannot be firmly identified at this time. © 1998 American Institute of Physics. [S0003-6951(98)01704-5]

Rapid progress in the development of the blue light-emitting diodes, uv detectors, and high-temperature transistors in the III-V nitride system (GaN, AlGaIn, and InGaIn) has led to great activity in the growth and characterization of these materials.<sup>1,2</sup> In the early days of GaN growth, the electrical property was nearly always strongly *n* type, and it was thought that the donor was a native defect, the N vacancy ( $V_N$ ).<sup>3,4</sup> However, later studies have concluded that O (Ref. 5) and Si (Ref. 6) may be the prime candidates for residual donors. Recently, in samples of GaN grown by metalorganic chemical vapor deposition (MOCVD) and hydride vapor phase epitaxy, several deep levels located at 0.25, 0.60, 0.67, and 0.88 eV below the conduction band, with concentrations in the range  $10^{13}$ – $10^{15} \text{ cm}^{-3}$ , have been revealed by deep-level transient spectroscopy (DLTS).<sup>7–9</sup> Based on the effects of 270-keV  $N^{2+}$  implantation and annealing, two deep levels, with activation energies of 0.60 and 0.67 eV, are believed to be the N antisite and N interstitial, respectively.<sup>9</sup> Although vacancy defects in Si (Ref. 10) and GaAs (Refs. 11–13) induced by high-energy electron irradiation (EI) have been extensively studied in the past, only two recent EI studies have been conducted in GaN,<sup>14,15</sup> to our knowledge. In the first of these, Linde *et al.*<sup>14</sup> used optically detected magnetic resonance of a photoluminescence band at 0.93 eV, produced by 2-MeV electron irradiation, to obtain a tentative identification of a Ga-interstitial complex. In the second, Look *et al.*<sup>15</sup> used temperature-dependent Hall-effect measurements to identify N-vacancy/N-interstitial Frenkel pairs produced by 1-MeV electron irradiation. In the latter study, the N vacancy was shown to have a donor level at  $E_C - 0.07$  eV. In this letter, we present a DLTS study of 1-MeV electron-irradiated, *n*-type GaN. A defect center, located at about  $E_C - 0.18$  eV, is produced at a rate of approximately  $0.2 \text{ cm}^{-1}$ .

The *n*-type GaN sample used in the study was a 4.5- $\mu\text{m}$ -thick, unintentionally doped layer grown by MOCVD on sapphire and had a 300-K carrier concentration of  $2.3 \times 10^{16} \text{ cm}^{-3}$ , determined by both Hall-effect and capacitance-voltage ( $C$ - $V$ ) measurements, and a Hall mobility of  $765 \text{ cm}^2/\text{V s}$ . A single-donor analysis of the temperature-dependent carrier concentration, corrected for the Hall  $r$ -factor, gave a donor concentration of  $7$

$7 \times 10^{16} \text{ cm}^{-3}$ , an acceptor concentration of  $4 \times 10^{16} \text{ cm}^{-3}$ , and a donor activation energy of 16 meV, which is typical for  $\text{Si}_{\text{Ga}}$  donors in GaN.<sup>6</sup> Schottky barrier diodes (SBDs) with a planar structure (i.e., 0.5-mm Au/Ni dots surrounded by large-area Ti/Al/Ti/Au Ohmic contacts with a 10- $\mu\text{m}$  spacing) were fabricated by using electron-beam evaporation and lithographic processing. SBD's with a small leakage current ( $\leq 1 \mu\text{A}$  at 6 V reverse bias) were chosen for the irradiation study. Electron irradiation was carried out in a Van de Graaff accelerator at a voltage of 1 MeV and beam current density of  $10 \mu\text{A}/\text{cm}^2$ . The sample temperature was held at close to 300 K by water cooling of the sample holder. Two separate doses, each of  $5 \times 10^{14} \text{ cm}^{-2}$ , were employed to check for variations in the production rate. A Bio-Rad DL4600 DLTS system with a 100-mV test signal at 1 MHz was used to carry out  $C$ - $V$  and DLTS measurements. The  $C$ - $V$  data, which establish carrier profiles, were taken at different temperatures to determine if the carrier concentration was changing with temperature. As long as the carrier concentration is much larger than the deep-level concentration at all temperatures, the DLTS system can display the trap concentration versus temperature directly. During the DLTS measurements, a reverse bias of 6 V was applied on the SBD and periodically pulsed to 0 V with a pulse width of 1 ms to fill the traps. To determine the apparent parameters of the deep levels, i.e., the activation energy  $E_T$  and capture cross section  $\sigma_T$ , the DLTS spectra were taken at different rate windows, from 20 to  $1000 \text{ s}^{-1}$ .

Before irradiation, the  $C$ - $V$  concentrations are uniform with depth, as shown in Fig. 1, and decrease only slightly as  $T$  is lowered from 400 to 100 K. Thus, there is little carrier freeze-out, which is due to the shallowness of the donor (16 meV, from Hall measurements). After irradiation,  $n_{C-V}$  is nearly the same as before irradiation, as was found earlier even at much heavier doses.<sup>15</sup> The constancy of  $n$  is due to the fact that shallow donors (N vacancies) and acceptors (N interstitials) are produced by the irradiation at equal rates, about  $1 \text{ cm}^{-1}$ .<sup>15</sup> The DLTS spectra after 1-MeV electron doses of  $5 \times 10^{14}$  and  $1 \times 10^{15} \text{ cm}^{-2}$ , respectively, are shown in Fig. 2. From Fig. 2, it can be seen that in addition to the three preexisting deep-levels B, C, and D, which are not affected by the EI, a new deep-level E appears, with a production rate of approximately  $0.2 \text{ cm}^{-1}$ . The Arrhenius plots of  $T_m^2/e_n$  for all of the deep levels are presented in Fig. 3, from which the apparent parameters  $E_T$  and  $\sigma_T$  can be de-

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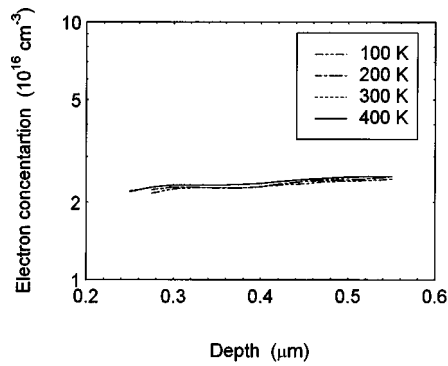


FIG. 1. Electron concentration profiles in the depletion region, measured by C-V at different temperatures before electron irradiation, for a MOCVD GaN Schottky barrier diode.

terminated by using the equation  $e_n/T^2 = \gamma_n \sigma_T \exp(-E_T/kT)$ . Here,  $\gamma_n$  is a constant comprised of the thermal velocity of electrons, the degeneracy of the deep level, and the effective density of states at the bottom of the conduction band, and is equal to  $3.3 \times 10^{20} \text{ cm}^{-2} \text{ s}^{-1} \text{ K}^{-2}$  for *n*-type GaN. The  $E_T$  and  $\sigma_T$  for levels B, C, and D are 0.62 eV and  $7.4 \times 10^{-15} \text{ cm}^2$ , 0.45 eV and  $1.5 \times 10^{-13} \text{ cm}^2$ , and 0.24 eV and  $2.0 \times 10^{-15} \text{ cm}^2$ , respectively, which except for level C have been previously reported.<sup>7-9</sup> Level E, induced by the irradiation, has an Arrhenius energy  $E_T = 0.18 \text{ eV}$  (uncorrected for possible temperature dependence of the capture cross section) and a capture cross section  $\sigma_T = 2.5 \times 10^{-15} \text{ cm}^2$ .

It is difficult to determine the origin of level E at this time. Clearly, it is much shallower than the  $\text{Ga}_i$  complex found by Linde *et al.* at 0.93 eV,<sup>14</sup> and somewhat deeper than  $V_N$  at  $E_C - 0.07 \text{ eV}$ , which was determined by Look *et al.*<sup>15</sup> However, it must be remembered that the  $E_T$  determined from a DLTS Arrhenius plot is really  $E_0 + E_\sigma$ , where  $E_0$  is the thermal activation energy at  $T = 0 \text{ K}$  and  $E_\sigma$  is the energy of the capture-cross-section barrier. Thus, if  $E_\sigma$  were as high as 0.11 eV for  $V_N$ , then level E could possibly be related to  $V_N$ . Note that the production rate of level E is only  $0.2 \text{ cm}^{-1}$ , significantly lower than the  $V_N$  rate of  $1 \text{ cm}^{-1}$ , however, the DLTS line is broad, and may consist of multiple levels, which would raise the calculated production rate. This possibility must be investigated further. Other DLTS investigations of as-grown MOCVD GaN have found nearby

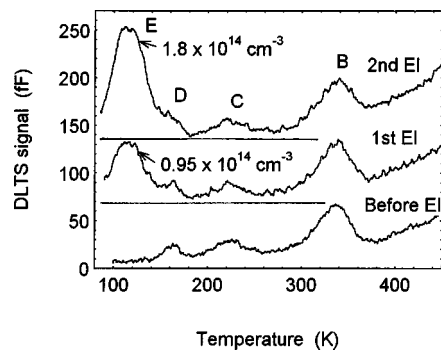


FIG. 2. DLTS spectra, measured before and after electron irradiation, for a MOCVD GaN Schottky barrier diode (using a rate window of  $200 \text{ s}^{-1}$ ). For clarity, the curves for first and second EI were shifted up by 67.5 and 135 fF, respectively. Trap densities for the first and second EI induced trap E are shown in the figure.

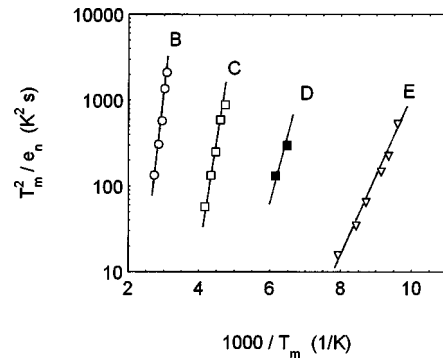


FIG. 3. Arrhenius plots of  $T_m^2/e_n$  for deep levels observed in MOCVD GaN Schottky barrier diodes irradiated by 1-MeV electrons with a total dose of  $1 \times 10^{15} \text{ cm}^{-2}$ .

electron traps at 0.18 (Ref. 7) and 0.14 eV,<sup>16</sup> but again there were no identifications. Further studies with this particular sample were precluded by a degradation of the Schottky barrier, for unknown reason, after the second irradiation. Future work will involve the energy dependence of the defect production and the annealing dynamics.

In summary, we have studied the electron-irradiation-induced deep level measured by DLTS. The apparent energy, at  $E_C - 0.18 \text{ eV}$ , is fairly close to that of  $V_N$  at  $E_C - 0.07 \text{ eV}$ , while the apparent capture cross section of  $2.5 \times 10^{-15} \text{ cm}^2$  is reasonable for electron capture on an ionized donor. A firm identification of the defect is not possible at this time.

The authors wish to thank T. Cooper for the Hall-effect measurements and D. Via for fabricating the Schottky barrier diodes. Two of the authors (Z-Q.F. and D.C.L.) were supported by U.S. Air Force Contract No. F33615-95-C-1619. Part of the work was performed at the Avionics Directorate, Wright Laboratory, Wright-Patterson Air Force Base, Ohio, and partial support was received from the Air Force Office of Scientific Research.

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