1-26-1998

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

Z-Q. Fang

Joseph W. Hemsky
Wright State University - Main Campus, joseph.hemsky@wright.edu

David C. Look
Wright State University - Main Campus, david.look@wright.edu

M. P. Mack

AIP Applied Physics Letters

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

Z.-Q. Fang, J. W. Hemsky, D. C. Look, and M. P. Mack

Citation: Appl. Phys. Lett. **72**, 448 (1998); doi: 10.1063/1.120783
View online: http://dx.doi.org/10.1063/1.120783
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v72/i4
Published by the American Institute of Physics.

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

Z.-Q. Fang, J. W. Hemsky, and D. C. Look
Physics Department, Wright State University, Dayton, Ohio 45435

M. P. Mack[a)]
Electrical and Computer Engineering and Materials Department, University of California, Santa Barbara, California 93106

(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 cm^{-1}, lower than the rate of 1 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, AlGaN, and InGaN) has led to great activity in the growth and characterization of these materials.[1,2] 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).[3,4] 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} cm^{-3}, have been revealed by deep-level transient spectroscopy (DLTS).[7–9] 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.[9] 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,[14,15] to our knowledge. In the first of these, Linde *et al.*[14] 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.*[15] 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 cm^{-1}.

The *n*-type GaN sample used in the study was a 4.5-μm-thick, unintentionally doped layer grown by MOCVD on sapphire and had a 300-K carrier concentration of 2.3×10^{16} cm^{-3}, determined by both Hall-effect and capacitance–voltage ($C-V$) measurements, and a Hall mobility of 765 cm^2/V s. A single-donor analysis of the temperature-dependent carrier concentration, corrected for the Hall r-factor, gave a donor concentration of 7×10^{16} cm^{-3}, an acceptor concentration of 4×10^{16} cm^{-3}, and a donor activation energy of 16 meV, which is typical for Si_{Ga} donors in GaN.[6] 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-μm spacing) were fabricated by using electron-beam evaporation and lithographic processing. SBD's with a small leakage current ($\leqslant 1$ μA 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 μA/cm^2. The sample temperature was held at close to 300 K by water cooling of the sample holder. Two separate doses, each of 5×10^{14} 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 σ_T, the DLTS spectra were taken at different rate windows, from 20 to 1000 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.[15] 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 cm^{-1}.[15] The DLTS spectra after 1-MeV electron doses of 5×10^{14} and 1×10^{15} 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 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 σ_T can be de-

[a)]Permanent address: Avionics Directorate, Wright Laboratory, Wright–Patterson Air Force Base, OH 45433.

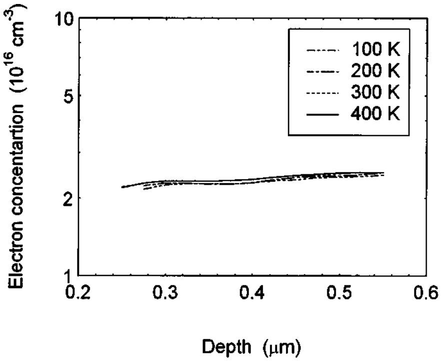

FIG. 1. Electron concentration profiles in the depletion region, measured by $C-V$ at different temperatures before electron irradiation, for a MOCVD GaN Schottky barrier diode.

termined by using the equation $e_n/T^2 = \gamma_n \sigma_T \exp(-E_T/kT)$. Here, γ_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 3.3×10^{20} cm^{-2} s^{-1} K^{-2} for *n*-type GaN. The E_T and σ_T for levels B, C, and D are 0.62 eV and 7.4×10^{-15} cm^2, 0.45 eV and 1.5×10^{-13} cm^2, and 0.24 eV and 2.0×10^{-15} cm^2, respectively, which except for level C have been previously reported.[7–9] Level E, induced by the irradiation, has an Arrhenius energy $E_T = 0.18$ eV (uncorrected for possible temperature dependence of the capture cross section) and a capture cross section $\sigma_T = 2.5\times10^{-15}$ cm^{-2}.

It is difficult to determine the origin of level E at this time. Clearly, it is much shallower than the Ga_I complex found by Linde *et al.* at 0.93 eV,[14] and somewhat deeper than V_N at $E_C - 0.07$ eV, which was determined by Look *et al.*[15] 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 $T = 0$ K and E_σ is the energy of the capture–cross-section barrier. Thus, if E_σ 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 cm^{-1}, significantly lower than the V_N rate of 1 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

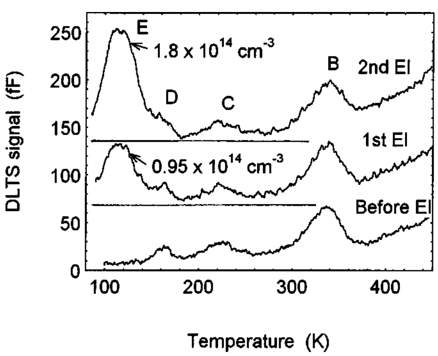

FIG. 2. DLTS spectra, measured before and after electron irradiation, for a MOCVD GaN Schottky barrier diode (using a rate window of 200 s^{-1}). For clarity, the curves for first and second EI were shifted up by 67.5 and 135 fF, respectively. Trap densities for the first and second EI induced trap E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

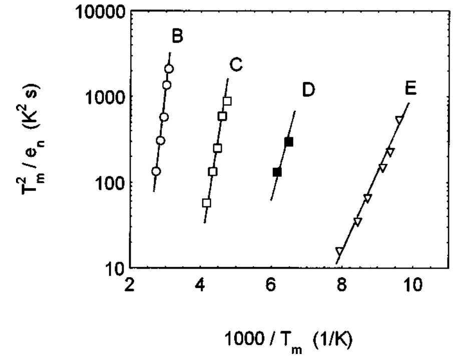

FIG. 3. Arrhenius plots of T_m^2/e_n for deep levels observed in MOCVD GaN Schottky barrier diodes irradiated by 1-MeV electrons with a total dose of 1×10^{15} cm^{-2}.

electron traps at 0.18 (Ref. 7) and 0.14 eV,[16] 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 $E_C - 0.18$ eV, is fairly close to that of V_N at $E_C - 0.07$ eV, while the apparent capture cross section of 2.5×10^{-15} 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.

[1] For a device review, see S. N. Mohammad, A. A. Salvador, and H. Morkoç, Proc. IEEE **83**, 1306 (1995).
[2] For a materials review, see S. Strite and H. Morkoç, J. Vac. Sci. Technol. B **10**, 1237 (1992).
[3] H. P. Maruska and J. J. Tietjen, Appl. Phys. Lett. **15**, 327 (1969).
[4] P. Perlin, T. Suski, H. Teisseyre, M. Leszczynski, I. Grzegory, J. Jun, S. Porowski, P. Boguslawski, J. Bernholc, J. C. Chervin, A. Polian, and T. D. Moustakas, Phys. Rev. Lett. **75**, 296 (1995).
[5] B-C. Chung and M. Gershenzon, J. Appl. Phys. **72**, 651 (1992).
[6] W. Götz, N. M. Johnson, C. Chen, H. Liu, C. Kuo, and W. Imler, Appl. Phys. Lett. **68**, 3144 (1996).
[7] W. Götz, N. M. Johnson, H. Amano, and I. Akasaki, Appl. Phys. Lett. **65**, 463 (1994).
[8] P. Hacke, T. Detchprohm, K. Hiramatsu, N. Sawaki, K. Tadatomo, and K. Miyake, J. Appl. Phys. **76**, 304 (1994).
[9] D. Haase, M. Schmid, W. Kurner, A. Dornen, V. Harle, F. Scholz, M. Burkard, and H. Scheizer, Appl. Phys. Lett. **69**, 2525 (1996).
[10] G. D. Watkins and J. R. Troxell, Phys. Rev. Lett. **44**, 593 (1980).
[11] D. Pons and J. C. Bourgoin, J. Phys. C **18**, 3839 (1985).
[12] B. Ziebro, J. W. Hemsky, and D. C. Look, J. Appl. Phys. **72**, 78 (1992).
[13] D. C. Look, Z-Q. Fang, J. W. Hemsky, and P. Kengkan, Phys. Rev. B **55**, 2214 (1997).
[14] M. Linde, S. J. Uftring, G. D. Watkins, V. Harle, and F. Scholz, Phys. Rev. B **55**, R10 177 (1997).
[15] D. C. Look, D. C. Reynolds, J. W. Hemsky, J. R. Sizelove, R. L. Jones, and R. J. Molnar, Phys. Rev. Lett. **79**, 2273 (1997).
[16] W. I. Lee, T. C. Huang, J. D. Guo, and M. S. Feng, Appl. Phys. Lett. **67**, 1721 (1995).