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Electron Irradiation Effects in GaN/InGaN Multiple Quantum Well Structures

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Capacitance-voltage profiles, admittance spectra, deep-level spectra, current-voltage characteristics, and microcathodoluminescence (MCL) spectra were measured before and after electron irradiation of n-GaN/InGaN multi-quantum-well (MQW) structures typical of the active region of GaN/InGaN blue light emitting diodes. Electron irradiation produces strong compensation of the conductivity in the MQW and introduces interface traps with ionization energies of 100 and 190 meV, in addition to a broad band of interface traps closer to the middle of the bandgap, acceptor traps near $E_c - 1.1$ eV and hole traps near $E_v + 0.9$ eV in the GaN barriers and at the GaN/InGaN interfaces in the QWs. The dose of electrons at which measurable changes occur in the MCL spectra is 10^{15} cm^{-2}, while measurable changes in the electrical properties are observed after doses exceeding 10^{16} cm^{-2} electrons.
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Heterojunctions and quantum wells (QWs) of GaN and related InGaAlN alloys are of great importance for visible/UV light emitting diodes (LEDs) and laser diodes (LDs),[1] high-power/high-frequency/high-temperature field effect and bipolar transistors,[2] and solar-blind photodetectors.[2] For some applications it is essential for the devices to operate in the harsh radiation environment encountered in open-space modules or in military systems. The radiation hardness of GaN-based devices is 1–2 orders of magnitude higher than for their AlGaAs/GaAs counterparts, mainly due to the higher bond strength in GaN, leading to a lower number of primary radiation defects per incident particle.[3-6] The main defects introduced in GaN by electron or proton irradiation are several nitrogen-vacancy-related or nitrogen interstitial/gallium vacancy-related electron traps with levels $\sim$0.13 to 0.2 eV.[7-12] Neutron irradiation was shown to create disordered regions in which the Fermi level is pinned near $E_c - (0.9–1)$ eV.[13] The Fermi level pinning position is believed to be due to nitrogen-interstitial-related deep acceptors near $E_c - 1$ eV and gallium interstitial-related deep donors near $E_c - (0.8–0.9)$ eV.[14] The latter centers were also observed in GaN samples irradiated with high-energy electrons, protons, or heavy ions.[10-14]

For GaN/InGaN heterojunctions, QWs, and multiple QWs (MQWs), data on radiation defects is scarce. Irradiation of single-QW GaN/InGaN blue LEDs with fast neutrons leads to substantial degradation of parameters after the dose of 10^{14} n/cm^2.[15] Proton irradiation of green LEDs resulted in $\sim$40% decrease of the light output after irradiation with 1.7×10^{12} cm^{-2} of 2 MeV protons.[16,17] The nature of radiation defects in QWs has not been studied in detail, and a better understanding of radiation-damage processes is necessary to optimize device performance. We performed experiments on undoped GaN/InGaN MQW structures mimicking the active layers of GaN/InGaN LEDs.

Experimental

The MQWs were grown by metallorganic chemical vapor deposition on basal-plane sapphire substrates. The samples consisted of a low-temperature GaN buffer, 2 μm undoped n-GaN, 2 μm Si-doped n$^+$ GaN ($n \approx 2 \times 10^{18}$ cm^{-3}), and 5 QWs of InGaN (3 nm) with undoped n-GaN barriers (15 nm) capped with undoped n-GaN (60 nm). The composition of the InGaN QWs corresponded to an emission wavelength of 0.465 μm. The GaN barriers in the QWs were grown at 850°C, the InGaN QWs were grown at 725°C, and the GaN cap layer was grown at 970°C. The only difference in these structures from LED structures was that an undoped n-GaN cap was used instead of a heavily Mg-doped p-GaN layer.

The samples were characterized by capacitance-voltage ($C–V$) profiling, current-voltage ($I–V$) measurements in the temperature range 85–400 K, temperature dependence of capacitance/ac conductance at various frequencies (admittance spectroscopy[18]), deep-level transient spectroscopy (DLTS) with electrical or optical injection,[19] and microcathodoluminescence (MCL) spectra measurements.[20,21] For $C–V$, admittance, $I–V$, and DLTS measurements, Au Schottky diodes (0.75 × 0.75 mm rectangles) were prepared by vacuum deposition through a shadow mask. The samples were irradiated at room temperature with 10 MeV electrons with doses of 10^{15}, 10^{16}, 5×10^{16}, and 10^{17} cm^{-2} using the linear electron accelerator of the Institute of Physical Chemistry at Obninsk.

Results and Discussion

C–V and C/G–T characteristics.— Carrier concentration profiles derived from $C–V$ measurements at 1 kHz at 85 K for the virgin sample and samples irradiated with various doses of 10 MeV electrons are shown in Fig. 1. For the virgin sample, one can see four QWs with a total barrier well thickness of 17–18 nm. The Fermi level at 0 V bias was locked in the uppermost first well. Figure 2 presents the temperature dependence of capacitance and ac conductance G for various probing frequencies f for the virgin Schottky diode sample kept at 0 V (the conductance in the figure is divided by the circular frequency $\omega = 2\pi f$ to equalize the amplitudes of admittance peaks for different frequencies[18]). There are two steps/peaks in capacitance/admittance, and the temperature of these shifts to higher values with increasing frequency. Application of the standard Arrhenius analysis to the characteristic relaxation time $\tau = 1/\omega$[18] yields 20 and 60 meV as the activation energies of the process. The corresponding Arrhenius plot for the 20 meV center is shown in Fig. 3. When admittance spectra were measured at −3 V so that the space-charge region (SCR) boundary was locked in the

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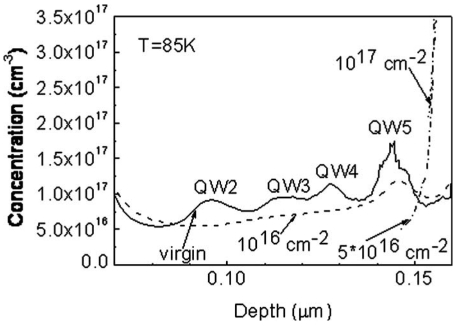

Figure 1. *C–V* profiles 85 K and 1 kHz measured in the virgin and 10 MeV electron-irradiated MQW structures.

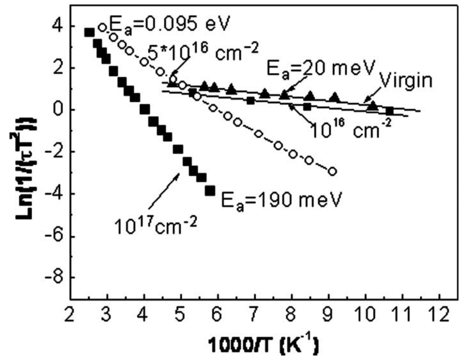

Figure 3. Arrhenius plots calculated from admittance spectra of the virgin and irradiated samples.

lowermost QW, the activation energy was 60 meV, with an Arrhenius plot similar to that of the 60 meV trap in Fig. 2. In both cases the effective activation energy is far from the value of the conduction band offset between the GaN barrier and the InGaN QW (about 0.7 eV). For a normal over-the-barrier motion, the activation energy deduced from the admittance spectra should be close to the latter magnitude, minus the energy of the first localized level in the QW.[22,23] The absence of such a high activation energy suggests that tunneling is dominant in the ac electron transport through the MQW region. The centers observed in admittance should be localized, most likely interface traps in the QWs, and the profiles calculated from *C–V* measurements could be partly due to decoration of the GaN/InGaN interfaces with these traps. (The difference in the activation energies measured for the lowermost and the topmost QWs could stem in this case from heavier compensation of the lowermost QW, so that the more shallow interface traps are empty; also, the lowermost QW is adjacent to a SCR layer in the GaN buffer.) Because the centers are shallow and because of pronounced tunneling, the QW-related modulation in the *C–V* profiles became blurred inside the MQW region at 300 K and above, so that only the lowermost QW could still be seen as a kink (see Fig. 4 for 400 K, solid curve, the kink is marked with an arrow).

Irradiation with a dose of 10^{15} cm^{-2} did not change the electrical characteristics of our MQW Schottky diodes. After irradiation with a dose of 10^{16} cm^{-2}, the carrier concentration in the MQW region deduced from *C–V* data taken at 1 kHz, 85 K became measurably lower than in the virgin sample due to introduction of compensating centers. Tunneling became more pronounced as evidenced by less-sharp inner QW features in *C–V* profiles compared to the virgin sample (see Fig. 1, dashed curve). The activation energy in admittance spectra also became slightly lower, 15 meV instead of 20 meV (see Fig. 3, closed squares; however, because the values of activation energies before and after irradiation with this dose are close, we cannot claim with assurance that this signifies the introduction of new centers). After irradiation with a dose of 5×10^{16} cm^{-2} the entire MQW region became depleted at 85 K (Fig. 1 dash-dotted curve). Admittance spectra obtained at 0 V yielded an activation energy of 0.1 eV, much higher than in the virgin sample (Fig. 3). At the same time, the features in *C–V* profiles due to the QW modulation became clearly visible up to 400 K for the four QWs nearest to the substrate (see Fig. 4, dashed curve). After irradiation with the highest dose of 10^{17} cm^{-2} electrons, the MQW structure was fully depleted at 0 V at 85 K (Fig. 1). Admittance spectra gave an activation energy of 190 meV (Fig. 3). The carrier profile measured at 400 K at low frequency (1 kHz) clearly showed the first two QWs adjacent to the surface, and the apparent carrier concentration was high (see Fig. 4, dash-dotted curve; in previous measurements for the virgin sample and the samples irradiated with lower doses we could not detect the first QW nearest to the surface). High-dose electron irradiation produced a high density of relatively deep radiation defects in the GaN cap and at the GaN/InGaN interface, giving rise to increased interfacial charge and "modulation" doping of the QWs. The centers are relatively deep and their response time at low temperatures was too slow to follow the probing electric field, thus resulting in the MQW region behaving as a dielectric layer at 85 K. The activation energy deduced from admittance-spectra measurements in the 10^{17} cm^{-2} irradiated sample is close to the activation energy of the dominant nitrogen-vacancy-related radiation defects observed in n-GaN films (0.13 and 0.18 eV[7-12]).

I–V and I–V-T characteristics.— The 400 K *I–V* characteristics of Schottky diodes on the virgin sample and the samples irradiated with various doses of 10 MeV electrons are compared in Fig. 5. For the virgin sample, the ideality factor for the forward current was 1.1 and the activation energy of the saturation current obtained from a

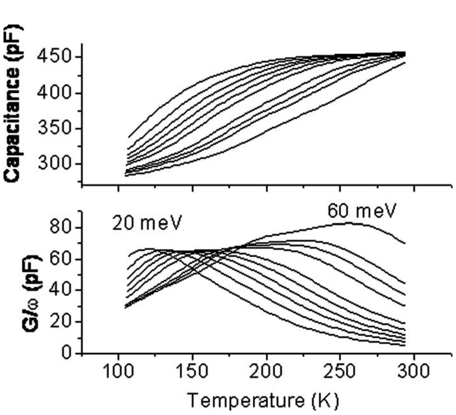

Figure 2. Temperature dependence of capacitance (upper panel) and G/ω for the virgin sample (measurement frequencies of 70, 100, 130, 160, 200, 250, 400, 500, 600, and 1000 kHz).

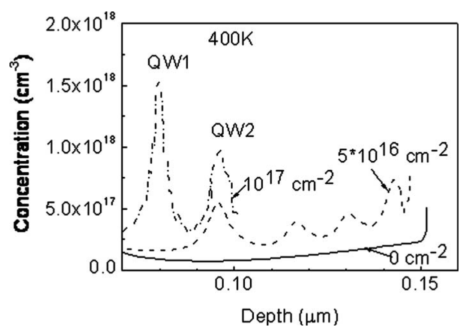

Figure 4. *C–V* profiles 400 K and 1 kHz measured before and after irradiation with doses of 5×10^{16} and 10^{17} cm^{-3} 10 MeV electrons.

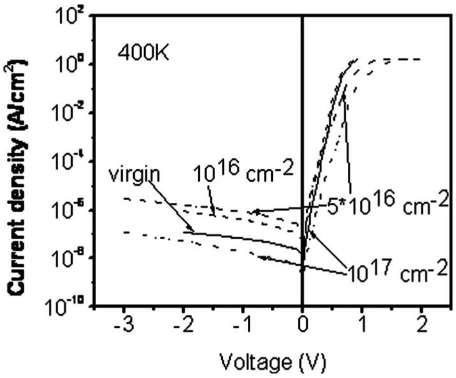

Figure 5. *I–V* characteristics 400 K measured before and after irradiation with doses of 10^{16} and 10^{17} cm^{-2} 10 MeV electrons (the data for the 5 $\times$ 10^{16} cm^{-2} is not shown so as not to clutter the figure; at this dose the reverse current further increased by three times compared to the previous dose).

set of forward *I–V* characteristics measured at various temperatures was 0.6 eV for temperatures $>$200 K. For lower temperatures, the activation energy became low and the ideality factor was much above unity, pointing to the predominant role of tunneling (corresponding data are not shown to save space).

Irradiation with electron doses of 10^{16} and 5 $\times$ 10^{16} cm^{-2} led to an increase in the reverse-current value and in the ideality factor due to the presence of radiation defects (the data for the latter dose is not shown to avoid cluttering the figure). After irradiation with 10^{17} cm^{-2} electrons, the reverse current was much lower than in the virgin sample and the series resistance was considerably higher. Both effects are mainly due to the strong compensation of the n-GaN cap layer.

DLTS and DLTS with optical injection spectra.— DLTS spectra taken with injection pulse lengths of 100 and 2000 ms are shown for the virgin sample in Fig. 6. The spectra were taken with the bias pulsed from -3 to -0 V, so that the edge of the SCR moved from the lowermost QW to the edge of the uppermost QW. No standard DLTS peaks, i.e., peaks corresponding to capacitance increasing with time after the injection pulse, as it should for normal Schottky diodes,[19] were detected (such peaks are shown as positive peaks according to conventions adopted in this paper), indicating a low density of deep interface states in our MQW structure. We observed a well-pronounced, negative hole-trap-like peak with activation energy of 1 eV at temperatures $\sim$350 K. The magnitude of this unusual peak strongly increased with increased length of the injection pulse. This peak could be related to the transient processes in screening of the piezoelectric charges at the GaN/InGaN interfaces. Such piezoelectric charges incline the bottom of the QWs and create

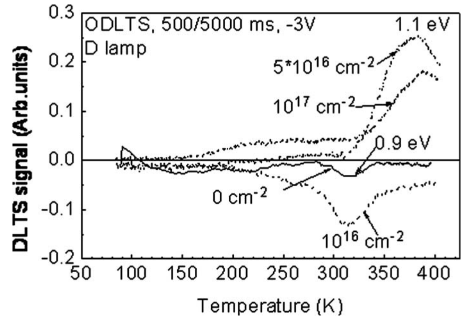

Figure 7. DLTS spectra with optical injection from deuterium UV lamp measured before and after irradiation with 10 MeV electrons, doses 10^{16}, 5 $\times$ 10^{16}, 10^{17} cm^{-2}; reverse bias of -3 V, optical injection pulse 5 s long, time windows 500/5000 ms.

an additional SCR in the GaN buffer, while the direction of the piezoelectric field is opposite the direction of the field in the Schottky diode.[24,25]

For the spectra taken with optical injection with a deuterium UV lamp, the dominant feature was a hole-trap signal with an activation energy 0.9 eV (Fig. 7). These hole traps are common for n-GaN films,[26] so we believe the respective centers to be located in the GaN barriers.

Electron irradiation with doses of 10^{16} cm^{-2} and 5 $\times$ 10^{16} cm^{-2} produced a broadband-like DLTS spectrum with the signal increasing with dose (broad signal extending from 85 to 400 K in Fig. 8). On this broad spectrum, a discrete peak with apparent activation energy of 1.1 eV was superimposed. This peak has a signature similar to the signature of 1.1 eV traps produced in n-GaN films by 10 MeV electron irradiation.[12] Moreover, both traps demonstrate a characteristic logarithmic dependence of the peak amplitude on the injection-pulse length.[12] The peak in n-GaN has been associated with nitrogen interstitial acceptors[14] based on theoretical predictions for the level of corresponding defects.[27] The logarithmic dependence of amplitude on injection-pulse duration for this center could indicate that the traps decorate dislocations,[28,29] but other possible reasons for the phenomenon exist[30] and more detailed study is necessary. These traps are most likely formed in the GaN barriers and at the GaN/InGaN interfaces. For the highest dose of 10^{17} cm^{-2}, the amplitude of the interface-trap-related band and the 1.1 eV peak further increased (a slight decrease of the signal for heavily irradiated samples at low temperatures is due to the capacitance freeze-out discussed above).

The spectra measured with optical injection are presented in Fig. 7. Irradiation with 10^{16} cm^{-2} electrons led to strong enhancement of the signal due to the 0.9 eV hole traps. For higher doses, however,

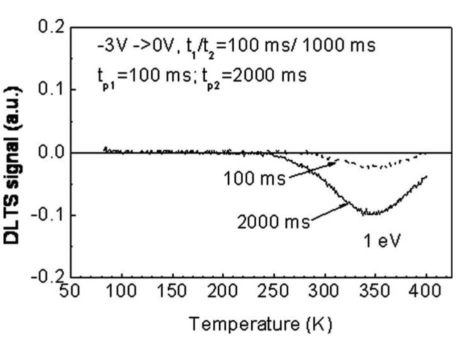

Figure 6. DLTS spectra measured on the virgin sample with reverse bias of -3 V and forward bias of 0 V for forward bias pulse durations of 100 and 2000 ms (time windows 100/1000 ms).

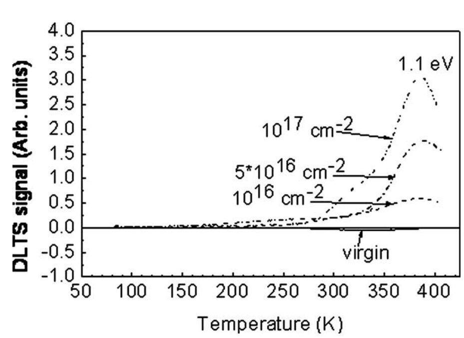

Figure 8. DLTS spectra measured before and after irradiation with 10^{16}, 5 $\times$ 10^{16}, 10^{17} cm^{-2} 10 MeV electrons; reverse bias -3 V, forward bias pulse 0 V (2 s long), time windows 500/5000 ms.

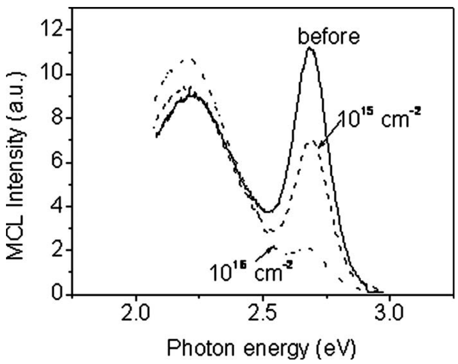

Figure 9. MCL spectra (90 K) measured at low injection level before and after irradiation with 10 MeV electrons with doses of 10^{15} and 10^{16} cm^{-2}.

this trend could not be confirmed because the spectra with optical injection were dominated by the radiation-induced electron-trap signal.

MCL spectra.— MCL spectra measured with electron beam energy of 15 kV at 90 K are compared for the virgin and irradiated samples in Fig. 9. The spectra of the virgin samples were dominated by the MQW-related 2.67 eV line and the broad defect yellow luminescence band at 2.25 eV. The position of the MQW peak shifted by ~ 10 meV to higher energy for a beam current density (i.e., injection level) increase by about 4 orders of magnitude. It also shifted by about 20 meV toward higher energy when the bias applied to the Schottky diode was changed from +1.5 V forward to −1.5 V reverse bias. (In the latter measurements the SCR boundary was located near the edge of the second QW, which means that the electric mean electric field in these measurements was around 3×10^5 V/cm.) These are the usual consequences of the existence of a strong piezoelectric field with a direction opposite to the built-in electric field of the Schottky diode.[24,25]

In contrast to the results for the electrical measurements, electron irradiation at 10^{15} cm^{-2} led to a measurable (about 35%) decrease of the MQW peak-intensity signal, with no change in the intensity of the yellow defect band (the relative intensity of the defect yellow band increased; these results are in good agreement with the reported data on changes in the yellow-band luminescence intensity produced by various implantation species, which show that increase in the density of intrinsic point radiation defects does not influence the yellow-band intensity but decreases the intensity of the band-edge luminescence due to the introduction of nonradiative recombination centers[31,32]).

After irradiation with 10^{16} cm^{-2} electrons, the intensity of the MQW line decreased by a factor of 5 compared to the virgin sample, with a 10 meV lowering of the peak energy, most likely due to the decreased lifetime in the QWs and lower injection level leading to a weaker screening of the piezoelectric field by excited carriers.[24,25] There was a 20% increase in the intensity of the yellow band. For higher irradiation doses, the intensity of the QW band further decreased and the relative intensities of the QW line to the yellow band also decreased.

Conclusion

The usual behavior of admittance spectra for MQW structures requires that at certain temperatures, the capacitance strongly freezes out because when the SCR of a Schottky diode is swept through the QW the energy required for emission from the QW should be close to the conduction band offset.[22,23] In the structures we studied, no freeze-out was observed. Rather, the activation energies in admittance spectra were low, from 20 to 60 meV depending on temperature and the QW probed. This strongly suggests that the electron motion between the QWs occurs by tunneling, while the activation energies in admittance spectra are determined by trapping at shallow states most likely located at the GaN/InGaN interface. At zero bias the SCR boundary is locked, according to our measurements, in the first QW from the surface, and the activation energies in admittance spectra are 20 and 60 meV, typical of the dominant shallow donors in GaN.[33] Different QWs slightly differ in terms of compensation and the type of shallow centers, as is obvious from the *C–V* profiling results presented above.

The electron irradiation of the MQWs has two main effects. It compensates the conductivity and drives the quasi-Fermi level down so that fewer of the shallow interface traps are occupied. As a result, the apparent concentration in *C–V* profiles calculated after irradiation with 10^{16} cm^{-2} electrons decreases. (The amount of changes in the density of compensating centers is not directly related to the apparent changes in the measured *C–V* profiles but gives a reasonable order-of-magnitude estimate of its value). Irradiation also introduces new deeper traps that manifest themselves in admittance spectra of heavily irradiated samples (0.1 eV defects in the 5×10^{16} cm^{-2} dose sample and 0.19 eV traps in the 10^{17} cm^{-2} dose samples, Fig. 3). These traps are too slow to respond to the probing field at low temperatures, where the entire MQW region behaves as a dielectric, but become visible as the space charge decorates the interfaces at high temperatures (compare Fig. 1 and 4 above). The energy of these states, determined from admittance spectra, is close to the energy of the dominant V_N-related radiation defects in n-GaN films, which suggests that the centers we see are located on the GaN side of the interface.

As shown previously,[12] the main compensating agents in electron-irradiated n-GaN films are the 1.1 eV acceptors often associated with nitrogen interstitials. These are observed in DLTS spectra of our irradiated QWs, and the similarity of the trap signature and the dependence on the length of the injection pulse prove that they are the same as in "bulk" n-GaN. These centers are mainly introduced in the GaN barriers and at the GaN/InGaN interface on the GaN side.

Another prominent feature of DLTS spectra of irradiated MQW samples is the emergence of a broad band extending from 150 to ~ 330 K. The magnitude of this signal increases with dose. We believe this band to be associated with interface traps in the MQW region. The emergence of these states correlates with a strong decrease in the QW line luminescence intensity (Fig. 9), suggesting that the traps in question could act as nonradiative recombination centers in the QWs.

DLTS spectra with optical injection (Fig. 7) reveal the presence in our virgin MQW samples of the 0.9 eV hole traps common for n-GaN layers and often associated with the yellow luminescence band.[33] Irradiation with low doses increased the signal from this trap, which correlates with the increase in intensity of yellow luminescence and suggests that this band in our samples could be due to radiative recombination at the QW interfaces. Further increase of irradiation dose made the contribution of the electron interface traps dominant even in the DLTS spectra with optical injection. These traps provide the main path for recombination of nonequilibrium charge carriers and limit the effective lifetime in the QWs, which explains why the intensity of the yellow luminescence band does not further increase even though we expect the concentration of 0.9 eV hole traps to keep increasing with dose. It is intriguing, of course, that little evidence has been found of the impact of electron irradiation on the InGaN QWs. A possible explanation could that the electrical neutrality level in InN and InGaN is located deep inside the conduction band of the material and the levels of the introduced radiation defects would also fall into the conduction band and behave as resonances that also produce hydrogen-like donor states.[34] Direct measurements of radiation effects on thick InN layers indeed show that irradiation leads to an increase in the concentration of electrons rather than to compensation by deep centers.[7] But this matter needs further study.

The most sensitive properties to radiation are luminescence and electroluminescence, for which measurable changes start after irradiation with 10^{15} cm^{-2} electrons. Electrical properties of LEDs would start to change after irradiation with 10^{16} cm^{-2} of 10 MeV electrons. Taking into account the number of displaced atoms in each case, these threshold doses are in reasonable agreement with the results of neutron and proton irradiation of GaN LEDs.[15,17]

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References

1. S. Nakamura, in *GaN and Related Materials II*, S. J. Pearton, Editor, pp. 1–45, Gordon and Breach, New York (1999).
2. M. S. Shur and M. A. Khan, in *GaN and Related Materials II*, S. J. Pearton, Editor, pp. 47–92, Gordon and Breach, New York (1999).
3. 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).
4. J. Nord, K. Nordlund, and J. Keinonen, *Phys. Rev. B*, **68**, 184104 (2002).
5. S. A. Goodman, F. D. Auret, F. K. Koschnick, J.-M. Spaeth, B. Baumont, and P. Gibart, *Mater. Sci. Eng., B*, **71**, 100 (2000).
6. S. O. Kucheyev, C. Jagadish, and J. S. Williams, *Phys. Rev. B*, **64**, 035202 (2001).
7. V. V. Emtsev, *Physica B*, **308–310**, 58 (2001).
8. Z.-Q. Fang, D. C. Look, W. Kim, Z. Fan, A. Botchkarev, and H. Morkoc, *Appl. Phys. Lett.*, **72**, 2277 (1998).
9. M. Hayes, F. D. Auret, L. Wu, W. E. Meyer, J. M. Nel, and M. J. Legodi, *Physica B*, **340–342**, 421 (2003).
10. P. Hacke, T. Detchprom, K. Hiramatsu, and N. Sawaki, *Appl. Phys. Lett.*, **63**, 2676 (1993).
11. A. Y. Polyakov, A. S. Usikov, B. Theys, N. B. Smirnov, A. V. Govorkov, F. Jomard, N. M. Shmidt, and W. V. Lundin, *Solid-State Electron.*, **44**, 1971 (2000).
12. A. Y. Polyakov, N. B. Smirnov, A. V. Govorkov, A. V. Markov, C.-R. Lee, I.-H. Lee, N. G. Kolin, D. I. Merkurisov, V. M. Boiko, J. S. Wright, and S. J. Pearton, in *Advances in III-V Nitride Semiconductor Materials and Devices*, C. R. Abernathy, H. Jiang, and J. M. Zavada, Editors, Paper 0955-I07-46, Materials Research Society, Warrendale, PA (2007).
13. A. Y. Polyakov, N. B. Smirnov, A. V. Govorkov, A. V. Markov, S. J. Pearton, N. G. Kolin, D. I. Merkurisov, V. M. Boiko, C.-R. Lee, and I.-H. Lee, *J. Vac. Sci. Technol. B*, **25**, 436 (2007).
14. A. Y. Polyakov, N. B. Smirnov, A. V. Govorkov, A. V. Markov, N. G. Kolin, D. I. Merkurisov, V. M. Boiko, K. D. Shcherbatchev, V. T. Bublik, M. I. Voronova et al., *J. Appl. Phys.*, **100**, 093715 (2006).
15. C.-S. Li and S. Subramian, *IEEE Trans. Nucl. Sci.*, **50**, 1998 (2003).
16. M. Osinski, P. Perlin, H. Schone, A. H. Paxton, and E. W. Taylor, *Electron. Lett.*, **33**, 1252 (1997).
17. F. Gaundreau, C. Carlone, A. Hondayer, and S. M. Khanna, *IEEE Trans. Nucl. Sci.*, **48**, 1778 (2001).
18. D. L. Losee, *J. Appl. Phys.*, **46**, 2204 (1975).
19. G. M. Martin, A. Mitonneau, D. Pons, A. Mircea, and D. W. Woodard, *J. Phys. C*, **13**, 3855 (1980).
20. A. Y. Polyakov, N. B. Smirnov, A. V. Govorkov, M. G. Mil'vidskii, A. S. Usikov, B. V. Pushnyi, and W. V. Lundin, *Solid-State Electron.*, **43**, 1929 (1999).
21. A. Y. Polyakov, N. B. Smirnov, A. V. Govorkov, M. Shin, M. Skowronski, and D. W. Greve, *J. Appl. Phys.*, **84**, 870 (1998).
22. D. V. Lang, M. B. Panish, F. Capasso, J. Alam, R. A. Hamm, A. M. Sergent, and W. T. Tsang, *Appl. Phys. Lett.*, **50**, 736 (1987).
23. D. V. Lang, A. M. Sergent, M. B. Panish, and H. Temkin, *Appl. Phys. Lett.*, **49**, 812 (1986).
24. J. S. Im, H. Kollmer, O. Gfrorer, J. Off, F. Scholz, and A. Hangleiter, *MRS Internet J. Nitride Semicond. Res.*, **4S1**, G6.20 (1999).
25. A. Sohmer, J. Off, H. Bolay, V. Harle, V. Syganow, J. S. Im, V. Wagner, F. Adler, A. Hangleiter, A. Dornen, et al., *MRS Internet J. Nitride Semicond. Res.*, **2**, article 14, p. 1 (1997).
26. M. A. Reshchikov and H. Morkoc, *J. Appl. Phys.*, **97**, 061301 (2005).
27. J. Neugebauer and C. G. Van de Walle, *Phys. Rev. B*, **50**, 8067 (1994).
28. F. D. Auret, S. A. Goodman, F. K. Koschnick, J.-M. Spaeth, B. Beaumont, and P. Gibart, *Appl. Phys. Lett.*, **73**, 3745 (1998).
29. T. Wosinsky, *J. Appl. Phys.*, **65**, 1566 (1988).
30. Y. Tokuda, Y. Matuoka, K. Yoshida, H. Ueda, O. Ishiguro, N. Soejima, and T. Kachi, *Phys. Status Solidi C*, **4**, 2568 (2007); D. Pons, *J. Appl. Phys.*, **55**, 3644 (1984).
31. H. Boudinov, S. O. Kucheyev, J. S. Williams, and C. Jagadish, *Appl. Phys. Lett.*, **78**, 943 (2001).
32. S. O Kucheyev, M. Toth, M. R. Phillips, J. S. Wiliams, C. Jagadish, and G. Li, *J. Appl. Phys.*, **91**, 5867 (2002).
33. A. Y. Polyakov, in *GaN and Related Materials II*, S. Pearton, Editor, pp. 173–233, Gordon and Breach, New York (1999).
34. J. W. Ager, R. E. Jones, D. M. Yamaguchi, K. M. Yu, W. Walukiewicz, S. X. Li, E. E. Haller, H. Lu, and W. J. Schaff, *Phys. Status Solidi B*, **244**, 1820 (2007).