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Deep levels and irradiation effects in n-GaN

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Abstract. The electrical activity of defects was investigated in hydride vapour phase epitaxy n-type gallium nitride (GaN) grown on sapphire by deep level transient spectroscopy, iso-thermal current spectroscopy, photoconductivity decay measurements and the electron beam induced current (EBIC) method. In order to identify the defect origin, the epilayers were irradiated by high energy protons, and their characteristics before and after irradiation were compared. Irradiation generates two new deep levels and significantly increases the electron carrier concentration of the as-grown epilayer levels. The photocurrent decay is characterized by a stretched exponential law, the slope and time constant of which dramatically decrease after irradiation. The results are discussed in terms of carrier capture at deep levels. EBIC analyses, according to the DLTS findings, revealed an increase in recombination, and also a different distribution of the recombining centres.

1. Introduction

There is considerable current interest in the role defects play in the electrical and optical properties of gallium nitride (GaN), stimulated by the successful applications of it and its ternary compounds with Al and In not only in light emitting and laser diodes but also in field effect transistors and detectors. Indeed, deep defects cause non-radiative transitions and control the compensation mechanism in weakly doped or undoped GaN layers. However, the study of the interaction of extended and point defects in GaN is still in a pioneering state in comparison to Si. In this respect, particle irradiation was widely used in the past as a powerful tool to study defects in Si and GaAs, whilst a limited activity was up to recent time performed on GaN, even though the device performance of several device types was improved by subjecting the devices to controlled doses of particle irradiation. Recently a strong effort by several groups was devoted to the analyses of electrical and optical properties of defects and their interaction by irradiating GaN with electrons, ions and protons [1–4].

In the present paper we report results on defects in GaN obtained by deep level transient spectroscopy (DLTS), isothermal current transient spectroscopy (ICTS), persistent photoconductivity (PPC) measurements and electron beam induced current (EBIC) analyses. Most of the results are still not fully understood, but some useful conclusions have been drawn.

2. Experiment

The GaN sample (263Q) examined in this study was grown by hydride vapour phase epitaxy (HVPE) on a (0001) Al_2O_3 substrate to a thickness of 70 μm. The substrate was first

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coated with a 200–300 nm thick RF-sputter-deposited ZnO pre-treatment layer, which was thermochemically desorbed at the beginning of the GaN HVPE overgrowth. The main function of this pre-treatment was to promote the dense, homogeneous nucleation of GaN on the sapphire substrate [5]. The film was grown at 1050 °C at a growth rate of 15–20 μm/hour. The unintentionally doped sample was n-type with a room temperature carrier concentration of $n = 6.8 \times 10^{16}$ cm^{-3}, and an electron mobility of $\mu_n = 880$ cm^2 V^{-1} s^{-1} [5, 6]. The sample was cleaned in acetone and then methanol to remove organic contaminants. Subsequently, the sample was put into boiling aqua regia for 10 minutes and finally rinsed in distilled water. A Schottky diode 200 Å thick was formed on the GaN film by gold evaporation. Its barrier height φ_B was equal to 0.64 eV. The ohmic contacts were prepared using an In–Ga eutectic solution or by soldered indium at a distance equal to 2 mm from the Schottky diode. The samples were irradiated with protons of energy equal to 24 GeV at a fluence $\varphi_P = 7.5 \times 10^{13}$ p cm^{-2}. After irradiation the room temperature carrier concentration was $n = 9 \times 10^{16}$ cm^{-3}, as obtained by capacitance–voltage characteristics. DLTS and ICTS measurements [7, 8] were carried out from liquid nitrogen to 420 K. The persistent photoconductivity [9], consisting in the light induced change of the free carrier concentration which lasts after turning off the light, was analysed in the temperature range 200–330 K. The samples were kept at the measurement temperature until they reached the equilibrium state before the excitation light was turned on. The excitation light was sub-band-gap light (wavelength $\lambda = 356$ nm) close to the band edge with photon flux $\varphi = 10^{13}$ photons (cm^2 s^{-1}). The PPC measurements were performed by impinging the light onto the reverse biased ($V = -3$ V) Schottky diode and recording the current transients, analysed by a current amplifier (Keithley, model 428) after switching off the light. EBIC analyses were carried out at room temperature with beam voltage ranging from 5 to 15 kV. The area recombination and other features of the micrographs obtained were analysed by means of the software package Image Tools.

3. Results and discussion

For long time the nitrogen vacancy V_N has been considered the dominant donor in GaN. Even if it has been recently shown that this is not true, however a lively debate is still active on its origin. It has been shown that the dominant Hall effect defect produced by 1 MeV electrons is a donor with energy $E_C - E_T = 0.06$ eV, and has been assigned to the N vacancy [1]. DLTS measurements [2, 3, 10] after electron irradiation found a level at about 0.18/0.20 eV from the conduction band. The position of this level may be close to that of V_N, but no firm identification has yet been made. The major difficulty in the identification of this DLTS peak is its close proximity to the pre-existing level at $E_C - 0.25$ eV, labelled the D peak in [2, 10], and to another irradiation induced peak in between these two.

24 GeV proton irradiation produced defects, the DLTS spectra of which enabled us to separate three peaks in such a clear way as never seen before to authors' knowledge.

Figure 1 shows the spectra of the as-grown epilayer (continuous line) and of the irradiated one (dashed line) obtained with a reverse quiescent voltage V_R of −5 V, a filling voltage V_F of 5 V and an emission rate e_n equal to 232 s^{-1}. The irradiation does not affect the pre-existing peak at $E_C - 0.20$ eV, the feature of which well corresponds to that of the D peak, while the other two peaks at, respectively, $E_C - 0.12$ eV and $E_C - 0.16$ eV are generated by irradiation. The activation energies above reported were determined by the Arrhenius plots relevant to the experimental peak positions in terms of temperature for different emission rates, that is $\ln(T^2/e_n)$ against $1/T$, where T is the temperature at the signal peak [7]. These energy values, however, do not take into account, as explained in [10], that the close vicinity of the three peaks strongly influences the resulting spectrum. The actual activation energy of the

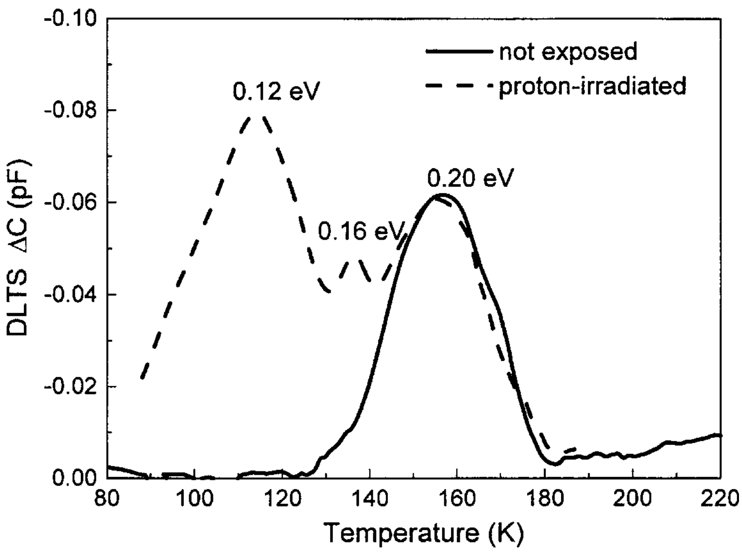


Figure 1. DLTS spectra in the low temperature range before and after irradiation; emission rate $e_n = 232\ \mathrm{s}^{-1}$. The temperature raise is very slow to better separate the peaks.

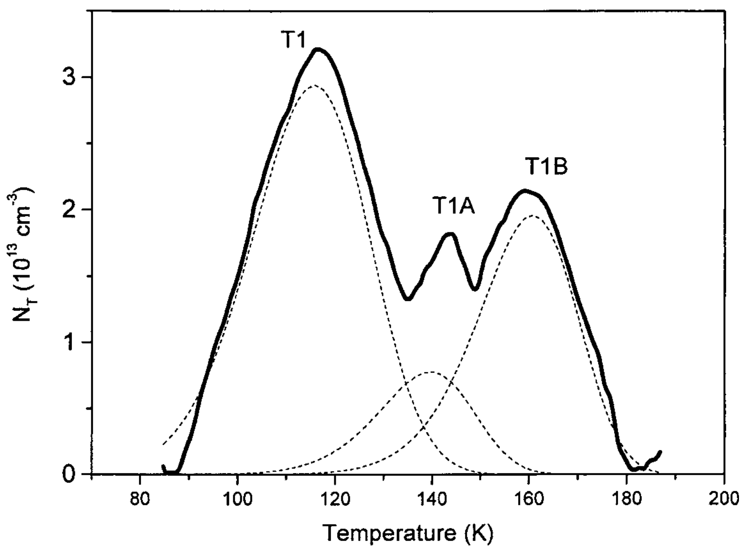


Figure 2. Fitting deconvolution of the spectrum of figure 1, relevant to irradiated material.

signal peaks was obtained by fitting spectra by the general expression for trap filling [11]. Figure 2 shows the same experimental spectrum of the irradiated epilayer as in figure 1 (continuous line) and the relevant fitting curves (dashed lines). The very good approximation obtained is evident from which it was possible to achieve the authentic activation energy (table 1) of the three low temperature levels, from now on labelled T1, T1A and T1B. While the energy values of T1A and T1B coincide with those found from the Arrhenius plot, the activation energy of T1 from the fitting procedure is $E_C - 0.08$ eV, very close to the value $E_C - 0.06$ eV determined by the Hall effect. Table 1 reports the activation energy determined

Table 1. Activation energy, capture cross section and concentration corrected for the λ-effect of the detected levels. The defect structure proposals are given on the basis of previous studies and references, as reported in the text.

	Label					
	T1	T1A	T1B	T2	T3	T4
Energy (eV)	0.12 (0.08[a])	0.16	0.20	0.52	0.59	0.90
σ (10^{-17} cm^2)	1.3	2.7	5	16	20	5000
N_T (10^{13} cm^{-3}) not irradiated	—	—	3.3	17	12	7
N_T (10^{13} cm^{-3}) irradiated	4.6	2.5	3.3	32	62	40
Proposed structure	V_N [10]	V_N [10]		Chemical species [21]	—	N_I, V_{Ga}–N_I [13]

[a] From DLTS spectra fitting.

by the Arrhenius plot and by the fitting procedure, the trap density N_T evaluated accounting for the λ-value [12] and the possible identification performed by comparing the DLTS results of the present work to literature results. In particular, it is worth noting that the introduction rate of the trap T1 equals 0.6 cm^{-1} and it can be compared, with the circumspection due to the different particles (electron, ions, protons) used, to the values found in the literature [1, 10, 13], although rigorously quantitative information such as NIEL (non-ionizing energy loss) would be necessary. Despite the difference in energy (24 GeV in this work and some MeV in previous literature) the same defects should expectedly be generated, as experienced in GaAs where the damage function has only small changes in this range. The trap T1A, introduced together with T1, should also be assigned to N-vacancy related defects, but further work is needed to doubtless identify the origin of this trap. From these findings it has therefore emerged that irradiation influences the low-T transport properties of GaN epilayers.

High-temperature DLTS investigations detected further three electron traps at $E_C - 0.52$ eV, $E_C - 0.59$ eV and $E_C - 0.90$ eV, the characteristics of which are also reported in table 1. Since at temperatures exceeding $T = 380$ K the noise strongly increases, we performed also ICTS measurements in the high-T range to support the result reliability. According to the ICTS method [8], the transient following the filling pulse is analysed in the time domain by means of the function $S(t) = t\,\mathrm{d}f(t)/\mathrm{d}t$, where $f(t)$ is defined as

$$f(t) \equiv C^2(t) - C_0^2$$

with C_0 the capacitance before the filling pulse and $C(t)$ the capacitance transient.

Figure 3 shows an ICTS spectrum of an irradiated epilayer obtained at $T = 330$ K with a quiescent reverse bias V_R equal to -5 V and a filling pulse V_F of +5 V with a pulse width of 1 ms. The presence of the three high-T traps is well evidenced. The density of all three experiences a significant increase after irradiation, as reported in table 1. The electron trap T4 at a depth of 0.90 eV from the conduction band edge corresponds to the trap ER5 found by Goodman and co-workers [13], and as in that case also in our samples it shows a filling behaviour which is peculiar to deep levels associated with extended defects. From the comparison of these findings, previous works and theoretical study results [14, 15, 16], some possible structures are proposed (table 1).

Photoconductivity persistence (PPC) measurements were performed before and after irradiation to check whether the irradiation-induced changes in the deep level findings are in some way reflected in the PPC features, one of the major peculiarities of GaN [9, 17].

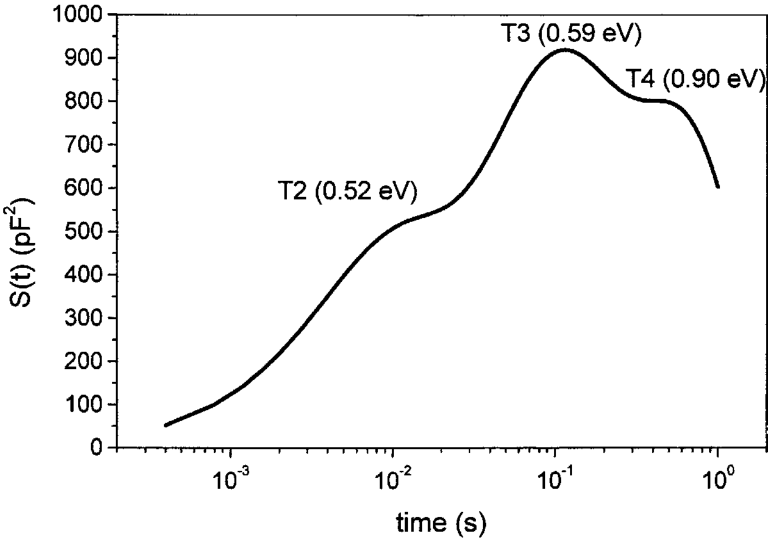


Figure 3. ICTS spectrum taken at $T = 330$ K.

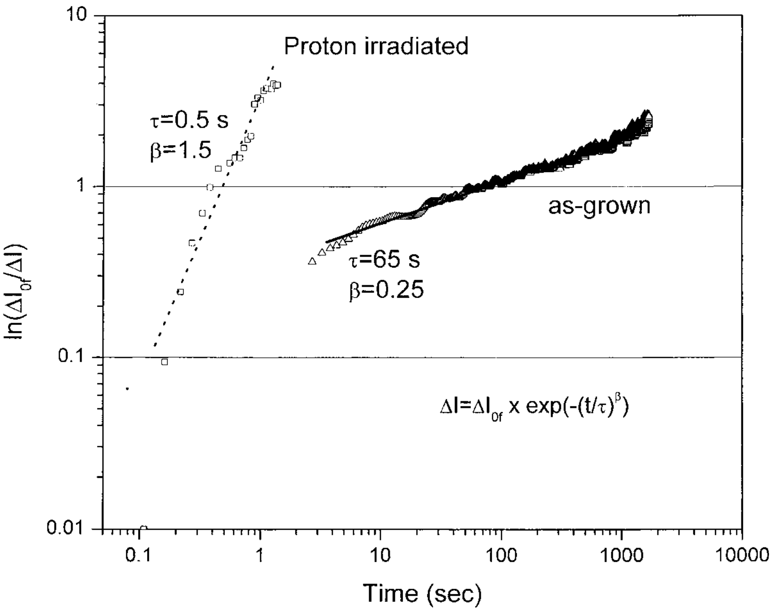
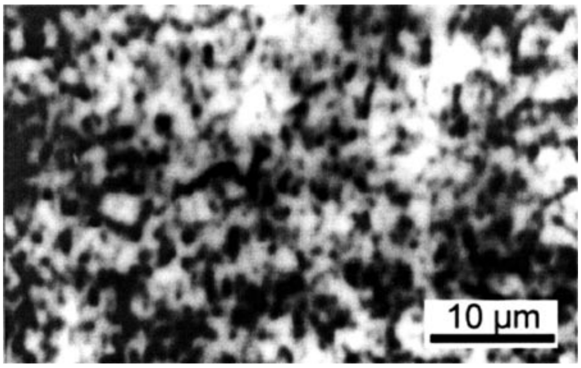
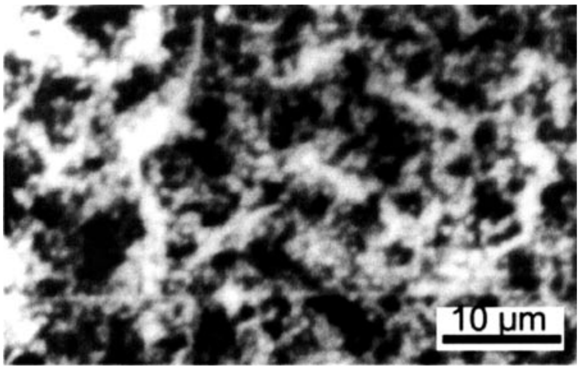


Figure 4. Persistent photocurrent (PPC) data comparison for as-grown and proton-irradiated gallium nitride.

Photoconductivity is a light induced change in the free carrier concentration. Photoconductivity persistence occurs when, after turning off the light, the enhanced conductivity is observed to last for an extremely long time, which becomes longer with decreasing temperature (also days for $T < 77$ K). This phenomenon, which has been related [18] to the photoluminescence yellow band, is of course of major importance for optoelectronics applications of GaN. Figure 4 shows the PPC diagrams of the as-grown epilayer and of the irradiated one, reporting a plot



(a)



(b)

Figure 5. EBIC micrographs showing the recombination activity distribution in (a) as-grown and (b) proton-irradiated GaN. The electron beam energy was 15 kV.

of $\ln(\Delta I_{of}/\Delta I)$ against log(time), where ΔI_{of} is the enhanced photocurrent just after turning off the light and I is the enhanced photocurrent as a function of time. As already reported in literature, in such a plot the PPC phenomenon is described by a stretched exponential law $\Delta I = \Delta I_{of} \exp[-(t/\tau)^{\beta}]$. The as-grown material PPC has a behaviour described by a stretching factor $\beta = 0.25$, similar to the values of the literature [9], and a constant time τ of 65 s. After irradiation the stretching factor is 1.5 and the time constant is $\tau = 0.5$ s. This feature, corresponding to a much faster photocurrent decay, means that the defects induced by irradiation quench the PPC. The persistent photoconductivity phenomenon, observed in many semiconductors [19] and in many cases explained by the presence of bistable defects [20], has been recently attributed in GaN to a distribution of capture barriers with a mean value of 0.2 eV [17]. Even if further study is needed of the PPC in our samples, it is worth noting that a strong correlation should be found among irradiation-induced defects and PPC quenching.

Finally, EBIC analyses were performed to detect the distribution of the electrical recombination activity in GaN and its changes induced by irradiation. In figure 5 micrographs of the epilayer before (a) and after (b) irradiation are shown. While the average defect contrast is not irradiation affected, the recombination activity, which corresponds to the dark regions, extends to areas that are 13% larger than before irradiation. Also the distribution of the recombination activity changes and the average distance between dark regions enlarges.

4. Conclusions

In summary, two new electron traps were generated by proton irradiation. The characteristics of one of these (T1) closely correspond to the trap at about $E_C - 0.6$ eV found by the Hall effect and attributed to the nitrogen vacancy. The density of the other pre-existing traps significantly increases after irradiation.

Further study will be carried out on the temperature and spectral dependence of PPC in order to determine which defect is dominant in determining the PPC, but it has already clearly emerged that the persistent photoconductivity decay is quenched by the irradiation induced defects. A similarly strong effect of irradiation was evidenced in the EBIC features of the electrically active regions: the EBIC contrast keeps constant while the area recombination ratio increases by a factor equal to 13%. At the same time the average distance among recombination regions significantly increases.

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