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Effects of 5 MeV Electron Irradiation on Deep Traps and Electroluminescence from Near-UV InGaN/GaN Single Quantum Well Light-Emitting Diodes With and Without InAlN Superlattice Underlayer

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ABSTRACT

The electrical properties, electroluminescence (EL) power output and deep trap spectra were studied before and after 5 MeV electron irradiation of near-UV single-quantum-well (SQW) light emitting device (LED) structures differing by the presence or absence of InAlN superlattice underlayers (InAlN SL UL). The presence of the underlayer is found to remarkably increase the EL output power and the radiation tolerance of LEDs, which correlates with a much lower and more slowly changing density of deep traps in the QW region with radiation dose, and the higher lifetime of charge carriers, manifested by higher short-circuit current and open-circuit voltage in current-voltage characteristics under illumination. The observed phenomena are explained by the capture of native defects segregated at the growing surface by In atoms in the underlayer which traps them in the underlayer and prevents their penetration into the QW region.

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I.INTRODUCTION

Blue and near-UV (NUV) light emitting diodes (LEDs) based on GaN/InGaN quantum wells constitute the basis of light emitting devices widely used in general lighting, displays, indicators, data storage systems, metrology, biology and medicine[1, 2]. Although the efficiency of these devices is quite high, further improvements of their efficiency are still necessary for their wider implementation in practical optoelectronic systems. To expand the applications into new areas, a better knowledge is needed of the devices performance in harsh operation conditions. For example, in space applications, the detailed knowledge of radiation tolerance of devices and factors influencing this tolerance is of importance.

The efficiency of blue and NUV GaN/InGaN quantum well or multi-quantum well (QW or MQW) LEDs is a function of multiple factors, including dislocation density, localization of charge carriers in In-rich potential fluctuations in the QWs, the density of point defects that are deep non-radiative recombination centers in the QWs or recombination and trapping centers in QW barriers, changes in strain varying the magnitude of the quantum-confined Stark effect (QCSE) [1, 2]. Detailed studies have shown that dislocations, while being prominent local recombination centers, play a significant role in the efficiency of LEDs only for structures with dislocation density exceeding ~5×10^{8} cm^{-2} [3=6]. Moreover, their detrimental effects can be seriously alleviated by the formation of so called V-defects often terminating dislocations near the surface (see e.g. a discussion in Ref. [4]). Localization of charge carriers in potential fluctuations is a serious concern, but seems to be much more pronounced for LEDs emitting in the green spectral range where the In concentration is high and close to the onset of spinodal decomposition of InGaN ternaries (see e.g. Ref. [1, 5]). Green LEDs are also much more susceptible to the detrimental effects of QCSE because of the higher lattice mismatch and strain, so that serious efforts have been necessary to develop and optimize various strain-relieving schemes and to improve the design of the QW regions that minimizes electron-holes separation and efficiency loss in the QW due to QCSE [5]. For advanced state-of-the-art blue or NUV

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LEDs, there is a growing consensus that the peak efficiency of these devices is determined by the density of centers of non-radiative recombination in the QWs and QW barriers [6]. The former centers directly affect the radiative recombination efficiency in the QW, while the latter cause a decrease in injection efficiency via recombination and trapping in the QW barriers [7]. The work on classification and identification of such centers and on determining the factors influencing the density of such states is far from being finished. Among the factors seriously impacting the spectra and density of deep traps in the QWs and QW barriers are the temperature of growth of the barriers [8, 9], the use of growth schemes improving the overall crystalline quality of the QW region, such as lateral overgrowth of nanopillar templates [10], the use of In-containing underlayers [11], irradiation of the structures and subjecting them to electric stress.

Various techniques, such as positron annihilation spectroscopy (PAS), studies of photoluminescence (PL) spectra, kinetics and quantum efficiency, direct measurements of deep traps spectra using deep levels transient spectroscopy (DLTS), deep level optical spectroscopy (DLOS), steady-state photocapacitance spectra (SSPS), and capacitance-voltage C-V profiling with monochromatic optical excitation (LCV) have been used to pinpoint the types of traps most relevant to non-radiative recombination processes in GaN-based structures.

In combined PAS and PL studies of as-grown and irradiated GaN and AlN-based structures [12, 13] strong evidence was obtained in favor of V_{Ga}-V_N divacancies in GaN or V_{Al}-V_N divacancies in AlN being prominent in non-radiative recombination (V_{Ga} or V_{Al} standing for group III vacancies, V_N - for nitrogen vacancies).

For moderate and low dislocation densities GaN films and crystals, and for LEDs of various designs irradiated with electrons or subjected to electrical stress, recent DLTS studies have earmarked several suspect centers whose concentration consistently correlates with changes in electroluminescence efficiency or with lifetimes of non-equilibrium charge carriers [7, 14-19]. In radiation experiments, the centers associated with nitrogen interstitial acceptors N_i and Ga interstitial donors Ga_i with levels approximately tied to the level of vacuum in different III-

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Nitrides have been shown to actively participate in non-radiative recombination, together with as yet unidentified ubiquitous centers with levels near E_c-0.6 eV in GaN [15-19, 20, 21]. Among the major centers with levels in the lower half of the bandgap of GaN, defects with levels near E_v+(0.9-1.2) eV are major hole traps whose levels are tied to the level of vacuum in III-Nitrides [15-19, 22]. In n-GaN, these hole traps do not seem to be effective in non-radiative recombination because of the very slow electron capture [15-19], which is corroborated by ab initio theoretical calculations of electron and hole capture rates by these centers. However, for narrow-bandgap In-rich InGaN QWs, it is predicted that such deep acceptors can become effective recombination centers [23].

Increasing the growth temperature of GaN barriers in GaN/InGaN MQW structures has been shown to increase the quantum efficiency of PL [9] which can be tied up to the observed decrease of the density of the N_i-related E_c-1 eV recombination centers in GaN barriers and V_{Ga}-related E_v+0.7 eV centers in InGaN QWs as determined by DLTS in Ref. [8].

The changes induced in the spectra of deep centers in QW LEDs by application of In-containing underlayers are of special interest because such underlayers are commonly integral parts of strain-relieving routines in good quality QW structures. It has been noted for some time that such underlayers are often advantageous to the LEDs efficiency [11]. Deep traps studies of GaN/InGaN MQW LEDs with InGaN underlayer (InGaN UL) were performed in Ref. [24] using DLOS, SSPC, LCV techniques. A close correlation has been reported between a higher efficiency of LEDs with InGaN UL and a decreased concentration of deep traps with optical ionization threshold near 1.6 eV in DLOS/LCV spectra.

The latter observation was recently explained by a model taking into account segregation of native point defects near the growing GaN surface. It is suggested that the presence of In atoms stabilizes these surface defects, which are converted into non-radiative recombination centers and handicap radiative recombination efficiency. If this process takes place in the QW it very adversely affects the photoluminescence (PL) efficiency and strongly decreases the PL lifetime.

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Introduction of In-containing underlayers (UL), say InGaN or InAlN, allows to capture these surface defects and prevents them from propagating into the QW region, increasing the luminescence efficiency [25-28]. The model explains the behavior of single QW (SQW) LED structures with InGaN, InAlN or GaN/InAlN superlatice (SL) underlayers (ULs) as a function of UL composition, thickness or growth temperature [25-27]. It should be noted that no conclusive results regarding deep electron or hole traps spectra in QW structures with InGaN or InAlN ULs were reported for ordinary DLTS measurements in Ref. [24]. Such detailed DLTS studies of the LEDs with InAlN SL ULs showed [28] no detectable concentrations of electron or hole traps either in the QW or in the UL region, in contrast to structures without the UL in which electron traps with levels near E_c-0.6 eV and E_c-0.8 eV were seen in the GaN underlayer, and hole traps with levels near E_v+0.75 eV were detected in the QW, together with traps with optical ionization threshold of 1.5 eV in LCV spectra. Irradiation with a low fluence of 7×10^{15} cm^{-2} of 5 MeV electrons had little effect on the density of traps in DLTS, but increased the density of the traps with the optical ionization threshold energy of 1.5 eV in LCV spectra of the sample without the UL while seriously decreasing the EL efficiency of such samples. Based on that, the observed changes in EL efficiency in these samples were attributed to increased density of the centers with optical ionization threshold of 1.5 eV. For the samples with the InAlN SL UL, the density of the E_c-0.6 eV and E_c-0.8 eV electron traps and of the E_v+0.75 eV hole traps in DLTS were introduced, but the concentration was very much lower than in the LEDs without the UL and there were no changes in EL efficiency after irradiation with this low electron fluence. The interest of these preliminary results is two-fold. First practical: the introduction of the InAlN SL UL increases the radiation tolerance of the SQW NUV LEDs. But in that respect it is necessary to find the fluence of electrons for which the EL efficiency of the LEDs with InAlN SL UL starts to decrease. Second scientific: in the studied NUV SQW LEDs the EL efficiency degradation at low electron fluences seems to be related to the increase in the concentration of midgap centers with optical ionization threshold near 1.5 eV rather than to the introduction of Ni deep acceptors

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or Gai deep donors as reported in our earlier work on radiation effects in GaN/InGaN MQW blue and NUV LEDs [7, 14]. In order to clarify both issues in what follows we studied the effects of electron irradiation with higher fluences on EL efficiency and deep traps spectra of SQW LEDs with and without InAlN SL UL.

II.EXPERIMENTAL

The LED structures investigated were similar to the InGaN/GaN single QW LED structures with and without InAlN/GaN superlattice (SL) underlayer (UL) described previously [27]. They were prepared by metalorganic vapor phase epitaxy (MOVPE) on GaN-on-sapphire templates in an Aixtron 200/4 RF-S horizontal reactor. The design of the LED layer structure with InAlN SL UL was as follows. First, a 2-μm-thick Si-doped GaN buffer was grown, followed by a Si doped $In_{0.17}Al_{0.83}N$:Si(2.1 nm)/GaN:Si(1.75 nm) SL with 22 periods and Si doping of 3×10^{18} cm^{-3}. Then two more periods of the InAlN:Si/GaN:Si SL doped to 1.5×10^{20} cm^{-3} were grown on top and capped with a 5-nm-thick GaN layer with the same doping level and followed by a 20-nm-thick GaN spacer doped with Si to ~3×10^{18} cm^{-3}. Above this strain-relieving layer sequence, the $In_{0.1}Ga_{0.9}N$ QW with 2.7-nm thickness sandwiched between two 7.5 nm-thick *n*-GaN barriers ([Si] = 1×10^{18} cm^{-3}) was grown and capped with a 20 nm thick undoped GaN spacer. The structure was completed with the growth of a 20-nm-thick *p*-$Al_{0.2}Ga_{0.8}N$:Mg electron blocking layer (EBL), a 200-nm-thick *p*-GaN:Mg layer ([Mg] ≈1×10^{19} cm^{-3}), and a 25-nm-thick *p*-GaN:Mg film doped to 1×10^{20} cm^{-3} . This sample is labelled below InAlN SL UL LED.

The sample without InAlN SL UL differed by the growth of the 5-nm-thick GaN spacer with the Si doping of 3×10^{18} cm^{-3} right after the 2-μm-thick Si-doped GaN buffer layer, i.e., the absence of the InAlN:Si/GaN:Si SL sequence. This sample, is labelled NO UL LED.

The samples were processed into LEDs using conventional photolithography and dry etching. Ohmic contacts were fabricated by deposition of Pd/Au as p-type ohmic contacts to p-

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GaN and of Ti/Al/Ti/Au as ohmic contacts to n-GaN. All measurements were completed on 300 × 300 μm^2 chips contacted by wire bonding.

Characterization included current-voltage (*I-V*), capacitance-voltage (C-V), admittance spectroscopy (AS) and DLTS [29] measurements in the temperature range 77-400 K [30-32]. The relative EL intensities as a function of driving current were measured using 100 ms long forward current pulses with a 500 ms period as provided by a Keysight Instruments current-voltage source meter B2902A (USA). The EL signal was measured as a current of a Si photodiode biased at +2 V [7]. Absolute measurements of the EL output power and IQE were not done in these experiments, but were performed for LEDs before irradiation in the earlier work [27]. These preliminary measurements showed the EL spectrum to be peaked near 3 eV for both samples and the internal quantum efficiency (IQE) to be ~ 70% for the InAlN SL UL LED and 9% for the NO UL LED before irradiation [27].

The measurements were repeated after irradiation at room temperature with 5 MeV electrons with fluences of 7×10^{15} and 3×10^{16} cm^{-2}, performed on the linear electron accelerator Linac UELV-10-10-C-70 [33, 34] at the Center of Collective Use "Physical Measurements Investigations" (CCU PMI) of the Institute of Physical Chemistry and Electrochemistry of the Russian Academy of Sciences.

III.RESULTS AND DISCUSSION

We begin by comparing the I-V characteristics of the two types of structures in the dark and under illumination with high-power (250 mW output power) LED with peak photon wavelength of 400 nm (this illumination creates electrons and holes resonantly in the QW). The results are shown before and after irradiation with fluencies of 7×10^{15} cm^{-2} and 3×10^{16} cm^{-2} of 5 MeV electrons in Fig. 1(a, b). The defining features of these I-V characteristics before irradiation are the much lower leakage current in reverse direction and at low forward voltages, a higher short-circuit current I_{sc}, and much higher open circuit voltage V_{oc} for the LED with InAlN SLs UL. For the sample without the UL, the higher leakage is a consequence of a stronger tunneling that

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could be linked to the higher density of deep hole traps. The lower I_{sc} and V_{oc} in this sample are the results of the shorter lifetime in the QW region as determined by time resolved photoluminescence (TRPL) decay measurements published earlier [27] and of the enhanced leakage current. Both the decreased lifetime and the increased leakage are expected to contribute to the decrease of V_{oc} [35]). In addition, the series resistance of the LED without the underlayer was found to be 2.4 times higher than for the sample with the underlayer which, as shown in our earlier paper [28], is one of the consequences of the stronger compensation of Mg acceptors in p-GaN emitter by V_N-related donors that propagate from the n-type part of the structure during growth.

Electron irradiation steadily increased the series resistance of both types of LEDs, at least in part due to increasing compensation of Mg acceptors in p-GaN [28]. It also decreased the I_{sc} and V_{oc} in both types of structures, but at a much faster rate for the sample without the InAlN SLs UL, which indicates a much stronger decrease with irradiation of the lifetime in the QW region. The results of these measurements are summarized in Fig. 2(a, b, c).

The depth profiles of the charge concentration in the two types of structures as affected by electron irradiation are shown in Fig. 3(a, b). Fig. 4 (a, b) presents these concentrations as a function of applied voltage. Both figures were obtained in a standard fashion [29] from experimental C-V characteristics measured at room temperature at high frequency of 100 kHz. For the LED structure without the InAlN SL UL, we can access the region of the QW lying inside the space charge region at 0V and accessible to C-V probing by application of positive bias (the peak in concentration in Fig. 3(a) and 4 (a)). The region of GaN barrier can be probed by application of reverse biases between -3V and 0V (Fig. 3(b)). Electron irradiation leads to the charge concentration slightly decreasing with increasing electron fluence.

The charge concentration profiles as a function of depth and of voltage are shown for the sample with InAlN SL UL in Fig. 3(b), 4(b). In this sample, the QW region was not accessible to C-V probing even for high forward voltages. Only the InAlN SL region could be observed in

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depth profiles or charge concentration versus voltage profiles in Fig. 3(b), 4(b). In contrast to the sample without the underlayer, the charge concentration in this region slightly increased after irradiation, the reason for which has yet to be understood.

The conditions of biasing and pulsing for DLTS probing of the traps in the QW region and in the GaN barrier region of the LED structure without InAlN SL UL are clear from Fig. 4(a). To probe electron traps in the GaN barrier, the sample has to be kept at -3V and pulsed to 0V. For the QW region, the sample has to be biased at -0.5 V and pulsed to 3V in the forward direction. With forward pulsing, both electrons and holes are injected. The ability to detect both electron and hole traps separately depends on their relative concentrations. As shown below, hole traps in the QW absolutely dominate under such injection conditions.

For the LED structure with InAlN SL UL, probing of the SL portion of the structure in DLTS was done by biasing the sample at -5V and pulsing to 0V. For probing the QW region, we kept the sample at -0.5V and pulsed it to 3V. As follows from the I-V data in Fig. 1 and the electroluminescence signal measurements, these biasing conditions ensured efficient injection of charge carriers into the QW.

The results of DLTS measurements for electron traps in the LED without InAlN SL UL are shown before and after electron irradiation in Fig. 5(a). Fig. 5(b) shows the spectra for the QW region. The convention in the figures is that the peak of electron traps is positive while, for hole traps, it is negative. Before irradiation, a very weak electron trap feature belonging to traps with levels near E_c-0.6 eV (electron capture cross section of $\sigma_n=8.2\times10^{-16}$ cm^2) (E1 trap) and E_c-0.8 eV ($\sigma_n=2.3\times10^{-15}$ cm^2) (E2 trap) were observed for the GaN barrier. Their concentrations were not changed after irradiation with the low electron fluence of 7×10^{15} cm^{-2}, but markedly increased after irradiation with a high fluence of 3×10^{16} cm^{-2}, which also introduced a very prominent peak of electron traps with level near E_c-0.55 eV ($\sigma_n=1.5\times10^{-14}$ cm^2) (E3 trap). Electron traps at E_c-0.8 eV (our E2 traps) are quite common radiation defects in n-GaN films often associated with the interstitial Ga donors Ga_i [7] on account of their level being close to the

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theoretically predicted charge transfer level of such defects [36]. The E_c-0.6 eV centers (our E1 traps) are quite similar to the ubiquitous defect in n-GaN shown to be a prominent recombination center [15-17]. They are also held responsible for current collapse of GaN-based high electron mobility transistors (HEMTs) after electric stress [37]. However, the concentration of these traps has not been previously reported to increase after electron irradiation [14-16]. The nature of these centers is still under debate, but they have been attributed to dislocation related states [38, 39]. The origin of the E_c-0.55 eV (E3) traps observed after heavy electron irradiation is not clear. Centers with levels in the vicinity of the E3 traps have been reported for some n-GaN samples, but no consistent assumptions regarding their possible nature have been made [20].

In DLTS spectra of the QW region of the sample without InAlN SL the absolutely dominant defects before irradiation were hole traps with levels near E_v+0.75 eV (hole capture cross section $\sigma_p=2.3\times10^{-14}$ cm^2) (Fig. 5(b)). Electron irradiation with a low fluence of 7×10^{15} cm^{-2} only very slightly increased the peak magnitude of these hole traps, while irradiation with a higher fluence of 3×10^{16} cm^{-2} markedly enhanced the concentration of these defects. Similar hole traps were previously observed by us in NUV LEDs of different design [14, 19]. Their concentration was shown to correlate with the increase of leakage current at low forward voltages after electron irradiation and prolonged operation at high injection current [14, 19]. The effect was attributed to enhanced tunneling via these levels [19]. These traps do not directly impact the non-radiative recombination efficiency in NUV LEDs [14, 19]. They have been attributed to complexes of V_{Ga} acceptors with shallow donors in Ref. [21].

For the sample with InAlN SL UL, we could detect neither electron nor hole traps when probing the InAlN SL or the QW regions of the structure prior to irradiation. After irradiation with 7×10^{15} cm^{-2} electron fluence, electron traps' peaks close to the location of the E1, E2, E3 centers could be detected in the InAlN SL region. Their concentration became much higher after irradiation with the fluence of 3×10^{16} cm^{-2} (Fig. 6(a)). In DLTS spectra collected from the QW region of these structures, a hole trap near E_v+0.75 eV emerged after irradiation with 7×10^{15} cm^{-2}

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fluence of 5 MeV electrons. Its amplitude greatly increased after irradiation with high fluence of 3×10^{16} cm^{-2} (Fig. 6(b)). Note, however, that the magnitudes of electron traps E1, E2, E3 peaks and the hole trap E_v+0.75 eV peak in the sample with InAlN SL UL after irradiation were always much lower than for the sample without the InAlN SL UL before the irradiation.

For LCV spectra measurements, we could only perform them in a reliable fashion for the QW regions of the sample without the InAlN SLs UL. The phoconcentration ΔN_{Ph} (i.e. the concentration in the QW obtained from C-V profiling under illumination with monochromatic light minus the dark concentration) measured as a function of the photon energy of the excitation light is shown before irradiation and after irradiation with the two used fluences in Fig. 7. Before irradiation, the spectra showed an onset for photon energies close to 1.5 eV, a narrow plateau between 1.8 and 2 eV, another onset near 2 eV with a peak near 2.3 eV. Respective concentrations of the centers were 4.3×10^{16} cm^{-3} for the traps with the optical ionization threshold of 1.5 eV (henceforth to be called the 1.5 eV centers) and ~10^{16} cm^{-3} for the centers with optical ionization threshold of 2 eV (henceforth called the 2 eV centers; the concentrations in the spectra are taken as the concentration on the 2 eV plateau for the 1.5 eV centers and as the difference with the concentration on the plateau and the photoconcentration at 2.3 eV energy for the 2 eV centers). Irradiation with 7×10^{15} cm^{-2} 5 MeV electrons increased the density of the 1.5 eV centers to 8.5×10^{16} cm^{-3}, with the concentration of the 2 eV centers remaining the same. After irradiation with the fluence of 3×10^{16} cm^{-2} of electrons, the increase in the density of the 1.5 eV centers was very moderate, only to 1.3×10^{17} cm^{-3} , with a stronger increase of the concentration of the 2 eV centers (Fig. 7). The LCV spectra in the figure are qualitatively similar to the LCV spectra of LEDs with InGaN underlayer in Ref. [24]. Irradiation with lower dose of 7×10^{15} cm^{-2} mainly changes the density of the 1.5 eV centers, whose introduction rate slows down considerably for the higher dose of 3×10^{16} cm^{-3}. The concentration of the 2 eV centers is not seriously affected by irradiation with lower dose, but tends to increase substantially for the higher dose. The behavior of these LCV centers is very similar to the behavior of the E_v+0.75 eV

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hole traps in DLTS spectra collected from the QW regions and strongly suggests that one is dealing here with the same defects, most likely due to V_{Ga} acceptors complexed with shallow donors [14, 19, 21].

The evolution of the relative EL output as a function of the electron fluence is compared for the two types of studied LEDs in Fig. 8(a, b). For the sample with InAlN SL UL (Fig. 8(a)), irradiation with a low dose hardly changed the EL output at high driving current. For higher fluence of 3×10^{16} cm^{-2} the EL signal seriously decreased. For low driving currents, the main effect seems to be due to an increase of the series resistance that shifts to higher values the level of driving current necessary to produce measurable EL signal (see Fig. 2(a)).

For the sample without the InAlN SL UL, irradiation with the low electron fluence already causes a lot of damage both at low and high driving currents, suggesting a stronger impact of non-radiative recombination via point defects (it generally determines the peak value of EL efficiency and changes in EL at low driving current are expected to be strongly affected by the increased concentration of these centers [6]). DLTS measurements do not register an increase in the density of deep traps in the GaN barrier or hole traps in the QW of this sample. The only obvious effect is the strong increase of the concentration of the 1.5 eV centers in the LCV spectra in Fig. 7. Thus, it makes sense to assume, that these centers are responsible for the non-radiative recombination in the sample without InAlN SL UL before irradiation and after electron irradiation with 7×10^{15} cm^{-2} fluence. The optical threshold of ionization for these traps is close to the optical ionization threshold of major LCV and DLOS traps in LEDs held responsible for the higher efficiency of LEDs with InGaN underlayer [24]. The position of the level involved in this ionization process is quite favorable for the center being active in multiphonon capture of both electrons and holes, i.e. of the defect being an efficient recombination center [23].

If one remembers the results of PAS probing of III-Nitrides in Ref. [12, 13], it seems reasonable to attribute the 1.5 eV defects to the V_{Ga}-V_N divacancies formed under irradiation. If this is true, then the process of such divacancies formation seems to slow down at high doses of

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electron irradiation. Yet, the EL output continues to decrease, as well as the lifetime of charge carriers when judged by the changes observed in I_{sc} and V_{oc} in Fig. 1(b), 2 (b, c). The 2 eV LCV centers/E_v+0.75 eV V_{Ga}-related hole traps, whose concentration strongly increases at high dose, do not fit the role of effective recombination centers [23]. One has to consider, however, that electron traps in the QW are difficult to detect in DLTS with strong hole injection [14, 19]. At the same time, both the E1 and E2 electron traps in the GaN barrier are known to be effective recombination centers [15-17] and their concentration strongly increases at high doses. This could easily handicap the injection efficiency and indirectly drive down the EL efficiency. Moreover, similar lifetime-killer traps not visible in DLTS because they are masked by the hole traps signal are very likely to be also formed in the QW and directly handicap the internal quantum efficiency. Such processes have been observed for NUV LEDs of a different design [14, 19].

For the LEDs with InAlN SL UL, LCV spectra measurements were not practical because the QW region was not accessible to C-V profiling. The starting EL output of these LEDs was 7 times higher than for LEDs without the underlayer and so were the I_{sc} and the V_{oc} indicating a much higher lifetime in the QW, as directly demonstrated by TRPL decay measurements [27]. The nature of the centers responsible for non-radiative recombination in these LEDs is not clear, but it seems reasonable to assume that these are the same 1.5 eV centers seen in LCV spectra of LEDs without the underlayer (note the negligible concentrations of all traps in DLTS of the sample with InAlN before irradiation). The electron traps introduced by irradiation into the InAlN SL UL and hole traps introduced into the QW are similar to the ones produced in the sample without the underlayer, but the introduction rate is very much lower, so that even at high doses they are not expected to contribute to non-radiative recombination at the same scale as in the LEDs without the underlayer. This suggests that even at high doses, the non-radiative recombination in LEDs with InAlN SL UL is still provided by the 1.5 eV centers tentatively associated with divacancies. However, the introduction rate of all centers is about an order of

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magnitude lower resulting in a much higher radiation tolerance of the NUV LEDs with InAlN SL UL.

A key question is whether this is a defining feature of the In-containing underlayer or whether other strain-relieving schemes could be equally effective. The data in Fig. 9 seems to indicate that the strain-relieving scheme using the InAlN SL could be advantageous. In the figure we compare the normalized changes of EL signal at low driving current of 20 mA (for which the contribution of non-radiative recombination centers is maximal) for the two LED structures described in this paper and for the NUV LED structure studied earlier [14]. The difference with this latter structure is that the active region comprises 6 QWs instead of a single QW and that the strain-relieving layer is formed by AlGaN/GaN superlattice instead of the InAlN/GaN superlattice as in the present work. It can be seen that the radiation tolerance of the sample with InAlN SL UL is the highest suggesting that the InAlN UL could provide better performance. However, this conclusion is not unambiguous, because of the higher number of QWs in the samples with AlGaN/GaN strain- relieving layer. Increased thickness is conducive to accumulation of higher radiation damage produced by incident electrons of the same energy. For clearer comparison structures with a similar number of QWs would be preferable.

IV. SUMMARY AND CONCLUSIONS

Studies of single GaN/InGaN QW NUV LED structures with and without InAlN SL UL measured before and after electron irradiation show that the introduction of the underlayer decreases the leakage current at reverse voltage and low forward voltage, increases the short-circuit current I_{sc} and open-circuit voltage V_{oc} in I-V characteristics. This indicates a lower tunneling via deep defect states and a higher lifetime of charge carriers in the QW. The radiation induced decreases of I_{sc} and V_{oc} proceed much faster for LEDs without the InAlN SL UL.

For samples without the underlayer, deep trap spectra in the GaN barrier are dominated by electron traps with levels E_c-0.6 eV (E1) and E_c-0.8 eV(E2) while in the QW region the dominant feature in DLTS spectra is due to hole traps with levels near E_v+0.75 eV. Centers with

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optical ionization threshold near 1.5 eV and 2 eV (1.5 eV centers and 2 eV centers) are observed in LCV spectra measurements. Electron irradiation with a low dose only very slightly increases the concentration of the E1 and E2 electron traps in GaN barrier and the E_v+0.75 eV hole traps in the QW, but strongly enhances the density of the 1.5 eV centers. For higher dose a strong increase of the E1 and E2 electron traps and the emergence of a prominent trap near E_c-0.55 eV (E3 trap) was detected in n-GaN barrier, with the density of the hole traps E_v+0.75 eV in the QW also strongly increasing. The increase in concentration of the 2 eV centers in LCV spectra closely follows the increase in density of the E_v+0.75 eV traps, while the rate of increase with fluence of the density of the 1.5 eV centers in LCV slows down for higher dose.

For the LED structure with InAlN SL UL, no electron traps or hole traps could be detected in the InAlN SL UL or in the QW. Irradiation induced electron traps similar to the E1, E2, E3 centers, their concentration greatly increased after irradiation, hole traps at E_v+0.75 eV were introduced in the QW region and their concentration also strongly increased with irradiation, but the introduction rate of all electron and hole traps was much lower than for samples without the InAlN SL UL.

Before irradiation, the EL output power of NUV LEDs with InAlN SL UL was about 5 times higher than for the sample without the underlayer, in agreement with earlier reports on lifetime measurements and with the observed differences in I_{sc} and V_{oc} values. Electron irradiation with low dose of 7×10^{15} cm^{-2} greatly decreased the EL output power of the LEDs without the InAlN SL UL, while the only change detected in deep trap spectra was the strong increase of the 1.5 eV centers concentration in LCV spectra of the QW region. This points to the 1.5 eV centers as the main cause of non-radiative recombination. We somewhat tentatively associate these defects with the deep non-radiative recombination centers in GaN attributed to V_{Ga}-V_N divacancies on the strength of PAS measurements [12, 13]. Heavy electron radiation with the fluence of 3×10^{16} cm^{-2} led to a further degradation of the EL output of the LEDs without the InAlN SL UL, while the introduction rate of the 1.5 eV centers was reduced and the

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introduction rate of deep traps in DLTS markedly increased for this higher dose. This suggests that the role of major recombination centers has been taken on by other defects, likely the traps in the QW similar to the E1, E2 electron traps in n-GaN barrier known from previous studies to be effective lifetime killers [15-17].

The EL output decrease with electron irradiation for LEDs with the InAlN SL UL was very much slower than for LEDs without the underlayer, even despite the very much higher starting value for the former. Since the defects introduced by irradiation and detected in DLTS spectra were of the same kind in both types of LED structures, it would seem reasonable that the 1.5 eV centers would also be introduced in the QW of the structure with underlayer. Because the introduction rate of centers in DLTS is about an order of magnitude lower in these structures, it stands to reason to assume that the 1.5 eV centers still remain the major non-radiative recombination centers in irradiated LEDs with InAlN SL UL. The lower starting density of these defects confirms the predictions of the model put forward earlier [25-27]. This model assumes that native surface defects are segregated at the growing surface of GaN and trapped by In atoms to form non-radiative recombination sites in the InGaN QW, thus decreasing the EL efficiency. The introduction of In-containing underlayers helps to prevent these surface defects from propagating into the QW region and thus leads to increased EL efficiency. The mechanism causing the radiation-induced introduction rate of lifetime killers to be lower in LEDs with In-containing underlayers still needs to be understood. But whatever the exact reason of the observed improvements it is clear that the use of InAlN SL UL has very positive effect on the starting EL efficiency of LEDs and on their radiation tolerance that is at least an order of magnitude higher than for LEDs not employing InAlN SL UL for strain relief.

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FIGURE CAPTIONS

Fig. 1(Color online) (a) Room temperature I-V characteristics measured for the LED sample with no InAlN SL UL in the dark (black curve, irradiation had only very slight effect on IVs), and light I-V characteristics measured with: 400-nm-wavelength LED illumination before irradiation (output power 250 mW, red line), the same after irradiation with 7×10^{15} cm^{-2} fluence of 5 MeV electrons (magenta line), and 3×10^{16} cm^{-2} fluence (olive line); (b) same data for the LED with InAlN SL UL (the color codings the same as in (a))

Fig. 2 (Color online) (a) Variations of series resistance in dark room temperature I-V characteristics as a function of 5 MeV electrons fluence for the LED without the InAlN SL UL (red curve) and with InAlN SL UL (blue curve); (b) the dependence of the short-circuit current in I-V characteristics measured with 400-nm-wavelength LED excitation as a function of 5 MeV electrons fluence; (c) the dependence of the open-circuit voltage in I-V characteristics measured with 400-nm-wavelength LED excitation as a function of 5 MeV electrons fluence; (the color codings are the same in all three panels)

Fig. 3(Color online) (a) Charge concentration density dependence on depth for the sample with no InAln SL UL; (b) same for the sample with InAlN SL UL

Fig. 4(Color online) Charge concentration profiles calculated for the sample with no InAlN SL UL (a) and with InAlN SL UL (b), red lines are before the irradiation, magenta lines after irradiation with 7×10^{15} cm^{-2} fluence, olive lines for the fluence of 3×10^{16} cm^{-2}

Fig. 5(Color online) (a) DLTS spectra measured on the LED without the InAlN SL UL with bias of -3V, pulsing to 0V (pulse length 3 s) (probing the GaN barrier region) with time windows 150 ms/ 1500 ms, at frequency of 100 kHz, red line- before irradiation and after irradiation with 7×10^{15} cm^{-2} 5 MeV, olive line-after irradiation with fluence of 3×10^{16} cm^{-2}; (b) probing the QW region of the sample without the InAlN UL (pulsing from -0.5V to 3V), red line-before irradiation, magenta line-after irradiation with 7×10^{15} cm^{-2} fluence, olive line-after irradiation

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with the fluence of 3×10^{16} cm^{-2}, time windows, pulse length, and probing frequency the same as in (a)

Fig. 6(Color online) (a) DLTS spectra for the sample with InAlN SL UL after irradiation with 5 MeV electrons with fluencies 7×10^{15} cm^{-2} (magenta line) and 3×10^{16} cm^{-2} (olive line) with probing the InAlN SL UL region by pulsing from -5V to 0V; (b) DLTS probing the QW region by pulsing from -0.5V to 3V; the spectra are shown for measurements after 5 MeV electron irradiation with fluences of 7×10^{15} cm^{-2} (magenta line) and 3×10^{16} cm^{-2} (olive line); before irradiation no measurable DLTS signal could be detected in either region

Fig. 7 (Color online) LCV spectra of the QW region of the sample without InAlN SL UL measured before irradiation (red line) and after irradiation with 5 MeV electrons with fluencies of 7×10^{15} cm^{-2} (magenta line), and 3×10^{16} cm^{-2} (olive line)

Fig. 8(Color online) EL signal as a function of driving current before irradiation (red line), after irradiation with 7×10^{15} cm^{-2} 5 MeV electrons (magenta line), and 3×10^{16} cm^{-2} fluence (olive line) for (a) sample with InAlN SL UL; (b) sample without the underlayer

Fig.9 (Color online) EL power output at 20 mA driving current normalized by the starting EL output built as a function of electron fluence for the two samples studied in this paper, the one with the InAlN SL UL (blue line) and without the underlayer (red line). The data are compared to performance under electron irradiation of a previously studied MQW NUV LED with AlGaN/GaN strain-relieving underlayer

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FIGURES

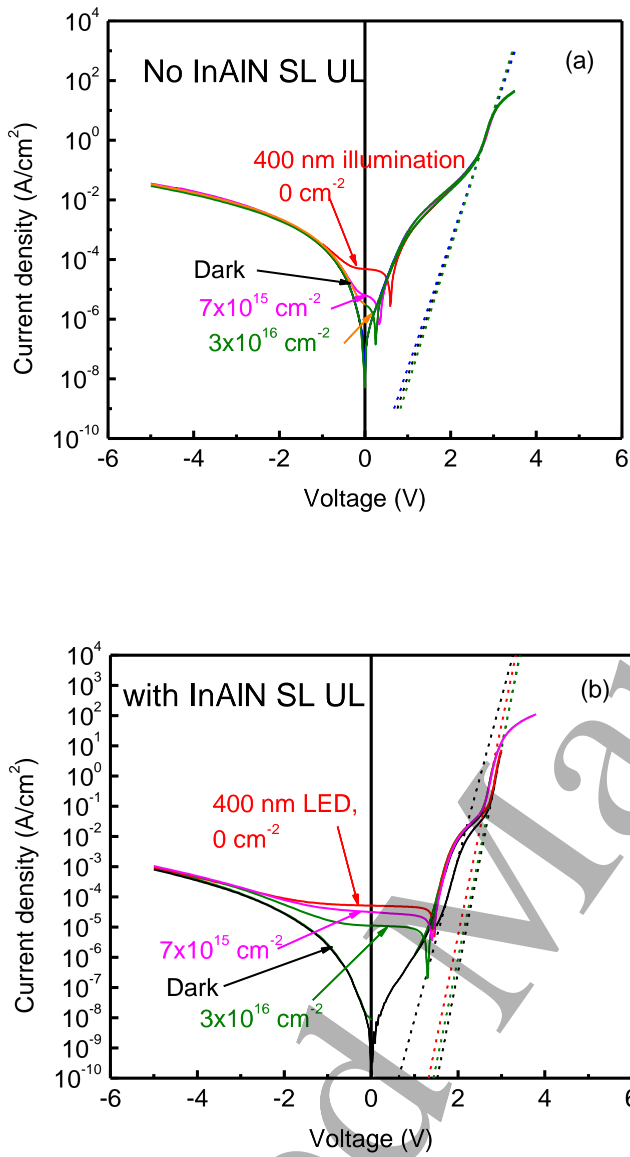

Fig. 1(Color online) (a) Room temperature I-V characteristics measured for the LED sample with no InAlN SL UL in the dark (black curve, irradiation had only very slight effect on IVs), and light I-V characteristics measured with: 400-nm-wavelength LED illumination before irradiation (output power 250 mW, red line), the same after irradiation with 7×10^{15} cm^{-2} fluence of 5 MeV electrons (magenta line), and 3×10^{16} cm^{-2} fluence (olive line); (b) same data for the LED with InAlN SL UL (the color codings the same as in (a))

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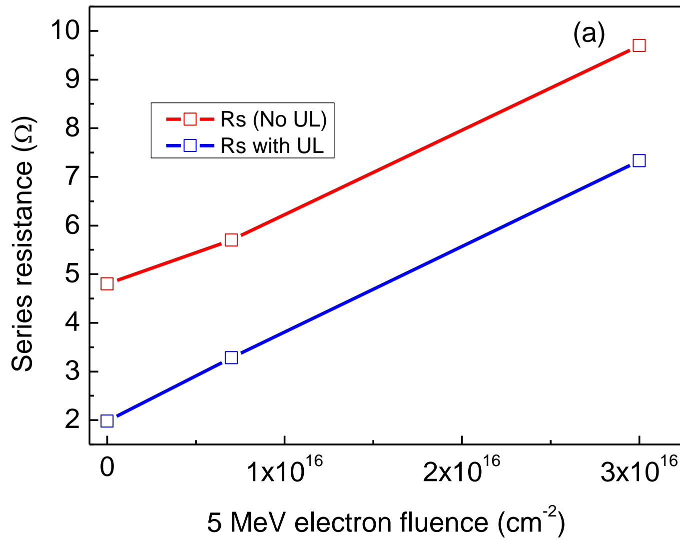

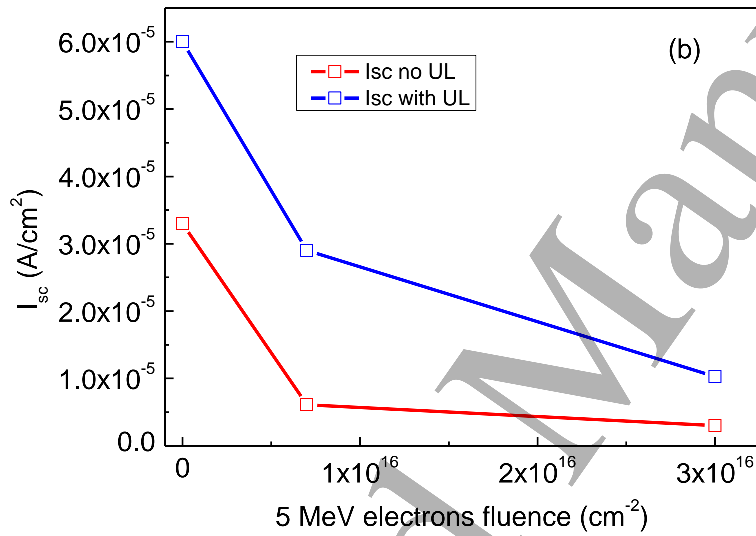

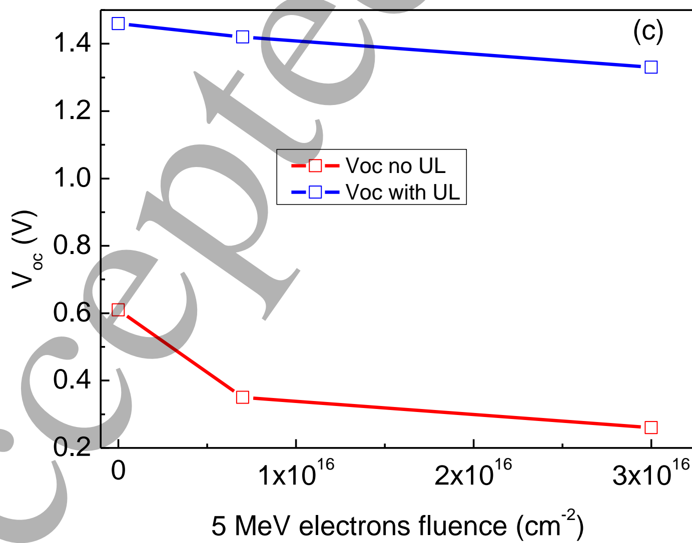

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Fig. 2 (Color online) (a) Variations of series resistance in dark room temperature I-V characteristics as a function of 5 MeV electrons fluence for the LED without the InAlN SL UL (red curve) and with InAlN SL UL (blue curve); (b) the dependence of the short-circuit current in I-V characteristics measured with 400-nm-wavelength LED excitation as a function of 5 MeV electrons fluence; (c) the dependence of the open-circuit voltage in I-V characteristics measured with 400-nm-wavelength LED excitation as a function of 5 MeV electrons fluence; (the color codings are the same in all three panels)

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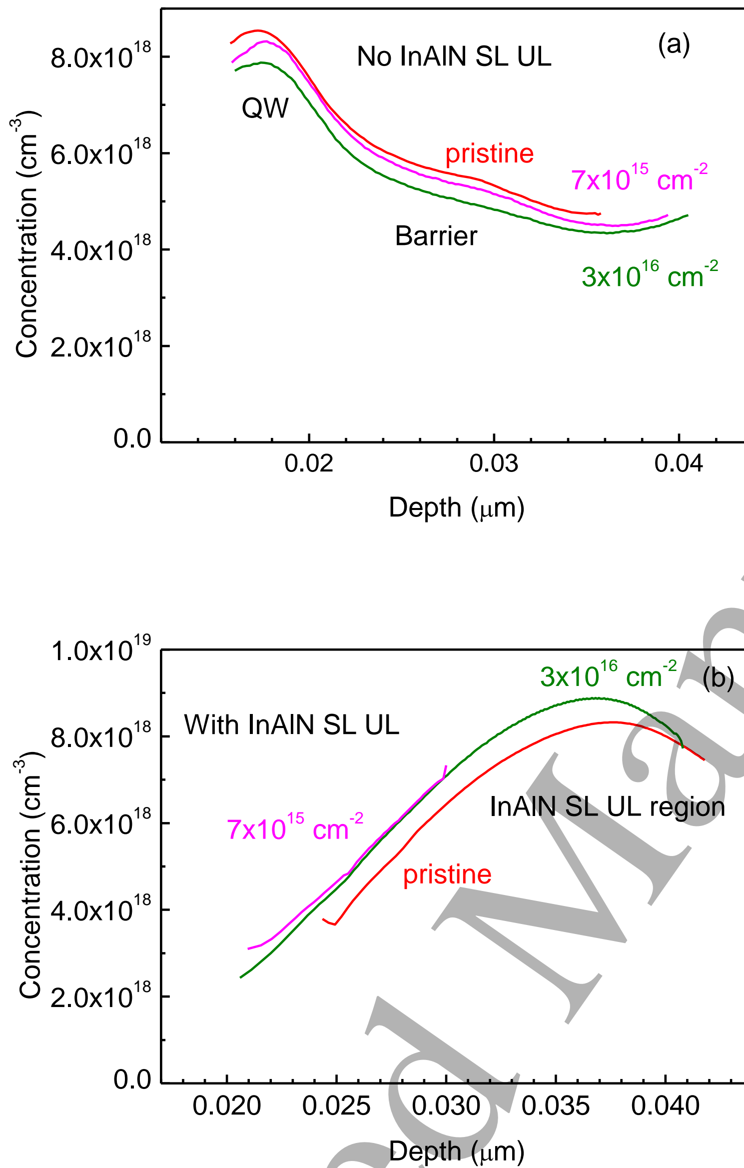

Fig. 3(Color online) (a) Charge concentration density dependence on depth for the sample with no InAln SL UL; (b) same for the sample with InAlN SL UL

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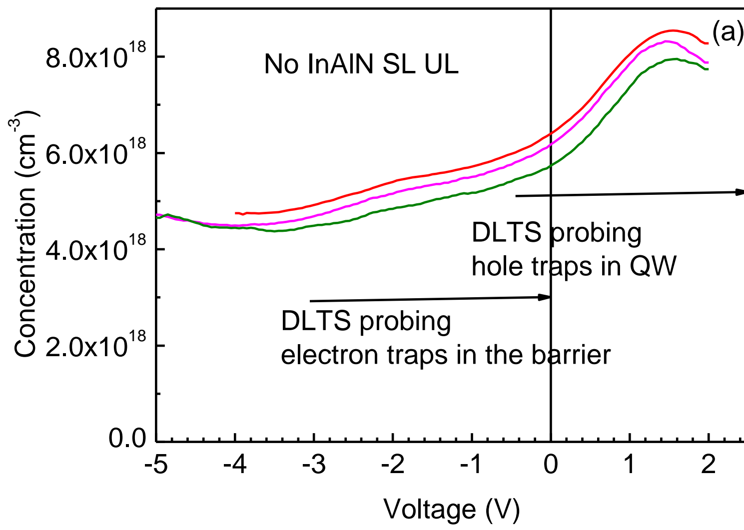

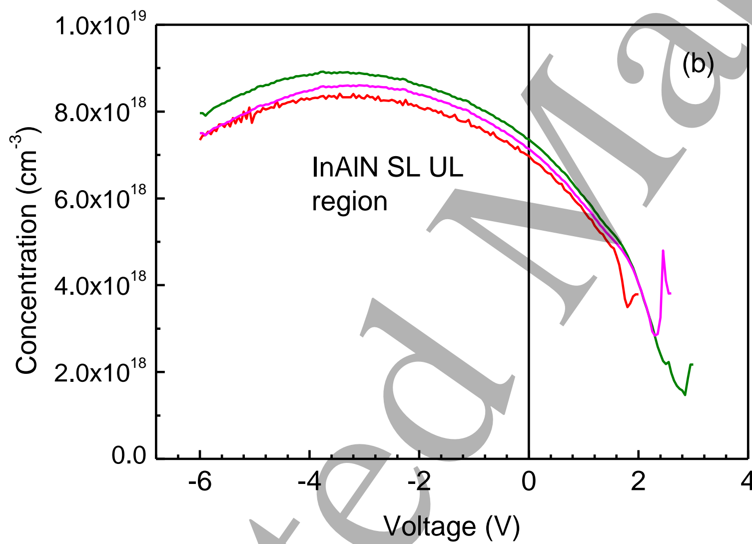

Fig. 4(Color online) Charge concentration profiles calculated for the sample with no InAlN SL UL (a) and with InAlN SL UL (b), red lines are before the irradiation, magenta lines after irradiation with 7×10^{15} cm^{-2} fluence, olive lines for the fluence of 3×10^{16} cm^{-2}

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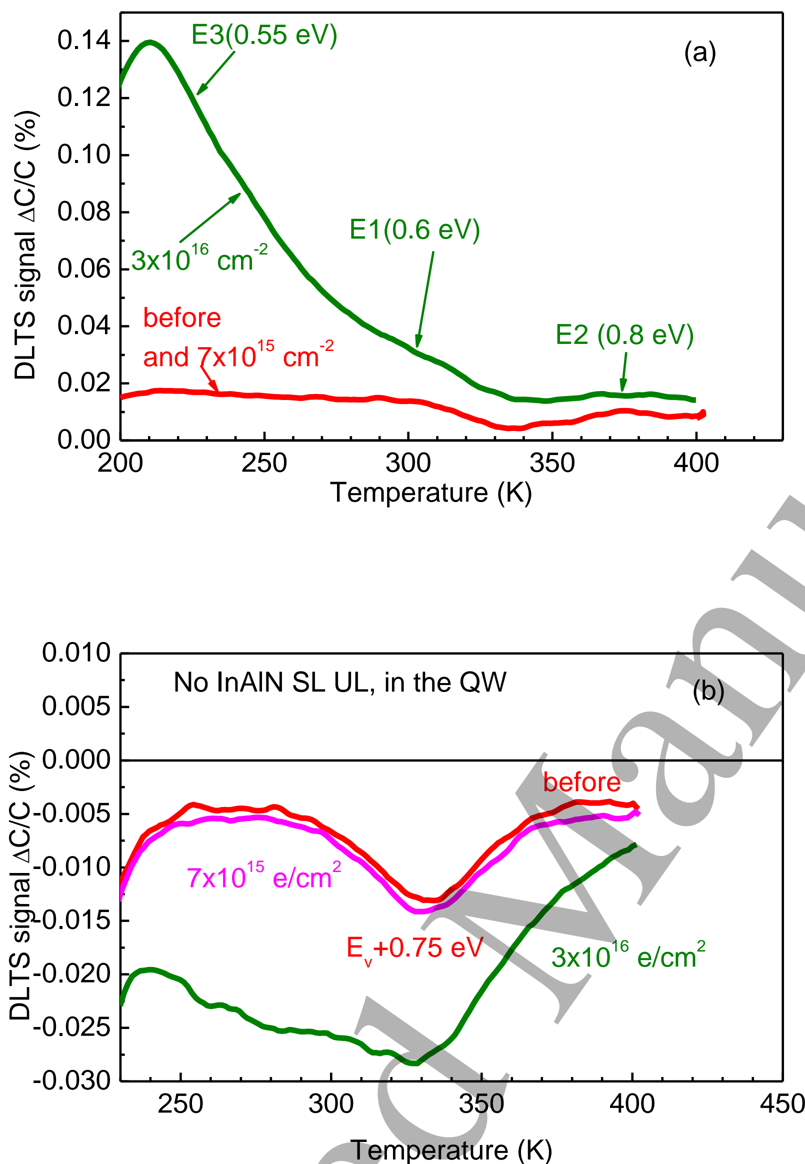

Fig. 5(Color online) (a) DLTS spectra measured on the LED without the InAlN SL UL with bias of -3V, pulsing to 0V (pulse length 3 s) (probing the GaN barrier region) with time windows 150 ms/ 1500 ms, at frequency of 100 kHz, red line- before irradiation and after irradiation with 7×10^{15} cm^{-2} 5 MeV, olive line-after irradiation with fluence of 3×10^{16} cm^{-2}; (b) probing the QW region of the sample without the InAlN UL (pulsing from -0.5V to 3V), red line-before irradiation, magenta line-after irradiation with 7×10^{15} cm^{-2} fluence, olive line-after irradiation with the fluence of 3×10^{16} cm^{-2}, time windows, pulse length, and probing frequency the same as in (a)

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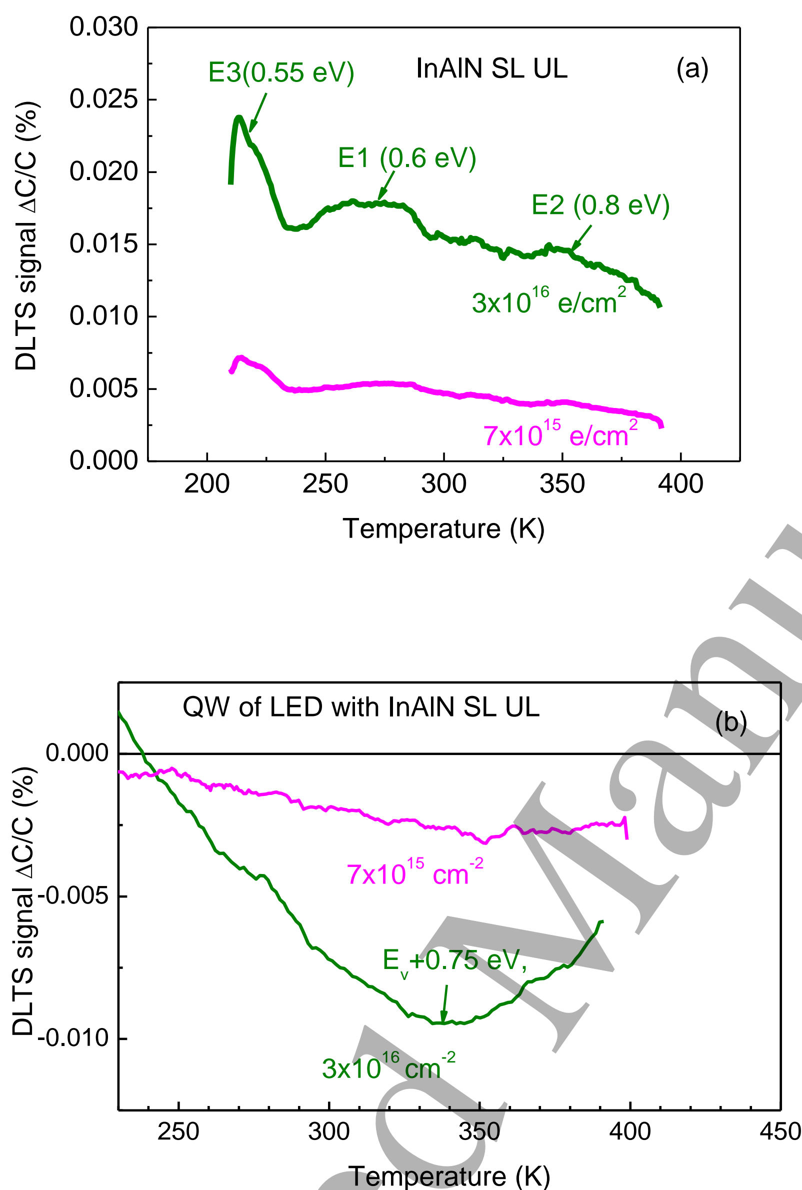

Fig. 6(Color online) (a) DLTS spectra for the sample with InAlN SL UL after irradiation with 5 MeV electrons with fluencies 7×10^{15} cm^{-2} (magenta line) and 3×10^{16} cm^{-2} (olive line) with probing the InAlN SL UL region by pulsing from -5V to 0V; (b) DLTS probing the QW region by pulsing from -0.5V to 3V; the spectra are shown for measurements after 5 MeV electron irradiation with fluences of 7×10^{15} cm^{-2} (magenta line) and 3×10^{16} cm^{-2} (olive line); before irradiation no measurable DLTS signal could be detected in either region

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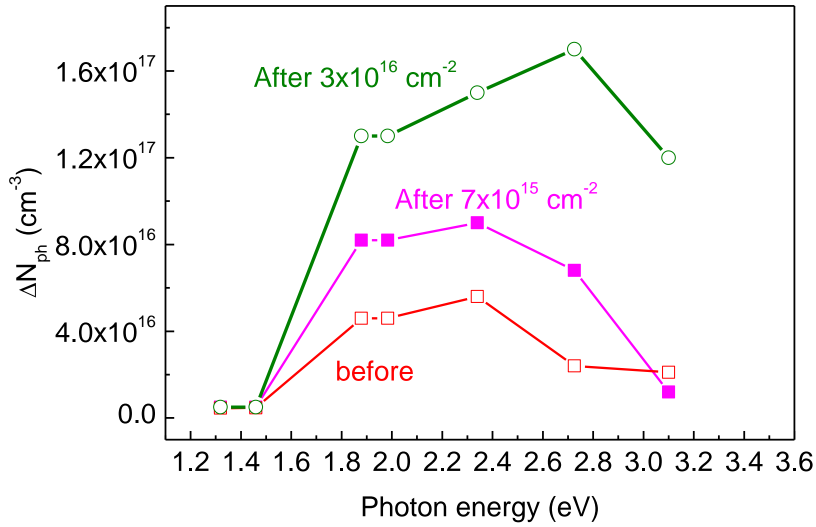

Fig. 7 (Color online) LCV spectra of the QW region of the sample without InAlN SL UL measured before irradiation (red line) and after irradiation with 5 MeV electrons with fluencies of 7×10^{15} cm^{-2} (magenta line), and 3×10^{16} cm^{-2} (olive line)

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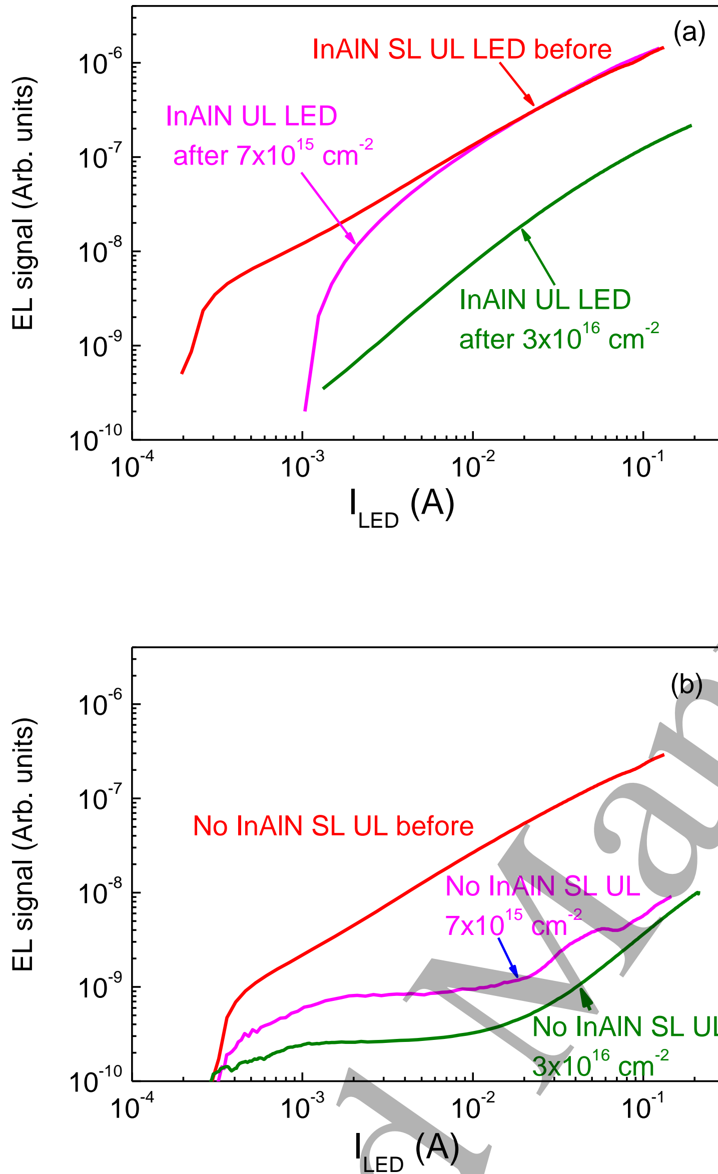

Fig. 8(Color online) EL signal as a function of driving current before irradiation (red line), after irradiation with 7×10^{15} cm^{-2} 5 MeV electrons (magenta line), and 3×10^{16} cm^{-2} fluence (olive line) for (a) sample with InAlN SL UL; (b) sample without the underlayer

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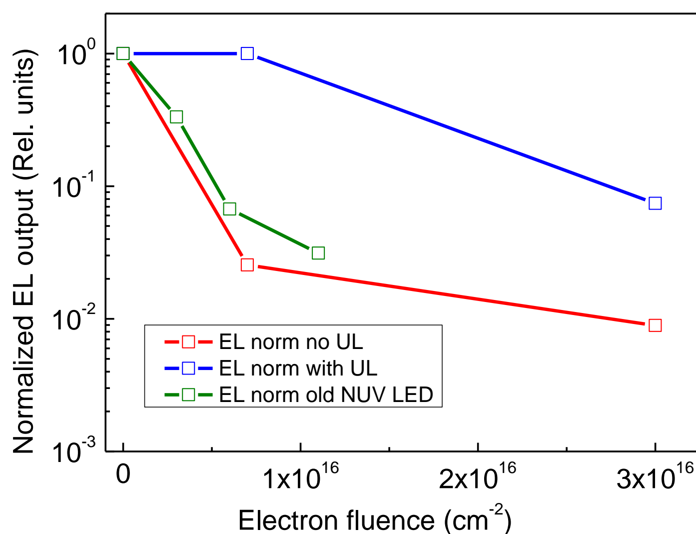

Fig.9 (Color online) EL power output at 20 mA driving current normalized by the starting EL output built as a function of electron fluence for the two samples studied in this paper, the one with the InAlN SL UL (blue line) and without the underlayer (red line). The data are compared to performance under electron irradiation of a previously studied MQW NUV LED with AlGaN/GaN strain-relieving underlayer

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