Influence of electron irradiation on the electroluminescence spectra of white InGaN light emitting diodes

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Abstract. We analyze the influence of electron irradiation on the electroluminescence spectra of white light emitting diodes (LEDs) based on indium gallium nitride. Three different irradiation fluences, 9.90×10^{15}, 1.32×10^{16} and 1.98×10^{16} cm^{-2}, are studied. For all 27 samples of LEDs of the commercially available models VAOL-5GWY4, VAOL-10GWY4 and OVL-3321, we observe a significant decrease in the emission light intensity after the irradiation. Degradation of the overall light intensity is believed to be due to irradiation-induced defects which act as nonradiative recombination centres. We also study the emission intensities and the central wavelengths of the LED samples subjected to electron irradiation under conditions of different injection currents. After irradiation with the fluence 1.98×10^{16} cm^{-2}, the blue peak located at 453 nm experiences severe degradation, so that only the yellow luminescence at 590 nm remains. This yellow band is related to radiative transitions from donor bands to the levels associated with gallium vacancies.

Keywords: electroluminescence, optical characterization, light emitting diodes, indium gallium nitride, injection current.

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1. Introduction

White indium gallium nitride light emitting diodes (LEDs) attract a great interest of researchers and technologists due to their low power consumption, high operating temperatures and high-energy efficiency, which make these LEDs suitable for using in both normal and extreme environments. White InGaN LEDs are usually produced by coating a blue InGaN-based light emitter with a layer of yellow phosphor embedded inside an epoxy resin [1–4]. The blue light that comes from InGaN-based light emitter is filtered through the phosphor, resulting in an apparently cool white light [5]. The yellow-phosphor materials such as cerium(III)-doped YAG absorb the blue light and can produce the light in a broad colour range from greenish to reddish, with a dominant yellow output. As a consequence, the yellow and blue light components are combined together, thus giving the white output [1-4].

InGaN LEDs are often used as illumination sources in many space and military fields, as well as in the visible-light communications [6]. Note that a presence of a Van Allen belt in space makes these LEDs vulnerable to irradiation effects, which are mainly caused by protons in the inner belt and high-energy electrons in the outer belt. Nowadays, most of telecommunication satellites are located at the very edge of the Van Allen belt, causing satellites to be greatly exposed by the electron irradiation, including its high-energy component. Collisions among external high-energy electrons and atoms in a semiconductor lattice lead to appearance of defects that eventually degrade the performance of semiconductor devices [7]. Hence, it is important to study the degradation effects experienced by the white InGaN LEDs in order to understand their hardness to the electron irradiation.

In this report we present the experimental details of electron irradiation process and the data of optical characterization of the commercial white InGaN LEDs before and after irradiation.

2. Experimental

Below we present the experimental results and their discussion, which are associated with electroluminescence (EL) measurements on 27 samples of the commercial white InGaN LEDs. The LEDs are characterized by the emission wavelengths 453 nm (a blue emission) and 550 nm (a yellow emission). In particular, we study such commercially available LEDs as VCC VAOL-5GWY4 (denoted as sample A), VCC VAOL-10GWY4 (sample B) and Multicomp OVL-3321 (sample C).

Three devices referring to each of the samples were irradiated with different irradiation doses, using a flux of 2 MeV electrons. The appropriate fluences were equal to 9.90×10^{15}, 1.32×10^{16} and 1.98×10^{16} cm^{-2}. The irradiation process was performed using an electron-beam facility at the Malaysia Nuclear Agency.

The EL spectra were measured at different injection currents ranging from 0.1 to 10 mA. Then the data were integrated to measure, in a qualitative manner, the total amount of luminescence collected before and after electron irradiation. In these experiments, the exact position of the devices during the experiments was carefully optimized prior to the measurements. The optical characterization was performed in a ‘dark setup’ at the room temperature, using a spectrometer HORIBA i320.

3. Results and discussion

Fig. 1 displays dependences of the EL intensity for the InGaN LEDs on the light wavelength. These dependences are detected at a constant injection current (10 mA) before irradiation and after electron irradiation of different fluence levels. A number of observations should be noticed. As seen from the inserts in Fig. 1, the intensity of the blue peak centred at 453 nm decreases two orders of magnitude with increasing irradiation dose. This holds true for all of our samples. The above degradation is often associated with irradiation-induced defects present in the quantum-well region due to electron irradiation. The irradiation-induced defects are believed to act as nonradiative recombination centres, thus leading to decrease in the emission intensity [8, 9]. Meanwhile, the yellow luminescence at 550 nm is increased as the irradiation fluence increases up to 1.32×10^{16} cm^{-2}. The yellow luminescence comes from the recombination from shallow donor to deep states [10]. The electron irradiation leads to formation of various defects such as vacancies causing the appearance of deep defect levels in the bandgap [11]. Hence, the increase in the yellow luminescence occurring after irradiation can be associated with irradiation-induced creation of gallium vacancies. In fact, here we deal with the defects introduced by electron irradiation in the bandgap of semiconductor [5, 11]. It is noteworthy that the yellow-emission intensity decreases with further increase in the fluence. The reason can be appearance of some complexes formed by irradiation-induced defects, which cause quenching of the emission with increasing fluence.

We have further studied the characteristics of the white LEDs before and after irradiation for different injection currents, with the irradiation fluence fixed at 1.98×10^{16} cm^{-2}. Fig. 2a shows the emission intensity curves measured for nine values of the injection currents ranging from 0.01 to 10 mA. These curves refer to irradiated sample A. This example is quite representative since the data for the other samples are similar.

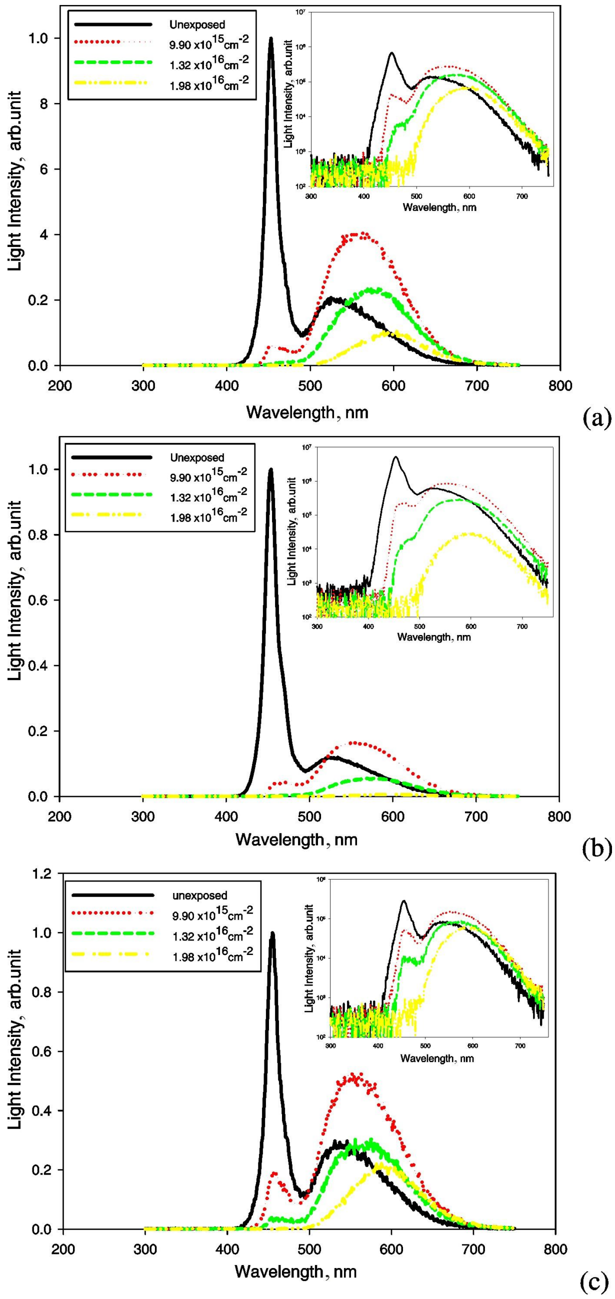

Fig. 1. EL intensity spectra measured for samples A (a), B (b) and C (c) before irradiation (black solid lines) and after irradiation (broken lines of different colours) with the fluences shown in the legend. Inset shows the same spectra on a semi-logarithmic scale. The injection current is equal to 10 mA.

As seen from Fig. 2, the emission intensity increases with increasing injection current. Furthermore, there is a blue shift 2 nm when the injection current increases from 0.01 to 10 mA. This shift should be due to a known band-filling effect [3, 12, 13]. It is caused by the InGaN quantum well which produces discrete energy levels. When the electron concentrations are high enough so that the lowest-energy levels are totally occupied, the electrons located at the higher levels undergo recombination with holes in the valence band. Then there is an increase in the energy released from the recombination, which leads to the blue shift.

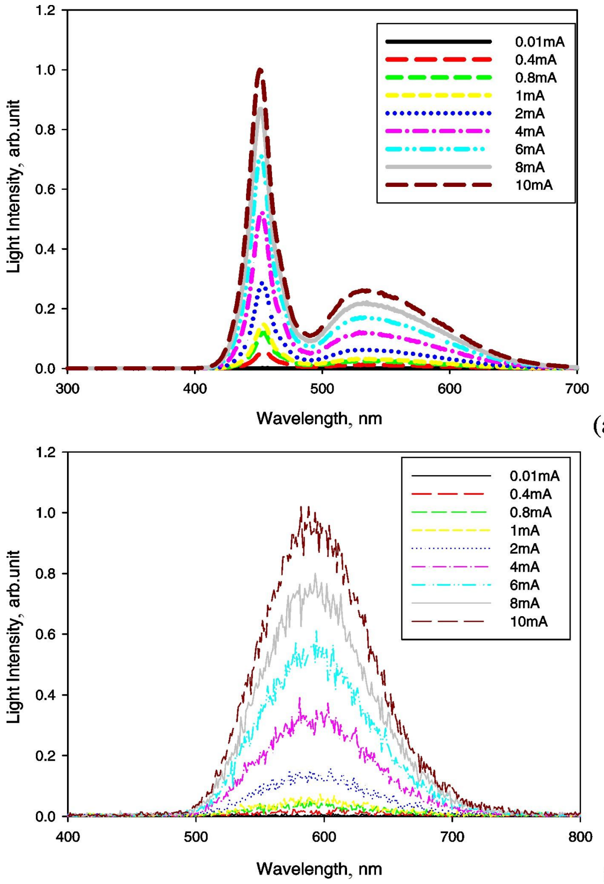

Fig. 2. EL spectra of white InGaN LED (sample A) measured at different injection currents (0.01–10 mA) before irradiation (a) and after electron irradiation with the fluence 1.98×10^{16} cm^{-2} (b).

As seen from Fig. 2b, the blue-peak intensity at 453 nm experiences severe degradation after the sample is irradiated with the fluence 1.98×10^{16} cm^{-2}. In other words, only the yellow EL located near 590 nm remains in the spectrum. The presence of the yellow emission after the irradiation is related to radiative transitions of gallium from the donor band and/or nitrogen vacancies introduced by the irradiation, or the native defects located at the shallow band, to the acceptor levels associated with Ga vacancies [14]. One can also observe that the yellow luminescence experiences a red shift from 550 to 590 nm after the sample is irradiated by electrons.

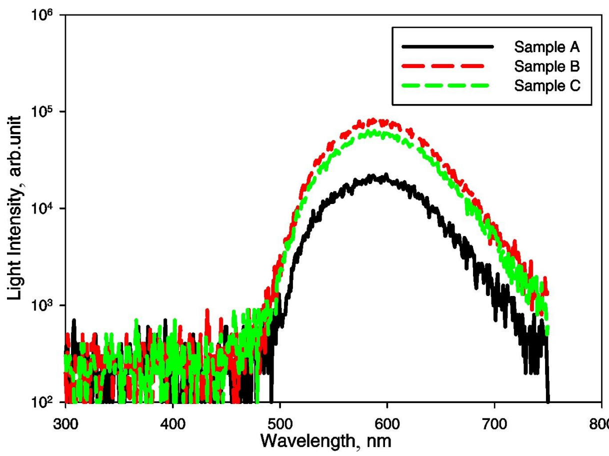

Fig. 3. EL spectra of samples A, B and C measured after irradiation with the fluence 1.98×10^{16} cm^{-2} at a constant current injection, 10 mA.

Fig. 3 shows the EL spectra for the samples A, B and C, which have been detected before and after irradiation at a constant injection current (10 mA). Here the irradiation fluence 1.98×10^{16} cm^{-2} is used. It is evident that the sample A experiences higher EL degradation (26%), when compared with the samples B and C. Meanwhile, the latter samples reveal almost the same emission intensity. One can also see from Fig. 3 that the sample C manifests stronger yellow luminescence, when compared with the sample B. Hence it turns out that the sample B is more irradiation-hard than the sample A. Finally, it is the sample B that appears to be the most preferable, among the three samples, as an optical source for the applications that demand high radiation hardness.

4. Conclusion

We have studied the EL spectra of the commercial white InGaN LEDs at the room temperature before and after these LEDs have been irradiated by electrons. The fluences 9.90×10^{15}, 1.32×10^{16} and 1.98×10^{16} cm^{-2} are used to reveal the effect of irradiation on the optical characteristics of the devices. Our primary aim is to analyze the changes in the light intensities and the emission-peak wavelengths, which are typical for the InGaN LEDs produced by different manufacturers, VCC and Multicomp. The emission intensity for all of our LEDs decreases with increasing dose of the electron irradiation. The reason is irradiation-induced defects that play a role of nonradiative recombination centres. As the injection current increases from 0.01 to 10 mA under the condition of no irradiation, all the samples under test manifest the blue emission shift 2 nm, which is believed to be associated with the band-filling effect. When the samples are irradiated by the fluence 1.98×10^{16} cm^{-2}, the intensity of the blue peak located at 453 nm degrades severely, so that only the yellow EL centred at 590 nm remains for all the samples. This is associated with the radiative transitions from donor band to gallium vacancies. A comparison of degradations experienced by the samples A, B and C leads to conclusion that the sample B (VCC VAOL-10GWY4) reveals the highest hardness with respect to the effect of electron irradiation. The information revealed in this work can contribute to creating better models of white InGaN LED, which are aimed to utilize in space or in some other extreme environments.

References

1. Narendran N, Gu Y, Freyssinier J P, Yu H, Deng L, 2004. Solid-state lighting: failure analysis of white LEDs. J. Cryst. Growth. **268**: 449–456.
2. Sheu J K, Chang S J, Kuo C H, Su YK, Wu LW, Lin YC, Lai WC, Tsai JM, Chi GC, Wu RK, 2003. White-light emission from near UV InGaN-GaN LED chip precoated with blue/green/red phosphors. IEEE Photon. Technol. Lett. **15**: 18–20.
3. Jen-Cheng Wang, Chia-Hui Fang, Ya-Fen Wu, Wei-Jen Chen, Da-Chuan Kuo, Ping-Lin Fan, Joe-Air Jiang, Tzer-En Nee, 2012. The effect of junction temperature on the optoelectrical properties of InGaN/GaN multiple quantum well light-emitting diodes. J. Lumin. **132**: 429–433.
4. Prathika Appaiah, Nadarajah Narendran, Indika U Perera, Yiting Zhu, Yi-wei Liu , 2015. Effect of thermal stress and short-wavelength visible radiation on phosphor-embedded LED encapsulant degradation. Opt. Mater. **46**: 6–11.
5. Saarinen K, Suski T, Grzegory I and Look D C, 2001. Ga vacancies in electron irradiated GaN: Introduction, stability and temperature dependence of positron trapping. Physica B Cond.Matt. **308**: 77–80.
6. Polyakov A Y, Smirnov N B, Govorkov A V, In-Hwan Lee, Jong Hyeob Baek, Kolind N G,

Boiko V M, Merkurisov D I and S. J. Pearton, 2008. Electron irradiation effects in GaN/InGaN multiple quantum well structures. J. Electrochem. Soc. **155**: H31.

7. Pearton S J, Ren F, Patrick E, Law M E, and Polyakov Alexander Y, 2016. Review – Ionizing radiation damage effects on GaN devices. ECS J. Solid State Sci. Technol. **5**: Q35–Q60.
8. Li C and Subramanian S, 2003. Neutron irradiation effects in GaN-based blue LEDs. IEEE Trans. Nucl. Sci. **50**: 1998–2002.
9. Kuriyama K, Kondo H and Okada M, 2001. A point defect complex related to the yellow luminescence in electron irradiated GaN. Solid State Commun. **119**: 559–562.
10. Julkarnain M, Kamata N, Fukuda T and Arakawa Y, 2016. Yellow luminescence band in undoped GaN revealed by two-wavelength excited photoluminescence. Opt. Mater. **60**: 481–486.
11. Hayashi Y, Soga T, Umeno M and Jimbo T, 2001. Origin of yellow luminescence in n-GaN induced by high-energy 7 MeV electron irradiation. Physica B. **304**: 12–17.
12. Su Y, Chi G and Sheu J, 2000. Optical properties in InGaN/GaN multiple quantum wells and blue LEDs. Opt. Mater. **14**: 205–209.
13. Kawakami Y, Omae K, Kaneta A, Okamoto K, Izumi T, Sajou S, Inoue K, Narukawa Y, Mukai T, Fujita Sg., 2001. Radiative and nonradiative recombination processes in GaN-based semiconductors. Phys. Stat. Solidi (a). **183**: 41–50.
14. Demchenko D O, Diallo I C and Reshchikov M A, 2013. Yellow luminescence of gallium nitride generated by carbon defect complexes. Phys. Rev. Lett. **110**: 1–5.

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Анотація. *Проаналізовано вплив електронного опромінення на спектри електролюмінесценції білих світлодіодів на основі нітриду галію індію. Досліджено три різні дози опромінення – 9,90×10^{15}, 1,32×10^{16} і 1,98×10^{16}см$^{-2}$. Для всіх 27 зразків світлодіодів комерційних моделей VAOL-5GWY4, VAOL-10GWY4 і OVL-3321 спостерігаємо суттєве зниження інтенсивності світлового випромінювання після опромінення. Можна вважати, що деградація загальної інтенсивності світла обумовлена викликаними опроміненням дефектами, які діють як центри безвипромінювальної рекомбінації. Вивчено також інтенсивності піків та центральні довжини хвиль випромінювання світлодіодів, підданих електронному опроміненню за умов різного інжекційних струмів. Після опромінення з потужністю 1,98×10^{16} см$^{-2}$ синя смуга, розташована при 453 нм, зазнає серйозної деградації, так що залишається лише жовта люмінесценція на 590 нм. Ця жовта смуга пов'язана з випромінювальними переходами від донорних смуг на рівні, пов'язані з вакансіями галію.*