Evidence for recombination-induced degradation processes in InGaN-based optoelectronic devices

<u>Carlo De Santi</u>^{*1,2}, Matteo Meneghini¹, Alessandro Caria¹, Nicola Renso¹, Ezgi Dogmus³, Malek Zegaoui³, Farid Medjdoub³, Enrico Zanoni¹, and Gaudenzio Meneghesso¹

¹ Department of Information Engineering, University of Padova, Padova, 35131, Italy

² Centro Giorgio Levi Cases, University of Padova, Via Marzolo 9, 35131, Padova, Italy

³ IEMN-CNRS, Avenue Poincaré CS 60069, 59652, Villeneuve d'Ascq, France

For the first time, we demonstrate recombination-induced defect generation in InGaN/GaN-based optoelectronic devices, by stressing InGaN/GaN high periodicity MQW structures: the results will significantly improve the understanding of the degradation of LEDs, lasers and photodetectors, since – so far – only current-driven or temperature-induced degradation processes have been investigated. Photocurrent spectroscopy was used to provide insight in the degradation process.

The devices under test are 25 pairs of $In_{0.15}Ga_{0.85}N/GaN$ (2.2 nm and 4.8 nm thick, respectively) multi quantum-wells, sandwiched between a Mg:GaN (5×10¹⁷ cm⁻³) and a Si:GaN (5×10¹⁸ cm⁻³) layer grown on a sapphire substrate (inset of Fig. 1). During stress in <u>short-circuit</u> condition under illumination with a 405 nm, 361 W/cm² laser diode, the short circuit current was found to decrease significantly (see Fig. 1). This reduction can be detected also by current-voltage characterization under optical excitation (Fig. 2 (a)), providing additional information on the reduction in open circuit voltage and in the maximum electrical power that the cell can supply (Fig. 2 (b)). The variation over time is reported in Fig. 3, showing also a stable fill factor.

By means of photocurrent spectroscopy experiments we detected a clear increase in a broad photocurrent edge at 530 nm (Fig. 4), which is compatible with the yellow luminescence of gallium nitride and, therefore, with the increase in concentration of gallium vacancies [1] and/or complexes involving carbon in nitrogen substitutional position [2] or oxygen [3]. The good correlation between the decrease in the maximum electrical power and the increase in the photocurrent signal of gallium vacancies (inset in Fig. 4) suggests that the generation of gallium vacancies and/or their complexes is the most likely cause for the degradation of the device.

Those devices are ideal structures for testing additional degradation modes. Degradation involves exchange of energy between sources in the device and its atoms. Typical sources investigated in the literature are energetic electrons (current) and phonons (temperature). In an optoelectronic device, photons with energy higher than the bandgap are present in high density and may be an additional cause for degradation, especially in devices for UV applications where the photon energy is higher. Several studies analyze the catastrophic [4] or time-dependent [5] optical damage at the facets of lasers or the damage induced by low-energy photons [6], but up to now no experiment was designed in order to understand if GaN itself may be affected by high energy photon-related degradation. We submitted a device to stress in open circuit condition, i.e. without any contribution to the degradation from current flow, at 1164 W/cm². The photoluminescence maps reported in Fig. 5 show a clear degradation in the device after stress (b) with respect to before stress (a), confirming that a recombination-induced degradation process may take place. This variation does not originate from a change in the device reflectivity, which was found to be uniform (Fig. 6). By means of an infrared thermal camera, we estimated the temperature of the device under stress to be 30 °C, a value that should induce no temperature-related damage in the highly stable gallium nitride. Additional tests to investigate the possible effect of the temperature on this degradation process are currently in progress.



Fig. 1. Schematic cross section of the device under test Fig. 2. (a) Illuminated I-V after every stress step in and short-circuit current degradation during stress in short-circuit condition.







Wavelength (nm)

Fig. 3. Dependence on short-circuit stress time of (a) short-circuit current and open circuit voltage and (b) maximum supplied electrical power and fill factor.



Fig. 4. Increase in photocurrent edge at 530 nm and (inset) its correlation with the reduction in the supplied electrical power during stress in short-circuit condition.



Fig. 5. Photoluminescence map of a device stressed in open circuit condition (a) before and (b) after stress

Fig. 6. Reflectivity map of the device stressed in open circuit condition showing no variation causing the difference detected in Fig. 5.

References: [1] P. Kamyczek et al., J. Appl. Phys. 111 (2012) 113105. [2] J.L. Lyons et al., Phys. Rev. B. 89 [3] J. Neugebauer et al., Appl. Phys. Lett. 69 (1996) 503-505. (2014) 35204. [4] M. Hempel et al., 2015 Semicond. Sci. Technol. 30 072001. [5] T. Schoedl et al., J. Appl Phys. 97, 123102 (2005). [6] S. Elhadj et al., Opt. Mater. Express 7, 202-212 (2017).

Acknowledgements: This research activity was partially supported by University of Padova under research grant BIRD167052/16, "Solar cells based on InGaN for high efficiency photovoltaics and wireless power transmission", and by the Interdepartmental Centre Giorgio Levi Cases under research grant 2017LC2, "Celle solari basate su InGaN per fotovoltaico ad alta efficienza e trasmissione wireless dell'energia".