

Photon-driven degradation processes in GaN-based optoelectronic devices

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In order to ensure a complete transition from conventional light sources to gallium nitride based devices it is important to guarantee an improvement in device lifetime. Common degradation driving factors include temperature and bias, and most reports in the literature suggest that degradation processes in nominal operating conditions are current-driven and thermally-activated. Given the high optical power densities needed in high brightness applications, such as micro-displays and projection systems, the possible role of the extreme photon flux in limiting the lifetime of the device needs to be investigated.

The devices under test are photodetectors composed of 25 pairs of In_{0.15}Ga_{0.85}N/GaN multi-quantum wells, with a well thickness of 2.2 nm and a barrier thickness of 4.8 nm. They are grown on a sapphire substrate, the n-GaN layer is 5×10^{18} cm⁻³ silicon doped and 2 μm thick, whereas the p-GaN layer is 5×10^{17} cm⁻³ magnesium doped and 100 nm thick. The device was stressed in open circuit condition under resonant excitation with a 405 nm laser diode at 361 W/cm².

After stress, the current-voltage characteristic shows a clear increase in leakage current in reverse and low forward conduction, demonstrated in the literature to be caused by an increase in deep level concentration inside the active region. The degradation caused by the optical stress is visible also in the monochromatic photoluminescence maps recorded at 437 nm, showing a clear decrease in photoluminescence in the region where the laser was focused. This variation could also be caused by a local change in the surface reflectivity, leading to a lower number of photons in the active region, but the measured reflectivity map does not show any variation compatible with the degraded area.

Since the stress is carried out in open circuit condition, current flow can not be the cause of the degradation. Given the high laser intensity on the device under test during stress, it is still possible that the corresponding increase in temperature is causing the detected PL variation. For this reason, we measured the temperature of the photodetector under stress by means of an infrared thermal camera, obtaining a peak temperature of 30 °C. This temperature evaluation method is known to introduce an error related to the low resolution of the IR camera, which by comparison with the literature was estimated to be 60 °C in the worst case (10 °C in a more likely case). For this reason, we submitted an unaged device to purely thermal stress at 100 °C, i.e. a temperature higher than the worst case estimate, for the same amount of time, finding no electrical degradation of the device. The PL maps highlight some degradation, stronger at the edges, that is likely caused by intake of impurities from air, given that the devices are not passivated. In order to verify that temperature effectively induces a different degradation mode with respect to the one detected during the optical stress, we submitted the optically-degraded sample to the same thermal stress. This additional treatment caused a recovery of the leakage current and no preferential PL degradation or annealing in the optically-degraded region, proving that temperature is not causing the damage detected during the optical stress.

Since the two main driving forces have been ruled out, the only remaining source of energy that can lead to the degradation are the photons. Direct lattice damage is unlikely, given the high GaN bond energy (~ 8.9 eV). A more likely hypothesis is the de-hydrogenation of gallium vacancies, a process leading to a worsening of the optical performance of GaN-based devices [H. Nykänen APL 100 122105 (2012)]. The energy required for this process was computed to be lower than the energy gap in GaN [Van de Walle, Phys. Rev. B. 56 10020 (1997)], suggesting that the degradation may be caused by the de-hydrogenation of gallium vacancies promoted by the photons. This hypothesis is supported by the increase in yellow luminescence detected in the optically-degraded region, and by previous stress tests carried out on the same devices in short circuit condition, showing an increase in optically-active gallium vacancies by photocurrent spectroscopy.

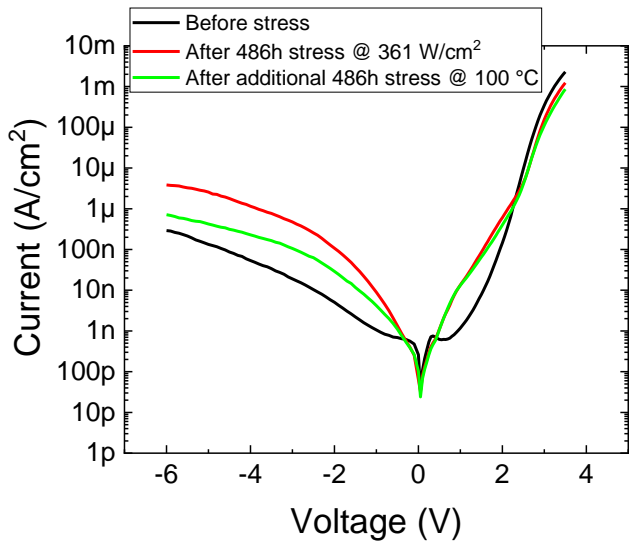


Fig. 1: Degradation caused by optical stress and recovery induced by subsequent thermal stress.

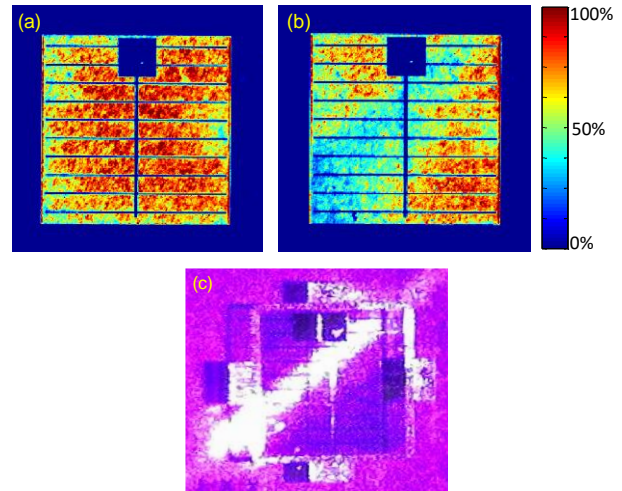


Fig. 2: Monochromatic (437 nm) resonant PL maps of a device (a) before and (b) after optical stress. (c) shows a DUT picture during the stress.

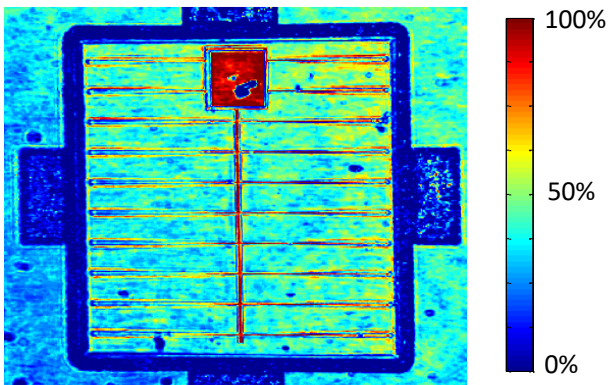


Fig. 3: Surface reflectivity map of the optically-stressed device, showing that it is not causing the PL variation.

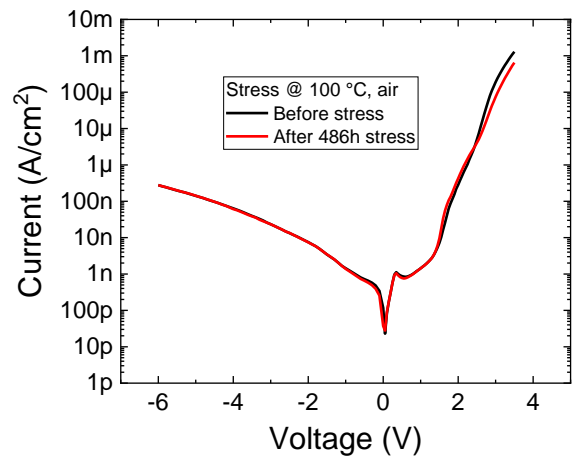


Fig. 4: Stability of an untreated device after thermal stress at a temperature comparable to the one of the optical stress.

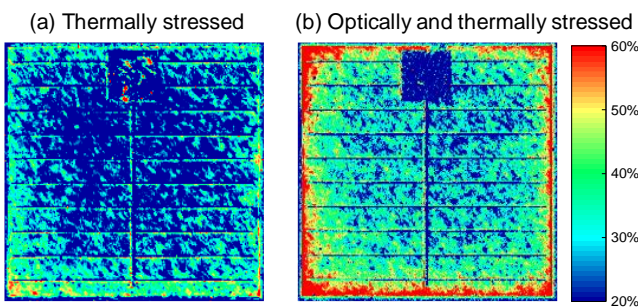


Fig. 5: PL degradation maps of the thermal stress on (a) untreated and (b) optically-stressed device, showing no preferential degradation or recovery in the optically-degraded region.

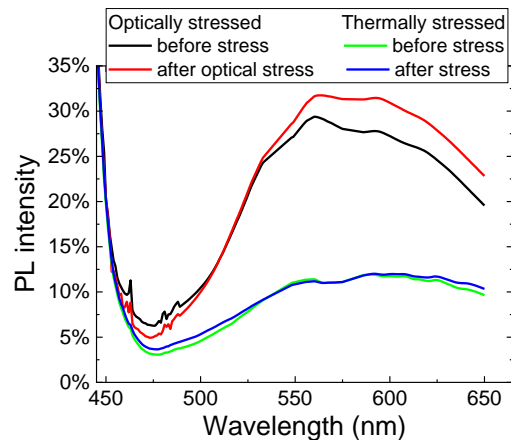


Fig. 6: PL spectra of the degraded region, supporting the assumption that the cause of the degradation is the increase in optically-active gallium vacancies.