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Abstract

Within this paper we analyze the reliability of 25x multi quantum well InGaN-based devices, designed to be used as high power photodetectors or in multi-junction solar cells. Under stress with monochromatic excitation at 405 nm by means of a laser diode, we detect degradation at optical power levels significantly above the common AM1.5 spectrum; the main degradation modes are a reduction in short circuit current and in open circuit voltage, and an improvement in fill factor. The analysis of the wavelength-dependent EQE highlights, as a consequence of stress, the increase in concentration of a deep level compatible with the yellow luminescence in gallium nitride, suggesting that gallium vacancies may play a role in the degradation of the detectors.

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1. Introduction

InGaN-based multi-quantum well structures are widely adopted for the fabrication of LEDs, for application in general lighting. These devices employ a limited number of quantum wells to promote carrier transport and enable high quantum efficiency.

Over the last few years a growing interest was given to devices with higher periodicity, up to 50 multi-quantum wells (MQW) [1]. The field of application of these structures ranges from wavelength-sensitive photodetectors able to withstand high optical power densities [2], to receivers in LiFi communication systems. Additionally, InGaN-based structures can be used to increase the efficiency of multi-junction solar cells, improving the absorption in the blue spectral range, not covered by lower-bandgap materials [3]. Moreover, they can enable entirely new products and applications, such as long-distance wireless power transfer, which is, for the moment, analyzed only in the IR region [4].

Although many papers discuss the effect of the structure and design parameters on the performance of InGaN photodetectors [1,5–10], no paper in the literature analyses the reliability of these devices, a critical parameter taking into account the high power density they need to collect in solar cell systems with light concentration or in power transfer systems.

In this paper, for the first time we will carry out a reliability study on MQW photodetectors under high power excitation provided by a 405 nm laser diode. We provide experimental evidence that the photodetectors are stable up to high excitation power densities (5 W/cm^2), and that the degradation consists in a reduction in the short circuit current (I_{sc}) and in the open circuit voltage (V_{oc}), leading to a lower maximum electrical power at the output of the detector and to an improvement of the fill factor. Based on C-V and photocurrent characterization, we attribute the variation in the device performance to an increased SRH recombination inside the active region, caused by the generation of deep levels during the stress.

2. Experimental details

The devices under test are MQW solar cells grown on c-plane sapphire by metal-organic chemical vapor deposition (MOCVD). After a buffer layer, a 2 µm thick n-GaN:Si (5 × 10^{18} cm^{-3}) is grown before the active region, consisting in 25 pairs of nominally undoped $In_{0.15}Ga_{0.85}N$/GaN quantum wells. The p-GaN:Mg (5 × 10^{17} cm^{-3}) layer is 100 nm thick and lies below a semi-transparent Ni/Au current spreading layer with Ni/Au grids. Additional details on the final device structure and material quality can be found in [11]. The average short circuit current under AM1.5 excitation is 0.5 mA/cm^2.

The optical excitation was provided by means of a high power 405 nm laser diode (nominal output power 2.3 W at 1.5 A). The laser was cooled by a Peltier element to prevent its degradation, and an optical feedback was present in the system to obtain a stable output optical power.

Preliminary tests (not shown) confirmed stable behavior of the devices up to 5 W/cm^2 excitation power density. Therefore, the first test we carried out is a step-stress experiment, i.e. the analysis of the degradation caused by 30 minutes under increasing optical excitation levels from 60.4 W/cm^2 to 117 W/cm^2 in short-circuit bias condition. By means of the information obtained during this first test, we choose an appropriate optical power density, equal to 364 W/cm^2, for a stress test under constant illumination conditions. During the stresses, we monitored the dark and under laser light I-V behavior of the detector, the C-V characteristic and the photocurrent under calibrated monochromatic excitation.

3. Step-stress tests

The variation of the short circuit output current from one device under test is reported in Fig. 1 (a). As can be noticed, the current variation is minor up to 174 W/cm^2, and shows a sharp decrease only at 759 W/cm^2 or higher. Taking into account that the short circuit current under AM1.5 illumination is 0.5 mA/cm^2, those values indicate an excellent reliability of the detector. This is confirmed also by the stability of the current-voltage curves in dark condition (see Fig. 1 (b)).

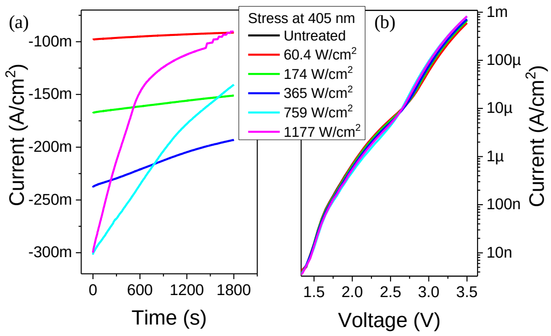

Fig. 1: (a) short circuit current of a photodetector stressed under increasing optical power density levels and (b) corresponding stability of the I-V curves in dark condition.

The same effect can be detected by the analysis of the electrical behavior under illumination at 405 nm and 0.755 W/cm^2. A strong variation in short circuit current is visible after the stress at 759 W/cm^2, causing a sharp decrease in the overall output electrical power curve (see Fig. 2).

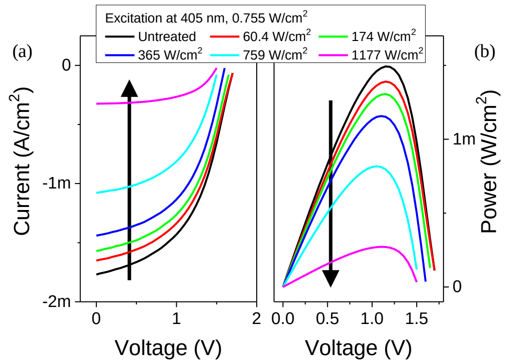

Fig. 2: (a) I-V curves under excitation at 0.755 W/cm^2 after stress at several excitation power densities, along with the computed output power curves (b).

For a clearer understanding, the values of I_{sc} and the maximum of the electrical power are plotted, as a function of time, in Fig. 3 (a) and (b), respectively. Along with the short circuit current, Fig. 3 (a) shows the variation of a second important parameter: the open circuit voltage. The value of V_{oc} significantly decreases during stress, possibly due to an improvement in dopant activation or contact quality [3,12]. The lower value of the open circuit voltage and the higher slope of the I-V curve at voltages slightly lower than V_{oc} cause an unexpected positive side-effect: the fill factor improves after stress, as reported in Fig. 3 (b).

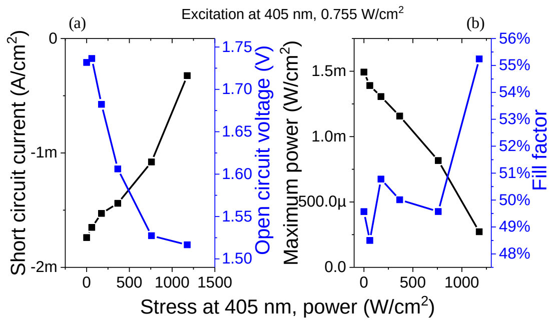

Fig. 3: (a) variation of the short circuit current and open circuit voltage after stress at various optical power densities, causing (b) a reduction in the maximum electrical power from the detector and an improvement in the fill factor.

The strong variation in short circuit current corresponds to a reduction in external quantum efficiency (EQE), as can be noticed in Fig. 4 (a) (the magnitude of the changes is different since Isc and EQE are measured under different excitation conditions [13,14,2]).

Fig. 4 (b) reports the apparent free charge profiles extrapolated from C-V measurements. A clear decrease in charge density in one sharp position is visible, which could correspond to one of the 25 quantum wells.

All the experimental data suggest that the effect of the stress is the creation of defects inside the active region of the detector. A higher concentration of deep levels leads to a stronger Shockley-Read-Hall recombination, causing a larger part of the electron-hole pairs generated by the excitation laser to recombine non-radiatively. Therefore, a lower amount of carriers can be collected at the output, lowering the short circuit current, and a lower amount of free charge is present in the device for the same bias voltage, causing the detected variation in the apparent charge profile.

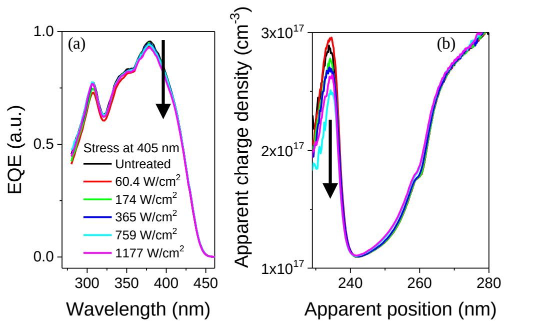

Fig. 4: Decrease in the (a) EQE and (b) apparent charge profile after stress at 405 nm and various optical power densities.

To confirm this hypothesis, we carried out additional stress tests under constant excitation power density, in order to monitor the time-dependence of the degradation.

4. Constant excitation stress tests

The results of the constant excitation stress tests confirm the trend detected in the previous section. As can be seen in Fig. 5 (a), the stress causes a decrease over time in the short circuit current and in the open circuit voltage. These two changes lower the maximum electrical power that the detector is able to supply, as reported in Fig. 5 (b), and the improvement in fill factor is confirmed by a monotonic behavior over stress time.

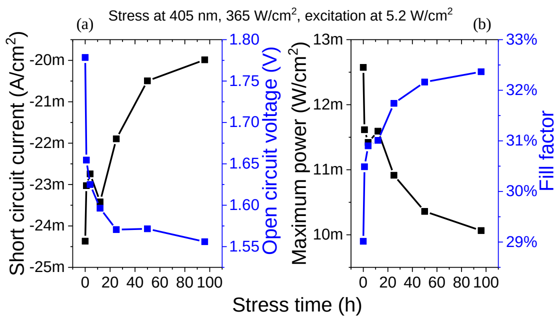

Fig. 5: (a) variation of the short circuit current and open circuit voltage during stress at 405 nm and 365 W/cm^2, causing (b) a reduction in the maximum electrical power from the detector and an improvement in the fill factor.

The analysis of the EQE curves, shown in Fig. 6, confirms in a clearer way the findings in Fig. 4 (a). The stress causes a reduction in both peak EQE and EQE at 405 nm, i.e. at the laser wavelength. This effect is consistent with the detected change in short circuit current and suggests the creation of deep levels in the active region.

This assumption is confirmed by an increase over time in a photocurrent edge around 530 nm (see the inset in Fig. 6), compatible with the yellow luminescence band in gallium nitride [15]. The yellow luminescence is commonly ascribed to the presence of gallium vacancies [15], possibly in a bonded state with oxygen [16,17] or carbon [18–20]. A higher photocurrent signal reveals the presence of a higher concentration of gallium vacancies, defects created as a consequence of the stress that may play a role in the variation of the detector performance.

Fig. 6 highlights a variation in a EQE peak at 306 nm, whose analysis will be given in the extended version of the paper due to length constraints. The behavior over stress time of the relevant values is reported in Fig. 7 for clarity.

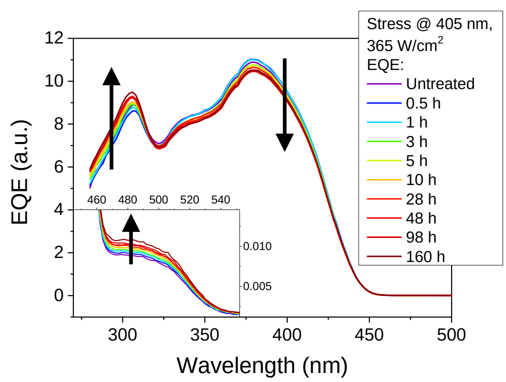

Fig. 6: variation in the spectrally-resolved EQE of a

detector during stress at 405 nm, 365 W/cm^2. Inset: increase in photocurrent signal from a deep level at about 530 nm.

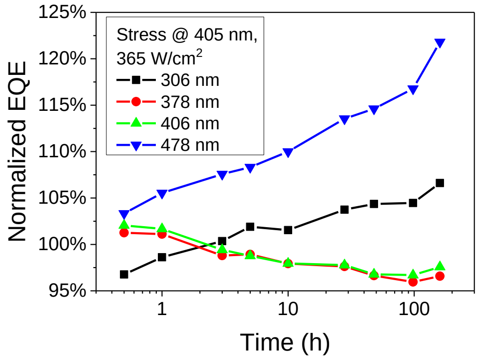

Fig. 7: variation over time of the most relevant EQE values.

5. Conclusions

In summary, within this paper we provide experimental evidence that the degradation of MQW InGaN photodetectors under laser excitation is caused by the generation of defects inside the active region, which act as a parasitic recombination channel leaking part of the photogenerated electron-hole pairs.

By means of spectrally-resolved EQE analysis, we detect the increase in concentration of a deep level, whose signature is compatible with the yellow luminescence in gallium nitride. Therefore, gallium vacancies or their complexes could be responsible for the variation in the performance of the detectors.

Acknowledgements

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