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Understanding the Physics of Electro-Optical Degradation

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ABSTRACT

III-N optoelectronic devices are of great interest for many applications. Visible emitters (based on InGaN) are widely used in the lighting, display and automotive fields. Ultraviolet LEDs (based on AlGaN) are expected to be widely used for disinfection, medical treatments, surface curing and sensing. Photodetectors and solar cells based on InGaN are also of interest, thanks to their great robustness and wavelength tunability.

III-N semiconductors are expected to be robust, thanks to the wide bandgap (allowing high temperature operation) and to the high breakdown field (favoring the robustness against electrostatic discharges and electrical overstress). However, InGaN- and AlGaN-based devices can show a significant degradation when submitted to long-term ageing. Several driving forces can contribute to the worsening of the electrical and optical characteristics, including the operating temperature, the current, and the rate of non-radiative recombination in the quantum wells. The goal of this paper is to discuss the physics of degradation of III-V devices, by presenting a set of recent case studies, evaluated in our laboratories.

Keywords: III-N, gallium nitride, defect, degradation, reliability, LED, light-emitting diode

1. INTRODUCTION

In the past two decades, the III-N material system has demonstrated to be ideal for the fabrication of visible and ultraviolet (UV) light-emitting diodes. By using InGaN, devices emitting in the visible spectral range can be fabricated. On the other hand, the AlGaN ternary is used to extend the wavelength range towards the ultraviolet spectral range.

This paper describes the physical processes responsible for the degradation of III-N optoelectronic devices, by presenting recent experiments carried out in our group on this topic.

First, we briefly discuss the physical properties of defects in III-N LEDs, by presenting an analysis based on deep-level optical spectroscopy. The results of this analysis provide information on the ionization energy of defects correlated to non-radiative recombination, and on their spatial distribution/density. Hypotheses on the physical nature of defects are formulated, based on the comparison with previous literature reports.

Second, we describe the impact of current stress on the electrical and optical characteristics of the devices. The results demonstrate that – after a mid-term stress test – a variation in optical power may be measured, and discuss the interplay between the different involved mechanisms.

Third, we demonstrate that electrical stress may induce a significant change in the electrical characteristics of light-emitting diodes. This process is modeled by considering an increase in trap density within the active region of the devices, due to the generation/propagation of defects, and the degradation of the ohmic contacts at the p-side.

TCAD modeling is used to describe the impact of defects on the electrical and optical efficiency of the devices, and to provide a more complete description of the degradation processes.

2. SUMMARY OF MAIN RESULTS

2.1 Defects in III-N materials

III-N light-emitting diodes are typically grown heteroepitaxially, on a foreign substrate that has a significant lattice mismatch with the semiconductor material. As a consequence, extended defects are generated at the interface. Also point defects are generated within the epitaxy, depending mainly on the growth conditions. Common point defects related to non-radiative recombination may include group-III vacancies and related complexes [REF], and di-vacancy complexes [REF]. Foreign impurities that may alter the electro-optical characteristics of the devices include carbon [REF], magnesium [REF], and calcium [REF], among others. In recent reports [REF], by using deep-level optical spectroscopy (DLOS) we demonstrated that (i) in visible LEDs the density of point defects responsible for non-radiative recombination is higher in In-containing layers; (ii) such defects are located near midgap, thus representing relevant non-radiative recombination centers; (iii) the density of defects in the quantum wells strongly depends on the indium content. A large database of the properties of defects in GaN has been created [REF Buffolo], and can be used to identify defects detected experimentally.

2.2 Impact of mid-term and long-term stress

During a mid-term stress test, III-N based light-emitting diodes can show a variation in the optical power. Here we observed a change in the light output vs. current (L-I) curves. When – during a high-current degradation test - the optical degradation is analyzed at low-injection levels, a stronger decrease may be observed [REF], due to the generation/propagation of non-radiative defects and the increase in the related recombination rate. In the high (measuring) current regime, a decrease in optical power may be ascribed to a worsening of the injection efficiency, and/or to an increased trap-assisted Auger-Meitner (TAAM) recombination [REF].

Other devices showed an increase in the optical power. This effect is ascribed to a larger overlap of the electron-hole wavefunction, due to the creation of charged defects near the active region, and/or to an improvement in the carrier injection efficiency after stress [REF]. In visible LEDs, devices with higher indium content in the quantum wells were found to show a stronger degradation rate during step-stress experiments, possibly due to the higher initial density of defects [REF https://iopscience.iop.org/article/10.1088/1361-6463/ac2693/pdf].

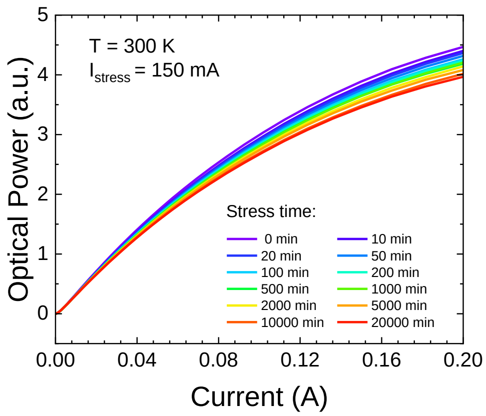

Figure 1: example of optical power vs current characteristics measured on a visible LED during a mid-term ageing experiment

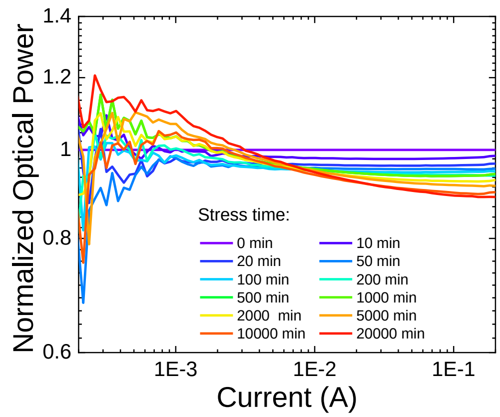

Figure 2: relative variation in optical power measured at different current levels on the same LED as in Figure 1

2.3 Degradation of the electrical characteristics

The electrical characteristics of the devices can be significantly modified during long-term operation; the analysis of the semi-logarithmic current-voltage plots can provide relevant information on the physics of degradation. A first degradation mode that can be observed both in visible and UV LEDs is an increase in the series resistance, which is typically ascribed to the degradation of the electrical properties at the p-side/p-contact of the diodes, due to the passivation of the Mg-doping by hydrogen [REF TED Meneghini 2006]. A second ageing indicator for both InGaN and AlGaN LEDs is the increase in the sub turn-on I-V characteristics of the devices, consisting in a variation in the leakage in the low-moderate voltage range [REF papers Roccato]. An example is shown in Figure 3, for a visible InGaN LED: sub turn-on leakage increases significantly for voltages between 0.5 V and 2.5 V. This effect was modeled by considering an increase in trap-assisted tunneling (TAT), related to the generation of trap-levels near/within the space charge region. The adopted model considers TAT to originate from a SRH-like process, consisting in the combination of two capture/emission mechanisms: a phonon-assisted inelastic process and an elastic transition process [REF ROCCATO+MANDURRINO]. A schematic representation is given in Figure 4 [see also REF ESREF Roccato], while an expression of the recombination rate is given by

$$R_{TAT} = \frac{N_T c_n c_p (np - n_i^2)}{c_n \left(n + \frac{n_i}{g_n} e^{\frac{E_{T,i}}{k_B T}} \right) + c_p \left(p + \frac{n_i}{g_p} e^{-\frac{E_{T,i}}{k_B T}} \right)}$$

TCAD simulations were carried out to reproduce this process, showing a good agreement with the experimental data. The properties (density, ionization energy) of defects to be used in simulations can be extracted from deep-level optical spectroscopy analysis, see for instance [REF JPhysD and ESREF2022Roccato].

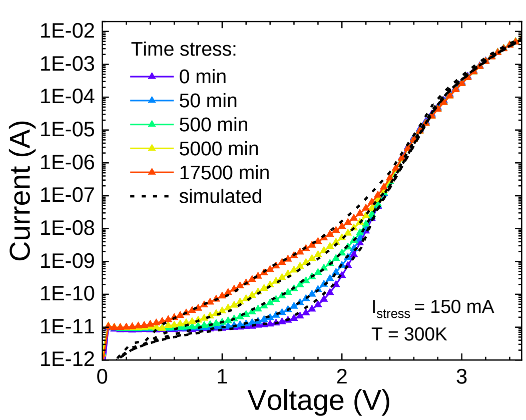

Figure 3: changes in the sub turn-on region of the I-V characteristics of an InGaN LED, due to the increase in defect-related leakage current

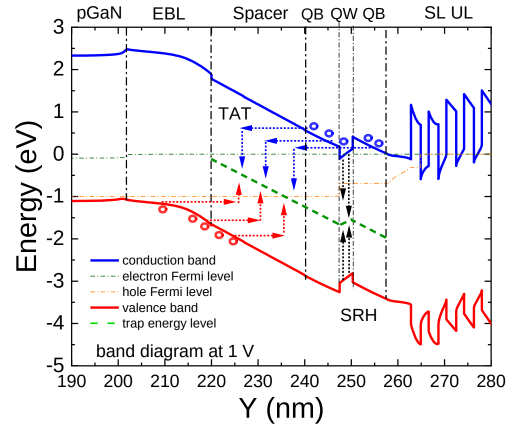

Figure 4: schematic representation of the TAT mechanism responsible for the variation in the electrical characteristics in Figure 3, overlayed with a TCAD-simulated band diagram

2.4 Modeling the changes in the optical efficiency

The generation of traps near or within the active region can significantly impact on the optical efficiency of the devices. Results of electro-optical simulations (Figure 5, 6) indicate that traps have the maximum impact on the electro-optical efficiency when they are located in the quantum wells; traps located in the barriers/spacers can impact on the injection efficiency and/or on the tunneling components. Another important effect of the presence of traps in the QWs is a decrease in carrier density, which originates from the increased non-radiative recombination. This may result in a lower screening of the quantum confined Stark effect (QCSE), which further reduces the overlap of electron-hole wavefunctions, and can imply a red-shift of the emission peak.

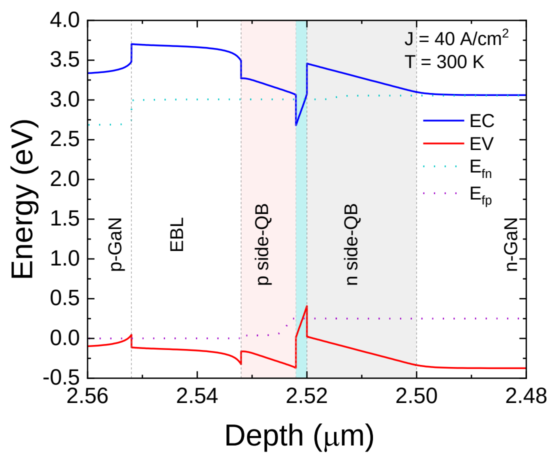

Figure 5: simulated band diagram for an InGaN SQW LED

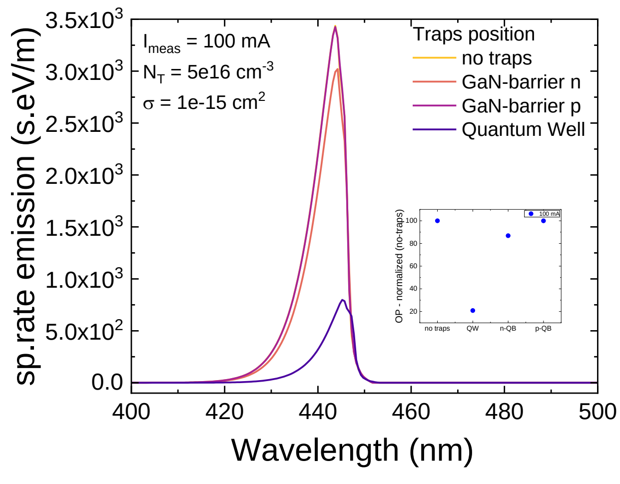

Figure 6: simulated spectra for an InGaN QW, without traps, and with traps in individual layers

3. CONCLUSIONS

In summary, several processes may limit the performance and the lifetime of light-emitting diodes based on III-N semiconductors. Starting from a detailed analysis of the main electrical and optical ageing indicators, it is possible to identify such processes, that include: a) an increase in the non-radiative recombination rate, due to the generation of traps in the active layer of the devices; b) a variation in the injection efficiency, due to the redistribution of charge within the device structure; c) a degradation of the resistivity of the contact at the p-type of the devices, resulting in an increased series resistance and turn-on voltage; d) an increase in trap-assisted tunneling, that impacts on the electrical characteristics of the devices in the sub turn-on regime. Through combined electro-optical characterization and device modeling it is possible to achieve a detailed description of the related phenomena.

REFERENCES

[1] Booth, N. and Smith, A. S., [Infrared Detectors], Goodwin House Publishers, New York & Boston, 241-248 (1997).
[2] Davis, A. R., Bush, C., Harvey, J. C. and Foley, M. F., "Fresnel lenses in rear projection displays," SID Int. Symp. Digest Tech. Papers 32(1), 934-937 (2001).
[3] Van Derlofske, J. F., "Computer modeling of LED light pipe systems for uniform display illumination," Proc. SPIE 4445, 119-129 (2001).
[4] Myhrvold, N., “Confessions of a cybershaman,” Slate, 12 June 1997, <http://www.slate.com/CriticalMass/97-06-12/CriticalMass.asp> (19 October 1997). www.optics4yurresearch.com/7752.html
[5] Jones, C. J., Director, Miscellaneous Optics Corporation, interview, Sept. 23 2011
[6] FamilyName, GivenName Initial., "Title," Source, pg# (year).