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Unveiling charge carrier dynamics of GaN-based materials through a combined Cathodoluminescence and Kelvin Probe Force Microscopy under variable illumination protocol

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In this study, we developed a method combining cathodoluminescence (CL) and KPFM under variable illumination to study GaN-based materials, by showing two case studies: n.i.d. GaN-on-Si and GaN/InGaN MQW mesa structures. These two techniques were chosen for their complementarity (CL has access to the radiative recombination and KPFM to radiative and non-radiative recombination) and their nanometric spatial resolution (well suited to study dislocations).

Kelvin Probe Force Microscopy (KPFM) is a relatively widespread technique that permits to map the Contact Potential Difference (CPD) between a probing tip and the sample with nanometric resolution. By measuring the CPD in darkness and under illumination, we can map the Surface Photo-Voltage (SPV), defined as the change in the surface potential induced by the reorganization of the photo-generated carriers. The SPV, therefore, can shed light onto the different processes of charge transport, recombination and trapping in the material. The measurement protocol (see Fig. 1) consists on dividing the sample surface to study into a grid of pixels and measure simultaneously the topography (by AFM) and the CPD as a function of the laser power used to illuminate the sample. During the measurement, the laser is turned on, its power is increased linearly until arriving to a plateau of the CPD and, finally, the laser is switched off, measuring until the CPD comes back to the initial state in darkness. This method allows us to follow the SPV during the generation and recombination of charges, giving us information about the charge transfer dynamics on the system rather than a static picture. Furthermore, we performed these measurements at low temperatures in order to see the effect of this parameter on the material's surface potential.
Regarding CL, we developed a protocol to measure the same sample area at different temperatures, in order to obtain an estimation of the internal quantum efficiency (IQE), and different electron beam energies, to probe different depths of the sample.

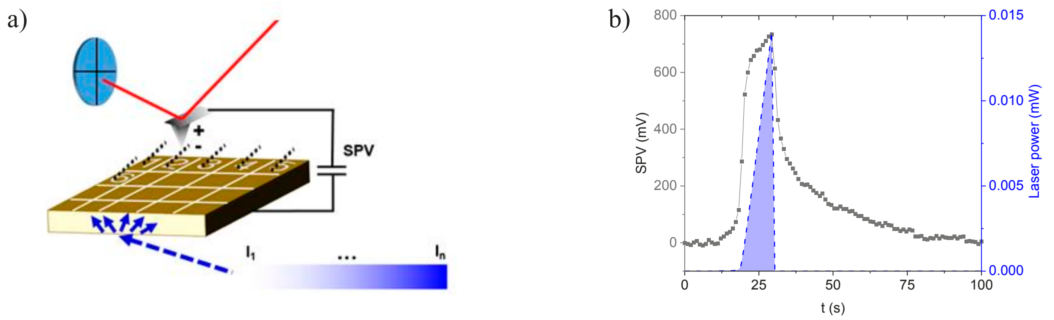

Figure 1: a) Scheme of the KPFM under variable illumination protocol. b) Example of the SPV curve (gray squares) respect to the laser power (blue dashed line) obtained in one pixel of a MQW GaN/InGaN LED illuminated with a laser with 405 nm emission.

For both studied samples, we found a considerably long decay time (around 70 s), compared to the carrier lifetimes reported on bibliography, on the order of ns or ps. These data suggest that the observed slow decay does not correspond to the recombination of carriers but to de-trapping from deep defect energy levels. Regarding this sample, we measured longer time decay constants around dislocation pits (Fig. 2.c), identified by AFM (Fig. 2.a), which indicates more trapping of negative charges on dislocations. This is also in agreement with the lower SPV signal found around pits (Fig. 2.b). Furthermore, the low temperature measurements reveal two different components contributing to the SPV with different sign (Fig. 2.d). We propose a hypothesis for this behavior, attributing the positive contribution to the SPV to the transfer and trapping of holes to surface states due to the upwards surface band bending, and the negative signal to the trapping of electrons on dislocation-related defect levels. The CL measurements showed less light emission from dislocations. Therefore, from these two techniques combined, we can conclude that the trapping of charges on dislocations decreases the radiative recombination activity.

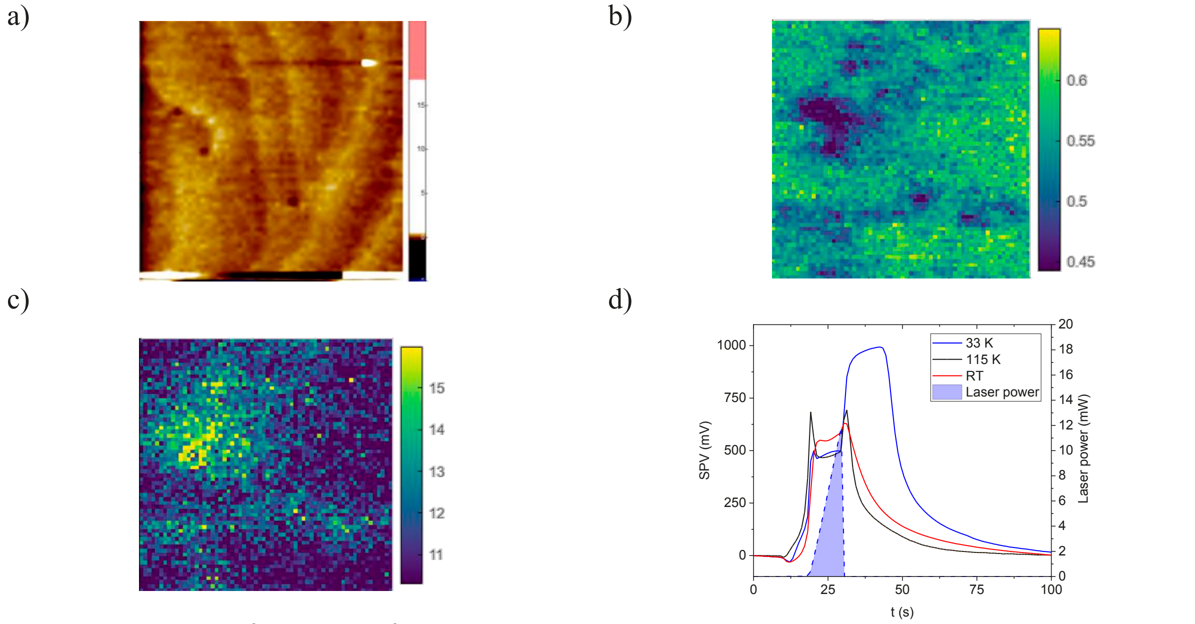

Figure 2: 800 x 800 nm^2, 64 x 64 px^2 image on GaN-on-Si: a) topography (AFM) in nm, b) SPV at maximum illumination in mV, c) time decay constant map from the fit in each pixel in seconds and d) SPV vs. time as a function of laser power at three different temperatures.

With respect to the GaN/InGan MQW mesas, we also observed long decay of the SPV, however, in this case, this decay could be better described by a double exponential, indicating the presence of at least two different dynamics on the de-trapping process with the same sign. By CL, we observed a reduction of the light MQW emitting efficiency on the border of the mesas, known to be a problem for the miniaturization of LEDs. However, no border effect was observed through KPFM, from which we can conclude that the well reported border effect on LEDs is not caused by trapping of charges but by other mechanism.

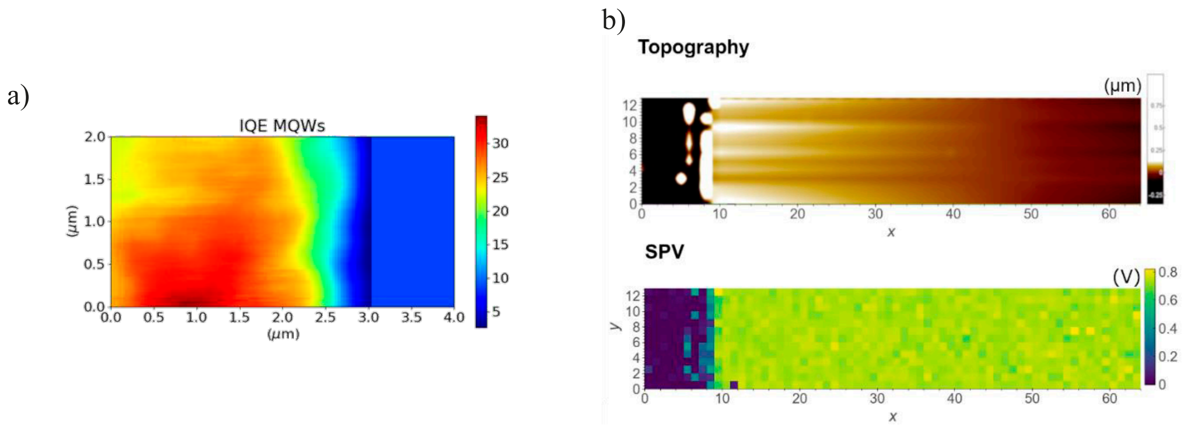

Figure 3: a) Internal quantum efficiency map (obtained from dividing the maps measured at room temperature and low temperature) and b) topography and SPV under maximum illumination maps (4 x 0.8 µm^2, 64 x 13 px^2) on the border of a 1 x 1 mm^2 mesa.

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