Cathodoluminescence spectroscopy of InGaN LEDs under applied bias

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Background/motivation

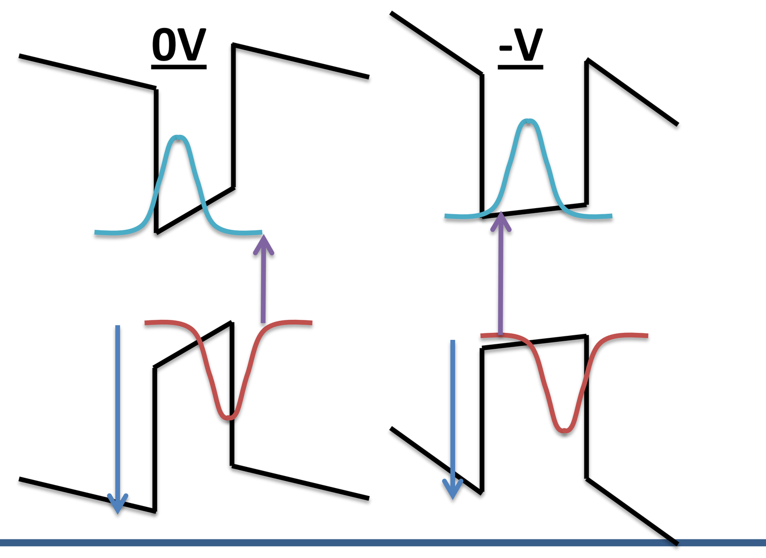
- The effect of electric fields and carrier dynamics upon the recombination characteristics of InGaN light emitters is not fully understood.
- Cathodoluminescence (CL) is a common tool for the investigation of carrier behaviour in semiconductors, but in uncontacted structures it cannot take into account the changing junction fields intrinsic to the operation of devices.
- Bias dependent CL allows for the independent control of excitation conditions and junction field.

Depth dependent and Hyperspectral CL

- By employing CL as a function of beam energy we generate carrier distributions which peak at depths in and around the quantum well region and p/n junction of our LED. At each of these beam energies the applied bias is change to investigate vertical carrier transport into the active region.
- Hyperspectral datasets, where a CL spectrum is collected at each point in a high resolution raster scan of the LED, were obtained at +2V, 0V and -2V to determine lateral luminescence properties.

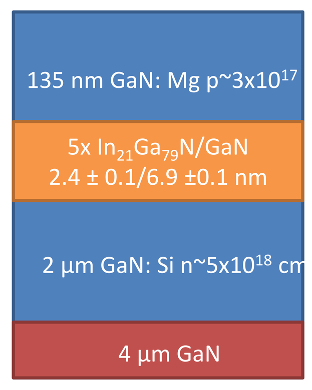
Bias dependent spectroscopy

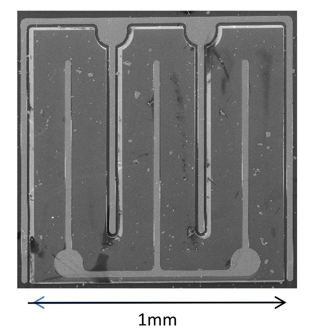
- In InGaN LEDs, the built in field of the p/n junction opposes the piezoelectric field created at the barrier of GaN and InGaN
- Applying reverse bias compensates the quantum confined Stark Effect (QCSE) and lowers of the potential barrier for carrier tunnelling. Consequently, emission under reverse bias is blue shifted and decreased in intensity.



Sample details

- Five period $In_{21}Ga_{79}N$/GaN c-plane with 2.4nm wells and 6.9nm barriers and emitting at ~495nm at 10mA
- 135nm p-GaN layer and 2µm n-GaN layer
- Device fabricated into 1mm^2 chips with an interdigitated contact structure

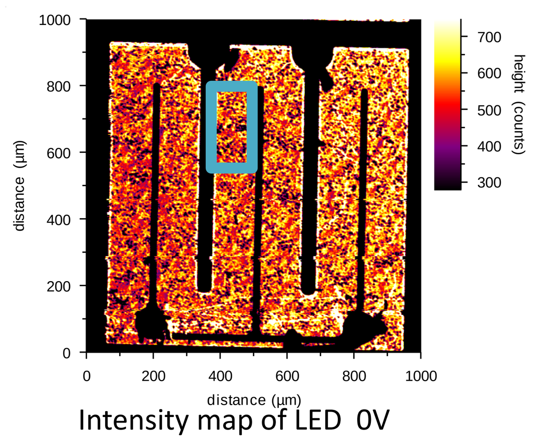




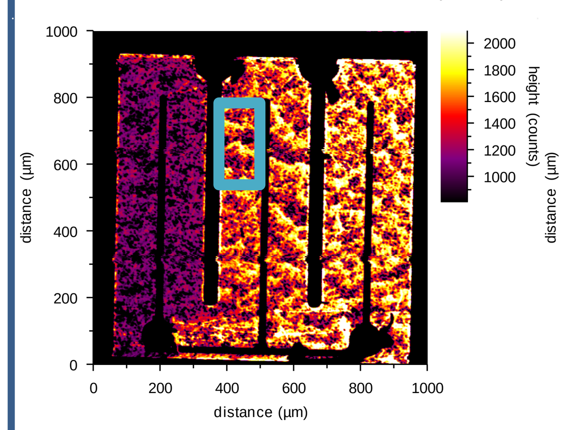
SEM image of single chip

CL Hyperspectral Imaging

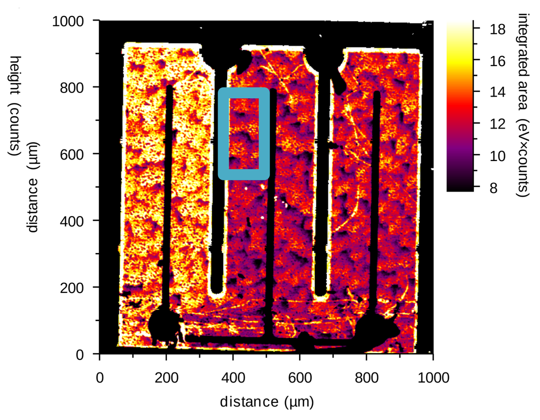
- Hyperspectral data sets of a single LED die were collected with a beam energy of 9kV in 2µm steps and at -2, 0 and +2V



Intensity map of LED 0V

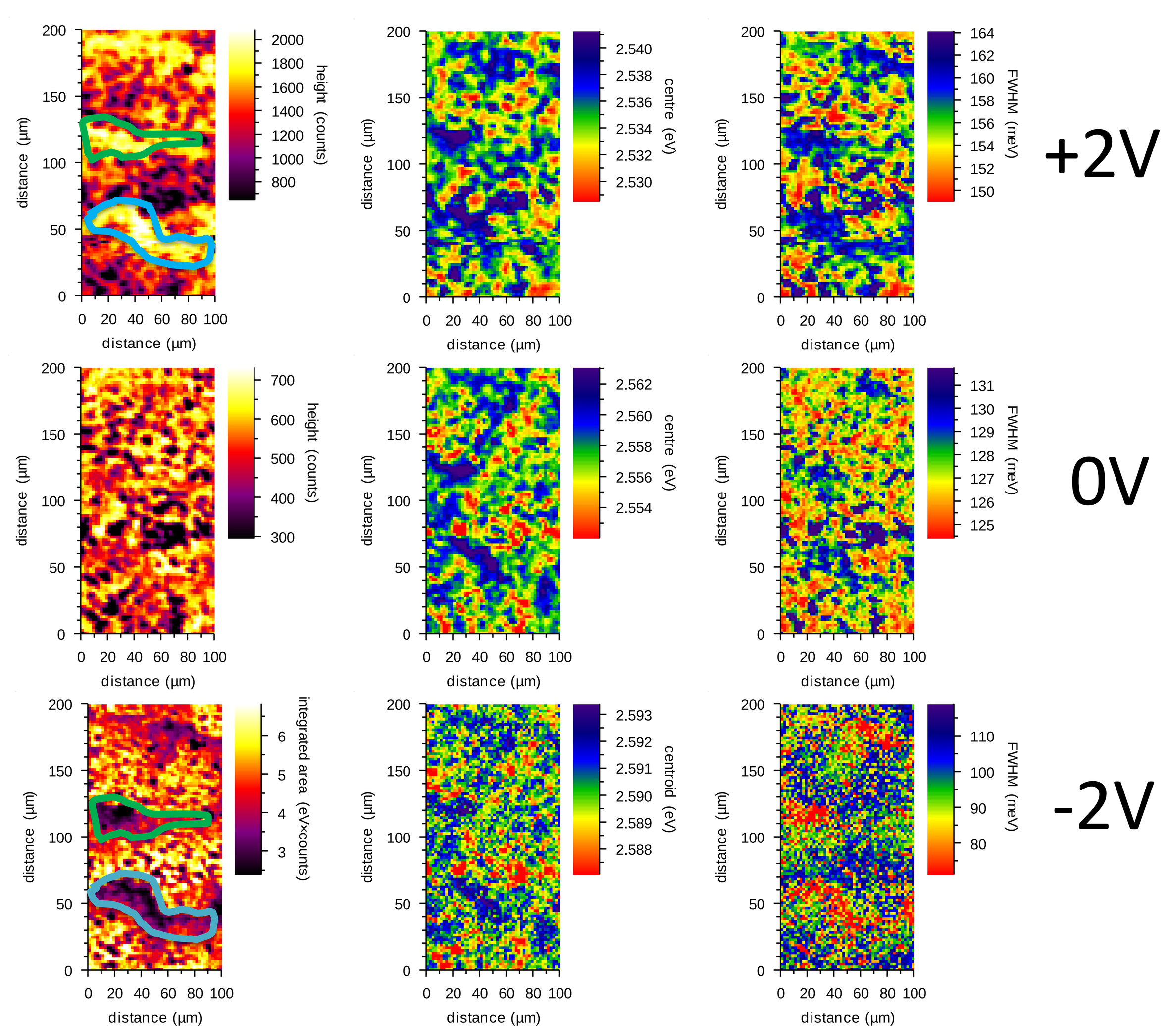


Intensity map of LED +2V



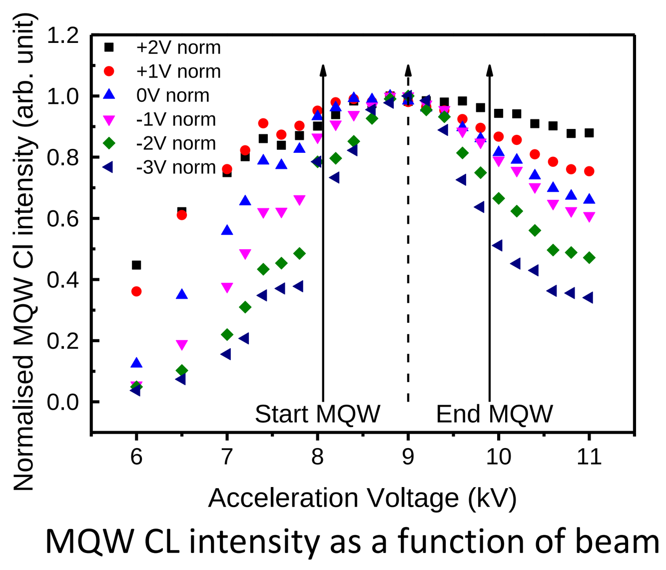
Intensity map of LED -2V

- At 0V the relationship between intensity, peak energy and peak width is consistent across the entire sample; namely areas of higher intensity have a blue shifted and narrowed line.
- At +2 and -2V CL intensity is less homogenous than at 0V; large domains extending between contact legs and around 10-20µm wide, which are locally brighter, were observed.
- An anti-correlation exists at these areas between +/- 2V, i.e. what is locally brighter at +2V is locally darker at -2V.
- In the bright domains there is a correlation between intensity and energy/width, with an anti-correlation in the neighbouring darker domains.
- The existence and behaviour of these domains w.r.t. voltage changes and spectral correlations suggests that the voltage drop is causing lateral carrier confinement;
- Regions which confine carriers at +ve leak them to the surroundings at –ve bias and are thus relatively depleted. The increase of peak width and peak energy within the bright regions is evidence of increased carrier concentration

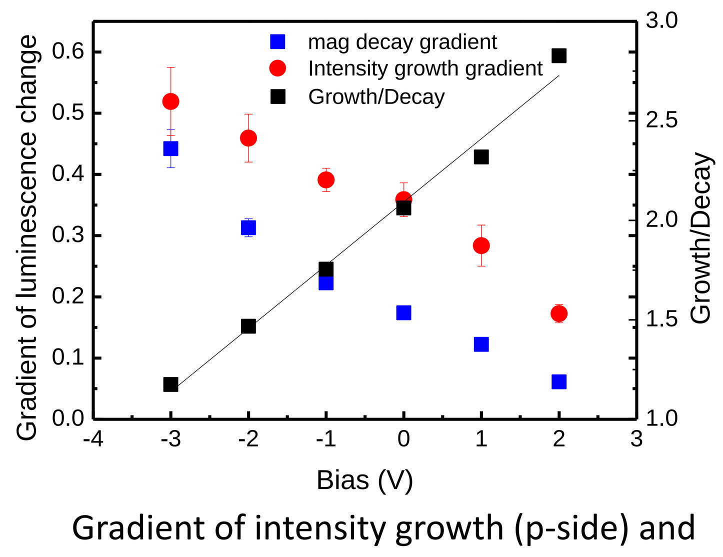


CL depth and bias dependence

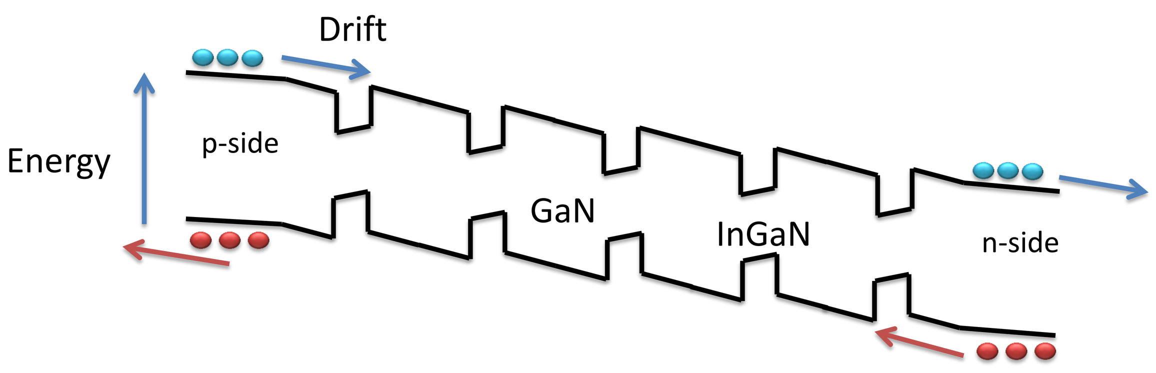
- Beam energy was varied between 6 and 11 kV in 0.2 kV steps with a fixed power and the applied bias was varied between -3V and +2V.
- Point spectra were collected from the same position on the LED and the intensity at each beam energy was recorded for each applied bias series



MQW CL intensity as a function of beam energy for the six different applied biases. Intensity drop off on p and n side increases with increasing reverse bias

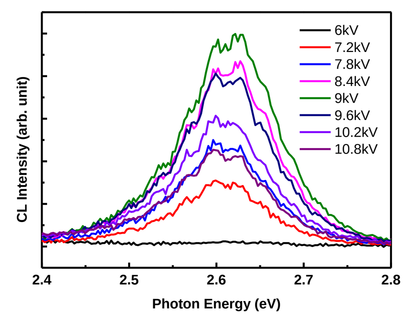


Gradient of intensity growth (p-side) and decay (n-side) as a function of bias. Ratio (black line) shows decay increases faster than growth with increasing reverse bias

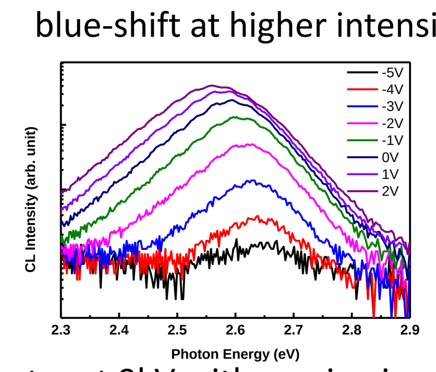


- Carrier pairs generated on the n-side move oppositely due to drift; holes toward the MQW, electrons away. The reverse is true on the p-side where holes move away and electrons toward the MQW
- Due to the lower mobility of holes, their response to the field is weaker. On the n-side, the net flux of carriers toward the active region is lower than on the p-side .
- Since a reverse bias increases the field, the disparity between electron and hole motion on the two sides increases. As such the probability of radiative recombination drops faster with increasing reverse bias, on the n-side than the p-side.

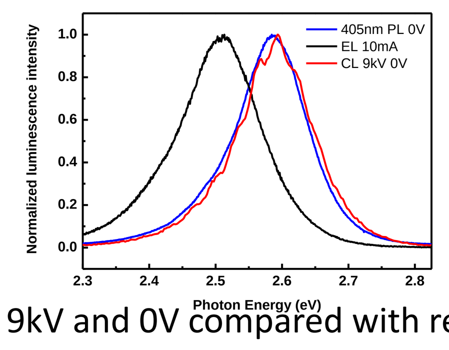
CL spectra



CL spectra at -2V with varying beam voltage. The intensity peaks at 9kV and shows a slight blue-shift at higher intensities



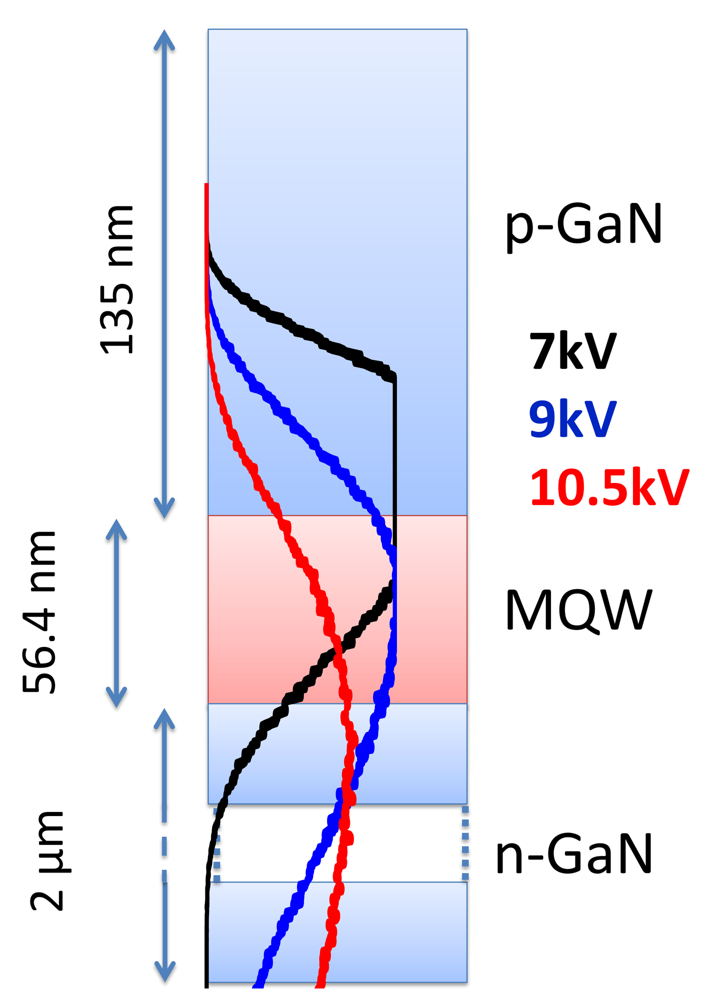
CL spectra at 9kV with varying junction bias. The peak redshifts, broadens and intensifies with increasing forward bias.



CL at 9kV and 0V compared with resonant PL from a 405nm diode at 0V and EL at 10mA. EL is red-shifted by nearly 0.1eV

Monte Carlo Simulations

Monte-Carlo simulation using CASINO show that at 9kV the maximum of the beam energy deposition profile is coincident with the centre of the QW stack.



Conclusions

- Carrier transport in InGaN LEDs has investigated by biased CL imaging and spectroscopy
- High resolution CL hyperspectral imaging at forward and reverse bias shows localisation of carriers via bright (at +2V) and dark (at -2V) regions not seen at 0V.
- Depth and biased dependent CL spectroscopy reveals bias dependent asymmetry of carrier transport above and below MQW region.
- Future work involving drift/diffusion and carrier generation modelling may reveal details on hole transport properties

Acknowledgements

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