

## Low-Temperature Cathodoluminescence Mapping of Green, Blue, and UV GaInN/GaN LED Dies

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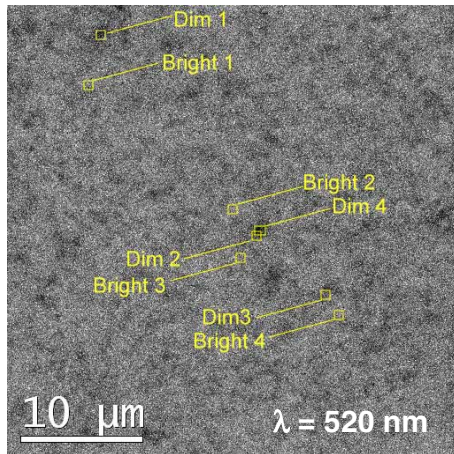
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### ABSTRACT

GaN based light emitting diodes (LEDs) play an important role as energy efficient light sources in solid state lighting. A controversial discussion addresses the origin of lateral light emission variations and their correlation with either of the identified defects, e.g., threading dislocations and V-defects. In order to establish any possible correlation of defects and luminescence centers, we analyze three UV, blue and green LED dies by microscopic mapping of spectroscopic cathodoluminescence and secondary electrons at variable low temperature from 7 K to room temperature. Particular effort is being placed on a quantitative analysis of the luminescence signal. Image intensities are not being scaled and offset for highest contrast as otherwise typical for imaging mode. In standard configuration, we analyze image areas of  $(0.037 \text{ mm})^2$  with pixel resolution of 72 nm. Following regions of strong and weak emission we find that remain bright and dark respectively even at low temperature. Those variations increase with the mean emission wavelength of the LEDs and with temperature. The largest peak wavelength variation associated with the intensity contrast was observed in the green LEDs and amounts to 5 nm. Here the peak wavelength is higher in the dark spots than in the bright ones. This finding corresponds to the general trend when comparing the lower efficiency in longer wavelength green emitters to the blue ones.

### INTRODUCTION

GaN based semiconductors are promising materials to make green, blue and UV light emitting diodes (LEDs) and laser diodes (LDs) due to their suitable bandgap energies. The bandgap energies of InN, GaN and AlN are 0.7 eV, 3.4 eV and 6.0 eV, respectively.[1] By adjusting the alloy composition, the bandgap energy of their alloy nitride could be tuned from the near-infrared to the UV regime. The multi-quantum well (MQW) structure is usually used to confine the carriers in order to increase the light emission. Metal organic vapor phase epitaxy (MOVPE) and molecular beam epitaxy (MBE) are two main techniques to grow the MQW structure LEDs. Due to lacking of the ideal GaN substrate, threading dislocations (TDs) form during the hetero epitaxy growth. The typical density of TD could reach  $10^9$ - $10^{10} \text{ cm}^{-2}$ . TDs make the lateral light emission from the LED inhomogeneous. At the TD region the light emission decreases. However, there is a debate about the role of TDs for the lateral light emission variations.[2-3] Whether TDs are nonradiative recombination centers of carriers or carriers don't recombine radiatively at the TD regions is still not clear. For this reason we use cathodoluminescence (CL) technique to analyze three green, blue and UV dies, that each has been optimized to its best performance.



**Figure 1** CL image of the green LED which was taken at 520 nm.

## EXPERIMENTAL

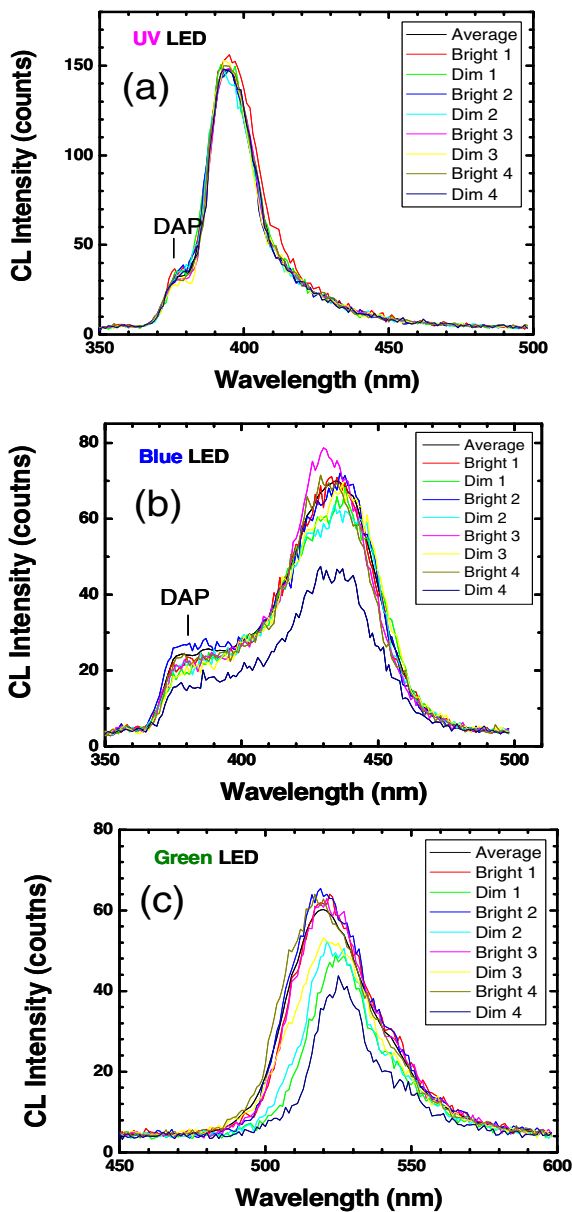
The three samples are GaInN/GaN multiple quantum well structure LEDs. The In fraction for UV, blue and green LEDs are  $\sim 0.07$ ,  $\sim 0.15$  and  $\sim 0.25$ , respectively. Five QWs are embedded in a p-n junction. Similar to 525 nm green LEDs [4], the thickness of each well layer amounts to 3 nm. The samples were grown by an Emcore D-180 SpectraGaN rotating disc multiwafer system. A JEOL 6400 Scanning

Electron Microscope (SEM) was upgraded with a Gatan MonoCL3 cathodoluminescence setup. Using a precision machined collector off-axis parabolic mirror stretched into the column, light emitted from the sample is being collected and guided in a light pipe out of the vacuum chamber of the SEM. Due to the low working distance of the electron optics the entire arrangement is limited to a total height of some 7 mm. By means of liquid nitrogen or liquid helium, the sample stage and sample itself can be cooled to variable low temperatures as low as 5 K. By means of a monochromator and photomultiplier tube, the emitted light is recorded and the signal is then being correlated with the electron beam for all further image processing. Moreover, the grating can be bypassed so that the system can work in panchromatic mode. The CL image is taken by synchronizing the scanning of electron beam and the signal from photo multiplier tube.

The CL spectra are derived from several locations with sampling size of 70 nm by 70 nm inside each frame of the CL images collected from 450 to 600 nm at a wavelength interval of 1 nm for the green LED. Within 8 s an entire frame is being scanned to minimize the beam exposure rate. The spatial CL signal resolution due to large volume secondary excitation is determined to be 200 nm. The average spectrum represents average intensity derived from the whole scanning area of 37  $\mu\text{m}$  by 37  $\mu\text{m}$ . The advantage over a conventional high magnification CL spectrum is that it prevents the damage of the sample due to a slow moving electron beam. Also the spectral information from any pixel or any interested area could be achieved.

## RESULTS AND DISCUSSION

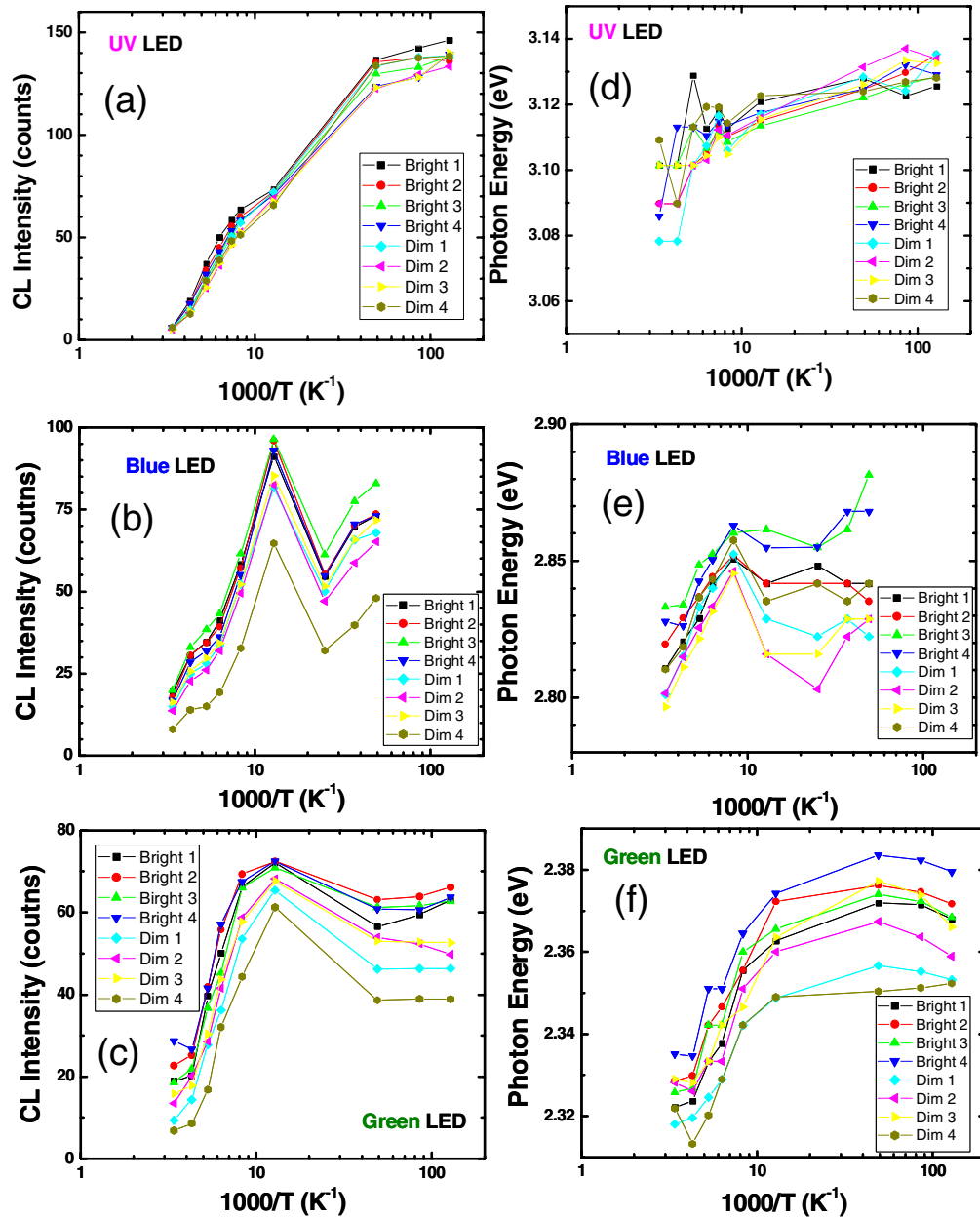
Fig. 1 shows the CL image of the green LED which was taken at 520 nm. The area is 37  $\mu\text{m}$  by 37  $\mu\text{m}$ . From this image we can see the lateral light emission is not uniform. Dark regions and bright regions are distributed everywhere. Here we chose four dark spots and four bright spots for microscopic mapping of spectroscopic CL. The sampling size is 10 by 10 pixels equivalent to 70 nm by 70 nm.



**Figure 2** Spectra of bright and dim regions for UV (a), blue (b), and green (c) LEDs.

By digital data processing, the CL intensity of those selected bright and dark spots is retrieved quantitatively from all the CL images which are taken at different wavelengths and the CL spectra are reconstructed. Fig. 2 shows the CL spectra of UV, blue and green LEDs derived from the spectroscopic sequence of quantitative CL images. The CL images for UV, blue, and green LEDs were taken at the temperature of 7.8 K, 20.4 K and 7.8 K, respectively. The measured wavelength ranges for UV, blue, and green LEDs are 350 – 500 nm, 350 – 500 nm and 450 – 600 nm, respectively.

From Fig. 2 we can see the peak wavelength for UV, blue, and green LEDs are 396, 435 and 522 nm, respectively. For UV, and blue LEDs, the spectra show a shorter wavelength emission at 378 nm which is due to donor-acceptor pair (DAP) recombination in the GaN layers. For the green LED we can not see this DAP recombination since it is out of the range of our measurement. For blue and green LED dies, the peak wavelength is longer in the darker spots than in the bright ones. For the green LED this trend is even clearer. For example, the peak wavelength from the darkest region is 525 nm, while the peak wavelength from the brightest region is 520 nm. The intensity contrast of the bright and dim region of blue and green LEDs is also relative high. For the case of the green LED, the peak intensity of the darkest region is about 44 counts while the peak intensity of the brightest region is about 64 counts. The



**Figure 3** Arrhenius plot of CL peak intensity vs. temperature of UV (a), blue (b) and green (c) LEDs. The microscopic sample spot location is a parameter. Location dependence of CL peak photon energy of UV (d), blue (e) and green (f) LEDs as the function of  $1/T$ .

average peak intensity of the whole CL images is about 60 counts. However, the CL peak intensities and peak wavelengths are relatively more uniform in the UV LED.

The full temperature dependence of CL mapping is measured by increasing the temperature monotonically. The mechanical shift of the sample stage with temperature was accounted for in the mapping. Fig. 3(a)-(c) show the Arrhenius plot vs. CL peak intensity for the different bright and dim spots on all 3 LEDs. As the temperature decreases, the peak intensity of the UV LED monotonically increases. The slope is reduced below 20 K. While for the blue and green LEDs, the Arrhenius plot shows an artificial peak at 78 K which is due to the change of cooling medium from liquid nitrogen to liquid helium. The peak intensities at RT is found to be 4 %, 20 % and 34 % of the corresponding maximum at low temperature for the UV, blue, and green LEDs, respectively. This behavior sheds doubt on the common assumption that an internal quantum efficiency can be estimated from such an Arrhenius plot by assuming a 100 % efficiency at the lowest measured temperature. This limitation, however, may be specific to CL.

With the help of the quantitative CL mapping data we can selectively follow the dark and bright regions as a function of temperature, i.e. 7.8 – 298 K, after the measurement by analyzing the full data set. Such an analysis is not possible with analog image processing that typically uses brightness and contrast functions to emphasize features of interest. In this way, we find that there is a much larger CL contrast in the blue and green LEDs than in the UV LED. This contrast increases as the temperature increases. The contrast for the UV LED at all temperatures is rather small. The maximum intensity variations at 7 K are 9 %, 50 %, and 51 % at 394 nm, 434 nm, and 520 nm respectively. At RT, they increase to 23 %, 73 %, and 126 %, respectively when scaled to the average intensity. Apparently the relative intensity contrast increases with temperature and it also increases with longer mean emission wavelength. This information can further be analyzed to identify the role of the dark area as a site of no recombination or a site of non-radiative recombination.

For the same temperature range, the maximum spectral variation associated with these was observed in the green die at 7 K: 520 – 525 nm. Within that variation for all three colors, the longer wavelength emission always was the lower intensity one. Similarities with other samples suggest that the dim areas are formed by open core V-defects. In our case, no such dark V-defect exhibits a radiative emission at higher energy.

Fig. 3(d)-(f) show the location dependence of CL peak photon energy of UV, blue and green LED as a function of  $1/T$ . For blue and green LEDs, there is a clear trend that CL spectra reveal lower photon energies at peak wavelength in lower emission intensity area. On the contrary, CL spectra with higher photon energies at peak wavelength are detected for higher emission intensity area. These results suggest a quantum confined Stark effect (QCSE) in the blue and green LEDs.[5-6] In the dim regions, the QCSE effect is higher, which results in lower energy photons. In the bright regions, the QCSE effect is smaller, which results in higher energy photons. For blue and green LEDs, there is a blue shift in photon energy at peak wavelength when the sample temperature decreases from RT to 78 K. When the temperature is further decreased toward 7.8 K a red shift is observed. This behavior corresponds to the “s-shape” behavior well-known otherwise from photoluminescence.[7-8] For the UV LED there is no “s-shape” behavior. The blue shift of the peak photon energy continues from RT towards 7.8 K.

## CONCLUSIONS

A new rapid scanning technique is proposed to acquire CL mapping spectra from submicron sized sample areas while minimizing the local electron beam exposure. Particular effort is being

placed on a quantitative analysis of a series of CL images which are taken at a wavelength interval of 1 nm. The spectrum of any interesting area can be generated by acquiring the intensity information from continuous CL image frames. This allows meaningful comparisons and quantitative statistical analysis, e.g. of the temperature behavior.

By following bright and dim regions, it can be seen that the CL intensity contrast increases for longer dominant emission wavelength between the UV, blue, and green LEDs. This contrast is also higher at room temperature than at 7.8 K. Furthermore, bright and dark areas remain so throughout the temperature range studied. For blue and green LED dies, we find that the peak wavelength is longer in the darker spots than in the bright ones. This trend is not clear for the UV LED. For blue and green LEDs, there is a clear trend that the emission intensity becomes higher at larger photon energy. These findings suggest QCSE in the blue and green LEDs.

## ACKNOWLEDGMENTS

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