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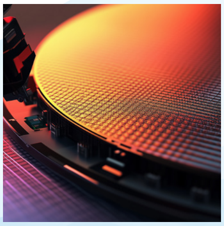
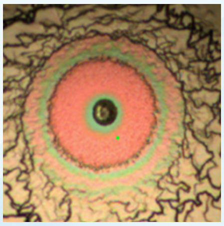
Spectroscopic characterization and detection of yield-killing defects in micro-LED wafers





Application Note

µLED Wafers
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Emerging display technologies demand high brightness, low power consumption and longer lifetime. Arrays, of self-emitting, micron-sized LEDs or Micro-LED (µLED), are considered a strong contender to replace current OLED or LCD displays. The estimated growth of the micro-LED (µLED) market is USD 21 billion by 2028. [1] Increasing demand for brighter & more power-efficient displays in automotive panels, smartwatches, mobile devices are some of the factors driving the growth of the segment.

Despite the huge potential, µLED technology is not yet fully commercialized. This is mainly due to the cost and challenges involved in the production process. For example, wearable devices, such as smart watches or augmented reality (AR) glasses, demand high resolution or high pixel density. To achieve high pixel density, the size of the µLEDs should go down to 3 µm or lower. At this length scale transferring the dies to the wafer and improving the yield is challenging, Low yields can drastically increase production costs.

Commonly used µLED display production consists of two separate steps where backplane and µLEDs are produced separately and then µLEDs are transferred to the backplane.

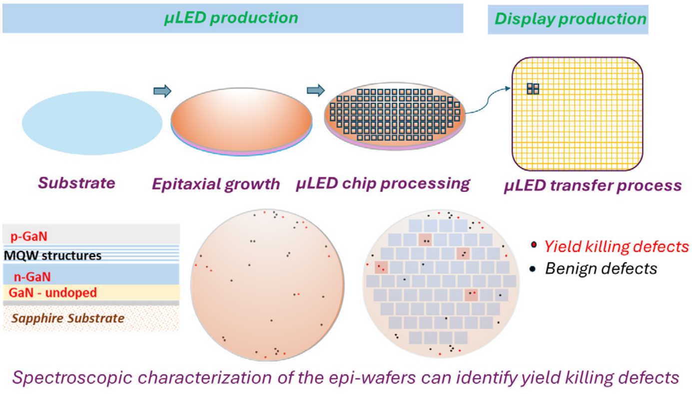

Figure 1. Schematic illustration of µLED based display production process. [2]

In the first stage, an epitaxially grown wafer (Epi-wafer) is produced. While in the second stage, the epi-wafer is diced and processed further to add contact pads to individual LEDs. Imperfection or defects in epitaxially grown wafers affect the final performance of the µLED produced. Defective dies lead to uneven color uniformity, low brightness or dead pixels. Identifying the microscopic defects at the wafer stage would enhance the die yield and save cost for µLED manufacturers. External defects or contaminants can be identified with imaging inspection tools, but structural defects or epitaxial growth imperfections can only be identified with the help of various spectroscopy tools. This application note demonstrates how HORIBA spectroscopic tools can be applied to characterize the epi-wafers and to identify microscopic defects.

HORIBA LabRAM Odyssey and SMS320 are multimodal spectroscopy metrology tools capable of high spatial and spectral resolution analysis of up to 300 mm semiconductor wafers (Figure 2). The possibility of doing Raman, Photoluminescence (PL) and Time-Resolved Photoluminescence (TRPL) mapping is a unique advantage.

Figure 2. Photograph of the multimodal industrial SMS system (above) and the LabRAM Odyssey (below)

In the first stage of µLED production, large area PL mapping can be used to identify defective regions within the epi-wafer. Since millions of µLEDs are made from one wafer, rejection of a wafer due to the coating imperfection, increases the production cost significantly and demands further research and development of the epitaxy process.

Commercially available, 2-inch GaN-based epitaxial wafers that emit blue and green lights are used in this study. To identify the imperfections on an epi-wafer, full wafer PL mapping was performed using 375 nm excitation source (Fig.3). Both blue and green LED wafers showed non-uniformity, while the green LED wafer edges had a higher degree of non-uniformity and showed a high degree of bowing. The edges of the epitaxial wafers are typically not used for die making, and these are called exclusion zones. Chips cut from these areas are not counted during the production process and this yield loss is always present. Industry standard of an exclusion zone is 3 mm.

If deposition conditions are not optimized properly, it is possible to have a larger defective region in the vicinity of this zone. Close examination of the PL map (Fig.3b) revealed low intensity regions (cold spots) within the 532 nm µLED wafer. As we moved from the center to the edge of the wafer, both samples showed significant PL emission shift (Fig.3 e &f), indicating presence of structural defects. Cold spots may arise due to intrinsic or external defects, while peak shifts are associated with epitaxial growth imperfections or residual stresses.

The structural defects are yield killing defects and wafers with such defects need to be discarded, which will affect the yield. To improve the die yield, one should minimize structural defects induced by the deposition parameters. Spectroscopic analysis of the defects can indicate the origin of the defects. In this regard, a high-resolution PL map and additional spectroscopic characterizations were performed on the cold spots (defects) marked in Fig.3b.

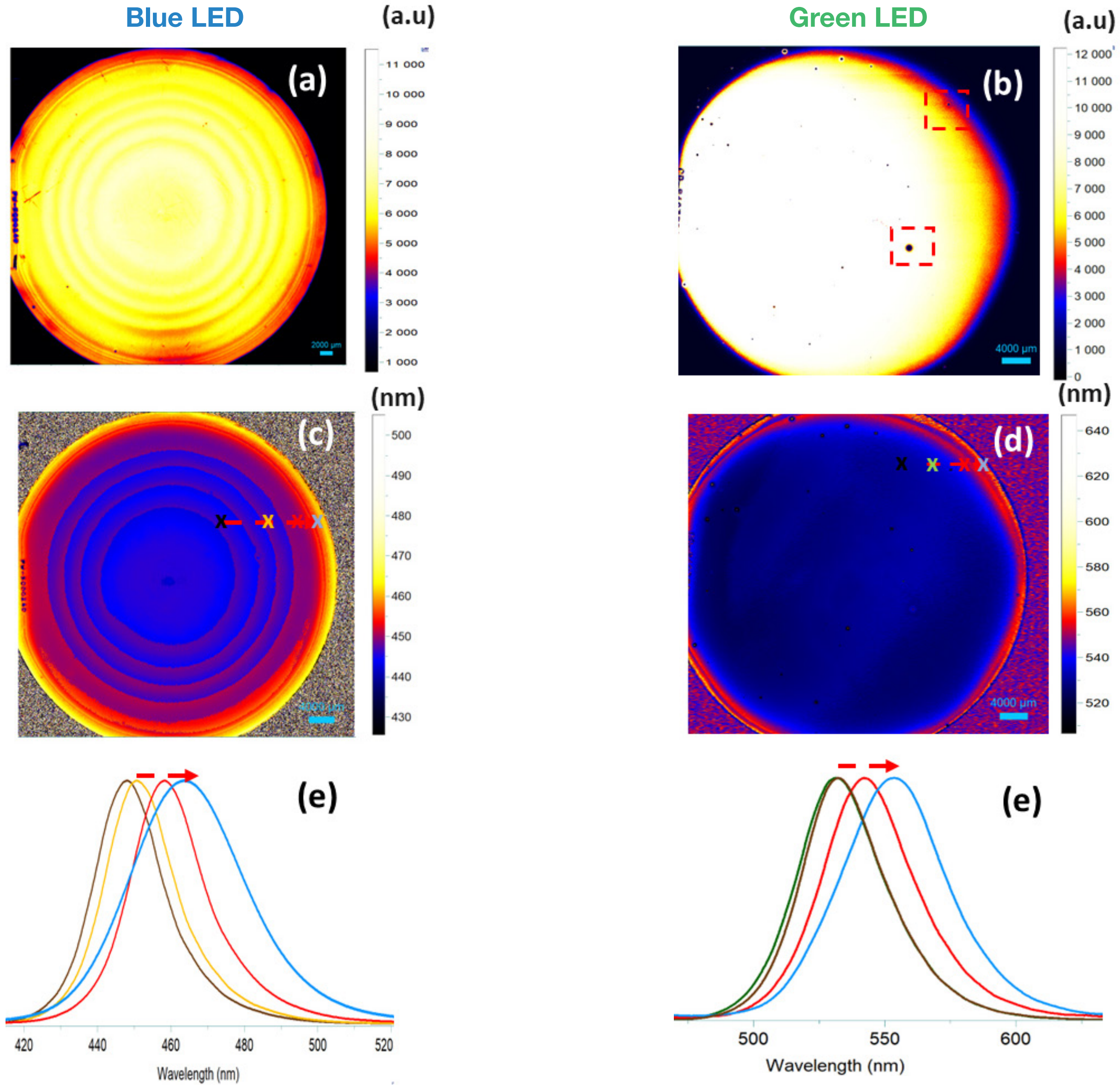

Figure 3. (a & b) Full wafer PL map, showing 450 and 532 nm peak intensity variations. (c & d) Variation in emission wavelengths. (e & f) PL point spectra extracted from the four points marked on (c &d). Both wafers showed a significant shift in the PL emission, indicating structural defects.

The optical micrograph of the cold spot (defect) region revealed clusters of the defects on the wafer surface (Fig.4a). For III–V nitride epitaxial structures, understanding the growth process is extremely important. Imperfect stoichiometry, local strain due to lattice mismatch, leads to point defects. These defects have adverse effects on the device performance. As demonstrated in the high-resolution PL map of Fig. 4b, defect regions showed a shift in the PL emission frequencies. Displays made of dies with point defects such as the one shown in Fig.4, will show non-uniform illumination and poor contrast.

The defects will also alter the carrier dynamics, or in other words, the electronic properties. Decrease in the radiative recombination will result in a loss of efficiency. Time- resolved photoluminescence (TRPL) can identify the lifetime of minority carriers. TRPL spectra recorded at the defect and the neighboring non-defective region are shown in Fig.4c. A significant drop in the carrier lifetime is observed at the defect region. The defects act as non-radiative recombination sites and reduces the overall PL emission intensity of the die.

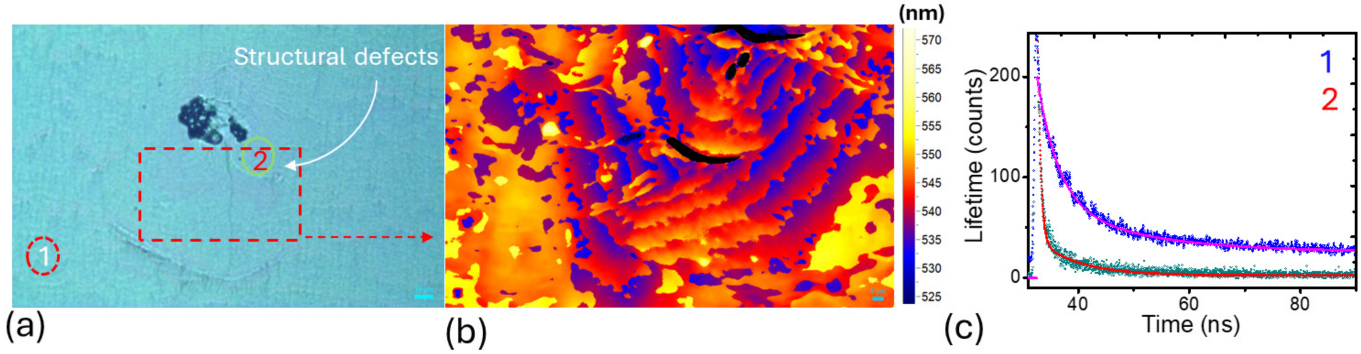

Figure 4. Effect of yield killing structural defects on emission wavelength and carrier dynamics. (a) optical image of the defect region, (b) high resolution PL map (200 nm, step size) showing changes in the emission wavelength, (c) TRPL spectra recorded at defect and clean region, showing drastic changes in the carrier lifetime.

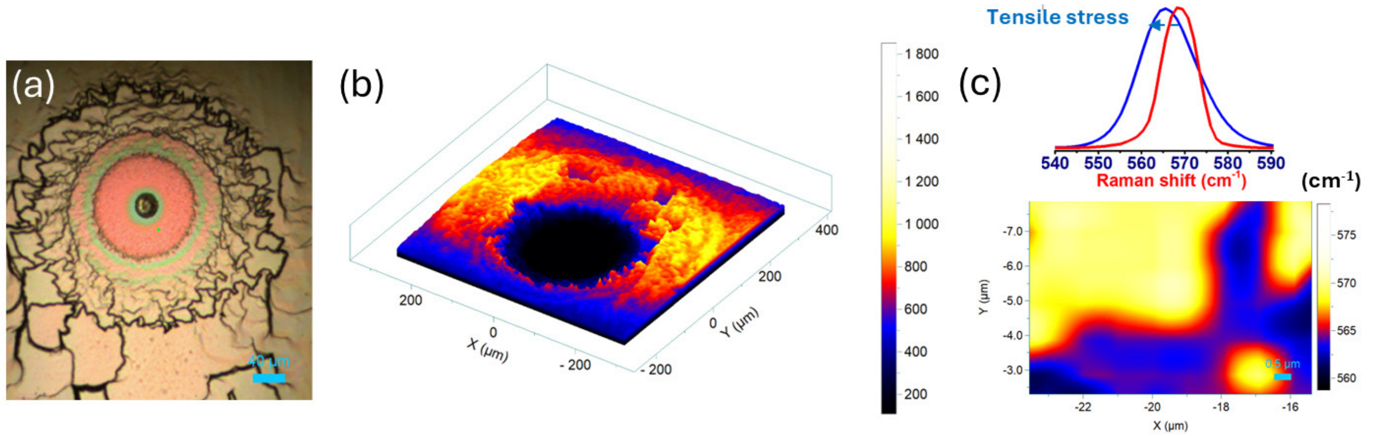

Figure 5. (a) Optical micrograph of the surface defect and micro-cracks (b) Raman map, showing GaN, peak intensity variation near the defect region, (c) Stress induced spectral changes near the defect region.

Figure 3b, also showed large cold spots. An optical micrograph of the large defect showed a structure identical to the micro-pit (Fig.5a). The micro-pit was surrounded by micro-cracks. The origin of surface pit is generally associated with the presence of threading dislocations (Screw). During deposition, these screw dislocations act as a nucleation site. [3] Since the deposition conditions are unknown for the sample tested in this study, it is difficult to pin-point the exact cause. Having said that, the HORIBA spectroscopic tool is capable enough to detect such microscopic defects. Furthermore, Raman spectroscopy is a very versatile tool to detect residual stress. Shift in the E2 phonon modes of the GaN are used to identify the residual stress. The Raman map of the pit region is shown in Fig.5b, and the Raman map of the crack region is shown in fig.5c. The red shift of the E2 phonon mode indicates the presence of Tensile stress.

Overall, the PL mapping of the epitaxial wafers identified wafer uniformity, cold spots and yield-killing structural defects, which emit different frequencies. During the production process, the epitaxial wafers are diced into micron-sized dies and mass transferred onto a back panel.[2] With the pixel size being decreased to a few microns, the final display panel inspection becomes extremely challenging. At this length scale, conventional electroluminescence techniques do not work well as making contacts are difficult. Large panels and photoluminescence mapping can identify defective pixels and map brightness in homogeneity. To demonstrate this capability, using the HORIBA SMS system, large area PL mapping on a commercially available LED display panel was done (Fig.6). The PL map identified low brightness, and defective pixels (Fig. 6a). Further, high-resolution PL mapping with 5 µm step size, revealed local PL intensity variations within the defective and normal pixels.

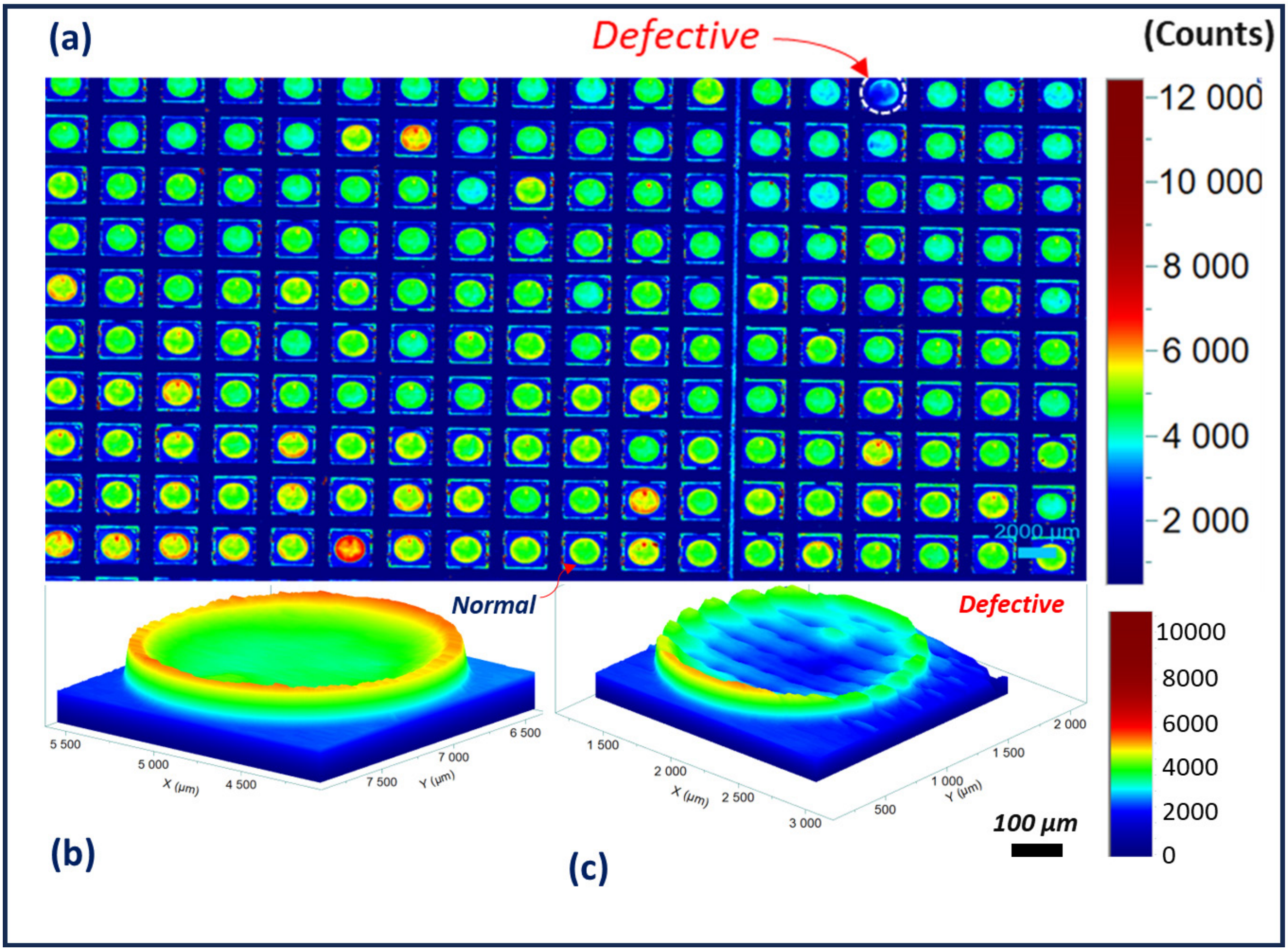

Figure 6. (a) Large area PL map of a commercially available LED display panel, showing defective pixels. (b &c) High resolution PL map of normal and defective pixels showing brightness variations.

Note that both HORIBA SMS and LabRAM Odyssey systems can accommodate up to 300 mm sized wafers or display panels. In summary, both these techniques can significantly enhance the µLED research and development. Further, additional modalities such as Time-resolved Photoluminescence, photocurrent, electroluminescence reflectance/transmittance, darkfield imaging/spectroscopy can be added to extend its spectroscopic capabilities.

Click here to learn more.

References

[1] Explosive Growth in the Micro-LED Market: Trends, Drivers, Industry Challenges and Future Outlook to 2027, November 13, 2024, Source: Markets and Markets Research Pvt. Ltd

[2] The MicroLED yield challenge, and strategies to overcome by the MicroLED Industry Association https://www.microledassociation.com/wp-content/uploads/2023/02/MicroLED-yields-2023-02.pdf

[3] Investigation of surface defect structure originating in dislocations in AlGaN/GaN epitaxial layer grown on a Si substrate. Hitoshi Sasaki *et al.* Journal of Crystal Growth Volume 298, January 2007, Pages 305-309