Characterization of GaN-on-Si micro LEDs matrix using a new ultra wide field of view imaging photometer resolving micro LED pixel size down to 2.5 µm

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Abstract

GaN micro LEDs are promising devices for realizing bright micro displays with pixel pitches down to a few micrometers, suitable for AR or VR applications and parallel optical communication. Compared to alternative technologies such as organic LEDs, GaN devices can achieve very high luminance but suffer also from important pixel-to-pixel dispersion. We present an instrumentation system developed to characterize GaN-on-Si microdisplays integrated onto ASICs at wafer level. We have fabricated a 200mm passive micro display on a GaN-on-Si epitaxial wafer, featuring a fully on 330x185 display with a 20µm pitch. The newly developed imaging photometer with an 8x6mm field of view is able to measure the luminance of each 10µm wide microLED of the matrix in a single 12bits image. This capability enables the assessment of the epitaxial wafer and microLED process quality at the wafer level. Acquiring the luminance of each pixel is also essential for adjusting the uniformity of brightness of GaN micro display.

Author Keywords

GaN, LED, display, instrumentation, characterization, photometer, AR, VR, VLC, epitaxy

Objective and background

Considerable progress has been made on Gallium Nitride micro LED display in the past decade, making their arrival on the market imminent. MicroLED offer the promises of very high brightness necessary of VR and AR application and visible light communication(1). Conventional, GaN grown on Sapphire substrate offer better performance in term of efficiency and material quality compared to GaN-on-Si(2). Nevertheless, cost of 200mm Sapphire substrate remain high, and move to 300mm Sapphire substrate is unlikely to happen in the near future (3). On the other hand, GaN-on-Si 200mm epitaxial wafer is now commercially available, but realizing 200mm, and tomorrow 300mm wafer, with high uniformity and high performance is still challenging (4). In addition to non-uniformity in epitaxial wafer, dispersion might come from the 200mm or 300mm micro LED process itself, in which each process step must stay compatible with a CMOS process.

The uniformity of microLED is a figure of merit that must be carefully monitored while developing new epitaxial wafer or process in 200mm or 300mm. Additionally, being able to measure the luminance of each pixel of a display is an information that may be used by the backplane ASIC controlling the display. In (5) has been proposed a brightness correction FPGA to compensate the non-uniformity of luminance of a microLED display. In (6) CEA-Leti has designed a CMOS ASIC backplane integrated with a GaN microLED display that is able to adjust each pixel luminance in function of a stored information. With pixel luminance information available for each pixel, it becomes possible to compensate for the non-uniformity of the display.

Capturing a complete micro display, while being able to extract the luminance of each pixel is a challenging task for optical design. It requires a tradeoff between the field of view, the resolution and focusing. Additionally, performing characterization at wafer level is highly desirable, to avoid unnecessary package cost and time while being still in the process maturation step. To perform wafer characterization through individual probes, or probing card placed at the top of the display, the imaging photometer must be placed at a sufficient working distance to let enough space for the probes contacting the pad.

In this presentation, we report the characterization of a full 330x180 matrix with 10µm pixels at a pitch of 20µm using a newly developed ELDIM imaging photometer that is able to acquire the luminance of each pixel. After presenting the fabrication of the GaN-on-Si 200mm sample, we will show the measurement bench and the characteristic of the newly developed instrument. Then we will report and discuss the experimental results obtained.

Results

Today, although GaN epitaxial wafer are commercially available on Sapphire and Si, research on new epitaxial stack focus on multiple realization: red microLED, optimization of epitaxial stack for VLC, development of semipolar GaN-on-Si device, and development of 300mm GaN-on-Si substrate. In order to assess the quality of the device realized, we have developed a new 200mm LED process flow that has the fewest number of steps, in order to limit the cycle time and avoid unnecessary clean room overloading, but which is representative of a more complex flow. This process makes possible the realization of microLED down to 5µm. The lack of mirror may limit the performance in term of extraction and may result in optical crosstalk.

<u>Fabrication of the sample</u>

The first batch of this new process flow has been developed on a commercial epitaxy GaN-on-Si conventional c-plane epitaxy targeting 450nm wavelength emission. First, 60nm of ITO is deposited on GaN wafer, then, after passivation, GaN mesas are etched, top and bottom P-GaN and N-GaN contact are opened, and metal electrodes are deposited. MicroLED are partially occulted by the P-metal electrode. The fabricated devices are single variable size microLEDs ranging from 5 to 50µm, macro LED, small microLED matrices (Figure 1), dedicated test structures, and two 330x185 pixels displays.

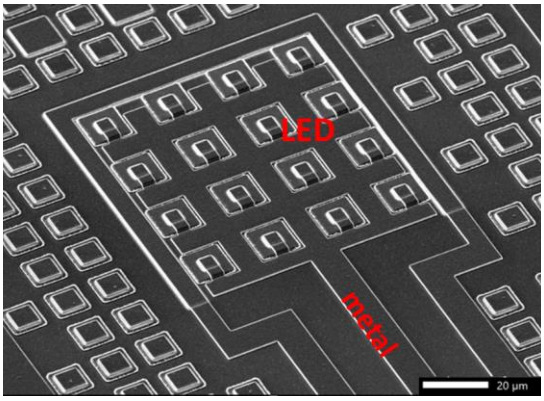

Figure 1 Tilted SEM view of a 4x4 matrix of 5µm LED after metal deposition

Experimental bench

The bench is composed of a fully automated probe station TS3500 from MPI. It has the ability to switch between two instruments: an alignment camera and a measurement camera, which is our case the newly developed X-scope 400 imaging photometer from ELDIM. The support of the photometer is able to adjust its X,Y,Z position with 1µm accuracy. The wafer may be loaded from a cassette using an automated loader. The electrical instruments (SMU, power supply or digital pattern) that drive the test structure or control the ASIC are composed of PXI card provided by National Instruments. Figure 2 shows a picture of the experimental bench.

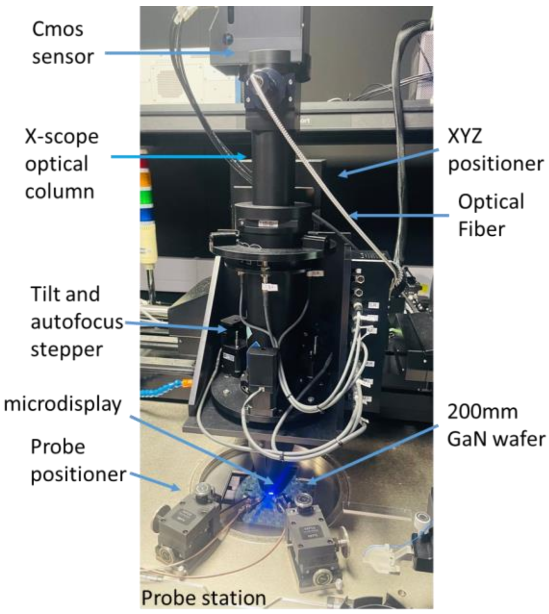

Figure 2 Experimental bench composed of a probe station and an a photometer Xscope 400

Characteristic of the imaging photometer

ELDIM has developed X-scope, a new range of imaging photometers for measuring micro displays. It offers a precision of 1µm object size per pixel in a field of 8x6 mm. The system is composed of an optical column, a high resolution tempered CMOS sensor with 47 million of pixels (7920x6004 pixels) and a spectrometer path, an optical fiber connected to an Ocean Optics spectrometer QEPro. The spectrometer analyses the center zone (1 mm diameter) of the DUT with a wavelength resolution of 2 nm. Software adjusts autofocus and tilt automatically using three stepper motors. The sensor makes a luminance map of all the field of view in one acquisition in less than 5 seconds. Accuracy of the measurement is 3% for luminance and 0.003 for chromaticity. The measured characteristics of the imaging photometer are summarized in Table 1.

Table 1 Figure of merit of the newly developed photometer ELDIM Xscope 400

Working distance	17mm
Luminance range	0.005 to 1 million Nits
Field of View	8mm x 6mm
MTF (measured on USAF-1951)	> 10% at 400 lp/mm (*)
Image dynamic	12bits, monochrome
Image size	7920x6004 pixels
Spectre	RGB and spectrum
Minimum LED size observed	2.5µm

Design of the imaging photometer

X-scope 400 has been designed to get a perfect image of a DUT with a magnitude of x4.5.To achieve the best MTF (Modulation Transfer Function), over 10% for 400 lpm in the whole image, it has been necessary to design an home-made optical design : not less than 12 different lenses including aspherical ones to have the best performance in the visible range. After nominal design with Zemax software, a large tolerancing analysis was necessary to determine critical parameters. It appears that the design was very sensitive and the main drawback came from lens assembly in the mechanics, potentially variation of optical index of certain glasses and air gap tolerancing.

The assembly line was crucial using automatic adjustment for each lens to achieve the target tolerance accepted of each subassembly. For any information, each lens had to be assembled with an average precision down to 5µm shift and 20µm tilt. After all assembly, optical column performance was measured with USAF 1951 Test Target imaging results after automatically autofocus and correction of tilt (Figure 3). A computation software was dedicated to get the color map of the display and detect default pixels

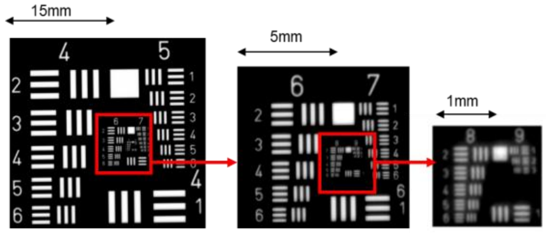

Figure 3 Measurement of the MTF with USAF 1951 resolution test target

<u>MicroLED matrix characterization results</u>

We are presenting here a few examples of the imaging possibilities offered by the new imaging photometer. We have captured the photography of two fully-on matrices of microLEDs. In Figure 4, macroscopic defects, in which the LEDs have lower luminance appear clearly. Those defects probably comes from the fabrication process and can now be analyzed. On the contrary, the LED matrix presented in Figure 5 does not reveal macroscopic defects, but shows the dispersion of the epitaxy at a local scale.

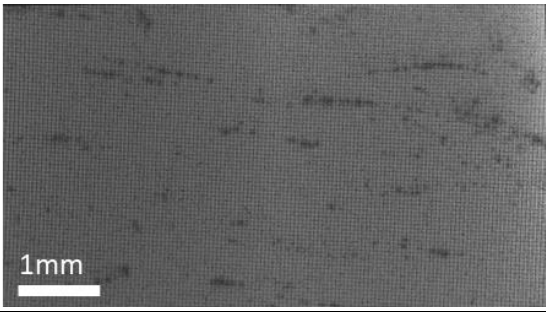

Figure 4 Photography of a matrix of 330x185 10µm micro LED pixel presenting some macroscopic defects

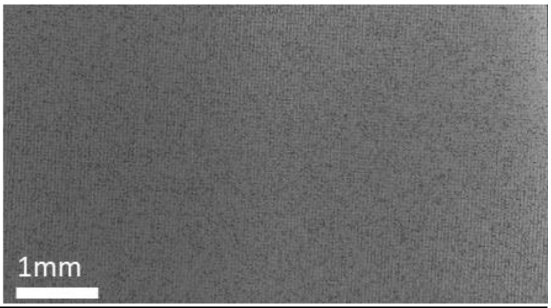

Figure 5 photography of a matrix of 330x185 10µm micro LED pixel without any macroscopic default or dead pixel, but showing dispersion in pixel luminance

The resolution of the camera makes possible to analyze each pixel. In Figure 6 is shown a close view of a matrix presenting an image in which microLED arrays has been partially contacted to form a fix image. The 3µm wide metal contact partially occulting the 10µm LED is clearly distinguishable on the picture.

Figure 6 Close view of an image formed by a 10µm micro LED matrix acquired by the new imaging photometer, in which the pixel geometry and LED contacts are visible.

<u>Extraction of pixel luminance</u>

After acquiring the microLED matrix, the Xscope 400 software generates a low-resolution image. In this image, each pixel picture corresponds to one microLED pixel, with a 12-bit dynamic range. This enables the extraction of the relative luminance for each microLED pixel. A thermal map representing the relative luminance of each pixel, and its distribution is shown in Figure 7. This image shows that luminance is not homogenous at display scale. This is explained by the disposition of the two probes (anode and cathode) and current distribution though metal wire. Additionally, local non-uniformity appears clearly. A calibrated spectrum is also obtained through the optical fiber. The spectrum is collected from a 1 mm diameter area at the center of the camera's field of view, allowing for the determination of each pixel's absolute luminance in cd/m².

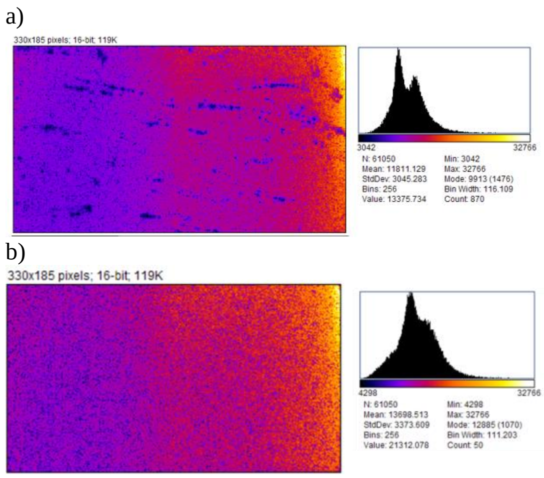

Figure 7 Thermal map of the pixel relative luminance of the two displays a) display with macroscopic defects. B) display without macroscopic defects

Impact

The development of a new photometer enables the extraction of luminance from a matrix of LED pixels on a large scale without requiring complex stitching techniques. The capability of this instrument has been demonstrated using GaN-on-Si micro LED matrices produced using a novel process flow designed to facilitate the characterization of epitaxial wafers. Although epitaxial wafers are characterized at the wafer scale in terms of photoluminescence wavelength and relative intensity before processing, this innovative methodology enables the analysis of process and epitaxial impact on electroluminescence at the pixel level. The luminance range, the minimum resolution, the large field of view and the working distance are particularly well adapted to the wafer level characterization of bright microLED displays build above ASIC. The information will greatly contribute to enhancing the epitaxial performance and process maturity. It may also be used by the backplane ASIC to compensate any non-uniformity in pixel brightness.

Acknowledgments

This work is part of the IPCEI Microelectronics and Connectivity and was supported by the French Public Authorities within the frame of France 2030.

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