Instrument Systems
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# LumiTop system enables rapid testing of µLEDs

The emerging µLED display technology promises high contrast, fast response times, wide color gamut, low power consumption and a long lifetime. However, the technology presents a challenge not only for the mass transfer of µLEDs from wafers to displays, but also for the massive parallelization of optical quality control in different manufacturing steps. Speed is a fundamental requirement for µLED wafer testing, since millions of µLEDs must be tested. Using traditional testing methods with integrating spheres, testing times may no longer be economical. A very fast alternative test option is parallel testing using 2D imaging light measurement devices, especially when spectral accuracy is maintained by referencing to a traceable spectroradiometer.

In this paper, we show experimental data demonstrating the ultra-fast speed of µLED quality tests using the LumiTop system: a 2D imaging light measurement device combined with a highly accurate reference spectroradiometer of the CAS series. Two test cases were examined, photoluminescence of a µLED wafer and electroluminescence of a complete µOLED microdisplay. The analysis algorithms of the LumiTop system provide spectral and spatial data for each individual emitter. The measured analysis speed is about 10-20µs per µLED, bringing the testing speed of an entire wafer with millions of µLEDs down to a few minutes or even seconds.

## \\ 1. INTRODUCTION

The emerging µLED display technology promises high contrast, fast response time, wide color gamut, low power consumption and a long lifetime. However, the technology presents a challenge not only for the mass transfer of µLEDs from wafers to displays, but also for the massive parallelization of optical quality control in different manufacturing steps. Measurement challenges also arise from the small size of µLEDs, narrow bandwidth and substantial manufacturing tolerances of the emission peak wavelength and bandwidth [1]. For speed and resolution, a high-resolution camera is the preferred testing option, because the display pixels or individual µLEDs on a wafer can be measured simultaneously in a single shot. For absolute color and spectral power distribution, however, spectroradiometry is the most accurate method. Consequently, we combined the two techniques in the LumiTop spectrally enhanced imaging light measuring system [2]. Fast analysis algorithms and calibration based on the live spectrum of the device under test can bring down test times for a complete wafer from hours to a few minutes or even seconds without compromising accuracy.

In this paper, we show experimental data demonstrating the ultra-fast speed of µLED quality tests using the LumiTop camera as imaging light measurement device combined with a highly accurate reference spectroradiometer of the CAS series, which is traceable to national standards. In the following, we refer to this combination as the LumiTop system. Key parameters are a dominant wavelength correlated to the peak wavelength of the individual emitters, as well as luminance and chromaticity. For display applications, luminance and chromaticity are important standard parameters to describe the perception of brightness and color of a standard human observer looking at a display. Luminance and chromaticity are therefore the required quality parameters for µLEDs in display applications. Further µLED analysis parameters include purity, tristimulus values X, Y and Z, location and size of the emitter. This information allows for a complete analysis of every µLED on a wafer. Our system approach has two advantages: Very fast testing speeds due to the 2D imaging camera as well as spectral accuracy due to the combined spectroradiometer.

## \\ 2. SPECTRALLY ENHANCED COLOR CALIBRATION OF THE CAMERA IMAGE

In principle, all colorimeters require color calibration, because the physical color filters used to mimic the eye's sensitivity to visible light do not perfectly match the theoretical CIE 1931 functions. In particular, µLEDs may exhibit strong color variation across the wafer on which they are produced – typically around 5nm [3]. Consequently, we developed an enhanced "live" color calibration method [4] for our well-known 3-in-1 LumiTop system in order to consider spectral variation of the DUT and variations in between different DUTs.

The LumiTop system comprises a calibrated RGB Bayer-pattern camera, an absolutely and traceably calibrated spectroradiometer and a flicker diode [2]. With the attached spectroradiometer of the CAS series, we are able to simultaneously take a reference spectrum along with every RGB camera image to adapt the camera calibration on-the-fly to potential variations. Even if the DUT spectrum changes due to manufacturing tolerances or different electronic driving parameters, for example, the color calibration will always be adapted live for each image.

The additional use of a spectroradiometer guarantees highly accurate measurements, since the measured DUT spectrum contains the complete information of the spectral power distribution. The used CAS spectroradiometer itself is calibrated in Instrument Systems' test lab accredited to ISO 11664 for the measurement of colorimetric quantities. All standards used for calibration are directly traceable to the reference standard of the national metrology institute PTB (Germany) or NIST (USA).

## \\ 3. SET UP 1: WAFER-LEVEL CHARACTERIZATION BY PHOTOLUMINESCENCE IMAGING

The best quality control at wafer-level is achieved by inline process monitoring within the manufacturing process. Short cycle times do not permit a detailed wafer analysis, which usually requires a technical setup such as mechanical contacts. Photoluminescence imaging is a fast alternative to establish a first quality control and detect defects already on wafer level.

Our first example to calculate the testing time of the LumiTop system is such a photoluminescence wafer test. We used a microscopic lens to adjust to sufficient optical resolution. The µLED wafer was photo-excited using a laser diode. The resulting photoluminescence was captured by a LumiTop 4000 2D imaging camera. The reference spectrum was simultaneously captured by the spectroradiometer for live calibration. Figure 1 shows a schematic sketch of the experimental setup and detected image. The grid pattern in the image redraws the detected µLED pattern. In this case, the detected cells are rectangular, reflecting the different horizontal and vertical size of the µLEDs.

The field of view of the camera was such that the 4-inch wafer was scanned by 165 images by stepping the wafer using a motorized stage. Each image captured the emission of approximately 10,000 µLEDs. It was possible to measure and analyze the entire µLED wafer within 3.6 minutes with a stepper moving time of 0.3 seconds for each step. This corresponds to an average measuring time of approximately 130 µs/µLED. The setup is a demonstration assembly and we estimate that the use of parallel computing and fast stepper motors (100ms) could bring down the total wafer test time to less than 60 seconds for bright emitters, where camera exposure time is not a limiting factor.

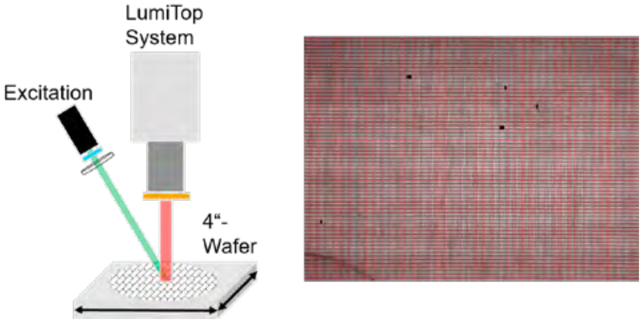

*Figure 1: Imaging colorimeter on the left, detection image on the right.*

## \\ 4. SET UP 2: MICRODISPLAY CHARACTERIZATION BY ELECTROLUMINESCENCE MEASUREMENTS

In a second experiment, we simulated the quality control for an OLED-based microdisplay to calculate the testing time of the LumiTop system for this application. In this setup we used a LumiTop X150 camera that provides a 150MP resolution for each color channel. As described above, a CAS spectroradiometer is coupled to the optical path of the camera in order to provide live spectral information. We used a RGBW microdisplay [5] as DUT. Its pixel size is 5 µm at a pitch of 11 µm. The microdisplay consists of approximately 1.7 million µOLEDs.

Our LumiSuite software offers a single pixel evaluation (SPE) algorithm that finds and evaluates the brightness, wavelength and spatial properties of each emitter. The SPE comprises dominant wavelength, chromaticity, luminance, tristimulus values X, Y, Z and location and size of the emitter, as well as purity. All this measurement data is reported for each µLED.

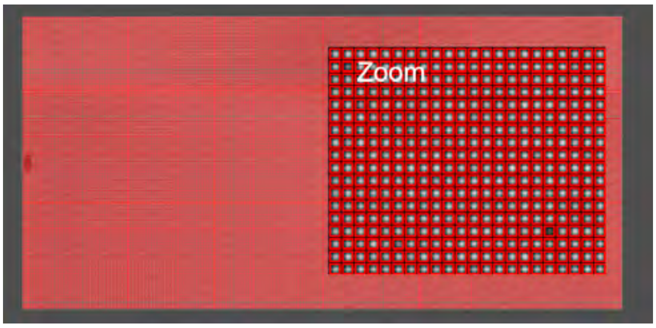

*Figure 2: Detection image of a microdisplay. The zoom inlet shows the detected grid cells (red squares). Inside the cell 5µm LEDs are visible.*

In a first step, we measured the RGBW microdisplay [5] in one image per display color. All µLEDs were switched on at the same time. Figure 2 shows the detection image supplemented with an overlay grid of square cells. These cells are detected as the grid area surrounding individual pixels with an expected pitch of 11 µm. The inlet in Figure 2 is a zoom into the detection image, and one can identify the individual emitters. An even stronger zoom verifies that the µLEDs are located well within the cells (Figure 3). The cell position is part of the readings as well as the centroid position of the emitting area (height and width) within the cell. The detected cells are square: the horizontal and vertical pitch are equal.

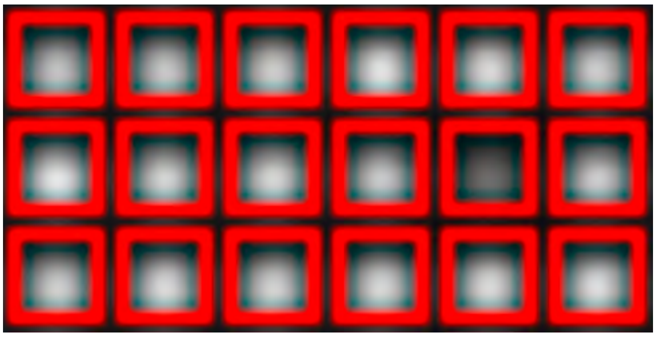

*Figure 3: Zoom into detected µOLEDs. The red squares represent the detected grid of emitters, indicating that the horizontal and vertical pitch is identical. The white dots in the cells are the emitters.*

In a second step, we analyzed the dependence of the testing time on the algorithm, the amount of considered LEDs as well as the computational power. We measured several analysis parameters for different sized display regions using respectively a notebook (i9), desktop (core i5) and a desktop (core i9). The data shown was made with the desktop (core i5).

We took one image of the µLED display with all 1.7 million pixels per RGB color using the LumiTop X150 system including the spectroradiometer. We then defined different sized regions of interest (ROI) within this image. The smallest region includes approximately 1,000 and the largest approximately 1,700,000 µLED emitters. For each ROI we applied the entire single pixel/emitter evaluation (SPE) algorithm. Figure 4 shows the results for the analysis speed. All the way up to 1,700,000 µLEDs the analysis time increases linearly and is approximately 17 µs/LED. Using different computer power, we see that the speed may drop to 25 µs/LED for the notebook (i9) and speed up to 12 µs/LED for the desktop (core i9). The speed can be further increased, if the scope of the analysis is reduced, e.g. for defect detection only.

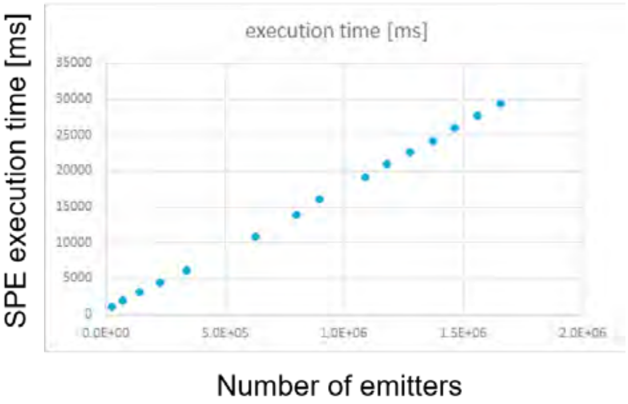

*Figure 4: Execution time of an entire single pixel analysis with LumiTop X150 system for up to 1.7 million µLEDs.*

## \\ 5. CONCLUSIONS

Spectral and spatial properties of individual emitters on a wafer or display can be tested very quickly using imaging light measurement devices that combine a fast high-resolution camera for speed and a reference spectroradiometer for traceable accuracy. With the presented single pixel/emitter evaluation algorithm (SPE), µLED wafers or displays can be optically tested in a few minutes. Conventional methods based on integrating spheres usually take several hours.

For both applications, photoluminescence at wafer-level and electroluminescence at display-level, we have shown that individual µLEDs can be rapidly detected and analyzed. The scaling factor between emitter number and analysis time was linear in both experiments. This linear scaling test speeds promises similarly fast testing times for even higher emitter numbers. This is particularly interesting for photoluminescence µLED wafer testing where very large numbers of emitters can be simultaneously excited. We anticipate that the execution time can be further improved using a faster computer equipment.

SPE analysis delivers a large set of parameters relevant to quality tests, especially for display applications: standard tristimulus values X, Y, Z and hence luminance and chromaticity. A spectrum and peak wavelength are also measured by the reference spectroradiometer for every image. The dominant wavelength is calculated based on the tristimulus values for every single emitter. In [6] we calculated chromaticity of individual µLEDs on a display from the µLED spectrum measured by a spectroradiometer. We compared these chromaticity values to camera measurements using the measurement LumiTop system. We determined that the chromaticity values are practically identical and vary on average by no more than one color point. Therefore, we can conclude that the dominant wavelength derived from chromaticity measurements correlates well with the spectrum and peak wavelength.

Figure 5 depicts the setup for an imaging light measurement of a) a photo-excited wafer measured with a camera system (left) and b) electroluminescence by contacting with an integrating sphere (right). It is noteworthy that the field of view is different for the two approaches. While the integrating sphere measures the light from a large emission angle of the LED, the camera practically “looks” at the emission like a human observer. This can be an advantage for quality tests of µLEDs that are produced for display applications, where the human observer is located at a comparatively large real or virtual image distance.

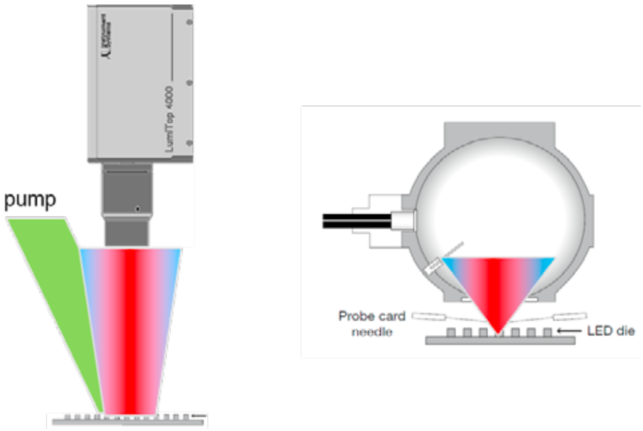

*Figure 5: Different field of view of an imaging light measurement device using a camera on the left and spot measurement using an integrating sphere on the right.*

## \\ 6. SUMMARY

Speed is a fundamental requirement for µLED wafer testing, since millions of µLEDs must be tested within a short time. Using traditional testing methods with integrating spheres, testing times may no longer be economical. Parallel testing using 2D imaging light measurement devices is a very fast alternative test option, especially when spectral accuracy is maintained by referencing to a traceable spectroradiometer.

Combining camera based optical test systems and a spectroradiometer based live calibration with a fast single pixel/emitter analysis (SPE) provides a powerful tool for highly accurate and ultra-fast optical testing of µLEDs on wafers or displays. The testing method provides optical parameters that are particularly relevant to display applications for every single µLED on wafer or display. The measurement results can be used for correct calibration of color and luminance of microdisplays (demura) on pixel level or analyzing the spectral and spatial defects of µLEDs on a wafer or display. The imaging test method dramatically reduces testing time for an entire wafer from many hours to a few minutes or even seconds for microdisplays. The combination of camera, spectroradiometer and live calibration may substantially improve quality and economy of µLED testing applications.

## \\ REFERENCES

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