LED measurements in the production line

Optical measurements in LED mass production must be fast and precise. Various methods can be used in the individual production stages, in order to produce reliable results.

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In the LED manufacturing process, electrical, optical and thermal measurements are performed directly in the production line. The LEDs are thereby sorted into quality classes in a process referred to as "binning" to separate the defective from high-quality production. Each bin contains LEDs with the same electro-optical properties that can be precisely specified despite the strong fluctuations within a production batch. Furthermore, the results of inline tests are used to adjust the process during manufacturing to enhance the production yield. This chapter outlines important aspects of optical measurement in a production environment.

Conditions and requirements for production tests

The main distinction between production tests and laboratory measurements is speed. In a production line about ten LEDs are measured per second.

Optical measurement instruments must be synchronized with the speed of the production line and measurement times kept as short as possible. Alongside mechanical and pneumatic positioning, contacting and visual inspection equipment, space for the optical probe and other test facilities is extremely limited. Temperature and humidity in the production facility are often inadequately controlled and may be subject to significant fluctuations. In addition, the test equipment is exposed to vibrations and must be capable of continuous operation. Highly robust and low maintenance devices that nevertheless supply precise and reproducible results are thus necessary for measurements in production.

The measurement of LED parameters in production is particularly challenging for metrology equipment, because of the low light throughput of CIE-compliant measurement adapters and a wide range of different products from low- to high-power LEDs must be tested. At the same time measuring times must be short, to ensure maximum unit production per hour (UPH).

Photometers and colorimeter heads for integral measurements are generally used in production control, because measurement speed is the critical factor here. However, in the production line their measurement accuracy is not sufficient for testing blue and white LEDs. As a rule, spectrometers are therefore used here.

Thanks to their robustness and short measuring times, array spectroradiometers are ideal for use in production. Previously, their greatest disadvantage was inadequate sensitivity and a small dynamic range. Integration times in the millisecond range could not be achieved by using an optical probe compliant with CIE Condition B or with a diffusor that severely limited light throughput.

This restriction was overcome with the development of high-quality "back illuminated" CCD sensors with significantly higher sensitivity. The increase in effective full quantum well capacity by using the area detector increases the usable dynamic range and at the same time reduces the noise level, in turn improving reproducibility (**figure 1**). Array spectroradiometers of this type are best suited to the production control of LEDs, as they eliminate the disadvantages of the photometer without compromising measurement time.

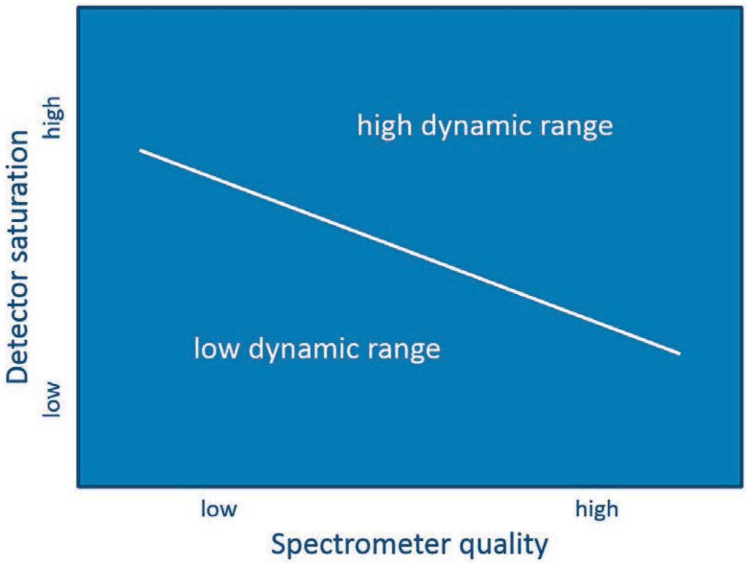

Figure 1: Line integration of area detectors results in a less noisy signal, enabling a larger measurement range due to a good signal-to-noise ratio, even at lower detector saturation

Use in practice

The production process relevant to the optical tests of LEDs can be subdivided into a number of stages. Typically, it starts with a wafer being cut into so-called dies, which are then separated from one another. To a certain extent this changes their optical properties. For phosphor-converted white LEDs in a downstream production stage a suitable phosphor is selected and applied to the die in various procedures. For multi-chip

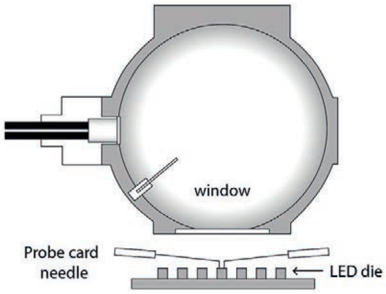

Figure 2: Wafer testing configuration, consisting of an integrating sphere with a diameter of 100 mm and silica glass for dust protection

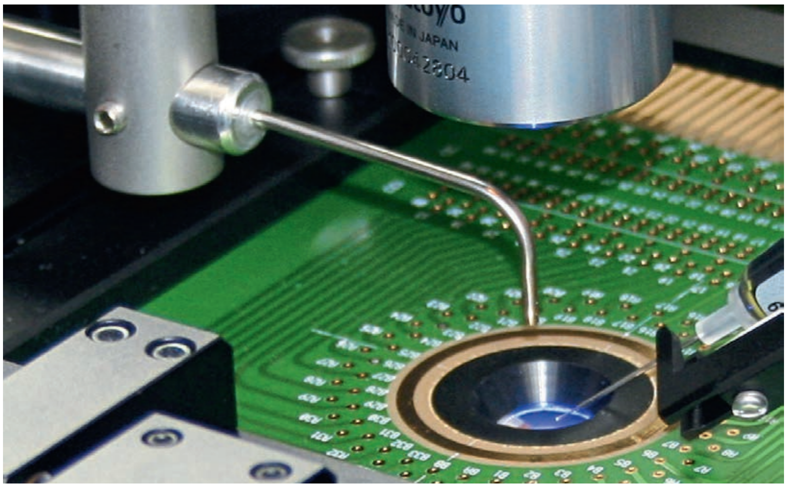

Figure 4: Optical fiber probe for fast wafer testing

LEDs for white light, three or four dies are combined. The chips thus contacted are finally packaged to create an LED. Depending on the final purpose, the LEDs can be mounted on circuit boards and combined with control electronics and, as necessary, lenses and reflectors.

The following sections provide an insight into classical optical measurement procedures along the four main production stages, whereby a focus should be placed on white LEDs, as they are in greatest demand and the most complex.

Wafer level testing

Measurements at the wafer stage of manufacturing are necessary at an early stage for the right decisions on further process steps, and thus optimization of the yield [1]. Wafers must be handled in clean room conditions and are usually tested by mounting an integrating sphere above them. The wafer is positioned opposite the center of the sphere port and contacted by probing needles (**figure 2**). A so-called wafer map (**figure 3**) is generated on the basis of the optical tests, which usually measure the luminous flux and dominant wavelength. The luminous intensity of the dies is color-coded via the x and y local coordinates of the wafer.

Wafer testing with an integrating sphere

Due to the limited space for wafer testing equipment and the need to keep optical integration times to a minimum, the integrating sphere should be as small as necessary, but as large as possible. Spheres with a diameter of 100 mm best satisfy the requirements for precision and size in wafer testing. Depending on the use, however, diameters between 75 and 250 mm can also be applied. The measurement port should be no more than one third of the sphere diameter; in the case of a sphere with a diameter of 100 mm this corresponds to a port of 33 mm. A silica window is recommended to protect the barium sulfate coating of the sphere from contamination and environmental influences (**figure 2**).

For the measurement of flip-chip LEDs the integrating sphere may be positioned close to the bottom of the LED. The distance may be less than 1 mm and enables a good approximation in measurement of total luminous flux.

Wafer testing with an optical fiber

The use of optical fibers as optical probe enables fast wafer measurements without hindering visual inspection. This kind of coupling in the spectroradiometer features particularly high light throughput and ensures extremely short measurement times, even with low luminous intensity. The compact design of this optical probe enables the optical fiber to be positioned between the alignment microscope and wafer without obstructing the visual inspection of the contacts (**figure 4**). The probe is usually calibrated for illuminance or at known measurement distances for luminous intensity, but not for luminous flux. A diffusor can be mounted for measuring with less dependency on the coupling angle. The optical fiber is likewise suitable for measuring separated dies.

Wafer testing with a microscope

The optical measurement of LED dies in wafer testing systems often takes place by microscope. This imaging procedure actually measures luminance and is not suitable for luminous flux or intensity, as the inhomogeneity of the emitting chips can result in measurement errors. Color deviations are also likely due to spectral transmission of the microscope.

Multiple die testing

Multiple die testing can speed up the wafer test. To minimize the number of time-consuming mechanical movements 4, 8, 16 or more dies are contacted simultaneously and the optical probe is positioned above this group of dies (**figure 5**). By electrical multiplexing the current source is switched from die to die. This multiple die testing procedure thus permits the successive measurement of multiple dies without moving the wafer. Since the electrical switching times (one or several milliseconds) are significantly shorter than the travel time of the positioner (ten or >

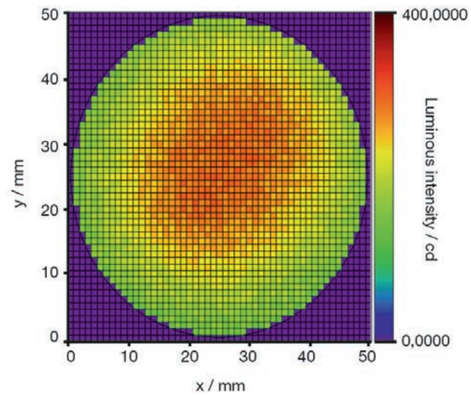

Figure 3: Wafer testing produces wafer maps on which the luminous intensity of the dies is color-coded via the x and y local coordinates of the wafer

several dozen milliseconds), throughput is increased. While multiple die tests with multiplexing can normally boost throughput by a typical factor of four, multiple channel current sources that operate in parallel are an even faster method, as the electric testing of all contacted dies is performed simultaneously. Subsequently, optical testing determines the emitted radiation of the separated dies.

Die level testing

The electro-optical properties of a die change when it is isolated from the wafer. In the next production stage the optical and electrical tests are performed on the isolated chips. With lower quality LEDs this step can be skipped. Process control at this point is critical for the production of high-quality products.

Separation takes place by means of a so-called blue tape made of polymer foil, on which the sliced wafer is placed. When the foil expands, the dies separate. Special probers contact the dies for electrical and optical testing. A further possibility is to pick up the dies one by one with a mechanical handler and place them on a separate test table.

In optical tests the luminous flux and dominant wavelength are usually measured. For white LEDs with luminescence conversion the phosphor plates are included in the binning process in order to produce the desired white. Because the optical properties of the phosphors can be adapted by the combination of several types of phosphor, a matching phosphor bin can be produced for each die bin. With the right matching of the phosphor bins to the die bins, the desired white is produced from different die bins and the production yield is thus increased. Another possibility is to apply the phosphor directly to the chip. This calls for an in-depth knowledge of the coating process, in order to regulate the phosphor concentration and mixtures.

The preferred optical probe for the optical testing system is an integrating sphere with a diameter of 75 to 150 mm (depending on LED type and available space in the handling equipment).

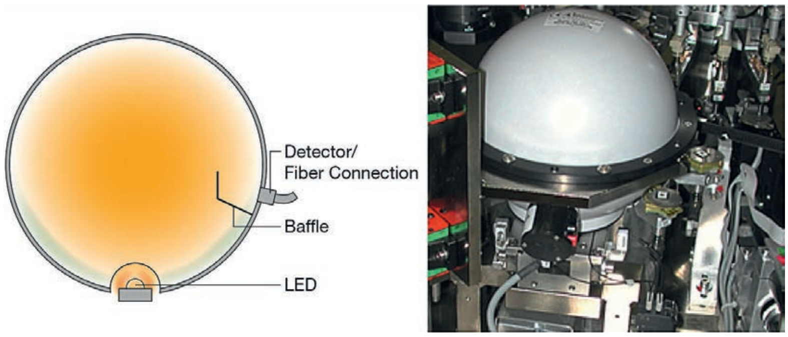

Figure 6: Integrating sphere for package testing with a diameter of 100 mm and a silica dome (left). The integrating sphere is designed for minimum directional sensitivity due to the homogeneous surface opposite the entrance port. The right side shows an example of a setup in an LED handler.

LED testing

In already packaged LEDs the measured values are different compared to wafer and die testing. In optical tests of white LEDs, the usual tests performed are for luminous flux, luminous intensity, color coordinates and correlated color temperature (CCT). For LEDs generally intended for illumination purposes, the color rendering index (CRI) is used as a variable for binning. Some LED manufacturers specify LED production batches with either a fixed CRI value with a defined tolerance range, or with a minimum CRI value.

Compared to the bare dies, the directionality of the light differs in the packaged LEDs due to contacting, packaging and light propagation in the phosphor or an adapter lens. Manufacturing tolerances lead to very individual directional characteristics.

LED testing with an integrating sphere

In luminous flux measurement the individual spatial radiation properties of different LEDs mean that the emitted light will each time strike at a different position on the inside of the integrating sphere. Irregularities in the sphere coating and form will result in deviations, which is why it is important to use a high-quality sphere in order to guarantee sufficient reproducibility of the measurement results. High-quality integrating spheres that are suitable for production have no optical elements directly opposite the entering light. At this point there is only the homogeneous barium sulfate-coated wall, which diminishes the directional dependence of the measurement.

If the sphere can be positioned very close to the LED, or the LED is mechanically positioned just inside the (theoretical) sphere radius, a silica dome must be used to protect the sphere from dust or loose particles. A flat window would reduce the effective acceptance angle due to the strong reflections resulting from large entry angles. **Figure 6** (left) shows the configuration. A greater distance between the LED package and sphere also permits the use of a flat glass window.

LED tests with an LED luminous measurement adapter

Luminous intensity is measured with a special adapter that contains a cosine-corrected detector with a precisely defined detection area. The LED is placed at a given distance from the adapter in order not to hinder the movement of the positioner. As a consequence, stray light can enter in the space between the emitter and detector, and light from the inside of the adapter can escape to the outside. This distorts the measurement. Although the detector is shielded by the

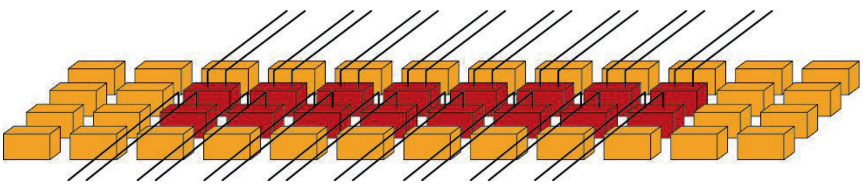

Figure 5: LED chips on the wafer are contacted with a special probe card for testing several dies simultaneously

adapter housing and two baffles (schematic drawing on the left in **figure** 7), a sufficiently darkened measurement environment is recommended. The measurement port for the adapter can be protected from dust by a pane of glass. The transmittance of the optical fiber that connects the measurement adapter to the spectrometer may not be influenced by the mechanical vibrations caused by the movements of the positioner.

Due to the high directionality of the LED emissions, precise positioning of the mechanical axis of the LED along the optical axis of the intensity sensor is critical, as even minor deviations may result in noticeably different measurements. This places exacting demands on the accuracy of mechanical positioning.

Module level testing

A module that includes the current feed to the LEDs and possibly contains multiple LEDs adds a level of complexity to the test procedure. Because the optical properties of an LED depend on the current feed, testing can only be carried out for a specific state. Additionally, testing can be performed in different operating conditions. This generates the necessary measurement data for intelligent control of the optical characteristics of the final product.

If the LED bins were intended only for single LEDs, more bins would be needed for modules with several LEDs due to the large number of possible combinations. Binning is thus simplified by simultaneous measurement and combination of all LEDs. To this end, either all LEDs must be powered up together, or their individually measured spectra combined by software to derive the colorimetric and photometric quantities.

Because the current feed is now part of the measured system, for many customers the lumen per watt may be made a parameter for binning.

Due to its dimensions and light output, the testing of entire modules requires integrating spheres with a diameter of 250 to 1000 mm. The test sequence is otherwise as described in the above sections.

[1] Đ. Konjhodžić, Contribution to Technical Report from CIE TC 2-64, "High speed testing methods for LEDs", to be published by CIE

[2] T. Kawabata, Y. Ohno, "Optical measurements of OLED panels for lighting applications", Journal of Modern Optics, 2013

Measured value	LED	OLED
Luminous flux	Yes	Yes
Radiant flux	Non-visible (UV/NIR) LEDs	No
Luminous intensity	Yes	No
Radiant intensity	Non-visible (UV/NIR) LEDs	No
Luminance	No	Yes
Luminance homogeneity	No	Yes
Color coordinates	Yes	Yes
CCT	Yes	Yes
CRI	Yes	Yes
Dominant wavelength	Monochrome, e.g. blue chip for white LEDs	Rarely
Centroid wavelength	Rarely	No
Angular characterization	Only in laboratory	Laboratory and pilot lines

Table 1: Summary of measured properties for LEDs and OLEDs

OLED testing

There are many similarities when it comes to optical measurements in the fledgling field of OLED mass production. The larger light-emitting surface calls for larger integrating spheres for the measurement of luminous flux in 2π configuration. Luminance is measured with optical probes, which are uncommon in classical LED production, although they are widely used for testing in display manufacturing. Display measurement equipment can also be used for the measurement of luminance homogeneity and angle characterization.

Optical measurement procedures have hitherto been the exception in OLED manufacturing. Modules of different manufacturers, however, point to common properties whose measurement may be helpful [2]. **Table 1** lists properties likely to be tested in mature production lines.

This article is based on the "Handbook of LED and SSL Metrology" by Günther Leschhorn and Richard Young. Visit **www.instrumentsystems.com/handbook** for further information. ■

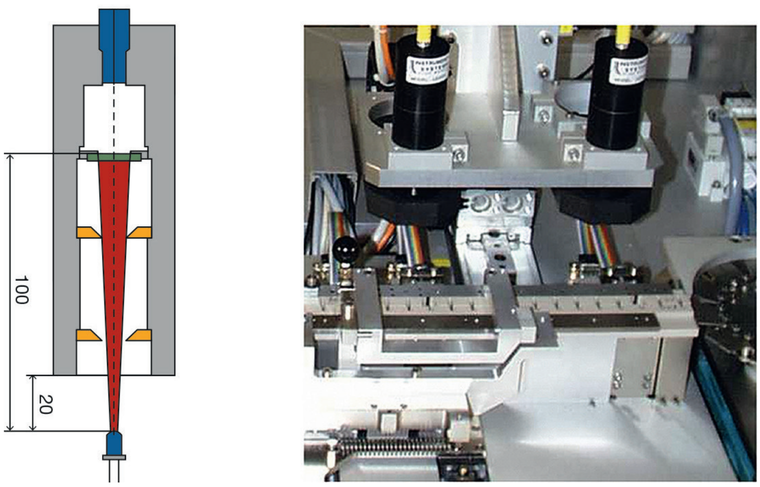

Figure 7: Schematic drawing (left) of a CIE Condition B averaged LED intensity adapter for production applications. On the right the optical measurement setup has been integrated into an LED sorting system.

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