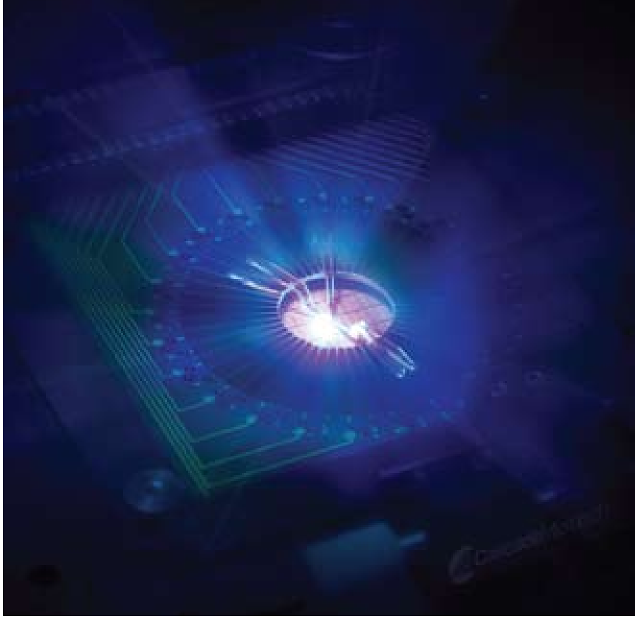


As markets for display backlighting and solid-state lighting grow, equipment vendors adapt to meet the needs of a rapidly changing industry.

LED test

BY BRYAN BOLT, CASCADE MICROTECH

Rapid market growth for HB (high-brightness) LEDs is driving what was once a niche industry into full-fledged high-volume production. With the emergence of applications such as display backlighting, and with the brass ring of SSL (solid-state lighting) almost within reach, some analysts are projecting a CAGR (compound annual growth rate) of greater than 30% over the next several years (Ref. 1).

New players are scrambling to enter the market, and established manufacturers are retooling to compete for their share of the new business. The rapid growth is adding complexity to an already complicated IP (intellectual-property) landscape. New device architectures, materials, and processes are being introduced—in some cases to get around existing IP and in others to attain a cost or performance advantage over the competition (see "A growth industry" in the online version of this article at www.tmworld.com/2010_09).

These factors combined with a shortage of industry standards and the lack of a common technology roadmap present major challenges for manufacturers of equipment used in LED production. This is certainly true for the providers of wafer-level test systems, which are used for in-process testing of optical and electrical properties for each die on every HB LED wafer produced. New equipment must accommodate the range of test configurations found across the spectrum of manufacturers. At the same time, the equipment must keep the cost of test low to help reduce the overall cost of LEDs and contribute to the successful adoption of LED technology in consumer applications.

LED manufacturers need equipment that is designed especially for LED test, because general-purpose test equipment that requires significant customization results in unacceptable levels of R&D spending. Likewise, repurposing semiconductor test equipment for LEDs imposes a similar overhead—the effort needed to modify the equipment would distract LED manufacturers from their actual objective.

LED test equipment should have a modular and flexible design so it can support the broad and changing needs of LED manufacturing. Purpose-built tools, integrated with all necessary instrumentation and automation, will provide improved cost of ownership and will allow LED manufacturers to focus on the production of LEDs (see "Manufacturing in transition," in the online version of this article).

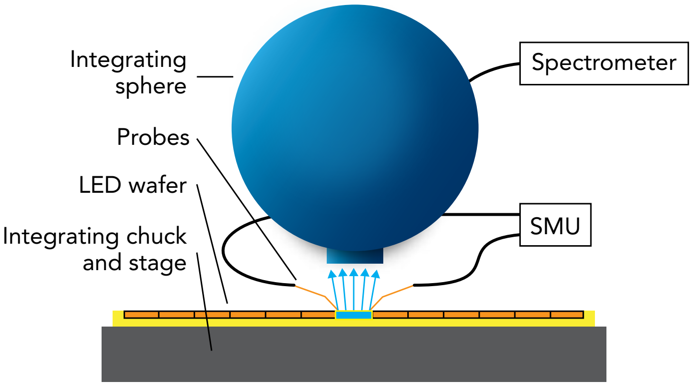


FIGURE 1. Typical wafer-level LED test components include a wafer prober, an SMU (source measure unit), and probes to apply an electrical current to the DUT (device under test) and to measure its electrical parameters. An LED test system also includes light-collection optics, such as an integrating sphere or optical fiber, and a spectrometer to measure the spectral output and optical power of the DUT.

In-process test

Testing of in-process LED devices to determine their characteristics is an essential element of the manufacturing process. In-process testing is conducted for a number of purposes at both the wafer level and the die level. The full test suite varies from manufacturer to manufacturer, but all manufacturers include tests to identify defective dice and to determine electrical properties, optical power output, and spectral output for each die (see "White-light LEDs," p. 40).

The typical setup used for LED measurements (**Figure 1**) consists of a wafer prober, an SMU (source-measure unit), and probes that apply an electrical current to the DUT (device under test) and measure its electrical parameters. An LED test system also includes light-collection optics, such as an integrating sphere or optical fiber, and a spectrometer to measure the spectral output and optical power of the DUT.

Testing takes place throughout the value chain, including at the epi-houses that produce and sell undiced LED wafers (epi-wafers), packaging houses that dice and package chips from procured epi-wafers, and vertically integrated LED manufacturers that carry out all process steps from bare wafer through packaged device. Each die may be tested up to four times before the packaged device is qualified and ready for sale.

After epitaxial film growth, lithography, and metallization, the wafer is populated with thousands or tens of thousands of operational LED chips, depending on device and wafer dimensions. At this point, each die is tested for functionality, and results are recorded to a wafer map to ensure that no avoidable downstream process costs, such as packaging, are wasted on bad dice. Initial functionality may be determined by a simple light/no-light test, or it may be determined on the basis of electrical and optical performance criteria.

Because subsequent wafer-processing steps could affect a device's characteristics, a manufacturer may choose to test device performance at several additional points. For example, after wafer dicing, stress relief of the device and changes in geometry can alter flux output, spectral output, and the light-extraction efficiency of individual dice. Therefore, testing is sometimes performed on the diced wafer mounted to a film-frame carrier to ensure the best possible measurement accuracy. Similarly, processes such as laser lift-off, which involves transferring of the LED's active film layers from one substrate to another, can alter device performance and may necessitate another round of test. Testing of white-light LEDs may be performed before and after application of the phosphor that is used to produce a broad (white) spectral output from blue or ultraviolet LEDs. Finally, packaged devices must undergo a last round of testing to account for performance changes encountered during the packaging process.

The requirement for this substantial test burden is driven by the demanding applications that will ultimately make use of the LEDs. The human eye is remarkably sensitive to variations in color and

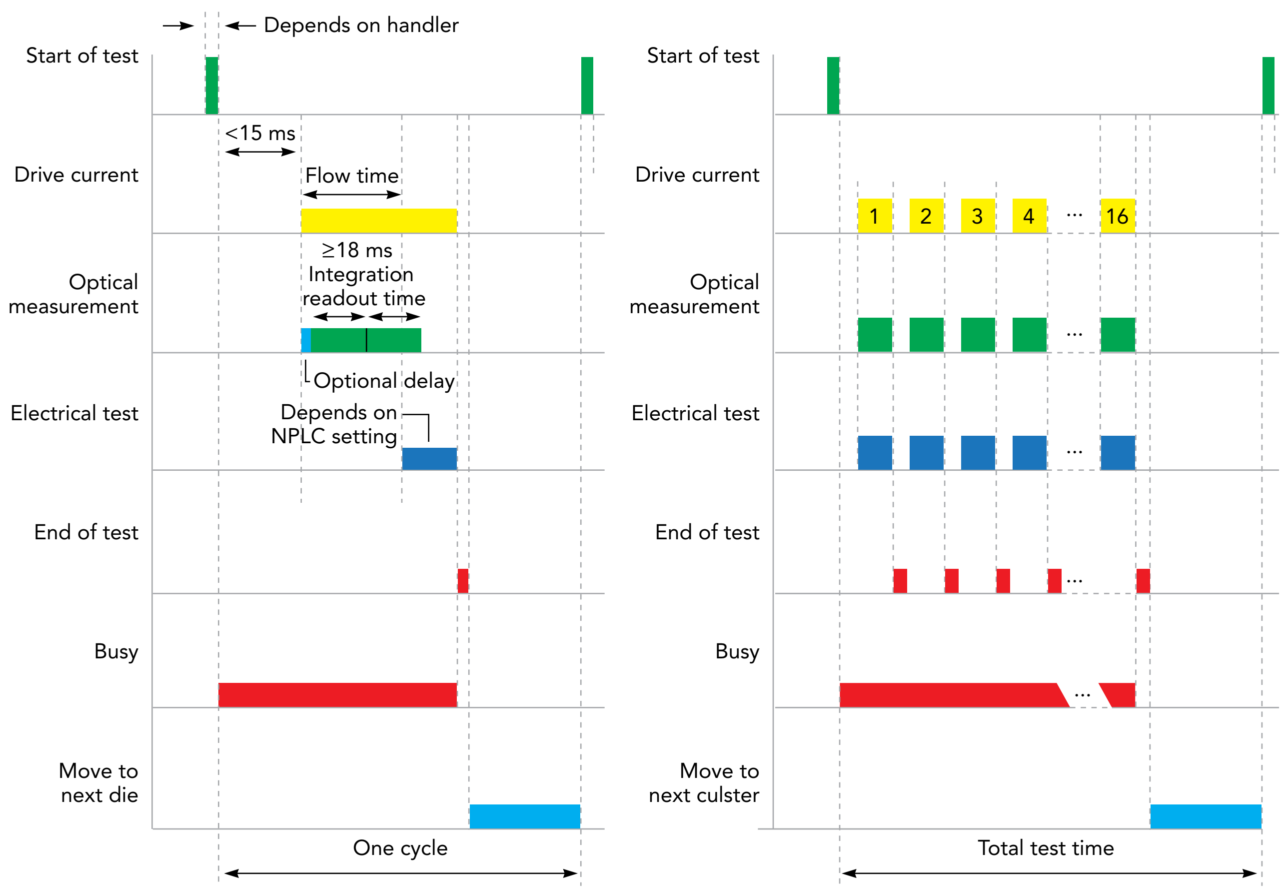


FIGURE 2. These timing diagrams for (left) single-die test and (right) multidie test show that a time-consuming move to the next test region is performed after every die for single-die testing, but only once for every 16 dice tested using multidie test.

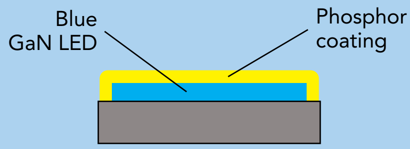
White-light LEDs

Two principal methods exist for producing white light using LEDs (Ref. A). In the first method, red, blue, and green chips are combined to achieve a broad color gamut. LEDs made using this method can achieve excellent results for color rendering, but it may be difficult to maintain proper color mixing over the life of the lamp due to differing degradation rates between the three components.

The second method, which is more commonly used for solid-state lighting applications, is based on a single LED and a phosphor (**Figure A**). Most often, a blue GaN or InGaN LED is coated with a phosphor such as Ce:YAG (cerium doped yttrium-aluminum-garnet).

Blue light emitted by the LED undergoes Stokes scattering in the phosphor to create a broad output spectrum like that shown in **Figure B**. Note the large blue peak from the light which makes it through the phosphor without being Stokes shifted.—*Bryan Bolt*

FIGURE A. (right) This white LED includes a single blue GaN chip with a phosphor coating instead of red, blue, and green chips.



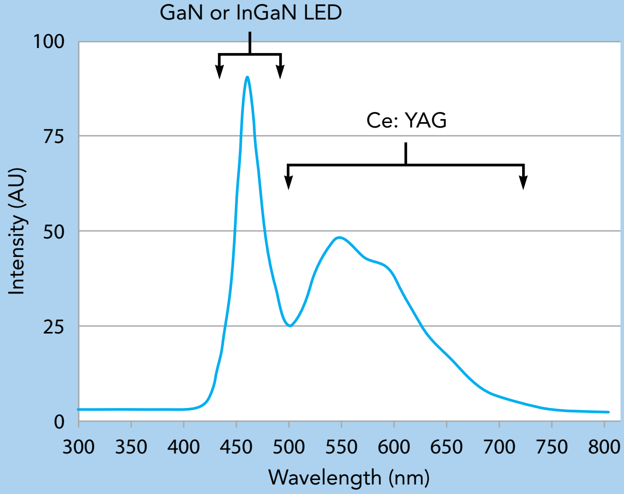


FIGURE B. (above) Stokes scattering of blue light results in this output spectrum, with intensity shown in AUs (arbitrary units).

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intensity. For colors near the peak of the visual wavelength-discrimination function, variations of 1 or 2 nm can be detected by the eye. The eye can also see intensity variations as small as 1% or 2% under ideal viewing conditions (Ref. 2).

According to Sudhakar Raman, VP of business development for Veeco's LED/Solar MOCVD business, "The epitaxial process defines wavelength and initial brightness." Raman added, "Variations in the epitaxial growth conditions during processing can show differences within each wafer, wafer to wafer, run to run, and tool to tool. These contributors can result in significant variations in color and intensity for older processes, while state-of-the-art processes and equipment can achieve yield variation of <10 nm for color and <10% for intensity."

When LEDs are used in arrays such as those used to illuminate a room or the taillight of an automobile, die-to-die variations in color and intensity can be visible to the observer and lend a non-uniform appearance to the illumination. Although process improvements have been significant in recent years, die-to-die variations in color and intensity are still at levels that are easily detected by the human eye. Testing and sorting is therefore required to make use of the maximum number of dice produced. This sorting process, called binning, ensures that all LEDs in a given lot will meet customer requirements for color, output power (flux), and electrical properties. Tightly binned LEDs command higher prices due to the added value they offer consumers. The need for tight binning, among other factors, is pushing demand for higher and higher test accuracy.

Challenges for equipment suppliers

A range of new device technologies, along with increasing demands for performance, contributes to the challenges faced by manufacturers of LED production and test equipment. In addition, the lack of a clear LED technology roadmap that is consistent from manufacturer to manufacturer translates into uncertainty regarding the features that will be needed to serve the majority of the customer base. Innovations spurred by the many competing companies in this space have led to wide variability even in areas where some level of standardization might be expected.

One example is the wide range of substrates used across LED manufacturing, which places considerable demands on the wafer-handling subsystems of manufacturing equipment. Most of the current LED production is carried out on 2-, 3-, and 4-in. wafers. Some manufacturers will introduce 6-in. processes this year, while others are discussing 8-in. and beyond for the near future.

Sapphire is the leading substrate material, SiC is in production with some manufacturers, and processes based on bulk GaN, silicon, and other materials are also in the works. Devices may need to be tested on noncircular submounts, thinned wafers, or diced wafers as well.

Unlike with most silicon-semiconductor equipment, new offerings for LED must often serve legacy technologies (for example, 2-in. wafers) yet also meet the latest requirements for performance, such as higher throughput or increased accuracy. Wafer-level test systems must accommodate a number of other configuration variations. For example, some devices require electrical contact on the top surface, while others require top and bottom side contact. Optical test for devices built on transparent substrates may require light collection to be made from beneath the wafer, while opaque substrates force light collection to be performed above the wafer surface. Device dimensions ranging from around 250 µm up to 10 mm wide require significantly different collection optics to effectively sample light from across the spatial and angular ranges of their outputs. HB LED drive currents range from hundreds of milliamps to several amps with accompanying output fluxes varying similarly (Ref. 3).

Many areas of uncertainty and inconsistency can be found throughout LED manufacturing (see "A lack of standards," in the online version of this article). For LED test, the top priorities are to continue to improve test accuracy while significantly driving down the cost of test.

Reduction in equipment COO (cost of ownership) will be a critical step in bringing down the cost of LED technology. According to the US DOE SSL Manufacturing Roadmap, a 2X improvement in COO every five years is the recommended target (Ref. 4).

Improving throughput is a key factor in improving COO for wafer-level test systems. One way to do this is by performing multidie test rather than traditional single-die test. In multidie test, a probe card contacts a number of dice simultaneously. Electrical test may be performed sequentially or in parallel by the use of multiple SMUs. Optical test is performed sequentially to avoid optical crosstalk between adjacent dice under test.

ON THE WEB

The online version of this article includes sidebars that discuss the reasons the market for LEDs is burgeoning ("A growth industry"), the need for new tools for LED production ("Manufacturing in transition"), and a proposed new standard for evaluating LED quality ("A lack of standards").
www.tmworld.com/2010_09

Because only a single wafer-stage move is required for each group of LEDs contacted by the probe card, multidie test reduces test time while still providing sufficient integration time for optical measurements (**Figure 2**). Depending on cluster size and test parameters, throughputs as high as 70,000 dice per hour may be achieved on multidie test systems such as the Cascade Microtech BlueRay.

Additional reductions in COO can be realized by increasing the level of test-system automation. Even in low-cost regions, the labor cost associated with manual loading and alignment of each wafer is too high for high-volume production. Test systems must take over some of the repetitive tasks that are commonly performed manually today.

Equipment makers will play an important role in contributing to the overall cost reductions that are needed to enable mass adoption of LED lighting. As processes, technologies, and standards continue to mature, test manufacturers must remain agile and continue to cooperate with customers and other industry suppliers in order to provide lasting solutions. T&MW

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Bryan C. Bolt *is technology development manager for test systems at Cascade Microtech, Beaverton, OR. He has worked in the fields of optics and semiconductor capital equipment since 1988 in various engineering and technical management roles with companies including Etec Systems, Applied Materials, ESI, and Novellus Systems. He holds a PhD in electrical engineering from the University of North Carolina at Charlotte and is a licensed professional mechanical engineer in the state of Oregon.*