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High Value HBLED Testing

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High brightness LEDs (HBLEDs) offer much higher performance than traditional LEDs, but come with significantly higher cost. These two factors drive the way HBLEDs are tested in both R&D and Production.

Testing Needs

The demand for High Brightness Light Emitting Diodes (HBLEDs) is growing rapidly because of their high efficiency, long life, and wide range of available colors. These characteristics are driving their use in applications such as architectural lighting, automotive lighting, medical equipment, military systems, and even general illumination. The demand for these devices will grow even faster with lower prices and increased efficiency, but these two steps require refined testing methodology and instrumentation.

To take advantage of the new opportunities that HBLEDs bring, manufacturers are looking for ways to increase production volumes and reduce unit costs of existing HBLED designs. In R&D labs, new III-V materials and phosphors (for white light) are being investigated to find those that allow HBLEDs to be produced cheaply and with better performance. Major objectives include higher efficiency, more colors, higher current density and optical output, and better packaging with increased cooling capabilities. These aims are especially important for HBLEDs used in illumination, where incandescent and fluorescent lamps currently have a significant unit price advantage.

Effective electrical measurements must be carried through R&D into production, and this often takes place while technical issues are still being worked out. Meticulous production testing is critical for refining processes and improving yields as new technology is commercialized. Nevertheless, rapid automated measurements are also crucial for high production throughput, while maintaining high precision and sensitivity over wide parameter ranges. These requirements must be met in testing individual devices (for example, with handler systems testing chips or packaged parts) and when doing initial upstream screening with on-wafer testing of many devices in parallel.

Alternate Testing Needs

Recent advances in High Brightness Light Emitting Diodes (HBLEDs) have caused demand to increase significantly. The higher efficiencies, longer lifetimes, and an increased assortment of colors available with this new breed of LED have allowed the device to expand on its old role as an indicator lamp and move into more widespread applications. Today, LEDs are being used for specialty and automotive lighting, medical equipment, and military systems. There have even been significant strides towards replacing fluorescent and incandescent lighting for general illumination. This expansion of applications and widespread implementation of LED-based lighting systems has created a tenuous situation for manufacturers. There is a strong need to decrease the unit costs of these devices by dialing in manufacturing process and increasing throughput while maintaining innovation and a technological foothold through continued R&D.

In order to simultaneously achieve these goals, the device characterization becomes all the more important. Test engineers must build systems that maintain the thorough nature of R&D testing with increased throughput for effective production. This carry-through of high accuracy testing is critical for refining processes and improving yields as new technology is commercialized, while implementation of automated measurement and handling techniques help to increase the production throughput without compromising high precision and sensitivity. These requirements must be met in the testing of individual devices (for example, with handler systems testing chips or packaged parts), and during initial upstream screening with on-wafer testing of many devices in parallel.

LED Attributes Define Testing

In their simplest form, traditional LEDs have homogeneous structures that use the same type of material for the P and N junction. This minimizes lattice matching difficulties and simplifies processing, which makes them inexpensive but not especially efficient at light generation. A typical operating condition is a drive current of 20mA at a forward bias of 2V. Depending on the range of products and drive currents, luminous intensity could range from 1 to 100mcd. One of these LEDs, designed for use as an indicator lamp, might cost $0.30.

HBLEDs have more complicated semiconductor structures (***Figure 1***) created using multiple materials. These heterogeneous junctions, or heterojunctions, are constructed with multiple III-V materials such as AlGaN. These structures are designed to optimize the generation of photons from the recombination of charge. By combining these structures with better light extraction techniques, luminous outputs can range from one hundred to several thousand mcd.

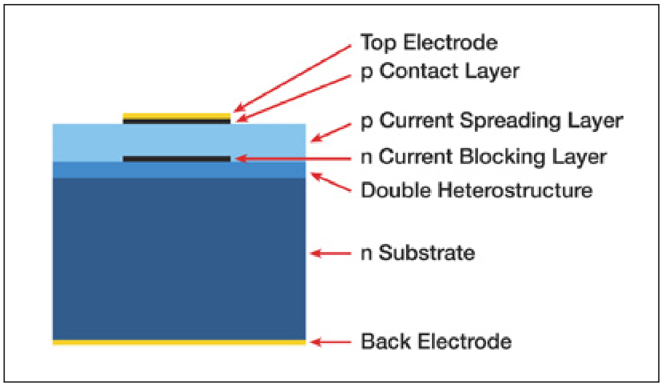

Figure 1. Diagram of a multilayer HBLED.

To reach this level, an HBLED may operate at a forward bias condition of 4V or more and 1A. Such a high source current requires an electron blocking layer between junctions to increase the radiative recombination rate and lessen the self heating (I^2R) of the junction. In addition, HBLED packaging must be designed to dissipate more heat and maintain the LED junction temperature at an appropriate level (typically, below 120°C). For more efficient thermal transfer, the package may utilize a current spreading layer and more robust wire bonding.

With these additional attributes, HBLEDs are not easy to produce. Currently, due to poor lattice matching that results from process difficulties, production wafers can have a large number of defects that must be weeded out via testing. The complicated packaging and many value added steps in production add substantial cost. Therefore, a cutting edge HBLED designed for a specialty lighting application could cost as much as $30.

Test Programs

As implied above, a product's intended application and cost structure are key determinants of its production test regimen. For example, an HBLED designed for highly aesthetic architectural illumination may need to meet or exceed the performance characteristics of an incandescent bulb or fluorescent lamp. Similarly, HBLEDs used in automobiles must pass stringent optical and electrical limits over a wide range of operating conditions (typically –30°C to +85°C).

For demanding applications like these, HBLEDs typically are 100% tested on the wafer. Standard measurements include optical output power and spectrum performed at one or more forward bias conditions (V and I measurements), reverse bias leakage current measured at a specific voltage, and ESD tolerance. After packaging, up to 100% of the devices may be tested yet again in a final characterization and binning operation. The sheer volume of testing time consumed in these steps amounts to a substantial portion of the production throughput time. Because HBLED applications require all these tests, the only option for increased throughput is increased test speed (i.e., decreased measurement time).

This is in stark contrast to the test strategy for traditional LEDs. They are typically lot tested at a sample rate of 1-10% on packaged parts, and rarely on the wafer. This low sample rate allows a few more tests to be run, such as far field pattern/optical axis, in addition to the tests mentioned for HBLEDs, but the total number of devices tested still remains small and the test time has a relatively small impact on production throughput.

Test Methodologies

HBLEDs applications and increased processing require a melding of test strategies and instrumentation. The basic measurement methodology in most component testing is to apply a current or voltage source to the device under test (DUT), and then measure its response to that stimulus.

In the case of HBLEDs, the following tests are typically performed:

- Luminous Intensity (L): Source +I, Measure L (***Figure 2***)
- Forward Voltage (V_f): Source +I, Measure V_f (***Figure 3***)
- Reverse Breakdown Voltage (V_r): Source –I, Measure V_r
- Reverse Bias Leakage Current (I_r): Source –V, Measure I_r
- Junction Temperature (T): Pulse Source I, Measure V_T and estimate junction temperature
- ESD – Electrostatic Discharge Damage/Lifetime Testing: Source a known voltage in a short period of time and then retest Reverse Bias Leakage on the DUT.

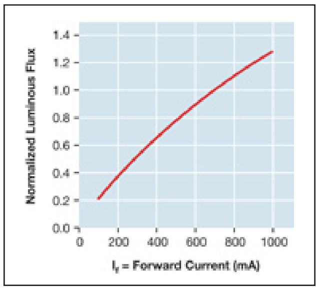

Figure 2. L-I curve.

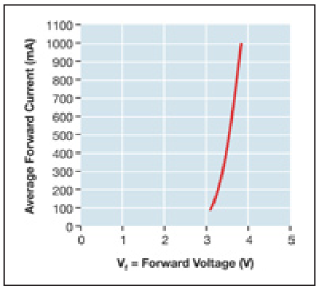

Figure 3. Forward I-V curve.

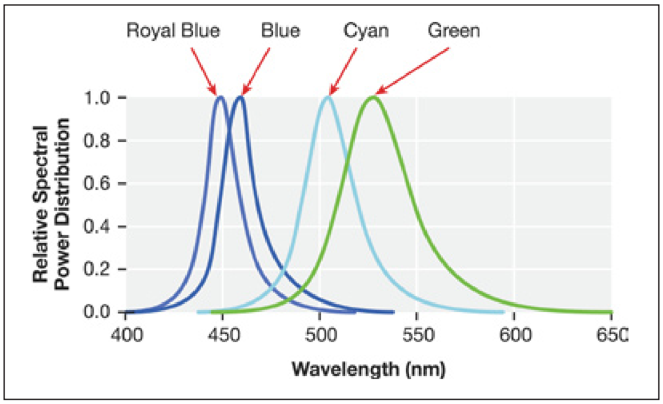

Figure 4. Relative spectral power distributions for various HBLED colors.

Forward voltage, spectral output (***Figure 4***), luminous intensity, and breakdown characteristics are very important for device binning and operation. These characteristics may also need to be correlated with junction temperature (T_j). See ***Figure 5***.

For example, in many HBLED applications, multiple devices are mounted in a fixture and wired in a parallel to provide a larger area of illumination. Automotive taillights use this arrangement. In such a configuration, it is important to ensure that the I-V characteristic of

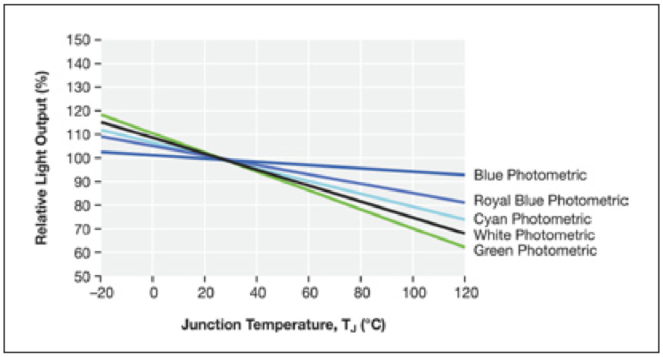

Figure 5. Light output vs. junction temperature derating curve.

each LED is similar. Differences may cause some LEDs to draw more current and raise the junction temperature of those devices, which can lead to premature failure. Replacement of a complete LED assembly because of a single failure can be quite costly. These occurrences can be minimized by matching LED V_t parameters, i.e., the voltage measurement at a given junction temperature. This temperature can be described by:

$$T_j = T_a + \Delta T_j,$$

where T_j (°C) is the junction temperature, T_a (°C) is the ambient temperature, and ΔT_j (°C) is the temperature rise of the LED junction above ambient.

During testing, ΔT_j is highly dependent on the current being sourced as well as the behavior of the HBLED junction. Many devices have a small thermal mass, so high current density can make the measurement of T_j nearly impossible with a standard DC current source. This has created a new test dimension – pulsed measurements to keep the source current contribution to ΔTj as low as possible.

The junction temperature can be estimated by a straightforward manner. First, place the device in a temperature chamber and let the system come to thermal equilibrium at a set temperature (°C). Then, a current pulse is sent through the device and the forward voltage of the junction (V_t) is measured. This is then done at a number of temperatures, and a curve of junction temperature vs. voltage can be obtained. Devices can then be grouped according to their V_t values.

Although pulse testing adds complexity to the instrumentation, it is commonly used in R&D and is growing rapidly in off-line production testing (i.e., for QA where performance specs must be accurately verified, especially near the junction temperature limit).

Instrumentation

Whether in an R&D lab or production environment, a high precision optical spectrum analyzer (OSA) and single DC source-measure unit (SMU) can be used to characterize new HBLED designs. (See ***Figure 6***.) To characterize traditional LEDs during production, less expensive laboratory instruments and homemade systems have typically been used, because of the lower accuracy and lower rate of testing required. Such equipment includes inexpensive power supplies, DMMs for electrical measurements, and lower cost spectrometers, all tied together by the GPIB.

The new demands of HBLED characterization have changed the instrument needs significantly. Because of its high accuracy and speed, the SMU has become a standard instrument for HBLED characterization. Besides speed and accuracy, additional features of an SMU make it a perfect instrument for performing Forward Voltage (V_f), Reverse Breakdown Voltage (V_r), and Reverse Bias Leakage Current (I_r) tests. These features include four-quadrant current and voltage sourcing, which facilitates not only I-V testing, but also optical power measurements.

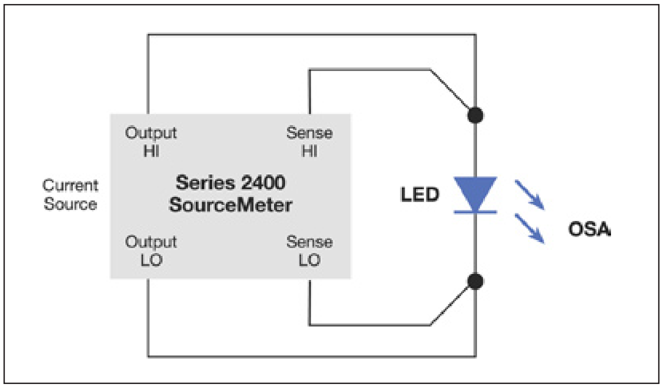

Figure 6. Single LED laboratory test system.

As an HBLED design moves towards production, the need for high test speed increases. At some point, it simply is not enough to test each device more quickly; then parallel device testing becomes an important option for increasing throughput. In addition, measurements must be highly repeatable for valid comparisons between devices and production lots.

To address these needs, multiple SMUs can be tied together via external trigger lines. Another alternative is an integrated high precision, high-speed multi-channel SMU system. See ***Figure 7***. These precision measurement systems are designed for high throughput, are robust enough for the production floor, and have control features that increase test efficiency.

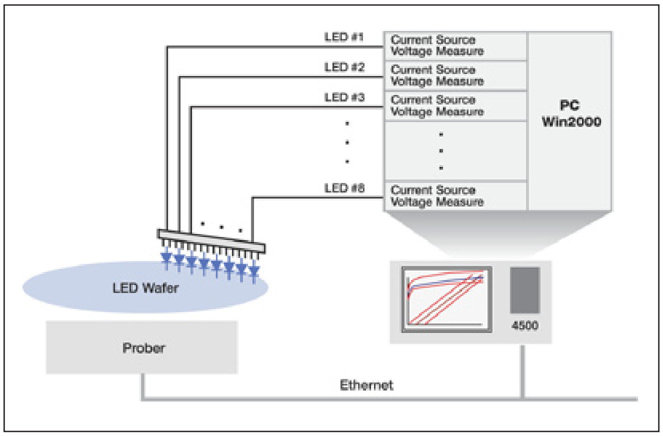

Figure 7. Keithley multi-channel HBLED wafer test system.

Except for the prober, the instrumentation pictured in ***Figure 7*** is completely contained within a single chassis-mounted backplane enclosure. This system provides real-time parallel test and "cable out" capabilities (a cable interface to the wafer prober), which in this case uses a fast Ethernet connection. Such a system allows accurate, high-speed, and fully parallel testing of multiple DUTs that is needed for efficient HBLED production. Because data communications take place over the PCI backplane or the Ethernet link, latencies and decreased throughput associated with the GPIB are eliminated.

The system design allows integration of optical collection elements into the probe card, so that parallel optical and electrical device characterization can be performed on the wafer. The tester's PCI backplane can accommodate up to nine SMU cards, each one capable of electrically testing four HBLEDs simultaneously at DC levels up to 10V and 1A. This is like having 36 tightly integrated test instruments in one box. (The actual number of devices that can be contacted at the same time depends on the pitch of the die and arrangement of electrical pads.) Alternatively, the four current sources on each SMU card can be connected in parallel to simultaneously test nine HBLEDs at current levels up to 4A.

If necessary, OSA measurements can be added to the system via a spectrometer PCI card interface. With this functionality a typical test sequence would be as follows:

1. The prober moves a wafer into position and lands probe pins on a number of individual HBLED die.
2. Forward current is sourced by the tester to each die simultaneously, at five separate current levels. The forward voltage drop at each die is then measured simultaneously by the tester.
3. Reverse voltage is simultaneously sourced to each die by the tester. The leakage current from each die is then measured simultaneously by the tester.
4. Data is recorded.
5. The prober moves to the next wafer location.
6. Steps 1–5 are repeated until the entire wafer (or predetermined sample size) is completely tested.

It's possible to use DC measurements in place of some direct optical measurements. For example, light intensity can be measured using a photodetector (PD). The amount of photocurrent present through the PD is proportional to the amount of light shining on it. Light intensity can be calculated by directing the HBLEDs luminous output to the PD and measuring the corresponding leakage current. Using this method to perform light intensity measurement allows most testing to be conducted with high-speed DC instruments.

Other Instrumentation Issues

The accuracy, repeatability, and throughput issues discussed above are fundamental considerations in test equipment selection. It's generally understood that there is always a tradeoff between speed and accuracy, but sometimes the combined impact of these variables is not clear. Accuracy and repeatability should be high enough to avoid yield problems, i.e., passing bad parts or rejecting good ones. Therefore, measurement speed should be programmable to allow optimization of throughput and yield. This can be accomplished with programmable SMU signal integration periods that are adjusted for the best combination of measurement aperture and noise rejection.

However, you can't get performance that wasn't built into the system in the first place. The tester design needs to be built around a low noise, high current DC power source and distribution system that makes precision high speed sourcing and measuring possible. This design should incorporate precise drive current control, fast settling time, and high resolution to round out its capabilities.

The instrumentation architecture and control scheme can also have a major impact on throughput and other system performance parameters. A trigger bus simplifies intercard hardware synchronization. The chassis controller PC should be compatible with industry standard test development and execution environments. The firmware should shield system integrators from the fine details of embedded controller programming so they don't have to learn a new language or process.

For example, the SMU card software drivers should allow a test engineer to incorporate much of the production test cell control into the tester chassis. This reduces system complexity and speeds up both test program development and execution. In a similar vein, it should be easy to interface the tester to other instrumentation, which is the case with a PCI backplane that accepts a wide range of cards from third party vendors.

Besides improving performance and making the test system operator friendly, features such as these can reduce the system's overall size, an important consideration in facilities short on floor space. Furthermore, an open architecture and modular design allow a system to be adapted quickly to product line changes and emerging test requirements in a dynamic market environment. All this reduces capital, system integration, and operating expenses, resulting in a much lower cost of test and higher yields.

More information on LEDs and their testing is available at www.lightemittingdiodes.org, and www.keithley.com. KEITHLEY

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