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# Review

LpR

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# Reboot With Plenty of Opportunities

The beginning of the year is always a good time for reorientation in our private and business lives.

With this Jan/Feb 2021 LpR issue, we want to set an impulse for a reboot and so have compiled some interesting topics for you that will accompany us in the lighting sector this year.

In his LpS Digital lecture, Mark Ridler talks about his view of the Circular Economy and how this important topic will be incorporated into lighting projects. Then we had an in-depth conversation with Patrick Durand, who was able to explain the advantages of Bluetooth Mesh and its practical implementation concepts. One focus, of course, remains "healthy light" and the orientation of lighting solutions to human needs. Here you will find several TOP contributions from projects to business and product solutions. With Double Dynamic Lighting we also present a new approach to dynamic lighting design - a study conducted by the University of Aaalborg. Besides design and applications, technology is the driver for lighting innovations. We present dynamic lighting solutions, MicroLED displays, simulation support, UV-LED curing and LED testing. All areas that can provide us with new impulses in technological sectors.

But perhaps more important than the introduction, I want to wish you a Happy New Year with lots of new impulses and, above all, good health for you and your family.

PS: Call for Papers for the LpS Digital 2021 is now open. Take the opportunity to submit your idea for a paper or present your latest innovations http://www.LpS-Digital.global.

Yours Sincerely,

Siegfried Luger

Luger Research e.U., Founder & CEO
LED professional, Trends in Lighting, LpS Digital & Global Lighting Directory
Photonics21, Member of the Board of Stakeholders
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## ADVERTISING INDEX

# Short-Pulse Testing Eliminates Self-Heating Errors to Produce True L-I Graphs

Since the rise of LEDs as the preferred light source, accurate determination of their parameters has become crucial. One of these parameters - and a standard measure - is measuring LED light output vs current (L-I). Unfortunately, the result is not independent of other parameters. The environment, the package type and many other factors may distort the result. Some of these impacts can be minimized by reducing the measurement time by using ultra-short pulses in the domain of microseconds. Vektrex has designed such a measurement system. Jeff HULETT from Vektrex, and Markus SCHNEIDER from from OSRAM Optosemiconductors explain in detail, the basic problem, why short-pulse testing is relevant, what such a system-setup looks like and how such measurement results differ from standard measurements.

**LED Professionals are finding that measuring LED light output vs current (L-I) for next-generation LEDs is increasingly difficult using widely established test methods. These methods use DC current steps or ≈ 20 ms current pulses to power the LED during measurements and they assume that the LED continues to operate close to the ambient temperature throughout the measurement. As this article will show using example data from LEDs manufactured by three different companies, this assumption is increasingly invalid due to advancements in LED technology. To combat this problem, this article presents a method that will accurately measure these next-generation parts using short (< 40 µs) current pulses instead of the longer ≈ 20 ms pulses that are the foundation of existing test methods.**

## Advanced LED Package Designs Tax Existing Testing Methods

To reduce cost, recently introduced LEDs often incorporate package designs that eliminate the internal heat spreading elements that were present in previous-generation LEDs. In those older LEDs, these heat-spreaders acted like heat reservoirs during testing, slowing the LED's junction-temperature rise during measurements. The newer LEDs, on the other hand, heat quickly during a single long-pulse measurement and, when an L-I sweep is made, the cumulative heating from multiple measurements can result in a heating-induced droop that masks the LED's true L-I characteristic.

**Figure** 1 and **Figure** 2 show thermal simulations of two LEDs from Manufacturer 1 driven by a long (30 ms) current pulse. The two parts employ different state-of-the-art LED packaging principles. One features a heat-spreading element. The other does not.

**Figure** 3 shows the simulated junction temperature over time, for the two package types, per 1 W dissipated heating power. The simulation is done without heat transfer to the ambient environment. This is the typical measurement condition for an LED during production binning. The simulation covers a 20 ms time span – a typical long-pulse testing time.

The simulation begins with the LED at a junction temperature of 25 °C, and within the first millisecond, the temperature rises to 27 °C. One millisecond is about the time constant for the internal heat flow of a typical vertical chip design; during this time the heat flow is still concentrated within the chip itself. After about 1 ms, the heat flow reaches the interface between the chip and the package, and the two graphs fork due to the different heat-flow characteristics of the two package designs. The temperature increases further to approximately 30 °C (per 1 W heating power) after 10 ms, and to 33 °C after 20 ms.

One can conclude first that measurement results are independent of the package design if the measurements are ended within 1ms. Second, a junction temperature increase cannot be avoided. It can be minimized however, not only by ending the measurement within the first millisecond, but also by reducing the measurement time as much as possible.

## Existing Testing Methods Did Not Anticipate High-Luminance LED Applications

Next-generation LEDs also increasingly target high-luminance applications such as machine vision, video projection, specialty lighting and automobile lighting. For these applications, a point-source-like surface emitter is favored to simplify optics design, and overall efficiency is traded off for increased light output. Thus, instead of large-area LEDs operated very efficiently at low current density (<1 A/mm$^2$), high-luminance LEDs feature small light-emitting-area LEDs operated at current densities well above the traditional 1 A/mm$^2$ limit. At these high current densities, electrical conversion efficiency is significantly lower. This, along with the small light emitting area, results in a high power dissipated per unit area. Like the optimized parts above, high luminance LEDs experience rapid junction heating during testing, and when these high-luminance LEDs are tested with long-pulse techniques, the LED's junction temperature can shift by forty degrees or more, greatly distorting the resulting L-I curves.

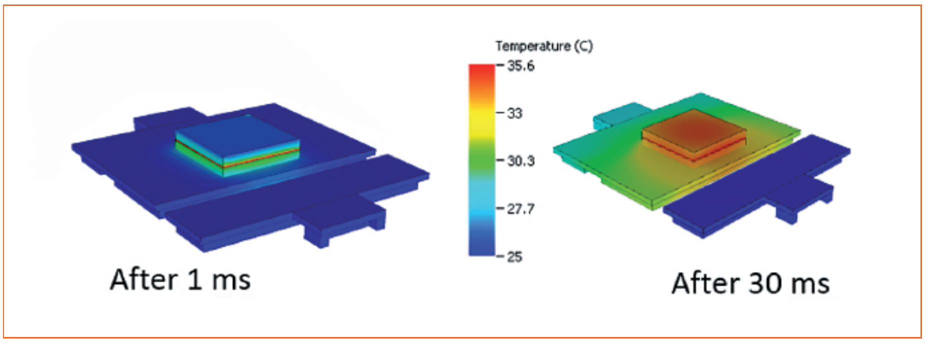


Figure 1: Manufacturer 1, Package Type A – uses a heat-spreading element

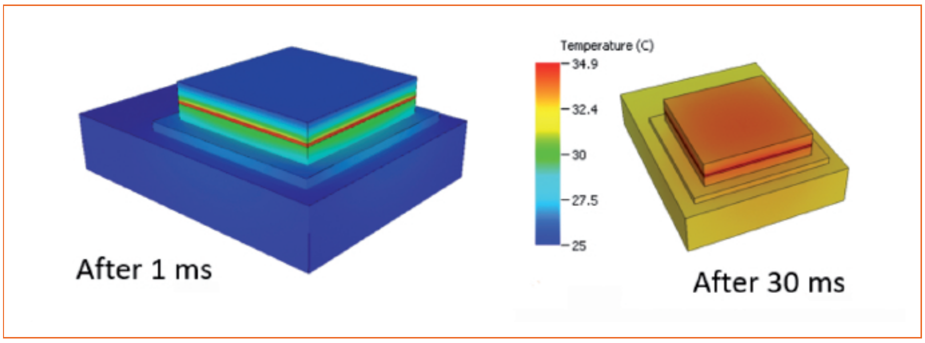


Figure 2: Manufacturer 1, Package Type B – no heat-spreading element is used

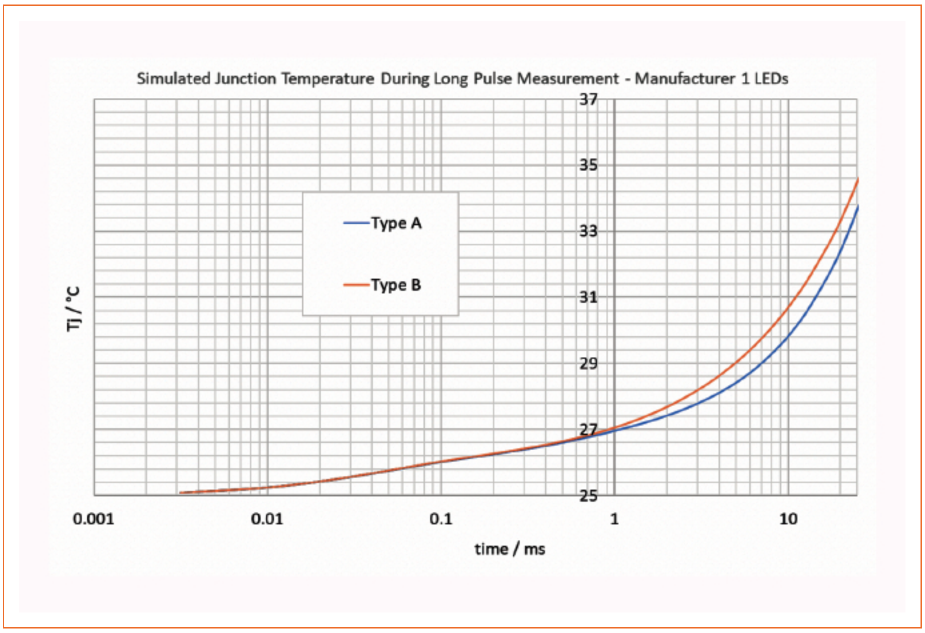


Figure 3: Manufacturer 1's LED junction temperatures diverge after 1ms during a long-pulse measurement

## Correct L-I Curves Allow Designers to Produce More Cost-Effective Products

An LED's light-vs-current (L-I) curve quantifies its primary functional characteristic: how well the device converts current to light. Lighting designers use L-I curves to predict how much current will be needed to produce the light required for an application. They also use related current-vs-voltage (I-V) curves to determine the voltage needed to drive the current.

LED manufacturers specify L-I and I-V curves at a nominal temperature, for example 85 °C. But in many LED application situations, operating conditions deviate from this temperature. In these situations, lighting designers must calculate predictions of electrical and optical parameters using the nominal curves along with LED-manufacturer-supplied thermal coefficients or temperature dependence curves.

If the sample LEDs that the manufacturer used when creating the product datasheet experienced self-heating effects when the nominal I-V and L-I curves were measured, the graphed curves will deviate from true, constant-temperature curves. The magnitude of the deviation depends on the applied current (**Figure 11**). When the distorted curves are used by designers, this deviation results in a prediction error that is virtually impossible to account for. The prediction error is greatest at high current values.

Predictions based upon these distorted I-V curves can lead designers to design larger power and cooling systems than would be necessary if correct data was available, thus increasing product size and costs. Using both L-I and I-V curves the LED's efficiency can also be calculated. For most

LEDs the primary efficiency metric is known as the *Wall Plug Efficiency* (WPE or radiant efficiency $\eta e$).

WPE includes three components:

1. Internal quantum conversion efficiency – how well electrons are converted to photons,
2. Light extraction efficiency – how much of that light escapes the package, and
3. Electrical efficiency – how much power is dissipated in resistive losses. LED WPE is low at very low current density, it quickly rises to a maximum, and then it falls as current density increases. **Figure 4** shows the WPE for a phosphor-converted white LED.

This characteristic of decreasing WPE with increased current density is known as *"droop"*. Droop is mainly caused by a decline in the internal quantum-conversion efficiency subcomponent. Instead of holes and electrons combining to produce photons, at high current densities they instead combine non-radiatively, in what is known as *Shockley-Read-Hall recombination* and *auger recombination*. LED designers strive to improve WPE overall, and to delay the onset of these non-radiative recombination processes to higher current densities, especially in high-luminance applications.

While WPE depends primarily on the LED chip's construction (including the material system used), temperature also greatly influences WPE. Increased temperature reduces both quantum-conversion efficiency and electrical efficiency. In addition, for phosphor-converted LEDs, phosphor down-conversion efficiency decreases with increased temperature through a process called *phosphor quenching*.

## Traditional L-I and I-V Sweep Measurements Have Timing and Heat-Induced Distortions

Historically the L-I and I-V curves that form the basis of WPE graphs have been drawn using a *sweep measurement* – that is a series of single measurements made at increasing currents. The sweep can utilize pulsed current, or it may use contiguous current steps – what is known as a staircase sweep (**Figure 5**).

Staircase sweeps have two primary issues. First, because the LED is driven continuously, heat accumulates from the beginning of the sweep until the end. Thus, early measurements occur at a

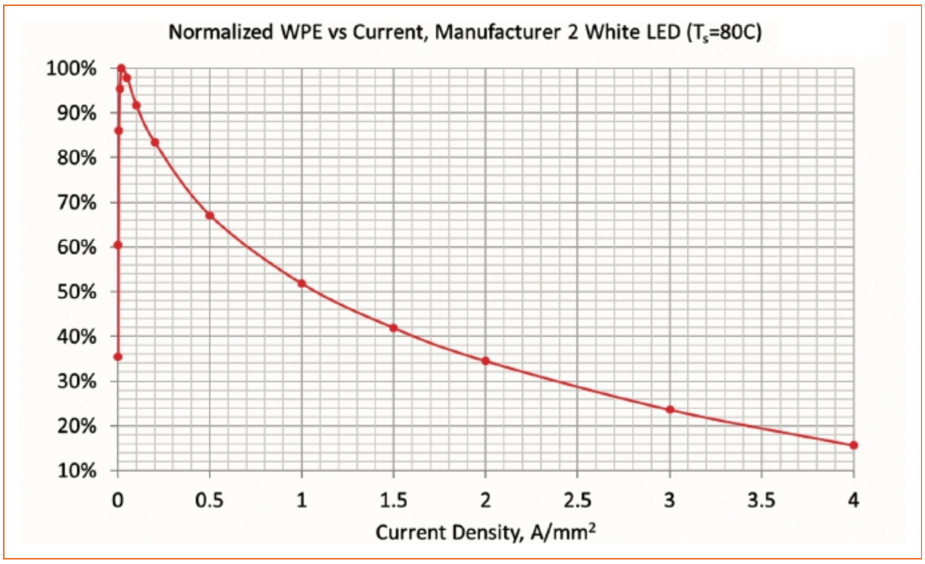


Figure 4: Manufacturer 2 Warm white LED wall plug efficiency (WPE), measured with long-pulse technique, normalized to the peak WPE, declines to 16% at 4 A/mm$^2$

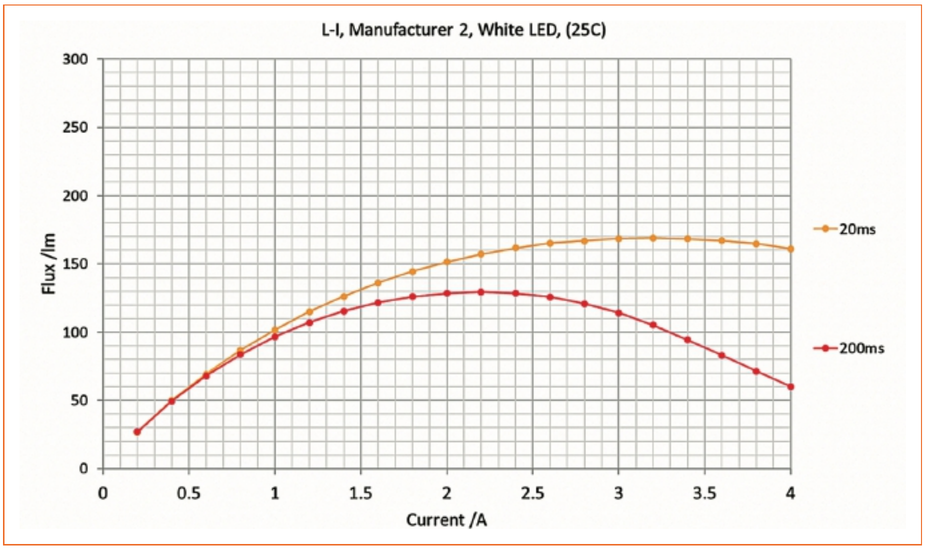


Figure 6: Manufacturer 2, White LED I-V sweep exhibits thermal rollover if the LED is operated at or above the maximum allowed forward current

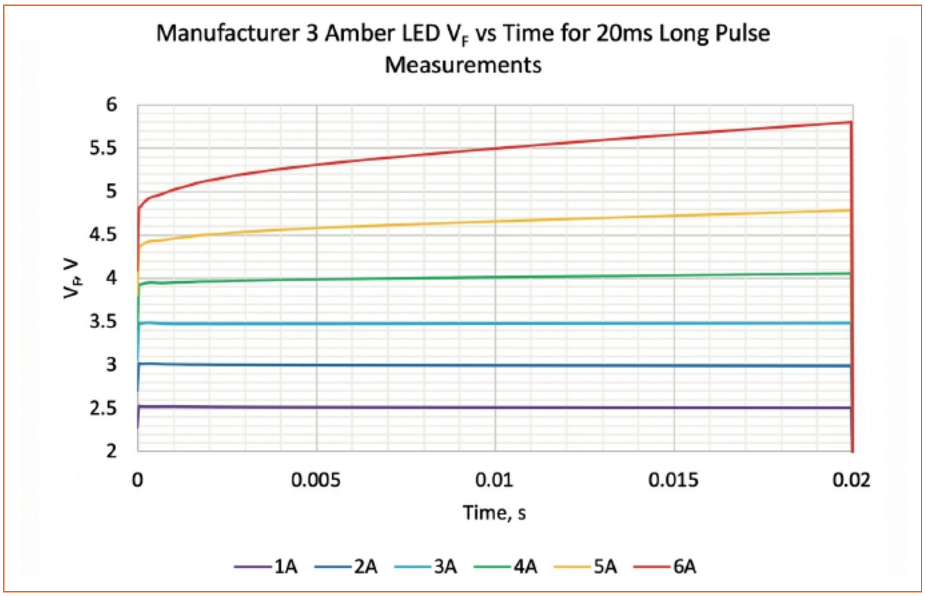


Figure 7: Manufacturer 3 Amber LED $V_F$ vs time for 20 ms measurements reveals distortion caused by interconnect heating

temperature close to the LED's ambient condition, but later measurements are at a higher temperature. Second, step timing is often controlled via software algorithms that have indeterminate timing delays. This variability ultimately results in additional distortions in the resulting L-I or I-V curve.

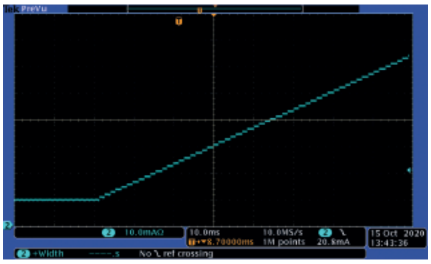

Figure 5: Oscilloscope capture of "Staircase" current sweep shows timing variations caused by software delays

## The LED Industry Turned to Pulsed Current to Reduce Heating

To reduce heating, the industry switched from staircase steps to a pulsed-current measurement technique called Single Pulse, documented in the IES LM-85 standard and CIE Technical Reports CIE TR 225/ TR 226. Single Pulse sweeps reduce heating by powering the LED only briefly during a measurement and then driving the current off for the time between measurements. If the off time is long enough (several tens or hundreds of milliseconds), and the DUT is also mounted to a thermal platform, junction heat has time to escape to the outside environment, and cumulative heating is eliminated. However, these pulsed measurements can still result in significant junction heating during the duration of the pulse – especially at the higher current points.

The LM-85 standard and CIE Technical Reports CIE TR 225/ TR 226 specify that optical and electrical measurements should begin once the DUT has reached a *"quasi-stable"* condition, that is when the rate of temperature rise slows, purportedly at approximately 5 ms. Optical and electrical measurements are then made within the next 20 ms. Single Pulse measurements like these have been used by LED manufacturers for at least two decades. They were satisfactory because the first commercially-available LEDs operated at low current density and their package thermal elements provided significant heat reservoirs. Thus, heating-induced errors were usually insignificant, and they could be ignored. Much of the industry standardized on Single Pulse measurements, for internal R&D testing, datasheet development, and production binning.

As LEDs evolved to higher currents and current densities exceeding 350 mA/mm$^2$ in the last decade, Single Pulse remained the widely-used method even though the underlying assumption – that heating-induced errors were insignificant – became increasingly invalid.

## An Example: L-I Plot for 1 A Phosphor-Converted White LED

**Figure 6** shows an L-I sweep for a 1 A high-power white LED. Two curves are shown. One used 200 ms current pulses with minimal time between measurements (approximating the staircase sweep). The other used 20 ms pulses with an off time for cooling. The tested LED has a die area of 1 mm$^2$, so the maximum current density tested was 4 A/mm$^2$. As the curves show, the 200 ms and 20 ms curves are similar up to the nominal operating current. But above the nominal level the output is degraded by heating. At 2 A the 200 ms curve starts to decline with increasing current, a phenomenon called *"roll-over."*

High current-density testing also generates heating in LED internal electrical interconnect structures like bond wires. The resistance changes caused by this heating can significantly increase forward voltage ($V_F$) values if it is not mitigated with appropriate interconnect structures and materials. The resistance changes further if the package power dissipation increases. At high currents the resulting heating spiral can destroy interconnect structures and even melt bond wires.

**Figure 7** shows an amber AlGaInP LED driven with a 20 ms single pulse. At currents above 4 A $V_F$ increases dramatically during the pulse.


Figure 8: Precision pulsed source/measure instrument used for article's fast-pulse and long-pulse testing

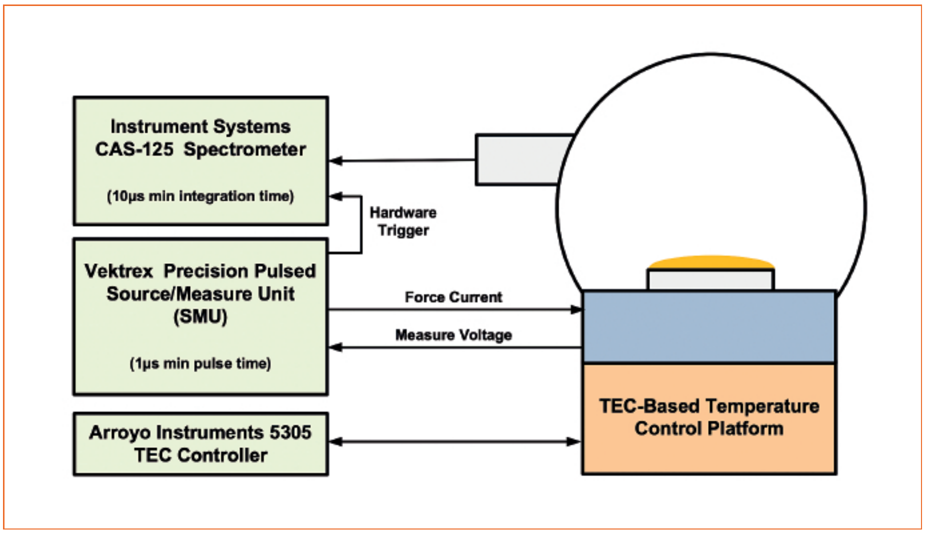


Figure 9: This fast-pulse testing setup was used for this article's measurements

## Much Shorter Pulses Are Needed

To reduce heating during characterization of high current-density LEDs with smaller heat reservoirs, tests must use much shorter pulses. As the example simulation showed, pulses should be shorter than 1 ms to avoid being influenced by the outside environment, and the best results are obtained if the pulse width is well below 40 µs.

Such pulses are possible using *precision pulsed current sources* that feature fast (<3 µs) current rise and fall (**Figure** 8). These instruments also have hardware-based timing to ensure that the spectrometer measurement is always made at the same place within the pulse. For Single Pulse short-pulse testing, spectrometers that can accurately trigger and integrate in the sub-millisecond range are also required. When using short pulses are used, a delay for the quasi-stable time is not required, measurements may be made as soon as the current is stable.

**Figure** 9 shows the fast-pulse testing setup used to make the measurements in this article. In addition to the precision pulsed current source, a Thermoelectric Cooler (TEC)-based temperature platform was used to control the LED case temperature, and a spectrometer that supports microsecond integration times performed the optical measurements.

## Tips for Successful Short-Pulse Testing

Successful short-pulse measurements depend on flat current pulses with fast rise and fall times. To accommodate cable inductance and device capacitance, most fast sources include response-tuning settings. Adjust these settings for best waveshape with actual cable and load conditions. If the current waveform is within compliance and flat during the measurement window, the setpoint current may be taken as the stimulus current. If it is not, the current must be measured with an external instrument and the average current during the measurement window should be used. A high-frequency shunt and a fast digitizer may be used for this average current correction/measurement.

With fast rise times, cable inductance has a significant effect on pulse shape. Minimize inductance by shortening cables and twisting wires. Since $dI/dt = V/L$, the current source's maximum compliance setting can also be increased to improve pulse shape.

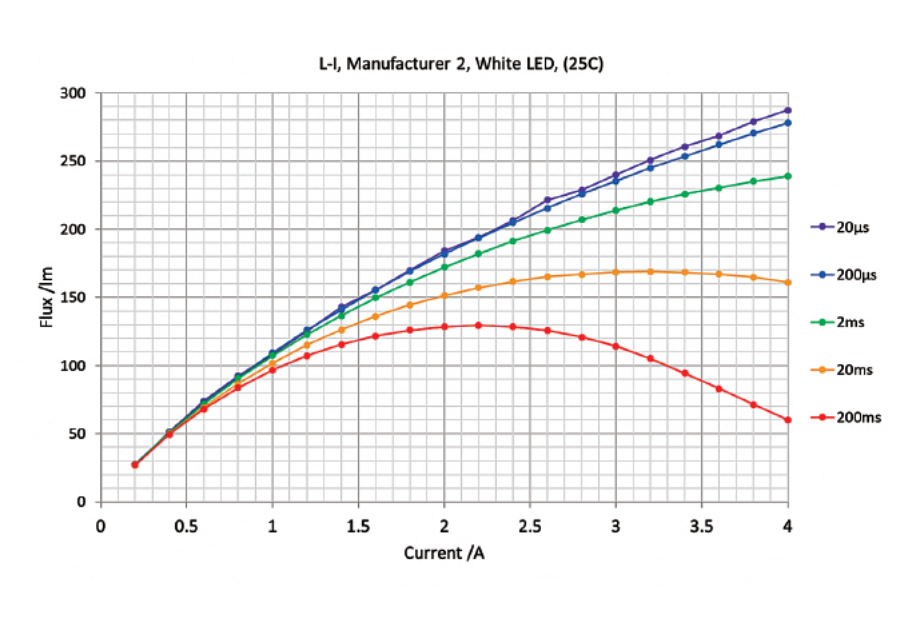


Figure 10: Short-pulse testing reveals Manufacturer 2's White LED true L-I characteristics

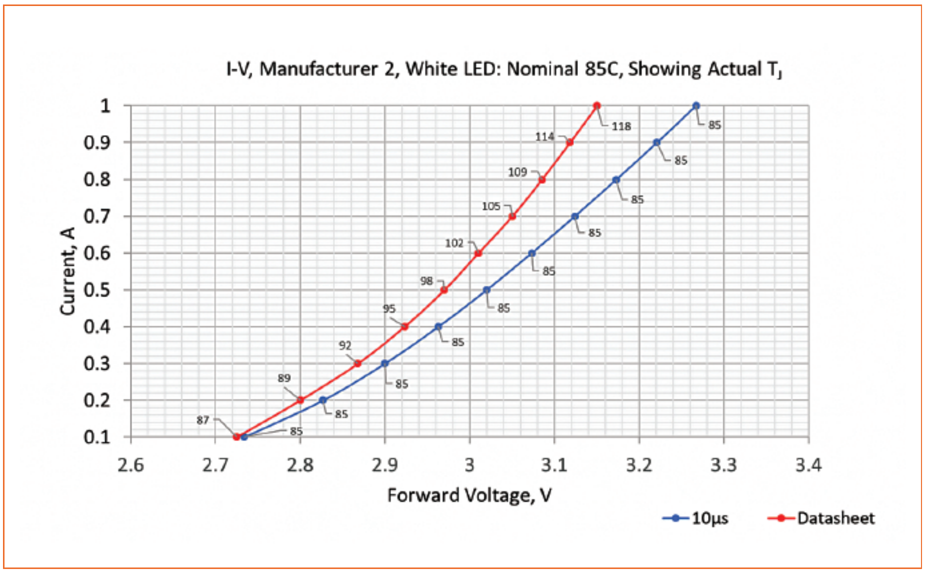


Figure 11: Manufacturer 2's white LED long pulse and short pulse I-V curves illustrate distortion caused by $T_J$ error

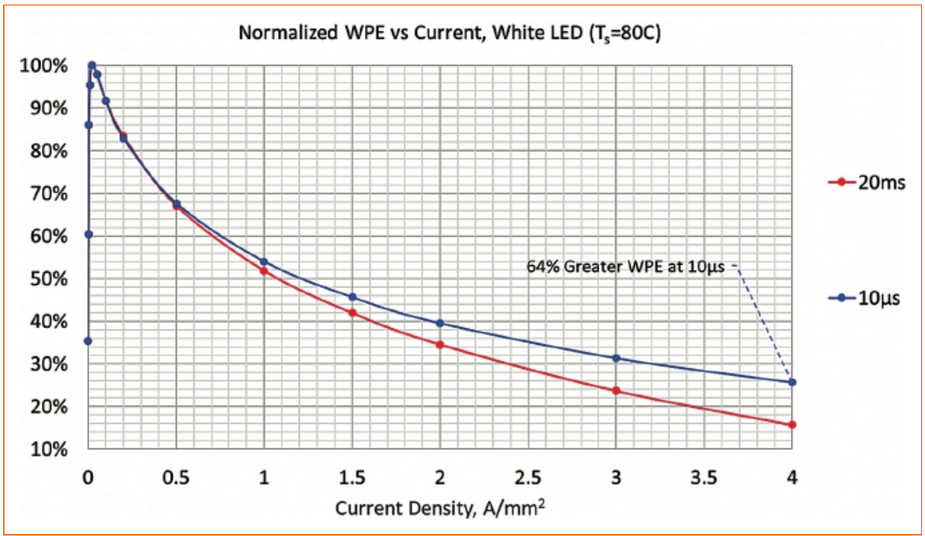


Figure 12: Short-pulse testing shows WPE at 4 A/mm$^2$ is actually 26%, 64% better than long-pulse testing indicated

When sweep testing over a current range of more than 10:1 or 20:1, break the sweep up into multiple sweeps, to take advantage of the current source's multiple current ranges. Low-current sweeps may also be performed with longer pulses as the energy delivered per pulse at lower currents is much less. Longer pulses at low currents are easier for the current source to produce, and they provide additional light for the spectrometer measurement.

## Short Pulses Eliminate Heating-Induced Droop

When Manufacturer 2's white LED is retested using short pulses, heating-induced droop is greatly reduced and the roll-over is eliminated, revealing the device's true characteristics. **Figure 10** shows the part's L-I characteristic tested with pulse widths from approximately 200 ms to 20 µs. For the shortest pulse, a spectrometer integration time of 20 µs was used.

## Shorter Pulses Improve I-V Curves

Short pulse testing also improves I-V curves. **Figure 11** compares Manufacturer 2's white LED datasheet I-V curve (published as an 85 °C junction temperature curve and measured with long pulses) against an 85 °C L-I curve measured with 10 µs short pulses. The shifted long-pulse curve underrepresents the maximum current compliance voltage by 117 mV. Actual $T_J$ values for the measurement points are also shown. These were obtained by duplicating the pulsed sweeps with sweeps that included a small DC bias current. The $T_J$ values were then calculated using the JESD 51-51 Electrical Test Method.

## Short Pulse Testing Reveals True WPE

When correct L-I curves are combined with correct I-V curves, the LED's true WPE at the designated junction temperature is revealed. **Figure 12** shows the Manufacturer 2 white LED WPE vs current curve up to 4 A/mm$^2$, 4× the normal current density. 20 ms long-pulse and 20 µs short-pulse curves are shown; both were performed at a TEC temperature of 85 °C. The plots show that the 4 A/mm$^2$ WPE is 64% better than long-pulse testing indicates. Such a difference can have profound implications for LED chip designers and for lighting engineers, especially those working on high-luminance applications.

## Conclusions

Long-pulse testing has served the LED industry well over the last two decades, but the heating-induced errors that accompany this method can no longer be ignored, especially for upcoming LED designs and high-luminance applications. Fortunately, recent advances in instrumentation enable a shift to short-pulse testing that greatly reduces heating. The resulting improved curves will enable lighting designers to create more efficient lamps and luminaires. They will also allow chip developers to more quickly discern a device's actual characteristics and make comparisons with design simulations. The time is right to switch to short-pulse testing. ■

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HULETT is the founder and CTO of Vektrex Electronic Systems, Inc., a manufacturer and supplier of precision pulsed current sources, and systems used world-wide for reliability test, burn-in, and photometric measurement. He is the chief designer for Vektrex's SpikeSafe SMU source/measure product. Hulett holds a BSEE from the Illinois Institute of Technology, and he has been awarded several US and international patents. Hulett is an active member of the Illumination Engineering Society of North America (IESNA) where he chairs the LM-80 working group. He also participates in the IES LM-85 committee and the CIE TC2-63 committees, where he is focused on improving measurement accuracy and repeatability.

**About Vektrex:**
Vektrex designs, develops, manufactures and markets advanced precision current source instruments and systems for specialized needs of LED manufacturers and the SSL marketplace. Our products include current sources, thermal control chambers, light measurement systems, LM 80 systems, LM 85 systems, software, and accessories. https://www.vektrex.com

**CO-AUTHOR: Markus SCHNEIDER, Dr.**
Markus Schneider is employed at OSRAM Opto Semiconductors GmbH, Regensburg, Germany, a global leader in the field of optical semiconductors and high-quality products in the fields of illumination, visualization and sensor technology. He takes the responsibility for the characterization of LED products and development of advanced optical measurement procedures and has been awarded several international patents. SCHNEIDER holds a diploma in physics and a doctoral degree in natural sciences. He is a member of the Illumination Engineering Society (IES) of North America, CEN/TC 169 WG7 (light and lighting), DIN - the German Institute for Standardization, and chairs the CIE Technical Committee 2-91 that is focused on optical measurement methods of LED packages.

**About OSRAM:**
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