UV-LED

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UV-LEDs and Curing Applications:
Technology and Market Developments

By Robert F. Karlicek, Jr.

This article summarizes the technology and market trends related to LEDs and their impact on the development of UV-LEDs for curing applications.

The light-emitting diode (LED) industry is undergoing rapid technological and market changes driven by the development of efficient, white LEDs for liquid crystal displays (LCDs) and lighting. UV-LEDs are poised to benefit from these developments (including higher efficiency, higher output power and lower cost), largely because UV and white LEDs are technically similar. However, there are market-related challenges slowing continued improvements in UV-LED performance. This article provides a broad overview of recent UV and visible-LED technology improvements and discusses market developments and the impact that these developments may have on the development of UV-LED systems for UV-curing applications.

Introduction

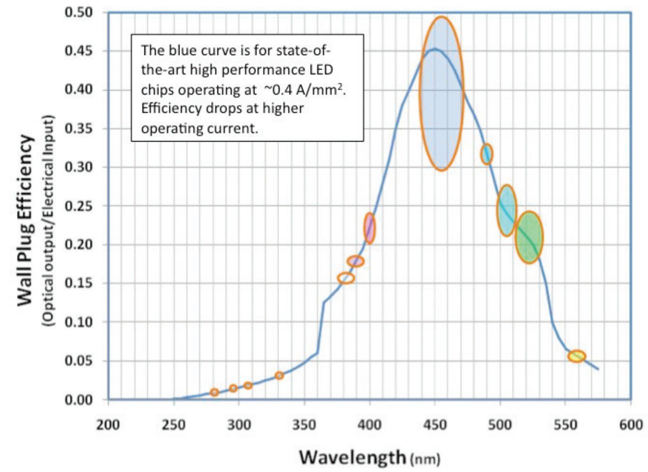
LEDs are beginning to challenge existing lamps used for lighting and UV-curing applications. In general lighting, white LEDs are becoming bright enough to replace mercury lamps and sodium vapor lamps in street lighting applications. There is also progress in developing UV-LEDs for curing applications, but progress is being made at a much slower pace. The LEDs that are used for UV curing and lighting applications are technically similar, as are the challenges of using them in either UV curing or lighting applications. Regardless of whether LEDs emit in the UV or are used for lighting, both markets are demanding the same things from LED manufacturers:

- More light (or UV) output
- Higher operating efficiency (more electrical input converted to light)
- Lower cost for LEDs
- LED system designs more suitable for putting the right amount of light (or radiation) where needed

These market demands are driving rapid technical changes in LED designs; improvement in performance; and reductions in cost. Innovation at the system level is also proceeding rapidly, as lighting fixture designers and UV-system integrators wrestle with how best to implement the visible or UV-LEDs that are commercially available today. LEDs are a disruptive technology promising superior efficiency and reliability for creating UV and visible radiation when compared to conventional UV and visible lamps. Because of this LED potential, LED technology and even the business structures and supply chain models associated with LEDs and the systems that use them are evolving rapidly. This is especially true for visible-LEDs and LED system designers in the LCD display and general lighting markets where the revenue potential is huge and there is a strong focus on replacing conventional incandescent and mercury-based lighting sources. These technical and market developments (driven primarily by visible-LED manufacturers and customers) present both opportunities and challenges for the development of UV-LED-based curing systems. This article summarizes the technology and market trends related to LEDs and their impact on the development of UV-LEDs for curing applications.

Figure 1

Approximate efficiency versus wavelength for nitride LEDs



LEDs can be made at any wavelength along the curve, and the colored markers are positioned at commercially important wavelengths where relative size of the marker suggests market size for LEDs at those wavelengths. If UV-LED efficiencies improve to the levels of today's 450nm LEDs, they would be more than twice as efficient as mercury lamps and offer a wider range of UV wavelengths.

LED Technical Overview

LEDs are made from crystalline compound semiconductors resembling silicon (used for conventional electronics). Unlike silicon used in computer and memory chips, compound semiconductors can emit light when energized. LEDs are monochromatic (single color) emitters and the wavelength (color of the light) from an LED depends on the chemical composition of the semiconductor material. For both UV curing and lighting applications, the semiconductor material is made from alloys of AlN, GaN and InN (aluminum nitride, gallium nitride and indium nitride, respectively). Increasing the indium concentration causes the LEDs to emit blue or green light. Reducing the indium concentration and increasing the aluminum concentration causes the wavelength to move from blue into the UV. In principle, any wavelength from 250 nm (UVC) to 570 nm (greenish yellow) can be manufactured by adjusting the semiconductor composition.

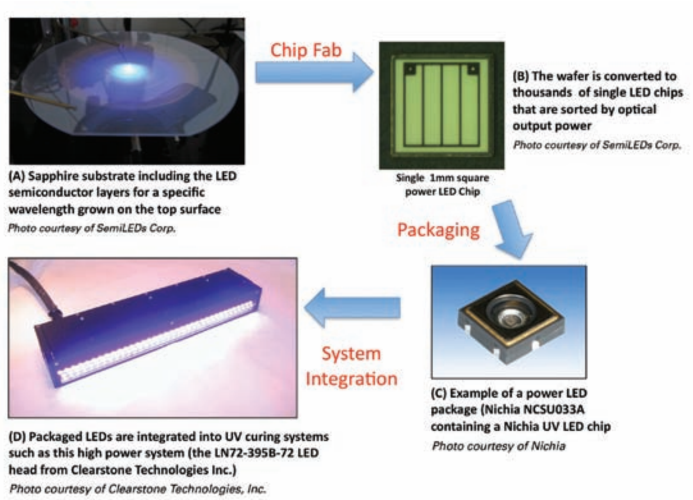
With today's technology, the intensity of light (visible or UV) emitted by an LED depends strongly on the wavelength (Figure 1). Blue LEDs are the most efficient of all the nitride LEDs. The intensity drops quickly as the wavelength gets shorter, especially below 365 nm where there are special technical and manufacturing challenges related to growing high aluminum content nitride materials needed for UV emission. As research continues on short-wavelength UV semiconductors, these problems will be solved and much higher power UVC-LEDs will become available.

Regardless of wavelength, the design of an LED is extremely complex, requiring the crystal growth of many extremely thin (just a few atoms thick) layers of various alloys of these nitride semiconductors on a substrate. The design, purity and crystalline quality of these layers control not only the emission wavelength but also the output power and lifetime of the LED. The LED and LED systems supply chain from semiconductor to applications is shown in Figure 2. The substrate with the crystalline layers grown on it is typically called an LED wafer (Figure 2A). After it is grown, standard semiconductor processing technology is used to convert the wafer into thousands of small LED chips (Figure 2B). These chips are tested at the manufacturer for wavelength and brightness (and a host of other

Figure 2

Typical supply chain for UV-LED curing equipment

UV-LED system manufacturers typically integrate either bare chips (B) or packaged chips (C) to build a UV-LED system.



semiconductor properties), and sorted into different performance bins. Due to the complexity of wafer and chip fabrication processes, the light output power (UV or visible wavelength) can vary by as much as a factor of two, even for chips coming from the same wafer! Binned chips are then sold to a packager where the chip is placed in a protective package with optics and solderable leads. System integrators then purchase the packaged LEDs, adding electronics, thermal management, optics and housings to create a finished module.

From Packaged LED to Systems (for UV Curing or Lighting)

Individual packaged LEDs are not bright enough for many UV curing or lighting applications, but have made some inroads in niche applications. The biggest challenge for system integrators is that while LEDs can be very efficient, a single, packaged LED doesn't really produce much optical output (whether in the visible or UV). The earliest applications for single visible or UV-LEDs include flashlights and fiber illuminators. (UV-LEDs are beginning to appear from some system integrators in spot-curing systems.)

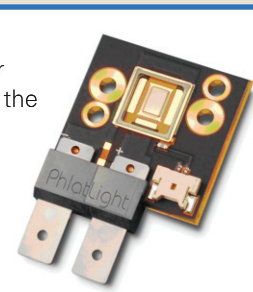
To get higher irradiance (for UV applications) or high illuminance (irradiance corrected for eye sensitivity at visible wavelengths), many LED packages are typically combined into a single fixture (such as in Figure 2D for the UV flood illuminator from Clearstone Technologies, Inc.). The visible-LED analog to UV flood cure LED arrays would include the LED-based light bars now used on law enforcement vehicles, or LED street lights that are now beginning to appear in some areas. Applications for arrays of single packaged LEDs (visible or UV wavelength) are typically limited to flood applications.

Moving beyond flood applications requires much higher optical output from individual LED chips or packages. For that reason, there is an increasing trend to put multiple LED chips in a single package to increase the concentration of optical output (W/cm^2 of either UV or visible radiation). This introduces some new challenges for LEDs for thermal reasons. Unlike relatively inefficient incandescent light bulbs and high-power, mercury-arc lamps which convert a high percentage of their electrical input power to infrared radiation (IR heat), LEDs emit no IR radiation but still generate heat and must be cooled by conducting that heat out of the package. Significant research efforts are focused on the development of advanced, high-power packages and thermal management systems for visible-LEDs. These system-level technical developments will be useful for evolving high-power, UV-LED curing system designs as well.

Figure 3

A very large power UV-LED

The emitting area is 12 mm^2 (rectangular chip in the center of the package) and is the largest power LED on the market today. The large copper submount is required for adequate thermal management. The package is also equipped with a thermistor for thermal sensing.

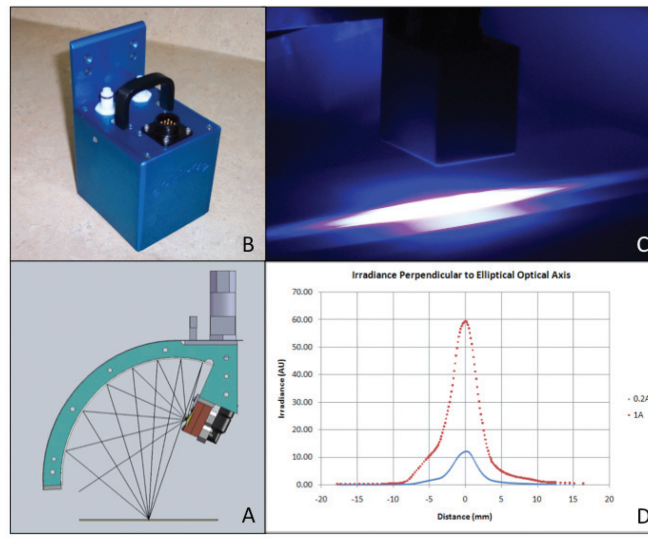


Recently, there has also been an interest in making very large power LED chips (not arrays of smaller chips) for high-power visible and UV applications. Most visible or UV-LEDs range in size from 0.25 mm to 1.5 mm (10 to 60 mils) on an edge, but larger chips (up to many millimeters on an edge) can be manufactured (such as in Figure 3). Large, high-powered LEDs like these are manufactured using highly specialized fabrication techniques. There are both advantages and challenges in using very large, high-power LED chips. Since the main reason to use a very large LED chip is to generate a very concentrated, intense light source, these LEDs are typically operated at very high input current and high input electrical power (over 50 W per single LED chip!). These LEDs are ideal for fiber illuminators since they can produce a very bright point source that is easily coupled to a fiber guide for spot irradiation.

Using very large LED chips can also be advantageous for projecting very high irradiance using systems much like those designed around high-power mercury lamps. Novel optical and special thermal designs are being investigated using very large power LED chips so that geometric optics (elliptical or parabolic reflectors) can be used to re-image the intense surface irradiance from large LED chips to produce uniform high irradiance patterns very similar to those obtained from conventional mercury lamp systems (Figure 4).

Figure 4

An experimental high-power, UV-LED system



The operating concept is shown in (A) and a finished module in (B), actual operation in (C) and an intensity profile measured 80 mm from the base of the unit in (D). Operation is based on a proprietary LED and optical design intended to emulate the power levels and emission patterns of high-power, mercury-arc lamp systems.

LED Technology Trends

Since visible-LEDs were first developed in the early 1960s, technical improvements have led to tremendous increases in brightness and large reductions in cost. On average, LED brightness has increased about 10 fold per decade and LED price has dropped about 10 fold per decade — but recent demand for improved white LEDs has produced even faster brightness increases and cost reductions. Continued pressure on improving light-emitting performance and reducing cost are driving technology changes in all parts of the LED manufacturing supply chain, as shown in Table 1. Some of these developments will prove useful for UV-LEDs, especially the longer UVA wavelengths in which the nitride semiconductor compositions in the LED wafer are the most similar to those of the blue LEDs which are used for display and lighting applications.

The large drop in LED efficiency at wavelengths at and below 365 nm (Figure 1) will require significant advancement in LED-chip technology. In principle, shorter wavelength UV-LEDs could be as efficient as visible-blue LEDs, but major technical breakthroughs will be required for this to happen. Over the past few years, more research has focused on the development of UVC-LEDs for germicidal applications, and the market interest for UVC-LEDs in germicidal applications is driving more investment in the research needed to improve UVC-LED performance. Since the nitride materials used to make LEDs are closely related, the technology leading to improvements in UVC-LED performance for germicidal applications will be directly applicable to making much better UV-LEDs at UVB and UVA wavelengths as well. This is a normal part of the evolution of new LEDs operating at new wavelengths. As the nitride semiconductor material qualities improve, UV-LEDs at any wavelength needed for UV curing will be available with efficiencies exceeding those of the mercury lamps used today.

TABLE 1

Technology trends in various portions of the LED supply chain driving increased LED light output power and price reduction

UV-LEDs stand to profit from LED performance and price improvements largely directed at visible-LED applications.

Component	Industry Trend	Primary Impact	Impact on UV LEDs
Substrate	Moving from 2" to 4"and 6" substrates	Reduced LED cost	Lower cost of chips
	GaN and AlN substrates replacing sapphire	Much higher power LEDs but at a higher price	Improved performance, especially below 380 nm
Wafer	New designs for high efficiency at high current operation	More light from a single LED by increasing input current	Higher irradiance from a single LED by increasing input current
	Higher quality nitride semiconductors with high aluminum concentrations	Higher efficiency LEDs	Improved UVB, UVC performance
Chip Designs	Surface emitting vertical style LEDs with good thermal conductivity	Higher power LEDs, No brightness penalty with larger chip sizes	Higher Irradiance
	Larger LED chips	Useful for very high power point sources (spot lighting)	Higher irradiance, lower cost
Package Design	Larger LEDs in smaller packages	Greater system design flexibility	Useful for spot curing applications, simpler UV fixture designs
	Multi-chip packages	More light over a larger area	Useful for flood applications
	Improved thermal performance	Enables high power operation	Higher Irradiance

LED Market Evolution and UV-LEDs for Curing

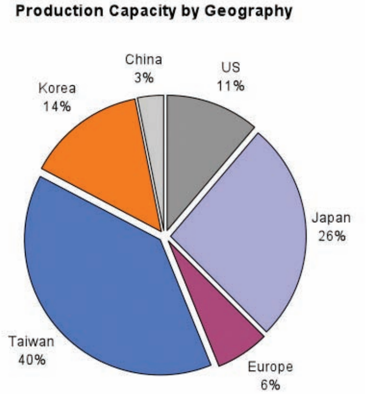
The economies of scale needed to make LED chips and packages (visible or UV wavelength) affordable require LED chip manufacturers to make and sell hundreds of millions of LED chips per month, so LED developers tend to focus on those markets and applications that can absorb high quantities of LED chips and packages. The technical challenges of making LEDs at high yield drive manufacturers to focus on making and selling only those particular colors of LEDs needed for high-volume applications. While it is possible to make an LED at almost any wavelength, it is usually possible to purchase LEDs only at particular wavelengths tied to high-volume applications (450 nm blue for white, 508 nm for traffic signal green, and so on). The greatest present demand for LEDs is for mobile display applications with demand for LEDs for notebook computers and LCD TVs increasing rapidly. This focus has made "blue for white" LEDs the best performing and lowest cost nitride-based LEDs available.

Because LEDs are primarily used in consumer electronics with the associated pricing sensitivity characteristic of those markets, the preponderance of LED manufacturing now takes place in Asia (Figure 5). Almost all new investment for LED manufacturing, including R&D investment for LED performance improvement, is also in Asia. Because market opportunities for visible-LEDs are much larger than those for UV-LEDs, there are many more suppliers of visible-LEDs than there are of UV-LEDs for curing applications. While most white LEDs are made from blue LED chips, some white LEDs are also made from near UV (~400 nm)-LEDs and multiple wavelength converting phosphors. It is possible to argue that 400 nm LEDs are available for UV-curing applications because they were first developed for lighting markets.

FIGURE 5

LED production capacity by region*

Today, the largest LED capacity expansion investments are being made in China, Taiwan and Korea, largely being driven by interest in LEDs for displays and lighting applications.



* *Courtesy of Canacord Adams*

From an applications point of view, both white-power LEDs for lighting (referred to as solid state lighting) and UV power LEDs for curing applications face similar technical and market challenges. Some of these are outlined in Table 2. While the history of UV curing with mercury lamps is considerably shorter than that of electrical lighting, both markets have evolved application designs and product distribution structures geared toward a bulb/fixture model. This is a model not well suited for manufacturers of LED systems (lighting or UV curing).

The adoption of these disruptive LED-based technologies (in both lighting and UV curing) will require new market structures. In the lighting market, this is already happening with companies that formerly made only LED chips now vertically integrating to become lighting companies (Cree, for example, with many others following suit). Similarly, most conventional light fixture companies are working to acquire or partner with LED companies (Philips/LumiLEDs acquisition of Genlyte, one of the world's largest lighting fixture manufacturers). The size of the market opportunity for LEDs in displays and lighting is driving a lot of creative business development, and some of this activity will impact the availability of UV-LEDs for curing applications.

Similarly, many larger UV-mercury lamp system suppliers are actively developing curing systems based on UV-LEDs, and a host of small companies are currently selling specialized UV-LED curing systems for niche applications. The smaller market opportunities for UV-curing systems relative to LCD displays and lighting markets have several effects on the development of semiconductors used to manufacture UV-LEDs:

- Reduced incentives to make R&D investment for higher power and shorter wavelength UV-LED materials, delaying the development of higher power UV-LEDs operating below 390 nm (and especially below 365 nm).
- Reduced market incentives for manufacturers to develop and sell UV-LED chips. (Today, there are really only two to three suppliers of very high-performance UV-LED chips, compared to several dozen manufacturers of blue-LED chips for display and lighting applications.)
- Inflated pricing for UV-LED curing systems due to high LED chip and packaged LED pricing as limited competition provides no incentive to reduce pricing. If one compares the prices of similarly designed blue and UV-LED devices on a price per optical output power (or price per photon) basis, UVA-LEDs are at least 10 times more expensive than their blue LED cousins.

The UV curing market itself introduces another challenging wrinkle for the development of UV-LEDs and the curing systems using them—most coatings and inks are developed and coating processes optimized for the complex mix of narrow UV wavelengths produced by mercury lamps (among them the 254 nm, 315 nm, 365 nm emission lines of atomic mercury). Coating formulations and processes will need to be developed specifically for the monochromatic nature of UV-LEDs if UV-LED curing systems are to be more widely adopted. This work is already underway as formulators explore the use of new photoinitiators and processes optimized for wavelengths other than those that come from mercury lamps. The absence of very high irradiance UV-LED systems; insignificant irradiance at shorter wavelengths;

Table 2

Comparison of market forces and their impact on both visible and UV-LED developments

Market trends and pressures for both lighting and UV curing are quite similar, suggesting that UV-LED systems will profit from riding the coattails of LED-based, solid-state lighting improvements.

Market Drivers and Barriers	Lighting Systems and Applications/Challenges	UV Curing Systems and Applications/Challenges
Incumbent Lamp Technology	Lamp Socket/Fixture Model not well suited for LEDs	
Highly Fractured Market	Many fixture designs with a high degree of customization supports many small companies with niche specialties	
Economics	Lamp sources much brighter and less expensive than LEDs	
Associated Technology Development	LED systems require special thermal management techniques, special optical systems and specialized electronic drivers	
	Specialized phosphors for efficient white LEDs with improved lighting characteristics	Specialized formulations that can be cured at available LED wavelengths need to be developed
Market Forces Driving LED Adoption	• Energy Savings • Mercury Elimination • "Smart" lighting (digital dimming, color control, other features)	• Lower heat generation • Energy Savings • Improved Reliability • UV systems that easier to use

surface curing issues; and high line speeds will limit the deployment of UV-LED systems until new coating formulations designed to work specifically with LEDs are available.

Summary

Visible and UV-LED technology has improved tremendously in recent years, with improvements in the performance and value of white LEDs for lighting applications now allowing LEDs to challenge conventional lighting sources. Improvements in the performance of UV-LEDs has been slower because the UV-curing market is much smaller than the display and lighting markets requiring white LEDs, but even now UV-LEDs are being considered for some specialized curing applications. The history of LED development strongly suggests that UV-LEDs will continue to develop, offering higher irradiance and new, shorter wavelengths. Combined with improved energy efficiency, cool operation and much longer lifetimes, the evolution of UV-LED curing systems will track the development of LED lighting, following the technical progress at the chip, package and system level, as well as emulating the business models now being developed in the lighting industry to replace the incumbent incandescent, fluorescent and UV-curing bulbs used today.

Acknowledgments

The contributions of photographs and data from SemiLEDs Corporation, Clearstone Technologies, Inc., Nichia Corporation, Luminus Devices, Inc. and Canaccord Adams are gratefully acknowledged.

—Robert F. Karlicek, Jr. is president of SolidUV, Inc., in Chelmsford, Mass.

UV-LED Overview Part I — Operation and Measurement

By Jennifer Heathcote

Ultraviolet-curing systems that incorporate light-emitting diodes (UV-LEDs) and applications utilizing UV-LED technology have been highlighted at conferences, profiled at tradeshows and incorporated into both prototype and production systems (albeit to varying degrees of success) since the turn of the 21st century. It's hard to believe that in some markets, particularly UV digital ink jet, we have been studying, trialing, promoting and integrating UV-LED systems for nearly a decade. With the most recent advancements in the technology, we are now achieving comparable

This new, pro-LED climate is great for generating activity in many diverse markets, but the challenge has now become one in which the majority of those who are newly interested in UV-LEDs have insufficient understanding of the underlying technology.

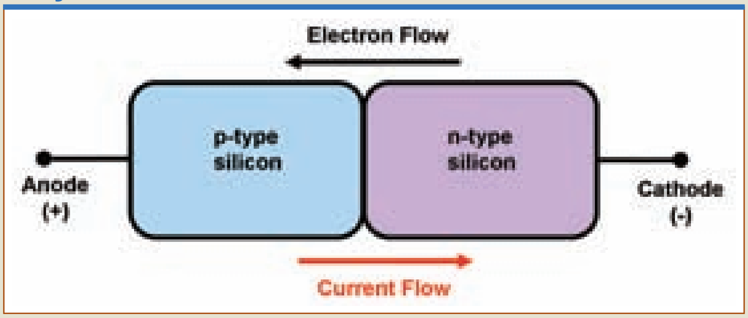
production speeds and throughcures to those found in setups using traditional forms of electrode and microwave UV curing. While UV-LEDs are still not the right fit for many applications, the momentum of technological advancement and implementation continues to increase at an astonishing and exciting rate, thus making many more applications a plausible reality.

Most UV-LED articles and professional society presentations delivered during the previous decade of development have predominantly revolved around two distinct topics. The first promotes the technology by touting the limitless number of environmental, process and integration benefits that UV-LEDs have over conventional UV curing systems. The second topic cautions against practical limitations, lack of established installations, limited availability of inks and coatings, and uncertainties regarding the UV-LED development timeline. These latter communications have been more of an effort not to oversell the capabilities of the technology and to counter the potentially disruptive nature of LEDs toward electrode and microwave UV-curing systems. Well, I think it's finally safe to say, "Message received." Most users involved in UV curing and related technologies now readily accept the fact that UV-LEDs are the present and the future, while at the same time they realistically understand that UV-LEDs may not yet fit all their curing needs today.

This new, pro-LED climate is great for generating activity in many diverse markets, but the challenge has now become one in which the majority of those who are newly interested in UV-LEDs have insufficient understanding of the underlying technology. Those of us promoting UV-LEDs have successfully sold potential users on the concept but then left many of them unsure as to how and when to actually implement the technology into their processes. They don't always know what questions to ask or fully grasp the information they are provided. Through no fault of their own, many users simply don't have a sufficient foundation to compare available UV-LED systems or understand how to correlate product and performance

Figure 1

P-n junction



information against traditional curing lines. This means that suppliers must spend a good portion of our time educating and refining expectations, while at the same time continuing to learn alongside our ink, coating and dispensing partners.

In an effort to consolidate some key principles and technical information regarding the science and engineering behind UV-LEDs, I will attempt to present an elementary foundation through a series of three articles. The first article is meant to cover LED operation and measurement and will include information on (1) the p-n junction, which is the basic building block of the LED; (2) the LED p-n junction; (3) characteristics of UV output from LEDs as compared to conventional UV bulbs; and (4) the challenges associated with measuring UV output from LED sources. The two subsequent articles will focus on integration of UV-LED chips into actual curing systems, as well as the history of LED development and current diode manufacturing methods. Each article will conclude with a brief summary consisting of a series of questions intended to guide the reader as he/she compares UV-LEDs and benchmarks them against conventional UV systems.

The P-N Junction

In electrical circuits, conventional current flows from a positive terminal to a negative terminal. In order for current to flow in this direction, electrons must simultaneously flow through the same circuit in the reverse direction (i.e., from a negative to a positive terminal). One does not happen without the other. A diode is a common electrical device that is added to a circuit as a means of restricting the flow of electricity. It can generically be thought of as a switch or a valve. A key property of a diode is that it conducts electricity in only one direction. A p-n junction (positive-negative junction) is a specially engineered diode that is made of many layers of semi-conductive materials where each layer is less than half a micron thick. The concept is commonly illustrated with the diagram in Figure 1.

A p-n junction is engineered from a single piece of semi-conductive crystal. Impurities are impregnated or doped into the semiconductor and the two sides (p and n) undergo a manufacturing process that results in the p-side of the junction becoming a positively charged electrode while the n-side becomes a negatively charged electrode. The two sides of the diode are referred to as the anode (+) and the cathode (-) respectively. Current is able to flow from the p-side of the diode to the n-side, but it cannot flow in the reverse direction. Electrons, however, only flow from the n-side to the p-side.

The junction boundary where the p-side and the n-side meet is called the depletion zone. While both the p-side and the n-side are relatively conductive, the depletion zone is not. This means that without altering the characteristics of the depletion zone, current and electrons will not flow through the p-n junction at all. If the depletion zone is minimized in both size and effectiveness, electrons will be able to penetrate the boundary and move from n to p. The result is that electricity is able to flow from the positive terminal to the negative terminal of a low-voltage supply when the supply is connected directly to the anode and cathode of the junction.

In Figure 2, a voltage supply is added to the diagram. When the anode

Figure 2

Forward bias

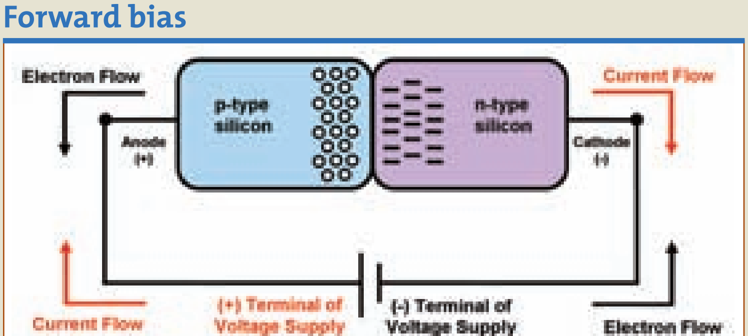


Figure 3

Reverse bias with sufficient voltage supply

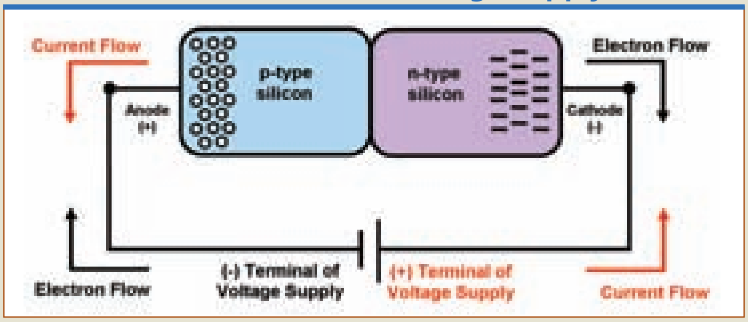
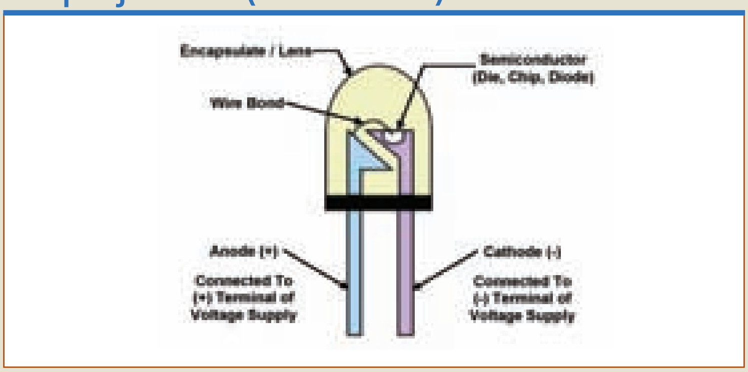


Figure 4

LED p-n junction (forward bias)



is connected to the positive terminal of the voltage supply and the cathode is connected to the negative terminal, a forward bias is created. Imagine that the p-side of the junction is composed of tiny, positively charged holes while the n-side contains a lot of negatively charged electrons. The effect of a forward bias voltage is that the positive holes in the p-region and the negative electrons in the n-region are pushed from opposite directions toward the depletion zone. This significantly reduces the width of the depletion zone, causing the electrons on the n-side to respond to the attractive forces of the holes on the p-side. When a sufficient voltage is used, the electrons penetrate through the barrier to fill the holes on the p-side. This is called recombination.

Switching the connections on the voltage supply creates a reverse bias situation. In this case, the negative terminal of a voltage supply is connected to the anode and the positive terminal is connected to cathode. The resulting effect is that the positive holes in the p-region and the negative electrons in the n-region move away from the depletion zone as they are attracted to the opposing charge on the voltage supply. This increases the width of the depletion zone and inhibits the flow of electricity. In certain cases where a high enough voltage is applied, the p-n junction can break down causing current to flow from the positive terminal of the voltage supply through the n-side, across the depletion zone and through the p-side to the negative terminal of the supply. Zener or avalanche diodes are based on this scenario.

The LED P-N Junction

A light-emitting diode is a p-n junction which, depending on the semiconductor structure, could theoretically be designed to emit monochromatic wavelengths throughout the entire electromagnetic spectrum. This is known as electroluminescense and it occurs at room temperature—as opposed to the more familiar incandescence which is only produced when materials are heated to temperatures above 750°C (heat glow). A physical example of an actual LED p-n junction is illustrated in Figure 4. Both the anode (+) and cathode (-) connections—as well as the semiconductor, wire bond and protective outer case or lens—are shown in the sketch. Today, LEDs that emit infrared (870-980 nm), visible (390-780 nm), and some ultraviolet (365-405 nm), as shown in Figures 5 and 6, are used in a wide variety of applications.

All of the concepts presented for the simple p-n junction apply to the LED. When a voltage source is connected to the LED with a forward bias, current flows from the p-side to the n-side (anode to cathode). As the electrons cross the depletion zone and fill a hole, they drop into a state of lower energy. The excess energy is released in the form of a photon that can transport electromagnetic radiation of all wavelengths, including infrared (IR), visible and UV light. The selection of semiconductor and doping materials determines the exact wavelengths emitted from the diode when the photon is released. Different dopants possess varying band gap energies that, at an atomic level and

Figure 5

Electromagnetic spectrum

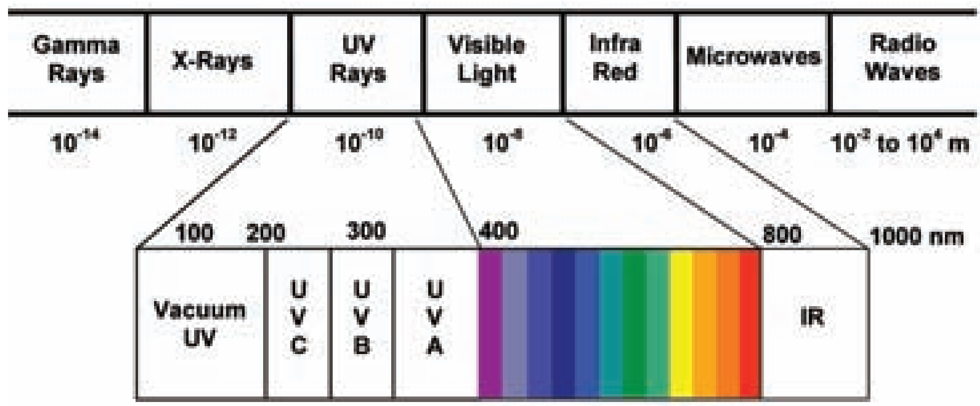


Figure 6

Examples of (a) UV (b) visible and (c) IR-LEDs

(a) (b) (c)

not something covered in this article, determine the specific wavelength that is emitted from an LED.

While the LED was first observed in 1907, it was only in the last 50 years that LEDs emitting sustainable and useful wavelength(s) have truly evolved. Optimal combinations of semiconductor materials and dopants were intentionally and unintentionally identified through experimentation and trial-and-error. The primary challenge has always been that these experiments could not be easily controlled, and it was difficult to understand exactly how the emission occurred or what was causing it. Early successes were achieved with longer wavelength visible light and infrared. It wasn't until 1992 that a UV-LED with an efficiency of around 1% was produced in a lab environment in Japan, and it wasn't until about 2002 that UV-LED curing systems with efficiencies in the single digits began to enter the market. Tables 1 and 2 provide common examples of inorganic semiconductor materials as well as the corresponding wavelength regions.

It is possible to follow the evolution of LEDs over the last 50 years by considering the introduction of standard household goods into daily life. Red LEDs were first used as status and function indicators on mainframe computers, circuit boards and multiline telephones in the mid 1960s. In the '70s and '80s, TV remotes and garage door openers (which both employ

Table 1

Core semiconductor materials[1]

Materials	Wavelength
Silicon	190-1,100
Germanium	400-1,700
Indium gallium arsenide	800-2,600
Lead sulfide	1,000-3,500

Table 2

Engineered semiconductor combinations[1]

Materials	Wavelength
Aluminum gallium arsenide (AlGaAs)	Red and Infrared
Aluminum gallium phosphide (AlGaP)	Green
Aluminum gallium indium phosphide (AlGaInP)	Bright orange red, orange, yellow, green
Aluminum gallium indium nitride (AlGaInN)	Ultraviolet - down to 210 nm
Aluminum gallium nitrate (AlGaN)	Near to far ultraviolet, violet
Aluminum nitrate (AlN)	Near to far ultraviolet
Boron Nitride	Ultraviolet
Diamond (C)	Ultraviolet
Gallium arsenide phosphide (GaAsP)	Red, orange and red, orange, yellow
Gallium Arsenide (GaAs)	Infrared
Gallium phosphide (GaP)	Red, orange, yellow, green
Gallium nitrate (GaN)	Green, emerald green
Gallium nitrate (GaN) with AlGan quantum barrier	Blue, white
Indium gallium nitrate (InGaN)	Bluish green, blue, near ultraviolet
Sapphire (Al2O3) as substrate	Blue
Silicon (Si) as substrate	Blue (under development)
Silicon carbide (SiC)	Blue
Zinc selenide (ZnSe)	Blue

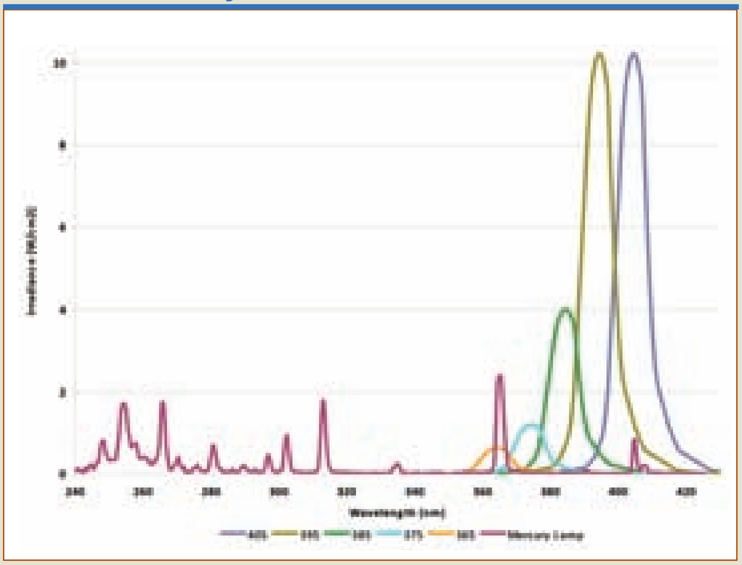
IR-LEDs) were introduced, as well as red indicator LEDs on appliances and electronics. Green LEDs were used to illuminate the dial pads on early push-button telephones, and LEDs used for alphanumerical displays on digital calculators, watches and signs became common.

By the beginning of the 1980s, liquid crystal displays (LCDs) replaced LEDs on watches and calculators; however, LEDs continued to be used as back lighting. In the late '90s, as engineers gained greater understanding and control of the manufacturing materials, more visible colors entered the market and were subsequently used in all types of electronics, as well as for both decoration and function in automobiles, airplanes and buildings. Extremely bright LED flashlights came onto the market around the turn of the century, and IR-LEDs were introduced for use in security cameras. They are now commonly used for video and audio controls as well as for local area communication networks. Starting in 2004, arrays of red, white and green LEDs were designed for use as automotive headlights and taillights as well as traffic and pedestrian crossing signals.

In the last 10 years, the technology underlying white light LEDs has emerged and the overall cost of visible LEDs has been driven down to the point that they are readily available at any brick-and-mortar or online electronics store. Red indicator LEDs can now be purchased for pennies as opposed to the several hundred dollar-per-unit price of the '60s. Today's blue LEDs, which are a more recent development, still cost several dollars in comparison. Larger urban areas have recently become populated with electronic LED billboards that can quickly change display as traffic streams past. Despite all these advances, further expansion of LED

Figure 7

Spectral output of LED systems compared to traditional UV system



technology across both the visible and UV spectrum still presents many challenges and will continue to do so into the foreseeable future.

The specific design of an individual UV-LED chip or diode depends on the desired wavelength, peak UV irradiance and capabilities of the LED chip manufacturer. While the physical size of the chip can vary by design or supplier, the device tends to be around 1 mm square. The individual LED diodes are then combined and packaged in various ways to produce larger arrays targeted to specific applications. The actual packaging and integration of these chips into larger diode assemblies or a full UV-curing system will be covered in article two. For the purposes of this article, use of the words chip, diode or die refers to the individual LED semiconductor, while LED array implies the full curing assembly, historically known as the lamp head or irradiator. Any given LED array will incorporate tens, hundreds or even thousands of LED chips in its overall design.

UV-LED Output as Compared to Arc and Microwave

While LED, mercury arc and microwave systems all emit UV energy, UV-LEDs have unique characteristics that make the spectral output very different from that of more conventional systems. First of all, UV-LEDs emit a relatively monochromatic band of UV that is centered at a specified peak wavelength; whereas, arc and microwave systems are broadband emitters with a range of output between 200 and 445 nm. Common wavelength peaks for UV-LED systems are 365, 375, 385, 395 and 405 nm. Figure 7 illustrates this difference. The magenta spectral output in the chart is from one conventional UV-arc system; whereas, the five monochromatic peaks toward the right half of the chart were emitted from five separate LED chips with outputs centered at their respective peak wavelength.

Over the past 60 years, UV chemistry has been formulated to react with broadband spectrums utilizing the shorter wavelengths for surface cure and the longer wavelengths for penetration and adhesion. Much of that chemistry relies heavily on photoinitiators tuned to 365 nm. As a result, not all previously formulated broadband UV ink chemistry will work with monochromatic LEDs. In many cases, the chemistry must be reformulated to react and accomplish the same or similar cure results within the more restrictive but also incredibly more intense band of LED output. While this no doubt presents challenges, it also yields the positive aspect of eliminating the infrared and UVC components. As a result, when compared to conventional curing, there is less heat transfer to the substrate (no IR) and no harmful UVC rays or resulting ozone to address. The UV from current LEDs is all UVA with a slight visible component in the violet wavelength range.

Secondly, what is often surprising to those new to UV-LED technology is that longer wavelength UV-LEDs (385, 395 and 405 nm) actually emit more UV irradiance at their peak wavelength than conventional UV bulbs. This is also illustrated in Figure 7 which shows peak irradiance at 395 nm and 405 nm of 10 W/cm^2 for the LED system and 2 W/cm^2 at 365 nm for a conventional UV system. The LED chips used to create the chart emit up to five times the peak irradiance of microwave and mercury arc systems; however, it is concentrated in a very narrow bandwidth. When users first view an LED system in operation, they often comment that the light appears "brighter" or "more purple" than conventional UV systems. This is due to the greater irradiance of UV-LEDs and the fact that for 395 and 405 nm LEDs, a portion of the UV output curve is actually in the visible portion of the spectrum.

Thirdly, the output of a UV-LED is based on the amount of current flowing through the chip. This will be covered in more detail in article two as well as LED and total power consumption. For now, simply note that the irradiance of an LED chip increases or decreases as the forward current through the chip changes. This is different than arc and microwave systems which require more energy from physical ballasts and magnetrons to produce additional UV. While there are many advantages to this that will be covered in article two, one primary advantage that anyone who has experience handling UV systems can appreciate is that the power supplies for LED systems are significantly smaller and lighter than those needed for conventional UV systems.

Finally, UV-LED chips are currently less efficient than conventional UV systems as well as visible and IR-LEDs. This is often a surprise to most people as visible LEDs have become increasingly common in everyday society and their high energy efficiencies have been strongly promoted in recent news features. Seasonal holiday decorations now incorporate visible LEDs that require little if any cooling, claim to last indefinitely, are 80-90% more efficient than normal lights and are relatively inexpensive. If only this were the case for UV-LEDs. Unfortunately, present technical limitations render UV-LEDs around 10 to 20% efficient for longer wavelengths (395 and 405 nm) and less than 10% for shorter wavelengths (365 nm). This is because UV-LED dies have only recently evolved out of IR and visible LED developments and have not yet been optimized for the UV region.

As more and better combinations of semiconductors and dopants have been discovered and engineered, a wider, more intense and increasingly efficient range of wavelengths and outputs could be produced. The longer wavelength UV-LEDs (395 and 405 nm) more closely resemble LEDs in the visible spectrum. Since the visible technology is more established, it is easier for chip manufacturers to produce more powerful and more efficient LEDs at wavelengths closer to the visible spectrum as compared to shorter wavelength UV-LEDs (365 and 375 nm). This is exemplified by the decreasing UV peaks shown in Figure 7 as one moves left along the chart. With continued improvements in the science and manufacturing process, UV-LEDs will increase in both output and electrical efficiency. For now, it is important to simply realize that with today's technology it may take more total consumed energy to produce the necessary UV output for your specific application than would be the case with conventional curing.

The fact that today's UV-LEDs are inefficient is the only reason that liquid chillers must be used for cooling the higher output arrays as opposed to using air cooling. Less than 20% of the electrical energy supplied to the LED system is actually converted into UV. As a result, the remaining energy is wasted as heat. The amount of heat energy is so significant that the only way to effectively remove it from the system is by circulating a liquid coolant around a heat sink attached to the chips. In general, systems that are rated below 4 W/cm^2 can be effectively cooled with air; however, less than 4 W/cm^2 is not normally a sufficient irradiance for most curing applications. All arrays rated at 4 W/cm^2 or higher must presently be cooled with a liquid chiller.

As the individual chip technology improves, the higher output systems will eventually be cooled with air. It is even possible that one day little to no additional cooling will be needed. Unfortunately, it is difficult to know if that reality is five or 50 years into the future. For now, simply know that UV-LEDs have the promise of being incredibly energy efficient and, in certain applications in which the LED array and the chemistry are precisely matched, the application can be considered more efficient than conventional UV curing. The energy savings for most current LED applications, however, is negligible when compared to conventional curing applications due to the need for the chiller. Don't just assume that UV-LEDs translate into direct energy savings. Sometimes it is the case and sometimes it isn't. One must run the numbers to be sure.

Measuring UV-LED Output

Before discussing how to measure UV output from LEDs, let's review the definitions of irradiance (intensity) and energy density (dose). In the RadTech UV Glossary and in many articles written by Jim Raymont of EIT that have been published in previous issues of the *RadTech Report*, irradiance and energy density are defined as follows.

Irradiance is the radiant power arriving at a surface-per-unit area. With UV curing, the surface is most often the substrate and a square centimeter is the unit area. Irradiance is expressed in units of watts or milliwatts per square centimeter (W/cm^2 or mW/cm^2). In UV curing, the term intensity is also commonly used to describe irradiance; however, irradiance more correctly describes the concept of UV arriving at a two-dimensional substrate.[2]

Radiant energy density is the energy arriving at a surface per unit area. A square centimeter is again the unit area and radiant energy density is expressed in units of joules or millijoules per square centimeter (J/cm^2 or mJ/cm^2). The radiant energy density is the time integration of irradiance. In UV curing, the term dose is also commonly used to describe radiant energy density.[2]

It should be noted that there is a maximum irradiance output from a UV system at a given power level that is concentrated at a specified location underneath the UV emitter. While irradiance attenuates as distance away from the specified location increases, most applications orient the UV source and setup so that the curing surface is always in the spot of maximum irradiance. As a result, irradiance is treated as a fixed value, while radiant energy density is variable and can be increased by slowing the line speed, increasing the number of UV systems directed at the curing area or by passing the UV source over the curing surface multiple times. This fact applies to mercury arc, microwave and LED systems alike.

With traditional UV systems, we tend to communicate in nominal terms of Watts/cm or Watts/inch. While this terminology loosely applies to electrode and microwave UV systems, it doesn't apply to LED systems at all. On the other hand, both irradiance (W/cm^2) and energy density (J/cm^2) at the curing surface for a given wavelength are important whether the emitter is mercury arc, microwave or LED. While the values themselves do not necessarily need to be measured, the curing system and setup must yield the UV requirements of the ink or coating chemistry in order to obtain full cure.

The irradiance value of 2, 4, 8 or 10 W/cm^2 for a given LED system (and commonly quoted by LED equipment manufacturers) is typically measured at the emitting window of the LED array. It attenuates significantly as the distance between the emitting window and the curing surface increases. It should be noted that the focal point commonly referenced with conventional UV systems is not typically applicable for LED systems. While LED chips can be packaged in an arrangement so that all UV energy is directed to a specified focal point, this is not common practice. Current UV-LED systems more closely resemble the flood profile of traditional systems.

The number of LED chips in the actual array, the way the chips are powered and arranged, the line speed and the number of passes under the LED will affect the total energy density at the curing surface. As a result, it is important to first select or arrange the UV-LED array(s) to cover the desired curing surface in one direction. The corresponding number of LED chips or the length of the LED array(s) in the perpendicular direction is then determined by the application's energy density requirements. This is a variable factor based on chemistry and line speed.

Both applications with faster line speeds and chemistry that requires greater energy density will result in the need for LED arrays with more LED chips, the use of multiple LED arrays or arrays that have been optimized for greater output, or the use of repeated passes underneath the LED array(s) as demonstrated by scanning head wide-format UV printers. All of this currently complicates the process of selecting an LED system for a given application. In other words, several different LED systems all rated at 8 W/cm^2 will all produce 8 W/cm^2 at the emitting window; however, this rating

Figure 8

Table-top integrating sphere and floor-standing integrating sphere

does nothing to communicate the overall dimensions of the curing area; the number of LED chips; the packing density or optimization of the diodes; or the resulting energy density (J/cm^2) for your specific setup and line speed. The best advice is to work closely with your ink and coating manufacturer as well as your UV-LED and dispensing supplier; and, if at all possible, conduct trials to determine whether UV-LEDs are currently a fit for your application.

There are a wide range of UV radiometers on the market designed to measure UV generated by traditional broadband mercury arc and microwave UV systems. There have been many articles written on these meters as well as their proper use, limitations and design variations. As a result, I won't cover this material other than to make it very clear that none of the existing broadband meters can be used to measure the output from UV-LEDs. I cannot emphasize this enough. **UV radiometers designed for use with broad band mercury arc and microwave UV systems will not correctly measure the UV output generated by UV-LEDs.**

There are only a few companies in the world currently manufacturing UV-LED chips or dies. Each manufacturer measures the UV output of the LEDs in an integrating sphere, also known as an Ulbricht sphere. This device is best described as a hollow sphere with a highly reflective coating on the interior surface that allows for uniform scattering of light. Photos of typical integrating spheres are shown in Figure 8. *Light rays incident on any point on the inner surface are, by multiple scattering reflections, distributed equally to all other such points and effects of the original direction of such light are minimized.*[3]

Chip manufacturers place a single LED die or arrangement of dies inside the integrating sphere and close the door. The die is powered and the UV energy is released from the LED over its entire viewing angle. The emitted UV bounces around inside the sphere and the energy that is radiated onto a detector of known area and located somewhere on the sphere's inside surface is measured. Measurements are taken in 1 nm bands and a mathematical computation that includes the sphere's circumference and the LED size is used to determine the total UV output in W/cm.^{2} For most current and potential users of UV-LEDs, it's not necessary to understand all the

Figure 9

Power output representation for a 405 nm LED source

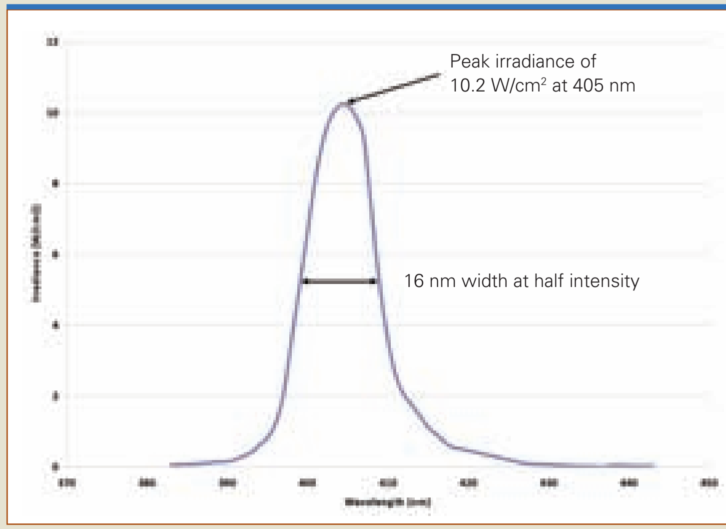
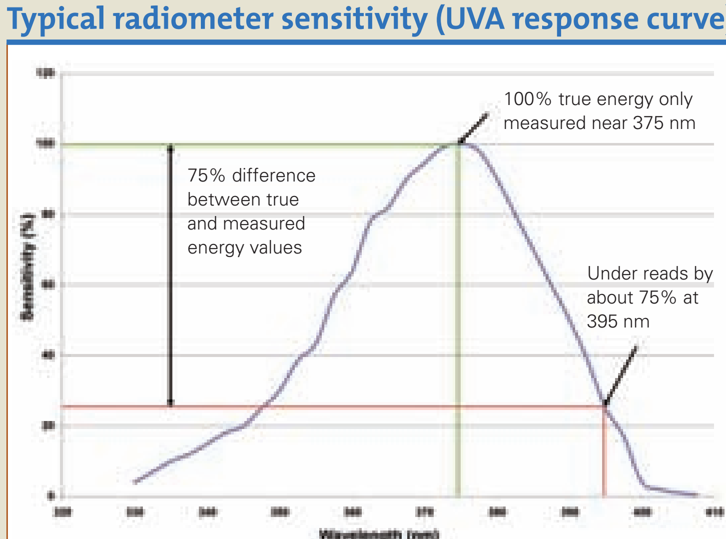


Figure 10

Typical radiometer sensitivity (UVA response curve)



physics behind an integrating sphere or how the irradiance is exactly calculated. What you should take away, however, is an appreciation of the complexities involved in accurately measuring UV-LED irradiance and how integrating spheres, due to their shape and size, aren't practical measuring tools for most commercial UV-LED applications.

LED chip manufacturers specify LEDs based on the tolerance of the peak wavelength. The tolerance is not something that is engineered into the manufacturing process, but rather something that is measured after production. The peak wavelength of a finished chip is determined using an integrating sphere and the chip is categorized or binned with other LEDs that have a peak wavelength that falls within the same tolerance range. The tighter the bin width (i.e., the smaller the tolerance), the more expensive the dies become. Typical wavelength tolerances are +/- 5 nm, +/- 10 nm and +/- 15 nm. In general, the greater the diode's irradiance and the tighter the binning, the more expensive the chip.

While looser bin selection results in cheaper dies, the process cannot be guaranteed. In other words, a wider bin selection does not mean a wider width of wavelengths. It just means less control over the wavelength. A randomly selected range of dies between 380 nm and 420 nm could all be 380 nm, 420 nm or some mixed variation between the limits. In practice, however, most chips within a given bin range tend to be skewed toward the upper limits.

A narrow bell-shaped curve, as shown in Figure 9, provides a generic representation of the UV distribution from an LED source centered at 405 nm. In this case, the LED has a peak value of 10.2 W/cm^2 at 405 nm at the chip surface. At 8 nm on either side of the peak (397 nm and 413 nm), the intensity falls to 2.0 W/cm.^{2} While this particular LED may provide sufficient UV to cure a given ink or coating, it is difficult to quantify the amount of UV that actually reaches the curing surface. This is because integrating spheres are not a practical tool to use in a production environment, and most radiometers are not tuned to the specific wavelengths emitted by UV-LEDs.

In the lab and in the field, many UV-LED trials have produced desired curing results; however, the results have often been downplayed since the radiometer readings produced irradiance and energy density values significantly lower than those recorded with mercury arc and microwave curing

Figure 11

Typical radiometer sensitivity (UVV response curve)

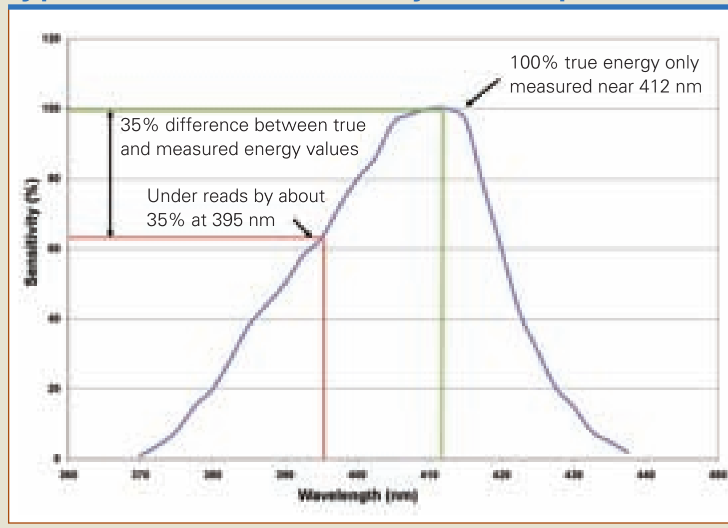
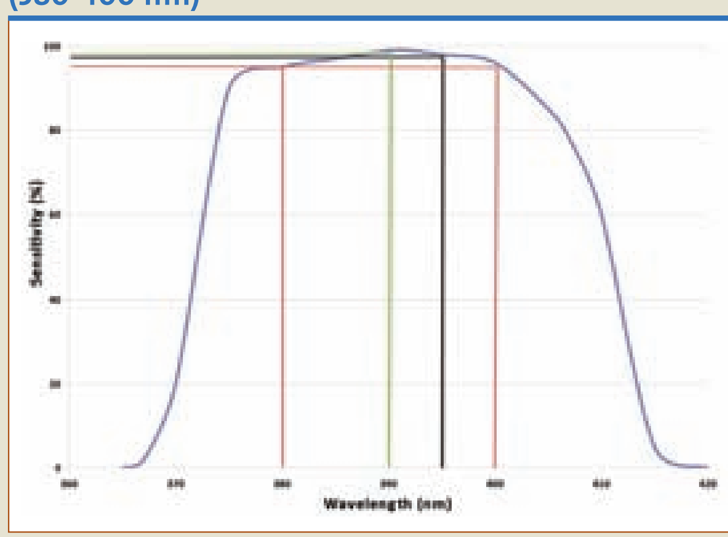


Figure 12

Radiometer sensitivity required for UV-LEDs (380-400 nm)



systems. Measuring UV output is an extremely important tool in maintaining and comparing UV processes; however, if incorrect and inappropriate tools are used, it's simply a meaningless exercise.

Commonly used devices for measuring UV irradiance and energy density are fitted with four distinct sensors, each designed to measure one of the four UV bandwidths (UVV, UVA, UVB and UVC). The individual sensors have a response curve that was engineered to fit conventional broadband UV-curing systems and were never intended to capture output concentrated in the 380-400 nm range. The graphs in Figures 10 and 11 represent the sensitivity response curves of typical UVA and UVV sensors. The UVA sensor is centered at 375 nm and under reads the peak UV irradiance of a 395 nm LED system by 75%. Conversely, the UVV sensor is centered slightly above 410 nm and under reads the peak output of a 395 nm LED system by approximately 35%.

Only radiometers with flat response curves, as illustrated in Figure 12, are capable of producing accurate UV irradiance (W/cm^2) and energy density (J/cm^2) readings from UV-LED systems in the 380-400 nm bandwidth range. A single channel radiometer specifically fitted to this measurement profile and contained in the well-known hockey puck style transporter was introduced to the market in early 2010. Only by using meters of this specific design can accurate measurements of UV output from a UV-LED curing system be obtained. Please keep in mind, however, that all instruments have some inherent measuring error and you should contact the manufacturer or read the manual to adequately understand the device's limitations. For example, radiometers are typically accurate to +/-10% from the calibrated value and repeatable to +/-5%. In addition, temperature variations of 0.2% / °C can also affect readings.

Comparing LED Technologies

As you begin or continue to conduct your own evaluation of LED technology, there are several questions that you should consider.

- What is the peak wavelength and bin tolerance of the LED array, and what is the impact on the ink or coating chemistry?
- What is the irradiance specification of the LED array?
- Where and how was the irradiance specification measured?
- What are the requirements of the curing application in terms of irradiance and energy density?
- Does the broadband ink or coating chemistry cure with UV-LEDs or does it need to be reformulated to match the narrow band UV-LED wavelengths?
- Can similar LED performance results be achieved at the same operational line speed or throughput used with conventional UV systems?
- What are the criteria for the physical installation of the LED array (moving or static head, single or multiple pass, area to be cured, existence and types of space restrictions)?
- What is gained or lost in using LEDs (power consumption, heat, efficiency, operating cost, purchase price)?

It is important to note that there are no dumb questions when it comes to UV-LEDs. It is equally important to note that suppliers don't yet have all the answers. If you ask a question and don't get an answer or the answer doesn't make sense, please keep asking. We are all still learning and sometimes the answers aren't yet known. In other cases, the answers may change quickly with rapid advancements in the technology. Please don't let this discourage you. If it turns you off to the technology, you may quickly find yourself left behind. As I mentioned at the beginning of the article and will now reiterate, while UV-LEDs are still not the right fit for many applications, the momentum of technological advancement and implementation continues to increase at an astonishing and exciting rate, thus making more and more applications more plausible! ◗

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UV-LED Overview Part II — Curing Systems

By Jennifer Heathcote

This article is the second installment in a three-part series designed to consolidate key principles and technical information regarding the science and engineering behind ultraviolet light-emitting diodes (UV-LEDs). If you have not yet read "Part I—Operation and Measurement" in the July/August 2010 issue, you may want to do so before continuing with Part II.

The best approach when tackling any new topic is to begin with a study of relevant terminology within the context of the defined subject matter. Without a firm grasp of the common language, key concepts often appear disconnected and it can be difficult to achieve full comprehension or communicate effectively within the marketplace. With emerging technologies such as UV-LEDs, an additional challenge in learning the jargon lies in the fact that the language has not yet been properly established or defined with respect to the UV curing industry, let alone consolidated for easy reference. This increases the chances that many of us are not using the same words or are using them incorrectly.

Furthermore, if the words have multiple meanings or if the definitions of the words are not apparent, their usage can lead to confusion or misunderstandings between suppliers and customers as well as within companies. How many conversations have each of us had regarding UV-LEDs in which we either assumed the other party understood what we were saying or we pretended to understand what

Figure 1

UV-LED system components

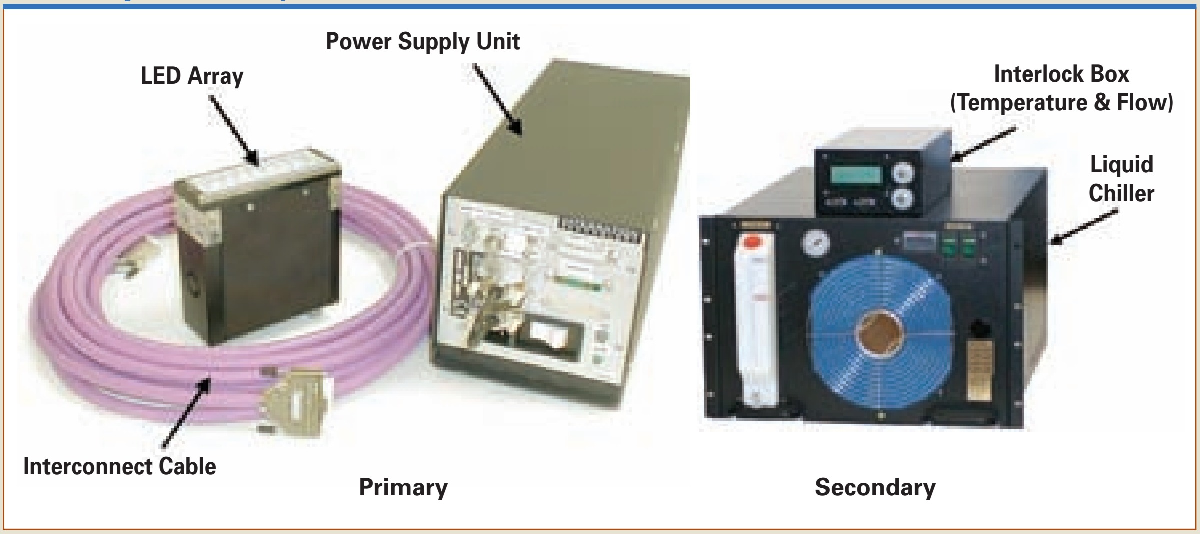
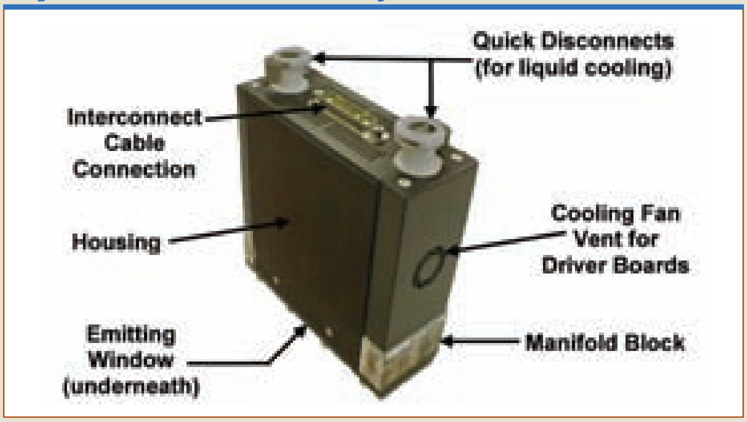


Figure 2

Liquid-cooled, UV-LED array



they were communicating to us simply because of insufficient knowledge of the words being used in the conversation? In order to document the language of UV-LEDs, educate the UV-curing industry and separate the truth from current marketing claims, this article will outline key terminology within a larger discussion of the integration of LED chips into UV-curing systems.

UV-LED System Components

All UV-LED systems designed for integration onto an OEM or host machine consist of three primary and two secondary components. While some companies within the industry may elect to use unique marketing names for these items, the primary components are generally known as the LED array, the power supply unit (PSU) and the interconnect cable. Two common secondary components generally necessary for LED arrays currently rated at or above 4 W/cm^2 are the liquid chiller and the flow and temperature interlock. Sample images of the primary and secondary components are provided in Figure 1. Ancillary items not shown would include material handling equipment, mounting brackets and light shielding.

The LED array of Figure 1 is a curing assembly that provides a function similar to that of a traditional UV lamp head or irradiator. Often the name “LED array” is shortened to array or generically referred to as the head. It is not uncommon to hear an array incorrectly called a lamp head as this has always been a frequently used term in the UV-curing industry. A standard UV-curing array houses the LED chips and, in many cases, includes a self-contained cooling fan when the maximum UV irradiance is less than 4 W/cm^2. In arrays designed for peak irradiances above 4 W/cm^2, liquid cooling is more commonly used. For these arrays, tube fittings or quick disconnect couplings are attached to the housing or manifold, and the LED-chip cooling fan is removed. The fittings or disconnects are the means by which the liquid circulation chiller is connected to the head and its internal cooling tubes. If a cooling fan is present in the array of a liquid-cooled system, it is specifically for cooling other electrical components such as the driver boards. A detailed photo of a liquid-cooled LED array is provided in Figure 2. It should be noted that LED arrays are supplied in a wide range of shapes, sizes and designs and while Figure 2 highlights common features of a standard array, it is just one example.

A fully assembled LED irradiator typically includes an emitting window that physically protects the LED chips within the assembly. The window is commonly made from a flat piece of quartz or borosilicate glass located on the head between the LED chips and the media or part being cured. Borosilicate—which is a colorless, silica glass with a minimum of five percent boric oxide—is less expensive than pure quartz and offers exceptional thermal-shock resistance and strength in comparison to both pure quartz and lower quality glass. The emitting window is sometimes chemically treated to further enhance its optical properties. This treatment can give the window a purplish or yellowish tint. The actual emitting window is hidden from view in Figure 2, but it can be seen on the exposed top surface of the LED array in Figure 1.

The power supply unit, often called a PSU, is an electrical enclosure that contains the parts necessary to power and control the array. It also serves as the communication link to a host machine. The driver board(s), which will be discussed in more detail in “Driving the LED Array,” directly power the LED chips and can either be mounted inside the array housing as in Figure 2 or in the PSU itself. The interconnect cable is the final piece of primary equipment. It provides the electrical connection between the LED array and the power supply.

The array, power supply and interconnect cable are required for a fully operating UV-LED system; however, not all three components necessarily need to be supplied by the UV equipment manufacturer. In some cases, integrators or end-users may elect to design their own power supply and/or interconnect cable. Though great care should be taken to assure that the proper specifications are met, they may even decide to buy smaller LED array packages (called modules) and build their own irradiator.

A liquid chiller is the cooling system most often required for LED arrays with UV outputs greater than 4 W/cm^2. The chiller is used to ensure the LED chips and wire bonds remain at the correct operating temperature. It does this by removing unwanted heat that is a by-product of the electroluminescence process discussed in Part I. While the UV supplier can furnish the chiller as part of the curing system, it is often more cost-effective for the integrator or end-user to purchase an off-the-shelf chiller locally or to design their own. The required cooling capacity will vary depending on the array configuration, so be sure to consult with the UV system's operating manual or with the supplier before making a decision. If the cooling system is not correctly designed or integrated into the system, the LED chips will fail prematurely.

The temperature sensor and flow meter monitor the coolant conditions at the inlet and outlet of the array. If the temperature of the circulating coolant at the array inlet and outlet exceeds a specified set point or if the outlet flow rate drops below its predetermined setting, the interlock circuit switches off the LED array. This is a safety feature designed to ensure that the correct operating temperature of the LED diode is maintained and that overheating and destroying the wire bonds is avoided. It should be noted that the interlocks can either be supplied by the LED system manufacturer or furnished by the integrator or end-user.

Packaging UV-LEDs

LED, chip, die and diode all refer to discrete, individual semiconductors that emit light when current flows through them. These four terms are used interchangeably whether referring to single or multiple LEDs. (For additional information on diode operation, refer to Part I.)

In general, UV system designers source LED chips directly from semiconductor manufacturers who have binned or categorized them according to a desired wavelength tolerance and forward voltage. UV system designers engineer the chips into an irradiator assembly that is like electrically powered, cooled with air or liquid, and equipped with a controls interface and, sometimes, optics. This is similar to the way in which electrode and microwave bulbs are sourced and then integrated into a lamp head assembly or irradiator and connected to a power supply unit. A basic LED package can consist of one or several chips, while an LED array usually contains a large number of chips arranged in a matrix pattern. Both terms refer to an arrangement of LEDs that are physically and electrically assembled together and include a means for the entire assembly to be electrically connected to another device. When a heat sink and, occasionally, optics are added to the LED package, it is often referred to as an LED module. Several LED modules can be joined together to form an even larger LED array.

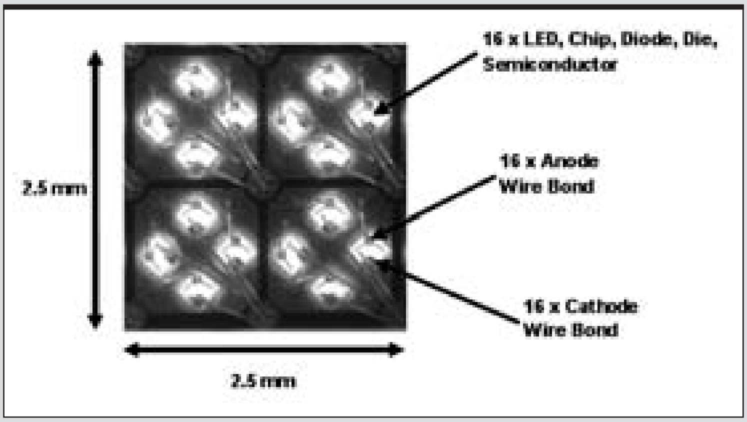
Some LED chip suppliers sell individual diodes that can be fully integrated by the UV system manufacturer into customized modules or LED arrays while others only provide their own engineered modules. Purchasing individual diodes enables the UV system manufacturer to better control and differentiate the final system design. Purchasing pre-packaged modules, on the other hand, eliminates some of the engineering but also forces UV system developers to work within the size and performance constraints of an existing assembly that may not have been designed with the necessary curing application in mind.

While there are many manufacturers of visible LEDs with production facilities located throughout the world, only about half a dozen are capable of developing and producing chips that emit wavelengths in the ultraviolet region. Some of these manufacturers include large, well-known, multinational brands such as Nichia, Fox, Nitride and Cree. As with any business, each manufacturer of UV-LED diodes has strengths and weaknesses, as well as established corporate strategies that determine which markets they pursue. Since the UV-LED market is extremely small in comparison to that of the visible and infrared LED markets targeted toward the commercial lighting, automotive, communications and securities industries, not all of the capable manufacturers are interested in producing chips for UV-curing applications. Furthermore, the flexibility of the UV-LED manufacturers with respect to the diode or module configurations they are willing to sell varies among an already small list of potential producers.

LED chips are made from very tiny slices of semiconductive material such as silicon or germanium that are doped or impregnated with additives to produce specific n-type and p-type conductivity (as discussed in Part I). This should not be confused with additive UV lamps in which the internal gas mixture is doped with iron, gallium and indium (among others) in order to shift the spectral output of a standard mercury lamp. Individual LED chips vary in size from a fraction of a millimeter to a few millimeters square and are typically less than a hundred microns thick. A wire bonding process that employs ultrasonic

Figure 3

16 LEDs with a wire bond at each anode and cathode



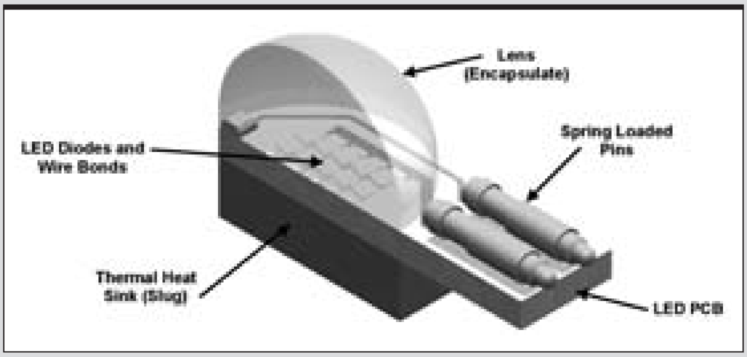
welding or thermal compression is used to electrically connect LED chips to a printed circuit board (PCB). One wire bond is made at the chip's positive terminal or anode while the other is made at the negative connection or cathode.

One of the many advantages characterized by LED sources is the inherent "scalability" of the technology. An LED package can consist of just a single LED chip or thousands of interconnected dies. As a result, an LED source could, in principle, be fabricated to any size and shape; whereas, conventional microwave and electrode UV sources are restricted to a much narrower envelope based on bulb technology and microwave cavity sizes.

In practice, most UV-LED arrays are likely to contain hundreds or even thousands of LED chips in a given assembly. The more chips, the more involved the manufacturing process and the more expensive the final assembly. For example, if there are 400 LED chips in an array, then 800 wire bonds are required. It should be noted that the wire bond is thermally sensitive and can be destroyed if the heat, an unwanted by-product of the electroluminescence process, is not sufficiently removed. Figure 3 shows a magnified image of 16 separate LED diodes taken from a larger assembly consisting of 100 chips. Two wire bonds are visible for each diode with all 16 mounted in a matrix to form a larger square pattern.

Figure 4

Cross section of a 25 die LED module

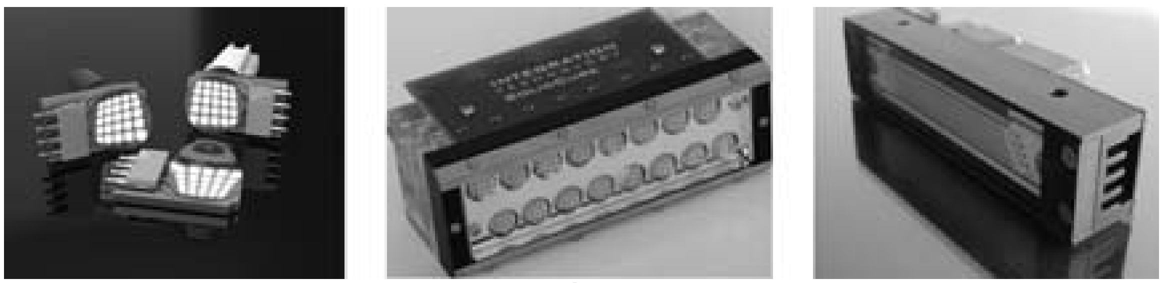


The wire-bonded diodes and PCB are secured to a metallic heat sink or slug. The heat sink is used to draw heat away from the diode and wire bonds. A flat encapsulate that is transparent and made of silicone, borosilicate glass or quartz is placed over an individual LED chip or over several LED chips for added protection. Alternatively, a dome-shaped lens made of silicone is sometimes used to control the UV rays so that they are uniformly directed at the media or part being cured. A cross sectional illustration of one type of LED package with a lens is shown in Figure 4. In this assembly, there are a total of 25 LED chips. There are 10 diodes shown in full while the cross section of the drawing splits one row of five in half.

As previously mentioned, several LED modules can be arranged together to create a physically larger LED matrix or head. The use of multiple plug-in modules, each containing a diode matrix, provides the benefit of being able to make "plug-and-play" repairs in the field. This reduces downtime or the need for a backup array as only faulty or spent modules need to be replaced. Alternatively, LED arrays are sometimes designed so that the UV-LED chips, PCB and metallic heat sink form one large, uniform assembly that spans the desired curing width. Arrays of this nature are non-serviceable and cannot be taken apart in the field as all chips in the assembly are wire bonded directly to a single PCB and heat sink. As a result, the entire array must be returned to the manufacturer for any necessary die repairs. Figure 5 provides examples of plug-in modules,

Figure 5

UV-LED arrays (a) three plug-in modules, (b) 1 LED array encompassing 16 plug-in modules, and (c) 1 LED array with 100 diodes all mounted to a single PCB and heat sink



a b c

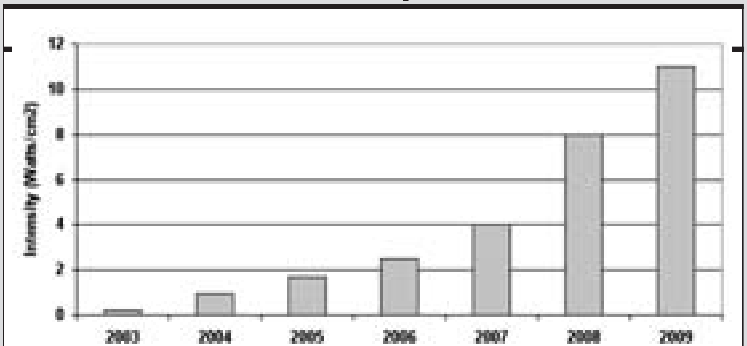
a serviceable LED array and a non-serviceable LED array.

Part I discussed the nearly monochromatic nature of UV-LEDs and how LEDs rated at 395 nm and greater emit more than five times the UVA intensity at these wavelengths than conventional electrode and microwave UV-curing lamps do at their respective peaks. Even greater irradiance levels can be achieved through the use of optics and driving techniques. Figure 6 illustrates the rapid growth in UV output for a 395 nm chip over the past seven years. The increase can be attributed to gains in understanding the science behind LEDs, improvements in the manufacturing and quality processes, and new combinations of semiconductor materials.

As with traditional microwave and electrode UV-curing applications, sufficient levels of both irradiance and energy density over a specific range of ultraviolet wavelengths are required for complete cure. When UV irradiance is taken over a period of time, it is known as the energy density or dose. For example, an intensity of 1 W/cm^2 exposed for 1 second is equal to 1 J/cm^2 of energy density. The design and manufacture of the LED chip, the current flow through the die and the distance of the array from the substrate all contribute significantly to the array's UV irradiance or intensity at the substrate surface. Alternatively, the total dose delivered to the substrate is a factor of the output of the individual dies, the total number of chips used and the end-use process speed. Both irradiance and energy density measurements should be referenced with the wavelengths generated by the array. Today, only longer UV and shorter visible wavelengths in the range of 350 nm to 430 nm are generated by LEDs for use in UV-curing applications. Commercially, these dies have peak irradiances at 365, 375, 385, 395 and 405 nm with tolerances of up to ±15 nm.

Figure 6

Advancement of UV intensity for 395 nm LEDs



For certain types of inks and coatings, a fourth variable (heat) is sometimes necessary to achieve a successful cure. In most cases, heat transferred to the cure surface by the LED array is negligible as there is no infrared component in the spectral output of an LED array. For slower process speeds, however, some of the radiated UV energy that is not absorbed by the chemistry is converted to heat at the substrate. This heat, however, is less than what is generated by electrode and microwave UV systems. The advantage of using UV-LEDs is that if heat is required for the application, it can be controlled independently of the UV device and, if it is not required, it is essentially eliminated.

It is critical that the correct combination of irradiance, energy density, wavelength and heat be used in order to cure a given ink or coating at the desired application process speed. For a properly selected wavelength source, irradiance and energy density work together like time and temperature in a thermal process. Fortunately, there are various combinations of irradiance and energy density that may result in an optimally cured product. Most UV-curing processes, therefore, occur not at a single irradiance or energy density level, but within a "process window" that should be established during the process specification trials.

Confusion in selecting the optimal UV-LED product originates in the fact that most UV-LED suppliers simply quote the peak wavelength and maximum irradiance at the emitting window as well as the physical dimensions of the LED matrix. Not all arrays that seem to be identical in these specifications, however, will provide similar irradiance, energy density and heat at the substrate over an identical range of wavelengths. This can be a bit misleading and is the single biggest difficulty in comparing UV-LED systems or in selecting the best system for a given application.

Cooling the LED Array

The overall efficiency of an LED semiconductor chip refers to how much of the electrical energy supplied to the system is directly converted into useable light energy. Technical limitations presently render UV-LEDs around 10 to 20% efficient for longer wavelengths (395 and 405 nm) and less than 10% for shorter wavelengths (365 nm). Visible and infrared LEDs, on the other hand, are in the range of 40 to 50% efficient while electrode UV systems are around 25% efficient.

Inefficiencies with UV-LEDs result in the production of large quantities of heat. In general, diodes with greater irradiance ratings generate more heat than diodes with lower irradiance ratings. Since LEDs with longer wavelengths such as 395 and 405 nm currently emit the most irradiance, they generate more heat than shorter wavelengths and must be liquid-cooled for maximum output. The heat is not radiated in the form of infrared energy but is instead a by-product of the electroluminescence process. If the heat is not removed, the wire bonds and LED chips, which cannot exceed a sustained temperature of around 125°C, will suffer catastrophic failure. In addition, the surrounding frame, manifold or housing of the array assembly will absorb the heat and radiate it out toward the substrate or part being cured.

In the near future, UV-LED efficiencies will improve and the cooling requirements will gradually decrease. While there are always exceptions, the general rule of thumb today is that arrays with outputs of less than 4 W/cm^2 can be sufficiently cooled with air; anything greater is typically cooled with a liquid-circulation chiller. An advantage of liquid-cooled systems is that there is minimal air movement around the UV-light source. This makes for a cleaner process since cooling air frequently stirs up airborne contaminants and allows arrays to be mounted close to thin or fragile substrates without disturbing them. In addition, liquid-cooled systems are typically more compact and can be more easily located in tight spaces. It is always important to note that exact cooling requirements vary depending on the array design and size so be sure to consult with the supplier or respective operating manual. In the case of air-cooled systems, the fan will likely be provided as part of the array assembly. Liquid chillers, on the other hand, can be provided by either the UV system manufacturer or sourced independently by the integrator or end-user.

Most industrial chiller companies recommend using a mixture of industrial inhibited glycol and water as the circulation coolant. An inhibited coolant prevents the formation of scale and corrosion while simultaneously protecting the metals. In addition, it also offers protection against algae and bacteria, provided a minimum concentration level is used. Ethylene glycol has better thermal transfer properties; however, propylene glycol is more environmentally friendly. Both are marketed in North America under the brands DOWTHERM™ and DOWFROST™, respectively, and can typically be purchased in either concentrated or diluted form in small volumes through chiller suppliers. It is good practice not to mix different types or brands of glycol as this can precipitate some inhibitors out of solution. The net effect is a reduction in the effectiveness of the coolant and possible particulate buildup at various locations within the closed-loop system.

The DOW Chemical Company recommends that concentrations of its products be maintained between 25% and 60% glycol. Concentrations in the lower range result in better heat transfer; however, using less than 25% glycol can lead to corrosion and less than 20% glycol will result in bacterial contamination. Commonly used proportions are 25%-30% glycol to water. Distilled or reverse-osmosis water can be used to dilute the glycol. De-ionized water can sometimes be used for dilution as long as the de-ionized state of the liquid is not maintained. Maintaining a de-ionized state can result in the breakdown of certain metals in the system. Most chiller suppliers strongly discourage against the use of regular tap water. Similar inhibited coolants are available from other manufacturers and may be more accessible given your location. Before selecting a chiller or before filling the reservoir, make sure you consult with the UV-LED system and chiller suppliers, their respective manuals, state and local codes, and the corresponding Material Safety Data Sheet.

Today, the decision of whether to cool an LED array with air or liquid is primarily based on the maximum irradiance level. Higher irradiance LED systems tend to incorporate liquid chillers because they are the most effective way to remove unwanted heat and result in a more compact array. Lower irradiance LED systems that incorporate air-cooled arrays emit less UV, making it more difficult to cure some materials at faster speeds. This is the trade-off when air cooling is used. Failure to provide sufficient cooling with either air or liquid will result in catastrophic and premature failure of the wire bonds and LED chips. A temperature sensor and flow meter interlock is a great safety feature that can and should be built into systems using liquid chillers. If the temperature of the circulating coolant at the array inlet and outlet exceeds a specified set point or if the outlet flow rate drops below its predetermined setting, the interlock circuit switches off the LED array. Do not assume, however, that your system is equipped with an interlock. You should always consult with the operations manual or your supplier to be sure.

Driving the LED Array

Traditional electrode UV-curing systems utilize an ignitor to strike a 2 to 4 kilovolt arc across the bulb in order to vaporize the mercury and emit UV. Ballast, choke or transformer combinations are wired into the circuit to stabilize the amount of current flowing through a struck bulb and provide for various UV power output levels. LEDs, on the other hand, are entirely solid-state devices that emit ultraviolet light immediately when connected to a low-voltage, DC power source and do not require a high-voltage ignitor. Each LED chip is designed to operate between 20 and 500 mA and between 2 and 4 volts DC. The amount of UV irradiance emitted from an LED is directly proportional to the amount of current passing through the device; however, if the design voltage or current rating of any individual LED chip is exceeded for an extended period of time during operation, the chip will fail.

LEDs can be connected in series or parallel circuits as illustrated in Figures 7, 8 and 9. While all three simple circuits demonstrate the connection of four diodes, UV-curing arrays will typically have hundreds or even thousands of individual LEDs wired into a single chain. In a series installation, if one LED fails, current flow through the circuit is interrupted downstream from the faulty LED. Parallel circuits have the

Figure 7

Four LEDs wired in series with resistors and a DC power supply

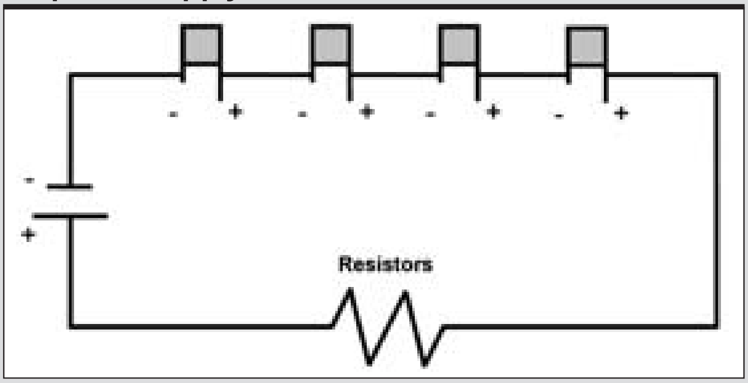


Figure 8

Four LEDs with identical voltage ratings wired in parallel with resistors and a DC power supply

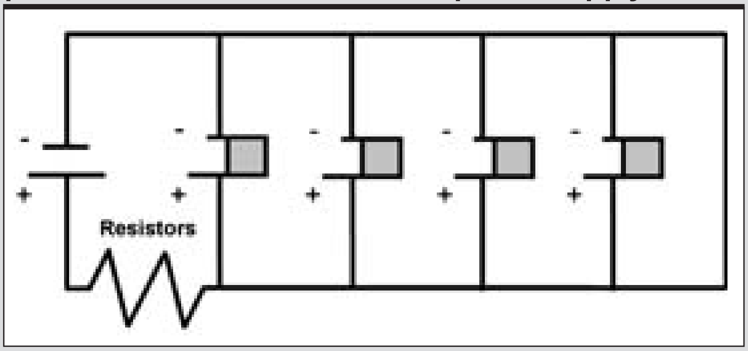
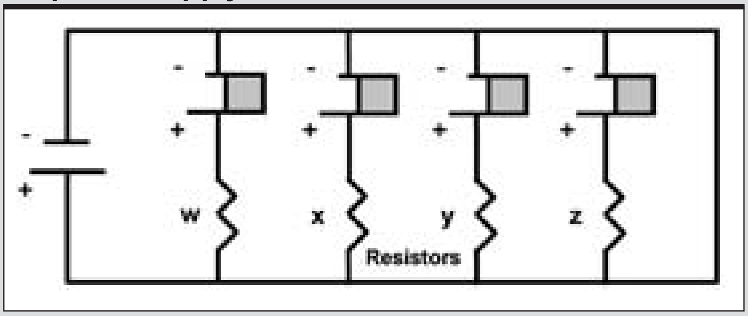


Figure 9

Four LEDs with different voltage ratings wired in parallel with four different resistors and a DC power supply



advantage of continued operation of all functioning LEDs even if one or more LEDs fail. In either type of circuit, it is important that the anode and cathode connections be alternated. This is because LEDs have polarity and current will only flow in one direction. Placing two anodes or two cathodes in sequence will disable the circuit.

In all three simple circuits, resistors are precisely sized to ensure the correct voltage drop and current flow across each LED. Insufficient voltage and current will yield less than optimal UV output, while too much can lead to premature failure of the dies. When LEDs are wired in parallel, as illustrated in Figure 8, they must all have the same voltage rating. Otherwise, current flowing through each leg of the circuit will vary and result in some LEDs not lighting or not all LEDs emitting the same light output. If LEDs have different voltage ratings, then appropriately sized resistors must be placed in each leg of the circuit to balance the current flow. This is illustrated in Figure 9 with resistors w, x, y and z rated at different values.

In practice, the use of resistors to regulate voltage and current within an LED circuit is actually quite inefficient as resistors generate heat and cannot easily accommodate fluctuations in die tolerances and operating temperatures. Even the slightest variation in running conditions can produce wide swings in UV output and chip lifetime hours. Producing systems with multiple power levels is also challenging since it requires the use of many different resistance levels in order to vary the current through the circuit as a means of changing the amount of UV emitted from each diode. As a result, UV equipment manufacturers generally power LEDs with regulated, constant-current drivers and employ an optional technique known as Pulse Width Modulation (PWM) when it is necessary to vary the UV output.

The use of constant-current drivers enables each and every LED chip to always experience a non-fluctuating and continuous current when powered. The LEDs are either ON or OFF with no variability in irradiance. For applications that require multiple power levels, PWM is used to generate an almost infinite number of outputs. PWM takes advantage of the nearly instantaneous response time of LEDs and works by quickly and efficiently switching current to the diodes between ON and OFF. The length of the pulsed current varies the proportion of ON and OFF time per cycle.

Figure 10 illustrates PWM output levels of 25, 50, 75 and 100% power. Duty cycle is defined as the proportion of ON time to the total cycle time (ON + OFF) and is expressed as a percentage. A low duty cycle corresponds to low power because the power is OFF most of the time, whereas 100% is fully ON, 0% is fully OFF and 50% means that the power is ON half the time and OFF half the time. It should be noted that the total cycle time or period, indicated by “P” in Figure 10, is constant across all four duty cycles.

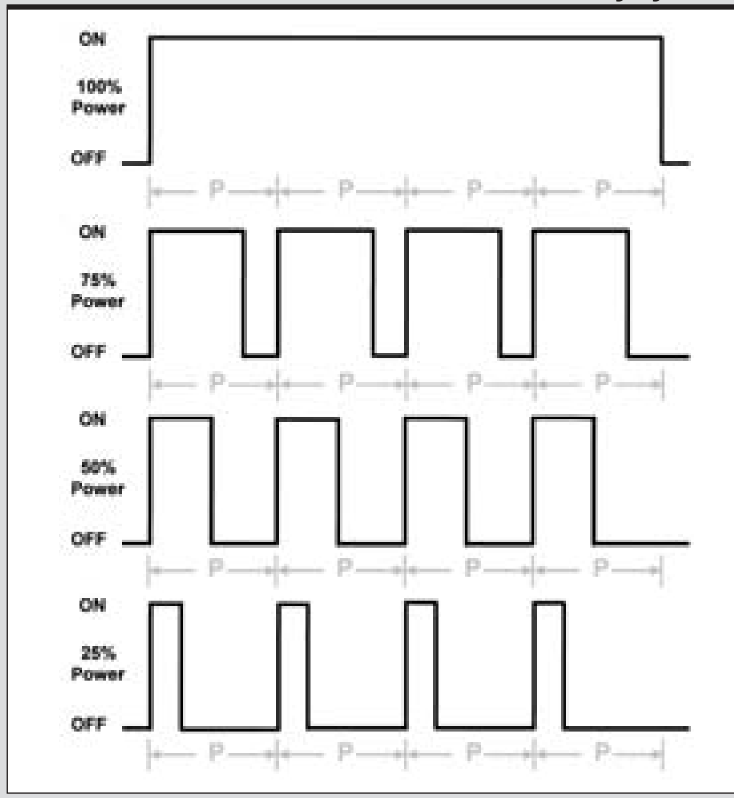
With PWM, the peak irradiance (W/cm^2) is the same for all power levels, but the duration of the pulsed current and, therefore, the duration of the pulsed irradiance, is varied so as to increase or decrease the total exposure time or energy density (J/cm^2). The two main reasons for using PWM to drive the UV-LED power levels, as opposed to varying the actual drive current through the LED circuit with resistors, are that PWM (1) provides truly instantaneous and infinitely variable control of the UV output and (2) prolongs the life of the chips. In addition, PWM provides for easy addressability of individual banks of LEDs or modules within an array.

The fast cycling or strobing of LEDs using PWM occurs at frequencies of 2 KHz or greater. A 2 KHz frequency means that there are 2,000 cycles (or current pulses) every second. While this high of a frequency cannot be detected by the human eye, an observer will notice that the LEDs become increasingly dimmer in appearance as the relative output decreases. With respect to an application using a PWM frequency of 2 KHz in which the media is traveling beneath the array at 0.5 meters per second, the UV source illuminates once every 0.25 millimeters of media travel.

The array driver boards are essentially printed circuit boards, (PCBs), although they are entirely different PCBs than the ones to which the individual diodes are wire bonded. The purpose of the driver boards is to distribute the DC voltage to the LED chips or modules in an array; deliver the necessary constant current; and provide the PWM capability of the system. The driver boards can either be mounted on the array or located remotely in the power supply unit. The advantage of mounting the boards on the array is that electrical noise can be minimized and the diameter of the interconnect cable can be reduced. There are many different types of drivers used to perform a wide variety of functions. As a result, the style of driver board used in LED systems will vary significantly between manufacturers.

Figure 10

PWM illustration of 25, 50, 75 and 100% duty cycles



Installing UV-LED Systems

The task of installing a UV-LED system is similar to that of installing a conventional UV system, but in some ways it is actually a bit simpler. Unlike conventional UV systems, LEDs generate no ozone; do not emit short wavelength UV which can attack many materials; do not require special filters for observation windows; often draw far less electrical power; create less airborne contamination near the media when liquid chillers are used; and possess none of the handling and disposal issues associated with conventional medium-pressure mercury vapor lamps. Installations on a host machine typically require mounting the array(s); frequently purchasing or designing and then connecting the chiller system; electrically powering the PSU; connecting the interconnect cable between the power supply and the array; providing a means for the I/O interface; and ensuring safe operation for the operator and the UV-LED system, as well as the host and ancillary equipment.

All UV output attenuates or decreases in magnitude as the distance between the emitting window and the substrate increases. As a result, most LED arrays currently on the market are typically mounted as close as possible to the substrate or object being cured. This distance is usually between 5 and 15 mm; although, it does vary by supplier and application. Most arrays are equipped with mounting holes or threaded inserts that allow the device to be secured to a host machine with a simple bracket designed by the integrator or the end-user. The array should be mounted so that it either spans the curing width of a static installation or can be physically moved by the host machine to cover a greater curing area. The duty cycle of an array equipped with PWM and the speed of the line can both be adjusted to achieve a range of energy density while maintaining a constant irradiance. In some cases, multiple arrays will need to be used to achieve the required energy density. Keep in mind that the focal point commonly referenced with conventional UV systems employing elliptical reflectors is not typically applicable for LED systems. While LED chips can be packaged in an arrangement so that all the UV rays are directed to a common location or manipulated with optics, this is not standard practice. Current UV-LED systems more closely resemble the flood profile of traditional arc or microwave systems.

The wavelengths emitted from diodes used in curing systems are

UV-LED TERMINOLOGY

Anode—positive terminal of an LED.

Binning—process of sorting LED chips into groups according to peak irradiance, wavelength tolerance and forward voltage.

Borosilicate—strong, heat-resistant, colorless, silica glass that contains a minimum of five percent boric oxide, exhibits exceptional thermal shock resistance, and transmits a greater percentage of ultraviolet energy than glass. Common material used for the emitting window on a UV-LED head.

Cathode—negative terminal of an LED.

Chip—a fully functioning, minute slice of a semiconducting material (such as silicon, germanium and gallium arsenide) doped and processed to have p-n junction characteristics. Specifically, gallium nitride (GaN) is used to generate longer ultraviolet and blue-visible wavelengths. In referring to LEDs, chip is often used interchangeably with diode, die and semiconductor.

Coolant—liquid circulation material that flows over the heat sink in the LED array or module in order to (1) remove wasted heat energy produced by the electroluminescence process and (2) maintain the correct operating temperature of the LED chips and wire bonds.

Depletion Zone—the non-conductive boundary where the positive and negative sides of a p-n junction meet.

Die—a fully functioning, minute slice of a semiconducting material (such as silicon, germanium and gallium arsenide) doped and processed to have p-n junction characteristics. Specifically, gallium nitride (GaN) is used to generate longer ultraviolet and blue visible wavelengths. In referring to LEDs, chip is often used interchangeably with diode, chip and semiconductor.

Diode—common semiconductor device which is added to a circuit as a means of restricting the flow of electricity. It can generically be thought of as a switch or a valve. A key property of a diode is that it only conducts electricity in one direction. In referring to LEDs, diode is often used interchangeably with chip, die and semiconductor.

Doped—refers to an LED semiconductor material that has been impregnated with impurities to produce a specific n-type or p-type conductivity.

Driver Board—a printed circuit board (PCB) that distributes the DC voltage to the LED chips or modules in an array and provides the pulse width modulation (PWM) capability of the system.

Duty Cycle—the proportion of ON time in a pulse width modulation cycle to the total cycle time (ON + OFF) expressed as a percentage. A low duty cycle corresponds to low power because the power is off most of the time, whereas 100% is fully ON, 0% is fully OFF and 50% means that the power is ON half the time and OFF half the time.

Electroluminescence—an optical and electrical phenomenon inherent to LEDs in which a material emits light energy when an electric current is passed through it.

Emitting Window—flat, rectangular piece of quartz or borosilicate typically secured at the base of an LED head to protect the dies while simultaneously transmitting ultraviolet wavelengths.

Encapsulate—a transparent material used to physically protect dies and block moisture. It can either be flat or shaped into a convex lens. Modern LEDs use encapsulates made of silicone, while older LEDs were made of epoxy resins. Both silicone and epoxy resins fully surround the LED chip(s). Encapsulates made of quartz or glass generally do not surround the LED chip(s), but are used as a hard protective outer cover.

Forward Bias—occurs when the anode of an LED is connected to the positive terminal of a voltage supply and the cathode of the LED is connected to the negative terminal. The effect of a forward bias is that the positive holes in the p region and the negative electrons in the n region of a p-n junction are pushed from opposite directions toward the depletion zone. This significantly reduces the width of the depletion zone causing the electrons on the n-side to respond to the attractive forces of the holes on the p-side. The end result is the flow of electricity and the emission of photons.

Forward Voltage—the actual voltage across a semiconductor diode carrying a forward current.

Interconnect Cable—electrically connects the LED irradiator and the power supply unit.

Interlock—a temperature sensor and/or flow meter designed into the LED-cooling system to monitor conditions at the inlet and outlet of the array. If the coolant temperature exceeds a specified set point or the flow rate drops below a specified set point, the interlock circuit switches off the LED array in order to avoid overheating and destroying the individual diodes and wire bonds.

LED (light emitting diode)—semiconductive device containing a p-n junction designed to emit specific narrow band wavelengths within the electromagnetic spectrum via a process known as electroluminescence. When a forward bias voltage is applied to the LED, current flows from the p-side to the n-side (anode to cathode). As the electrons cross the depletion zone and fill a hole, they drop into a state of lower energy. The excess energy is released in the form of a photon. The energy of the photon is directly related to the amount of excess energy, while the wavelength of the photon is inversely related to the excess energy. In other words, the higher the excess energy, the shorter the wavelength.

LED Array—(1) packaged sub-assembly or module typically consisting of multiple LED diodes or chips that are individually wire bonded to a printed circuit board and then secured to a heat sink; (2) also refers to a full curing assembly which includes numerous modules or LED chips, as well as a cooling fan or tube fittings, a manifold block, an emitting window and a sheet metal or plastic outer housing. In some cases, a complete array assembly will also contain the driver boards. The array is similar in concept to a lamp head or irradiator in traditional UV-curing systems.

LED Irradiator, LED Head or LED Light Engine—a UV-curing assembly which includes multiple LED chips or modules, a thermal heat sink, a cooling fan or tube fittings, a manifold block, an emitting window, a sheet metal or plastic outer housing and, sometimes, the driver boards.

LED Package—an assembly containing one or several chips physically and electrically assembled together with a means of electrically connecting the entire assembly to another device.

Lens—transparent device used to physically protect LED chips, block moisture and evenly manipulate or spread the emitted UV radiation. Often made of silicone, borosilicate or quartz. See *encapsulate.*

Liquid Chiller—cooling system used to (1) ensure the LED chips and wire bonds remain at the correct operating temperature and (2) to remove wasted heat energy from the electroluminescence process.

Module—packaged assembly consisting of one or multiple LED diodes that are individually wire bonded to a printed circuit board which is then secured to a heat sink. A module often includes a silicone encapsulate or lens over the chips for protection and to block moisture. A module is an array, but several modules can also be assembled together to form a larger array known as a head or irradiator.

Optical Device—used to evenly spread or sometimes focus the emitted UV radiation from an LED module or array.

Printed Circuit Board (PCB)—part of the LED module or array to which the individual LED chips or diodes are wire bonded. The PCB provides the electrical interface between the LED chip(s) and the driver board(s).

Plug-in-module—packaged assembly consisting of one or multiple LED diodes that are individually wire bonded to a PCB which is then secured to a heat sink. A module often includes a silicone encapsulate or lens over the chips for protection and to block moisture. A module is an array, but several modules can also be assembled together to form a larger array known as a head or irradiator.

Positive-Negative Junction (p-n junction)—a specially engineered diode made by forming layers of semiconductive materials. Impurities or dopants are impregnated or doped into the semiconductor layers to create p- and n-type regions. These regions can be made from the same or different semiconductor materials. The two sides of the diode are referred to as the anode (+) and the cathode (-), respectively. Current is able to flow from the p-side of the diode to the n-side, but it cannot flow in the reverse direction.

Power Supply Unit (PSU)—a generic term often used to describe an electrical cabinet containing the DC voltage supply, I/O interface and AC power connection for an LED array. The power supply unit may also contain the driver boards. Alternatively, the driver boards can be mounted on the array.

Pulse Width Modulation (PWM)—efficient way of providing intermediate amounts of electrical power by varying the proportion of ON and OFF time per cycle. The peak irradiance (W/cm^2) is the same for all power levels, but the duration of the pulsed irradiance is varied so as to increase or decrease the exposure time or energy density (Joules/cm^2).

Semiconductor—a substance that can be made to conduct electricity or be an electrical insulator depending on its chemical composition. The conductivity of the semiconductor varies depending on the impurity (or dopant) concentration created during the manufacturing processes. Common semiconductor base materials include silicon, gallium nitride, gallium arsenide and gallium phosphide.

Wire Bond—refers to the electrical connection between the LED chip and the PCB. There are two wire bonds between each LED chip and the PCB. These wire bonds are made at the anode and the cathode of the chip.

Wire Bonding—the method of making an electrical connection between the LED chip and the PCB using ultrasonic welding or thermal compression.

currently between 350 nm and 430 nm. This renders all of it in the UVA and visible bandwidth range and none of it in the UVB and harmful UVC range. As a result, shielding is only necessary to reduce visual discomfort due to brightness and can be addressed using sheet metal, tinted polycarbonate and various other low-cost plastics. Potential eye and skin issues due to UVC are not typically a safety concern with the UV-LEDs presently on the market; however, it is always best to review this with the supplier and err on the side of caution.

Longer wavelengths also mean no ozone is produced since ozone is only generated when wavelengths shorter than 250 nm interact with oxygen. As a result, it is not necessary to ventilate or exhaust the system unless you are working with extremely heat-sensitive substrates when it is desirable to remove additional heat from the electroluminescence process. With UV-LEDs, there can be a buildup of heat around the exterior of the array depending on the design. While this is typically fine for the operation of the UV-LED equipment, it can create a situation in which the array may be hot to the touch. As a result, it is recommended that protection be provided to ensure that the operator or maintenance staff does not unwillingly come in contact with the surface of a powered array.

Power supply units for UV-LED systems are more commonly solid-state devices where the main electrical supply power can typically be anywhere between 100 and 240 Volts AC at either 50 or 60 Hz. Solid-state power supplies automatically accommodate for the given voltage, frequency connection and minor variations on the line; however, you should always consult with the UV-LED system's operating manual or with the supplier to be sure. A DC-voltage power supply is installed in the

UV system's PSU to power the driver boards and LEDs. Current draw on the main AC line for products presently on the market vary from a few amps to more than 20 amps for larger arrays. For some applications that require thousands of LEDs, current draw will be higher.

The interconnect cable connections, I/O interface and liquid cooling capacity, while straight forward, will vary with each UV-LED system. As a result, these specifications are not covered by this article and should instead be discussed directly with the supplier.

Comparing LED Technologies

The following questions can be used as means of comparing UV-LED products on the market or can serve as a guide through the integration process.

- What terminology is being used that you do not understand? Always ask the supplier to clarify anything that is confusing.
- What components are supplied by the UV system manufacturer (module, array, interconnect cable, power supply unit, cooling fan, chiller, interlock, mounting bracket)?
- What components do you want to source locally or design yourself (power supply unit, chiller, interlock, mounting bracket)?
- If supplying the chiller yourself, what size tube fittings or disconnects are supplied with the array?
- What is the necessary cooling capacity for the chiller in terms of wattage, flow rate, temperature and pressure?
- What type of coolant mixtures are required or restricted by the chiller and UV-LED system suppliers?
- Are there any health or safety concerns regarding the coolant?
- What are the local and state codes for use and disposal of the coolant?
- Can the array be repaired in the field or must it be returned to the manufacturer?
- Is the UV array powered with PWM or a constant current? Which is better for your application?
- What length interconnect cable does the application require?
- If the UV-LED array must move to provide full UV coverage, is the interconnect cable high-flex and what is the minimum bend radius?
- At what distance should the UV-LED array be mounted from the substrate or part being cured?
- What is the I/O interface?
- Does the UV system need to be controlled by a host system or is it equipped with a local operator interface?
- Do you want a "plug-and-play" solution or a partial solution that requires additional engineering?
- What is the supply voltage and main AC current draw for the entire system?

As you move forward with your investigative study of UV-LEDs, make sure you are comfortable with the terminology. For convenience, a glossary of commonly used UV-LED terms has been provided as an appendix to this article. The importance of word usage cannot be emphasized enough. Without a firm grasp of the common language, the progress of your project will likely be delayed. Worse yet, you could proceed down a development path that is not best for your particular application or you could completely miss an opportunity that may propel you ahead of your competition. If you ever find yourself uncertain of UV-LED words used in conversation, please ask. It will be a good test for those of us promoting the technology and will hasten the learning curve for all of us. ◗

—Jennifer Heathcote is general manager, North America, for Integration Technology in Chicago, Ill.

UV-LED Overview Part III: Diode Evolution and Manufacturing

By Jennifer Heathcote

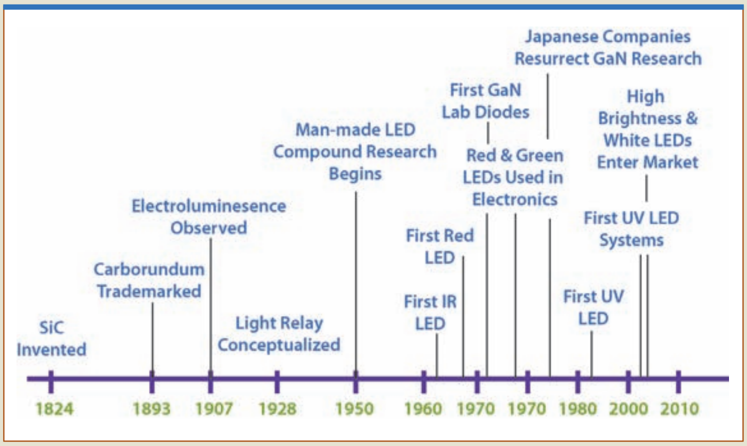
This abridged article is the third installment in a three-part series designed to consolidate key principles and technical information regarding the science and engineering behind UV-LEDs. If you have not yet read "Part I—Operation and Measurement" (July/August 2010) or "Part II—Curing Systems" (Sept/Oct 2010), you may want to do so before continuing with Part III. For the complete, unabridged version of this article, please visit the "Members Only" area at www.RadTech.org.

Light Emitting Diodes (LEDs) are engineered to produce discrete infrared, visible or ultraviolet (UV) wavelengths when a DC voltage is applied. The type of output, overall performance and operating efficiency of any given die is directly related to its material composition and the manufacturing methods employed. As a result, there has been a concerted effort for the last 60 years to identify new semiconductive compounds, improve chip structures and optimize processing techniques. Much of this activity has been concentrated in the longer wavelength visible and infrared ranges; and has directly led to improved yield rates, lower power consumptions, brighter colors and increased operating efficiencies as well as a steady decline in unit costs.

By comparison, UV-LED technology is relatively new, and engineers and developers are still hard at work trying to understand and optimize the core technology as well as implement reliable manufacturing methods. The purpose of this paper is to provide a brief history of LED development as well as an overview of typical processes employed in chip production. It is only with an understanding of how far the technology has come, as well as what is involved in producing LED emitters, that one can truly appreciate the potential of where the technology has yet to take us.

FIGURE 1

Timeline for evolution of LEDs



Brief History

Engineers and research scientists have been formulating and experimenting for nearly 60 years with an ever increasing portfolio of man-made semiconductor compounds that emit infrared, visible and, most recently, UV wavelengths. These compounds have been engineered to embody specific electrochemical and emissive properties, while operating at increasingly higher efficiencies and consuming less power. Since each compound emits a different wavelength and/or amount of energy, an entire portfolio of materials is necessary in order to produce dies for various applications. The final diode performance determines which compounds are used for which applications. Some of the more widely used compounds include Aluminum Gallium Arsenide (AlGaAs), Gallium Arsenide Phosphide (GaAsP), and Gallium Nitride (GaN). It should be emphasized that research in this field is far from exhausted, and there are presently complex high brightness alloys still in development, including GaN/SiC, GaN/Sapphire, GaN/ZnO and GaN/B-GaN/pAIN. Very preliminary research into materials that emit shorter wavelength UV-A, UV-B and UV-C is also currently underway. A timeline summarizing key breakthroughs in development since the discovery of the first semiconductive compound, Silicon Carbide (SiC), is illustrated in Figure 1.

Semiconductor Manufacturing

The spectral emission, electrical-to-optical power-conversion efficiency, unit cost, quality, yield rate and lifetime hours of each die depend not only on the substrate material, but also on each additional processing step and manufacturing method employed. As a result, significant investment has gone into developing and controlling the production of LEDs.

Actual manufacturing yield rates vary significantly depending on the type of LED. Yield rates for standard infrared and visible LEDs have improved drastically over the past 50 years as most of the production issues have been resolved. Yield rates for white and visible spectrum high-brightness LEDs are increasing rapidly; although, there is still room for improvement. The current quality of UV-LED production, unfortunately, is not very good and much optimization work remains to be done. With UV-LEDs, there is a significant amount of scrap generated during production that has a direct impact on the final die cost and performance.

Every single stage and step of the production process—from raw material selection through to packaging—is critical. Each has the potential to introduce defects or foreign matter, resulting in lower efficiencies and insufficient performance in the final dies. As a result, numerous quality assurance checks are performed, and most processes take place in Class 1 and Class 10 clean rooms. Each and every step of the manufacturing process, therefore, is a distinct and challenging engineering and quality improvement project that takes years, if not decades, to perfect.

An overly simplified description of this process can be segmented into three parts that focus on the ingot, wafer and die. It should be noted that there are many variations to the production methods described; not all steps have been included in this document; and each manufacturer likely incorporates proprietary processing that is not generally known to the public. As a result, the following sections are meant to give the reader some general insight into a typical LED manufacturing process and are by no means meant to be fully comprehensive.

The Ingot

The manufacture of LED semiconductors starts with the production of a long, cylindrical ingot, also called a boule. The ingot is typically formed to diameters of 2, 4, 6, 8 or 12 inches and can be grown to any desired length. The material properties are uniform throughout the ingot, and the crystalline structure contains relatively few impurities or contaminants. This is achieved through precision temperature and pressure control in a clean environment, and by using only the highest purity of raw materials.

Formation of the ingot begins when high-grade raw materials are mixed together in a specially designed reactor chamber as illustrated in Figure 2. When elevated temperatures and pressures are applied, the materials combine to form a uniform molten solution that is covered with a layer of liquid boron oxide to prevent vaporization. A rod or chuck is then lowered toward the solution (2-a). On the end of the chuck is a tiny, purified seed that contains the exact properties of the mixture. When the seed reaches the solution, a chemical bond begins to form between the seed and the molten material (2-b).

FIGURE 2

Forming the ingot

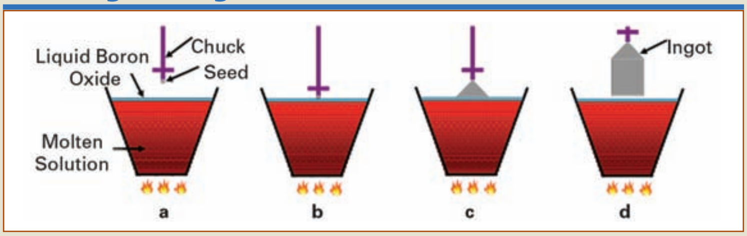


FIGURE 3

Fully formed ingots

As the rod is rotated and withdrawn at a slow and constant rate of speed, some of the mixture begins to cool and solidify on the seed. The top of the ingot takes the shape of a cone that tapers from the seed outward to the desired diameter (2-c). The crystals continue to grow in length as long as the process conditions are maintained. The applied temperatures and pressures, as well as the rotation and extraction speed, all have a direct effect on the diameter and the quality of the ingot. When the desired growth is reached, the seed and bonded ingot are removed from the chamber. The result is an ingot with all the physical characteristics of the original seed material (2-d). A photo showing typical ingots is provided in Figure 3. Before moving to the next stage of production, a diamond saw is used to remove the cone and the remaining cylindrical ingot is ground and polished.

The Wafer

A diamond saw is used to slice the ingot into crystalline wafers or substrates that are less than 250 microns thick (10 mils). This is illustrated in Figure 4. After slicing, the wafer is subjected to a lapping and/or etching process in order to carefully remove unnecessary or damaged particles from the surface. Lapping is a physical process that involves moving the wafer over a plane of liquid abrasive, while etching is a chemical process intended to dissolve unwanted material. Both are used to ensure a smooth surface. Next, the thickness and flatness of each wafer is measured; and the wafers are sorted and polished in order to improve the efficiency and quality of downstream processing and make the wafers more receptive to additional layers of semiconductive material.

Any imperfections created when the ingot is formed and sliced—or when the wafer is lapped, etched or polished—will lead to a poorly functioning or non-functioning LED. Unclean wafers also have a negative effect on the performance of the final diodes. As a result, all wafers are cleaned using ultrasonic or solvent-based methods in order to remove any remaining dirt, dust or foreign matter.

Next, a process known as Liquid Phase Epitaxy is used to grow additional layers of semiconductive material on top of each wafer. These layers often contain intentionally added impurities or dopants that improve the emissive characteristics and efficiencies of the final diodes. The dopants interfere with the crystalline structure of the die resulting in an altered output when a voltage is applied. All epitaxial layers have the same crystal orientation as the ingot; however, the existence of dopants means that each layer has a different electronic density.

Each epitaxial layer is several microns thick, and the process involves passing each wafer underneath various reservoirs of molten material or melt as illustrated in Figure 5. A melt can contain one or several types of dopants. If multiple dopants are needed to produce the desired effect, they can either be grown on the wafer structure in sequential layers or all at once.

Sometimes it is necessary to further increase the quantity of dopants or

FIGURE 4

Wafers being sliced from ingot

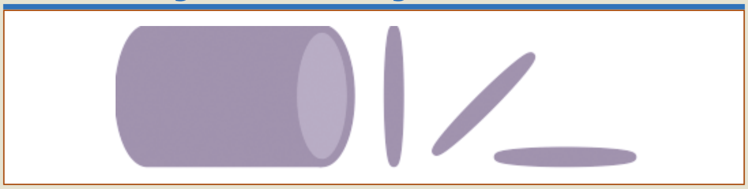


FIGURE 5

Wafer processing—liquid phase epitaxy

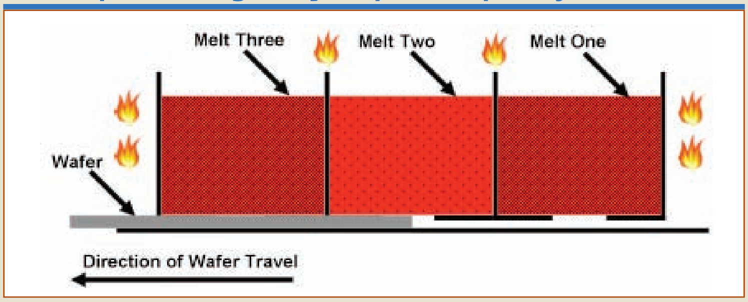


Figure 6

Wafers in front of furnace tube entrance

introduce new dopants into the wafer structure after the epitaxial layers are grown. This step is often administered using a continuous diffusion furnace or furnace tube where dopants are forced into the upper layer(s) using high-temperature gases. A photo of one such furnace is shown in Figure 6.

The next step is to add conductive metal contacts or circuitry to the wafer. This may be done all at once or built up sequentially by repeating the following photoresist and vapor deposition process several times. First, a light-sensitive, liquid material called a photoresist is applied to the top surface of the wafer while it spins. Spinning ensures that the material is evenly distributed across the entire surface. Next, the wafer and applied resist are baked at a low temperature in order to harden the resist surface. A mask (also called a "reticule") containing the metallic contact pattern is placed over the wafer. The entire wafer is then exposed to UV light. All exposed areas of the resist material that are not blocked by the reticule cure underneath the light and are subsequently washed away in a developer bath. The resist that was under the mask remains on top of the semiconductor layers. It will be removed in a later step.

Contact metal is then evaporated onto the wafer in the areas where the resist was removed. This is done in a high-temperature, vacuum-sealed chamber flooded with a mixture of hydrogen and nitrogen gas. High temperatures are used to vaporize the metal contact material inside the chamber. Once the metal is vaporized, the chamber conditions are adjusted in order to condense the metal onto the wafer in the areas where the resist was removed. The remaining resist is then stripped in a chemical bath leaving just the epitaxial wafer and metal contacts. Finally, the contact pattern is annealed to the wafer in a high temperature furnace over a period of several hours. The end result is a chemical bond between the semiconductor and the contacts. An example of processed wafer is provided in Figure 7.

The Die (Chip, Diode, Semiconductor)

Depending on the diameter, a fully processed wafer is made up of thousands or even tens of thousands of individual light-emitting diodes all with the same general material structure

Figure 7

Processed wafer

and metallic contact pattern. Figure 8 shows one LED die resting on the face of a U.S. penny. This single die would have been one of many cut from a 2-, 4-, 6-, 8- or 12-inch diameter wafer using a laser or diamond saw.

After the dies are extracted from the wafer, a forward voltage is applied to each and every die, and the output is measured using an integrating sphere. It is only at this time that manufacturers know whether the production process was successful. Each functioning LED is then binned according to wavelength, peak irradiance and forward voltage. For additional information on integrating spheres and binning,

Figure 8

Completed individual die shown in proportion to a U.S. penny

refer to "UV-LED Overview Part I—Operation and Measurement."

After the diodes are binned, they must be packaged according to the intended application. The semiconductor manufacturer will often package the dies itself before selling the LEDs to the market as modules. Alternatively, some semiconductor manufacturers will sell the individual dies without further packaging. In this case, the packaging is done directly by the final equipment manufacturer or other supplier. The packaging of UV-LEDs was detailed in "UV-LED Overview Part II—UV Curing Systems."

Conclusion

The evolution of LEDs has spanned 187 years since the invention of Silicon Carbide; 118 years since the commercialization of Carborundum; 104 years since the discovery of electroluminescence; 83 years since the light relay was first conceptualized; 56 years since the initiative to engineer semiconductive man-made compounds; 19 years since the first UV-LED was produced in a lab; and eight years since UV-LED curing systems were first offered to the market. It has been a long and remarkable journey that has involved extensive development of previously unknown compounds; the creation of diverse diode structures; and the invention and optimization of precision manufacturing methods. Despite all the amazing accomplishments, this is a journey that is still far from over. During the foreseeable future, UV-LED performance will continue to improve. More wavelengths will become available; higher irradiances will be generated; efficiencies will increase; lifetime hours will improve; and costs will become more attractive. These breakthroughs will not necessarily happen overnight, but recent advancements evaluated in the historical context of LED evolution make it hard not to be excited about the technology's future and all its possibilities.

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UV-LED Curing Systems: Not Created Equal

By Sara Jennings, Bonnie Larson and Chad Taggard

The ultraviolet (UV)-light emitting diode (LED) curing market has enjoyed considerable growth over the past several years as both new and existing markets recognize the inherent benefits of UV-LEDs. This paper will focus on the potential differences in UV-LED systems. Additionally, measurement methods that can be used to contrast and compare the differences in performance of the various available UV-LED based systems will be discussed. The reader can then quantitatively determine the performance of a UV-LED curing system and see that not all UV-LED curing systems are created equal.

UV-LED Curing Advantages

Application after application across many market segments have moved to UV curing using photopolymer chemistry and away from solvent-based formulations that contain volatile organic compounds (VOCs) and require large, power-hungry furnaces. The advantages of UV-curable formulation systems versus conventionally cured solvent-based formulation systems are well documented. The advantages of UV-LED curing over UV curing using traditional mercury lamps for specific applications have also been well documented in previous articles.

Most, though not all, UV-LED lamps are focused on the UV-A range and the ability to generate high-irradiance UV light with sufficient energy levels to cure most materials. However, due to its focused wavelength characteristics, the typical UV-LED lamp doesn't generate UV-B, UV-C or even infrared emissions that are sometimes useful for certain curing applications. With the wide variety of inks, coatings and adhesives having been formulated to take advantage of UV-LED curing, there are no substantive reasons that UV-LED curing systems will not continue to enjoy rapid growth in the marketplace.

Components and Comparisons

UV-LED curing lamp systems consist of multiple sub-components which taken together can be used to define

Table 1

UV-LED light source components

	Component	Purpose
I	LED	Solid-state component that generates UV light.
II	Array	Grouping of LEDs to maximize UV output to achieve desired curing rate.
III	Thermal Cooling	A properly designed thermal management system for the removal of heat generated by LED array to ensure low operating temperature and long life.
IV	Optics	The shaping, molding, reflecting and guiding of the UV-LED light to insure maximum light reaches the media.

the system's overall performance. The key design subcomponents are outlined in Table 1.

UV-LED Light Source Components

Examining these components in closer detail along with their interactions and interdependencies will provide the reader with a better understanding of how UV-LED curing lamps are not created equal.

I. LEDs—The Base Building Block

Let's start with the LED. As the base building block, this is the first choice a UV-LED lamp supplier has to make. It is a critical choice that impacts the remainder of the system's architecture and design. A pictorial example of an LED's construction is shown in Figure 1.

LED Construction

Simply put, an LED is a solid-state device that produces light when an electrical current is allowed to flow from the positive (anode) side of the circuit to the negative (cathode) side.

Not all LEDs are built the same nor do they exhibit the same characteristics. UV-LED lamp suppliers have critical choices to make as to the quality, type, material and shape of LED for their systems. Key LED characteristics considered by each UV-LED lamp supplier include wavelength and UV output.

Wavelength

The wavelength emitted from an LED is controlled using differing amounts of dopants such as aluminum, gallium or indium derivatives during the manufacture of the LED. The general rule of thumb is that the shorter the wavelength, the lower the peak UV output available from the die, as shown in Figure 2.

The UV-LED supplier must weigh the trade-offs between wavelength and the associated total energy with cure rate. Chemistry plays a significant role in this discussion. Some applications, due to their specific chemistry, require a given wavelength. However, for many applications a small shift in the peak wavelength will have little impact as the photoinitiator that kicks off the reaction has a broad absorption range. For example, as you can see in Figure 3, three-fourths of the LED energy output (with a peak at 385 nm versus a peak at 395 nm) share the same wavelength band. Material testing

Figure 1

LED construction

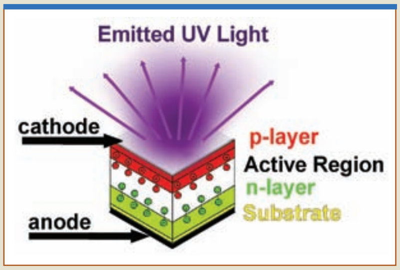


Figure 2

Wavelength characteristics

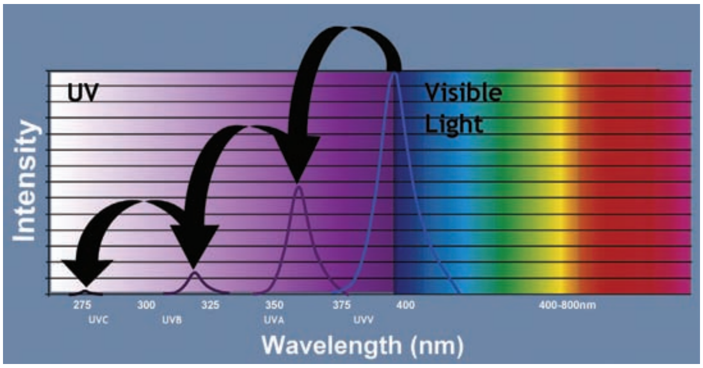


Figure 3

Wavelength comparison

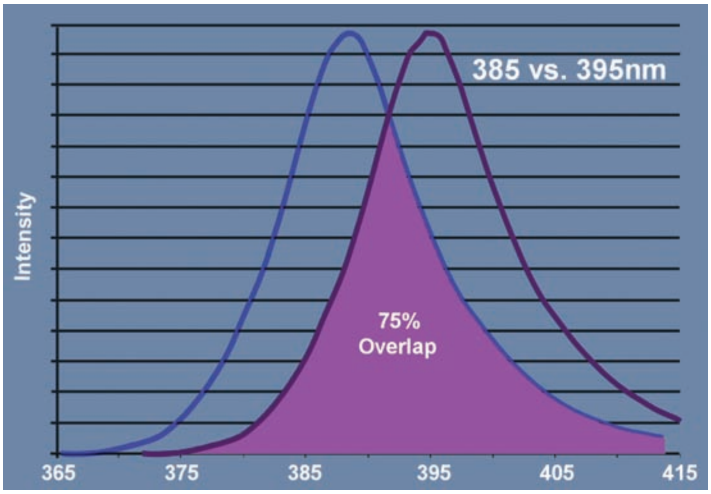
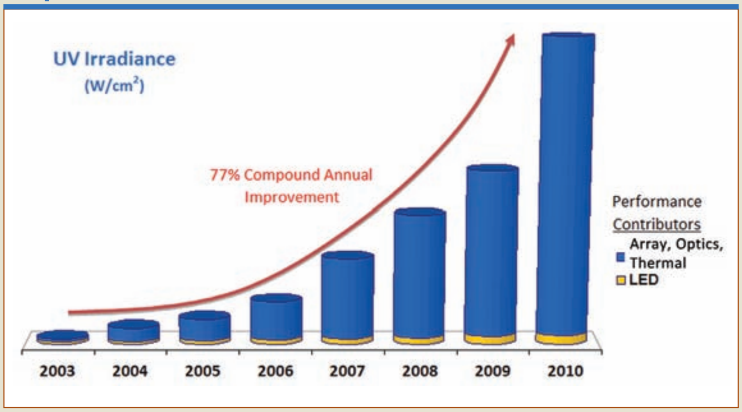


Figure 4

Contributing factors of peak irradiance improvement



confirms that the difference in either cure rate or quality when using die with peak outputs centered at 385 nm and 395 nm is negligible.

Therefore, UV suppliers will typically select the longer wavelength to achieve the highest UV output that allows for higher application throughput.

UV Output

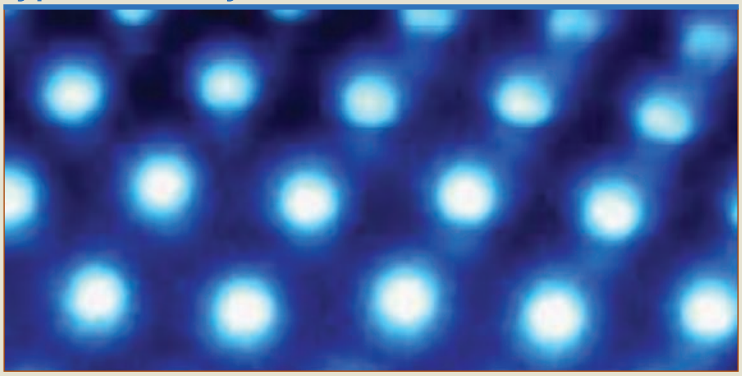
The output of a single UV-LED is measured in milliwatts (mW) at a nominal input voltage and current. UV-LED output has shown considerable improvement in recent years where specifications for LEDs from various vendors have improved from 2005 to 2011 with a compound annual growth of 5-10%. This improvement shows the LED vendors have and will continue to improve the output of UV-LEDs, which only provides a better foundation for the UV-LED curing lamps that utilize them.

While it would be tempting to jump to the conclusion that UV-LEDs are the single biggest contributor to UV-LED lamp performance, Figure 4 shows that UV-LED curing system suppliers have more opportunity to differentiate themselves in the areas that go beyond the base LED. A close examination of the LED performance, while contributing, was not the major factor in improved peak irradiance over time.

The other three factors (arrays, cooling and optics) significantly outweigh the increase in LED capability. This answers the question asked by UV-LED naysayers, "If all LED suppliers are eating from the same bowl, then won't all the products essentially be the same?" Therefore, let's continue examining the other components that make up the system.

Figure 5

Typical LED array



II. Array—Grouping of LEDs

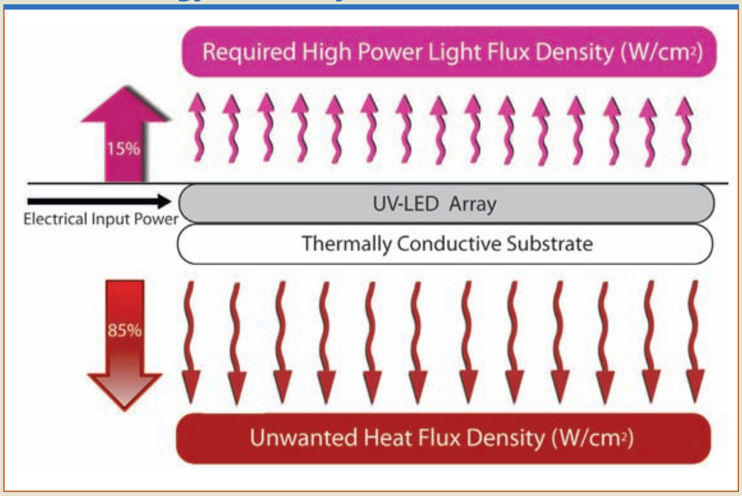
Arrays are the second area in which suppliers can begin to differentiate their product offerings. How the LEDs are combined; the number and type of LEDs chosen; the shape of the array; the method of electrically connecting the LEDs; and even the size of the LEDs all have significant impact on the performance of the system.

Most applications require UV-LED curing systems that consist of more than one LED or LED array in order to achieve not only the desired throughput but to meet the demands for curing applications where the media can be 1-2m wide. Therefore, a key question is "can the LED array be uniformly scaled?" UV-LED curing lamps can have a continuous scalable array that provides for better uniformity or a discrete array package that can be scaled, but doesn't provide the same uniformity of output. See Figure 5.

This is an area where UV-LED lamp suppliers can differentiate themselves based on the LED suppliers' architecture, modules and their own engineering capability where two suppliers can take the same batch of LEDs and achieve very different performance in the end product.

Figure 6

UV-LED energy efficiency



III. Thermals—Keeping it Cool

The third component is cooling. As any reader knows after using a notebook PC on their lap for a length of time, the byproduct of solid-state devices is heat. UV-LEDs transfer about 15-25% of the received electrical energy into light with the remaining 75-85% transferred as heat; thus, the need to cool the LED arrays. See Figure 6.

Currently, UV-LED arrays are cooled with either air or liquid. Table 2 lists a comparison of the two most common methods used for cooling LED arrays.

It is important to note that as the LEDs emit more light, they also generate more heat, which must be managed. Thus, in the race to build even higher irradiance products, the ability of suppliers to control and remove heat has become more crucial to building reliable systems. This is analogous to microprocessors where heat became a constraining factor (due to increasing gigahertz performance) by increasing the number of transistors while decreasing the trace width. Manufacturers eventually turned toward increasing the number of processing cores at lower clock speeds to stay within functioning thermal thresholds. UV-LED lamps face a similar challenge. As the quality of LEDs improves and the irradiance increases, so does the need to remove the heat. Original equipment manufacturers (OEMs) and end-users do not want to spend more on the cooling of the lamps than the lamps themselves. Thus, the third area of differentiation is in the cooling technologies and capabilities that suppliers choose.

IV. Optics—Guiding the Light

The final component and one of the most important differentiators is optics. The science/art of optically improving the LEDs to maximize their UV output is key to the lamp's final capability. Based on the end application, the optical engineer has to decide what shape, form and material best utilizes the LED's unique characteristics. Next, they have to balance the fact that LEDs are a "flood" type of light, unlike a focused mercury lamp where the light is captured by a reflector and directed to a specific-point focal length. See Figure 7.

The optical engineer is challenged to use methods to ensure the maximum amount of light "escapes" at the desired irradiance through the

Table 2

Air versus liquid-cooled light sources

Air-cooled	Liquid-cooled
Less expensive total UV light source solution.	More expensive due to need for external cooling source.
Lower irradiance levels as irradiance is directly proportional to ability to cool the LED array. Air is not as efficient at cooling.	Higher irradiance levels as water's thermal conductivity is higher than air's (0.6 vs 0.025 W/(m·K)), which means water cannot only absorb more heat, but can do it faster than air.
For given irradiance, larger lamp size due to fan size.	For given irradiance, UV source and cooling mechanism are separated allowing a smaller lamp size as no need for a fan.

window/glass toward the material. LED lamp suppliers have used various, confidential methods to maximize the UV-LED light. A high level summary of optics typically used by UV-LED suppliers with their pros and cons is shown in Table 3.

As shown, this is a small subset of the myriad of choices an UV-LED supplier has to make concerning the light distribution generated by their chosen LEDs, whether individual diodes or previously assembled. Hence, it is the third major area for differentiation among UV-LED suppliers.

Measuring the Differences Between UV-LED Curing Systems

Regardless of the LED, array, thermal and optics design employed, the end result that matters to end-users

Figure 7

Traditional mercury lamp optics versus LED optics

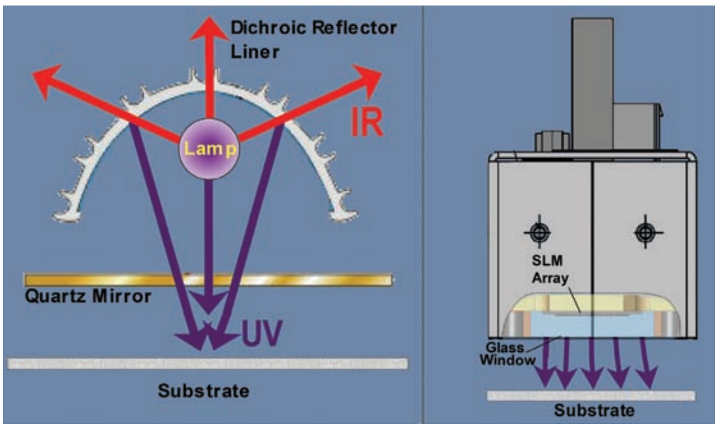


Table 3

UV-LED optical options

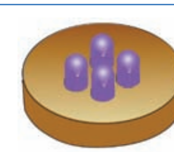
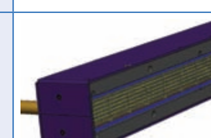
Optics	Pros	Cons	Example
Macro—LED array inside reflector optic	High peak irradiance over small area.	LED array cannot be scaled uniformly.	
Micro—Each packaged LED has an individual optic	Can be scaled uniformly.	LED-to-LED spacing and, therefore, maximum UV output limited by packaged LED size.	
Integrated Optic—Optic part of LED formation process	Increased optical efficiency.	Expensive and array is hard to scale uniformly.	
Directional optic	Increased peak irradiance over narrow band.	Optics configuration limits number of LEDs that can be configured in system, limiting total available UV output.	
Scalable micro optic	SLM module can be scaled uniformly while maintaining high peak irradiance.	Light is not focused and diverges over distance.	

Table 4

Peak irradiance versus energy density

	Peak Irradiance	Energy Density
Definition	Radiant power per-unit-area	Radiant power per area per unit time
Measurement	Watt per centimeter squared (W/cm^2)	Joules/cm^2 or mJoules/cm^2
Impacted by	Distance from material	Material speed Emitting window size

is that their material is properly cured. The two measurement parameters for this are peak irradiance and energy density (sometimes referred to as "dose"), and are outlined in Table 4. These two parameters work together and understanding their measurement method will allow OEMs and end-users to properly characterize the UV-LED curing system.

OEMs and end-users should consider two key questions when measuring UV-LED Lamp output:

1. Where is the peak irradiance specification point of reference?
2. Over what area is the peak irradiance being delivered?

Table 5 shows some of the typical measurement locations for measuring/specifying peak irradiance and the pros and cons of each approach.

Table 5

UV-LED measurement options

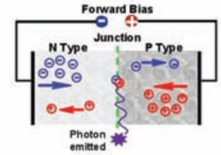
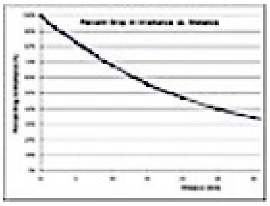
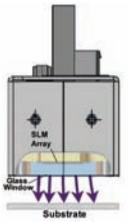
Usefulness	Location	Pros	Cons	Example
Poor	At the LED	Gives some indication of the base LED, but this is only a small component of the performance of a UV-LED curing system.	Cannot be measured. No practical application.	Photon emitted at Junction 
Better	At the media	Most relevant to end-user.	Each customer's operating distance can be different and, as noted above, the emitted UV light is divergent which means even though there is UV light, the measured peak changes with distance.	Irradiance vs. Distance 
Best	At the emitting window	Consistent metric regardless of application.	Where on the glass should the irradiance be measured? In the middle? At the edges? The corners? Average across various locations?	

Figure 8

Irradiance profile

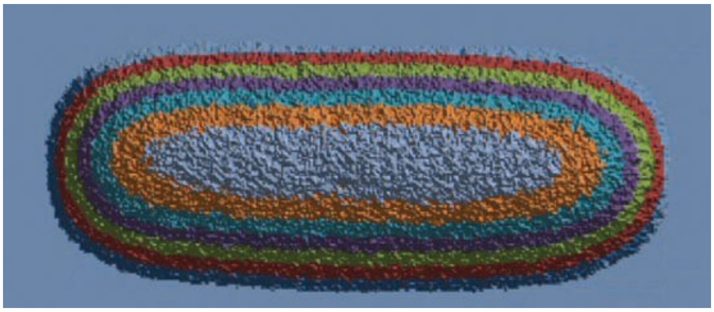
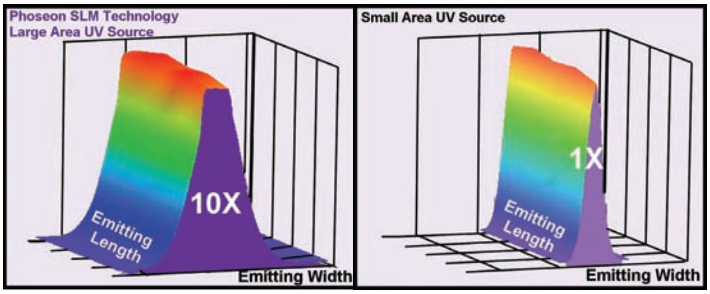


Figure 9

Uniformity along emitting width



OEMs or end-users could be misled by a single number that was taken along a single axis. Knowing the location of the measurement and how that measurement metric changes over the UV emission area will give the best overall characterization of the UV-LED curing system.

Figure 8 is a thermal image which depicts a UV emission area. The center is the maximum UV irradiance and as the emission "falls" off from the center the irradiance impacting the substrate decreases, which is shown as the series of concentric circles. Each color is a lower irradiance value.

The impact to the OEM or end-user is they may believe they have purchased a UV-LED system that delivers 4 W/cm^2 across the entire emission area when, in fact, only 2 W/cm^2 is delivered at the edges.

Figure 9 shows a 3D model of a wide area source and a narrow emitting source that have the same peak irradiance, but that deliver very different total energy to the material, which is the topic of the next section, energy density.

Energy Density

Energy density can be a very misunderstood concept and is also variously called density, dose or exposure. Energy density is the time integral of irradiance; thus, the higher the peak irradiance and/or the longer the exposure time, the higher the energy density. Consequently, even with the same lamp unit operating at the same peak irradiance and same distance, media exposed at different belt speeds do not receive the same energy density.

Conversely, even as the measured peak irradiance decreases with distance away from the media, if the media's exposure time remains the same, the measured dose remains the same. This decreased peak irradiance is due to the divergent nature of the LEDs.

Figure 10

Energy density versus height (same speed)

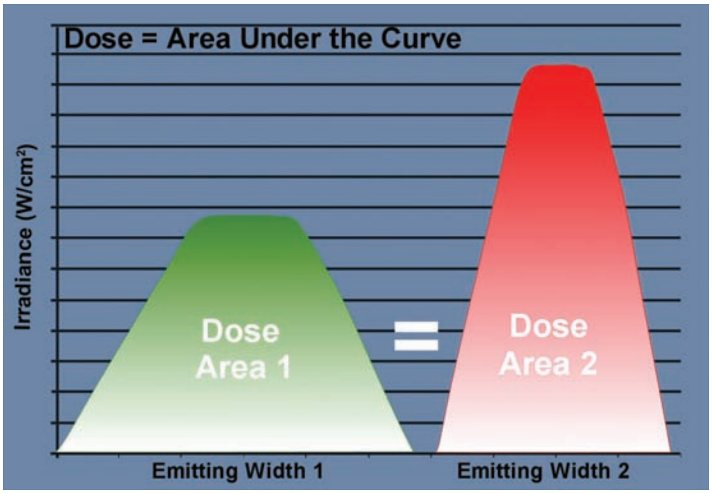
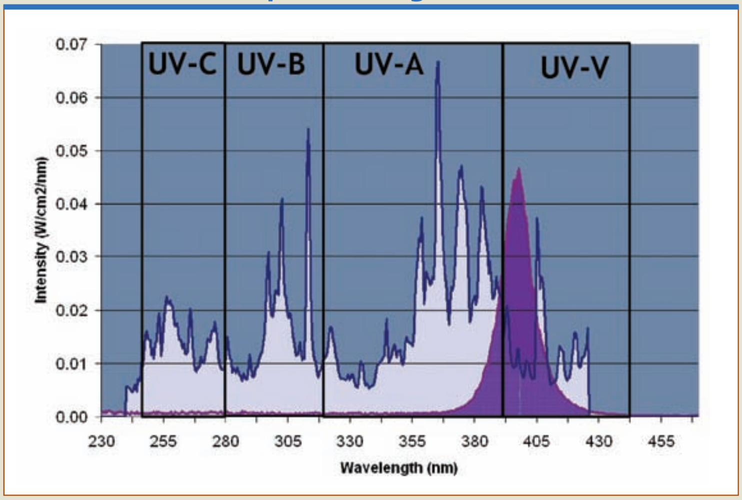


Figure 11

LED versus arc lamp wavelength



The light spreads out as the distance is increased, but the total amount of light delivered to the surface stays the same.

This is an important point. So said another way, for a given media speed, altering the height of the UV-LED light source from the media does not change the total amount of light delivered to the surface, but rather the peak irradiance decreases.

To show this graphically, see Figure 10. The red curve has a peak irradiance of 8 W/cm² while the green curve shows a peak irradiance of 5 W/cm². The key is that the area under the curve is equal. The peak irradiance is lower but the overall energy density remains the same.

The quickest way for an OEM to improve the speed of their machines is to either (1) utilize UV-LED lamps with higher peak irradiance or (2) utilize UV-LED lamps with larger arrays. Either of these will deliver more total energy density to the curing surface, and allow faster cure speeds.

Measuring Irradiance and Energy Density

Lastly, what device should be used to measure UV-LED lamp output?

There are several manufacturers that provide products to measure irradiance. Most of these were converted from mercury lamp measurement devices and have not fully comprehended the unique LED characteristics. The sensors used in radiometers have been characterized and calibrated to work with the output profiles of mercury lamps (Figure 11). Since UV-LEDs have a very different output profile, the sensor calibration for a given wavelength band is the most important characteristic. A radiometer that crops or doesn't count all of the UV emission based on a normal LED wavelength tolerance can lead to measurement errors and should therefore not be used to set irradiance and dose specifications.

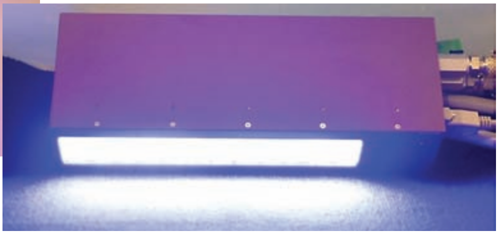
The spectral characteristics of UV-LED lamps are significantly different than traditional systems and UV meters are just coming onto the market that will accurately measure UV-LED lamps.

Even then, radiometers need to be calibrated for specific LED characteristics of the lamp manufacturers. A "generic" UV-LED radiometer that can be used between different UV-LED lamps does not currently exist. For process control, it is important for OEMs and end-users to utilize a UV-LED radiometer that is calibrated to the UV-LED lamp provider's specifications. Otherwise, false readings and/or improper conclusions are the likely results.

As shown, measuring irradiance and energy density is not a simple task. The authors believe the industry, including UV-LED lamp manufacturers, measurement device manufacturers, OEMs and end-users should align around a single industry standard that can be used to consistently, accurately and succinctly report irradiance and energy density measurements.

Result: UV-LED Lamps Aren't Created Equal

UV-LED lamps are not created equal. Suppliers of UV-LED lamps have significant architectural and implementation decisions that significantly impact their product's performance. The end result will be a UV-LED curing system with optimized LEDs, arrays, optics and cooling for a specific application. Knowing how to



Different types of UV-LED lamps.

characterize the performance allows the user to identify the best overall system to meet their specific needs. OEMs and end-users would be wise to learn these differences and ensure their chosen suppliers are capable of not only meeting their needs today, but have the technical ability to design, manufacture and support their needs in the future.

This article has attempted to build on previous work by highlighting the myriad of architectural and design trade-offs UV-LED lamp makers have at their disposal. More importantly, OEM and end-users considering the transition from mercury tubes to solid-state UV-LED technology must understand that (1) UV-LED isn't for every application and (2) not all UV-LED lamp systems are created equal. It is vitally important they consider the needs of their application as well as the capabilities of their supplier. Lastly, the authors believe the UV-LED industry must band together to create industry standards and capabilities that simplify OEM's transition to a bright UV-LED future.

—Sara Jennings, Bonnie Larson and Chad Taggard are part of the marketing team at Phoseon Technology in Portland, Ore.

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Measuring the Output of Ultraviolet Light Emitting Diodes

By Jim Raymont and Abhinav Kashyap

This article is based on a submitted paper and presentation delivered at the RadTech 2010 Conference in Baltimore, Md.

Multiple articles and papers are available that discuss the construction, advantages and disadvantages of Ultraviolet (UV) Light Emitting Diodes (LEDs) sources. This article will focus on understanding and measuring the output of UV-LEDs.

Medium-pressure UV lamps (microwave and arc) emit radiation across a broad electromagnetic spectrum. Output from these types of sources includes UV, visible and infrared (IR) energy.

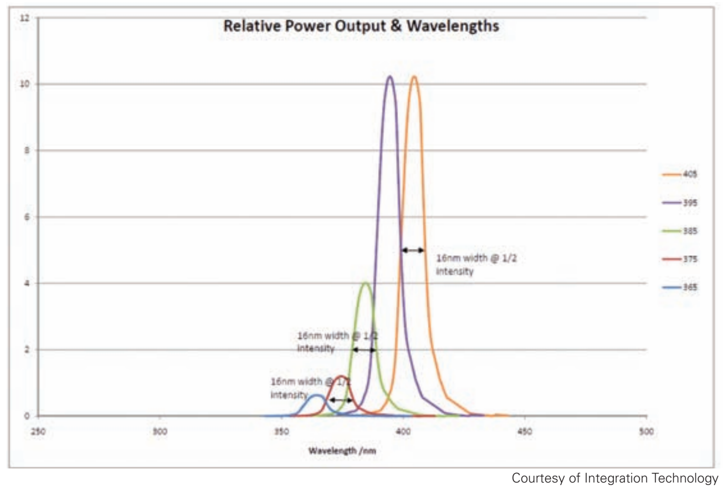
UV-LEDs are narrow band sources. Production UV-LED sources have their spectral emissions somewhere in the 365 to 405-plus nm region. UV-LEDs are described and identified by their most dominant (395 nm, etc.) spectral output. If measured with a spectral radiometer, the user would see that the manufacturer has binned the individual LED chips so that the most intense UV output is clustered around the dominant name line (i.e., 395 nm if the source is a 395 nm source). It would be very expensive to only use 395 nm LED chips in this example and, in reality, it is common for the actual spectral emission of a UV-LED to extend plus/minus 8-15 nm in either direction at the half-maximum power point from the maximum.

Autobond inkjet spot varnish system with UV-LED curing.

Courtesy of Autobond Ltd.

Figure 1

Relative UV-LED output for various wavelengths



Courtesy of Integration Technology

Measuring and characterizing LEDs requires an understanding of your UV source and UV measurement instrument. Instruments used to measure broadband, medium-pressure UV microwave or arc lamps may or may not be suitable for use with UV-LED sources.

UV LED Output Power—Déjà Vu All Over Again?

UV-LED sources continue to increase in power. The output of UV-LEDs has gone from milliWatts/cm^2 of irradiance to Watts/cm^2 of irradiance, with some systems going over or in the neighborhood of 10W/cm^2.

Output irradiance is usually one of the first numbers an LED manufacturer will share with you. Do the discussions (and claims) of increased output from UV-LEDs sound similar to discussions on computer processor speeds, computer memory sizes or the number of megapixels from a digital camera?

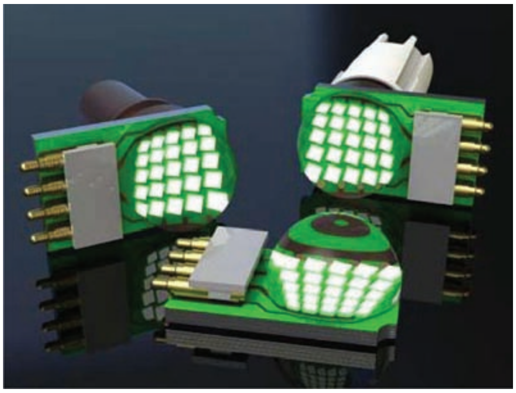
A little closer to our UV world, do the discussions (and claims) sound similar to discussions (and claims) that were held in the ’70s and ’80s with traditional UV-arc lamps? In the ’70s and ’80s, a lamp with more “applied electrical power” certainly “had” to be better than a lamp with less applied electrical power. A system with 400 watts/inch of applied electrical power was certainly better than a system with only 200 watts/inch of applied power. Which company would be the first to reach 600 watts/inch of applied power? 800? 1,000?

Many were quick to realize that comparing the power applied to the lamp is not as meaningful a measure in the curing process as measuring the amount of useful UV energy delivered to the product. Sometimes, for design and engineering reasons, a UV source with higher applied electrical power actually delivered less usable UV.

As discovered with arc lamps, increasing the applied power or amount of UV delivered to the cure surface was not always beneficial to the cure process or substrate. For each application, a balance needed to be found between the amount of UV and other types of radiation (visible, IR) produced, along with the formulation, substrate, application, needed processing speed and desired results. This balance or “process window” also needs to be found with applications using UV generated from LED sources.

With traditional UV sources, it is important to understand, document and maintain your UV system. This includes bulb type (mercury, mercury-iron, mercury-gallium); how the system is set up (focused, non-focused, additional equipment such as quartz plates); and the irradiance (W/cm^2) and energy density (J/cm^2) values expected.

It is also important to understand, document and maintain your UV-LED system. The spectral output of LEDs is described in nanometers (nm) such as 395 nm. The actual plus/minus range of the spectral output of the

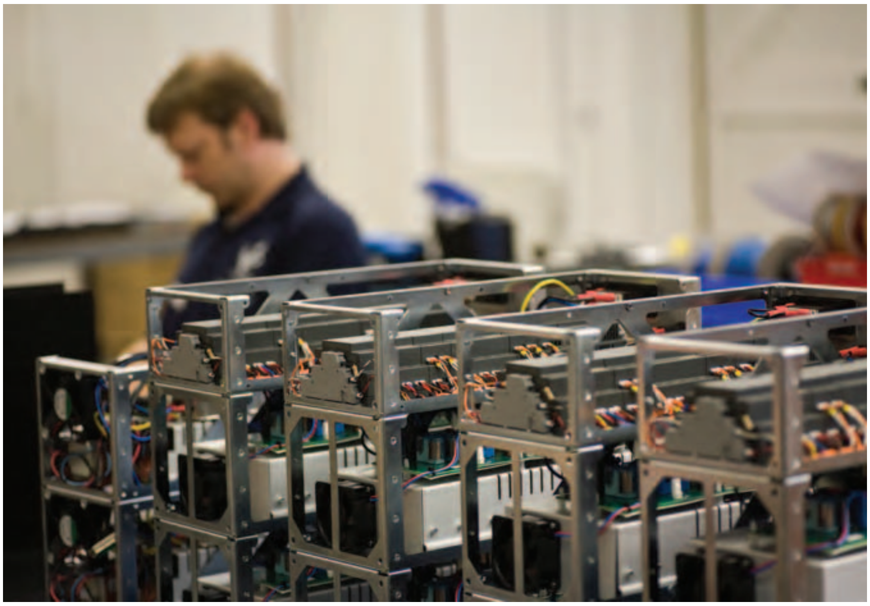


Courtesy of Integration Techonology

UV-LED modules.

Courtesy of Integration Techonology

LEDZero Solidcure™ assembled modules.



Power supplies being assembled for a UV system.

LED will vary from manufacturer to manufacturer.

UV-LEDs are being packaged in a wide range of shapes and sizes—from large discrete devices to hundreds of nearly microscopic individual LED dies arranged into powerful arrays. Manufacturers of UV-LED sources use a variety of techniques to assemble, direct and deliver the UV energy to the cure surface from the actual LED "chip" or "die." Manufacturers have proprietary processes to "bin" LEDS by their spectral output, forward voltage and intensity.

Many UV-LED systems were developed for a specific application and fit into areas that will not support other types of UV technologies. Manufacturers are concerned with keeping the array stable over time. Ask questions and evaluate the equipment carefully. In the "more is better" approach, manufacturers of LED systems may use different techniques to determine the power rating of their systems. The techniques can include theoretical calculations of the output and measurement of the UV at different points. Some manufacturers may measure the output at the chip surface while others measure at the cure surface. Ask questions and evaluate the equipment carefully; making apples-to-apples comparisons.

The Lab-to-Production Transition Is Work

How a specific UV-LED system performs for your application is more important than the maximum power output number on a sheet of product literature. Do you get the results that you are looking for at the manufacturing speed that you need for production?

There has been impressive progress made in the development of coatings that are specifically formulated to work with LED systems. Because LEDs are relatively monochromatic, they lack the shorter UV-C wavelengths that are traditionally used to establish surface cure properties such as tack, scratch, stain and chemical resistance. This is not the show limiter/stopper that it once was and you need to work with both your formulator and the LED supplier to achieve the properties desired in the final cured product.

You do not get a free "go directly to production manufacturing" pass when working with LEDs. The laws of physics and photochemistry do not cease to exist when you use LEDs. They are present and lurking but can be minimized by taking some precautions:

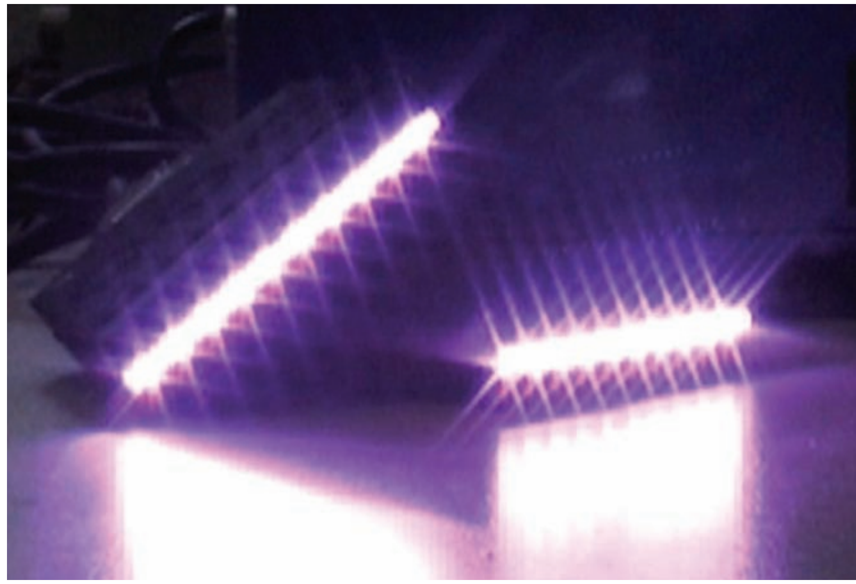
- During process design and testing, establish how you are going to measure the UV output of the LED.
- Define the key process variables that need to be monitored and controlled in production.
- Establish your process window in the lab and carry it over to production.
- Exercise caution when you communicate radiometric values either within your company or to your supply chain.
- Specify the process you used to obtain the readings and the instrument/bandwidth used.
- Determine how often you need to take readings based on your process.
- While it is true that LEDs will last longer than many other types of UV sources, be aware of anything in the process between the LEDs and the cure surface that could change and alter the amount of UV delivered to the cure surface.

Absolute values established during the design phase often become relative readings during day-to-day production. With relative readings, you are looking for day-to-day or week-to-week changes and working to make sure that the UV levels stay within the process window established during process design and testing.

Measurement of UV-Arc and Microwave Sources

Radiometers used for measurement of UV-arc and microwave sources have bandwidths (UV-A, UV-B, UV-C, and UV-V) that match the broadband arc and microwave sources. Instrument bandwidths vary from manufacturer to manufacturer. Some instruments have "narrow" bands (UV-A classified between 320-390 nm) while others have "wide" bands (UV-A classified between 250-415 nm). Because of these differences, it is important to specify the instrument used to obtain the reading.

What happens if you use these popular radiometers to measure the output of an LED source? Will you get a reading with one of the radiometer bandwidths above with a UV-LED? It depends on the type of UV-LED and the bandwidth(s) of the instrument. Just because there are values on the instrument display does not mean that the UV-LED has been properly characterized.



Courtesy of Integration Techonology

UV-LED arrays.

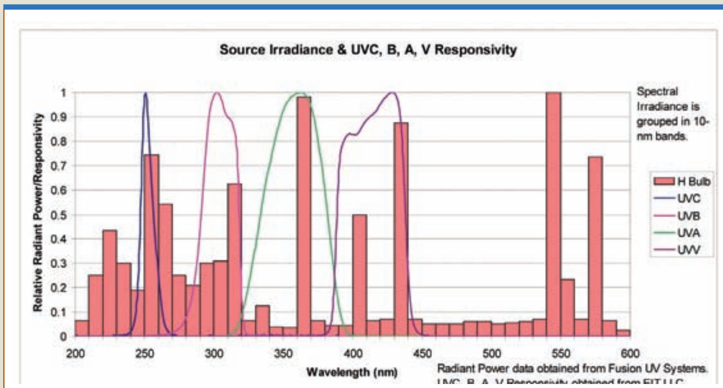
LED Intensity Measurement and Challenges

The same challenges that exist for measuring visible LEDs also exist for measuring UV-LEDs. The light emission from an LED is vastly different than a point source. This poses challenges in quantifying its intensity. Limitations in standardizing the measuring techniques of LEDs include:

- A point source, by definition, has a constant radiant flux in all directions but LEDs do not follow equal radiant flux rule. This is because most of the LEDs have micro-optics built into the LED packaging.
- LEDs do not follow the inverse square law (i.e., intensity of light reduces by square of the distance) similar to extended sources. That means that even for the same solid angle, intensity measurements could vary with distance and could be unpredictable.

Figure 2

Spectral output of H bulb and spectral response of different UV bands of radiometer



There has been an incredible amount of research done in recent years at various public and private organizations for developing measurement techniques. Due to several variances affecting intensity measurement of an LED, the Commission on Illumination (CIE) established a standard method guide for LED measurement document (CIE 127:1997).

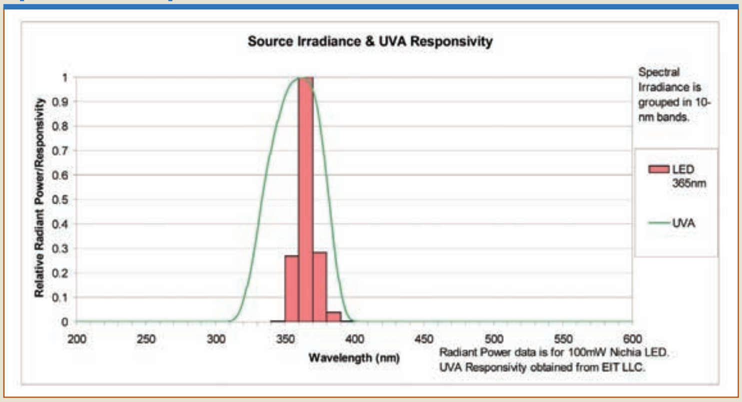
> **RadTech UV Glossary Definition:**
> **Flux (radiant flux):** The flow of photons, in einstein/second; one einstein = one mole of photons.

One of the most popular ways of measuring radiant flux for an LED is using a photometer at a specified distance and specified area recommended by the CIE. Individual LEDs may be characterized this way under controlled laboratory conditions, but the recommended procedure cannot be easily applied to LED clusters and arrays (the arrangement of UV-LEDs used for UV production curing applications).

In order to measure total radiant flux, an integrating sphere is used. CIE 127:1997 describes the placement of an

Figure 3

Spectral output of 365 nm LED source and EIT UV-A spectral response



LED in a calibrated integrating sphere and measuring total radiant flux. When performing a measurement using an integrating sphere, the intention is to capture all energy.

In real-world applications, the user might be more interested in capturing the LED radiant flux for a small solid angle that is also sometimes referred to as "useful radiant flux." In order to make this measurement, the CIE updated their guidelines in the recently published CIE 127:2007 document to include the term "partial" radiant flux.

Traditionally, intensity measurements of a point source are done using luminous intensity. As described earlier, most LEDs are not point source and do not follow the inverse square law. LED intensity measurements claimed by a manufacturer could vary when the end-user performs a similar measurement. When performing a measurement, it is always important to know conditions and uncertainties associated with the measurement. Sources of uncertainties that can contribute to the uncertainty of the measurement include:

- Radiometer calibration uncertainties
- LED short-term wavelength drift
- LED temperature drift
- DC current regulation for LED
- Optical alignment

Industrial applications and setups make it more challenging to easily control and measure the above parameters.

As stated, LEDs have a narrow band emission and, hence, could have short-term or long-term wavelength drifts due to temperature variations or degradation over a period of time. Most integrating type radiometers were originally designed for UV-arc and microwave sources, and have a bell-shaped response curve across the UV band of interest.

365 nm LED

Using a radiometer designed for arc and microwave sources can lead to large errors in measurement if UV-LED output happens to fall on the rising or falling edge of the optical stack response. Figure 3 shows a 365 nm (UV-A) LED source and EIT's UV-A response. The responses have been normalized. If the LED is binned very close to 365 nm, the EIT UV-A response does a good job of measuring this source.

But even a small drift in the LED spectral output or variations in how the LED dies are binned can generate different responses in the radiometer, which can have a pronounced impact on the measurement.

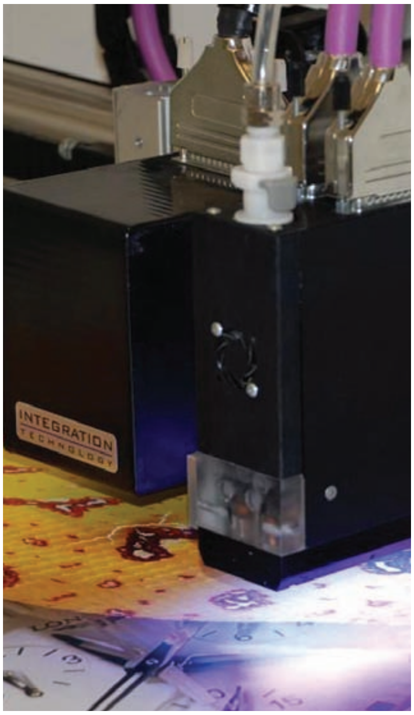
395 nm LED

Measuring the output of a 395 nm LED with a radiometer utilizing an EIT UV-A or EIT UV-V response can lead to wide variations in the reported irradiance values.

The output of a 395 nm source is grouped "around the 395 nm line" with variations based on how individual LED dies are binned; how the array is assembled; and the stability of the product over time. These slight variations are normal. It is also normal to expect slight variations in each radiometer due to slight variations in the optical components (filters, detectors, etc.) and electronics.

In Figure 4, the output from a 395 nm LED clearly falls between the EIT UV-A and EIT UV-V response curves.

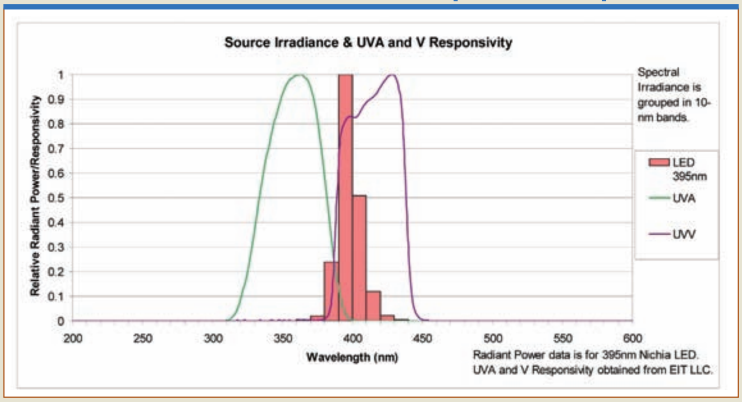
Courtesy of Integration Technology



UV-LEDs used in UV coating.

Figure 4

Spectral output of a 395 nm LED source and EIT UV-A and EIT UV-V radiometer spectral response



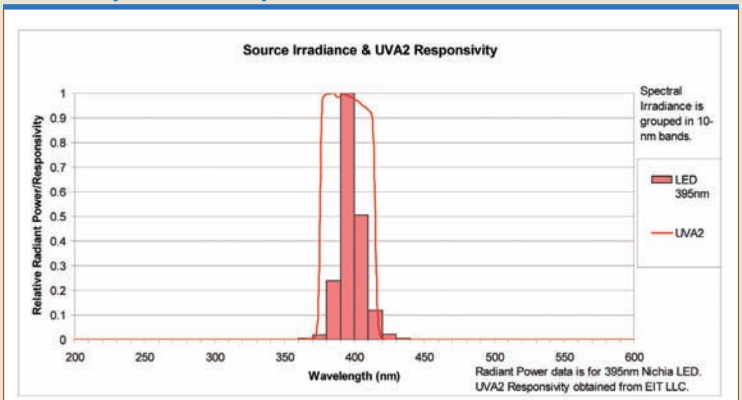
The steepest part of the shoulder of each optical response curve is in the output range of the 395 nm LED. So, while it is possible to get a reading with a UV-A or UV-V bandwidth radiometer, the sharp cutoff at this wavelength means that the readings may reflect only 5-50% of the actual 395 nm LED. The large variation can result from the output being on the steep slope of the response curve, variations between measuring instruments and variations between the LEDs themselves. Because of these variables and their combinations, it is hard to apply a correction "factor" to the UV-A reading or UV-V readings to any single instrument.

A better approach to measuring LEDs in the 395 nm range is to use an instrument with a response curve that better matches the source. EIT has developed a subset of our 320-390 nm UV-A bandwidth now designated as UV-A2 (Figure 5). The UV-A2 response curve is especially sensitive in the 380-410 nm regions. This region better covers the 395 nm LED since under normal conditions the source does not fall on the steep shoulder of the response curve. Extensive testing was done to get the UV-A2 radiometer optical response to proximate a "flat top" response. A "flat top" response limits the shifts in the measured values due to slight spectral variations in the source.

The UV-A2 response bandwidth inherits a Lambertian spatial response by design from early generation radiometers that further reduces measurement errors due to LED alignment.

Figure 5

Spectral output of a 395 nm LED source and EIT UV-A2 spectral response



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The UV-LED Paradigm Shift

By Paul Mills and Jim Raymont

On the game show *Jeopardy!*, the program turns the tables on contestants by presenting them with an answer and challenging them to come up with the right question. Sometimes it seems that the UV-LED market is engaged in its own version of *Jeopardy!* There are plenty of good answers—if we can only figure out what are the right questions.

With the game show, only the host starts the dialog with the answer. In the UV-LED world, there could be 25-plus UV-LED source/array integrators asking questions along with formulators, machine integrators and customers.

Some of the questions that seem important to guiding the discussion on proper LED measurement are:

- What are the wavelengths of the UV sources?
- What is their expected dynamic range?
- How fast should an instrument sample?
- Where is the right place to measure the LED?

From a measurement perspective, it feels like the clock has been turned back to the late 1980s or early 1990s. It feels as if we are answering many of the same questions for UV-LED users that we have answered for arc or microwave users. In the established world of mercury-based lamps these questions have long been settled and products have evolved based on broad industry consensus. You press a button and the instrument provides "a value." The user of the instrument still needs to understand what the value means and whether or not it is the "correct" value.

Care needs to be exercised when communicating. Differences between different brands of radiometers or instrument types with different features and responses can lead to different answers. Instruments have evolved over the years and their combination of electronics, optics and software are designed to provide solutions to the challenges of cosine response; the nature of the mercury spectrum; and the predictable effects of parabolic and elliptical reflectors.

If it seems as if mercury lamp suppliers and UV-LED manufacturers are sometimes speaking two different languages—that's because they are. The advent of UV-LEDs has resulted in a paradigm shift. This shift doesn't just require a new language, it also shatters some of the conventional wisdom and time-honored approaches to UV measurement. Developing a new prescription for how to measure LEDs has been made more difficult by the moving target nature of a solid-state technology that continues to morph and obsolete itself at a rapid pace.

The goal of this article is to suggest a number of important, but as yet unresolved questions that are fundamental to measuring UV-LED performance. The answers to these questions will determine if current measurement solutions will work; need to be modified; or if a new class of UV-measurement devices will best address the needs of its users.

What is the Spectral Output of a UV-LED Light Source?

Any device that measures a source of irradiation—whether it's visible light, Infrared (IR) or ultraviolet—requires a sensor that is sensitive to that portion of the spectrum under test. These detectors must accurately convert small changes in the incoming energy into corresponding changes in electrical energy while discriminating against wavelengths outside the band of interest.

For example, suppose that you are a camera buff who wants to accurately measure light so you can take proper photos. Your goal is to design a very accurate and sensitive photographic light meter. Since you might photograph under a range of different light sources (i.e., tungsten, fluorescent, sodium vapor, sunlight and candlelight), you need an instrument that measures across a wide band of light sources.

The sources generally emit light in a range of about 380 nanometers (violet) up to about 740 nanometers (red). In designing your light meter, you come across a light sensor that uses a popular photodiode. It's affordable, the right size and the manufacturer provides a chart that shows its optical characteristics. Figure 1 is, in fact, a fairly representative optical response for many popular photoelectric diodes. Note that the detector's response curve is pretty close to linear in the visible portion of the spectrum (see inset). Though the response curve is not "flat" in the 380-740 nm band, it's known and predictable. Through some clever engineering and using a combination of mechanical (optical) components and electronic circuitry, you can build a light meter that provides you with reliable measurements.

Suppose one day you decide that you want to start doing IR photography instead. This involves working with sources in the 750-950 nm IR range. There's a problem with your old light meter. Measuring 900 nm with a detector, filters and circuitry engineered for visible light causes

Figure 1

Optical response of a typical photodiode sensor

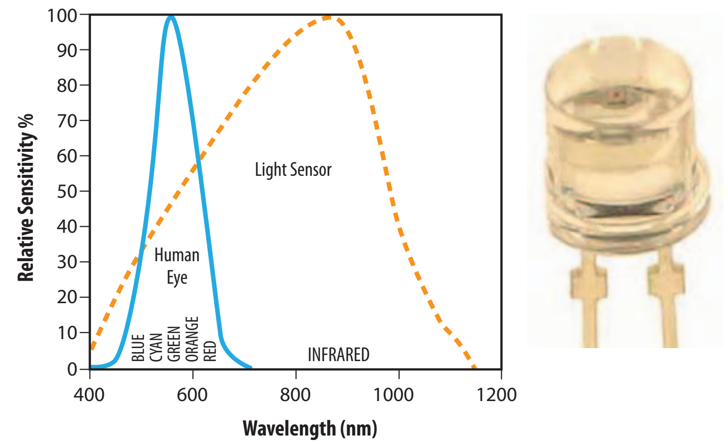


Figure 2

Typical bandpass filters used across the UV spectrum

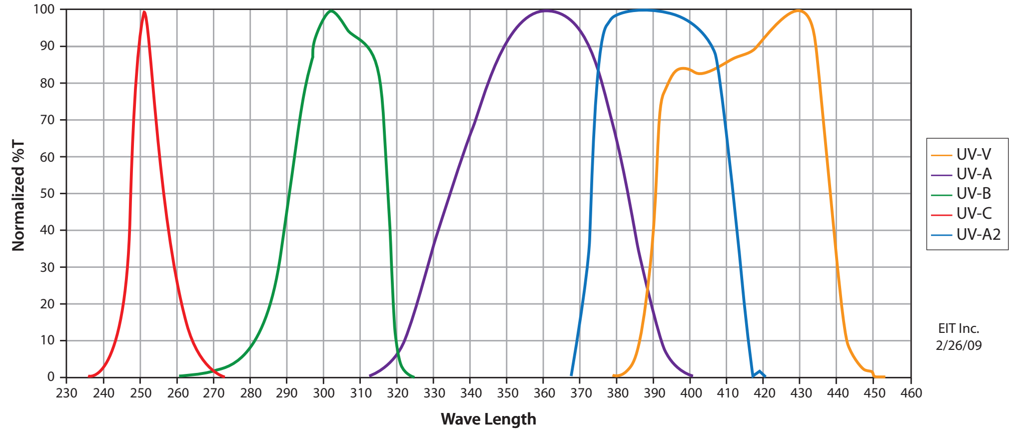
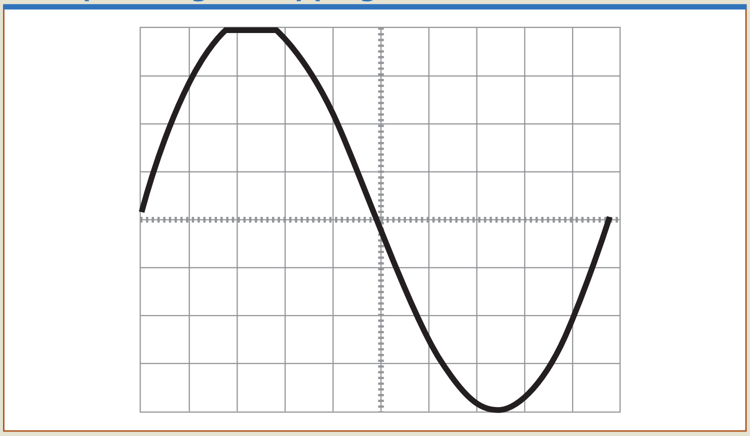


Figure 3

Example of signal clipping



some measurement problems when used with infrared. It produces a reading, but the reading is likely to be misleading since the instrument is intended for a different range of light sources.

That's the UV measurement problem with LEDs. The existing instruments were designed for light sources that are in a different spectral region. They produce a reading, but the reading can be misleading when used with new LED light sources. The chart in Figure 2 shows the bandwidth configurations developed over many years for arc and microwave-type lamps. You can see that a 395 nm LED would fall to the high side of the UV-A band and the lower edge of the UV-V band.

The solution has been to engineer a device optimized for 395 nm and the answer was a new combination of optics, detector and circuitry dubbed UV-A2. The chart in Figure 2 illustrates how the UV-A2 band satisfies the need for a better (more linear) response in the long wavelength LED market.

But there is still much uncertainty about what wavelength for the LEDs will emerge from the chip manufacturers; whether a new bandwidth will be required; or which broad range detector will emerge as the best solution.

What is the Anticipated Power Output of a UV-LED?

The minimum and maximum expected amplitude of an incoming signal is an important determinant for designing a measuring device. It must be sensitive enough to measure the weakest signal and of sufficient dynamic range to accommodate the strongest signal. UV-LED output has increased steadily from only a couple of hundred milliwatts per square centimeter a few years ago to more than 10W per square centimeter today (and twice that much in the current development labs). This poses a problem for existing radiometers.

Most conventional radiometers were intended to measure light sources up to about 10W per square centimeter. Though most users mistakenly regard LEDs as less powerful sources than arc or microwave lamps, their intensity in a narrow-band region is very potent. The latest generation of LEDs challenges the dynamic range of existing instruments. You may be familiar with clipping in audio applications where loud peaks are artificially attenuated by amplifiers. The result of trying to measure with a device that has inadequate dynamic range is "clipping" that results from overpowering the device. Clipping produces a lower irradiance measurement than the LED may be generating. See Figure 3.

To design a proper UV-measurement instrument, engineers need to anticipate the appropriate dynamic range of the source. In a market environment where the light source output power doubles every couple of years, this is an engineering challenge.

Figure 4

Cosine effect on UV irradiance

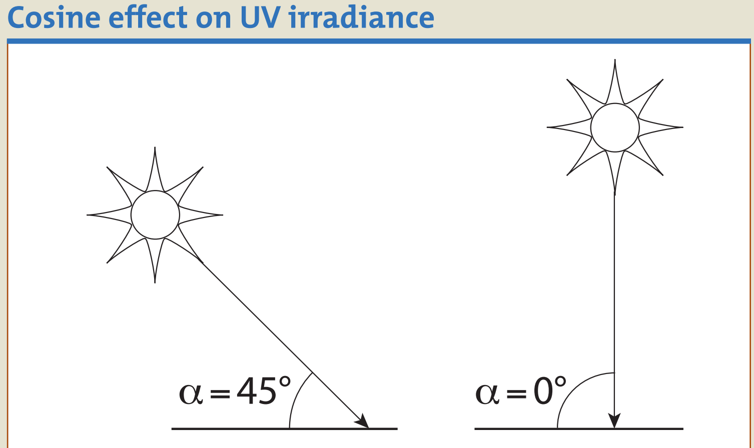
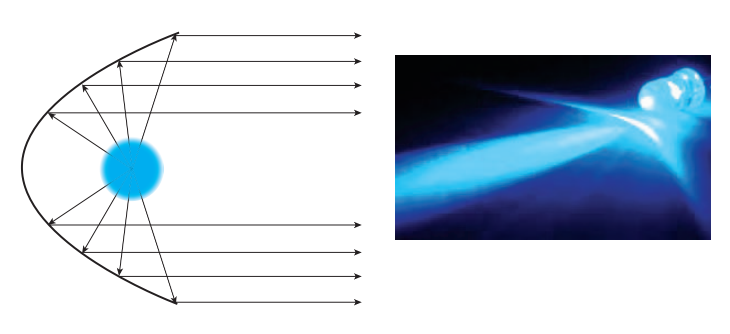


Figure 5

The optical footprint: traditional lamp vs. LED



Still, it's important to not become so caught up in the numbers that we miss what's really important—which is how the chemistry reacts. As long as there is adequate irradiance and energy density to fully cure the material in the process time desired, anything else is really just excess energy.

Where do you Measure an LED?

If the UV light that emanates from a source were uniform everywhere, it would be much simpler to measure—but this is not the case. UV intensity falls off the farther distance it is away from the light source. In fact, the fundamental principle is that "if a point source radiates light uniformly in all directions through a nonabsorptive medium, then the irradiance decreases in proportion to the square of the distance from the object." But that is a big "if" since real-world UV-LEDs are neither point sources nor do they operate in a nonabsorptive medium.

Traditional UV lamps are not always single-point sources either. UV light from a lamp strikes the radiometer's detector from many angles as shown in the Figure 4 diagram. Light from directly above the radiometer produces a different reading than light coming from a slight angle. This causes an error referred to as cosine error. In order to properly measure the light coming from various angles, the instrument must correct for the effect of the angle between the detector and light source.

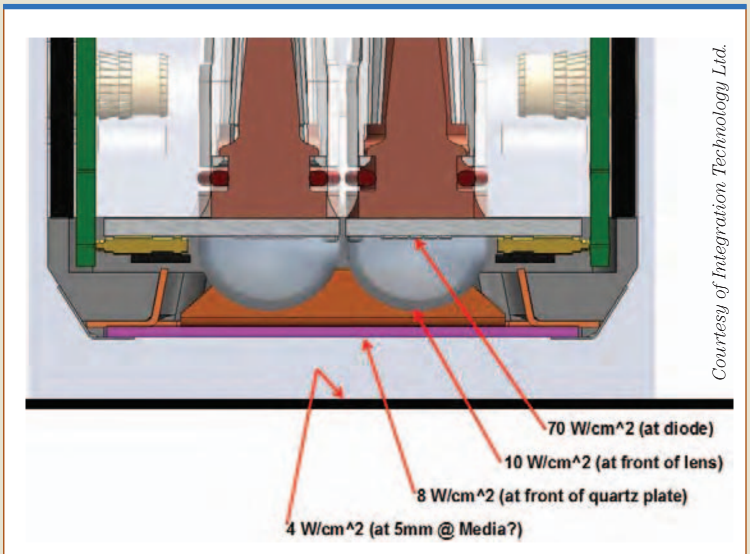
The angular cosine correction is achieved by tinkering with the response of the detector and optical components such as a diffuser. A perfect detector and diffuser combination has an angular cosine correction of unity, regardless of the angle of incidence. For existing instruments, the optical components are designed to achieve or replicate a cosine response in the instrument. This response is not always able to distinguish tightly packed UV-LEDs.

A second complication in the geometry of measurement is that those tiny LEDs do not radiate light uniformly in all directions, especially compared to traditional lamps with reflectors (Figure 5). The optical characteristics of current LED sources make it more challenging to decide where to best measure their UV output.

Recently, the LED lamp manufacturers have begun to develop optical components that can alter the output of their arrays again, sometimes with the goal of producing a higher irradiance specification. When comparing manufacturer specifications, be aware that there is no agreement, let alone industry standards, for reporting UV-LED measurements. As the illustration in Figure 6 shows, this can make it difficult to compare the

Figure 6

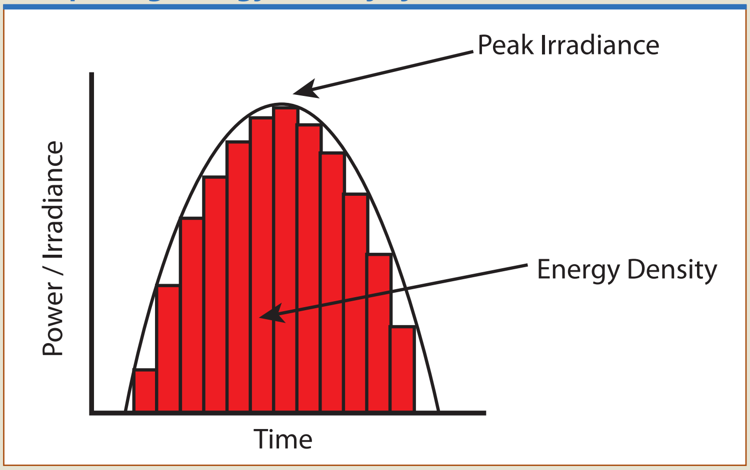
The "Where Do I Measure?" dilemma



Courtesy of Integration Technology Ltd.

FIGURE 7

Computing energy density (joules)



manufacturer's specifications without knowing much more about how the measurement was taken. Measurements made even a couple of centimeters apart can be dramatically different.

It's likely that the question of where to measure—such as always "at the glass"—can be answered without difficulty. But if various manufacturers continue to develop LED sources which focus their power further out from the LED array, they may be understandably reluctant to accept this method since these arrays will be intentionally designed to provide even greater irradiance at another, somewhat further distance. The question of where to make a standardized measurement of LEDs may, therefore, remain understandably unresolved as competing ideas about their optical characteristics are sorted out.

How do Sampling Rates Affect Irradiance and Energy Density Calculations?

For thermal processes such as curing paints and baking cookies, two key parameters are vital—temperature and time. Proper results depend on both measures. Successful UV curing relies on two similar measures—irradiance (a measure of UV intensity) and time. Without sufficient time, UV curing may be incomplete and the result compromised. In fact, the combination of irradiance and time is so important that a measure known as energy density (sometimes referred to as "dose") is almost always provided when specifying a UV-cure process.

(Note: It is important to stress that an energy-density value by itself is not enough to properly define a cure specification. From a UV-source standpoint, the irradiance value; type of spectral output; and the absence/presence of infrared all contribute to the cure process for a specific application. Parameters such as the coating thickness also need to be specified.)

In a mathematical sense, energy density can be thought of as the area under a curve that measures irradiance over time. See Figure 7.

You might remember from math class that finding the area under a curve is called integration, and that one technique to find this area is to break the area up into narrow rectangles and then add them all together. Obviously, the narrower the rectangles, the more precisely the area can be measured without missing the peak irradiance value. This is how many radiometers (originally dubbed "integrating radiometers") measure energy density.

The instrument takes many irradiance (sample) measurements every second, and then adds the values together. The push has been to faster and faster sampling rates in order to achieve high resolution and accurate irradiance calculations that can lead to more consistent energy-density calculations. The more samples that are taken over time, the "narrower the rectangles," so to speak. Today's radiometers sample hundreds (even thousands) of times per second.

But what happens when you are trying to measure something that's also changing at the same time? Some LED electronic control systems use a scheme called Pulse Width Modulation (PWM). With PWM, the supply voltage is turned on and off rapidly to alter the output of the light source as illustrated in Figure 8. The strobing of the LED is normally so rapid that it's invisible to the eye and, for many curing processes, it works perfectly well.

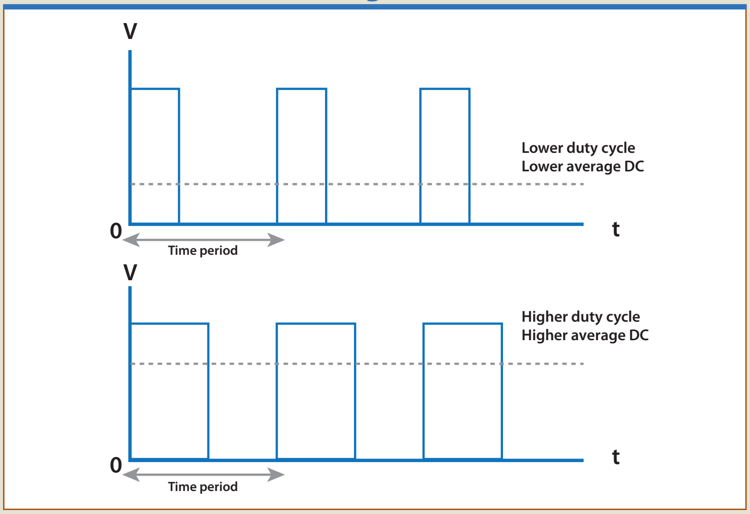
While PWM may allow the manufacturer to vary the output power of the array, turning the light source off and on very rapidly can create a challenge when taking samples at the same time. It can be like trying to take photos of a spinning fan blade—it's hit-or-miss. The sample energy-density readings may not accurately reflect the true measure and, depending on the algorithm used to used to calculate the irradiance and energy density, it may be higher or lower than the true values.

What are the Right Questions?

The preceding questions address important technical matters. The

Figure 8

Pulse width modulated signal



answers affect the design of radiometers intended for measuring UV-LED performance. But they do not address all of the unresolved issues. Many of the existing UV instruments were designed with popular applications in mind. The versatile Power Puck®, for instance, is well-suited for use on industrial conveyorized systems. But the Palm Probe® was designed to reach into recesses and areas where a Power Puck will not physically fit.

What are the likely uses for LED and how does the packaging of the test instrument need to be adapted? Perhaps LEDs will someday replace conventional lamps in applications where an LED analog of existing measurement tools will fit the bill. But LEDs also open up new applications, such as digital printing, where a different size or shape may be useful.

At this time, there are more than 25 manufacturers of commercial UV-LED sources targeting industrial UV applications that we are aware of (and probably a number that we are not). The industry is nascent and changes significantly from year to year, making it challenging to design a measuring device for equipment that moves from undefined to obsolete within a short time span.

UV-LEDs have opened up new markets to UV curing, in addition to being a possible solution for existing UV applications. Many people have the opportunity to use UV sources for the first time and do not have the experience that many of us have gained over the years with spot, arc or microwave UV sources. We need to:

- Welcome them to our industry
- Continue to offer educational opportunities
- Honestly present the advantages and disadvantages of UV-LEDs
- Target applications that are best suited for UV-LEDs

With years of proven performance and expertise at measuring UV, there is no shortage of solutions and good answers. The problem is agreeing on the right questions.

—Paul Mills is a UV marketing consultant and Jim Raymont is director of sales for EIT Instrument Markets in Sterling, Va.

The State of UV-LED Curing: An Investigation of Chemistry and Applications

By Ed Kiyoi

Light-emitting diodes for ultraviolet-curing applications (UV-LEDs) have been commercially available for nearly 10 years. However, their unique output characteristics require newly formulated UV chemistries in order to take advantage of UV-LEDs' many benefits. This paper discusses the characteristics of UV-LED lamps; the importance of properly formulating chemistries; the benefits to end-users; commercial applications of UV-LEDs; and future expected developments.

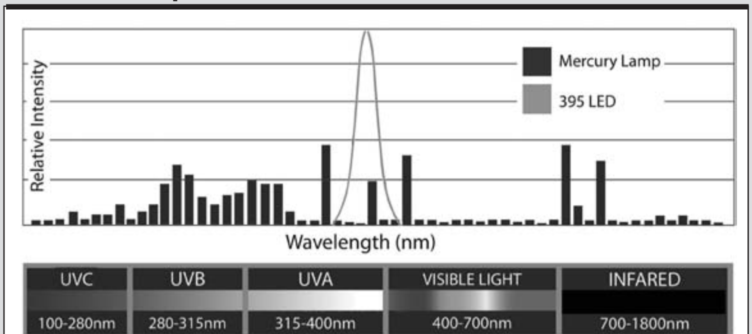
Characteristics of UV-LED lamps

Traditional UV arc lamps produce UV energy by generating an electric arc inside an ionized gas (typically mercury) chamber to excite atoms, which then decay and emit photons. The emitted photons cover a broad range of the electromagnetic spectrum, including some infrared and even visible light as shown in Figure 1. Only about 25% is in the safer UV-A range.

A UV-LED generates UV energy in an entirely different way. As an electric current (or electrons) move through a semiconductor device called a diode, it emits energy in the form of photons. The specific materials in the diode determine the wavelengths of these photons and, in the case of UV-LEDs, the output is typically in a very narrow band +/- 20 nm. The wavelength is dependent on the band gap between excited state and the ground state of the semiconductor material. The chart in Figure 1 compares the output of a 395 nm, UV-LED lamp with a typical mercury-arc lamp. It is important to note the difference in intensity and wavelength of the output as both are key to understanding a UV-curing process.

Figure 1

Wavelength output comparison of mercury-arc and UV-LED lamps

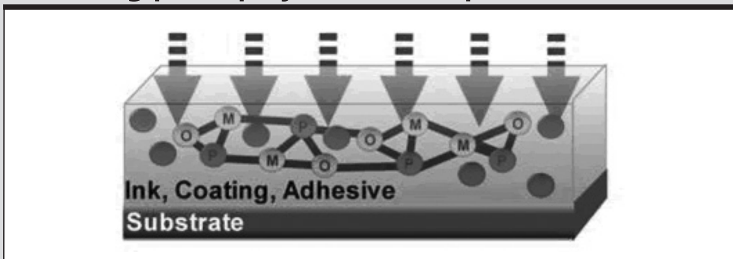


The UV-Curing Process

UV curing is a photopolymerization process that uses UV energy to change a liquid to a solid. Upon absorption of the UV energy (as shown in Figure 2), the photoinitiator (PI) produces free radicals that initiate crosslinking with binders (monomers and oligomers) in a polymerization reaction to cure or solidify the ink, coating or adhesive. UV formulations also incorporate various additives such as stabilizers, wetting agents, adhesion promoters, defoamers and pigments to provide desirable characteristics or color of the cured material.

Figure 2

UV curing photopolymerization process



Comparison of Solvent and Waterborne to UV Processes

Solvent and waterborne formulations change from a liquid to a solid (“dry”) via evaporation of the solvent—typically volatile organic compounds (VOCs) or water. This drying process (often requiring an oven) takes time, generates VOCs and the dried film thickness is less than originally applied. UV curing happens much faster (typically less than a second), does not generate VOCs and the film thickness applied is what remains as a solid (critical for certain end-use applications). UV-curing processes are environmentally friendly, save energy costs and floor space, and typically increase production rates while reducing scrap or waste streams.

Formulating UV Chemistries for UV-LED Lamps

For efficient and effective UV curing of an ink, coating or adhesive, the formulator seeks to overlap the UV lamp output with the spectral absorption of the PI. The amount of PI in a typical UV formulation is usually very small, less than 5%. PIs typically absorb across a range of wavelengths, not a narrow band. For example, Figure 3 shows the spectral absorption for different PIs and the wavelength output for mercury-arc UV lamps. Many existing UV formulations developed for curing with a typical mercury-arc lamp (shown as H-bulb) use a broad spectrum PI. While there is often some absorption within the UV-LED output range, it is clear to see that much of the PI absorption range is wasted. A more efficient cure is possible with a formulation designed specifically for UV-LED curing using a PI with concentrated absorption in the UV-A range such as those shown in Figure 4.

The monomers in the formulation serve as the reactive diluent enabling the formulator to control viscosity for proper application (spraying, rolling, screen printing, etc.) of the uncured material. Rather than volatilizing, as is typical with conventional formulations, the monomer reacts and becomes part of the UV-cured material. The oligomers (and their backbone structure) determine the overall properties of the material. Monomers and oligomers are generally derivatives of acrylates or methacrylates containing polyurethanes, polyesters or polyethers.

The longer wavelength output—such as the UV-A range seen from UV-LEDs—penetrates through thick and pigmented systems producing through-cure of the material that ensures surface adhesion and the ability to cure thicker screen ink or pigmented wood coatings. Short wavelength output (200-280 nm) is unable to penetrate very far into a material, but provides surface curing which is important for surface properties such as scratch and chemical resistance.

Overcoming Surface Cure Issues

Surface curing due to oxygen inhibition was often an issue for UV-LED curing, but has largely been overcome by various means. Of course curing in an inert (nitrogen) atmosphere is one option, but it adds cost and complexity to the system. Another option is to add in oxygen-

Figure 3

Photoinitiator spectral absorbance compared to traditional UV lamp output

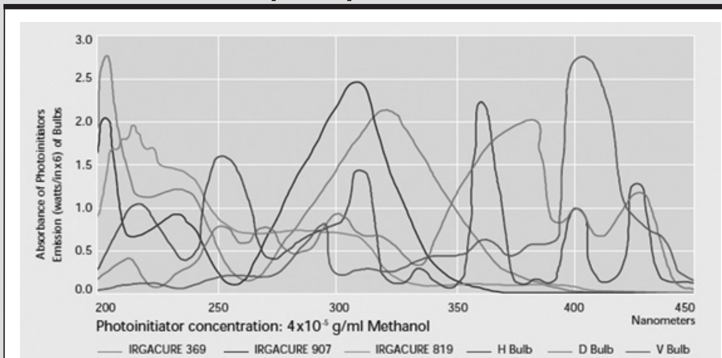
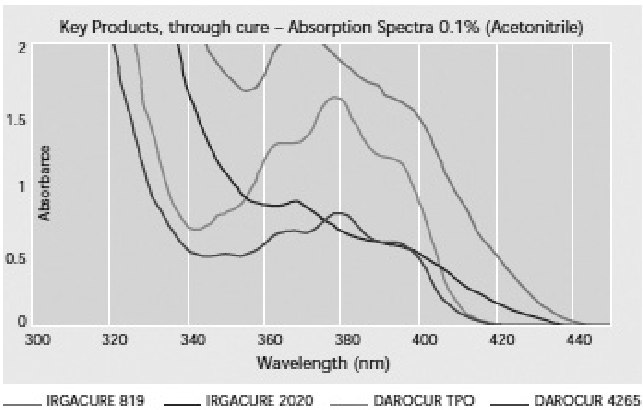


Figure 4

Examples of longer wavelength absorption photoinitiators



consuming or scavenging compounds such as amines or aminoacrylates to overcome oxygen inhibition.[1]

Research has indicated that peak irradiance (W/cm²) and total UV-A energy (mJ/ cm²) delivered are more important than a precise wavelength match on formulations developed to cure in the UV-A region. Peak irradiance is an important metric since intensity is required to initiate the polymerization. Higher peak irradiance (such as that found in UV-LEDs) results in a more aggressive polymerization mechanism helping to overcome oxygen inhibition at the surface and achieving the required cure rate.[2]

More recently, it has been shown that higher functional oligomers can also minimize the oxygen inhibition and improve surface curing. Commercially, Cytec offers a co-resin called ADDITOL® LED 01, a mercapto-modified, polyester-acrylate resin that replaces a portion of the oligomer in a UV formulation to improve surface curing under UV-LED lamps. This co-resin is compatible with urethane acrylates, some epoxy and polyester acrylates, and acidic adhesion promoters and typically accounts for 20-40% of the formulation by weight. Mono- (MAPO) and bisacylphospineoxides (BAPO) are recommended photoinitiator types for UV-LED curing. Some commercial examples are IRGACURE® 2100, LUCIRIN® TPO-L and ADDITOL® TPO.[3]

In September 2012, Eileen Jaranilla-Tran with the Rahn-Group reported on her investigation of overprint varnishes (OPV), flexographic inks and inkjet inks. She found that Norrish Type I PIs such as BAPO are effective to achieve good surface cure (and preferable to TPO and BDMM), especially when combined with highly reactive acrylate oligomers and it minimizes yellowing. ITX (Type II) was more reactive, but caused too much yellowing for OPV and white inks. She also noted that pigment selection is key because pigments compete with the PI for UV energy.[4]

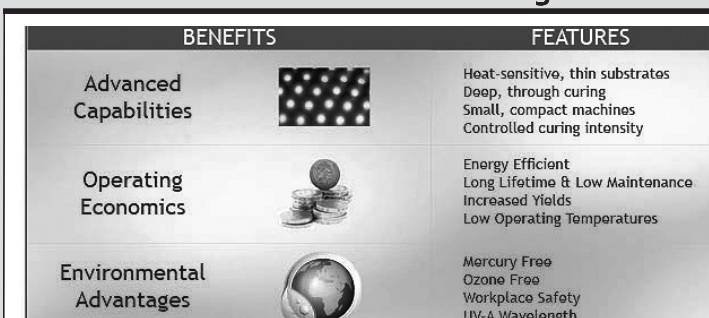
Many advances have been and are being made by raw material suppliers and, in turn, more UV-LED formulations are being commercialized that result in production speeds comparable to traditional mercury lamp processes. Formulators should work closely with their suppliers to develop new UV-LED cure chemistries which are non-yellowing, will overcome surface cure issues and meet the end-use production requirements.

Benefits UV-LED Curing Delivers to End-Users

The benefits of UV-LED as compared to traditional mercury-arc UV lamps are numerous and significant as shown in Figure 5. UV-LEDs are more environmentally friendly because they do not generate ozone and contain no mercury as arc lamps do. They are a cool source compared to arc lamps, largely due to no output in the infrared range. This reduced heat eliminates complicated cooling mechanisms such as chill rolls and external shutters, and

Figure 5

Benefits and features of UV-LED curing



enables applications on heat-sensitive substrates. The electrical-to-optical conversion efficiency of UV-LEDs is much better and the ability to instantly turn the unit off and on enables saving about 50-75% on electricity.

Table 1 shows a comparison of key characteristics of UV-LEDs versus traditional mercury-arc UV lamps. Compared to an arc lamp's 500-2,000-hour life, most UV-LEDs are specified for 10,000 hours, but can last more than 20,000 hours. It's also important to note that over this lifetime UV-LED output only drops about 5%, compared to arc lamps that can lose about 50% of their original output by the end of their life. In a production environment, UV-LEDs require significantly less space, monitoring, maintenance and downtime. That translates into higher productivity rates, less scrap and higher quality end products. Paybacks for retrofitting onto existing machines or replacing existing UV arc lamps can be as low as 12 months.

Commercial Applications of UV-LEDs

Some of the earliest UV-LED commercial applications were small area adhesive and bonding applications such as medical device assembly; low-end thermal inkjet printing applications such as marking, coding and variable printing; and field repair of fiberglass composites. These early applications took advantage of UV-LEDs' form factor (lightweight and small), through-cure capabilities and the increased safety inherent with longer wavelengths. In fact, many of the earliest applications were actually in the visible wavelength range. Today, as the energy density has increased and costs have decreased (especially for 395 nm output), UV-LED is commercial in the graphic arts market, wood coatings, electronics, composites and others.

Commercial UV-LED applications in the graphic arts market (especially digital inkjet applications) advanced first owing to their form factor, low heat and energy savings advantages. Commercial inkjet applications today include all inkjet segments, including wide-web printing on a variety of substrates for many end-use applications. There are many UV-LED-specific inkjet inks and most inkjet printing presses are available with UV-LEDs. For example, EFI Inkjet Solutions offers a 126-inch wide, UV-LED curing printer capable of 1,000 dpi and eight-color (plus white) with speeds of up to 1,200 ft^2/hr. End-users are able to print on thinner, more heat-sensitive materials reducing material costs in half without sacrificing any quality or speed.[5]

Table 1

Comparison of UV-LED to mercury-arc UV lamps

	UV-LED	Mercury Arc
Life	20,000+ hrs	500-2,000 hrs
On/Off	Instant	10 Minutes
Output Consistency	Very Good. 95%+	Drops up to 50%
Heat Generated	60°C	~350°C
Energy Efficiency	Saves 50-75%	
Environmental	Mercury Free, Ozone Free	Mercury Waste, Generates Ozone
Footprint	30-50% less	

Narrow Web Flexo Takes Off

More recently, UV-LED inks are being used for screen printing (rotary, flatbed and container) and narrow web flexographic printing. Flint Group introduced the first UV-LED combination print inks, flexographic four-color process and rotary screen white inks branded as EkoCure™ at Label Expo in September 2012. In October, they began working closely with a beta customer (a large label converter) to validate the inks and process in a commercial setting. The customer had a narrow web flexographic press running waterborne inks. They simply installed UV-LED lamps to run the new EkoCure™ inks. Since the UV-LED lamps run cool, there was no need to use chill rolls or other web cooling devices as would typically be required for mercury-arc lamps. They have seen no film distortion, even on heat-sensitive, low-gauge films such as shrink films.

"Our beta site customer runs a variety of different commercial products. So, as they needed something new, we formulated it for them," said Tom Hammer, product manager, Narrow Web North America, Flint Group. "We started with flexographic inks, but have also done clearcoats and adhesives, both PSAs and laminates. Nothing has been a problem and the customer is very impressed."

The beta customer has been running the 10-station, 17" press since October on a 24/7 schedule. No matter what they've been running—shrink films, four-color processes, pressure-sensitive labels, lamination and others—they are seeing faster line speeds than with traditional UV. They are currently on track to see a payback for the press retrofit in less than 12 months. The beta customer is also adding a rotary head to the press and will run the opaque white ink already developed for UV-LED curing. Flint Group plans to further develop rotary screen inks in a variety of colors for UV-LED cure.

"Formulating inks for UV-LED curing does not require starting from scratch, but it is also not as simple as just replacing the photoinitiator with one that has a longer wavelength absorption. The pigments used in the flexographic and rotary inks are similar to those used in traditional UV-cured inks as are some of the oligomers and monomers," added Hammer. "However, there are fewer choices of photoinitiators (longer wavelength) to use and it is more challenging to get cure performance (surface and through-cure) while still keeping costs for the end-user in mind."

Wood Coating Applications

Sherwin Williams introduced its Becker Acroma™ UV-LED coatings for wood in January 2012 and their customer BJS has been successfully using the UV-LED coatings since June 2012.

"The primary driver for developing these UV-LED coatings was to extend the use of UV curing to heat-sensitive wood substrates such as pine (< 45°C) and other resinous woods. Most end-users in Europe face strict limits on VOC emissions and traditional UV arc lamps cause problems on heat-sensitive wood material," said Lars Sandqvist, technical project manager at Sherwin-Williams Sweden. "With the UV-LED coatings, end-users have a choice of arc or LED, or even a combination. Customers who have a UV line, but have heat problems, can retrofit the line with LED in a couple of positions to get the temperature down and keep the rest of the arc lamps to minimize investment."

BJS (which runs both arc lamps and UV-LEDs on the same line) has seen a 60% energy savings with the UV-LED compared to the arc lamps. In addition to energy cost savings, the UV-LED lamps provide consistent output, require less maintenance and reduce the fire hazard. Gloss control has been an issue when applying thick, pigmented layers (>15g/m^2) via roll coating or with spray application (rarely used). When the customer needs to produce matte finishes they simply use a combination of arc lamps and the UV-LED. Gloss control is not an issue for thinner topcoats. There is also an EU framework project FP7 (*http://www.fp7-uvled.eu*) focused on researching UV-LED wood coatings. Findings were expected in early 2013.

Future UV-LED Applications

The future for UV-LEDs looks very bright given the progress made to date by raw material suppliers and formulators. And, if the trends for UV-LED development continue—namely increasing peak irradiance (77% compound annual improvement) and decreasing costs—we should see rapid adoption by end-users in the near future for many new applications.

According to Hammer, Flint Group is developing UV-LED inks for offset and letterpress applications and he fully expects this to translate to sheet-fed and wide-web applications as well. Hammer also sees food packaging as a growth area, once low migration inks are available. Right now, most of the photoinitiators approved for food packaging are not appropriate for UV-LED ink formulations.

Sherwin-Williams is developing UV-LED fillers for use by furniture manufacturers who want to use lower cost particle board, but need a smooth edge after cutting and shaping. The clear, thick fillers are an ideal application for UV-LEDs. According to Sandqvist, another application that will soon be available is UV-LED coatings on wood moldings. The coatings are ready and shown to cure at the required speeds of 40-100 m/min. All that is needed is an end customer willing to be first, as is so often the case with "new" technologies.

Richard Baird, a process engineer for Boeing, wrote in the fall 2011 issue of the *RadTech Report* that he expects UV-LED curing to become a viable option for large-scale aerospace paint curing in the very near future.[6] By all indications, this and many other UV-LED curing applications will indeed be taking off soon. ◗

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—Ed Kiyoi is a technical marketing engineer at Phoseon Technology in Hillsboro, Oregon.

Market Overview of UV-LED Applications: Not a One-Size-Fits-All Approach

By Jennifer Heathcote

Anyone who has ever investigated UV-LED curing has likely encountered contradictory statements and claims regarding the viability of the technology as well as its future. Why does UV-LED technology garner such varied support from industry experts? Quite simply, it is because there is no such thing as a universal UV-LED solution that works for every UV-curing application in existence in exactly the same way. Or in other words, UV-LED technology is not a one-size-fits-all substitute for conventional UV arc and microwave curing. What works for one application does not necessarily work for another. As a result, opposing statements generally directed at the UV curing industry as a whole are really only credible—and much less contradictory—when given correct application context.

Many readers of this article are likely familiar with the UV-LED curing benefits championed by those operating within the UV-LED supply chain. For convenience, a short list is provided in Figure 1. The cost savings as well as process and safety improvement benefits are often the impetus that leads individuals to investigate LED curing in the first place.

Figure 1

UV-LED curing system benefits

- Solid-state technology
- Easy integration
- Near-ambient array housing temperatures
- Negligible heat transfer to cure surfaces
- Instant on/off curing
- No warm-up/cool-down cycles
- No shutters needed
- Diode life in excess of 20,000 hours
- Consistent UV output over time
- No mercury-filled UV bulbs
- No ozone production
- No system exhaust
- No conditioned plant makeup air
- No radio frequency emissions
- Lower total cost of ownership

But even the strongest and most persuasive list of benefits has little to do with whether an application is practically or economically viable. Focusing solely on a generalized list of benefits excludes everything that makes an installation successful. That includes hours of formulation and engineering work to adapt the technology to the specific process, field tests, general technology improvements, safety certification and the cost analysis needed to justify the business case for adoption.

In order to achieve a better understanding of when and why

Figure 2

General market diffusion of UV-LED innovation

First Movers	Second Movers	Later Adopters
Inkjet Pinning and Full Cure—Slower Speed Inline Graphics	Inkjet Full Cure—Scanning Graphics	Litho/Offset
Inkjet Marking and Coding	Inkjet—Under White	3-D Finishing
Spot-Cure Adhesives and Sealants	Inkjet Industrial	High-Speed Coatings
Slow-Speed Coatings	Screen	High-Speed Adhesives
	Flexo	UV-B Curables
	Wider Area Sealants/Adhesives	UV-C Curables
	Photoresist	

UV-LED curing makes sense, it is helpful to survey the markets that are embracing the technology today, and evaluate the industry and application factors that are enabling successful installations as well as the processes that guided the evolution. Conversely, factors that hinder adoption and penetration in other markets can also provide notable insight regarding the technical issues that must yet be overcome.

It should not be any surprise that a 30-second static exposure bonding application over a ¼-inch or one-inch square area; a 10 fpm, 22-inch wide electronics coating line; a 60 fpm, six-inch wide multicolor inkjet; a 48-inch wide screen graphic application; a 250 fpm, ½-inch wide single color inkjet coding application; a 650 fpm 17-inch wide eight-station flexo printer; a 2,000 fpm, 60-inch wide lithography line; and a 3-D UV-curing chamber all have very different UV process and integration requirements. The type of ink, coating or adhesive; desired post-cure functional properties; substrate width or part profile; line speed; and distance of the UV source from its cure surface all influence which UV configuration is needed. Just as these applications employ very different conventional UV solutions, they also require very different UV-LED solutions.

First Movers

Generally speaking, UV-LED curing is most commonly used in slower speed applications, including inkjet, coatings and spot-cure adhesives and sealants. It also tends to be employed for relatively flat substrate surfaces. While the activity across the early adopter markets is diverse, it is often driven by:

- Heat-sensitive applications that cannot use conventional UV due to the emitted infrared;
- Wavelength-sensitive applications that utilize the relatively monochromatic output of UV-LEDs to avoid product-damaging wavelength regions;
- Industrial coating and bonding applications at larger manufacturing facilities that have additional engineering resources available to support development and integration;
- Applications that lend themselves to UV-LED systems with smaller form factors easily positioned within a half inch of the cure surface; and
- Applications where the chemistry has been tweaked to react within the 365-405 nm output range emitted by most UV-LED systems.

A few more specific examples include inkjet marking and coding of gift, security and hotel cards; inkjet for narrow web labels; coating, bonding and sealing electronic displays and devices as well as smaller automotive assemblies; inkjet product decoration, particularly on heat-sensitive materials; and coatings applied to thin films.

As UV-LED innovations diffuse the broader market, UV-LED first-mover applications have and continue to receive the vast majority of engineering effort and comprise the most significant UV-LED revenue stream for system manufacturers, formulators and integrators. For this portion of the industry, listed in column one in Figure 2, UV-LED technology has increasingly become the preferred solution and is truly the result of a full decade of development.

Second Movers

In other applications such as screen, flexo and both scanning and industrial inkjet, formulators see great near-term potential and have subsequently invested heavily in research and development in recent years to make the applications work. These suppliers become strong promoters of the technology even if there are few, if any, installations to reference and even if more development work needs to be done. Many formulators and LED equipment manufacturers have produced successful field trials while some integrators are leading the industry by developing custom LED-curing machines and printers. All continue to improve and optimize the technology as they hunt for end-users ready to embrace LED curing.

The greatest hurdle, however, is that while the technology works or can be made to work, the business case is not always sufficiently demonstrated as to what is often a very price-sensitive machine builder or end-user. While it is typically much easier to make the business case for using UV-LEDs on new machines, field retrofits can be a bit more challenging. The large and still functioning installed base of conventional UV; the obligation to requalify the curing process for use in particular segments such as food packaging; and the need for customized, longer or multiple arrays on wider and faster speed machines make the initial capital investment or development more expensive. All of this contributes to slower market penetration.

Later Adopters

At the far end of the spectrum are the LED-lagging applications that operate at extremely fast speeds; handle complicated 3-D part profiles; require UV-B and UV-C outputs; or exist within machine frameworks that prevent the curing system from getting sufficiently close to the cure surface. For these applications, today's UV-LED curing technology often does not make commercial sense from a technical or economic perspective—no matter how the numbers are run. In fact, these applications *may* even require another big leap in the evolution of the base chemistry or LED technology, or possibly necessitate peripheral array enhancements in order to get sufficient UV irradiance and energy density at the optimal wavelength to the cure surface. All of this takes time and money.

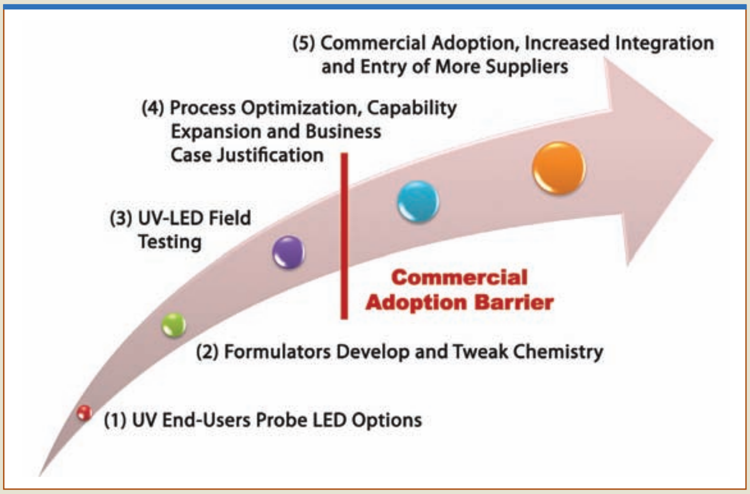
It should also be noted that for many of these applications, some of the touted UV-LED benefits—such as lower total cost of ownership—don't really hold up. Even in applications where the technology can be made to work, it is often not economically feasible at the desired production speeds. While each application should be evaluated individually, economics, line speed and distance are the key reasons why there has not been any significant migration toward adoption. Nevertheless, many suppliers are actively engaged in these areas as customers have demonstrated interest in the technology based on the potential benefits, and suppliers want to provide these users with a solution…someday.

Market Evolution

Figure 3 provides an illustration of the general market evolution for an application. First, machine builders and end-users of conventional UV-curing and drying methods become aware of the benefits and successes of UV-LED technology in early adopter and second-mover markets. (1) In an effort to determine whether UV-LEDs are an option for their application, they begin calling formulators, LED system suppliers and machine builders. (2) When a critical mass of interest is generated, or possibly even before this point, formulators begin experimenting with LED chemistry in the lab. (3) Once formulators achieve working samples, they partner with LED-system manufacturers who have been working on their own technology in parallel. Together, formulators and LED-system suppliers perform field trials on existing process equipment at true production speeds. (4) Successful trials demonstrate the viability of the technology and highlight weaknesses. Without a strong economic business case, however, the technology hits a *Commercial Adoption Barrier*. It is only when the UV-LED curing system and the formulation material meet a sufficient level of the end-user's process requirements and the business case for adoption is economically justifiable that end-users begin embracing the technology. The time duration between stages 3 and 4 can be a few months, a few years or even decades, depending on the application. (5) But once stage 4 is reached, it is typically not too long before commercial adoption accelerates, bringing more and more end-users and suppliers onto the scene.

FIGURE 3

UV-LED market evolution



Science of UV Curing

It is often helpful to review the basic science behind UV curing as a means of understanding what is necessary to move through stages 2, 3 and 4 as illustrated in Figure 3. All UV processes require a certain combination of wavelength (nm), irradiance (watts/cm^2) and energy density (joules/cm^2) in order for sufficient photopolymerization to occur. The material being cured does not care how the UV energy is supplied (arc, microwave, fluorescent tube, sunlight, LED, xenon pulse, electron beam, etc.) as long as the formulation's minimum threshold reaction parameters are met. As a result, the total UV energy (wavelength, irradiance *and* energy density) required by the formulation at the cure surface for a given process speed dictates whether an LED solution is even possible with today's technology, as well as how much the total solution will cost. See Figure 4.

Wavelength

UV-LED outputs are relatively monochromatic with peak intensities between 365 and 405 nm. UV-LED wavelengths shorter than 365 nm are not generally available on the commercial market, at least not at the intensities necessary for industrial photopolymerization. Formulators are constrained to an existing selection of raw materials developed to be most reactive at 365 nm or shorter. Some applications such as inkjet have overcome less reactive photoinitiator zones by leveraging the higher peak irradiances emitted by UV-LEDs at longer wavelengths. These values commonly exceed those emitted by conventional UV systems. While it is certainly possible to produce increasingly higher peak irradiance and energy density levels for longer wavelength LEDs (395-405 nm), doing so leads to greater junction inefficiencies; potentially shorter diode life; significantly larger input power requirements; and increased cooling—all of which leads to both a larger capital investment and generally higher running costs.

Irradiance

For any UV reaction, a minimum irradiance (watts/cm^2) threshold is necessary to start the polymerization process and counter oxygen inhibition at the cure surface. As previously mentioned, UV-LED irradiance is typically higher than that of conventional UV systems. The LED irradiance increases as current through the diodes increases, but it also decreases as the junction temperature rises. In addition, the relationship between irradiance and current is not a linear one and eventually it saturates. Further increases in current lead to even greater inefficiencies in the conversion of electricity to UV output and the need for more total cooling capacity and AC power. Irradiance also decreases as the array moves away from the cure surface. This alone makes applications such as sheet metal offset decorating and 3-D finishing—where machine frameworks or complicated part profiles prevent the LED array from being mounted close to the cure surface—very difficult and generally impossible with today's technology.

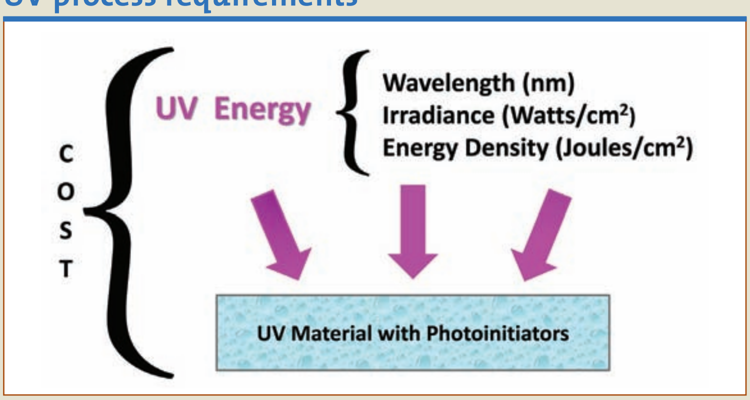
Energy Density

While some UV-LED curing systems use higher irradiances to generate more energy density (Joules/cm^2), energy density is more effectively increased by adding more diodes to an array; increasing the number of LED arrays in a process; or increasing the overall dwell time. The latter method is accomplished by decreasing the line speed; increasing the number of passes under the UV source; or extending the time the cure surface is parked beneath the UV source.

Presently, the most expensive component in a UV-LED curing system is the diode. This means that increasing the total number of diodes or arrays proportionally increases the total cost of the curing and cooling systems. As a result, application speed is an important factor in determining whether a process is economically viable since speed can play such a large part in dictating how much energy density is required and, therefore, how many diodes or arrays are needed. Faster applications such as lithography simply require more total energy due to the fact that the media is under the UV source for a shorter period of time.

Figure 4

UV process requirements



For example, if achieving proper cure for a given application at a specified wavelength and irradiance occurs at a maximum speed of 100 fpm using an existing UV-LED system that costs X, in order to cure at 1,000 fpm under the same conditions, the application will typically require 10 UV-LED curing systems (or a single array with 10 times the diodes) at a total cost of 10X. Chemistry, array cooling and AC power consumption aside, this scaling investment cost is the primary factor that makes many high-speed, wide-web presses economically unattractive for LED curing today.

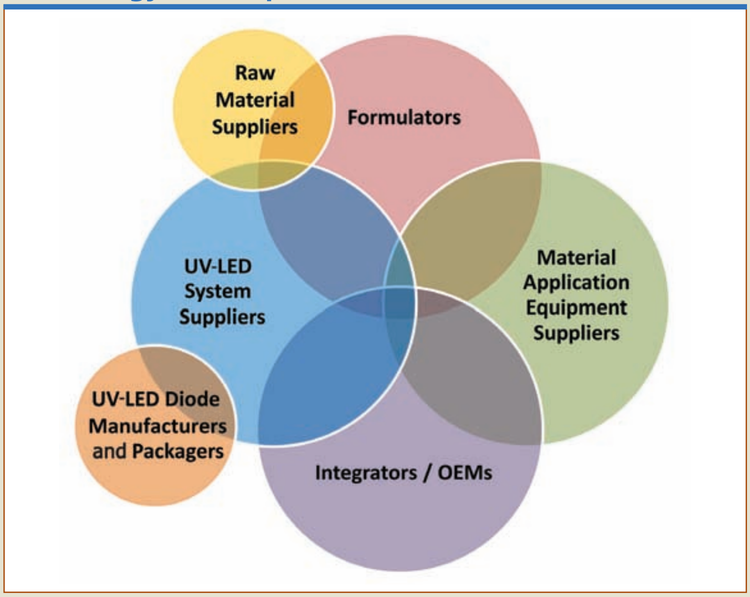
UV-LED Supply Chain

Since financial resources for product development are finite, key suppliers focus on the markets that are most conducive to the UV-output levels delivered by today's LED technology as well as markets where UV-LED technology is more economically viable for the end-user. These markets are most likely to produce the best rate-of-return for technology developers. That does not mean that suppliers are ignoring slower developing markets—the activity is simply at a research-and-development stage as opposed to a commercial one. Typically, this research and development is spearheaded by multiyear partnerships involving large end-users or machine builders, UV-LED system suppliers and formulators.

As the technology diffuses into new markets, suppliers rely on the development network illustrated in Figure 5. All of the entities in this network contribute and collaborate in order to propel successful applications toward more efficient evolution. It often takes an application champion to introduce, educate and focus co-suppliers on a new opportunity. It also means that the markets that have the most champions as well as the most promise draw the most attention.

Figure 5

Technology development network



For the sake of clarity, let's focus on the lower left hand quadrant of Figure 5. This area consists of four distinct equipment supplier segments that are further detailed in Figure 6. *Please note that Figure 6 is not a fully comprehensive representation. While specific companies are referenced, this is for illustrative purposes only. Please also note that it is not uncommon for some companies to operate within multiple segments, while others elect to specialize in only one area.*

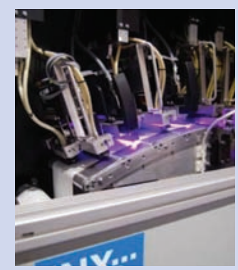
Within the equipment portion of the supply chain, discrete UV-LED diodes, diode packages or modules are purchased from a finite list of seven semiconductor manufacturers shown in Column 1. Before individual diodes can be used in a curing system, they must be properly packaged either by the semiconductor supplier or another company in the supply chain. In general, packaging diodes includes wire bonding the anodes (+) and cathodes (-); securing the dies to a heat sink; and providing an encapsulate for physical protection and to seal out dirt and moisture.

UV-LED system manufacturers then arrange the packaged diodes into a final assembly; provide a means for cooling the diodes (air or liquid); and engineer the base controls for host interface and connection to a DC power source. Finally, other original equipment manufacturers (OEMs) or system integrators purchase the entire plug-and-play, UV-LED system or simply the LED array for integration onto a larger machine. While all parties collaborate as previously discussed, the integrator is ultimately responsible for making sure that the curing system, formulation, formulation delivery/dispensing system and the material handling equipment all seamlessly work together for the end-user.

By now, it should no longer be a surprise that many statements generally directed at the UV-curing industry as a whole are really only credible and often not so contradictory when given correct application context. The UV-LED reality is that

Figure 6

UV-LED supplier segments

UV-LED Diode Manufacturers	UV-LED Diode Packagers	UV-LED System Manufacturers	System Integrators
Cree Fox LG Nichia Nitride Phillips SemiLEDs	Diode Manufacturers (1) LED System Manufacturers (3) Specialist Electronics Manufacturers LED Engin Luminus Devices	Integration Technology IST Heraeus Noblelight Honle Lumen Dynamics Luminus Devices Phoseon	Machine Builders Branded OEMs End-Users General Integrators
			

for every successful application in operation today, there are many more examples where only conventional UV technology is employed. Businesses must invest time and resources to develop specific UV-LED solutions for each market application. While some markets may require years or possibly decades for viable economic solutions to mature, many others are successfully using UV-LED technology right now. Various UV applications that were not possible with conventional arc or microwave systems have also become possible with LEDs; thus, expanding the total UV-curing pie. No matter how much LED technology suppliers and end-users may want to utilize LED curing for specific applications, the technology is simply not a drop-in solution. As a result, the industry plugs away within the technology development network one application and one market at a time, learning more and more as it anxiously anticipates the next big market breakthrough.

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