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

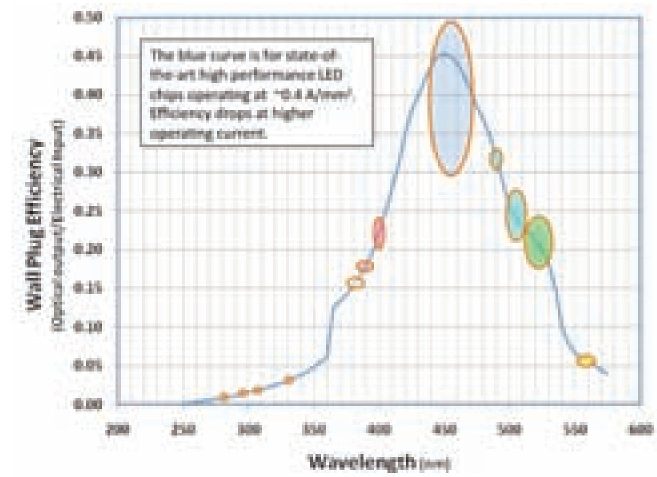
LEDs are beginning to challenge existing lamps used for lighting and UV-curing applications. In general lighting, white LEDs are becoming bright enough to replace mercury lamps and sodium vapor lamps in street lighting applications. There is also progress in developing UV-LEDs for curing applications, 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.

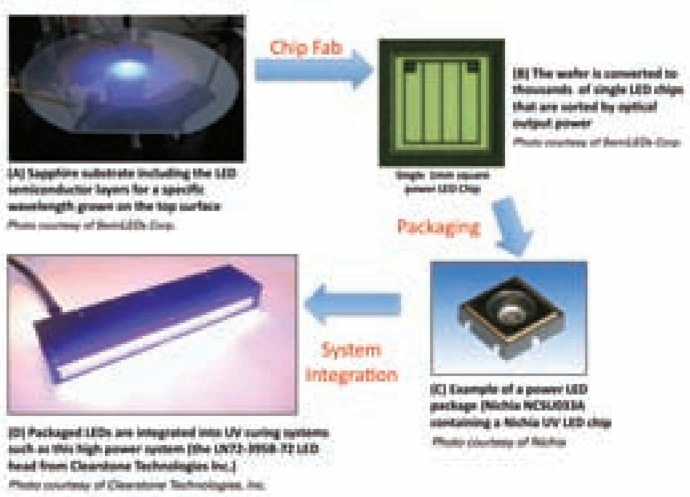
With today's technology, the intensity of light (visible or UV) emitted by an LED depends strongly on the wavelength (Figure 1). Blue LEDs are the most efficient of all the nitride LEDs. The intensity drops quickly as the wavelength gets shorter, especially below 365 nm where there are special technical 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

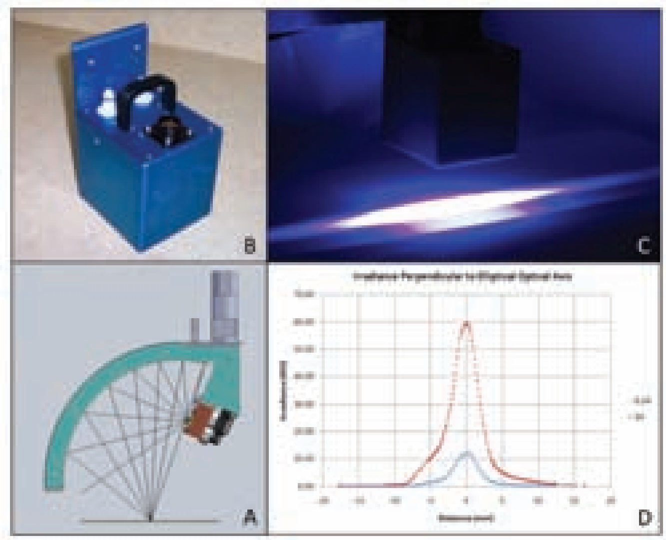
The emitting area is 12 mm^2 (rectangular chip in the center of the package) and is the largest power LED on the market today. The large copper submount is required for adequate thermal management. The package is also equipped with a thermistor for thermal sensing.

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.

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.

Table 1

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

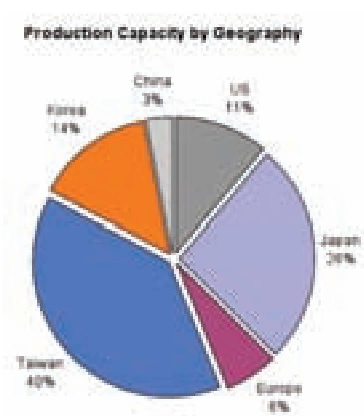
UV-LEDs stand to profit from LED performance and price improvements largely directed at visible-LED applications.

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

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.

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