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 single 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 make-up 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 1-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 8 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.

Early Adopters

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, illustrated by 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.

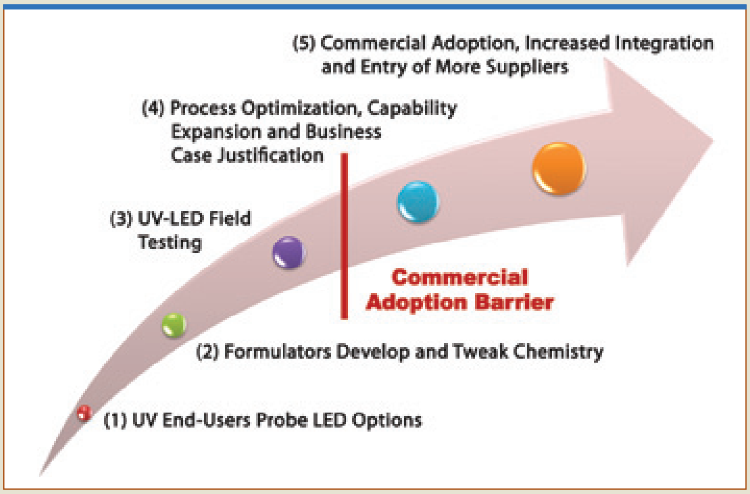
It should also be noted that for many of these applications, some of the touted UV-LED benefits—such as lower total cost of ownership—don't really hold up. Even in applications where the technology can be made to work, it is often not economically feasible at the desired production speeds. While each 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 typically is 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.

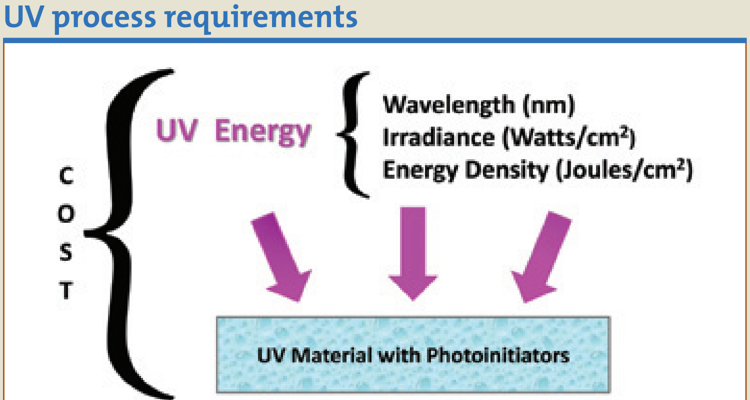
Energy Density

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.

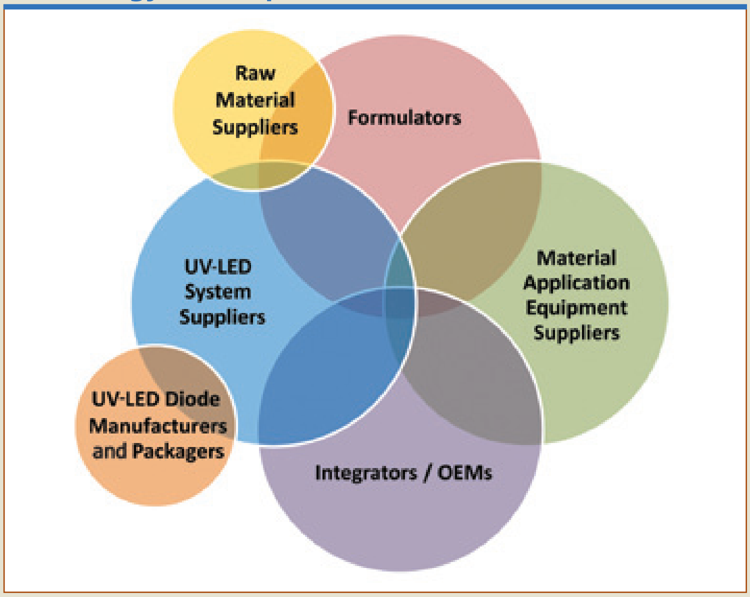
UV-LED Supply Chain

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 to 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.*

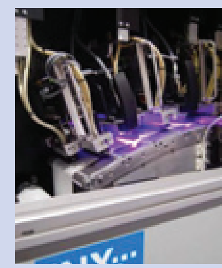
Within the equipment portion of the supply chain, discrete UV-LED diodes, diode packages or modules are purchased from a finite list of seven semiconductor manufacturers shown in Column 1. Before individual diodes can be used in a curing system, they must be properly packaged either by the semiconductor 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 Nobelight 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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