# Solid-State UV Curing Technology Comes of Age

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**Abstract:** The capability to produce large area, solid state UV curing heads with outputs similar to traditional UV curing lamp technology is finally at hand. This paper discusses the latest developments in solid state, semiconductor based, ultraviolet light technology and compares it to traditional arc lamp, flash lamp, and microwave curing technology. Some of the key advantages of a very high intensity and narrow wavelength band source are discussed as well as some of the key differences between this solid state technology and LED solutions. Experimental results are reported showing light source life exceeding 10,000 hours, excellent spectral uniformity, low heat load into target substrate and excellent curing results.

## Introduction:

Photopolymer material chemistries were introduced in the 1960's as an alternative for solvent-based material chemistries, and their advantages were so readily apparent that they were quickly adopted for many industrial applications.[1] Photopolymer chemistry offers an attractive replacement for solvents by eliminating the need for large, power hungry furnaces and the environmental issues associated with the volatile organic compounds that solvents produce when heated. Our industry has watched the exciting transformation of application after application across many industries to UV curing, now approaching a $5B market of materials, equipment and curing sources, with double digit growth rates in many of these applications.

Forty years ago, mercury-based arc lamps were the only UV light source available for activating these new photopolymer materials. In the 40 years since additional bulb-based light sources such as Excimer bulbs, microwave sources, etc. have been added, but essentially this industry remains dependent on a light source which predates the Edison light bulb. While they have been amazingly useful, these bulb based light sources have a variety of disadvantages:

- **Dangerous** – light, heat, electricity, explosions, toxic materials, environmental
- **Expensive to operate** – facilities consumption (air/water/electricity), frequent replacements, equipment downtime, cleaning/maintenance, requires filters and shutters to operate, etc.
- **Cause Process Variability** – heat damage to parts, degradation of light over life, bulb to bulb variability, etc.

Solid state, or semiconductor devices, have replaced most other bulb and tube based technologies. For instance, tubes have long ago been replaced with transistors, and LEDs are rapidly displacing light bulbs in indicators, traffic signals, and headlamps. Solid state lasers have replaced excimers and arc lamp sources in many production processes, but have had little impact in industrial UV curing applications. Recent developments with solid state sources are providing a new alternative with significant advantages in operating costs, processing speed, quality, reliability, safety, and enabling new applications to be possible for the first time.

**What are solid-state light sources?**

Light-emitting solid-state devices (SSDs) consist of a pn junction formed by two dissimilarly doped semiconductors (see Figure 1). By applying an external electric field across the junction, current can be made to flow, and when the holes from the p-type and electrons from the n-type meet at the junction they combine and release a photon of light. The wavelength of the light depends on the bandgap energy of the materials used in the pn junction. By adjusting the materials used and the doping, a wide range of wavelengths are possible, including wavelengths in the ultraviolet (UV) portion of the electromagnetic spectrum.

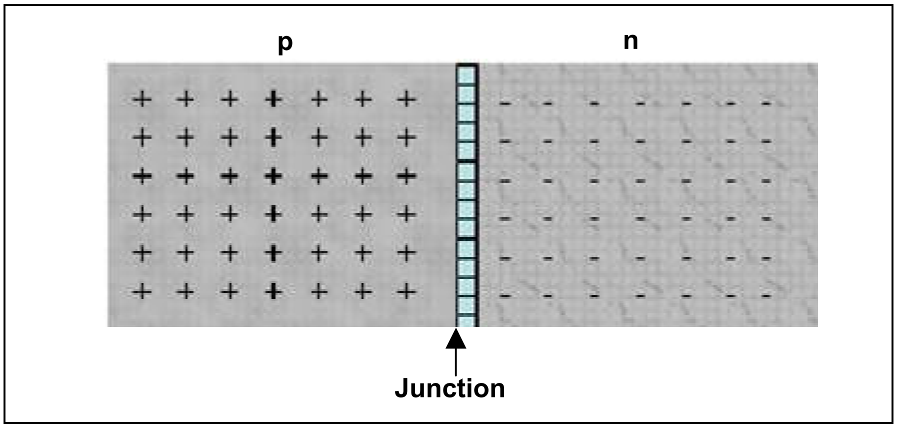


**Figure 1.** SSD semiconductor chip p and n regions

UV light sources constructed with SSDs could be as simple as an LED array, but to address industrial applications a number of other issues must be addressed:

1. The light must be efficiently collected and directed at the target.
2. The heat must be properly managed.
3. The uniformity, intensity, and size must meet or exceed production requirements at acceptable cost.
4. Electronic control must allow on/off, pulsing, and intensity control and be insensitive to failures of individual SSDs.

**Benefits of solid-state light sources**

The benefits of SSDs are numerous and varied, as shown in the table in figure 2. Some of the more significant advantages include the ability to manufacture solid state UV light "modules" that produce efficient output of high intensity, uniform, narrow emission band of UV light. These "modules" are truly modular – they can be placed in a line, wrapped around an object, or cover an area to accomplish a wide variety of applications. In the following sections the topics summarized in the table below will be explored in greater detail.

| Description | Arc Lamp | Flash Lamp | Microwave | Solid State |
|---|---|---|---|---|
| Performance: | | | | |
| Cost of Ownership | High | High | High | **Low** |
| Light Source Life Time | 200-2,000hrs | 200-2,000hrs | 3,000-6,000 hrs | **>10,000 hrs** |
| Consistency of output over time | Continual drop over time | Continual drop over time | Good | **Excellent** |
| Output Uniformity source to source | Good | Poor | Good | **Excellent** |
| Light source Uniformity at work surface | <20% | | | **<5%** |
| Spectral distribution | Wide spectral bandwidth where only 5% of light generated useful for curing | | | **Narrow band (40 nm typical)** |
| Irradiance | > 1 $Watt/cm^2$ | | | **> 1 $Watt/cm^2$** |
| Ease of Integration: | | | | |
| Size- | Bulb with bulk optics and power supplies | Bulb with bulk optics and large power supplies | Bulb with bulk optics. large and expensive magnetrons | **Thin, flat panel** |
| Electrical | High power, complex supplies | | | **Low Power, PC control** |
| Cooling | Air or water | | | **Air or water** |
| Safety | High voltage<br>Possible ozone, bulb breakage | | | **Low-voltage No ozone, no bulb to break** |
| Efficiency: | | | | |
| Electrical-to-optical efficiency (for light used in curing process) | 5% of light output is used for curing | 5% of light output is used for curing | 5% of light output is used for curing | **>10%** |
| Thermal efficiency | 5% | 5% | 5%[2] | **> 5X arc lamp, depending on application** |
| Production issues: | | | | |
| Warm-up time | 30min | High-speed on/off | Slow on/off | **Instant On/Off** |
| Consumables | Bulbs | Bulbs | Microwave components | **None** |
| Preventive Maintenance | Replace bulbs Clean Reflectors | Replace bulbs Clean Reflectors | Repair/maintain magnetron and other microwave components | **None** |

**Figure 2.** Summary table comparing various UV Light Sources.

As the table in figure 2 indicates, there are clear advantages of solid state light sources. Detailed descriptions and examples of the key benefits related to performance, ease of integration, and efficiency of the solid state light source are described in the following sections.

**Performance: Cost of ownership**

There are several dimensions to the cost of ownership of a UV light source, including power used, cooling water required, the cost of consumables (including bulbs) and the labor cost required to maintain the equipment.

When considering the cost of ownership, SSD light sources have significant advantages over traditional UV light sources. The optional cability to pulse the SSD or to turn it on/off during the curing cycle not only saves money by reducing electrical use, it enables "recipes" for the light profile not previously possible, and it reduces the cooling requirements – allowing SSDs to be used with air cooling in many applications that would otherwise require water-cooled arc lamps. Thee SSD source also eliminates the need for shutter, Faraday cages, heat filters, and spinning or cooling stations in the integrated solution. The table in figure 3 summarizes and compares the cost of ownership between an arc lamp and an SSD source.

| **COO Base Parameters** | | | | |
|---|---|---|---|---|
| Work schedule | 24 hours/day, 5 days/week, 52 weeks/year = 6,240 hours/year | | | |
| Utilities cost | $0.08 per KWH (EU mean) | | | |
| Facilities cost | $0.03 per KWH used for air conditioning | | | |
| Light source duty cycle | Exposure time ÷ cycle time = 0.3 | | | |
| Cooling water | $0.15/100 liter | | | |
| Burdened labor cost | $25/hr | | | |
| **Operating Cost Assumptions** | | | | |
| | Arc Lamp | | SSD Light Source | |
| Average input power required<br>Cost of energy/year | 3 kW | $1498 | 0.9 kW | $449 |
| Cooling water<br>Cost of water/year | 180 liter/hr | $1,685 | None | $0 |
| Average lifetime of bulb<br>Cost of bulbs/yr @ $800/bulb | 1500 hr | $3,328 | NA | $0 |
| Labor to replace a bulb<br>Labor cost/yr for maintenance | 15 min | $26 | NA | $0 |
| Preventive maintenance kits (lamp reflector maintenance kit, mercury lamp cleanup kit, solution, and protective gloves) | | $352 | | $0 |
| **Total operating cost** | | **$6889** | | **$449** |

**Figure 3.** Summary table compares cost of ownership for SSDs and arc lamps.

**Performance: Light Source Lifetime**

One of the most substantial advantages of SSDs is lifetime. Arc lamps have a well-known characteristic of power drop off as a function of time. Failure can result from several causes, including contamination of the quartz envelope encasing the ionized gas, and degradation of the electrodes of arc lamps. Unless the bulb breaks, the output of arc lamps will gradually decrease in radiant output and the relative intensity of each wavelength will change during this degradation. This can effectively limit their use in many applications to less than 1000 hours (see figure 4), which results not only significant cost in replacement of bulbs, but also significant cost in lost productivity due to the time required to cool the bulbs before they can be physically removed and replaced at the end of their lifetimes. There is also a hidden design cost since engineers specify their systems with a certain amount of "padding" to ensure that the rated output of the bulb will remain above the required specification for its expected lifetime.

In contrast, SSDs show virtually no degradation over more than a thousand hours of operation as shown in figure 4. Projected lifetimes based on these stressed tests predict useful lifetimes in excess of 10,000 hours.

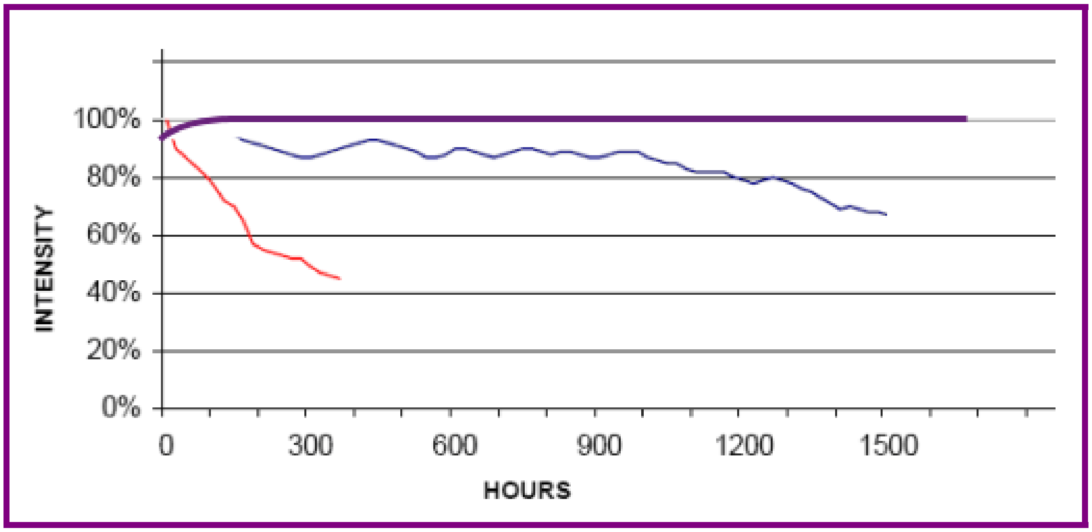


**Figure 4**. Lifetime data for two commercially available arc lamps and SSD Light Source. While no appreciable degradation was observed during this test, > 10,000 hrs is estimated for the SSD.

**Performance: Output uniformity**

SSDs light sources have an impressive range of control that is unavailable from any other light source. Stable optical power over time is one clear example, but another example is the uniform power density available from these devices. Figure 5 shows the power density of the Phoseon RX20 UV light source over an area measuring 8inches by 8 inches. The power density of the center 95% of the illumination pattern has an RMS value of less than 4%.

The output intensity can be set at any value between the minimum and maximum by simply adjusting the current, almost linear from zero to maximum output with no variation in the uniformity.

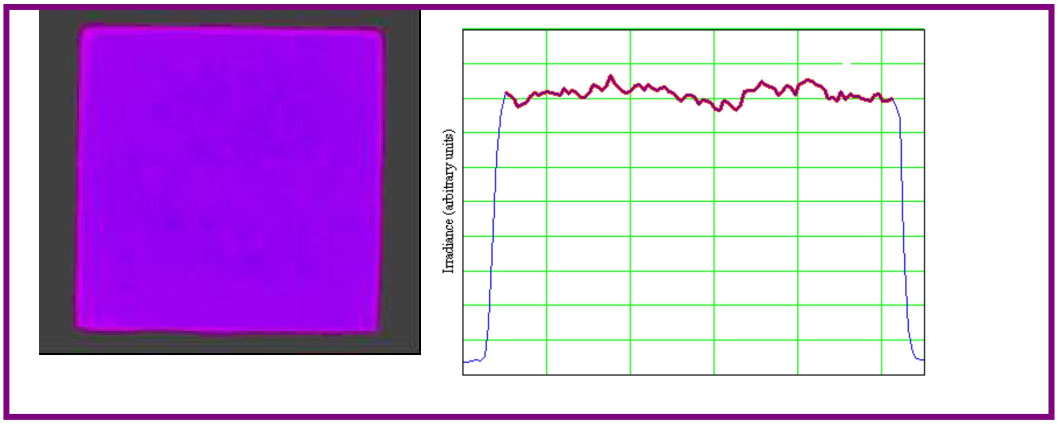


**Figure 5.** Illumination pattern (8 inch by 8 inch) produced SSD light source shows uniformity variation less than 4% at curing intensities.

**Performance: Spectral Distribution**

Light from the mercury arc lamp is distributed over the spectrum, from deep UV to the infrared. Some of the long IR is due to the fact that the surface temperature of an ultraviolet lamp under normal operating conditions is between 600° C and 800° C, which means these lamps can cause significant heating of the work piece.

By contrast, the spectral distribution from the SSD is concentrated in an intense narrow spectral range as shown in figure 6. Since the photons generated by SSDs have a narrow spectral distribution (typically 40nm), all the light produced is useful for initiating the desired chemical reactions.

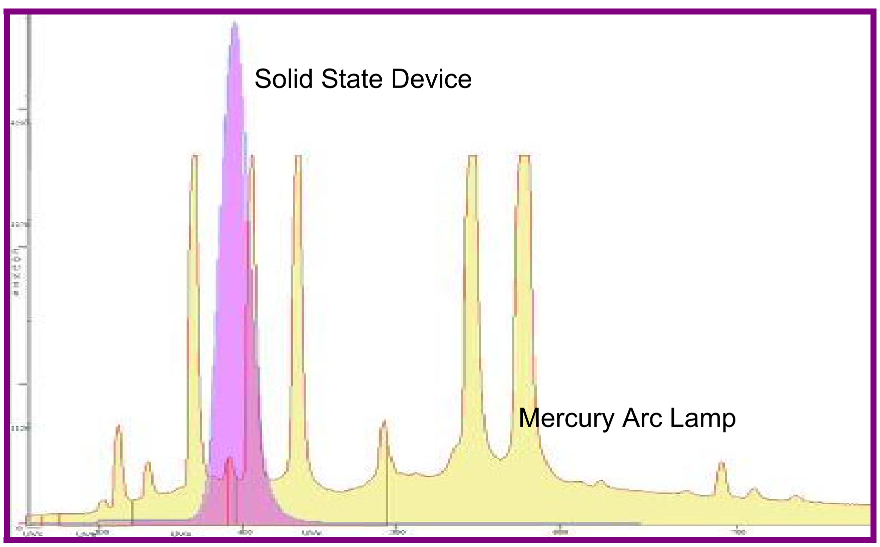


**Figure 6.** Spectral output of a medium-pressure mercury arc lamp and SSD, showing the SSD to be both more intense and have a more narrow band of emission.

While many polymer materials have photoinitiators today that are not designed for the SSDs, it is much simpler to develop a polymer system for such a uniform, high intensity source. Internal studies have confirmed that there are significant advantages to increasing the intensity at the same dose for any given material, that longer UV wavelengths allow deeper penetration and inside-out curing, and other advantages which will be published in separate papers.

**Ease of Integration**

The advantages of SSDs are not just improved curing and the optical and performance advantages stated previously. The solid state curing systems are also significantly easier to integrate for the following reasons:

- **Size.** Commercially available units are capable of producing over 100 watts of UV light over an area up to 8 inches square, while occupying a volume less than 0.2 cubic feet (350 cubic inches) complete with an integrated cooling fan and heat sink (see figure 7). The total volume burden of a lamp system is not just a function of the size of the bulb, but also the associated optics, shutters, filters, and utilities required to the curing head. This includes power supplies and cooling air/water. The lower power consumption of SSDs allows small/efficient computer controlled power supplies and movement to air cooled heat sinks in most applications.
- **Weight.** Not only are SSD-based UV light sources small, they are low weight (often just a few pounds). This makes them an ideal solution for applications (such as print heads) that mount the light source on a piece of moving equipment.
- **Control.** SSD light modules can be computer controlled, or can be turned on/off with TTL signals, shut-off in response to interlocks or fault detectors, or programmed with custom recipes involving a mixture of intensities levels.


**Figure 7**. Integrated solid-state UV light source and power supply (RX10 manufactured by Phoseon Technology) and a 5 kW high-pressure mercury arc lamp.

## Efficiency

SSDs produce light efficiently, converting 15-30% of the input electrical power into useful UV light.[3,4] As a point of reference, note incandescent bulbs convert only about 3.5% of the input power into visible light.

In addition to the electrical-to-optical efficiency, which is the efficiency with which input electrical energy is converted into optical energy, another helpful figure of merit is the ratio of cure cycle to total cycle time or duty factor. Since the mercury arc lamp must be left on continuously to maintain proper illumination uniformity and balance, the duty factor will always be 100%. While SSD light sources which can be turned on/off instantly will always have a better efficiency and offer the following advantages:

1. During the “off” time the SSDs don’t draw power. For high-power systems this can result in significant energy and cost savings, and also elimination of the shutter.
2. The ability to turn the SSDs on when they are needed, and off when they aren’t, means the cooling systems can be designed with less average capacity. This reduced thermal load can result in the possibility of using air cooling instead of water cooling.
3. Limiting the “on” time to time actually used extends the life of the SSDs, which already have a >10x advantage in lifetime over lamp sources.

## Curing Results

The ability to pulse the light source also allows the user to program complicated “recipes” that might, for example, involve a high intensity pulse followed by a lower intensity continuous dose of a lower amplitude, and then turning off between cure cycles. The number of possible pulse/intensity/ duration recipes is virtually infinite and opens up whole new possibilities for UV curing applications.

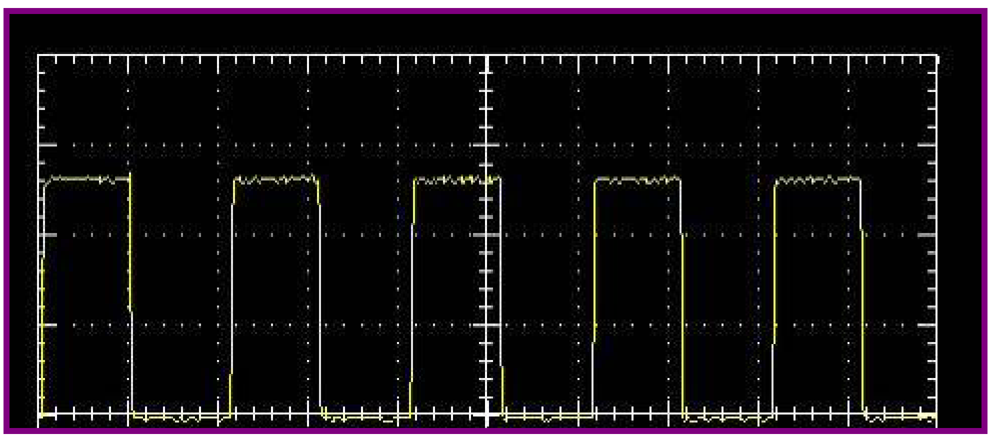

**Figure 8.** SSD sources can provide instantaneous pulses with <1 msec rise times, allowing variable intensities, on/off control, and programmable cure recipes in addition to traditional continuous cures.

One of the key benefits of this ability to pulse involves overcoming the problem of tacky surface curing due to oxygen inhibition. Most UV-curable resins use acrylate monomers and oligomers that create cross-linked polymers through photoinitiation of radical polymerization.

In the presence of oxygen, however, the free radicals created by the photolysis of the initiator react with $O_2$ molecules to yield peroxyl radicals.[5] This presents a problem, however, since peroxyl radicals don't react with the acrylate double bounds and therefore cannot initiate or participate in the polymerization reaction. Since UV-curing is typically done in the presence of air, oxygen inhibition has been a persistent problem.[6,7,8]. Several techniques are used to overcome this problem, with pulses of high-intensity light and inert gas envelopes being two of the most common.[9]

Because of oxygen inhibition, there are times when designers need a brief but powerful blast of UV radiation for a proper cure, yet don't want or need to leave the light source operating at such elevated power levels for an extended period of time. In such applications, SSD arrays provide an immediate and important advantage.

In addition, excess heat produced by other light sources can cause heating of parts. SSD light sources do not introduce excess heat to the device being cured. Figure 9 shows that curing of inks, coating, or adhesives on wafers or other media can be done without significantly heating the media above ambient temperatures. For many materials, such as thin films and plastic parts, this will be an enabling capability.

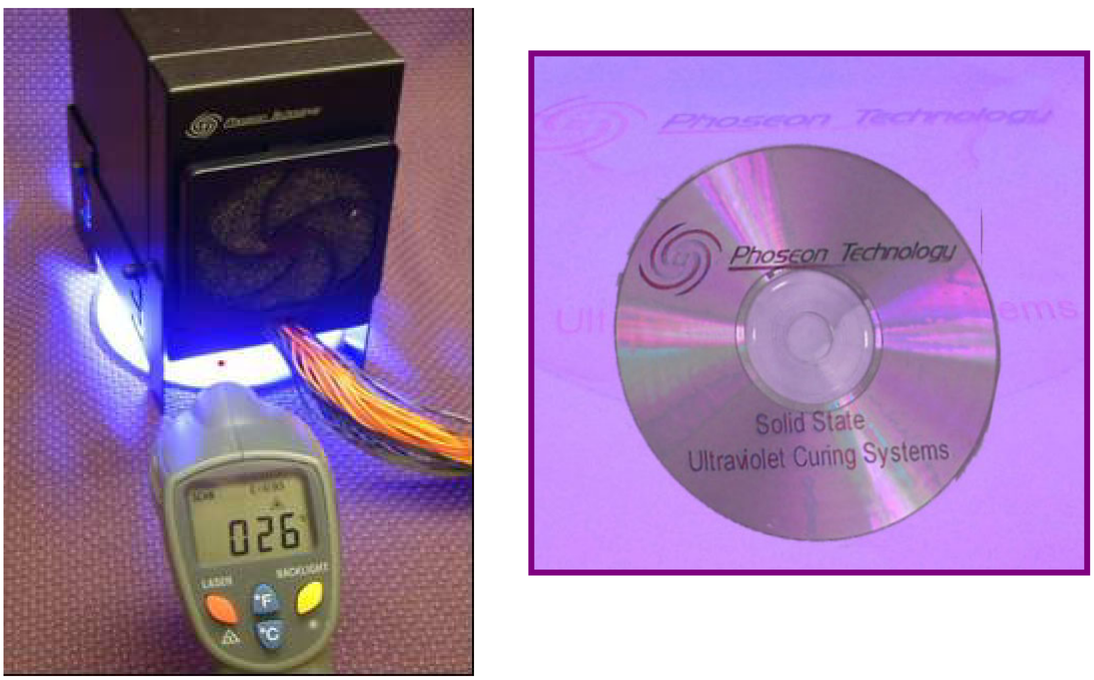


**Figure 9.** Heat sensitive media are an ideal fit with SSD devices, which only heat the media slightly above ambient temperatures during the cure cycle.

## Safety considerations

Modern high-power arc lamps operate at high temperature and pressure to produce the maximum amount of output optical power. The internal pressure of a xenon arc lamp, for example, can exceed 10 atmospheres, even when not in operation. While broken tubes are relatively rare, the possibility of breaking does entail an element of risk and subsequent caution and procedures to ensure the safety of workers who handle the bulbs. Because of this risk, handling procedures require that personnel always wear eye, face, and body protection when handling arc lamps, and extreme care to ensure the bulbs are not bumped, dropped, or excessively stressed or scratched. These lamps must also be disposed of in accordance with local laws for the disposal of hazardous waste and to avoid injury after disposal.

Another safety concern when using certain types of lamps is the production of ozone. Ozone is a molecule consisting of three oxygen atoms. Under normal conditions it is a pale blue gas toxic to humans, and must be vented to ensure worker safety. Ozone is produced by ultraviolet radiation when a photon of wavelength less than 240 nm breaks an $O_2$ molecule into two oxygen atoms, whereupon the free oxygen atoms bond to other $O_2$ molecules:

$$O_2 + h\nu_{<240nm} \rightarrow O + O$$
$$O + O_2 \rightarrow O_3$$

In contrast to arc lamps, SSDs present no inherent health risks for personnel using them, beyond the obvious (and necessary) requirement that proper eye protection is used to guard against their bright light. SSDs outputs do not include any wavelengths less than 240nm, so they inherently do not produce ozone, and contain no toxic waste products.

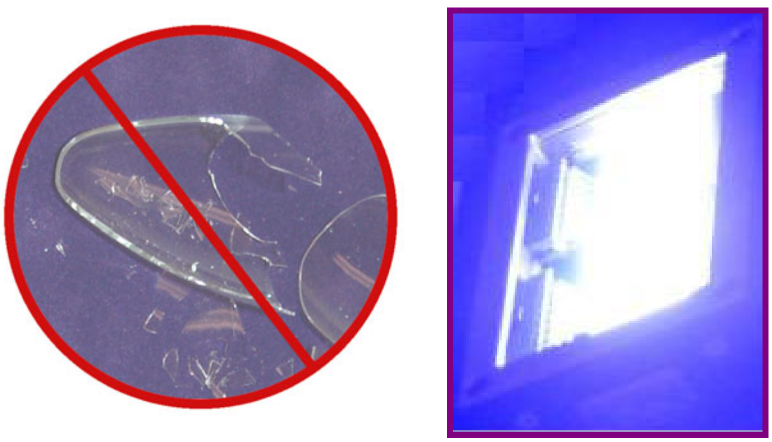

**Figure 10.** SSDs like the one on the right avoid all the key safety issues of arc lamps: they have no high pressures, no burning heat, no toxic materials, and operate in visually safer optical ranges.

**Conclusions**

Arc lamps are a traditional and established source of UV radiation based on technology that has remained essentially unchanged for over half a century. While they continue to play an important roll whenever brilliant, broad spectral UV light is required, the ground work is laid and the process is in motion for replacing, yet again, another “tube” with the efficiency, reliability, compactness and versatility of a semiconductor device.

Results show significant advantages of a newly developed solid state device (SSD) now in production, which eliminates the heat, electromagnetic interference, dangers, process variations, and power degradation associated with traditional bulb based sources. Additionally, it has been shown to offer cost, speed, modularity, processing advantages, and is enabling new applications not previously possible.

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