UV LEDs for Disinfection

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INTRODUCTION

The ultraviolet (UV) disinfection market continues to grow and expand for municipal, industrial, and private applications because of UV's numerous benefits. These benefits include the ability to inactivate chlorine-resistant microorganisms, such as *Cryptosporidium*, while minimizing regulated disinfection byproducts (in drinking water applications) and to provide effective disinfection without the need for chemical chlorination and dechlorination (in wastewater applications). Typical criticisms of current UV disinfection systems include the mercury content of the UV lamps, lamp replacement costs, and high energy usage. Thus, alternative sources of UV radiation, specifically within the germicidal or UV-C range, continue to be investigated (Heering, 2004). One promising technology is UV light emitting diodes (UV LEDs). UV LEDs do not contain mercury, do not require a significant warm-up time period, provide design flexibility due to their small size, and have the potential for a longer operational life than conventional mercury lamps (Bowker et al., 2010).

The potential applications for more efficient UV LEDs are considerable as companies continue to expand the efficiency and availability of these devices. UV LED technology delivers several value-added solutions to industries, in applications where traditional UV sources are too bulky, slow switching, or not capable of providing the desired wavelength spectrum. Some examples of current markets include: protein analysis, medical diagnostics, drug discovery, gas detection, end point detection and bio-threat detection (Birtalan, 2010; Shur & Gaska, 2010). Similar to existing technologies, accelerating UV LED production is expected to significantly drive down the cost and further improve the performance. This reduction in cost will open several large consumer-oriented markets, such as phototherapy, UV curing, and water and air disinfection.

UV LED ARCHITECTURE

Light emitting diodes (LEDs) are created by combining a p-type semiconductor with an n-type semiconductor. When connected to a power source, electrons will flow to the junction of the p-type and n-type semiconductors, fall into the empty orbitals of the valence band and cause energy to be released as light (Casiday and Frey, 2007). Over recent decades, visible LED technology emerged from low intensity indicators to LED backlit TVs and lighting. Advanced red and blue LEDs can now deliver wall plug efficiency (WPE) values above 60 percent (Semiconductor Today, 2011; Laubsch et al., 2010). Wall plug efficiency can be defined as the ratio between the total output radiant power to the input electrical power. The LED theory and recent experiments show that LED WPE could, in principle, exceed 100 percent (Zukauskas et al., 2002; Santhanam et al., 2012).

The wavelength of the electromagnetic energy emitted by an LED depends on the bandgap between the semiconductor materials. The use of LEDs to produce red light was discovered in the 1960s and, since then, the implementation of various materials as semiconductors has allowed the emission of wavelengths ranging from the infrared range through the visible range and into the UV range. The semiconductor materials that display the most potential for LEDs in the UV-B and UV-C spectral range are gallium nitride (GaN) and aluminum nitride (AlN) (Kneissl et al., 2010). UV LEDs consist of a semiconductor chip packaged into a transistor outline (TO) or surface mount device (SMD) to facilitate electrical connections. For the emission in the UV-C spectral range (i.e., $\lambda < 280$ nm), all of the layers of the LED chip are typically made of AlGaN epitaxially grown on sapphire or AlN substrate. As shown in Figure 1, after the growth and device fabrication steps, the UV LED chips are cingulated and flip-chip bonded on to carriers for electrical connections and heat-sinking. UV emission is generated in the multiple quantum well region (MQW) surrounded by the p- and n-AlGaN layers that form the p-n junction (Zhang et al., 2005).

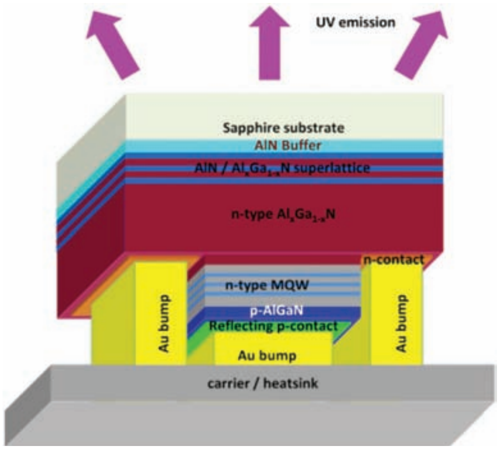

Figure 1. Schematic View of a UV LED Chip Structure.

Figure 2. Typical package types of single chip UVTOP® LEDs and multiple chip UVCLEAN® LED lamps (www.s-et.com)

A standard UV LED from SETi is packaged into a TO-39 can with a diameter of 0.32 inch (see Figure 2). Packages can be supplied with variety of optics ranging from flat window (e.g., UVTOP-270-TO39-FW) to hemispherical (e.g., UVTOP-270-TO39-HS) or ball (e.g., UVTOP-270-TO39-BL) lenses that allow the angular emission distribution to vary from +/- 60o (FW) to 6o (HS) divergence or achievement of a focused spot (BL). Multiple chip UVCLEAN LED "lamps" can be supplied with output power ranges of 1-3mW, 3-5mW, 10-15mW, and 30-50mW packaged in either TO-39 or larger TO-3 packages depending on the number of LED chips, wavelengths, and built-in optical power thermal controls.

UV INTENSITY, EFFICIENCY, AND ELECTRICAL REQUIREMENTS

Most commercially-available UV LEDs have typical wall plug efficiencies of 0.5-2 percent, which is primarily related to the quality of the epitaxialy-grown AlGaN layers and optical losses during extraction of generated light from the LED chip. Several UV LED developers address these deficiencies under the support from DARPA's (Defense Advanced Research Projects Agency) Compact Mid-Ultraviolet Technology (CMUVT) program that targets development of 100 milliwatt (mW) LEDs operating in the range of 250 – 275 nanometers (nm) with 20 percent wall-plug efficiency. Each of the manufacturing techniques currently in use has unique challenges in achieving high quality conduction layers. For example, with LED layers deposited on sapphire, issues can arise from an atomic mismatch between the substrate and nitride layers, which generates a very high density of dislocations (up to 1010 cm-2). By tuning proprietary material deposition processes and using patent-pending designs of LED chips and packages, a 278 nm UV LED with wall-plug efficiency well over 5 percent has been recently demonstrated (SETi and US Army Research Laboratory: Shatalov et al., 2012).

Since the technology is still in its infancy, there are many challenges with UV LEDs in the germicidal range (also referred to as deep UV LEDs or UVC LEDs). Issues with the current technology include the potential for device self heating and defect formation in the active region of the chips. The result of these issues include power outputs around 1 mW at 20 mA, low wall-plug efficiencies, and typical device lifetimes of approximately 1,000 hours (Hwang et al., 2011; Shatalov et al., 2010). Researchers are therefore focusing on improving and optimizing the UV LED design and packaging to improve output power and device reliability (Hwang et al., 2011).

Table 1 displays the power output and wavelength of UV LEDs represented in the literature. As shown, UV LEDs in the literature have generally produced a power output of 1 mW or less per LED, with a few exceptions. The UV LEDs with significantly higher output correspond with a higher input current than the commonly used 20 mA. The power outputs are a function of the emitting wavelength and the current provided. However, a higher input current will generally lead to an increased tendency for self-heating, causing shorter lifetimes. Electrical current values above the common 20-25 mA will lead to more heat being dissipated than the amount of the UV energy emitted by the LED. As the manufacturing technology improves, this excess heat problem may be lessened.

A few manufacturers are trying to improve the deep UV LED technology by growing a low defect bulk AlN substrate (Khan, 2008). Grandusky et al. grew the AlN substrates for this configuration using "conventional metal organic chemical vapor disposition" (2010). For a 248 nm UV LED, pulsed operation provided an output power ranging from 1.44 mW to 16.3 mW, depending on the input current. Continuous wave mode for a 243 nm UV LED provided an output power of 1 mW at 25 mA, but it was reported that the continuously running LEDs had the tendency for self heating (Grandusky et al., 2010).

As with most semiconductor devices, the manufacturing techniques and material combinations are extensive for production of UV LEDs. Several studies have investigated the use of a single large area chip design as opposed to the more commonly used small active area chip for UV LEDs. Adivarahan et al. (2009) used a large area chip combined with a flip-chip packaging scheme for the design of a 280 nm UV LED and reported a maximum output power of 42 mW at 1 A with a lifetime over 1,500 hours. Shatalov et al. (2010) also reported improved power by utilizing a single large area chip design. For a 273 nm emission, a peak UV LED output of 30 mW at 700 mA was reached, while a 247 nm emission produced an output of 6 mW at 300 mA. However, the wall-plug efficiency for the 247 nm UV LED setup remained at a low value of 0.25 percent (Shatalov et al., 2010). Recently, SETi has achieved a considerable improvement of LED performance in the 275-280 nm spectral range with the peak wall-plug efficiency reaching 8 percent (Shatalov et al., 2012).

Table 1. UV LED Wavelength and Power Outputs

Wavelength (nm)	Output (mW)*	Reference
268.6	5.8 (10 LEDs)	Vilhunen et al. 2009
276.1	11.6 (10 LEDs)	Vilhunen et al. 2009
280	22 (400 mA input)	Adivarahan et al. 2009
265	unknown	Chatterley and Linden 2010
255	0.3	Bowker et al. 2010
275	0.5	Bowker et al. 2010
247	6 (300 mA input)	Shatalov et al. 2010
243	1	Grandusky et al. 2010
273	30 (700 mA input)	Shatalov et al. 2010
269	0.33	Wurtele et al. 2011
282	0.65	Wurtele et al. 2011
276	0.4	Hwang et al. 2011
278	9.8	Shatalov et al. 2012
* Power output varies greatly by input current. Higher power outputs require higher currents that may lead to shorter lifetimes.		

To address power-demanding applications, such as microbial and viral disinfection, SETi has developed and launched multiple chip UVCLEAN® LED lamps and products with powers over 100 mW at 275 nm. Efforts at producing high-power single-chip LEDs with similar output are underway and 100 mW output from a single LED chip with an active area of 1 mm2 has been demonstrated.

COMPARISON TO MERCURY EXCITATION LAMPS

Through the years, UV electromagnetic radiation has primarily been based on tube technology first developed in the early 20th century (Hewitt, 1901). UV lamps are capable of generating high optical output levels but have several potential drawbacks. The advantages and disadvantages of mercury-filled lamps compared to UV LEDs are shown in Table 2.

Unlike mercury arc lamps, UV LED sources consume relatively low current (<1A) with a typical operating voltage less than 10 V. A mercury lamp requires a switching and startup time on the order of several seconds to minutes, whereas the switch-on time characteristic of a UV LED is measured in nanoseconds. Much faster switching provides the possibility of constructing on-demand disinfection systems, which can be normally switched off and turned on only when needed. This added flexibility translates into a tremendous increase of the system life even if the LED and lamp continuous operation lifetimes are comparable. Further, the emission wavelength from a UV LED can be tuned to a specific target required by the application, which can allow more flexibility in design.

In comparison to the UV LED output values, low-pressure UV mercury lamps currently have a higher electrical to germicidal efficiency of around 35-38 percent and generate a higher germicidal UV output of 0.2 W/cm (USEPA, 2006). Thus, the use of LEDs for water disinfection is now limited to very low flow and batch-type devices. Although deep UV LEDs still suffer from low efficiency and low power output, researchers predict that the technology will improve dramatically within several years. Khan (2008) describes the current UV LED progress as similar to the mid-1990s visible nitride LEDs. Blue visible nitride LEDs have since reached wall-plug efficiencies of 60 percent (Kneissl et al., 2010).

DISINFECTION RESEARCH WITH UV LEDS

Several studies have researched the effects of irradiation by UV LEDs on different strains of *E. coli*. Mori et al. (2007) investigated the inactivation of *E. coli* DH5**α** when exposed to irradiation from a sterilization device that connected 8 UV-A LEDs emitting at a wavelength of 365 nm. Mori et al. (2007) also conducted batch experiments to find the *E. coli* inactivation due to an LED emitting light at 405 nm and a low-pressure mercury lamp emitting light at 254 nm. Results showed that a UV-A fluence (365 nm) of 54 J/cm2 resulted in a 3.9 log reduction of *E. coli* DH5□, while irradiation by the 405 nm UV LED resulted in no inactivation (Mori et al., 2007).

Table 2. Advantages and Disadvantages of UV LEDs and Mercury Vapor Lamps

	Advantages *	Disadvantages *
UV Mercury Vapor Lamps	• High wall plug efficiency compared to LEDs • High output power • Readily available • Long lamp life	• Fragile • Mercury poses a potential biological hazard • Potential for ozone production • Used lamps require proper disposal or recycling • Fixed spectral output • Slow on/off switching
UV LEDs	• Consume low current (<1 A) • Typical operating voltages less than 10 V • Nanosecond switch on/off time • Emission wavelength can be tuned to application	• Low output power • Low efficiency • High unit price • Sensitive to input power magnitude and fluctuation • Short usable life
*Based on current technologies.		

Vilhunen et al. (2009) investigated the effect of UV irradiation from 269 and 276 nm UV LEDs on another strain of *E. coli* (K12). The setup consisted of two batch reactors with ten LEDs in each. The radiant fluxes from the 269 and 276 nm LED systems were measured as 5.8 and 11.6 mW, respectively. Results showed 3- to 4-log reductions within 5 minutes for experiments using both wavelengths (Vilhunen et al., 2009). However, since the results were not reported in terms of UV fluence or UV dose, they are difficult to compare to other UV LED disinfection literature results.

Chatterley and Linden (2010) also evaluated UV LEDs (265 nm) for the inactivation of *E. coli* K12 by comparing the results to inactivation caused by low-pressure mercury lamps. Along with bench scale experiments, their research also involved an evaluation of a flow-through UV LED reactor using biodosimetry with the same strain of *E. coli*. It was reported that for the same UV dose, *E. coli* inactivation was not statistically different for LED and low-pressure mercury lamp irradiation at a 95 percent confidence interval. For the flow-through experiments, the reactor consisted of 40 LEDs at 265 nm producing an approximate dose of 40 mJ/cm2 at a flow rate of 11.1 mL/min (Chatterley and Linden, 2010).

More recently, Wurtele et al. (2011) investigated the inactivation of *B. subtilis* spores using irradiation by 269 nm and 282 nm UV LEDs, including flow-through experiments using the 282 nm LEDs. The results indicated that both wavelengths produced effective *B. subtilis* inactivation, but only after exposure times longer than three minutes. Also, despite the germicidal effectiveness of the 269 nm LEDs being greater than the 282 nm LEDs, the higher power output allowed the 282 nm LEDs to produce higher *B. subtilis* inactivation.

Bowker et al. (2010) conducted collimated beam experiments with UV LEDs to determine the UV response kinetics of three different challenge microorganisms (MS-2, T7, and *E. coli*). Experimental tests were performed with UV LEDs emitting two unique wavelengths (255 and 275 nm). The LED arrays used within the collimated beam apparatus for each of these wavelengths is shown in Figure 3. The collimated beam apparatus used 8 UV LEDs for the 255 nm setup and 4 UV LEDs for the 275 nm setup. For a manufacturer-recommended current value of 20 mA, the 255 nm and 275 nm UV LEDs produced a power output of approximately 0.3 mW and 0.5 mW, respectively. One objective of the study was to determine the impact, if any, on the UV response kinetics of the microorganisms given the difference in wavelengths and power outputs. The results were compared with the dose-response from a low-pressure mercury lamp (Bowker et al., 2010).

The range of average UV fluences used in Bowker et al. (2010) paralleled the UV fluence ranges in Sommer et al. (1998) and Bohrerova et al. (2008), which contain the UV dose-response curves for MS-2, *E. coli*, and T7 irradiated by a UV low-pressure mercury lamp (0-60 mJ/cm2 for MS-2, 0-20 mJ/cm2 for T7, and 0-12 mJ/

cm2 for *E. coli*). To illustrate the effect of decrease in light source power output on the exposure time to achieve a specific dose, the average exposure time required to achieve 45 mJ/cm2 for the MS-2 experiments is shown for each light source in Table 3.

(a) (b)
Figure 3. LED Arrays Within Collimated Beam for 255-nm (a) and 275-nm (b)

Table 3. Exposure Times Required to achieve 45 mJ/cm² for the MS-2 Experiments (Bowker et al., 2010)

UV Light Source	Low-Pressure Lamp	255 nm LED	275 nm LED
Average Exposure Time (sec)	160	1,200	640

Table 4 displays a subset of the results of the bench scale collimated beam experiments in Bowker et al. (2010). The MS-2 bacteriophage responded with lower reduction rates for the 255 nm UV LED experiments than for the low-pressure mercury lamp experiments. However, the decrease in inactivation rates from low-pressure to 255 nm UV LEDs was much smaller than with the *E. coli* experiments. The MS-2 experiments with UV LEDs emitting at 275 nm resulted in very similar UV dose response kinetics to the 255 nm LED experiments with slightly lower inactivation values at higher UV doses. The spectral sensitivity of MS-2 displays a peak around 260 nm, which may explain the slightly higher inactivation for 255 nm compared to 275 nm LEDs (Mamane-Gravetz et al., 2005). The results for *E. coli* and T7 are reported in Bowker et al. (2010).

Table 4. MS-2 Inactivation by UV LEDs and Low-Pressure Lamps (Bowker et al., 2010)

	255 nm LED		275 nm LED		Low-Pressure Lamp	
Dose (mJ/cm²)	Log (N0/N)	Std Dev	Log (N0/N)	Std Dev	Log (N0/N)	Std Dev
15	0.636	0.109	0.678	0.109	0.848	0.211
30	1.208	0.031	1.182	0.031	1.562	0.069
45	1.848	0.095	1.776	0.095	2.165	0.242

Table 5. T7 Inactivation by UV LEDs and Low-Pressure Lamps (Bowker et al., 2010)

	255 nm LED		275 nm LED		Low-Pressure Lamp	
Dose (mJ/cm²)	Log (N0/N)	Std Dev	Log (N0/N)	Std Dev	Log (N0/N)	Std Dev
5	1.697	0.144	1.797	0.016	1.785	0.051
10	2.465	0.163	2.703	0.042	2.798	0.140
15	3.162	0.215	3.639	0.018	3.572	-

As shown in Table 5, T7 bacteriophage experiments resulted in slightly lower inactivation values for the same UV fluences with irradiation by 255 nm UV LEDs compared to low-pressure mercury lamp irradiation. Unlike MS-2, the T7 275 nm LED experiments resulted in very similar UV fluence-response kinetics to the low-pressure mercury lamp results and a slightly higher log inactivation for each UV fluence value when compared to the 255 nm UV LED experiments (Bowker et al., 2010). The action spectrum of T7 displays a small peak around 270 nm, which may explain the increased inactivation by the 275 nm UV LEDs compared to the 255 nm UV LEDs (Ronto et al., 1992).

Low-Flow Reactors

While the efficiency of deep UV LEDs is still being improved, LED sources are already being used in various water disinfection studies (Gaska et al., 2011; Bowker et al., 2011; Vilhunen et al., 2009; Wurtele et al., 2011). SETi reported the design and fabrication of several low-flow UV LED water disinfection chambers. Intense effort was placed on designing a unit that could meet Class A drinking water standards as categorized under the NSF 55 standard for point-of-use (POU) and point-of-entry (POE) non-public water supply (non-PWS) ultraviolet systems. Testing was geared towards achieving the NSF-55 standard 6-log reduction of bacterial contamination and 4-log reduction of viruses in drinking water. In a recent report, a small point-of-use chamber (~0.7L) based on four UVCLEAN® LED lamps was designed for water flow rates ranging from 0.5 L/min to 2 L/min (Gaska et al., 2011). E.coli (ATCC 11303) and Enterococcus (ATCC 10541) were selected as bacterial contaminants for reactor testing. At an input power of less than 20 W, an almost 7-log reduction of E.coli and a 5-log reduction of Enterococcus were achieved, as shown in Figure 4. As expected, the disinfection efficacy of the chamber declined with increased flow rate up to 2 liters per minute. Additional tests performed for MS-2 showed more than 2-log reduction at 0.5 L/min flow rate.

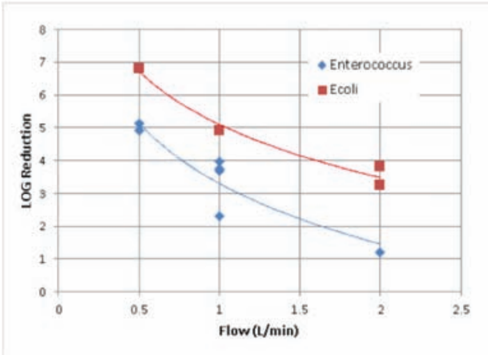

Figure 4. LED-based POU Disinfection Chamber Performance for *Enterococcus* and *E.coli* at Different Flow Rates.

While UV LEDS have the potential to increase the design flexibility of continuous flow UV reactors, current arrangements that have been proposed with these point light sources still include almost standard configurations used today (i.e., LEDs placed in a cylindrical quartz sleeve or placed along the walls). One of the challenges that remains is the ability to energize these UV LEDs at optimal locations that may be difficult to place due to reactor manufacturing limitations. UV LEDs will still require a quartz window as a barrier between the LED chip and the surrounding water. Inductive coupling to wirelessly power electronic devices dispersed in water is being developed and will significantly affect how UV LEDs are deployed spatially within continuous flow UV reactors (Kuipers et al, 2012).

RESEARCH & PRODUCT DEVELOPMENT NEEDS

Research using UV LEDs for water disinfection has proven that UV LED technology is capable of microbial inactivation but only with long exposure times or very low flow rates in continuous flow-through systems. The application of UV LEDs to date under these conditions is mainly due to the currently low-power output of the LED technology. Thus, the primary product development need continues to be improving the design and manufacture of the LED chip to increase both wall plug efficiency and overall output power. However, if the growth curve associated with visible light LEDs is any indication, UV LED efficiencies should grow exponentially over the next decade. The main aspects of the UV LED technology under investigation now are the material selection and chip manufacturing, as characteristics such as substrate and dislocation density ultimately influence LED efficiency and output. With the current technologies under development, projected values have been estimated at 20 mW output and 5% efficiency, with a large-step decrease in unit price, within the next 24 months.

CONCLUSIONS AND RECOMMENDATIONS

UV LED technology, especially for water disinfection, can still be considered to be in the development stage. The output powers and radiant efficiencies are currently too low, and the LED unit cost too high, for UV LEDs in the germicidal wavelength range to be considered practical for municipal water disinfection applications. UV LEDs, however, could be viable for point of use applications in a much shorter time frame than their projected application in larger municipal systems. Moreover, the current market is strong for UV LEDs in various other industries. IUVA recently co-sponsored a webinar on UV LEDs and panelists presented many current and potential uses within the health, water, air, energy, and food applications. UV LEDs are proposed to replace mercury lamps within some applications as well as open up new opportunities for UV-driven processes.

Given the current UV LED power output characteristics, the first commercial markets are, and will likely continue to be, industrial applications such as security identification, medical disinfection and food safety. Flow-through UV LED water disinfection devices are currently limited to very low flows (< 1 gallon per minute) for effective disinfection, due to the significant long exposure times required.

However, the predicted increase in power and efficiency in the near future may allow more cost effective point-of-use devices to be developed. Further, size and lifecycle advantages of UV LEDs may eventually lead to more rigorous water treatment devices for use in developing countries.

The mercury-based UV lamp remains the market choice for UV disinfection systems. The disadvantages of existing lamps are driving research of alternative germicidal UV sources. UV LEDs have come a long way over the past decade and based on the current levels of research funding and venture capital being invested in the technology, UV LEDs may eventually develop into a cost-effective option for water disinfection. Currently, several companies have made UV LEDs in the UV-C spectrum commercially available, while others are in the research and development stages. For example, UV LEDs with emission wavelength from 240 nm to 355 nm are commercially available from SETi with a pricing strategy that is aligned for early adopters that are relatively cost-insensitive to design and prototype systems based on emerging LED technology. As the UV LED market grows, commodity products are expected to demand low price, which will be achieved through large volume manufacturing and corresponding LED price reductions predicted to be in the $10 per unit price for larger volumes (above 1 million pieces). For additional information on the availability and uses of UV LEDs, readers are encouraged to visit the following websites:

Sensor Electronic Technology, Inc.: *http://www.s-et.com/*

Aquionics: *http://www.aquionics.com/main/*

Dot Metrics: *www.dotmetricstech.com/*

Crystal IS, Inc.: *http://www.crystal-is.com/*

Seoul Semiconductor: *http://www.acrich.com/en/*

HexaTech, Inc.: *http://www.hexatechinc.com/*

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