UV LED Technology: The Times They are A-Changin’

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“Come writers and critics
Who prophesize with your pen
And keep your eyes wide
The chance won’t come again
And don’t speak too soon
For the wheel’s still in spin
And there’s no tellin’ who
That it’s namin’
For the loser now
Will be later to win
For the times they are a-changin’.”
— Bob Dylan

Introduction
UV photonics, photoreaction and photoreactor systems are the key elements of many industries. Recent advances in a new UV source, the ultraviolet light emitting diode (UV LED), create the opportunity for the development of novel UV-based technologies and devices. In fact, UV LEDs could potentially transform the UV-based industry by not only advancing the design and application of current UV modules, but also enabling the creation of entirely new products and markets.

LEDs are semiconductor devices that emit radiation of a single wavelength. With recent breakthroughs in the development of new material synthesis and device technologies, LEDs can now be designed to produce UV radiation at a range of peak wavelengths. LEDs offer several advantages compared to conventional UV sources, such as UV lamps. These include compact and robust design, lower voltages and power requirements, longer lifetime and the ability to turn on and off instantly and with very high frequency. The specific features of UV LEDs make them an attractive alternative for replacing UV lamps in a number of applications. However, UV LEDs can offer much more than replacing conventional UV sources in existing systems.

The generation of high-energy UV photons from a solid-state miniature form-factor operating at low power makes UV LED a technology enabler. Presenting major advances in design, performance and application of the existing UV-based systems is an important function of UV LEDs, but, perhaps, much more important is providing the ability of creating novel UV-based technologies and devices that are made possible for the first time.

Here is a brief overview of UV LED development, followed by a discussion on UV LED system development, including UV LED reactors for water treatment, as well as other potential applications.

UV LED development
A great deal of progress has been made toward the performance of UV LEDs in the past several years. Starting in early 2000s with the appearance of the deep UV LED operating at 280s nm with only a few tens of microwatt power (Adivarahan et al., 2002a-b), many innovations in material growth and processing have led in high-efficient UV LEDs, with powers exceeding over tens or even hundreds of milliwatt output. Visible LEDs can operate at over 75% efficiency for more than 10 years. Currently, the efficiency and lifetime of UV LEDs are far less evolved than those of visible LEDs, although recent developments are showing impressive improvement in power output and efficiency.

Commercial deep UV LEDs have seen a major performance enhancement in terms of both efficiency and power, as well as cost reduction. It is predicted that UV LED’s recent price reduction will see the UV disinfection/purification market, which employs UVC, take over the UV curing market, which utilizes UV-A, by 2019 to 2020 (UV LED Market, 2016). Although the UV-A LED market is expected to grow substantially from US$107 million in 2015 to US$357 million by 2021, the UV-C LED market is predicted to grow even more dramatically from US$7 million in 2015 to US$610 million by 2021, according to the technology market analyst company Yole Développement (UV LED Market, 2016). The potential could be even greater, when considering UV LEDs’ ability to enable new technologies and devices. It is suggested that, while for many high-end applications UV LEDs are already competitive since they facilitate major advances and contribute only a small fraction to the overall cost, as UV LED performance improves over time, many more application areas will be determined (Kneissl, 2016).

UV LED reactor for water treatment
UV LEDs can be designed to produce UV radiation at an
optimal germicidal wavelength. The advantages of UV LEDs, compared to traditional low- and medium-pressure UV lamps, make them an appealing substitute for UV lamps in water treatment systems, in particular for applications with low and intermittent flows. At present, UV-C LEDs cannot compete with UV lamps in terms of power output, efficiency and energy cost. However, there are still various possible applications for UV LED technology within the water sector, including UV water treatment systems for drinking water, such as point-of-use (POU) applications.

The POU water purification market is undergoing a major transition due to an unprecedented growth in demand, resulting from higher awareness and economic growth, particularly in developing countries. This massive growth has not been accompanied by a corresponding development of new technologies and products, which has created a technology gap. This technology gap can be addressed by developing UV LED reactors that eliminate microbial contaminants, operate at low power and are practically maintenance-free. The conventional UV reactors operating with UV lamps have several limitations, including high power/voltage operation, high maintenance and high operating cost, which may limit their use in non-municipal water treatment systems. The UV LED reactors may have the potential to overcome many of the limitations of the existing UV lamp reactors and other currently used water treatment solutions.

For example, when a continuous supply of electricity is available, many technologies for POU water treatment are possible; however, rural communities, especially in developing countries, often do not have continuous access to electricity and are at great risk of being exposed to unsafe water supplies. This shortcoming can be addressed by designing UV LED water treatment systems, which can be battery or solar cell operated and use renewable energy.

UV LEDs possess important features that do not exist in UV lamps. Some of those features, e.g., wavelength diversity and the ability to generate pulsed irradiation, could potentially impact the inactivation of microorganisms and reactor efficiency (Song et al., 2016). With regard to wavelength diversity, UV-C wavelengths (e.g., 250 to 280 nm) cause damage to both the DNA and proteins of microorganisms by the formation of pyrimidine dimers, while UV-A wavelengths (e.g., 360 to 400 nm) are responsible for the oxidative disturbance of bacterial membranes and enzymes by producing active species and photo-modification of tRNAs (Oppezzo, 2001). Therefore, a combination of both wavelengths could have a synergistic effect on the inactivation of microorganisms. With respect to pulsed irradiation, several mechanisms may contribute to inactivation effectiveness by pulsed irradiation; these include photo-chemical, photo-thermal and photo-physical (repeated disturbance of high-intensity pulses on bacterial structure) effects (Krishnamurthy et al., 2007). Thus, the special features of UV LEDs could be explored and adjusted for developing better water treatment reactors.

One of the most significant advantages of UV LEDs is the flexibility they offer in reactor design by providing a higher degree of freedom in reactor configuration and optimization. The performance of UV reactor systems used for any photoreactions or photo-initiated reactions is a function of the interaction of three phenomena: fluid dynamics, radiation distribution and kinetics. All these phenomena can be better controlled in a UV LED reactor compared to a UV lamp reactor (Taghipour, 2013), as explained in the following sections (Fig. 1).

**Figure 1.** Controlling kinetics, radiation distribution and hydrodynamics in UV LED reactors: (1) Adjustable wavelength for promoting targeted photoreaction, (2) Focusable radiation for producing suitable fluence distribution, (3) Controllable hydrodynamics for generating appropriate velocity distribution.

**Hydrodynamics**

The fluid dynamics of UV lamp reactors can be controlled by specifying the reactor geometry or using internal flow modifiers; however, the typical shapes and sizes of UV lamps limit variations in reactor geometry and positioning of flow restrainers. Further, UV lamps are typically placed inside of the reactors, which causes interference with the reactor fluid flow, often without much control over the resulting velocity distribution. However, small UV LEDs can be positioned in different places and configured to different settings inside and outside of the reactor. As a result, the hydrodynamics of UV LED reactors can be better controlled. For example, LEDs can be placed at the reactor wall, allowing different kinds of static mixers or vortex generators to be used in desired locations in the reactor for generating an appropriate fluid flow and velocity distribution.

**Radiation**

The radiation distribution of UV lamps is mainly of a cylindrical profile that cannot easily be altered. On the other hand,
the UV LED radiation profile has a principal direction and can be emitted at various angular views with adjustable radiation profiles. As a result, their radiation patterns can be tailored for different reactor configurations. For example, different optical lenses could be applied to create the desirable radiation pattern. In addition, the layout of small-size individual LEDs can be optimized with greater flexibility than cylindrical UV lamps. While UV lamps often offer one degree of freedom for controlling radiation distribution, which is the position, UV LEDs offer three degrees of freedom, which are the position, direction and pattern.

Kinetics
The kinetic parameters of photoreaction or photo-initiated reactions are largely fixed for UV lamp reactors. This is because the low- and medium-pressure UV lamps which are used in reactors – for example, in water treatment systems – have particular emission spectra. UV LEDs, on the other hand, can be made to produce UV radiation of a specific peak wavelength with a narrow bandwidth. Their emission spectra can be tailored to maximize a specific reaction, e.g., the inactivation of particular microorganisms or the degradation of certain contaminants through photochemical or photocatalytic reactions. In addition, UV reactors can be designed to deliver radiation energy with a combination of particular wavelengths to produce a potentially synergistic effect.

UV LED systems of new applications
Emission of UV photons of various wavelengths, intensities and patterns from a robust and compact source offered by UV LEDs makes possible several important applications. Here, we briefly review a few of these applications; in particular, we look at actuators, sensors and micro-optical devices (Fig. 2).

Actuators
Certain molecules undergo reversible shape changes that can be driven directly by photons, often in the UV range. UV LEDs open new avenues for the potential of direct conversion of UV energy into mechanical energy at the molecular scale. This makes possible the development of diverse actuators needed by the upcoming robotics revolution. One recent study, for example, demonstrated the fabrication of UV-driven micro-actuators utilizing epitaxial piezoelectric thin films (Kurokawa, 2015). When the UV LED radiation was irradiated to the surface of the thin film, the cantilever deflected proportional to the UV intensity, due to the coupling of photovoltaic and piezoelectric properties. UV radiation-driven piezoelectric thin-film actuators could open a new avenue for remote controlled micro-actuators.

Sensors
UV LEDs can be applied as the excitation source for fluorescence-based biological agent detection or as the activation source of a photo-activated sensing layer for gas and liquid detection. This is significant, particularly for gas sensing, because detecting and monitoring hazardous gases and gas pollutants in industrial and urban settings is of increasing importance. Among the variety of sensors currently available, chemical sensors are one of the most promising types of device that can be used for gas detection. However, a drawback of conventional chemical-resistive gas sensors is their high operating temperature (200°C to 500°C), which results in high cost and power consumption, and limits their technical applicability in the detection of flammable gases. UV LED irradiation could be an alternative method of activating the semiconductor layer and lead to the development of highly effective photo-activation sensors that operate at ambient temperatures (Espid & Taghipour, 2016). One recent study has demonstrated that coupling n-type metal-oxide nano-cristalline composites provides excellent sensing performance toward low concentrations of some model chemicals under UV LED irradiation (Espid & Taghipour, 2017). UV LEDs have the potential to greatly contribute to the development of a new generation of sensors and portable monitoring systems.

Optofluidic devices
Optofluidics is a merging of the fields of optics and microfluidics, with many applications, including displays, biosensors, lab-on-chip devices, lenses and molecular imaging tools. With the recent advances in UV LED and the generation of UV radiation from miniature dimensions, the boundary of optics in optofluidic devices can be expanded to high-energy UV photons. The UV LED can give rise to the creation of the next generation of optofluidic devices operating with UV energy with broad capabilities and applications.
Final thoughts
The unique features of UV LEDs make them an attractive alternative to UV lamps in a number of systems, including POU water treatment reactors. They could enable reactor optimization through creative reactor design options for flow and radiation distribution. UV LEDs could offer advances in performance and application of the existing UV-based systems. Further, as an enabling technology, UV LEDs create the opportunity for novel applications and devices that have never been possible. This is an exciting time for those involved in UV-related technologies – the time that UV systems could expand to new applications and markets, the time that an emerging technological opportunity could be applied to the creation of innovative products and industries ... the times they are a-changin’!

References


