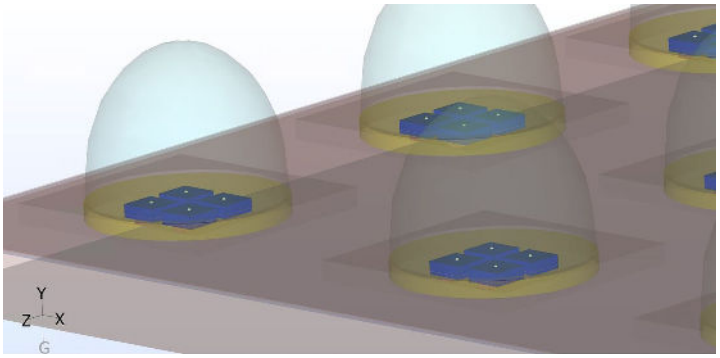
violumas
High Power UV LED Solutions

Technical Article

UV LED 101: The Basics of UV LED Technology



Introduction

With tremendous improvement in the light-emitting diode (LED) technology over the past decade, and with an increased awareness and concern about the usage of mercury, the ultra-violet LED (UV LED) is becoming a viable alternative to the traditional mercury-based lamps [1]. With greater design flexibilities, potentially longer lifetimes, and no warm-up times, UV LEDs are emerging as promising candidates for a wide variety of applications - from disinfection light sources used for inactivating microbes, to excitation light sources for spectroscopy [2].

This article is aimed to provide an understanding of the fundamentals of the UV LED, the challenges in improving the efficiency and the optical output, and information on important parameters.

Basics and General Principles

UV LED is a solid-state semiconductor device consisting of a p-n junction, similar to the traditional diode, formed by doping the semiconductor with p- and n-type impurities. At the junction boundary, a depletion region is created which inhibits the flow of charge carriers. Application of a forward bias (positive voltage to the p-side) allows for the reduction of the depletion zone width, thereby allowing the movement of charge carriers across the junction (as shown in Figure 1), leading to a flow of current.

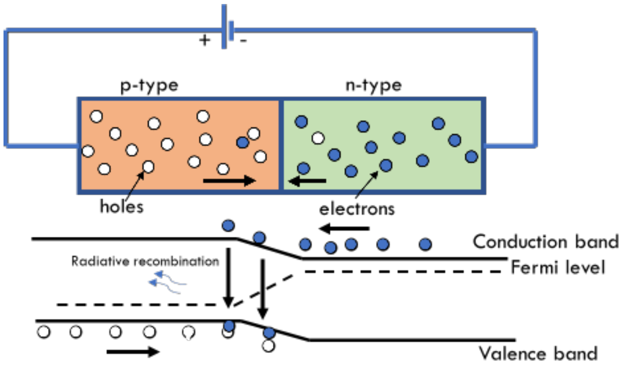


Figure 1: Operation of a p-n junction diode

Electrons from the n-side recombine with the holes either radiatively (light emission) or non-radiatively (heat generation). During radiative recombination, a photon is emitted with a wavelength which corresponds to the bandgap of the semiconductor. Therefore, by changing the semiconductor material, its bandgap can be altered and hence the light emission can be tuned from ultra-violet to infra-red frequencies [3].

High-bandgap (shorter wavelength) materials formed by combination of III-V semiconductors allow for radiative emissions in the UV range. By varying the ratio of Aluminum, Indium and Gallium, specific emission wavelengths can be obtained. UV LEDs are further classified as UVA, UVB and UVC LEDs, based on their emission wavelengths. Near UV and UVA LEDs use InGaN in the active region and are mostly grown on sapphire substrates. Aluminum gallium nitride is the preferred material for wavelengths below 365 nm. For devices emitting shorter UV wavelengths, compositions with a greater aluminum content are required. Sapphire substrates with aluminum nitride or aluminum gallium nitride buffer layers are also used to improve LED quality of shorter wavelengths [4].

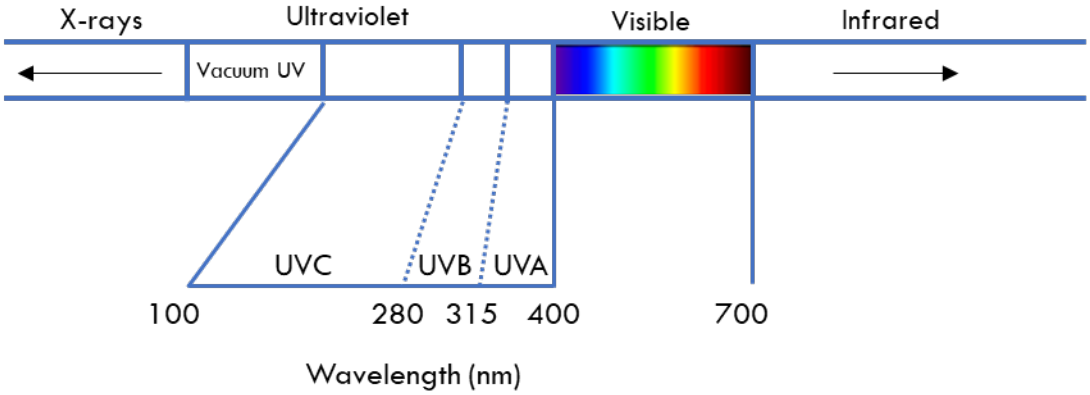


Figure 2: UV wavelengths are divided into UVA, UVB, and UVC bands

UV LED Efficiency

The conversion efficiency of UV LED devices can be expressed in the form of the wall-plug efficiencies (WPE) defined as follows [4]:

$$WPE = \frac{P_{out}}{I \times V} = n_{EQE} \frac{hv}{e \times V}$$

Where P_{out} is the optical output power, I is the forward current, V is the voltage of operation, n_{EQE} is the external quantum efficiency, $h\nu$ is the photon energy and e is the electronic charge. This implies that the WPE is directly proportional to the external quantum efficiency (EQE) of the device. The EQE is determined by the internal quantum efficiency and the light extraction efficiency of the LED. While InGaN-based blue LEDs boast EQEs greater than 84 %, UV LEDs lag far behind with UVA wavelengths reaching up to 30% and UVC wavelengths still presenting below 10% EQEs. The prime reason for the low internal quantum efficiencies in UV LEDs can be attributed to the relatively high defect densities in the AlN and AlGaN materials on sapphire substrates leading to greater rate of non-radiative recombination. Lower defect densities can be achieved by using AlN substrates, improving the EQE, however the costs can be quite high. The presence of impurities can also reduce transmission in the UVC bands for bulk AlN [5].

Improving the light extraction efficiency from UV LEDs is an important challenge for increasing the EQE and WPE of UV LEDs. One method of increasing the LEE is by the use of reflective p-contacts [6]. In addition, finding suitable encapsulation and packaging materials becomes challenging as many high-index transparent silicones and polymers become unstable at high UV energies, making them unsuitable for shorter UVC wavelengths.

Thermal Characteristics

Thermal management plays an important role in determining the overall lifetime, reliability, and the light output of an LED, more so in the case of a UV LED, where the non-radiative recombination is high and EQEs are already low. When a certain forward voltage or current is applied across the p-n junction of an LED, the junction temperature increases and leads to an increase in the electron and hole concentration and a decrease in the band gap. The probability of radiative recombination of electrons and holes decreases, resulting in higher non-radiative recombination (heat generation), thereby decreasing the internal quantum efficiency of the LED.

This implies a reduction in the light output with junction temperature as shown in Figure 3. Continual operation at higher junction temperatures can also lead to early device failures and significantly reduced reliability. Therefore, while research on better materials and new techniques is on the rise, the need for optimal thermal solutions, specifically for mid and high-power UV LEDs, is of high importance as well.

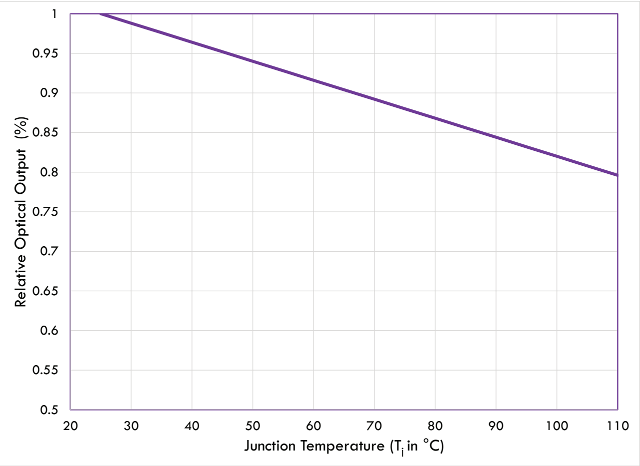


Figure 3: Reduction in light output as a function of Tj

Driving UV LEDs

The current-voltage (I-V) characteristics of a UV LED provide valuable information on its operational characteristics. Figure 4(a) shows the I-V curve of a UVC LED. UVC LEDs operate like visible LEDs, but with a much larger forward voltage requirement due to the high bandgap energy associated with their shorter emission wavelength.

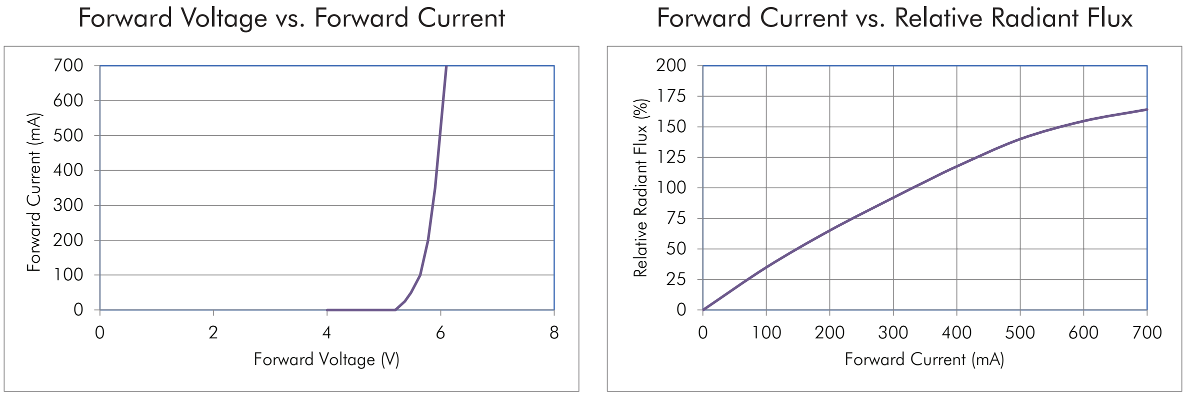


Figure 4: (a) Driving current as a function of forward voltage and (b) Relative radiant flux as a function of drive current for a 265 nm UV LED [7]

Similar to the visible LEDs, the output radiant flux is proportional to the drive current. However, since the non-radiative recombination dominates at high junction temperatures, the forward current values can influence junction temperatures and lead to a reduction in the light output.

Conclusion

While the fundamental knowledge about the UV LEDs is well-known, the challenges associated with material quality, leading to a lower wall-plug efficiency, still exist. However, the benefits associated with using UV LEDs and their potential in replacing the UV lamp in many applications has fueled the research and development in this area. Fundamental research to reduce defect densities and improving EQEs is continuing and performance improvements have been accelerated. With several technological advances in the making, the UV LED technology promises to provide environmental, societal and economic benefits for several new and upcoming applications.

Article #2 discusses the current status of UV LEDs in terms of their efficiency and cost and why UV LEDs hold the key to enabling new applications in the future, not previously considered feasible using the UV lamp technology.

References

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