UV-C LEDs and lasers: low-voltage light sources for killing germs

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Aluminum gallium nitride UV-C LED devices fabricated with novel epitaxial techniques show improved efficiency and have longer operating lifetimes.

Systems used in biomedicine, purification of air, water, and food, and polymer curing and biochemical identification require the use of UV light with wavelengths in the range of 250–300nm. Currently, the primary light sources for these UV-C wavelengths are mercury lamps and gas lasers, which are big and bulky and require high voltages for their operation. The use of mercury also leads to significant environmental concerns. As a result, intense research activity has focused on replacing these conventional UV-C light sources with solid-state microdevices based on semiconductors, which would have potential advantages in terms of size, cost, and efficiency.

Developers of UV-C LEDs and lasers are using the compound semiconductor aluminum gallium nitride (Al\textsubscript{x}Ga\textsubscript{1-x}N) as a base material because of its direct bandgap, which can be tuned to cover the entire UV-C spectrum. However, a major drawback is the unavailability of bulk AlGaN substrates. This has led to the use of sapphire substrates, which are readily available and UV-C-transparent. Figure 1 shows a typical layer structure for a UV-C LED.

The fabrication of high-efficiency and low-cost UV-C LEDs and lasers requires several key developments in AlGaN materials and device technologies. Low-defect material layers with high n- and p-type doping are essential to achieve high internal quantum efficiency (the ratio of light energy produced internally to the device input current). Other requirements include extraction of light generated inside the device, a large device active area, and high input electrical pump currents. Only by meeting these needs can UV-C LEDs and lasers produce light output powers matching those of conventional UV-C lamps and lasers. To achieve all this at low cost requires large-scale manufacturing processes.

The shorter the wavelength of the LED/laser light emission, the more difficult it is to satisfy the above requirements. Lattice-mismatched growth of Al\textsubscript{x}Ga\textsubscript{1-x}N over sapphire leads to a large number of threading dislocations (defects), and the high aluminum compositions needed for UV-C emission also make p-type doping difficult, thereby reducing the internal quantum efficiency. Furthermore, strain from the heteroepitaxy also limits the maximum thickness of the current-carrying layers. This leads to a reduction in conductivity and self-heating of the device, which severely limits the emission area. The heating and defects also cause a significant reduction in the device lifetime. In the past, these issues limited external quantum efficiencies to approximately 1%. The lifetime for continuous-wave operation was also limited to approximately 500 hours.

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To improve UV-C LED performance to the levels needed for commercial applications, researchers have adopted new and innovative approaches to mitigate the problems that limited the device efficiency and lifetime. Our group has pioneered a high-temperature lateral epitaxy approach, where we grew aluminum nitride (AlN) single-crystal layers on patterned low-quality AlN layers (defects > $10^9 \text{cm}^{-2}$). This resulted in AlN buffer layers with defects in the range $(1-2) \times 10^8 \text{cm}^{-2}$. More recently, we have adopted a modified temperature-modulated random lateral epitaxy approach, which yields high-quality AlN template layers without the need for patterning. We also developed a new quasi-pseudomorphic device design, which is simple to manufacture on commercial multiwafer metalorganic-chemical-vapor deposition (MOCVD) systems. For improved p-type doping of the high-Al Al$_x$Ga$_{1-x}$N layers, we now use a polarization doping approach. These improvements, when combined with a flip-chip device design (using solder bumps to interconnect devices, rather than wires) and some new UV-transparent epoxies, have led to an increase in the device powers to nearly 3mW (at 20mA pump current) and an efficiency of nearly 3%. Improved device design and packaging schemes have further increased the device lifetimes to well over 2000 hours.

We and other researchers in the field have also succeeded in making large-area UV-C LED lamps by monolithic integration of small area pixels to yield a large-area device. This parallel connection approach has enabled UV-C LED lamps with powers as high as 30mW for pump currents of 350mA. Several groups have now reported on such devices with a surface-mounted diode packaging scheme. Another major development is the transfer of the deep UV LED material fabrication technology for commercial MOCVD systems. This should lead to a significant cost reduction, making the UV-C LEDs competitive with conventional mercury lamps, and thereby accelerating their system adoption. In summary, we have developed a new high-efficiency UV-C LED design that is easy to manufacture, and we have presented several potential approaches to improve the external quantum efficiency to 10%. Researchers are now developing UV-transparent metallic n-/p-contact layers, and shaping sapphire substrates to significantly improve extraction of the UV-C light from the current values of 5–7%. This is expected to increase the external quantum efficiency to well over 10%. Several groups, including ours, have recently reported on optically pumped UV-C lasing structures with very low threshold pump powers. This, combined with improved p-doped Al$_x$Ga$_{1-x}$N layers, can potentially lead to electrically pumped UV-C lasing. UV-C LEDs are now ready for insertion in home water faucets, refrigerators, and home/automobile air vents to supply point-of-use clean air and water.

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Asif Khan is a Carolina Distinguished Professor of Engineering. His research area is GaN-AlGaN-based high-power microwave transistors and UV-C light emitters. He has authored more than 375 refereed papers, several book chapters, more than 100 invited papers, and more than 30 patents.

References