AlInGaN-Based Deep Ultraviolet Light-Emitting Diodes and Their Applications Technology

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Keywords: Light emitting diode, multiple quantum wells, sapphire substrates, deep ultraviolet.

Abstract

In this paper, we will review the results and the current research focus in the development of deep ultraviolet (DUV) light-emitting diodes (LEDs) with peak emission in the 250-300 nm spectral region. In addition to the materials and device development, we will also discuss some potential application areas which represent a significant business opportunity for the AlInGaN-based DUV LEDs and Lamps.

INTRODUCTION

Several key application systems for air-water purification, polymer curing and bio-medicine require the use of ultraviolet light with wavelengths in the 250-300 nm range. Currently, the primary UV light source for deep ultraviolet (DUV) applications is the mercury lamp. As its potential replacement, globally, several research teams are developing AlInGaN-based DUV light-emitting diodes (LEDs) and lamps over sapphire and AlN substrates. Nearly all the research works involving sapphire have followed the material improvement strategies and the device structures that our group was the first to report in early 2000.[1,2] This early work demonstrated milliwatt power devices with emission below 290 nm. They were intended for applications in air-water purification and polymer curing, which represent very large markets requiring high power, stable and eco-friendly light sources. The initial research efforts in the United States (US) were supported by the Defense Advanced Products Research Agency (DARPA) SUVOS Program. About the same time, several other research groups in Japan initiated research programs aimed at developing UVB and UVC LEDs.[3]

FIRST GENERATION LED DEVICES

In order to realize DUV LEDs almost all research groups employ AlGaN or AlInGaN multiple quantum wells (MQWs)-based *pn*-junctions over sapphire substrates. However, with the recent availability of improved AlN substrates, Crystal IS and Hexatech reported DUV LEDs over bulk AlN. The use of sapphire was primarily dictated by the substrate transparency requirements for the emitted light. A representative device structure is shown in Figure 1. As seen it consists of an AlGaN pn-junction with an $Al_{0.6}Ga_{0.4}N/Al_{0.4}Ga_{0.6}N$ MQW active region. A 2 µm thick n^+-$Al_{0.6}Ga_{0.4}N$ layer is used to form the *n*-contacts after accessing it with an ICP RIE dry etch. To manage the strain that usually leads to the epilayers cracking, we inserted a 10-period $AlN/Al_{0.8}Ga_{0.2}N$ short-period superlattice between the *n*-contact layer and the AlN buffer layer. These first generation devices suffered from three major problems. First, their *cw*-powers exhibited a fast saturation due to device heating in-spite of using the flip-chip package. Secondly, their wall-plug efficiencies were only about 1% because of both the large number of dislocations resulting from the lattice-mismatched growth of large Al-mole fraction AlGaN layers over sapphire and the optical absorption from the p-GaN layer used for the p-contact. Finally, the self-heating effects and the defects generated in the epilayers led to the devices' premature and rapid degradation with lifetimes of only 200-400 hours under 20 mA continuous-wave operation. Despite these short comings, the first generation devices were successfully marketed by SET Inc. and Seoul Opto-devices Company (SOC) using the technology developed by our laboratory at the University of South Carolina.

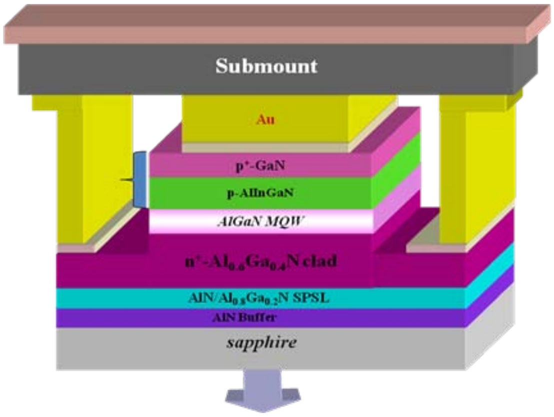

Figure 1: Schematic of the First generation AlInGaN MQW-based flip-chip DUV LED structure on sapphire.

The device design strategy for AlN substrates utilizes a quasi-pseudomorphic structure where the *n*-AlGaN is directly grown over the bulk AlN followed by the AlGaN MQW active region.

LED LAMPS WITH MICRO-PIXEL DESIGN (GENERATION 1)

Fabrication of large area DUV lamps is challenging due to the issue of lateral current crowding. This arises from the limitation on the thickness of the high-Al content *n*- AlGaN contact layer of our MQW-based deep UV LED design. To avoid cracking, the maximum allowable thickness and doping for the *n*-$Al_{0.5}Ga_{0.5}N$ layer are such that its sheet resistivity is limited to approximately 200-300 Ω/□. This in-turn leads to severe current crowding when the device size is increased to above 70 µm x 70 µm. A consequence of this device size limitation is an increase of the device self-heating and hence a significant reduction in the LED lifetime to well below 200 hours for *cw*-operation. In the past, we have reported on a large-periphery monolithic 280 nm deep UV LED lamp with a micro-pixel p-electrode geometry that provides a good thermal management and reduces the device thermal impedance. As shown in Figure 2 below, for a lamp with an 880 µm x 880 µm active area a record room-temperature cw power of ~42 mW for a pump current of 1000 mA was reported. The device lifetime was well in excess of 1500 hours when it was stressed at 400 mA.[4]

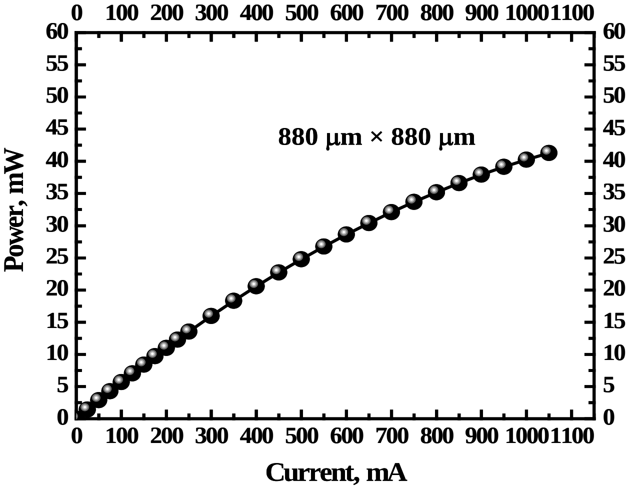

Figure 2: Optical power versus forward current for a Generation 1 Micro-pixel DUV LED Lamp.

CURRENT RESEARCH FOCUS

The recent focus in research on 250-280 nm nitride LEDs has been primarily towards increasing the devices output power, wall-plug efficiency (WPE) and long-term reliability. To improve the internal quantum efficiency (IQE) in sapphire-based DUV LEDs, innovative materials growth approaches are being pursued to produce low-defect $Al_xGa_{1-x}N$ ($x > 0.4$) templates, heterojunctions and multiple-quantum-wells. These encompass the new high-temperature pulsed epitaxy technique that we successfully implemented to reduce the defects density in AlGaN templates to less than $10^7 cm^{-2}$.[5] Also, new doping schemes are now being used to grow highly conductive *n*- and *p*-type $Al_xGa_{1-x}N$ ($x > 0.4$) layers. In contrast to the first generation devices (with WPE < 1%), these new *p*-GaN-free epilayer structures with the low-resitivity $Al_xGa_{1-x}N$ layers increase the output power by suppressing absorption of the light travelling towards the *p*-contact.

In addition to the IQE improvement, research efforts are also targeting improved light extraction. This can be achieved by texturing the substrate or using reflective *p*-contacts coupled with the exploration of new device geometries. The enhancement in both the LEDs IQE and light extraction has now yielded 270-280 nm light emitters with WPE values as high as 3-6 % at 20 mA pump current. The external quantum efficiency (EQE), however, was found to decrease to values as low as 1.5-3 % when the pump currents were increased to 100 mA and beyond. Furthermore, all reports to date contain no information on the devices lifetimes, especially at high injection currents.

Recently, using a micro-pixel geometry we fabricated 268 nm emission LED lamps on sapphire substrates. The devices epilayer structure was similar to that shown in Fig. 1. The defects in the AlN buffer layer were reduced by our previously reported pulsed lateral overgrowth technique to values as low as 10^7 cm^{-2}. The lamps geometry consisted of a 6x6 micro-pixels array with a total *p*-active area of 360 µm x 360 µm. They were flip-chip mounted on TO-03 headers.

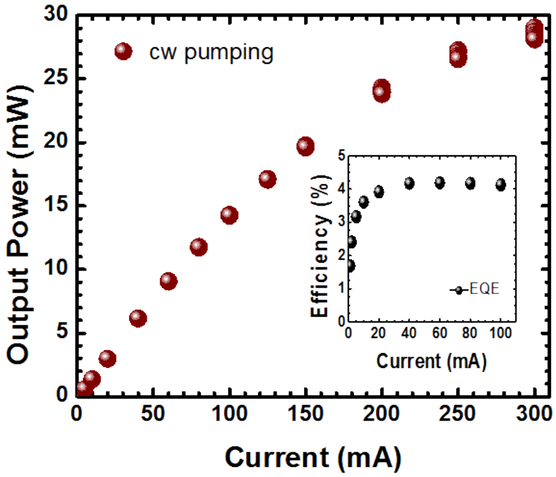

Figure 3: 268 nm DUV Micro-pixel Lamp power versus current. Shown in the inset is EQE versus the pump current.

In Figure 3 we have plotted the output power and the EQE values as a function of pump current. As seen from the data, power levels as high as 15 mW were attained at 100 mA and they approach the 30 mW mark when the pump current is raised up to 300 mA. The EQE, on the other hand, increases with pump current to a peak value of 4 % at 40 mA. It remains nearly constant till 100 mA and then decreases slowly with further increase of the current. This decrease can be overcome with a better thermal management. Note that with the incorporation of backside roughening and Al-based UV-reflective n- and p-type electrodes, the EQE values are expected to increase by at least 50 %.

Figure 4 illustrates the evolution of the 268 nm lamp output power as a function of time when stressed at a constant cw current density of ~ 77 A/cm^2. After an initial 20 % drop in the device output power, the rate of power degradation slows down and one could estimate the lifetime to be well over 800 hours. In this paper, details of our ongoing research work together with the results of the monolithic DUV LED lamps characterization measurements will be presented and discussed.

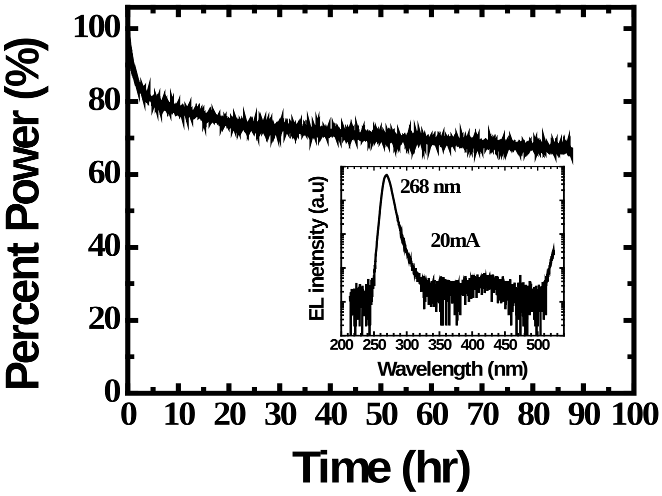

Figure 4: 268 nm DUV Micro-pixel Lamp power versus time at a pump current of 100 mA. Shown in the inset is the device emission spectrum at 20 mA.

FUTURE RESEARCH

More recently, we have also reported a 1 x 1 mm^2 vertical conduction thin-film (VTF) LED emitting at 280 nm.[6] To fabricate this device, the *p*-type side of the sample was bonded to a metalized SiC carrier, then the sapphire substrate was removed using a new excimer laser-assisted lift-off (LLO) process. The thin-film technology was a key development for effectively enhancing light extraction in InGaN-based visible LEDs due not only to the diodes lower series-resistance, higher power saturation current, and improved thermal impedance, but also to the realization of efficient light out-coupling structures on the exposed backside epilayer. For DUV LEDs, however, the vertical injection thin-film device geometry was more difficult to implement as it required low-temperature annealing conditions for the *n*-contact metallization scheme evaporated on the high Al-content and nitrogen polar *n*-AlGaN layers, which in-turn cause the LEDs to exhibit a high turn-on voltage and a large series resistance. Moreover, a mesh-like electrode is usually patterned on the *n*-AlGaN, which invariably blocks, along with the top-side wire bonds, part of the emitted light. To alleviate the common problems encountered in VTF technology, Shchekin *et al.* introduced the concept of substrate-free flip-chip (SFFC) visible LEDs, with lateral conduction geometry.[7] This advanced device geometry retains the advantages offered by the VTF approach while adding to it the merits of the conventional FC process mentioned above.

We have now fabricated lateral-conduction, substrate-free flip-chip (SFFC) light-emitting diodes (LEDs) with peak emission at 276 nm.[8] The AlGaN multiple quantum well LED structures were grown by MOCVD on thick-AlN laterally overgrown on sapphire substrates. The chips had physical dimensions of 1100 x 900 µm^2, and were comprised of four devices each with a 100 x 100 µm^2 junction area. Electrical and optical characterization of the devices revealed no noticeable degradation to their performance due to the laser-lift-off process. After the chips were bonded to TO-39 headers the individual SFFC LEDs yielded a cw output power of 0.4 mW at 20 mA injection current. Future developments are needed to improve the lift-off technique and packaging technology to produce large area SFFC DUV LED Lamps.

CONCLUSIONS

We have reviewed the development of AlInGaN-based deep ultraviolet light-emitting diodes and lamps. The recent results on high efficiency devices clearly indicate a maturation of the technology to the point where the development of systems for air- and water-purification and bio-medical applications is very feasible. Several companies in the US, Japan, Korea, China and Europe are scaling up their production lines. This will certainly lead to large volume LEDs sales and a reduction of their unit price.

ACKNOWLEDGEMENTS

The author would like to thank all researchers at the University of South Carolina and Nitek Inc., whose contributions made this review paper possible. In particular the help of Dr. M. Lachab in preparing this manuscript is acknowledged.

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ACRONYMS

DUV: Deep Ultraviolet
LED: Light Emitting Diode
MQW: Multiple Quantum Well