Abstract

In the past few decades, remarkable progress has been made on the research and development of gallium nitride (GaN)-based light sources. Among those, GaN-based blue and ultraviolet (UV) light-emitting diodes (LEDs) achieve great success and attract considerable attention in a wide range of application. GaN-based blue LEDs are highly efficient and reliable visible light sources and thus have found broad applications in solid-state lighting (SSL), automobile headlights, LED displays, liquid crystal display (LCD) backlights, flash units, compact projectors and compact scanners. GaN-based UV LEDs are energy efficient and robust UV light sources and thus they have great potential in UV curing, counterfeit detection, UV lithography, photo-catalysis, air purification and tanning (UV-A or near-UV), medical phototherapy, protein analysis and drug discovery (UV-B), water/air disinfection and bioagents sensing (UV-C or deep-UV). With the GaN-based blue LED platform that we developed, in this thesis, we extend our work into UV-A and towards UV-C research. We aim to improve the performance of GaN-based UV LEDs through novel structural and device solutions including size effect, Al incorporated quantum barriers (QB), electroluminescent cooling effect and electron beam (e-beam) pumping.

In this thesis, various structures have been designed, grown and fabricated for the performance enhancement of InGaN/(Al)GaN blue and near-UV LEDs. The InGaN/(Al)GaN multiple quantum wells (MQWs) blue and near-UV LED epitaxial wafers have been grown along c-axis on sapphire wafers with designed structures by commercial metal-organic chemical vapour deposition (MOCVD) system. The fabrication process of LED devices have been designed, optimized through iteration, and tested for the grown epitaxial LED wafers. Based on this platform, novel structures have been designed for the performance enhancement of InGaN/(Al)GaN blue and near-UV LED.

It is well-known that size shrinking of a LED device will improve radiative recombination rate, enhance light extraction efficiency (LEE), and reduce current spreading and thermal effects. The size effect has been investigated on the efficiency droop of InGaN/GaN blue LEDs. The efficiency droop behaviours are compared for GaN-based blue LED devices with different mesa dimensions. We found that the external quantum efficiency (EQE) and wall-plug efficiency (WPE) droop start at a higher current injection for a LED device with a larger mesa dimension due to reduced injection current density but the EQE droop begin at a lower injection current density for a LED with a larger mesa dimension because of the increased current crowding. However, the WPE droop begins at a slightly higher injection current density with further enlarging the mesa dimension of a LED. This is ascribed to the shallow slope of the I-V characteristics around the position of the EQE peak. Besides, the series resistance (SRRS) and ideality factor are derived for the LED devices with different mesa dimension by fitting the measured I-V characteristics to the diode I-V model. Both the SRRS and ideality factor decrease as the mesa dimension of the LEDs increase. This suggests that the I-V characteristics of a real LED approaches that of an ideal LED as the mesa dimension of the LEDs increase.

Size shrinking has also been proved effective in reducing current crowding, enhanced output power density and increased power roll-over current density UV micro-LEDs. We systematically investigated the size effect on the electrical and optical characteristics of these near-UV micro-LEDs. We observed EQE enhances with the decrease of size but the enhancement went marginal as the size reduced from 50×50 μm^2 to 25×25 μm^2. Besides, efficiency droop reduction reversed as the size decreased from 50×50 μm^2 to 25×25 μm^2. In addition to the current spreading effect, strain relaxation, sidewall defect and p-contact resistance were found to be the root cause of the size effect. We demonstrated that the 50×50 μm^2 micro-LED produces the highest performance in terms of efficiency and droop, which provide design rules of thumb for UV LED.

The MQWs structure is a critical component that determines the performance of the near-UV LED. As the emission wavelength shifts from blue to near-UV, the *In* incorporation in the MQWs decreases and thus the quantum wells (QWs) become shallow. This weakens the confinement of the MQWs and increases the carriers overflow. For these reasons, it necessitates the incorporation of *Al* into the QBs and increase the confinement of the MQWs. Therefore, in this thesis, the effect of *Al* incorporation on the performance of the near-UV LED was systematically investigated by changing the *Al* mole concentration in the QBs and comparing optical power and EQE from the UV LEDs with different *Al* incorporation. Besides uniform *Al* incorporation, the effect of *Al* graded AlGaN QBs and *Si* doped QBs on the performance of UV LEDs has also been studied.

In this thesis, we also designed experiment to couple the excitons in the MQWs structure to phonons by electroluminescent cooling effect. Electroluminescent cooling effect has been reported to thermally enhance the efficiency of GaN based LEDs in theory. The carriers absorb energy from the phonons and thus gain energy to overcome the potential barriers and subsequently radiate in QWs, contributing to the power efficiency. In this work, we have observed and demonstrated the electroluminescent cooling effect in UV LEDs and support our

observations with theoretical modelling and numerical simulation. Efficiency and electrical characteristics have been measured under different controlled temperatures and the effect of temperature on the efficiency has been investigated in different bias regimes. We have demonstrated that the efficiency of the UV LEDs can be enhanced by elevated temperature below certain bias voltage with electroluminescent cooling effect.

As the emission wavelength shifts further from near-UV to deep-UV, the performance of GaN-based UV LEDs has been held back by low doping efficiency of p-AlGaN (p-type doped AlGaN) and thus non-Ohmic p-contact and electron leakage. Therefore, e-beam pumping has been proposed as a potential technique for the next generation UV light source with great environmental and economic benefits. We have started developing e-beam pumped light sources in the near-UV range and applied our findings to deep-UV light sources based on e-beam pumping. The Cathodoluminescence (CL) characteristics of near-UV InGaN/AlGaN MQWs structures with 8, 10, 15 and 20 QWs have been systematically studied and the acceleration voltages where the CL power efficiency (PE) reaches the maximum have been recorded. We have established the relationship between the acceleration voltage and QW number by introducing the contribution to MQWs absorption from carriers generated within the diffusion length below the MQWs. This new understanding will help researchers in designing efficient CL based UV devices. In this work, we have also tested and demonstrated GaN-based deep-UV cathodoluminescence, which will be critical for the development of efficient deep-UV emitters.