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Quaternary AlInGaN multiple quantum well 368 nm light-emitting diode

Te-Chung Wang[a,b,*], Hao-Chung Kuo[a], Zheng-Hong Lee[b], Chang-Cheng Chuo[b], Min-Ying Tsai[a], Ching-En Tsai[b], Tsin-Dong Lee[b], Tien-Chang Lu[a], Jim Chi[b]

[a]*Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan, Republic of China*
[b]*Opto-Electronics and System Laboratories, Industrial Technology Research Institute, Hsinchu, Taiwan, Republic of China*

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Abstract

We report high output power from AlInGaN multiple quantum well (MQW) ultraviolet light-emitting diodes. The high Al containing cladding layer, electron blocking layer and p-contact layer were chosen for transparency at 365 nm to reduce the internal absorption, reduce electron overflow and enhance output power. The UV output power was as high as 1.52 mW at 20 mA at 368 nm under room temperature CW operation. The maximum output power in CW operation is 11 mW at 170 mA. In this letter, we demonstrate a helpful and easy way to measure and calculate the junction temperature of AlInGaN UVLEDs.

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1. Introduction

Ultraviolet light-emitting diodes (UV-LEDs) based on wide band gap III-nitride compound semiconductors have attracted the attention of researchers because of their potential applications, especially for solid state white lighting and detection of biological/chemical agents. $Al_xGa_{1-x}N$ ternary compounds possess a wide direct band gap that varies from 3.4 eV for GaN to 6.2 eV for AlN, corresponding to a wavelength range of 200–360 nm. Due to the wide band gap of AlGaN, this material is a promising candidate for optoelectronic devices that cover a broad portion of the UV spectrum. However, various problems are associated with the growth of high Al-content $Al_xGa_{1-x}N$ layers. Specifically, high dislocation densities and insufficient conductivity of doped epilayers present serious problems. However, rapid progress in the growth of III-nitride materials has helped to mitigate some of these problems. To date, AlGaN-based UVLEDs with peak emissions from 230 to 380 nm have been demonstrated by several groups [1–8].

According to some reports, the color rendering index (CRI) of triphosphor by UV light excitation is better as the wavelength is shorter [9]. But the external quantum efficiency (EQE) of short-wavelength (below 365 nm) LEDs is still quite low compared with blue LEDs so that the device characteristics of a UV-excited phosphor-based LED lamp is not good enough for high brightness white light applications now. In this paper, we design an AlInGaN MQW UVLED structure for emission near 365 nm, less absorption and high optical output power.

Many kinds of applications of UV light need high output radiant flux, which can be obtained using high current injection and/or large area. But the higher resistivity caused by higher Al content leads to a self-heating problem so that the junction temperature rises and the wavelength rapidly red-shifts as the current increases. In this paper, we demonstrate a helpful and easy way to measure and calculate the junction temperature.

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[*] Corresponding author. Opto-Electronics and System Laboratories, Industrial Technology Research Institute, Hsinchu, Taiwan, Republic of China Tel.: +886 3 5912004; fax: +886 3 5915138.

E-mail address: WangWang@itri.org.tw (T.-C. Wang).

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2. Experimental procedure

For the desired short wavelengths below 365 nm, there exists strong internal absorption by GaN, leading to significant reduction in EQE. To prevent strong absorption by GaN, we set the wavelength a little longer than 365 nm and reduce the thickness of binary p-GaN contact layers as much as possible. Excluding the GaN template and two contact layers used for n-electrode and p-electrode, the LED structure is composed of ternary $Al_xGa_{1-x}N$. The AlInGaN MQW UVLED structure, as shown in Fig. 1, was grown on *c*-face sapphire substrates by low-pressure horizontal-flow metal–organic vapor phase epitaxy (MOVPE). Deposition began with a 30 nm low-temperature GaN nucleation layer grown at 550 °C followed by a 2 μm thick high-temperature undoped GaN buffer layer and 1 μm Si-doped GaN both grown at 1050 °C, to form the n-type contact layer. Next, 50 nm of graded *n*-$Al_xGa_{1-x}N$ ($x = 0.1$–0.14) was deposited to be a cladding layer. Thereafter, the temperature was gradually decreased to 850 °C to grow the active region consisting of quaternary AlInGaN multiple quantum wells. The compositions of the quaternary AlInGaN layers were theoretically estimated from PL emission and X-ray analysis by using the following expression for the AlInGaN band gap incorporating the recently revised InN band gap (~0.8 eV) [10] and an AlGaN bowing parameter of 1 eV [11].

$$E_g(Al_xIn_yGa_{1-x-y}N) = 6.2x + 0.8y + 3.42(1-x-y) - (1)(x)(1-x)(\mathrm{eV}). \tag{1}$$

The quantum wells and barriers were estimated to be 3-nm-thick $In_{0.02}Al_{0.005}Ga_{0.975}N$ and 9-nm-thick $In_{0.005}Al_{0.12}Ga_{0.875}N$, respectively. The temperature was then increased to 1050 °C and a 25 nm p-$Al_{0.19}Ga_{0.81}N$ electron blocking layer was deposited to prevent overflow of electrons out of the active region. The structure was completed with a 125 nm thick p-$Al_{0.09}Ga_{0.91}N$ layer followed by a 10 nm p-GaN contact layer. After MOVPE growth, the LED wafer was partially etched by reactive ion etching from the surface of the p-type GaN until the n-type GaN was exposed. A Ni/Au contacting metal layer was evaporated onto the p-type GaN contact layer, and a titanium/aluminum (Ti/Al) contact was evaporated onto the n-type GaN layer, respectively. Finally, for output power measurements, the UV LED chips were packaged into 5 mm lamps and TO cans by standard processes.

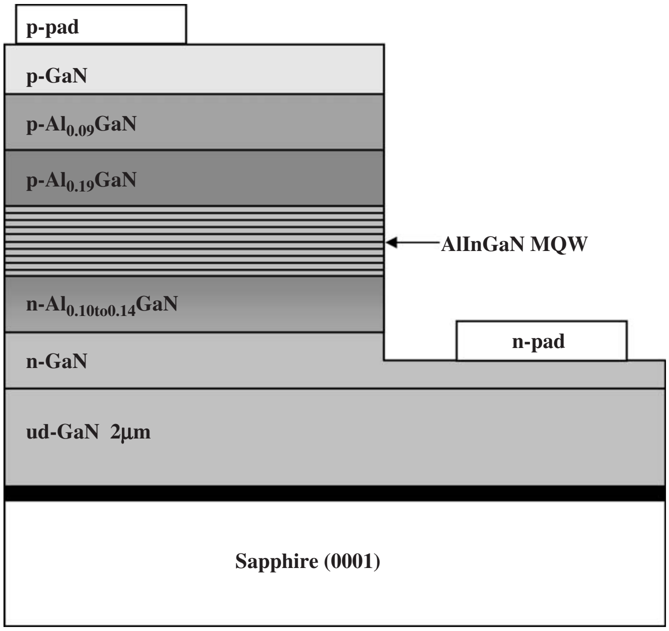

Fig. 1. Schematic of AlInGaN UV LED on sapphire.

3. Result and discussion

Fig. 2 shows the characteristics of an AlInGaN MQW UVLED lamp under pulse and CW operation, respectively. To eliminate the self-heating as much as possible, we choose 0.1% duty cycle and carefully make all transmission lines short and all contacts perfect to obtain a clean pulse shape on an oscilloscope. This measurement really has to be done carefully and is a little difficult. Under pulse operation, the output power and the forward voltage increase linearly with current. As shown in Fig. 3, in CW operation, when the current is smaller than 7 mA, the peak wavelength position is stable at 367.6 nm. When increasing the current over 7 mA, the main peak position red-shifts obviously at the same time as the peak intensity rises. These devices demonstrate 1.52 mW output power at DC 20 mA with 3.6 V operating voltage and the wall plug efficiency is as high as 2.1%.

Under CW operation, the output power saturates and then decreases at 170 mA. This phenomenon comes from

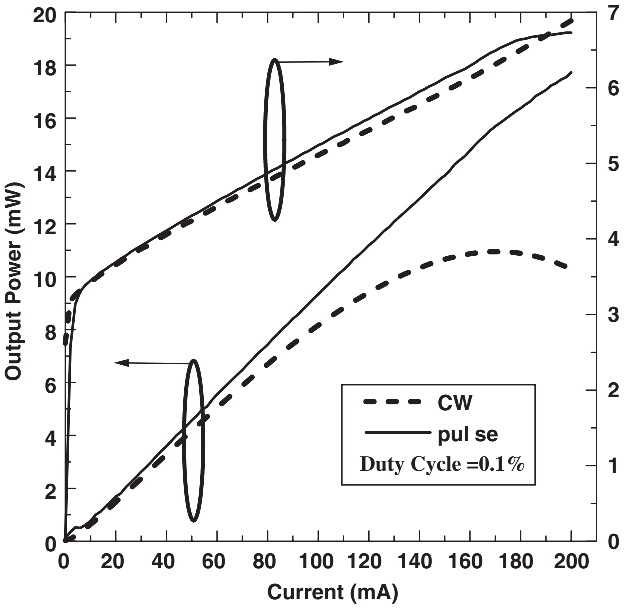

Fig. 2. *L–I–V* characteristics of AlInGaN UV LEDs under pulse and DC operation, respectively.

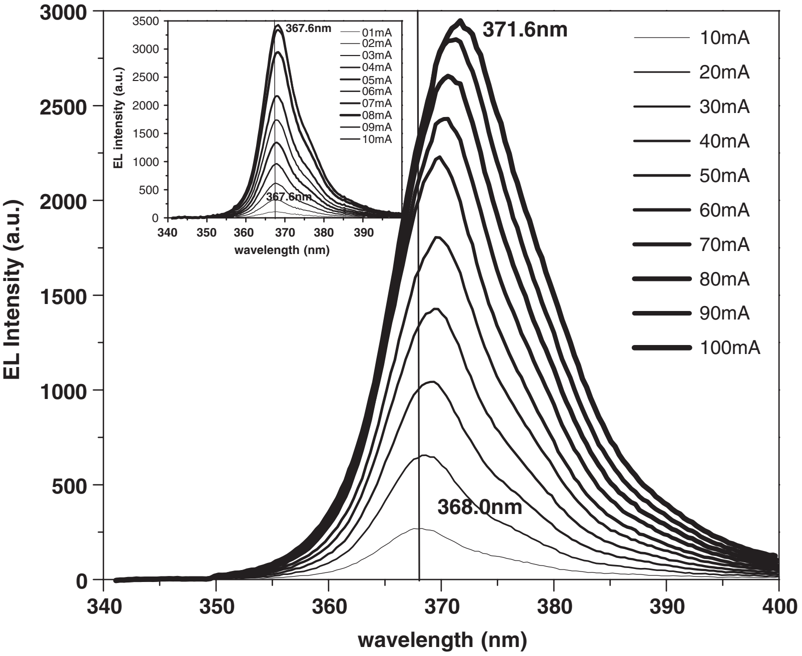

Fig. 3. Electroluminescence spectra of AlInGaN UV LED increasing the injection current from 1 to 100 mA.

self-heating, which leads to a red-shift in the emission peak. Assuming that the wavelength shift is determined by the temperature dependence of the band gap energy of the active layer, the wavelength shift is determined as

$$\frac{d\lambda_p}{dT} = -\frac{1239.85}{E_g^2}\frac{dE_g}{dT} = 0.064\,\text{nm/K}, \tag{2}$$

where λ_p is the emission wavelength of LED, E_g is the band gap energy of GaN, T is the absolute temperature and the temperature coefficient $dE_g/dT = -6.0\times10^{-4}\,\text{eV/K}$ [12]. Using this formula, we calculate that the junction temperature is 37.25 °C at 20 mA and 82.4 °C at 100 mA if the room temperature is 26 °C. By considering the difference in V_f at the same current between pulse and CW operation, from our experimental data,

$$\frac{dV_f}{dT} = -2.3\,\text{mV/K}. \tag{3}$$

The theoretical temperature coefficient calculated by a different group [13] is $-1.74\,\text{mV/K}$, a little lower but close to our experimentally determined coefficient. The difference could be due to a decrease in p-type GaN layer resistivity, caused by more complete acceptor activation at elevated temperature. This phenomenon could be enhanced by the bad thermal conductivity of epoxy, so that heat generated stays in the chip. To preclude the influence of epoxy, we packaged the chip in a TO can to measure the forward voltage versus temperature over the range 75–300 K for different pulsed injection currents. As Fig. 4 shows, at 10 mA with low temperature, the experimental temperature coefficient, $-1.69\,\text{mV/K}$, is very close to the theoretical calculation.

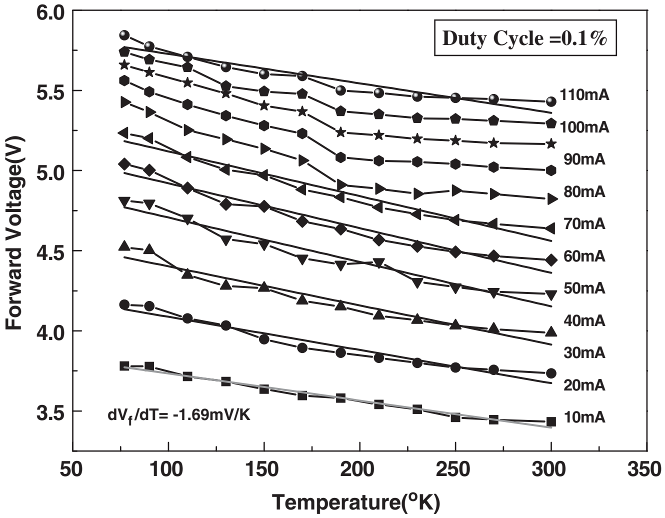

Fig. 4. Experimental forward voltage vs. temperature for different pulsed injection currents using TO can.

According to many reports from different groups, for blue or green LEDs, the InGaN/GaN MQWs will form localized states due to indium inhomogeneity, and the peak position first blue-shifts and then red-shifts as the driving current is increased. This phenomenon reduces the influence of dislocations and enhances the LED output power. However, we could not find any shift to shorter wavelength in our AlInGaN MQW UV LEDs as the current was increased. This could be due to the fact that the indium mole fraction of our AlInGaN MQWs is much less than in blue or green LEDs and the segregation of indium therefore does not have a dominant influence on the

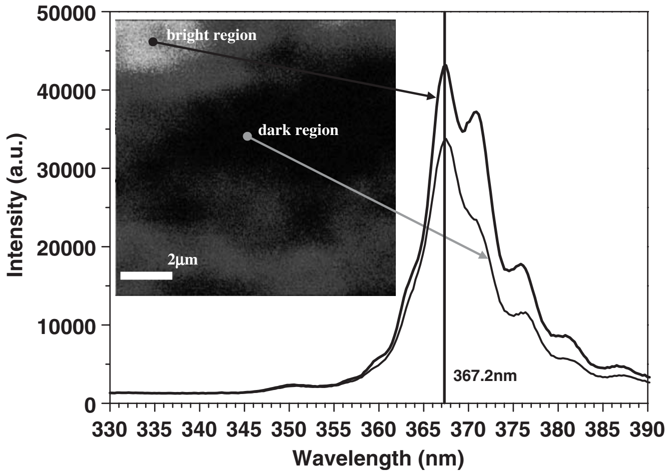

Fig. 5. Micro-PL of the quaternary AlInGaN MQW.

emission. Fig. 5 shows the micro-PL of the AlInGaN MQWs: the wavelength is uniform at 367.2 nm in different regions and the spectrum between the strongest- and the weakest-intensity points at 367.2 nm is just a little different. It means that the uniformity of the quaternary AlInGaN MQWs with low indium mole fraction is very good compared to blue or green LEDs. Consequently, localized states caused by indium segregation cannot be used to enhance the output power of AlGaInN MQW UVLEDs in which the indium mole fraction is low. To enhance the output power, one must look into reducing the density of defects, for example by growing on templates with fewer dislocations. The LED sample was etched in a 3:1 mixture of H_2SO_4 and H_3PO_4 at 250 °C for 20 min to observe the etching-pit density (EPD). The EPD amount was estimated to be approximately $2.0 \times 10^8\,\mathrm{cm}^{-2}$. We will focus on the study of UVLEDs on lower dislocation density templates in the future.

4. Conclusion

368 nm AlInGaN MQWs UVLEDs with high output power were demonstrated. By using a 25 nm p-$Al_{0.19}Ga_{0.81}N$ electron blocking layer and transparent-like p-$Al_{0.09}Ga_{0.91}N$ layers, the structure of AlInGaN MQWs UVLEDs could reduce the internal absorption and confine the electrons, and finally enhance the output power. Our study also shows self-heating of the device to be the cause for output power saturation at CW high current operation. When an AlInGaN MQW LED structure was grown on a usual GaN template on sapphire, the UV output power was as high as 1.52 mW at 20 mA and the wall plug efficiency is as high as 2.1% under room temperature DC operation. The maximum output power at DC operation reaches 11 mW at 170 mA. And last, we demonstrated an easy way to measure and calculate the junction temperature of an AlInGaN UVLED by using the $\mathrm{d}\lambda_p/\mathrm{d}T$ or $\mathrm{d}V_f/\mathrm{d}T$ coefficient.

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