A STUDY ON NUMBER AND THICKNESS OF InGaN/AlGaN MULTIPLE QUANTUM WELL STRUCTURE FOR 365nm - 385nm ULTRAVIOLET LIGHT-EMITTING DIODES

NGHIÊN CỨU SỐ LƯỢNG VÀ ĐỘ DÀY CỦA InGaN/AlGaN ĐA GIẾNG LƯỢNG TỬ CHO ĐIỐT PHÁT XẠ CỰC TÍM 365nm - 385nm

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ABSTRACT

In this paper, the authors report a study on number of layers and thickness of InGaN/AlGaN multiple quantum well (MQW) structure based ultraviolet (UV) light emitting diode (LED) heterostructures with emission at the wavelength within the range from 365nm to 385nm, which has been studied by means of SiLENSe software and drift-diffusion transport equations for electron and hole concentrations. The multiple quantum well active region in UV LED heterostructures consists of i-$In_{0.05}Ga_{0.95}N$ well layers and i-$Al_{0.22}Ga_{0.78}N$ barrier layers. The thickness of each $In_{0.05}Ga_{0.95}N$ well layer or $Al_{0.22}Ga_{0.78}N$ barrier layer of quantum well is increased from 1.0nm to 5.0nm. Based on the UV LED emission spectrums, the authors have found that emitting wavelength changed from 364nm (five pairs of MQW layers with d = 2.0nm) to 412nm (four pairs of MQW layers with d = 5.0nm). The peak wavelength of emission spectra of UV LED structure with five pairs $In_{0.05}Ga_{0.95}N$ (3.0nm-thick) well layer and $Al_{0.22}Ga_{0.78}N$ (3.0nm-thick) barrier layer of MQW active region was 377.5nm. Results of the studies are almost in good agreement with other experimental results.

Keywords: *InGaN; AlGaN; UV LED; MQWs; wavelength.*

TÓM TẮT

Trong bài báo này, tác giả trình bày nghiên cứu về số lớp và độ dày của InGaN/AlGaN đa giếng lượng tử (MQW) cho điốt phát xạ cực tím với bước sóng phát xạ từ 365nm đến 385nm, nghiên cứu được thực hiện dựa trên phần mềm SiLENSe và các phương trình vận chuyển trôi-khuếch tán của nồng độ điện tử và lỗ trống. Vùng hoạt động đa giếng lượng tử MQW trong UV LED dị cấu trúc gồm có những lớp i-$In_{0.05}Ga_{0.95}N$ giếng và những lớp i-$Al_{0.22}Ga_{0.78}N$ rào cản. Độ dày của mỗi lớp i-$In_{0.05}Ga_{0.95}N$ giếng hoặc lớp i-$Al_{0.22}Ga_{0.78}N$ rào cản của giếng lượng tử (QW) được tăng từ 1.0nm đến 5.0nm. Dựa trên những phổ phát xạ của UV LED, tác giả nhận thấy rằng bước sóng phát xạ thay đổi từ 364nm (5 lớp MQW với d = 2.0nm) đến 413nm (4 lớp MQW với d =5.0nm). Đỉnh phổ phát xạ của cấu trúc UV LED với 5 cặp InGaN/AlGaN của vùng hoạt động MQW là 377.5nm. Những kết quả nghiên cứu đạt được phù hợp tốt với những kết quả thực nghiệm công bố gần đây.

Từ khóa: *InGaN; AlGaN; LED cực tím; đa giếng lượng tử; bước sóng.*

1. INTRODUCTION

Several research groups developed an interest in the UV region because of its wide range of applications as a function of wavelength [1-3]. The UV spectrum encompasses all wavelengths between 100 and 400 nm in length. It’s commonly broken down into three distinct subfields: The UV-A region of 315nm to 400nm is useful for UV curing, counterfeit banknote detection, tanning, polymer and ink printing, photo catalysis air purification, and lighting applications. The UV-B region of 280nm to 315nm is useful for phototherapy, the treatment of skin disease, protein analysis, DNA analysis, drug discovery, and chemical sensor applications. The UV-C region under 280nm is useful for laser knives, sterilizers, and water or air purifiers [4,5]. Traditional UV lamps, such as mercury, metal halide, and xenon lamps, have been used for many of these applications, but in the future, UV lamps will be replaced with UV LEDs, owing to significant advantages in size, power consumption, lifetime, wavelength control, and safety. III-V nitride semiconductors with the wurtzite crystal structure, AlN (6.2eV), GaN (3.4eV), and InN (0.8eV), have a direct band gap and cover a wide wavelength range of ultraviolet to visible red [6,7].

The research on AlGaN-based UVLEDs for wavelengths between 330-355nm [8-10] was initiated by some research groups 20 years ago. Asif Khan's group at the University of South Carolina have reported the 270-280nm band AlGaN LEDs in 2002-2004 [8,9]. They set records of efficiency in the short-wavelength range between244-280nm [10].The shortest wavelength nitride LED was reported in 2006 [9]. However, the internal quantum efficiency (IQE) was quite low because they did not obtain sufficient electron-hole confinement or efficient carrier injection because of using the highest band-gap AlN for the emitting region.

Hideki Hirayama's team in Japan RIKEN research deep UVLED based on AlGaN in 1997. The first report performance DUV (230nm) luminescence (PL) from the AlGaN QWS [10], and UVLED AlGaN-QW 333nm on SiC in 1999. The group also developed high-performance UV LED using InAlGaN-based QWs four components [11-13]. This group has achieved a high IQE of 47% for InAlGaN QWS 338nm and 352nm four component activities of a DC line 7.4mW UV InAlGaN QW LEDs on AlN substrates [13].

Recently, N. V. Hieu *et al.* reported on the lamp of LED with 365nm of ultraviolet wavelength for E. coli and Coliform bacteria sterilization in running water [14]. Recently, our research group have studied, designed and developed system measure the ozone density in the air by UV LED sensor [15].

The modeling study reported in this paper is aimed at better understanding the operation of MQW LED with the focus on number and thickness of InGaN/AlGaN MQW structure based UV LEDs with emission at the wavelength in the range from 365nm to 385nm by SiLENSe software.

2. UV LED STRUCTURE

The UV LED used as a reference for subsequent simulation are grown on a (0001) patterned sapphire substrate using low-pressure horizontal-flow metal organic chemical vapor deposition (MOCVD). Fig.1 depicts the structure of UV LED used in this study. Firstly, a sapphire substrate was cleaned under H_2 at 1020^oC. After, the UV LED structure of a 3μm-thick AlN layer, a

1µm-thick undoped $Al_{0.3}Ga_{0.7}N$ layer, a 2µm-thick $Al_{0.22}Ga_{0.78}N$ cladding layer with $N_d = 5.10^{18}cm^{-3}$, from one to six pairs of $In_{0.05}Ga_{0.95}N/Al_{0.22}Ga_{0.78}N$ MQW layers, the thickness d of $In_{0.05}Ga_{0.95}N$ well layer and $Al_{0.22}Ga_{0.78}N$ barrier layer of each quantum wells change from 1.0nm to 5.0nm, a 300nm-thick p-$Al_{0.3}Ga_{0.7}N$ electron blocking layer with $N_a = 5.10^{17}cm^{-3}$, and a 100nm-thick p-GaN contact layer with $N_a = 10^{18}cm^{-3}$.

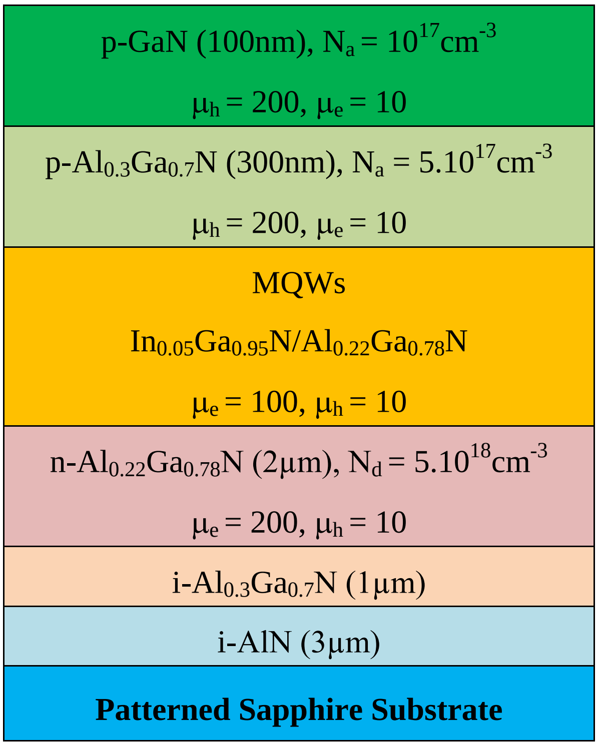


Figure 1. *Schematic structure view of 365nm - 385nm UV LED.*

A quantum well (QW) is a potential well with only discrete energy values. Quantum wells are formed in semiconductors by having a material, like gallium arsenide, sandwiched between two layers of a material with a wider bandgap, like aluminium arsenide. Consider two semiconductors with band gap $E_{g\text{-barrier}}$ and $E_{g\text{-well}}$. Band gap energy of the QW [16] will be given by equation:

$$E_{g\text{-}QW} = E_{g\text{-well}} + E_{0,e} + E_{0,h} \quad (1)$$

where $E_{0,e}$, $E_{0,h}$ are quantized energy of electron and hole, respectively.

The unstrained $Al_xGa_{1-x}N$ band gap energies [17-20] are calculated:

$$E_g(x) = 3.42eV + x2.86eV - x(1-x)1eV \quad (2)$$

and $In_xGa_{1-x}N$ band gap energies are calculated:

$$E_g(x) = 3.42eV - x2.65eV - x(1-x)2.4eV \quad (3)$$

In this The UV LED has the structure of multi-quantum wells (MQWs) of i-$In_{0.05}Ga_{0.95}N$ well layers and i-$Al_{0.22}Ga_{0.78}N$ barrier layers.

3. SILENSE FOR THE STRUCTURAL SIMULATION

SiLENSe (Simulator of Light Emitters based on Nitride Semiconductors) is a specialized software tool for modeling the characteristics of light emitting diodes (LEDs) made of wurtzite semiconductor materials.

The software allows simulation of an LED band diagram as a function of bias, electron and hole transport inside the structure, radiative and non-radiative carrier recombination, light emission efficiency, electric field distribution, and emission spectra from the LED. The software implements a one-dimensional drift-diffusion model with account for specific features of the nitride materials - strong piezoeffect, existence of spontaneous electric polarization, low efficiency of acceptor activation, and high threading dislocation denssity in the structure. The software enables the analysis of graded composition heterostructures, which is important for designing LED structures of a new generation on the basis of bandgap engineering principles.

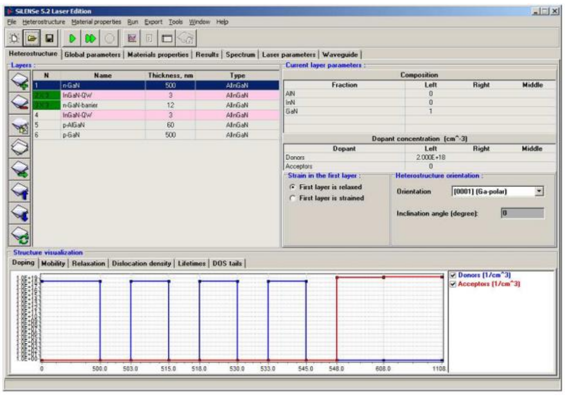


Figure 2. *Heterosture tab window of SiLENSe software.*

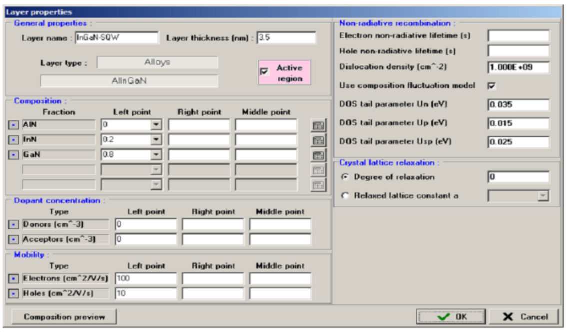


Figure 3. *Layer properties window*

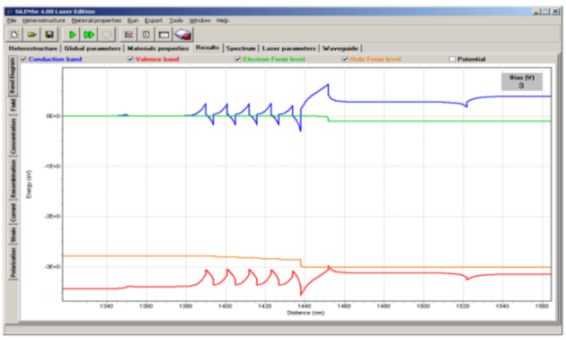


Figure 4. *Band diagram tab window.*

4. RESULTS AND DISCUSSION

4.1. Parameters simulation

The MQW LED structure in this study, the MQW layers n changes from one to six. The thickness d of $In_{0.05}Ga_{0.95}N$ well layer and $Al_{0.22}Ga_{0.78}N$ barrier layer of each quantum wells change from 1.0nm, 2.0nm, 3.0nm, 3.5nm, 4.0nm, 4.5nm, and 5.0nm. The survey characteristics UV LED is performed at 3.5V voltage.

4.2. Simulation results

4.2.1. Energy band structure

Fig.5 and Fig.6 shows the band diagrams versus distance in the MQW LED with three to five pairs of MQW layers and bias 3.5V, computed for practically important values of thickness d of MQW.

Fig.6 shows the energy of valence band (below) and the energy of conduction band (above) in the MQW LED structure. Fig.6 (b) shows the band diagram variation with 3.5V bias for five pairs of $In_{0.05}Ga_{0.95}N/Al_{0.22}Ga_{0.78}N$ MQW layers, it is seen MQW active region from 2000nm to 2030nm if each QW includes a 3.0nm-thick $In_{0.05}Ga_{0.95}N$ well and a 3.0nm-thick $Al_{0.22}Ga_{0.78}N$, from 2000nm to 2050nm if each QW includes a 5.0nm-thick $In_{0.05}Ga_{0.95}N$ well and a 5.0nm-thick $Al_{0.22}Ga_{0.78}N$.

Breadth direct energy gap in the two cases nearly do not change much in our anticipated emission wavelength of MQW LED large oscillations.

Fig.7 shows I-V characteristic and current density versus bias with five pairs of $In_{0.05}Ga_{0.95}N/Al_{0.22}Ga_{0.78}N$ MQW layers. Current was linear from the increasing of voltage 3.5V.

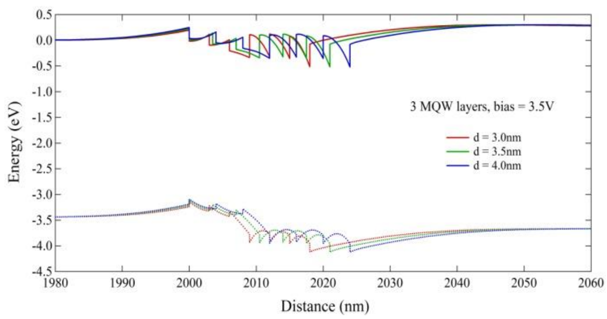
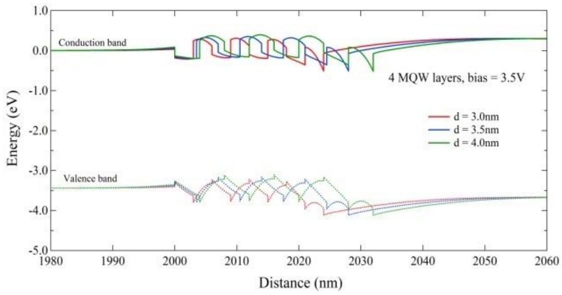
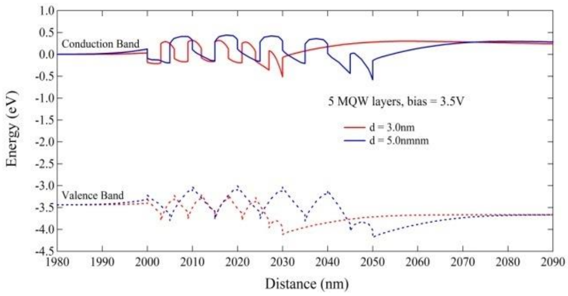


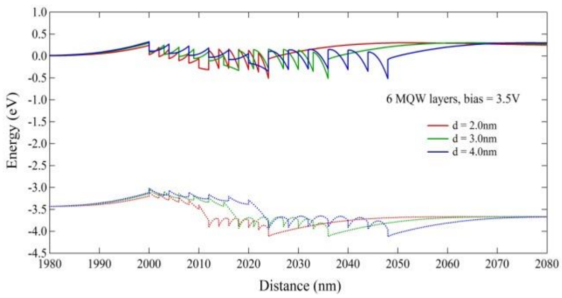
Figure 5. *Band diagrams variation with 3.5V bias for 3MQW.*



(a)



(b)



(c)

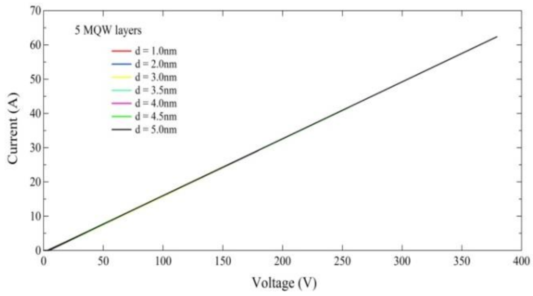
Figure 6. *Band diagrams variation with 3.5V bias for (a) 4MQW layers, (b) 5MQW layers, (c) 6 MQW layers.*

4.2.2. I-V characteristic and IQE

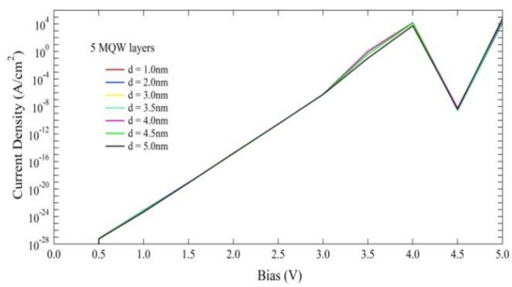
Internal quantum efficiency (IQE) is the ratio of photons emitted from the active region of the semiconductor to the number of electrons injected into the p-n junction of an LED. One can define the IQE as:

$$IQE = \frac{I_0/E_{ph}}{J_{in}/q} \quad (4)$$

where I_0 is the optical power at the central wavelength, E_{ph} is the photon energy, J_{in} is the current injected into the LED active region and q is the electron charge.



(a)



(b)

Figure 7. *I-V characteristic (a) and current density versus bias (b) with five pairs of MQW layers, each QW layer thick increased from 1.0nm to 5.0nm.*

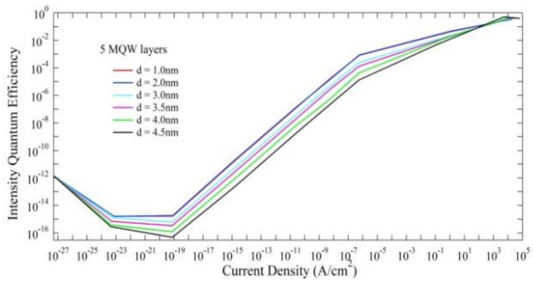


Figure 8. *Intensity quantum efficiency versus current density computed for thickness of five pairs $In_{0.05}Ga_{0.95}N/Al_{0.22}Ga_{0.78}N$ MQW layers.*

Fig.8 shows IQE (the ratio of the photon emission rate to the rate of electron-hole pair injection in the LED structure) as function of current density computed for five pairs of MQW layers, in two cases each QW consists a 3.0nm-thick InGaN well layer and a 3.0nm-thick AlGaN barrier layer, and a 5.0nm-thick InGaN well layer and a 5.0nm-thick AlGaN barrier layer. In Fig.8, intensity quantum efficiency (IQE) tends to hit 1 (100%) when the current density of great value.

4.2.3. Emitting wavelength

Fig.9 shows emission spectra from the UV LED structure with MQW layers n changes from one to six. The thickness d of $In_{0.05}Ga_{0.95}N$ well layer and $Al_{0.22}Ga_{0.78}N$ barrier layer of each quantum wells change from 1.0nm to 5.0nm at voltage 3.5V. Based on the UV LED emission spectrum, the authors found that emitting wavelength change from 364nm (five pairs of MQW layers with d = 2.0nm) to 412nm (four pairs of MQW layers with d = 5.0nm).

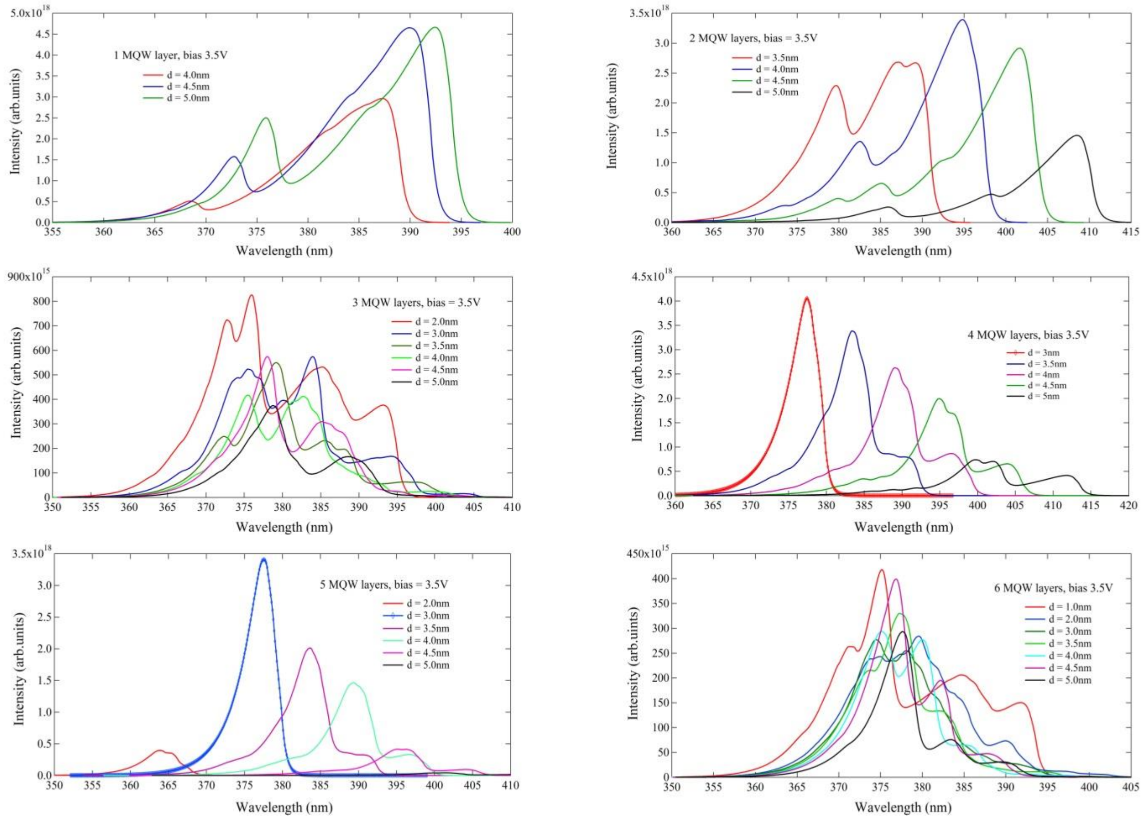


Figure 9. *Emission spectra from the UV LED structure with one to six pairs of $In_{0.05}Ga_{0.95}N/Al_{0.22}Ga_{0.78}N$ MQW layers, each QW layer thick increased from 1.0nm to 5.0nm.*

Fig.10 shows emission spectra from the UV LED structure with MQW layers n change from three to six, each QW consists a 3.0nm-thick $In_{0.05}Ga_{0.95}N$ well layer and a 3.0nm-thick $Al_{0.22}Ga_{0.78}N$ barrier layer at bias 3.5V.

In case, the structure consists three MQW layers and six MQW layers have appeared multiple peak wavelength. As the structure consists three MQW layers has three peak wavelength 376nm, 380nm, and 383nm.

The structure consists six MQW layers has two peak wavelength 374nm and 377nm. In case, both the structure consists four MQW layers and five MQW layers have peak wavelength of emission spectra is unique and valuable 377.5nm. Operation of UV LED be tested at bias 3.5V.

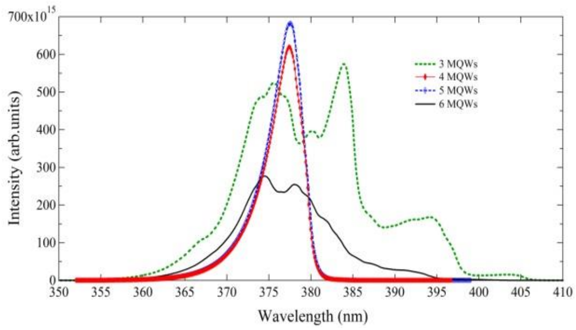


Figure 10. *Emission spectra from the LED structure with each QW consists a 3nm-thickInGaN well/3nm-thick AlGaN barrier.*

4.3. Discussion

This paper for 380nm UV LED will be useful to discuss with the UVLED structure of Sung Bum Bae *et al.* (Components & Materials Research Laboratory, ETRI, Daejeon, Korea [16]). The UV LED structure consists of five pairs of $In_{0.05}Ga_{0.95}N$ (3.0nm-thick)/ $Al_{0.05}Ga_{0.95}N$ (10nm-thick) MQW layers. Fig.11 shows the EL spectrum of the 380nm UV LED package. The peak wavelength is 383.3nm, and the full width at half maximum (FWHM) is 11.2nm. The P_0 of the UV LED is 51.3mW at 150mA and 118.4mW at 350mA, as measured by KOPTI (CA).

The UV LED structure of this paper was modified from the UV LED structure of Sung-Bum Bae et al with the various parameters.

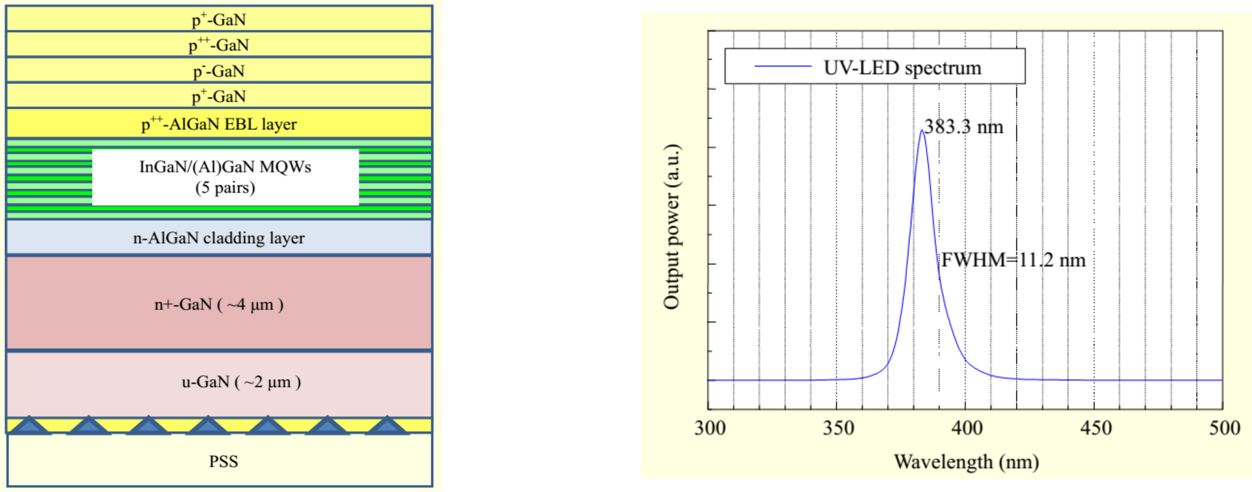


Figure 11. *Schematic view (left) and EL spectrum (right) of UV LED with five pairs$In_{0.05}Ga_{0.95}N$ (3mn)/$Al_{0.05}Ga_{0.95}N$ (10nm) MQW layers [16].*

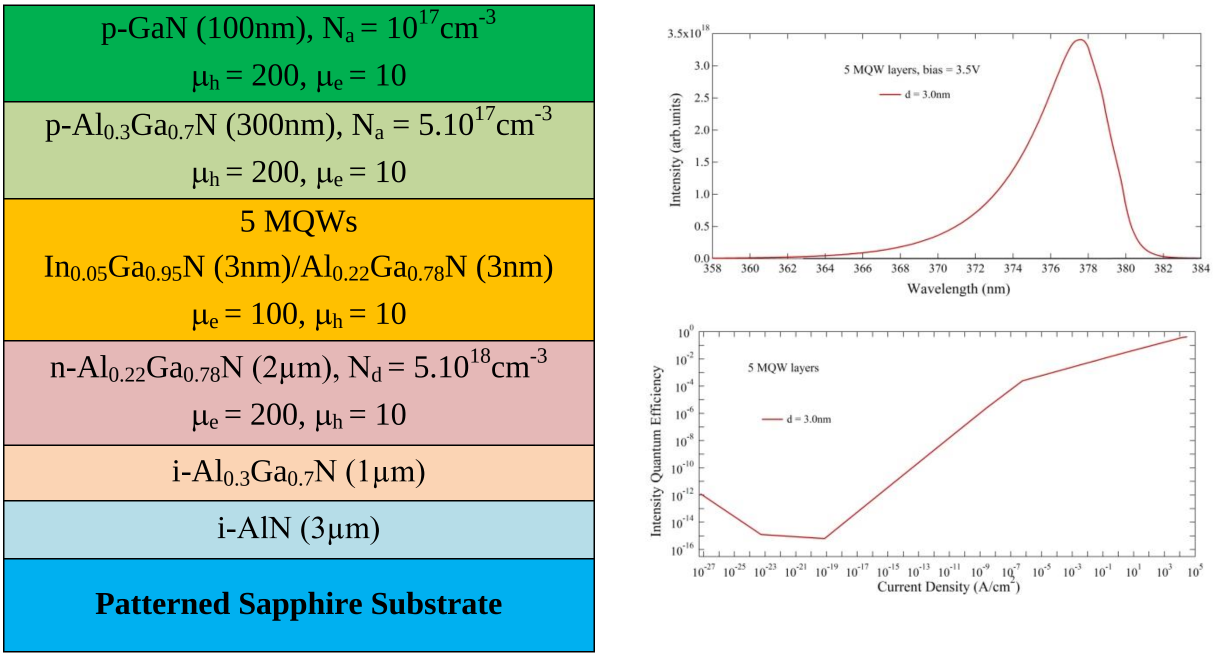


Figure 12. *The modeling structure, emission spectra, and intensity quantum efficiency versus current density of UV LED in the study with five pairs $In_{0.05}Ga_{0.95}N$ (3.0nm-thick) well layer and $Al_{0.22}Ga_{0.78}N$ (3.0nm-thick) barrier layer of MQW LED layers, peak wavelength is 377.5nm.*

Fig.12 shows MQW active region LED in this study consists four or five pairs of$In_{0.05}Ga_{0.95}N/Al_{0.22}Ga_{0.78}N$ MQW layers, each QW consists a 3.0nm-thick $In_{0.05}Ga_{0.95}N$ well layer and a 3.0nm-thick $Al_{0.22}Ga_{0.78}N$ barrier layer. The peak wavelength is 377.5nm. This results indicate the various parameters in the structure of UV LEDs to get many information in their physical and optical properties by many graphs and curves. They will be guided in the fabrication process in next time.

5. CONCLUSION

The behaviors and physical characteristic MQW LEDs heterostructures were found to focus on the carriers in the active region. The peak wavelength of emission spectra of UV LED structure is 377.5nm. The MQW active region consists five pairs of MQW layers, each QW consists a 3.0nm-thick $In_{0.05}Ga_{0.95}N$ well layer and a 3.0nm-thick $Al_{0.22}Ga_{0.78}N$ barrier layer, are parameters necessary for the fabrication process. Intensity quantum efficiency (IQE) tend to hit 1 (100%) when the current density of great value. The simulation results of the structure in this study is similar to the experimental results of the UV LED structure of Sung-Bum Bea et al.

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