Chapter4
Fabrication and Characteristics of GaN-based MCLED

4.1 Recent Status

With the achievement of optically pumped GaN-based VCSEL, the realization of electrically-injected GaN-based VCSEL has become promising. However, the road to the electrical-injected of GaN-based VCSEL is still difficult. Recently, some groups demonstrated the micro-cavity light emitting diodes (MCLEDs) [15-22], a quasi VCSEL structure. They mainly utilized an epitaxially growth nitride DBR as the bottom mirror and a dielectric DBR as the top mirror. This kind of device has several advantages comparable to VCSEL, such as circular beam shape, light emission in vertical direction, fully monolithic test and two dimensional arrays. Some GaN-based MCLEDs with an in-situ epitaxially grown nitride-based DBRs and dielectric DBRs as the bottom and upper mirror of the cavity were reported. Due to the lattice mismatch among nitride compound semiconductors, high reflectivity, crack-free, and wide stop band width DBRs were hard to grow. Therefore, most of the reported GaN-based MCLEDs used GaN/AlGaN DBRs as the high reflecting bottom mirror of the cavity. Diagne et al. [15] used 60 pairs of $GaN/Al_{0.25}Ga_{0.75}N$ DBR to form the bottom mirror with 99% reflectivity, Arita et al. [20] employed 26 pairs of $GaN/Al_{0.40}Ga_{0.60}N$ DBR to form bottom mirror with 91% reflectivity. However, the small index of refraction contrast between GaN and AlGaN results in small mirror stop band width about 13nm. In order to reduce the number of pairs of DBRs and increase the mirror stop band width, the use of materials with high Al content AlGaN/GaN DBRs or AlN/GaN DBRs is necessary. Mackowiak et al. [43] reported the designing of possible structures of nitride VCSELs were composed of 4 pairs of the dielectric SiO_2/TiO_2 DBR as upper resonator mirror and 24 pairs of the $AlN/Al_{0.15}Ga_{0.85}N$ DBR as the bottom resonator mirror. Recently, we have achieved high-reflectivity AlN/GaN DBR structure with a peak reflectance of 94% and a stop band about 18nm with relatively smooth surface morphology [23-24]. Here, we show the fabrication of GaN-based MCLED with hybrid structure, composed of high reflectivity, crack-free, wide stopband width in-situ grown AlN/GaN bottom DBRs and ex-situ deposited SiO_2/TiO_2 top DBRs, could be used as basis for the GaN-based VCSEL. In addition, compared to the conventional GaN-based LED, the EL of the MCLED was dominated by the resonant cavity mode. So far, the current and temperature dependent EL of the MCLED was not reported. In our work, the fabricated MCLED showed relative stable EL than the conventional LED while varying injected current and operating temperature.

4.2 Fabrication of GaN-based MCLED

4.2.1 Wafer Preparation

MOCVD grown structure and its reflectivity spectrum

The nitride heterostructure of GaN-based MCLED was grown by metal-organic chemical vapor deposition (MOCVD) system (EMCORE D-75) on the polished optical-grade c-face (0001) 2” diameter sapphire substrate, as shown in Fig. 4.1. Trimethylindium (TMIn), Trimethylgallium (TMGa), Trimethylaluminum (TMAl), and ammonia (NH_3) were used as the In, Ga, Al, and N sources, respectively. Initially, a thermal cleaning process was carried out at 1080°C for 10 minutes in a stream of hydrogen ambient before the growth of epitaxial layers. The 30nm thick GaN nucleation layer was first grown on the sapphire substrate at 530^{o}C, then 1μm thick undoped GaN buffer layer was grown on it at 1040^{o}C. After that, a 25 pairs of quarter-wave GaN/AlN structure was grown at 1040^{o}C under the fixed chamber pressure of 100Torr and used as the high reflectivity bottom DBR. Finally, the 3λ InGaN/GaN micro cavity structure was grown atop the GaN/AlN DBR, composed of ten pairs of InGaN/GaN MQW layers, surrounded by Si-doped n-type GaN and Mg-doped p-type GaN layers. The reflectivity spectrum of the 25 pairs of GaN/AlN DBR structure was measured by the n&k ultraviolet-visible spectrometer with normal incident at room temperature, as shown in Fig. 4.2. The reflectivity spectrum centered at 452nm with peak reflectivity of R=94% and stopband width of about 18nm.

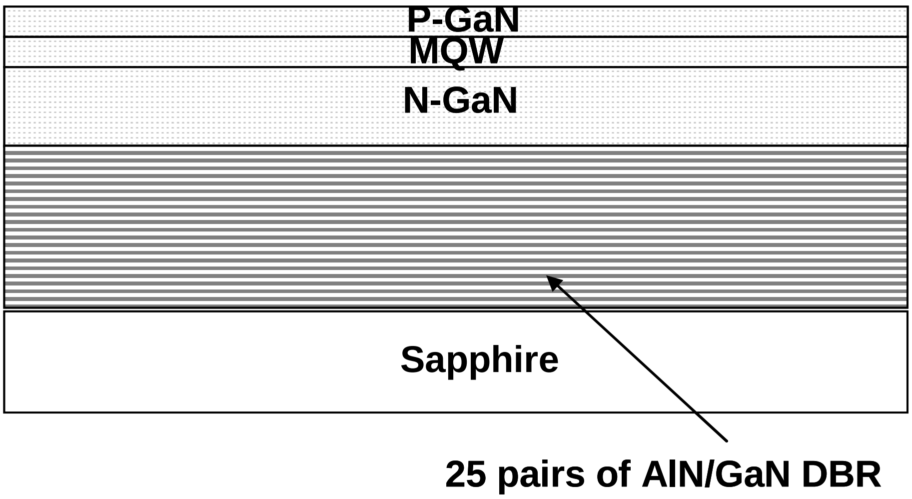


Figure 4.1 The schematic daigram of nitride heterostructure of GaN-based MCLED grown by MOCVD.

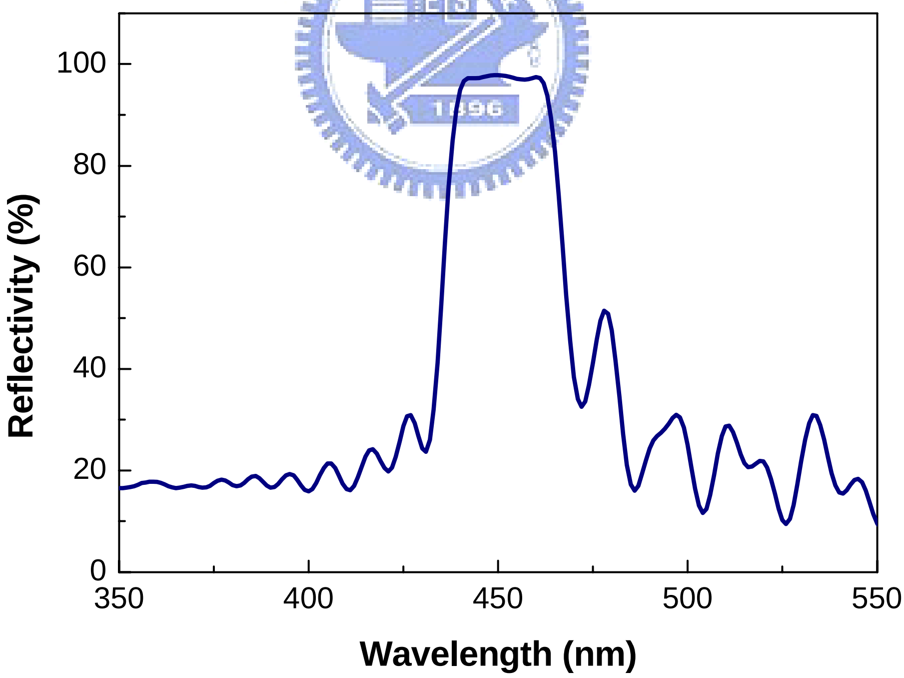


Figure 4.2 The reflectivity spectrum of the 25 pairs of GaN/AlN DBR structure measured by n&k ultraviolet-visible spectrometer with normal incident at room temperature

<u>**The PL of the MOCVD grown structure and reflectivity spectrum of dielectric DBR**</u>

The PL spectrum of the MOCVD grown structure was measured by a spectrometer/CCD (Jobin-Yvon Triax 320 Spectrometer) with a spectral resolution of ~0.1nm, as shown in Fig 4.3. The PL spectrum was located at 458.5 nm with 10.5 nm FWHM and well matched to high reflectance area (Fig. 4.2). To fabricate the high quality resonant cavity MCLED, the high reflectivity top dielectric DBR was necessary. In order to measure the reflectance spectrum, 6 periods SiO_2/TiO_2 DBR stack was also deposited on the glass by electron beam evaporation system. The reflectance spectrum of the dielectric mirrors is also shown in Fig. 4.4. Clearly, a high reflectivity (97.5%) DBR centered at 430nm with wide stop bandwidth about 100nm was obtained.

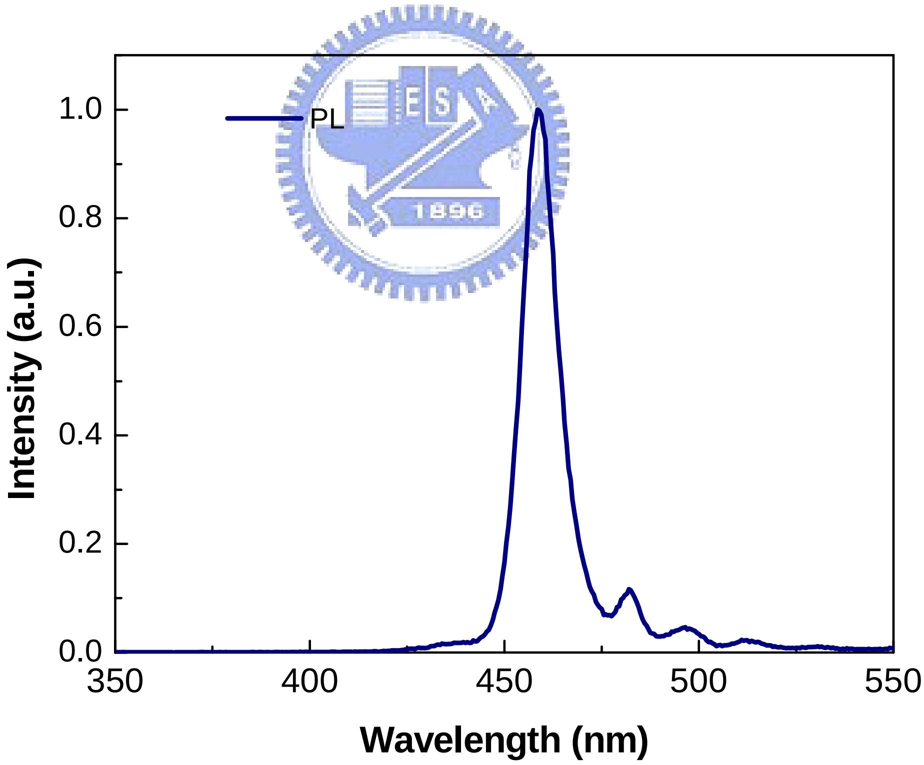


Figure 4.3 The PL spectrum of the MOCVD grown structure.

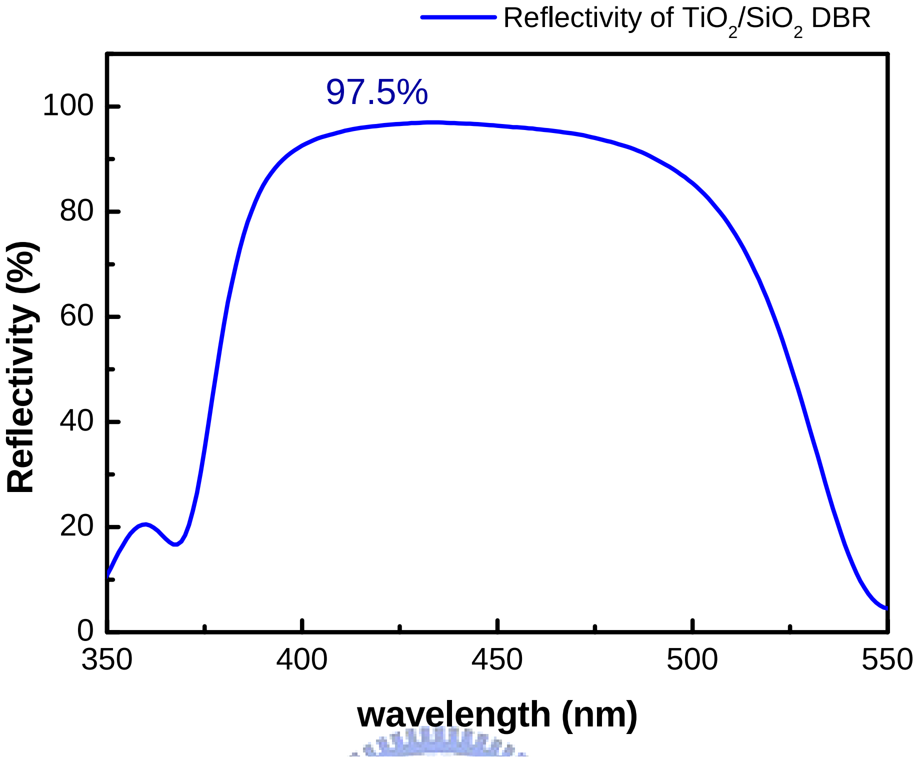


Figure 4.4 The reflectivity spectrum of 6 pairs of SiO_2/TiO_2 DBR.

4.2.2 Process Procedure

Initial clean (I.C.) and photolithography technique

During process of GaN-based MCLED, two basic skills will be widely used. One is the initial clean (I.C.), the other is photolithography technique. The purpose of the I.C. is to remove the small particle, and organism on the sample surface. The steps of I.C. are described as below.

1. Degreasing by ultrasonic baths in acetone (ACE) 5min.
2. Dipping by ultrasonic baths in isopropyl alcohol (IPA) 5min for organism removed.
3. Rising in de-ionized water (D.I. water) 5min for surface clean.
4. Blowing with N_2 gas for surface drying.
5. Baking by hot plate 120^{o}C, 5min, for wafer drying.

The purpose of the photolithography is to transfer the pattern drawn on the mask to the photoresist (PR) on the wafer. In the process of photolithography, a special positive photoresist AZ 5214E was used. Although it is positive photoresist (and may even be used in that way), it is capable of image reversal (IR) resulting in a negative pattern of the mask. In fact AZ 5214E is almost exclusively used in the IR-mode which is proper to be used in the lift-off process. Both positive exposure and IR exposure photolithography technique were employed in the fabrication of the MCLED. These photolithography techniques are described as below.

Positive exposure technique

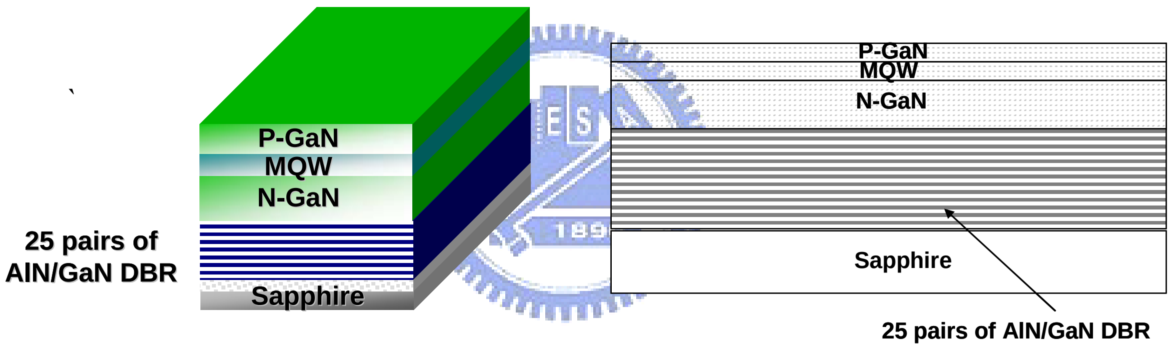
1. Spin coating by photoresist: AZ 5214E.
   a. first step : 1000 rpm for 10sec.
   b. second step : 3500 rpm for 30sec.
2. Soft bake: hot plate 90^{o}C, 90sec.
3. Alignment and exposure: 23sec.
4. Development: dipping in AZ-300 for 30sec.
5. Fixing: rising in D.I. water 30sec.
6. Blowing with N_2 gas for drying.
7. Hard bake: hot plate 120^{o}C, 4min.

IR exposure technique

1. Spin coating by photoresist: AZ 5214E.
   a. first step : 1000 rpm for 10sec.
   b. second step : 3500 rpm for30sec.
2. Soft bake: hot plate 90^{o}C, 90sec.
3. Alignment and exposure: 6sec.
4. Hard bake: hot plate 120^{o}C, 1min50sec.
5. Flood exposure: 57sec.
6. Development: dipping in AZ-300 for 30sec.
7. Fixing: rising in D.I. water 30sec.
8. Blowing with N_2 gas for drying.
9. Hard bake: hot plate 120^{o}C, 4min.

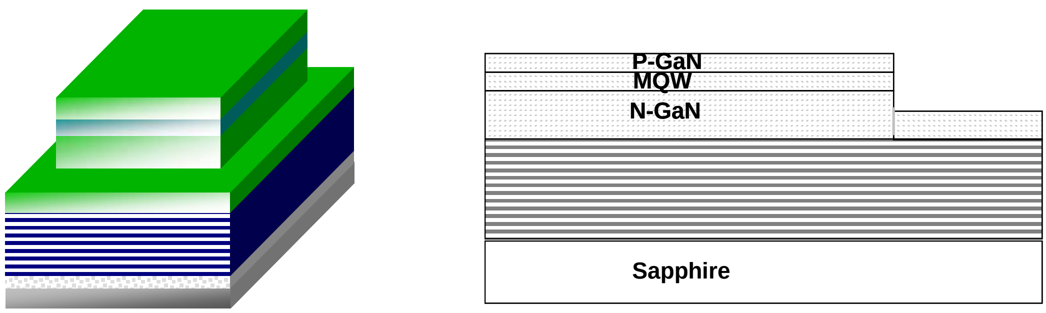
Process flowchart

Figure 4.5(a) and (b) show the schematic diagrams of nitride structure of MCLED grown by MOCVD. The MCLED was fabricated by six process steps. In the beginning, SiO_2 mesa etching mask and ICP dry etching machine were used to define the mesa region, as shown in Fig. 4.6(a) and (b). Then SiNx layer was grown by PECVD and patterned to define the current confinement layer with the effective optical aperture varying from 5μm to 30μm, as shown in Fig. 4.7(a) and (b). The Ni/Au (50Å/30Å) thin film deposited on the sample by electro beam evaporation system and annealed at 500^{o}C under nitrogen ambient was used for current spreading layer (or transparent contact layer, TCL), as shown in Fig. 4.8(a) and (b). The Ti/Al/Ni/Au and Ni/Au contacts were deposited to serve as n-type and p-type electrode, respectively, as shown in Fig. 4.9(a) and (b) and Fig. 4.10(a) and (b). The MCLED was completed by capping the structure with 6 periods of SiO_2/TiO_2 DBR stack (R~97.5%), as shown in Fig. 4.11(a) and (b).



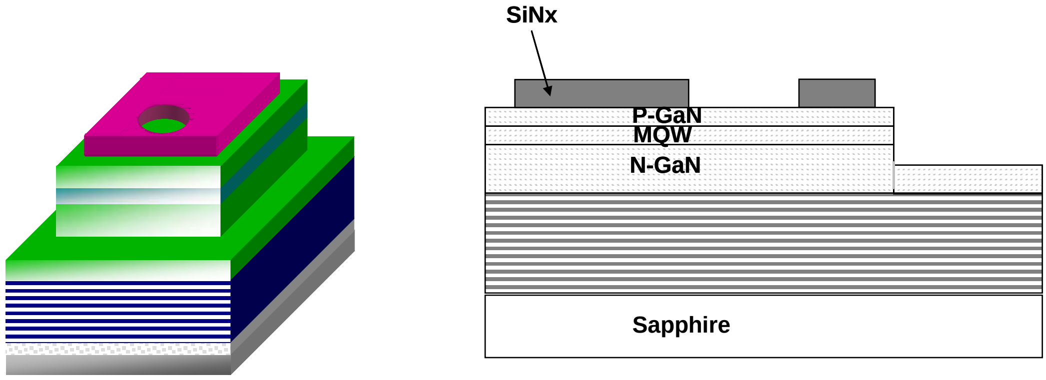
(a) (b)

Figure 4.5(a) The 3D schematic diagram of nitride structure of MCLED grown by MOCVD (b) The 2D schematic diagram of nitride structure of MCLED grown by MOCVD.



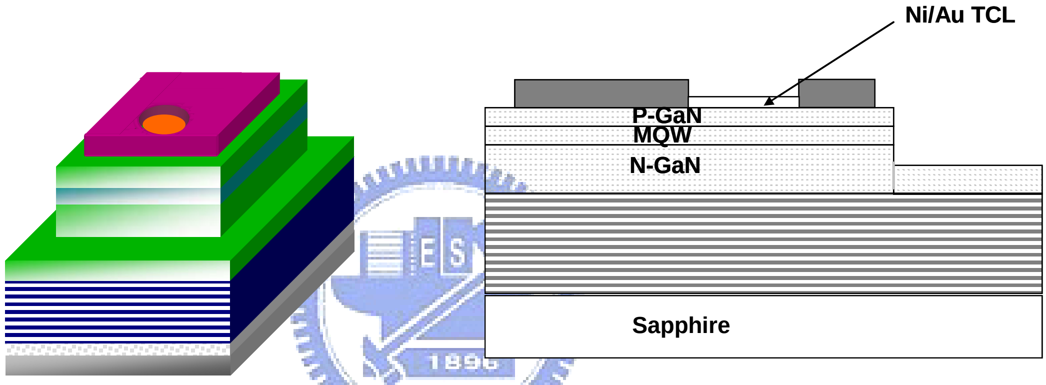
(a) (b)

Figure 4.6 First step of process: mesa. (a) 3D schematic diagram (b) 2D schematic diagram.



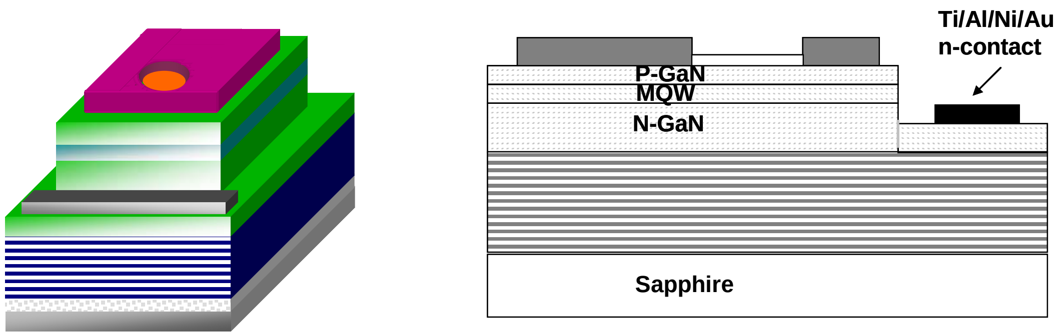
(a) (b)

Figure 4.7 Second step of process: passivated (a) 3D schematic diagram (b) 2D schematic diagram.



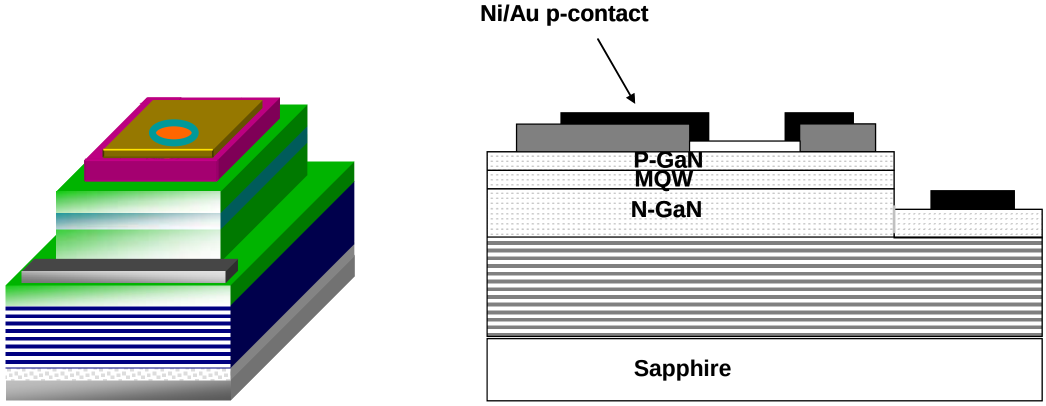
(a) (b)

Figure 4.8 Third step of process: TCL. (a) 3D schematic diagram (b) 2D schematic diagram.



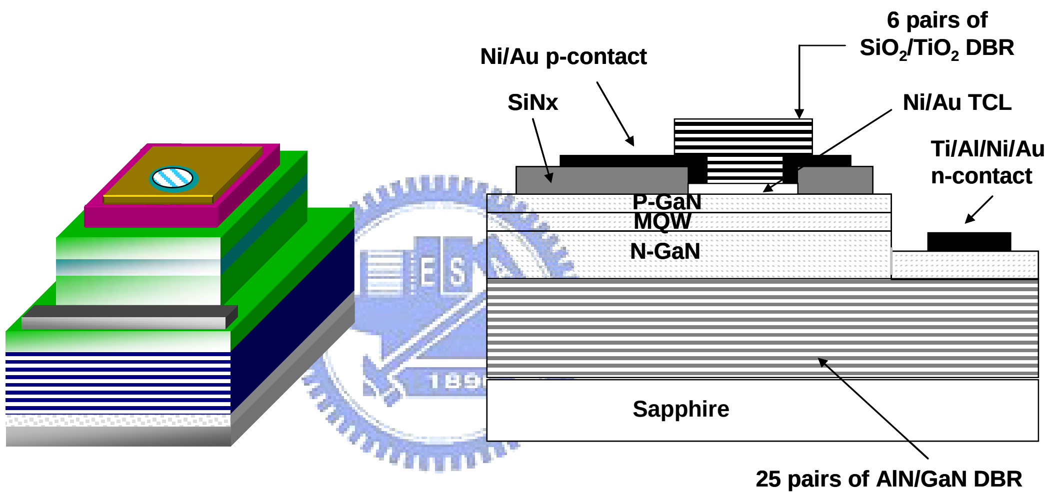
(a) (b)

Figure 4.9 Fourth step of process: N-contact. (a) 3D schematic diagram (b) 2D schematic diagram.



(a) (b)

Figure 4.10 Fifth step of process: P-contact. (a) 3D schematic diagram (b) 2D schematic diagram.



(a) (b)

Figure 4.11 Sixth step of process: DBR (a) 3D schematic diagram of completed MCLED (b) 2D schematic diagram of completed MCLED.

To completed describe the process flowchart, each process condition is entirely list in the table 4.1.

Table 4.1 Process flowchart

Step	Process	Conditions
1	Mesa	(1) I.C. (2)grow 300nm SiO_2 by PECVD (3)define pattern of mesa by photography (positive exposure) (4)dry etching by ICP to define the SiO_2 mesa etching mask (5)dry etching by ICP to form the mesa structure (6)remove SiO_2 mesa etching mask by BOE
2	Passivated	(1)I.C. (2)grow 200nm SiNx by PECVD (3)define pattern of passivated by photography (positive exposure) (4)dry etching by ICP to define the SiNx current confined layer
3	TCL	(1)I.C. (2)define pattern of TCL by photography (IR exposure) (3)Ni/Au(5nm/5nm) deposited by E-gun and lift-off
4	N-contact	(1)I.C. (2) define pattern of N-contact by photography (IR exposure) (3)Ti/Al/Ni/Au(20nm/150nm/20nm/200nm) deposited by E-gun and lift-off
5	P-contact	(1)I.C. (2) define pattern of P-contact by photography (IR exposure) (3)Ni/Au(20nm/200nm) deposited by E-gun and lift-off
6	DBR	(1)I.C. (2) define pattern of DBR by photography (IR exposure) (3)SiO_2/TiO_2 DBR deposited by E-gun and lift-off

4.3 Characteristics of GaN-based MCLED

The electroluminescence (EL) characteristics of fabricated MCLEDs were measured by Alpha-SNOM system and evaluated by injecting different current density or varying the operating temperature. Current-light output power and current-voltage measurements were performed using the probe station and drove by Keithley 238 CW Current Source. Figure 4.12 shows the electrical and optical measurement system.

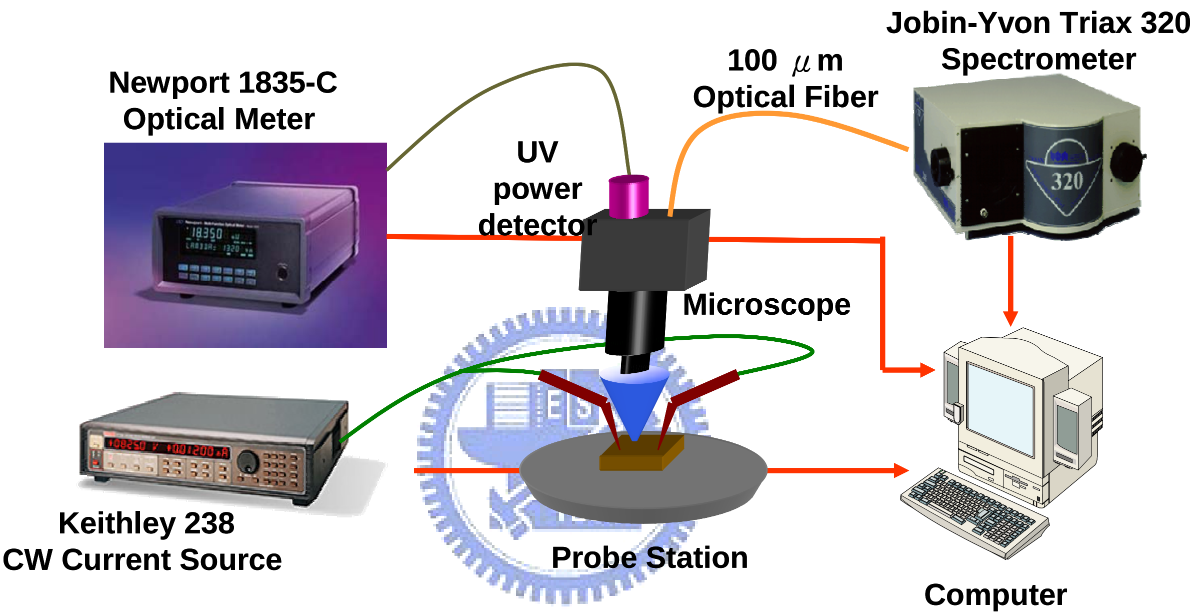
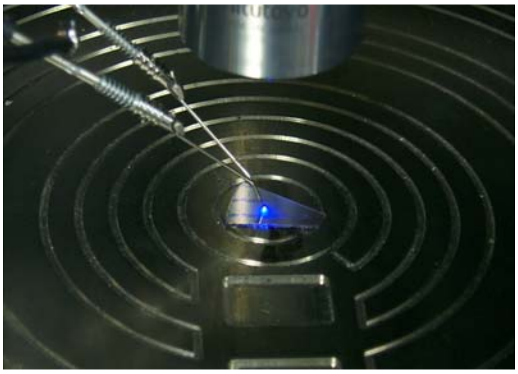


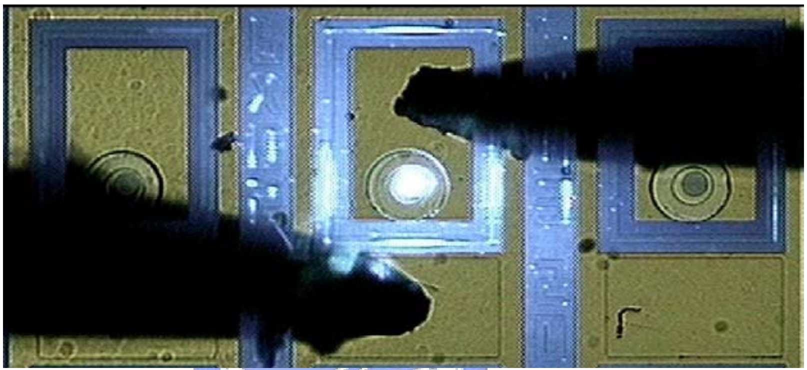
Figure 4.12 Electrical and optical measurement system.

4.3.1 Electrical Characteristics of GaN-based MCLED

Figure 4.13(a)(b)(c) show the light emission photograph of the MCLED at 20mA current injection. Current-light output power (L-I) and current-voltage (V-I) measurements of GaN-based MCLED were performed by using the probe station, Keithley 238 CW Current Source, UV power detector, Newport 1835-C optical meter, and computer with automatic control software. The light output power-current (L-I) and current-voltage (I-V) characteristic are shown in figure 4.14. The 20mA forward voltage and resistance of the MCLED were about 3.5V and 530Ω, respectively. Although the series resistance of the MCLED seemed high, it was reasonable and acceptable while using un-doped AlN/GaN DBRs as intra-cavity bottom reflection mirror.



(a) (b)



(c)

Figure 4.13(a)The photograph of MCLED tested at probe station. (b)Top view photograph of MCLED arrays. (c)Top view photograph of MCLED at 20mA current injection at room temperature.

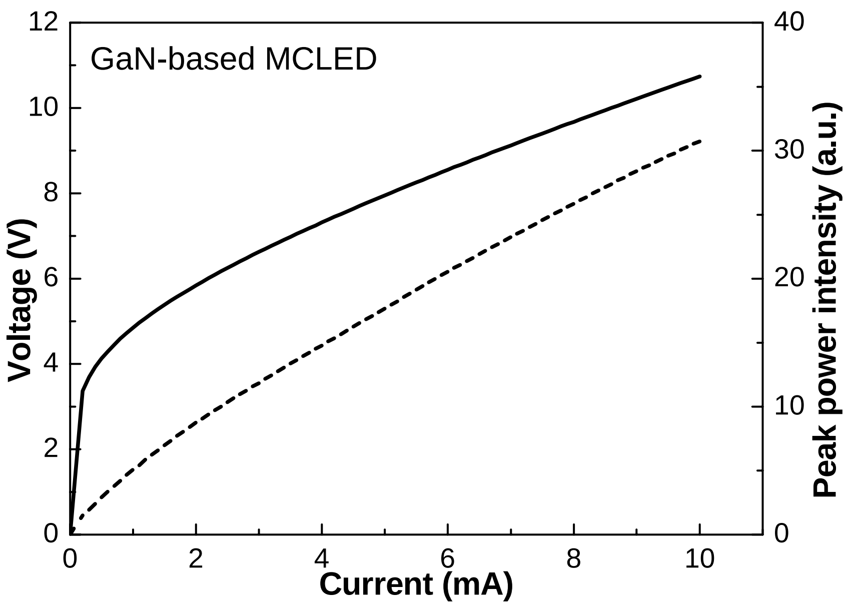
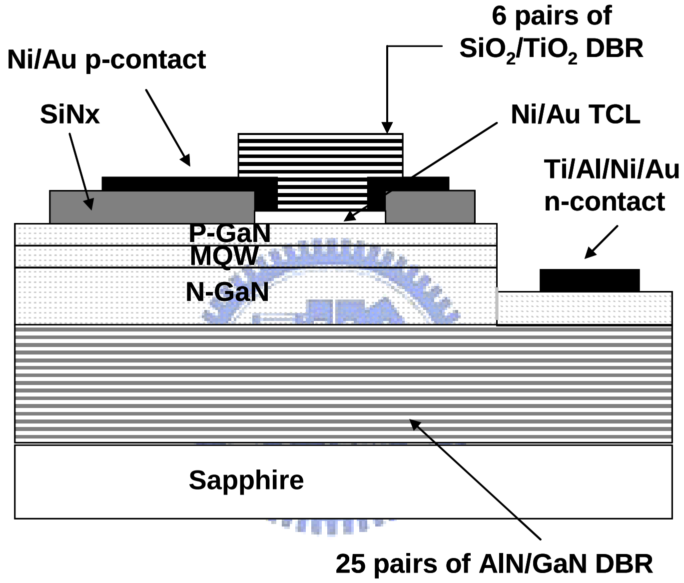


Figure 4.14 L-I-V characteristics of GaN-based MCLED.

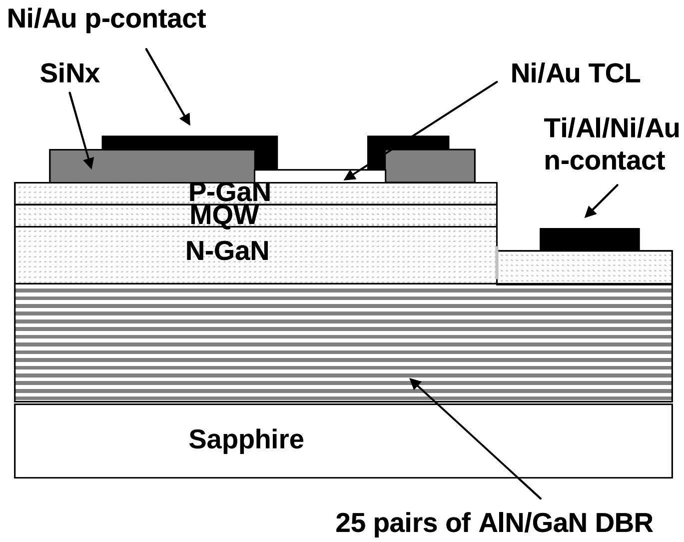
4.3.2 Optical Characteristics of GaN-based MCLED

<u>MCLED (completed device), MCLED without top DBR, and conventional LED</u>

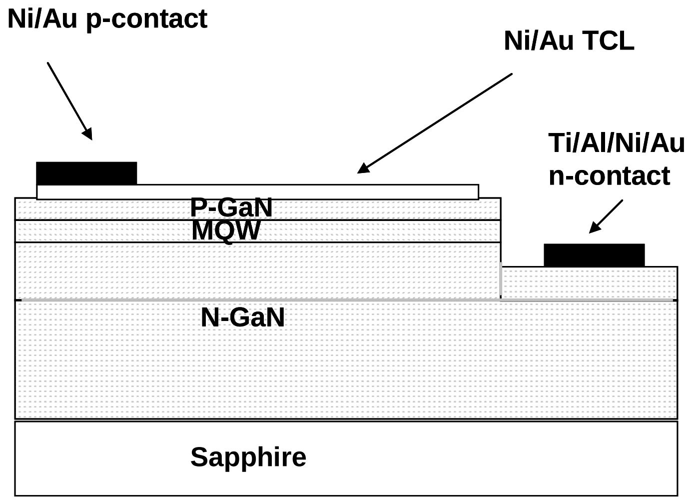
The EL spectrum of GaN-based MCLED was influenced by resonant cavity effect. In order to study the optical characteristics of the GaN-based MCLED, the EL spectrum of GaN-based MCLED was compared to that of MCLED without top DBR and conventional GaN-based blue LED. The schematic diagram of GaN-based MCLED with high-Q resonant cavity formed by a pair of high-reflectivity AlN/GaN bottom DBR and SiO2/TiO2 top DBR is shown in Fig. 4.15(a). The schematic diagram of GaN-based MCLED without top SiO2/TiO2 DBR is shown in Fig. 4.15(b). The schematic diagram of conventional GaN-based blue LED is shown in Fig. 4.15(c).



(a)GaN-based MCLED



(b)GaN-based MCLED without top DBR



(c)GaN-based conventional LED

Figure 4.15 (a)GaN-based MCLED (b)GaN-based MCLED without top DBR (c)GaN-based conventional LED

The EL spectrum of GaN-based MCLED

The electroluminescence (EL) of the fabricated MCLED with 30μm diameter at 20mA injection current is shown in Fig. 4.16. The measurement of emission spectrum was performed by collecting the EL into a 100μm diameter core fiber placed atop the surface emission device. The emission peak wavelength of the MCLED was located at 458.5nm with a narrow line width of 6.7nm. Note that the wavelength width of the regular InGaN/GaN MQW blue LED (with 300x300μm^2 emission area) was 18nm. The wavelength narrowing was caused by the micro resonant cavity effect.

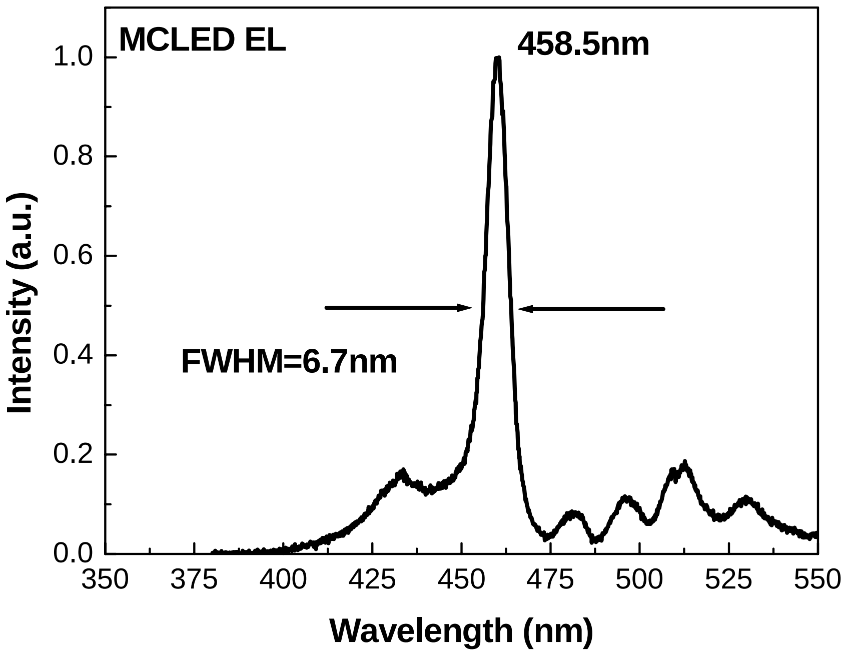


Figure 4.16 EL of GaN-based MCLED.

Varying injected current density

The emission peak wavelength of GaN-based MCLED, GaN-based MCLED without top DBR, and GaN-based conventional LED as a function of injected current density are shown in Fig. 4.17. The experiment was studied at injection current density varied from 0.14 KA/cm^2 to 4.24 KA/cm^2 at room temperature. The emission peak wavelength of GaN-based MCLED without top DBR shift from 459.5nm to 462.2nm and the red shift of 2.7nm should originate from the poor resonant cavity and heat effect. To the GaN-based conventional LED, a red shift about 8nm was observed with increasing injection current density due to heat effect. At high current density, the heat effect got seriously and the red shift became more obviously. However, the emission peak wavelength of the MCLED was free of the red shift at high current density injection. In other words, the emission peak wavelength of the MCLED dominated by resonant cavity mode was well stable than MCLED without top DBR and conventional LED as varying injected current density. It also means that the emission peak wavelength became more stable with the higher-Q resonant cavity.

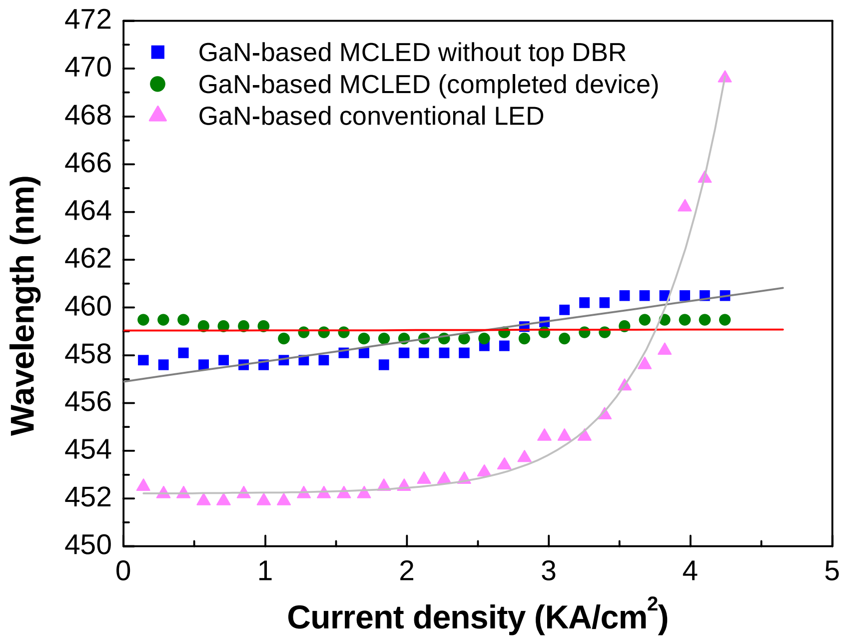


Figure 4.17 The emission peak wavelength of GaN-based MCLED, GaN-based MCLED without top DBR, and GaN-based conventional LED as a function of injection current density.

Varying operating temperature

The emission peak wavelength of GaN-based MCLED, GaN-based MCLED without top DBR, and GaN-based conventional LED as a function of operating temperature are shown in Fig. 4.18. The experiment was studied at operating temperature varied from temperature of 20^{o}C to 70^{o}C at injection current density of 1KA/cm^2. The emission peak wavelength of GaN-based MCLED without top DBR shift from 458nm to 469.6nm and the red shift of 1.6nm should originate from the poor resonant cavity and bandgap narrowing effect. The emission peak wavelength of the GaN-based conventional LED showed a clear red shift of about 2nm due to the bandgap narrowing caused by increasing temperature. However, the emission peak wavelength of the MCLED showed relatively stable. These results indicated the MCLED did have a stable cavity mode and perform better than MCLED without top DBR and conventional LED on stability of emission peak wavelength as arising operating temperature.

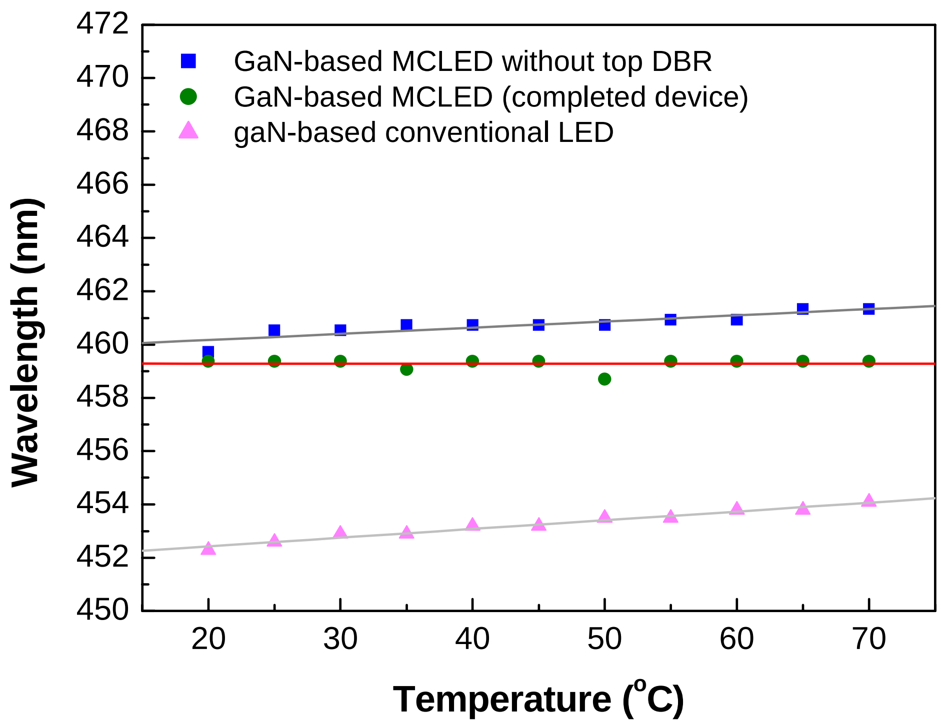


Figure 4.18 The emission peak wavelength of GaN-based MCLED, GaN-based MCLED without top DBR, and GaN-based conventional LED as a function of operating temperature

4.4 Summary

In summary, 3λ GaN-based MCLED structure was grown by MOCVD. The GaN-based MCLED composed of high-reflectivity AlN/GaN bottom DBRs (94%) and SiO_2/TiO_2 top DBRs (97.5%) has been fabricated. The emission peak wavelength of the MCLED was well matched with the high reflectance area of the top and bottom DBRs, and the emission wavelength width was narrower (about 6.7nm) than the regular LED (about 18nm), due to the resonant cavity effect. The 20mA forward voltage and resistance of the MCLED were about 3.5V and 530Ω, respectively. The MCLED also showed stable emission peak wavelength, while varying the injected current density and operating temperature. It indicated that a good resonant cavity was fabricated. Such MCLED could be the basis for electrically injected GaN-based VCSEL.