Nitride-based light emitting diode (LED) with dual-stage multiquantum well (MQW) structure is proposed and fabricated. It was found that we could improve crystal quality, reduce reverse leakage current, and reduce forward voltage of the LED by inserting the electron emitter MQW structure. With 20 mA current injection, it was found that measured output powers were 3.2 and 4.7 mW for the conventional single-stage MQW LED and the dual-stage MQW LED, respectively. Furthermore, it was found that electrostatic discharge characteristics of the dual-stage MQW LED are better.

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In recent years, insertion research efforts have been made on GaN-based devices. III-Nitride semiconductors have a great potential for applications in optoelectronic devices, such as high brightness light emitting diodes (LEDs), laser diodes (LDs), and photodetectors.

Indeed, nitride-based blue and green LEDs have already been extensively used in traffic light lamps and full color displays. To achieve highly efficient LEDs, one needs to enhance carrier recombination probability in the multiquantum well (MQW) active region of the devices since carriers not captured and/or confined inside the well layers of the MQW will be wasted and become leakage current. However, the carrier capture rate and carrier confinement effect depend strongly on carrier effective masses and quantum well parameters, such as well and barrier layer thickness and the number of quantum wells. For example, although a narrow quantum well can provide a large carrier confinement effect, lots of carriers will still recombine outside the active layer since the carrier capture rate of a narrow quantum well is low. As a result, LEDs with a narrow quantum well will still have low quantum efficiency.

Recently, it has been reported both theoretically and experimentally that the charge asymmetric resonance tunneling (CART) structure can significantly increase the electron capture rate of the MQW active region through electron tunneling. The CART structure acts to insert a wide electron emitter layer and a thin electron tunneling barrier in between the MQW active region and the n-cladding layer of the LED. Since the width of the electron emitter layer is large, electrons can be captured efficiently into the electron emitter layer. These captured electrons can subsequently tunnel through the tunneling barrier into the thin well layers of the MQW active region. Thus, one can achieve a large electron capture rate and a large carrier confinement effect simultaneously. However, dislocations at the interface between thick InGaN electron emitter layer and MQW might be generated due to the lattice constant mismatch between InGaN and GaN. These dislocations often result in higher leakage current, enhanced nonradiative recombination and thus heat generation in the devices. Instead of the thick InGaN electron emitter layer, we should be able to use another MQW structure to capture, confine and subsequently emit the electrons into the active MQW region. In this paper we present the fabrication of nitride-based LEDs with dual MQW stages. Physical, optical, and electrical properties of the fabricated LEDs will also be discussed.

**Experimental**

Samples used in this study were all grown on c-face (0001) 2 in. sapphire substrates by metalorganic vapor phase epitaxy. Details of the growth can be found elsewhere. During the growth, trimethylgallium (TMGa), trimethylindium (TMIn) and ammonia (NH3) were used as the gallium, indium, and nitrogen sources, respectively. On the other hand, bis-cyclopentadienyl magnesium (Cp2Mg) and disilane (Si2H6) were used as the p-type and n-type doping sources, respectively. Prior to epitaxial growth, we annealed the sapphire substrates at 1100°C in H2 ambient to remove surface contamination. We then grew a 30 nm thick low temperature GaN nucleation layer at 520°C followed by a 1 μm thick undoped GaN layer grown at 1050°C, a 2 μm thick Si-doped n-GaN layer grown at 1050°C and 10 nm thick Si-doped n-AlGaN layer at 1050°C. We subsequently grew an electron emitter MQW structure which consisted of five pairs of undoped 2 nm thick In0.23Ga0.77N (x = 0.16) well layers and 22 nm thick Si-doped GaN barrier layers.

On top of this electron emitter MQW structure, we deposited the active light emitting MQW structure which consists of five pairs of 3 nm thick undoped In0.23Ga0.77N (x = 0.23) well layers and 22 nm thick Si-doped GaN barrier layers. Finally, we grew a 20 nm thick Mg-doped p-AlGaN electron blocking layer at 1000°C and a 0.2 μm thick Mg-doped p-GaN cap layer also at 1000°C. For comparison, conventional LED with single active light emitting MQW structure was also prepared. The crystal qualities of these two epitaxial layers were then evaluated by room temperature photoluminescence (PL) and double crystal X-ray diffraction (DCXRD). A scanning electron microscope (SEM) was used to determine surface morphologies of the samples.

For the fabrication of LEDs, we partially etched the surface of these two samples until the n-type GaN layer was exposed. Ni/Au contact was subsequently evaporated onto the p-type GaN surface to serve as the transparent p-contact electrode. On the other hand, Ti/Al/Ti/Au contact was deposited onto the exposed n-type GaN layer to serve as the n-type electrode. The schematic diagram of the fabricated dual-stage MQW LED is shown in Fig. 1.

**Figure 1.** The schematic diagram of the dual-stage MQW LED.
subsequently lapped down the sapphire substrates to about 90 μm and then separated them into 14 mil InGaN/GaN LED chips. Room temperature electroluminescence (EL) characteristics of these fabricated LEDs were evaluated by injecting different amounts of dc current into these LEDs. The current-voltage (I-V) measurement was also performed at room temperature by a HP4156 semiconductor parameter analyzer. The electrostatic discharge (ESD) characteristics of these samples were also studied by an Electro-tech system ESD simulator model 910, which produces electrical pulses similar to those originated from the human body. In this study, we applied negative ESD biases onto the LEDs and successively increased the ESD pulse amplitude.

Results and Discussion

Figures 2a and b show SEM micrographs of the conventional single-stage MQW LED and the dual-stage MQW LED proposed in this study, respectively. It was found that surfaces of these two samples were both rough with pinholes. It was also found that pinhole density observed from the dual-stage MQW LED was lower than that observed from conventional single-stage MQW LED. It has been shown previously that these pinholes are related directly to the formation of V defects in the epitaxial layer. It should be noted that average indium composition in the inserted electron emitter MQW structure is smaller than that in the active light emitting MQW structure. Thus, average lattice constant in the inserted electron emitter MQW structure is smaller than that of active light emitting MQW structure and larger than that of GaN buffer. As a result, we should be able to partially relax lattice mismatch induced strain by inserting the electron emitter MQW structure and thus achieve smoother surface from the dual-stage MQW LED. Similar effect has also been reported from CART LEDs. In this study, we applied negative ESD biases onto the LEDs and successively increased the ESD pulse amplitude.

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20 mA operation voltages of the conventional single-stage MQW LED and the dual-stage MQW LED proposed in this study were 3.6 and 3.3 V, respectively. The lower forward voltage observed from the dual-stage MQW LED can also be attributed to the inserted electron emitter MQW structure since the captured electrons will spread out in the in-plane direction before they tunnel into the active light emitting MQW structure. As a result, we can achieve a better current spreading and thus a lower forward voltage for the dual-stage MQW LED. Room temperature EL spectrum of the dual-stage MQW LED under 20 mA current injection is shown in the inset of Fig. 6. It should be noted that we observed two PL peaks from the dual-stage MQW LED, as shown in Fig. 4. However, only one green EL peak at 530 nm was observed in the EL spectrum. This is probably due to the fact that electrons captured in the electron emitter MQW structure were all successfully tunneled into the active light emitting MQW structure. Thus, we could only observe green EL emission from the dual-stage MQW LED. Figure 6 shows measured intensity-current (I-I) characteristics of the two fabricated LEDs. It was found that EL intensity observed from dual-stage MQW LED was always larger than that of conventional single-stage MQW LED. With 20 mA current injection, it was found that measured output powers were 3.2 and 4.7 mW which correspond to external quantum efficiencies of 6.8% and 10% for the conventional single-stage MQW LED and the dual-stage MQW LED, respectively. The enhanced EL intensity observed from dual-stage MQW LED could be attributed to the improved crystal quality, as shown in Fig. 3. Similar to CART LEDs, it is also possible that the enhancement is related to the improved carrier capture rate and carrier confinement. Further experiments such as temperature-dependent EL should be performed to clarify this point.

Figures 7a and b show measured ESD results of the conventional single-stage MQW LED and the dual-stage MQW LED proposed in this study, respectively. The chips shown on the left side of Fig. 7a were the conventional single-stage MQW LEDs without ESD treatment. It was found that the conventional single-stage MQW LEDs can endure negative ESD stress only up to 2.5 kV. The chips shown on the right side of Fig. 7a were negative 3 kV ESD damaged conventional single-stage MQW LEDs. It can be seen clearly that the dead spots were randomly distributed across the LED surface. Such a pattern suggests that crystal quality of this sample is poor and the dead spots are related to the V-shaped defects, which are also the weakest points in the LEDs. The chips shown on the left side of Fig. 7b were the dual-stage MQW LEDs without ESD treatment. It was found that the dual-stage MQW LEDs can endure negative ESD stress up to 5 kV which was much higher than that of conventional single-stage MQW LEDs. It can be seen clearly that the dead spots were randomly distributed across the LED surface. Such a pattern suggests that crystal quality of this sample is poor and the dead spots are related to the V-shaped defects, which are also the weakest points in the LEDs. The chips shown on the left side of Fig. 7b were the dual-stage MQW LEDs without ESD treatment. It was found that the dual-stage MQW LEDs can endure negative ESD stress up to 5 kV which was much higher than that of conventional single-stage MQW LEDs. The chips shown on the right side of Fig. 7b were negative 5.5 kV ESD damaged dual-stage MQW LEDs. Instead of dead spots, a whole dead area was observed from the damaged dual-stage MQW LEDs. The dead area occurred at the place with the largest electric field. Such an observation suggests a number of weak spots in the epitaxial layer were small. This agrees well with the observation shown in Fig. 2b. The much larger ESD voltage and the observation of dead area should be attributed to the improved crystal quality of the dual-stage LED. Previously, it has been shown that one can improve ESD performance of nitride-based LEDs by using AlGaN/GaN superlattice structures. Similar phenomenon should occur in our dual-stage LEDs. When an electrical pulse is imposed onto the dual-stage LEDs, current will spread easily in the lateral directions. Thus, we can minimize the possibility of junction suffering a large current and improve ESD performance of the devices.
Conclusion

In summary, a nitride-based LED with dual-stage MQW structure is proposed and fabricated. It was found that we could reduce the number of pinholes and improve crystal quality by inserting the electron emitter MQW structure. It was also found that we could achieve smaller reverse leakage current and forward operation voltage from the dual-stage MQW LEDs. Furthermore, it was found that ESD characteristics of the dual-stage MQW LED are better.

National Cheng Kung University assisted in meeting the publication costs of this article.

References


Figure 7. (Color online) Measured ESD results of (a) the conventional single-stage MQW LED and (b) the dual-stage MQW LED. The chips shown on the left side of Fig. 7a and the left side of Fig. 7b were without ESD damaging. The chips shown on the right side of Fig. 7a and the right side of Fig. 7b were ESD damaged chips.