Si and Zn Co-Doped InGaN–GaN White Light-Emitting Diodes

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***Abstract*—InGaN–GaN double heterostructure (DH) and multi-quantum-well (MQW) light-emitting diodes (LEDs) with Si and Zn co-doped active well layers were prepared by metalorganic chemical vapor deposition (MOCVD). It was found that we could observe a broad long-wavelength donor–acceptor (D–A) pair-related emission at 500∼560 nm. White light can thus be achieved by the combination of such a long-wavelength D–A pair emission with the InGaN band-edge-related blue emission. By increasing the DMZn mole flow rate to 360 nmole/min, we could achieve a Si and Zn co-doped $In_{0.3}Ga_{0.7}N$–GaN MQW LED with color temperature of 4100 K, color rendering index of 70, and color coordinates $x = 0.383$, $y = 0.405$. It was also found that the 20-mA forward voltage and the breakdown voltage of such Si and Zn co-doped $In_{0.3}Ga_{0.7}N$–GaN MQW LEDs were both smaller than those of the conventional phosphor-converted white LEDs.**

High-brightness nitride-based light-emitting diodes (LEDs) were first demonstrated in 1993, and the development of these III-nitride LEDs has been very successful over the past ten years, resulting in a variety of applications such as traffic light, full color display, optical storage, and lighting. For the case of lighting, white LEDs can be used as the backlight of liquid crystal display panels. White LEDs can also be used to replace conventional light bulbs and/or fluorescent lamps [1]–[3]. The most commonly used method to achieve white LEDs is to combine a phosphor wavelength converter with a GaN blue LED chip. The blue light emitted from the GaN LED chip is absorbed by the phosphor and re-emitted as long-wavelength phosphorescence. Thus, white light can be generated by the combination of the two emission bands [1]. However, more packaging steps are needed to fabricate such phosphor-converted white LEDs. White light can also be generated by the combination of two or three different LED chips, if these LED chips emit photons at proper wavelengths with a proper power ratio. However, the driving circuits of these white LEDs are more complex. White light can also be generated by photon recycling technology [2]. However, photon recycling technology needs to bond a GaN-based LED wafer with an AlGaInP-based LED wafer, and it has been reported that such a method will need more processing steps. As a result, the production yield of photon-recycled white LEDs is low. Previously, we have shown that white light can also be generated from Si and Zn co-doped InGaN [4] since Si and Zn atoms can form donor and deep acceptor levels in InGaN, respectively. Thus, we could achieve white light by the combination of donor–acceptor (D–A) pair-related broad-band emission and the blue InGaN band-edge emission. In this paper, we present a more detailed study on the optical and electrical properties of these white LEDs.

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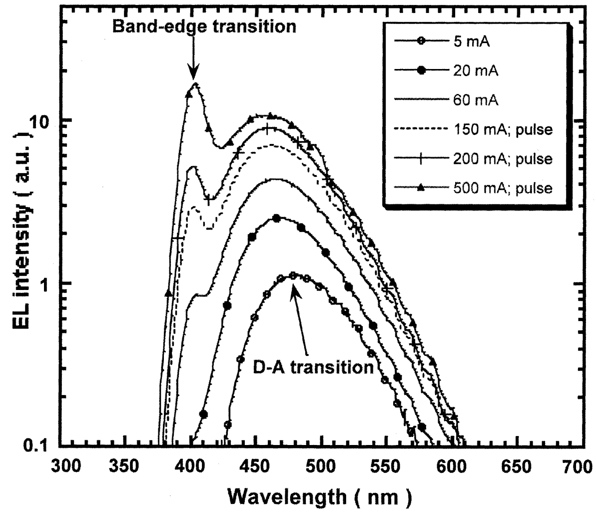

Fig. 1. EL spectra of the $In_{0.13}Ga_{0.87}N$–GaN DH LED with Si and Zn co-doped active region.

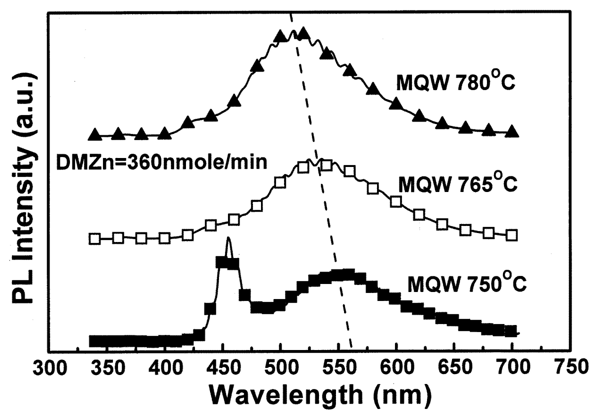

Fig. 2. PL spectra of three $In_{0.3}Ga_{0.7}N$–GaN MQW LEDs with Si and Zn codoped well layers.

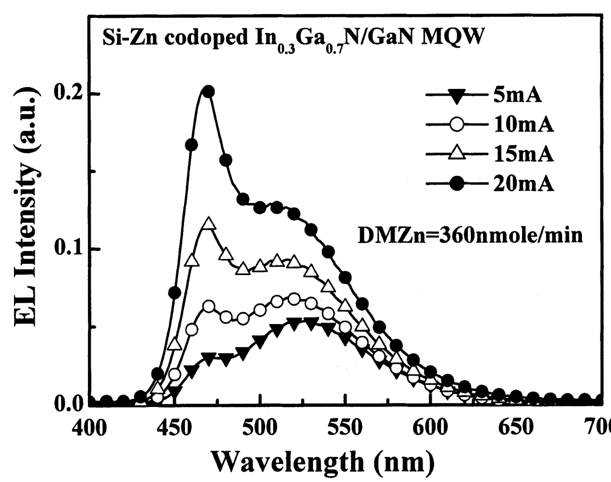

Fig. 3. EL spectra of $In_{0.3}Ga_{0.7}N$/GaN MQW LEDs with Si and Zn codoped well layers. The DMZn mole flow rate was d 360 nmole/min for the $In_{0.3}Ga_{0.7}N$–GaN MQW LED.

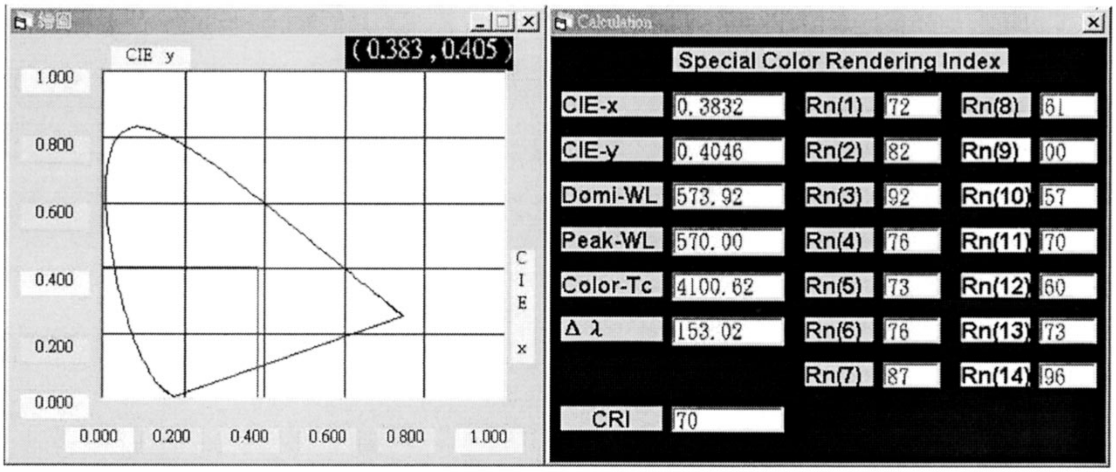

Fig. 4. CIE diagram of the LED used in Fig. 3.

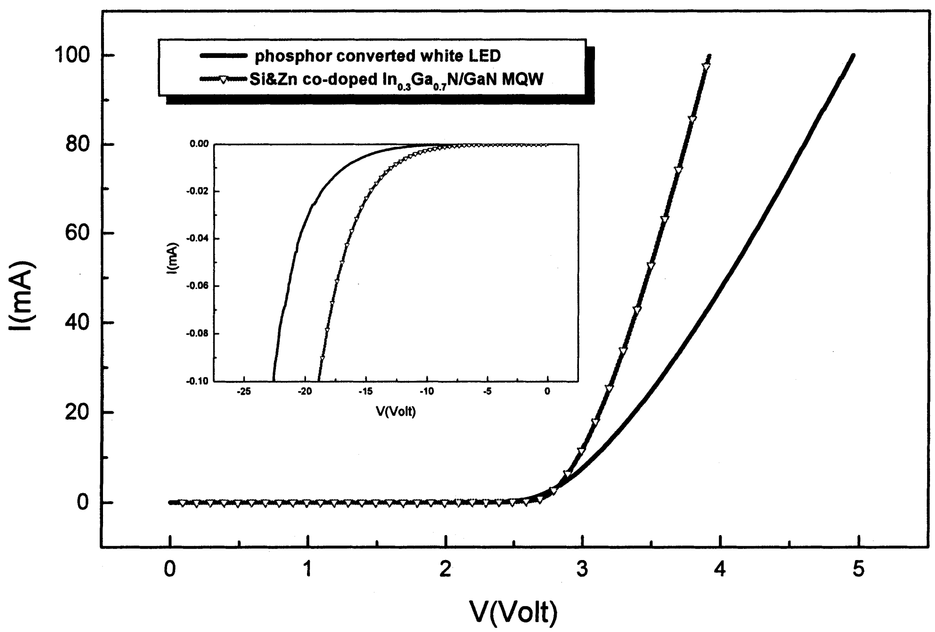

Fig. 5. I–V characteristics of the same LED used in Figs. 3 and 4.

Samples used in this study were all grown on (0001) sapphire substrates by metalorganic chemical vapor deposition (MOCVD). Details of the growth procedures can be found elsewhere [5]–[15]. In this study, both nitride-based double heterostructure (DH) LEDs and multiquantum-well (MQW) LEDs were prepared. Prior to the growth, sapphire substrates were thermally baked at 1100 °C in hydrogen gas to remove surface contamination. A low-temperature 30-nm-thick GaN nucleation layer was first grown at 560 °C. The reactor temperature was then raised to 1050 °C to grow the Si-doped GaN buffer layer. Subsequently, the temperature was ramped down either to 780 °C to grow the active region of DH LEDs or to 750 °C–780 °C to grow the active region of InGaN–GaN MQW LEDs. The active well region of the DH LEDs was a 50-nm-thick Si and Zn co-doped InGaN layer while the active region of InGaN–GaN MQW LEDs consisted of five periods of 3-nm-thick Si and Zn co-doped InGaN well layers and 7-nm-thick unintentionally doped GaN barrier layers. During the growth of codoped active region, the mole flow rate of Si_2H_6 was kept at 30 nmole/min while the DMZn mole flow rate was kept either at 90 nmole/min or at 360 nmole/min. After the growth of active region, the substrate temperature was elevated to 1020 °C to grow the 50-nm-thick Mg-doped $Al_{0.1}Ga_{0.9}N$ cladding layer and the 0.25-μm-thick Mg-doped GaN contact layer. In order to increase the indium incorporation rate, nitrogen was used as the carrier gas when we grew the active regions. On the other hand, hydrogen was used as the carrier gas when we grew the other parts of the samples. The as-grown samples were characterized by room temperature (RT) photoluminescence (PL) using an He–Cd laser as the excitation source. RT electroluminescence (EL) characteristics of the fabricated LEDs were also evaluated by injecting current into these samples. The current–voltage (I–V) measurements were also performed at RT by an HP4156 semiconductor parameter analyzer.

Fig. 1 shows EL spectra of the $In_{0.13}Ga_{0.87}N$–GaN DH LED with an Si and Zn codoped active region. It was found that only D–A pair-related emission was observed under low-level injection. However, a clear band-edge-related EL emission signal was also observed as the injection current increases. It was also found that EL intensity of the band-edge-related signal increases much faster than that of the D–A pair-related EL signal at high current injection. Furthermore, it was found that the peak position of the D–A pair-related EL signal blue shifts rapidly as the injection current increases. A similar blue shift has also been observed and it was concluded that D–A pair-related emission depends strongly on the exciting intensity [6], [8]. In order to increase emission efficiency, MQW LEDs with Si and Zn co-doped well layers were also fabricated. Fig. 2 shows the PL spectra of three $In_{0.3}Ga_{0.7}N$–GaN MQW LEDs with Si and Zn codoped well layers. The well layer DMZn mole flow rate was 360 nmole/min for all three samples while the MQW growth temperature was different. As shown in Fig. 2, we observed two PL peaks. The short wavelength peak was attributed to InGaN band-edge-related emission while the broad long wavelength peak was attributed to D–A pair-related emission originating from Si and Zn codoped well layers. It was also found that both PL peaks blue shifted toward the short-wavelength side as the MQW growth temperature was increased from 750 $^{\circ}$C to 780 $^{\circ}$C. Although one might suspect that the long-wavelength PL signal was the defect-related yellow luminescence (YL), the fact that the long-wavelength PL peak blue shifted together with short wavelength band-edge related PL signal as the MQW growth temperature increased indicated that the long-wavelength PL peak was indeed D–A pair-related emission instead of YL.

Fig. 3 shows EL spectra of $In_{0.3}Ga_{0.7}N$–GaN MQW LEDs with Si and Zn codoped well layers. The DMZn mole flow rate was 360 nmole/min and the MQW growth temperature was 750 $^{\circ}$C for this sample. It was again found that band-edge-related emission increased much faster than D–A pair emission as the injection current was increased. In other words, D–A pair emission saturates with increasing injection current so that the LED output color becomes bullish white with a 20-mA injection current. It could be seen that although D–A pair emission was stronger than band-edge emission at low injection currents, these two emission bands became more balanced as injection current increased. The color temperature and color coordinates of this particular LED were also measured. As shown in Fig. 4, it was found that measured color temperature was 4100 K, with a color rendering index of 70 and color coordinates $x = 0.383$, $y = 0.405$. These values suggest that such InGaN–GaN MQW LEDs with Si and Zn codoped well layers are potentially useful for lighting. However, the luminescence efficiency of these LEDs is still smaller than that of phosphor-converted white LEDs. Further studies to optimize device structure and doping concentration in each layer are needed. Fig. 5 shows I–V characteristics of the same LED used in Figs. 3 and 4. For comparison, the I–V characteristics of a phosphor-converted white LED were also plotted. It could be seen that the 20-mA forward voltage is 3.1 and 3.5 V for the Si and Zn codoped InGaN–GaN MQW LED and the phosphor-converted white LED, respectively. Such a result indicates that Si and Zn co-doping could effectively reduce forward voltage of white LEDs, probably due to the smaller resistivity in the active region. On the other hand, the 13-V breakdown voltage measure at 10 μA for Si and Zn codoped InGaN–GaN MQW LED is 4 V smaller than that of the phosphor-converted white LED, as shown in the inset of Fig. 5. Such a smaller breakdown voltage is again attributed to the Si and Zn codoped well layers.

In summary, InGaN–GaN DH and MQW LEDs with Si and Zn codoped active well layers were grown by MOCVD. It was found that we could observe a broad long-wavelength D–A pair-related emission at 500$\sim$560 nm. White light can thus be achieved by the combination of such a long-wavelength D–A pair emission with the InGaN band-edge-related blue emission. By increasing the DMZn mole flow rate to 360 nmole/min, we could achieve an Si and Zn codoped $In_{0.3}Ga_{0.7}N$–GaN MQW LED with color temperature of 4100 K, color rendering index of 70, and color coordinates $x = 0.383$, $y = 0.405$. It was also found that the 20-mA forward voltage and the breakdown voltage of such Si and Zn codoped $In_{0.3}Ga_{0.7}N$–GaN MQW LEDs were both smaller than those of the conventional phosphor-converted white LEDs.

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