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Dichromatic InGaN-based white light emitting diodes by using laser lift-off and wafer-bonding schemes

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An InGaN-based dual-wavelength blue/green (470 nm/550 nm) light emitting diode (LED) with three terminal operations has been designed and fabricated by using sapphire laser lift-off and wafer-bonding schemes. The device is equivalent to a parallel connection of blue and green LEDs; thus the effective electrical resistance of the device could be reduced. The luminous efficiency is 40 lm/W at 20 mA, accompanied by a broad electroluminescence emission with a combination of blue and green colors. This monolithically integrated dichromatic lighting structure has great potential in the application of the solid-state lighting. © 2007 American Institute of Physics.

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As compared to conventional illumination technologies, high brightness indium gallium nitride (InGaN)-based light emitting diodes (LEDs) have a huge impact on the solid-state lighting (SSL) market.¹ There are many approaches to fabricate white LEDs.²⁻⁵ Commercially available SSL sources are usually composed of InGaN LEDs in the blue or UV wavelengths and a combination of phosphors to produce a desired white-light spectrum.⁶ However, the degradation of phosphor during the long period of optical pumping would deteriorate the output efficiency of this phosphor-converted white-light LED. Mixing two LED sources emitting complementary colors is another promising approach to obtain white light. Li *et al.* revealed the great potential of dichromatic light sources in terms of a very high luminous efficiency.⁷ Their calculation shows that very high values of the luminous efficiency of 219 lm/W can potentially be reached, based on dichromatic white-light sources. A dual-wavelength indium gallium nitride quantum well light emitting diode with three terminals has been reported by Ozden *et al.*, where they inserted a p^{++}/n^{++} InGaN/GaN tunnel junction between separated blue and green active regions.⁸ Although the presence of the tunnel junction in the bottom device allowed for electrically isolated devices, an additional increase of about 1 V to the forward voltage characteristics of the bottom device was observed. Nicol *et al.* also employed the tunnel junction in LEDs to monolithically combine two emitters with distinct wavelengths and used them to excite two or more phosphors to produce white light.⁹ According to their study, it is a fundamental trade-off between the Mg concentration of a p^+ GaN layer and its crystalline quality. To eliminate the problems occurring in using tunnel junctions, in this letter, we use wafer bonding and sapphire laser lift-off (LLO) techniques to fabricate InGaN-based dichromatic LEDs emitting at 470 and 550 nm, respectively. The monolithically integrated dichromatic LED connecting blue and green LEDs in parallel can simultaneously emit a broad electroluminescence with efficiency of 40 lm/W at 20 mA, which could facilitate the early coming of SSL.

The cross section of the dichromatic white LED is schematically shown in Fig. 1(a). Both blue and green epitaxial wafers used in this study were grown using a low-pressure metal-organic chemical vapor deposition (Aixtron 2600G) system onto C-face (0001) sapphire substrates. The layer structure of blue LEDs comprised a 30-nm-thick GaN nucleation layer, a 2- μm -thick undoped GaN layer, a 2- μm -thick Si-doped n -type ($n=5 \times 10^{17} \text{ cm}^{-3}$) GaN cladding layer, an unintentionally doped active region of 470 nm emitting wavelength with five periods of 2/8-nm-thick InGaN/GaN multiple quantum wells (MQWs), and a 0.2- μm -thick Mg-doped p -type ($p=3 \times 10^{17} \text{ cm}^{-3}$) GaN cladding layer. The green wafer has almost the same epitaxial structure except for the indium composition of MQWs, which also comprise five periods of InGaN/GaN MQWs but emits a longer wavelength of 550 nm. Both p -side surfaces of blue and green wafers were deposited 300-nm-thick indium-tin-oxide (ITO) for serving as the transparent current-spreading layer. The blue wafer was flipped and then brought into contact with the green wafer by benzocyclobutene (BCB) at the operating temperature of 220 °C. Here, we have reduced the thickness of the BCB to as thin as 0.2 μm during the bonding process to minimize the impact of the relatively low thermal conductivity of BCB ($\sim 0.32 \text{ W/mK}$) on the overall device heat dissipation. The bonded structure was then subjected to the LLO process.¹⁰ A KrF excimer laser at a wavelength of 248 nm with a pulse width of 25 ns was used to remove the sapphire substrate. The laser was incident from the backside of the sapphire substrate onto the sapphire/GaN interface to decompose GaN into Ga and N_2 . After LLO, the subsequent processes involved sophisticated control of inductively coupled plasma (ICP). The fabrication of the dichromatic

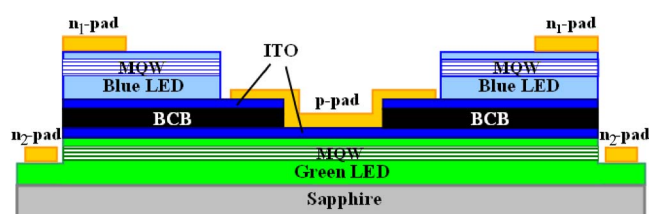


FIG. 1. (Color online) Schematic structure of InGaN-based dichromatic white LED by using laser lift-off and wafer-bonding schemes.

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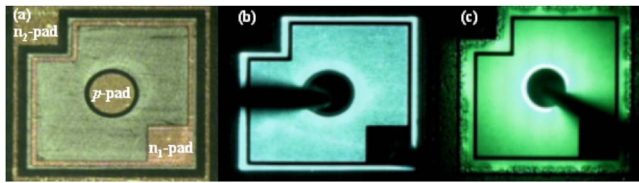


FIG. 2. (Color online) (a) Top view photograph of dichromatic white LED. (b) and (c) show photographs while turning on blue and green LEDs with an injection current of 20 mA, respectively.

white LEDs with three terminals involved standard lithography and several etching steps to define mesa regions. The LED mesa has a 100- μm -diameter hollow circle in the center for exposing the p -type contact region. Two dry-etching steps were required to reach the blue LED's ITO current-spreading layer and the n -type GaN layer of the green LED. Part of the insulated BCB bonding layer sandwiched between ITO layers was removed by using O_2 plasma to facilitate the current injection from the p pad to the ITO layer on green LED. Metal for all three terminals was formed by Cr/Au and alloyed at 200 °C in N_2 atmosphere for 5 min. In order to further improve current spreading of n -type GaN layers, both n -type metals of blue and green LEDs were designed with finger patterns. The wafer was then cut into $480 \times 480 \mu\text{m}^2$ chips and packaged into TO-18 without the epoxy resin for subsequent measurements.

Figure 2(a) shows the top view photograph of a dichromatic LED. The blue and green LEDs share the same p -contact metal, thus the emission wavelength of the device can be chosen for either blue or green color by locating the cathode probe on either the n_1 pad or the n_2 pad. For the simplest case of electric circuits, the device could be regarded as a parallel connection of blue and green LEDs. Figures 2(b) and 2(c) show photographs while turning on blue and green LEDs with the injection current of 20 mA, respectively. Dark shadows on chip surfaces in both figures are due to the blocking of electrical probes. According to this figure, by selectively probing the cathode terminal metals, the device can alternatively emit blue or green colors, revealing another potential application of the dichromatic LED for optical modulators.⁸ The electroluminescence (EL) spectra, while locating the cathode probe at the n_1 pad (blue emission) and the n_2 pad (green emission), were shown in Figs. 3(a) and 3(b), respectively. In Fig. 3(a) a pure blue emission with an emitting wavelength around 470 nm was observed. With increasing injection current up to 50 mA, the peak position shifts toward a short wavelength (blueshift) with a shifting rate of 0.18 nm/mA. This could be due to the well-known quantum-confined Stark effect. However, the shifting rate reduced to about 0.09 nm/mA, while locating the cathode probe at the n_2 pad, as shown in Fig. 3(b). Typically, the separation of electron and hole wave functions in the quantum well was more severe for long-wavelength InGaN-based LEDs since more indium was incorporated into the epitaxial structure, inducing stronger piezoelectric fields in the quantum well region. Thus, a faster wavelength shifting rate shall be observed for the green LED. However, an opposite behavior was observed in Figs. 3(a) and 3(b). We believe this could be attributed to the current-crowding effect on the green LED. As shown in Fig. 2(c), current was crowded near the p -pad region for the green LED, which could raise the junction temperature and lead to a redshift of

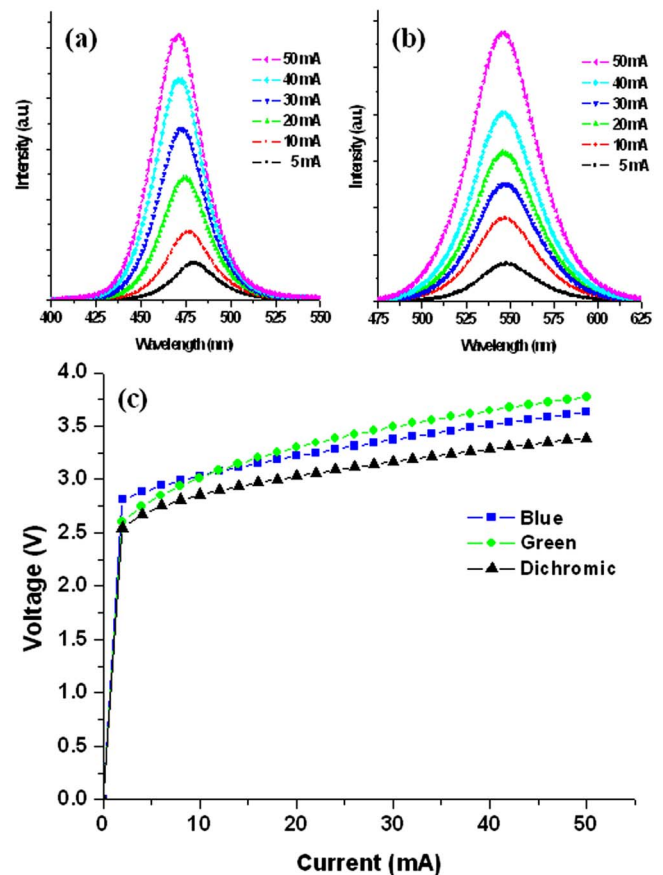


FIG. 3. (Color online) Electroluminescence (EL) spectra while locating the cathode probe at the (a) n_1 pad (blue emission) and (b) n_2 pad (green emission). (c) The current-voltage (I - V curves) characteristic of blue, green, and dichromatic white LEDs.

emission wavelength. Therefore, as compared to Fig. 3(a), a slighter shifting rate was observed in Fig. 3(b). The current-voltage (I - V curves) characteristics of blue, green, and dichromatic white LEDs were shown in Fig. 3(c). The series resistances are about 14 and 17 Ω for blue and green LEDs, respectively. The higher series resistance of the green LED was mainly attributed to the current-crowding effect, as mentioned above. The possible reason for the current-crowding effect on the green LED could be due to the damage of the ITO current-spreading layer. Before using ICP to dry-etch the green LED's mesa region, we used chemical wet etching to remove the ITO current-spreading layer. The etching solution could leak and penetrate into chip sidewalls, thus damaging part of the ITO current-spreading layer on the top of the green LED. This electrical characteristic issue could be overcome by further modifying process procedures. When we simultaneously located cathode probes at n_1 and n_2 pads, the series resistance was reduced to about 12 Ω . Because the device could be regarded as a parallel connection of blue and green LEDs, series resistance of the device shall be reduced.

Figure 4(a) shows EL spectra of dichromatic white LEDs packaged on TO-18 with an increase of injection currents. According to Fig. 4(a), below an injection current of 20 mA, a broadband illumination of a combination of blue and green colors could be observed. Then, the blue peak becomes higher and dominates EL spectra when the injection current is larger than 40 mA. Gaussian profiles are fitted to the two peaks of the EL spectra in Fig. 4(a) to determine the integrated emission intensity of the two emission bands. The

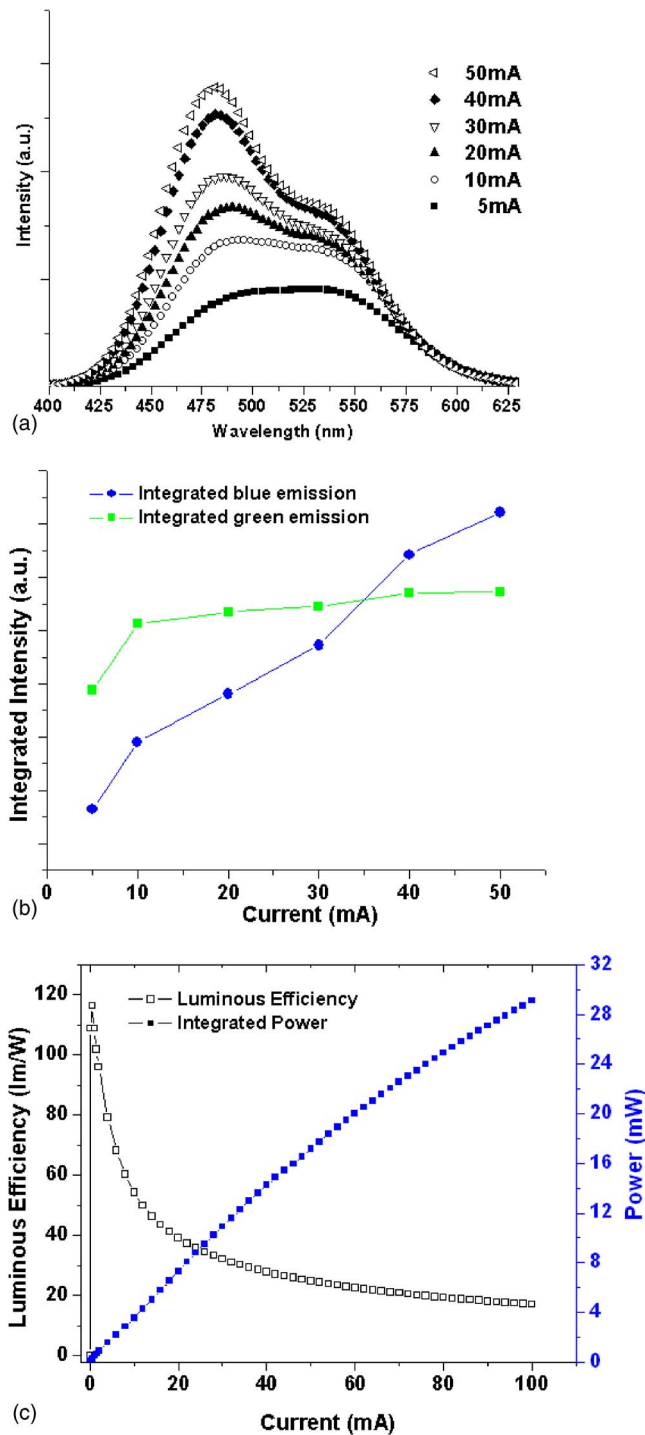


FIG. 4. (Color online) (a) EL spectra of dichromatic white LEDs packaged on TO-18 with injection currents from 5 to 50 mA. (b) The plot of integrated intensity vs injection currents at room temperature. (c) The luminous efficiency and total output power of dichromatic white LEDs with injection currents from 5 to 50 mA.

integrated emission intensity versus injection currents, obtained from the EL measurements, is shown in Fig. 4(b). As compared to the green emission, the larger increment in integrated EL spectra of the blue emission with injection current was mainly attributed to the better internal quantum ef-

iciency of blue LEDs and the relatively uniform current-spreading characteristic of the ITO layer on its *p*-type surface. Figure 4(c) shows the luminous efficiency (lm/W) and output power (mW) of dichromatic white LEDs with the increasing injection current. The output power increases linearly with the injection current under all our measurement conditions, indicating good optical characteristics of the device. The luminous efficiency is 116 lm/W at 1 mA and rapidly drops to 40 lm/W at 20 mA. In Fig. 4(c), the rapid decline of luminous efficiency with the increasing injection current could be due to the follow-up domination of blue emission since human eyes are less sensitive to blue color. Thus, the total integrated flux of the device is decreased with the injection current, further reducing luminous efficiency. However, by carefully choosing the color combination of LEDs, this dichromatic lighting structure could have great potential in the realization of SSL.

In summary, InGaN-based dichromatic-color blue/green (470 nm/550 nm) LEDs were well designed and fabricated by using sapphire laser lift-off and wafer-bonding schemes. The blue and green LEDs connecting in parallel can be addressed individually and can also simultaneously emit broad EL spectra with a combination of blue and green colors, with the luminous efficiency ranging from 116 to 40 lm/W (<20 mA). The decline of the luminous efficiency could be due to the follow-up domination of the blue emission with the increasing injection current. By carefully choosing the color combination of LEDs, this integrated dichromatic lighting structure has a great potential to facilitate the early coming of SSL.

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