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Light extraction enhancement of InGaN-based green LEDs with a composite omnidirectional reflector

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Abstract

We have designed, fabricated and measured the electroluminescence of InGaN-based green light-emitting diodes (LEDs) having composite omni-directional reflectors (ODRs) deposited on their backside. The composite ODR is composed of a stack of two individual ODRs, each of which is made of alternating layers of TiO₂ and SiO₂ with a thickness ratio that gives the largest possible 1D photonic bandgap. The lattice constants of these individual ODRs are chosen so that the effective bandgap of the resulting ODR completely covers the emission spectrum of the LEDs. The effective bandgap of our ODR extends from 498 nm to 548 nm. At a driving current of 300 mA, and with the LED emission peak at about 525 nm and a FWHM of about 35 nm, the light output powers of the LED with the composite ODR and the LED with a conventional Ti/Al metal reflector are found to be 52.9 mW and 40.7 mW, respectively. This 30% light extraction enhancement can be attributed to our composite ODR which has a higher reflectance, a lower optical absorption and a wider reflection angle compared with the Ti/Al reflector.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Enhancements in the efficiency and the reliability of light-emitting diodes (LEDs) of different colours, as well as the reduction in their manufacturing costs, continue to be exciting areas of research and development. The demand for white LEDs in particular continues to accelerate, as their applications in a multitude of consumer electronics, including televisions and many hand-held devices, and in various indoor and outdoor lightings, proliferate.

There are currently several ways of producing white LEDs [1, 2], including mixing the light generated by red (R), green (G) and blue (B) LEDs, the use of blue or UV LEDs with a layer of yellow phosphor grains and the use of quantum dots

[3–6]. Each method has its own advantages and disadvantages [7–15]. In the case of the RGB solution, the potential to generate white light with a wider colour gamut, especially for LCD back-lighting applications, is rather promising. However, the main challenge remains to be the performance of the green LEDs because the inherent lower efficiency of InGaN-based green LEDs compared with those of the corresponding red and blue LEDs.

An important way to improve the performance of LEDs is to enhance their light extraction efficiency using mirrors to reflect light within the device upwards, towards the top. Metallic mirrors, DBRs and omnidirectional reflectors (ODRs) have been used for this purpose. The advantages of ODRs over the other alternatives have been fully demonstrated and will

not be elaborated here [16]. They are made with optically transparent dielectric materials with alternating layers of high and low refractive indices. Typically, pairs of TiO_2 and SiO_2 are used because of their excellent optical and mechanical properties. The relative thicknesses of the layers are optimized to have the largest possible fractional bandgap for their given refractive indices. The lattice constant is then chosen so that this bandgap lies in the middle of the emission spectrum of the LED.

The relatively poorer performance of the InGaN-based green LEDs compared with their red and blue counterparts is due primarily to the poorer performance of the quantum efficiency and epitaxial quality. These problems, in turn, stem from the significantly larger relative width of the emission spectrum of the green LEDs. For example, our blue LEDs at 455 nm have a FWHM of 20 nm. This amounts to a fractional width of 4.4%. On the other hand, our green LEDs at 525 nm have a FWHM of 35 nm, and therefore have a fractional width of 6.6%. Thus the green LEDs have an emission spectrum that is 50% wider than that of the blue LEDs. Therefore although an ODR with a complete 1D photonic bandgap that covers the entire emission spectrum can be achieved for the blue LEDs using pairs of TiO_2 and SiO_2 with appropriate thicknesses, similar optimization for the green LEDs gives the best complete 1D photonic bandgap that covers only 80% of the emission spectrum.

Our solution here is to use a composite ODR made by stacking two individual ODRs on the backside of the LED. Each of the individual ODR has a thickness ratio for the TiO_2 and SiO_2 that gives the largest possible 1D photonic bandgap. The lattice constants of these individual ODRs are chosen so that the combined photonic bandgap completely covers the entire emission spectrum of the green LED. We have designed, fabricated and measured the electroluminescence of green LEDs having such a composite ODR. The 60 nm effective bandgap size of our ODR is significantly larger than the full width of the emission spectrum. With the LED emission peak at about 525 nm and a driving current of 300 mA, it is found that the light output powers of our LED with the composite ODR and the LED with a Ti/Al metal reflector are about 52.9 mW and 40.7 mW, respectively. This 30% improvement in the light output power of the device is attributed to the higher reflectivity, the lower absorption loss and a wider reflection angle of the LEDs with composite ODRs compared with those with Ti/Al reflectors.

2. Composite ODR design and LED fabrication

We computed, using the modal transmission line method [17], the fractional bandgap size of a single ODR having alternating layers of TiO_2 and SiO_2 as a function of the thickness of the TiO_2 layer relative to the lattice constant, a . The result, which assumes an infinite number of TiO_2 and SiO_2 layers and ignores dispersion effects, which are negligible within the entire emission spectrum, is shown in figure 1. It shows that the maximum achievable fractional bandgap size is 5.25% for a TiO_2 layer thickness of $0.43a$. Although this fractional gap is sufficient for the blue LEDs, it is unfortunately inadequate for the present green LEDs. It is 20% less than what is required to completely cover the entire emission spectrum of our green

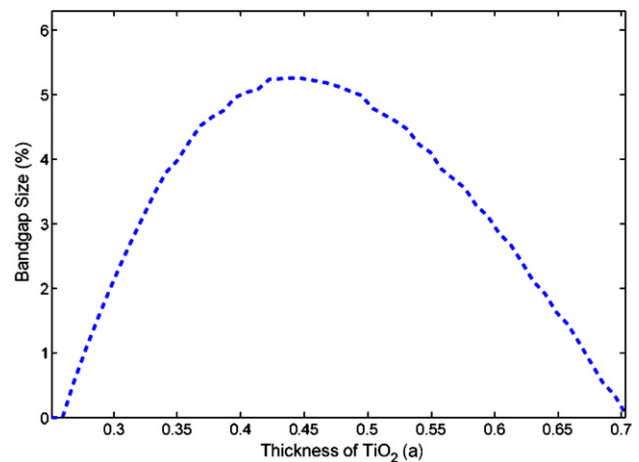


Figure 1. The fractional bandgap size of a 1D photonic crystal composed of alternating layers of TiO_2 and SiO_2 as a function of the thickness of the TiO_2 layer (in units of the lattice constant). The refractive indices are $n_{\text{TiO}_2} = 2.45$, $n_{\text{SiO}_2} = 1.47$.

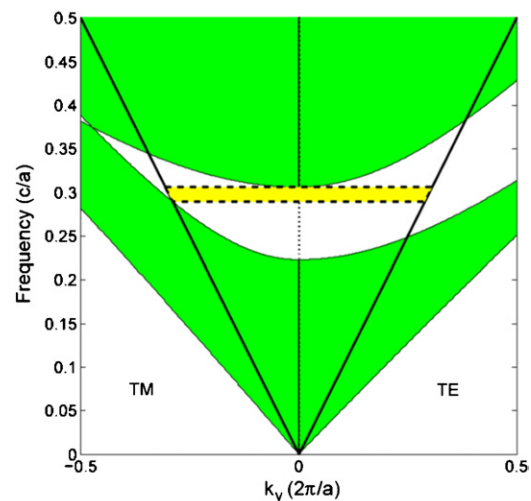


Figure 2. Photonic band diagram for a 1D photonic crystal composed of TiO_2 and SiO_2 with thicknesses $0.43a$ and $0.57a$, where a is the lattice constant. The green and white regions distinguish between the allowed and forbidden photon states, respectively. The lines along the diagonal directions identify the edges of the light cone. The yellow area gives the complete photonic band gap and represents an omnidirectional reflection region.

LED. Thus no single ODR made of TiO_2 and SiO_2 layers can be acceptable as a reflector for the green LEDs, no matter what the layer thicknesses or the total number of layers used. Figure 2 shows the photonic band structure of this optimized ODR where the thicknesses of the TiO_2 and SiO_2 layers are given by $0.43a$ and $0.57a$, respectively.

To overcome this inadequacy of a single ODR for our green LED, we use a composite ODR which is made up of two individual ODRs stacked together at the backside of the LED chip. Each individual ODR has a relative TiO_2 thickness of about $0.43a$ that maximizes the fractional bandgap size. The lattice constants of the two individual ODRs are chosen to have slightly different values in order that their bandgaps overlap in such a way that the effective bandgap of the composite ODR covers the entire emission spectrum of our green LED.

Specifically ODR-I is designed to have a bandgap around 510 nm. We find that it has a bandgap from 498 nm to 525 nm if the lattice spacing, a_1 is given by 152 nm. The thicknesses of the TiO_2 and SiO_2 layers are given by $0.43a_1$ and $0.57a_1$, respectively. On the other hand, ODR-II is designed to have a bandgap around 535 nm. It has a bandgap from 522 nm to 548 nm if the lattice spacing, a_2 , is given by 160 nm. The thicknesses of the TiO_2 and SiO_2 layers are given by $0.43a_2$ and $0.57a_2$, respectively. Thus the composite ODR has an effective bandgap extending from 498 nm to 548 nm, and thus possesses a bandgap of 60 nm. This bandgap is significantly larger than the 35 nm FWHM of the emission spectrum of our green LED.

The InGaN-based green LED samples were grown by metal-organic chemical vapor deposition (MOCVD) with a rotating-disc reactor (Emcore) on a c -axis sapphire (0001) substrate at a growth pressure of 200 mbar. The LED structure consists of a 50 nm thick GaN nucleation layer grown at 550 °C, a 3 μm thick Si-doped n-GaN buffer layer grown at 1050 °C, an unintentionally doped InGaN/GaN multiple quantum well (MQW) active region grown at 770 °C, a 50 nm thick Mg-doped p-AlGaIn electron blocking layer grown at 1050 °C, a 0.25 μm thick Mg-doped p-GaN contact layer grown at 1050 °C and a Si-doped n InGaN/GaN short period superlattice (SPS) structure. After annealing to activate the Mg in the p-type layers, a 0.5 μm SiO_2 layer was then deposited on top of the LED samples by plasma-enhanced chemical vapor deposition (PECVD). Standard photolithography was subsequently used to define a 40 mil \times 40 mil SiO_2 mesa mask. Spiral electrodes design was used to improve current spreading for our 40 mil \times 40 mil power chip. Mesa etching was then performed and the sample was then subjected to ICP processing using Cl_2/Ar as the etching gas in an ICP-RIE system. Figure 3 is a schematic diagram of our InGaN green LED with (a) a Ti/Al reflector of thicknesses 50 Å/3000 Å and an 80% reflectivity and (b) a composite ODR made of $\text{TiO}_2/\text{SiO}_2$. A 300 nm thick indium–tin oxide (ITO) layer was subsequently evaporated at 300 °C onto the LED sample surfaces to serve as the upper electrical contact. The highly conductive ITO also has a high transparency, and thus a much larger light output from the LED surface can be achieved [18]. Cr/Au contact was deposited onto the exposed n-type GaN layer to serve as the n-type electrode. After lapping and polishing the samples, composite ODRs were deposited by an E-beam evaporator at the bottom. ODR-II is first deposited on the sapphire substrate and then followed by ODR-I. Each individual ODR is made up of 12 pairs of TiO_2 and SiO_2 layers. Details of the $\text{TiO}_2/\text{SiO}_2$ deposition were described in our previous work [16]. Finally, $\text{Au}_{80}\text{Sn}_{20}$ solder was deposited at the bottom of the reflectors to improve the thermal conduction of the LED chip.

3. Results and discussion

We performed electroluminescence (EL) measurements by injecting a continuous current into our InGaN-based green LED chips at room temperature. The light output was detected by a calibrated integrating sphere with Si photodiode on the package device (TO-46 package).

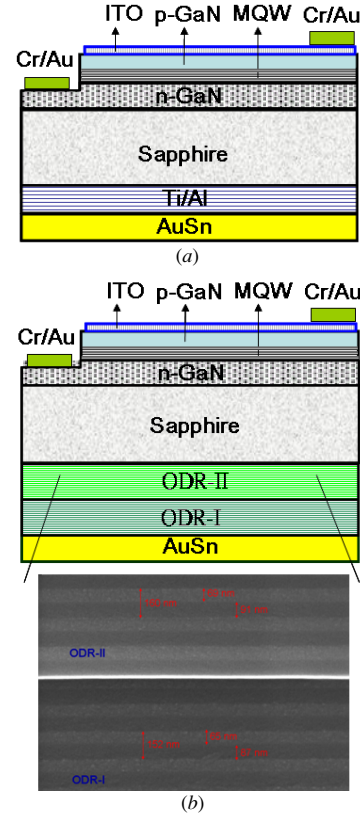


Figure 3. Schematic diagram of the InGaN-based green LEDs (a) with a Ti/Al reflector, and (b) with our composite ODR. The inset shows the SEM picture of the ODR.

We first check the quality of our composite ODR. Figure 4 shows the measured transmittances of the composite-ODR as a function of wavelength at different incident angles (0° , 30° , 50° , 70°) for unpolarized light. Up to maximum incidence angle 70° , the transmittance falls below 0.5% for wavelengths between 500 nm and 564 nm. For even larger incident angle, the long wavelength edge of the bandgap shifts to shorter wavelength. The measured stop band will be closer to the bandgap (the region bounded by the dash lines in figure 4) as predicted by our theoretical calculation.

Figure 5(a) shows the forward current–voltage (I – V) characteristics. At a driving current of 300 mA, the forward voltages of the InGaN-based LED with Ti/Al reflector and the InGaN-based LED with the composite ODR were 3.16 V and 3.21 V, respectively. The slightly higher forward voltage of the LEDs with the composite ODR compared with the LEDs with Ti/Al reflector can be attributed to additional thermal processes during the deposition of the $\text{TiO}_2/\text{SiO}_2$ layers. We believe that the ITO/SPS layer interfacial mixing could result in a higher specific contact resistance and hence could raise the LEDs operation voltage.

Figure 5(b) shows the typical intensity–current (L – I) characteristics of our LEDs with Ti/Al reflector and our LEDs with the composite ODR. At an injection current of 300 mA, the light output powers of these LEDs were approximately 40.7 mW and 52.9 mW, respectively. The LEDs with the composite ODR have light extraction enhancement by 30% compared with the LEDs with Ti/Al reflector. The light

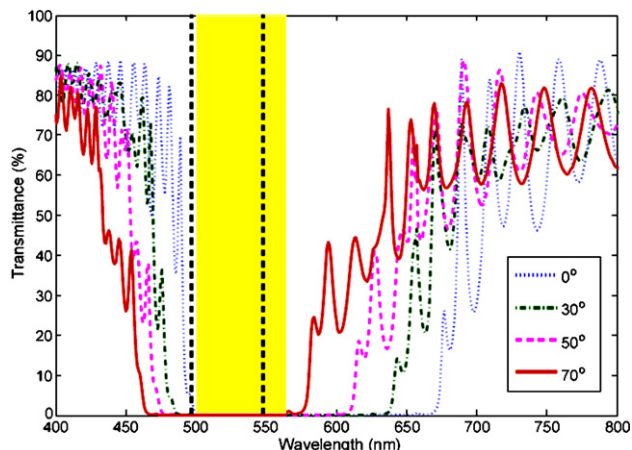


Figure 4. The measured transmittance of unpolarized light of our composite ODR at different incident angles (0° , 30° , 50° , 70°) as a function of the wavelength.

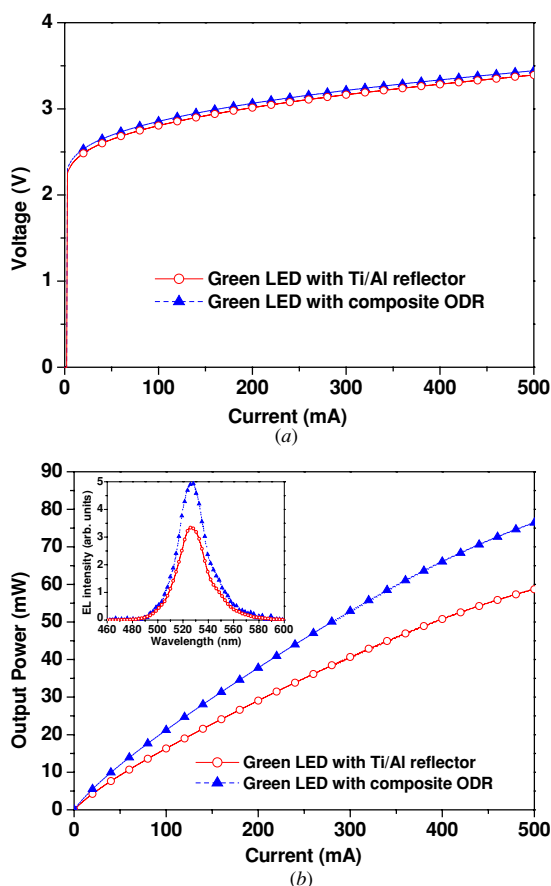


Figure 5. The measured (a) current–voltage (I – V) and (b) intensity–current (L – I) characteristics of the InGaN-based green LED with a composite ODR and with a Ti/Al reflector. The inset shows their room temperature EL spectra.

enhancement can be attributed to the composite ODR which has a higher reflectance, a lower absorption and a wider reflection angle compared with Ti/Al reflector. The inset in figure 5(b) shows the typical room temperature EL spectra of these LEDs at a driving current of 300 mA.

To further investigate the influence of our composite ODR on the light output of our LED chips, we also measured the light

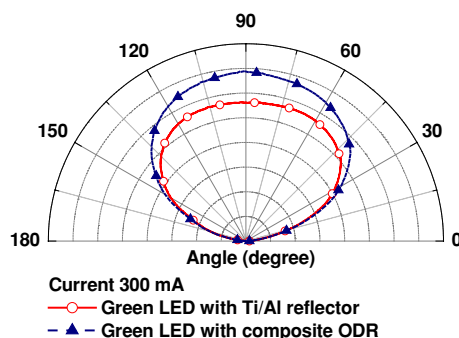


Figure 6. The measured far-field angular distribution of light emitted from our green LED with a composite ODR and with a Ti/Al reflector.

output radiation patterns of our two types of LEDs at a driving current of 300 mA. The results are shown in figure 6. It is clear that our green LEDs with the composite ODR have higher extraction efficiency and a wider view angle compared to LEDs with Ti/Al reflector. The detailed radiation patterns also show a stronger enhancement around the vertical direction. This enhancement is attributed to the higher reflectance of the composite ODR compared to the Ti/Al reflector.

4. Conclusion

In conclusion, we have successfully designed and fabricated InGaN-based green LEDs with composite ODRs. The composite ODR is made up of two ODRs stacked back-to-back. It is designed to have very high reflectivity at wavelengths from 498 nm to 548 nm. With the LED emission peak at about 525 nm with a FWHM of 35 nm and a driving current of 300 mA, it is found that the light output powers of the LEDs with composite ODRs and the LEDs with Ti/Al metal reflectors are about 52.9 mW and 40.7 mW, respectively. The 30% light extraction enhancement can be attributed to the higher reflectivity, lower absorption and a wider reflection angle compared with Ti/Al reflector. Our work offers a promising potential for enhancing output powers of green light-emitting devices.

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