Improved light output power of GaN-based ultraviolet light-emitting diode using a mesh-type GaN/SiO$_2$/Al omnidirectional reflector

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We investigated the effect of a mesh-type GaN/SiO$_2$/Al omnidirectional reflector (ODR) on the light output power of AlGaN/InGaN-based ultraviolet (365 nm) LEDs and compared their performance with that of LEDs with a GaN/ITO/Al reflector. Using the scattering matrix method, the normal incidence reflectance was calculated to be 93.7% for the GaN/SiO$_2$ (62 nm)/Al ODR and 79% for the GaN/ITO (30 nm)/Al reflector. The Ag/Ni/Al/Ni (52 nm/10 nm/200 nm/20 nm) contact showed a specific contact resistance of 3.2 $\times$ 10$^{-5}$ &ohm;cm$^2$ after annealing at 500 °C for 1 min. The forward-bias voltages at 20 mA of LEDs with ODR were in the range of 3.49–3.54 V, which were similar to that of LEDs with an ITO/Al reflector (3.51 V). The LEDs with ODR had series resistances in the range of 14.8–12.5 V, whereas the LED with an ITO/Al reflector showed 11.7 V. The LEDs with ODR yielded 9.3–19.9% higher light output power at 20 mA than the LED with an ITO/Al reflector. The improved light output power was attributed to the optimization of the high reflectance of the ODR (reflective area) and contact area.

1 Introduction AlGaN/InGaN-based ultraviolet (UV) light-emitting diodes (LEDs) are important for their applications in water and air purification, and chemical and biological detection systems [1, 2]. However, there are important technological issues that need to be solved for the realization of high external quantum efficiency (EQE) of UV LEDs. For example, injection and current-spreading efficiencies ought to be further enhanced [3, 4]. In particular, high light extraction efficiency (LEE) should be attained [5]. Flip-chip LEDs and vertical LEDs require reliable reflectors that have high reflectance as well as low contact resistance. In this regard, Ag-based schemes have been widely used, because they have high reflectance in the visible spectrum (>90%) and relatively low contact resistance [6–9]. Nonetheless, Ag contacts have very low reflectance in the UV spectrum [10]. Thus, Al-based reflectors have increasingly attracted interest as an alternative, because they have high reflectance in the visible and UV spectra. However, there is a critical problem with Al-based reflectors; Al has a low work function, and therefore, Al can form ohmic contacts only to n-type GaN, but not to p-type GaN [11, 12]. To solve this problem, nanopixel contacts (size: 1 $\times$ 1 &mu;m$^2$) were combined with Al reflectors to enhance the light extraction in UV LEDs [13]. It was shown that LEDs fabricated with nanopixel contacts yielded 90% higher light-output power than LEDs with conventional Pd contacts. It was also reported that the use of Ag/ITO (3 nm/100 nm) interlayers was effective in forming Al-based p-type ohmic contacts for GaN-based flip-chip LEDs [14]. The Ag/ITO/Al reflector had a specific contact resistance of $\sim$10$^{-5}$ &ohm;cm$^2$ and a reflectance of 85% at 460 nm, which were better than those of the conventional Ni/Au contacts. Furthermore, to obtain high reflectance, different
types of reflectors have been investigated, including distributed Bragg reflectors (DBRs) and omnidirectional reflectors (ODRs). Incidentally, ODRs have an advantage over DBRs. Specifically, unlike a DBR, an ODR can maintain a high reflectivity in wider ranges of wavelength and incidence angle. For instance, an Ag-based ODR consisting of RuO$_2$, SiO$_2$, and p-GaN for GaInN-based flip-chip LEDs was calculated to give an angle-averaged reflectance of 98% at 450 nm, which is larger than those for a 20 period Al$_{0.25}$Ga$_{0.75}$N/GaN DBR (49%) and an Ag reflector (94%) [15]. Consequently, GaInN LEDs with the RuO$_2$/SiO$_2$/Ag ODR showed higher light output power at 20 mA than those with a conventional Ni/Au contacts. These results indicate that for the fabrication of high-EQE UV LEDs, the development of optimal Al-based ODRs with high reflectance in the UV spectrum and low-resistance ohmic contacts is crucial. Thus, in this study, high-UV-reflectance Al was combined with SiO$_2$ and p-GaN to form mesh-type Al-based ODRs. AlGaN/InGaN-based UV (365 nm) LEDs were fabricated with the ODRs and an Ag/Ni mesh ohmic contact. For comparison, UV (365 nm) LEDs with ITO/Al reflectors were also fabricated.

2 Experimental UV (365 nm) AlGaN/InGaN multiple quantum-well (MQW) LED structures were grown on (0001) sapphire substrates by a metalorganic chemical vapor deposition (MOCVD) system. The LED structures consisted of a 2-nm thick $p$-GaN:Mg layer, 100-nm thick p-AlGaN:Mg ($n_a = 5 \times 10^{17}$ cm$^{-3}$) layer, 20-nm thick AlGaN electron-blocking layer, 100-nm thick active layer, 200-nm thick spreading layer, 2.0-$\mu$m thick n-type AlGaN:Si ($n_n = 5 \times 10^{18}$ cm$^{-3}$) layer, and a 2.0-$\mu$m thick undoped GaN layer on a sapphire substrate. Before the chip process, the samples were cleaned with acetone, methanol, and DI water for 5 min per cleaning agent and finally dried in a N$_2$ stream. A quarter-wavelength thick ($\lambda/(4n_h)$) SiO$_2$ layer was deposited on the LED structure by a plasma enhanced chemical vapor deposition (PECVD) system. A mesh structure was patterned on the SiO$_2$ layer by standard photolithography (Fig. 1), followed by a buffered oxide etch solution-etching to expose the p-GaN. Subsequently, Ag/Ni (52 nm/10 nm) layers were electron-beam (e-beam)-evaporated on the mesh-patterned LED structures. The widths of the mesh patterns were 10, 15, and 20 $\mu$m. To form Ag/Ni ohmic contacts, the samples were rapid-thermal-annealed at 500 °C for 1 min in air, where the Ni (10 nm) layer was capped to suppress Ag agglomeration, namely, to improve the thermal stability of the Ag contact [16]. Finally, an Al/Ni (200 nm/20 nm) layer was e-beam-evaporated on the entire sample surface. The samples fabricated with the mesh structures with line widths of 10, 15, and 20 $\mu$m are referred to herein as “ODR 1,” “ODR 2,” and “ODR 3,” respectively. For the purpose of comparison, a LED with an ITO/Al/Ni (30 nm/200 nm/20 nm) reflector was also fabricated and is referred to herein as an “ITO/Al reflector.” For all LED chips, a Ni (20 nm) layer was deposited on the Al (200 nm) layer to prevent the oxidation of Al, and a Cr/Ni/Au (20 nm/25 nm/30 nm) layer was deposited as an n-type electrode. For the Ag/Ni and Ag/Ni/Al/Ni contacts, circular transfer length method (CTLM) patterns were formed by the standard photolithographic technique to measure the specific contact resistance. The outer radius of the pattern was 200 $\mu$m and the gap spacing between the outer and inner circles was varied from 5 to 40 $\mu$m. Current–voltage (I–V) measurements were performed with a high-current source-measuring unit (Keithley 238). The output powers of the UV LED chips (800 × 300 $\mu$m$^2$) were characterized by a Newport dual-channel powermeter. A scattering matrix method was used to calculate the reflectivity $R(\theta)$ at 365 nm of the GaN/SiO$_2$/Al ODR and a GaN/ITO/Al layer.

3 Results and discussion Figure 1 shows a schematic diagram of an LED with a mesh-type GaN/SiO$_2$/Al ODR, and cross-sectional views of a GaN/SiO$_2$/Al ODR and an ITO/Al reflector. Figure 2 exhibits the reflectances of GaN/ITO/Al and GaN/SiO$_2$/Al mirrors at 365 nm as functions of incidence angle. The scattering matrix method was used to calculate their angular reflectance for two orthogonal polarizations (i.e., transverse electric [TE] and transverse magnetic [TM]) with a SiO$_2$ layer thickness of 62 nm. For the calculation, the employed parameters were the refractive index of GaN ($n_{GaN} = 2.65$, the extinction coefficient of GaN ($k_{GaN} = 0.26$, $n_{SiO2} = 1.47$, $n_{Al} = 0.41$).

![Figure 1](image_url) Figure 1 (a) Schematic diagram of 3-D LED structure fabricated with GaN/SiO$_2$/Al ODR. Schematic cross-sectional views of LED structures fabricated with (b) GaN/SiO$_2$/Al ODR, and (c) ITO/Al reflector.
$k_{Al} = 4.43$, $n_{ITO} = 2.10$, and $k_{ITO} = 0.02$ [17–20]. A plane wave of $\lambda = 365$ nm was incident from a GaN medium. Both TE and TM calculation results (Fig. 2a and b, respectively) illustrate that the SiO$_2$/Al ODR offers a decent reflectance below and above the critical angle ($\theta_c = 34^\circ$). This is because a constructive interference condition with partial reflected waves was satisfied. The calculation shows that the normal-incidence reflectance is higher for the GaN/SiO$_2$/Al ODR than for the GaN/ITO/Al reflector. The normal incidence reflectance is 93.7% for the GaN/SiO$_2$/Al ODR and 79% for the GaN/ITO/Al reflector. The large dips in the GaN/ITO/Al and GaN/SiO$_2$/Al reflectors below the total reflection angle are caused by Brewster’s angle, which is the angle of incidence at which light with a particular polarization is transmitted through a surface without reflection [21]. Meanwhile, the side dips in the GaN/SiO$_2$/Al ODR are due to the surface plasmon effect [22].

Figure 3 shows the $I$–$V$ characteristics of the Ag/Ni and Ag/Ni/Al/Ni ohmic contacts. The Ag/Ni layers were annealed at 500°C for 1 min in air, after which an Al/Ni layer was deposited to form Ag/Ni/Al/Ni contacts. Measurements showed that the specific contact resistances of the Ag/Ni and Ag/Ni/Al/Ni contacts were $9.4 \times 10^{-4}$ and $3.2 \times 10^{-5}$ $\Omega$cm$^2$, respectively.

Figure 4 exhibits typical $I$–$V$ characteristics of the UV (365 nm) AlGaN/InGaN MQW LEDs fabricated with GaN/SiO$_2$/Al and ITO/Al reflectors, and Ag/Ni/Al/Ni mesh contacts. The forward-bias voltages at 20 mA of the LEDs with ODR 1, ODR 2, and ODR 3 are estimated to be 3.54, 3.49, and 3.49 V, respectively, which are nearly equal to that of the LED with an ITO/Al reflector (reference), 3.51 V. The LEDs with ODR 1, ODR 2, and ODR 3 gave series resistances of 14.8, 13.1, and 12.5 $\Omega$, respectively, whereas the LED with an ITO/Al reflector had a series resistance of 11.7 $\Omega$. The forward-bias voltages and series resistances decrease with increasing mesh width. This is attributed to the increase in p-type contact area from 12.8 to 25.6%.

Figure 5 displays the light–output-current ($L$–$I$) characteristics of the UV LEDs fabricated with ODRs and an ITO/Al reflector. The LEDs fabricated with ODR 1, ODR 2, and ODR 3 yielded 9.3, 19.9, and 16.8% higher light
output power at 20 mA, respectively, than the LED with an ITO/Al reflector. The improved light output power (LOP) can be attributed to the higher reflectance of the SiO$_2$/Al ODR, that is, the enhanced LEE of the UV LEDs. The LED with the 15-μm wide mesh contact (ODR 2) exhibited the highest light output power. Kim et al. [23], investigating the effect of the microcontact size on the LOP of near UV (400 nm) LEDs with GaN/SiO$_2$/Al ODR, reported that the LOP increased with increasing the size of the NiZn/Ag microcontact. This was attributed to the larger effective light-emitting area, that is, the optimization of the area of all the microcontacts and the current-spread area. Thus, in a similar manner, the higher LOP of the LED with ODR 2 can also be attributed to the optimal emitting area and contact area. The LOP of the LED with ODR 3, which has the widest contact area (25.6%), has a lower LOP than the LED with ODR 2. This could be explained in terms of the smaller effective area of ODR 3 due to the increased Ag/Ni mesh area, leading to less reflective area [24]. This indicates that the LOP and forward voltage of UV LEDs with GaN/SiO$_2$/Al ODR can be further improved by the optimization of the line width and the mesh structure patterns.

4 Conclusions GaN/SiO$_2$/Al ODRs were used to improve the light output power of AlGaN/InGaN-based UV (365 nm) LEDs and their performance was compared with that of a GaN/ITO/Al reflector. The calculated normal incidence reflectances of the GaN/SiO$_2$ (62 nm)/Al and GaN/ITO (30 nm)/Al reflectors were 93.7 and 79%, respectively. The Ag/Ni/Al/Ni contact provided a specific contact resistance of $3.2 \times 10^{-5} \Omega \text{ cm}^2$. The LEDs with ODRs showed similar forward-bias voltages at 20 mA compared to the LED with an ITO/Al reflector. The LEDs with ODRs yielded higher light output power at 20 mA than the LED with an ITO/Al reflector. This result implies that the use of the GaN/SiO$_2$/Al ODRs with Ag/Ni mesh contacts could serve as a promising reflector for the fabrication of high-performance UV LEDs.

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