Enhanced light-extraction in GaInN near-ultraviolet light-emitting diode with Al-based omnidirectional reflector having NiZn/Ag microcontacts

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Enhancement of light extraction in a GaInN near-ultraviolet light-emitting diode (LED) employing an Al-based omnidirectional reflector (ODR) consisting of GaN, a SiO_2 low-refractive-index layer perforated by an array of NiZn/Ag microcontacts, and an Al layer is presented. A theoretical calculation reveals that a SiO_2/Al ODR has much higher reflectivity than both a SiO_2/Ag ODR and a Ag reflector at a wavelength of 400 nm. It is experimentally shown that GaInN near-ultraviolet LEDs with GaN/SiO_2/Al ODR have 16% and 38% higher light output than LEDs with SiO_2/Ag ODR and Ag reflector, respectively. The higher light output is attributed to enhanced reflectivity of the Al-based ODR in the near-ultraviolet wavelength range. © *2006 American Institute of Physics*.
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GaN-based ultraviolet (UV) light-emitting diodes (LEDs) are attracting much attention for applications such as chemical and biological detection systems, water and air sterilization, and primary light source for phosphor-based white LEDs.[1–4] Particularly, GaN-based near-UV LEDs emitting at ~400 nm are being widely used as efficient excitation sources for organic and inorganic luminescent materials for white-light generation. For example, an UV-emitting GaInN LED chip pumping a red-green-blue or a yellow-green-blue phosphor mix results in white light with excellent color-rendering index and high efficacy by means of mixing complementary colors. However, there is still a great need for improvement of the light-extraction efficiency as well as the internal quantum efficiency of GaInN LEDs. There are several ways to obtain high extraction efficiency including shaping of LED dies,[5] flip-chip mounting,[6] roughening of the top LED surface,[7] and introducing reflectors with high reflectivity.[8,9] Recently, blue LEDs ($\lambda = 470$ nm) with triple-layer omnidirectional reflectors (ODRs) comprising GaN/SiO_2/Ag (Ref. 8) or GaN/nanorod ITO/Ag (Ref. 9) have been demonstrated to have higher reflectivity than conventional Ag reflectors.

Ag-based reflectors have been widely used for GaInN green and blue LEDs because Ag shows high reflectivity at *visible* wavelengths and good Ohmic properties with *p*-type GaN when used with an adhesion-promotion layer such as NiZn. However, the reflectivity of Ag-based reflectors decreases rapidly as the emission wavelength approaches the UV range due to a rapid decrease of the Ag extinction coefficient and increase of the Ag index of refraction. Al-based reflectors can be a good alternative because of the relatively high extinction coefficient and low index of refraction of Al in the UV wavelength range. However, Al shows poor Ohmic contact properties to *p*-type GaN due to its low work function of 4.26 eV.[10]

In this work, an Al-based ODR with NiZn/Ag microcontacts is incorporated into a GaInN UV LED emitting at 400 nm. The ODR comprises GaN, a quarter-wave thick SiO_2 low-refractive-index layer perforated by an array of NiZn/Ag microcontacts, and an Al layer. Theoretical calculations reveal that the reflectivity of Al-based ODRs is significantly higher than that of Ag-based ODRs and Ag metal reflectors. It is experimentally shown that the GaInN UV LEDs with GaN/SiO_2/Al ODR show higher light output than LEDs with both SiO_2/Ag ODR and Ag reflector.

A schematic cross-sectional view of the metal reflector and triple-layer ODR is shown in the inset of Fig. 1. The triple-layer ODR consists of the LED semiconductor emitting at a wavelength λ, a low-refractive-index layer (n_{li}) with a thickness of $\lambda/(4n_{li})$, and a metal with a complex refractive index $N_m = n_m + ik_m$, where k_m is the extinction coefficient. The reflectivity of the semiconductor/metal reflector [see Eq. (1)] and triple-layer ODR [see Eq. (2)] as a function of the polar angle of incidence in the semiconductor, θ_1 are given by[11]

$$R_{TE} = \left| \frac{n_s \cos\theta_1 - N_m \cos\theta_2}{n_s \cos\theta_1 + N_m \cos\theta_2} \right|^2, \qquad R_{TM} = \left| \frac{n_s/\cos\theta_1 - N_m/\cos\theta_2}{n_s/\cos\theta_1 + N_m/\cos\theta_2} \right|^2, \tag{1}$$

$$R = \left| \frac{r_{12} + r_{23}\exp(2i\phi)}{1 + r_{12}r_{23}\exp(2i\phi)} \right|^2, \tag{2}$$

where, $r_{12,TE} = (n_s\cos\theta_1 - n_{li}\cos\theta_2)/(n_s\cos\theta_1 + n_{li}\cos\theta_2)$, $r_{12,TM} = (n_{li}\cos\theta_1 - n_s\cos\theta_2)/(n_{li}\cos\theta_1 + n_s\cos\theta_2)$, $r_{23,TE} = (n_{li}\cos\theta_2 - N_m\cos\theta_3)/(n_{li}\cos\theta_2 + N_m\cos\theta_3)$, $r_{23,TM} = (N_m\cos\theta_2 - n_{li}\cos\theta_3)/(N_m\cos\theta_2 + n_{li}\cos\theta_3)$, and $\phi = (2\pi/\lambda)n_{li}h\cos\theta_2$. Figure 1 shows the calculated reflectivity, $R(\theta) = (R_{TE} + R_{TM})/2$, of two ODRs (GaN/$SiO_2$/Ag and GaN/$SiO_2$/Al) and Ag reflector as a function of detection angle θ at $\lambda = 400$ nm. The reflectivity curves were calculated using parameters $n_{GaN} = 2.5$, $n_{SiO_2} = 1.47$, $n_{Ag} = 0.17$, $k_{Ag} = 1.95$, $n_{Al} = 0.49$, and $k_{Al} = 4.86$.[12] Inspection of the figure

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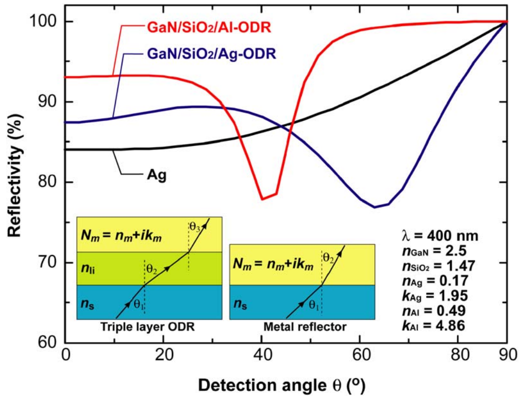

FIG. 1. (Color online) Calculated reflectivity inside GaN, $R(\theta)$, of two ODRs ($GaN/SiO_2/Ag$ and $GaN/SiO_2/Al$) and a Ag reflector on GaN as a function of angle θ (λ=400 nm).

clearly reveals that the normal-incidence reflectivity is enhanced for the $GaN/SiO_2/Al$ ODR compared with both the $GaN/SiO_2/Ag$ ODR and the Ag reflector. The normal-incidence reflectivities are 93.3%, 87.7%, and 84.2% for the $GaN/SiO_2/Al$ ODR, $GaN/SiO_2/Ag$ ODR, and Ag reflector, respectively. In addition to the normal-incidence results, the angle-dependent reflectivity is also enhanced for the $GaN/SiO_2/Al$ ODR compared with the $GaN/SiO_2/Ag$ ODR and Ag reflector. This is attributed to the higher reflectivity of triple-layer ODRs compared to metal reflectors and due to the higher extinction coefficient of Al (k_{Al}=4.86) than that of Ag (k_{Ag}=1.95) at λ=400 nm.

In order to experimentally demonstrate the viability of the Al-based ODRs, GaInN LEDs emitting at λ=400 nm with $GaN/SiO_2/Al$ ODRs, $GaN/SiO_2/Ag$ ODRs, and Ag reflectors were fabricated. The GaInN LED structure was grown by metal-organic chemical vapor deposition on *c*-plane sapphire substrate. The uniformity in PL intensity across the 2 in. wafer is 10.3% (standard deviation). LED mesa structures were obtained by standard photolithographic patterning followed by chemically assisted ion beam etching using Cl_2 and Ar to expose the *n*-type cladding layer. A quarter-wavelength-thick SiO_2 was deposited using plasma-enhanced chemical vapor deposition. An array of microcontacts was patterned on SiO_2 and etched using buffered oxide etching solution to expose the p-type GaN layer, followed by the deposition of NiZn (10 wt % of Zn)/Ag (60 nm) and lift-off of the metal outside the microcontact areas. The array of NiZn/Ag microcontacts was annealed in O_2 ambient for 1 min to form a low-resistance Ohmic contact. Then, the Al layer was deposited by electron-beam evaporation on the entire *p*-type GaN area. For comparison, LEDs with NiZn/Ag (2/60 nm) contacts and LEDs with $GaN/SiO_2/Ag$ ODRs were fabricated on pieces of the same wafer, in which both types of contacts, NiZn/Ag contact and NiZn/Ag microcontacts, were annealed in O_2 ambient for 1 min. The *n*-type contacts for the samples were fabricated by electron-beam evaporation of Ti/Al/Ni/Au.

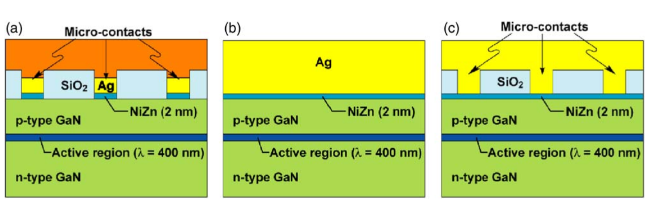

FIG. 2. (Color online) Schematic cross-sectional view of GaInN LED with (a) $GaN/SiO_2/Al$ ODR with NiZn/Ag microcontacts, (b) Ag reflector, and (c) $GaN/SiO_2/Ag$ ODR. In structures (b) and (c), a thin NiZn layer (~2 nm) was used under the Ag.

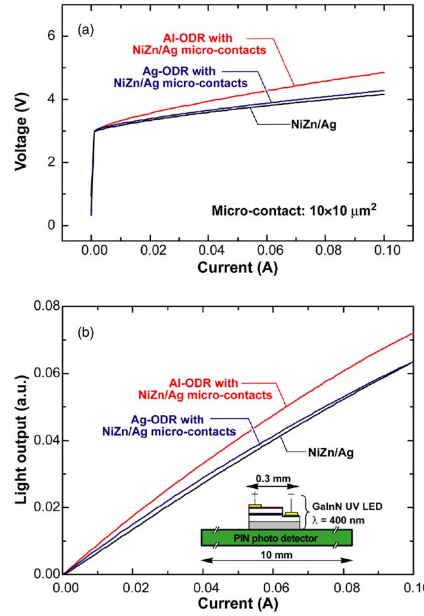

FIG. 3. (Color online) (a) Current-voltage characteristics and (b) light output vs injection current for GaInN LED emitting at 400 nm with $GaN/SiO_2/Al$ ODR with NiZn/Ag microcontacts, $GaN/SiO_2/Ag$ ODR, and Ag reflector.

Figure 2(a) shows a schematic cross-sectional view of the GaInN LED with $GaN/SiO_2/Al$ ODR and NiZn/Ag microcontacts. There is an array of square-shaped NiZn/Ag microcontacts on the *p*-type GaN, enabling low-resistance Ohmic contacts as well as electrical conductivity between the *p*-type GaN layer and Al through the insulating SiO_2 low-index layer. The chip dimension is $300 \times 300\ \mu m^2$, the dimensions of the microcontacts are 4×4, 6×6, and $10 \times 10\ \mu m^2$, and the number of the microcontacts is 105 per device. Figures 2(b) and 2(c) show schematic cross-sectional views of the GaInN LED with NiZn/Ag reflector and with $GaN/SiO_2/Ag$ ODR, respectively.

Figure 3(a) shows typical current-voltage characteristics of the LEDs with NiZn/Ag reflector, $GaN/SiO_2/Ag$ ODR, and $GaN/SiO_2/Al$ ODR with NiZn/Ag microcontacts with the dimension of $10\times 10\ \mu m^2$ and 15 μm interval, i.e., distance between edges of metal microcontacts. The forward voltage at 20 mA for the $GaN/SiO_2/Ag$ ODR LEDs is 3.37 V, almost same as that for the LEDs with NiZn/Ag reflector, 3.32 V. This is attributed to the fact that the oxidized NiZn layer could be a current spreading and "adhesion-promoting" contact layer to *p*-type GaN with low contact resistivity. However, the forward voltage of the $GaN/SiO_2/Al$ ODR LEDs is slightly higher, 3.55 V, than that of other devices. We attribute the higher forward voltage to the higher series resistance caused by smaller effective contact area to *p*-type GaN.

The electroluminescence intensity was measured directly from the back side of the LED by placing it on a large-size ($10\times 10\ mm^2$) Si *p-i-n* photodetector. Average light output versus current characteristics of 30 representative LEDs are shown in Fig. 3(b). The standard deviations between the individual values of light output from each sample are very low, 1.1% for Al ODR LEDs, 2.0% for Ag ODR LEDs, and 3.7% for Ag LEDs at 20 mA. At an injection current of

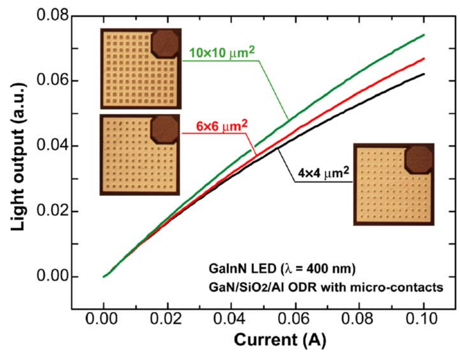

FIG. 4. (Color online) Light output vs injection current for GaInN LED with GaN/SiO_2/Al ODR with 4×4, 6×6, and 10×10 μm^2 sizes of NiZn/Ag microcontacts.

20 mA, the GaInN ultraviolet LEDs with GaN/SiO_2/Al ODR show 16% and 38% higher light outputs than LEDs with SiO_2/Ag ODR and Ag reflector, respectively. The increased light output of the LEDs with GaN/SiO_2/Ag and GaN/SiO_2/Al ODRs compared to LEDs with NiZn/Ag reflector is attributed to enhanced reflectivity of the ODR structures. In addition, the higher light output of the LEDs with GaN/SiO_2/Al ODR compared with the LEDs with GaN/SiO_2/Ag ODR is attributed to enhanced reflectivity of the Al-based ODR at UV wavelengths, as expected from the theoretical calculation shown in Fig. 1. It is worthwhile to mention possible reasons why an ~10% enhancement of normal-incidence reflectivity leads to an enhancement of LED light output as high as 38%. Multiple reflection events of trapped light within high refractive index semiconductor are one of the possible reasons. If the bottom reflector has the reflectivity R, the light intensity after N reflection events is given by R^N. This shows that a small difference in reflectivity can make a large difference in light output. In addition, the NiZn layer is a light-absorbing layer, thereby lowering the reflectivity of the reflectors with continuous NiZn layer. The LEDs with GaN/SiO_2/Al ODR with Ag microcontacts on continuous NiZn layer, not shown here, showed an enhancement of 23%, which is lower than the 38% enhancement obtained for the LEDs with ODR structure shown in Fig. 2(a).

Because SiO_2 is an insulator, the current can only flow into p-type GaN through the microcontacts, resulting in a higher forward voltage due to reduced effective contact area on the p-type GaN and possibly a current crowding problem. Therefore, not only the size of the microcontacts but also the spacing between the microcontacts can significantly affect both optical and electrical properties of the LEDs with ODRs. Figure 4 shows the electroluminescence intensity measured directly from the back side of the LED with GaN/SiO_2/Al ODR with different sizes of NiZn/Ag microcontacts, 4×4, 6×6, and 10×10 μm^2. As the size of the microcontacts increases from 4×4 to 10×10 μm^2, the forward voltage decreases by 0.2 V. This is due to the increase of effective total microcontact area from 2.1% to 13.1% on the p-type GaN. Furthermore, the light output clearly increases with increasing microcontact size. This result can be understood by considering the current spreading in the p-type GaN layer. The hole current can spread into the region beneath the SiO_2 with current spreading length L_S.[13] The lower the current density, the larger the current spreading length. Since the number of the microcontacts is constant, microcontact size directly affects the current density and hence the current spreading length. This indicates that the effective light-emitting area, i.e., the area of all the microcontacts plus current-spread area which is a function of current density, is larger for the LEDs with 10×10 μm^2 microcontacts than the LEDs with smaller microcontacts. We believe that the light output of the GaInN LEDs with ODRs can be further increased and, at the same time, the forward voltage can be decreased by optimizing the number and size of microcontacts, so that both the effective contact area and light-emitting area increase.

In summary, we presented enhanced light extraction in GaInN UV LEDs emitting at 400 nm by employing an Al-based ODR. Theoretical calculations reveal that SiO_2/Al ODRs show much higher reflectivity than both SiO_2/Ag ODRs and Ag metal reflectors. The GaInN near ultraviolet LED with GaN/SiO_2/Al ODR shows 16% and 38% higher light output than LEDs with SiO_2/Ag ODR and Ag reflector, respectively. This is attributed to enhanced reflectivity of the Al-based ODR in the near-ultraviolet wavelength range. Further enhancement in light output and reducing of forward voltage of the GaInN ODR LEDs is expected by optimizing the number and size of NiZn/Ag microcontacts.

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