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GaInN light-emitting diodes with $RuO_2/SiO_2/Ag$ omni-directional reflector

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A GaInN light-emitting diode (LED) employing an omni-directional reflector (ODR) is presented. The ODR consists of a RuO_2 ohmic contact to *p*-type GaN, a quarter-wave thick SiO_2 low-index layer perforated by an array of micro-contacts, and an Ag layer. Calculations predict a 98% angle-averaged reflectivity at $\lambda=450$ nm for an GaN/SiO_2/Ag ODR, much higher than that for a 20 period $Al_{0.25}Ga_{0.75}N$/GaN distributed Bragg reflector (49%) and an Ag reflector (94%). It is shown that the $RuO_2/SiO_2/Ag$ ODR has higher reflectivity than Ni/Au and even Ag reflectors, leading to a higher light extraction efficiency of GaInN LEDs with ODR. The electrical properties of the ODR-LED are comparable to those LEDs with a conventional Ni/Au contact. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1757634]

GaN-based light-emitting diodes (LEDs) provide higher performance in the short-wavelength part of the visible and ultraviolet spectrum than any other material system.[1] However, there is still a great need for improvement of the internal quantum efficiency as well as extraction efficiency. Flip-chip mounted high-power LEDs were demonstrated[2] attaining high extraction efficiency, in which light is extracted through the transparent sapphire substrate instead of through partially absorbing metal contacts as for the case of top-emitting conventional LEDs. In flip-chip LEDs, the light emitted toward metal contacts is reflected up, increasing light extraction. Therefore, the employment of highly reflective metal ohmic contacts with a low contact resistivity could substantially improve the flip-chip mounted GaN-based LEDs.

In order to obtain high reflectivity, various reflectors have been suggested including metal mirrors, distributed Bragg reflectors (DBRs), and omni-directional reflectors (ODRs). Ag metal mirrors the show highest reflectivity among metal mirrors in the visible wavelength region. However, the reflectivity of GaN/Ag is limited to about 94%,[3] and the contact resistivity for Ag/*p*-type GaN is expected to be high due to a low work function of Ag.[4] DBRs have been used in GaAs-based[5] and AlGaInP[6] LEDs. The reflectivity, however, decreases dramatically at oblique angles of incidence resulting in high optical losses. Recently, different types of ODRs with high reflectivity, wide stop band, and omni-directional reflection characteristics have been demonstrated.[7,8] A conductive ODR consisting of GaN, Ag, and intermediate ITO layer has been incorporated into an AlGaInN LED and improvement in light output was shown.[3] The ODR is based on the high/low/high complex refractive index of the Ag ($n_{Ag}=0.132$, $k_{Ag}=2.72$ at 450 nm), ITO ($n_{ITO}=2.06$ at 450 nm), and GaN ($n_{GaN}=2.45$ at 450 nm). However, the ODR-LED showed high operation voltages ($\sim$7 V) possibly due to a high contact resistivity of ITO/*p*-GaN.

In this letter, an omni-directional planar reflector is reported that is incorporated into GaInN blue LED as *p*-type ohmic contact. The ODR comprises GaN, a thin layer of oxidized Ru used as semitransparent low-resistance *p*-type ohmic contact, a quarter-wave thick SiO_2 low-refractive index ($n_{SiO_2}=1.46$ at 450 nm) layer perforated by an array of Ag micro-contacts, and a thick Ag layer. It is shown that the ODR has a much higher reflectivity than conventional Ni/Au contacts and has the potential to outperform Ag metal mirror on GaN. Furthermore, it is shown that the forward voltage of the ODR-LEDs is lower than that of the LED with Ag contact and is comparable to that of conventional LEDs with Ni/Au contacts.

The GaInN LED structure was grown by metalorganic chemical vapor deposition on *c*-plane sapphire and consists of a thick *n*-type GaN buffer layer, an *n*-type GaN lower cladding layer, a GaInN/GaN multiple quantum well active region, a *p*-type GaN upper cladding, and a highly doped contact layer. LED mesa structures were obtained by standard photolithographic patterning followed by dry-etching to expose the *n*-type cladding layer. After 10 min dip in aqua regia solution to remove native oxide on *p*-type GaN, Ru (50 Å) was deposited and annealed at 500 °C under O_2 ambient to form RuO_2 acting as ohmic contact to *p*-type GaN. The RuO_2 obtained by this oxidation annealing was virtually colorless and transparent. RuO_2 is one of the few electrically conductive, optically transparent metal oxides. Quarter-wave thick SiO_2 was deposited on the RuO_2 using plasma-enhanced chemical vapor deposition. Then, an array of circular micro-contacts was patterned on SiO_2 and etched using HF solution to expose the conducting RuO_2 layer. Ag (200 nm) and Au (20 nm) were deposited by electron-beam evaporation at a pressure lower than 5×10^{-7} Torr on top of the SiO_2 with perforated micro-contact holes. For comparison, LEDs with conventional Ni/Au and Ag contacts were fabricated on the same wafer. The *n*-type contacts for the samples were fabricated by electron-beam evaporation of Ti/Al/Ni/Au contacts without oxide removal or subsequent annealing. A Xe-arc lamp and a monochromator were used to

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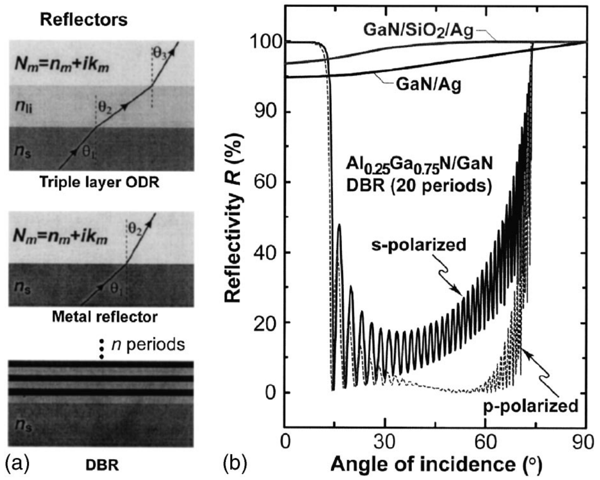

FIG. 1. (a) Schematic cross-sectional view of triple-layer ODR, metal reflector, and DBR. (b) Calculated reflectivity $R(\theta)$ at $\lambda=450$ nm of triple layer ODR (GaN/SiO$_2$/Ag), metal reflector (GaN/Ag and GaN/Ni/Au), and 20 period Al$_{0.25}$Ga$_{0.75}$N/GaN DBR, assuming $n_{\mathrm{Ag}}=0.132$, $k_{\mathrm{Ag}}=2.72$, $n_{\mathrm{SiO}_2}=1.46$, $n_{\mathrm{GaN}}=2.45$ at 450 nm.

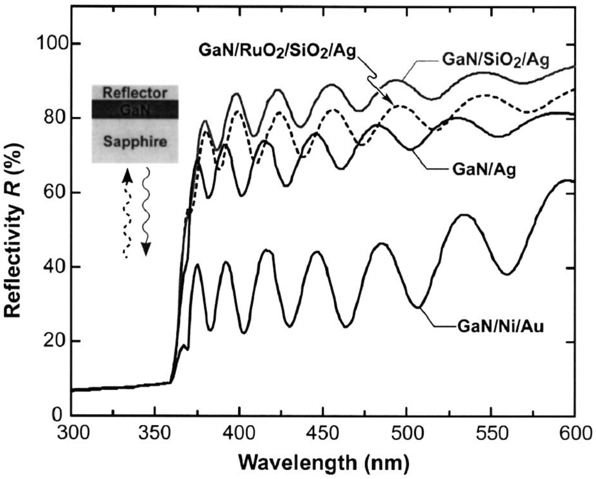

FIG. 2. Normal incidence reflectivity spectra for GaN/SiO$_2$/Ag ODR, GaN/RuO$_2$/SiO$_2$/Ag ODR, GaN/Ag, and GaN/Ni/Au.

measure normal-incidence reflectivity of sapphire/GaN/reflectors (the ODR and metal reflectors). To measure the reflectivity, the reflected monochromatic light was colliminated and focused onto a calibrated UV-enhanced Si photodetector using an optical lens system.

Figure 1(a) shows a schematic cross-sectional view of the triple-layer ODR, the metal reflector, and the DBR. The planar ODR consists of the LED semiconductor material emitting at a wavelength λ_0, a low refractive index layer (n_{li}), and a metal with a complex refractive index $N_m=n_m+ik_m$, where k_m is extinction coefficient. The reflectivity of (1) the semiconductor/metal reflector and (2) the triple-layer ODR as a function of the polar angle θ_1 are given by[9]

$$R=\left|\frac{n_s\cos\theta_1-N_m\cos\theta_2}{n_s\cos\theta_1+N_m\cos\theta_2}\right|^2, \tag{1}$$

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

where

$$r_{12}=\frac{n_s\cos\theta_1-n_{\mathrm{li}}\cos\theta_2}{n_s\cos\theta_1+n_{\mathrm{li}}\cos\theta_2},$$

$$r_{23}=\frac{n_{\mathrm{li}}\cos\theta_2-N_m\cos\theta_3}{n_{\mathrm{li}}\cos\theta_2+N_m\cos\theta_3}, \qquad \phi=\frac{2\pi}{\lambda_0}n_{\mathrm{li}}h\cos\theta_2.$$

Equation (2) applies to a low-index dielectric layer thickness of $\lambda_0/(4n_{\mathrm{li}})$, i.e., to a quarter wavelength layer. Figure 1(b) shows the reflectivity $R(\theta)$ at $\lambda=450$ nm of triple layer ODR (GaN/SiO$_2$/Ag), metal reflectors (GaN/Ag and GaN/Ni/Au), and 20 periods of Al$_{0.25}$Ga$_{0.75}$N/GaN DBR. The reflectivity curves were calculated using the optical transfer matrix method[10] and using parameters, $n_{\mathrm{Ag}}=0.132$, $k_{\mathrm{Ag}}=2.72$, $n_{\mathrm{SiO}_2}=1.46$, $n_{\mathrm{GaN}}=2.45$ at 450 nm.[11] As opposed to the ODR and metal reflectors, $R(\theta)$ of the DBR sharply drops above 14° and recovers only at angles close to grazing incidence. As a result, the angle averaged reflectivity R' is much larger for a GaN/SiO$_2$/Ag ODR ($R'=0.98$ at $\lambda=450$ nm) and Ag reflector ($R'=0.94$ at $\lambda=450$ nm) than for the DBR ($R'=0.49$ for s-polarized, $R'=0.38$ for p-polarized at $\lambda=450$ nm). Since the LED active region emits light isotropically, R' is a suitable figure-of-merit to describe reflector performance. Note that the reflectivity of the GaN/SiO$_2$/Ag ODR is higher than that of the GaN/Ag reflector for all angles of incidence.

Figure 2 presents experimental normal-incidence reflectivity spectra measured for the GaN/SiO$_2$/Ag ODR, GaN/RuO$_2$/SiO$_2$/Ag ODR, GaN/Ag, and GaN/Ni/Au systems. The reflectivity spectra show interference fringes due to interfaces shown in the inset of Fig. 2, and have an abrupt cutoff at wavelength around the absorption edge of GaN, ~360 nm. The experimental data clearly show that the ODRs have higher reflectivity in visible wavelengths than conventional Ni/Au contact and even Ag mirror on GaN, confirming the reflectivity calculation in Fig. 1(b). The reflectivity of GaN/RuO$_2$/SiO$_2$/Ag ODR is slightly lower than that of the GaN/SiO$_2$/Ag ODR due to a thin, semi-transparent RuO$_2$ intermediate layer for p-type contact, but still higher than that of Ag metal reflector. The measured reflectivities were lower than the calculated ones possibly due to absorption and scattering in back-side-polished sapphire.

Figure 3(a) shows a top view and Fig. 3(b) shows a schematic cross-sectional view of the GaInN LED with GaN/RuO$_2$/SiO$_2$/Ag ODR. The dashed line in Fig. 3(a) represents the cross-sectional cut shown in Fig. 3(b). The chip dimensions are 300×300 μm^2. There is an array of circular

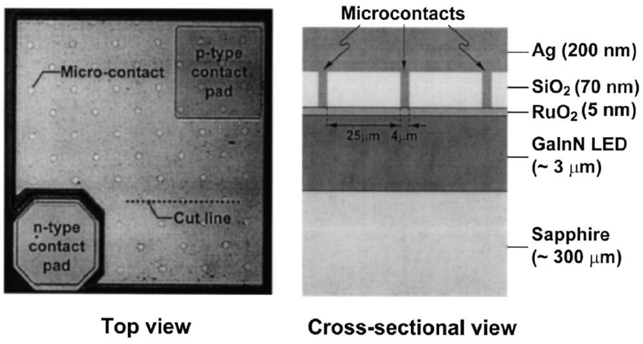

FIG. 3. Top view and schematic cross-sectional view of GaInN LED with GaN/RuO$_2$/SiO$_2$/Ag ODR.

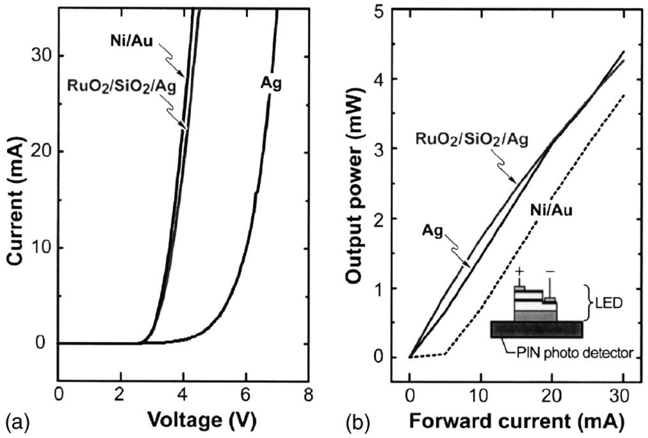

FIG. 4. (a) Current–voltage characteristics and (b) light-output-vs-current characteristic of GaInN LEDs with GaN/RuO_2/SiO_2/Ag ODRs and LEDs with Ni/Au and Ag contacts.

micro-contacts in the p-contact area, enabling electrical conductivity between the RuO_2 contact layer and Ag through the insulating SiO_2 low-index layer. The radius of the micro-contacts is 4 μm. The micro-contact array covers only about 2% of the entire back side lit area of the LED chip. Therefore, assuming a reflectivity of 90% of the micro-contacts, the overall ODR reflectivity is reduced by an insignificant amount. Because of the low resistivity ($\sim$50 $\mu\Omega$cm) and its high work function ($>$5eV),[12,13] RuO_2 is expected to be an excellent current spreading and contact layer to p-type GaN. with low contact resisitivity.[14]

Figure 4(a) shows the current–voltage characteristics of the LED with GaN/RuO_2/SiO_2/Ag ODR and the conventional LEDs with Ni/Au and Ag contacts. The forward voltage at 20 mA for the LED with GaN/RuO_2/SiO_2/Ag ODR is 4.0 V, comparable to that of the conventional LED with Ni/Au contact, 3.9 V. This indicates that the contact resistivity of RuO_2 on p-type GaN is comparable to that of Ni/Au. On the other hand, the forward voltage of the LED with Ag contact is as high as 6.5 V. This is due to a low work function of Ag, resulting in a high potential barrier between Ag and p-type GaN. The electroluminescence intensities from the back sides of the LEDs were measured directly on a large-size (10×10 mm^2) Si PIN photodetector. The light-output-versus-current characteristic of the LEDs is shown in Fig. 4(b). At small forward currents ($I<20$ mA), the light power extracted from the LED with ODR is slightly larger than the output from the LED with Ag contact, but significantly larger than that from the LED with Ni/Au contact. The increased light output of the LED with ODR can be attributed to higher reflectivity, and hence better light extraction efficiency due to the use of the ODR. In addition, a saturation of the light output power with increasing current level is not observed for the LED with GaN/RuO_2/SiO_2/Ag ODR, indicating that the resistivity of the RuO_2 layer and specific contact resistance of the GaN/RuO_2 contact is low enough for LED applications.

In summary, a GaN LED with an ODR has been presented. The ODR consists of p-type GaN, a thin layer of RuO_2 acting as ohmic contact to p-type GaN, an Ag layer, and an intermediate low-refractive index dielectric layer, SiO_2, perforated by an array of Ag micro-contacts, thus enabling electrical conductivity. Calculations predicts a 98% angle averaged reflectivity at $\lambda=450$ nm for a GaN/SiO_2/Ag ODR, which is higher than that for a 20 period $Al_{0.25}Ga_{0.75}N$/GaN DBR (49%) and even for an Ag reflector (94%). Consistent with the calculated results, the ODR has higher reflectivity than Ag and Ni/Au reflectors. Furthermore, LEDs with GaN/RuO_2/SiO_2/Ag ODRs show better electrical properties than LEDs with Ag mirrors, and much higher light-extraction efficiency than LEDs with conventional Ni/Au contacts.

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