GaInN light-emitting diodes with omni-directional reflector using nanoporous SnO_2 film

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Enhancement of light extraction in a GaInN light-emitting diode (LED) employing an omni-directional reflector (ODR) consisting of GaN, SnO_2 nanorod and an Ag layer was presented. The ODR comprises a transparent, quarterwave layer of SnO_2 nanorod claded by silver and serves as an ohmic contact to p-type GaN. Transparent SnO_2 sols were obtained by sol-gel method from $SnC1_2{\cdot}2H_2O$, and SnO_2 thin films were prepared by dip-coating technique. The average size of the spherical SnO_2 particles obtained is 200 nm. The refractive index of the nanorod SnO_2 film layer is 2.01. The GaInN LEDs with GaN/SnO_2/Ag ODR show a lower forward voltage. This was attributed to the enhanced reflectivity of the ODR that employs the nanorod SnO_2 film layer. Experimental results show that ODR-LEDs have lower optical losses and higher extraction efficiency as compared to conventional LEDs with Ni/Au contacts and conventional LEDs employing a distributed Bragg reflector (DBR).

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GaN-based light-emitting diodes (LEDs) provide a higher performance in the short-wavelength part of the visible and ultraviolet (UV) spectrum compared with any other semiconductor material system[1,2]. There are many applications for such devices including communications and solid-state lighting[3−5]. There is currently a great need for improving the extraction efficiency in nitride LED structures. Different techniques have been employed to improve the light-extraction efficiency of spontaneous light emitters, including flip chip packaging and the employment of triple-layer omni-directional reflectors (ODRs)[6−9].

In this paper, we presented a novel approach for increasing extraction efficiency of GaInN mesa-structure LEDs grown on transparent sapphire substrates. This approach is based on an ODR consisting of GaN, a quarter-wave layer of SnO_2 nanorod and an Ag layer. It is shown that this reflector possesses high reflectivity, omni-directionality, and a spectrally broad high-reflectivity band. In particular, the ODR has better properties than conventional contacts and even Ag metal mirrors on GaN.

A mixture of 50 mmol $SnCl_2{\cdot}2H_2O$ and 100 mL absolute ethyl alcohol was stirred for 3 h in a closed container. After cooling in room temperature for 24 h, the transparent SnO_2 sol was obtained. The SnO_2 film was grown on the Ag substrate by dip-coating technique at the speed of 80 mm/min. After drying and heating the film and substrate in the muffle furnace for 15 min at 100 °C and 500 °C for 2 h, respectively, the nanoporous SnO_2 film was obtained by repeating those all processes several times. The 25-layer nanoporous SnO_2 film's X-ray diffraction (XRD) spectrum was shown in Fig. 1. Inspection of Fig. 1 reveals that it has three typical characteristic diffraction peaks at (110), (101), and (211). The particle of the film has the good crystallinity. The average size of the spherical SnO_2 particles obtained is 200 nm, and matches well with the theoretical size of 195 nm calculating by the formula of $D = k\lambda/\beta\cos\theta$. The refractive index of the nanorod SnO_2 film layer is 2.01.

The GaInN LED's device structure is shown in Fig. 2. The p-type contact consists of the SnO_2 nanorod of quarter-wave thickness that is covered by a thick Ag layer. The figure shows that the p-type contact is close to the light-generating region indicating the importance of reducing any optical losses at the p-type contact. The reflectivity along the surface normal direction of a semiconductor/metal reflector is given by

$$R = ((n_\mathrm{s} - n_\mathrm{m})^2 + k_\mathrm{m}^2)/((n_\mathrm{s} + n_\mathrm{m})^2 + k_\mathrm{m}^2), \qquad (1)$$

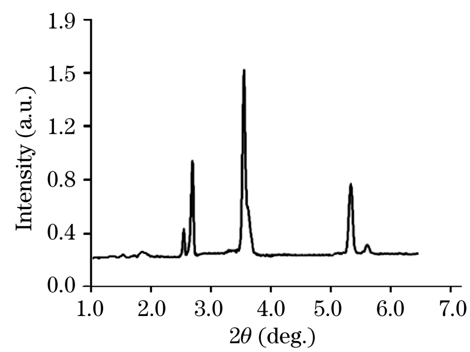

Fig. 1. XRD pattern of 25-layer SnO_2 film.

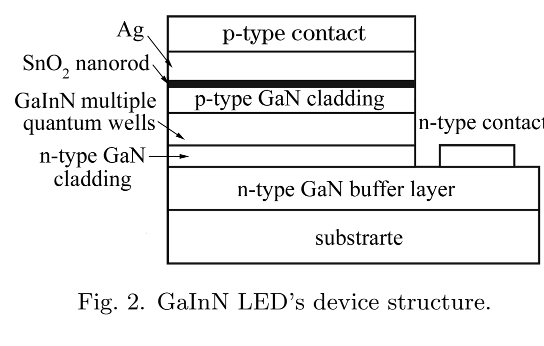

Fig. 2. GaInN LED's device structure.

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where n_s is the refractive index of the semiconductor, and n_m and k_m are the refractive index and the extinction coefficient of the metal, respectively. For a GaN/Ni reflector and a typical contact metalization for p-type ohmic contacts, the reflectivity calculated from Eq. (1) at $\lambda = 450$ nm is about 30%. For a GaN/Ag metal reflector, a reflectivity of 92% is inferred form Eq. (1)[4]. The reflectivity along the surface normal direction of a semiconductor/dielectric/metal reflector is given by

$$R = \{[(n_s - n_i)(n_i + n_m) + (n_s + n_i)k_m]^2 + [(n_s - n_i)k_m + (n_s + n_i)(n_i - n_m)]^2\} \times \{[(n_s + n_i)(n_i + n_m) + (n_s - n_i)k_m]^2 + [(n_s + n_i)k_m + (n_s - n_i)(n_i - n_m)]^2\}^{-1}, \quad (2)$$

where n_i is the refractive index of the nanoporous SnO_2 layer. For a GaN/SnO_2/Ag metal reflector, a reflectivity of about 97% is inferred form Eq. (2).

The measured reflectivity $R(\theta)$ of the internal ODR with nanoporous SnO_2 used as dielectric material layer, the conventional LEDs with Ni/Au contacts and conventional LEDs employing a distributed Bragg reflector (DBR) are 97.7%, 92.9% and 93.6%, respectively. For comparison, the calculated reflectivities at normal incidence, the angle-integrated reflectivities for the ODR with nanoporous SnO_2, the Ni/Au interface (without the dielectric layer), and conventional LEDs employing a DBR are listed in Table 1.

Table 1. Measured and Calculated Reflectivity at 450 nm (%)

Reflectivity	ODR with Nanoporous SnO_2	Ni/Au	DBR
Measured	97.7	92.9	93.6
Calculated	98.6	93.1	93.9

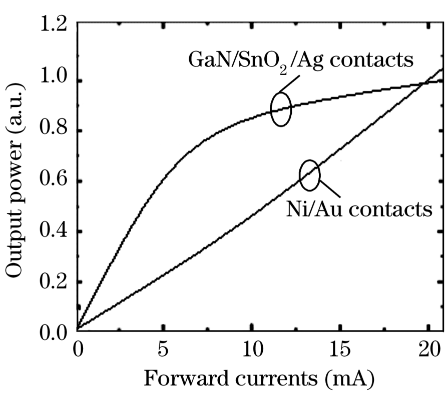

Fig. 3. Relationship between the light output and forward currents.

The light-output-versus-current characteristic of the device is shown in Fig. 3. Under small forward currents, the light power extracted from the ODR-LED is significantly larger than that from the conventional LED. The increased light output of the ODR-LED can therefore be attributed to better light extraction efficiency due to the use of the ODR.

An internal ODR that consists of a semiconductor, a nanoporous SnO_2 film, and an Ag layer has been reported. The angle-dependent reflectivities of the ODRs were measured at 450 nm and compared with calculations. Experimental results show that, for an ODR employing nanoporous SnO_2, the reflectivity significantly exceed the corresponding values of the Ni/Au interface (without the dielectric layer), and conventional LEDs employing a DBR. And the GaInN LEDs with GaN/SnO_2/Ag ODR show a lower forward voltage as compared to conventional LEDs with Ni/Au contacts. Those can be directly attributed to ODR consisting of the nanoporous SnO_2 film.

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