GaInN light-emitting diodes with omni directional reflectors

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ABSTRACT

A high-reflectivity omni directional reflector (ODR) has been incorporated into a GaInN light-emitting diode (LED) structure. The ODR comprises a transparent, electrically conductive quarter-wave layer of indium tin oxide clad by silver and serves as an ohmic contact to p-type GaN. It is shown that ODR-LEDs have low optical losses and high extraction efficiency. Mesa-structure GaInN / GaN ODR-LEDs emitting in the blue wavelength range are demonstrated and compared to GaInN / GaN LEDs with semitransparent Ni / Au top contacts. The extraction efficiency of ODR-LEDs is higher as compared to conventional LEDs with Ni / Au contacts.

Keywords: GaInN, light-emitting diodes, light extraction, omni directional reflectors

1. INTRODUCTION

GaN-based LEDs provide a higher performance in the short-wavelength part of the visible and ultraviolet (UV) spectrum than any other semiconductor material system[1, 2, 3]. There are many applications for such devices including chemical and biological agent detection, communications, and solid-state lighting. There is currently a great need for improvement of the internal quantum efficiency as well as of the extraction-efficiency in III–V nitride LED structures. High extraction efficiency designs include flip-chip mounted high-power devices[4], transparent indium-tin-oxide current-spreading layers[5], thin semi-transparent Ni / Au ohmic contacts[6], and resonant-cavity approaches[7].

In this publication, we present a novel approach for increased extraction efficiency in GaInN mesa-structure LEDs grown on transparent sapphire substrates. This approach is based on an omni-directional reflector (ODR) consisting of GaN, a quarter-wave layer of indium tin oxide (ITO)[8], and a Ag layer. It is shown that this reflector possesses high reflectivity, omni-directionality, and a spectrally broad high-reflectivity band. In particular, it is shown that the ODR has better properties than conventional contacts and even Ag metal mirrors on GaN[9]. In a related way the performance of AlGaInP devices was improved utilizing substrate-less thin film LEDs[10, 11]. The epitaxially grown AlGaInP semiconductor layers, including the active region, are placed on a highly reflective mirror before bonding the wafer to a new carrier. Particular emphasis is being paid to the shaping of micro-reflectors which increase light extraction through the device top surface.

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2. THEORY AND EXPERIMENT

The device structure, shown in ***Figure*** 1, consists of a mesa with the common “p-side-up” growth. The p-type contact consists of the large-area ITO of quarter-wave thickness that is completely covered by a thick Ag layer. Flip-chip mounting is preferred for increased light outcoupling efficiency. 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.

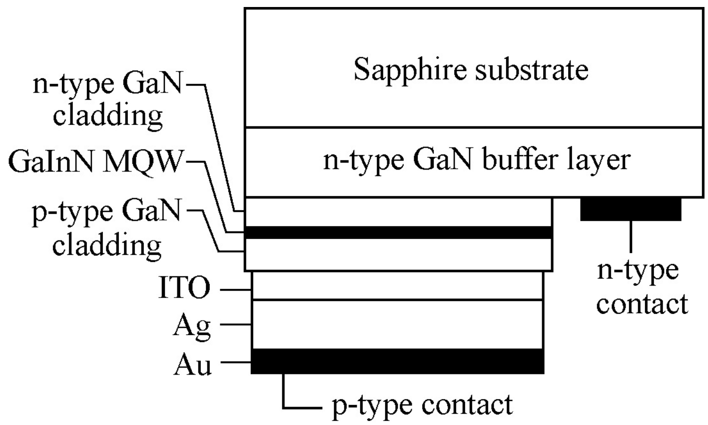

FIG. 1. Mesa structure GaInN LED employing an omni directional GaN / ITO / Ag reflector.

The reflectivity along the surface normal direction of a semiconductor / metal reflector is given by

$$R = \frac{(n_s - n_m)^2 + k_m{}^2}{(n_s + n_m)^2 + k_m{}^2} \tag{1}$$

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[12], a typical contact metalization for p-type ohmic contacts, the reflectivity calculated from Eq. (1) at $\lambda = 440$ nm is about 30 %. For a GaN / Ag metal reflector[12], a reflectivity of 92 % is inferred form Eq. (1).

The reflectivity along the surface normal direction of a semiconductor / dielectric / metal reflector can be calculated as

$$R = \frac{\{(n_S - n_{li})(n_{li} + n_m) + (n_S + n_{li})k_m\}^2 + \{(n_S - n_{li})k_m + (n_S + n_{li})(n_{li} - n_m)\}^2}{\{(n_S + n_{li})(n_{li} + n_m) + (n_S - n_{li})k_m\}^2 + \{(n_S + n_{li})k_m + (n_S - n_{li})(n_{li} - n_m)\}^2} \tag{2}$$

where n_{li} is the refractive index of the low-index ITO layer. For a GaN / ITO / Ag metal reflector[12], a reflectivity of about 94 % is inferred form Eq. (2). Note that the extinction coefficient of ITO increases with the conductivity[8, 13]. Because current is conducted *normal* to the film plane, a low conductivity of the ITO can be afforded in the LED structure presented here but not in the LED structure in which ITO is used as a current-spreading layer. The extinction coefficient of ITO is therefore neglected and the calculated reflectivity is valid in the low-conductivity limit of ITO. Note that even very small differences in reflectivity can improve LED performance significantly since waveguide modes undergo multiple or even many reflection events.

The LEDs were grown by organo-metallic vapor-phase epitaxy and consist of a 4 μm thick n-type GaN buffer layer, an n-type GaN lower cladding layer, a GaInN / GaN multiple quantum well active region, a p-type upper cladding layer, and a highly Mg-doped GaN contact layer. LED mesa structures were obtained by standard photolithographic pattering steps defining circular p-type contact areas (200 μm diameter) followed by dry-etching to expose the n-type cladding layer surrounding the p-type contact areas.

After a 3 min dip in buffered oxide etchant (BOE) to remove native oxide, p-type contacts for the ODR-LEDs were deposited in a two-step process: first, ITO films of about quarter wave thickness ($d \approx 55$ nm) were deposited in an RF-assisted sputtering system using a 99.99-pure In_2O_3 / SnO_2 target. The sputtering was carried out in an Argon plasma with an ion acceleration voltage of 1 kV and an ion beam current of 24 mA. A constant oxygen flow rate of 3.5 sccm and a total pressure in the sputtering chamber of 4.3×10^{-4} Torr resulted in an ITO growth rate of about 0.2 nm / s. The ITO was then annealed in a rapid thermal annealing furnace at 600 °C for 30 s in a flowing N_2 ambient. The ITO-film obtained this way was virtually colorless and transparent. In the second step, Ag (200 nm) and Au (20 nm) were deposited on top of the annealed ITO layer by electron-beam evaporation at a pressure of about 8×10^{-7} Torr.

Semi-transparent p-type contacts for reference LEDs were obtained by deposition of Ni (20 nm) and Au (20 nm) in the electron beam evaporator at a pressure of about 1×10^{-6} mbar followed by annealing in dry air at 530° C for 3 min. Prior to the deposition native oxide was removed by BOE. The n-type contacts for both samples (conventional LED and ODR-LED) were fabricated by electron beam evaporation of Ti (60 nm) and Al (60 nm) at about 3×10^{-7} Torr without oxide removal or subsequent annealing.

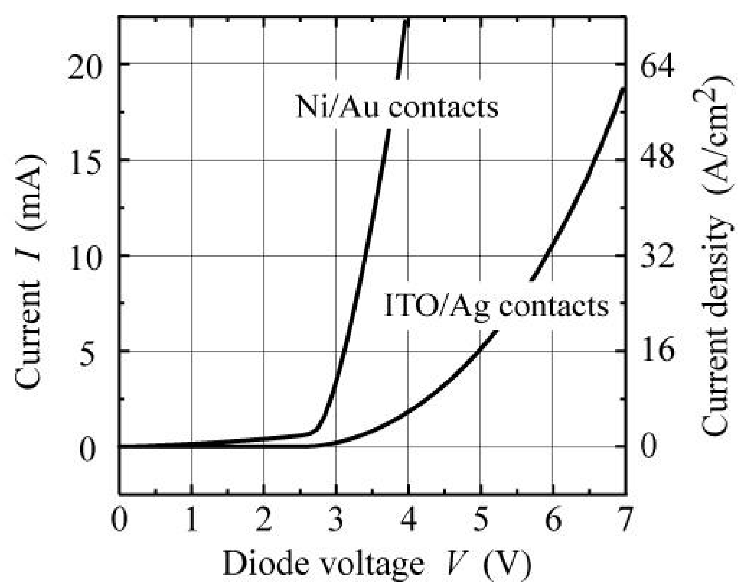

FIG. 2. Current-voltage curves of the ODR-LED and a conventional reference LED with an identical mesa structure and contact diameter of 200 μm.

The electroluminescence intensity and current voltage for the conventional and the ODR-LED's were measured simultaneously in an integrating sphere with the sample positioned on a transparent glass holder. ***Figure*** 2 shows the current voltage characteristic of the ODR-LED and the conventional LED. The voltage required to drive a forward current of 15 mA through the conventional LED is about 3.6 V and about 6.6 V for the ODR-LED. The slope resistances at these voltages are $R_s = 33\ \Omega$ for the conventional LED, and $R_s = 143\ \Omega$ for the ODR-LED.

Figure 3 shows the optical spectrum of the ODR-LED and the conventional LED at a pump current I = 12 mA. A peak emission wavelength of about 440 nm can be inferred from the figure. The Full-Width-Half-Maximum is about 55 nm in both cases.

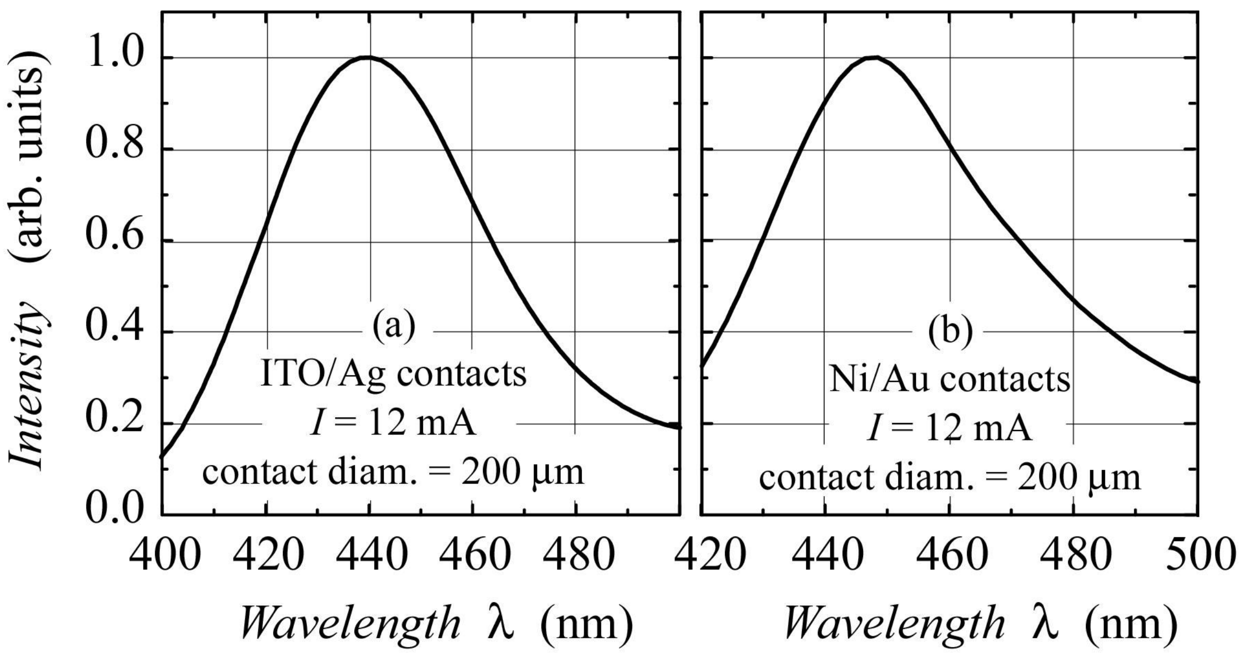

FIG. 3. Emission spectrum of (a) ODR-LED and (b) conventional LED.

The light-output-versus-current characteristic of the device is shown in ***Figure*** 4. At small forward currents (I < 17 mA) the light power extracted from the ODR-LED is significantly larger than the output from the conventional LED. As outlined above, a reflectivity of about 94 % is expected for the ITO / Ag mirror utilized in the present ODR LED; this is clearly a better figure-of-merit than the transmittance $T \approx 65$ % of the semitransparent Ni (20 nm) / Au (20 nm) contact of the conventional LED. Typically transmittance values for semitransparent contacts are between T = 85 % and T = 38 % for Ni (2 nm) / Au (5 nm)[6] and Ni (50 nm) / Au (50 nm), respectively[14]. The increased light output of the ODR-LED can therefore be attributed to better light extraction efficiency due to the use of an omni directional mirror.

However, with increasing current levels saturation of the output power is observed for the ODR-LED, whereas the conventional LED maintains an almost linear L-vs.-I-relationship up to 20 mA as inferred from Fig. 4. This is most likely due to heating of the ODR-LED caused by the large resistance $R_s = 143\ \Omega$ exceeding the R_s value of the conventional LED by almost a factor of three. The larger R_s value corresponds to an additional drive voltage drop of about 3 V at a forward current I = 15 mA as compared to the conventional LED (see Fig. 2). It is interesting to note that a similar voltage drop of about 2 V has been reported for a blue LED employing a single ITO layer of 25 nm thickness as p-type contact material[15]. We therefore attribute the higher device resistance to the resistivity of the ITO-layer or to a poorer specific contact resistance of the GaN/ITO contact. Note that the ITO deposition parameters were adjusted to obtain maximum transparency which usually results in low conductivity[8, 13].

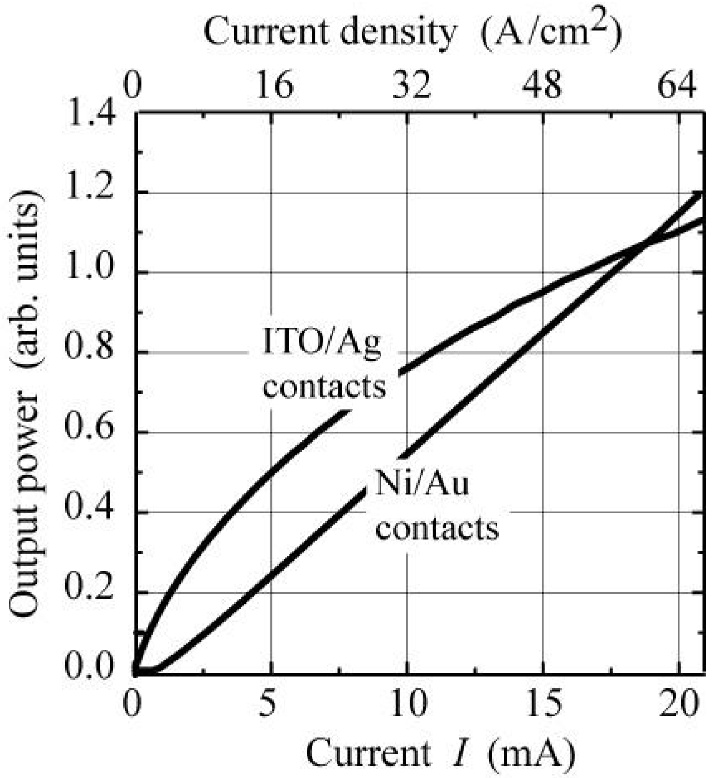

FIG. 4. Light-output-vs.-current of (a) ODR-LED and (b) conventional LED. The power is measured with an integrating sphere with the samples mounted on a transparent glass holder.

3. CONCLUSION

In conclusion, a novel LED structure comprising an omni directional reflector (ODR) has been presented. The triple-layer ODR consists of GaN, a quarter-wave thick ITO layer, and a Ag-layer and forms the p-type contact to the LED wafer. Calculations predict a 94 % reflectivity for the ODR, which exceeds the reflectivity of 30 % attainable with Ni contacts. Comparison to conventional LEDs fabricated from the same wafer employing semitransparent Ni (20 nm) / Au (20 nm) p-type contact with a transparency $T \approx 65$ % showed that the output power emitted by the ODR-LED is significantly larger. This difference is attributed to the higher light extraction efficiency caused by the ODR. However, the overall device resistance of the ODR LED was about a factor of three larger compared to the conventional LED due to the resistivity of the ITO layer or a poorer specific contact resistance of the GaN/ITO contact.

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