Omnidirectional Reflective Contacts for Light-Emitting Diodes

T. Gessmann, E. F. Schubert, J. W. Graff, K. Streubel, and C. Karnutsch

***Abstract*—An electrically conductive omnidirectional reflector (ODR) is demonstrated in an AlGaInP light-emitting diode (LED). The ODR serves as p-type contact and comprises the semiconductor, a metal layer and an intermediate low-refractive index dielectric layer. The dielectric layer is perforated by an array of AuZn microcontacts thus enabling electrical conductivity. It is shown that the ODR significantly increases light extraction from an AlGaInP LED as compared to a reference LED employing a distributed Bragg reflector (DBR). External quantum efficiencies of 18% and 11% are obtained for the ODR- and the DBR-LED, respectively.**

***Index Terms*—Light-emitting diodes (LEDs), lighting, omnidirectional reflectors (ODRs), optical materials, optical reflection, semiconductor materials, solid-state lighting.**

I. Introduction

THERE ARE two ways to attain efficient light extraction from a spontaneous light emitter, namely the use of a fully transparent structure or the employment of a highly reflective omnidirectional mirror. In common AlGaInP light emitting diodes (LEDs), the light-emitting epitaxial layers are grown on conducting GaAs, which is absorbing for light emitted by the active region. This type of LED, referred to as absorbing substrate (AS) LED, is therefore not suited for efficient light extraction.

Distributed Bragg reflectors (DBRs) have been used to coat the GaAs substrate [1], [2]. However, the DBR reflectivity decreases dramatically at oblique angles of incidence resulting in optical losses. Recently, there have been efforts to achieve DBRs with wide-angle reflection characteristics using aperiodically stacked multilayers [3], [4]. General design criterions to achieve true omnidirectional reflection in all wavelength regions were developed by Fink *et al.* [5] who demonstrated an omnidirectional reflector (ODR) made of polystyrene and Te multilayers for the infrared region. Another type of ODR employs birefringent materials [6]. All these ODRs could be used in LEDs [7], however, due to their lack of electrical conductivity they necessitate a highly conductive thick buffer layer, a side-by-side contact configuration, and a mesa-structure.

The absorbing GaAs substrate can be replaced by a transparent GaP substrate [8]. Such transparent-substrate LEDs (TS-LEDs) require a critical wafer-bonding process and use costly GaP wafers. Significantly improved luminous performance was achieved by substrateless thin film LEDs (TF-LEDs) [9], [10]. Here the AlGaInP layers are shaped to form microreflectors, then covered by a highly reflective mirror and bonded to a new carrier [9], [10].

In this letter, a new conducting omnidirectional planar reflector is reported that is incorporated into an LED structure as p-type ohmic contact. The ODR comprises the AlGaInP semiconductor, a metal layer, and an intermediate low-index dielectric layer of quarter-wave thickness. The dielectric layer is designed to enhance the reflectivity of the metal layer in a similar way as used for infrared hollow wave guides [11], [12]. However, the dielectric layer of the ODR is perforated by an array of metallic microcontacts thus enabling electrical conductivity for use in LEDs. It is shown that the optical properties of this ODR significantly exceed the reflection properties of a conductive DBR. In addition, the ODR-LED fabrication process does not rely on a complicated wafer-bonding process.

II. Experiments and Results

The planar omnidirectional reflector 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 $N_m = n_m + ik_m$. At normal incidence, the reflectance of the triple-layer ODR is given by (1) (shown at the bottom of the next page), and applies to a physical thickness $\lambda_0/(4\ n_{\mathrm{li}})$ of the low-index dielectric layer, i.e., to a quarter-wave layer. For an AlGaInP–SiO_2–Ag structure emitting at 630 nm, (1) yields a normal-incidence reflectance $R_{\mathrm{ODR}}(\theta = 0)$ of more than 98% compared to a value of about 96% for a structure without dielectric layer illustrating the beneficial effect of the low-index layer.

Fig. 1 shows the reflectivity $R(\lambda)$ and $R(\theta)$ of different triple-layer ODRs and a transparent conductive DBR widely used in AlGaInP LEDs. The reflectivity curves were calculated using the optical transfer matrix method [13]. As opposed to the ODR, $R(\theta)$ for the DBR sharply drops above 17° and can be recovered only at angles close to grazing incidence. As a result, the angle-averaged reflectivity $\bar{R}$ is much larger for an Ag–SiO_2 ODR ($\bar{R} > 0.98$ at $\lambda = 630$ nm) than for the DBR ($\bar{R} \approx 0.5$ at $\lambda = 630$ nm). Since the LED active region emits light isotropically, $\bar{R}$ is a suitable figure-of-merit to describe reflector performance.

The schematic structure of the ODR-LED is shown in Fig. 2. The epitaxial layers were grown on GaAs in the standard "p-side up" mode commonly employed in AlGaInP LEDs. As shown in Fig. 2, low-resistivity electrical contacts to the p-GaP layer

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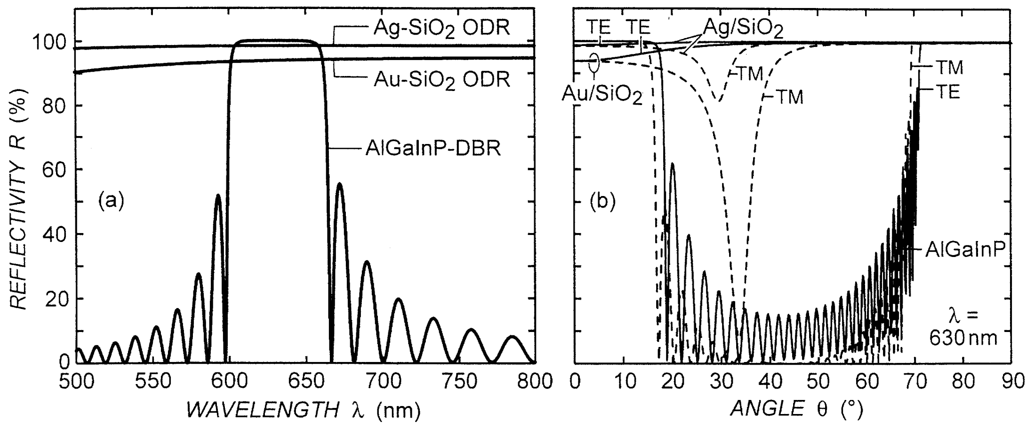

(a) (b)

Fig. 1. (a) Calculated reflectivity versus wavelength and versus (b) angle of incidence for two ODRs and a DBR with a Bragg wavelength of 630 nm. GaP is the external medium. The transparent and conductive AlGaInP-DBR consists of 35 $[(Al_{0.3}Ga_{0.7})_{0.5}In_{0.5}P/Al_{0.5}In_{0.5}P]$ quarter wave pairs. The ODRs comprise a 500-nm-thick metal layer of either Ag or Au covered by a quarter-wave SiO_2 layer. The solid and dashed lines correspond to TE- and TM-polarized waves, respectively.

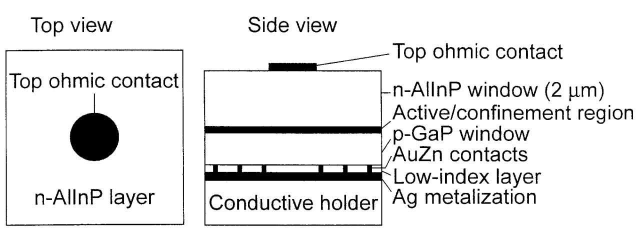

Fig. 2. Top and side view of an AlGaInP LED incorporating a conductive ODR. The original GaAs substrate has been removed and the LED is bonded "p-side down" to a new conductive holder. The ODR serves as p-type contact to the LED.

are established by an array of AuZn microcontacts. In order to avoid degradation of the ODR reflectivity the patterning, deposition and annealing of the microcontact array was performed before the deposition of Ag. The array covers only about 1% of the entire backside area of the LED die. Therefore, assuming a reflectivity of 0.5 of each microcontact, the overall ODR reflectivity is reduced by only 0.5%.

About (10×10) mm^2 pieces of the ODR-covered LED were then bonded to a conductive Si substrate using silver-loaded epoxy (Epo Tek H20E) dispensed on the Si as a uniform layer of about 20 μm thickness. The epoxy was cured at low temperatures (80 °C for about 12 h) to minimize stress due to thermal expansion mismatch between GaP, the epoxy and Si. The original GaAs substrate was removed by chemo-mechanical polishing and wet-chemical etching. Large area ohmic contacts to the exposed 2-μm-thick n-AlInP window layer were defined using AuGe as contact material. The AuGe contact resistance was improved by annealing at temperatures below the degradation temperature of the epoxy polymer at around 370 °C for about 40 min in nitrogen ambient. After annealing the LED surface was usually cracked due to stress caused by thermal mismatch.

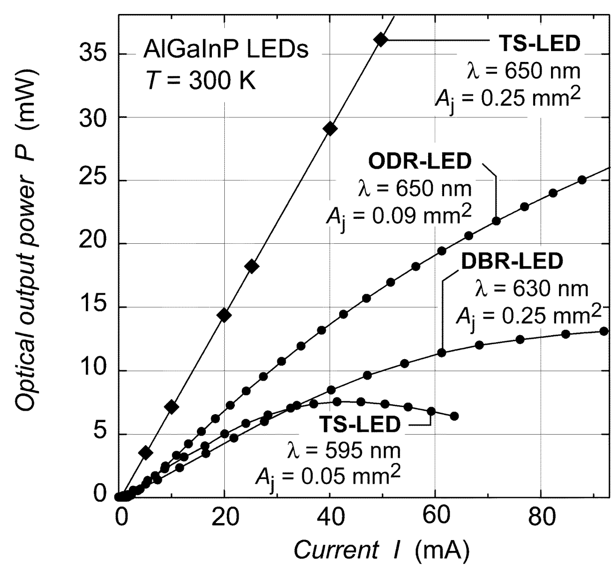

Fig. 3. Dependence of the total optical output power on the drive current for AlGaInP-LEDs with different emission wavelengths λ and junction areas A_j. The samples were placed on a reflective sample holder inside an integrating sphere for the measurements. The data for the red TS-LED were taken from [15].

Inspection under an optical microscope was performed to check the quality of the ODR after annealing. The ODR appeared as uniformly bright area interspersed by the dark pattern of low-reflectivity microcontacts.

The optical output power L versus forward current I for an ODR-LED, a DBR-LED, and a TS-LED with different peak wavelengths λ and junction areas A_j is shown in Fig. 3. For the measurements, the samples were placed inside an integrating sphere on a reflecting sample holder.

$$R_{\mathrm{ODR}} = \frac{\{(n_S - n_{\mathrm{li}})(n_{\mathrm{li}} + n_m) + (n_S + n_{\mathrm{li}})k_m\}^2 + \{(n_S - n_{\mathrm{li}})k_m + (n_S + n_{\mathrm{li}})(n_{\mathrm{li}} - n_m)\}^2}{\{(n_S + n_{\mathrm{li}})(n_{\mathrm{li}} + n_m) + (n_S - n_{\mathrm{li}})k_m\}^2 + \{(n_S + n_{\mathrm{li}})k_m + (n_S - n_{\mathrm{li}})(n_{\mathrm{li}} - n_m)\}^2} \quad (1)$$

Peak external quantum efficiencies $(\eta_{\rm ex})$ as determined from the $L-I$ curves are about 18% for the ODR-LED ($I_f = 27$ mA), 11% for the DBR-LED ($I_f = 27$ mA), and about 12% for the yellow TS-LED ($I_f = 11$ mA). We attribute the significant difference between the ODR- and DBR-LEDs to increased light extraction mediated by the omnidirectional reflector. The wide-angle reflectivity of the ODR allows wave guiding of light rays with much smaller attenuation than a DBR. As a result, light extraction at the edges of the LED chip is strongly increased. In addition, the top surface of the ODR-LED may be rougher than the surface of the DBR-LED due to the etching used for the substrate removal. Assuming random surface roughness, photons are either scattered isotropically or totally reflected with a random distribution of reflection angles. As a result, photon out-coupling from wave-guided modes into vertical radiation modes is enhanced during multiple round trips between surface and ODR. The external quantum efficiency of the ODR-LED is still smaller as compared to values of $\eta_{\rm ex} > 30\%$ for TS-LEDs operating at 630 or 650 nm [14], [15]. However, the TS-devices employ a very thick window layer ($t \approx 45$ μm) resulting in a better extraction efficiency as compared to the present ODR-LED with a 2-μm-thick window. It is reasonable to expect further improvement for ODR devices with thicker window layers.

Inspection of Fig. 3 reveals that saturation of the optical output power due to active region heating is smaller for the ODR-LED than for the DBR-LED. Taking into account the differences in the junction areas A_j this effect can be attributed to the better thermal conductivity of the Si holder as compared to the GaAs substrate. The more pronounced saturation effect in the case of the yellow TS-LED is caused by the relatively small confinement barrier height in the yellow wavelength region allowing more carriers to overflow the barrier at a given current density.

III. Conclusion

An AlGaInP-based LED structure comprising a conductive ODR has been presented and compared to a reference device employing a conductive DBR. The triple-layer ODR consists of the phosphide semiconductor, a quarter-wave thick low-index layer such as SiO_2, and an Ag-layer. The ODR serves as p-type contact to the LED. Electrical conductivity of the reflector is achieved by an array of AuZn microcontacts perforating the insulating low-index layer. The angle-averaged reflectivity $\bar{R}$ was taken as figure-of-merit for the reflector performance. Calculated values of $\bar{R}$ were above 98% for the ODR and about 50% for the conductive DBR. External quantum efficiencies of about 18% and 11% have been determined from L-versus-I measurements for the ODR-LED and the DBR-LED, respectively. This difference was attributed to the use of a highly reflective ODR enabling better light extraction through the rough surface and sidewalls of the ODR LED.

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