Omnidirectional reflector using nanoporous SiO_2 as a low-refractive-index material

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Triple-layer omnidirectional reflectors (ODRs) consisting of a semiconductor, a quarter-wavelength transparent dielectric layer, and a metal have high reflectivities for all angles of incidence. Internal ODRs (ambient material's refractive index $n \gg 1.0$) are demonstrated that incorporate nanoporous SiO_2, a low-refractive-index material ($n=1.23$), as well as dense SiO_2 ($n=1.46$). GaP and Ag serve as the semiconductor and the metal layer, respectively. Reflectivity measurements, including angular dependence, are presented. Calculated angle-integrated TE and TM reflectivities for ODRs employing nanoporous SiO_2 are $R_{\text{int}}|_{\text{TE}}=99.9\%$ and $R_{\text{int}}|_{\text{TM}}=98.9\%$, respectively, indicating the high potential of the ODRs for low-loss waveguide structures.

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III–V nitride LEDs are becoming increasingly important for visible-spectrum[1] and UV[2,3] emitters. Different techniques have been employed to improve the light-extraction efficiency,[4] including flip-chip packaging, interdigitated contacts, and triple-layer omnidirectional reflectors (ODRs).[5,6] Such triple-layer ODRs are internal reflectors that have an ambient material with $n \gg 1$. Metal reflectors' reflectivity is only around 95% with a semiconductor ambient. Much higher reflectivities can be obtained with triple-layer ODRs consisting of a semiconductor, a quarter-wavelength dielectric layer, and a metal layer as shown in Fig. 1(a). Triple-layer ODRs[5,6] possess a much higher angle-integrated TE–TM averaged reflectivity than conventional metal and distributed Bragg reflectors when used as internal reflectors. It is well known that the refractive-index contrast of optical components is an important figure of merit, which creates a strong demand for novel low-refractive-index (low-n) materials ($n \ll 1.46$).

In this Letter a triple-layer ODR using nanoporous SiO_2 as the dielectric layer is demonstrated and characterized in terms of its angular TE and TM reflectivity. Nanoporous SiO_2 has a typical average pore size of 4 nm and has been employed as a low-dielectric-constant material in microelectronics applications.[7–9] However, its transparency and favorable mechanical and thermal characteristics[8,9] make it an ideal candidate for numerous low-n applications.

To obtain high reflectivity in the visible and near-UV spectral range, we select Ag as the metal. A double-side-polished 300-μm-thick GaP wafer is selected as the semiconductor. At normal incidence, the reflectivity of the triple-layer ODR shown in Fig. 1(a) is given by[10]

$$R_{\text{normal}} = \left[\left| \frac{(n_{\text{semi}}-n_{\text{die}})(n_{\text{die}}+n_{\text{metal}}+i\kappa_{\text{metal}}) + (n_{\text{semi}}+n_{\text{die}})(n_{\text{die}}-n_{\text{metal}}-i\kappa_{\text{metal}})\exp(2i\beta h)}{(n_{\text{semi}}+n_{\text{die}})(n_{\text{die}}+n_{\text{metal}}+i\kappa_{\text{metal}}) + (n_{\text{semi}}-n_{\text{die}})(n_{\text{die}}-n_{\text{metal}}-i\kappa_{\text{metal}})\exp(2i\beta h)} \right| \right]^2, \qquad (1)$$

where h is the thickness of the dielectric layer; $\beta=(2\pi/\lambda)n_{\text{die}}$; and $n_{\text{semi}}, n_{\text{die}}, n_{\text{metal}}$, and κ_{metal} are the refractive indices[11] of GaP, the dielectric, Ag, and Ag's extinction coefficient, respectively. h is selected to yield constructive interference at normal incidence to maximize the reflectivity. The optimal value of h, h_{opt}, in Eq. (1) can be derived from[10]

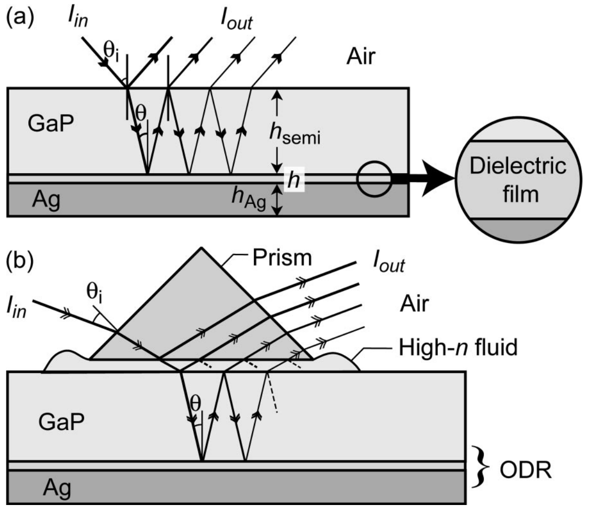

Fig. 1. (a) Schematic of a triple-layer ODR. (b) Setup using a prism and high-index fluid allowing coupling of light into GaP at angles of up to $\theta = 27.3°$.

$$2\beta + \varphi_{\text{normal}} = \frac{4\pi}{\lambda} n_{\text{die}} h_{\text{opt}} + \varphi_{\text{normal}} = 2\pi. \tag{2}$$

The phase change at the metal–dielectric interface for normal incidence, φ_{normal}, satisfies[10]

$$\tan \varphi_{\text{normal}} = \frac{2\kappa_{\text{metal}} n_{\text{die}}}{n_{\text{metal}}^2 + \kappa_{\text{metal}}^2 - n_{\text{die}}^2}. \tag{3}$$

Generally, the phase change is $\pi < \varphi_{\text{normal}} < (3/2)\pi$, so h_{opt} is slightly smaller than the quarter-wavelength thickness, $\lambda/(4n_{\text{die}})$. The angle-integrated reflectivity of the ODR, an important figure of merit for LEDs, can be calculated from

$$R_{\text{int}} = \int_0^{\pi/2} R(\theta)\sin(\theta)\mathrm{d}\theta \bigg/ \int_0^{\pi/2} \sin(\theta)\mathrm{d}\theta. \tag{4}$$

The angle-dependent reflectivities, $R(\theta)$, of the internal ODRs were measured by use of a 632.8-nm coherent He–Ne laser with the samples mounted on a goniometer. The detector is an Ando AQ2140 optical multimeter with an AQ2741 sensor. The precision of the measured reflectivity values at normal incidence is better than ±0.15%. Because of total internal reflection at the air–GaP interface, the setup shown in Fig. 1(a) can measure the internal ODR reflectivity up to $\theta = 17.6°$. However, in Fig. 1(b), a high-refractive-index prism ($n = 1.778$) and a high-index fluid ($n = 1.662$) are used to couple light into the GaP at higher angles of incidence. This extends the measurement with the maximum θ to 25.5° for TE polarization and 27.3° for TM polarization. The spectral dependence of the reflectivity is measured with a Jasco V-570 spectrophotometer. The angle-dependent reflectivity $R(\theta)$ of the ODR can be obtained by correcting the measured result, $I_{\text{out}}/I_{\text{in}}$, for losses caused by Fresnel reflections at the GaP–air interfaces [Fig. 1(a)], and GaP–high-n fluid–prism–air interfaces [Fig. 1(b)]. Multiple reflection events inside the GaP and high-n fluid layer are taken into account. However, small absorption effects in the GaP, the high-n fluid, and the prism are neglected, making the experimental reflectivities a lower limit of the actual internal ODR reflectivity.

Nanoporous SiO_2 was fabricated by a solgel process[7] with modifications to suit the very small optical thickness requirement. GaP was treated in oxygen plasma to enhance the adhesion between the substrate and the sol. The solgel solution was spun on the plasma-treated GaP. Surface modification of nanoporous SiO_2 was then performed with hexamethyl disilazane, which does not affect the adhesion of nanoporous SiO_2 film to the substrate. A 500-nm-thick Ag layer was deposited by electron-beam evaporation. A micrograph of the nanoporous SiO_2 thin film is shown in Fig. 2. The refractive index and the thickness of the nanoporous SiO_2 were obtained by ellipsometry as $n_{\text{low}} = 1.23$ and $h_{\text{low}} = 105$ nm, respectively. From Eqs. (2) and (3), $h_{\text{opt}} = 104$ nm. An ODR with dense SiO_2 was fabricated by plasma-enhanced chemical-vapor deposition of SiO_2 on GaP followed by electron-beam evaporation of deposited Ag (500 nm). The refractive index and the measured thickness are $n_{SiO_2} = 1.457$ (Ref. 11) and $h_{SiO_2} = 89$ nm, respectively. For dense SiO_2, $h_{\text{opt}} = 84$ nm. In addition, a simple metal reflector, 500-nm-thick Ag deposited on GaP, was fabricated for comparison.

The measured reflectivity $R(\theta)$ of the internal ODR with nanoporous SiO_2 used as a dielectric material layer is shown in Fig. 3(a). At near-normal incidence ($\theta = 1.2°$), a TE reflectivity of 97.6% and TM reflectivity of 97.7% are measured. Within the measured range, the TE reflectivity does not show a strong angular dependence. The experimental results closely follow the calculated reflectivity shown as solid curves in Fig. 3. At normal incidence, the calculated reflectivity is 98.6%. From Eq. (4), the triple-layer ODR employing nanoporous SiO_2 has outstanding angle-integrated reflectivity, $R_{\text{int}}|_{\text{TE}} = 99.9\%$ for the TE polarization and $R_{\text{int}}|_{\text{TM}} = 98.9\%$ for the TM polarization.

The measured reflectivity $R(\theta)$ of the internal ODR with dense SiO_2 as the dielectric material layer is shown in Fig. 4(a). The measured curves are qualitatively similar to the measurements shown in Fig. 3(a). However, the quantitative reflectivity values are lower. The measured near-normal incidence TE and

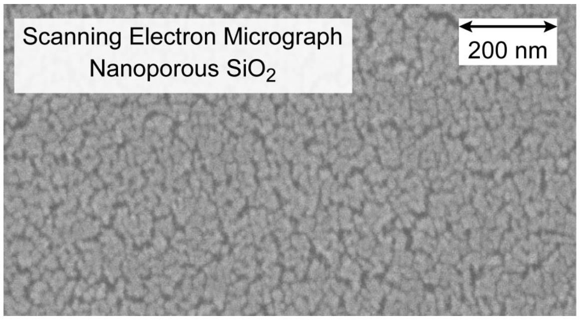

Fig. 2. Scanning electron micrograph of a 105-nm-thick nanoporous SiO_2 film.

TM polarization reflectivities are 97.3% and 97.4%, respectively. The calculated reflectivity at normal incidence is 98.1%, and the angle-integrated reflectivities are $R_{\mathrm{int}}|_{\mathrm{TE}}=99.8\%$ for the TE polarization and $R_{\mathrm{int}}|_{\mathrm{TM}}=97.8\%$ for the TM polarization. This trend is fully consistent with the higher refractive index of dense SiO_2 compared with that of nanoporous SiO_2.

For comparison, the measured reflectivities at near-normal incidence, the calculated reflectivities at normal incidence, and the angle-integrated reflectivities for the ODR with nanoporous SiO_2, the ODR with dense SiO_2, and the Ag–GaP interface (without the dielectric layer) are listed in Table 1. Comparison indicates that the angle-integrated reflectivity of the ODR employing nanoporous SiO_2 is highest. Note that mirror losses are given by $1-R$, so small changes in the reflectivity of reflectors with $R\approx 1.0$ are significant, in particular, if multiple reflection events occur, e.g., for waveguided modes in LEDs.

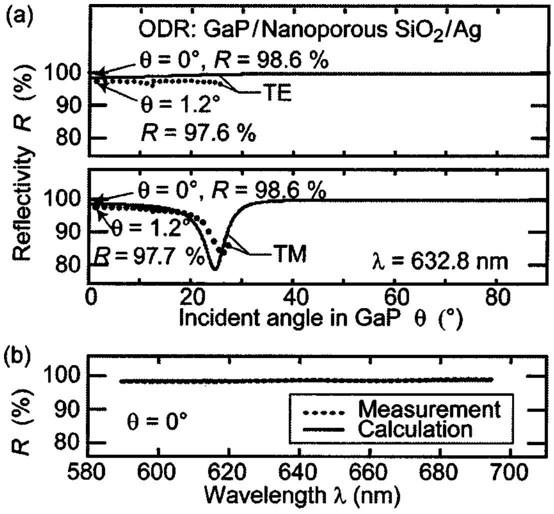

Fig. 3. Calculated (solid curves) and measured (dotted curves) reflectivity versus (a) angle of incidence and (b) wavelength for a triple-layer ODR with nanoporous SiO_2.

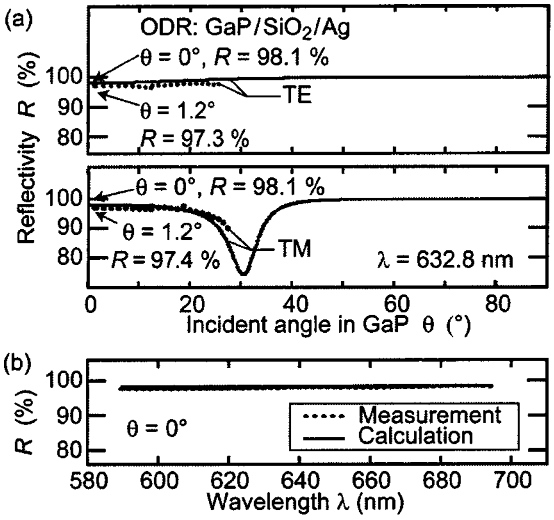

Fig. 4. Calculated (solid curves) and measured (dotted curves) reflectivity versus (a) angle of incidence and (b) wavelength for a triple-layer ODR with dense SiO_2.

Table 1. Measured and Calculated Reflectivity (%) at $\lambda=632.8$ nm for Different Reflectors

Reflectivity	ODR With Nanoporous SiO_2	 With Dense SiO_2	Ag/GaP
Measured R ($\theta=1.2°$)	97.7	97.4	94.9
Calculated R ($\theta=0°$)	98.6	98.1	93.6
Calculated $R_{\mathrm{int}}|\mathrm{TE}$	99.9	99.8	97.2
Calculated $R_{\mathrm{int}}|\mathrm{TM}$	98.9	97.8	94.4

In conclusion, an internal omnidirectional reflector has been reported that consists of a semiconductor, a low-refractive-index dielectric layer, and a metal. The angle-dependent reflectivities of the ODRs are measured at 632.8 nm for TE and TM polarization and compared with calculations. It is found that, for an ODR employing nanoporous SiO_2, the angle-integrated reflectivity of TE-polarized light, $R_{\mathrm{int}}|_{\mathrm{TE}}=99.9\%$ and that of TM-polarized light, $R_{\mathrm{int}}|_{\mathrm{TM}}=98.9\%$ significantly exceed the corresponding values $R_{\mathrm{int}}|_{\mathrm{TE}}=99.8\%$ and $R_{\mathrm{int}}|_{\mathrm{TM}}=97.8\%$ of an ODR with dense SiO_2. This can be directly attributed to the lower refractive index of the nanoporous SiO_2 compared with that of dense SiO_2.

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