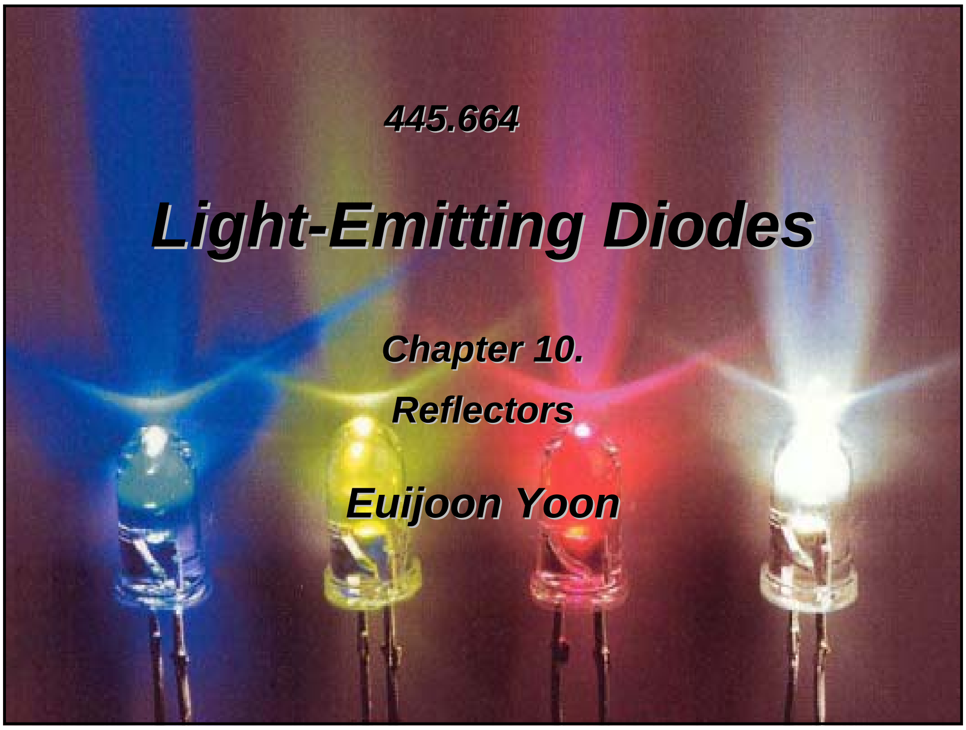

Different types of reflectors

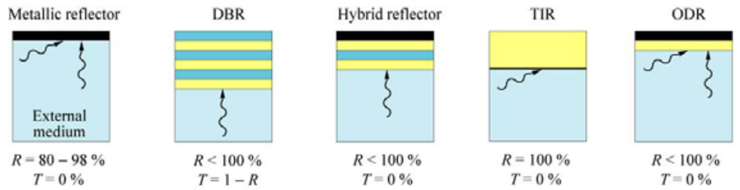

Fig. 10.1. Different types of reflectors including metallic reflector, distributed Bragg reflector (DBR), hybrid reflector, total internal reflector (TIR), and omni-directional reflector (ODR). Also given are angles of incidence for high reflectivity and typical reflectances and transmittances.

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- ***In an LED structure with a reflector, the external medium is a semiconductor***
- ***The external medium has a significant influence on the reflector properties***

(Ex. The reflectivity of a metal-semiconductor reflector is lower compared to a metal-air reflector)

Metal reflectors

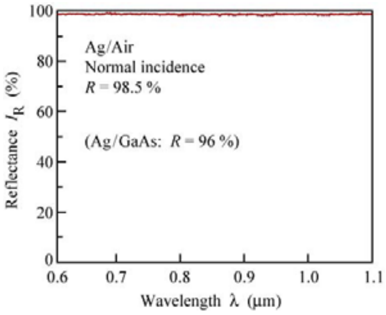

Fig. 10.2. Measured reflectance of a silver/air reflector for normal incidence. The average reflectivity in the visible spectrum is 98.5 %.

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- ***The reflectance spectrum is characterized by a broad spectral band of high reflectivity and an average reflectance of 98.5% and weak angular dependence.***
- ***The reflectance (amplitude reflection coefficient)***

$$r = \frac{E_r}{E_i} = \frac{\overline{N}_1 - \overline{N}_2}{\overline{N}_1 + \overline{N}_2}$$

Fresnel equation

,where N_1 , and N_2 are the complex refractive indices of two media

Metal reflectors

- ***The reflectivity or reflectance (power reflection coefficient)***

$$R = \frac{|E_r|^2}{|E_i|^2} = |r|^2 = \left|\frac{\overline{N}_1 - \overline{N}_2}{\overline{N}_1 + \overline{N}_2}\right|^2 = \frac{|\overline{N}_1 - \overline{N}_2|^2}{|\overline{N}_1 + \overline{N}_2|^2}$$

T = 1 - R in lossless reflector by energy conservation

$$\overline{N}_1 = \overline{n}_1 \quad and \quad \overline{N}_2 = \overline{n}_2 + i\overline{k}_2$$

$$r = \frac{\overline{n}_1 - \overline{n}_2 - i\overline{k}_2}{\overline{n}_1 + \overline{n}_2 + i\overline{k}_2} \quad and \quad R = \frac{(\overline{n}_1 - \overline{n}_2)^2 + \overline{k}_2^2}{(\overline{n}_1 + \overline{n}_2)^2 + \overline{k}_2^2}$$

- ***Ideal metal :** σ→∞ and therefore* $\overline{k} \to \infty$ **since** $\sigma = 2\overline{n}\varpi\varepsilon_0\overline{k}$

$$|r| \approx 1, \quad R \approx 1, \quad and \quad \phi_r = \pi$$

- ***Real metals have high conductivity (but not an infinitely high conductivity) and the reflectivity of any real metal is therefore less than unity.***

Reflection losses or mirror losses

- ***Although metals are simple and viable reflectors, the reflection losses or mirror losses are quite high.***
- ***The loss of one reflection event , (1-R) ≈ 5% for metal-semiconductor reflectors***
- ***The intensity of waveguided modes decays according to***

$$I/I_0 = R^N = (1-L)^N \approx 1 - NL$$

N	**Number of reflection events**
L	**Mirror loss (L=1-R)**

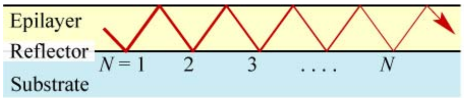

Fig. 10.3. Attenuation of waveguide mode due to lossy reflector.

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- **Thick metallic reflectors and hybrid reflectors are absorbing reflectors that should not be used as light-exit reflectors in LEDs and vertical-cavity surface emitting lasers.**
- **Metal contacts become practically opaque for thicknesses > 50 nm.**
- **Very thin metal contacts are semi-transparent. Most metal contacts have a transmittance of approximately 50 % at a metal thickness of 5~10 nm. However, very thin metallic contacts may form an islanded structure rather than a single continuous film. Furthermore, the electrical resistance of thin metal films can be large, in particular if an islanded structure is formed.**
- **Ag-loaded epoxy for die attachment provides a high conductivity as well as high reflectivity.**

Total internal reflectors

- ***Snell's law*** $\bar{n}_1 \sin\theta_1 = \bar{n}_2 \sin\theta_2$ ***Kepler's discovery in 1611*** $\bar{n}_1\theta_1 = \bar{n}_2\theta_2$

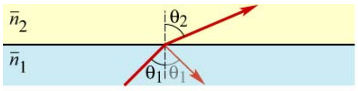

Fig. 10.4. Reflected and refracted light ray at the boundary between two media with refractive indices $\bar{n}_1$ and $\bar{n}_2$, where $\bar{n}_1 > \bar{n}_2$.

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- ***The critical angel for total internal reflection can be derived using the condition θ_2=90 º***

$$\theta_{1,crit} = \arcsin(\bar{n}_2 / \bar{n}_1)$$

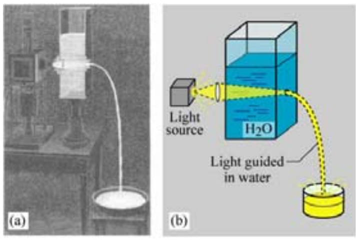

Fig. 10.5. (a) Historical drawing and (b) schematic illustration of apparatus used in 1841 by Swiss engineer Daniel Colladon to demonstrate the guiding of light by total internal reflection in a jet of water.

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LED with DBRs

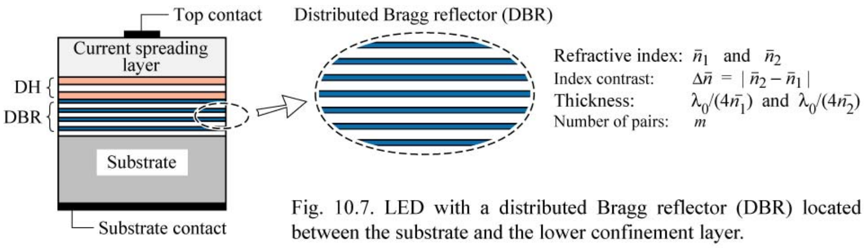

Fig. 10.7. LED with a distributed Bragg reflector (DBR) located between the substrate and the lower confinement layer.

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- ***The absorption of light in the substrate can be avoided by placing a reflector between substrate and the LED active layers.***
- ***DBR = Distributed Bragg Reflector***
- ***DBRs reduce reflection losses.***

Distributed Bragg Reflectors

- ***A DBR is a multi-layer reflector consisting of typically 5 ~ 50 pairs of two materials with different refractive indices.***

- ***The thickness of the two materials is chosen in such a way, that all reflected waves are in constructive interference.***

$$t_{l,h} = \lambda_{l,h} / 4 = \lambda_0 / (4\bar{n}_{l,h})$$ **(normal incidence)**

$$t_{l,h} = \lambda_{l,h} / (4\cos\Theta_{l,h}) = \lambda_0 / (4\bar{n}_{l,h} \cos\Theta_{l,h})$$ **(oblique incidence)**

λ_0 **: the vacuum Bragg wavelength of the light**
$t_{l,h}$ **: the thickness of the low-index (l) and high-index (h) material**
$\bar{n}_{l,h}$ **: the refractive index of the low-index (l) and high-index (h) material**

DBRs

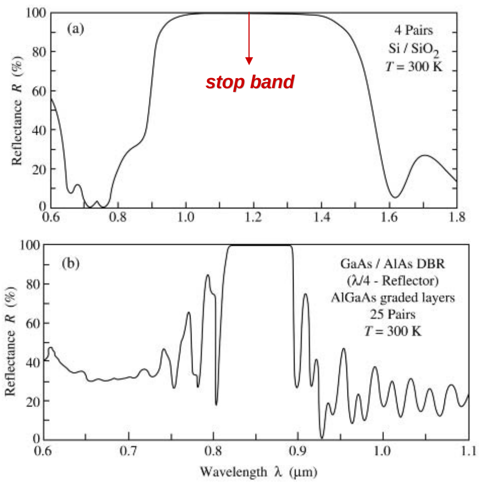

Fig. 6.19. Reflectance of two distributed Bragg reflectors (DBRs) versus wavelength. (a) 4 pair Si-SiO_2 reflector with high index contrast. (b) 25 pair AlAs-GaAs reflector. Note that the high-index-contrast DBR only needs 4 pairs to attain high reflectivity. Also note that the stop band of the high-index-contrast DBR is much wider as compared to the low- contrast DBR.

- ***The reflectivity of high-contrast DBRs(Si/SiO_2) is much higher than that of low-index contrast DBRs (AlAs/GaAs) for the same number of quarter-wave pairs.***

- ***The width of the stop band of the high-index difference DBR is much wider than that of low-contrast DBR.***

DBRs

- ***Multiple reflections at the interfaces of the DBR and constructive interference of the multiple reflected waves increases the reflectivity with increasing numbers of pairs.***

- ***The reflectivity at the Bragg wavelength of a DBR with m quarter -wave pairs ,***

$$R_{DBR} = |r_{DBR}|^2 = \left[\frac{1-(\bar{n}_l / \bar{n}_h)^{2m}}{1+(\bar{n}_l / \bar{n}_h)^{2m}} \right]^2$$

- ***For efficient operation of the LED, the stop band should be wider than the emission spectrum of the active region.***

- ***The spectral width of the stop band,***

$$\Delta\lambda_{stopband} = \frac{2\lambda_{Bragg} \Delta\bar{n}}{\bar{n}_{eff}} \qquad \Delta\bar{n} = \bar{n}_h - \bar{n}_l$$

DBRs

Material system	***Bragg wavelength***	$\bar{n}_{low}$	$\bar{n}_{high}$	$\Delta\bar{n}$	***Transparency range***
$Al_{0.5}In_{0.5}P$ / GaAs	590 nm	3.13	3.90	0.87	> 870 nm (lossy)
$Al_{0.5}In_{0.5}P$ / $Ga_{0.5}In_{0.5}P$	590 nm	3.13	3.74	0.87	> 649 nm (lossy)
$Al_{0.5}In_{0.5}P$ / $(Al_{0.3}Ga_{0.7})_{0.5}In_{0.5}P$	615 nm	3.08	3.45	0.37	> 592 nm
$Al_{0.5}In_{0.5}P$ / $(Al_{0.4}Ga_{0.6})_{0.5}In_{0.5}P$	590 nm	3.13	3.47	0.34	> 576 nm
$Al_{0.5}In_{0.5}P$ / $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$	570 nm	3.15	3.46	0.31	> 560 nm
AlAs / GaAs	900 nm	2.97	3.54	0.57	> 870 nm
SiO_2 / Si	1300 nm	1.46	3.51	2.05	> 1106 nm

Table 7.2. Properties of distributed Bragg reflector (DBR) materials used for visible and infrared LEDs. DBRs marked as 'lossy' are absorbing at Bragg wavelength (data after Adachi, 1990; Adachi *et al.*, 1994; Kish and Fletcher, 1997; Babic *et al.*, 1999; Palik, 1998).

Calculated reflectivity of DBR

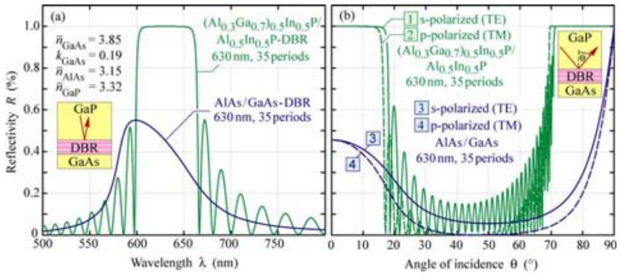

Fig. 10.10. Calculated reflectivity (inside the cladding GaP) versus (a) wavelength and (b) polar angle of a transparent AlGaInP/AlInP DBR and an absorbing AlAs/GaAs DBR.

- **The DBR made of the transparent materials has a reflectivity close to 100% at the Bragg wavelength.**
- **The DBR that includes the absorbing GaAs layers has a maximum reflectivity of about 55%.**
- **Major drawback of DBRs**
  - **Limitation of the high reflectivity band to small angles of incidence**
  - **Angles of incidence greater than 20 °, the reflectivity strongly decreases to assume values close to zero**
  - **Non-reflective for 20 ° < θ < 70 °**

Omnidirectional reflectors

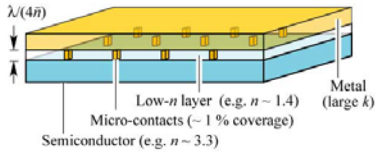

Fig. 10.12. Structure of omnidirectional reflector consisting of semiconductor, low-refractive index dielectric layer, and metal layer. The dielectric is perforated by an array of microcontacts providing electrical conductivity (after Gessmann *et al.*, 2003).

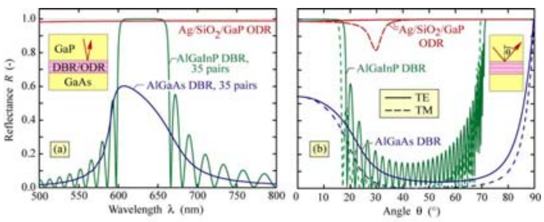

Fig. 10.13. (a) Calculated reflectivity at normal-incidence versus wavelength and (b) reflectivity versus angle of incidence for an omnidirectional reflcetor (ODR), a transparent AlGaInP/AlInP DBR, and an absorbing AlGaAs/GaAs DBR (after Gessmann et al., 2003).

- ***The triple-layer ODR provides a broad reflectivity and omnidirectional characteristics***
- ***A small dip in the reflectivity is found for the TM wave at an incidence angel of about 30 ° due to the reduced reflectivity of the semiconductor/dielectric interface at the Brewster angle***

Specular and diffuse reflectors

- ***Specular reflectors : the angle of reflected light ray is equal to that of incident ray.***
- ***Diffuse reflectors : the reflected intensity is distributed over a wide range of angles, independent of the incidence angel of the incoming ray***

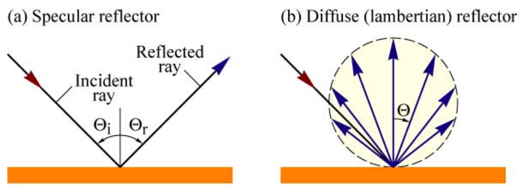

Fig. 10.16. Schematic of a specular and diffuse (lambertian) reflector. The reflected power distribution of a lambertian reflector follows a cos Θ dependence.

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- ***The source radiance (the optical power emitted per steradian per unit surface area of the source) : constant***
- ***The radiance and luminance of a lambertian source are independent of the viewing angle.***

Lambert's cosine law

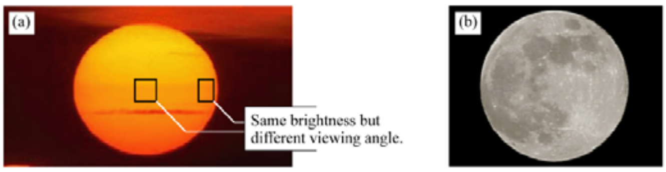


Fig. 10.17. (a) The sun's surface brightness is independent of viewing angle with respect to the sun's surface. It is a good example of a lambertian source. (b) The moon is a good example of a lambertian reflector.

- ***The sun and moon are good examples of lambertian source and reflector, respectively.***
- ***Lambert's cosine law***

$$I = I_n \cos\Theta$$

$$\text{Luminance} = \frac{I_n A\cos\Theta}{A\cos\Theta} = I_n$$

Constant source luminance

- ***Assumption***
  - ***Lambertian surface source with area A***
  - ***The projected area visible to an observer positioned at angle Θ is given by AcosΘ***

Light propagating in a cladding layer

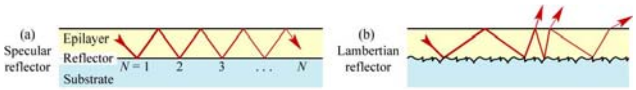
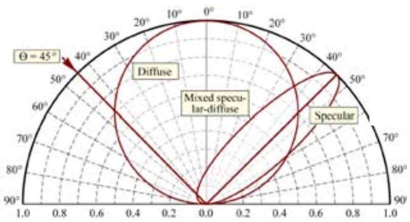


Fig. 10.18. (a) Optical mode guided by specular reflector at the epilayer/substrate interface and the epilayer/air interface. (b) Optical ray propagating in epilayer guided by lambertian reflector at the epilayer/substrate interface and the epilayer/air interface.

- ***In a layer clad by specular reflectors will be waveguided within the layer.***
- ***Light propagating in a layer clad by a lambertian reflector can be out-coupled into free space***



- ***Mechanical roughening of reflective surfaces generally results in a change from specular to diffuse reflection.***
- ***Ideal diffuse reflectors have a reflection characteristic that is independent of the angle of incidence***
- ***Many real surface-textured reflectors have a mixed specular-diffuse reflection characteristic.***