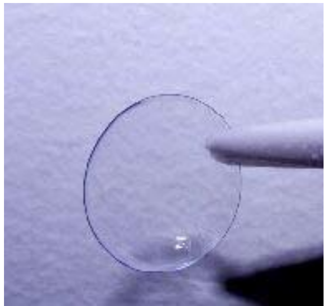
Chapter 8 Optical Properties

1. Light waves in a homogeneous medium
2. Refractive index
3. Dispersion: refractive index – wavelength behavior
4. Snell’s law and total internal reflection (TIR)
5. **Fresnel’s equation**
6. **Light absorption and scattering**
7. **Luminescence, phosphors, and white LED**

Exam briefing

Tutorial & Course review

Group presentation



Fresnel's equation（菲涅耳方程）

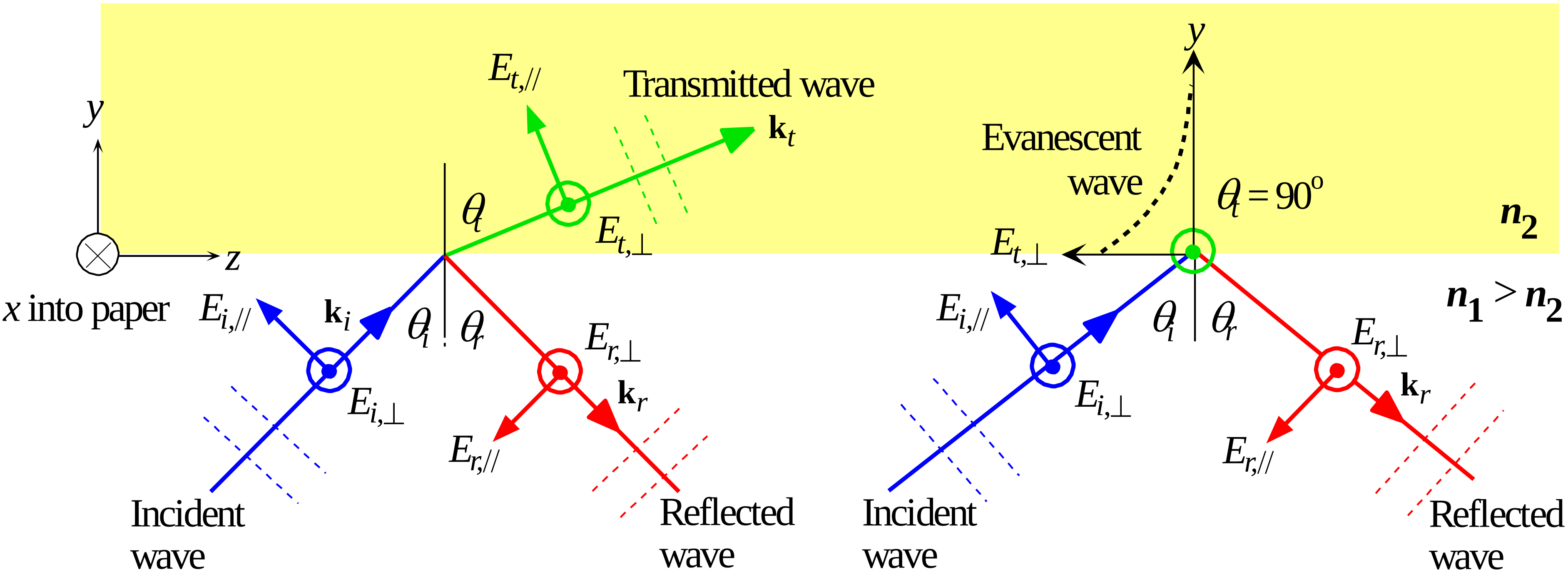
Incident wave $\boldsymbol{E}_i = \boldsymbol{E}_{i0} \exp j(\omega t - \vec{k}_i \cdot \vec{r})$

Reflected wave $\boldsymbol{E}_r = \boldsymbol{E}_{r0} \exp j(\omega t - \vec{k}_r \cdot \vec{r})$

Transmitted wave $\boldsymbol{E}_t = \boldsymbol{E}_{t0} \exp j(\omega t - \vec{k}_t \cdot \vec{r})$

phase changes $\boldsymbol{\phi_r}$ and $\boldsymbol{\phi_t}$ *are* incorporated into the complex **amplitudes $\boldsymbol{E_{ro}}$** and $\boldsymbol{E_{to}}$

plane of incidence



(a) $\theta_i < \theta_c$ some of the wave transmitted into the less dense medium, some of the wave is reflected.

(b) $\theta_i > \theta_c$ the incident wave suffers total internal reflection. There is a decaying evanescent wave into medium 2

Amplitude reflection and transmission coefficients

Fresnel's equations: if we define **n = n_2/n_1**, then for **$E_\perp$**:

reflection coefficient
反射系数

$$\boldsymbol{r}_\perp = \frac{E_{r0,\perp}}{E_{i0,\perp}} = \frac{\cos\theta_i - (n^2 - \sin^2\theta_i)^{1/2}}{\cos\theta_i + (n^2 - \sin^2\theta_i)^{1/2}}$$

transmission coefficient
折射系数

$$\boldsymbol{t}_\perp = \frac{E_{t0,\perp}}{E_{i0,\perp}} = \frac{2\cos\theta_i}{\cos\theta_i + (n^2 - \sin^2\theta_i)^{1/2}}$$

for **E_{II}**:

reflection coefficient

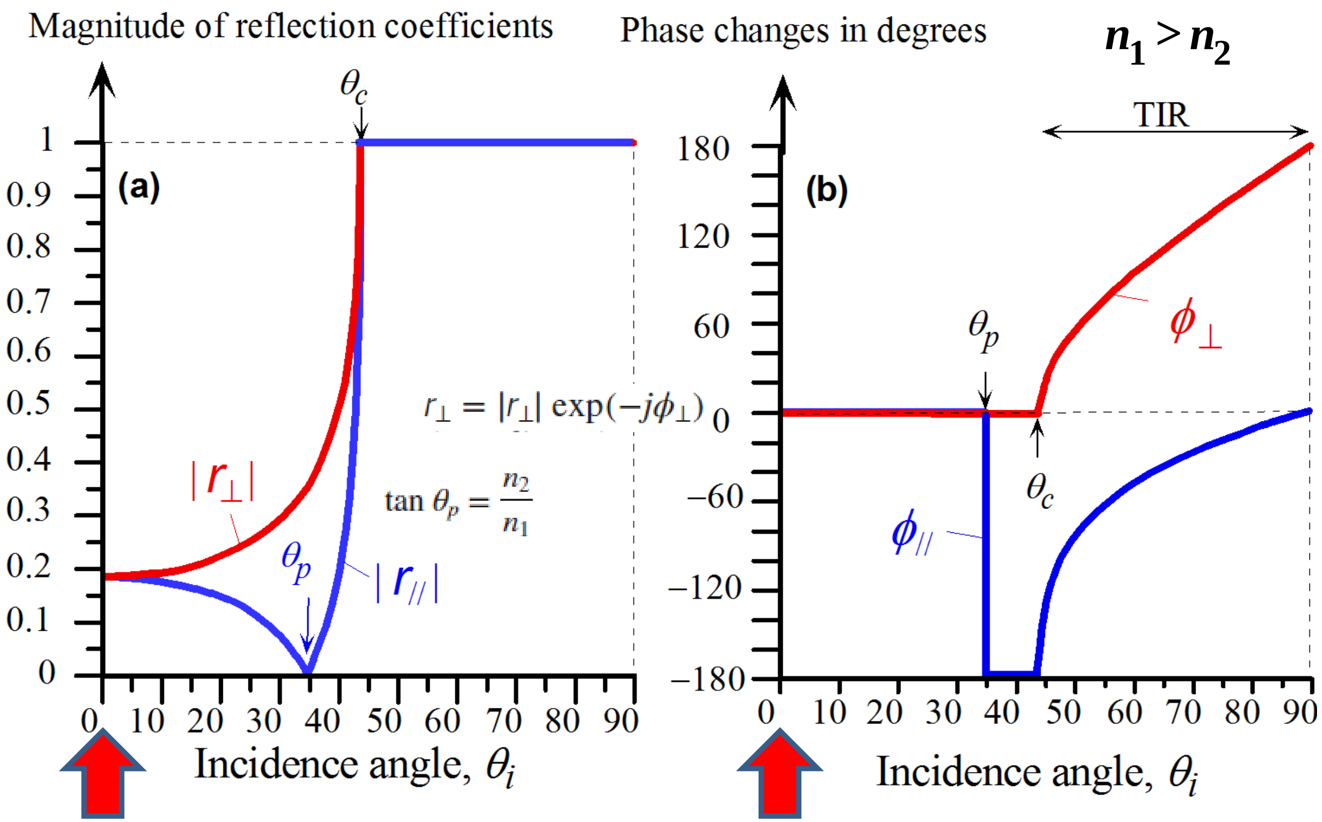
$$\boldsymbol{r}_{II} = \frac{E_{r0,II}}{E_{i0,II}} = \frac{(n^2 - \sin^2\theta_i)^{1/2} - n^2\cos\theta_i}{(n^2 - \sin^2\theta_i)^{1/2} + n^2\cos\theta_i}$$

transmission coefficient

$$\boldsymbol{t}_{II} = \frac{E_{t0,II}}{E_{i0,II}} = \frac{2n\cos\theta_i}{(n^2 - \sin^2\theta_i)^{1/2} + n^2\cos\theta_i}$$

Fresnel's equations allows the **amplitudes** and **phases** of the reflected and transmitted waves to be determined from the coefficients r⊥, rll, tll, t⊥.

Normal incidence ($\theta_i = 0$)



For **normal incidence 垂直入射 (θ_i = 0)**:

$$r_\perp = r_{II} = \frac{n_1 - n_2}{n_1 + n_2}$$

$n_1 > n_2$ (internal reflection)
r > 0: *no* phase change

$n_1 < n_2$ (external reflection)
r < 0: π phase change

Intensity, reflectance, and transmittance

For normal incidence ($\theta_i = 0$):

Reflectance R (反射率) is the **intensity** of the reflected light with respect to that of the incident light.

$$R_\perp = \frac{|E_{ro,\perp}|^2}{|E_{io,\perp}|^2} = |r_\perp|^2 \quad \text{and} \quad R_\parallel = \frac{|E_{ro,\parallel}|^2}{|E_{io,\parallel}|^2} = |r_\parallel|^2$$

$$R = R_\perp = R_{II} = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

Transmittance T (透光率) is the **intensity** of the transmitted light with respect to that of the incident light.

$$T_\perp = \frac{n_2|E_{to,\perp}|^2}{n_1|E_{io,\perp}|^2} = \left(\frac{n_2}{n_1}\right)|t_\perp|^2 \quad \text{and} \quad T_\parallel = \frac{n_2|E_{to,\parallel}|^2}{n_1|E_{io,\parallel}|^2} = \left(\frac{n_2}{n_1}\right)|t_\parallel|^2$$

$$T = T_\perp = T_{II} = \frac{4n_1 n_2}{(n_1 + n_2)^2}$$

$$R + T = 1$$

Which one is crystal (SiO_2) with n = 1.46?
Which one is diamond with n = 2.41?

Antireflection coating 增透膜

To reduce the reflected light, A and B must interfere destructively（相消干涉）. It requires the phase difference to be π or odd multiples of π, **mπ** with m = 1, 3, 5,…

from: $E = E_0 \cos(\omega t - kx)$

$$k_c(2d) = \left(\frac{2\pi n_2}{\lambda}\right)(2d) = m\pi \quad \text{or} \quad d = m\left(\frac{\lambda}{4n_2}\right)$$

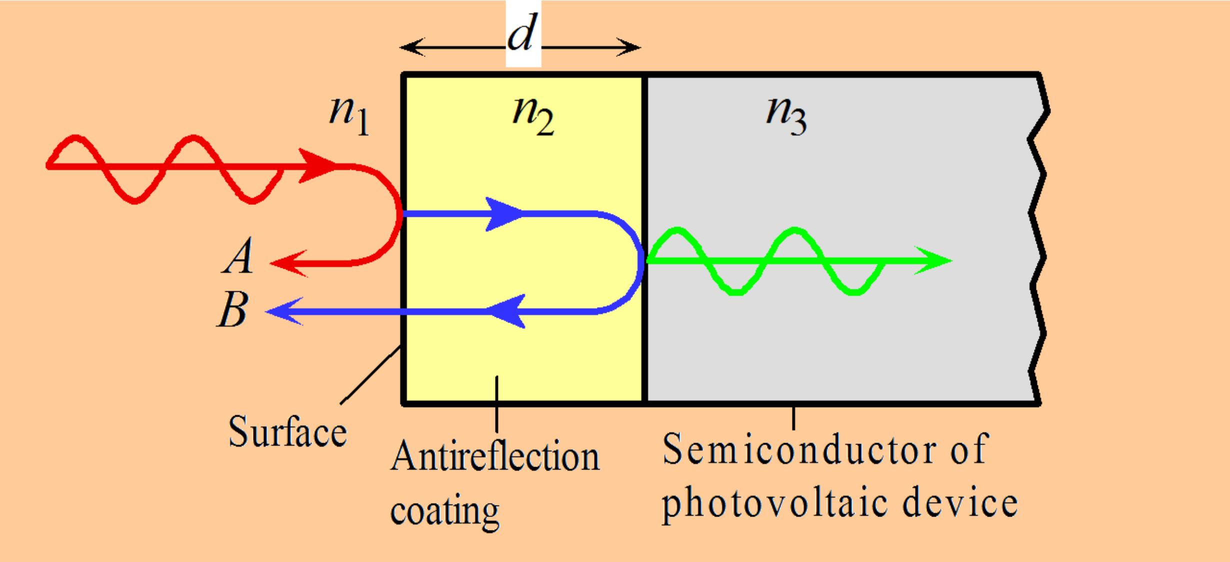
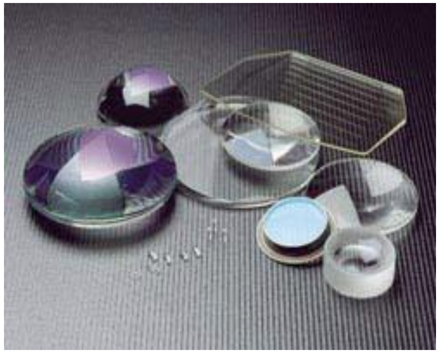


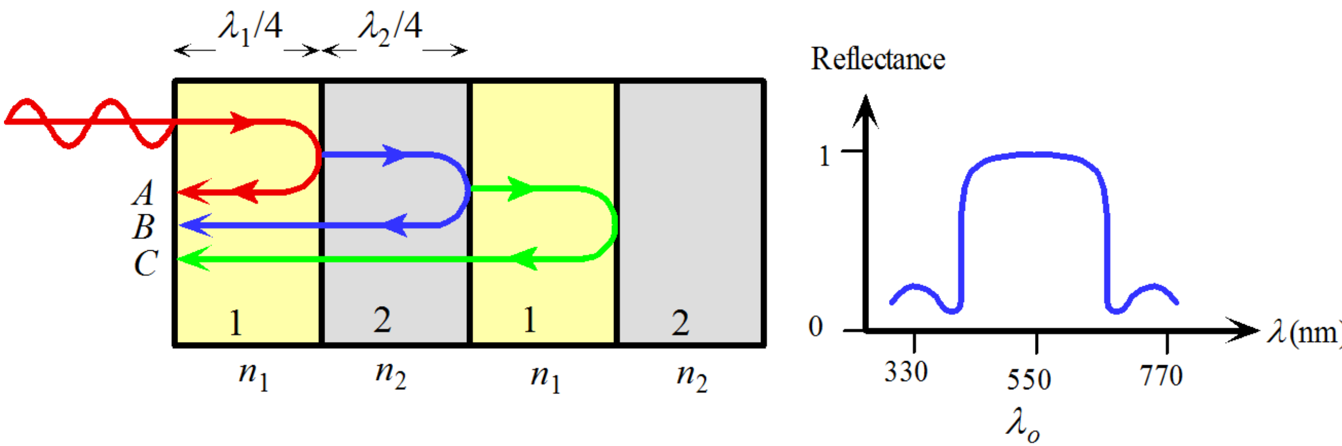
Illustration of how an antireflection coating reduces the reflected light intensity



Dielectric mirrors 介质镜

The reflected intensity is enhanced, if waves A and B are in phase and interfere constructively（相长干涉）

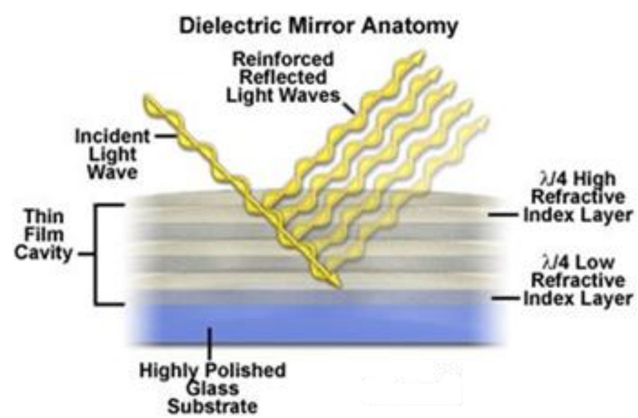
If there are sufficient number of layers, the reflectance can approach unity at the wavelength λ_0. ($\lambda_1 = \lambda_0/n_1$ & $\lambda_2 = \lambda_0/n_2$)



Schematic illustration of the principle of the dielectric mirror with many low and high refractive index layers and its reflectance.

quarter-wave dielectric stack $(n_1 > n_2)$

$r_{12} = (n_1 - n_2)/(n_1 + n_2)$ *positive*: no phase change
$r_{21} = (n_2 - n_1)/(n_2 + n_1)$ *negative*: π phase change

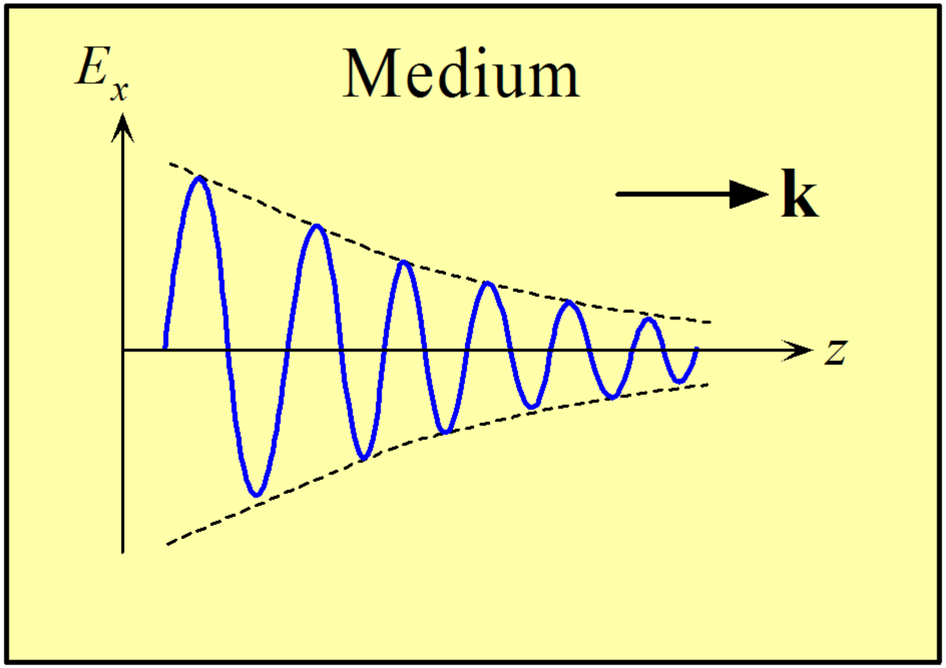


Complex refractive index and light absorption

When light propagates through a material, it becomes **attenuated**, due to absorption and scattering.

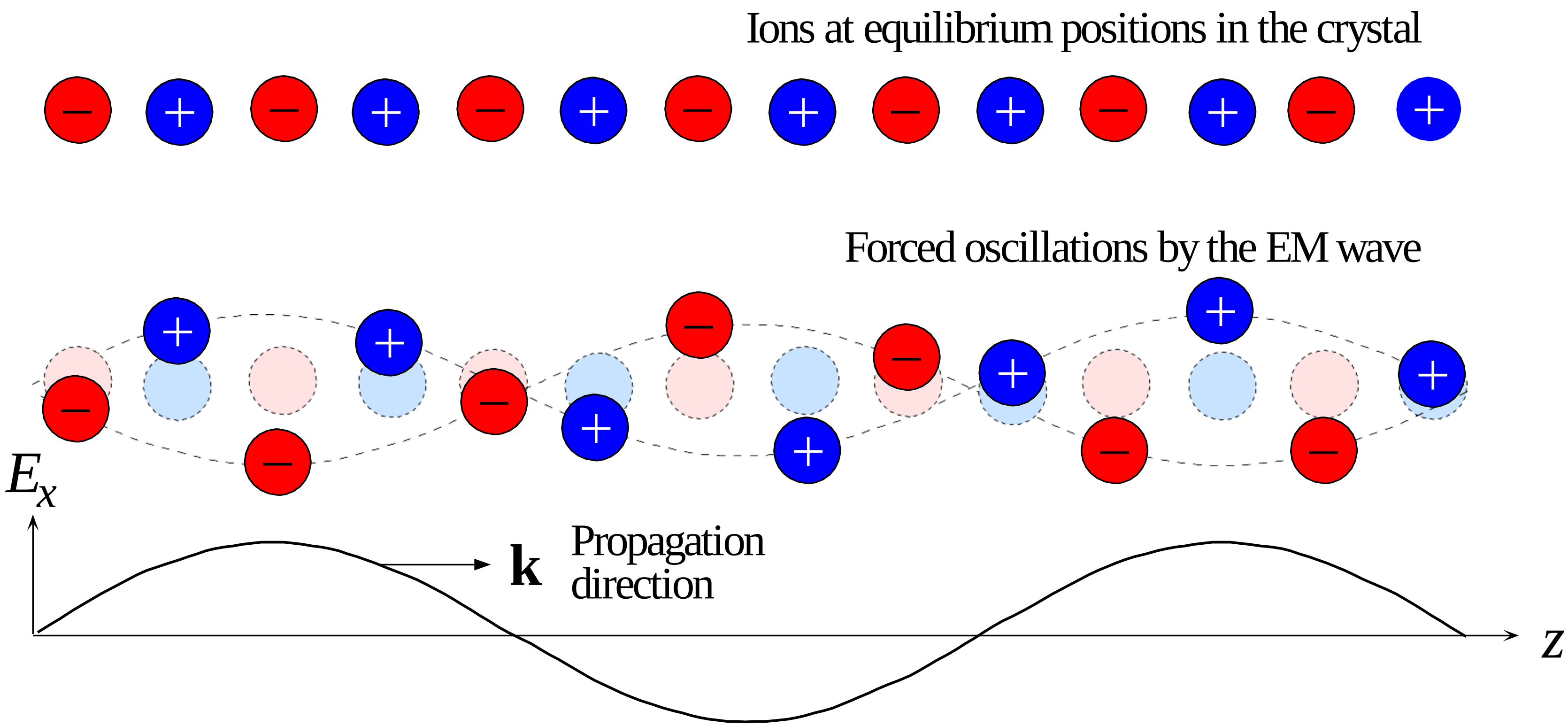
Absorption（吸收）: the loss of light energy to other forms of energy (**lattice vibration**, **electron excitation** etc)

Scattering（ 散射 ）: Redirection as secondary EM waves.



Attenuation of light in the direction of propagation.

Light absorption through lattice vibration



The field in the EM wave oscillates the ions of a crystal, which consequently generate "mechanical" waves in the crystal. Energy is thereby transferred from the EM wave to lattice vibrations.

Light absorption through electron excitation (band-to-band absorption)

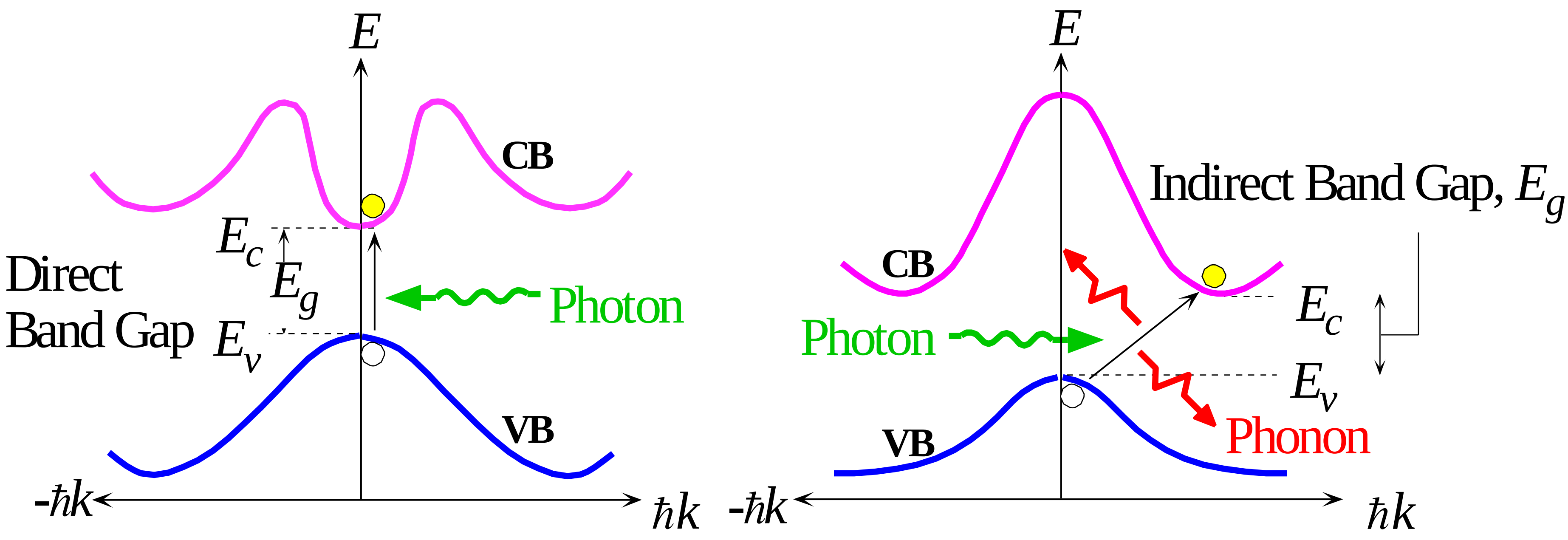
From $E_g = h(c/\lambda_g)$, the upper cut-off-wavelength:

$$\lambda_g(\mu m) = \frac{1.24}{E_g(eV)}$$

Table 9.3 Bandgap energy E_g at 300 K, cut-off wavelength λ_g, and type of bandgap (D = direct and I = indirect) for some photodetector materials

Semiconductor	E_g (eV)	λ_g (μm)	Type
InP	1.35	0.91	D
$GaAs_{0.88}Sb_{0.12}$	1.15	1.08	D
Si	1.12	1.11	I
$In_{0.7}Ga_{0.3}As_{0.64}P_{0.36}$	0.89	1.4	D
$In_{0.53}Ga_{0.47}As$	0.75	1.65	D
Ge	0.66	1.87	I
InAs	0.35	3.5	D
InSb	0.18	7	D

Incident photons with wavelengths shorter than λ_g become absorbed.

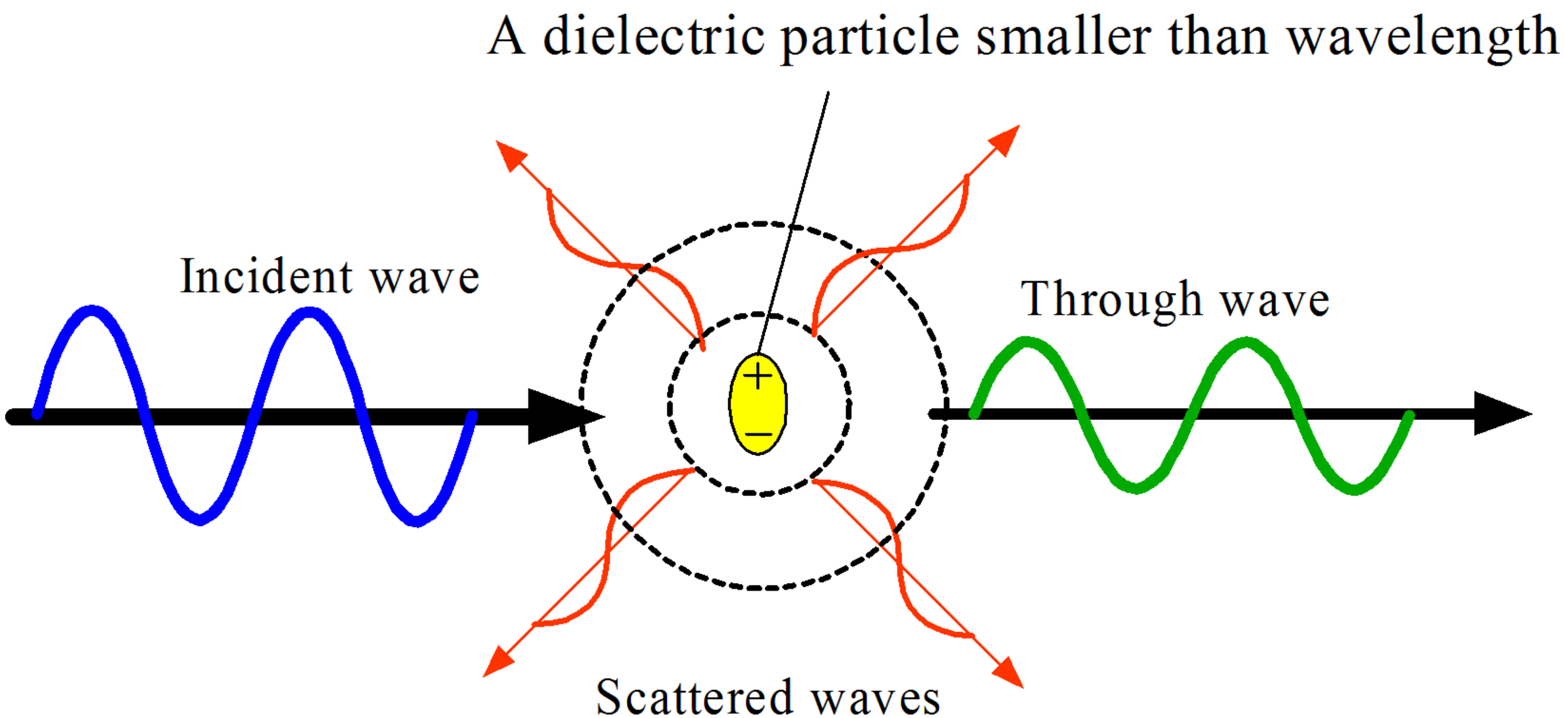


(a) GaAs (Direct bandgap) **(b)** Si (Indirect bandgap)

Electron energy (E) vs. crystal momentum $\hbar k$ and photon absorption.
(a) Photon absorption in a **direct bandgap** semiconductor.
(b) Photon absorption in an **indirect bandgap** semiconductor
(VB: valence band; CB: conduction band)

electron momentum (ħk) in the crystal: crystal momentum

Light scattering



Rayleigh scattering involves the polarization of a small dielectric particle or a region that is much smaller than the light wavelength. The field forces dipole oscillations in the particle (by polarizing it) which leads to the emission of EM waves in "many" directions so that a portion of the light energy is directed away from the incident beam.

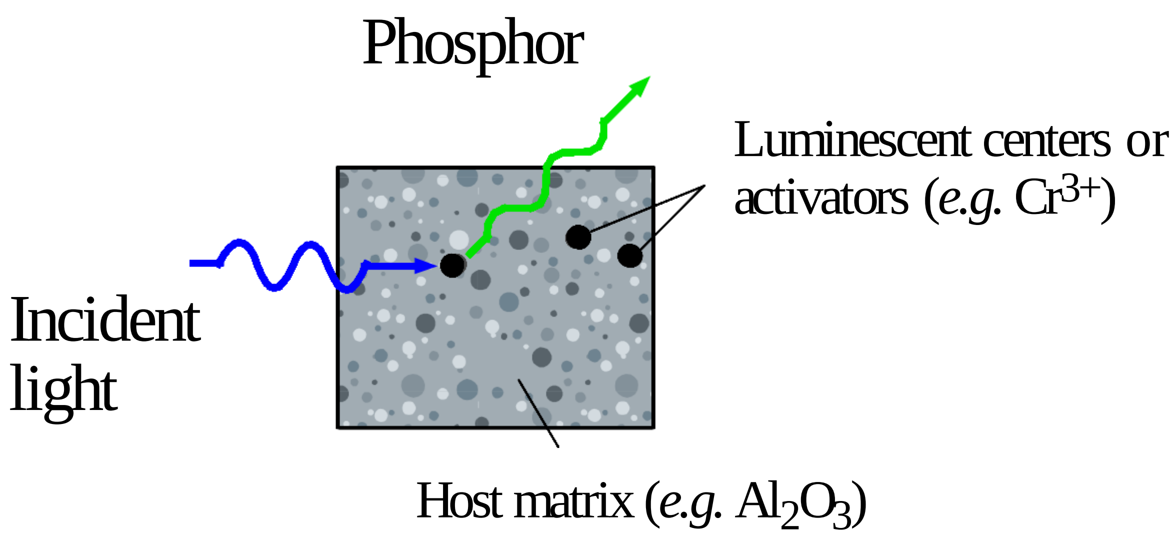
Scattering **decreases with increasing wavelength**, according to Lord Rayleigh, it is inversely proportional to λ^4.

Luminescence, phosphors, and white LED

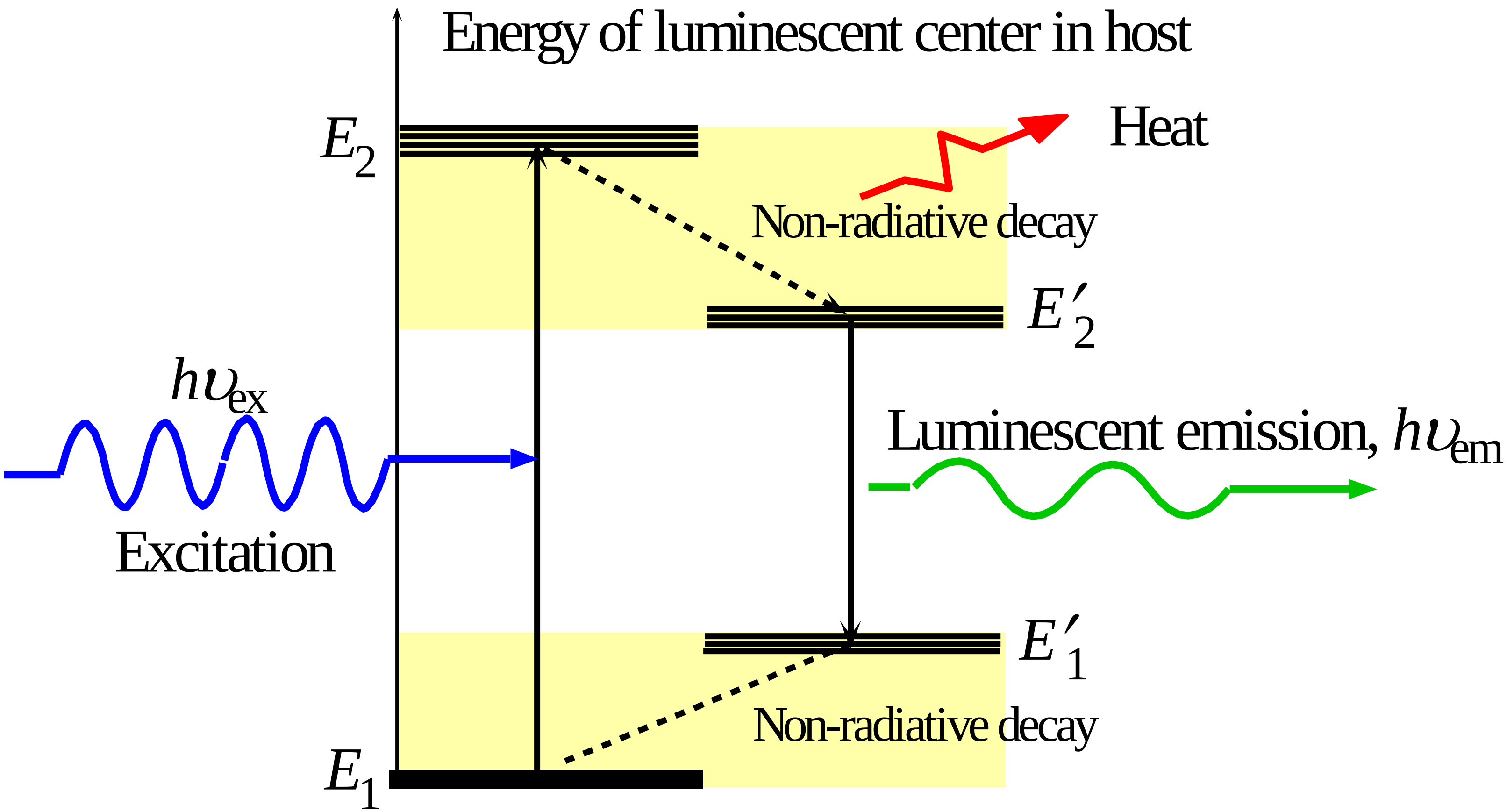
Luminescence（冷光）is light emitted by a nonthermal source when it is excited, due to the absorption and conversion of energy into EM radiation.

Typically, the emission of light occurs from certain dopants or defects, called **luminescent center** (**activator**). For example, in ruby红宝石, the Cr^{3+} ions are the luminescent centers in the sapphire蓝宝石(Al_2O_3) **crystal host**.

A **phosphor**（荧光体）= **host + activators**.

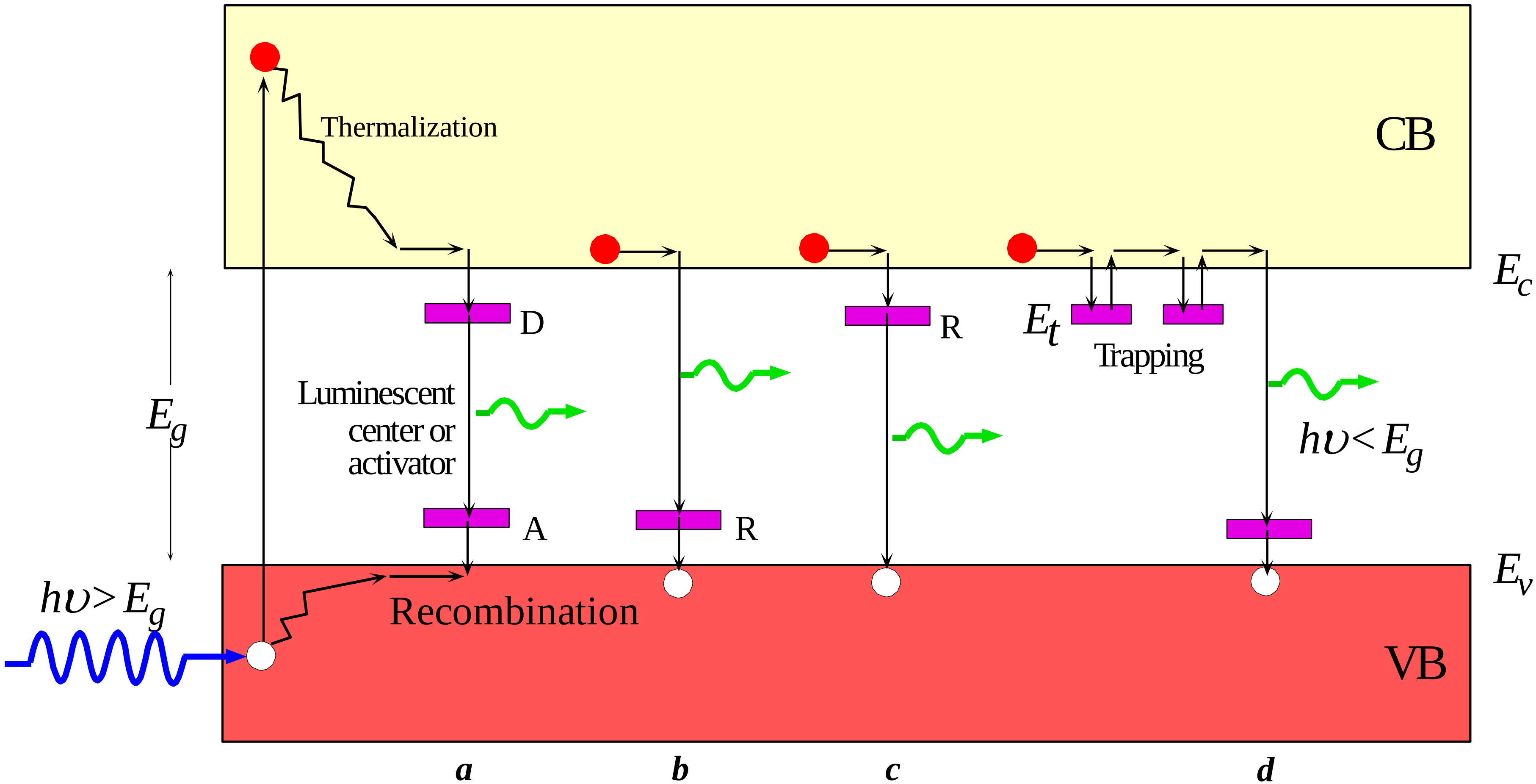


Example (Eu^{3+} luminescent centers in a Y_2O_3 host)



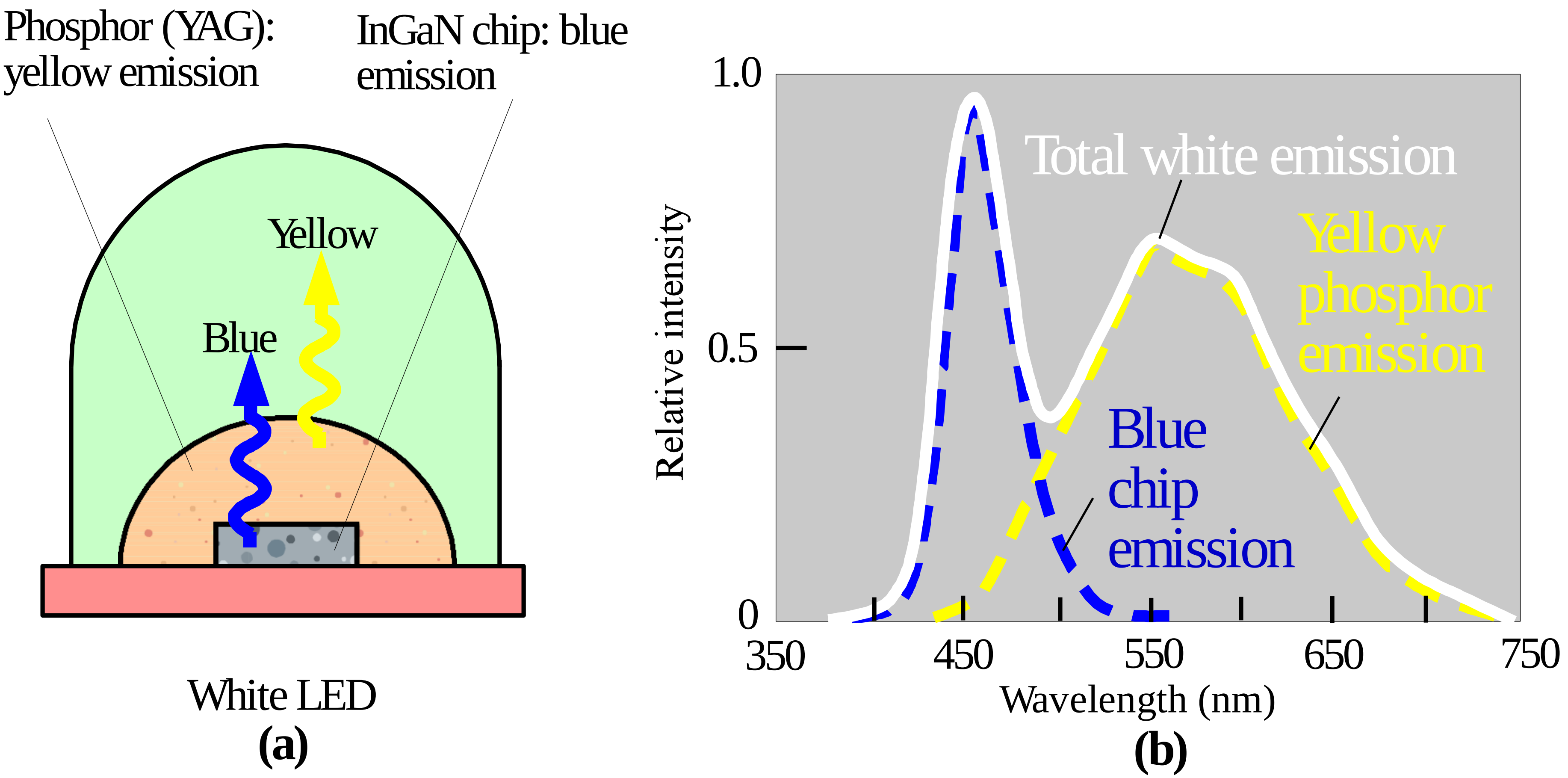
Photoluminescence: light absorption, excitation, non-radiative decay and light emission, and return to the ground state E_1.

Example (ZnS-based phosphors)



Optical absorption generates an electron-hole pair (EHP). There are a number of recombination processes via a dopant that can result in a luminescent emission.

White LED



(a) A typical “white” LED structure. (b) The spectral distribution of light emitted by a white LED. Blue luminescence is emitted by the GaInN chip and yellow luminescence is produced by a phosphor. The combined spectrum looks “white”.

Nakamura was awarded Noble prize in physics in 2014, for **Blue GaN LED**.