Lecture 10: Optical properties

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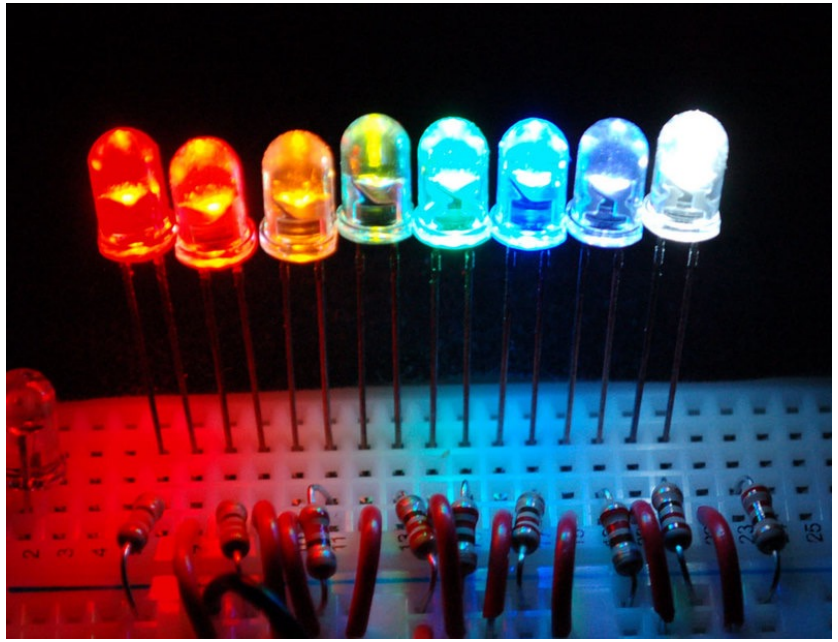
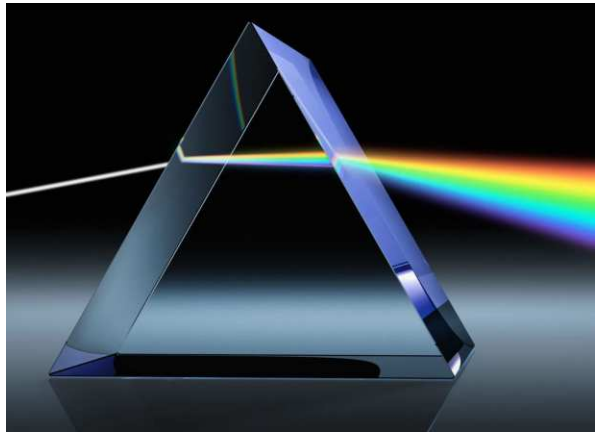
Today's subject is optical properties



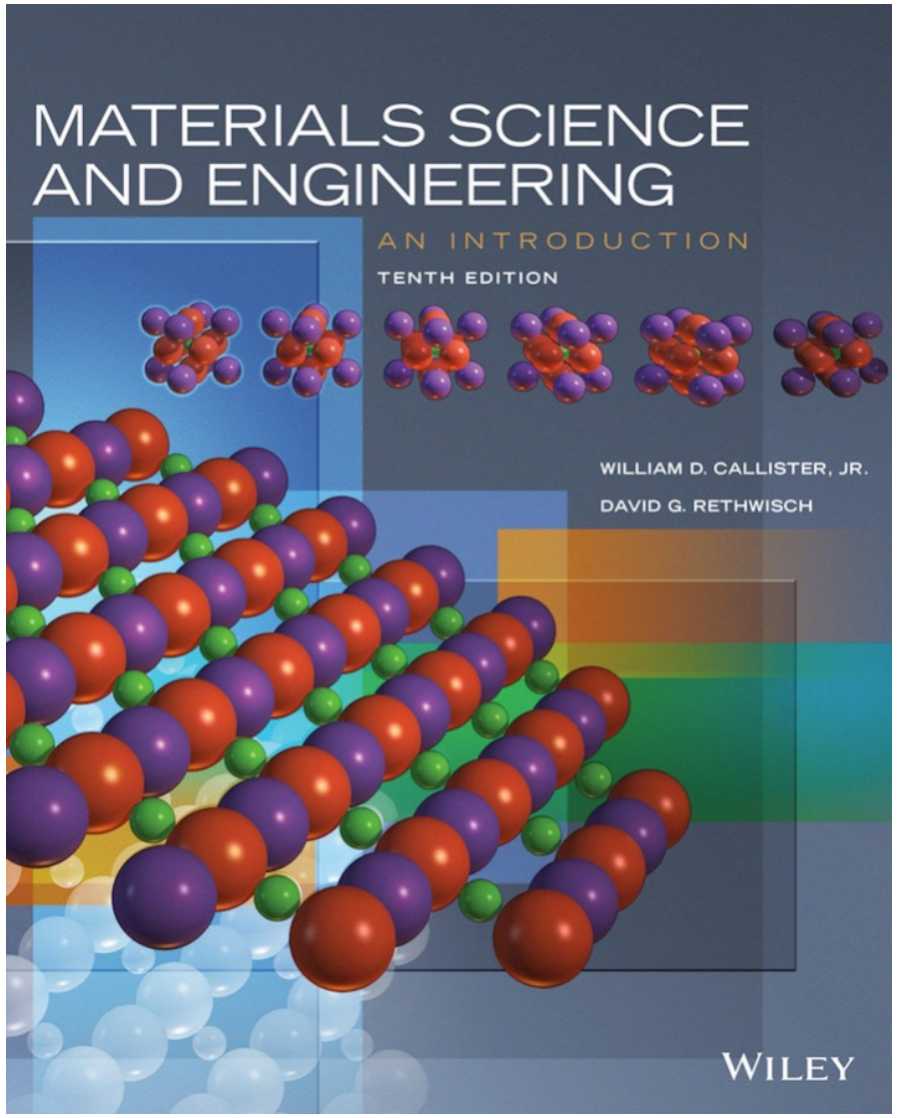








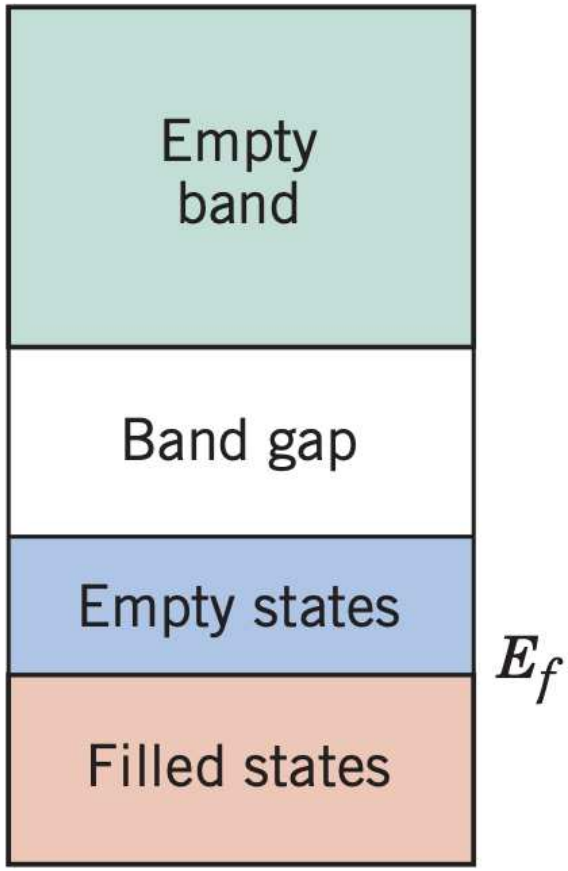
Reading for this subject: optical properties



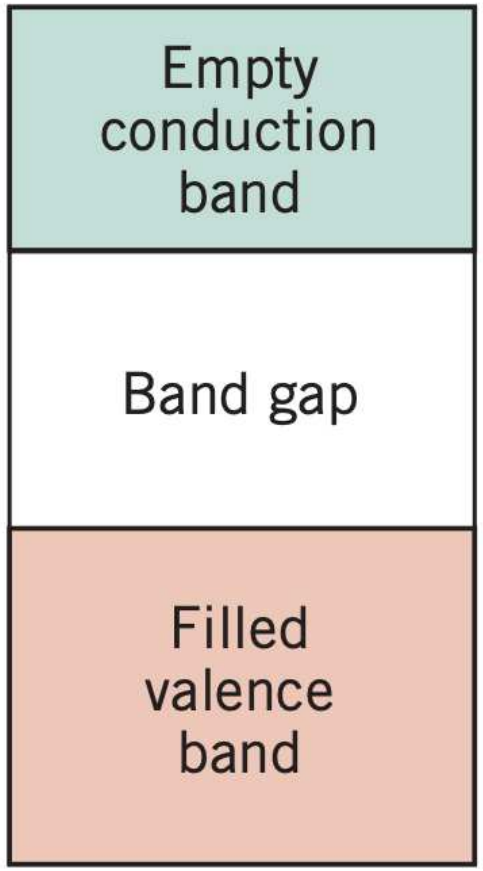
Chapter 21 Optical Properties

This discussion will closely follow **Chapter 21** of Callister, **pages 747-770** of the 10th edition.

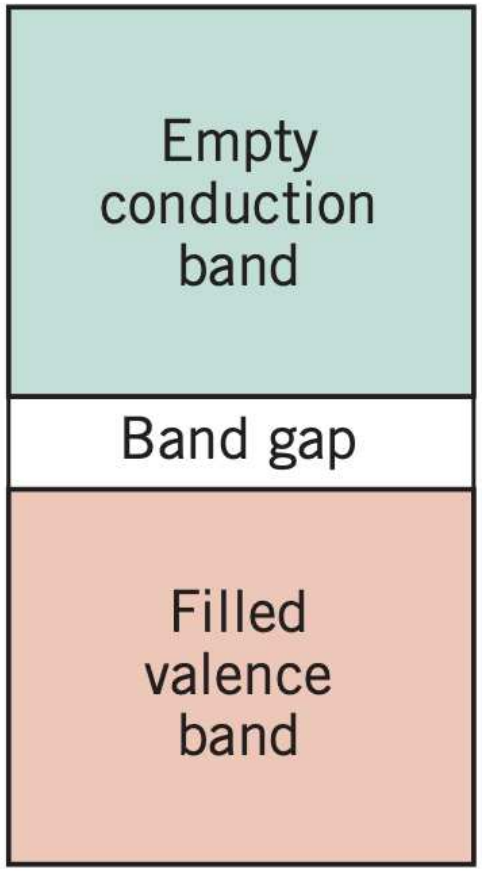
Last time, we discussed electrical properties



Metals



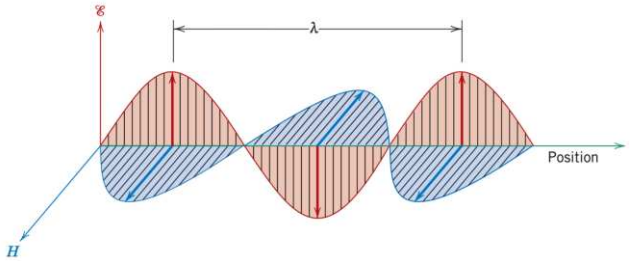
Insulators



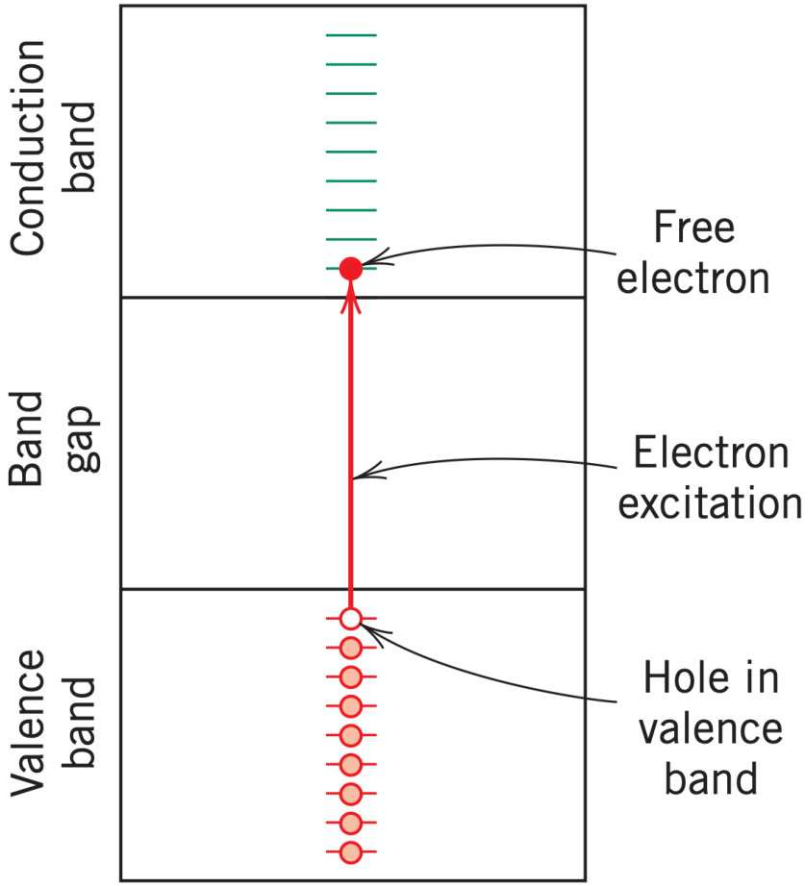
Semiconductors

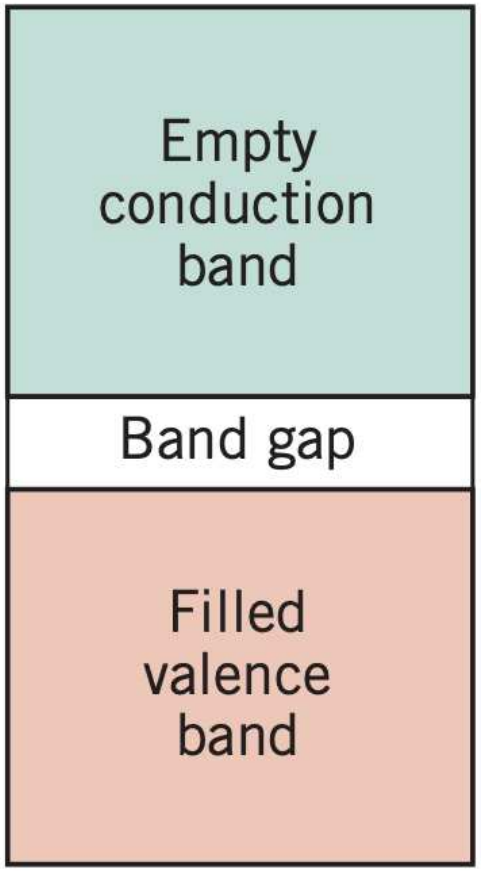
Last time, we discussed electrical properties

These same transitions dictate how materials **interact with light** (EM radiation)



→ **Optical properties!**

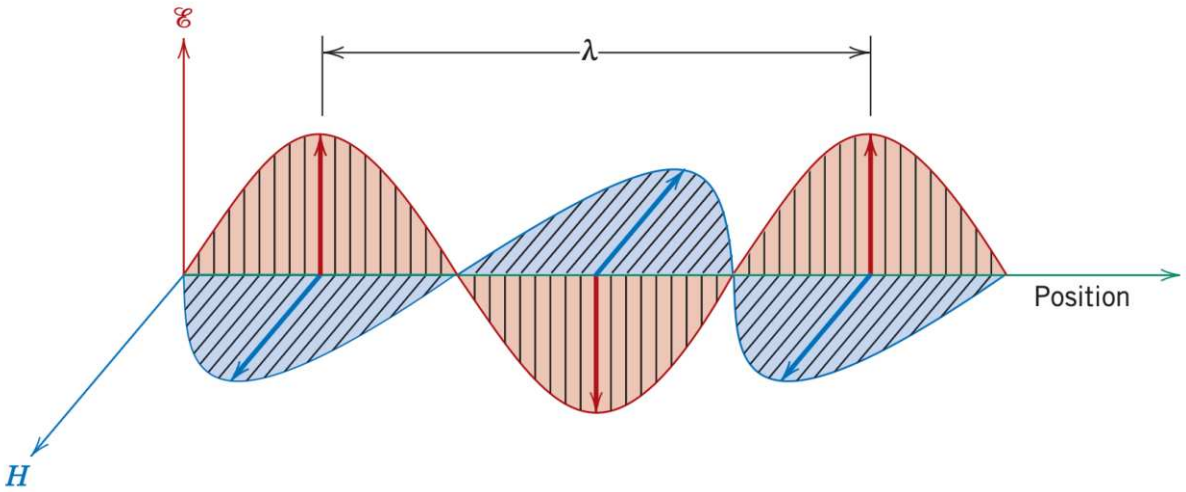




Semiconductors

Properties of electromagnetic radiation

$$E = h\nu = hc/\lambda$$



Remember that we can view this is a continuous wave (with wavelength λ) *or* as a quantized photon of energy E

E = energy of a photon

λ = wavelength of radiation

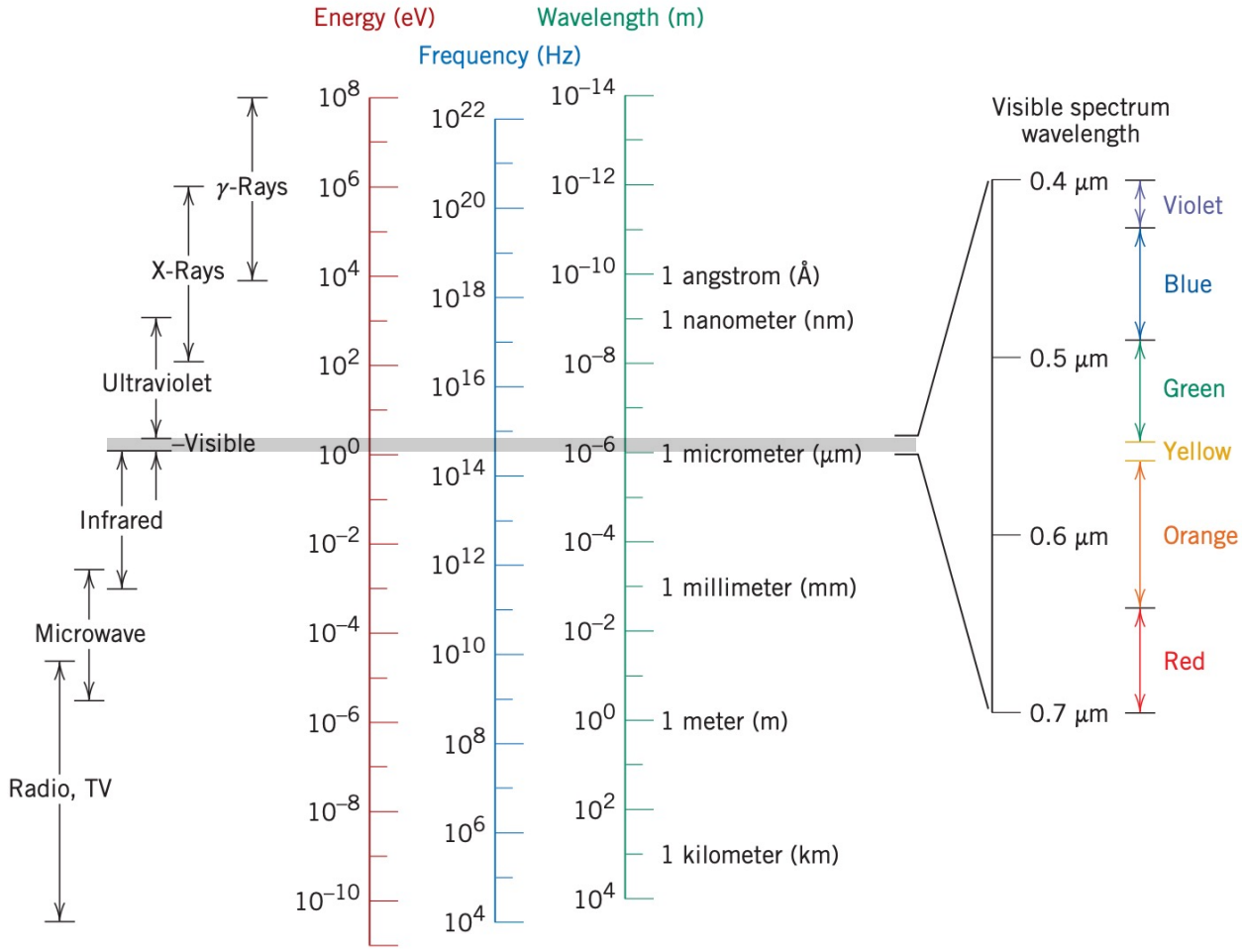
ν = frequency of radiation

h = Planck's constant (6.62×10^{-34} J·s)

c = speed of light in a vacuum (3.00×10^{8} m/s)

Properties of electromagnetic radiation

$$E = h\nu = hc/\lambda$$



E = energy of a photon

λ = wavelength of radiation

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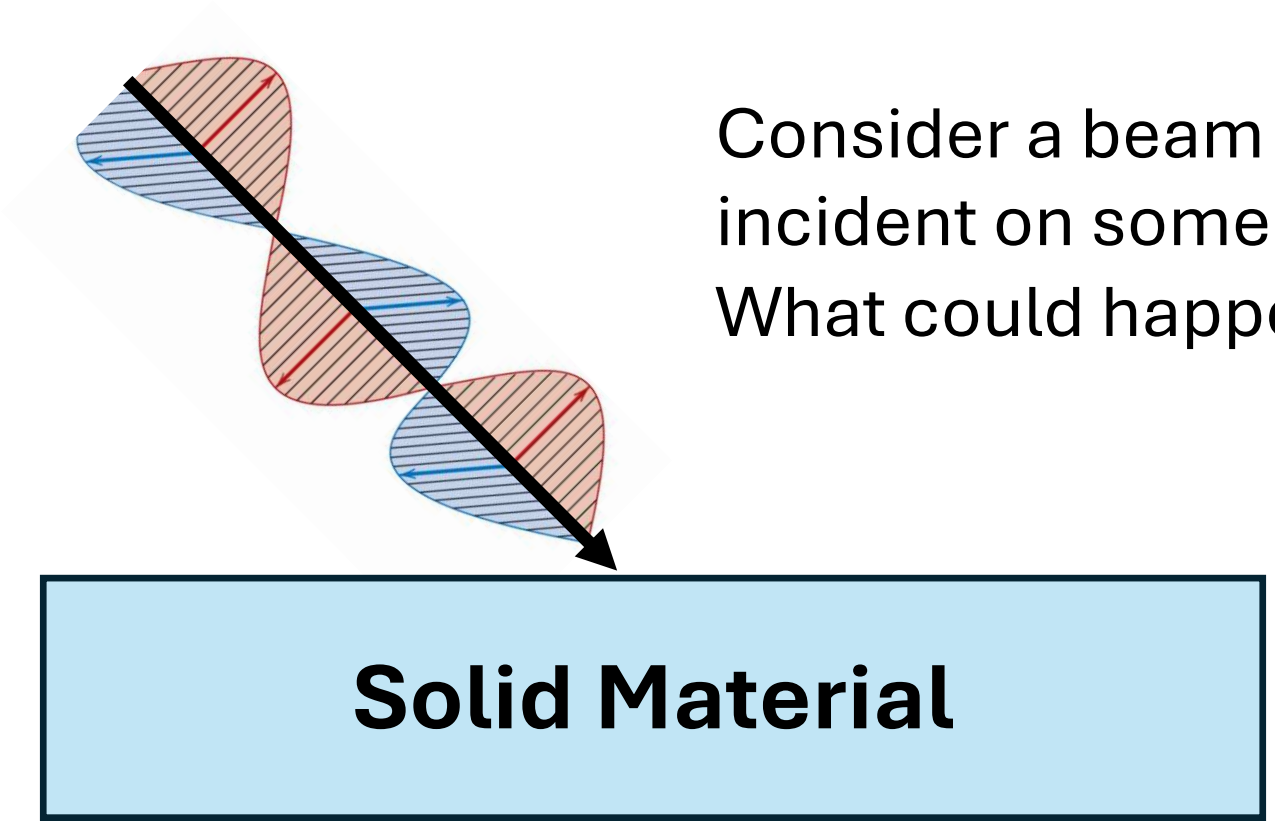
h = Planck's constant (6.62×10^{-34} J·s)

c = speed of light in a vacuum (3.00×10^{8} m/s)

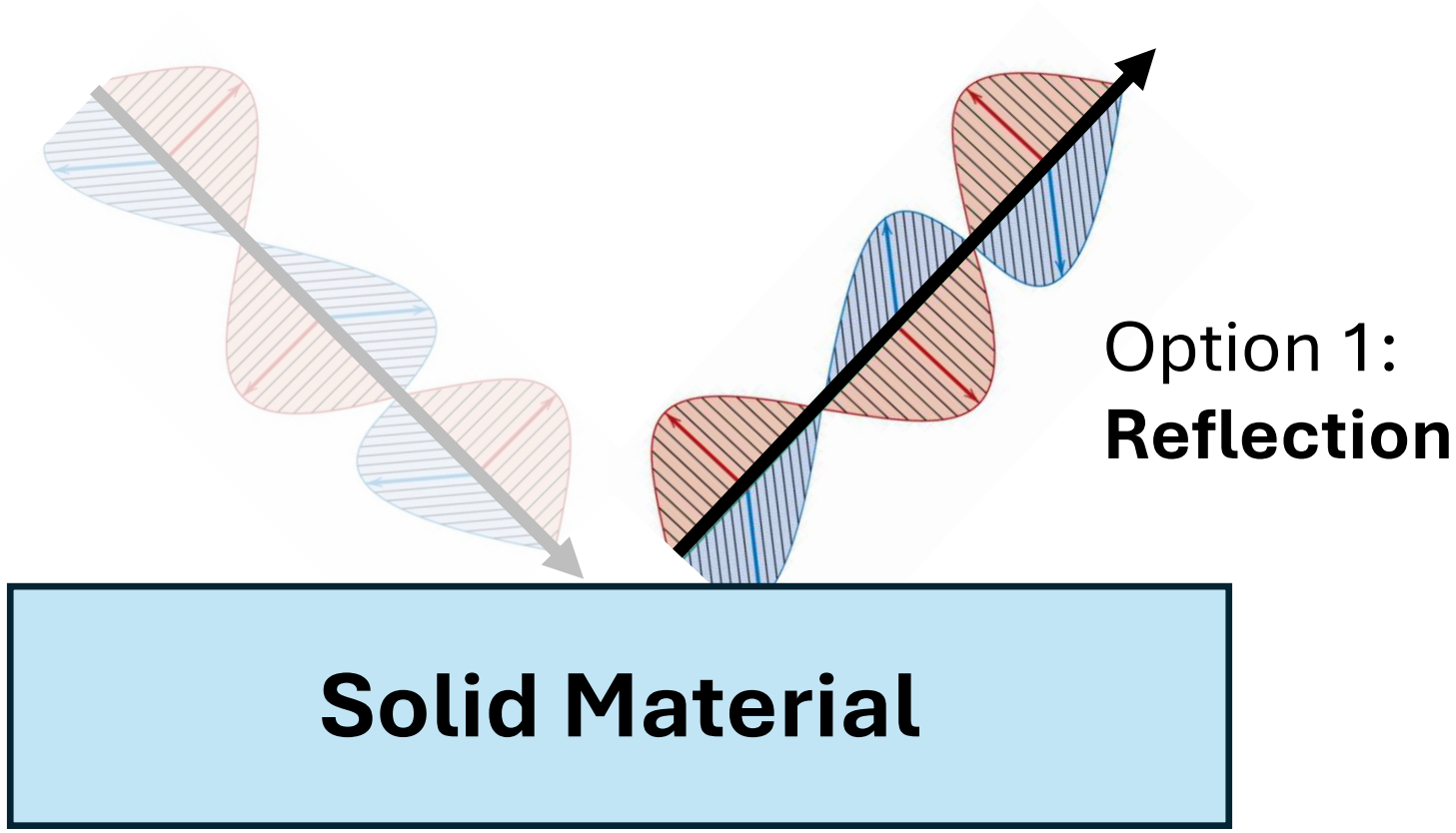
Visible light spans a relatively narrow range:
380-700 nm

Light-matter interactions



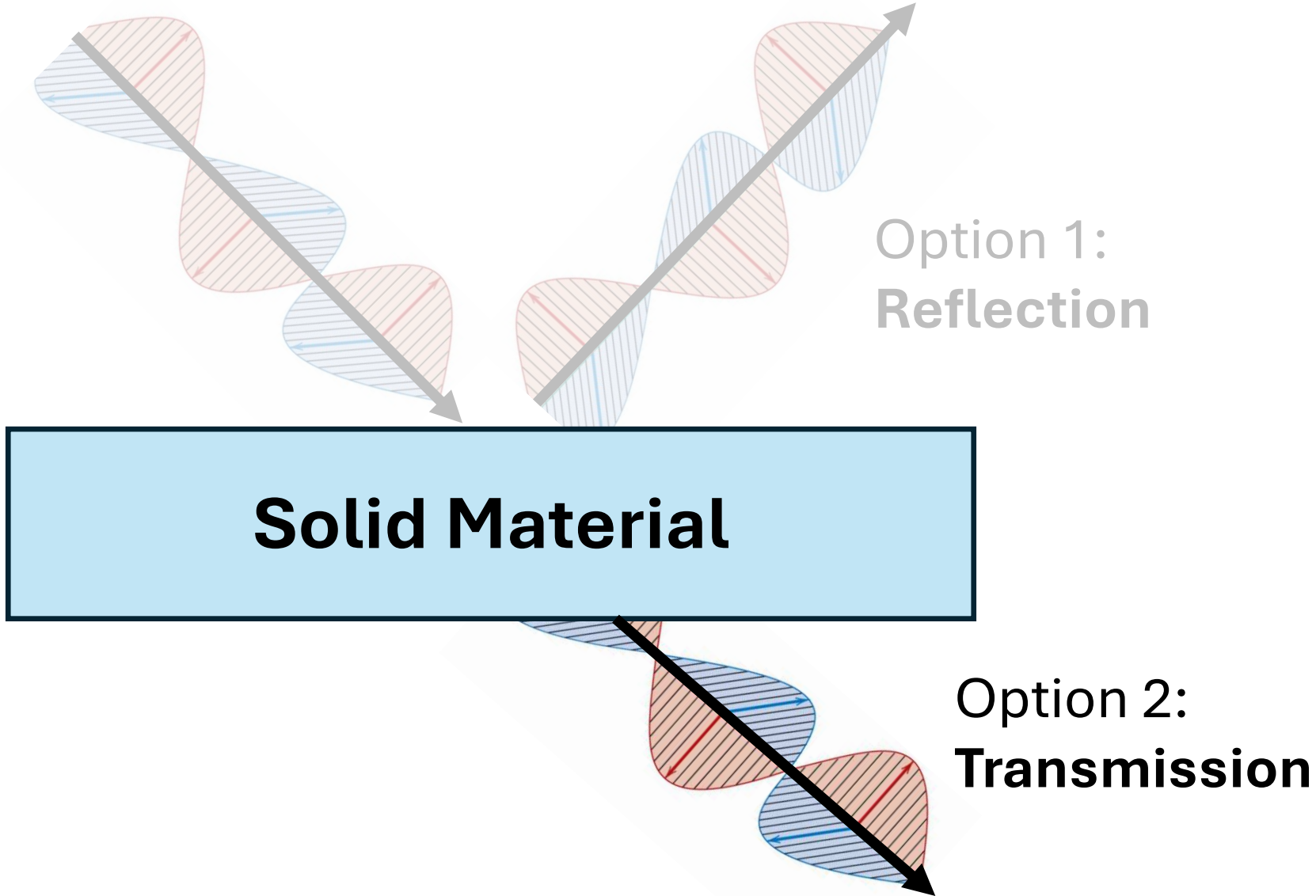
Consider a beam of light incident on some material. What could happen?

Light-matter interactions

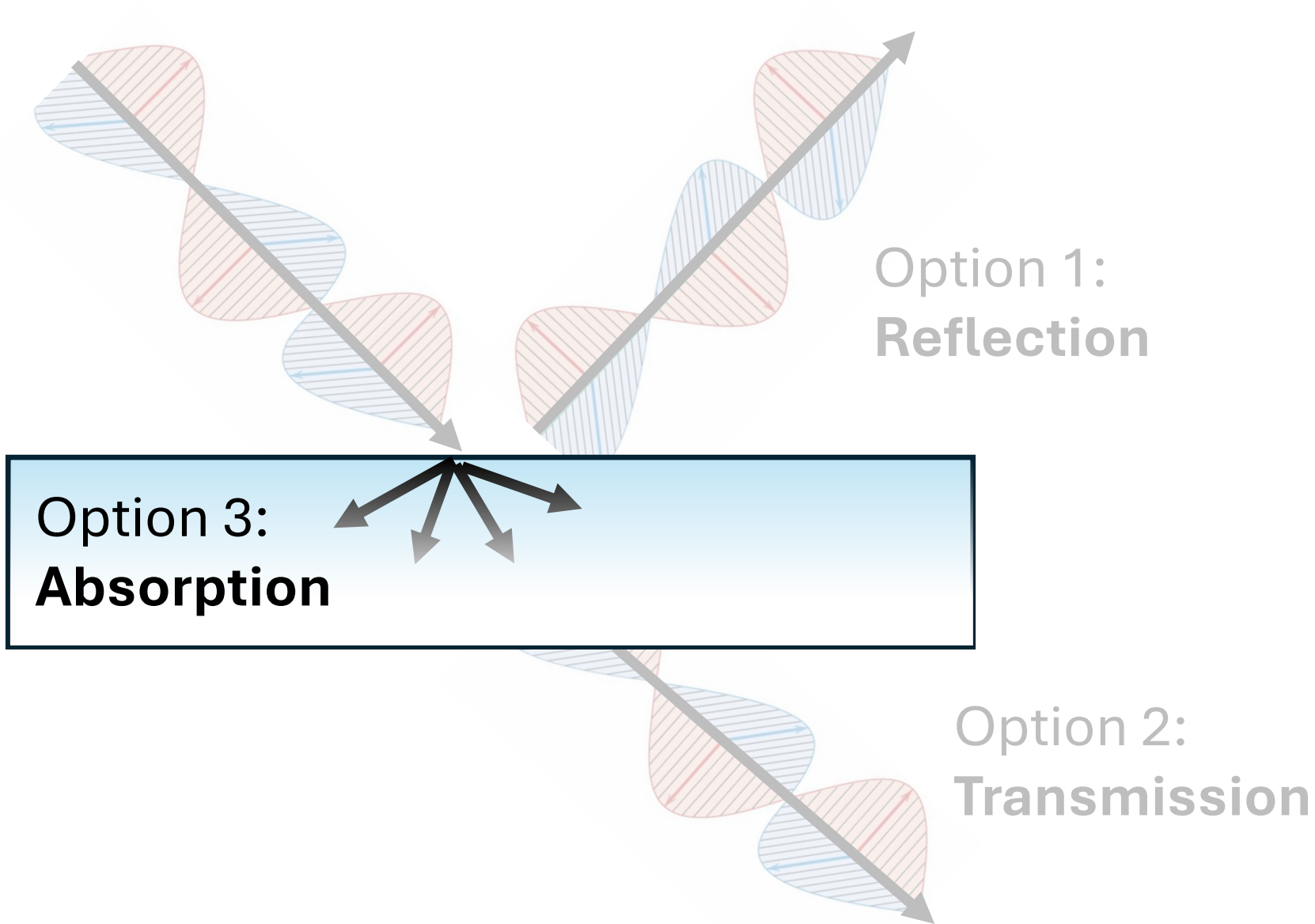


Option 1:
Reflection

Light-matter interactions



Light-matter interactions



Light-matter interactions

Energy is conserved, so all the photons must go somewhere:

$$I_0 = I_R + I_T + I_A$$

The **incident intensity** (units of W/m^2) is equal to the sum of reflected, transmitted, and absorbed intensities

The fraction of each will dictate how a material "looks"

- High transmission $(I_T \sim I_0) \rightarrow$ transparent material 
- High absorption $(I_T \sim I_0) \rightarrow$ opaque and dark material 
- High reflection $(I_R \sim I_0) \rightarrow$ opaque and shiny material 

Light-matter interactions

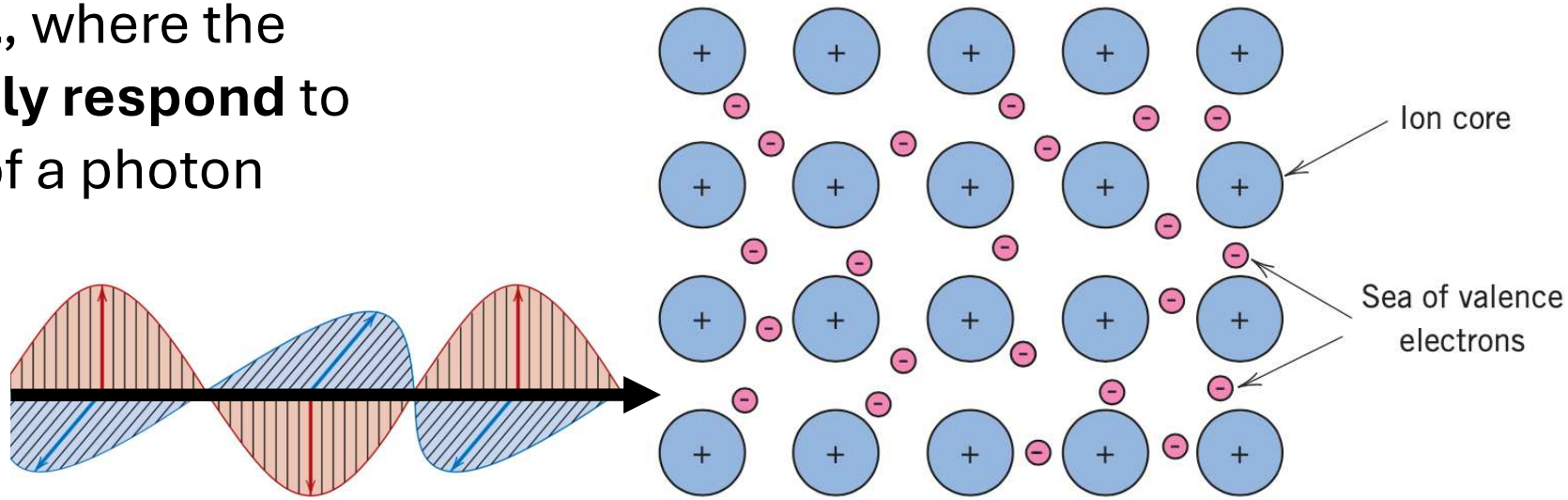
Energy is conserved, so all the photons must go somewhere:

$$I_0 = \boldsymbol{I_{\mathrm{R}}} + I_{\mathrm{T}} + I_{\mathrm{A}}$$

In what situation would a material ***reflect*** light?
And how?

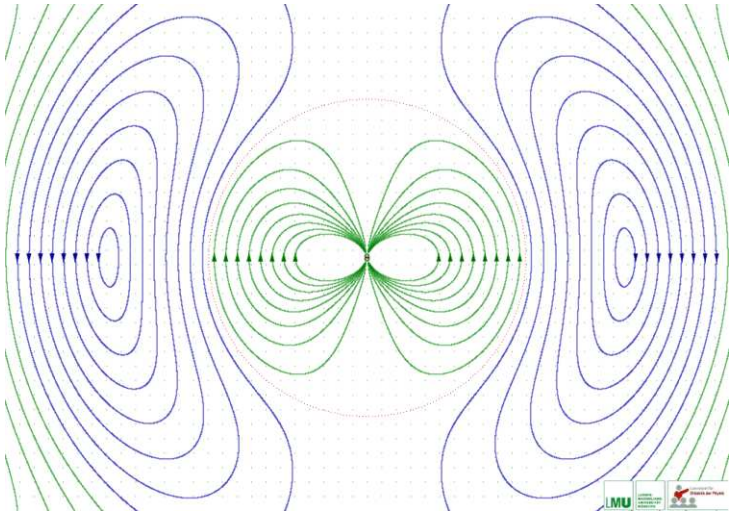
Light-matter interactions: reflection

Let's first consider a **metal**, where the valence electrons can **freely respond** to the electromagnetic field of a photon



This causes the **electrons to oscillate**, which in turn produces new electromagnetic wave that are then **reflected** back





Electric field lines of an oscillating charge



Metals are shiny

Light-matter interactions: reflection

Another way to think about this:

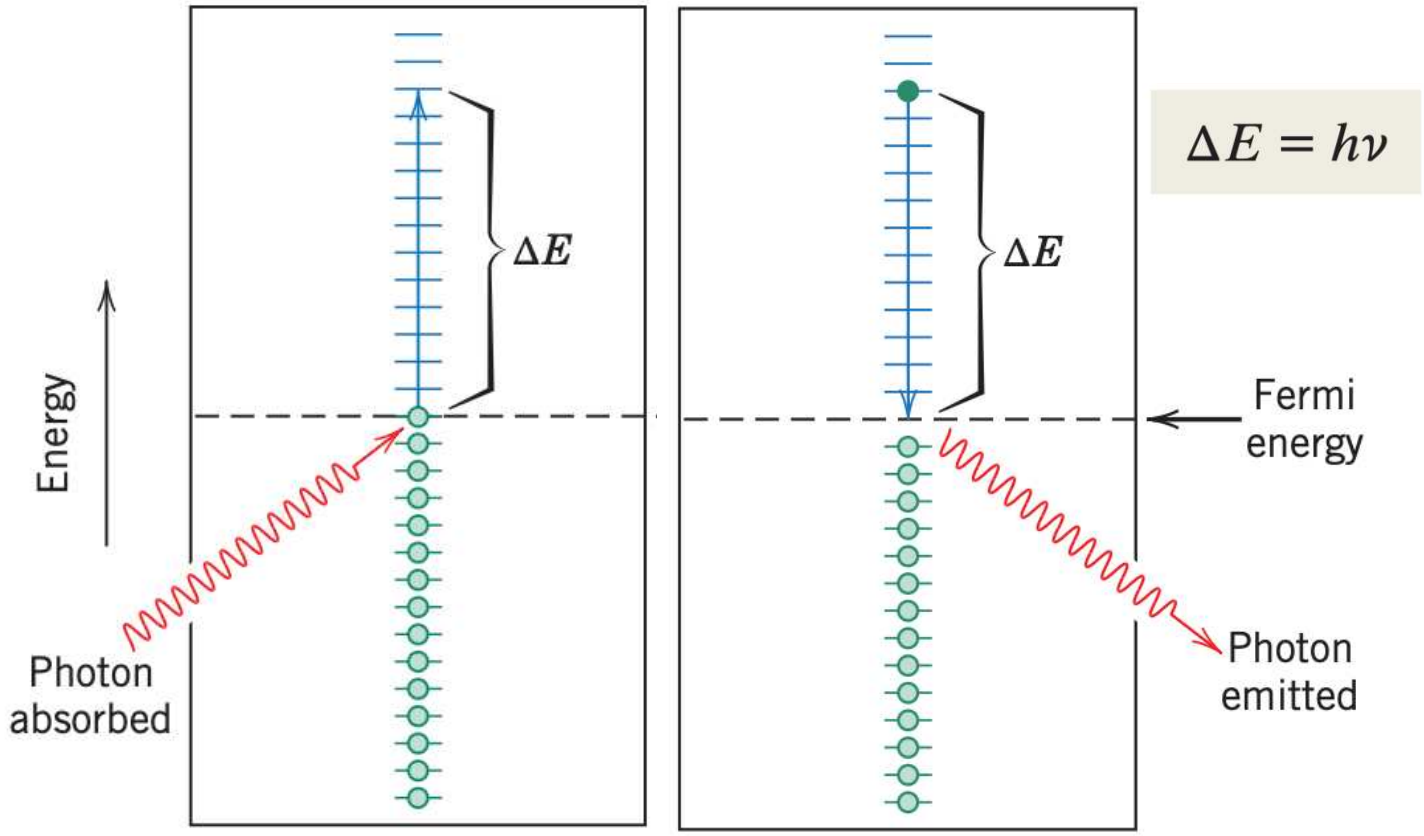
There are many closely spaced energy levels that electrons in a metal can be excited into.

This causes **absorption**.

But the excited excited electrons quickly relax back to low energy, emitting photons in the process

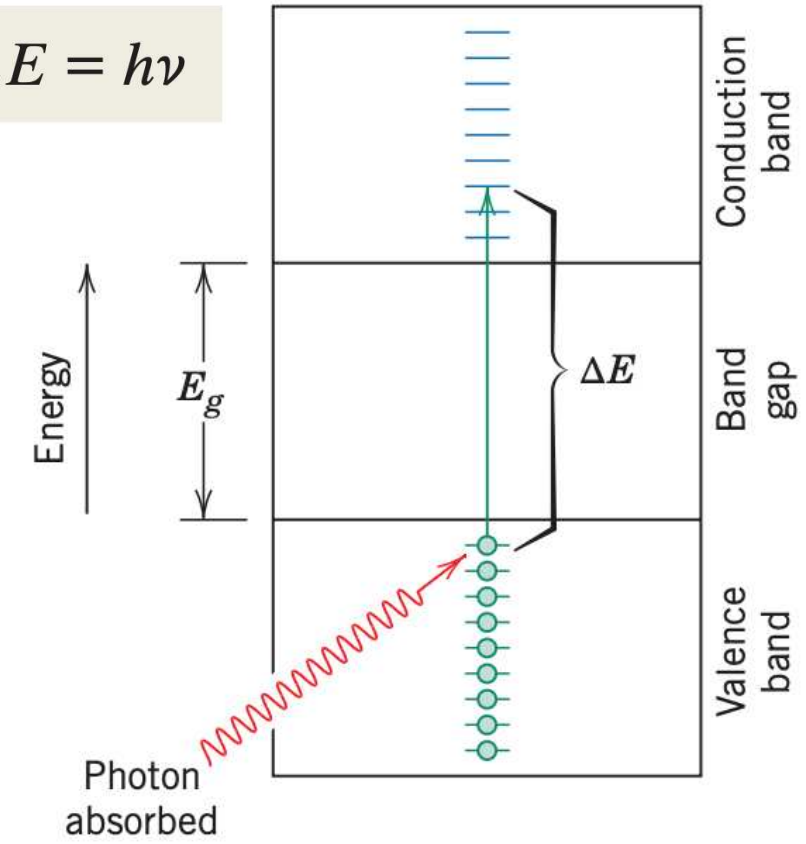
→ **Reflection**

What if these excited-state energy levels are not available?



Light-matter interactions: reflection

$$\Delta E = h\nu$$



What if these excited-state energy levels are not available?

For semiconductors and insulators:

Initial absorption (and subsequent emission) will happen ***only*** when the **photon energy exceeds the band gap energy ($h\nu \geq E_g$)**



Silicon
(1.12 eV gap)



Gallium nitride
(3.44 eV gap)

Visible light: 1.7 to 3.3 eV

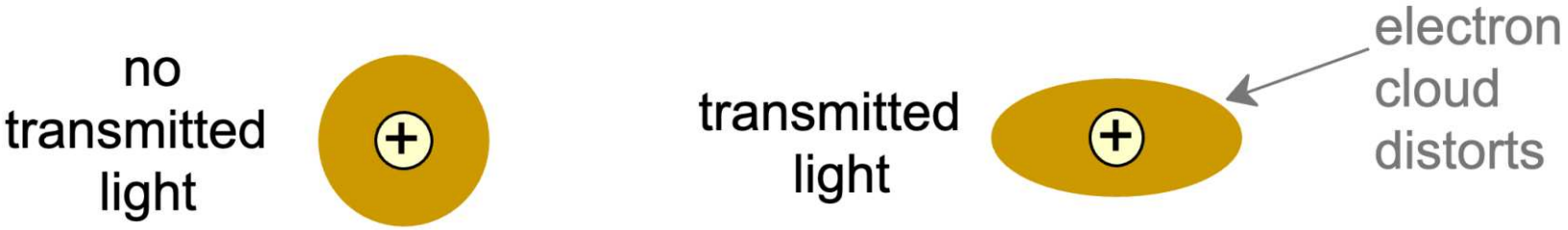
Questions on reflection?

Light-matter interactions: transmission

Energy is conserved, so all the photons must go somewhere:

$$I_0 = I_R + I_T + I_A$$

If light is not absorbed or reflected, it will be **transmitted** through the material. But it still interacts with the material in some way.





Gallium nitride
(3.44 eV gap)

This causes “drag” on the photon. As a result, **light travels slower through a material than in a vacuum.**

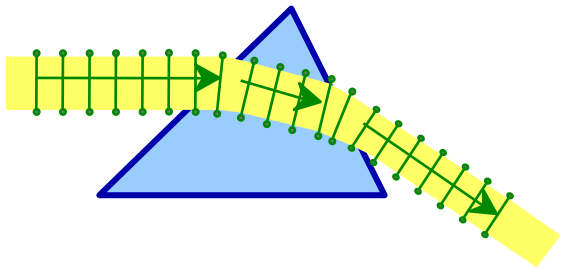
Light-matter interactions: transmission

The **index of refraction** measures how much slowing occurs:

$$n = \frac{c}{v}$$

c: Speed of light in a vacuum

v: Speed of light in the material



When n is large, light is "bent" as it crosses the boundary



This causes "drag" on the photon. As a result, **light travels slower through a material than in a vacuum.**

Light-matter interactions: transmission

The **index of refraction** measures how much slowing occurs:

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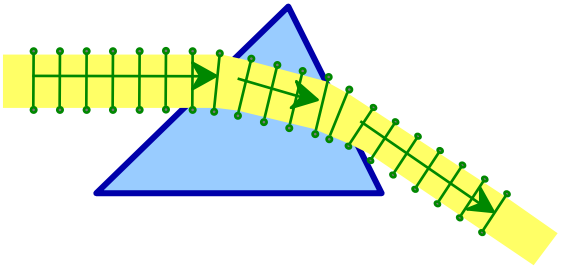

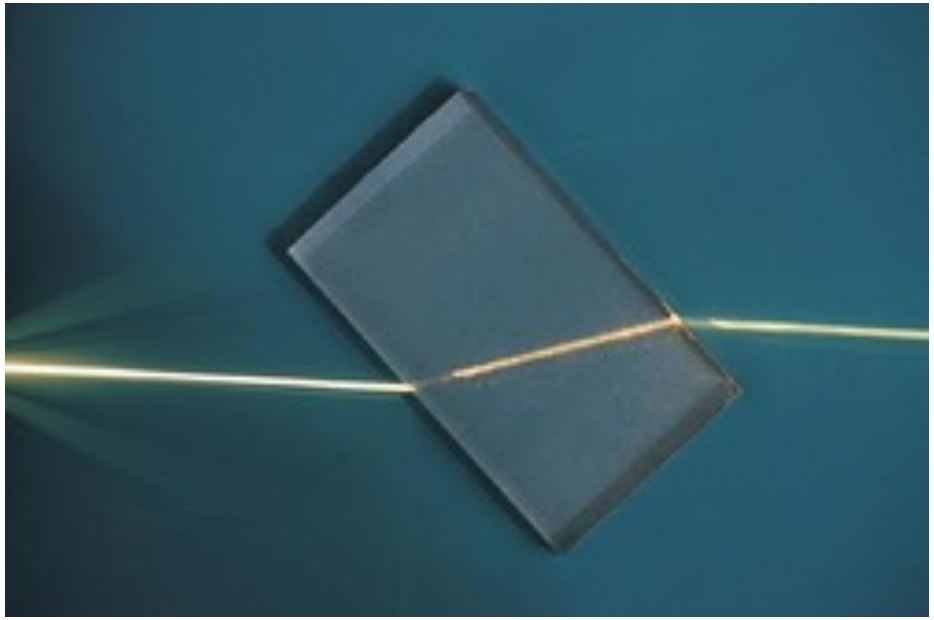



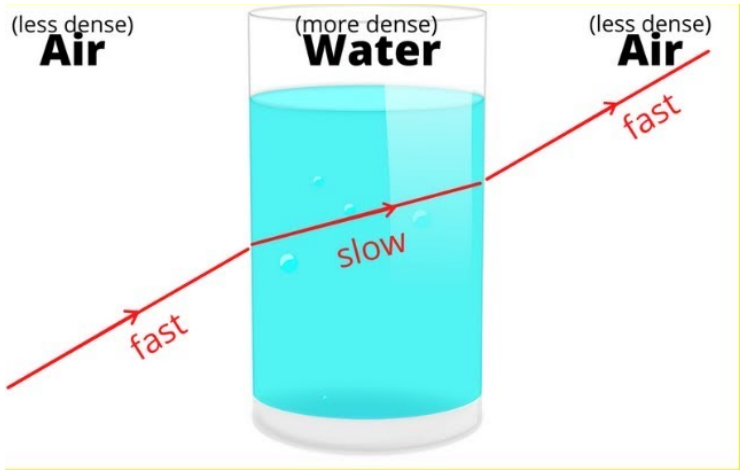

Light-matter interactions: transmission

The **index of refraction** measures how much slowing occurs:

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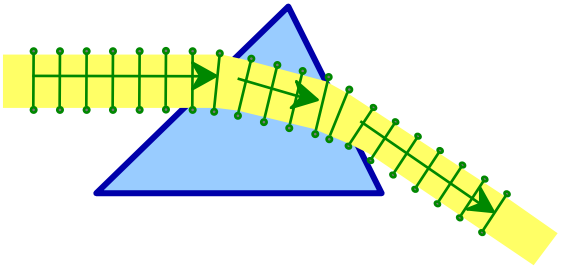
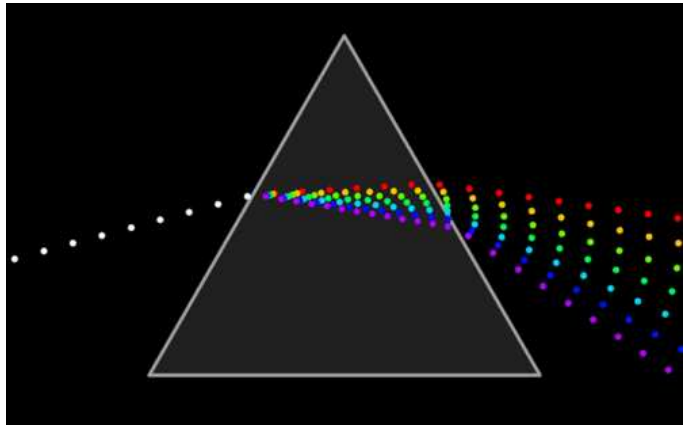
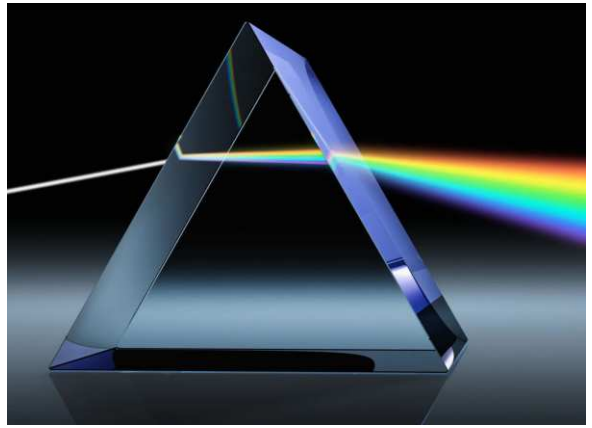


Material	*Average Index of Refraction*
Ceramics	
Silica glass	1.458
Borosilicate (Pyrex) glass	1.47
Soda–lime glass	1.51
Quartz (SiO_2)	1.55
Dense optical flint glass	1.65
Spinel ($MgAl_2O_4$)	1.72
Periclase (MgO)	1.74
Corundum (Al_2O_3)	1.76

In reality, the index of refraction varies with wavelength





Light-matter interactions: back to reflection

The **index of refraction** measures how much slowing occurs:

$$n = \frac{c}{v}$$

c: Speed of light in a vacuum

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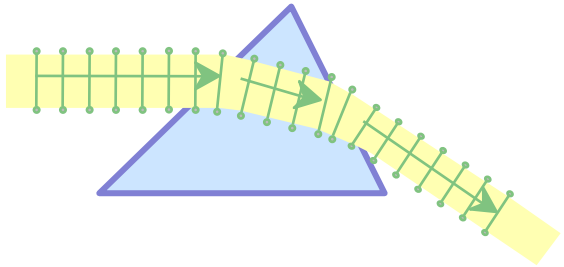


We can also use the index of refraction to calculate **reflectivity**, *i.e.*, the **fraction of incident light that gets reflected** (from air to solid):

$$R = \left(\frac{n_s - 1}{n_s + 1} \right)^2$$

n_s: Refractive index of solid

1: Refractive index of air

Large refractive index (n_s)
→ strong light-matter interactions
→ more light will be reflected at the interface

Light-matter interactions: back to transmission

The answer depends on microstructure and purity

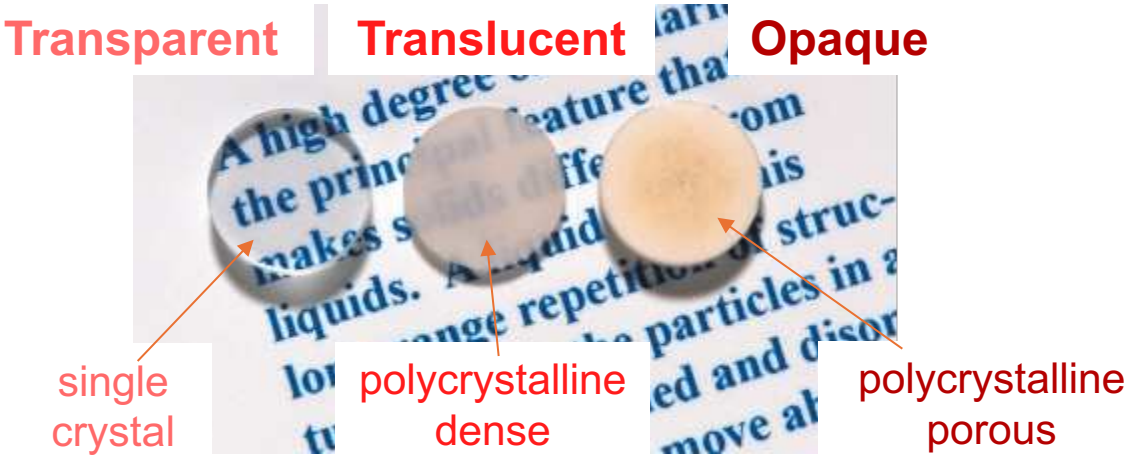
Suppose we have an **insulating** material with n_s **close to 1.** Will it be transparent?

$$R = \left(\frac{n_s - 1}{n_s + 1} \right)^2$$

Refractive index of solid

Refractive index of air

These are all the same material (Al_2O_3)!



Light can scatter off grain boundaries, air pockets, impurities, *etc.*

Large refractive index (n_s)
→ strong light-matter interactions
→ more light will be reflected at the interface

Light-matter interactions: absorption

Transparent | Translucent | Opaque



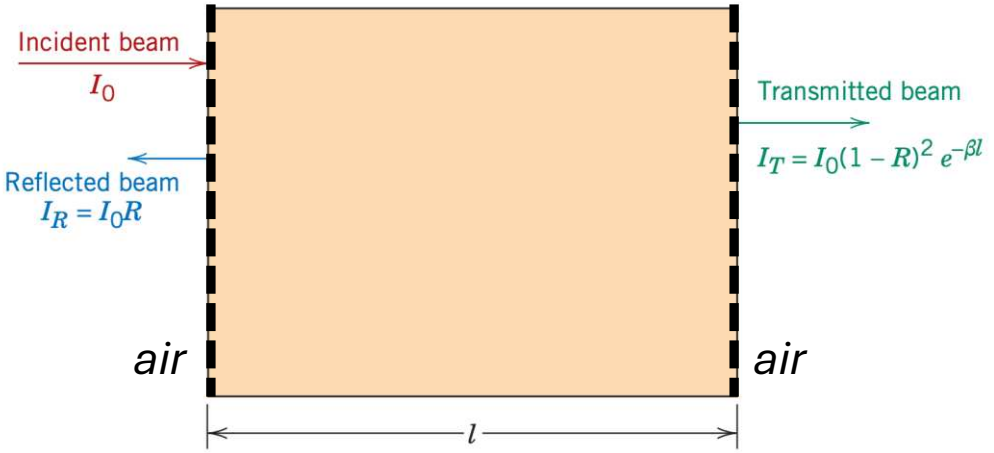
- We often want to quantify opaqueness in terms of how much light is transmitted
- This will depend on the **absorption coefficient (β)** of the material:

$$I'_T = I'_0 e^{-\beta x}$$

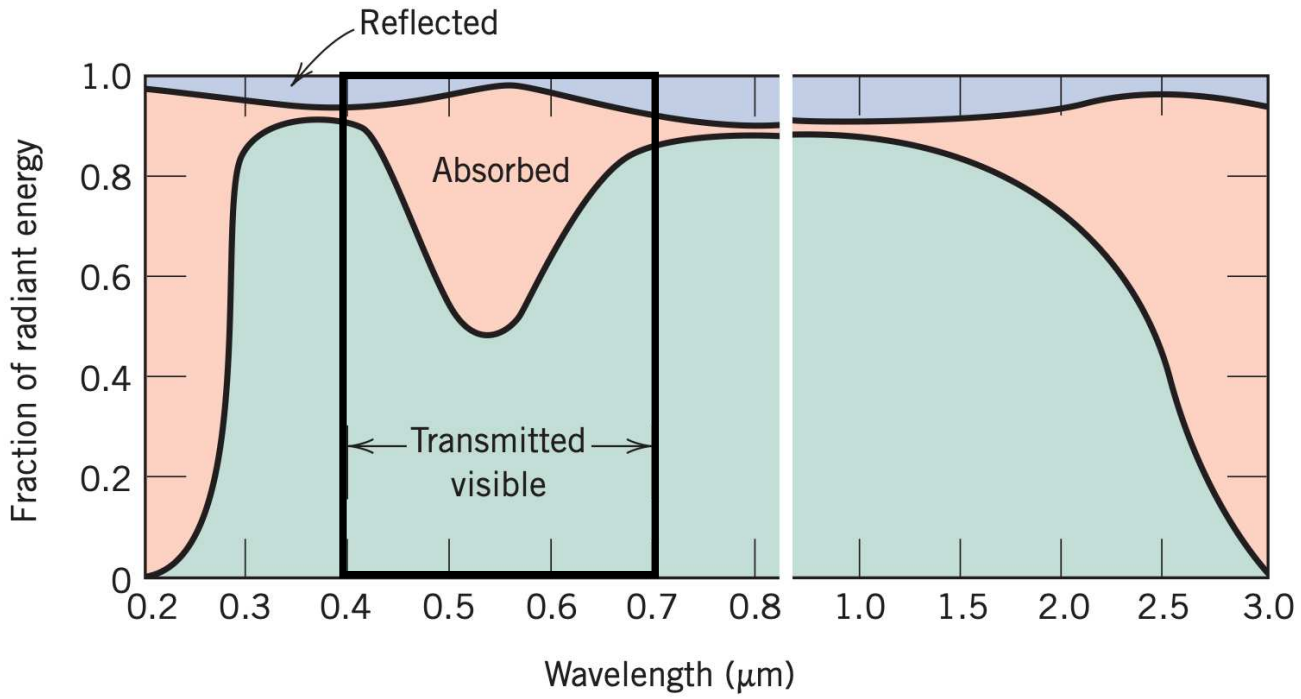
Less light is transmitted as light travels further (increasing x)

- We can break this down further to account for reflectivity (R)

$$I_T = I_0 (1 - R)^2 e^{-\beta l}$$

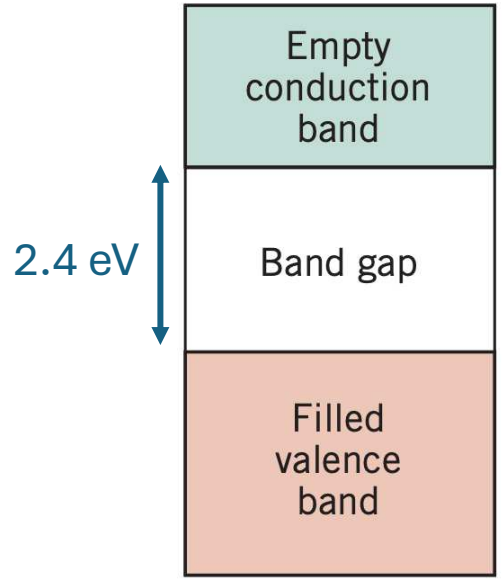


Light-matter interactions: color



How much light gets absorbed, reflected, and transmitted will depend on **wavelength** – which corresponds to **color** in the visible range

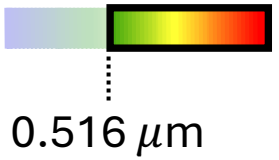
0.38 to 0.75 μm
(380 to 750 nm)





Example: Cadmium Sulfide (CdS)

- Has a **band gap of 2.4 eV**
- It **absorbs light with $\lambda < 0.516$ μm**
- **Light with $\lambda > 0.516$ μm gets reflected or transmitted**



Light-matter interactions: color



Example: Saphire (Al_2O_3)

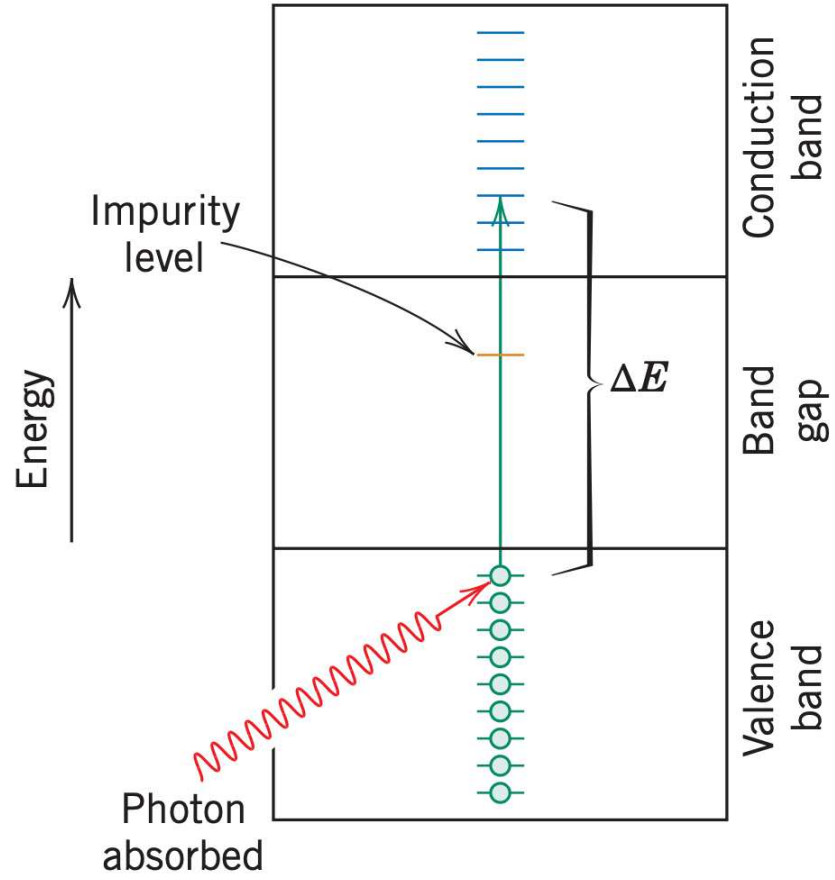
- Has a **band gap around 7 eV**
- It **does not absorb any visible light**
- **Completely transparent**



Example: Ruby (Al_2O_3 + 1% Cr_2O_3)

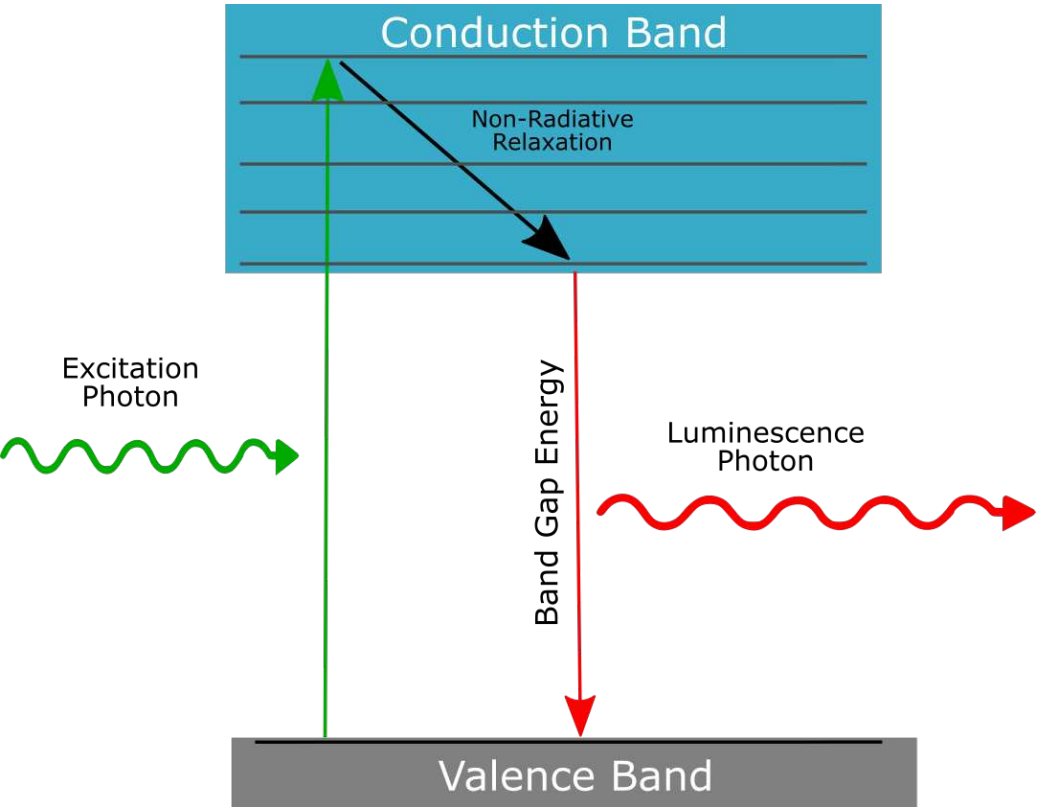
- Introduces impurity states into the middle of the band gap, leading to **absorption of blue/green light**
- **Result: ruby appears bright red!**



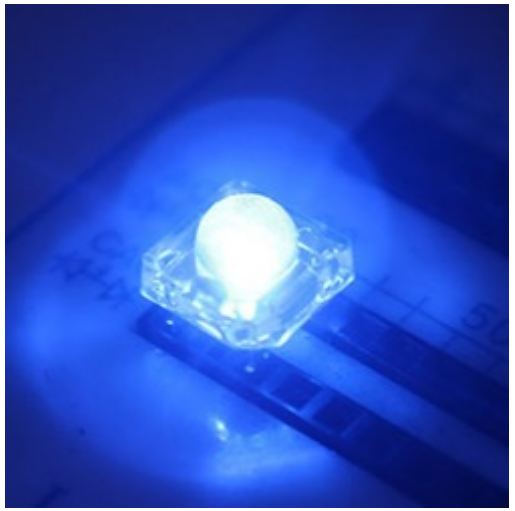


Questions on absorption?

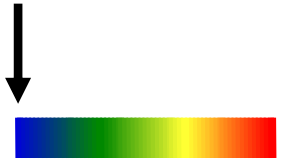
Luminescence



Recall that photons are emitted when electrons relax into lower energy states. This general process is **luminescence.** It often occurs at a specific wavelength in materials with a band gap.

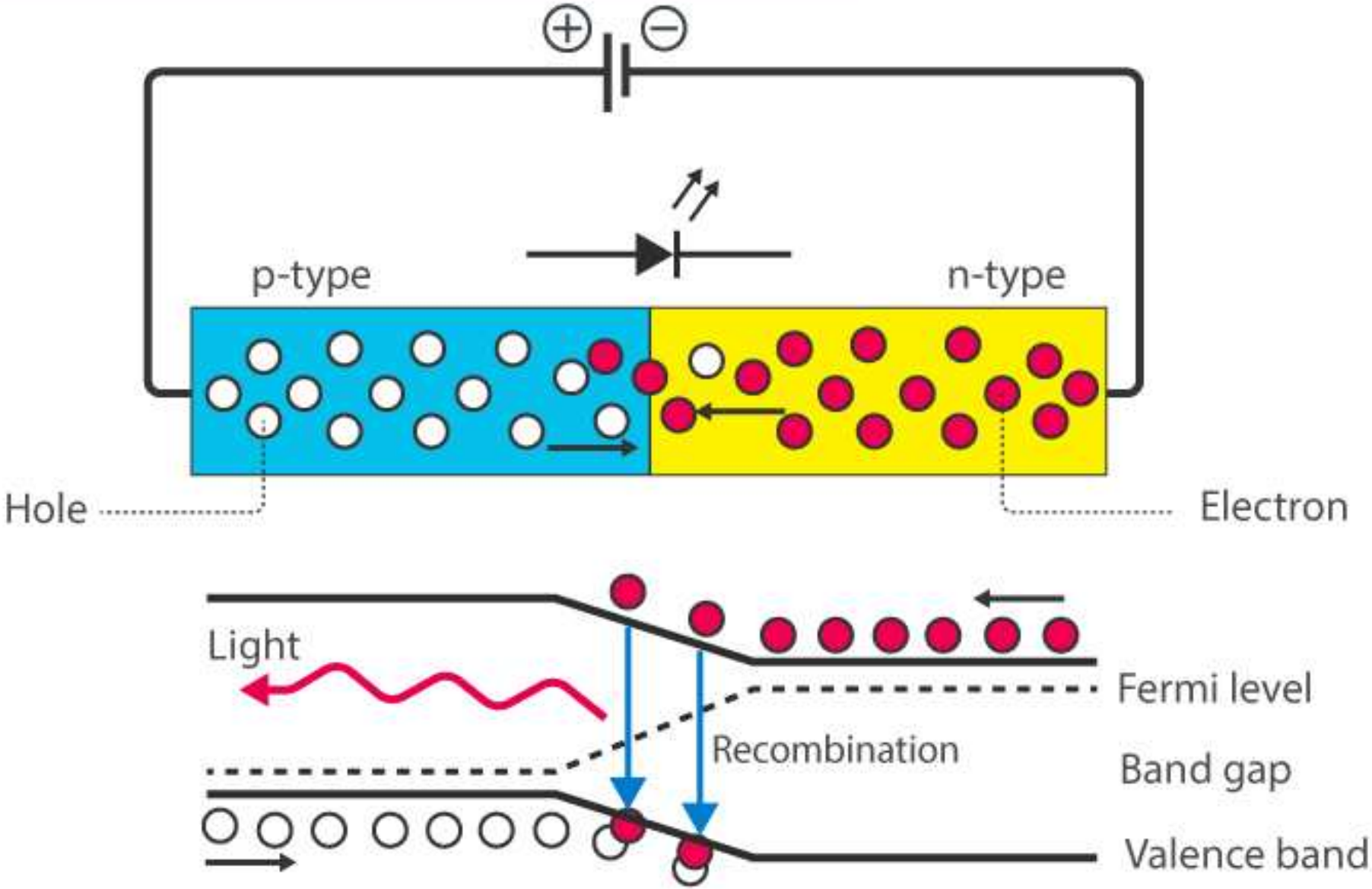


Light emitting diodes: GaN is used in blue LEDs since it has a band gap of about **3.4 eV**



LED = "light emitting diode"

WORKING PRINCIPLE OF LED



Luminescence

Fluorescence

Re-emission occurs very quickly (<< 1 sec)

UV light from an LED is converted into visible light by a thin coating of fluorescent material



Phosphorescence

Re-emission occurs relatively slowly



Glow-in-the-dark toys that stay lit up for a bit, even after turning off the lights



Luminescence

Fluorescence

Re-emission occurs very quickly (<< 1 sec)

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Phosphorescence

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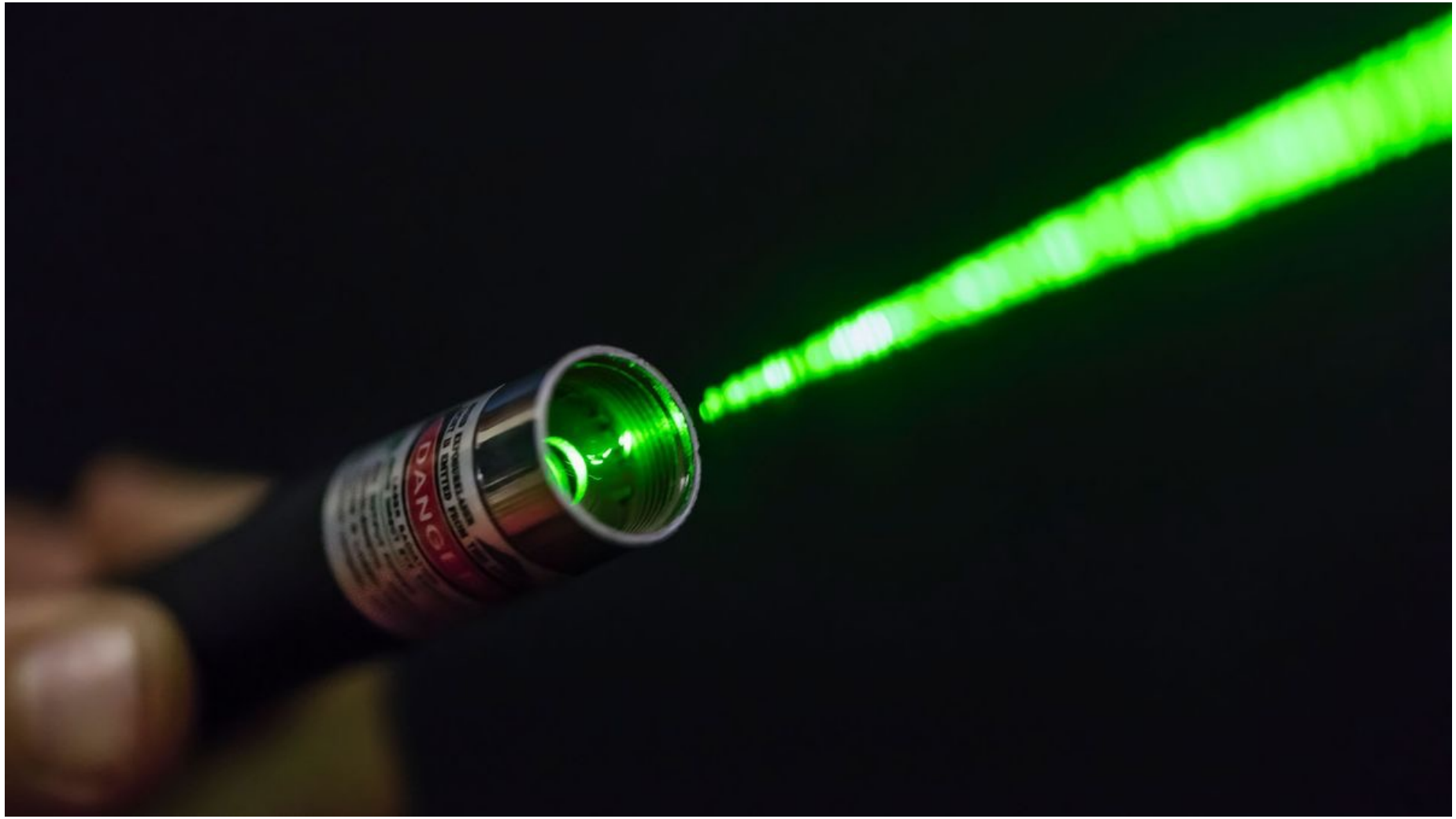
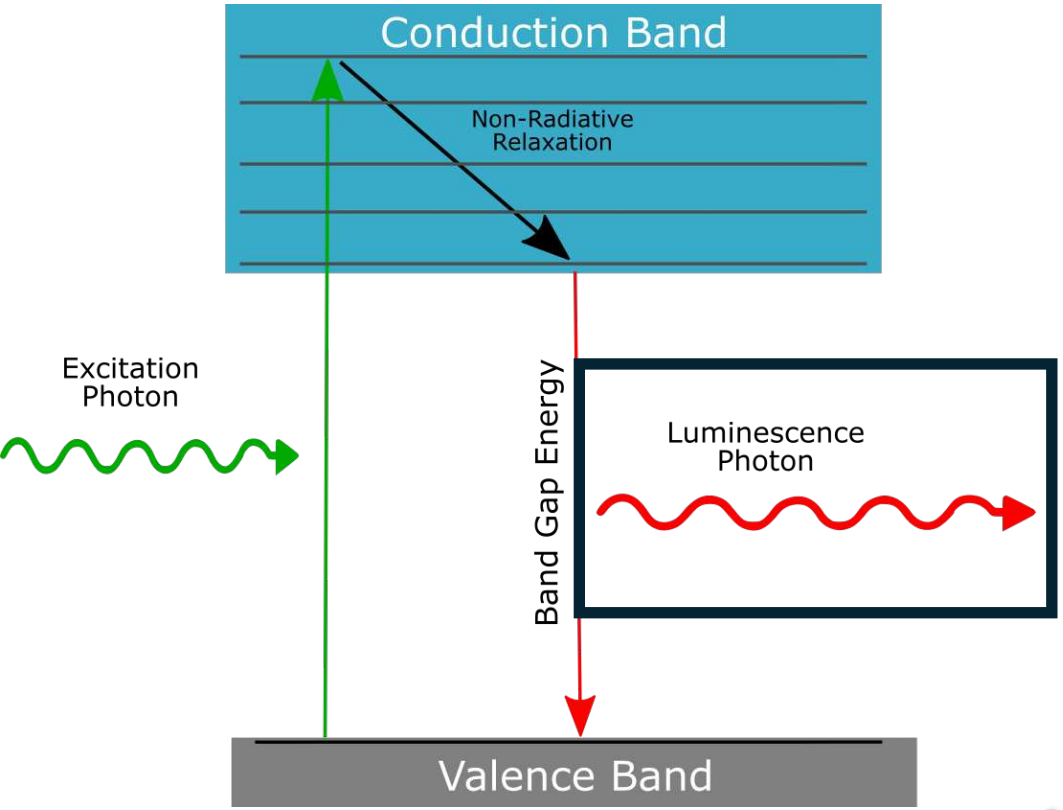
Lasers

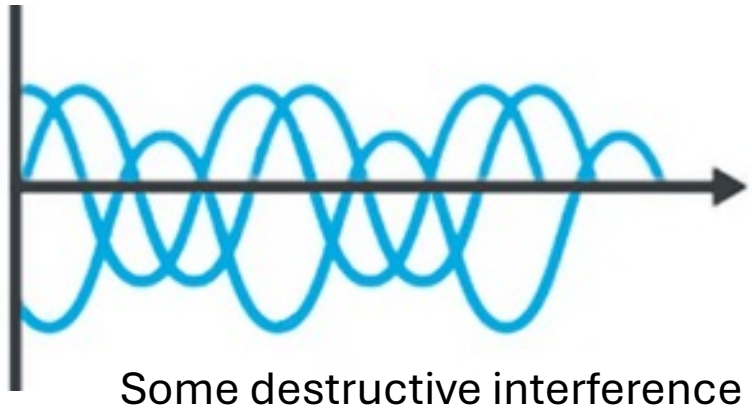


Very intense, coherent light with a single wavelength (color)

Lasers

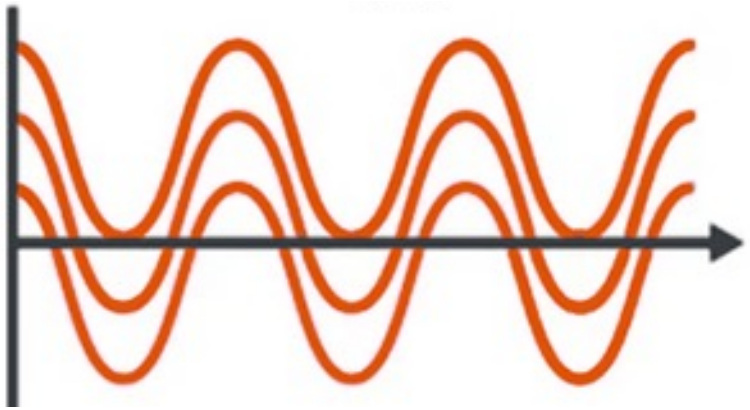


Typically, these emitted photons will be randomly oriented and **incoherent** with one another.



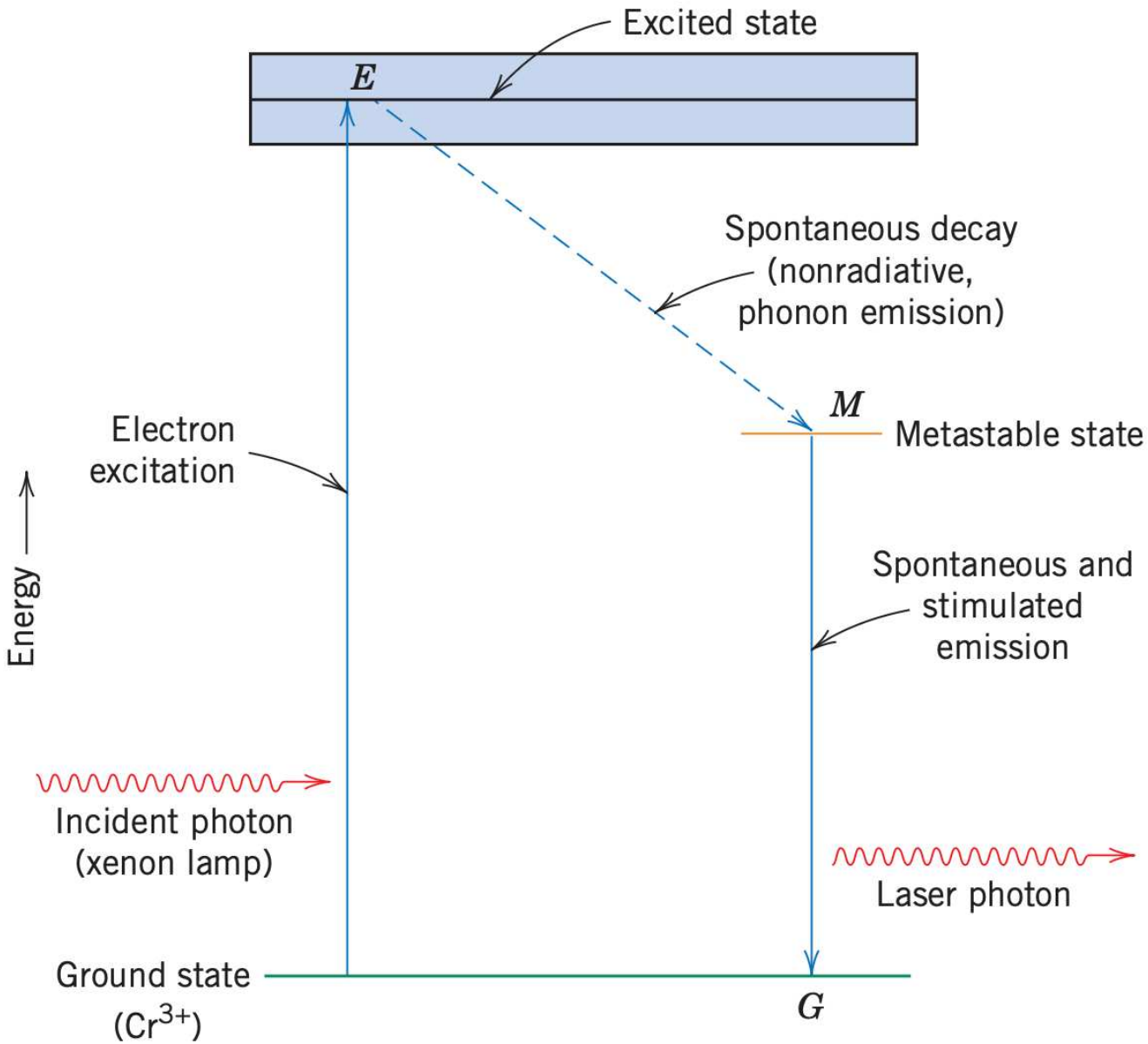
Some destructive interference

LASER = Light Amplification by Stimulated Emission of Radiation

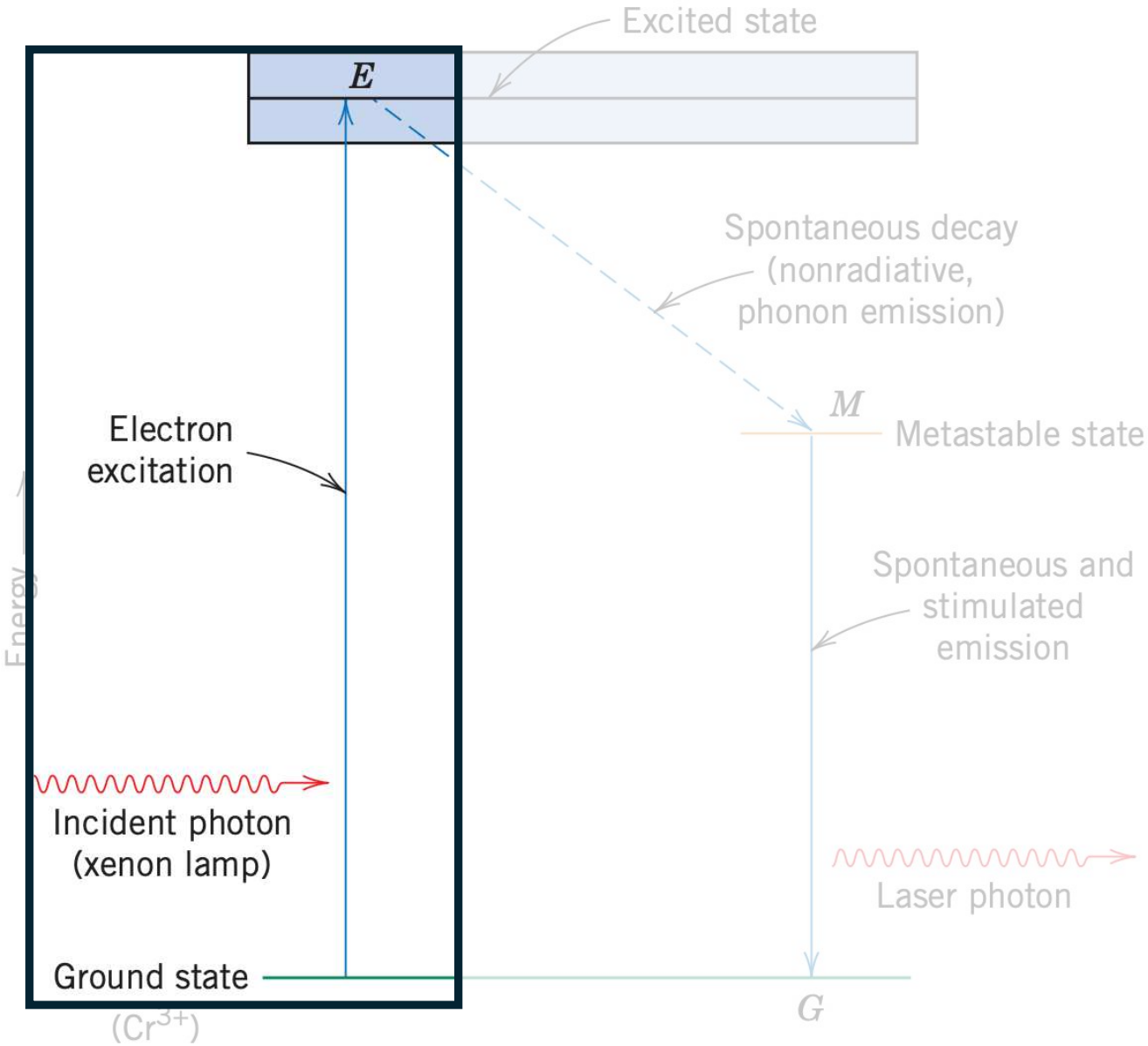


But what if we want nice & bright **coherent** light?

Lasers

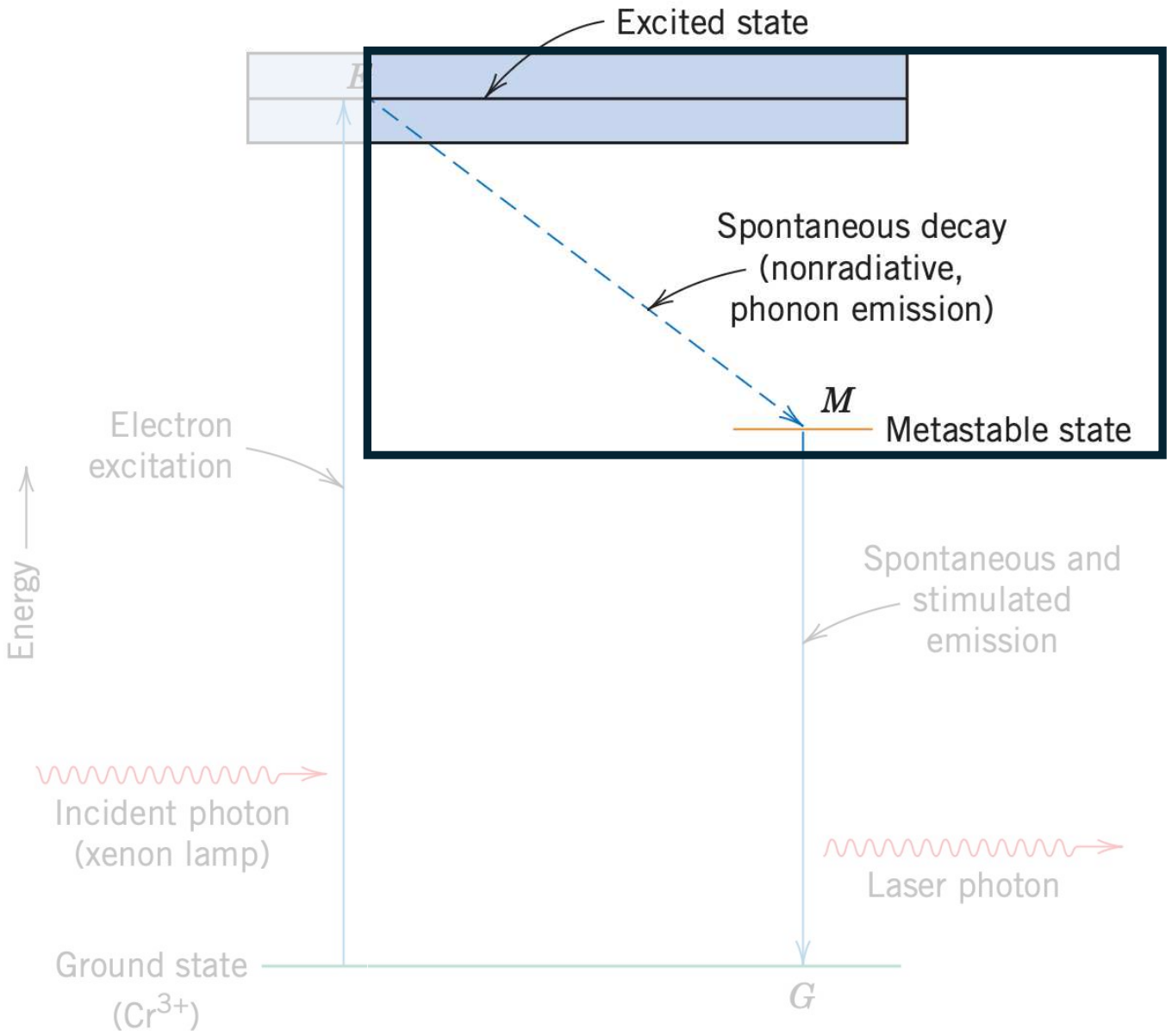

Excited state
E
Spontaneous decay
(nonradiative,
phonon emission)
M
Metastable state
Electron
excitation
Energy
Spontaneous and
stimulated
emission
Incident photon
(xenon lamp)
Laser photon
Ground state
(Cr3+)
G

Lasers



Step 1: illuminate the material to excite electrons into the conduction band

Lasers

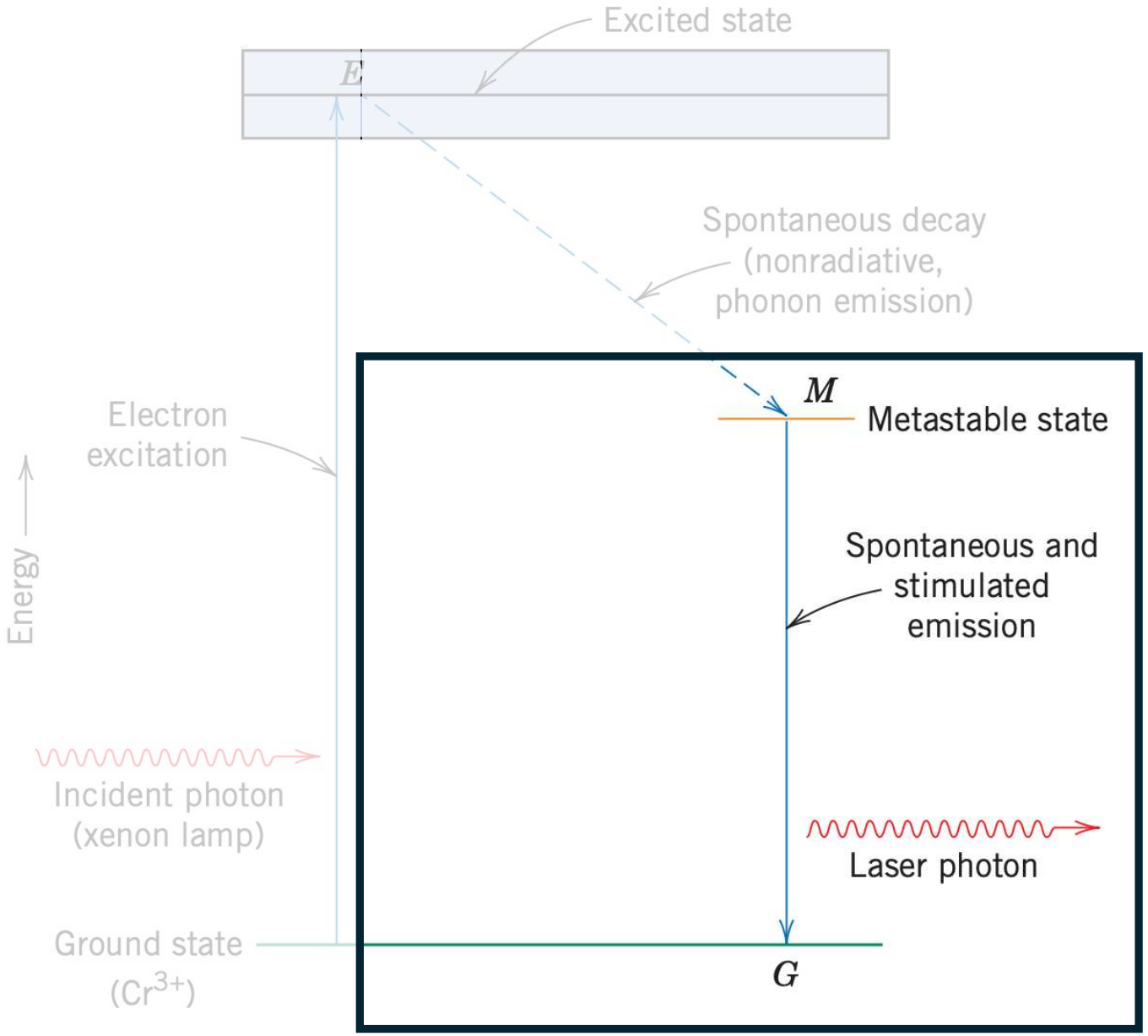


Step 1: illuminate the material to excite electrons into the conduction band

Step 2: these electrons relax down (releasing heat) into a **metastable state**

This happens *many* times, and the metastable state becomes **heavily populated…**

Lasers



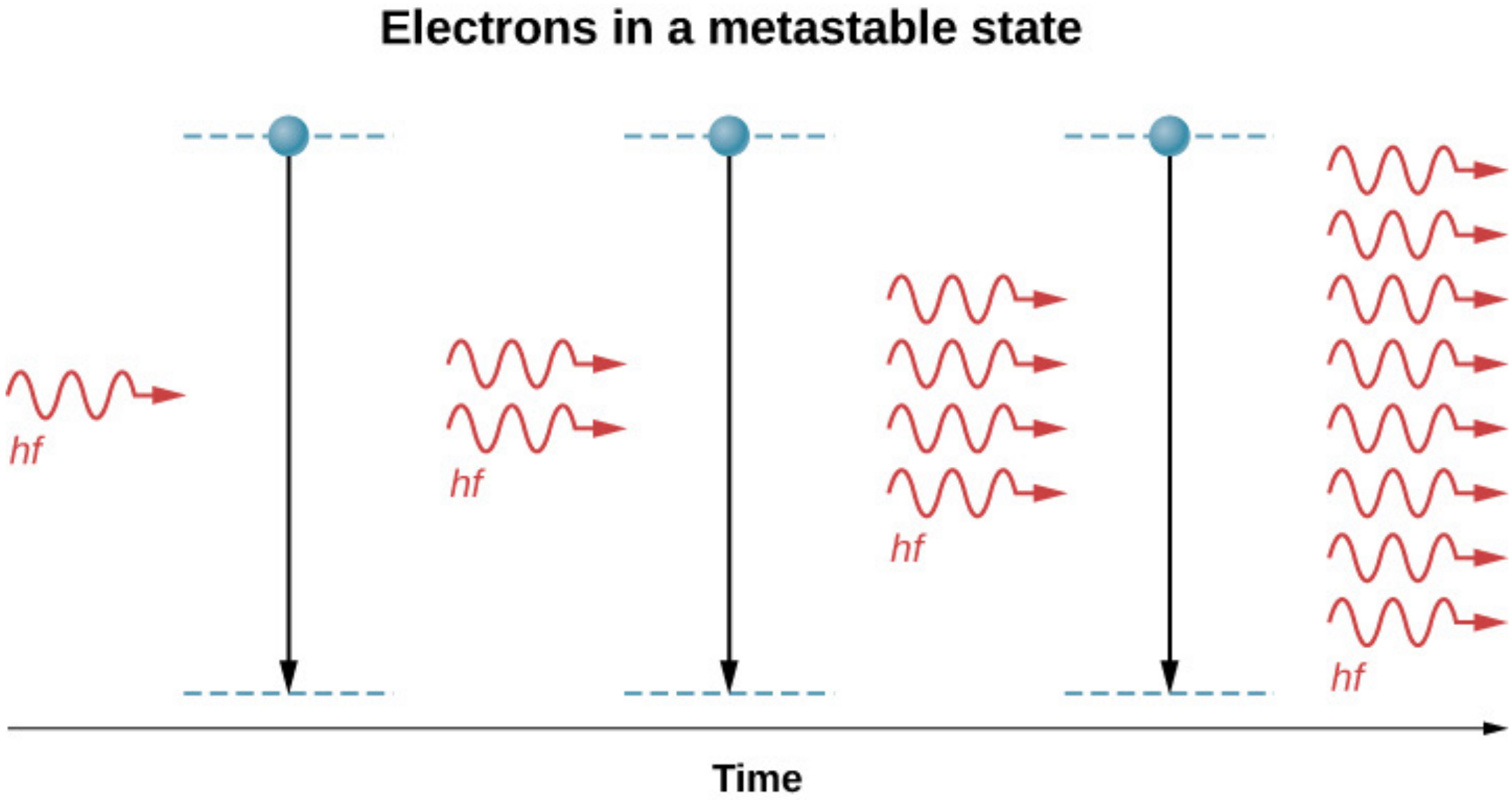
Step 1: illuminate the material to excite electrons into the conduction band

Step 2: these electrons relax down (releasing heat) into a **metastable state**

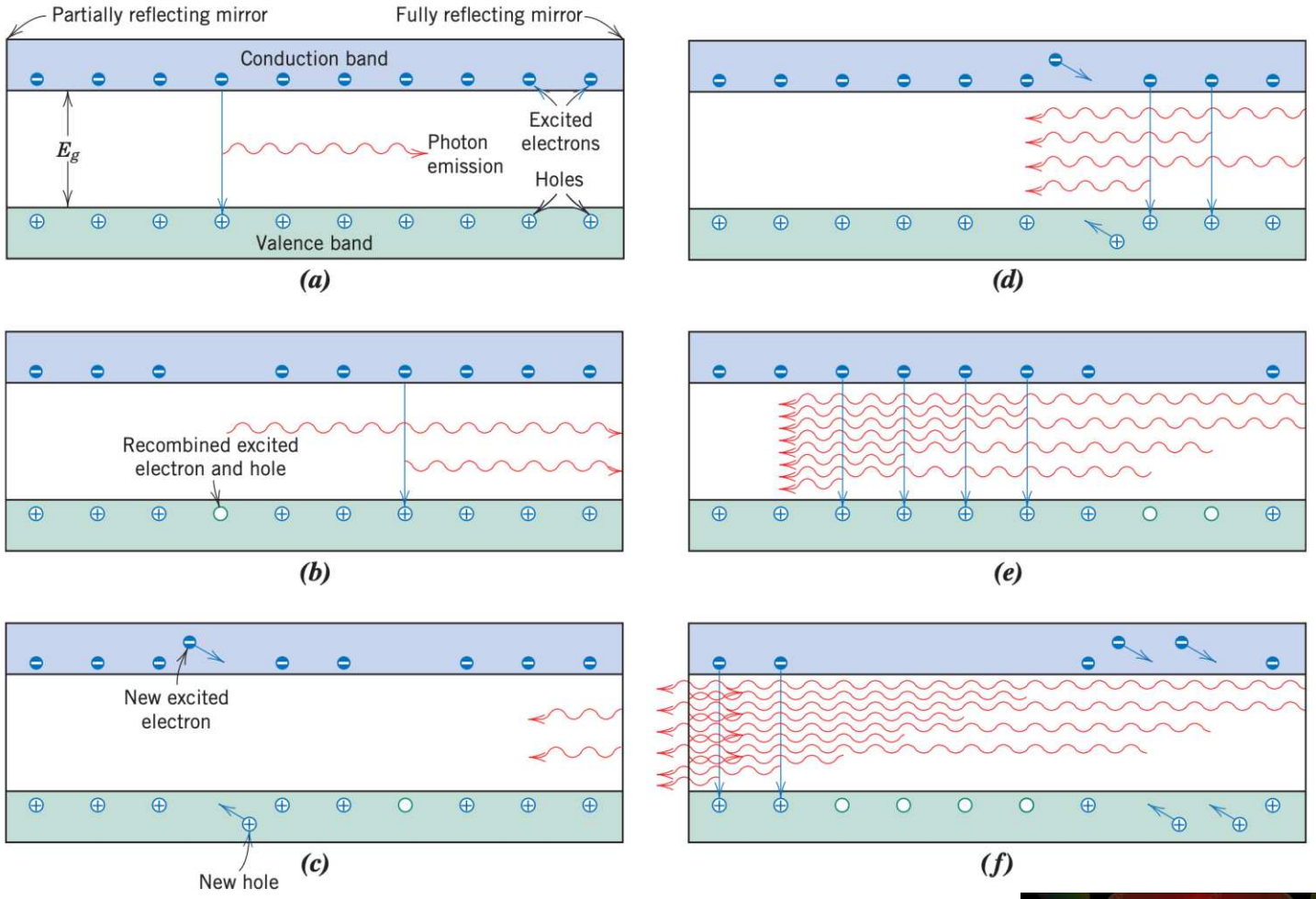
Step 3: after some time, a few initial electrons relax into the ground state**, releasing photons**

These photons stimulate an "avalanche" of subsequent photon emissions

Lasers

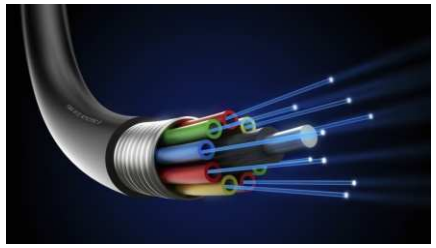


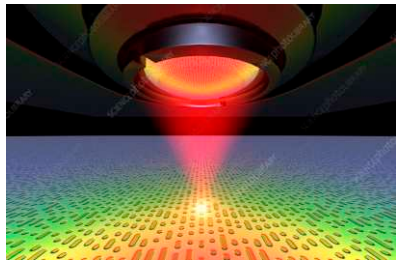
Lasers



Lasers are built in such a way that this stimulated emission builds up as photons bounce back and forth, eventually producing a very **intense** beam of photons that are **coherent and monochromatic**

Used in optical fibers, and for writing/cutting

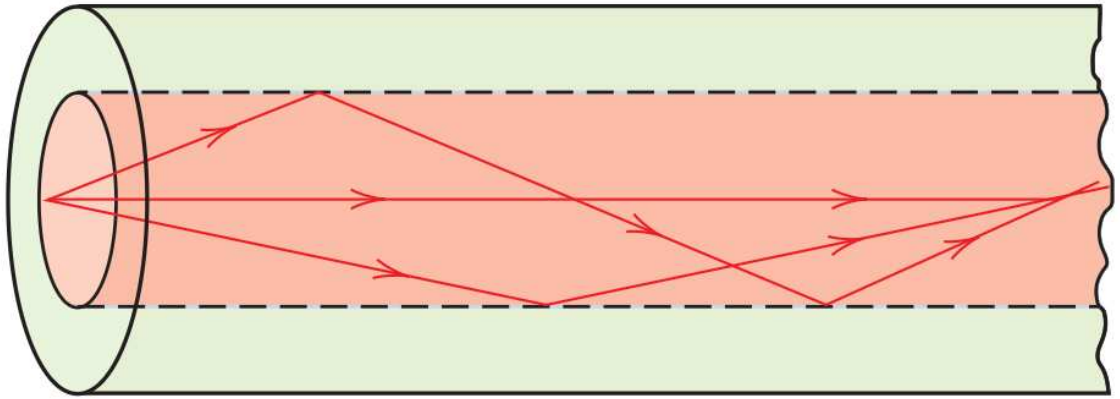






Optical fiber

Internet and telecommunication uses **optical fibers to transmit signal**

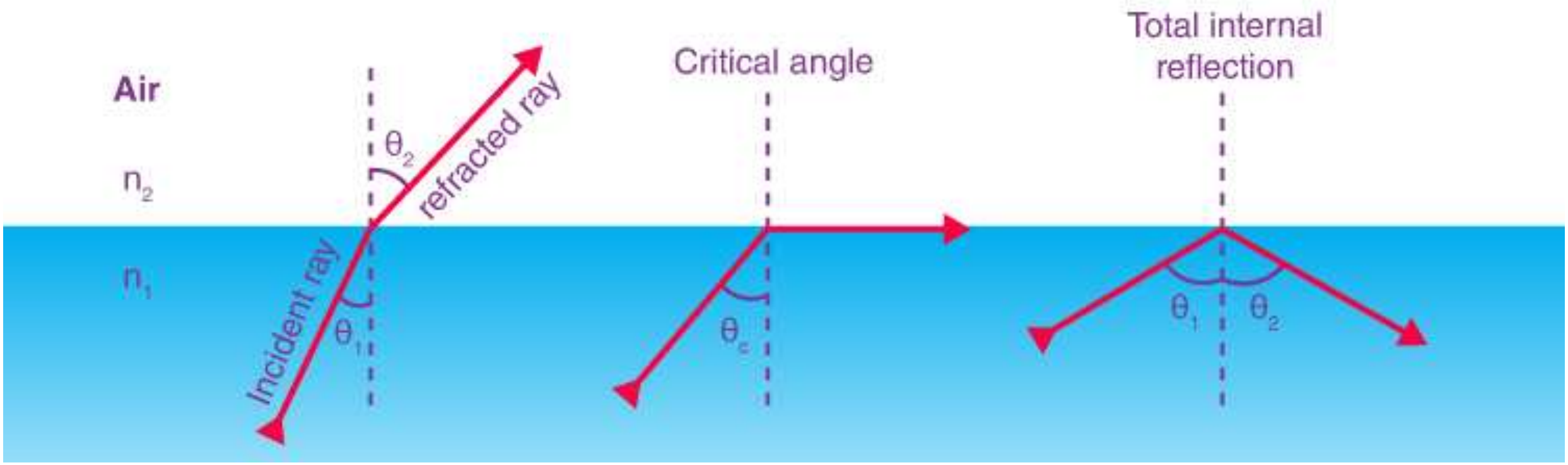


Doped silica with **lower n**

High-purity silica, 5-100 μm diameter

Signal (light from a laser source) is fed into the high-purity silica and transmitted with almost no loss due to **total internal reflection**

Total internal reflection



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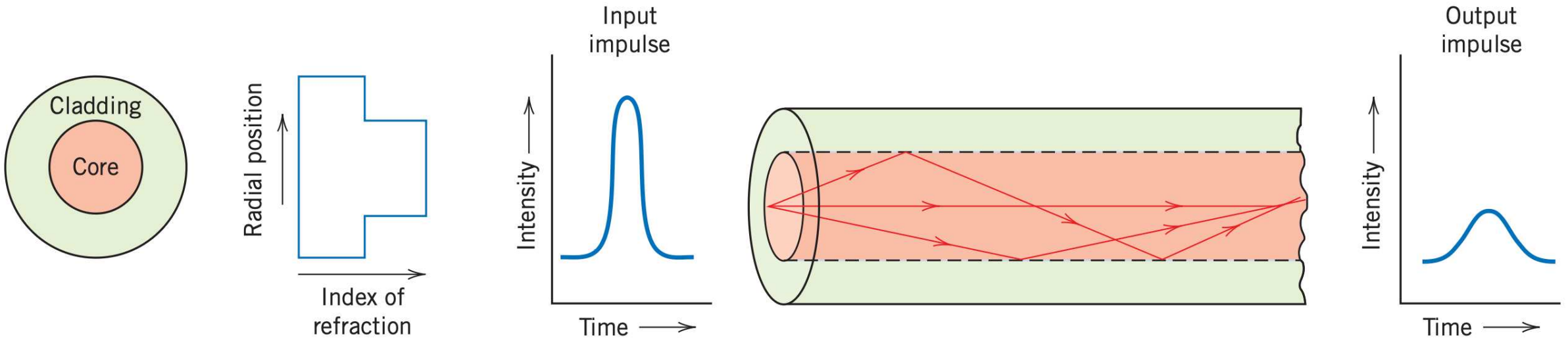
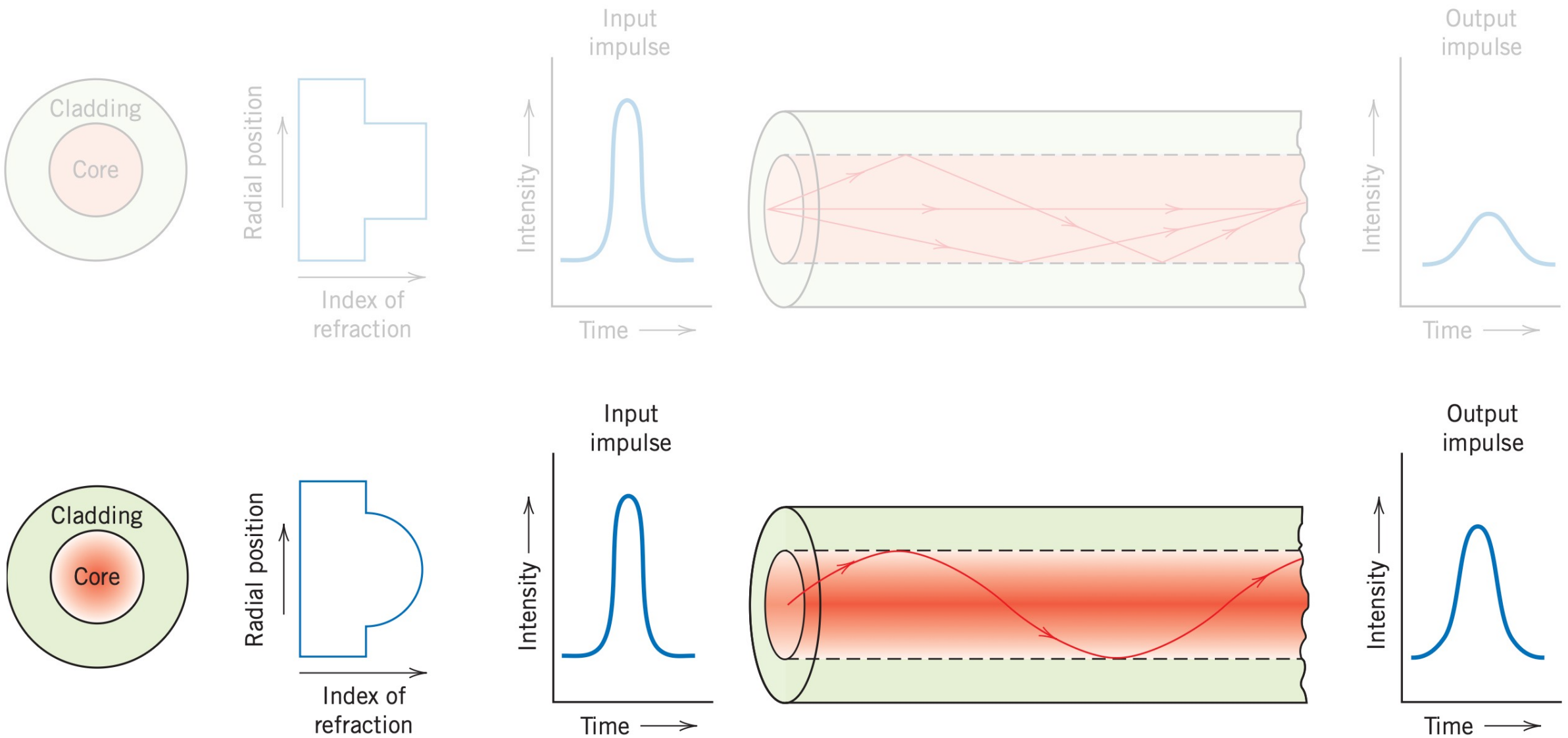
Optical fiber



In practice, there is *some* intensity loss due to imperfections at the sharp boundary

To solve this, we can instead use a ***graded* change in fiber composition**

Optical fiber



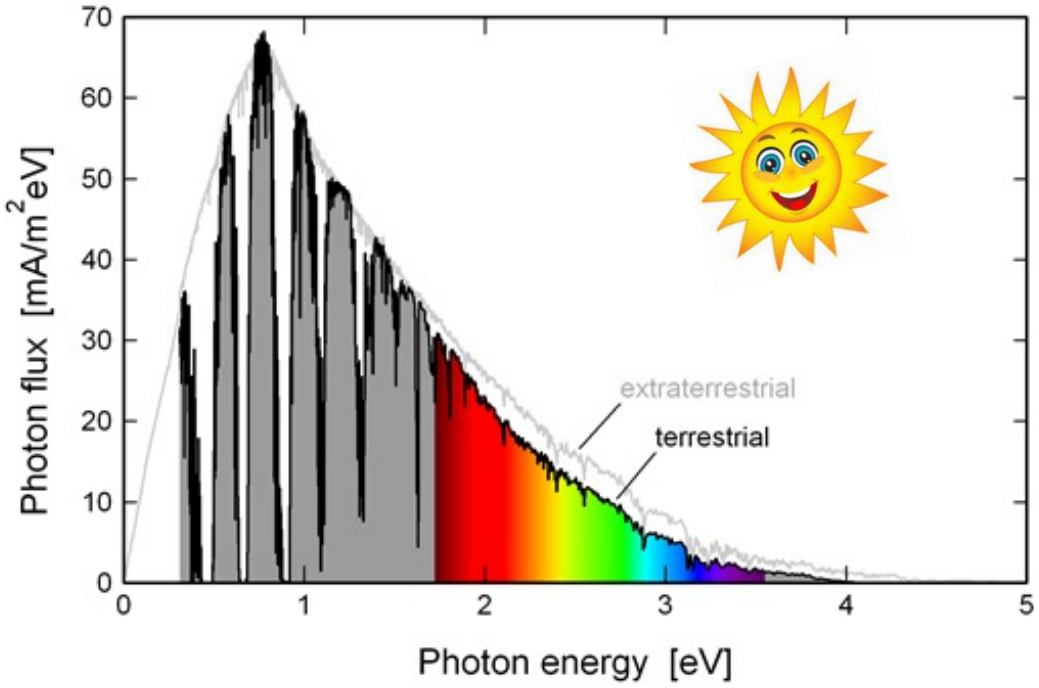
Questions on luminescence and lasers?

Solar cells

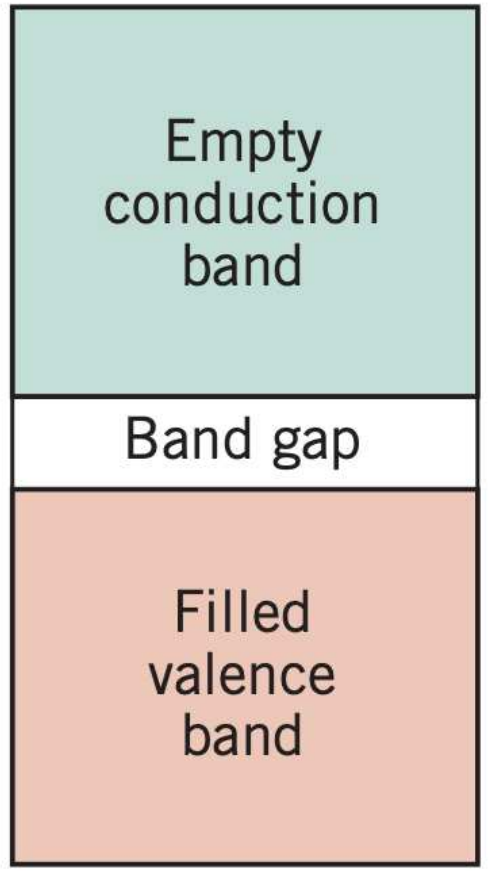


Objective: convert sunlight into electricity

- Semiconductors appear well suited for this, since they absorb photons in the visible-UV light range (*e.g.*, from the sun)



Absorption leads to electrons + holes; but how can we separate them and generate current?

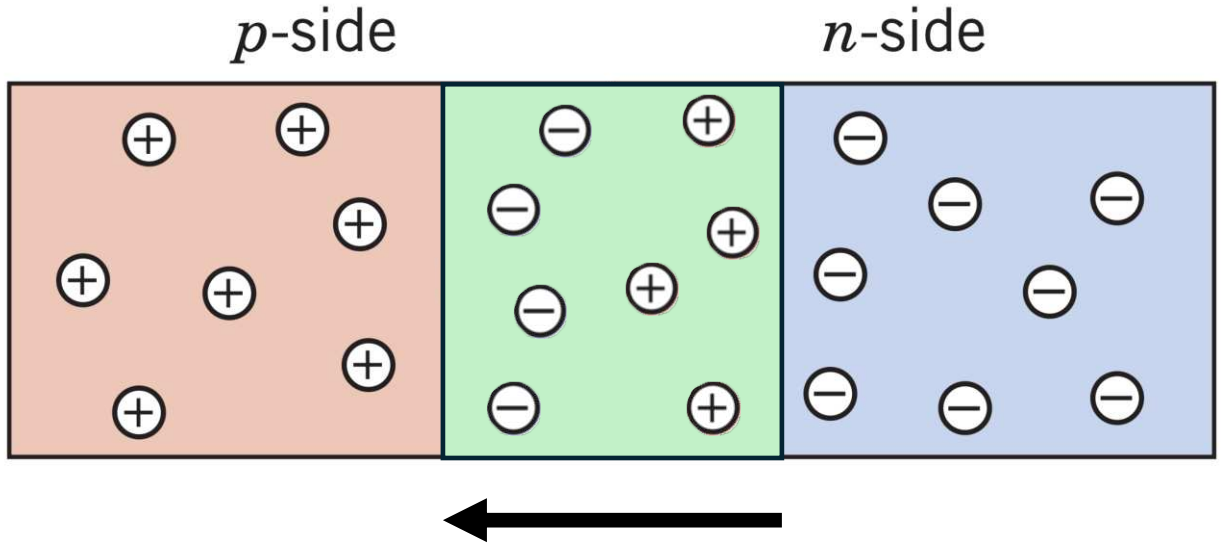


1-2 eV

Semiconductors

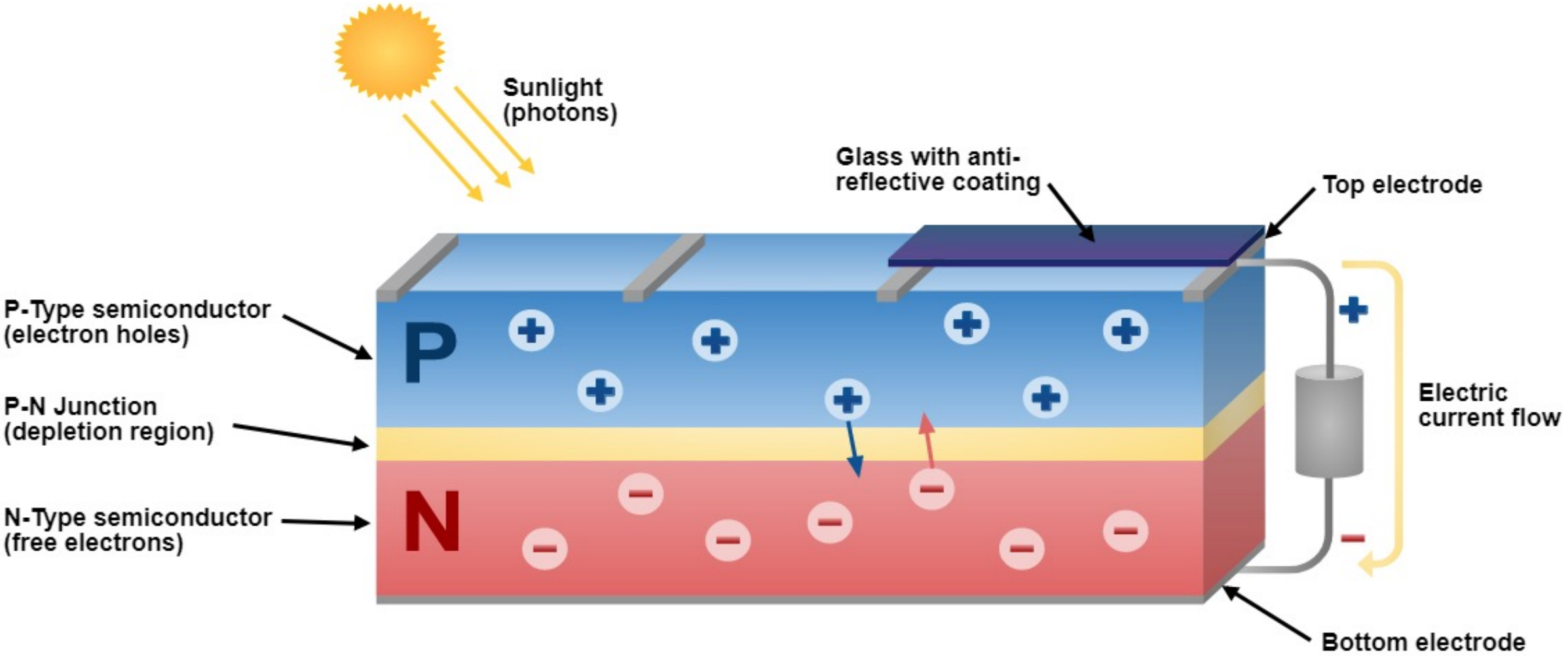
Solar cells

Objective: convert sunlight into electricity



Built-in electric field will separate newly created electrons and holes

Solar cells


Sunlight
(photons)
Glass with anti-
reflective coating
Top electrode
P-Type semiconductor
(electron holes)
P
P-N Junction
(depletion region)
N-Type semiconductor
(free electrons)
N
Electric
current flow
Bottom electrode

Some practice problems

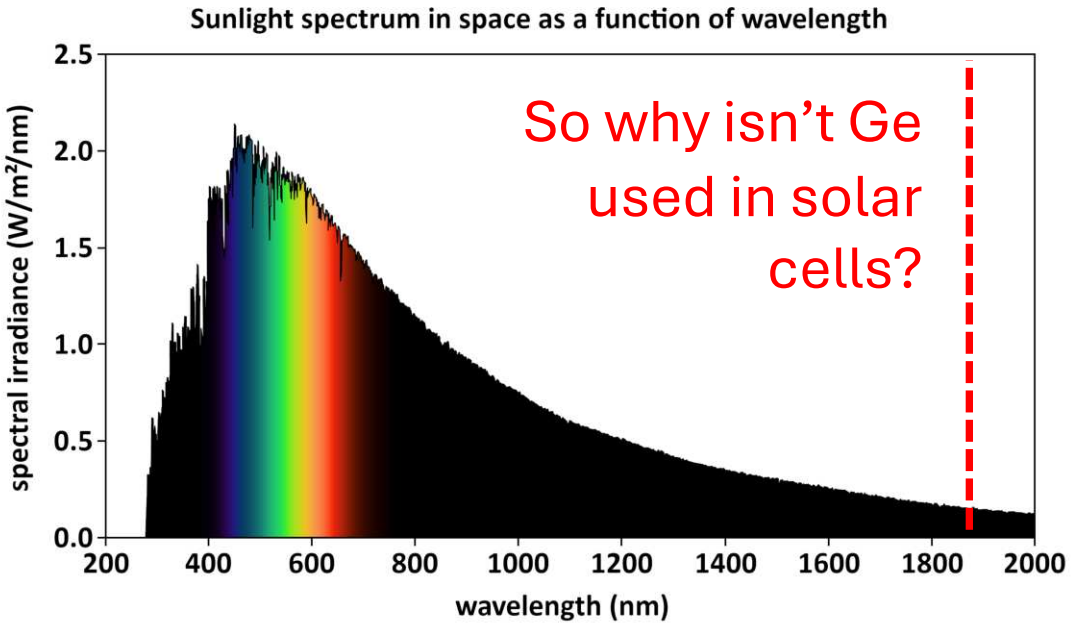
What is the **longest wavelength** absorbed by germanium ($\boldsymbol{E_{gap} \sim 0.67\ eV}$)?

$$E = h\nu = hc/\lambda$$

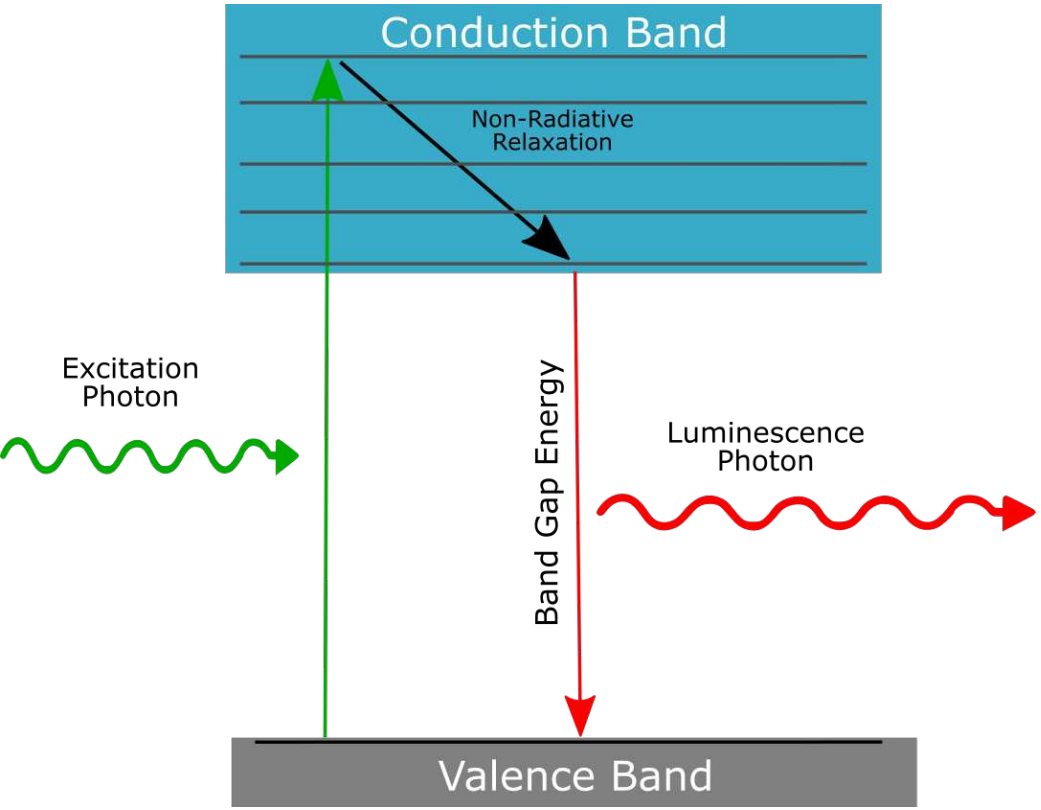
$$\lambda_{min} = \frac{hc}{E_{gap}} = \frac{(6.63\times10^{-34}\ \mathrm{J\cdot s})(3\times10^{8}\ \mathrm{m/s})}{(0.67\ \mathrm{eV})(1.6\times10^{-19}\ \mathrm{J/eV})} = 1.86\times10^{-6}\ \mathrm{m}$$

$$\boldsymbol{\lambda_{min} = 1860\ nm}$$

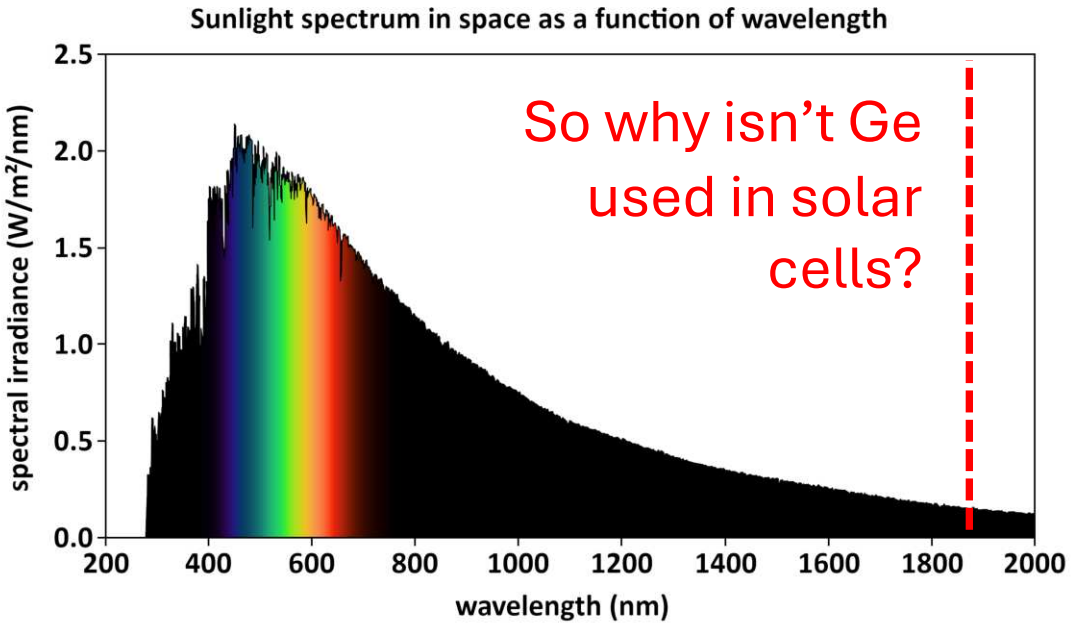
A rule of thumb for **eV-to-nm** conversion: $\boldsymbol{\lambda_{min} = \frac{1240}{E_{gap}}}$



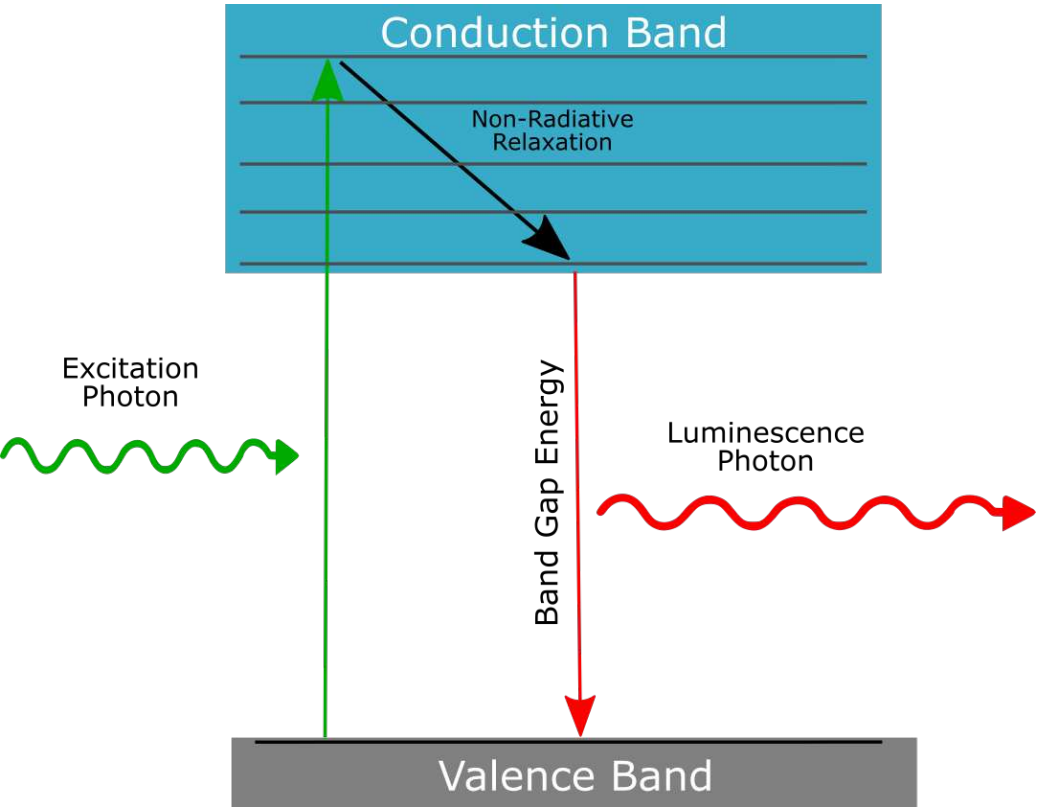
Some practice problems



- Much of the observed energy will be lost as heat
- The voltage drops as the band gap shrinks
- Electron-hole recombination is more frequent



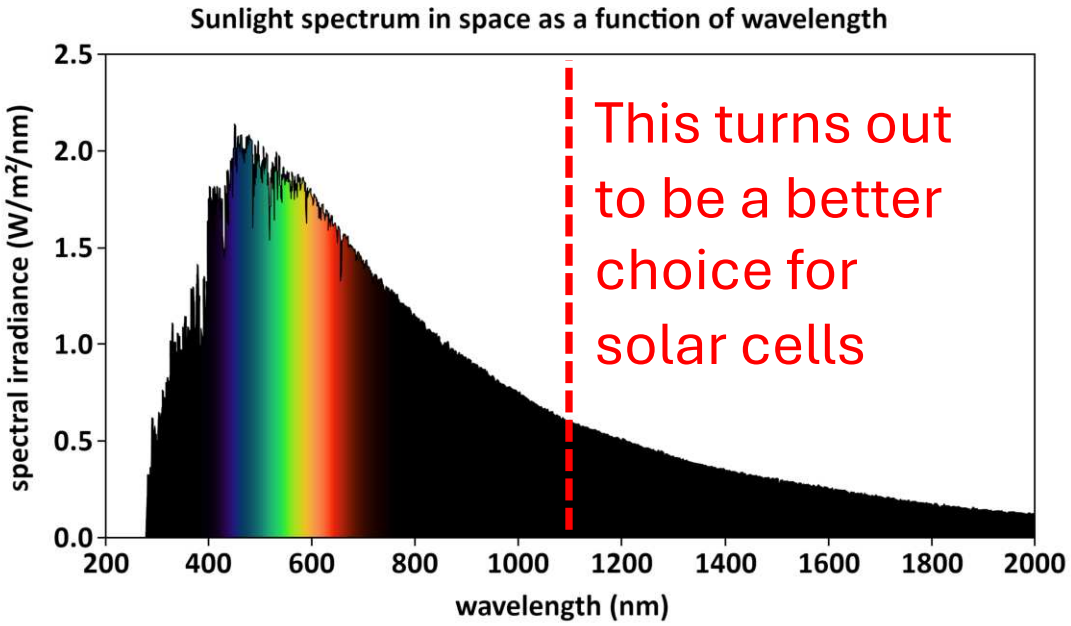
Some practice problems



- Much of the observed energy will be lost as heat
- The voltage drops as the band gap shrinks
- Electron-hole recombination is more frequent

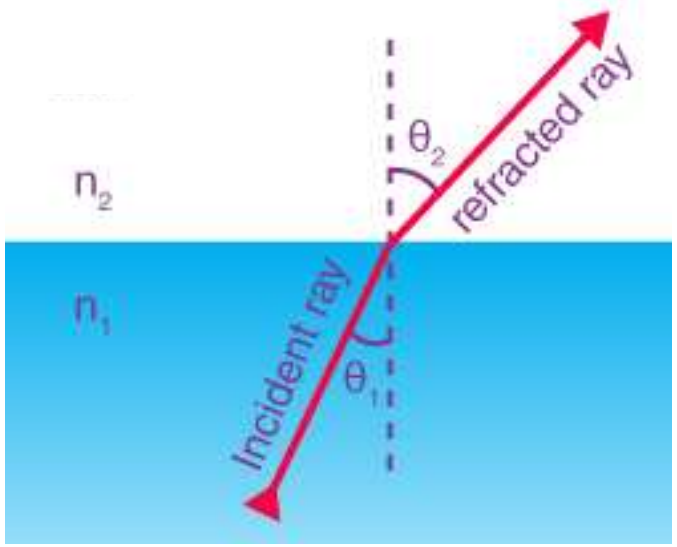
In contrast, silicon has

$E_{\mathbf{gap}} \sim 1.12\ \mathbf{eV} \sim 1107\ \mathbf{nm}$

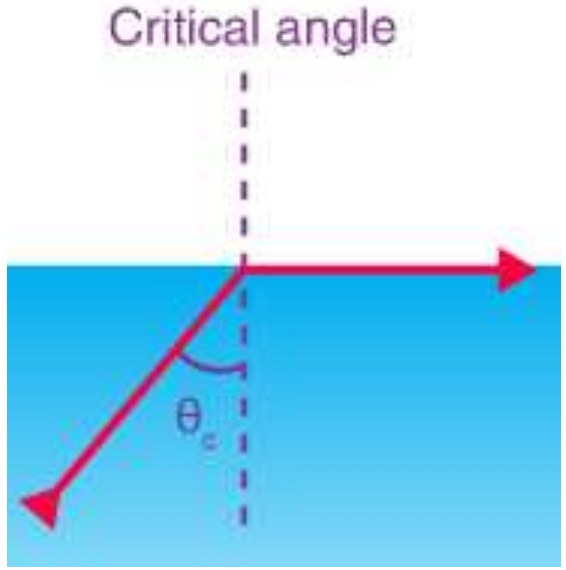


Some practice problems

Suppose we built a (very expensive) optical fiber made of diamond ($n = 2.41$) and surrounded by air. What is the critical angle for total internal reflection?



$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1}$$



Total internal reflection will begin when $\theta_2 = 90°$

$$\sin\theta_1 = \frac{n_2}{n_1}\sin\theta_2 = \frac{1}{2.41}\sin 90° = 0.414 \qquad \boldsymbol{\theta_1 = 24.5°}$$

Some practice problems

Consider **a 200-mm** film of glass that **transmits 98%** of all non-reflected light.

- What is the absorption coefficient of this material?
- What % of light would be transmitted if we tripled the film thickness?

$$I'_T = I'_0 e^{-\beta x}$$

$$\beta = -\frac{1}{x}\ln\left(\frac{I'_T}{I'_0}\right) \qquad \beta = -\frac{1}{200\ \text{mm}}\ln(0.98)$$

$$\boldsymbol{\beta = 1.01\times10^{-4}\ \text{mm}^{-1}}$$

At 600-mm thickness: $\frac{I'_T}{I'_0} = e^{-\beta x} = e^{(-1.01\times10^{-4}\ \text{mm}^{-1})(600\ \text{mm})} = \mathbf{94.1\%}$

Some practice problems

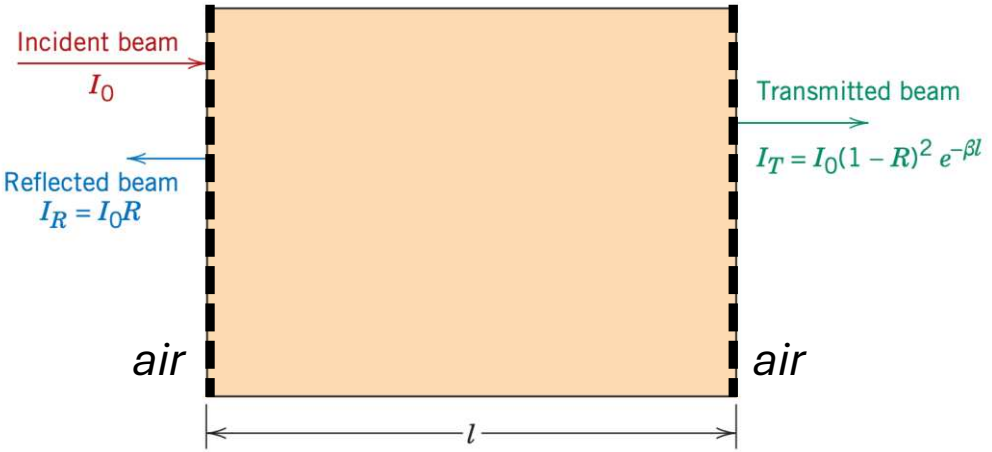
Consider **a 200-mm** film of glass that **transmits 98%** **of all non-reflected light.**

- What is the absorption coefficient of this material?
- What % of light would be transmitted if we tripled the film thickness?

If we account for reflection (R) at the interfaces, we should use this equation instead:

$$I_T = I_0 (1 - R)^2 e^{-\beta l}$$

$$R = \left(\frac{n_s - 1}{n_s + 1} \right)^2$$



Summary: what to know about optical properties

- How compute the fractions of transmitted, reflected, and absorbed light
- **The role of band gap in dictating absorption below some wavelength**
- **What makes a material appear a certain color?**
- Some math involving refraction