ECE 340 Lecture 13
Semiconductor Electronics

Spring 2022
10:00-10:50am
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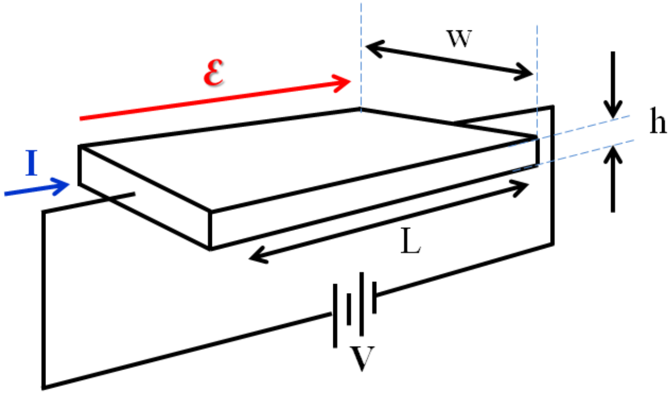
2062 ECE Building

Today's Discussion

- Optical absorption
- Excess carrier generation
- Direct Recombination of Electrons and Holes
- Steady State Carrier Generation
- Photoconductive Devices
- Quasi-Fermi Level

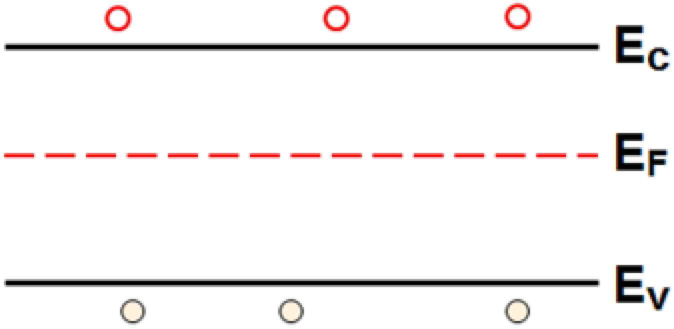
The key to many semiconductor devices

- **Generate charge carriers in excess of thermal equilibrium values.**



Example: intrinsic Si

- T = 300 K
- $n = n_i$
- $p = p_i$

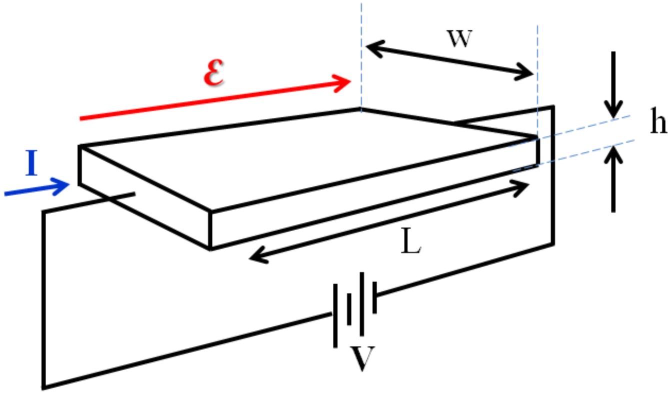


What happens if we connect a battery at the ends of a bar made of intrinsic Si? (assume ohmic contacts)

V = 10 V
L = 1.0 cm
A = h x w = 1.0 mm^2

There is not much of a current

- **Resistivity**



$$\rho = \frac{1}{q\mu_n n_i + q\mu_p n_i} = \frac{1}{qn_i\left(\mu_n + \mu_p\right)} =$$

$$= \frac{1}{1.6\times10^{-19}\times1.5\times10^{10}\left(1350+480\right)} = 227.4\ \mathrm{k\Omega\cdot cm}$$

$$R = \rho\frac{L}{A} = 227.4\times10^{3}\,\frac{1.0}{10^{-2}} = 22.74\times10^{6} = 22.74\ \mathrm{M\Omega}$$

$$I = \frac{V}{R} = \frac{10}{22.74\times10^{6}} = 0.44\,\mu\mathrm{A}$$

Can we increase the current somehow (i.e. increase carrier concentration)?

Some possible ways

We already know at least two ways:

- **Increase the temperature**
- **Introduce doping in the semiconductor to enhance free carriers**

(both imply increased scattering and lower mobility)

These modalities do not introduce “excess carriers” but rely on establishing a new equilibrium condition

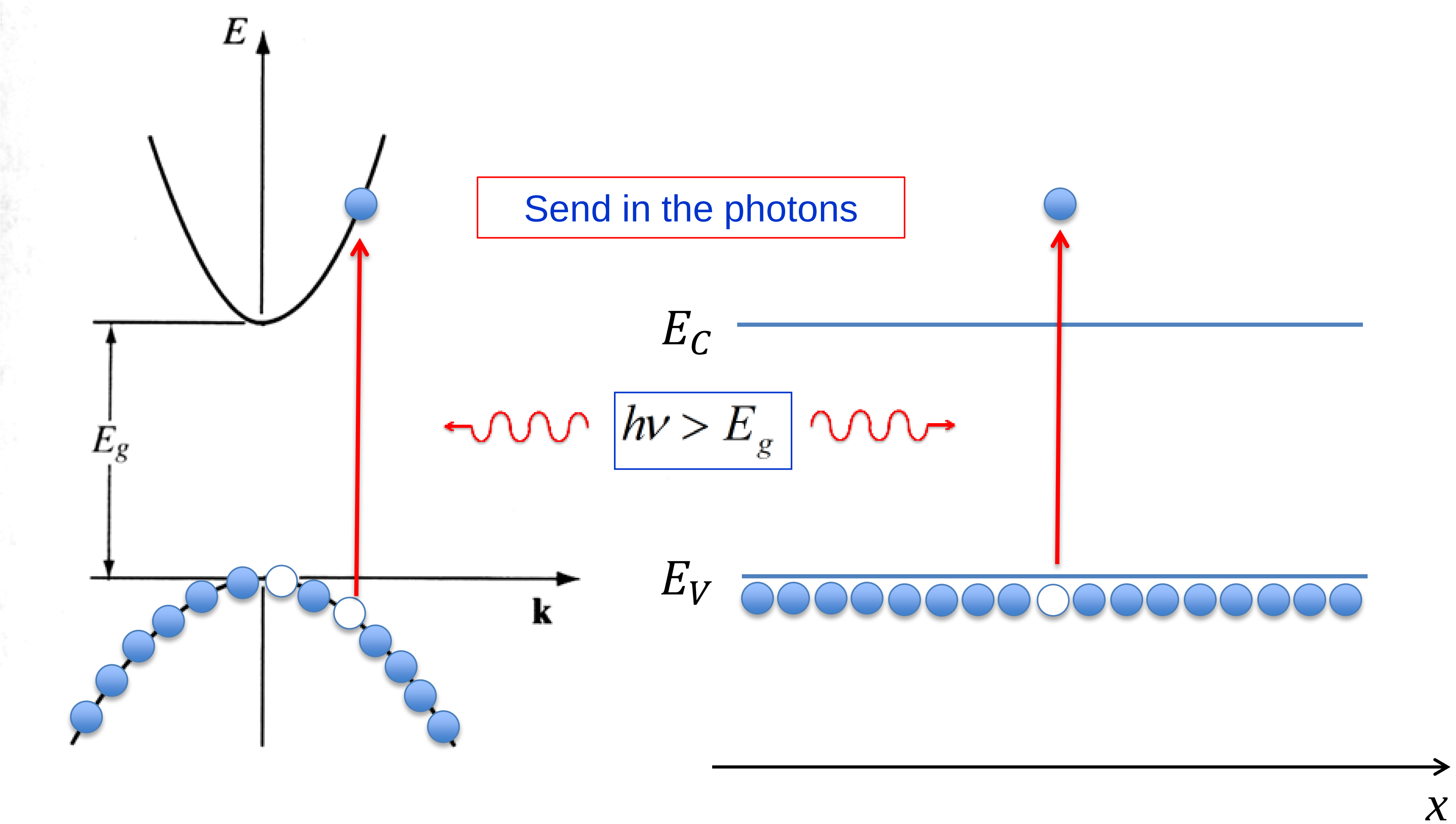
Shine EM waves (e.g., light) with photon Energy > Band gap

Field Effect: accumulate carriers with a “capacitive” structure

Design a structure that injects carriers from one region to another

Design a structure that energizes free carriers to knock off a lot of electrons from the valence band (and corresponding hole creation) with an “avalanche” multiplication process (impact ionization)

Let’s try light



Send in the photons

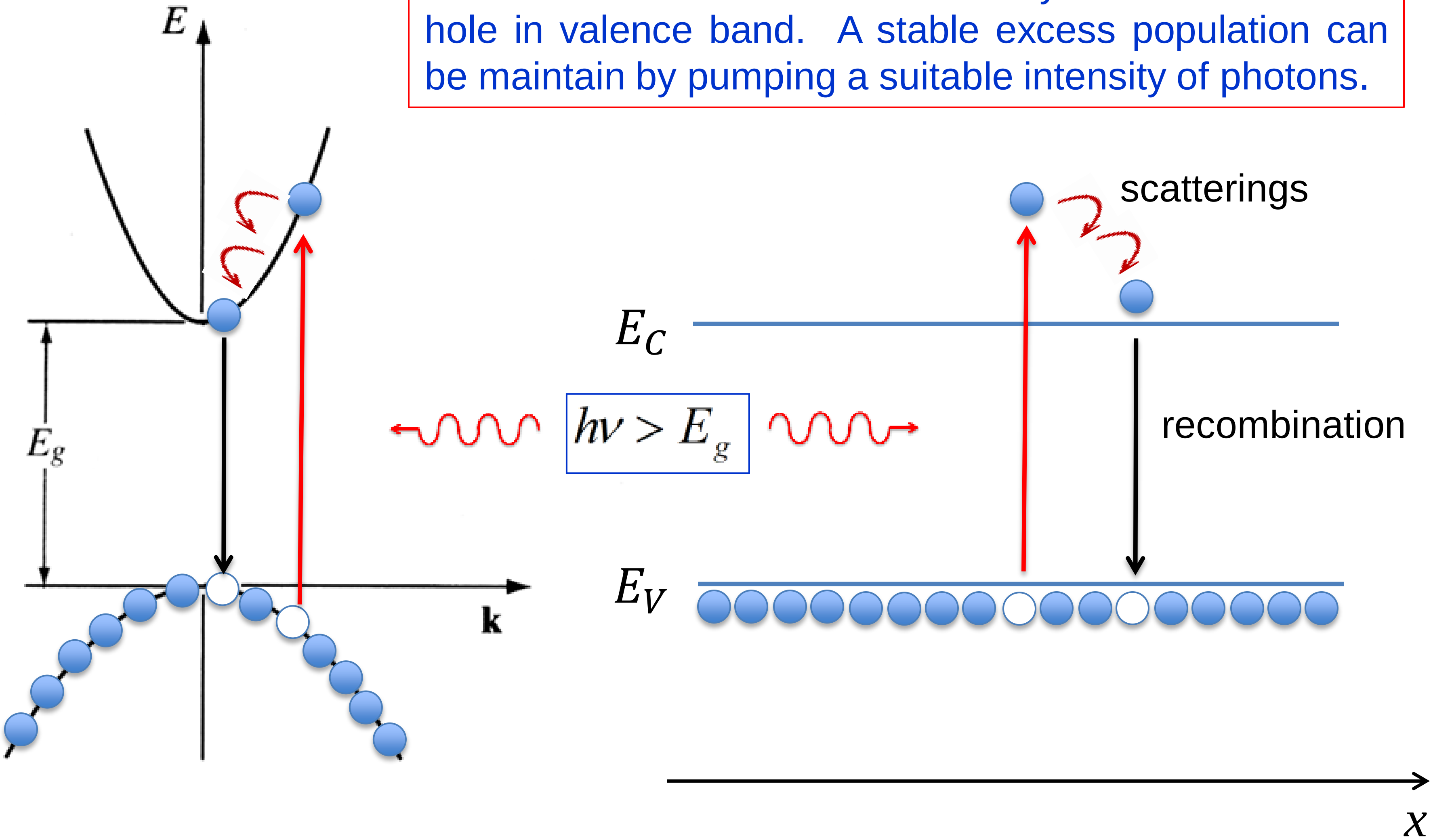
$h\nu > E_g$

Momentum space

Real space

Let’s try light

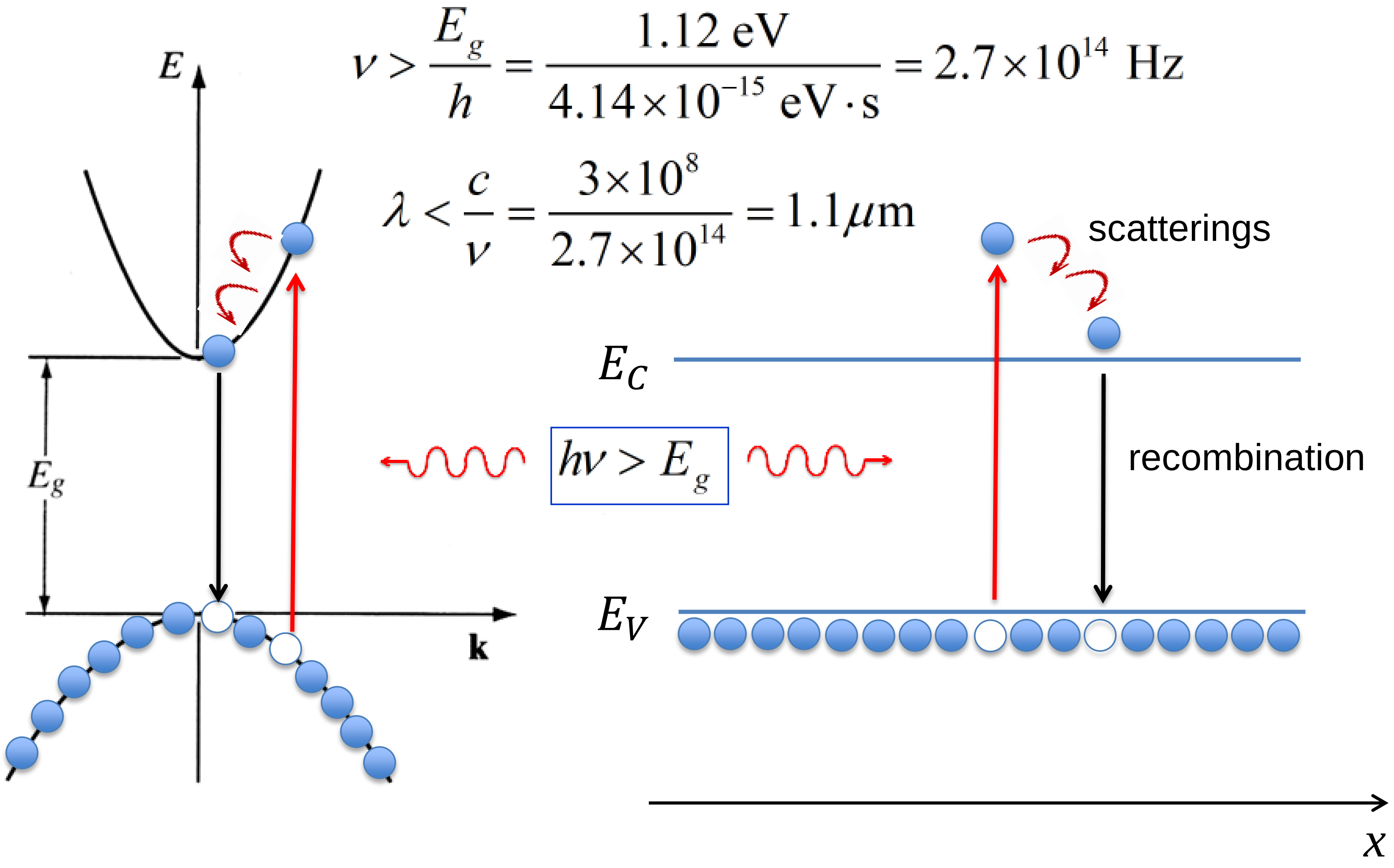
The excited electron will eventually recombine with a hole in valence band. A stable excess population can be maintain by pumping a suitable intensity of photons.



Momentum space

Real space

Let’s try light



$$\nu > \frac{E_g}{h} = \frac{1.12\ \text{eV}}{4.14\times10^{-15}\ \text{eV}\cdot\text{s}} = 2.7\times10^{14}\ \text{Hz}$$

$$\lambda < \frac{c}{\nu} = \frac{3\times10^{8}}{2.7\times10^{14}} = 1.1\mu\text{m}$$

$$\boxed{h\nu > E_g}$$

Momentum space

Real space

You can also use the handy formula

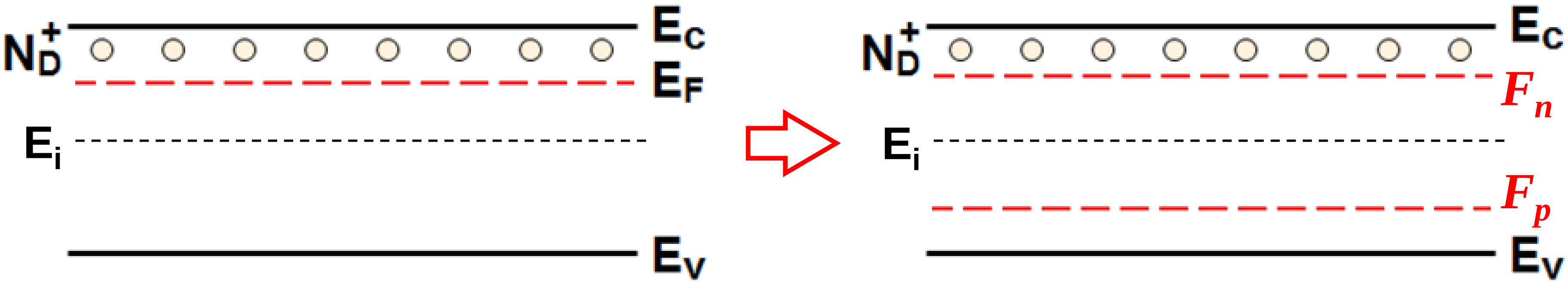
$$\lambda_0 = \frac{1.24}{E_g[\mathrm{eV}]} = [\mu\mathrm{m}] = \frac{1240}{E_g[\mathrm{eV}]}[\mathrm{nm}]$$

Keep in mind that this formula is for wavelength in vacuum

But what happens to the Fermi Level?

If we generate excess carriers so that $\Delta n = \Delta p > n_o, p_o$

F_n, F_p } Quasi-Fermi levels



n-type

$$n_0 = n_i e^{(E_F - E_i)/kT}$$

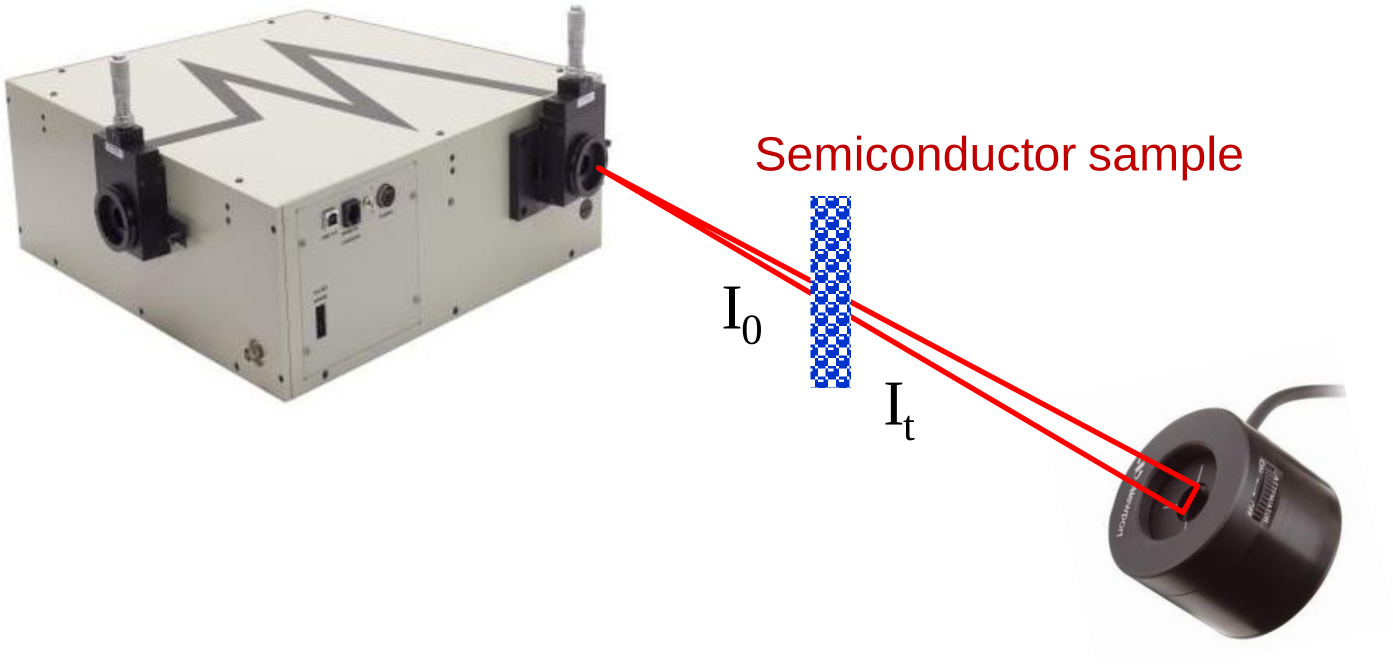
$$p_0 = n_i e^{(E_i - E_F)/kT}$$

$$n = n_i e^{(F_n - E_i)/kT}$$

$$p = n_i e^{(E_i - F_p)/kT}$$

Optical Absorption

Newport CS260 Monochromator + wide spectrum lamp
Select frequency with diffraction gratings



Semiconductor sample

I_0

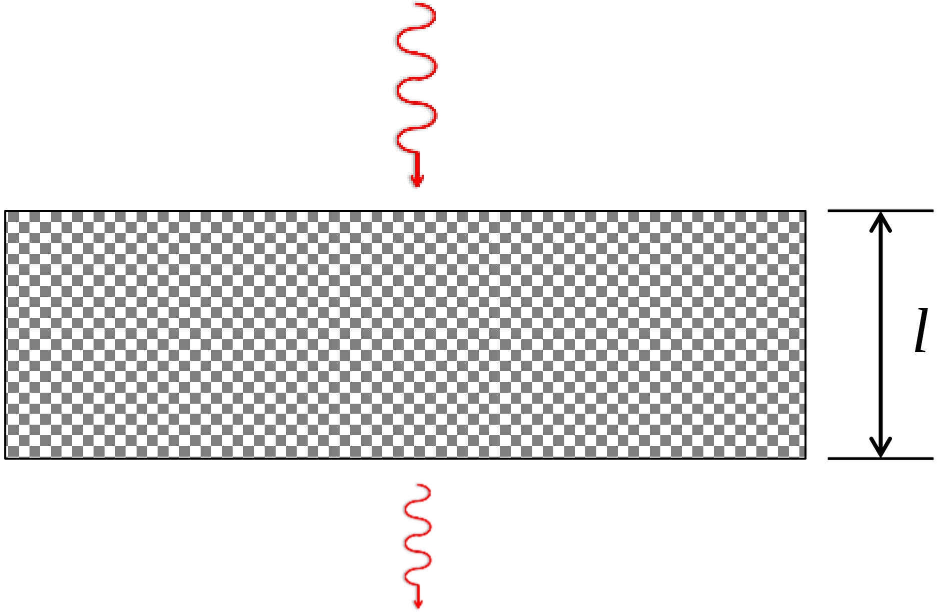
I_t

Newport 918D Photodiode Sensor

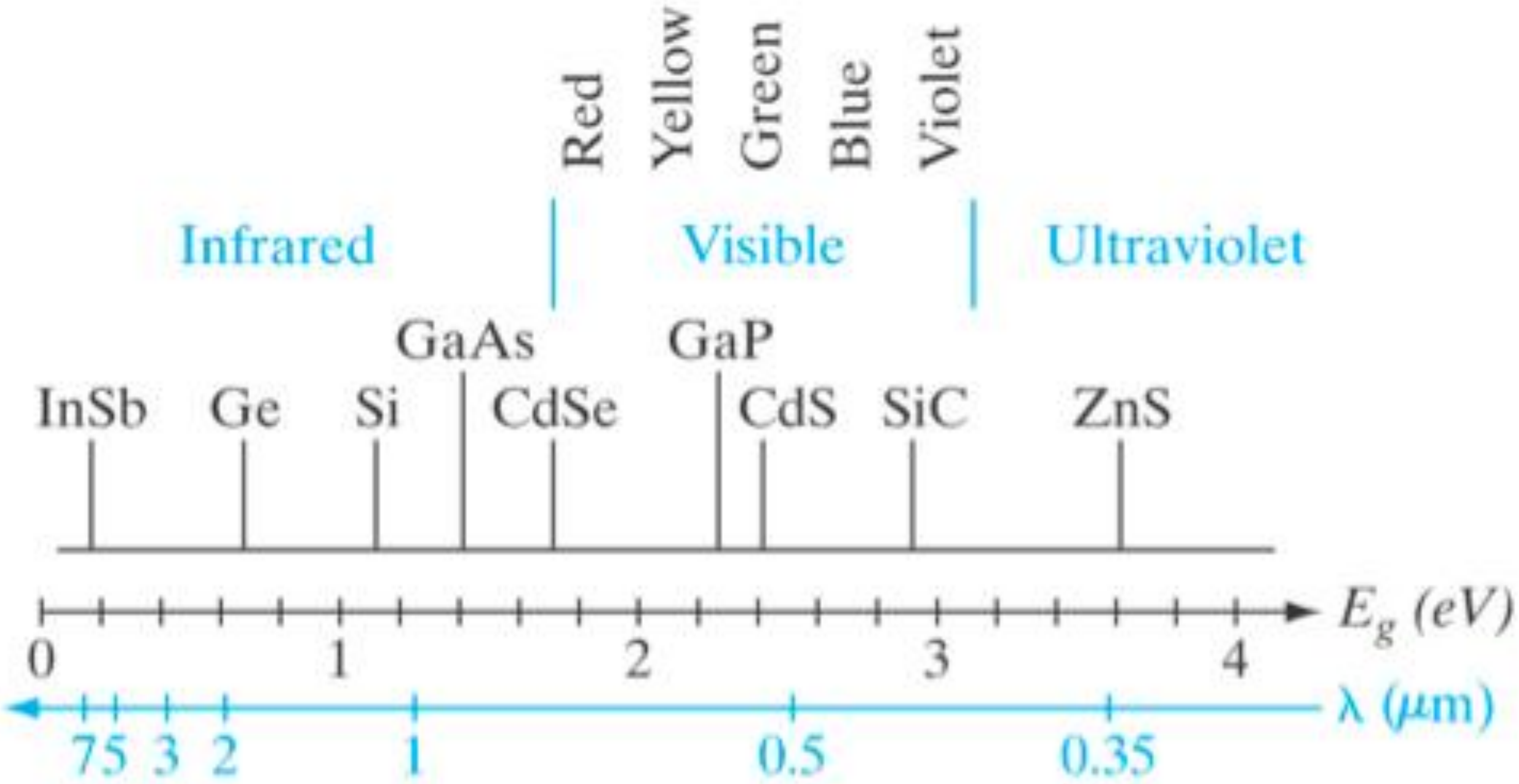
As the beam travels in the semiconductor it is absorbed at a rate proportional to the intensity

Optical Absorption

$h\nu > E_g$



Wavelengths and band gaps



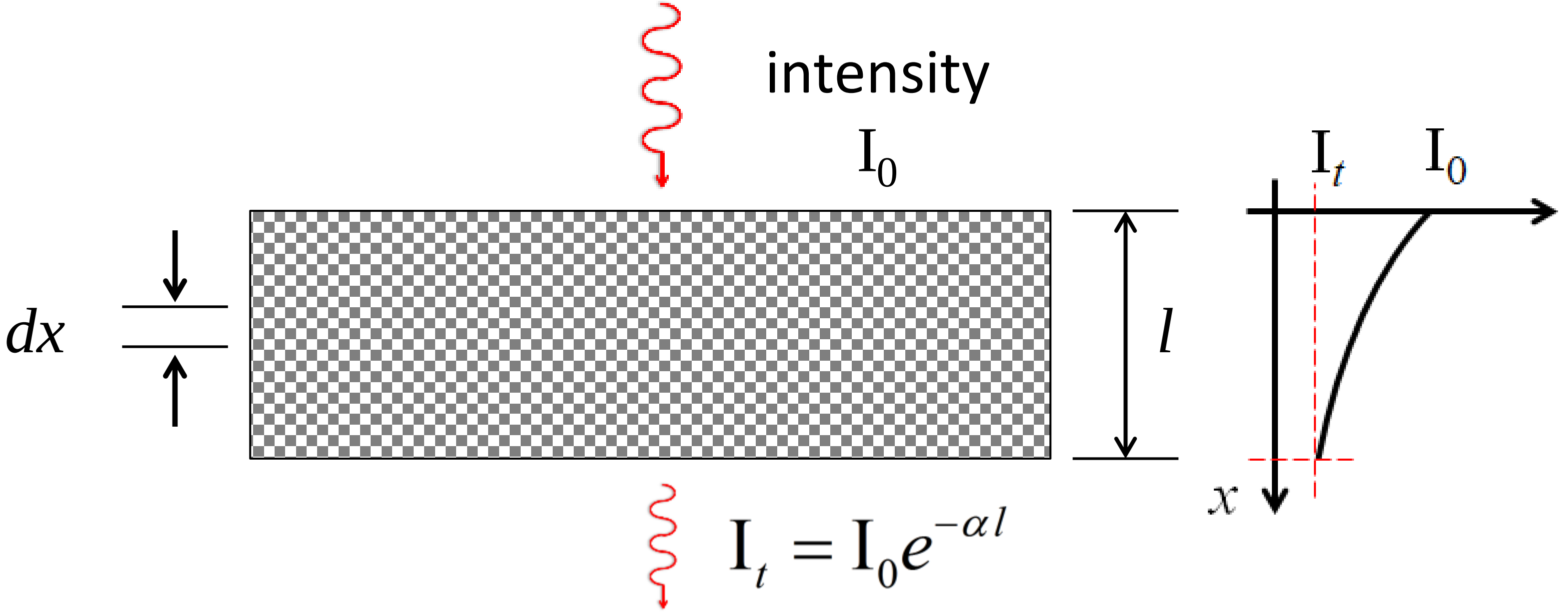
From *Solid State Electronic Devices,* Sixth Edition, by Ben G. Streetman and Sanjay Kumar Banerjee.
ISBN 0-13-149726-X.

Optical Absorption

I_0 [photons/cm^2-s]

α = absorption coefficient

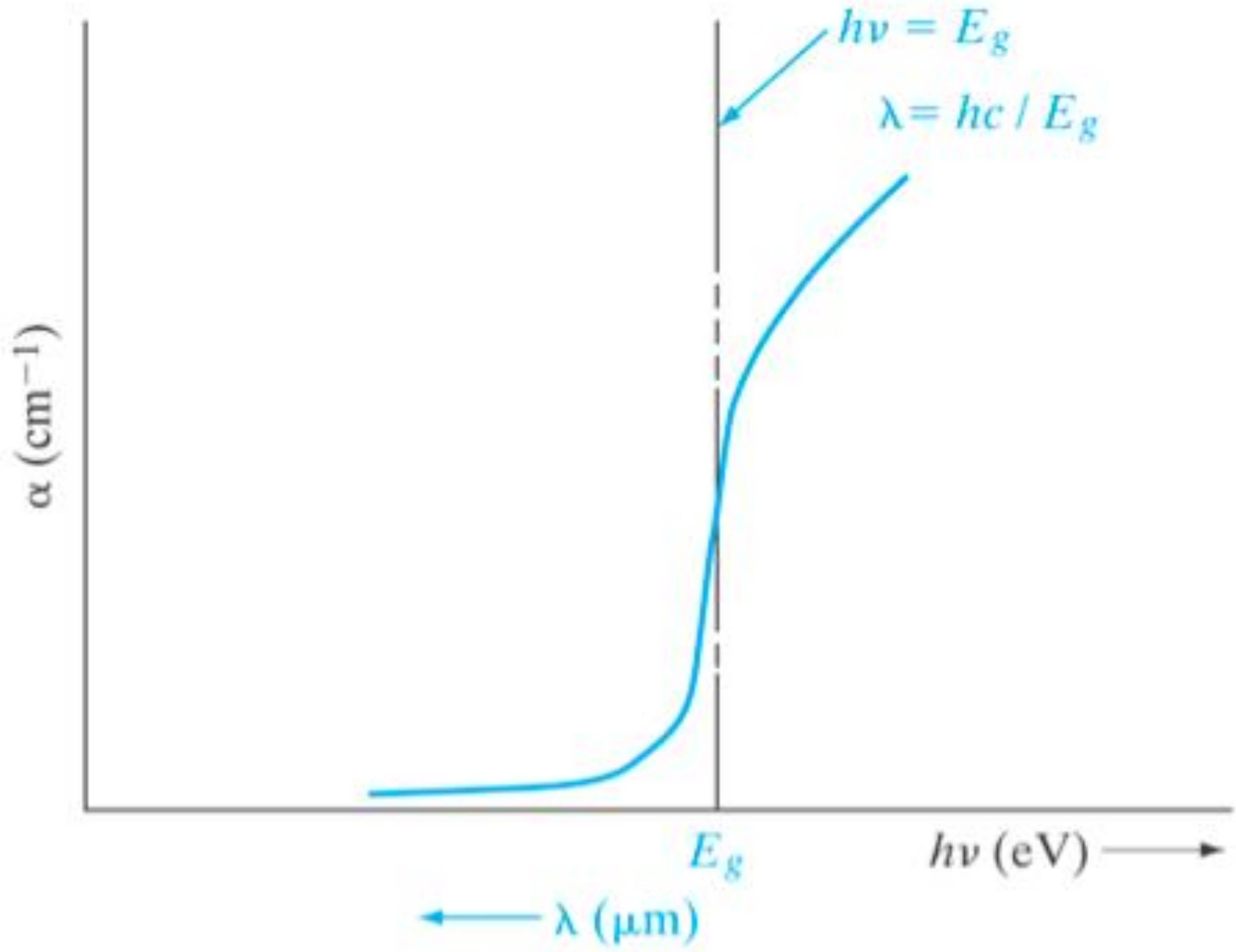
$$\boxed{h\nu > E_g}$$



$$I_t = I_0 e^{-\alpha l}$$

$$-\frac{d\,I(x)}{dx} = \alpha\, I(x) \quad \Longrightarrow \quad I(x) = I_0 e^{-\alpha x}$$

Optical Absorption Coefficient



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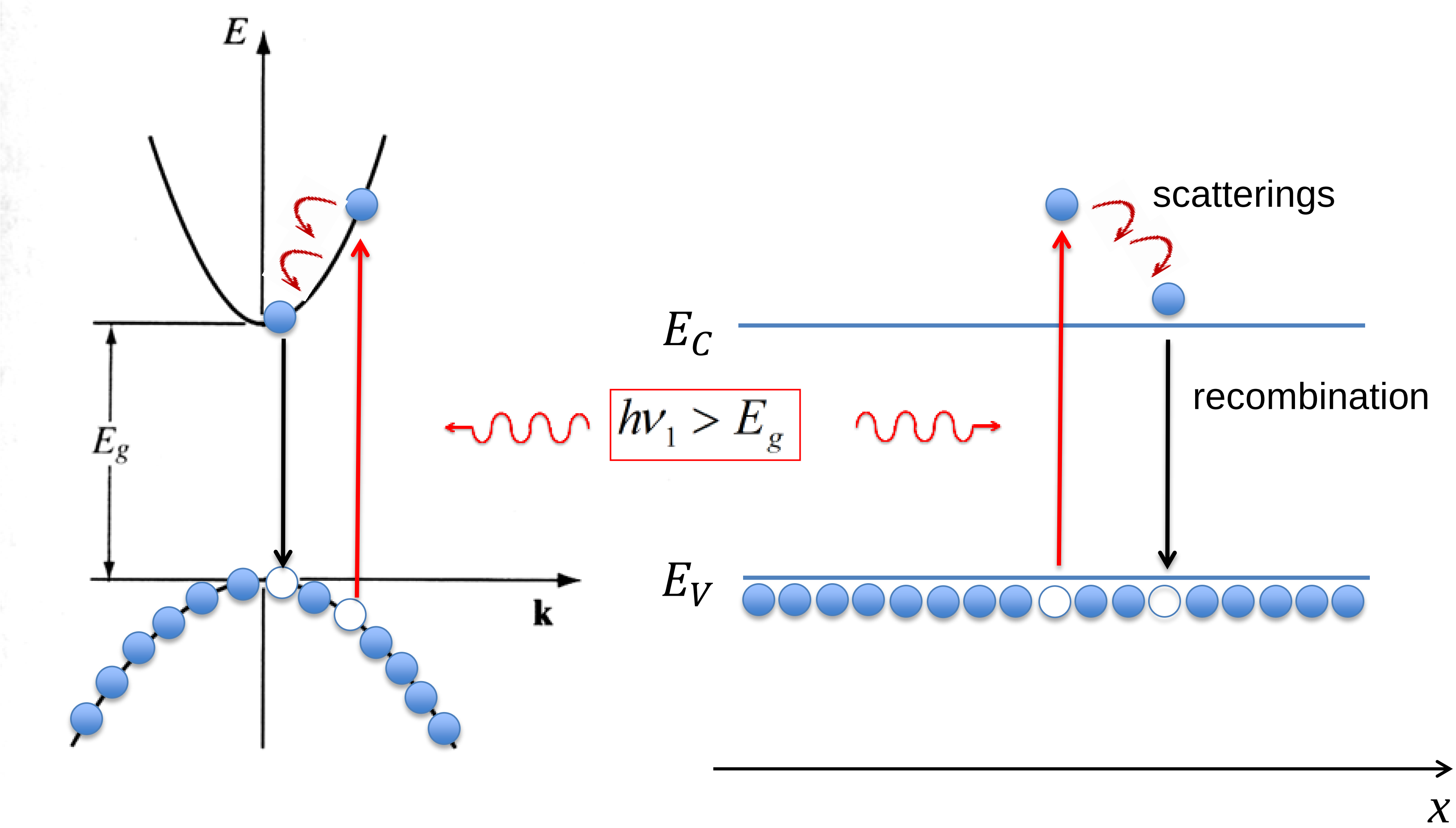
The competing process is recombination

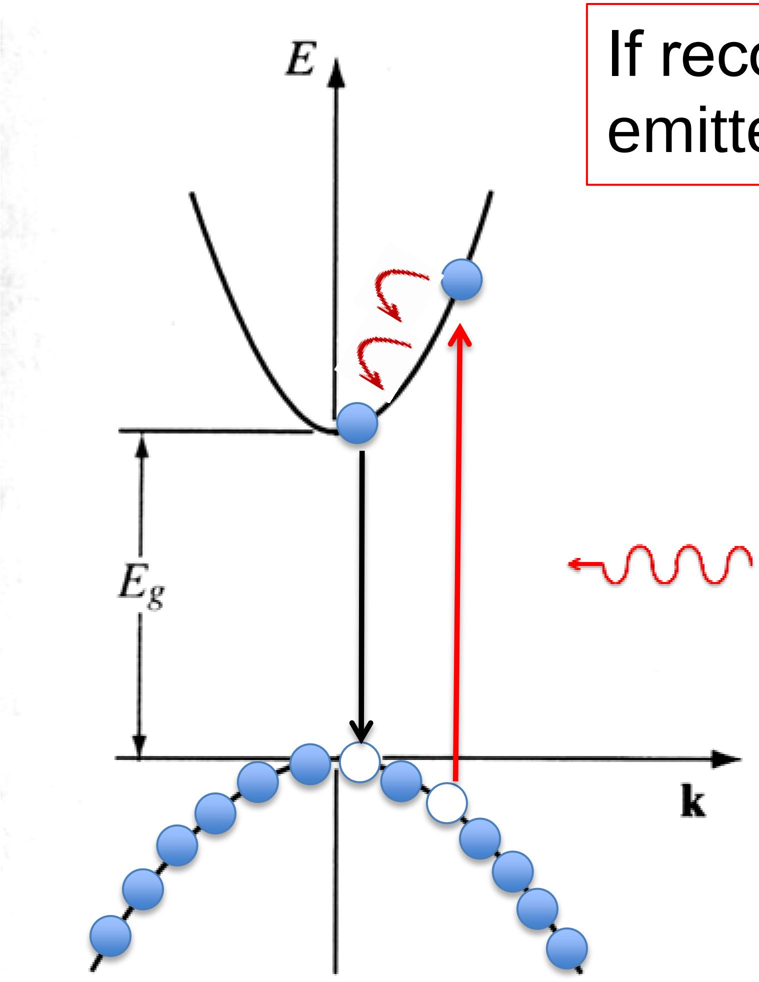


Momentum space

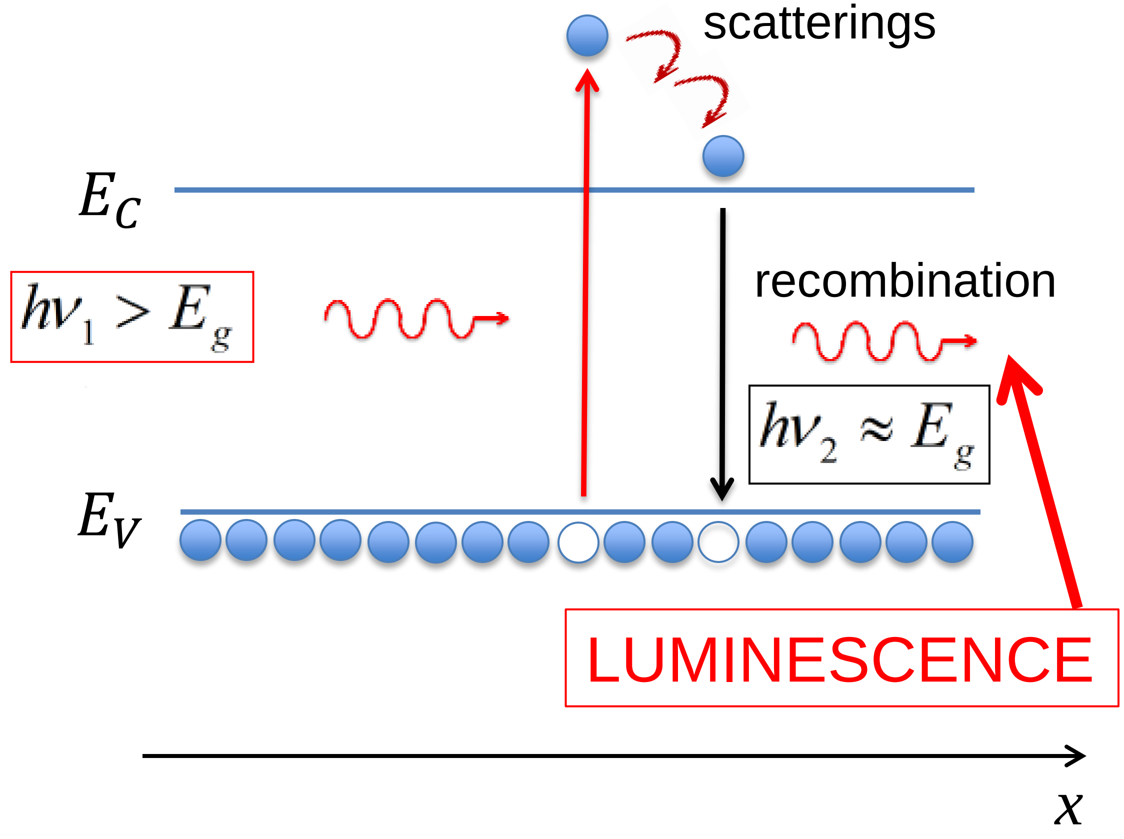
Real space

The competing process is recombination

If recombination is “radiative” a photon is emitted with frequency $\nu_2 \approx E_g/h$



Momentum space



Real space

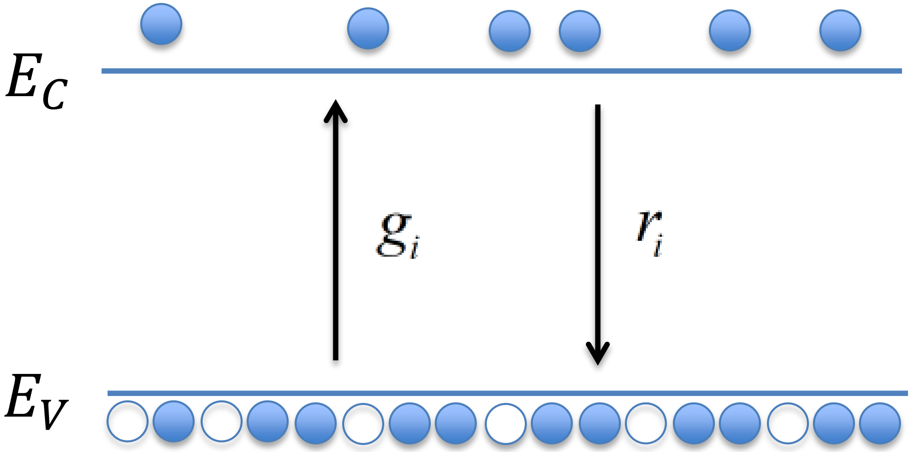
Recombination of Electrons and Holes

Thermal recombination rate = thermal generation rate

$$r_i = \alpha_r n_o p_o = \alpha_r n_i^2 = g_i$$

α_r is a proportionality constant that depends on the recombination mechanism

(NOTE – this is **NOT** the same as $\boldsymbol{\alpha}$ **=** absorption coefficient **)**



Recombination of Electrons and Holes

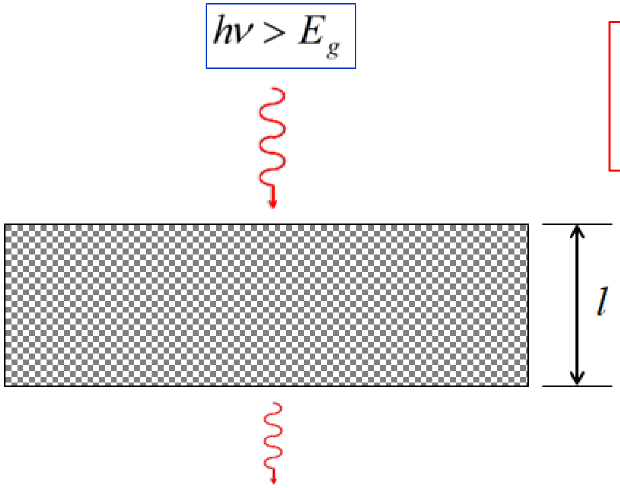
In equilibrium

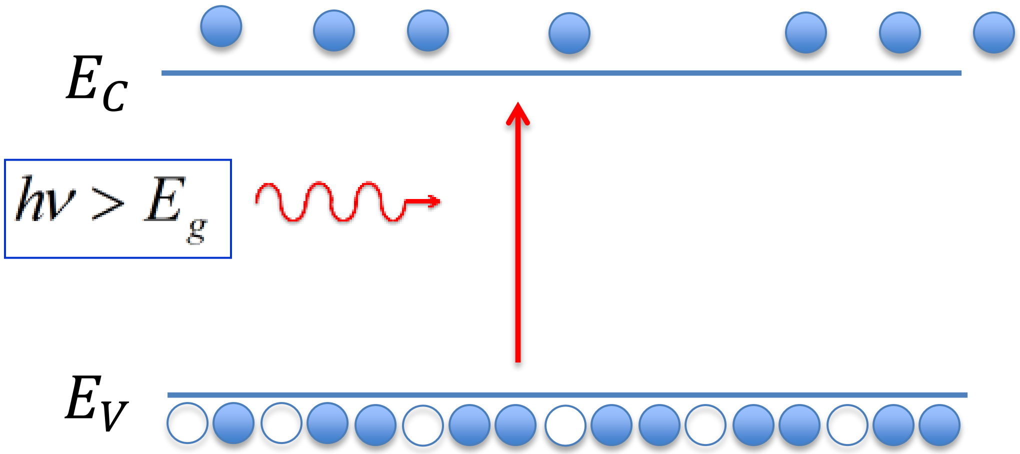
$$0 = \underbrace{\alpha_r n_i^2}_{\substack{\text{thermal}\\ \text{generation}}} - \underbrace{\alpha_r n_i^2}_{\text{recombination}} = \underbrace{\alpha_r n_i^2}_{\substack{\text{thermal}\\ \text{generation}}} - \underbrace{\alpha_r n_o p_o}_{\text{recombination}}$$

$$0 = \underbrace{\alpha_r n_o p_o}_{\substack{\text{thermal}\\ \text{generation}}} - \underbrace{\alpha_r n_o p_o}_{\text{recombination}}$$

Recombination of Electrons and Holes

Now we pump electrons into the conduction band by a short flash of light that ends at *t = 0*





initial condition
for recombination

$t = 0$

$\Delta n = \Delta p =$ initial excess concentration

$\delta n(t) =$ instantaneous concentration of excess electrons

$\delta p(t) =$ instantaneous concentration of excess holes

Recombination of Electrons and Holes

If we generate excess carriers, the net rate of change of electrons in the conduction band is given by

$$\underbrace{\frac{d\,n(t)}{d\,t}}_{\text{net rate of change}} = \underbrace{\alpha_r\, n_i^2}_{\text{thermal generation rate}} - \underbrace{\alpha_r\, n(t)\, p(t)}_{\text{recombination rate}}$$

$$\frac{d\left[n_o + \delta n(t)\right]}{d\,t} = \underbrace{\alpha_r n_i^2}_{\text{thermal generation}} - \underbrace{\alpha_r \left[n_o + \delta n(t)\right]\left[p_o + \delta p(t)\right]}_{\text{recombination}}$$

Recombination of Electrons and Holes

$t = 0$

$\Delta n = \Delta p =$ initial excess concentration

$$\boxed{\underbrace{\frac{d\,n(t)}{d\,t}}_{\text{net rate of change}} = \underbrace{\alpha_r n_i^2}_{\text{thermal generation rate}} - \underbrace{\alpha_r n(t)\,p(t)}_{\text{recombination rate}}}$$

Electrons and holes recombine in pairs

$$\delta n(t) = \delta p(t)$$

$$\frac{d\,\delta n(t)}{d\,t} = \alpha_r n_i^2 - \alpha_r\left[n_o + \delta n(t)\right]\left[p_o + \delta p(t)\right]$$

$$\frac{d\,\delta n(t)}{d\,t} = -\alpha_r\left[(n_o + p_o)\,\delta n(t) + \delta n^2(t)\right]$$

Use $\boxed{n_o p_o = n_i^2}$

to eliminate $\alpha_r n_i^2$

Low-level injection conditions → Simplification

$$\frac{d\,\delta n(t)}{d\,t} = -\alpha_r \left[(n_o + p_o)\,\delta n(t) + \underbrace{\delta n^2(t)}_{\text{can be neglected}} \right]$$

Extrinsic semiconductor *p*-type

$$\frac{d\,\delta n(t)}{d\,t} \simeq -\alpha_r\, p_o\, \delta n(t) \qquad p_o \gg n_o$$

Neglect equilibrium minority carriers

⇒

$$\boxed{\delta n(t) = \underbrace{\Delta n}_{\substack{\text{initial}\\ \text{condition}}} \exp\left(-\alpha_r\, p_o\, t\right) = \Delta n \exp\left(-\frac{t}{\tau_n}\right)}$$

$$\tau_n = \frac{1}{\alpha_r\, p_o} = \text{minority recombination lifetime}$$

Low-level injection conditions → Simplification

$$\frac{d\,\delta n(t)}{d\,t} = -\alpha_r\left[(n_o+p_o)\,\delta n(t) + \underbrace{\delta n^2(t)}_{\text{can be neglected}}\right]$$

Extrinsic semiconductor *n*-type

$$\frac{d\,\delta p(t)}{d\,t} \simeq -\alpha_r\, n_o\,\delta p(t) \qquad\qquad n_o \gg p_o$$

Neglect equilibrium minority carriers

⇨

$$\boxed{\delta p(t) = \underbrace{\Delta p}_{\substack{\text{initial}\\ \text{condition}}}\ \exp\left(-\alpha_r\, n_o\, t\right) = \Delta p\ \exp\left(-\frac{t}{\tau_p}\right)}$$

$$\tau_p = \frac{1}{\alpha_r\, n_o} = \text{minority recombination lifetime}$$

Low level injection conditions → Simplification

More generally you can use this formula

$$\tau = \frac{1}{\alpha_r \left(n_o + p_0\right)}$$

It works for both *p*- and *n*-type material in low level injection conditions