ECE 340 Lecture 15
Semiconductor Electronics

Spring 2022
10:00-10:50am
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Summary: Light-semiconductor interaction

- We have discussed:
  - How light is absorbed by a semiconductor material
  - How light is emitted by a semiconductor material
  - How excess carriers concentrations generated by light decay back to equilibrium by recombination
  - How a stable excess carrier population is generated under steady illumination
  - How, out of equilibrium, the Fermi level concept can still be utilized to compute excess electron hole densities with separate "quasi-Fermi levels"

Practice

- **Let’s work now on some problems on excess carriers and optical generation to solidify those concepts.**

Example 1: Steady-State Illumination

- Consider Si at T=300K and $n_o = 10^{14}\mathrm{cm}^{-3}$

- Optical generation $10^{19}\mathrm{EHP\ cm}^{-3}/\mathrm{s}$
- Recombination lifetimes

$$\tau_n = \tau_p = 2 \times 10^{-6}\mathrm{s}$$

- Steady-state concentration

$$\delta n = \delta p = g_{op}\tau_n =$$
$$= 10^{19} \times 2 \times 10^{-6} = 2 \times 10^{13}\mathrm{cm}^{-3}$$

Example 1

- Holes equilibrium concentration

$$p_o = \frac{n_i^2}{n_o} = \frac{2.25 \times 10^{20}}{10^{14}} = 2.25 \times 10^6 \mathrm{cm}^{-3}$$

- Holes total concentration

$$p_o + \delta p = 2.25 \times 10^6 + 2 \times 10^{13} \approx 2 \times 10^{13} \mathrm{cm}^{-3}$$

- Electrons total concentration

$$n_o + \delta n = 10^{14} + 2 \times 10^{13} = 1.2 \times 10^{14} \mathrm{cm}^{-3}$$

$$n_o p_o = n_i^2$$

$$\Rightarrow \quad np \neq n_i^2$$

Example 1

- In equilibrium (no optical generation)

$$n_o = 10^{14}\,\mathrm{cm}^{-3}$$

$$n_o = n_i \exp\left[\frac{E_F - E_i}{k_B T}\right]$$

$$E_F - E_i = k_B T \ln \frac{n_o}{n_i}$$

$$0.0259 \times \ln \frac{10^{14}}{1.5 \times 10^{10}} = E_F - E_i$$

$$E_F - E_i = 0.0259 \times \ln(6.\overline{6} \times 10^3) = 0.228\mathrm{eV}$$

Example 1

- Again with holes (no optical generation)

$$p_o = 2.25 \times 10^6 \mathrm{cm}^{-3}$$

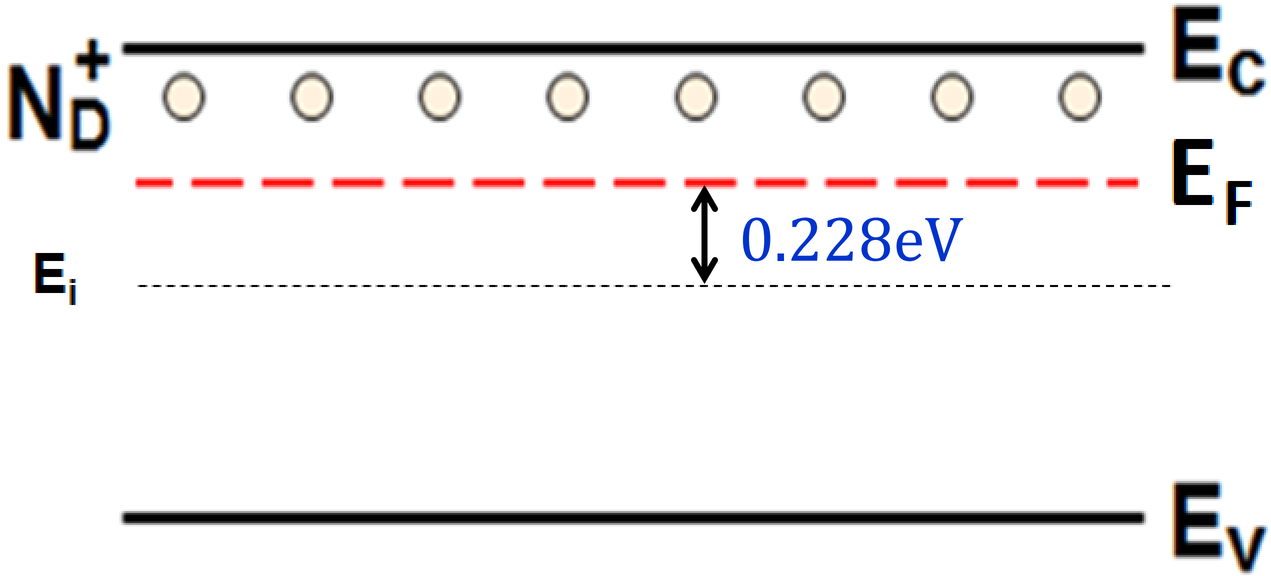
$$p_o = n_i \exp\left[\frac{E_i - E_F}{k_B T}\right]$$

$$E_i - E_F = k_B T \ln \frac{p_o}{n_i}$$

$$0.0259 \times \ln \frac{2.25 \times 10^6}{1.5 \times 10^{10}} = E_i - E_F$$

$$E_i - E_F = 0.0259 \times \ln(1.5 \times 10^{-4}) = -0.228 \mathrm{eV}$$

Example 1



$$n_o = n_i \exp\left[\frac{E_F - E_i}{k_B T}\right]$$

$$p_o = n_i \exp\left[\frac{E_i - E_F}{k_B T}\right]$$

Example 1: Now consider illumination

- Quasi-Fermi level for electrons

$$n_o + \delta n = n = 1.2 \times 10^{14}\text{cm}^{-3}$$

$$n = n_i \exp\left[\frac{F_n - E_i}{k_B T}\right]$$

$$F_n - E_i = k_B T \ln\frac{n}{n_i}$$

$$0.0259 \times \ln\frac{1.2 \times 10^{14}}{1.5 \times 10^{10}} = F_n - E_i$$

$$F_n - E_i = 0.0259 \times \ln(8 \times 10^3) = 0.233\text{eV}$$

Example

- Quasi-Fermi level for holes

$$p_o + \delta p = p = 2 \times 10^{13}\,\mathrm{cm}^{-3}$$

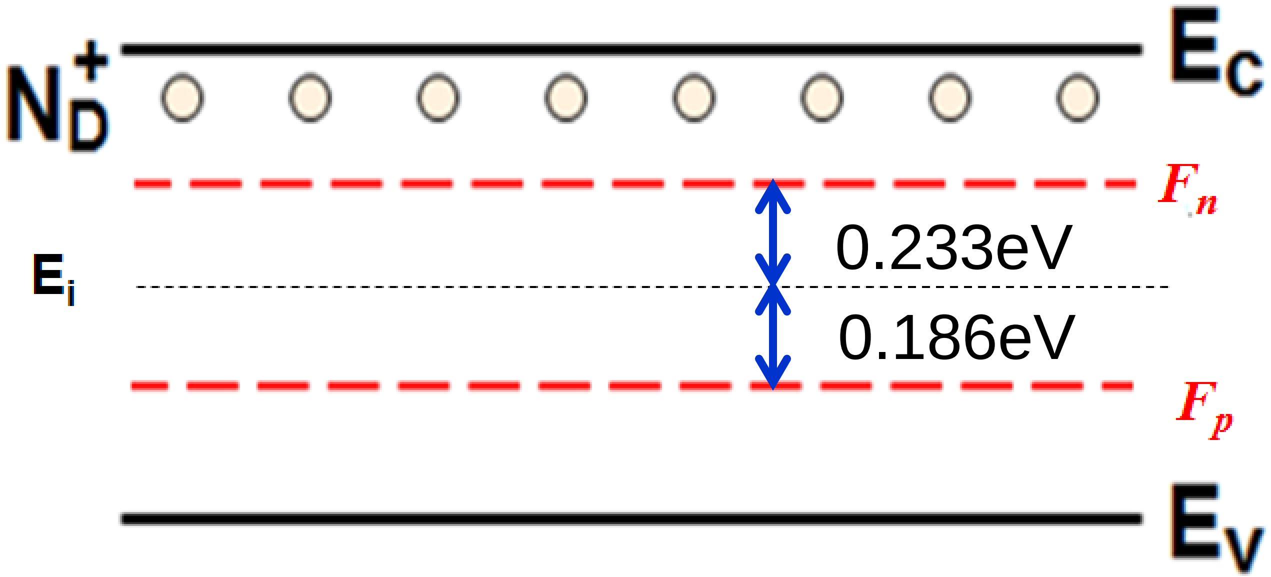
$$p = n_i \exp\left[\frac{E_i - F_p}{k_B T}\right]$$

$$E_i - F_p = k_B T \ln \frac{p}{n_i}$$

$$0.0259 \times \ln \frac{2 \times 10^{13}}{1.5 \times 10^{10}} = E_i - F_p$$

$$E_i - F_p = 0.0259 \times \ln(1.\overline{3} \times 10^3) = 0.1864\ \mathrm{eV}$$

Example 1: Quasi-Fermi levels



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

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

Carrier generation

- A Silicon sample is irradiated with light at frequency 435.235 THz. Can EHP's be generated at this frequency?

Recall:

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

This handy formula was written for band gap but it can be used for general calculations involving energy

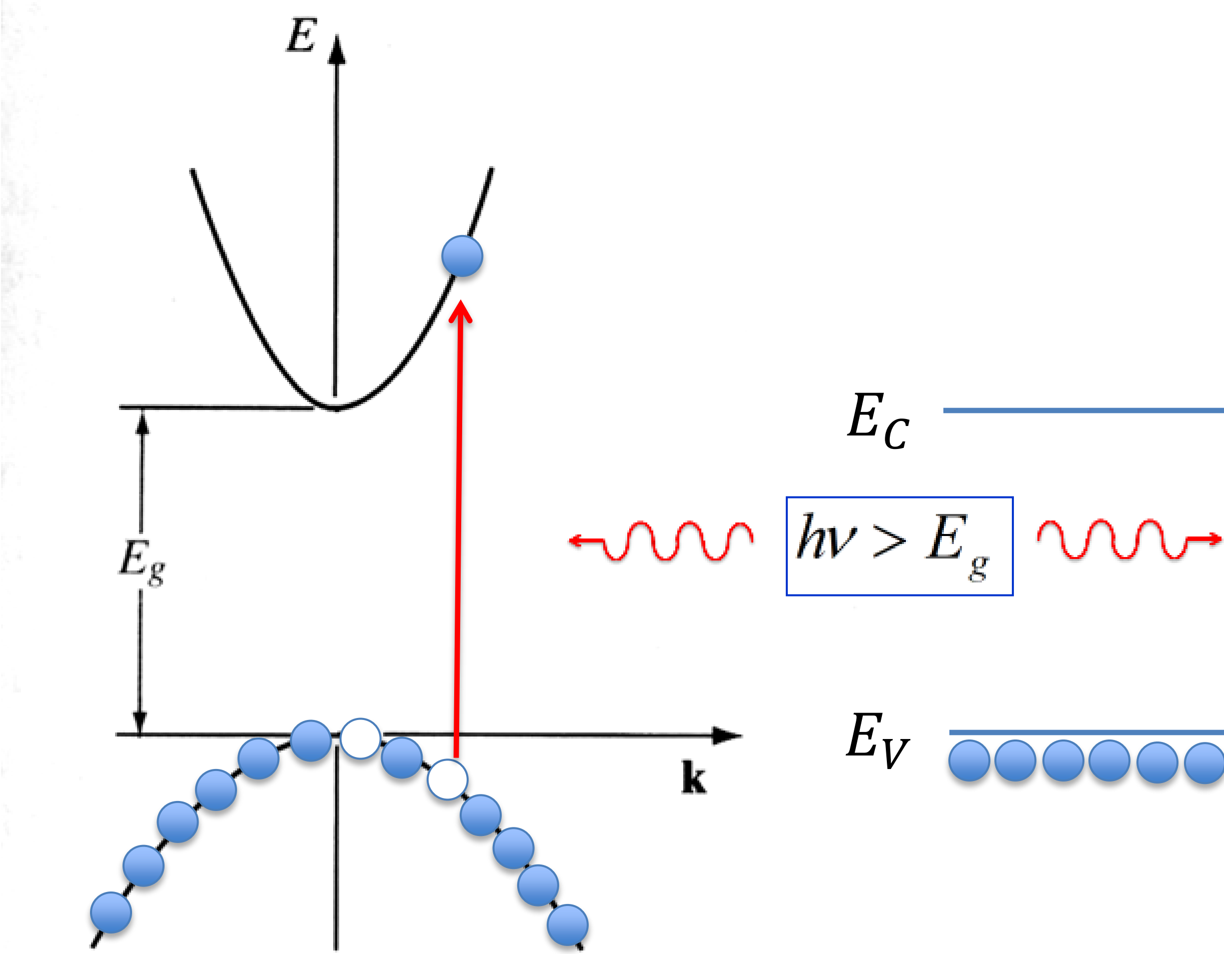
Carrier generation

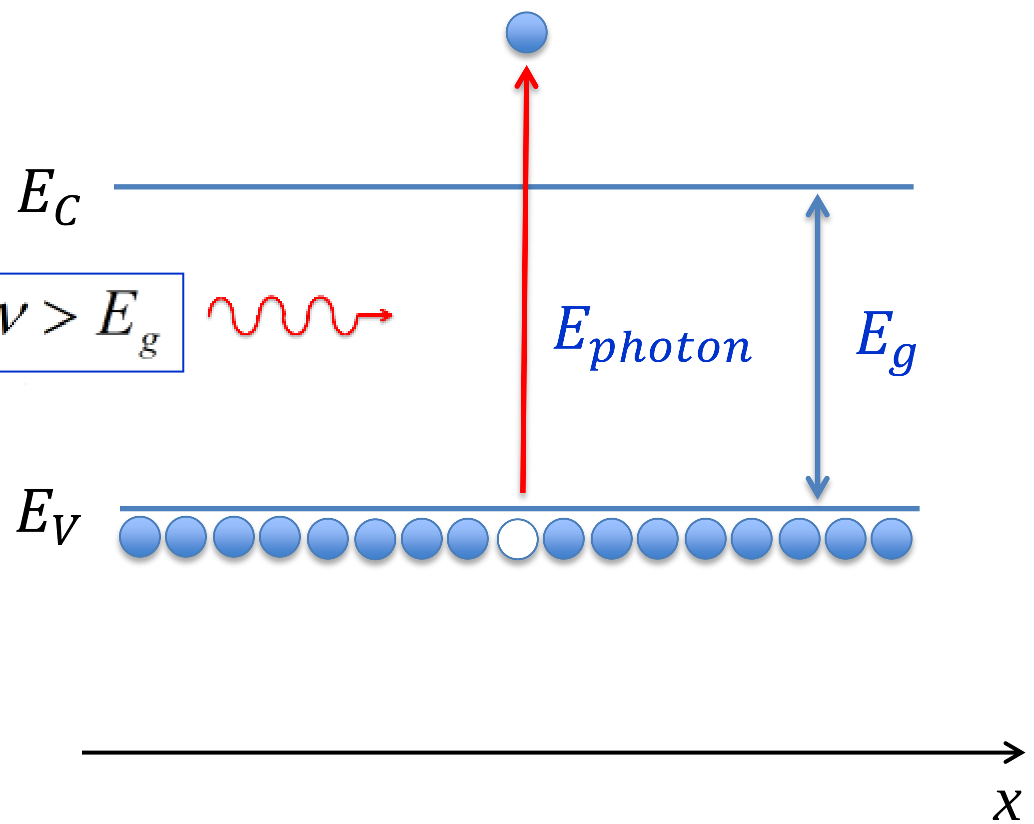
Let's examine the nature of the light source.

$$\lambda = \frac{c}{f} = \frac{3\times10^{8}}{435.235\times10^{12}} = 689.3 \text{ nm}$$ (red light band)

$$E_{photon}(\text{eV}) = 1240/689.3 \approx 1.8 \text{ eV}$$

Si has bandgap $E_g = 1.12\text{eV}$. Since $E_g < E_{photon}$ carriers can be generated.





Momentum space

Real space

Light emission

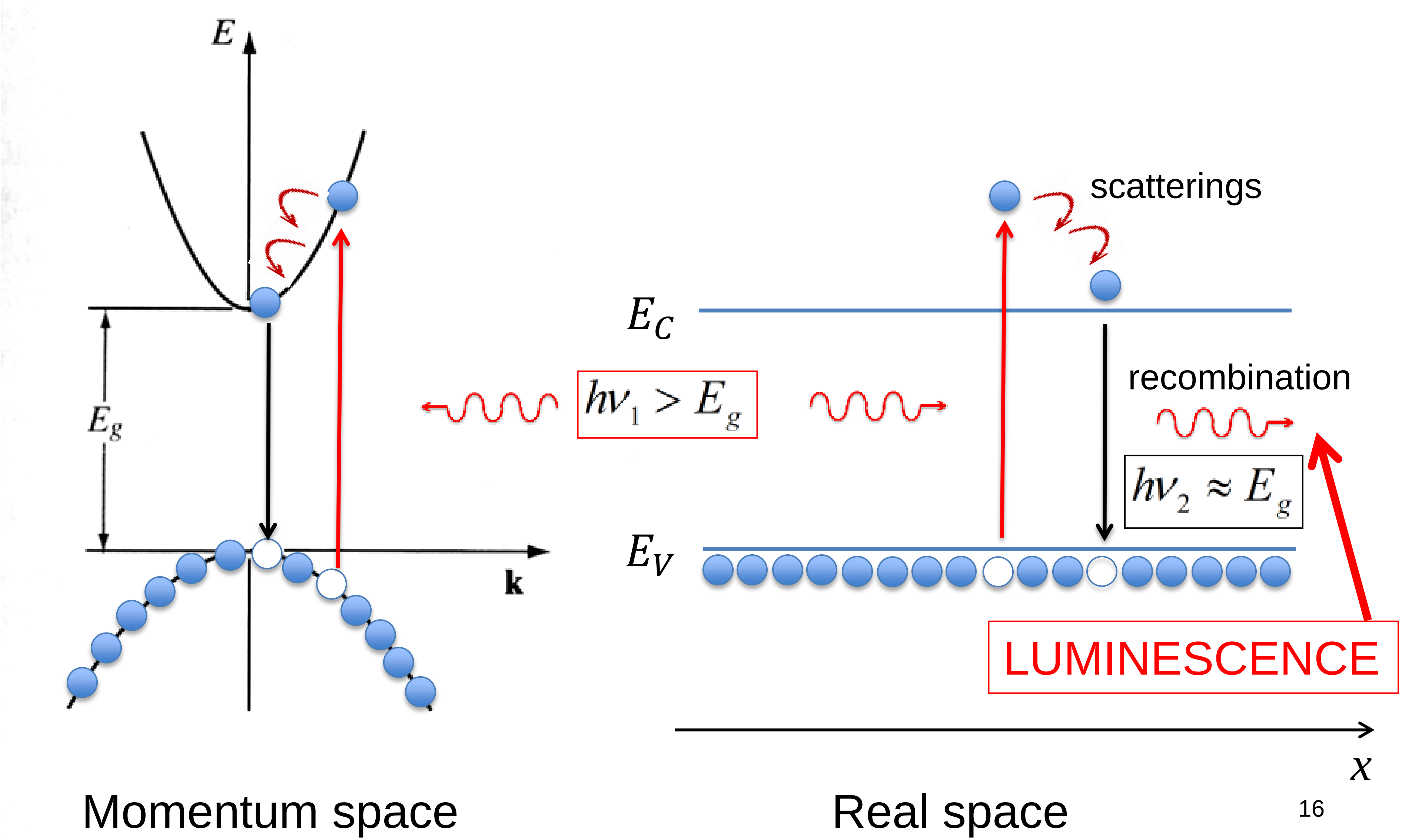
A thin semiconductor sample is irradiated with light having photon energy 2.5 eV. If the semiconductor in turn emits light at frequency 346 THz, what is the bandgap of the material?

$$\lambda = \frac{c}{f} = \frac{3 \times 10^{8}}{346 \times 10^{12}} = 866 \text{ nm}$$

(In which frequency band is this radiation?) Near Infrared

$$E_{gap}(\text{eV}) = 1240/866 \approx 1.43 \text{ eV}$$

GaAs has this band gap.



E
k
E_g
$hv_1 > E_g$
E_C
E_V
scatterings
recombination
$hv_2 \approx E_g$
LUMINESCENCE
x
Momentum space
Real space

Excess carriers in Si

A bar of silicon at T=300K is uniformly doped with $10^{18}\mathrm{cm}^{-3}$ phosphorous atoms and $0.9999 \times 10^{18}\mathrm{cm}^{-3}$boron atoms.

A strong ultraviolet light creates a uniform hole concentration Δp so that $\Delta p \ll n_0$; $\Delta p \gg p_0$ and it is turned off at $\boldsymbol{t=0}$.

1) Find the equilibrium concentration $p_o$in the sample

Phosphorous is a donor, Boron is an acceptor

$$N_D - N_A = 10^{18} - 0.9999 \times 10^{18} = 10^{14}\mathrm{cm}^{-3} \gg n_i$$

$$p_o = n_i^2 \,/ n_o = \frac{(1.5 \times 10^{10})^2}{10^{14}} = 2.25 \times 10^6 \mathrm{cm}^{-3}$$

Excess carriers in Si

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A strong ultraviolet light creates a uniform hole concentration Δp so that $\Delta p \ll n_0$; $\Delta p \gg p_0$and it is turned off at ***t* =0**.

2) Is the low-level injection condition valid at all times?

Low-level injection condition implies $\delta n = \delta p \ll n_o$ (the majority carrier concentration). Since $\Delta p = \Delta n$, with the above information, also $\Delta n \ll n_o$. If the irradiation is tuned off, concentrations can only be lower than initial ones, so low-level injection conditions are always valid.

Excess carriers in Si

A bar of silicon at T=300K is uniformly doped with $10^{18}\mathrm{cm}^{-3}$ phosphorous atoms and $0.9999 \times 10^{18}\mathrm{cm}^{-3}$boron atoms.

A strong ultraviolet light creates a uniform hole concentration Δp so that $\Delta p \ll n_0$; $\Delta p \gg p_0$and it is turned off at $\boldsymbol{t=0}$.

3) What if instead $\Delta p = 5.0 \times 10^{15}\mathrm{m}^{-3}$?

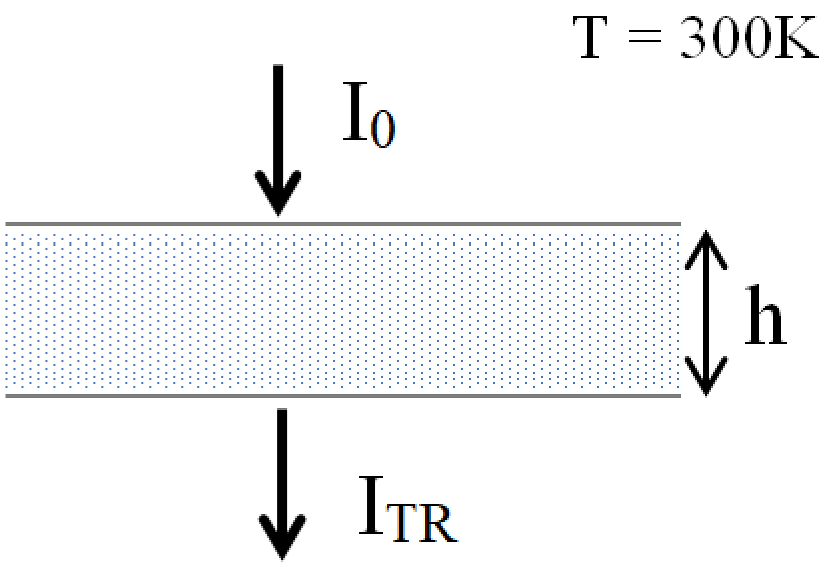
Trick question! $\Delta p = 5.0 \times 10^{15}\mathrm{m}^{-3} = 5.0 \times 10^{9}\mathrm{cm}^{-3}$ which is much lower than before.

With $\Delta p = 5.0 \times 10^{15}\mathrm{cm}^{-3} \gg 10^{14}\mathrm{cm}^{-3}$ the low-level injection condition would not be satisfied.

Light Absorption in Semiconductor

Incident power $I_0 = 10\text{mW}$
Transmitted power $I_{TR} = 1\text{mW}$
Absorption coefficient $\alpha = 5 \times 10^4 \text{cm}^{-1}$

Find the thickness of the semiconductor slab



Light Absorption in Semiconductor

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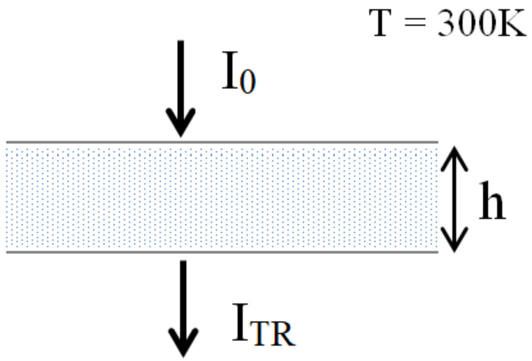


Find the thickness of the semiconductor slab

$$I_{TR} = I_0 e^{-\alpha \mathrm{h}}$$

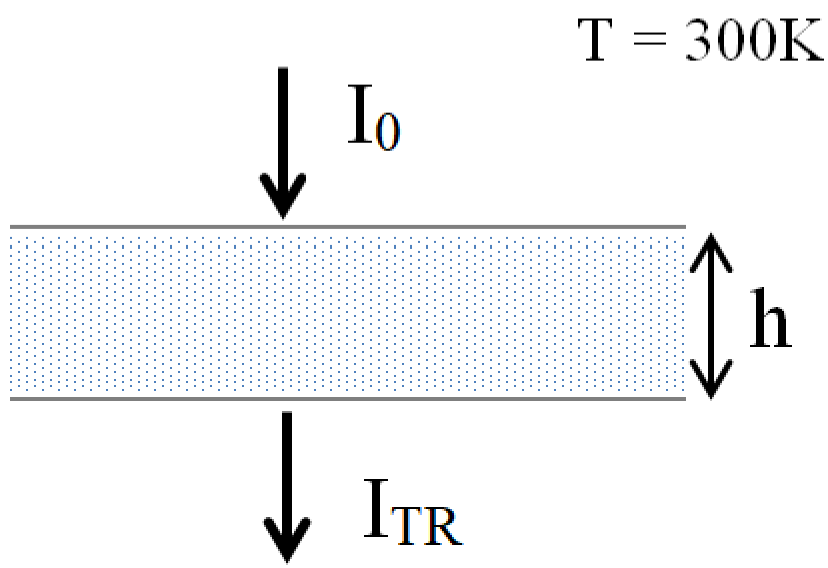
$$\mathrm{h} = \frac{1}{\alpha} \ln\left[\frac{I_0}{I_{TR}}\right] = \frac{1}{5 \times 10^4 \text{cm}^{-1}} \ln \frac{10\text{mW}}{1\text{mW}}$$

$$= 0.2 \times 10^{-4} \ln(10) = 4.605 \times 10^{-5} \text{m}$$

$$= 0.46 \mu\text{m}$$

Light Absorption in Semiconductor

A slab of semiconductor material is irradiated by a source of visible light with wavelength λ_0 = 620 nm. A measurement shows that upon irradiation the semiconductor emits infrared light with wavelength λ_{0E} = 1.24 μm.



Light Absorption in Semiconductor

A slab of semiconductor material is irradiated by a source of visible light with wavelength λ_0 = 620 nm. A measurement shows that upon irradiation the semiconductor emits infrared light with wavelength λ_{0E} = 1.24 μm.

(a) What is the photon energy for this light source?

$$E_{photon} = \frac{1240}{620\ [\mathrm{nm}]} = 2\mathrm{eV}$$

Light Absorption in Semiconductor

A slab of semiconductor material is irradiated by a source of visible light with wavelength λ_0 = 620 nm. A measurement shows that upon irradiation the semiconductor emits infrared light with wavelength λ_{0E} = 1.24 μm.

(b) What is the energy band gap of the semiconductor?

$$E_g = \frac{1.24}{1.24\ [\mu\mathrm{m}]} = 1\mathrm{eV}$$

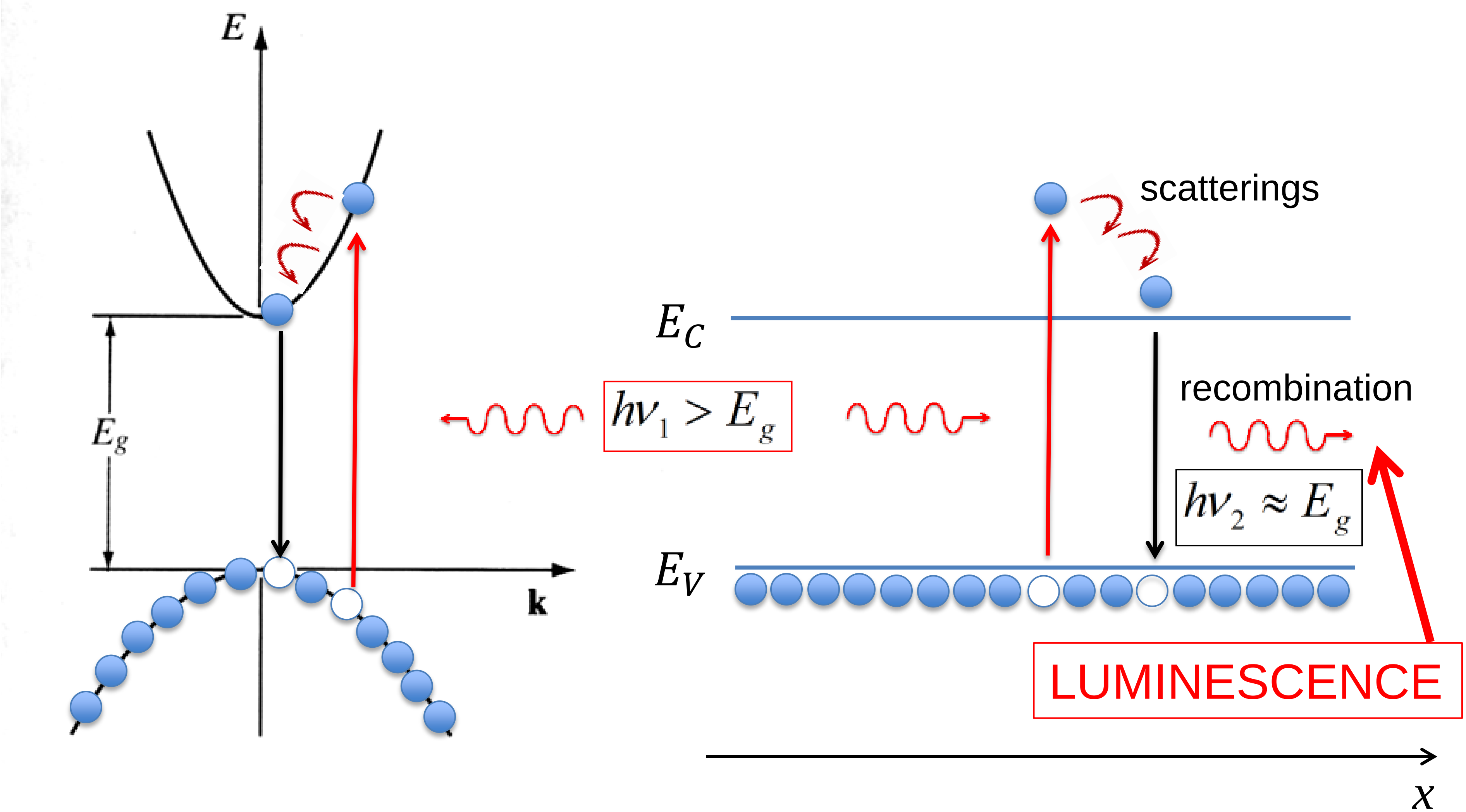
Light Absorption in Semiconductor

A slab of semiconductor material is irradiated by a source of visible light with wavelength λ_0 = 620 nm. A measurement shows that upon irradiation the semiconductor emits infrared light with wavelength λ_{0E} = 1.24 μm.

(c) Explain briefly why the semiconductor can re-emit light in the infrared band, although irradiated with visible light.

See picture on next slide

Light Absorption in Semiconductor



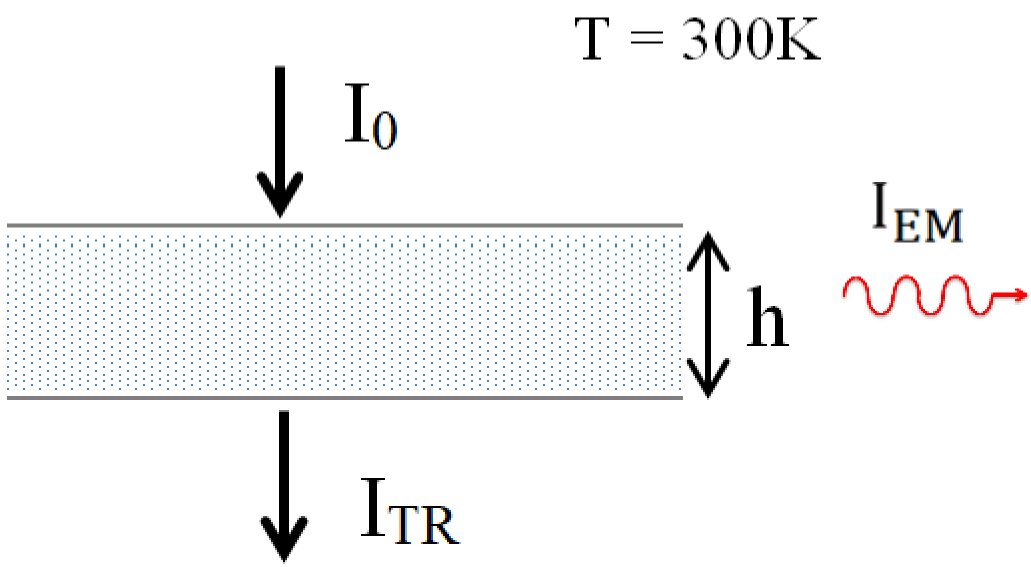
Momentum space

Real space

Light Absorption in Semiconductor

Now, a careful analysis is conducted to account for the energy involved in the experiment, by measuring the total power of the visible light incident onto the semiconductor slab, I_0; the power transmitted through the other side of the sample, I_{TR}; and the total power emitted as infrared radiation, I_{EM}. It is found that

$$I_0 - I_{TR} > I_{EM}$$



Light Absorption in Semiconductor

(d) Explain briefly what happens to the power which is not accounted for by the measurement.

In order for an excited electron to reach an energy level close to E_C, it must lose energy through scattering interaction. The most likely candidate is scattering by phonon emission, which means that the electron transfers thermal energy to the crystal lattice.

(Additionally, if the recombination process is non-radiative, a photon is not generated and energy is also lost to phonons in this case, which means there is not perfect quantum efficiency.)

Light Absorption in Semiconductor

It is known that the semiconductor material is doped with acceptors and the concentration is $N_A = 10^{15}\text{cm}^{-3}$.
The incident radiation at steady-state generates 10^{19}cm^{-3} electron-hole pairs every second, uniformly distributed in the semiconductor slab.
The intrinsic concentration of the material is $n_i = 10^{13}\ \text{cm}^{-3}$ and the carrier lifetimes are $\tau_n = \tau_p = 10^{-6}\text{s}$.

(e) Estimate the concentration of majority and minority carriers in steady state generation, assuming low-level excitation conditions and complete ionization of the dopants.

Light Absorption in Semiconductor

(e) Estimate the concentration of majority and minority carriers in steady state generation, assuming low-level excitation conditions and complete ionization of the dopants.

In low-level excitation conditions, we can write the optical generation rate as

$$\boxed{\tau_n = \tau_p = 10^{-6}\mathrm{s}}$$

$$g_{op} = \frac{\delta n}{\tau_n} = 10^{19}\mathrm{cm}^{-3}\mathrm{s}^{-1}$$

$$\boxed{g_{op} = 10^{19}\mathrm{cm}^{-3}s^{-1}}$$

$$\delta_n = g_{op}\tau_n = 10^{19} \times 10^{-6} = 10^{13}\mathrm{cm}^{-3}$$

Since $\tau_n = \tau_p$ we have also $\delta_n = \delta_p$.

$$\boxed{N_A = 10^{15}\mathrm{cm}^{-3}} \qquad \boxed{n_i = 10^{13}\ \mathrm{cm}^{-3}}$$

Majority carrier concentration $p = N_A + \delta_p = 10^{15} + 10^{13} = 1.01 \times 10^{15}\mathrm{cm}^{-3}$

Minority carrier concentration $n = \frac{n_i^2}{N_A} + \delta_n = 10^{11} + 10^{13} = 1.01 \times 10^{13}\mathrm{cm}^{-3}$

Light Absorption in Semiconductor

(f) Is the system really in low-level excitation conditions? Explain

In low-level excitation conditions, we need to have

$\delta_p \ll (n_0 + p_0) \approx p_0$ (for p-type material)

otherwise the term δn^2 is not negligible in the general expression. Since

$$\boxed{N_A = 10^{15}\mathrm{cm}^{-3}}$$

$$\delta_p = 10^{13}\mathrm{cm}^{-3} = 10^{-2} \times p_0 = 10^{-2} \times 10^{15} \ll p_0,$$

the low-level injection condition is reasonably satisfied.