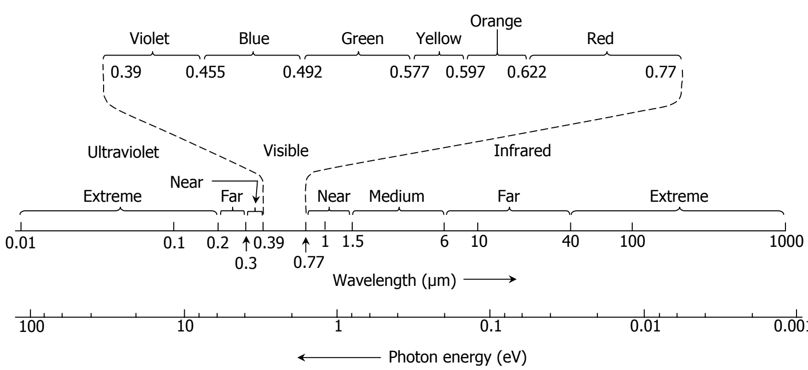
Photonic Devices

- Optical absorption and (non)-radiative transitions
- Photodetector
- Solar cell
- Light-emitting diode
- Semiconductor laser

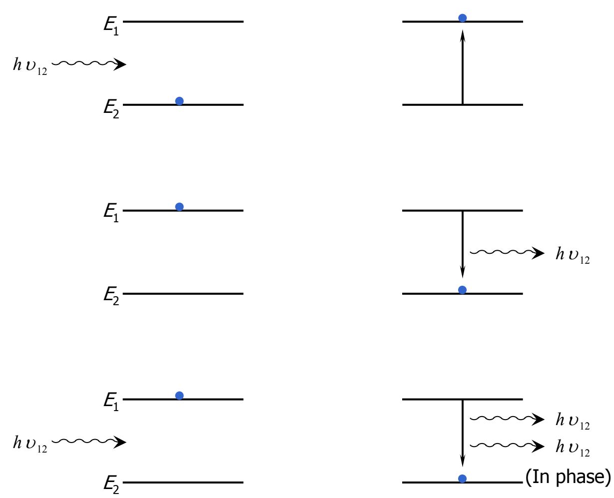
Electromagnetic spectrum



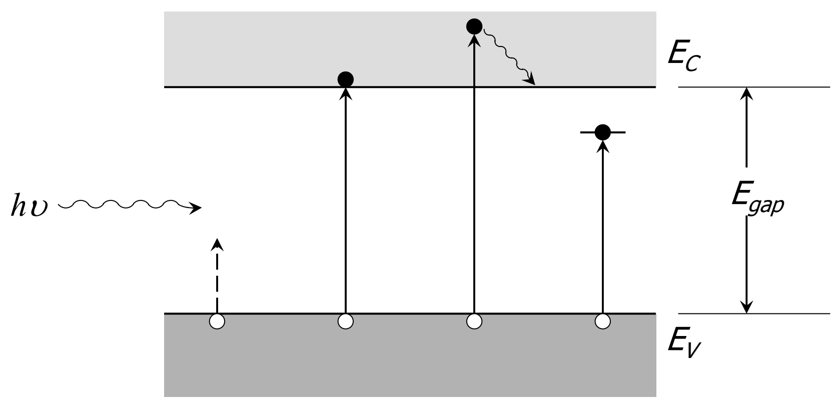
$$\lambda = \frac{c}{\upsilon} = \frac{hc}{E} = \frac{1.24}{E}\ \mu\text{m} = \frac{1240}{E}\ \text{nm}$$

S. M. Sze, Semiconductor Devices: Physics and Technology, 2nd edition, John Wiley & Sons, 2001.

Basic transitions



Optical absorption



Optical absorption

Energy per unit time over dx:

$$\alpha I_\nu(x)dx$$

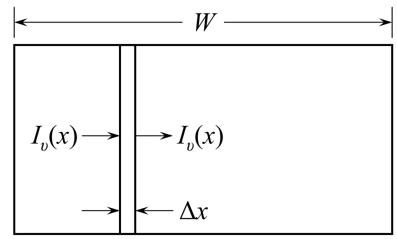
One obtains the following:

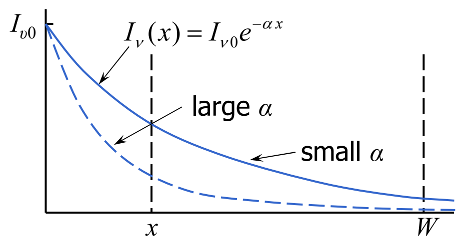
$$\frac{dI_\nu(x)}{dx} = -\alpha I_\nu(x)$$

With solution

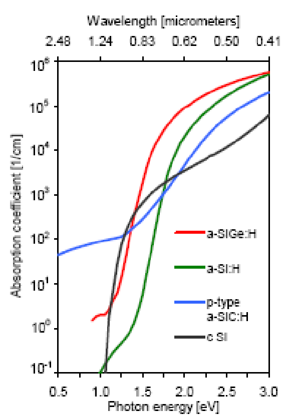
$$I_\nu(x) = I_{\nu 0} e^{-\alpha x}$$

Generation rate: $g' = \dfrac{\alpha I_\nu(x)}{h\nu}$



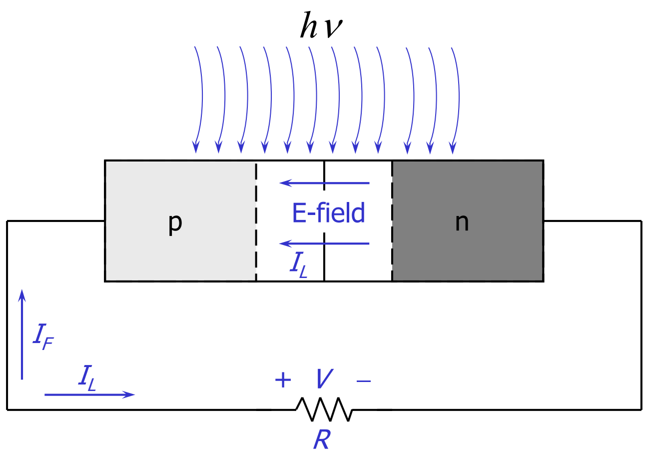


Optical absorption



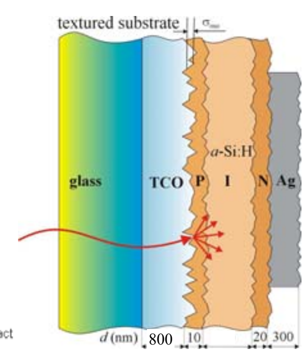
M. Zeman, reader lecture Solar Cells, ET4 149

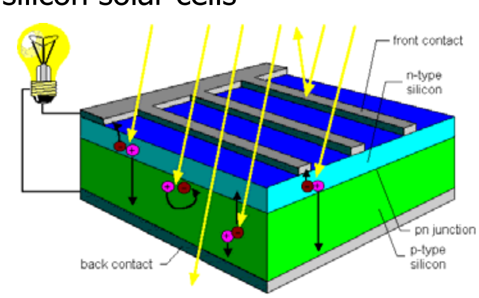
Solar cells



Solar cells

- Note that in reality light enters from n-type layer side for *c*-Si solar cells
- From TCO (transparent conductive oxide) side in thin-film silicon solar cells





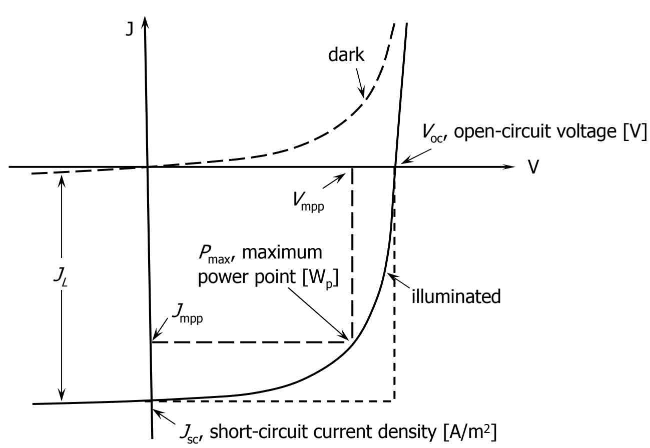
Solar cells

- Total current through solar cell:

$$J = J_L - J_F = J_L - J_S\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

- Photocurrent always in reverse-bias direction

External parameters



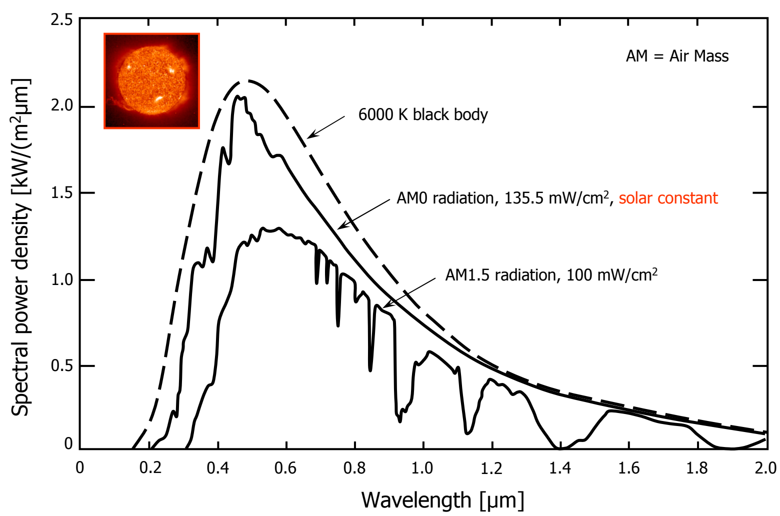
$$FF = \frac{P_{\max}}{J_{sc}V_{oc}}$$

External parameters

- Short-circuit current density, J_{sc}: $J_{sc} = J_L$
- Open-circuit voltage, V_{oc}: $V_{oc} = \frac{kT}{e} \ln\left(1 + \frac{J_L}{J_S}\right)$
- Energy conversion efficiency:

$$\eta = \frac{P_{max}}{P_{in}} \times 100\% = \frac{J_{mpp} V_{mpp}}{P_{in}} \times 100\% = \frac{J_{sc} V_{oc} FF}{P_{in}} \times 100\%$$

Solar spectral irradiance

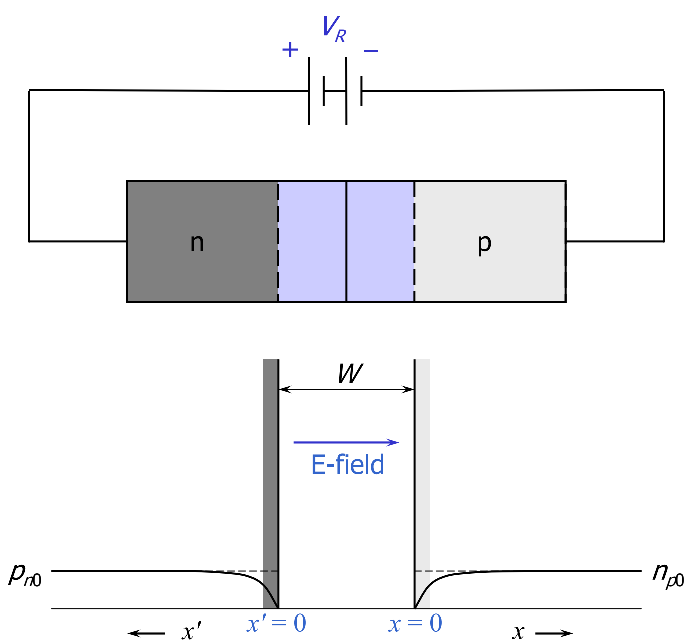


M. A. Green, Solar Cells; Operating Principles, Technology and System Applications, Prentice-Hall, 1982.

Photocurrent

- Charge carriers generated throughout the device, i.e., in the depletion region as well as in the quasi-neutral regions
- Photocurrent due to generation in the depletion region:

$$J_{L,\text{depl}} = e\int G_L dx = eG_L W$$



… generation in quasi-neutral region

Question 6

We consider a semi-infinite bar of p-type silicon with a "minority-carrier digester" at $x = 0$, such that the electron concentration, n_p, at this location is zero (i.e., $n_p(x = 0) = 0$). This bar is uniformly illuminated and as a results carriers are generated at a rate g'. The electric field in the bar is zero and we consider a steady-state situation.

a. The expression for the *excess* minority carrier concentration as a function of x is:

(a) $\delta n(x) = \left(g'\tau - n_{p0}\right)e^{-x/L_n}$.

(b) $\delta n(x) = g'\tau\left(1 - e^{-x/L_n}\right) - n_{p0}e^{-x/L_n}$.

(c) $\delta n(x) = g'\tau - n_{p0}e^{-x/L_n}$.

(d) $\delta n(x) = g'\tau$.

Calculate excess carrier concentration

Start with ambipolar transport equation for steady-state situation, no electric field:

$$D_n \frac{\partial^2(\delta n_p)}{\partial x^2} + G_L - \frac{\delta n_p}{\tau_{n0}} = 0$$

Boundary condition: $\delta n_p(x = 0) = -n_{p0}$

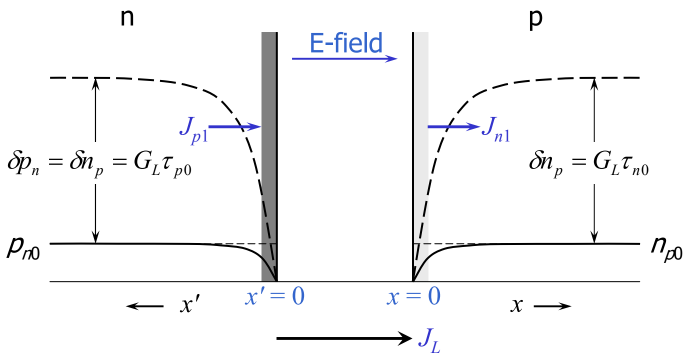
The solution becomes:

$$\begin{aligned}\delta n_p(x) &= G_L\tau_{n0} - \left(G\tau_{n0} + n_{p0}\right)e^{-x/L_n} \\ &= G_L\tau_{n0}\left(1 - e^{-x/L_n}\right) - n_{p0}e^{-x/L_n}\end{aligned}$$

… and finally the photocurrent

$$J_{p1} = eD_p \frac{d(\delta p_n)}{dx}\bigg|_{x=0} = \frac{eD_p}{L_n}\left(G_L \tau_{p0} + p_{n0}\right)$$

$$J_{n1} = eD_n \frac{d(\delta n_p)}{dx}\bigg|_{x=0} = \frac{eD_n}{L_n}\left(G_L \tau_{n0} + n_{p0}\right)$$



$$J_L = e\left(W + L_p + L_n\right)G_L$$

Some additional remarks

- In 'real' p-n junction solar cells the n-region is not very wide
- Most photons are absorbed in the quasi-neutral region of the p-type wafer
- Photo-generated charge carriers reach the depletion region by diffusion

$\Rightarrow$ p-n junction solar cells are so-called diffusion devices

More on this subject: lecture series Solar Cells (ET4 149), Dr Miro Zeman, 10 April 2008

Non-uniform absorption

Generation rate: $g' = \frac{\alpha I_\nu(x)}{h\nu} = \alpha \Phi_0 e^{-\alpha x}$

Take into account:

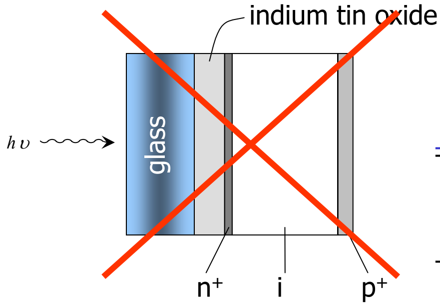
- Wavelength (or energy) dependent absorption
- Wavelength dependent reflection

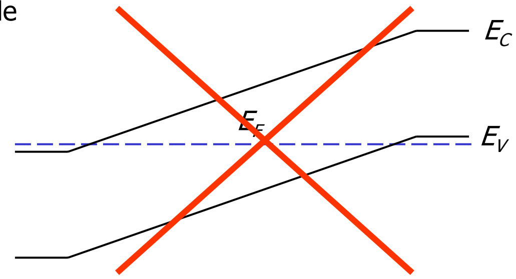
$$G_L = \alpha(\lambda)\Phi_0(\lambda)[1 - R(\lambda)]e^{-\alpha(\lambda)x}$$

Other solar-cell concepts

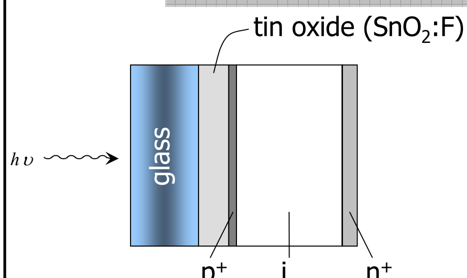
- Heterojunction solar cells
- Concentrator solar cells
- Thin-film solar cells

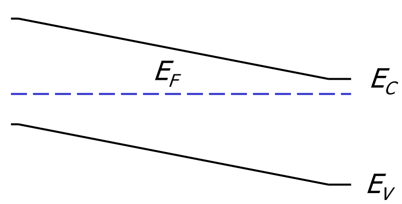
Amorphous silicon p-i-n solar cell

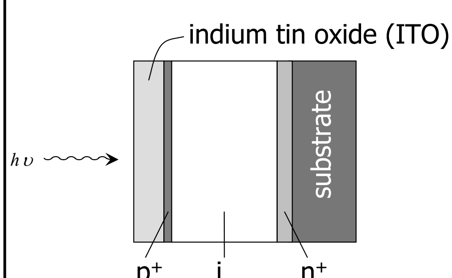




Amorphous silicon p-i-n solar cell





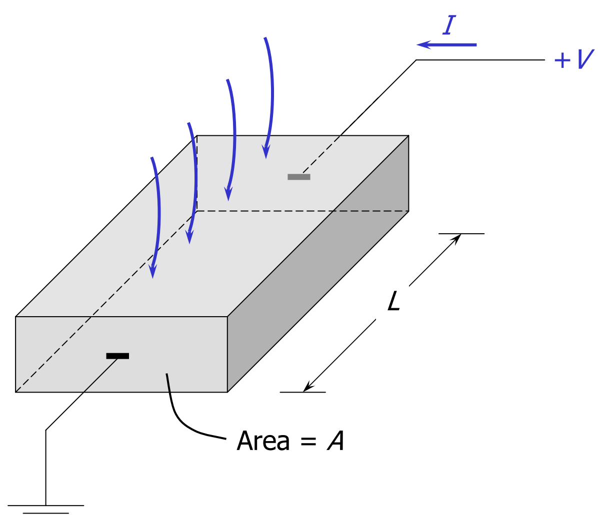


Photodetector

- Photoconductor
- Photodiode
- Phototransistor

⇒ Detect the presence of photons

Photoconductor



Photoconductor

- Measures the change in conductivity

$$\sigma = e(\mu_n n_0 + \mu_p p_0) + e(\mu_n \delta n + \mu_p \delta p)$$
$$= e(\mu_n n_0 + \mu_p p_0) + e(\delta p)(\mu_n + \mu_p)$$

- For uniform carrier generation one obtains

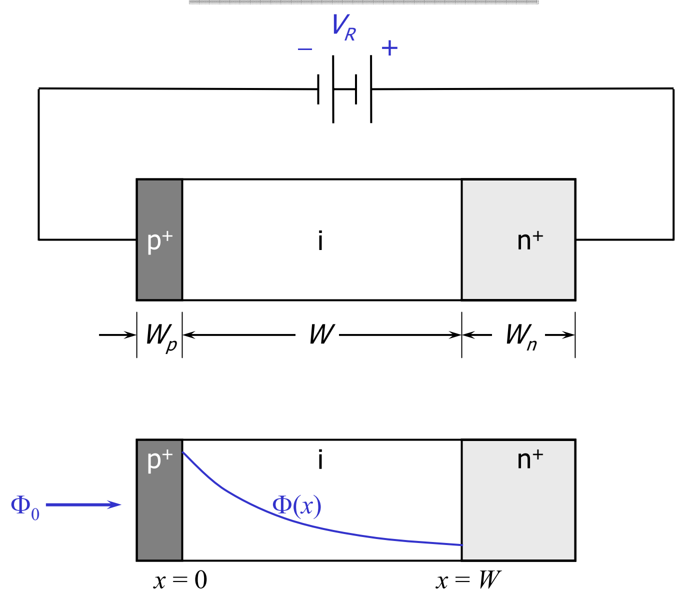
$$I_L = eG_L \tau_p (\mu_n + \mu_p) AL = eG_L \left(\frac{\tau_p}{t_n}\right)\left(1 + \frac{\mu_p}{\mu_n}\right) AL$$
$$= eG_L AL \Gamma_{\text{ph}}$$

with the gain, Γ_{ph}, defined as: $\Gamma_{\text{ph}} = \frac{\tau_p}{t_n}\left(1 + \frac{\mu_p}{\mu_n}\right)$

Photodiode

- Photodiode is a special version of p-n junction solar cell
- Solar cell operates at maximum power point in order to convert solar energy into electric energy as efficiently as possible
- Photodiode operates under reverse bias in order to sense illumination as accurately as possible
- Charge carriers generated in quasi-neutral regions reach junction by diffusion
- Time response of diffusion related collection is slow
- Drift related collection is fast

P-i-n photodiode



P-i-n photodiode

In order to speed up the response:

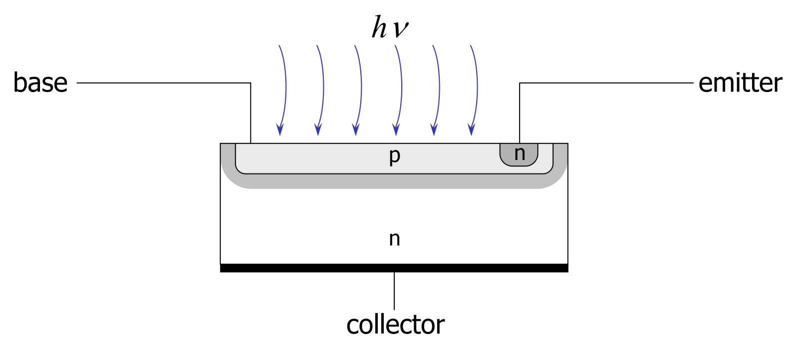
- Increase the depletion region width by implementing an intrinsic region
- More if not most carriers are collected due to drift processes

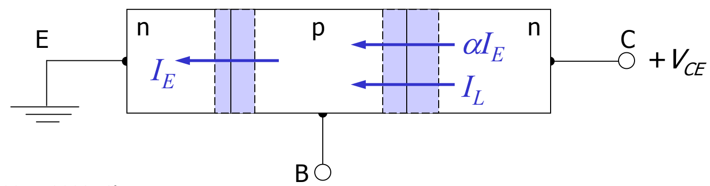
In case there is no electron-hole pair recombination:

$$J_L = e\int_0^W G_L dx = e\int_0^W \Phi_0 \alpha\, e^{-\alpha x} dx = e\Phi_0 (1 - e^{-\alpha W})$$

Is it reasonable to assume that under reverse bias there is no recombination?

Phototransistor





Phototransistor

- Gain of phototransistor can be high
- The phototransistor amplifies the photocurrent:

$$I_C = (1+\beta) I_L$$

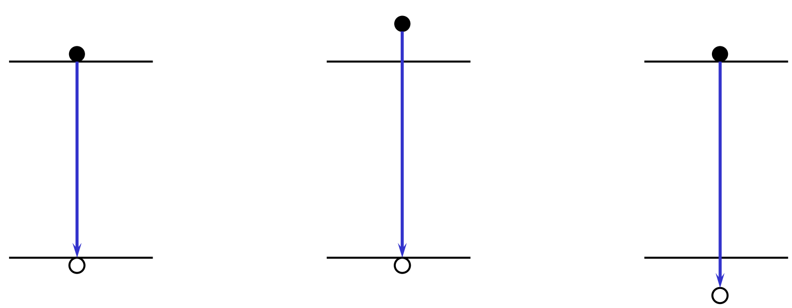
- Frequency response is limited due to the relatively large B-C junction capacitance

Luminescence

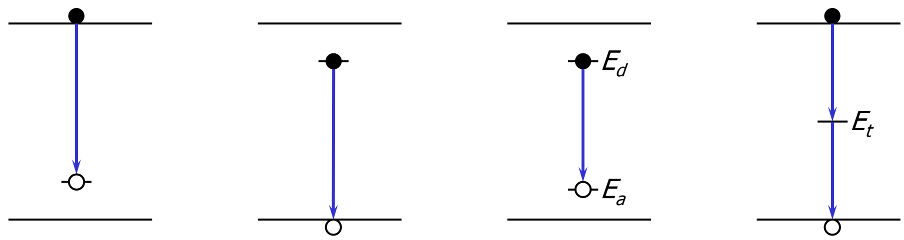
- So far we discussed devices that *absorb* light
- Now focus on emission → luminescence
  - Photoluminescence: light emission following radiative electron-hole pair recombination after aborption
  - Electroluminescence: light emission following radiative electron-hole pair recombination of carriers that were injected
- Luminescence efficiency:

$$\eta_q = \frac{R_r}{R} = \frac{\tau_{nr}}{\tau_{nr} + \tau_r} \quad \text{with:} \quad R_r = \frac{\delta n}{\tau_r} \quad \text{and} \quad R = \frac{\delta n}{\tau_{nr}} + \frac{\delta n}{\tau_r}$$

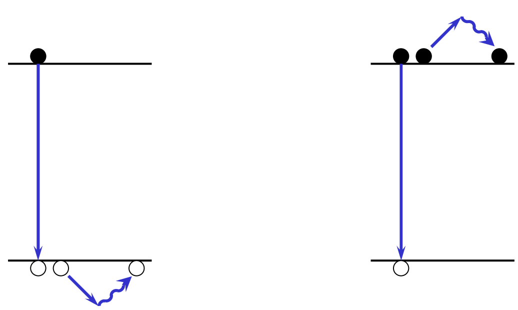
Basic interband transitions



Recombination involving impurities or defects

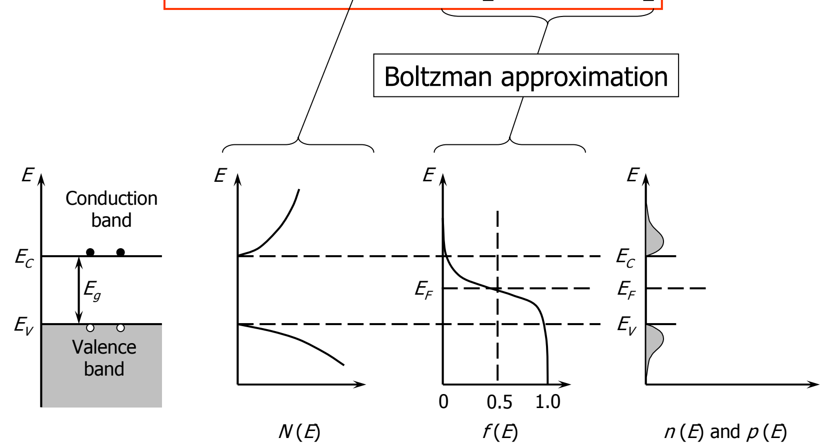


Auger recombination



Emission spectrum

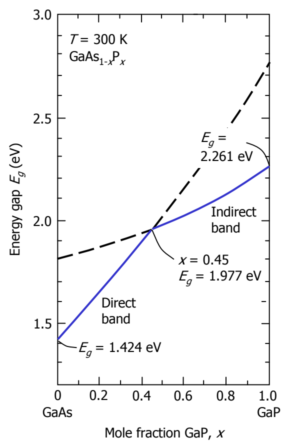
$$I(\nu) \propto \nu^2 (h\nu - E_g)^{1/2} \exp\left[\frac{-(h\nu - E_g)}{kT}\right]$$

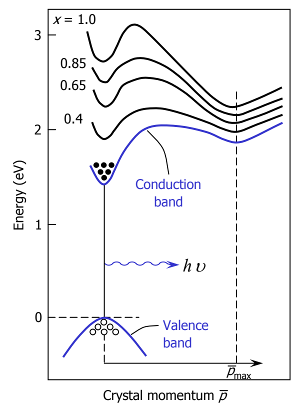


Material	Wavelength (nm)
InAsSbP/InAs	4200
InAs	3800
GaInAsP/GaSb	2000
GaSb	1800
$Ga_xIn_{1-x}As_{1-y}P_y$	1100-1600
$Ga_{0.47}In_{0.53}As$	1550
$Ga_{0.27}In_{0.73}As_{0.63}P_{0.37}$	1300
GaAs:Er,InP:Er	1540
Si:C	1300
GaAs:Yb,InP:Yb	1000
$Al_xGa_{1-x}As$:Si	650-940
GaAs:Si	940
$Al_{0.11}Ga_{0.89}As$:Si	830
$Al_{0.4}Ga_{0.6}As$:Si	650
$GaAs_{0.6}P_{0.4}$	660
$GaAs_{0.4}P_{0.6}$	620
$GaAs_{0.15}P_{0.85}$	590
$(Al_xGa_{1-x})_{0.5}In_{0.5}P$	655
GaP	690
GaP:N	550-570
$Ga_xIn_{1-x}N$	340,430,590
SiC	400-460
BN	260,310,490

S. M. Sze, Semiconductor Devices: Physics and Technology, 2nd edition, John Wiley & Sons, 2001.

Photonic materials





S. M. Sze, Semiconductor Devices: Physics and Technology, 2nd edition, John Wiley & Sons, 2001
→ M. G. Craford, IEEE Trans. Electron Devices **ED-24**, 935 (1977).

Light **E**mitting **D**iode

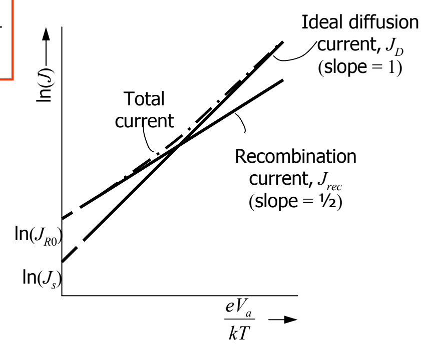
- Direct recombination in quasi-neutral regions
- Diode diffusion current proportional to recombination rate
- Also recombination current in depletion region plays a role
  - Electron-hole pair recombination through midgap states
  - This recombination process is **non**-radiative

Quantum efficiency

Injection efficiency: $\gamma = \frac{J_n}{J_n + J_p + J_R}$

Let γ approach unity by:

- Increase electron current by using n^+-p diode
- Apply sufficiently high forward bias, so diffusion current dominates total current

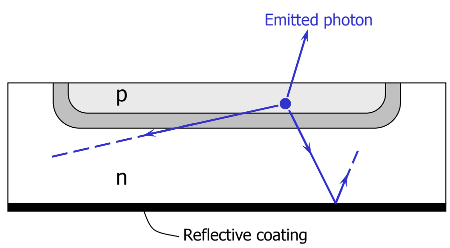


Internal quantum efficiency: $\eta_i = \gamma\eta$

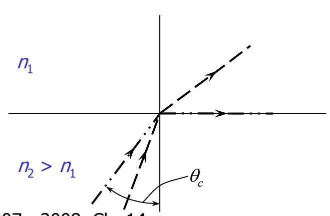
- Radiative efficiency, η, proportional to p-type doping
- Injection efficiency, γ, decreases with p-type doping

Light loss mechanisms

- Absorption of emitted light within the LED material
- Reflection loss at semiconductor-to-air interface
- Total internal reflection



Reflection: $R = \left(\frac{\bar{n}_2 - \bar{n}_1}{\bar{n}_2 + \bar{n}_1}\right)^2$



Snell's law: $\sin\theta_c = \frac{\bar{n}_1}{\bar{n}_2}$

Stimulated emission

$$\left.\begin{array}{l} N_1 \propto e^{-E_1/kT} \\ N_2 \propto e^{-E_2/kT} \end{array}\right\} \Rightarrow \frac{N_2}{N_1} = \exp\left[\frac{-(E_2 - E_1)}{kT}\right]$$

Light **A**mplification by **S**timulated **E**mission of **R**adiation

Population inversion

stimulated-emission rate + spontaneous emission rate = absorption rate

$$B_{21}N_2E(h\nu_{12}) \quad + \quad A_{21}N_2 \quad = \quad B_{12}N_1E(h\nu_{12})$$

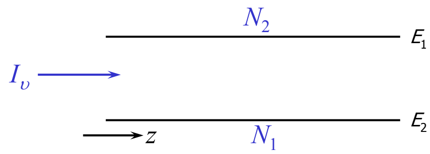
$$\frac{\text{stimulated-emission rate}}{\text{spontaneous-emission rate}} = \frac{B_{21}}{A_{21}}E(h\nu_{12})$$

Large $E(h\nu_{12}) \Rightarrow$ optical resonant cavity

$$\frac{\text{stimulated-emission rate}}{\text{absorption rate}} = \frac{B_{21}}{B_{12}} \cdot \frac{N_2}{N_1}$$

Condition for lasing: $N_2 > N_1 \Rightarrow$ population inversion

Light intensity

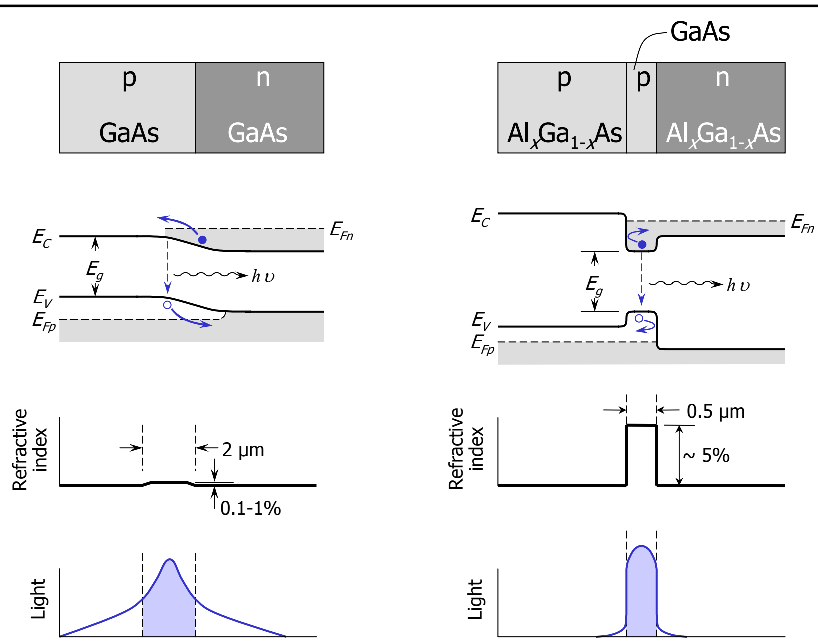


- Neglecting spontaneous emission, the change in intensity is:

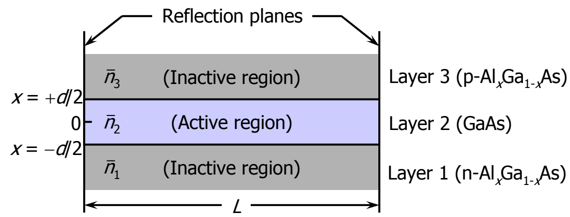
$$\frac{dI_\nu}{dz} \propto \frac{\#\,\text{photons emitted}}{\text{cm}^{-3}} - \frac{\#\,\text{photons absorbed}}{\text{cm}^{-3}}$$

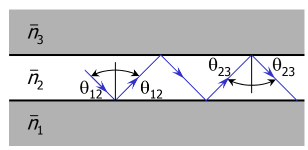
- The intensity is:

$$I_\nu = I_\nu(0)e^{\gamma(\nu)z} \text{ with } \gamma \propto (N_2 - N_1) \propto \left\{1 - \exp\left[\frac{h\nu - (E_{Fn} - E_{Fp})}{kT}\right]\right\}$$



Optical confinement





Optical cavity

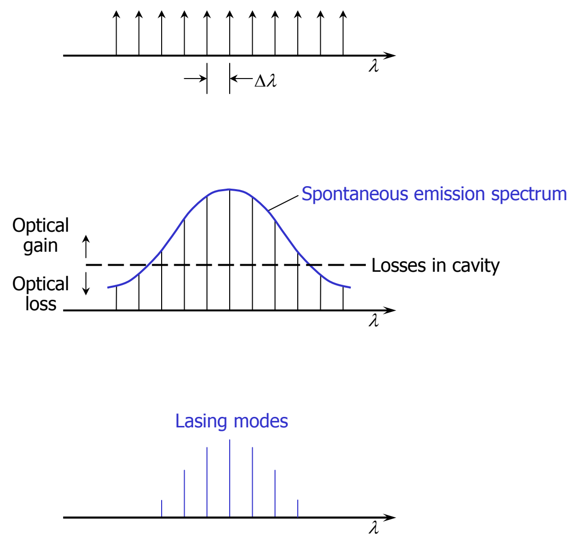
- Provided there is population inversion $\rightarrow$ photons following stimulated emission can stimulate further emissions

$\Rightarrow$ **Optical gain**

- Gain single pass is low $\rightarrow$ multiple passes to increase gain
- Condition for optical gain: $m\left(\frac{\lambda}{2\bar{n}}\right) = L$
- The wavelength separation in the cavity can be obtained by taking the derivative to λ:

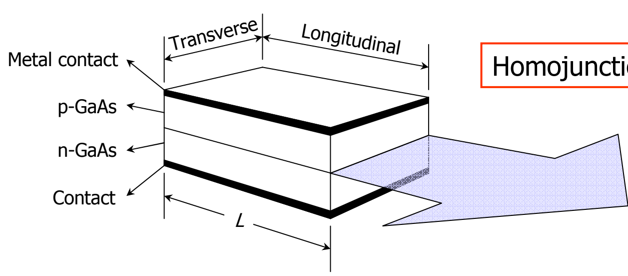
$$\Delta\lambda = \frac{\lambda^2 \Delta m}{2\bar{n}L\left[1-(\lambda/\bar{n})(d\bar{n}/d\lambda)\right]} \cong \frac{\lambda^2}{2\bar{n}L}$$

Optical cavity

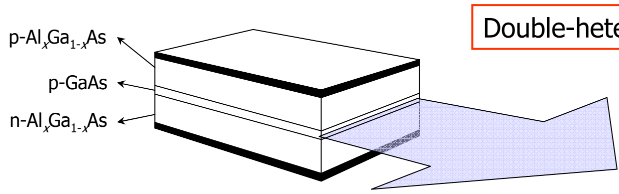


Fabry-Perot cavity

Homojunction laser



Double-heterostructure (DH) laser



Threshold current

- Lasing process competes with two loss mechanisms:
  - Optical intensity: $I_\nu \propto e^{\gamma(\nu)z}$
  - Photon absorption: $I_\nu \propto e^{-\alpha(\nu)z}$
  - Partial transmission/reflection, $\Gamma_{1,2}$
- At threshold optical loss offset by optical gain

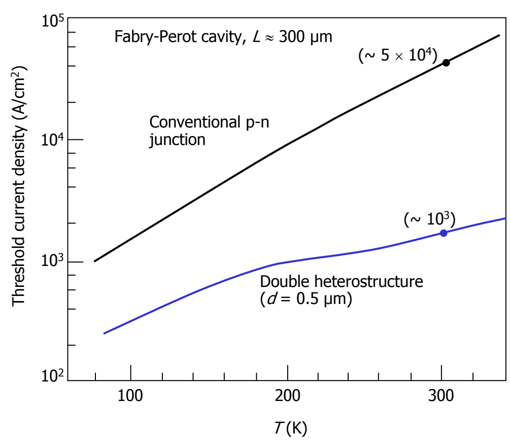
$$\Gamma_1\Gamma_2 \exp[(2\gamma_t(\nu) - 2\alpha(\nu))L] = 1$$

- Solving for the threshold optical gain, $\gamma_t(\nu)$, the threshold current can be calculated

$$J_{th} = \frac{1}{\beta}\left[\alpha + \frac{1}{2L}\ln\left(\frac{1}{\Gamma_1\Gamma_2}\right)\right]$$

β called 'gain factor'

Threshold current



S. M. Sze, Semiconductor Devices: Physics and Technology, 2nd edition, John Wiley & Sons, 2001
→ M. B. Panish, I. Hayashi, and S. Sumski, Appl. Phys. Lett. **16**, 326 (1970).