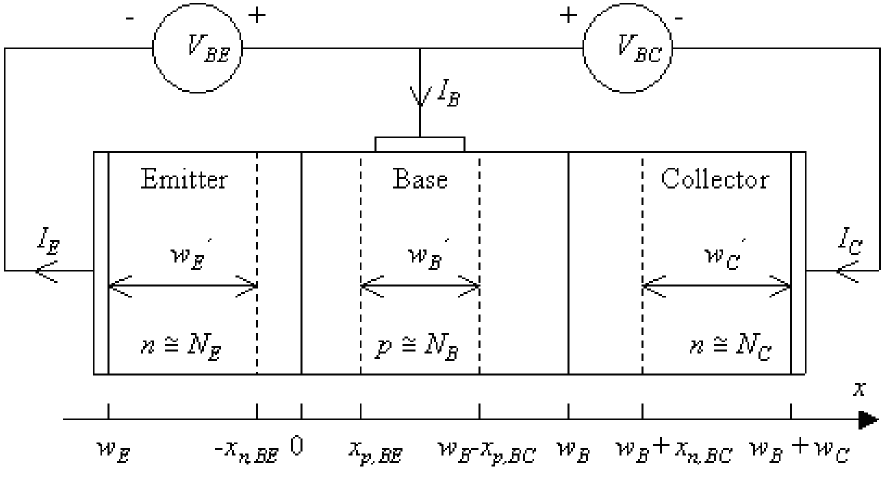
Bipolar Junction Transistors

A bipolar junction transistor consists of two back-to-back p-n junctions, who share a thin common region with width, w_B. Contacts are made to all three regions, the two outer regions called the emitter and collector and the middle region called the base. The device is called “bipolar” since its operation involves both types of mobile carriers, electrons and holes.



Structure and sign convention of a npn bipolar junction transistor.

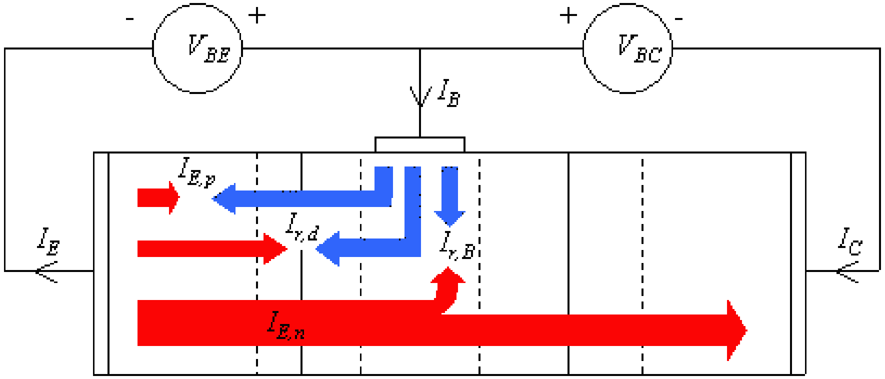
The current gain β, transport factor, α, the emitter efficiency, γ_E, the base transport factor, α_T, the depletion layer recombination factor, δ_r.

$$I_E = I_C + I_B$$

$$\alpha = \frac{I_C}{I_E}$$

$$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}$$

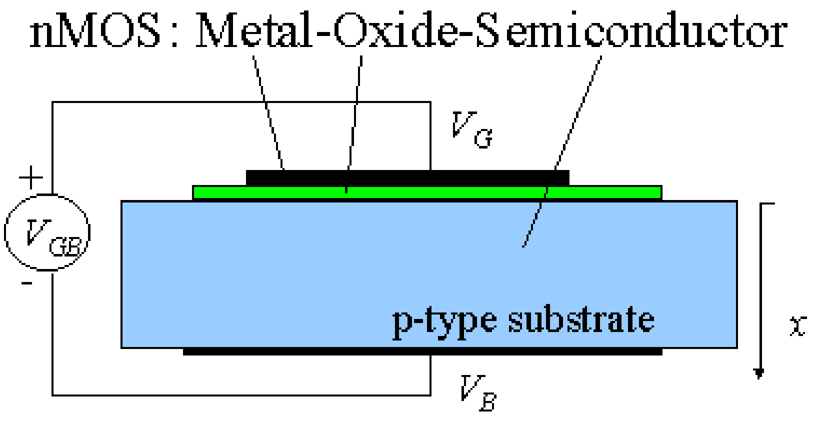
$$\alpha = \alpha_T \, \gamma_E \, \delta_r$$

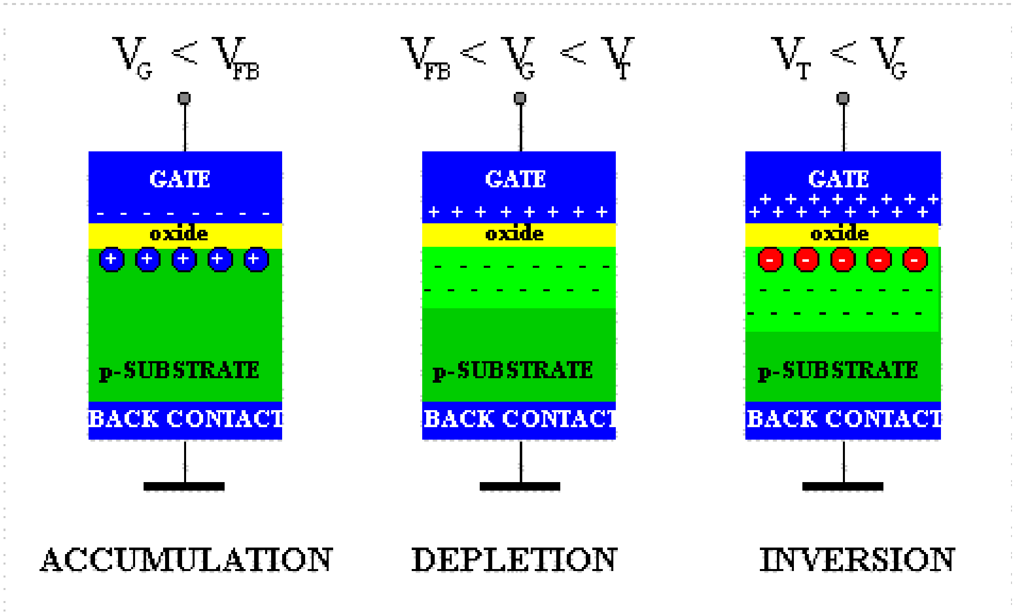


Electron and hole flow under forward active bias, $V_{BE} > 0$ and $V_{BC} = 0$.

MOS Capacitors

The MOS capacitor consists of a Metal-Oxide-Semiconductor structure





Three operating regions:

Accumulation: -V -- charges accumulate at oxide-semiconcutor surface

Depletion: +V -- pushes mobile holes into substrate. The semiconductor is depleted of mobile charge carriers at interface.

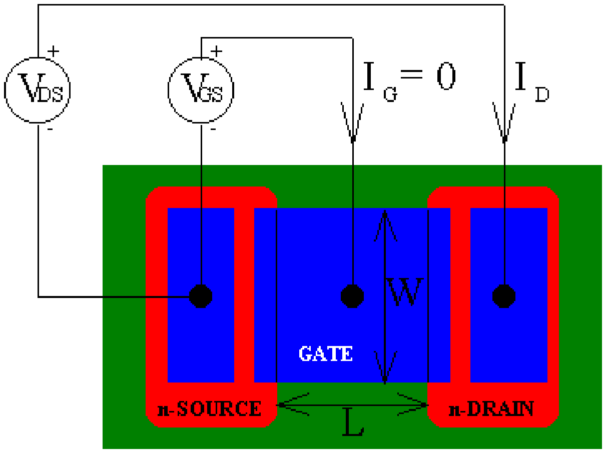
Inversion: ++V -- beyond VT, minority carriers are attracted to the interface forming a negative inversion layer.

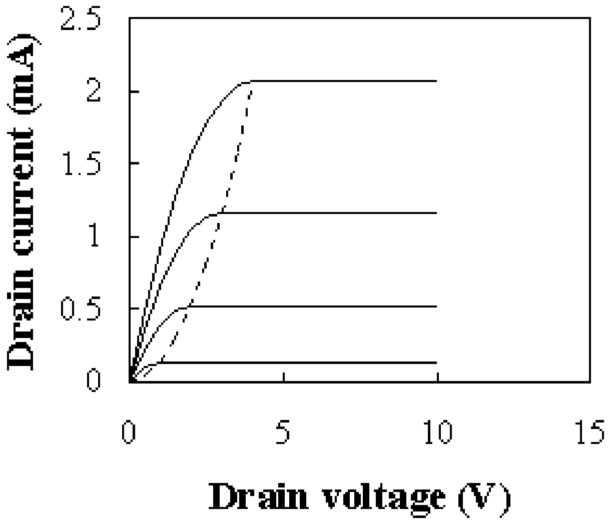
V_G = Gate Voltage

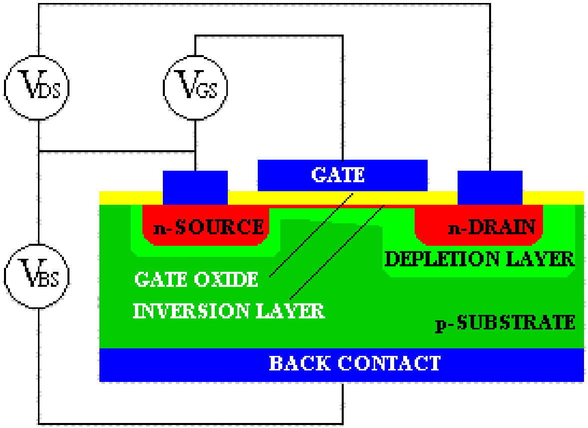
V_T = Threshold Voltage

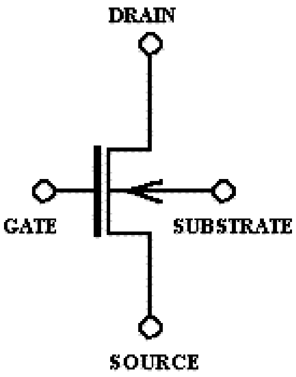
V_{FB} = Flat Band Voltage

MOSFETS:nMOS









- The voltage applied to the gate controls the flow of electrons from the source to the drain.
- A positive voltage applied to the gate attracts electrons to the interface between the gate dielectric and the semiconductor. These electrons form a conducting channel called the inversion layer.
- No gate current is required to maintain the inversion layer at the interface since the gate oxide blocks any carrier flow. The net result is that the applied gate voltage controls the current between drain and source.

Other Devices from p-n junctions

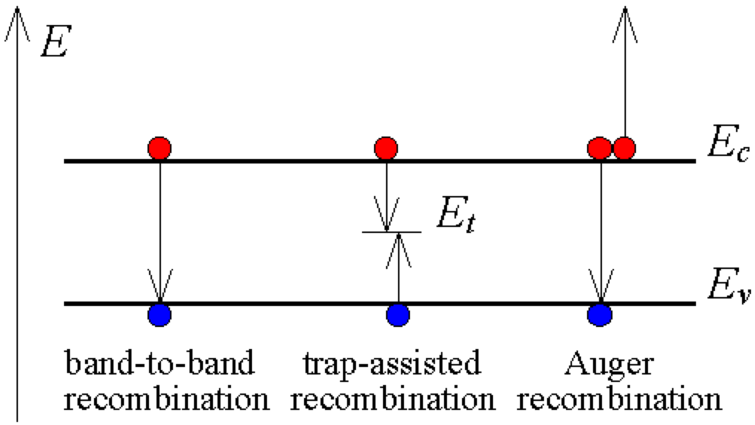
- Memory (5/7 -- Glenn Alers)

Electron to Photon conversion devices
- LEDs and SSL (5/5)
- Lasers (5/5)
- Solid State Lighting (5/12)
- Displays (5/12)

Photon to electron conversion devices
- Photodectors (5/12)
- Solar Cells (5/14)
- Displays and HW Review (5/19)

HW#3 on capaciators, transistors and LEDs/Lasers due 5/12
HW#4 on photodetectors and solar cells due 5/19
Midterm #2 5/21

Generation and Absorption in Semiconductors: Review



For electrons in a p-type semiconductor:

$$U_n = R_n - G_n = \frac{n_p - n_{p0}}{\tau_n}$$

For holes in a n-type semiconductor:

$$U_p = R_p - G_p = \frac{p_n - p_{n0}}{\tau_p}$$

$$G_{p,light} = G_{n,light} = \alpha \frac{P_{opt}(x)}{E_{ph} A}$$

$$\frac{dP_{opt}(x)}{dx} = -\alpha P_{opt}(x)$$

$$\delta n = \delta p = \tau_p G_p$$

$$U_{b-b} = b(np - n_i^2)$$

$$U_{SHR} = \frac{pn - n_i^2}{p + n + 2n_i \cosh(\frac{E_i - E_t}{kT})} N_t v_{th} \sigma$$

If p>>n, then $U_n = R_n - G_n = \frac{n_p - n_{p0}}{\tau_n}$

If n>>p, then $U_p = R_p - G_p = \frac{p_n - p_{n0}}{\tau_p}$

Optical Processes in Semiconductors

- **Absorption processes**
  - Band-to-band (bulk): indirect gap, direct gap, excitons
  - Quantum well: inter-band, intra-band: selection rules
  - Impurity level absorption
  - Free carrier absorption
- **Light emission**
  - Recombination processes
    - Band-to-band (direct vs. indirect)
    - Via mid-gap levels
    - Auger
    - Stimulated
  - Radiative vs. non-radiative transitions
  - Spontaneous vs. Stimulated Emission
- **Refraction and diffraction**
  - Directing and guiding light

Light (i.e. photon) Absorption

Absorption in semiconductors: processes

Within these energy level systems we can have a variety of mechanisms by which electrons (and holes) absorb optical energy. Most of these processes can occur in quantum wells, wires, and dots, as well as in bulk material. :

Band-to-band: an electron in the valence band absorbs a photon with enough energy to be excited to the conduction band, leaving a hole behind.

Band-to-exciton: an electron in the valence band absorbs almost enough energy to be excited to the conduction band. The electron and hole it leaves behind remain electrically "bound" together, much like the electron and proton of a hydrogen atom.

Band-to-impurity or impurity to band: an electron absorbs a photon that excites it from the valence band to an empty impurity atom, or from an occupied impurity atom to the conduction band.

Light (i.e. photon) Absorption

Absorption in semiconductors: processes cont.

Free carrier: an electron in the conduction band, or hole in the valence band, absorbs a photon an is excited to a higher energy level within the same set of bands (i.e, conduction or valence).

In quantum structures there can be photon absorption due to carriers being excited between the quantum levels within the same band (termed "intra-band"), as well as between the various quantum levels in one band and those in another "(inter-band"):

Intra-band: these transitions can occur only between even and odd index levels and are only operative for light polarized parallel to the direction of quantization. That is, in a quantum well the light must be polarized normal to the well itself, and in the direction of the composition variation.

Inter-band: inter-band transitions can occur between conduction and valence bands, or between different valence bands (light-hole, heavy-hole, and spin-off). There are transitions can be active for either polarization of the light, depending on the symmetries of the respective bands.

Light (i.e. photon) Absorption

Light normally incident on a solid will be partially reflected at the air (or vacuum) and solid interface, and the remaining light will enter the solid. If it is absorbed by the solid, its intensity will decrease exponentially with distance as $e^{-\alpha(\lambda)x}$, where $\alpha(\lambda)$ is the absorption coefficient.

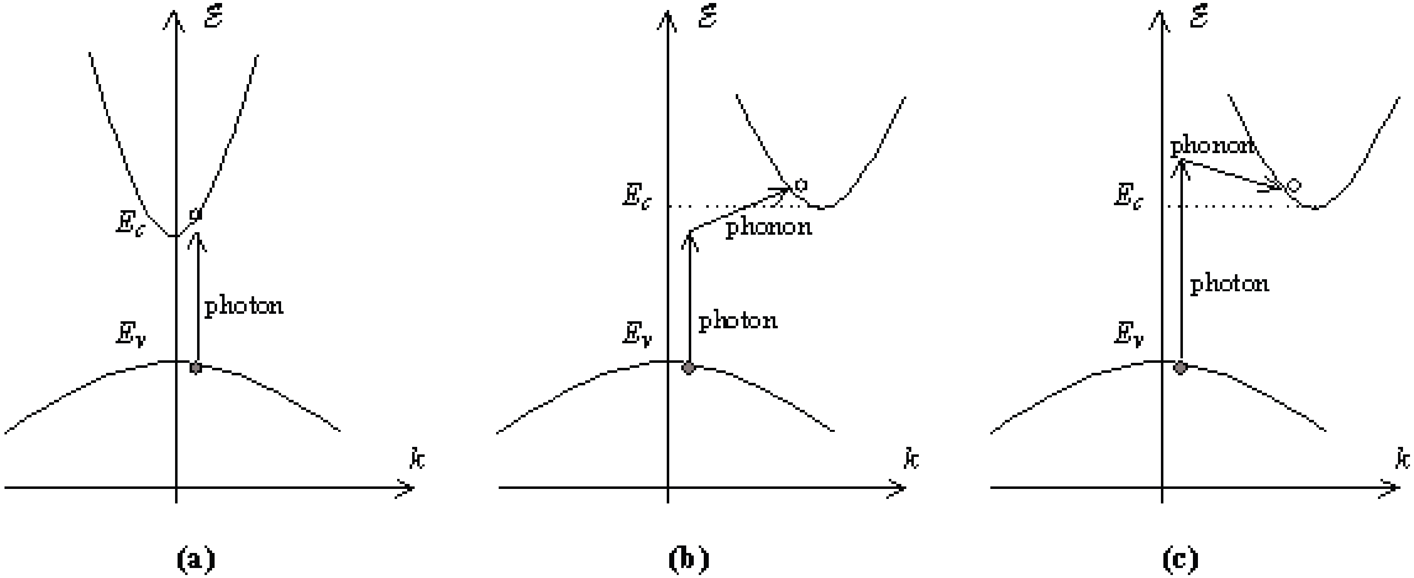
$$I(\lambda,x) = \left[1 - R(\lambda)\right] I_o(\lambda) e^{-\alpha(\lambda)x}$$

where $R(\lambda)$ is the reflection coefficient at the interface. We will say more about $R(\lambda)$ shortly, but first discuss $\alpha(\lambda)$.

Light (i.e. photon) Absorption

Direct: Absorption of a photon is obtained if an empty state in the conduction band is available for which the energy and momentum equals that of an electron in the valence band plus that of the incident photon. Photons have little momentum relative of their energy since they travel at the speed of light. The electron therefore makes an almost vertical transition on the E-k diagram.

Indirect: Absorption of light requires the help of another particle, namely a photon. Since a phonon has a relatively low velocity, it has a small energy and large momentum compared to that of a photon. Conservation of both energy and momentum can therefore be obtained in the absorption process if a phonon is created or an existing phonon participates. The probability of having an interaction take place involving all three particles will be lower than a simple electron-photon interaction in a direct bandgap semiconductor.



E-k diagram illustrating a) Photon absorption in a direct bandgap semiconductor b) Photon absorption in an indirect bandgap semiconductor assisted by phonon absorption and c) Photon absorption in an indirect bandgap semiconductor assisted by phonon emission.

Light (i.e. photon) Absorption

Absorption in semiconductors: band-to-band

Direct-gap: Direct-gap absorption involves only a single electron and a photon. Single electron theory (which ignors the possibility of excitons) tells us that the absorption coefficient for direct-gap absorption varies as the square-root of energy above the band edge:

$$\alpha_{\substack{direct\\gap}}(h\nu) = A_{\substack{direct\\gap}}\left[h\nu - E_g\right]^{1/2} u_1\left(h\nu - E_g\right)$$

Indirect-gap: Indirect-gap absorption requires the absorption or emission of a phonon, as well of a photon. In this case single electron theory tells us that the absorption coefficient for direct-gap absorption varies as the square of energy above onset:

$$\alpha_{\substack{indirct\\gap}}(h\nu) = A_{\substack{phonon\\absorption}}\left[h\nu - \left(E_g - E_{ph}\right)\right]^2 u_1\left(h\nu - E_g + E_{ph}\right)$$

$$+ A_{\substack{phonon\\absorption}}\left[h\nu - \left(E_g + E_{ph}\right)\right]^2 u_1\left(h\nu - E_g - E_{ph}\right)$$

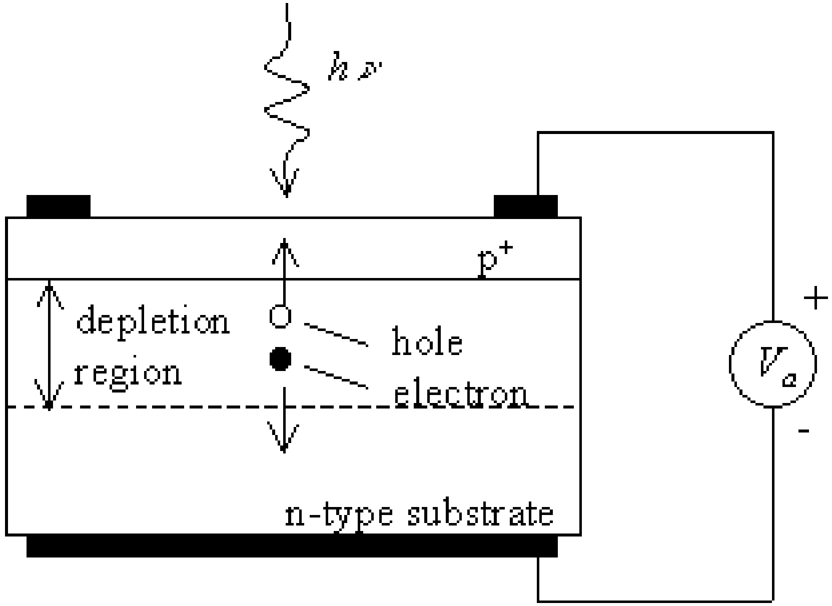
Bottom line: Direct-gap absorption is more abrupt, and more intense than indirect-gap absorption.

Basic Principles of Photodiodes

Photodiodes and crystalline solar cells are essentially the same as the p-n diodes

$$I = I_s\,(e^{V_a/V_t} - 1) - I_{ph}$$

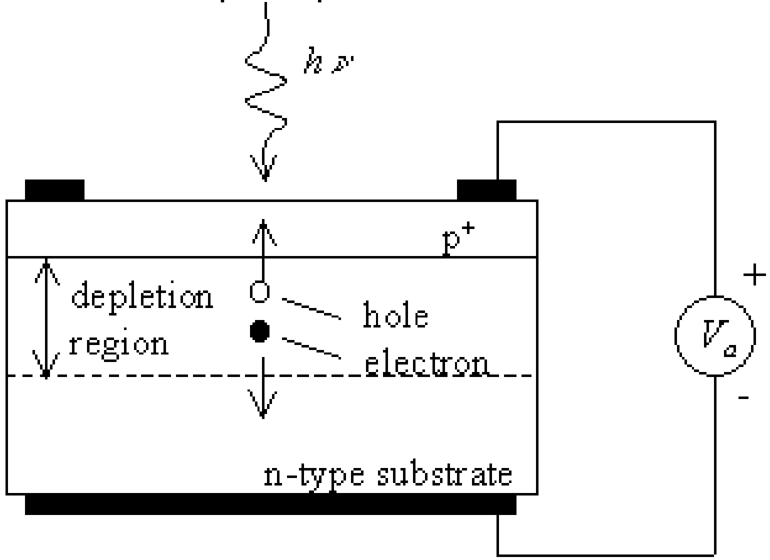
where the additional photocurrent, I_{ph},is due to photogeneration of electrons and holes



The photo-generated carriers cause a photocurrent, which opposes the diode current under forward bias. Therefore, the diode can be used as a photodetector - using a reverse or even zero bias voltage - as the measured photocurrent is proportional to the incident light intensity. The diode can also be used as a solar cell - under zero bias – to generate electrical power.

Basic Principles of Photodiodes

The primary characteristics of a photodiode are the responsivity, the dark current and the bandwidth. The responsivity is the photocurrent divided by the incident optical power. The maximum photocurrent in a photodiode equals:



$$I_{ph,\max} = \frac{q}{h\nu} P_{in}$$

where P_{in} is the incident optical power.

The maximum photocurrent in the presence of a reflection, R at the surface of the photodiode and an absorption over a thickness d, in a material with an absorption coefficient, α, is given by:

$$I_{ph} = (1-R)(1-e^{-\alpha d})\frac{qP_{in}}{h\nu}$$

This photocurrent is obtained by integrating the generation rate over the absorption region with thickness, d. The photocurrent is further reduced if photo-generated electron-hole pairs recombine within the photodiode instead of being swept into the regions where they are majority carriers.

Basic Principles of Photodiodes: Dark Current

The dark current is the current through the diode in the absence of light. This current is due to the ideal diode current, the generation/recombination of carriers in the depletion region and any surface leakage, which occurs in the diode. The dark current obviously limits the minimum power detected by the photodiode, since a photocurrent much smaller than the dark current would be hard to measure.

However, the true limitation is the shot noise generated by the current through the diode. The shot noise as quantified by the average of the square of the noise current is given by:

$$\langle i^2 \rangle = 2 q I \Delta f$$

Where I is the diode current and Δf is the bandwidth of the detector. The bandwidth of the diode is affected by the transit time of the photo-generated carriers through the diode and by the capacitance of the diode. The carrier transit time yields the intrinsic bandwidth of the diode while the capacitance together with the impedance of the amplifier or the transmission line connected to the diode yields a the parasitic RC delay.

Basic Principles of Solar Cells

$$I = I_s\left(e^{V_a/V_t} - 1\right) - I_{ph}$$

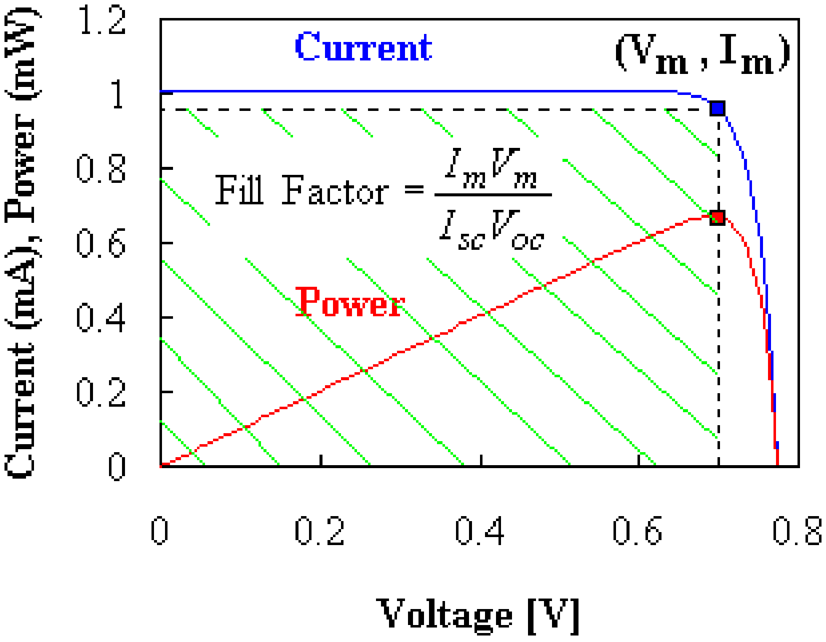
P = I*V

The maximum power is generated for:

$$\frac{dP}{dV_a} = 0 = I_s\left(e^{V_m/V_t} - 1\right) - I_{ph} + \frac{V_m}{V_t} I_s e^{V_m/V_t}$$

$$V_m = V_t \ln \frac{1 + I_{ph}/I_s}{1 + V_m/V_t}$$

$$\eta = \left|\frac{V_m I_m}{P_{in}}\right|$$



Basic Principles of Solar Cells

A 1 cm^2 silicon solar cell has a saturation current of 10^{-12} A and is illuminated with sunlight yielding a short-circuit photocurrent of 25 mA. Calculate the solar cell efficiency and fill factor.

Solution:
The maximum power is generated for:

$$V_m = V_t \ln \frac{1 + I_{ph} / I_s}{1 + V_m / V_t}$$

Using iteration and a starting value of 0.5 V one obtains the following successive values for V_m:

V_m = 0.5, 0.542, 0.540 V

and the efficiency equals:

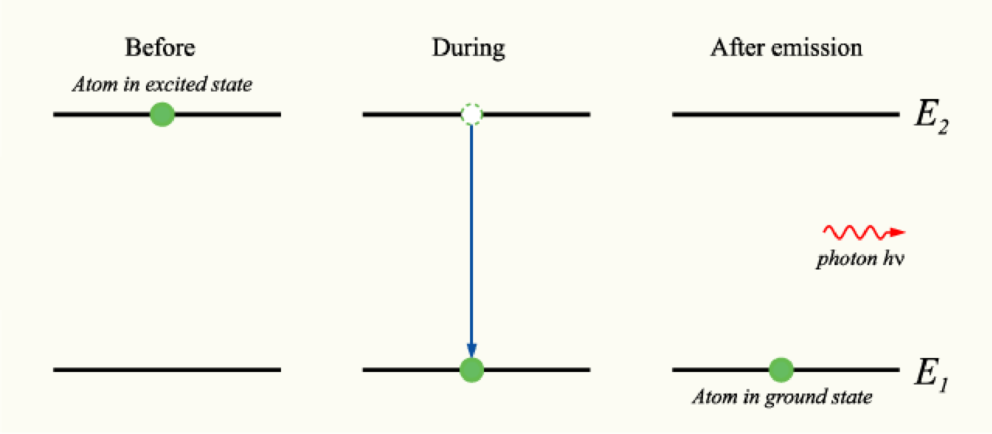
$$\eta = \left| \frac{V_m I_m}{P_{in}} \right| = \frac{0.54 \times 0.024}{0.1} = 13\%$$

The current, I_m, corresponding to the voltage, V_m, was calculated using equation (4.6.1) and the power of the sun was assumed 100 mW/cm^2. The fill factor equals:

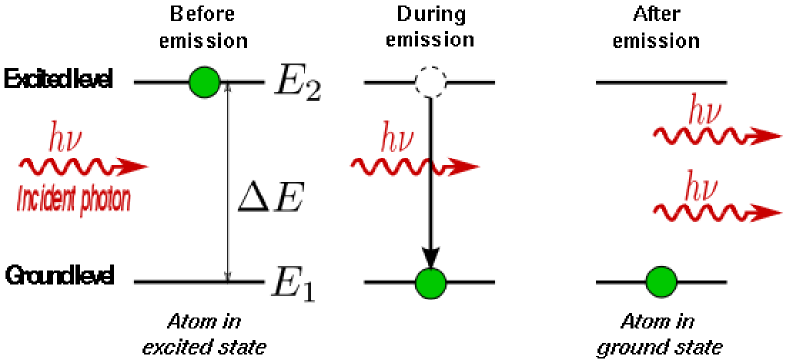
$$\text{fill factor} = \frac{V_m I_m}{V_{oc} I_{sc}} = \frac{0.54 \times 0.024}{0.62 \times 0.025} = 83\%$$

where the open circuit voltage is calculated using $I = I_s (e^{V_a / V_t} - 1) - I_{ph}$ and I = 0.
The short circuit current equals the photocurrent.

Spontaneous Emission



Stimulated Emission



$$E_2 - E_1 = \Delta E = h\nu$$

If the number of light sources in the excited state is given by N, the rate at which N decays is:

$$\frac{\partial N}{\partial t} = -A_{21} N$$

$$N(t) = N(0)e^{-A_{21}t} = N(0)e^{-\Gamma_{rad}t}$$

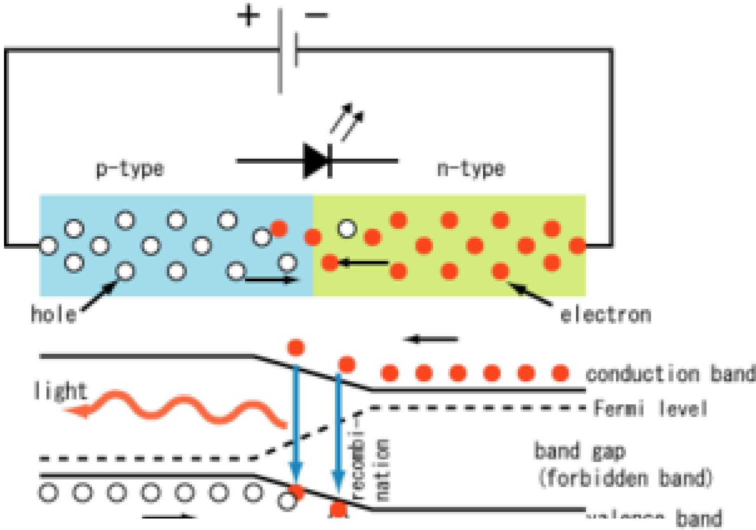
where N(0) is the initial number of light sources in the excited state, t is the time and Γ_{rad} is the radiative decay rate of the transition, and A_{21} (reffered to Einstein A coefficient) is the rate of spontaneous emission.

$$\frac{\partial N}{\partial t} = -B_{21}\rho(\nu)N$$

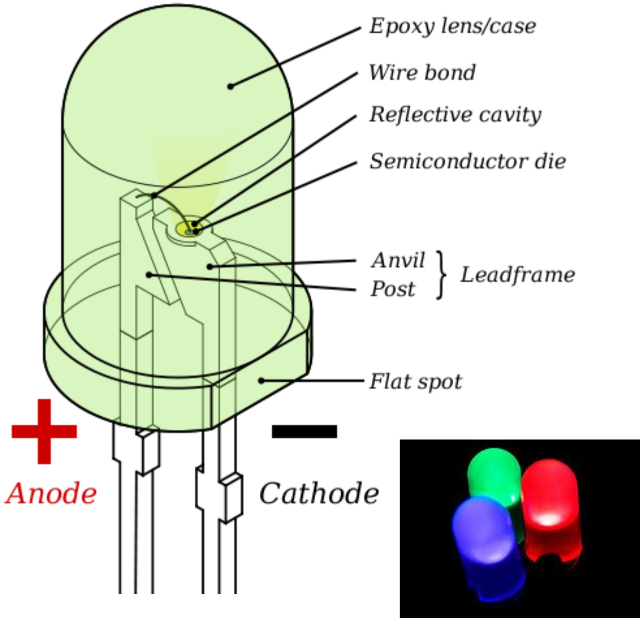
where B_{21} is a proportionality constant for stimulate emission in this particular atom (referred to as an Einstein B coefficient), and ρ(v) is the radiation density of photons of frequency v.

Basic Principles of LEDs

Light emitting diodes are p-n diodes in which the recombination of electrons and holes yields a photon. This radiative recombination process occurs primarily in direct bandgap semiconductors where the lowest conduction band minimum and the highest valence band maximum occur at k = 0, where k is the wavenumber. Examples of direct bandgap semiconductors are GaAs, InP, and GaN,



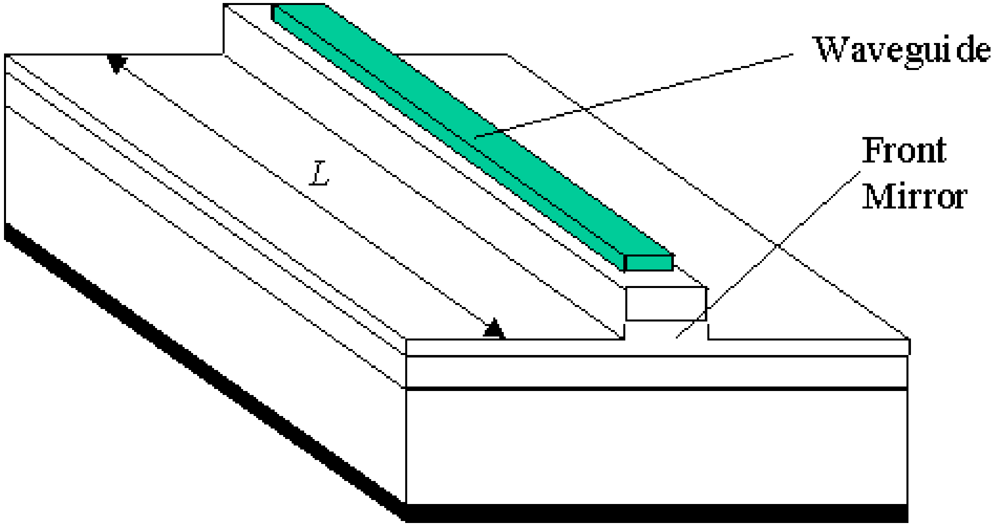
Radiative recombination competes with non-radiative recombination processes such as trap-assisted recombination. Radiative recombination dominates at high minority-carrier densities. Using a quantum well,, one can obtain high carrier densities at low current densities. These quantum well LEDs have high internal quantum efficiency as almost every electron injected in the quantum well recombines with a hole and yields a photon.



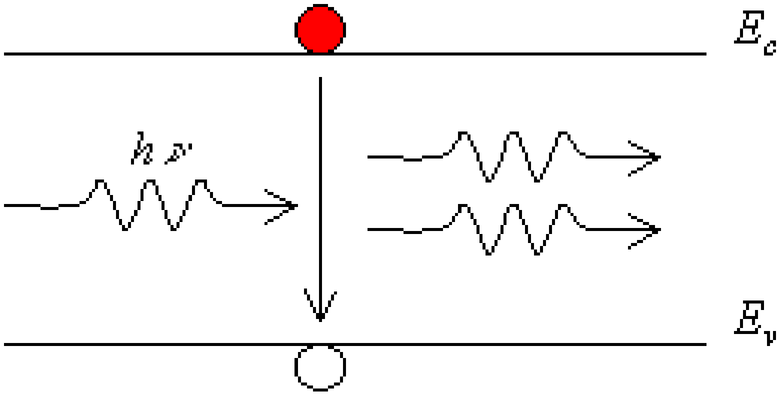
The external quantum efficiency of planar LEDs is much lower than unity due to total internal reflection. For GaAs with a refractive index of 3.5, the angle for total internal reflection equals 17^{o} so that only a few percent of the generated photons can escape the semiconductor. This effect can be avoided by having a spherical semiconductor shape, which ensures that most photons travel normal to the interface. The external quantum efficiency can thereby be increased to values larger than 50%.

Basic Principles of Laser diodes

Laser diodes are very similar to LEDs since they also consist of a p-n diode with an active region where electrons and holes recombine resulting in light emission. However, a laser diode also contains an optical cavity where stimulated emission takes place. The laser cavity consists of a waveguide terminated on each end by a mirror.



The light in the waveguide is amplified by stimulated emission. Stimulated emission is a process where a photon triggers the radiative recombination of an electron and hole thereby creating an additional photon with the same energy and phase as the incident photon. This "cloning" of photons results in a coherent beam.



Basic Principles of Laser diodes

The stimulated emission process yields an increase in photons as they travel along the waveguide. Combined with the waveguide losses, stimulated emission yields a net gain per unit length, g. The number of photons can therefore be maintained if the roundtrip amplification in a cavity of length, L, including the partial reflection at the mirrors with reflectivity R_1 and R_2 equals unity.

$$\text{Roundtrip amplification} = e^{2gL} R_1 R_2 = 1$$

If the roundtrip amplification is less than one, then the number of photons steadily decreases. If the roundtrip amplification is larger than one, the number of photons increases as the photons travel back and forth in the cavity, resulting in a gain g. Initially, the gain is negative if no current is applied to the laser diode as absorption dominates in the waveguide. As the laser current is increased, the absorption first decreases and the gain increases. The current for which the gain satisfies the lasing condition is the threshold current of the laser, I_{th}. Below the threshold current very little light is emitted by the laser structure. For an applied current larger than the threshold current, the output power, P_{out}, increases linearly with the applied current

$$g = \frac{1}{2L} \ln \frac{1}{R_1 R_2}$$

$$P_{out} = \eta \frac{h\nu}{q} (I - I_{th})$$