530192 “Photonics in semiconductors”, (5 op / 3 ov), period III and IV – Spring 2013

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Course webpage:
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Schedule

- Lectures:
  Thursdays: 10:15 – 12:00, 17.01.2013 – 02.05.2013,
  Lecture Room: PHYSICUM - PHY D116 SH;

- Exercises:
  Thursdays: 14:15 – 16:00, 17.01.2013 – 02.05.2013,
  Lecture Room: PHYSICUM - PHY D114 SH;

- Demonstrations:
  Electronics Laboratory: PHYSICUM - PHY C 312 - 316.
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Lecture 07

$pn$ Junction & LEDs
Consider what happens when one side of a sample of Si is doped \textit{n-type} and the other \textit{p-type}.

Assume that there is an \textit{abrupt discontinuity} between the \textit{p} and \textit{n} regions, which we call the \textit{metallurgical junction} (\textit{M}).

Due to the \textit{hole concentration gradient} from the \textit{p}-side (\( p = p_{po} \)) to the \textit{n}-side (\( p = p_{no} \)), holes \textit{diffuse towards the right}.

The \textit{n}-side near the junction therefore becomes \textit{depleted of majority carriers} (\( n_{no} \)).

Similarly, the electron concentration gradient drives the electrons by diffusion towards the left. Electrons diffusing into the \textit{p}-side \textit{recombine} with the holes (majority carrier in \textit{p}-type material).

The regions on both sides of the junction \textit{M} becomes \textit{depleted} of free carriers in comparison with the bulk \textit{p} and \textit{n} regions.
There is an internal electric field $E_0$, from positive ions to negative ions, that tries to drift the holes and the electrons back into the p & n-region in the opposite direction to their diffusion.

It is apparent that as more and more holes diffuse towards the right, and electron towards the left the internal field around $M$ will increase until eventually an equilibrium is reached when the rate of holes diffusing towards the right is just balanced by holes drifting back to the left, driven by the field $E_0$.

For uniformly doped $p$ and $n$ regions, the net space charge density $\rho_{net}$ is negative and equal to $-e N_a$ from $-W_p \leq x \leq 0$ in the space charge layer (SCL), also known as the depletion region around the metallurgical junction. $\rho_{net}$ is positive and equal to $+e N_d$ in the SCL from $0 \leq x \leq W_n$. (d)

$N_a > N_d$ donor and acceptor concentration - arbitrarily assumed in the figure.
The total charge on the left hand side of (e) must equal that on the right side for overall charge neutrality so that

\[ N_a W_p = N_d W_n \]  
\[(W_p, W_n - \text{depletion widths})\]  
\[(N_a, N_d \ \text{donor and acceptor concentration})\]

The variation of the electric field across the pn junction is shown in (e). The negative field means that it is in the -x direction. \( E(x) \) reaches a maximum value \( E_o \) at \( M \).

The potential \( V(x) \) at any point \( x \) can be found by integrating the electric field since by definition \( E = -dV/dx \). \( V(x) \) increases in the depletion region (starting from 0 – NO voltage applied) towards the n-side as indicated in (f) on the figure.

Notice that on the n-side the potential reaches \( V_0 \) which is called the built-in potential (potential barrier).
pn Junction: Open Circuit
Built-in Potential

The built-in electric field is given by

\[ E_o = -\frac{eN_d W_n}{\varepsilon} = -\frac{eN_a W_p}{\varepsilon} \]

\( W_p, W_n \) - depletion widths, \( N_a, N_d \) donor and acceptor concentration

The built-in potential is given by

\[ V_o = -\frac{1}{2} E_o W_o = \frac{eN_a N_d W_o^2}{2\varepsilon (N_a + N_d)} \]

\( \varepsilon \) - permittivity of the medium

where \( W_o = W_p + W_n = \left[ \frac{2\varepsilon (N_a + N_d) V_o}{eN_a N_d} \right]^{1/2} \)

\( W_o \) is the total width of the depletion region (SCL) under a zero-applied voltage.

If we know \( V_o \) we can calculate \( W_o \).
We can write the built-in potential in terms of the dopant concentrations:

\[ p_{po} = N_a, \quad p_{no} = \frac{n_i^2}{n_{no}} = \frac{n_i^2}{N_d} \]

The built-in potential is then given by:

\[ V_o = \frac{k_B T}{e} \ln \left( \frac{N_a N_d}{n_i^2} \right) \]

The built-in voltage \( V_o \) is the potential across a \textit{pn junction}, going from p to n-type semiconductor, in an open circuit.

It is not the voltage across the diode that is made up of \( V_o \) as well as the contact potentials at the metal to semiconductor junctions at the electrodes.

If we add \( V_o \) and the contact potentials at the electroded ends, we will find zero.
Consider what happens when a battery with a voltage $V$ is connected across a $pn$ junction so that the positive terminal of the battery is attached to the p-side and the negative terminal to the n-side (forward bias).

Forward biased $pn$ junction and the injection of minority carriers (a) Carrier concentration profiles across the device under forward bias. (b). The hole-potential energy with and without an applied bias. $W$ is the width of the SCL with forward bias.
pn Junction: Forward Bias

The negative polarity will reduce the potential barrier $V_o$ by $V$ as in Fig.(b).

The bulk regions outside the SCL have high conductivities.

⇒ The applied voltage drops mostly across the depletion width $W$.

The applied voltage effectively reduces the built-in potential (potential barrier) and hence the built-in field that acts against diffusion.

The probability that a hole in the p-side will surmount this (reduced) potential barrier and diffuse to the n-side is now proportional to

\[
\text{Probability} \propto \exp \left[ -e \frac{V_o-V}{k_B T} \right]
\]

Consequently, many holes can now diffuse across the depletion region and enter the n-side. This results in the injection of excess minority carriers, holes into n-region.

Similarly, excess electrons can now diffuse towards the p-side and enter this region and thereby become injected minority carriers.
The hole concentration, $p_n(0) = p_n(x' = 0)$, just outside the depletion region at $x' = 0$ ($x'$ is measured from $W_p$) is due to excess holes diffusing as a result of the reduction of the built-in potential barrier. This concentration, $p_n(0)$ is determined by the probability of surmounting the new potential energy barrier $e(V_o - V)$,

$$p_n(0) = p_{po} \exp \left[ \frac{-e(V_o - V)}{k_B T} \right]$$

This follows directly from the Boltzmann equation, by virtue of the hole potential energy rising by $e(V_o - V)$ from $x = -W_p$ to $x = W_n$ (b) and at the same time the hole concentration falling from $p_{no}$ to $p_n(0)$. After simple mathematical calculations we get the effect of the applied voltage out directly, which shows how the voltage $V$ determines the amount of excess holes diffusing and arriving at the n-region.
The new hole concentration \( p_n(0) \) just outside the depletion region is determined by the probability that a hole in the p-side will surmount this (reduced) potential barrier \( e(V_0 - V) \).

\[
 p_n(0) = p_{no} \exp \left[ \frac{eV}{k_B T} \right]
\]

The equation describes the effect of the applied voltage \( V \) on the injected minority carrier concentration just outside the depletion region, \( p_n(0) \) - obviously, with no applied voltage, \( V = 0 \) and \( p_n(0) = p_{n0} \).

This is called the law of the junction.
The electron concentration \( n_p(0) \) just outside the depletion region is given by the equivalent law of the junction equation.

\[
n_p(0) = n_{po} \exp \left[ \frac{eV}{k_B T} \right]
\]

It is apparent that an electric current can be maintained thru a pn junction under forward bias and that the current flow is due to the diffusion of minority carriers. There is some drift of majority carriers as well.
There will be a minority carrier concentration profile that arises from these carriers recombining. We define the length that results from the mean carrier lifetime.

\[ L_h = \sqrt{(D_h - \tau_h)} \]

- \( L_h \) – is the hole diffusion length
- \( D_h \) – is the diffusion coefficient for holes
- \( \tau_h \) – is the mean hole recombination lifetime (minority carrier lifetime).

The diffusion length is the average distance diffused by a minority carrier before it disappears by recombination.

By replacing \( h \) with \( e \), we will receive the equation for Diffusion Length of electrons.
The total diffusion current density is:

\[ J_{\text{diffusion}} = J_h + J_e \]

- \( J_h \) – hole diffusion current density
- \( J_e \) – electron diffusion current density

Although the hole diffusion current depends on location, the total current at any location is, however, the sum of hole and electron contributions, which is independent of \( x \).

The total current anywhere in the device is constant. Just outside the depletion region it is due to the diffusion of minority carriers.
The total diffusion current density is:

\[
J_{\text{diffusion}} = J_{so} \left[ \exp\left( \frac{eV}{k_B T} \right) - 1 \right]
\]

Where \( J_{so} \) is the net diffusion current flow from both electrons and holes.

The constant \( J_{so} \) depends not only on the doping, but also on the material. It is known as the reverse saturation current density.

The equation is known as the Shockley equation. It represents the diffusion of minority carriers in the neutral regions.
The total current into the diode will supply carriers for minority carrier diffusion in the neutral regions and recombination in the space charge layer. The diode current is given by

\[ I = I_o \left[ \exp \left( \frac{eV}{\eta k_B T} \right) - 1 \right] \]

Where \( I_o \) is a constant. The diode ideality factor \( \eta \) is either 1 or 2 depending on the diffusion mechanism of the particular situation.

Forward and reverse I-V characteristics of a pn junction (the positive and negative current axes have different scales).
When a **pn** junction is reverse biased, the reverse current is typically very small.

Reverse biased **pn** junction. (a) Minority carrier profiles and the origin of the reverse current. (b) Hole **PE** across the junction under reverse bias.
The applied voltage drops mainly across the resistive depletion region, which becomes wider.

The negative terminal will cause holes in the p-side to move away from the SCL, which results in more exposed negative acceptor ions and thus a wider SCL. Similarly, the positive terminal will attract electrons away from the SCL, which exposes more positively charged donors. The depletion width on the n-side therefore also widens.

There is a small concentration gradient and thus a small electron/hole diffusion current. This current $-J_{SO}$ is called the reverse saturation current density.
The *depletion region* of a pn junction has positive and negative charges separated over a distance \( W \) similar to a parallel plate capacitor.

\[
C_{\text{dep}} = \frac{A}{\sqrt{V_0 - V}} \sqrt{\frac{e \varepsilon (N_a N_d)}{2(N_a + N_d)}}
\]

Where \( A \) = the depletion region area, and \( \varepsilon = \varepsilon_0 \varepsilon_r \) permitivities.

- In general, \( C_{\text{dep}} \) decreases with increasing \( V \).
- Typically, \( C_{\text{dep}} \) under reverse bias is of the order of a few picofarads.
The semiconductor must maintain charge neutrality. At the same time electrons and holes are recombining. Thus the instantaneous rate of recombination depends on the electron/hole concentrations.

\[
\frac{\partial \Delta n_p}{\partial t} = - \frac{\Delta n_e}{\tau_e}
\]

\(\Delta n_e\) is the excess electron concentration and \(\Delta n_p\) is the excess hole concentration

Where \(\tau_e\) is the recombination time (for an electron in this case). The rate of carrier concentration change is given by \(\partial \Delta n_p / \partial t\).

Under high levels of carrier injection conditions the lifetime \(\tau_e\) is inversely proportional to the injected carrier concentration. Thus the lifetime is not constant under some conditions.
The pn junction energy band diagram for open circuit conditions.
The Fermi level must be uniform throughout the material under thermal equilibrium and in the dark.
Thus the bands are “bent” to reflect the relative position of the Fermi level.

The electrostatic potential energy (PE) of the electron decreases from 0 inside the p-region to \(-eV_o\) inside the n-region.

The total energy of the electron must therefore decrease going from the p- to the n-region by an amount \(eV_o\).

The electron in the n-side at \(E^c\) must overcome a PE barrier to go over to \(E^c\) in the p-side. This PE barrier is \(eV_o\) in which \(V_o\) is the built-in potential.
The pn Junction Band Diagram – **Forward Bias** conditions.

- The potential energy barrier has **shrunk by** V.
- Electron/holes can diffuse from the majority carrier side to become minority carriers in the other side.

Effect of forward bias, is to **reduce the PE barrier** from $eV_o$ to $e(V_o - V)$.

The electrons at $E_c$ in the n-side can now readily **overcome** the PE barrier and diffuse to the p-side.

The probability that an electron at $E_c$ in the n-side **overcomes the new PE barrier** and diffuses to $E_c$ in the p-side is now proportional to the Boltzmann factor

$$\exp \left[ \frac{-e(V_o - V)}{k_B T} \right]$$
The pn Junction Band Diagram – *Reverse Bias* conditions.

The potential energy barrier has grown by $V_r$.

**Shockley model**

**Thermal generation in the depletion region**

The small *reverse current* arises from thermal generation of minority carriers within a diffusion length to the SCL.
pn Junction: Band Diagram

Energy band diagrams for a *pn junction under* (a) open circuit, (b) forward bias and (c) reverse bias conditions. (d) Thermal generation of electron hole pairs in the depletion region results in a small reverse current.
Light Emitting Diode (LED)

LED is essentially a *pn junction diode* typically made from a *direct bandgap semiconductor*, for example GaAs, in which the electron hole pair recombination results in the emission of a photon. The emitted photon energy is therefore *equal* to the bandgap energy, $h\nu \approx E_g$.

![Energy band diagram of an unbiased pn+ junction device](image)

Energy band diagram of an unbiased *pn+ junction* device in which the n- side is more heavily doped than the p-side. The band diagram keeps the Fermi level uniform through the device, which is a *requirement of equilibrium with no applied bias*. 
As soon as a **forward bias** $V$ is applied the **voltage drops** across the depletion region since this is the most resistive part of the device.

Consequently the built-in potential $V_o$ is **reduced to** $V_o - V$, which then allows the electrons from the $n^+$ side to diffuse, or become injected, into the p-side.

![Diagram of LED](image)

The **hole injection** component from $p$ **into the** $n^+$ side is much smaller than the electron injection component from the n+ to p-side.

The **recombination of injected electrons** in the depletion region as well as in the neutral p-side results in the, **spontaneous** emission of photons.
Light Emitting Diode (LED)

![Diagram of LED with labels](image)

- $E_g$: Bandgap energy
- $V_0$: Built-in voltage
- $e$: Electron charge

Anode

Cathode

Active region
Light Emitting Diode (LED)

- $E_g$: Bandgap energy
- $V_0$: built-in voltage
- $e$: electron charge
- $e(V_0-V)$: Electron charge times the voltage drop

Diagram:
- Anode
- Cathode
- Depletion region

Equations:
- $V_0-V$
- $E_g$
Light Emitting Diode (LED)

$E_g$: Bandgap energy

$V_0$: built-in voltage

e: electron charge
Light Emitting Diodes (LED)

- $E_g$: Bandgap energy
- $V_0$: Built-in voltage
- $e$: Electron charge

**Diagram**
- Anode
- Cathode
- Active region
- Built-in voltage $V_0$
Carrier recombination primarily occurs within the depletion region and within a volume extending over the diffusion length $L_e$ of the electrons in the p-side.

The recombination zone is frequently called the active region.

The phenomenon of light emission from electron hole pair (EHP) recombination as a result of minority carrier injection as in this case is, called injection electroluminescence. Because of the statistical nature of the recombination process between electrons and holes, the emitted photons are in random directions; they result from spontaneous emission processes in contrast to stimulated emission.

The LED structure has to be such that the emitted photons can escape the device without being reabsorbed by the semiconductor material. This means the p-side has to be sufficiently narrow.
The diagram shows, that near to long wave border the factor of absorption is small, while for short-wave spectrum region it is extremely high.
In its simplest technological form, LEDs are typically fabricated by epitaxially growing doped semiconductor layers on a suitable substrate (e.g. GaAs or GaP).

This type of planar pn junction is formed by the epitaxial growth of first the n-layer and then the p-layer.

The substrate is essentially a mechanical support for the pn junction device (the layers) and can be of different material.

The p-side is on the surface from which light is emitted and is therefore made narrow (a few microns) to allow the photons to escape without being reabsorbed. To ensure that most of the recombination takes place in the p-side, the n-side is heavily doped (n+).

Those photons that are emitted towards the n-side become either absorbed or reflected back at the substrate interface depending on the substrate thickness and the exact structure of the LED.

The use of a segmented back electrode will encourage reflections from the semiconductor-air interface.
Not all light rays reaching the semiconductor-air interface can escape due to TIR. $\Theta_c$ in GaAs ($n \sim 3.6$) to air is only $16^\circ$, which means much of the light suffers TIR.
It is also possible to form the p-side by **diffusing** dopants into the epitaxial n⁺-layer, which is a diffused junction planar LED as illustrated in Fig. (b).

A schematic illustration of typical planar surface emitting LED devices. (a) p-layer grown epitaxially on an n⁺ substrate. (b) First n⁺ is epitaxially grown and then p region is formed by dopant diffusion into the epitaxial layer.
If the epitaxial layer and the substrate crystals have different crystal lattice parameters, then there is a lattice mismatch between the two crystal structures. This causes lattice strain in the LED layer and hence leads to crystal defects. Such crystal defects encourage radiationless EHP recombinations. The defect acts as a recombination center.

Such defects are reduced by lattice-matching the LED epitaxial layer to the substrate crystal.

For example, one of the AlGaAs alloys is a direct bandgap semiconductor that has a bandgap in the red-emission region. It can be grown on GaAs substrates with excellent lattice match, which results in high efficiency LED devices.
It is possible to shape the surface of the semiconductor into a dome or hemisphere, so that light rays strike the surface at angles less than $\Theta_c$.

An inexpensive solution is to encapsulate the LED within a transparent plastic medium that has a higher refracted index than air.
LED Materials

- Various direct bandgap semiconductor pn junctions can be used to make LEDs that emit in the red and infrared range.
- III-V ternary alloys based on GaAs and GaP allow emission in the visible spectrum.
- Doping of Ga materials with different As, P, and Al ratios maintains the lattice constant while allowing for precise control of the bandgap (photons emitted).
- GaAsP with As concentrations greater than 0.55% are direct bandgap semiconductors.
- GaAsP with As concentrations less than 0.55% are indirect bandgap semiconductors.
- However, adding isoelectronic impurities such as N (same group V as P) into the semiconductor to substitute for P atoms provides a trap for indirect recombination and generates direct bandgap emission between the trap and the hole.
- Impurities reduce the light efficiency and alters wavelengths.

\[ \text{GaAs}_{1-y}P_y \]
\[ y = 0.45 \]
\[ \lambda = 870 \text{ nm} \]
LED Materials

- **Blue** LED materials
- GaN is a direct bandgap with $E_g = 3.4$ eV
- InGaN alloy has $E_g = 2.7$ eV (blue)
- Less efficient is Al doped SiC (indirect)
  - Aluminum captures holes and in a similar manner to N in GaAsPN materials and reduces the effective direct emission energy and efficiency of the device
- II-VI ZnSe semiconductors provide a direct bandgap blue emission

(a) GaAs$_{1-y}$P$_y$  
(b) N doped GaP
(c) Al doped SiC

(a) Photon emission in a direct bandgap semiconductor. (b) GaP is an indirect bandgap semiconductor. When doped with nitrogen there is an electron trap at $E_N$. Direct recombination between a trapped electron at $E_N$ and a hole emits a photon. (c) In Al doped SiC, EHP recombination is through an acceptor level like $E_A$.  

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- **Red and Infrared**
- Three to four element alloys.
- $\text{Al}_{1-x}\text{Ga}_x\text{As}$ with $x<0.43$ gives 870 nm
- Composition variances provide 650 – 870 nm
- $\text{In}_{1-x}\text{Ga}_x\text{Al}_{1-y}\text{P}_y$ can be varied to span 870 nm (GaAs) to 3.5 um (InAs)
LED Materials: III – IV Binary Alloys

- 2.26 eV (549 nm) (Added N, 565 nm)
- 1.43 eV (870 nm)

![Graph showing energy bandgap and lattice constant against wavelength.](image-url)
LED Materials: III – IV Ternary Alloys

System AlGaAs

- $2.17 \text{eV (650nm)}$
- $1.42 \text{eV (904nm)}$
- Al$_x$Ga$_{1-x}$As Direct $x < 0.43$

Energy bandgap (eV) vs. Lattice constant (Å) vs. Wavelength (µm) chart.
LED Materials: III – IV Quaternary Alloys

![Graph showing energy bandgap and lattice constant](image)
Bandgap energy $E_g$ and lattice constant $a$ for various III-V alloys of GaP, GaAs, InP and InAs. A line represents a ternary alloy formed with compounds from the end points of the line. Solid lines are for direct bandgap alloys whereas dashed lines for indirect bandgap alloys. Regions between lines represent quaternary alloys. The line from X to InP represents quaternary alloys $\text{In}_{1-x}\text{Ga}_x\text{As}_{1-y}\text{P}_y$ made from $\text{In}_{0.535}\text{Ga}_{0.465}\text{As}$ and InP which are lattice matched to InP.
Homojunction vs. Heterojunction LEDs

- pn junctions between two materials doped components of the same material (and thus the same bandgap) are called homojunctions
- Require narrow p type wells to channel photons out of the device prior to absorption
- Narrow channels lead to indirect recombination of electrons that reach defects located at the top surface of the p-type material, thereby reducing efficiency
- Junctions formed by two different bandgap semiconductor materials are called heterojunctions
  - Heterostructure devices (HD) are devices between two different bandgap semiconductors such as AlGaNAs and GaAs
The refractive index, \( n \), depends directly on the bandgap.

- Wide bandgap semiconductors have lower refractive indices.
- We can engineer the dielectric waveguide within the device and channel the photons out from the recombination region.

Adding a double heterostructure (DH) to LEDs reduces radiationless recombination.

- Introduces a higher bandgap behind the pn junction that localizes the optical generation region.
- The additional p-type region is known as a confining layer.
- Since the bandgap of AlGaAs is larger than that of GaAs emitted photons cannot get reabsorbed in the AlGaAs regions.
- Metal reflects light from the back side of the confining layer improving efficiency.
- \( n^+ \) layer is used as topside of the device to reduce lattice defects in the active region and improve device efficiency.

DH LEDs are more efficient than homojunction LEDs.
Heterojunction LEDs
Heterojunction LEDs

\[ \Delta E_c \]
\[ \Delta E_v \]

\[ E_{cp} \]
\[ E_{gp} \]
\[ E_{vp} \]

\[ E_{FP} \]
\[ E_{FN} \]

\[ E_{p} \]
\[ E_{N} \]
Heterojunction LEDs

\[ \begin{align*}
  &E_{Fp} &E_{gp} &\Delta E_c \\
  &\Delta E_v &E_{gN} &E_{FN}
\end{align*} \]
Heterojunction LEDs

Diagram showing a heterojunction LED structure with layers labeled as N+, p, and P. The materials AlGaAs and GaAs are also indicated. The diagram includes energy level markers and notations such as 2eV, 1,4eV, and qUo.
Heterojunction LEDs

Diagram showing the structure of a heterojunction light-emitting diode (LED) with layers of N+, p, and P regions, as well as AlGaAs and GaAs materials. The diagram illustrates the potential barriers and energy levels, including the expression for the band gap energy as \(2 - (1,4)\) eV, and the Fermi level \(E_F\).
Heterojunction LEDs

N+  +  -  p  +  -  P

AlGaAs  +  -  GaAs  AlGaAs

U

Q(U - U)  2-1,4  2eV

1,4eV  2eV

2eV
Heterojunction LEDs

No reabsorption

Refractive index decreases as $E_g \uparrow$
LED Device Characteristics

- Spread of available carrier recombination probabilities generates a spread in optical wavelength emitted.
- Line width of the spectral output is typically between 2.5 and 3.5 $k_B T$.
- Turn on voltage is achieved at low operating currents and remains flat as current is increased.
- Below the turn on voltage, no light is emitted.
- The number of populated electrons in the p-type region CB increases and thus the relative light intensity also increases with increasing current.

(a) A typical output spectrum (relative intensity vs wavelength) from a red GaAsP LED. 
(b) Typical output light power vs. forward current. 
(c) Typical I-V characteristics of a red LED. The turn-on voltage is around 1.5V.
LED Device Characteristics

The output spectrum from AlGaAs LED. Values normalized to peak emission at 25°C.
**LED Characteristics**

**$g_c (E)$: Density of states:** The number of electronic states in a band per unit energy per unit volume of a crystal

\[
g(E) = \frac{4\pi}{\hbar^3} \left(2m_e^*\right)^{3/2} \sqrt{E - E_c}
\]

The Fermi-Dirac function $f(E)$

\[
f(E) = \frac{I}{e^{(E - E_f) / kT} + 1}
\]

$f(E)$ - the probability of finding an electron in a quantum state with energy $E$.

The product $g(E)f(E)$ is the actual number of electrons per unit energy per unit volume, $n_E(E)$, in the CB.
The highest electron concentration is \((l/2)kT\) above \(E_c\).

Energy distribution of electrons in the CB and holes in the VB.

The transitions that involve the largest electron and hole concentrations occur most frequently.
LED Characteristics

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Energy distribution of electrons in the CB and holes in the VB.

The transitions that involve the largest electron and hole concentrations occur most frequently.
LED: temperature dependance

Bandgap energy (eV) vs Temperature K

- GaAs
- InP
- Si
- Ge

Current (mA) vs Voltage (V)

- 300K
- 77K
Solide State Lightening

- For now, between 25 & 50% efficiency - traditional light bulb which has 5%!
- Still expensive, they could come in the market for residential lighting in the next 10 or 15 years
White LED

Eg. Coumarin 6

Absorption

Emission

Typical Spectrum

Relative Intensity vs. Wavelength (nm)

300 400 500 600 700 800
For short haul applications like local area networks (LANs), LEDs are:
1. Simpler to “drive.”
2. Cheaper
3. Longer life (~150,000 hours) than for laser diode
4. Provide the necessary output power.

The type of light source suitable for optical communications depends not only on the communication distance but also on the bandwidth requirement. But even with the LED virtues listed above, the output spectrum is much wider than that of a laser diode. The situation will dictate which compromises can be made.

There are essentially two types of LED devices.
If the emitted radiation emerges from an area in the plane of the recombination layer as in (a) then the device is a surface emitting LED.

If the emitted radiation emerges from an area on an edge of the crystal as in (b) then the LED is an edge emitting LED (ELED).
Coupling Methods
A microlens focuses diverging light from a surface emitting LED into a multimode optical fiber.
The light is guided to the edge of the crystal by a dielectric waveguide formed by the wider bandgap semiconductors surrounding a double heterostructure.
Coupling Methods

(a) Light from an edge emitting LED is coupled into a fiber typically by using a lens or a GRIN rod lens.