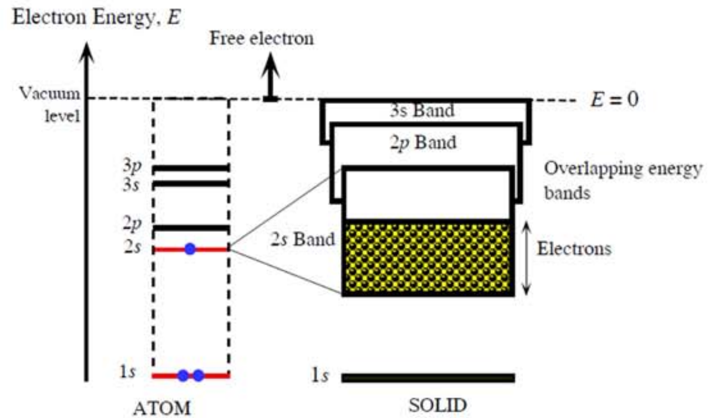
3. Semiconductor Science and Light Emitting Diodes

3.1. Semiconductor Concepts and Energy Bands

A. Energy Band Diagrams

When we bring 10^{23} Li atoms to form a metal crystal, interatomic interactions result in the formation of electron energy bands.



In a metal the various energy bands overlap to give a single band of energies that is only partially full of electrons. There are states with energies up to the vacuum level where the electron is free.

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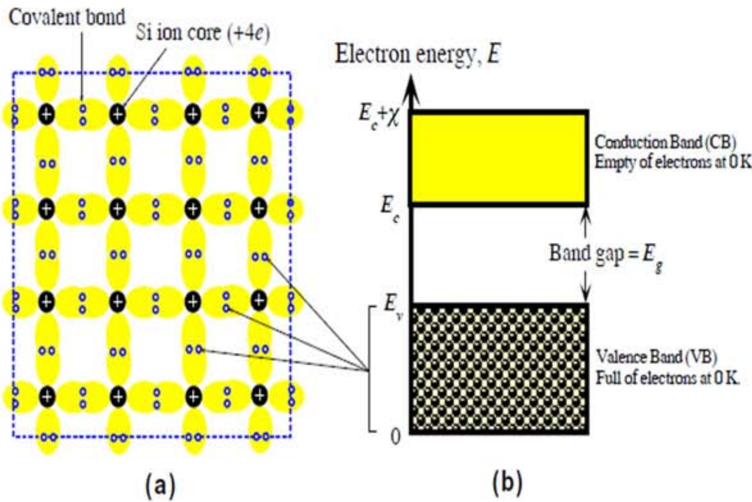
Figure 3.1



(a) A simplified two dimensional view of a region of the Si crystal showing covalent bonds. (b) The energy band diagram of electrons in the Si crystal at absolute zero of temperature.

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Figure 3.2

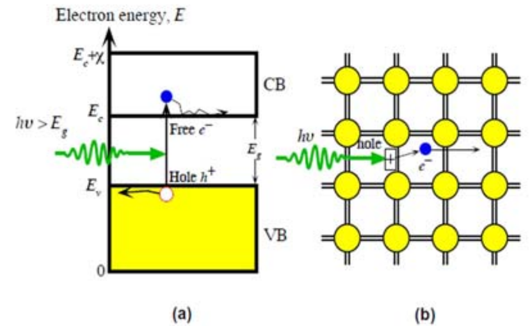
Conduction band (CB) and Valence band (VB) → separated by band gap E_g

CB → Electron wavefunctions in the crystal have higher energies
VB → than in the valence band.

$$E_g = E_c - E_v$$

Electron Affinity: χ → width of the CB.

Effective Mass, m_e^* of electron, is a Q.M. quantity; the electron in CB interacts with a periodic pot-en. as moving through the crystal.
∴ It's inertial resistance to acceleration (defn. of mass) is NOT the same as if it were in the vacuum.



(a) A photon with an energy greater than E_g can excite an electron from the VB to the CB. (b) Each line between Si-Si atoms is a valence electron in a bond. When a photon breaks a Si-Si bond, a free electron and a hole in the Si-Si bond is created.

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Figure 3.3

Hole → Empty electron state or the missing electron

Conduction in semiconductors occurs by both electrons and holes with charges $-e$ and $+e$ and their own effective masses m_e^* and m_h^*

- photogeneration of e-h pairs when $h\nu \geq E_g$
- Thermal generation → energetic vibrations due to thermal en. can rupture bonds and thereby create EHPs, by exciting VB → CB

- Recombination, The (excited) electron falls from CB to VB to fill the hole.

The excess energy → emitted by a photon in GaAs or InP
OR
→ lost by lattice vibrations (heat) in Si or Ge

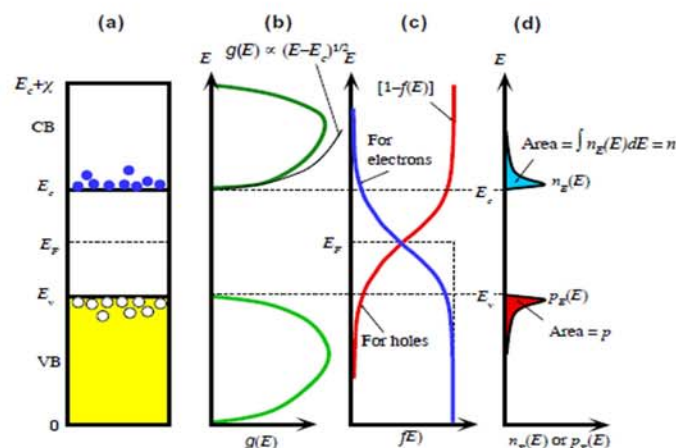
B. Semiconductor Statistics.

DOS. (Density of States), $g(E)$, represents # of electronic states (electron wavefunctions) in a band per unit energy, per unit vol. of crystal.

According to QM., an electron confined in a 3D-Q well, as a conduction electron in X-tal, DOS increases with:

$$g(E) \propto (E-E_c)^{1/2}$$

CB.DOS → gives information ONLY on available states, NOT on their actual occup.



(a) Energy band diagram. (b) Density of states (number of states per unit energy per unit volume). (c) Fermi-Dirac probability function (probability of occupancy of a state). (d) The product of $g(E)$ and $f(E)$ is the energy density of electrons in the CB (number of electrons per unit energy per unit volume). The area under $n_E(E)$ vs. E is the electron concentration.

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Figure 3.4

The Fermi-Dirac function, $f(E)$, probability of finding an electron in a Q state with energy E.

$$f(E) = \frac{1}{1+\exp\left(\frac{E-E_F}{k_BT}\right)}$$

E_F → Fermi En.

---

n → Electron concentration in C.B.

p → Hole concentration in V.B.

$f(E) \rightarrow$ probability of finding a electron in a Q state with energy E.

$1-f(E) \rightarrow$ probability of finding a hole in a Q-state with energy E.

$n_E(E) = g_{CB}(E) \cdot f(E) \longrightarrow$ actual # of electrons per unit en. per unit vol. in CB.

$n_E(E)dE = g_{CB}(E) f(E) dE \rightarrow$ # of el. within E and $E+dE$

$\therefore$ The # of per volume (el. conc.) is.

$$n = \int_{E_c}^{E_c+\chi} g_{CB}(E) f(E) dE$$

whenever $E_c - E_F \gg k_B T$, i.e. E_F is at least a few kT below E_c, then

$$f(E) \approx \exp[-\beta(E-E_F)]$$ $\longrightarrow$ F-D. reduced into M-B statistics.

Such semiconductors are called non-degenerate semiconductors.

For non-deg. s/cs

$$n = N_c \exp\left[-\frac{E_c - E_F}{k_B T}\right]$$

$$N_c = 2\left[2\pi m_e^* \frac{k_B T}{h^2}\right]^{3/2}$$ $\longrightarrow$ Called effective density of states at conduction band edge.

$N_c = 2.8 \times 10^{19}\ cm^{-3}$ for Si
$N_c = 4.7 \times 10^{17}\ cm^{-3}$ for GaAs

$$n = 4\pi\left(\frac{2m}{h^2}\right)^{3/2} \int_0^{\infty} E^{1/2} \exp\left[-\frac{E-E_F}{kT}\right] dE$$

$$= 4\pi\left(\frac{2m}{h^2}\right)^{3/2} (kT)^{3/2} \exp\left[\frac{E_F}{kT}\right] \underbrace{\int_0^{\infty} x^{1/2} e^{-x} dx}_{\sqrt{\pi}/2}$$

Similarly hole concentration in VB.

$$p = \int_{-\infty}^{E_v} g_{VB}(E) \cdot [1 - f(E)]\, dE$$

$$p \approx N_v \exp\left[-\frac{E_F - E_v}{k_B T}\right]$$

$N_v = 2\left[2\pi m_p^* \frac{k_B T}{h^2}\right]^{3/2}$ → effective DOS at VB edge.

$N_v = 1.04 \times 10^{19}\ cm^{-3}$ for Si
$N_v = 7.0 \times 10^{18}\ cm^{-3}$ for GaAs

- Fermi Level for i-type s/c by $n = p$!

$$E_F = E_i = E_{Fi} = \left(E_v + \frac{1}{2}E_g\right) + \frac{kT}{2} \ln \frac{N_v}{N_c}$$

$$E_{Fi} = \left(E_v + \frac{1}{2}E_g\right) + \frac{3kT}{2} \ln\left(\frac{m_p}{m_n}\right)$$

$E_g = E_c - E_v$

At RT $E_{Fi} \rightarrow E_v + \frac{1}{2}E_g$

- Intrinsic carrier density is found by

$$np = N_c N_v \exp\left(-\frac{E_g}{k_B T}\right) = n_i^2$$

$E_g = E_c - E_v$

Mass Action Law;

n_i^2 is a constant depending on T and material properties, depends on E_g but NOT on E_F

→ For an intrinsic s/c $p = n = n_i$ ∴ n_i is intrinsic carrier density.

$n_i = 1.45 \times 10^{+10}\ cm^{-3}$ for Si
$n_i = 1.79 \times 10^{6}\ cm^{-3}$ for GaAs → The larger E_g, the smaller n_i

The avg. en. of electrons in CB, since they are "free" in CB, with effective mass m_e^*. They wander around the x-tall with avg. kin. en. $\frac{3}{2}k_B T$ or

$$\left\langle \frac{1}{2} m_e^* v^2 \right\rangle = \frac{3}{2} k_B T$$

∴ Thermal velocity (or rms velocity $\sqrt{\langle v^2 \rangle}$) is

$$v_{th} \sim 10^5 \, m s^{-1}$$

→ The same idea applies to holes in VB with m_h^* !

C. Extrinsic S/Cs

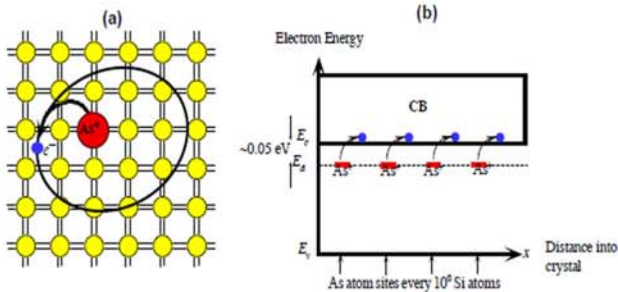
By introducing small amounts of impurities → extrinsic S/Cs.

Adding,

- pentavalent impurities, (such as As), electron. conc. becomes much higher.
- trivalent impurities, (such as Boron), hole " " " ".

→ Excess electrons → n-type S/C

→ Excess holes → p-type S/C



(a) The four valence electrons of As allow it to bond just like Si but the fifth electron is left orbiting the As site. The energy required to release to free fifth-electron into the CB is very small.

(b) Energy band diagram for an n-type Si doped with 1 ppm As. There are donor energy levels just below E_c around As^+ sites.

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Figure 3.5

$\sim k_B T = 0.025\ eV$

$E_d \sim 0.05\ eV$ for As

By thermal excitation (by lattice vibrations) one electron is excited from E_d into CB.

→ As the As atom donates elec. ⇒ is called DONORS

After full ionization

$$n = N_d$$

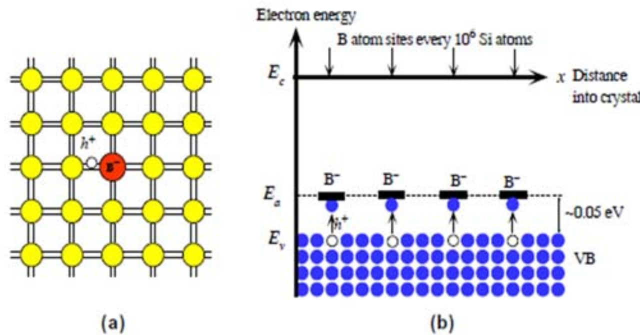
$$\therefore \quad p = n_i^2 / N_d$$

The conductivity σ of a s/c

$$\sigma = en\mu_e + ep\mu_h$$

$$\sigma = eN_d\mu_e + e\left(\frac{n_i^2}{N_d}\right)\mu_h \approx eN_d\mu_e$$

μ_e and μ_h : are drift mobilities of electrons and holes



(a) Boron doped Si crystal. B has only three valence electrons. When it substitutes for a Si atom one of its bonds has an electron missing and therefore a hole. (b) Energy band diagram for a p-type Si doped with 1 ppm B. There are acceptor energy levels just above E_v around B⁻ sites. These acceptor levels accept electrons from the VB and therefore create holes in the VB.

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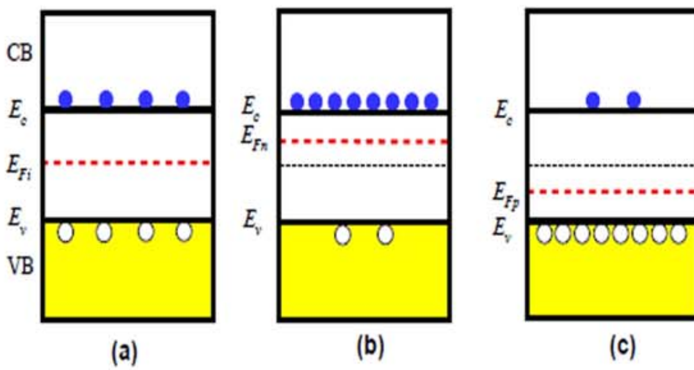
Figure 3.6

Boron doping.

$E_a \approx 0.05\,eV$ ——> Boron is an ACCEPTOR

$$\left.\begin{aligned} p &\approx N_a \\ n &= n_i^2/N_a \end{aligned}\right\} \therefore \quad \sigma = eN_a\mu_h$$



Energy band diagrams for (a) intrinsic (b) *n*-type and (c) *p*-type semiconductors. In all cases, $np = n_i^2$. Note that donor and acceptor energy levels are not shown.

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Location of Fermi-level; for i-type is E_{Fi}, for n-type is E_{Fn} for p-type is E_{Fp}.

	Majority Carriers	Minority Carriers
n-type	e	h
p-type	h	

n-type; n_{no} → majority in inequilibrium (no excitation)

Mass Action Law

$$n_{no} \cdot p_{no} = n_i^2$$

p-type

Mass-Action Law

$$n_{po} \, p_{po} = n_i^2$$

D. Compensation Doping

Doping with both Acceptors and Donors.

More Donors than Acceptors → $n = N_d - N_a$

More Acceptors than Donors → $p = N_a - N_d$

E. Degenerate and Non-Degenerate S/Cs

Since the # of states in CB is much larger than # of elec., so the likelihood of two electrons trying to occupy the same state is almost NIL.

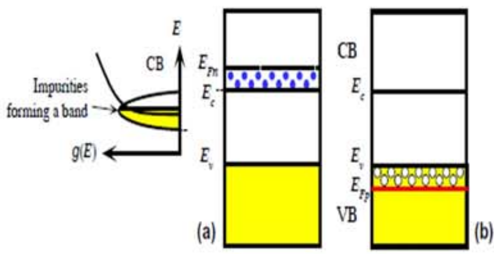
∴ The Pauli exclusion principle can be neglected. → Boltzmann Stat.

→ S/Cs with $n \ll N_c$ or $p \ll N_v$ is called NON-DEGENERATE S/C.

When doping occurs so large with $\sim 10^{19} - 10^{20}\ cm^{-3}$ (comparable to N_c and N_v) the Pauli exc. princ. becomes important, so does F-D stat.

Such a S/C behaves more a metal-like than a S/C like.

$n > N_c$ or $p > N_v$ are called DEGENERATE S/Cs.



(a) Degenerate n-type semiconductor. Large number of donors form a band that overlaps the CB. (b) Degenerate p-type semiconductor.

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Figure 3.8

- For a degenerate n-type S/C E_F lies in CB
  Majority of states between E_F and E_c are filled.
- For a degenerate p-type S/C E_F lies in VB.

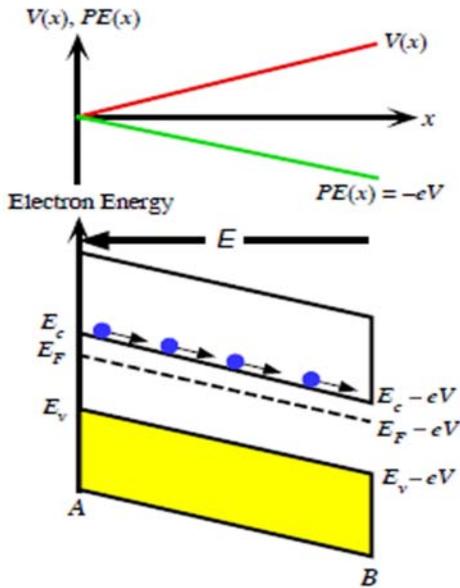
We can NOT simply assume $n = N_d$ or $p = N_a$ for a deg-S/C.

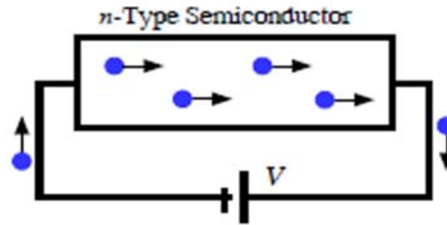
∵ Dopant conc. is so large, they interact with each other. Not all the dopants are able to ionize.

The carrier concentration reaches a saturation $\sim 10^{20}\ cm^{-3}$.

∴ MASS ACTION LAW IS NOT VALID !

F. Energy Band Diagram in an Applied Field





Energy band diagram of an n-type semiconductor connected to a voltage supply of V volts. The whole energy diagram tilts because the electron now has an electrostatic potential energy as well

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Figure 3.9

For a s/c in the dark, in equilibrium and with no app. voltage or no emf generated, E_F must be uniform. However, when electrical work is done (e.g. connected battery) the E_F is not uniform throughout the whole sys.

→ $E_c - E_F$ must be constant, from one end to the other end.

∴ CB, VB, E_F bend by the same amount.

Ex. 3.11. Fermi levels in s/cs

An n-type Si wafer doped with 10^{16} antimony (Sb) atoms cm^{-3}.

$E_F = ?$ with respect to E_{Fi}. (at 300K)

Then further doped with 2×10^{17} boron (B) atoms cm^{-3}.

$E_F = ?$ w.r.t E_{Fi}. (at 300K)

Soln. Sb → V^{th} group → n type with $N_d = 10^{16}\,cm^{-3}$. Since $N_d \gg n_i \left(= 1.45\times10^{+10}\,cm^{-3}\right)$

$$n = N_d = 10^{16}\,cm^{-3}$$

intrinsic Si $\quad n_i = N_c \exp\left[-(E_c - E_{Fi})/kT\right]$

Doped Si ↳

$$n = N_c \exp\left[-(E_c - E_{Fn})/kT\right] = N_d$$

$$\frac{N_d}{n} = \exp\left[(E_{Fn} - E_{Fi})/kT\right]$$

$$E_{Fn} - E_{Fi} = kT \ln(N_d/n_i) = (0.0259\,eV) \ln\left(10^{16}/1.45\times10^{10}\right) = 0.348\,eV$$

$$N_a = 2\times10^{17}\,cm^{-3} > N_d = 10^{16}\,cm^{-3}$$

↳ p-type

$$p = N_a - N_d = 2\times10^{17} - 1\times10^{16} = 1.9\times10^{17}\,cm^{-3}$$

intrinsic Si:

$$p = n_i = N_v \exp\left[-(E_{Fi} - E_v)/kT\right]$$

Doped Si ↳

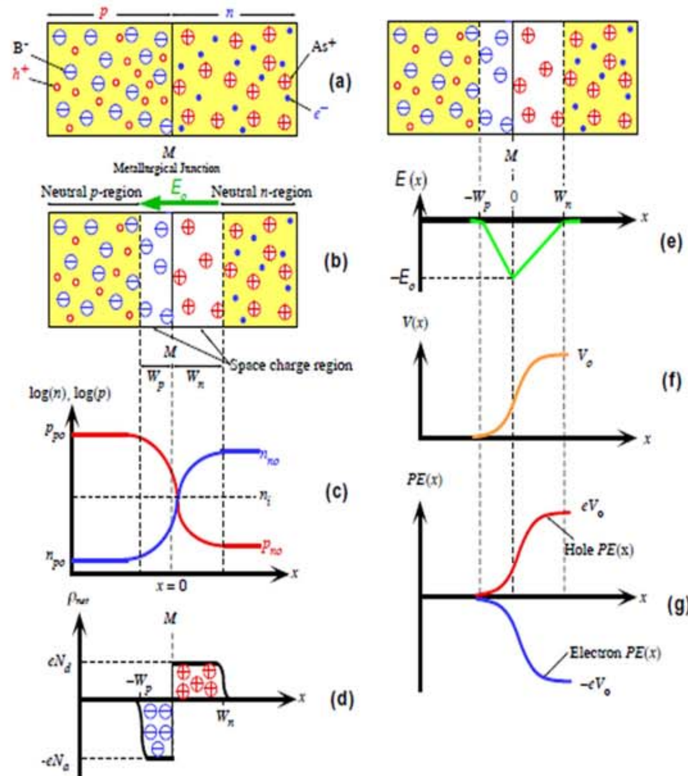
$$p = N_v \exp\left[-(E_{Fi} - E_v)/kT\right] = N_a - N_d$$

$$\frac{p}{n_i} = \exp\left[-(E_{Fp} - E_{Fi})/kT\right]$$

$$E_{Fp} - E_{Fi} = -kT \ln(p/n_i) = (-0.0259\,eV) \ln\left(\frac{1.9\times10^{17}}{1.45\times10^{10}}\right) = -0.424\,eV$$

3.3. pn Junction Principles

A. Open Circuit



Properties of the *pn* junction.

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Figure 3.13

Holes
- → Diff. Particle Flow → Diffusion Current Flow
- ← Drift Particle Flow ← Drift Current Flow

Electrons
- ← Diffusion Particle Flow → Diffusion Current Flow
- → Drift Particle Flow ← Drift Current Flow

<u>Depletion Region</u>, Space charge layer (SCL) is depleted of free charges.

Between $[-W_p, W_n]$

Since, <u>electrons</u> (minority carriers in p) diffusing p-side recombines with <u>holes</u> (majority carriers in n).

Internal electric field, E_o,

The net space charge density $\rho_{net}(x) = -eN_a$ in SCL for $x = -W_p \rightarrow 0$

$\rho_{net}(x) = +eN_d$ in SCL for $x = 0 \rightarrow W_n$

Charge Neutrality $\rightarrow$ $N_a W_p = N_d W_n$

$\rightarrow E(x)$,

$$\frac{dE}{dx} = \frac{\rho_{net}(x)}{\varepsilon} \quad ; \varepsilon = \varepsilon_o \varepsilon_r$$

$$E(x) = \int dE = \frac{1}{\varepsilon} \int_{-W_p}^{+W_n} \rho_{net}(x)\, dx$$

$x = 0 \rightarrow E(x) \rightarrow E_o$ which is max.

$\rightarrow V(x)$,

$$E = -\frac{dV}{dx}$$

$$V(x) = -\int E\, dx$$

$\rightarrow$ On the n-side potential reaches V_o

$V_o \rightarrow$ built in potential

$$E_o = -\frac{eN_d W_n}{\varepsilon} = -\frac{eN_a N_p}{\varepsilon}$$

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

$$W_o = W_n + W_p$$

Relate V_0 to the doping parameters, we use MB statistics

- The concentrations n_1 and n_2 of carriers E_1 and E_2

$$\frac{n_2}{n_1} = \exp\left[-\frac{E_2-E_1}{kT}\right]$$

Here E is pot.-en., that is qV,

→ On the p-side $E=0$ (away from M) where $n=n_{p0}$

n-side $E=-eV_0$ on the p-side where $n=n_{n0}$

$$\frac{n_{p0}}{n_{n0}} = \exp\left[-\frac{eV_0}{kT}\right]$$

corresponding eq.

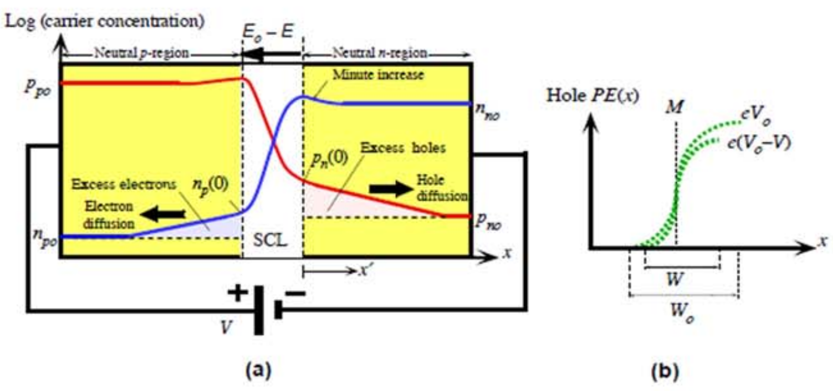
$$\frac{p_{n0}}{p_{p0}} = \exp\left[-\frac{eV_0}{kT}\right]$$

$$V_0 = \frac{kT}{e} \ln\left(\frac{n_{n0}}{n_{p0}}\right) \quad \text{and} \quad V_0 = \frac{kT}{e} \ln\left(\frac{p_{p0}}{p_{n0}}\right)$$

$$p_{p0} = N_a, \quad p_{n0} = n_i^2/n_{n0} = n_i^2/N_d$$

$$\therefore \quad \boxed{V_0 = \frac{kT}{e} \ln \frac{N_a N_d}{n_i^2}}$$

B. 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

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Figure 3.14

Applied voltage effectively reduces the built-in potential and hence the built-in field that acts diffusion.

This results in → the injection of minority carriers into the corresponding region.

→ Excess electrons can now diffuse towards p-side and become injected minority carriers.

→ Due to excess minority charges, some majority carriers are drawn from bulk region (and battery) to maintain the neutrality in the bulk regions.

Hole concentration

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

Using Eq. 5

$$\frac{p_{no}}{p_{po}} = \exp\left[-\frac{eV_o}{kT}\right]$$

Amount of excess holes diffusing and arriving at n-region.

$$p_n(0) = p_{no} \exp\left(\frac{eV}{kT}\right)$$

Law of Junction

$$n_p(0) = n_{po} \exp\left(\frac{eV}{kT}\right)$$

Diffusion of minority carriers,

If $\Delta p_n(x') = p_n(x') - p_{n0}$ excess minority car. conc.

$$\Delta p_n(x') = \Delta p_n(0) \exp\left(-\frac{x'}{L_h}\right)$$

$L_h \rightarrow$ hole diffusion length:

$$L_h = \sqrt{D_h \tau_h}$$

D_h : Diffusion coef.
τ_h : the mean hole rec. time.

$L_h \rightarrow$ avg. distance diffused by a minority carrier.

Hole current,

$$J_{D,hole} = -e D_h \frac{dp_n(x')}{dx'} = -e D_h \frac{d\Delta p_n(x')}{dx'}$$

hole diff flux!

$$J_{D,hole} = \frac{eD_h}{L_h} \cdot \Delta p_n(0) \exp\left(-\frac{x'}{L_h}\right)$$

From law of Junction:

$$J_{D,hole} = \frac{eD_h n_i^2}{L_h N_d} \left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$ Hole diffusion current

Similar expression for electrons

$$J = \left(\frac{eD_h}{L_h N_d} + \frac{eD_e}{L_e N_a}\right) n_i^2 \left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

$$J = J_{so} \left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

Schockley Diode equation

Recombination current

$$J_{recom} = J_{ro}\left[\exp\left(\frac{eV}{2kT}\right)-1\right]$$

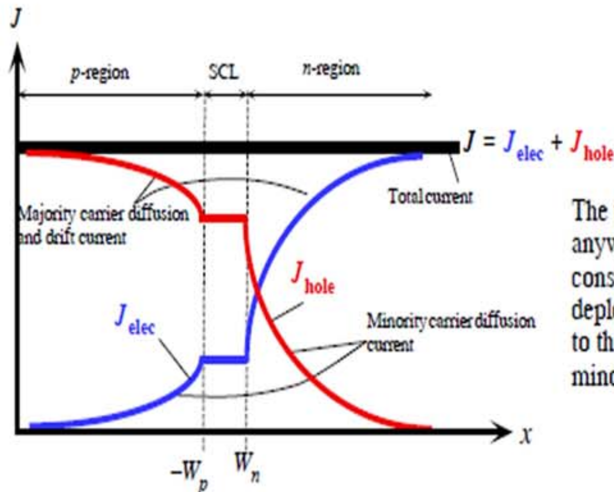
Diode Equation

$$I = I_0\left[\exp\left(\frac{eV}{\eta \cdot kT}\right)-1\right]$$

$\eta \rightarrow$ Diode ideality factor.

$\eta \rightarrow$ "1" $\Rightarrow$ diffusion controlled characteristics.

$\eta \rightarrow$ "2" $\Rightarrow$ recombination " "



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

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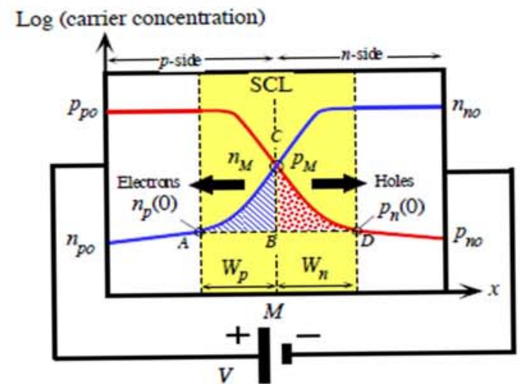
Figure 3.15



Forward biased *pn* junction and the injection of carriers and their recombination in the SCL.

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Figure 3.16

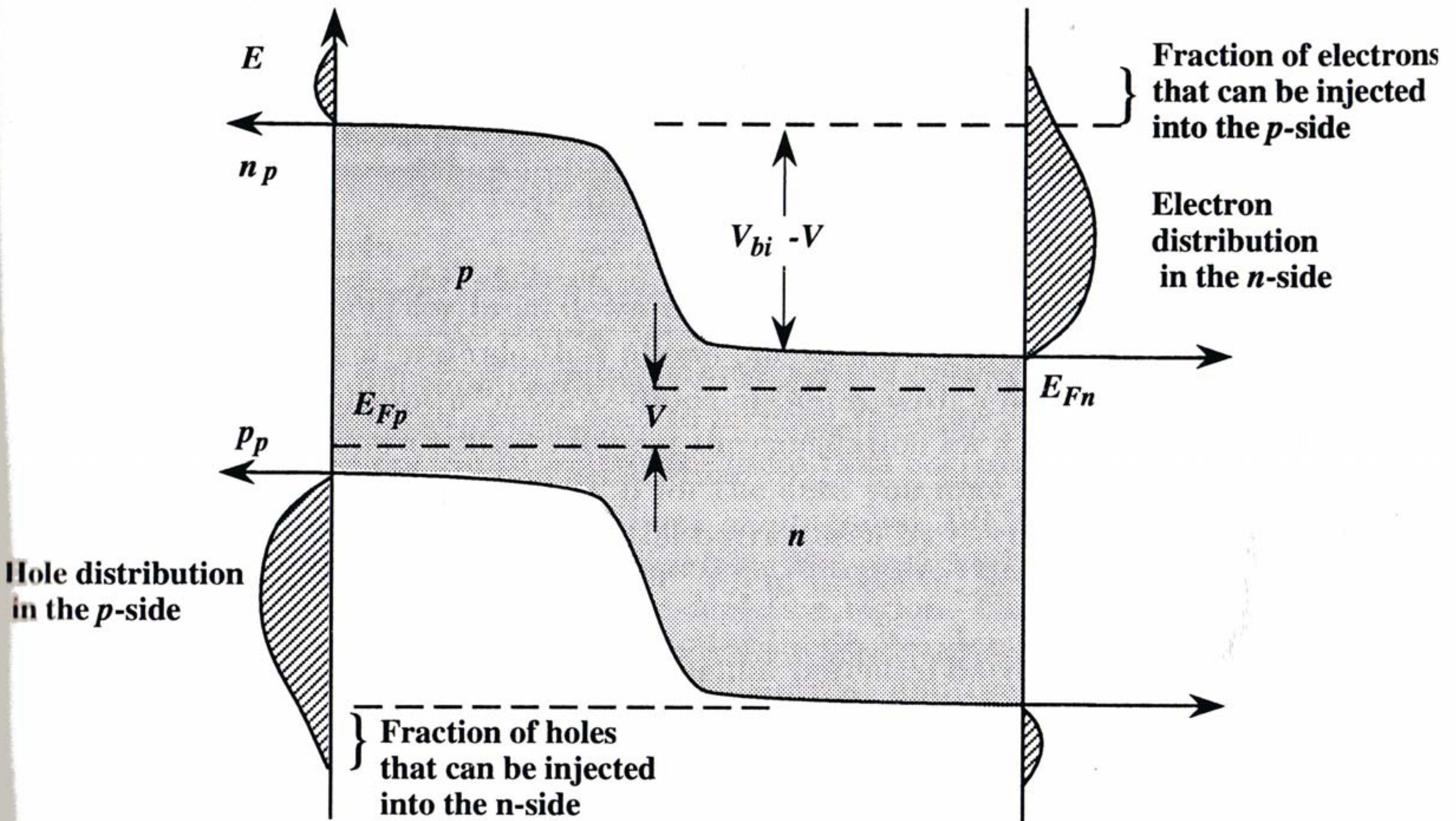
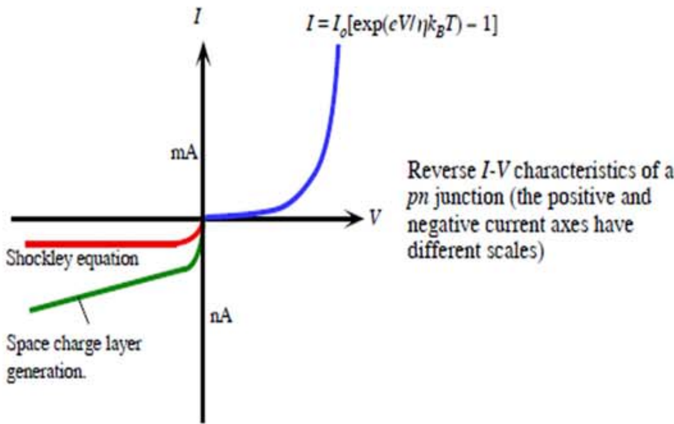


Figure 6.5: A schematic of the charge distribution in the n- and p-sides. The minority carrier injection (electrons from n-side to p-side or holes from p-side to n-side) is controlled by the applied bias as shown.

C. Reverse Bias

The applied voltage drops mainly across the resistive depletion region.



Reverse I-V characteristics of a pn junction (the positive and negative current axes have different scales)

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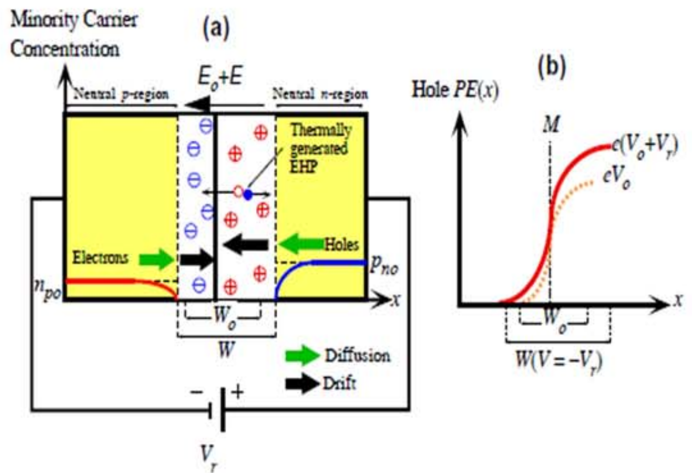
Figure 3.17



Reverse biased pn junction. (a) Minority carrier profiles and the origin of the reverse current. (b) Hole PE across the junction under reverse bias

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Figure 3.18

→ electrons move away from SCL by leaving (+)ve donors.

→ holes move away from SCL by leaving (−)ve acceptors.

→ The depletion region in both n-side and p-side widens.

→ No electrons can be supplied to the n-region from neither n-side nor p-side.

Small reverse current (J_{rev})

Applied voltage increases the built-in pot. barrier. → widens W

→ The small # of holes (n-side) near dep. reg. become extracted and swept by the field (across SCL).

→ Assuming $V_r > 25\,mV = \frac{kT}{e}$

Thermal generation of EHPs in SCL, can also contribute reverse current. This drift will result in an external current in addition to the reverse current due to diffusion of minority carriers.

→ The reverse current density due to thermal generation of EHPs in SCL.

$$J_{gen} = \frac{eWn_i}{\tau_g}$$

→ The reverse bias widens the width W, which increases J_{gen}.

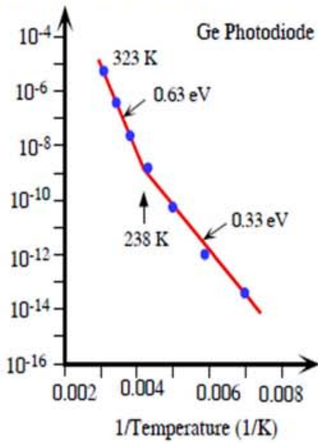
The total reverse current density due to diffusion and generation.

$$J_{rev} = \left(\frac{eD_h}{L_h N_d} + \frac{eD_e}{L_e N_a}\right)n_i^2 + \frac{eWn_i}{\tau_g}$$

→ $J_{rev} \uparrow$ as $V_r \uparrow$ ∵ $W \uparrow$ (SCL width) !

→ J_{rev} depends both n_i (material properties)

and therefore temperature (since $n_i \sim \exp[-\frac{E_g}{2kT}]$)



Reverse diode current in a Ge *pn* junction as a function of temperature in a $\ln(I_{rev})$ vs. $1/T$ plot. Above 238 K, I_{rev} is controlled by n_i^2 and below 238 K it is controlled by n_i. The vertical axis is a logarithmic scale with actual current values. (From D. Scansen and S.O. Kasap, *Cnd. J. Physics.* **70**, 1070-1075, 1992.)

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Figure 3.19

- above 238 K
  I_{rev} is controlled by n_i^2
  and slope yields $E_g = 0.66$ eV (Ge)
- below 238 K
  I_{rev} is controlled by n_i
  and slope yields $\frac{E_g}{2} = 0.33$ eV

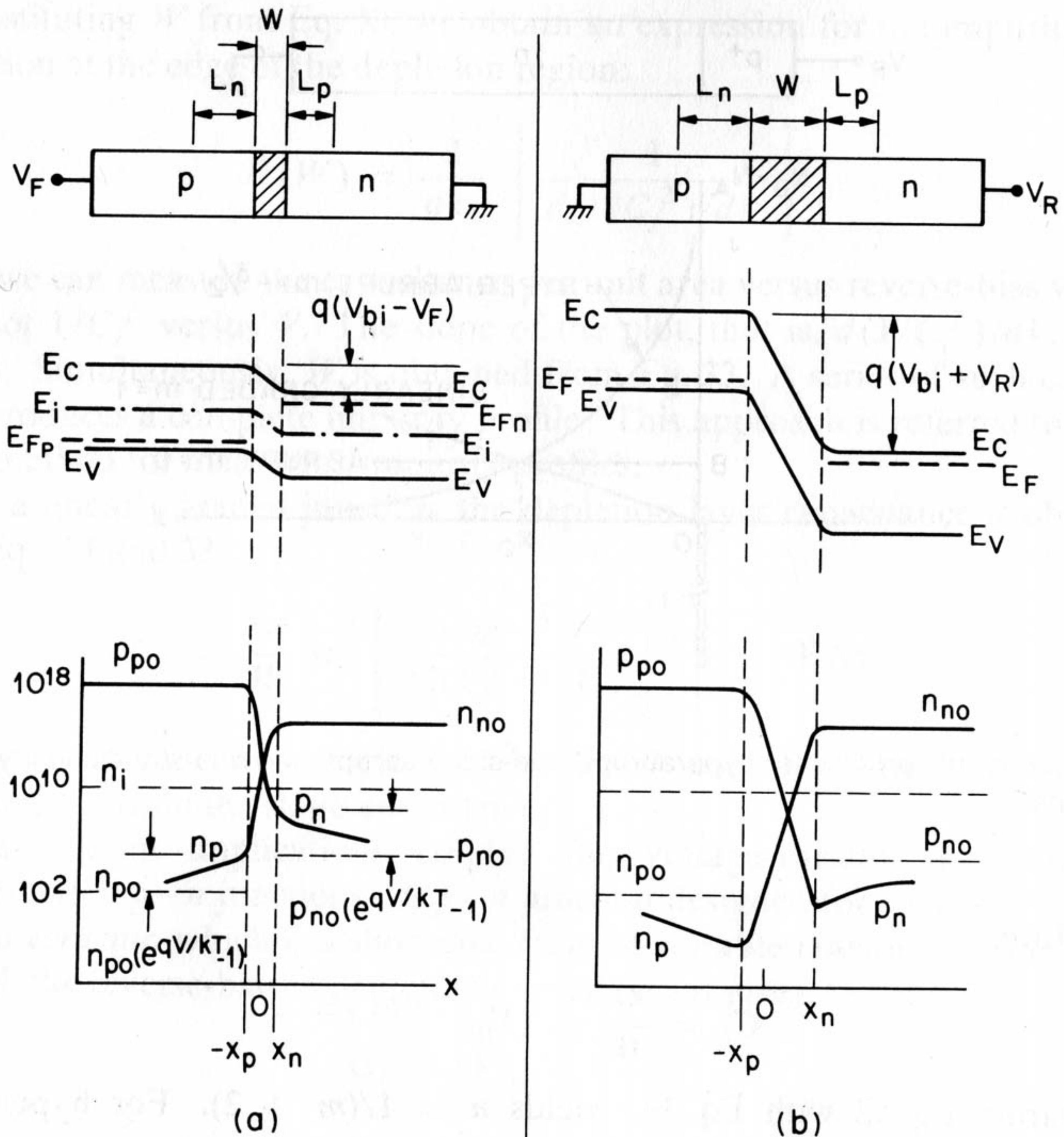


Fig. 14 Depletion region, energy band diagram, and carrier distribution. (*a*) Forward bias. (*b*) Reverse bias.

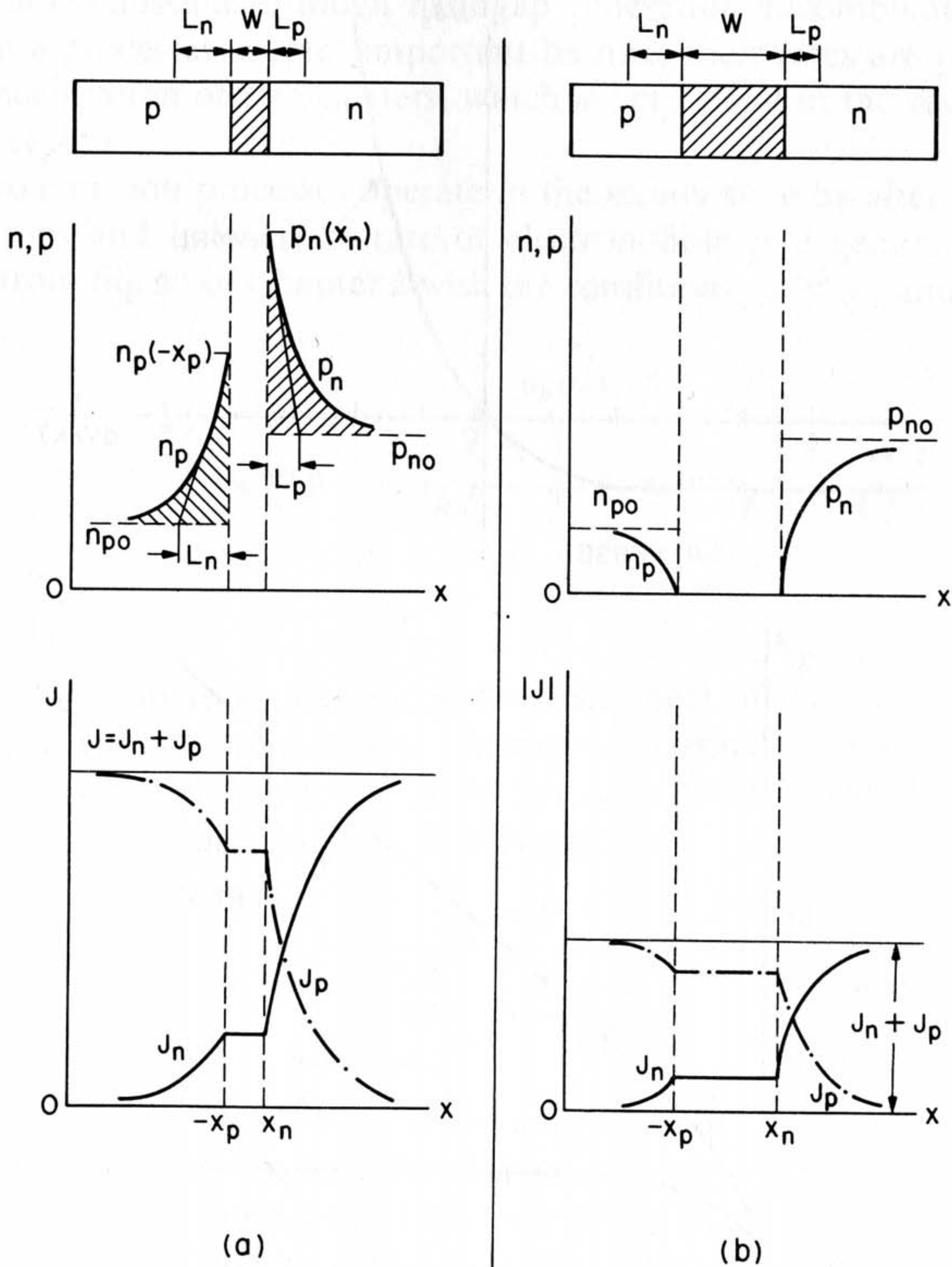
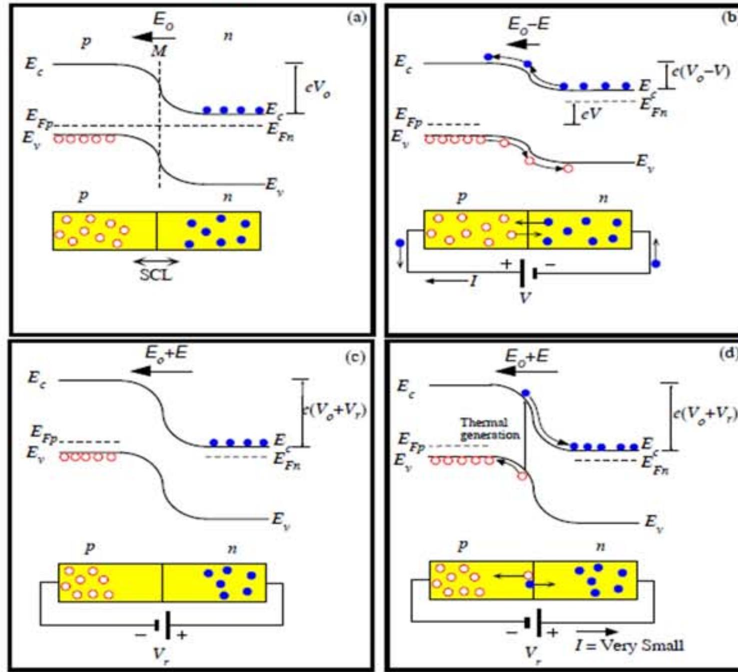


Fig. 15 Injected minority carrier distribution and electron and hole currents.[1] (*a*) Forward bias. (*b*) Reverse bias.

3.4. The 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.

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Figure 3.20

Forward Bias

→ When forward biased by V, PE barrier is reduced by eV $\left(\equiv e(V_o-V)\right)$

→ Upon reduction in PE barrier, diffusion of electrons from n-side
diffusion of holes from p-side

→ The probability that an electron at E_c in n-side overcomes PB is prop. to Boltzmann factor ⇒ $\exp\left[-e\frac{V_o-V}{kT}\right]$

With a small V, enormous amounts of diffusion takes place (toward either side)

Reverse Bias

→ When a reverse bias is present, PE barrier becomes $e(V_o+V_r)$

→ Field becomes E_o+E → almost no current

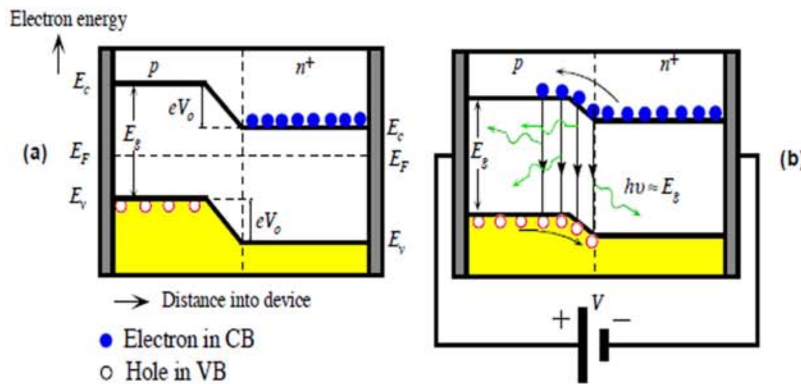
Thermal Gen.

→ A small reverse current arising from thermal generation of EHPs in SCL.

→ Both e and h falls down the corresponding PE hill.

→ A thermally generated hole in n-side within a diffusion length can diffuse to SCL and then drift across the SCL → Reverse current too.

3.5 LIGHT EMITTING DIODES



(a) The energy band diagram of a p-n^+ (heavily n-type doped) junction without any bias. Built-in potential V_o prevents electrons from diffusing from n^+ to p side. (b) The applied bias reduces V_o and thereby allows electrons to diffuse, be injected, into the p-side. Recombination around the junction and within the diffusion length of the electrons in the p-side leads to photon emission.

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Figure 3.21

→ Direct band-gap s/c (GaAs) ⟶ radiative recombination

→ PN^+ device extends mainly into p-side.

→ Built-in potential is reduced by V to $(V_o - V)$

→ Mostly diffusion of electrons into - p-side. Injection

→ Recombination primarily occurs within the DEPLETION REGION AND within a volume extending of diff. length L_e (of e's in p-side)

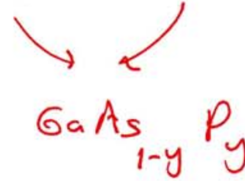
→ Light emission is a result of minority carrier injection (INJECTION LUMINESCENCE)

→ To ensure most of the recombinations take place in p-side, the n-side is heavily doped.

→ Lattice mismatch ⟷ defects ⟷ non-radiative recom.

3.6 LED Materials

III-V ternary alloys based on GaAs and GaP



$GaAs_{1-y}P_y$

- when $y < 0.45$; $GaAs_{1-y}P_y$ is a direct band-gap s/c. EHP rec. is direct!
  - emission wavelength is ~ 630nm for $y = 0.45$ ($GaAs_{0.55}P_{0.45}$)
  - ~ 870nm for $y = 0$ ($GaAs$)

- when $y > 0.45$; $GaAs_{1-y}P_y$ is an indirect band-gap s/c
  - However, if we add isoelectronic impurities, such as N
    - ⇒ Although having same number of (valence) electrons, (+ve) nucleus of N is less shielded.
    - ∴ A conduction electron can be trapped by an N atom.

A captured electron can attract a hole to radiatively recombine (less efficiently)

Since they are cheap to produce, N doped $GaAs_{1-y}P_y$ alloys are widely used in inexpensive GREEN, YELLOW, ORANGE LEDs.

Three types of blue LED materials

→ GaN is a direct bg s/c with 3.4eV.
Blue LEDs use GaN alloy ; InGaN has a blue emission (2.7eV)

→ Al-doped SiC (silicon carbide)
Acceptor type localized energy levels captures a hole from valence band.
Then this hole recombines with an electron from conduction band.
Al-doped SiC is less efficient to emit light, being indirect band gap.

→ ZnSe (II-VI compound)
This material is suitable to produce high efficiency LEDs.
The technological difficulty is in appropriately doping.

RED and IR emitter.

Various types of s/c emitting Red and IR, which are ternary and quarternary compounds

→ $Al_x Ga_{1-x} As$ (for $x<0{,}43$ direct bg)

$x=0 \Rightarrow$ emission at 870nm
$x=0.43 \Rightarrow$ emission at 640nm (deep red)

→ In-Ga-Al-P (III-V alloy)
with the composition of x, y ⟶ 870nm (GaAs) to 3.5μm (InAs)

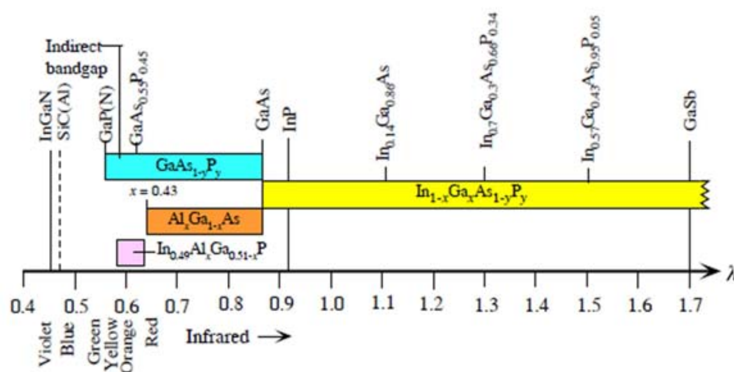
↓

Including the optical communication range of
1.3μm ⟶ 1.55μm

External efficiency, $\eta_{external}$

$$\eta_{extend} = \frac{P_{out}(\text{optical})}{IV}$$

External Quantum Efficiency



Free space wavelength coverage by different LED materials from the visible spectrum to the infrared including wavelengths used in optical communications. Hatched region and dashed lines are indirect E_g materials.

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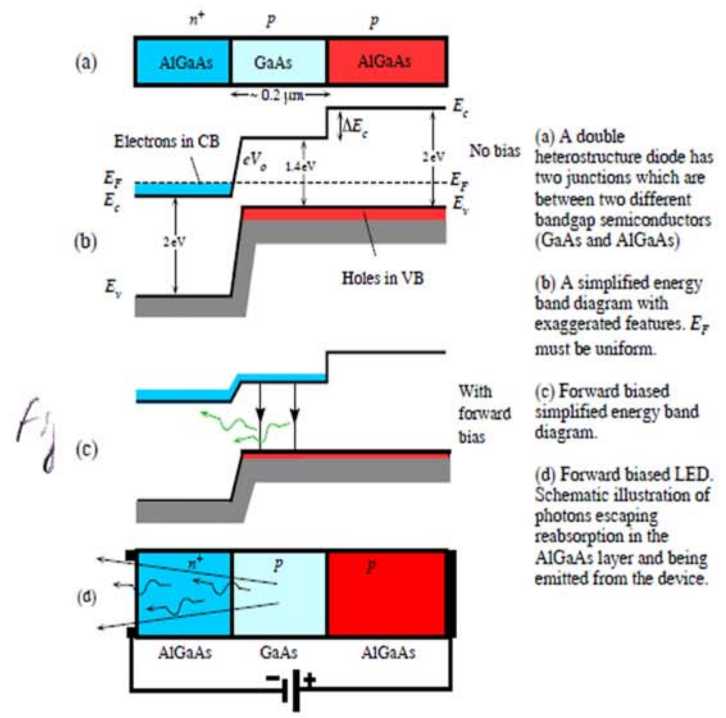
Figure 3.25

Table 3.25

3.7. Heterojunction high intensity LEDs

→ Homojunction
→ Heterojunction



(a) A double heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AlGaAs)

(b) A simplified energy band diagram with exaggerated features. E_F must be uniform.

(c) Forward biased simplified energy band diagram.

(d) Forward biased LED. Schematic illustration of photons escaping reabsorption in the AlGaAs layer and being emitted from the device.

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Figure 3.26

Fig

Two drawbacks of homojunction LEDs.

→ The p-region must be narrow to allow photons to escape without being absorped.

→ When the p-side is narrow, some of the injected electrons can reach the surface and recombine with surface defects.

- When the VOLUME increases, the amount of reabsorption increases as well.

DOUBLE HETEROSTRUCTURES → increse the light intensity

→ A pot. en. barrier of eV_o between n^+-AlGaAs and p-GaAs

→ A band-gap change (ΔE_c) between p-GaAs and p-AlGaAs.

ΔE_c prevents electrons in CB of p-GaAs passing to pAlGaAs.

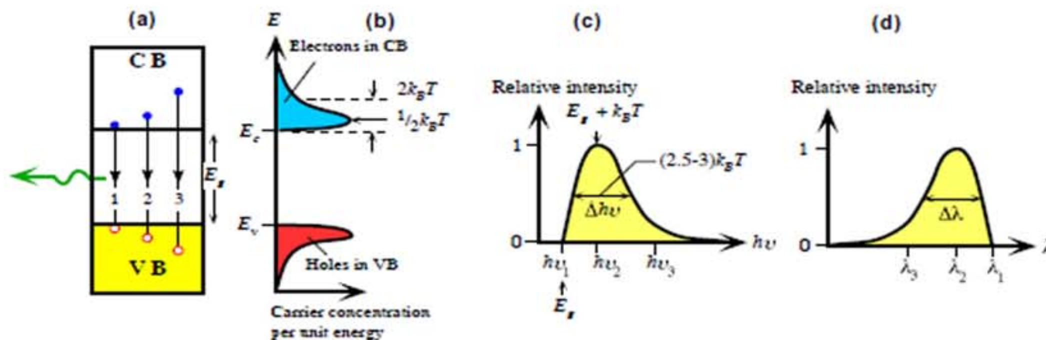
∴ restrict injected electrons to the p-GaAs layer.

∴ no reabsorption due to larger bandgap of AlGaAs.

3.8 LED Characteristics

→ The conc. of electrons in CB as a func. of energy and has a peak at $E_c + \frac{1}{2}kT$

→ The energy spread of electrons is typically about $2kT$ from E_c



(a) Energy band diagram with possible recombination paths. (b) Energy distribution of electrons in the CB and holes in the VB. The highest electron concentration is $(1/2)k_BT$ above E_c. (c) The relative light intensity as a function of photon energy based on (b). (d) Relative intensity as a function of wavelength in the output spectrum based on (b) and (c).

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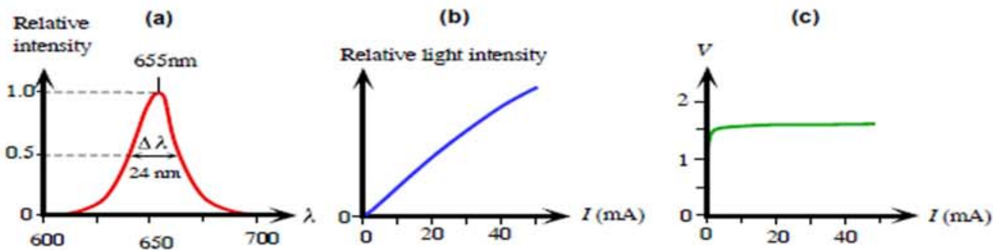
Figure 3.27

Relative light intensity is at a max at $E_c + kT$

→ The linewidth, $\Delta\nu$ or $\Delta\lambda$ is found by FWHM



(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.

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Figure 3.28

Turn on or cut-in voltage, is the point in I-V curve from which a sharp increase in current begins.

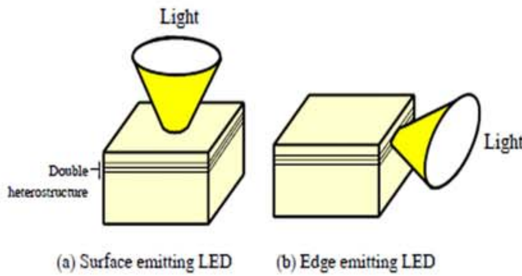
$V_{cut\text{-}in}$ (blue) = 3.5V – 4.5V

$V_{cut\text{-}in}$ (yellow) ≈ 2V

$V_{cut\text{-}in}$ (GaAs) ≈ 1V

3.9. LEDs for optical fiber communications

Surface emitting LED (SLED) and edge emitting LED (ELED)



(a) Surface emitting LED (b) Edge emitting LED

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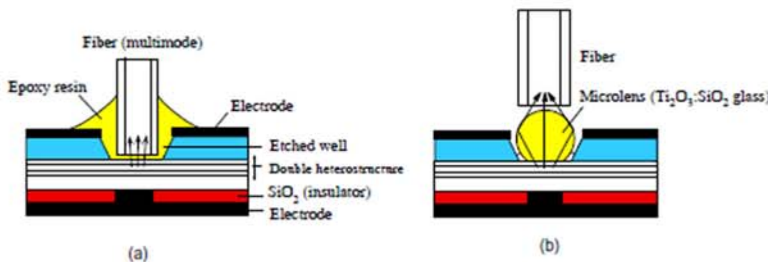
Figure 3.29



Light is coupled from a surface emitting LED into a multimode fiber using an index matching epoxy. The fiber is bonded to the LED structure.

A microlens focuses diverging light from a surface emitting LED into a multimode optical fiber.

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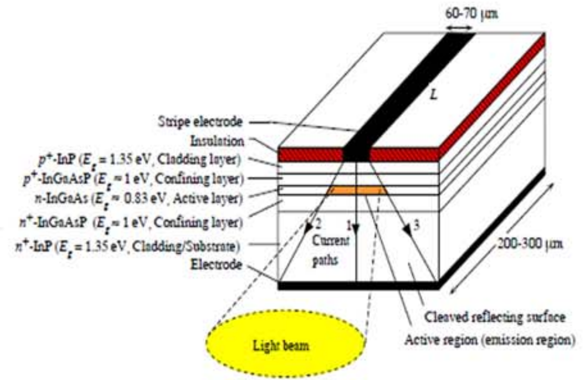
Figure 3.30



Schematic illustration of the the structure of a double heterojunction stripe contact edge emitting LED

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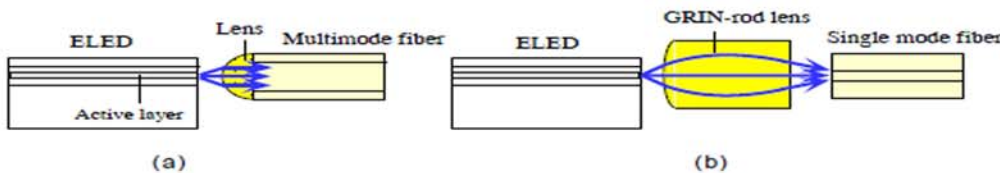
Figure 3.31

- ELEDs provide higher light intensity and more collimated laser beam.
- Conveniently coupling emitted light from ELED to a fiber,
  - hemispherical lens ↔ multimode fibers
  - A graded index (GRIN) rod-lens. → parabolic index glass rod. → single mode lasers with core diameters ~10 μm



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

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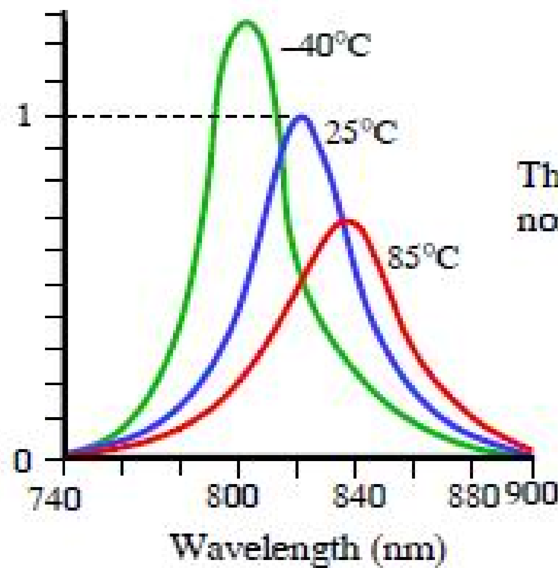
Figure 3.32



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

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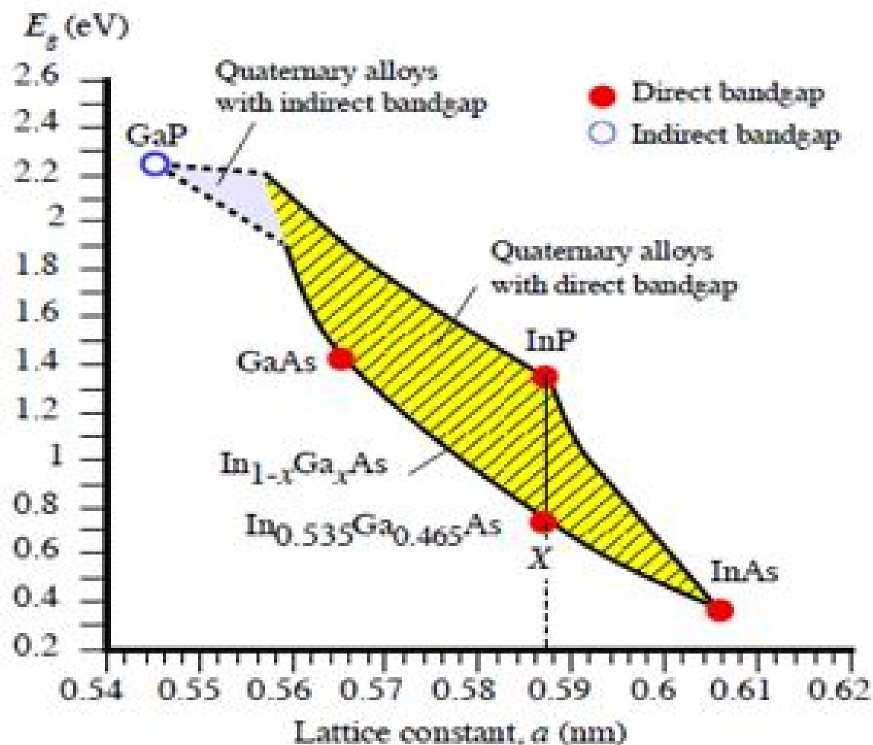
Figure 3.33



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 $In_{1-x}Ga_xAs_{1-y}P_y$ made from $In_{0.535}Ga_{0.465}As$ and InP which are lattice matched to InP.

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Figure 3.34