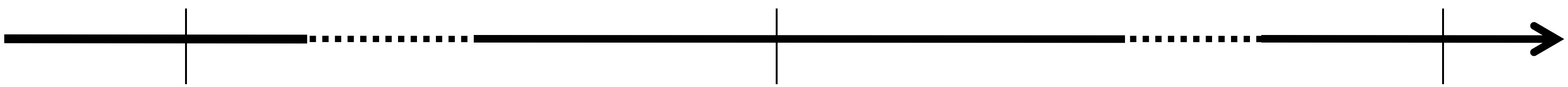
Optical Fiber Communications

Chapter 4

Optical Sources

Semiconductor Physics

Semiconductor



Insulator

High resistivity

Semiconductor

- Conductivity lies between conductor and insulator
- Becomes more or less conductive depending on the conditions
- Majority of semiconductors have crystalline structure

Conductor

Low resistivity

Semiconductor Materials

- Materials in use

Table 1.2 A portion of the periodic table

III	IV	V
5 **B** Boron	6 **C** Carbon	
13 **Al** Aluminum	14 **Si** Silicon	15 **P** Phosphorus
31 **Ga** Gallium	32 **Ge** Germanium	33 **As** Arsenic
49 **In** Indium		51 **Sb** Antimony

- Column 4 → 4 valence electron exists

- Semiconductor Materials

Table 1.1 A list of some semiconductor materials

Elemental semiconductors		Compound semiconductors	
Si	Silicon	GaAs	Gallium arsenide
Ge	Germanium	GaP	Gallium phosphide
		AlP	Aluminum phosphide
		AlAs	Aluminum arsenide
		InP	Indium phosphide

- Compound semicon
  - Has high performances
  - Used in opto-electronic app

Intrinsic Semiconductor-Si (Silicon)

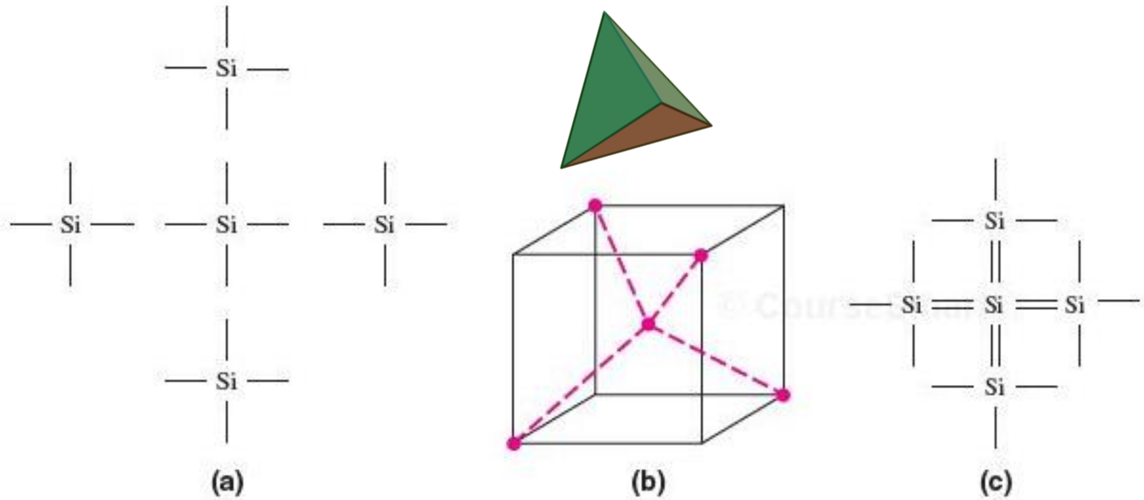


Figure 1.1 Silicon atoms in a crystal matrix: (a) five noninteracting silicon atoms, each with four valence electrons, (b) the tetrahedral configuration, (c) a two-dimensional representation showing the covalent bonding

- Silicon is a (elemental) semiconductor material
- Silicon has 4 valence electrons and forms ***covalent bonds*** with four nearest neighbors
- The final crystal structure is a tetrahedral configuration

Electron – hole pair generation

- Mobile carrier in Si
  - Conduction electron
    - Negatively charged
  - Holes
    - Positively charged

- Electron – hole pair generation method
  - Changing temperature
  - Applying electric field
  - Adding impurity
  - Irradiation

Electron – hole pair generation

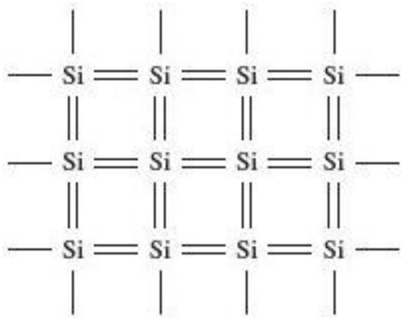


Figure 1.2 Two-dimensional representation of single crystal silicon at $T = 0$ K; all valence electrons are bound to the silicon atoms by covalent bonding

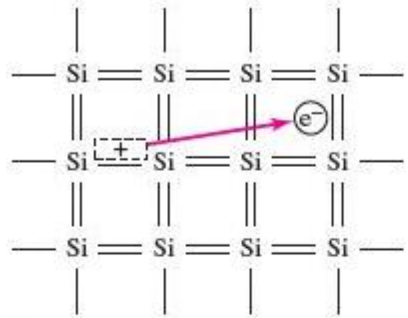


Figure 1.3 The breaking of a covalent bond for $T > 0$ K creating an electron in the conduction band and a positively charged "empty state"

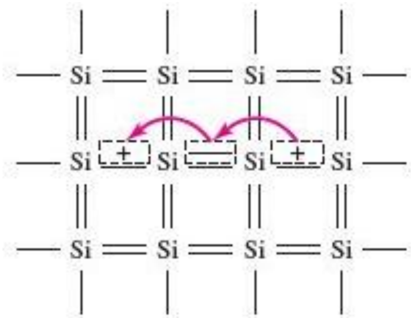


Figure 1.5 A two-dimensional representation of the silicon crystal showing the movement of the positively charged "empty state"

- A "conduction electron" is **thermally** generated
  - a hole is also generated (Fig 1.3)
- A "hole" is a positive charge, and it can move freely around Si lattice (Fig 1.5)

Bandgap Energy

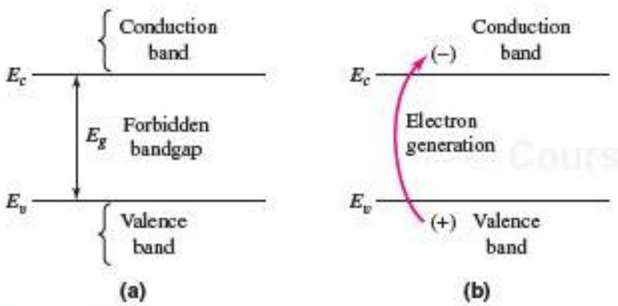


Figure 1.4 (a) Energy band diagram. Vertical scale is electron energy and horizontal scale is distance through the semiconductor, although these scales are normally not explicitly shown. (b) Energy band diagram showing the generation process of creating an electron in the conduction band and the positively charged "empty state" in the valence band.

- E_g : Bandgap Energy
  - Minimum energy needed to break covalent bond to free an electron
- E_v : maximum energy of valence energy band
- E_c : minimum energy of conduction energy band

Intrinsic Carrier Concentration

- B : coefficient for different semicon. mat.

Table 1.3 Semiconductor constants

Material	E_g (eV)	B (cm^{-3} K$^{-3/2}$)
Silicon (Si)	1.1	5.23×10^{15}
Gallium arsenide (GaAs)	1.4	2.10×10^{14}
Germanium (Ge)	0.66	1.66×10^{15}

→ Need to remember constants for Si

→ Boltzmann's constant : *k*
86 x 10^{-6} [eV/K]

- Intrinsic Semiconductor
  - Single-crystal semicon
  - No other types of atoms
  - Electron concentration = hole concentration

- n_i : Intrinsic carrier concentration (for Si)

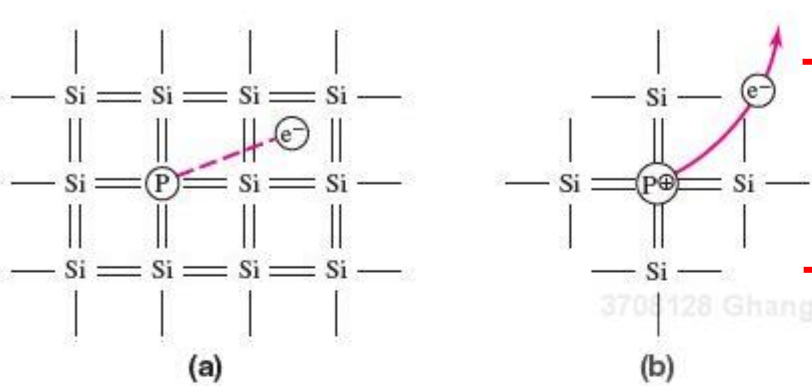
$$n_i = 5.23 \times 10^{15} \times T^{3/2} e^{\left(\frac{-E_g}{2kT}\right)}$$

Extrinsic Semiconductor

- Drawback for Intrinsic Semiconductor
  - Has small carrier concentration (n_i)
  - Which will lead to small current flow
- Extrinsic Semiconductor
  - Generated by adding controlled amount of impurities from group V and group III elements
  - Has enough thermal engergy to break bond at room temp
- 2 types exist depending on doping
  - N-type
  - P-type

Doping (N type)

- When Si is doped with group V elements
  - We call this N-type semiconductor
  - When P(phosphorus, V, donor impurity) atom substitutes for a Si atom, 4 valence electrons are used to satisfy covalent bond



→ 5th valence electron becomes free electron and contributes to electron current

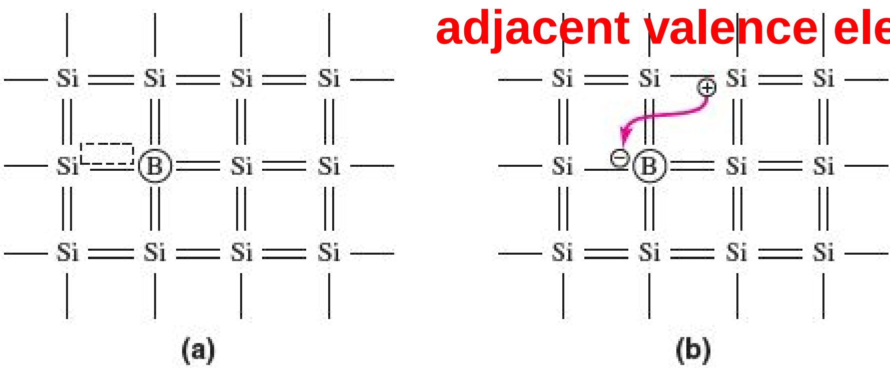
→ And positively charged P ion is created (Ionization)

Figure 1.6 (a) Two-dimensional representation of a silicon lattice doped with a phosphorus atom showing the fifth phosphorus valence electron, (b) the resulting positively charged phosphorus ion after the fifth valence electron has moved into the conduction band

Doping (P type)

- When Si is doped with group III elements
  - We call this P-type semiconductor
  - When B(boron, III, acceptor impurity) atom substitutes for a Si atom, 3 valence electrons are used to satisfy covalent bond

→This leaves 1 bond open
adjacent valence electron moves into this position



→ This creates hole that contributes to hole current

Figure 1.7 (a) Two-dimensional representation of a silicon lattice doped with a boron atom showing the vacant covalent bond position, (b) the resulting negatively charged boron ion after it has accepted an electron from the valence band. A positively charged hole is created.

Electron hole concentration

- In intrinsic semiconductor
  - We considered "***intrinsic carrier concentration***"
- For extrinsic semiconductors (we also call this doped semiconductors)
  - We have to consider amount of doping
    - Which allows us to control "***electron concentration***" and "***hole concentration***"
    - Which determines "***conductivity***" and "***current***" in the materials

Electron hole concentration

- Fundamental relationship between the electron and hole concentrations in a semiconductor in thermal equilibrium

$$n_0 p_0 = n_i^2$$

  - n_o : electron concentration
  - p_o : hole concentration

For N-type semiconductor

$$n_0 \approx N_d$$

Assuming $N_d >> n_i$

$$p_0 \approx \frac{n_i^2}{N_d}$$

N_d : donor concentration

For P-type semiconductor

$$p_0 \approx N_a$$

Assuming $N_a >> n_i$

$$n_0 \approx \frac{n_i^2}{N_a}$$

N_a : accptor concentration

Drift and Diffusion Current

- Carriers
  - **Charged electrons** and **charged holes** in semiconductor are called **carriers**
- Current generation
  - When charged carriers move it generates current
- Two types of carrier movements in semicon
  - ***Drift*** : movement caused by electric field
  - ***Diffusion*** : movement by variation in concentration

pn Junction Diode

pn Junction Diode

- The real power of semiconductor electronics occurs when p- and n-regions are directly adjacent to each other
- This is called pn junction diode

→ Doping concentration when equally doped

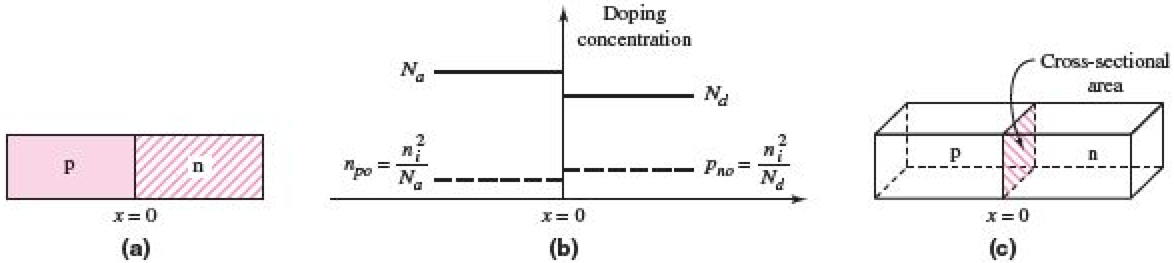


Figure 1.10 (a) The pn junction: (a) simplified one-dimensional geometry, (b) doping profile of an ideal uniformly doped pn junction, and (c) three-dimensional representation showing the cross-sectional area

→ in real world (IC), pn junction is formed on a single Si substrate with one p-doped region and other n-doped region

pn Junction Diode Operating Regions

- For the operation of a pn junction diode, it is necessary to categorize three different operating regions :
  - equilibrium, reverse bias, forward bias

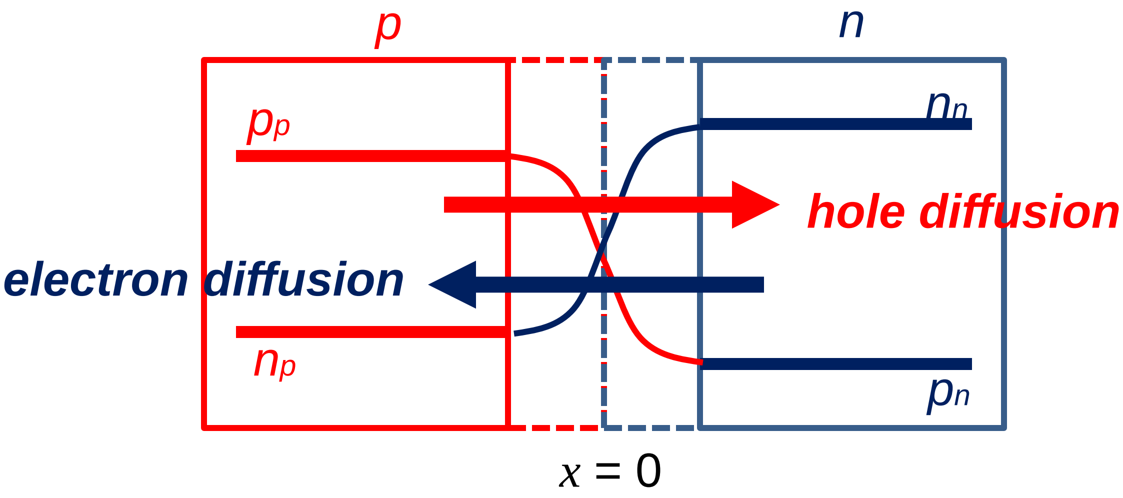
$V_D = 0$	$V_D < 0$	$V_D > 0$
Equilibrium pn Junction → Depletion Region → Built-in Potential	**Reverse Bias** pn Junction → Depletion Region Width → Junction Capacitance	**Forward Bias** pn Junction → Current-Voltage Relationship

pn Junction

(Equilibrium pn Junction)

Equilibrium pn Junction

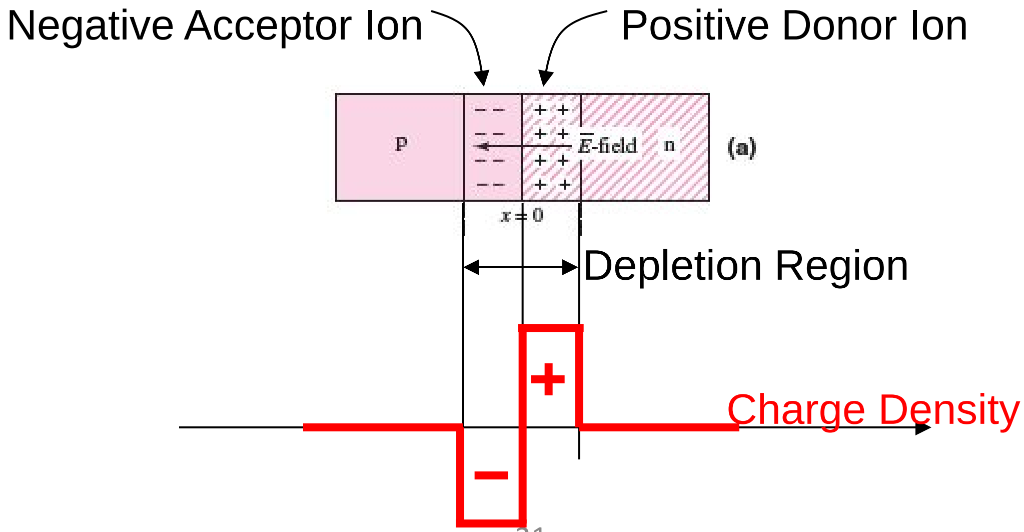
- Due to the difference in the electron and hole concentrations on each side of the junction, carriers diffuse across the junction → diffusion current



n_p : Electron concentration on p-region [cm^{-3}]
p_p : Hole concentration on p-region [cm^{-3}]
n_n : Electron concentration on n-region [cm^{-3}]
p_n : Hole concentration on n-region [cm^{-3}]

Depletion Region

- As electrons and holes diffuse across the junction, they leave negative acceptor ions (on p-region) and positive donor ions (on n-region) behind.
  - This forms “Depletion Region”
  - Where charge density is NOT zero



Drift Current and Built-in potential

- Due to non-zero charge density in depletion region
  - Electric fields exist in depletion region
  - which results in drift current
  - And also potential differences exist between the region
    (Built-in potential, or Built-in voltage)

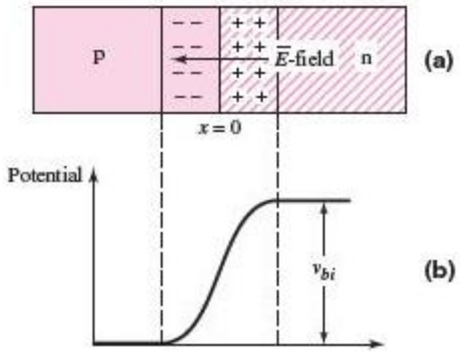


Figure 1.12 The pn junction in thermal equilibrium. (a) The space charge region with negatively charged acceptor ions in the p-region and positively charged donor ions in the n-region; the resulting electric field from the n- to the p-region. (b) The potential through the junction and the built-in potential barrier V_{bi} across the junction.

$$V_{bi} = \frac{kT}{e} \ln \frac{N_a N_d}{{n_i}^2}$$

N_a : Net acceptor concentration on p-region [cm^{-3}]
N_d : Net donor concentration on n-region [cm^{-3}]

pn Junction

(Reverse Bias pn Junction)

Reverse-biased pn Junction

- Positive voltage is applied to n-region of pn junction
  - The direction of electric field applied (E_A) is in the same direction as electric field in depletion region
  - The magnitude of electric field in depletion region increases above thermal equilibrium
  - Result in increased depletion region (width, W)

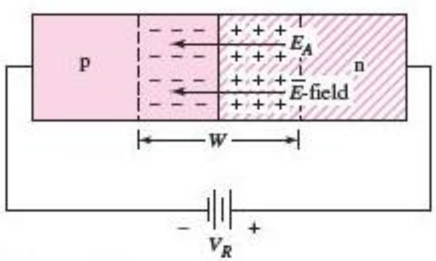


Figure 1.13 A pn junction with an applied reverse-bias voltage, showing the direction of the electric field induced by V_R and the direction of the original space-charge electric field. Both electric fields are in the same direction, resulting in a larger net electric field and a larger barrier between the p- and n-regions.

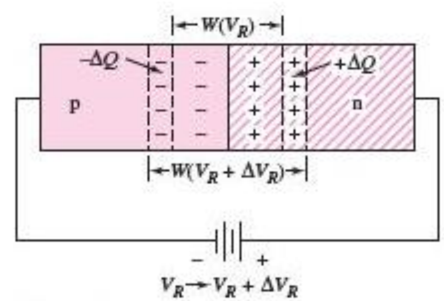


Figure 1.14 Increase in space-charge width with an increase in reverse bias voltage from V_R to $V_R + \Delta V_R$. Creation of additional charges $+\Delta Q$ and $-\Delta Q$ leads to a junction capacitance.

Junction Capacitance

- With additional positive and negative charges due to reverse bias voltage (V_R)
  - Depletion Region becomes similar to an insulator
  - And act as capacitance
  - This is called "***Junction Capacitance***" or "***Depletion Layer Capacitance***" and give by

$$C_j = C_{j0}\left(1+\frac{V_R}{V_{bi}}\right)^{-\frac{1}{2}}$$

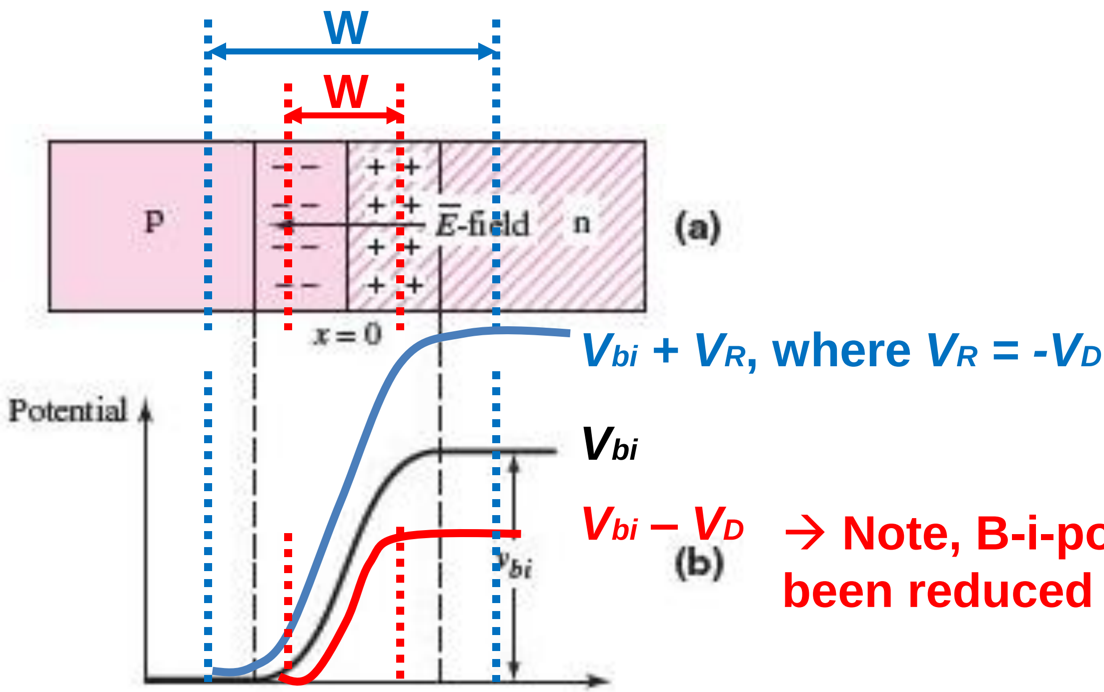
C_{j0} : Junction Capacitance at V_R = 0
V_R : Reverse-Bias Voltage

pn Junction

(Forward Bias pn Junction)

Dep Reg Width and Built-in Potential w.r.t. V_D

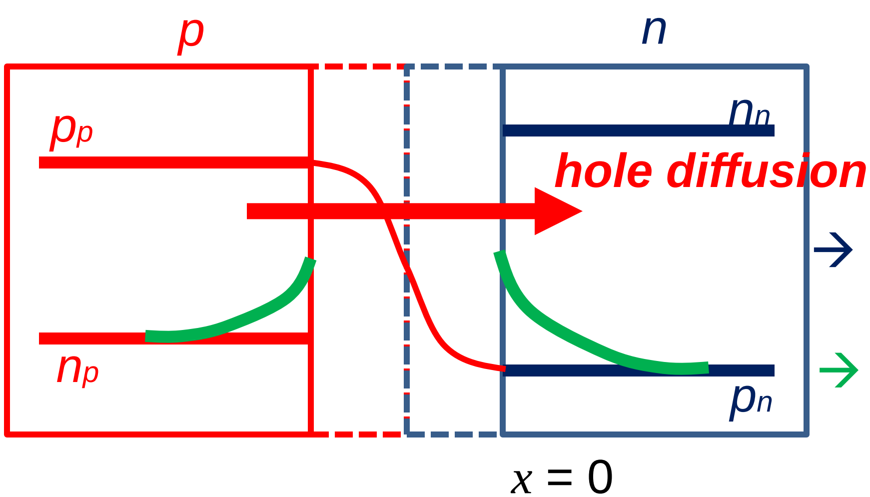
$V_D = 0$ **Equilibrium** pn Junction	$V_D < 0$ **Reverse Bias** pn Junction	$V_D > 0$ **Forward Bias** pn Junction
→ Depletion Region → Built-in Potential	→ Increase in Dep Region → Increase in B-i-Potential	→ Decrease in Dep Reg → Decrease in B-i-Potenti



→ **Note, B-i-potential barrier has been reduced due to forward bias**

Minority Carrier Injection

- Due to reduced built-in potential by forward bias, carriers diffuse across the junction
  - The carriers which diffuse across the junction become minority carriers in the p-region (for holes, n-region for electron)
  - They recombine with majority carriers and "recombine (dying out)" with distance



→ p_n (blue) : minority carrier density at equilibrium

→ p_n (green) : minority carrier density at forward bias (excess minority carriers)

Minority Carrier Injection (cont.)

- Minority Carrier Injection profile on both p- and n-region for forward bias

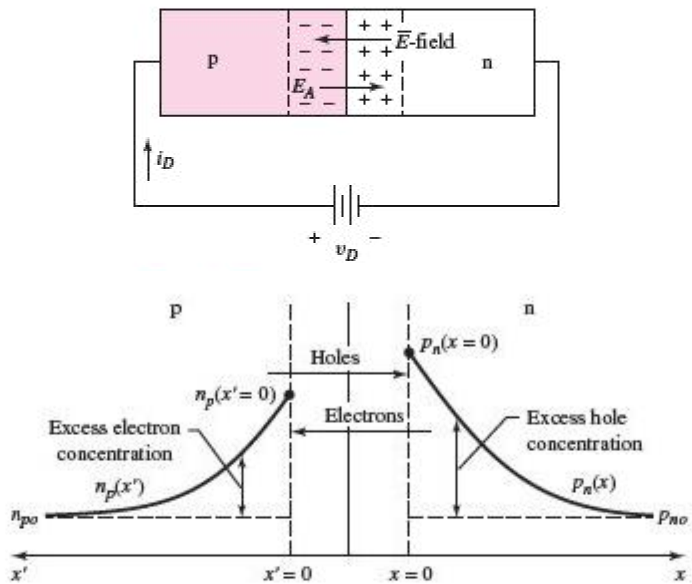


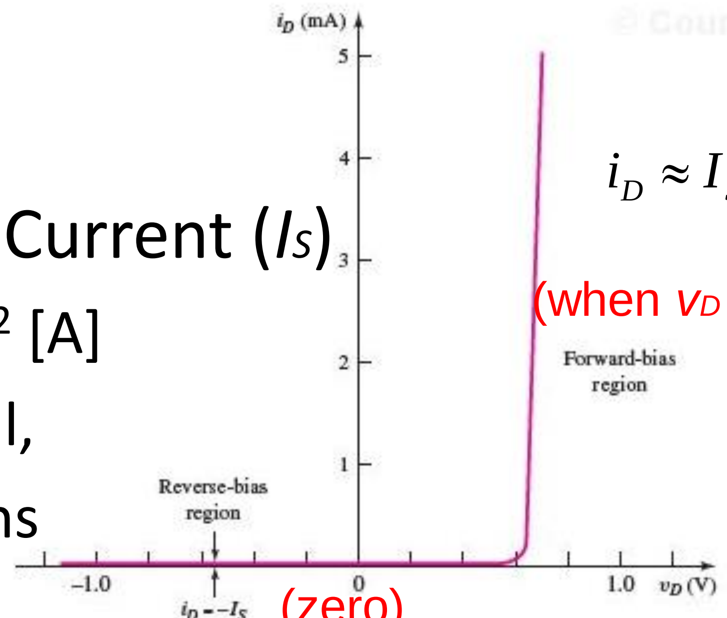
Figure 1.16 Steady-state minority carrier concentrations in a pn junction under forward bias. The gradients in the minority carrier concentrations generate diffusion currents in the device.

Ideal Current-Voltage Relationship

- Ideal I-V Equation for pn junction diode (i_D)
  - Exponentially proportional to forward bias voltage
  - “Saturates” at small negative current (zero)

$$i_D = I_S\left[e^{\frac{v_D}{nV_T}} - 1\right]$$

- Reverse-Bias Saturation Current (I_S)
  - Range within $10^{-18} \sim 10^{-12}$ [A]
  - Depend on area, material, and dopant concentrations



$$i_D \approx I_S\left[e^{\frac{v_D}{nV_T}}\right]$$

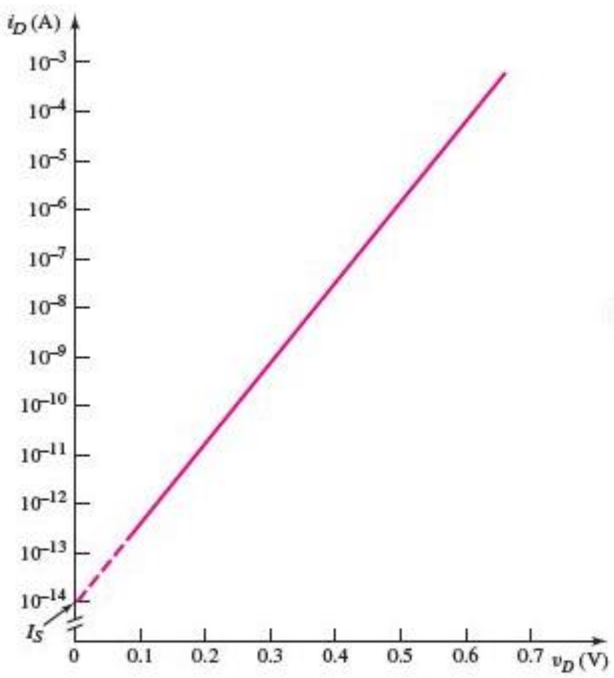
(when v_D > 0.1[V])

(zero)

Figure 1.17 Ideal I–V characteristics of a pn junction diode for $I_S = 10^{-14}$ A. The diode current is an exponential function of diode voltage in the forward-bias region and is very nearly zero in the reverse-bias region. The pn junction diode is a nonlinear electronic device.

pn Junction Diode

- Diode current (i_D) is exponentially proportional to applied voltage (v_D) at forward bias region
- Increased by a decade by ~60mV increase (ideal for sw)



- Temperature Dep.
  - Required diode voltage (v_D) decreases w.r.t. increase in temperature (thus V_T)

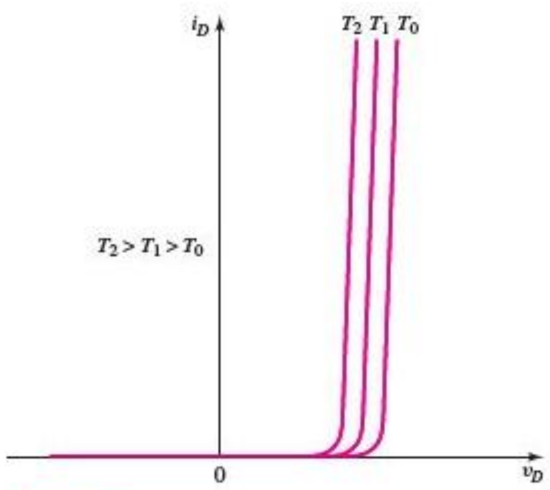
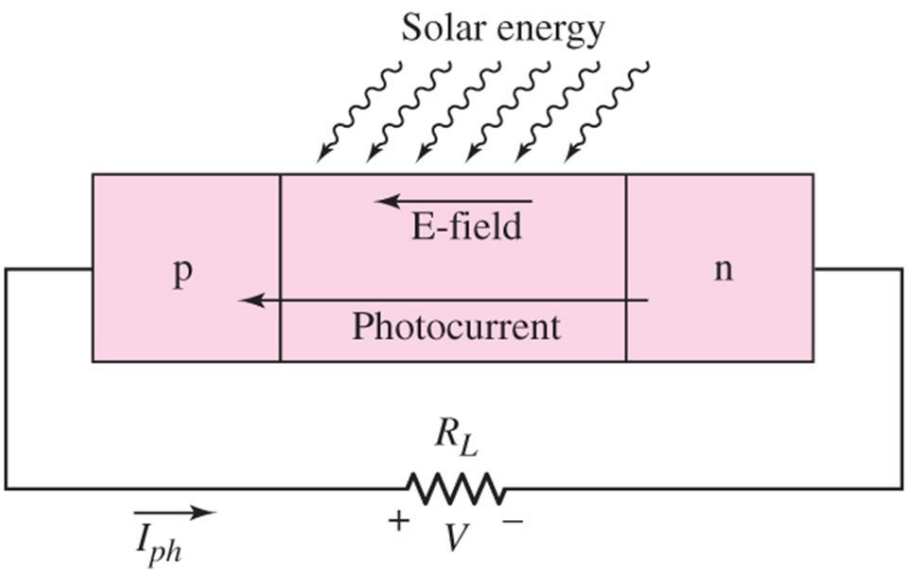


Figure 1.20 Forward-biased pn junction characteristics versus temperature. The required diode voltage to produce a given current decreases with an increase in temperature.

Solar Cell,

LED

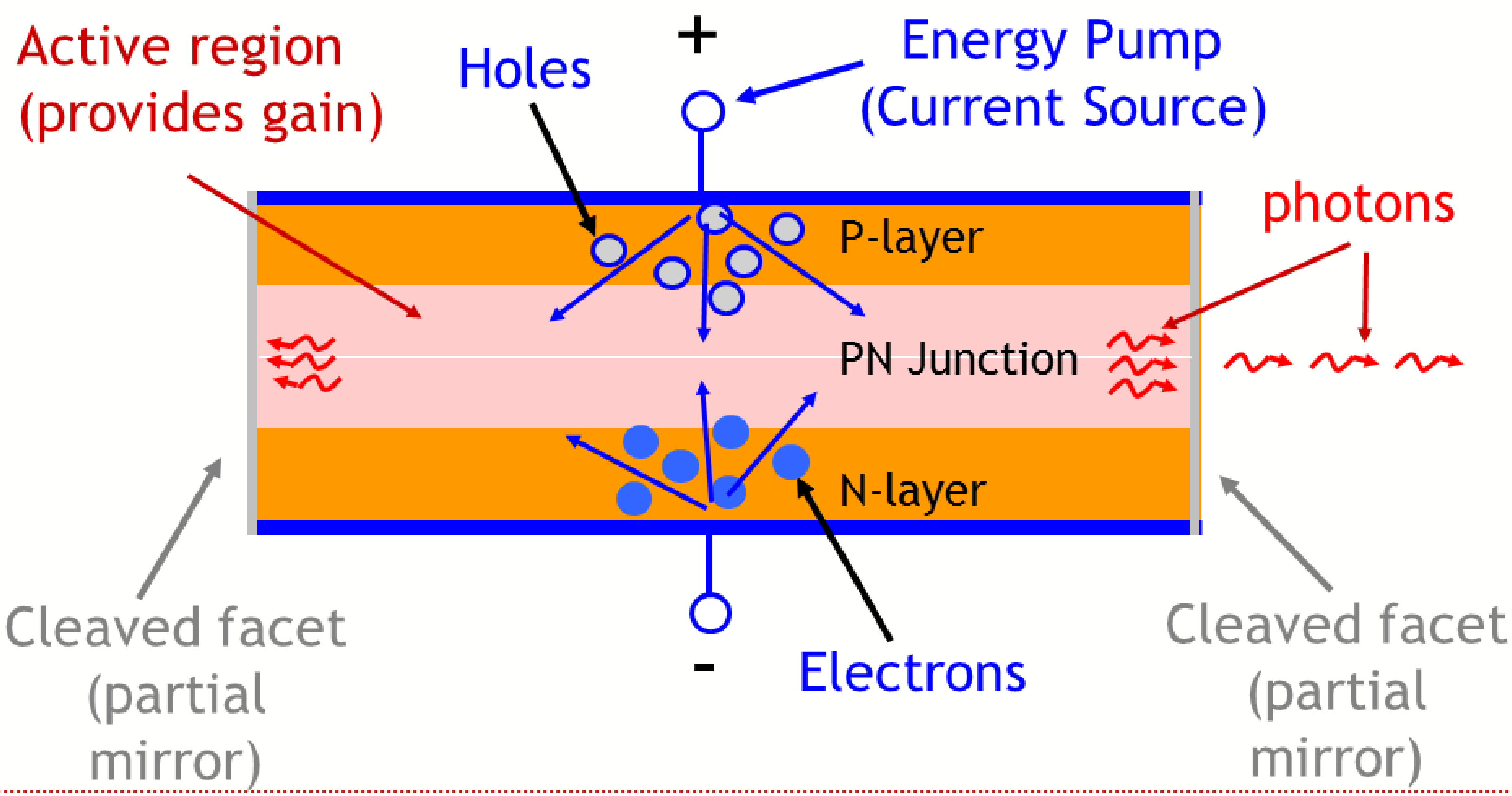
Solar Cell



- When “light” hits “depletion region”
  - “electron-hole pair” are generated
  - They are quickly separated and swept out of “depletion region”
  - Creating “photocurrent”

A Basic Laser Structure

Fabry-Perot Laser (longitudinal section)



Ref : VPI Photonics

LED (Light Emitting Diode)

Si

- Intrinsic Semiconductor
- Also called "indirect bandgap material"
- When "forward biased (V_D>0)
- electron – hole diffuses across "depletion region"
- "Minority carrier injection" occurs
- electron – hole recombines without any light emission

GaAs

- Extrinsic Semiconductor
- Also called "**direct** bandgap material"
- When "forward biased (V_D>0)
- electron – hole diffuses across "depletion region"
- "Minority carrier injection" occurs
- electron – hole recombines **Emitting LIGHT**