NANYANG TECHNOLOGICAL UNIVERSITY

Course: EE3013/ Semiconductor Devices and Processing

School: School of Electrical and Electronic Engineering

Week 10 – PN Junction Diodes

Learning Objectives

At the end of this lesson, you will be able to:

- Explain pn junction diode theory and operation mechanisms under different biasing conditions namely thermal equilibrium, forward bias and reverse bias
- Under different bias:
  - Draw the energy band diagram of the pn junction
  - Explain the concepts and determine the key parameters such as built-in voltage, depletion width, space charge, electric field, and junction capacitance
- Explain the concepts of injected minority carriers and current distributions, and calculation of electron and hole diffusion currents under different bias conditions
- Explain how useful capacitance versus voltage characteristics is to determine the built-in voltage and the impurity concentration in the semiconductor

Fundamentals of Semiconductors

- Semiconductors are mainly classified into two categories:
  - **Intrinsic** - Is chemically very pure and possesses poor conductivity, and
  - **Extrinsic** - Is an improved intrinsic semiconductor with a small amount of impurities which modifies its electrical properties and improves its conductivity.

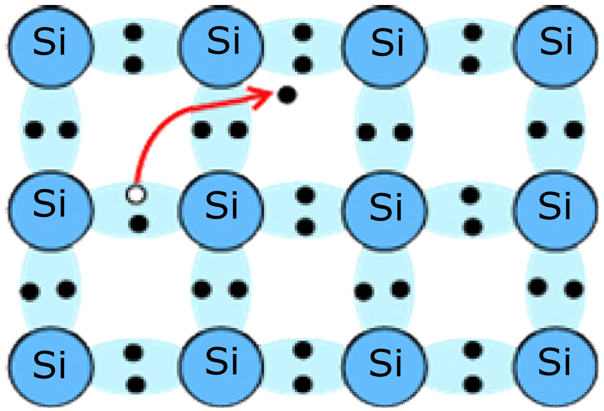


Figure 1.1 Intrinsic

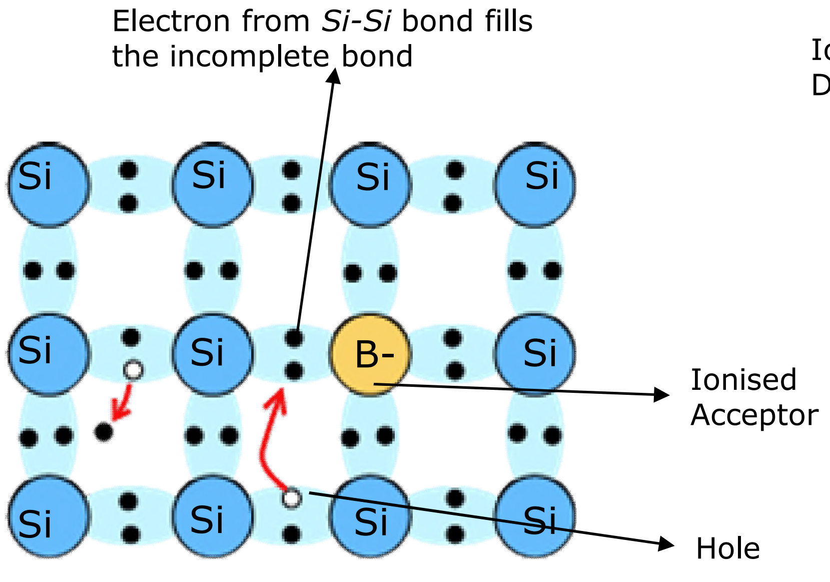


Figure 1.2 Extrinsic (p-type)

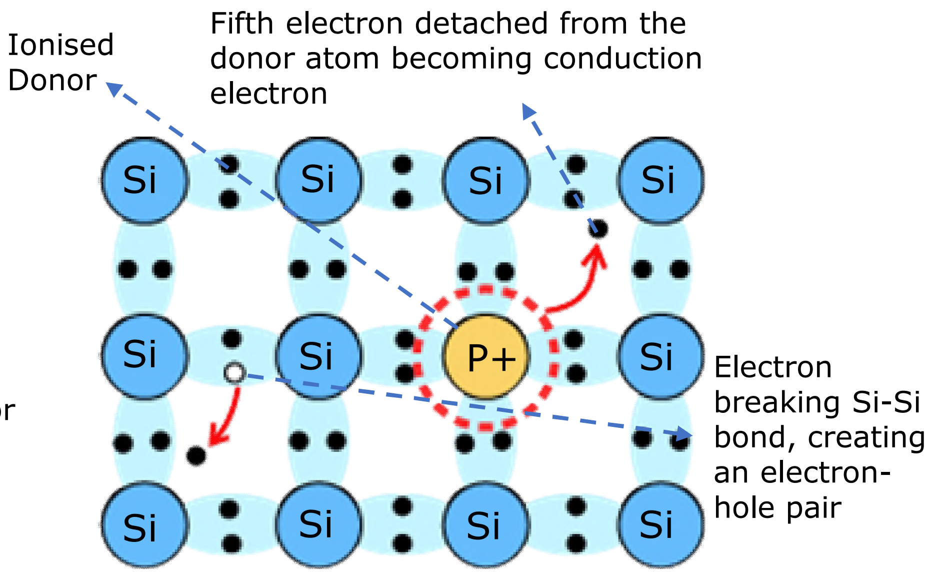


Fig. 1.3. Extrinsic (n-type)

- **P-type** - The addition of trivalent impurities (Group III elements such as Boron) to an intrinsic silicon creates deficiencies of valence electrons, called **holes**.
- **N-type** - The addition of pentavalent impurities (Group V elements such as Phosphorus) contributes free **electrons**.

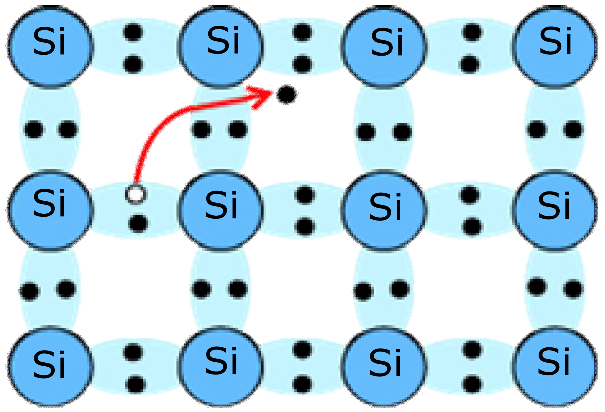


Figure 1.1 Intrinsic

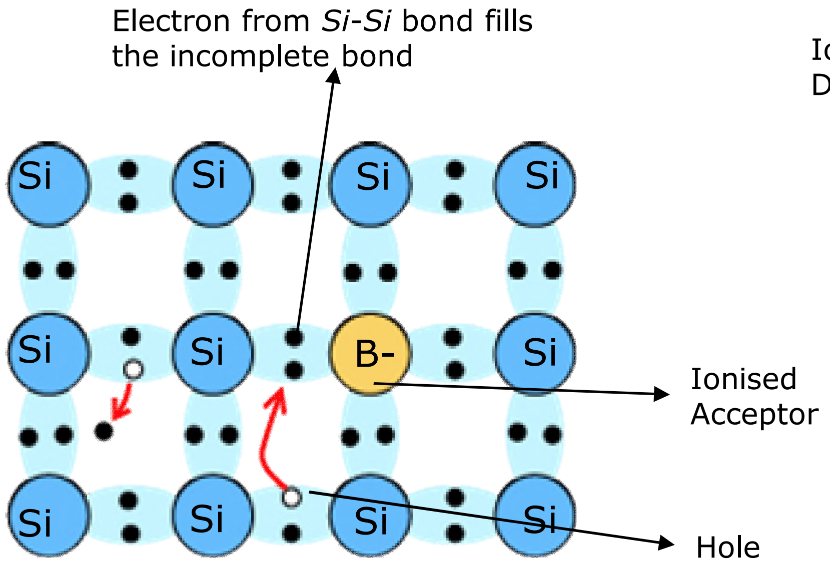


Figure 1.2 Extrinsic (p-type)

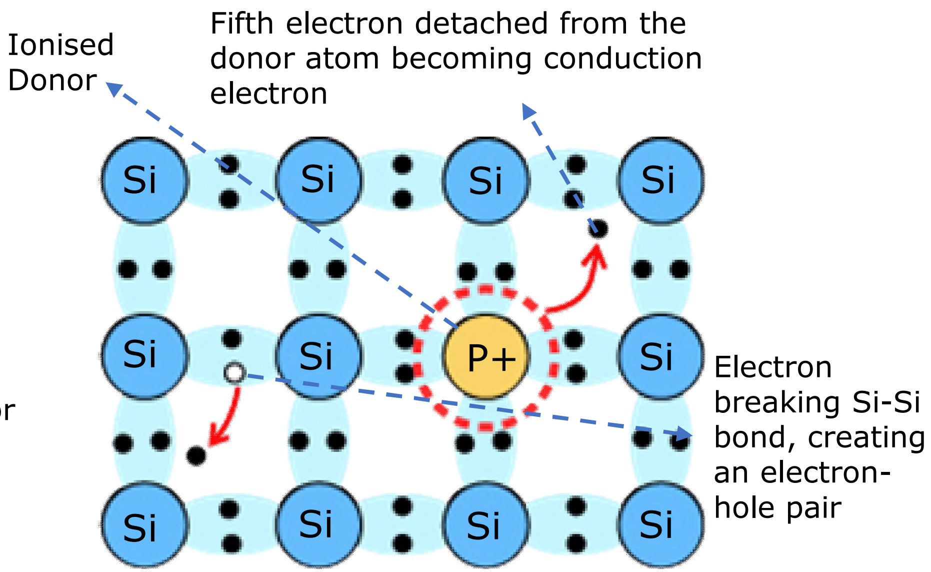


Fig. 1.3. Extrinsic (n-type)

Fundamentals of Semiconductors (Cont’d.)

- There are two basic transport mechanisms in a semiconductor crystal depending on the driving force:
  - **Drift:** movement of charge due to electric fields
  - **Diffusion:** flow of charge due to concentration gradients

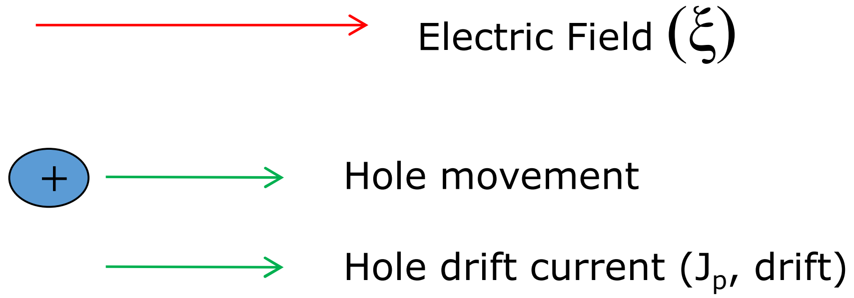


Figure 1.4 Drift current

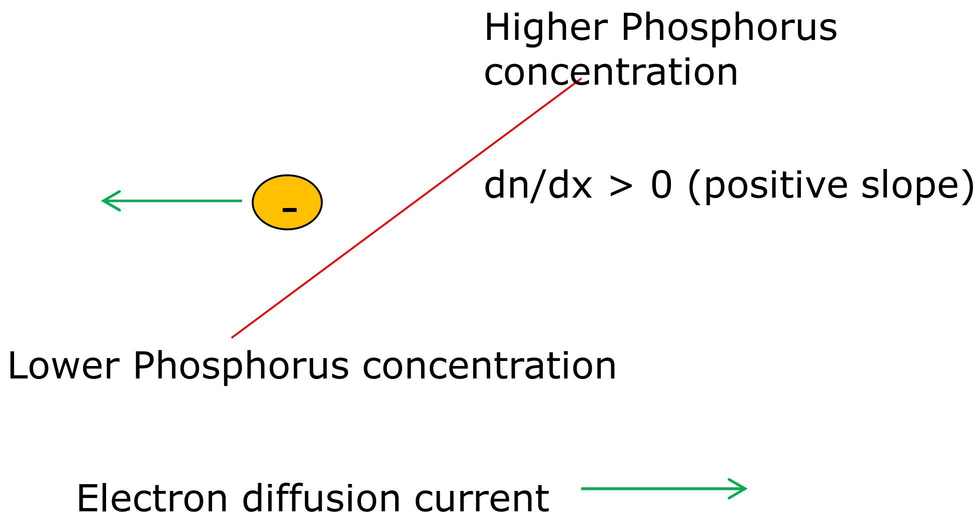
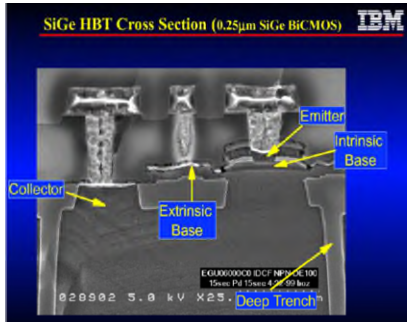
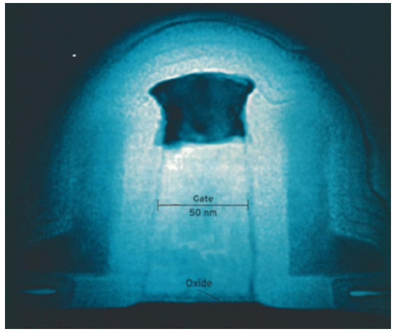


Figure 1.5 Diffusion current

- Some basic semiconductor devices are **BJT, MOSFET, LED, laser, and photo-detectors.**
  - Electronic devices: **BJT, MOSFET**
  - Optoelectronic devices: **LED, laser, and photo-detectors**

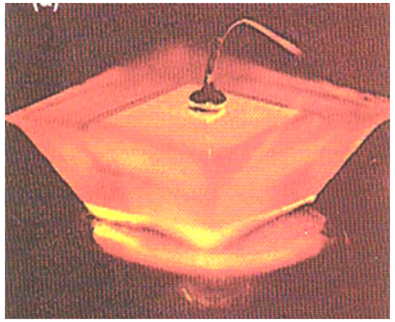


IBM's SiGe Bipolar Transistor

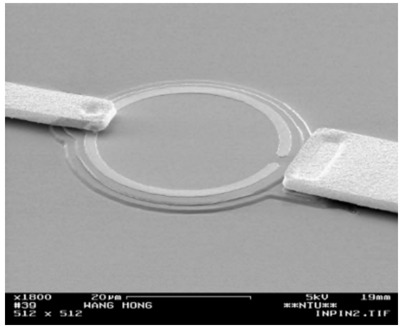


Intel's 65nm MOSFET

Figure 1.6 Electronic devices



Red LED



Photodetector

Figure 1.7 Optoelectronic devices

- In this course, we will mainly deal with electronic devices.

PN Junction Diodes

- **PN junction** is a boundary or interface between two types of semiconductor material, p-type and n-type.

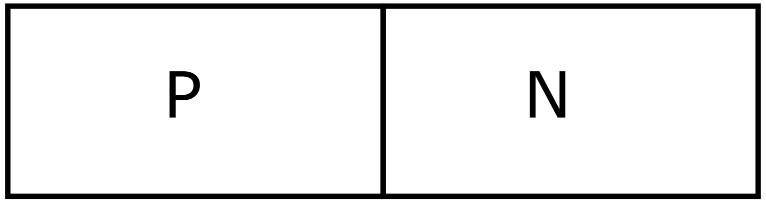


Figure 1.8 PN Junction

- PN junction serves an important role in:
  - Modern electronic and optoelectronic applications (used in rectification, switching, light emission and detection, and other operations) and
  - Understanding other semiconductor devices because it is the key building block for most of the devices, such as LEDs, photodetector, MOSFETs and BJTs, etc. as mentioned in previous slide.

Diode I-V Characteristics

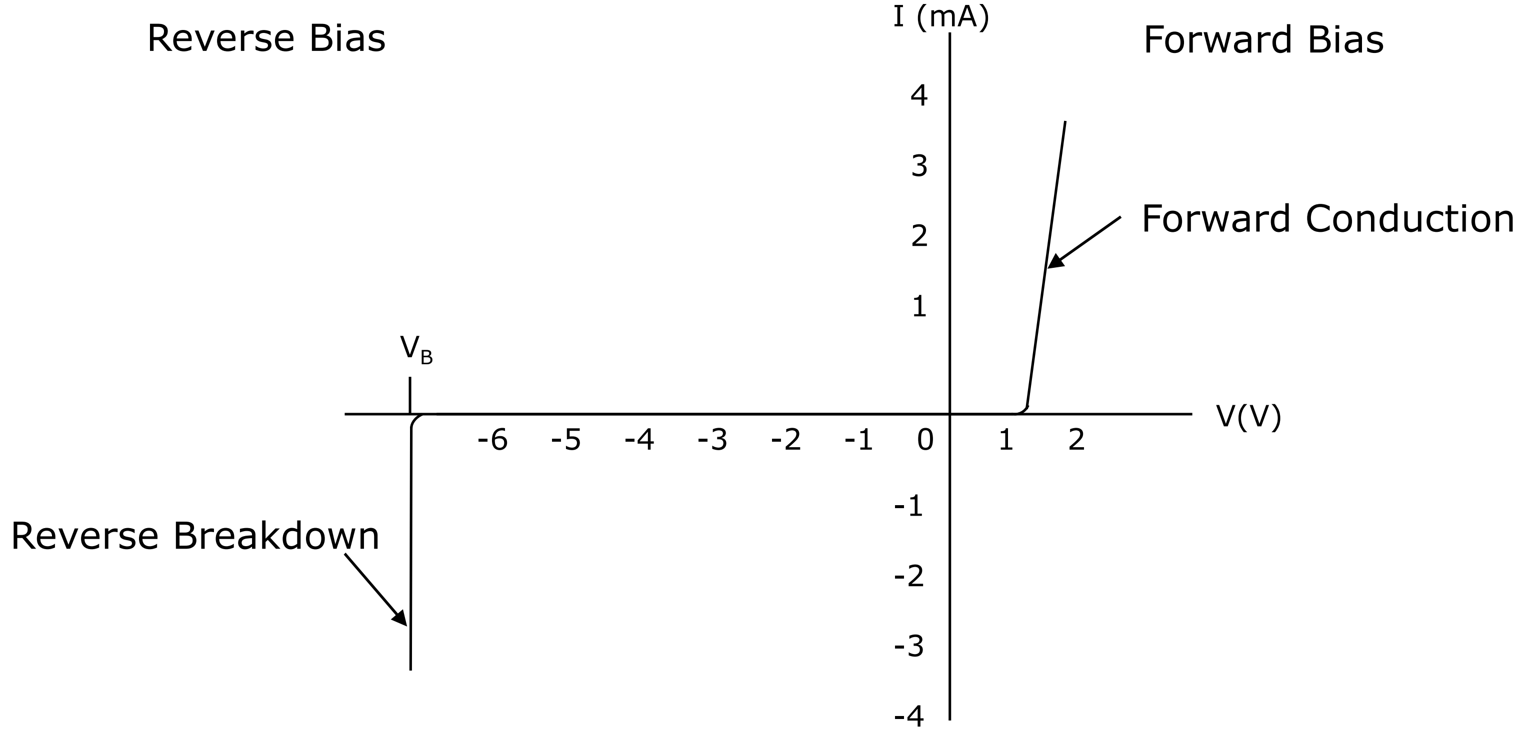


Figure 1.9 Diode I-V Characteristics

- Forward bias: p-side positive, I increases exponentially with V
- Reverse bias: p-side negative, current nearly 0 till junction breakdown
- A PN junction allows current to flow easily in only one direction

(Equation 1.1) $I = I_s\,(e^{qV/kT} - 1)$

where I_s is the reverse saturation current and V is the bias applied

P- and N-type Semiconductors

- Assume the p-type semiconductor materials are uniformly doped.

p-type silicon

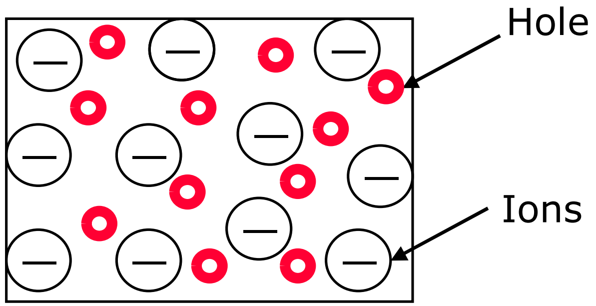
Doped by acceptors (Boron)

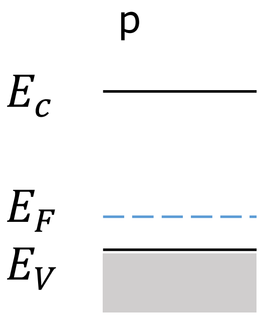
Majority carriers

(Equation 1.2) $p = N_A = n_i \, e^{\frac{E_1 - E_F}{kT}}$

Minority carriers

(Equation 1.3) $n = \dfrac{n_i^2}{N_A}$ where $p \gg n$





P- and N-type Semiconductors

- Assume the n-type semiconductor materials are uniformly doped.

n-type silicon

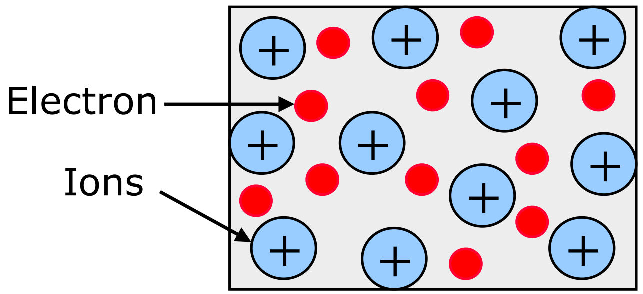
Doped by donors (Phosphorus)

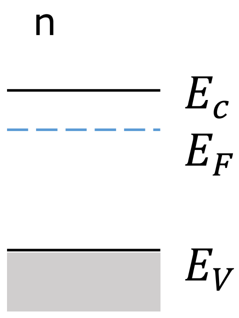
Majority carriers

(Equation 1.4) $n = N_D = n_i \, e^{\frac{E_F - E_i}{kT}}$

Minority carriers

(Equation 1.5) $p = \dfrac{n_i^2}{N_D}$ where $n \gg p$





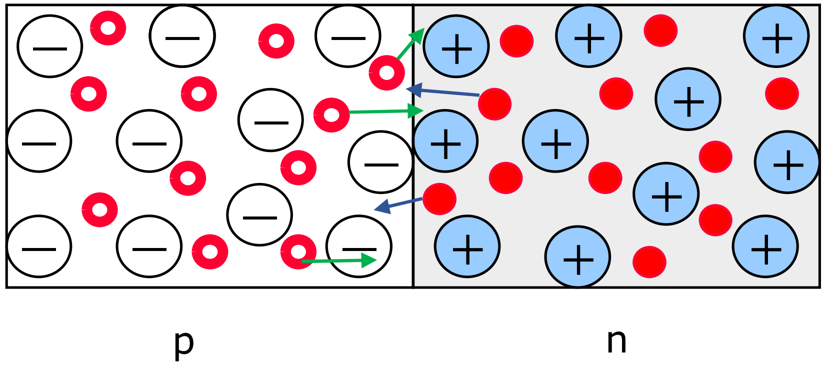
PN Junction Formation

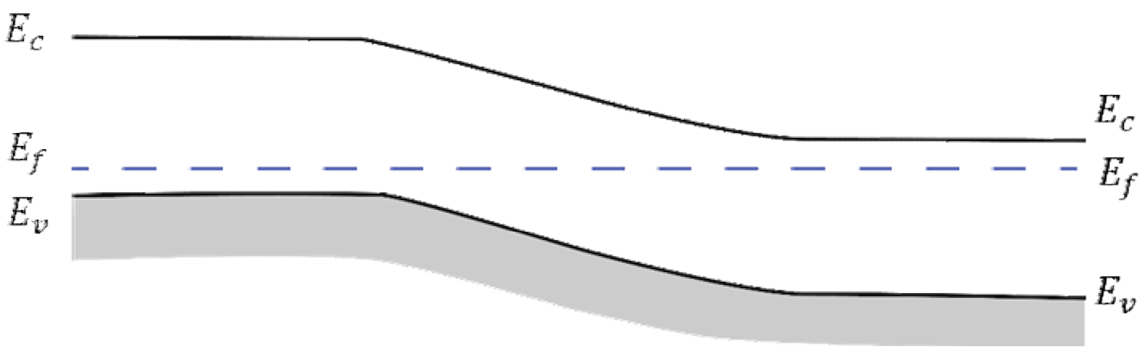
- When p- and n-type semiconductors contact together, large carrier concentration gradients at the junction cause carrier diffusion (diffusion currents $\boldsymbol{J_p}$ and $\boldsymbol{J_n}$).

Holes flow from left to right

Hole current density $\boldsymbol{J_p}$ ***to right***

$$J_p = -qD_p \frac{dp}{dx}$$ *(Equation 1.6)*





(Equation 1.7) $$J_n = -qD_n \frac{dn}{dx}$$

Electrons flow to left

But electron current density $\boldsymbol{J_n}$ to right

PN Junction Formation (Cont'd.)

- As holes leave the p-side, some negative acceptor ions ($\boldsymbol{N_A^-}$) near the junction are left uncompensated (since the acceptors are fixed in the semiconductor lattice while the holes are mobile).
- Similarly, some positive donor ions ($\boldsymbol{N_D^+}$) are left as electrons leave n-side.

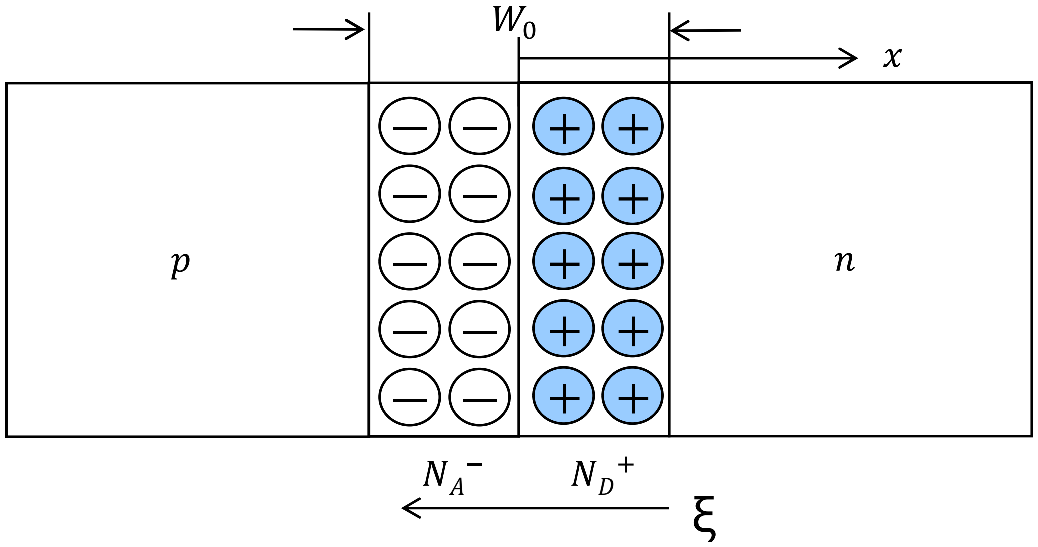
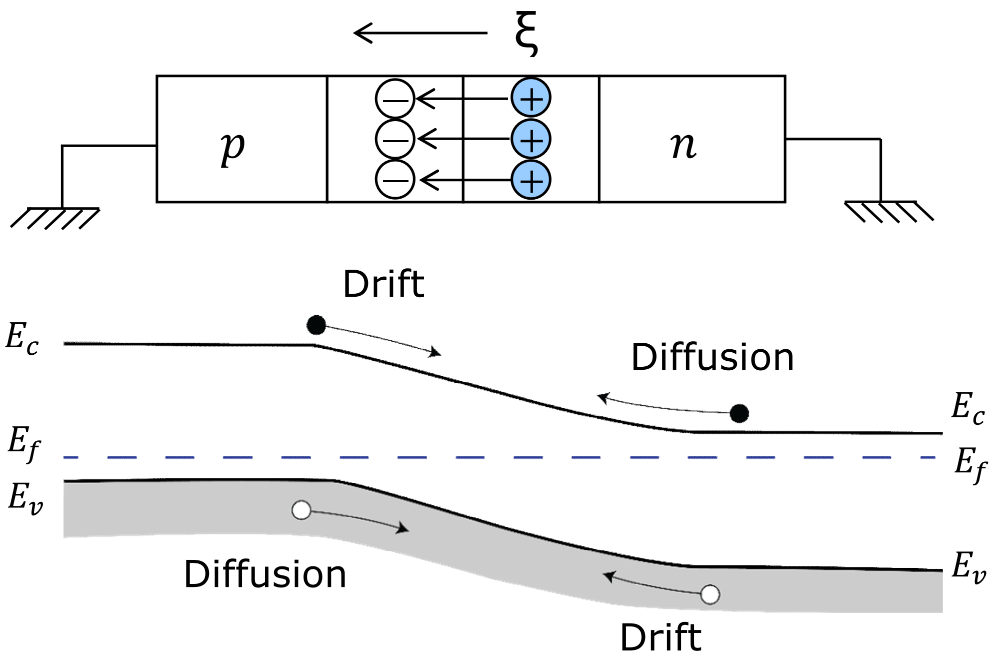


Figure 1.10

- Negative and positive space charges form a depletion region.
- They create an **electrical field,** ξ, directed from positive charges towards negative charges.

PN Junction Formation (Cont'd.)

- The electrical field creates two drift current components, J_P(drift) and J_n(drift), and in the directions opposite to the diffusion current components.



$$J_n(drift) = J_n\, diffusion \qquad \textit{(Equation 1.8)}$$

$$J_p(drift) = J_p\, diffusion \qquad \textit{(Equation 1.9)}$$

- At thermal equilibrium, (that is, the steady-state condition at a given temperature without any external excitation), the net electron and hole currents flowing across the junction are zero.

PN Junction Formation (Cont'd.)

- That is, each type of drift current must exactly cancel the diffusion current.

$$J_p = q\,\mu_p\, p\xi - qD_p\,\frac{dp}{dx} = 0 \qquad \textit{(Equation 1.10)}$$

$$J_n = q\,\mu_n n\xi + qD_n\,\frac{dn}{dx} = 0 \qquad \textit{(Equation 1.11)}$$

Where,

$D_p(D_n)$ is the diffusion coefficient of holes (electrons),

$\mu_p(\mu_n)$ is hole (electron) mobility,

$P\ (n)$ is the hole (electron) concentration,

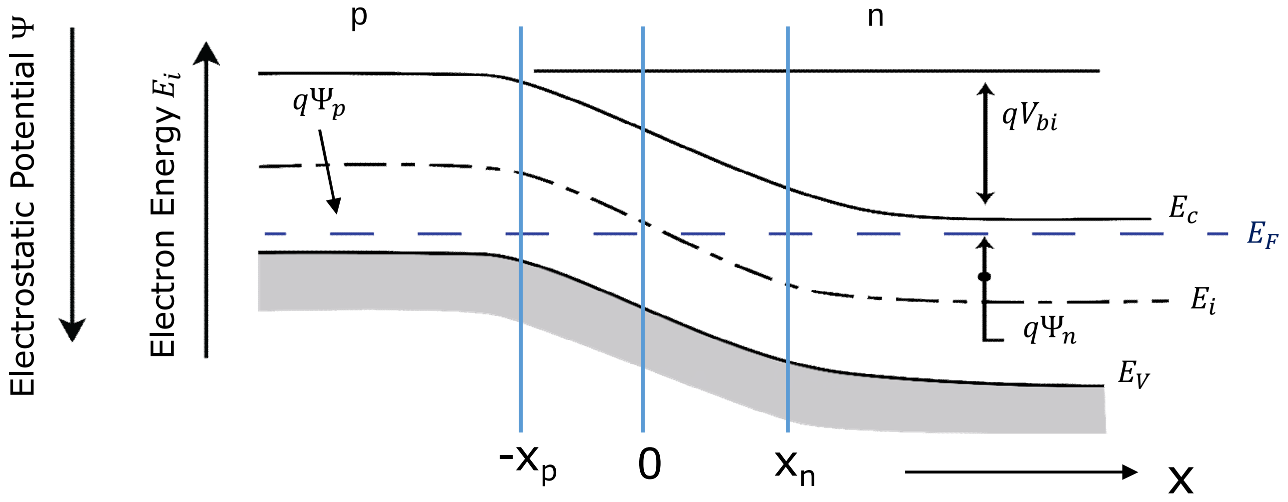
k is the Boltzmann constant, and

ξ is the electrical field.

- $D = (kT/q)\mu$ is the Einstein relation.
- Hence in thermal equilibrium, $J = J_n + J_p = 0$.

Built-in Potential V_{bi}

Figure 1.11



$\Psi_p \equiv -\frac{1}{q}(E_i - E_F)|\, x \leq -x_p = -\frac{kT}{q}\ln\frac{N_A}{n_i}$ *(Equation 1.12)*

$\Psi_n \equiv -\frac{1}{q}(E_i - E_F)|\, x \geq x_n = \frac{kT}{q}\ln\frac{N_D}{n_i}$ *(Equation 1.13)*

- The total electrostatic potential difference between the p-side and n-side neutral regions at thermal equilibrium is called the ***built-in potential*** V_{bi}.

$$V_{bi} = \Psi_n - \Psi_p = \frac{kT}{q}\ln\frac{N_A N_D}{n_i^2} \quad \textit{(Equation 1.14)}$$

- Note that there is an energy band bending at junction due to V_{bi}. this “potential barrier” that prevents any further flow of electrons and holes under thermal equilibrium.

Depletion Width and Maximum Electric Field

- Overall space charge neutrality requires:

$$N_A x_p = N_D x_n \quad \textit{(Equation 1.15)}$$

- The total depletion layer width is given by:

$$W = x_p + x_n = \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{N_A + N_D}{N_A N_D}\right] V_{bi}} \quad \textit{(Equation 1.16)}$$

- The electric field can be found by solving the Poisson's equation: $d^2\phi(x)/dx_2 = -\rho(x)/\varepsilon_s = -\, d\xi(x)/dx$ *(Equation 1.17)*
- This is equivalent to integrating the space charge density plot (a) which results in the electric field plot in (b).
- The maximum **electric field** ξ_m occurs at $x = 0$ is given by: $\xi_m = \frac{qN_D x_n}{\varepsilon_S} = \frac{qN_A x_p}{\varepsilon_S}$ *(Equation 1.18)*

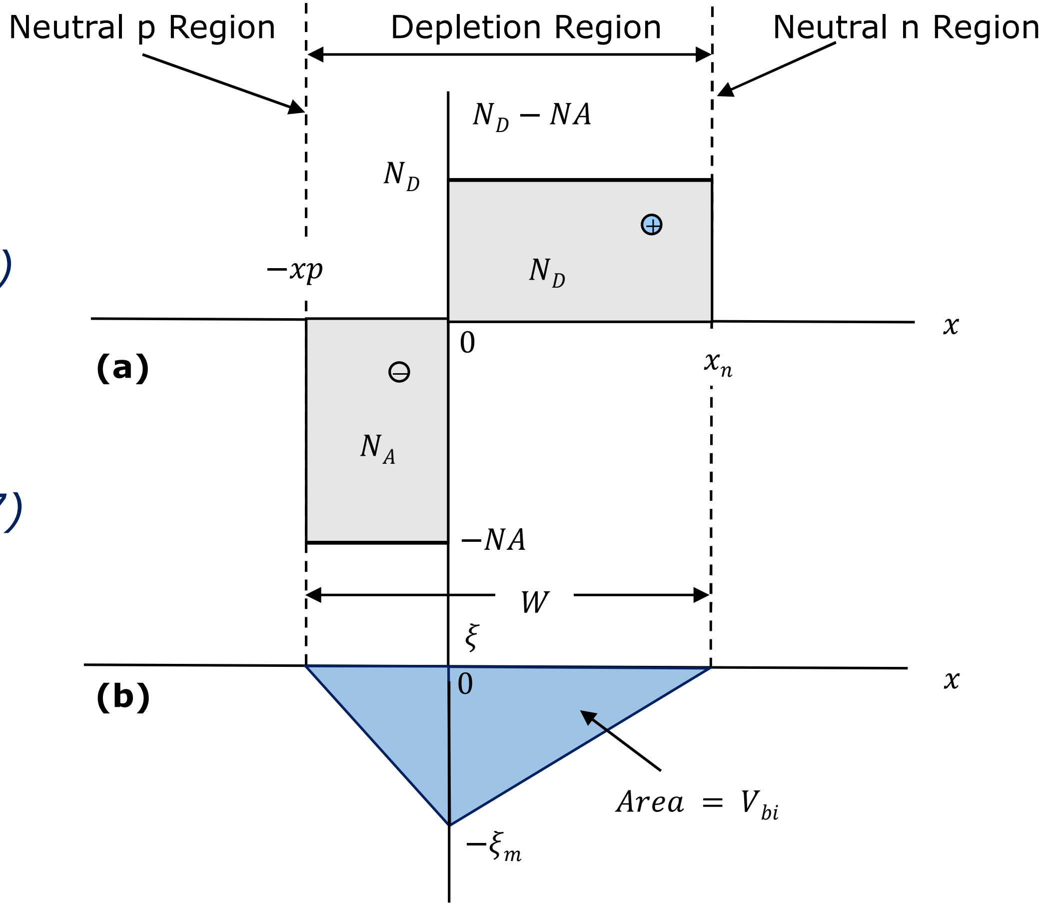


Figure 1.12

One-sided Abrupt Junction

- When the impurity concentration on one side of an abrupt junction is much higher than that of the other side, the junction is called a **one-sided abrupt junction,** e.g., a p⁺-n junction.
- $x_p << x_n$, and the W can be simplified to:

$$W \approx x_n = \sqrt{\frac{2\varepsilon_s V_{bi}}{qN_D}} \quad \text{(Equation 1.19)}$$

- The maximum electric field is $\xi_m = \frac{qN_B W}{\varepsilon_S}$ *(Equation 1.20)*

where N_B is the lightly doped bulk concentration.

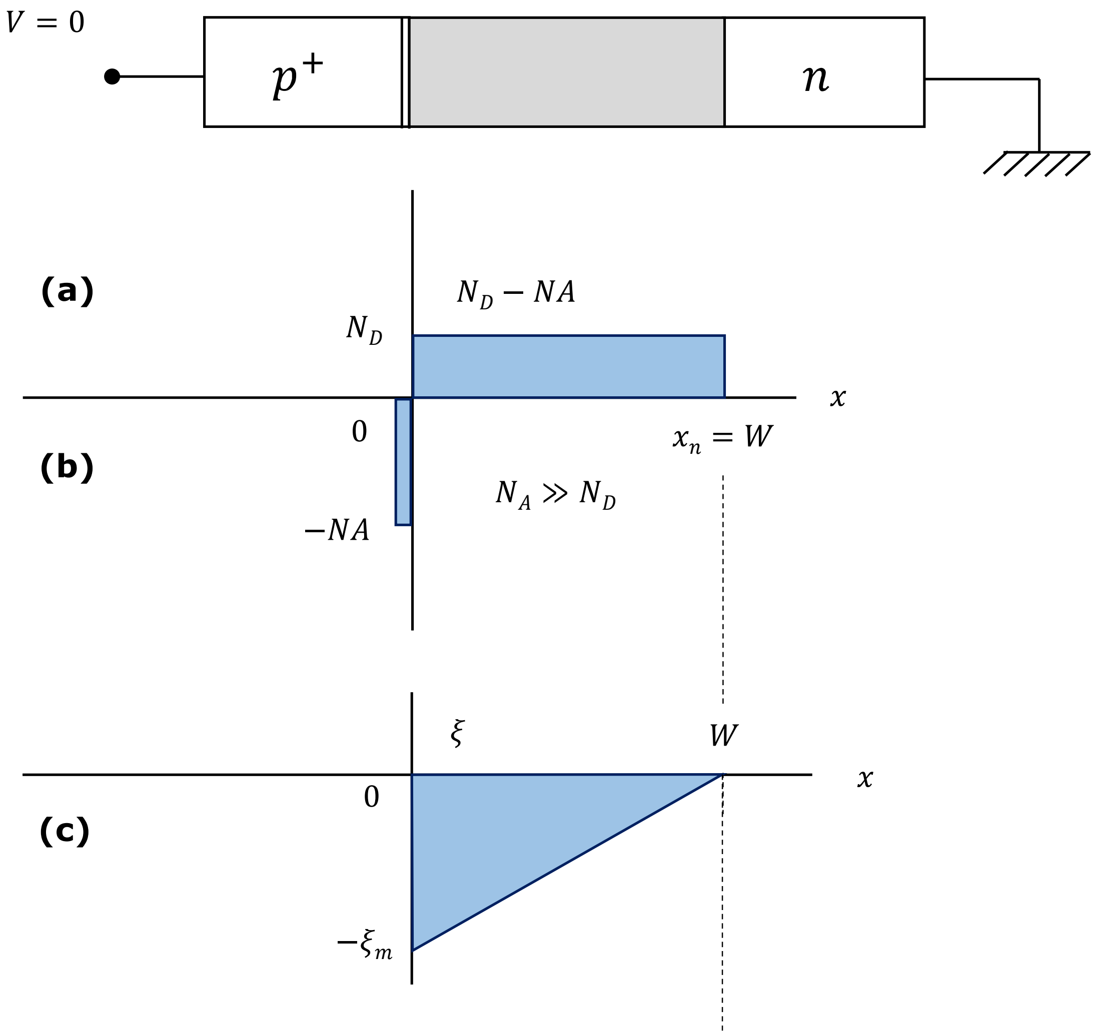
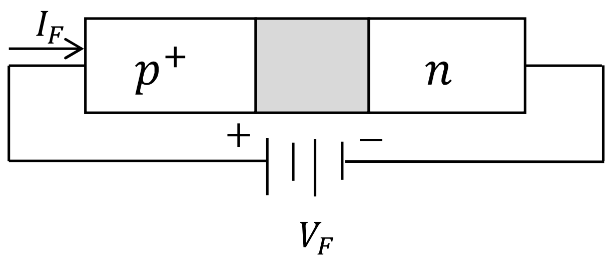


Figure 1.13

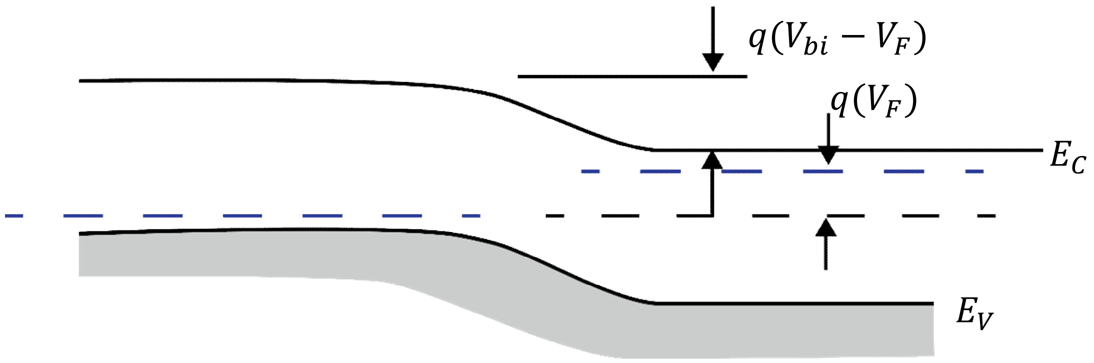
P-N Junction under Bias

Forward bias (V_F):

- Depletion layer width becomes smaller.



- The total electrostatic potential becomes $V_{bi} - V_F$.

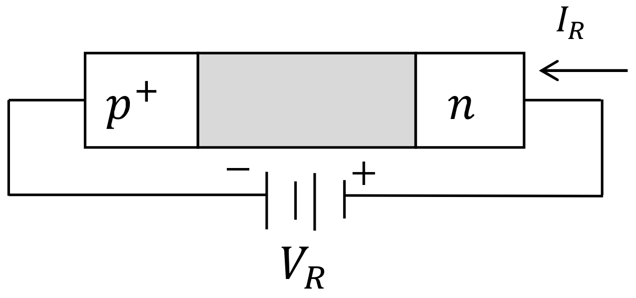


$$W_{FB} = \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{N_A + N_D}{N_A N_D}\right](V_{bi} - VF)} \quad \textit{(Equation 1.21)}$$

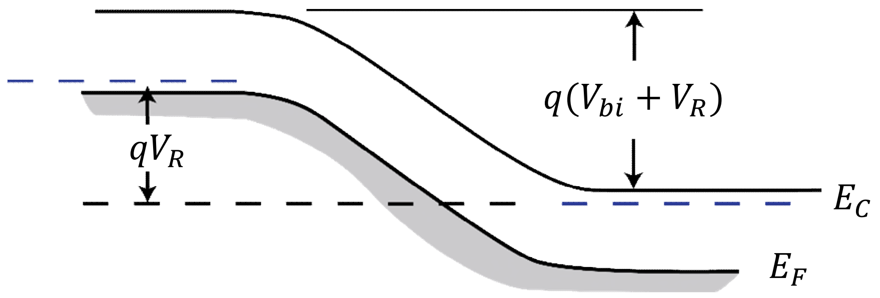
P-N Junction under Bias

Reverse bias (V_R):

- Depletion layer width increased.



- The total electrostatic potential becomes $V_{bi} - V_R$.



$$W_{RB} = \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{N_A + N_D}{N_A N_D}\right](V_{bi} + |V_R|)}$$

(Equation 1.22)

Injected Minority Carriers and Current Distributions

(a) Forward bias

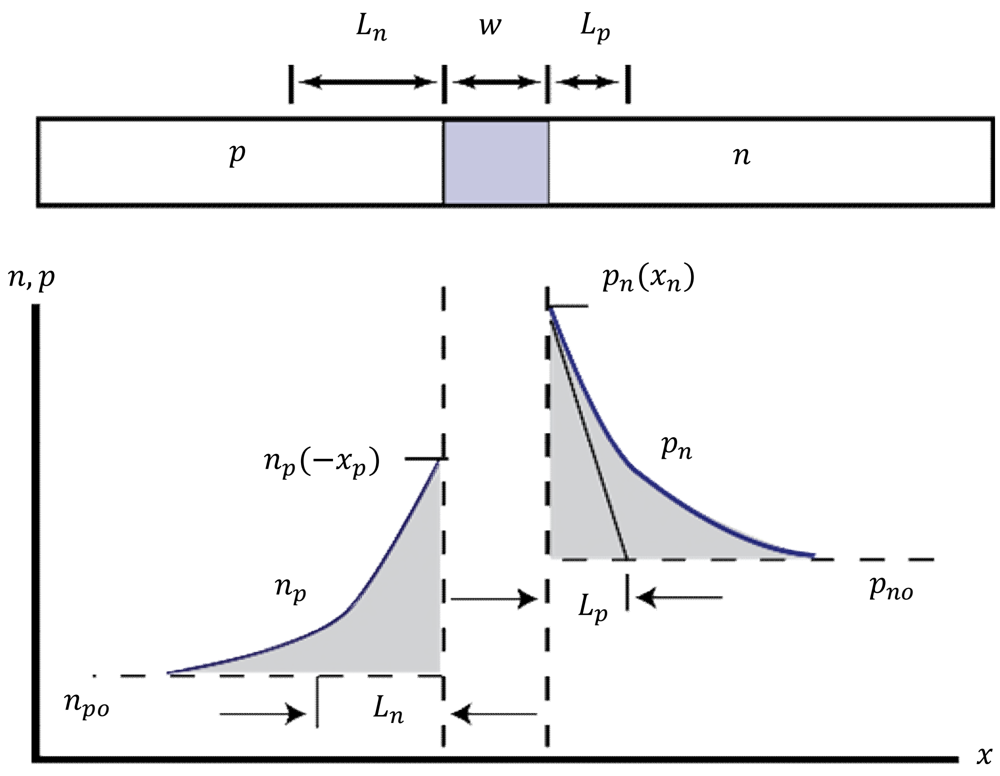


Figure 1.14

Minority carriers concentration at depletion edges:

$p_n(x=x_n) = P_{no}e^{qV_F/kT}$ *(Equation 1.23a)*

$n_p(x=-x_p) = n_{po}e^{qV_F/kT}$ *(Equation 1.23b)*

Diffusion currents:

$J_p(x) = -qD_p\, dp(x)/dx$ *(Equation 1.24a)*

$J_n(x) = -qD_n\, dn(x)/dx$ *(Equation 1.24b)*

Hole and electron diffusion current densities at depletion edges:

$I_p(x) = \left(\frac{qD_p p_{no}}{L_p}\right)\left[e^{qV_F/kT} - 1\right]$ *(Equation 1.25a)*

$I_n(x) = \left(\frac{qD_n n_{po}}{L_n}\right)\left[e^{qV_F/kT} - 1\right]$ *(Equation 1.25b)*

Injected Minority Carriers and Current Distributions

(a) Forward bias

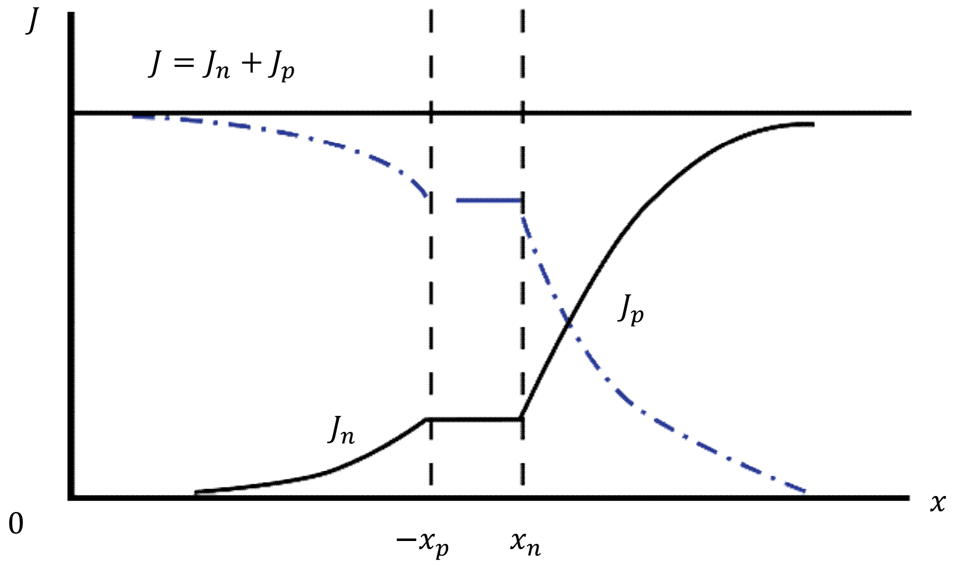


Figure 1.15

Total current density:

$$J = J_n(-\boldsymbol{x_p}) + J_p(\boldsymbol{x_n}) = \left(\frac{qD_p p_{no}}{L_p} + \frac{qD_p n_{po}}{L_n}\right)\left[e^{qV_F/kT} - 1\right]$$ *(Equation 1.26)*

Under Forward bias:

$$J_F \sim \left(\frac{qD_p p_{no}}{L_p} + \frac{qD_p n_{po}}{L_n}\right)\left[e^{qV_F/kT}\right] \text{ since } e^{qV_F/kT} >> 1$$ *(Equation 1.27)*

(b) Reverse bias

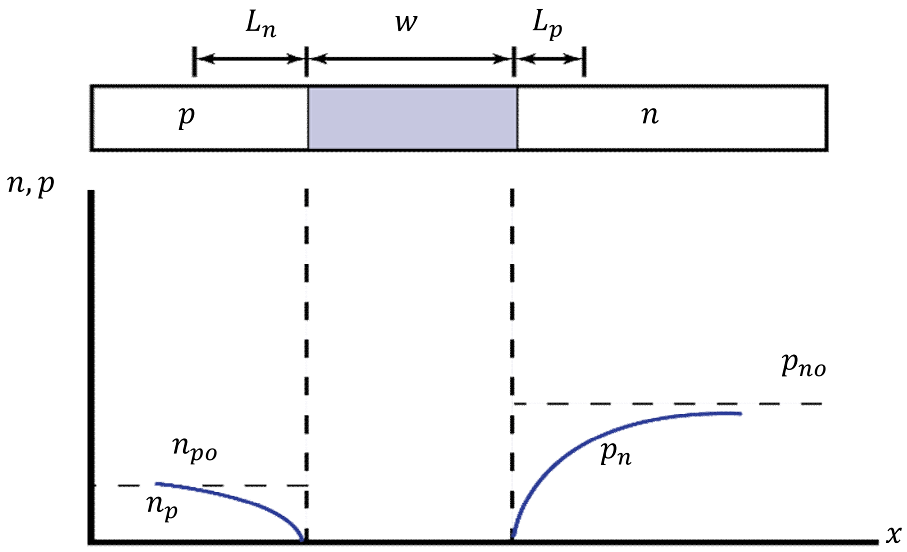


Figure 1.16

Minority carriers concentration at depletion edges:

$p_n(x=x_n) = P_{no}e^{-qV_{|R|}/kT} \ll p_{no}$ *(Equation 1.28a)*

$n_p(x=-x_p) = n_{po}e^{-qV_{|R|}/kT} \ll n_{po}$ *(Equation 1.28b)*

Diffusion currents:

$J_p(x) = -qD_p\, dp(x)/dx$ *(Equation 1.29a)*

$J_n(x) = -qD_n\, dn(x)/dx$ *(Equation 1.29b)*

Hole and electron diffusion current densities at depletion edges:

$I_p(x) = \left(\frac{qD_p p_{no}}{L_p}\right)\left[e^{-qV_{|R|}/kT} - 1\right] \sim 0$ *(Equation 1.30a)*

$I_n(x) = \left(\frac{qD_n n_{po}}{L_n}\right)\left[e^{-qV_{|R|}/kT} - 1\right] \sim 0$ *(Equation 1.30b)*

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(b) Reverse bias

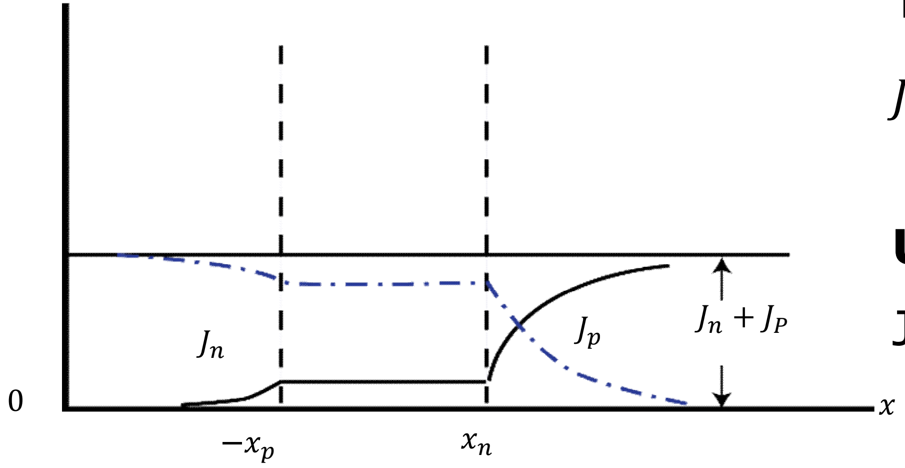


Figure 1.17

Total current density:

$$J = J_n(-\boldsymbol{x_p}) + J_p(\boldsymbol{x_n}) = \left(\frac{qD_p p_{no}}{L_p} + \frac{qD_p n_{po}}{L_n}\right)\left[e^{-qV|R|/kT} - 1\right] \sim 0 \quad \textit{(Equation 1.31)}$$

Under Reverse bias:

$$J_R \sim -\left(\frac{qD_p p_{no}}{L_p} + \frac{qD_p n_{po}}{L_n}\right) = J_{sat} \sim 0 \;\text{ since } e^{-qV_{|R|}/kT} << 1 \quad \textit{(Equation 1.32)}$$

Depletion Capacitance

- For one-sided abrupt junction, the depletion capacitance per unit area:

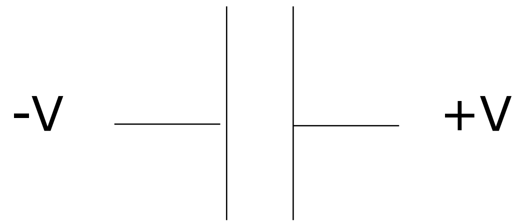
$$C_j = \frac{\varepsilon_s}{W} = \sqrt{\frac{q\varepsilon_s N_B}{2(V_{bi} - V)}} \quad \textit{(Equation 1.33)}$$

ε_s is the dielectric constant of the semiconductor material and W is the total depletion width.

- Or

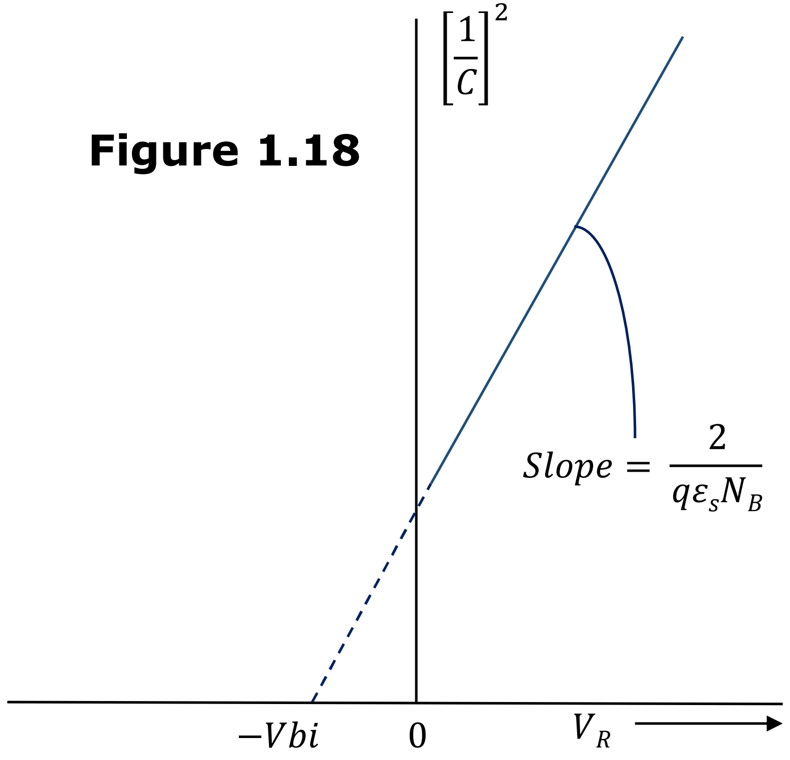
$$\frac{1}{{C_j}^2} = \frac{2(V_{bi} - V)}{q\varepsilon_s N_B} \quad \textit{(Equation 1.34)}$$

- A plot of $1/Cj^2$ versus *V* produces a straight line for a one-sided abrupt junction.
- The slope links to the impurity concentration N_B and the intercept at $(1/Cj^2 = 0)$ gives V_{bi}.



C=ε/d (capacitance per unit area)

Figure 1.18



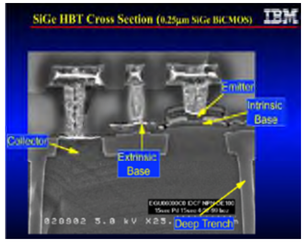
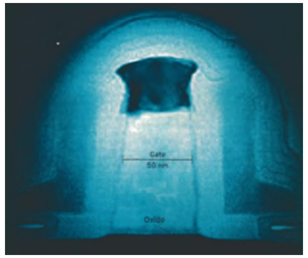
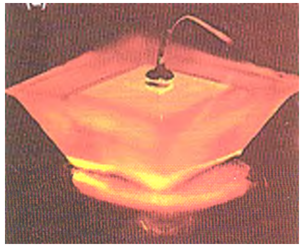
Lesson Summary

- It is important to understand the operation principles of PN junction as it is the basic building block for many other semiconductor devices.
- The key parameters of a PN junction are: built-in voltage (V_{bi}), depletion width (W), space charge densities ($N_A x_p = N_D x_n$), electric field(ξ) and depletion capacitance (C_j).
- Under Forward Bias ➔ $V=V_{bi}-V_F$ W decreases, $N_A x_p$ and $N_p x_n$ decreases, ξ decreases and C_j increases.
- Under Reverse Bias ➔ $V=V_{bi}+|V_R|$, W increases, $N_A x_p$ and $N_p x_n$ increases, ξ increases and C_j decreases.

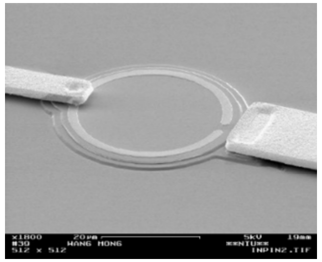
Lesson Summary

- Under forward bias, minority carriers injection gives rise to diffusion currents I_p and I_n. The total current $I_T = I_p + I_n$ increases.
- Under reverse bias, minority carriers get depleted and the total current (or reverse saturation current) is very small.
- The capacitance versus voltage characteristics can be used to determine the built-in voltage (V_{bi}) and impurity concentration (N_B) in the semiconductor.

References

No.	Slide No.	Image	Reference
1.	6		*D. (n.d.). Status and Trends of SiGe BiCMOS Technology. Retrieved March 8, 2017, from http://asia.stanford.edu/events/spring01/slides/harameSlides.pdf*
2.	6		*90nm_transistor. (n.d.). Retrieved March 08, 2017, from http://www.ixbt.com/*
3.	6		*Optoelectronic Devices-Types, Applications, Threshold Frequency Define. (2014, July 09). Retrieved March 08, 2017, from http://www.circuitstoday.com/optoelectronic-devices*

References

No.	Slide No.	Image	Reference
4.	6		*Silicon-Germanium multi-quantum . (n.d.). Retrieved March 08, 2017, from http://imagebank.osa.org/*