UESTC 3002/HN3008: Electronic Devices

Lecture 2.3: *p-n Junction (3)*

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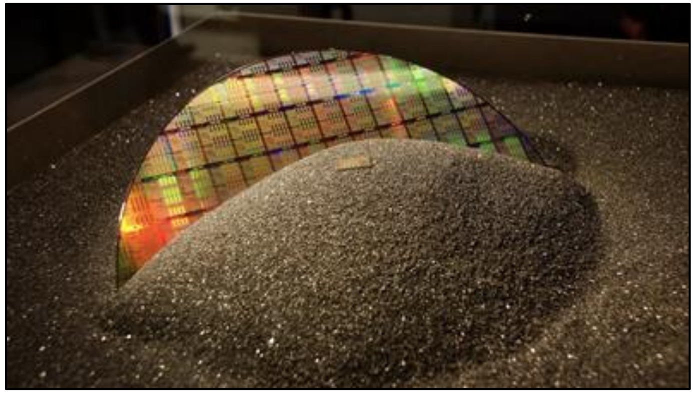
WORLD CHANGING GLASGOW

Reading: Chapter 5, Solid State Electronic Devices 7E, Ben G. Streetman, Sanjay K. Banerjee

In today's lesson

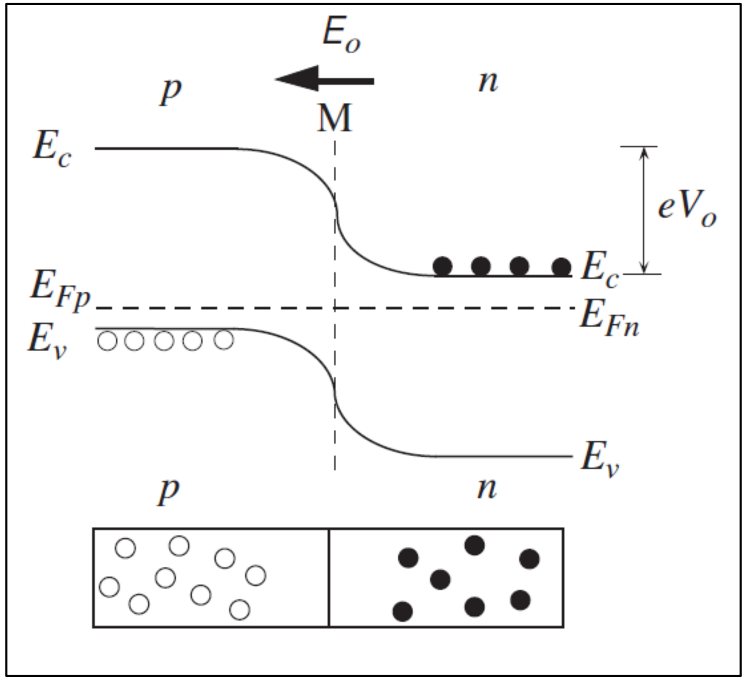
- Band Diagram of p-n junction
- Reverse Breakdown
- Calculating Junction Current in p-n Junctions
- Class Exercises



Source: newport.com

p-n Junction Band Diagram

- As a result of diffusion, the energy bands bend at the junction.
- The conduction band (CB) and valence band (VB) of the n-type and p-type materials are at different energy levels.
- The bending creates a potential barrier that must be overcome for the current to flow.
- The position of the Fermi level must be the same in both p and n sides.



p-n junction band diagram

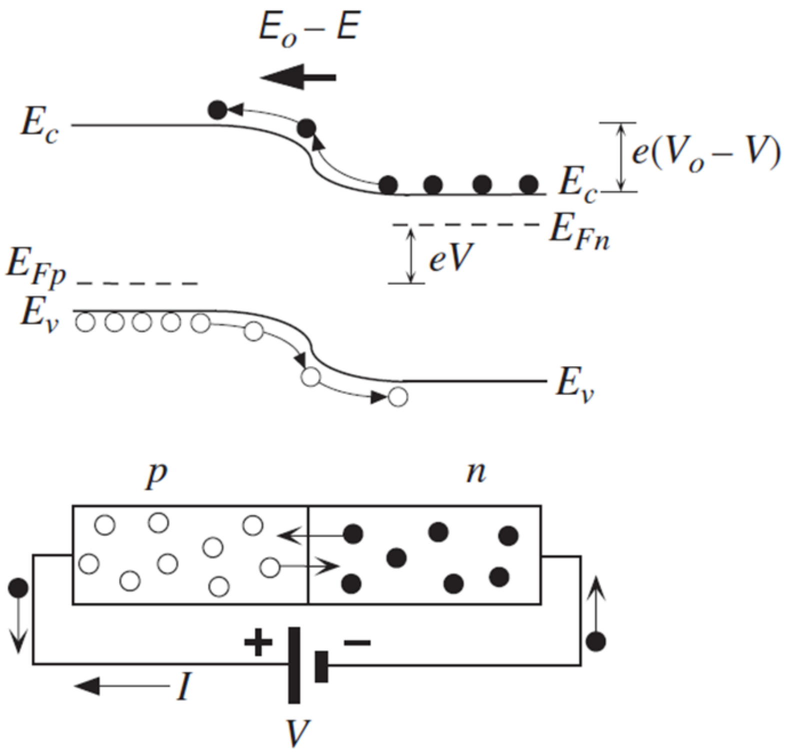
Source: Principles of Electronic Materials & DevicesS. O. Kasap

p-n Junction Band Diagram: Forward Bias

- The applied voltage is in opposition to the built-in potential and lowers the potential barrier at the junction.

- The depletion region narrows as more charge carriers (holes from the p-side and electrons from the n-side) are injected into the junction.

- Electrons from the n-type region are pushed toward the p-type region, and vice-versa, increasing recombination and current flow.



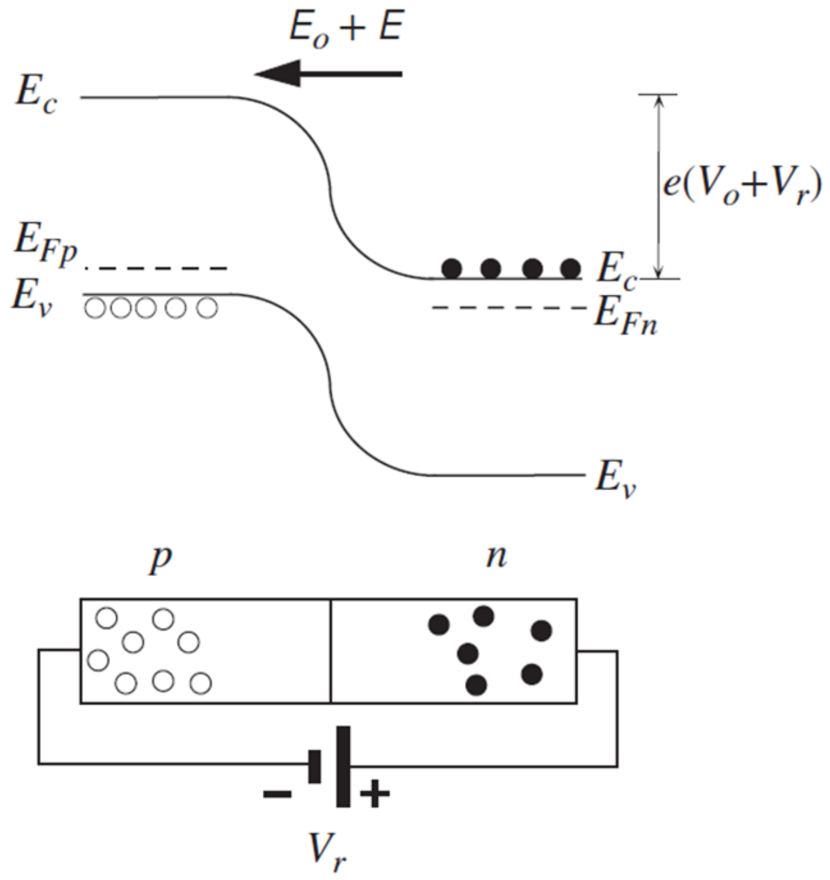
Source: Principles of Electronic Materials & DevicesS. O. Kasap

p-n Junction Band Diagram: Reverse Bias

The applied voltage increases the potential barrier at the junction.

The depletion region expands as more charge carriers are pulled away from the junction, increasing the width of the region devoid of carriers.

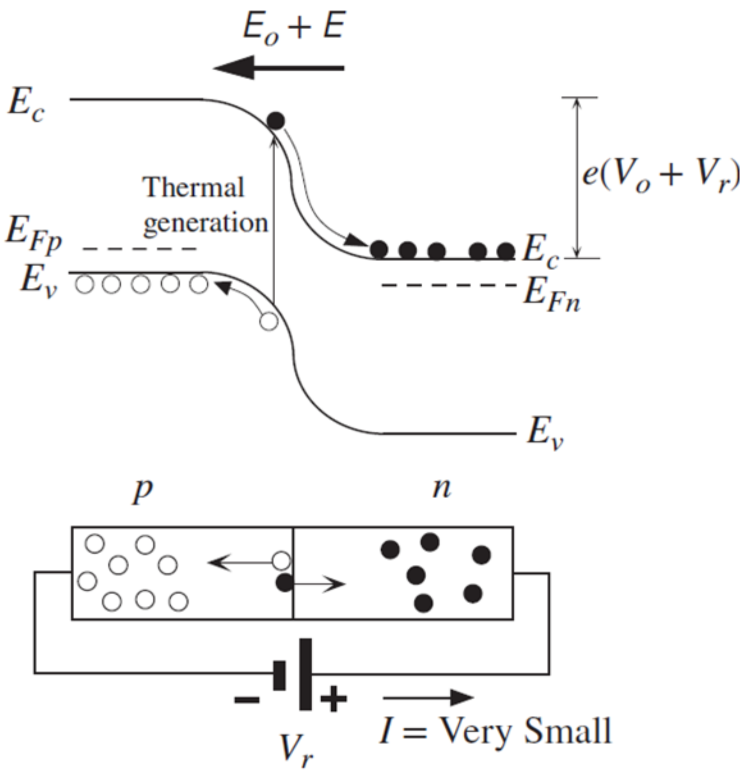
Only minority carriers (electrons in p-type and holes in n-type) contribute to the small reverse saturation current, which remains nearly constant regardless of the applied reverse voltage.



Source: Principles of Electronic Materials & DevicesS. O. Kasap

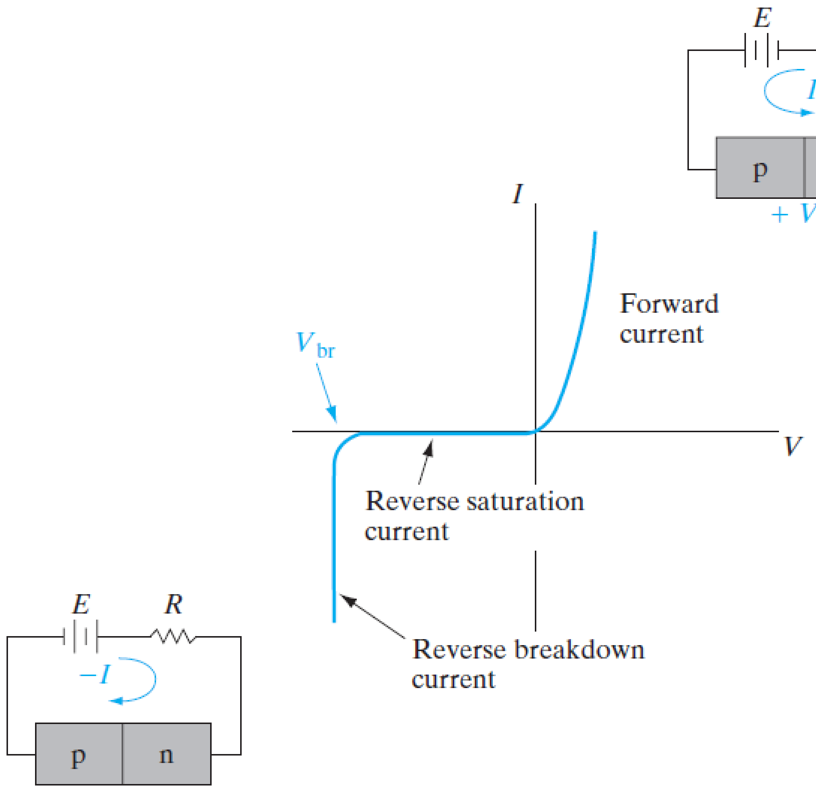
p-n Junction Band Diagram: Thermal generation

- Thermal generation is the process where electron-hole pairs are generated due to thermal energy.
- At any T above absolute zero, some electrons in the VB gain enough energy to jump into the CB. This process generates electron-hole pairs.
- In the band diagram, thermal generation can be visualized as electrons being excited from the VB to the CB, leaving behind holes in the VB.



Reverse Breakdown

The p-n junction breaks down either by the Avalanche or Zener breakdown mechanisms, which lead to large reverse currents.

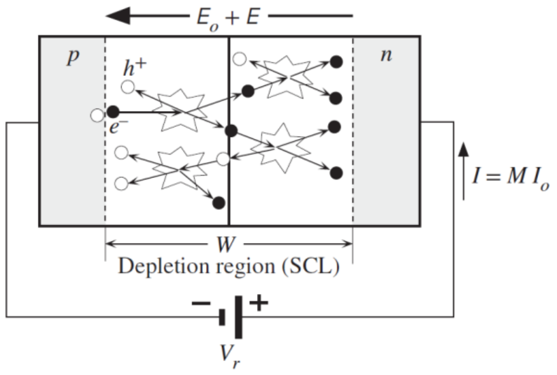


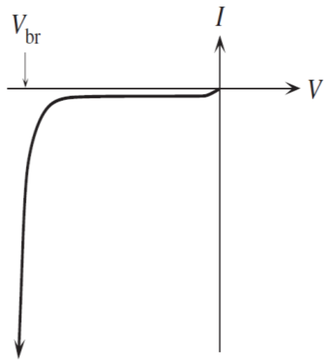
Avalanche breakdown

The field in the Depletion region can become so large (an increase of reverse bias) that an electron drifting in this region can gain sufficient KE to impact a Si atom and ionize it, or rupture a Si–Si bond.

The phenomenon by which a drifting electron gains sufficient energy from the field to ionize a host crystal atom by bombardment is termed impact ionization.

The EHPs generated by impact ionization themselves can now be accelerated by the field and will themselves give rise to further EHPs by ionizing collisions and so on, leading to an avalanche effect.





Source: Principles of Electronic Materials & DevicesS. O. Kasap

Zener Breakdown

Heavily doped p-n junctions, (narrow W, large E)

For a sufficient reverse bias (typically <10 V), E_c on the n-side may be lowered to be below E_v on the p-side.

This means that electrons at the top of the VB in the p-side are now at the same energy level as the empty states in the CB in the n-side.

As the separation between the VB and CB narrows, electrons easily tunnel from the VB in the p-side to the CB in the n-side, which leads to a current (Zener effect).

The Zener effect is crucial for the operation of Zener diodes, enabling precise voltage regulation in various electronic applications.

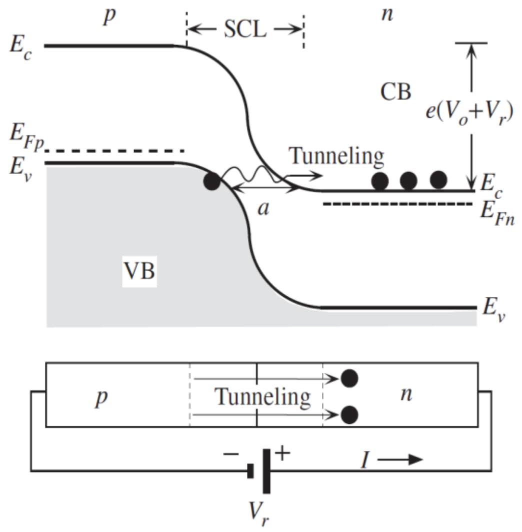


Figure 6.22 Zener breakdown involves electrons tunneling from the VB of *p*-side to the CB of *n*-side when the reverse bias reduces E_c to line up with E_v.

Source: Principles of Electronic Materials & DevicesS. O. Kasap

Class Task: Calculating Junction Current in p-n Junctions

Group of 3-4 students

Objective: To understand and apply two methods for calculating junction current based on excess minority carrier distributions in p-n junctions. Each group will focus on one of the following methods for calculating junction current:

Research and Analysis: (10 minutes)

Method 1: Diffusion Currents at the Edges of the Transition

Research how minority carriers diffuse across the transition region and how to calculate the diffusion current at the edges.

Method 2: Charge in the Distributions Divided by Minority Carrier Lifetimes

Investigate how the excess minority carrier concentration and their lifetimes contribute to the junction current.

Calculation and Example: (10 – 15 mins)

- Each group should explore the relevant equations used and work through them to achieve the diode equation. Explore diffusion length as well.
- Solve class exercise to illustrate how their method can be applied to find the junction current in a specific scenario.

Class Exercise - 1

An abrupt Si p-n junction ($A = 10^{-4}\ \text{cm}^2$) has the following properties at 300 K:

p side	*n side*
$N_a = 10^{17}\ \text{cm}^{-3}$	$N_d = 10^{15}$
$\tau_n = 0.1\ \mu\text{s}$	$\tau_p = 10\ \mu\text{s}$
$\mu_p = 200\ \text{cm}^2/\text{V}-\text{s}$	$\mu_n = 1300$
$\mu_n = 700$	$\mu_p = 450$

The junction is forward biased by 0.5 V. What is the forward current? What is the current at a reverse bias of –0.5 V?

Solution: Class Exercise - 1

$$I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)(e^{qV/kT} - 1) = I_0(e^{qV/kT} - 1)$$

$$p_n = \frac{n_i^2}{n_n} = \frac{(1.5 \times 10^{10})^2}{10^{15}} = 2.25 \times 10^5 \text{ cm}^{-3}$$

$$n_p = \frac{n_i^2}{p_p} = \frac{(1.5 \times 10^{10})^2}{10^{17}} = 2.25 \times 10^3 \text{ cm}^{-3}$$

For minority carriers,

$$D_p = \frac{kT}{q}\mu_p = 0.0259 \times 450 = 11.66 \text{ cm}^2/\text{s on the n side}$$

$$D_n = \frac{kT}{q}\mu_n = 0.0259 \times 700 = 18.13 \text{ cm}^2/\text{s on the p side}$$

$$L_p = \sqrt{D_p\tau_p} = \sqrt{11.66 \times 10 \times 10^{-6}} = 1.08 \times 10^{-2} \text{ cm}$$

$$L_n = \sqrt{D_n\tau_n} = \sqrt{18.13 \times 0.1 \times 10^{-6}} = 1.35 \times 10^{-3} \text{ cm}$$

$$I_0 = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)$$

$$= 1.6 \times 10^{-19} \times 0.0001\left(\frac{11.66}{0.0108}2.25 \times 10^5 + \frac{18.13}{0.00135}2.25 \times 10^3\right)$$

$$= 4.370 \times 10^{-15}\text{A}$$

$$I = I_0(e^{0.5/0.0259} - 1) \approx \mathbf{1.058} \times \mathbf{10^{-6}}\text{A in forward bias.}$$

$$I = -I_0 = -\mathbf{4.37} \times \mathbf{10^{-15}}\text{A in reverse bias.}$$

Class Exercise - 2

An abrupt Si p-n junction has $N_a = 10^{18}\,\text{cm}^{-3}$ on one side and $N_d = 5 \times 10^{15}\,\text{cm}^{-3}$ on the other.

(a) Calculate the Fermi level positions at 300 K in the p and n regions.

(b) Draw an equilibrium band diagram for the junction and determine the contact potential V_0 from the diagram.

(c) Compare the results of part (b) with V_0 as calculated from Eq.

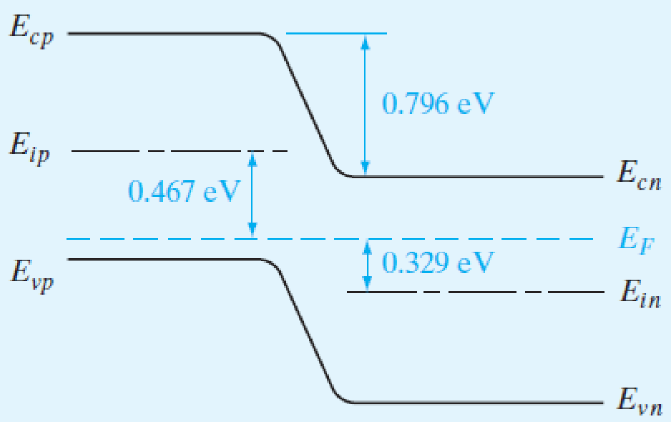
Class Exercise – 2: Solution

(a) $E_{ip} - E_F = kT \ln \frac{p_p}{n_i} = 0.0259 \ln \frac{10^{18}}{(1.5 \times 10^{10})} = \mathbf{0.467\ eV}$

$E_F - E_{in} = kT \ln \frac{n_n}{n_i} = 0.0259 \ln \frac{5 \times 10^{15}}{(1.5 \times 10^{10})} = \mathbf{0.329\ eV}$

(b) $qV_0 = 0.467 + 0.329 = \mathbf{0.796\ eV}$

(c) $qV_0 = kT \ln \frac{N_a N_d}{n_i^2} = 0.0259 \ln \frac{5 \times 10^{33}}{2.25 \times 10^{20}} = \mathbf{0.796\ eV}$



Class Exercise - 3

A Si sample is doped with 10^{17} As atoms/cm^3. What is the equilibrium hole concentration p_0 at 300 K? Where is E_F relative to E_i?

Class Exercise – 3: Solution

A Si sample is doped with 10^{17} As atoms/cm^3. What is the equilibrium hole concentration p_0 at 300 K? Where is E_F relative to E_i?

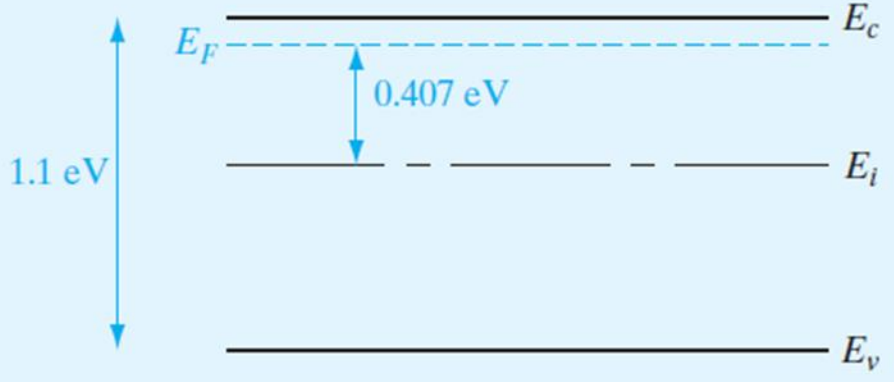
Since $N_d \gg n_i$, we can approximate $n_0 = N_d$ and

$$p_0 = \frac{n_i^2}{n_0} = \frac{2.25 \times 10^{20}}{10^{17}} = 2.25 \times 10^3 \text{ cm}^{-3}$$

From Eq. (3–25a), we have

$$E_F - E_i = kT \ln \frac{n_0}{n_i} = 0.0259 \ln \frac{10^{17}}{1.5 \times 10^{10}} = 0.407 \text{ eV}$$

The resulting band diagram is:



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Thank you

谢谢

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