# Semiconductor Physics and Devices

*Basic Principles*

**Third Edition**

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THIRD EDITION

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Objective

EXAMPLE 7.2

To calculate the space charge width and electric field in a pn junction.

Consider a silicon pn junction at T = 300 K with doping concentrations of $N_a = 10^{16}$ cm$^{-3}$ and $N_d = 10^{15}$ cm$^{-3}$.

■ Solution

In Example 7.1, we determined the built-in potential barrier as $V_{bi} = 0.635$ V. From Equation (7.31), the space charge width is

$$W = \left\{\frac{2\epsilon_s V_{bi}}{e}\left[\frac{N_a + N_d}{N_a N_d}\right]\right\}^{1/2}$$

$$= \left\{\frac{2(11.7)(8.85 \times 10^{-14})(0.635)}{1.6 \times 10^{-19}}\left[\frac{10^{16} + 10^{15}}{(10^{16})(10^{15})}\right]\right\}^{1/2}$$

$$= 0.951 \times 10^{-4} \text{ cm} = 0.951\ \mu\text{m}$$

Using Equations (7.28) and (7.29), we can find $x_n = 0.864\ \mu$m, and $x_p = 0.086\ \mu$m.

The peak electric field at the metallurgical junction, using Equation (7.16) for example, is

$$E_{max} = \frac{-eN_d x_n}{\epsilon_s} = \frac{-(1.6 \times 10^{-19})(10^{15})(0.864 \times 10^{-4})}{(11.7)(8.85 \times 10^{-14})} = -1.34 \times 10^4 \text{ V/cm}$$

■ Comment

The peak electric field in the space charge region of a pn junction is quite large. We must keep in mind, however, that there is no mobile charge in this region; hence there will be no drift current. We may also note, from this example, that the width of each space charge region is a reciprocal function of the doping concentration: The depletion region will extend further into the lower-doped region.

TEST YOUR UNDERSTANDING

E7.3 A silicon pn junction at T = 300 K with zero applied bias has doping concentrations of $N_d = 5 \times 10^{16}$ cm$^{-3}$ and $N_a = 5 \times 10^{15}$ cm$^{-3}$. Determine $x_n$, $x_p$, W, and $|E_{max}|$.

(Ans. $x_n = 4.11 \times 10^{-6}$ cm, $x_p = 4.52 \times 10^{-5}$ cm, $W = 4.11 \times 10^{-5}$ cm, $|E_{max}| = 3.18 \times 10^4$ V/cm)

E7.4 Repeat E7.3 for a GaAs pn junction.

(Ans. $x_n = 5.60 \times 10^{-6}$ cm, $x_p = 5.60 \times 10^{-5}$ cm, $W = 6.16 \times 10^{-5}$ cm, $|E_{max}| = 3.98 \times 10^4$ V/cm)

## 7.3 | REVERSE APPLIED BIAS

If we apply a potential between the p and n regions, we will no longer be in an equilibrium condition — the Fermi energy level will no longer be constant through the system. Figure 7.7 shows the energy-band diagram of the pn junction for the case

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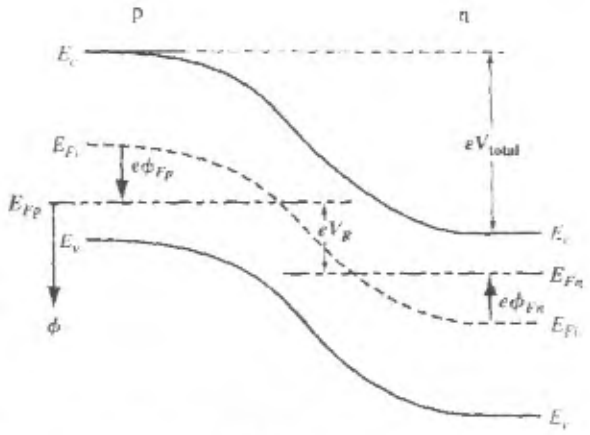


**Figure** 7.7 ! Energy-band diagram of a pn junction under reverse bias.

when a positive voltage is applied to the n region with respect to the p region. As the positive potential is downward, the Fermi level on then side is below the Fermi level on the p side. The difference between the two is equal to the applied voltage in units of energy.

The total potential barrier, indicated by $V_{total}$, has increased. The applied potential is the reverse-bias condition. The total potential harrier is now given by

$$V_{total} = |\phi_{Fn}| + |\phi_{Fp}| + V_R \tag{7.32}$$

where $V_R$ is the magnitude of the applied reverse-bias voltage. Equation (7.32) can he rewritten as

$$V_{total} = V_{bi} + V_R \tag{7.33}$$

where $V_{bi}$ is the same built-in potential bamer we had defined in thermal equilibrium.

### 7.3.1 Space Charge Width and Electric Field

Figure 7.8 shows a pn junction with an applied reverse-bias voltage $V_R$. Also indicated in the figure are the electric field in the space charge region and the electric field $E_{app}$, induced by the applied voltage. The electric fields in the neutral p and n regions are essentially zero, or at least very small, which means that the magnitude of the electric field in the space charge region must increase above the thermal-equilibrium value due to the applied voltage. The electric field originates on positive charge and terminates on negative charge; this means that the number of positive and negative charges must increase if the electric field increases. For given impurity dopingconcentrations, the number of positive and negative charges in the depletion region can be increased only if the space charge width W increases. The space charge width W increases,

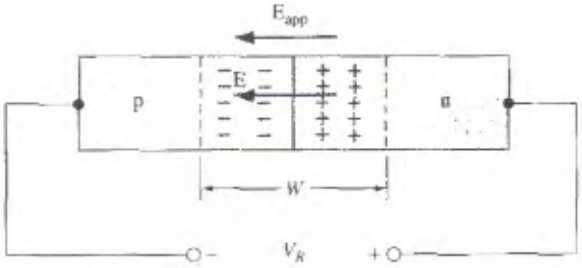


**Figure 7.8** | A pn junction, with an applied reverse-bias voltage, showing the directions of the electric field induced by $V_R$ and the space charge electric field.

therefore, with an increasing reverse-bias voltage $V_R$. We are assuming that the electric field in the bulk n and p regions is zero. This assumption will become clearer in the next chapter when we discuss the current-voltage characteristics.

In all of the previous equations, the built-in potential barrier can be replaced by the total potential barrier. The total space charge width can be written from Equation (7.31) as

$$W = \left\{\frac{2\epsilon_s(V_{bi} + V_R)}{e}\left[\frac{N_a + N_d}{N_a N_d}\right]\right\}^{1/2} \tag{7.34}$$

showing that the total space charge width increases as we apply a reverse-bias voltage. By substituting the total potential barrier $V_{total}$ into Equations (7.28) and (7.29), the space charge widths in the n and p regions, respectively, can be found as a function of applied reverse-bias voltage.

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**Objective** | **EXAMPLE 7.3**

To calculate the width of the space charge region in a pn junction when a reverse-bias voltage is applied.

Again consider a silicon pn junction at $T = 300$ K with doping concentrations of $N_a = 10^{16}$ cm$^{-3}$ and $N_d = 10^{15}$ cm$^{-3}$. Assume that $n_i = 1.5 \times 10^{10}$ cm$^{-3}$ and let $V_R = 5$ V.

**■ Solution**

The built-in potential barrier was calculated in Example 7.1 for this case and is $V_{bi} = 0.635$ V. The space charge width is determined from Equation (7.34). We have

$$W = \left\{\frac{2(11.7)(8.85 \times 10^{-14})(0.635 + 5)}{1.6 \times 10^{-19}}\left[\frac{10^{16} + 10^{15}}{(10^{16})(10^{15})}\right]\right\}^{1/2}$$

so that

$$W = 2.83 \times 10^{-4} \text{ cm} = 2.83\ \mu\text{m}$$

■ **Comment**

The space charge width has increased from 0.951 $\mu$m at zero bias to 2.83 $\mu$m at a reverse bias of 5 V.

The magnitude of the electric field in the depletion region increases with an applied reverse-bias voltage. The electric field is still given by Equations (7.14) and (7.16) and is still a linear function of distance through the space charge region. Since $x_n$ and $x_p$ increase with reverse-bias voltage, the magnitude of the electric field also increases. The maximum electric field still occurs at the metallurgical junction.

The maximum electric field at the metallurgical junction, from Equations (7.14) and (7.16), is

$$E_{max} = \frac{-eN_d x_n}{\epsilon_s} = \frac{-eN_a x_p}{\epsilon_s} \tag{7.35}$$

If we use either Equation (7.28) or (7.29) in conjunction with the total potential barrier, $V_{bi} + V_R$, then

$$\boxed{E_{max} = -\left\{\frac{2e(V_{bi} + V_R)}{\epsilon_s}\left(\frac{N_a N_d}{N_a + N_d}\right)\right\}^{1/2}} \tag{7.36}$$

We can show that the maximum electric field in the pn junction can also be written as

$$\boxed{E_{max} = \frac{-2(V_{bi} + V_R)}{W}} \tag{7.37}$$

where W is the total space charge width

DESIGN EXAMPLE 7.4

Objective

To design a pn junction to meet maximum electric field and voltage specifications.

Consider a silicon pn junction at T = 300 K with a p-type doping concentration of $N_a = 10^{18}$ cm$^{-3}$. Determine the n-type doping concentration such that the maximum electric field is $|E_{max}| = 3 \times 10^5$ V/cm at a reverse-bias voltage of $V_R = 25$ V.

■ **Solution**

The maximum electric field is given by Equation (7.36). Neglecting $V_{bi}$ compared to $V_R$, we can write

$$|E_{max}| \approx \left\{\frac{2eV_R}{\epsilon_s}\left(\frac{N_a N_d}{N_a + N_d}\right)\right\}^{1/2}$$

or

$$3 \times 10^5 = \left\{\frac{2(1.6 \times 10^{-19})(25)}{(11.7)(8.85 \times 10^{-14})}\left(\frac{10^{18} \cdot N_d}{10^{18} + N_d}\right)\right\}^{1/2}$$

From Equation (7.64), the parameter m required is found from

$$\frac{1}{m+2} = 2 \tag{7.66a}$$

or

$$m = -\frac{3}{2} \tag{7.66b}$$

A specific doping profile will yield the desired capacitance characteristic.

## 7.5 | SUMMARY

- A uniformly doped pn junction was initially considered, in which one region of a semiconductor is uniformly duped with acceptor impurities and the adjacent region is uniformly doped with donor impurities. This type of junction is called a homojunction.
- A space charge region, or depletion region, is formed on either side of the metallurgical junction separating the n and p regions. This region is essentially depleted of any mobile electrons or holes. A net positive charge density, due to the positively charged donor impurity ions, exists in the n region and a net negative charge density, due to the negatively charged acceptor impurity ions, exists in the p region.
- An electric field exists in the depletion region due to the net space charge density. The direction of the electric field is from the n region to the p region.
- A potential difference exists across the space-charge region. Under zero applied bias, this potential difference, known as the built-in potential barrier, maintains thermal equilibrium and holds back majority carrier electrons in the n-region and majority carrier holes in the p region.
- An applied reverse bias voltage (n region positive with respect to the p region) increases the potential barrier, increases the space charge width, and increases the magnitude of the electric field.
- As the reverse bias voltage changes, the amount of charge in the depletion region changes. This change in charge with voltage defines the junction capacitance.
- The linearly graded junction represents a nonuniformly doped pn junction. Expressions for the electric field, built-in potential barrier, and junction capacitance were derived. The functional relationships differ from those of the uniformly doped junction.
- Specific doping profiles can be used to obtain specific capacitance characteristics. A hyperabrupt junction is one in which the doping decreases away from the metallurgical junction. This type of junction is advantageous in varactor diodes that are used in resonant circuits.

## GLOSSARY OF IMPORTANT TERMS

**abrupt junction** approximation The assumption that there is an abrupt discontinuity in space charge density between the space charge region and neutral semiconductor region.

built-in potential barrier The electrostatic potential difference between the p and n regions of a pn junction in thermal equilibrium.

depletion layer capacitance Another term for junction capacitance.

depletion region Another term for space charge region.

hyperabrupt junction A pn junction in which the doping concentration on one side decreases away from the metallurgical junction to achieve a specific capacitance-voltage characteristic.

junction capacitance The capacitance of the pn junction under reverse bias.

linearly graded junction A pn junction in which the doping concentrations on either side of the metallurgical junction are approximated by a linear distribution.

metallurgical junction The interface between the p- and n-doped regions of a pn junction.

one-sided junction A pn junction in which one side of the junction is much more heavily doped than the adjacent side.

reverse bias The condition in which a positive voltage is applied to the n region with respect to the p region of a pn junction so that the potential barrier between the two regions increases above the thermal-equilibrium built-in potential barrier.

space charge region The region on either side of the metallurgical junction in which there is a net charge density due to ionized donors in the n-region and ionized acceptors in the p region.

space charge width The width of the space charge region, a function of doping concentrations and applied voltage.

varactor diode A diode whose reactance can be varied in a controlled manner with bias voltage.

## CHECKPOINT

After studying this chapter, the reader should have the ability to:

- Describe why and how the space charge region is formed.
- Draw the energy band diagram of a zero-biased and reverse-biased pn junction.
- Define and derive the expression of the built-in potential barrier voltage.
- Derive the expression for the electric field in space charge region of the pn junction.
- Describe what happens to the parameters of the space charge region when a reverse bias voltage is applied.
- Define and explain the junction capacitance.
- Describe the characteristics and properties of a one-sided pn junction.
- Describe how a linearly graded junction is formed.
- Define a hyperabrupt junction.

## REVIEW QUESTIONS

1. Define the built-in potential voltage and describe how it maintains thermal equilibrium.
2. Why is an electric field formed in the space charge region? Why is the electric field a linear function of distance in a uniformly doped pn junction?
3. Where does the maximum electric field occur in the space charge region?
4. Why is the space charge width larger in the lower doped side of a pn junction?
5. What is the functional dependence of the space charge width on reverse bias voltage?
6. Why does the space charge width increase with reverse bias voltage?
7. Why does a capacitance exist in a reverse-biased pn junction? Why does the capacitance decrease with increasing reverse bias voltage?

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