

# *Supplementary Reader III*

***EECS 40***

***Introduction to  
Microelectronic Circuits***

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## Chapter 3. Semiconductor Physics

### 3.1 Introduction to Silicon

Almost all semiconductors used in integrated circuit (IC) technology are single crystalline Silicon (Si) material. Si is element 14, in Group IV, with an electronic configuration of  $1s^2 2s^2 2p^6 3s^2 3p^2$ . From this electronic configuration, we can see that Si has 4 valence electrons in the  $n = 3$  energy level. A silicon crystal is tetrahedrally arranged in a diamond cubic unit cell, in which the valence orbital are  $sp^3$  hybridized.

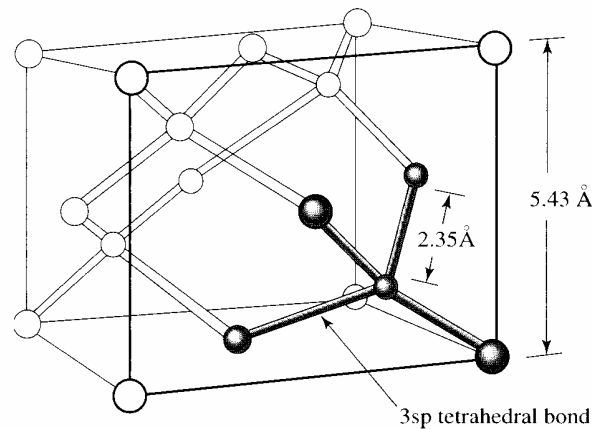


Fig. 1. Unit cell of crystalline silicon.

The atomic density of crystalline silicon can be calculated from its unit cell, shown in Fig. 1, by observing that there are 8 atoms in corners, each having  $1/8$  of the atom lie within the unit cell. There are 6 atoms on the faces of the cube, with  $1/2$  the atom inside the unit cell, and 4 more atoms completely inside the unit cell. Thus, the atomic density of silicon can be calculated, given the size of the unit cell, with length  $a_0$  on each side:

$$\frac{\# \text{ Atoms}}{\text{Volume}} = \frac{8 \times \frac{1}{8} + 6 \times \frac{1}{2} + 4}{a_0^3} = \frac{8}{(5.43 \times 10^{-8} \text{ cm})^3} = 5.00 \times 10^{22} \text{ cm}^{-3}$$

A common representation of the silicon crystal structure is given in Fig. 2. Each black line denotes a single bond, involving 2 electrons. Note that this does not represent a planar description of the crystalline structure of Si. Rather, this diagram demonstrates the bonding between each silicon atom and its 4 closest neighbors.

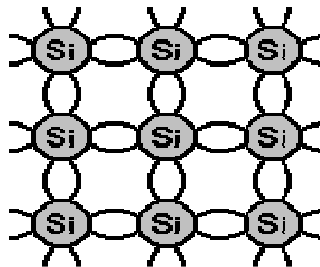


Fig. 2. Silicon bonding model.

#### 3.1.1 Bandgap Energy

Conduction occurs in a substance through the flow of electrons (negative charge) and holes, or the lack of an electron (positive charge). The arrangement of atoms bonded together produces for its electrons many

energy levels that are so close to each other that we may regard them as energy bands. Electrons are mobile in the high energy conduction band, while holes are mobile in the lower energy valence band. To form electron-hole pairs, electrons must have sufficient energy to overcome the bandgap energy, which is a region with no allowed energy levels. The excited electrons move from the valence band into the conduction band, leaving holes in the valence band. (See Fig. 3). Situations like this may occur when the crystal is illuminated with light or photons whose energy is larger than the bandgap energy, or when the crystal is sufficiently heated.

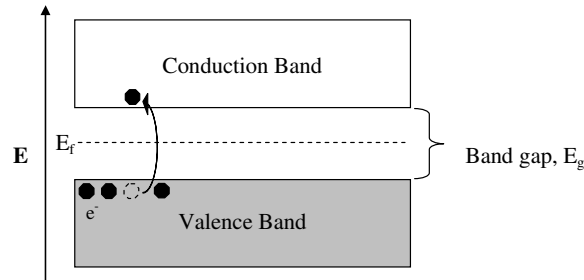


Fig. 3. Energy band diagram of semiconductors.

Insulators have a large band gap, usually 3.5 electron-volts (eV) or greater, preventing substantial amounts of charge carriers from flowing. Metals are good conductors, with electrons filling up into the conduction band. This means electrons are inherently mobile through a crystal, with thermal excitation producing even more electron-hole pairs. Semiconductors are in between, with band gaps ranging from 0.5 - 3.0 eV, allowing the easy excitation of electrons into the conduction band. However, it is the intermediate conductivity of semiconductors that is important for the electronics industry, along with their great flexibility in conductivity through doping.

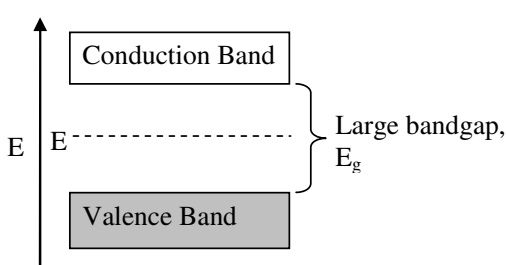


Fig. 4(a). Band diagram of an insulator.

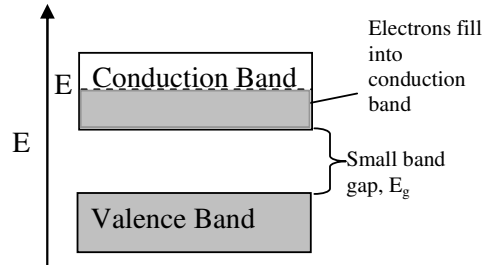


Fig. 4(b). Band diagram of a metal.

### 3.1.2 Fermi Energy

The Fermi-Dirac function provides the probability that an energy level is occupied by a fermion which is under thermal equilibrium. Electrons as well as holes are Fermions and hence obey Fermi-Dirac statistics. (A hole is simply “the lack” of an electron.) As electrons are added to an energy band, they will fill the available states in an energy band just like water fills a bucket. The states with the lowest energy are filled first, followed by the next higher ones. At the Fermi level, the probability of filling the state is exact 50%. The transition between completely filled states and completely empty states is gradual rather than abrupt, and the transition depends on temperature. The Fermi function which describes this behavior, which is given by:

$$f(E, T) = \frac{1}{1 + e^{(E - E_f)/kT}} \tag{1}$$

where  $k$  is the Boltzmann constant,  $E_f$  is the Fermi energy,  $E$  is the energy of concern and  $T$  is the temperature at which the material is kept.

Figs. 4(a) and (b) show the position of the Fermi level in an insulator and a metal, respectively. Fig. 5 shows the Fermi function plotted with the energy bands at different temperatures. The x-axis,  $f(E)$ , is the probability that an energy level is occupied. The lowest energy levels are almost always occupied, with a probability of 1, and the highest levels have a probability of nearly 0, but this probability increases with higher temperature. To be more precise, the sharp edge of Fermi function is smeared out due to the increase in temperature.

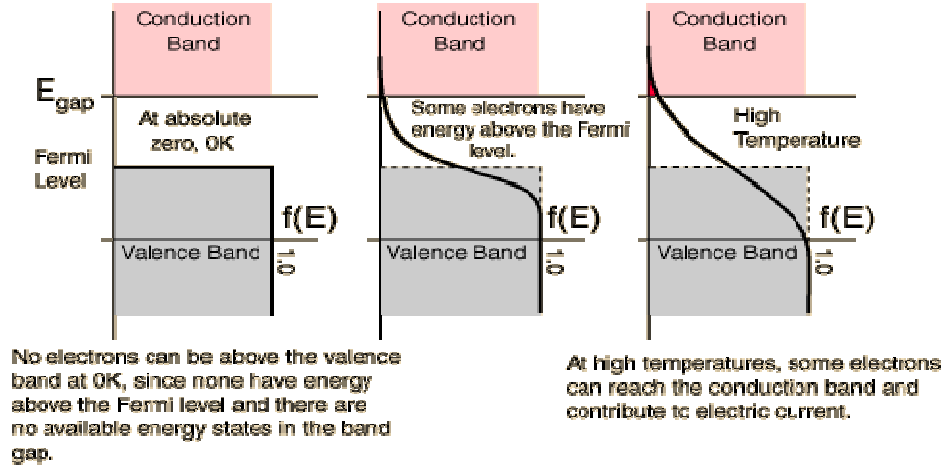


Fig. 5. Fermi function plots at absolute zero, mid-range, and high temperature.

For a given piece of semiconductor at a particular location (space coordinate) under thermal equilibrium, there is *only one Fermi level* for both the conduction and valence band, as it describes one equilibrium system.

For a semiconductor where  $E_v < E_f < E_c$ , we can derive the electron density,  $n$  and hole density,  $p$ , which are the density of states multiplied with Fermi probability function.

$$\begin{aligned}
 n &= N_c \frac{1}{1 + e^{(E_c - E_f)/kT}} \sim N_c e^{(E_f - E_c)/kT} \\
 p &= N_v \left[ 1 - \frac{1}{1 + e^{(E_v - E_f)/kT}} \right] \sim N_v e^{(E_v - E_f)/kT} \\
 np &= N_c e^{(E_f - E_c)/kT} N_v e^{(E_v - E_f)/kT} = N_c N_v e^{(E_v - E_c)/kT} = N_c N_v e^{-E_g/kT}
 \end{aligned}$$

Here,  $N_c$  and  $N_v$  are the effective density of states in the *conduction* and valence band, respectively, and  $E_g$  is the bandgap energy. All three are constants for Si at a given temperature. This property is referred to as the *mass action law*

For an intrinsic (undoped) Si, the electron density  $n_i$  equals to the hole density,  $p$ , which is thus:

$$\begin{aligned}
 n_i &= p_i \\
 n_i p_i &= n_i^2 \\
 n_i &= \sqrt{N_c N_v e^{-E_g/kT}}
 \end{aligned}$$

### 3.1.3 Doping

Doping a semiconductor refers to the careful addition of impurity atoms into the semiconductor. A doped semiconductor is considered extrinsic, and has enhanced conductivity due to additional charge carriers from the dopant atoms. The two categories of dopants are n-type, with excess electrons producing donor energy levels near the conduction band, and p-type, with holes (lack of electrons) producing acceptor energy levels just above the valence band. The two types of doped semiconductors are named for their majority charge carriers (the leading contributors to conduction in a material): n-type's majority charge carrier is electron (negative charge), while p-type's is hole (positive charge).

N-type dopants are typically group V elements, such as Phosphorus (P) and Arsenic (As), with five valence electrons. When a group V element is incorporated into Si and, in fact, replaces a Si atom in a lattice, it provides four of its outermost electrons to form covalent bonds with the surrounding Si atoms. However, there is an extra electron remaining, loosely orbiting the dopant atom, at a large radius, or high energy, as shown in Fig. 6(a). Thus, the extra electron form the donor electron that are close and easily excitable to the conduction band.

Typically, we may consider the electron density  $n = N_d$  where  $N_d$  is the n-doping density, which can be seen as an increased Fermi energy level, shifting it closer to the conduction band compared to an undoped semiconductor at the same temperature. (See Fig. 6(b).) We can calculate the Fermi level relative to the conduction band edge and the hole density using the following equations.

$$\begin{aligned} n &= N_d = N_c e^{(E_f - E_c)/kT} \\ p &= n_i^2 / N_d \end{aligned}$$

P-type dopants are typically Group III elements, such as Boron (B) and Gallium (Ga), with three valence electrons. Of the four covalent bonds with surrounding Si atoms in the crystal lattice, only three are filled with an electron from the dopant atom. This vacancy creates an acceptor energy level just above the top of the valence band, for surrounding electrons to fill with ease. An electron that fills this hole propagates the vacancy to a Si atom, which is now missing an electron and positively charged. In this manner, the hole represents a region of positive charge, and is mobile just as an electron is, as shown in Fig. 7(a).

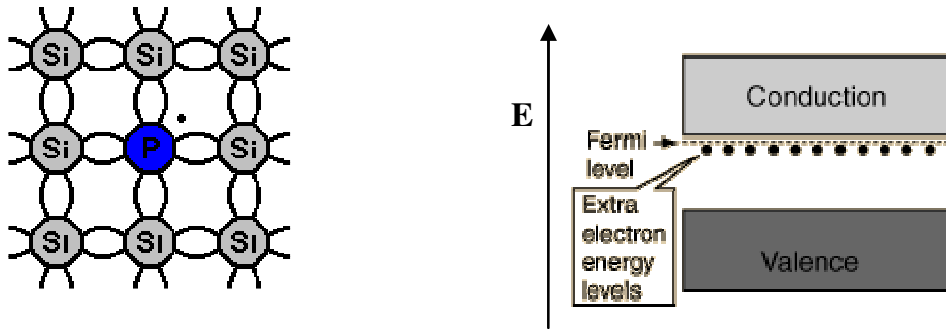


Fig. 6(a). Bonding model of n-type dopant (donor). Fig. 6(b). Band diagram of n-doped semiconductor.

The presence of holes shifts the effective Fermi level downwards. This means less electrons will be found in the conduction band (while more holes can be found in the valence band) than in an intrinsic semiconductor, and the positively charged holes serve as the majority charge carrier. Fig. 7(b) shows the energy band diagram, where electrons can easily occupy the low energy acceptor levels provided by the p-dopants. In this case, we will have:

$$\begin{aligned} p &= N_A = N_v e^{(E_v - E_f)/kT} \\ n &= n_i^2 / N_A \end{aligned}$$

It is amazing to see that a tiny amount of dopant is enough to achieve a great effect. For instance, typical doping concentrations are  $10^{16} - 10^{19} \text{ cm}^{-3}$ , but compared to the  $5.0 \times 10^{22} \text{ cm}^{-3}$  density of Si atoms, a  $10^{18}$  doping concentration means a 1:50,000 ratio of dopant atoms to Si atoms.

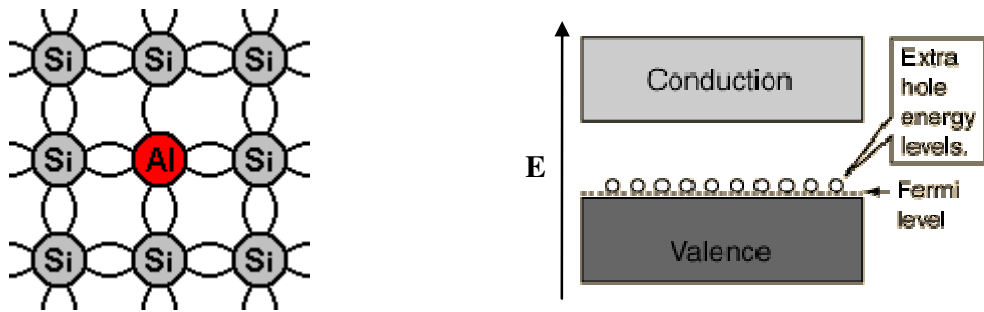


Figure 7(a). Bonding model of p-type dopant (acceptor). Figure 7(b). Band diagram of p-doped semiconductor.

### 3.1.4 Doping Methods

A common method of doping is diffusion. When a silicon crystal is exposed to high temperature dopants (gas phase), dopant atoms will diffuse against a concentration gradient into the silicon, where its concentration is much lower. Fig. 8(a) illustrates the process, where an oxide ( $\text{SiO}_2$ ) shields the silicon from the dopant. Fig. 8(b) plots the doping concentrations along the material, as a cutout from Fig. 8(a).

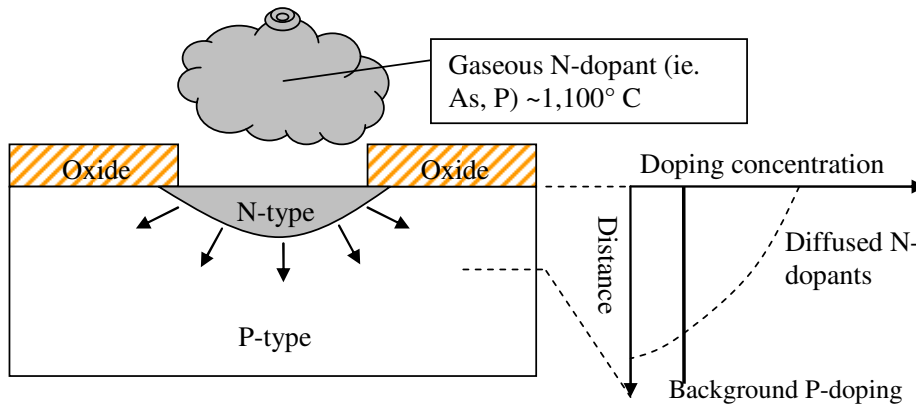


Fig. 8(a). Doping through diffusion of n-dopants into p-type silicon.

Fig. 8(b). Doping profile of the upper region of silicon in Fig. 8(a).

An alternative method to the high-temperature diffusion is ion implantation. Dopant ions are accelerated to high speed, and directed in a beam towards the silicon. This process allows more control of doping distribution than diffusion, because the penetration depth of the ions is directly correlated to their kinetic energy. Fig. 9(a) illustrates ion implantation, again in which an oxide shields areas to remain undoped. Fig. 9(b) shows the doping profile of the sample in Fig. 9 (a) after ion implantation.

Ion implantation allows silicon to be doped at lower temperatures than diffusion. However, the silicon crystal is damaged by the penetrating dopant atoms. Fortunately, a thermal treatment, annealing, of the silicon can remove most of the damage.

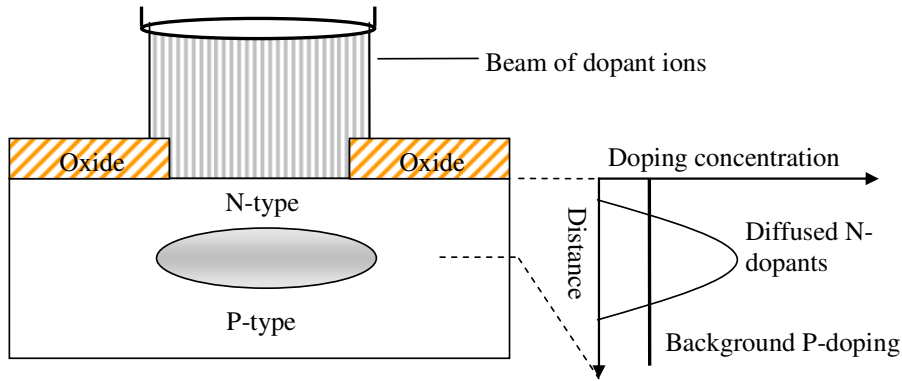


Fig. 9(a). Doping through ion implantation of N-dopants into P-type silicon.

Fig. 9(b). Doping profile of the upper region of silicon in Fig. 9(a).

## 3.2 Quantitative Analysis

### 3.2.1 Electric Fields

Gauss's law relates the electric field,  $\vec{E}$ , and charge. In differential form, Gauss's law is:

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon} \quad (1)$$

The divergence of the electric field from a point is equal to the volume charge density,  $\rho$  (units of Coulombs / cm<sup>3</sup>), divided by the electric permittivity,  $\epsilon$  (units of Farads / cm). Thus, the units of electric field,  $\vec{E}$ , are Volts / cm. The permittivity measures a material's ability to polarize in response to an electric field, and consequently cancel out the field. The permittivity of free space,  $\epsilon_0$ , is about  $8.85 \times 10^{-14}$  F/cm, while the permittivity of silicon is around  $11.7 \epsilon_0$ .

In integral form, Gauss's law is:

$$\oint_S \vec{E} \cdot d\vec{A} = \frac{1}{\epsilon} \oint_V \rho \cdot dV = \frac{Q_{encl}}{\epsilon}$$

The surface integral of electric flux is equal to the charge,  $Q$  (Coulombs), enclosed by the surface, divided by the electric permittivity.

In our study of semiconductors, we usually need only the 1-dimensional version of Gauss's law:

Differential form:

$$\boxed{\frac{dE}{dx} = \frac{\rho}{\epsilon}} \quad (2)$$

Integral form:

$$\begin{aligned} \int_{x_a}^{x_b} d[\epsilon E(x)] &= \epsilon_b E(x_b) - \epsilon_a E(x_a) \\ &= \int_{x_a}^{x_b} \rho(x) dx = Q_{encl} \Big|_{x_a}^{x_b} \end{aligned} \quad (3)$$

where  $Q_{\text{encl}}$  is the charge enclosed between  $x_a$  and  $x_b$ . The permittivity,  $\epsilon$ , may differ throughout a material, so it is included inside the differential, along with the electric field,  $E(x)$ .  $\epsilon_a$  is the permittivity at  $x_a$ , and likewise for  $\epsilon_b$ . We can find the electric field at a point  $b$ , by selecting a boundary point  $a$  that contains zero charge density. The electric field at the boundary location,  $E(x_a)$  would then be 0.

### 3.2.2 Electrostatic Potential

Poisson's Equation relates electrostatic potential,  $\phi$ , to the electric field,  $\vec{E}$ , and to charge density,  $\rho$ . The units of potential are Joules / Coulomb, or Volts.

In differential form, it is:

$$\nabla^2 \phi = -\nabla \cdot \vec{E} = -\frac{\rho}{\epsilon}$$

As before, we only need the one dimensional version in our analysis of semiconductors:

$$\boxed{\frac{d^2 \phi(x)}{dx^2} = -\frac{dE(x)}{dx} = -\frac{\rho(x)}{\epsilon}} \quad (4)$$

By definition, the electrostatic potential  $\phi(x)$  is found with respect to an arbitrary value at a reference point  $x_0$  as the integral of the negative of the electric field  $E$  from  $x_0$  to  $x$ :

$$\boxed{\phi(x) - \phi(x_0) = \int_{x_0}^x -E(x)dx} \quad (5)$$

Like any potential function, only the potential difference (voltage) between two points is physically meaningful, since any constant can be added to  $\phi$  without affecting  $\vec{E}$ . Thus, the usual value chosen for the potential at the reference point,  $x_0$ , is  $\phi(x_0) = 0$ .

### 3.3 PN Junction

A PN junction is formed when p-type material is in contact with an n-type material. This device allows considerable current to flow in only one direction (forward bias), while basically preventing current from flowing in the opposite direction (reverse bias) as shown in Fig. 14. Note that this semiconductor is a single crystal, in which one region is doped with acceptor impurity atoms (P-region), and the adjacent region is doped with donor atoms (N-region). For simplicity, we will consider a step junction where the doping concentration is uniform in each region, and there is an abrupt change in doping at the junction (see Fig. 15). Doping concentrations  $N_a$  in the P-region and  $N_d$  in the N-region are in units of  $\text{cm}^{-3}$ , denoting 1 impurity atom /  $\text{cm}^3$ .

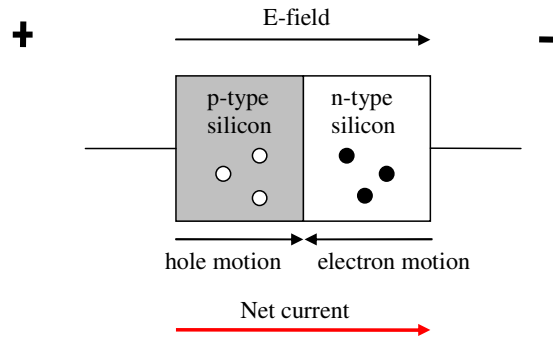


Fig. 14. PN junction with applied electric potential (forward bias).

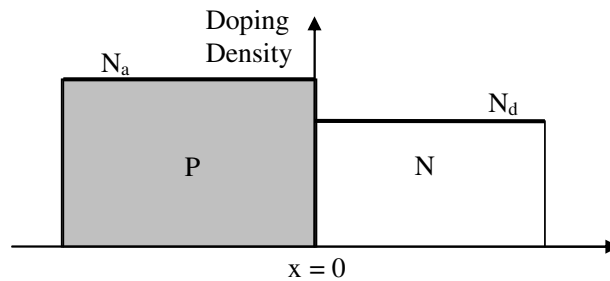


Fig. 15. Doping profile of a PN junction.

### 3.3.1 Depletion Approximation

The behavior of the PN junction can be understood by analyzing the physics of the diode as modeled in Fig. 16. Initially at the junction, there is a very large concentration gradient in the electron and hole concentrations. Majority carrier electrons in the N-region will begin diffusing into the p-region and majority carrier holes in the P-region will begin diffusing into the N-region. **Even though a doped semiconductor has excess electrons and holes, it is electrically neutral.** However, as electrons diffuse from the N-region, positively charged donor atoms are left behind (see Fig. 16). Likewise, holes diffusing from the P-region will leave negatively charged acceptor atoms.

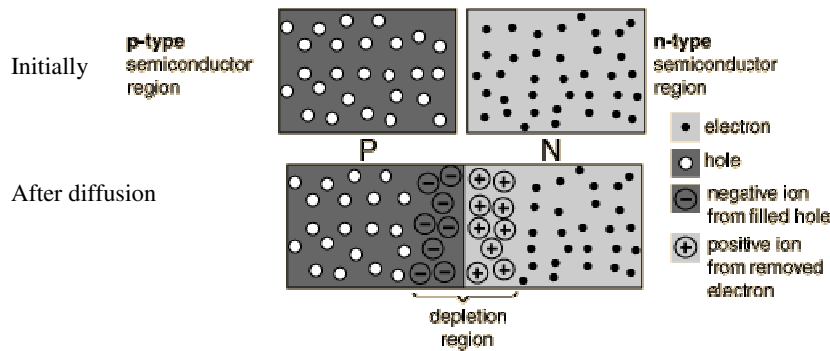


Fig. 16. Formation of the depletion region due to mobile charge carrier diffusion in a PN junction.

The dopant atoms, now ionized, are immobile because they are fixed in the crystal by their covalent bonds with surrounding silicon atoms. The regions on both sides of the junction are now depleted of mobile charge carriers, because the mobile carriers (electrons and holes) have diffused to the other side. The N-side is now positively charged with ionized donors near the junction, and the P-side is negatively charged with ionized acceptors, due to the ionized dopants. We call this the depletion region, which on either side, is depleted of mobile charge carriers and has a constant charge density due to the constant doping

concentration. The presence of immobile ions, as illustrated in Fig. 16, generates a built-in electric field pointing from N-side to the P-side within the depletion region. This built-in field will prevent mobile charge diffusion across the junction and balance the carrier motion in a PN junction under thermal equilibrium.

The portions of the semiconductor outside the depletion region are electrically neutral, due to the balance of charge carriers and dopant atoms. Reference 1 present a good quantitative treatment of the depletion approximation, in which we assume:

$$\rho_0(x) \approx \begin{cases} -qN_a & (-x_{p0} \leq x \leq 0) \\ qN_d & (0 \leq x \leq x_{n0}) \end{cases} \quad \text{and} \quad \rho_0(x) = 0 \quad (x < -x_{p0}, x > x_{n0}) \quad (10)$$

The charge distribution above in equation (10) describes the depletion region of a PN junction with the P-side between  $x = -x_{p0}$  and  $x = 0$ , while the N-side is between  $x = 0$  and  $x = x_{n0}$ . The P-side has a doping concentration of  $N_a$ , and its acceptor dopants ionize to negatively charged atoms, so the charge density,  $\rho_0$ , of this side is  $-qN_a$ . Likewise, the N-side has a doping concentration of  $N_d$ , with positively charged donor ions, giving a charge density,  $\rho_0$ , of  $qN_d$ . Keep in mind that the PN junction actually extends past  $-x_{p0}$  and  $x_{n0}$ , but this bulk silicon outside the depletion region is neutrally charged, so  $\rho_0 = 0$  in the regions where  $x < -x_{p0}$  and  $x > x_{n0}$ .

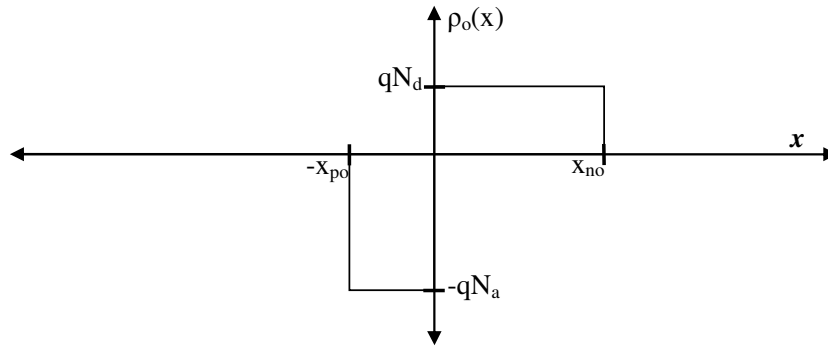


Fig. 17. Charge distribution,  $\rho_0(x)$ , of the PN junction, with depletion region as approximated in Equation (10).

### 3.3.1.1 Finding the electric field

The subscript 0 for the charge density  $\rho_0(x)$  indicates that our PN junction is in thermal equilibrium. We now integrate the charge density to find the electric field  $E_0(x)$  and then integrate again to find the electrostatic potential  $\phi_0(x)$ . Gauss's Law relates the charge density to the derivative of the electric field:

$$\frac{dE_0}{dx} = \frac{\rho_0(x)}{\epsilon_s} \quad (11)$$

where  $\epsilon_s = 11.7 \epsilon_0$  is the electric permittivity of silicon.

The PN junction in thermal equilibrium has no net current flow. In the formation of the depletion region, the total negative charge on the P-side is equal and opposite to the positive charge on the N-side, because an equal number of holes from the p-side and electrons from the n-side diffused and recombined at the interface. Thus, differing doping concentrations  $N_a$  and  $N_d$  will result in regions of different width, but the net charge on either side is the same:

$$qN_a x_{p0} = qN_d x_{n0} \quad (12)$$

This fact means that the electric field at the boundaries  $-x_{p0}$  and  $x_{n0}$  is 0, because the net enclosed charge in the depletion region is 0 (Gauss's Law states that if a surface encloses no net charge, there is no electric

flux through the surface). Also important, the adjacent bulk silicon outside the depletion region is neutrally charged.

On the P-side of the depletion region  $-x_{po} < x < 0$ , we integrate the charge distribution of equation (10) to obtain the electric field:

$$E_0(x) = \int_{-x_{po}}^x \frac{\rho_0(x)}{\epsilon_s} dx + E_0(-x_{po}) = \frac{-qN_a}{\epsilon_s} (x - (-x_{po})) + 0$$

where our constant of integration,  $E_0(-x_{po})$ , is 0, because at the edge of the depletion region, the electric field is 0. This is because there is no charge density on the left side (bulk p-silicon). Therefore,

$$E_0(x) = \frac{-qN_a}{\epsilon_s} (x + x_{po}) \quad (-x_{po} < x < 0) \quad (13)$$

In the N-region, the electric field can be found by noting that at the boundary of the depletion region with the bulk n-silicon,  $x_{no}$ , the electric field,  $E_0(x_{no})$ , is the sum of the electric field,  $E_0(x)$ , at the point  $x$ , and the contribution due to the charge between  $x$  and  $x_{no}$ , found by Gauss's law:

$$E_0(x_{no}) = E_0(x) + \int_x^{x_{no}} \frac{\rho_0(x)}{\epsilon_s} dx = 0$$

$E_0(x_{no})$  is also 0, because by Gauss's law, the entire depletion region has 0 net charge, so the electric flux must be 0 at its boundaries. Rearranging the above expression, we can find the electric field in the N-side of the depletion region:

$$E_0(x) = \int_x^{x_{no}} \frac{\rho_0(x)}{\epsilon_s} dx - E_0(x_{no}) = \frac{-qN_d}{\epsilon_s} (x_{no} - x) - 0 =$$

$$E_0(x) = \frac{qN_d}{\epsilon_s} (x - x_{no}) \quad (0 < x < x_{no}) \quad (14)$$

The electric field of our PN junction in thermal equilibrium, as described by Eqns. (13) and (14) is shown in Fig. 18.

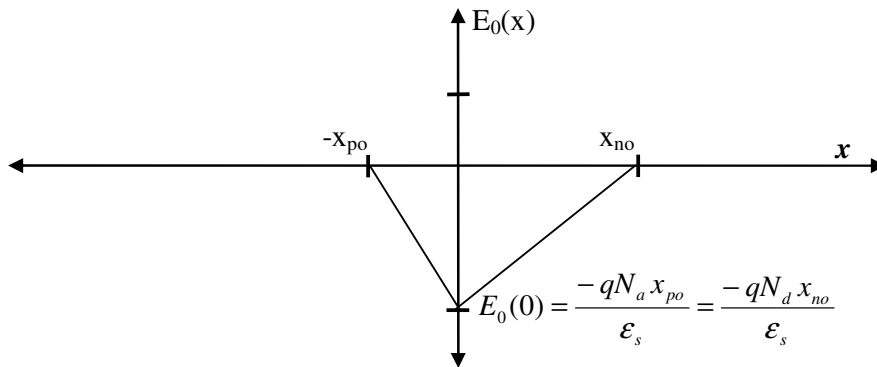


Fig. 18. Electric Field,  $E(x)$ , of the PN junction, with depletion region as approximated in Equation (10).

Note that the field is continuous, because we have considered two regions of finite charge density, and there is no sheet charge anywhere. At the interface,  $x = 0$ , the electric field reaches its maximum magnitude. Substituting for  $x$  in both Eqns. (13) and (14), we obtain:

$$E_0(0) = \frac{-qN_a x_{po}}{\epsilon_s} = \frac{-qN_d x_{no}}{\epsilon_s}$$

This is in agreement with our earlier observation in Eq. (12) that the net charge on both sides is equal. The electric field is a maximum at  $x = 0$  because both charged regions contribute fully to the electric flux. In either P or N regions, there is cancellation of charge, which reduces the electric flux (Gauss's Law).

### 3.3.1.2 Finding the Electric Potential

By applying Poisson's equation, Eq. (5), and integrating our expressions for electric field in Eqns. (13) and (14), we can obtain the potential throughout our PN junction.

$$\text{Poisson's Equation} \quad \phi(x) - \phi(x_0) = \int_{x_0}^x -E(x)dx \quad (5)$$

On the P-side of the depletion region,  $-x_{po} < x < 0$ ,

$$\begin{aligned} \phi_0(x) &= \int_{-x_{po}}^x -E_0(x)dx + \phi_0(-x_{po}) = \int_{-x_{po}}^x \frac{qN_a}{\epsilon_s}(x + x_{po})dx + 0 \\ &= \frac{qN_a}{\epsilon_s} \left( \int_{-x_{po}}^x x dx + \int_{-x_{po}}^x x_{po} dx \right) \end{aligned}$$

We usually set as 0, the reference potential,  $\phi_0(-x_{po})$ , at the boundary between the depletion region and bulk silicon on the P-side. The above integral solves to:

$$\phi_0(x) = \frac{qN_a}{2\epsilon_s}(x + x_{po})^2 \quad (-x_{po} < x < 0) \quad (15)$$

For the N-side of the depletion region, we can again integrate our expression for electric field on the N-side – Equation (14), but we must remember to add our constant of integration – the potential created by the charge and electric field of the P-side.

$$\begin{aligned} \phi_0(x) &= \int_0^x -E_0(x)dx + \phi_0(0) = \int_0^x -\frac{qN_d}{\epsilon_s}(x - x_{no})dx + \frac{qN_a}{2\epsilon_s}(0 + x_{po})^2 \\ &= \frac{qN_d}{\epsilon_s} \left( -\int_0^x x dx + \int_0^x x_{no} dx \right) + \frac{qN_a}{2\epsilon_s} x_{po}^2 \end{aligned}$$

Solving this expression, our potential on the N-side is found to be:

$$\phi_0(x) = \frac{qN_d}{2\epsilon_s} x(2x_{no} - x)^2 + \frac{qN_a}{2\epsilon_s} x_{po}^2 \quad (0 < x < x_{no}) \quad (16)$$

The electric potential of our PN junction in thermal equilibrium is shown in Fig. 19.

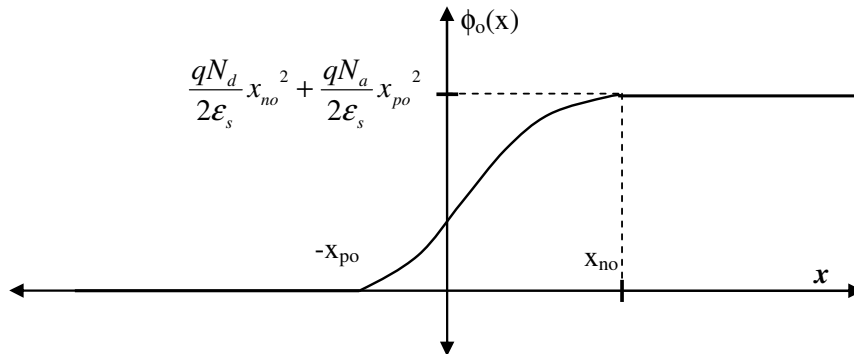


Fig. 19. Electric Potential,  $\phi_0(x)$ , of the PN junction, with depletion region as approximated in Equation (10).

The potential at  $x \geq x_{no}$  can be found by substituting  $x_{no}$  for  $x$  into Eq. (10). The value of this potential can be written multiple ways:

$$\begin{aligned} \phi_0(x \geq x_{no}) &= \frac{qN_d}{2\epsilon_s} x_{no}^2 + \frac{qN_a}{2\epsilon_s} x_{po}^2 = \frac{qN_d x_{no}}{2\epsilon_s} (x_{no} + x_{po}) \\ &= \frac{qN_a x_{po}}{2\epsilon_s} (x_{no} + x_{po}) \end{aligned} \tag{17}$$

This value in Eq. (17) represents a built-in potential of the PN junction that limits the flow of charge carriers. For example, positive charges naturally move from high potential to lower potential, so holes moving in the  $+x$  direction must possess sufficient energy to overcome the potential barrier, and make it into the bulk silicon region,  $x \geq x_{no}$ . Similarly, electrons naturally move from low to high potential, so for them to move in the  $-x$  direction also requires sufficient energy to overcome the built-in potential.

### 3.3.2 PN Junction in Equilibrium

The PN junction in thermal equilibrium, with no external applied electric field, does not have any current flow. In this case, the drift current due to the depletion region's built-in electric field is equal and opposite in magnitude to the diffusion current caused by the different doping concentrations. The built-in potential has the right size and height so the amount of electrons having enough energy to move up the potential by diffusion equals the amount of electrons moving down it, due to drift. Fig. 20 illustrates an energy level profile of the PN junction:

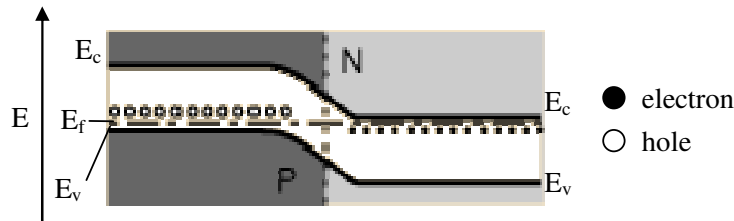


Fig. 20. Energy bands of PN Junction in Equilibrium.

**The Fermi level,  $E_f$ , is the same in both P-region and N-region, because it is in thermal equilibrium, but the bottom of conduction band,  $E_c$ , and the top of the valence band,  $E_v$ , are at different levels in the two regions, due to the built-in potential across the depletion region.**

Note that the direction of the energy barrier is opposite that of the potential diagram of Fig. 19. This is because Fig. 20 displays electron energy levels, increasing in the upward direction. In Fig. 19, the potential displayed is for positive charges, such as holes. Thus, holes moving from the P-side into the N-side (against the higher potential), require energy to push them down into the valence band, where they are mobile. Likewise, for electrons moving towards the left, the P-region is at lower potential (and thus unfavorable for negative charges). So for electrons to pass through to the bulk region of the P-side, they must have sufficient energy to push them up into the higher energy conduction band of the P-side.

### 3.3.3 Reverse Bias

When an electric potential, or voltage, is applied, with positive potential on the N-side of the diode, the diode will conduct only negligible current. Current flow through the device requires the combination of holes and electrons at the junction. Instead, the applied potential forces electrons on the N-side away from the junction, and forces holes on the P-side away as well. This results in widening of the depletion region, which increases the charge, electric field, and hence potential barrier across the junction, as shown in Fig. 22.

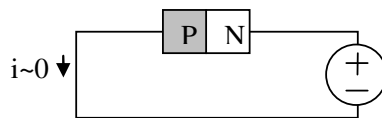


Fig. 21. Circuit of PN junction in reverse bias.

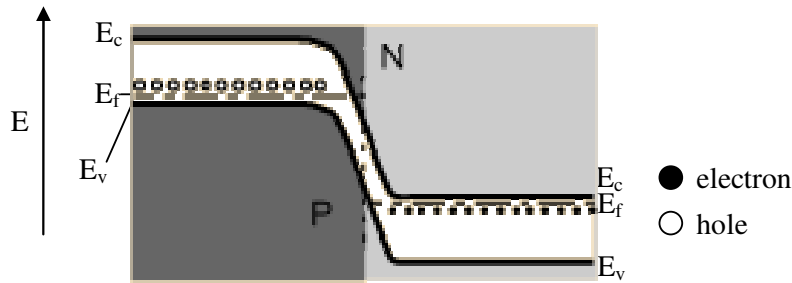


Fig. 22. Energy bands of PN junction in reverse bias.

The tiny amount of current that does flow is due to minority carriers (electrons in p-type and holes in n-type) from the neutral regions (p and n type semiconductors, respectively) diffusing across into the depletion region and drifting across the junction, due to the applied electric field.

### 3.3.4 Forward Bias

When a voltage is applied with its positive reference at the P-side of the diode, the diode can conduct considerable current.

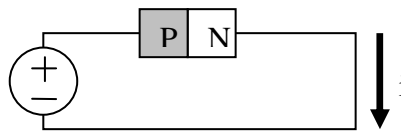


Fig. 23. Circuit of PN junction in forward bias.

The electric field created by the potential forces electrons on the N-side towards the junction, while holes on the P-side are pushed towards the junction as well. This causes current to flow (electrons from n-side to flow to p-side and vice versa), as the built-in potential is overcome by the applied voltage. Now, current can flow with very little resistance, because the depletion region has been diminished, and the built-in potential lowered.

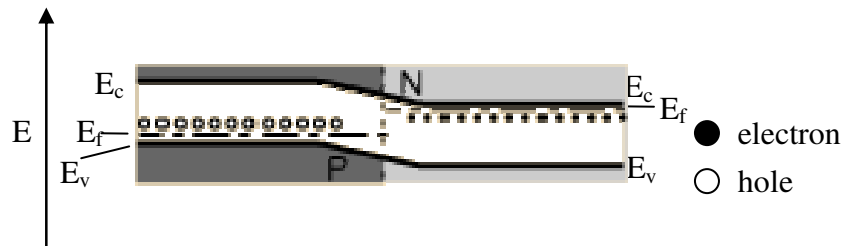


Fig. 24. Energy bands of PN Junction in forward bias.

As illustrated in Fig. 24, an applied voltage above that of the built-in potential will result in electrons high in energy on the N-side, above the conduction band of the P-side. Now the potential is “downhill” for electrons, meaning they can flow across with ease. When they enter the junction, they readily recombine with holes, resulting in a net current flow. It is in both directions in which this process of recombination occurs: majority carriers diffuse across the junction and then becoming minority carriers, combining with the majority carriers in the local region, and “dying out” far from the junction.

### 3.4 References

Fig. 1., Section 4.1 – Howe & Sodini, Microelectronics: An Integrated Approach, Prentice Hall, 1997.  
 Fig. 2, 5, 6(a)(b), 7(a)(b), 16, 20, 22, 24 – Hyperphysics, Internet. <http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html>