ENGR 305

Chapter 3 - Semiconductors

September 2, 2025

Semiconductors

In this chapter we learn about…

- The basic properties of semiconductors and in particular silicon, which is the material used to make most of today's electronic circuits.
- How doping a pure silicon crystal dramatically changes its electrical conductivity, which is the fundamental idea underlying the use of semiconductors in the implementation of electronic devices.
- The two mechanisms by which current flows in semiconductors: drift and diffusion of charge carriers.
- The structure and operation of the pn junction; a basic semiconductor structure that implements the diode and plays a dominant role in transistors.

Intrinsic semiconductors

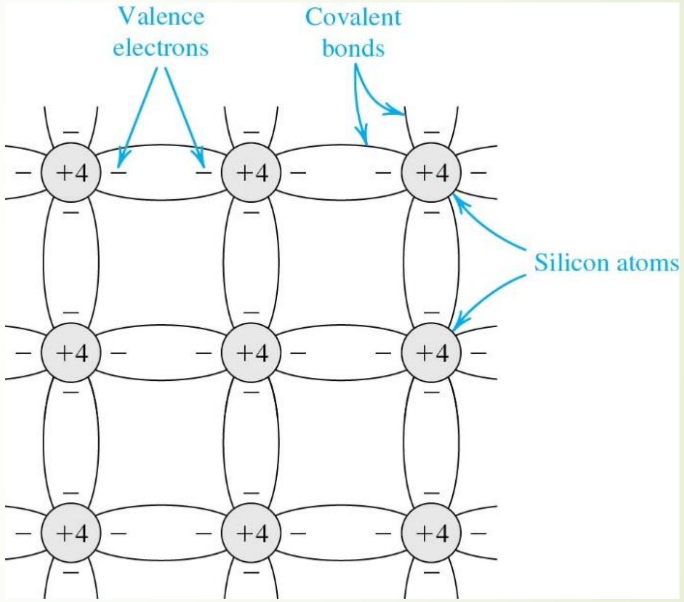
- Semiconductors have conductivity intermediate between
  - Conductors, i.e., copper
  - and
  - Insulators, i.e., glass
- Elemental semiconductors are in group IV of the periodic table
  - Germanium was used in very early transistors
  - Silicon became the predominant semiconductor used in integrated circuits
- Compound semiconductors
  - Formed by combining elements from groups III and V
  - Or formed by combining elements from groups II and VI

Intrinsic silicon

- A silicon atom has four valence electrons
  - Another four electrons are required to complete the outermost shell
  - Each pair of electrons forms a **covalent** bond
- A crystal of pure, or intrinsic, silicon has a regular lattice structure
- At temperatures approaching absolute zero (0 K), all the covalent bonds are intact and no electrons conduct electric current.

Fig. 3.1

Here is a two-dimensional representation of the silicon crystal. The circles represent the inner core of silicon atoms, with +4 indicating its positive charge of +4q, which is neutralized by the charge of the four valence electrons. Note how the covalent bonds are formed by sharing of the valence electrons. At 0 K, all bonds are intact and no free electrons are available for conduction.

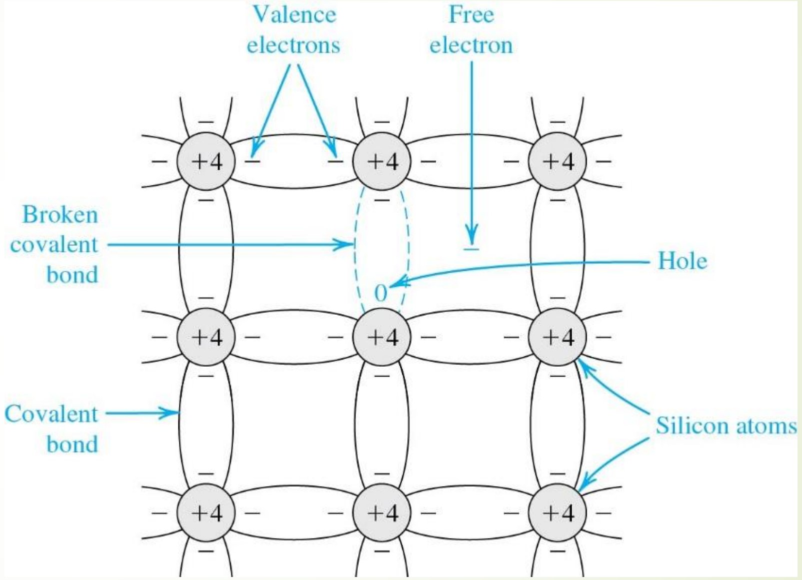


Room temperature – thermal generation

- At room temperature, there is thermal energy available to break covalent bonds
  - This process is called thermal generation
- In the process of breaking bonds, a **free electron** is created.
- The electron is available for current conduction, leaving behind a **hole.**
  - The hole is positively charged, having the same magnitude of charge as an electron.
- An electron from a neighboring atom may leave its parent atom and fill the “hole”.
  - Fills the “hole” that existed in the ionized atom but creates a new hole in the other atom.
  - As this process repeats, there is effectively movement of a positively charged carrier, or **hole.**

Thermal generation – room temperature

At room temperature, some of the covalent bonds are broken by thermal generation. Each broken bond gives rise to a free electron and a hole, both of which become available for current conduction.



Thermal generation of carriers

- Results in equal numbers of free electrons and holes
- Also results in equal concentrations of electrons and holes
  - Concentration refers to the number of charge carriers per unit volume ($\#/cm^3$)
- As the electrons move through the crystal, some of them may fill a hole, annihilating an electron-hole pair.
  - This is known as **recombination,** resulting in the disappearance of electrons and holes.
- The recombination rate is proportional to the number of electrons and holes.
  - This in turn is determined by the **generation** rate.
  - The generation rate depends on temperature.

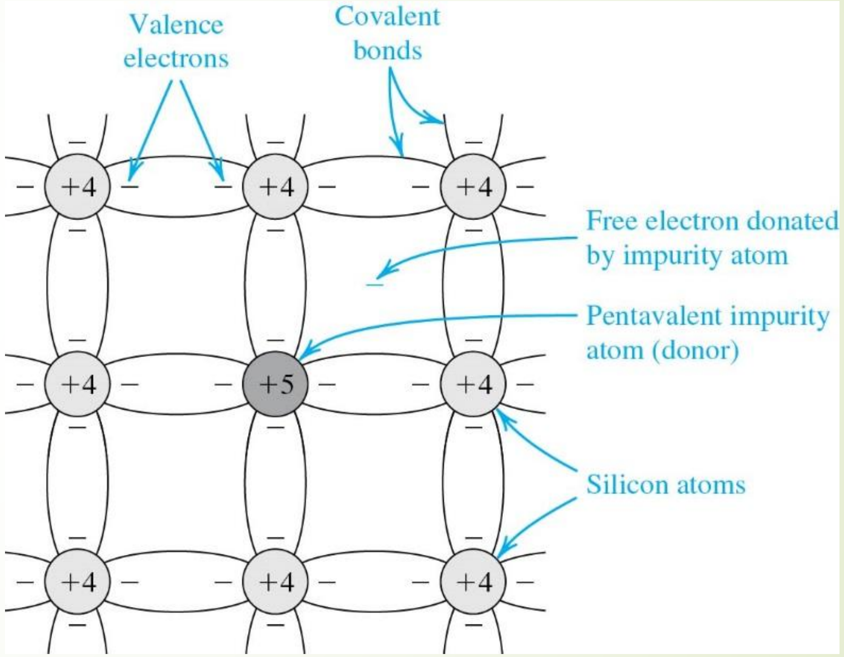
Thermal generation of carriers

- In thermal equilibrium, the recombination rate equals the generation rate
  - $n = p = n_i$
  - Concentration of free electrons **n** equals the concentration of free holes **p**
  - The intrinsic carrier concentration n_i denotes the number of free electrons and holes per unit volume of intrinsic silicon at a given temperature.
- From semiconductor physics, $n_i = BT^{3/2}e^{-E_g/2kT}$
  - B is a material-dependent parameter and equals $7.3 \times 10^{15} cm^{-3} K^{-3/2}$ for silicon
  - T is the temperature in K
  - E_g is the bandgap energy and equals 1.12 electron-volt (eV) for silicon
  - And k is Boltzmann's constant (8.62×10^{-5} eV/K)
  - The product of the free electron and hole concentration is $pn = n_i^2$

Doped semiconductors – n-type

A silicon crystal is doped by a pentavalent element. Each dopant atom donates a free electron and is thus called a donor. The doped semiconductor becomes *n*-type.

Phosphorus is a pentavalent element. It has 5 electrons in its outer shell and four of these form covalent bonds with neighboring atoms. The fifth electron becomes a free electron. Thus, each phosphorus atom *donates* a free electron and the phosphorus impurity is called a **donor.**



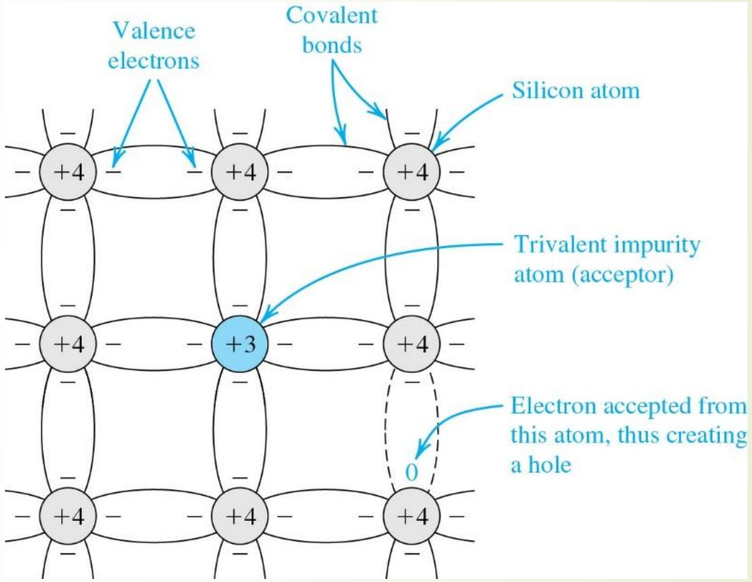
Doped semiconductors – n-type

- No excess holes are generated in the process of doping with phosphorus.
- The net positive charge is associated with the phosphorus atom is a **bound charge** and does not move through the crystal.
- Given a concentration of donor atoms N_D, where $N_D$is much greater than n_i, the concentration of free electrons in the n-type silicon will be $n_n = N_D$.
  - Electrons are the majority carriers in n-type silicon.
- The product of free electron and hole concentrations is $p_n n_n = n_i^2$
  - The subscript n denotes the carrier concentration in the n-type material.
- Substituting for n_n we obtain for p_n we obtain
  - $p_n \sim \frac{n_i^2}{N_D}$

Doped semiconductors – p-type

A silicon crystal is doped with boron, a trivalent impurity. Each dopant atom gives rise to a hole, and the semiconductor becomes *p* type.

Since each boron atom has three electrons in its outer shell, it **accepts** an electron from a neighboring atom, thus forming covalent bonds. This results in a hole in the neighboring atom and a bound **negative** charge at the **acceptor** atom.

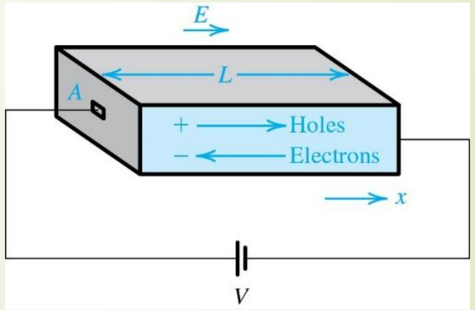


Doped semiconductors – p-type

- If the acceptor concentration is N_A where $N_A \gg n_i$, the hole concentration is
  - $p_p \sim N_A$
  - The subscript p denotes p-type silicon with holes being the majority carrier
- The concentration of minority carrier electrons is found using
  - $p_p n_p = n_i^2$
- Making the substitution for p_p, $n_p \sim \frac{n_i^2}{N_A}$
- Note that both n-type and p-type silicon are electrically neutral.
  - The charge of the majority free carriers is neutralized by the bound charges associated with the impurity atoms.

Drift Current in semiconductors

- When an electrical field E is applied in a semiconductor crystal, holes get accelerated in the direction of E and free electrons get accelerated in the opposite direction.
- Holes acquire a velocity $v_{p-drift} = \mu_p E$
- The **hole mobility** $\boldsymbol{\mu_p}$ represents the ease by which holes move through the crystal with the applied electric field E.
- Free electrons acquire a drift velocity
  - $v_{n-drift} = -\mu_n E$
  - Electron mobility is $\boldsymbol{\mu_n}$



Drift current in semiconductors

- We wish to calculate the current component due to hole flow in the silicon bar.
  - Consider a plane perpendicular to the x-direction having cross-sectional area A.
  - In one second, the hole charge that crosses that plane will be $Aqpv_{p-drift}$ coulombs.
  - This represents the hole component of drift current flowing through the bar.
  - $I_{S,p} = Aqpv_{p-drift}$
- Substituting for $v_{p-drift}$ gives $I_{S,p} = Aqp\mu_p E$
- The current density or current per unit cross-sectional area is
  - $J_{S,p} = \frac{I_{S,p}}{A} = qp\mu_p E$

Drift current in semiconductors

- The current due to drift of free electrons can be found similarly.
  - The direction of current flow is in the direction of positive charge flow and opposite to the direction of negative charge flow.
  - Then electrons drifting from right to left result in current flowing from left to right
  - $I_{S,n} = -Aqnv_{n-drift}$
  - Substituting for $v_{n\text{-drift}}$, the current density is $J_{S,n} = \frac{I_{S,n}}{A} = qn\mu_n E$
  - The total drift current density is then equal to $J_S = J_{S,p} + J_{S,n} = q(p\mu_p + n\mu_n)E$

Drift current in semiconductors

- We can express this as $J = E/\rho$
- The **resistivity** $\rho = \frac{1}{q(p\mu_p + n\mu_n)}$
- The expression for J above is an alternate form for Ohm's law
  - It can be written $\rho = \frac{E}{J}$
- The units for resistivity are: $\frac{V/cm}{A/cm^2} = \Omega \cdot cm$
  - Can find the resistance of the single-crystal silicon bar as $R = \frac{\rho L}{A}$
  - A is the cross-sectional area and L is the length of the bar

Diffusion current

A bar of silicon (a) into which we inject holes, thus creating the hole concentration profile along the x axis, shown in (b). The holes diffuse in the positive direction of x and give rise to a hole diffusion current in the same direction.

The magnitude of the current at any point is proportional to the slope of the concentration profile, or **concentration gradient:**

$$J_{D,p} = -qD_p \frac{dp(x)}{dx}$$

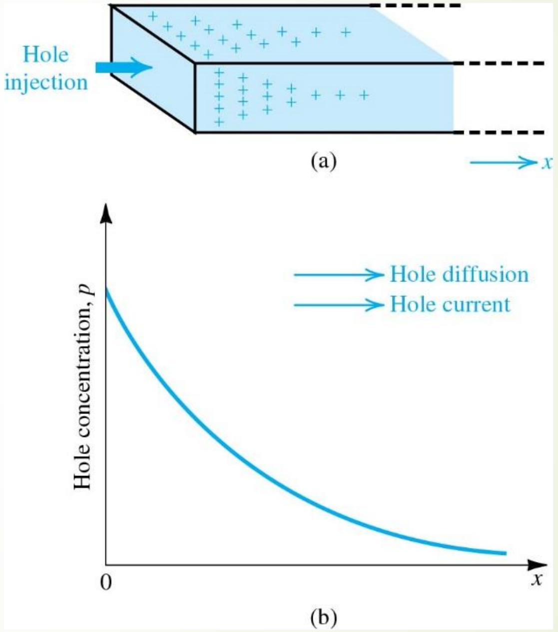
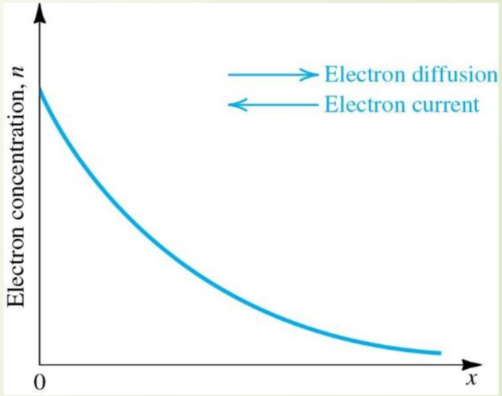


Fig. 3.7

- In the case of electron diffusion due to an electron concentration gradient,
  - $J_{D,n} = qD_n \frac{dn(x)}{dx}$
- D_n is the **diffusion constant** (units of cm^2/s)
- A negative concentration gradient gives rise to a negative current
- Typical values are $D_p = 12\ cm^2/s$ and $D_n = 35\ cm^2/s$
- Electron flow is in the positive x-direction
- Electron current is in the negative x-direction



The pn junction

- We consider our first semiconductor structure, the pn junction.
- The pn junction consists of a p-type semiconductor brought into close contact with an n-type semiconductor.
  - The device is created from a single piece of silicon where the n-type and p-type regions are formed by creating regions of different dopings.

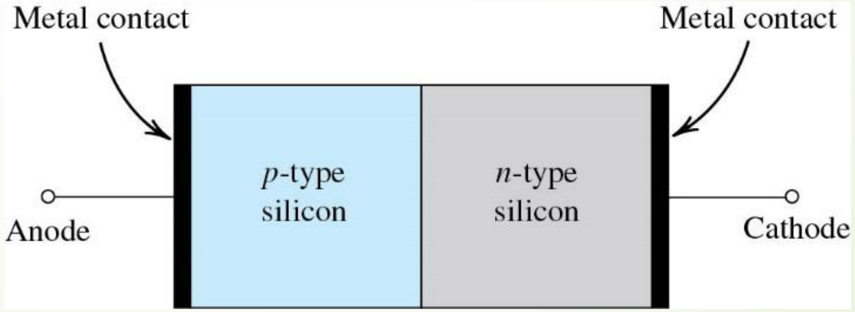
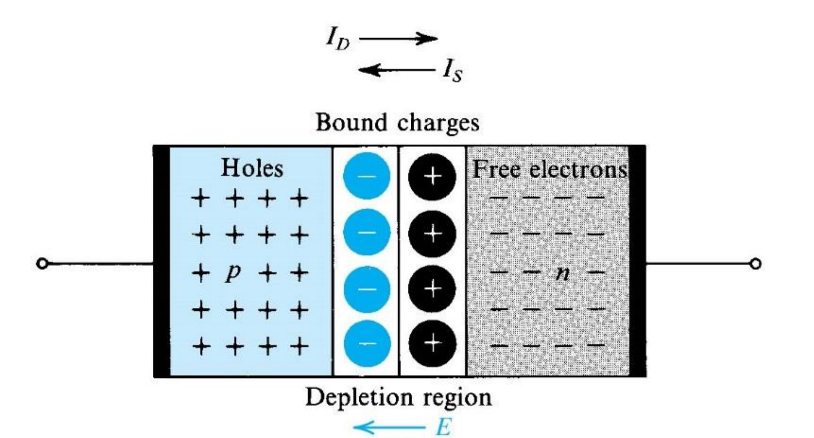
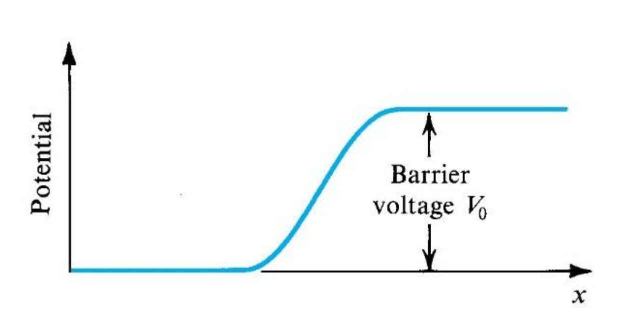


Fig. 3.9

In part (a) of the figure, we see the *pn* junction with no applied voltage (open-circuited terminals). In part (b) we see the potential distribution along an axis perpendicular to the junction.



(a)



(b)