

Lecture 6: Extrinsic semiconductors

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1 Introduction

The carrier concentration of intrinsic Si at room temperature is 10^{10} cm^{-3} and is a constant defined by the band gap of the material. This gives a conductivity of $3 \times 10^{-6} \Omega^{-1} \text{ cm}^{-1}$. To increase the conductivity one can use a lower band gap material, like Ge. But if the material cannot be changed from intrinsic Si, then the only way to increase carrier concentration is to increase temperature.

Doping is a method of *selectively increasing carrier concentration*, by addition of *selected impurities* to an intrinsic semiconductor. This is called an **extrinsic semiconductor**. In any semiconductor at equilibrium, the **law of mass action** should be satisfied i.e.

$$\boxed{np = n_i^2} \quad (1)$$

In an intrinsic semiconductor $n = p = n_i$, so equation 1 becomes trivial. But when impurities are added to a semiconductor, to increase the carrier concentration, equation 1 restricts the increase to *either* electrons or holes. Both cannot be increased simultaneously. If n increases, then p decreases,

and vice versa. Thus doping can selectively increase electron or hole concentration.

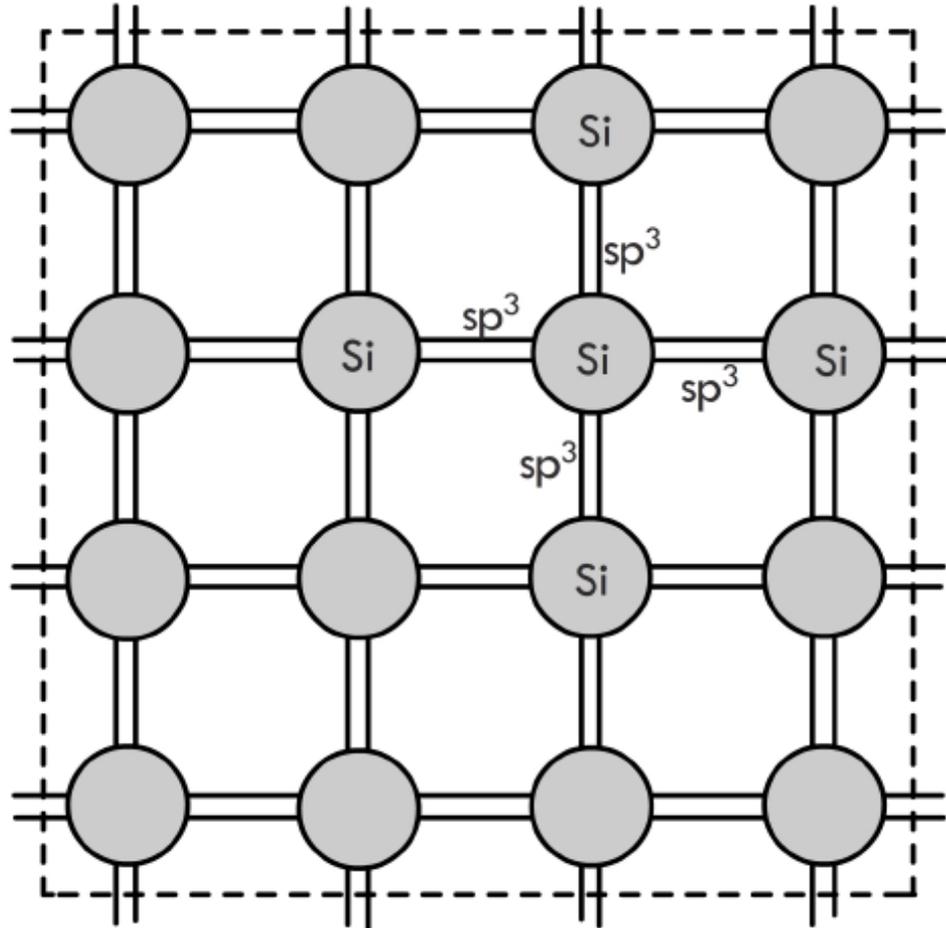
An extrinsic semiconductor is formed by adding a small amount of impurities to a pure semiconductor crystal to preferentially increase carrier concentration of one polarity. There are two important terms in this definition

1. 'small' - the concentration of impurities is very small, of the order of ppm (parts per million) or ppb (parts per billion).
2. 'impurities' - these are precisely controlled additions to a pure material. Not impurities in the sense of unwanted material. **Dopants** would be a better term for these additions.

2 n-type doping

Consider a two dimensional picture of Si, as shown in figure 1. Si, has 4 electrons in the outer shell. The s and p orbitals hybridize to form 4 sp^3 orbitals.

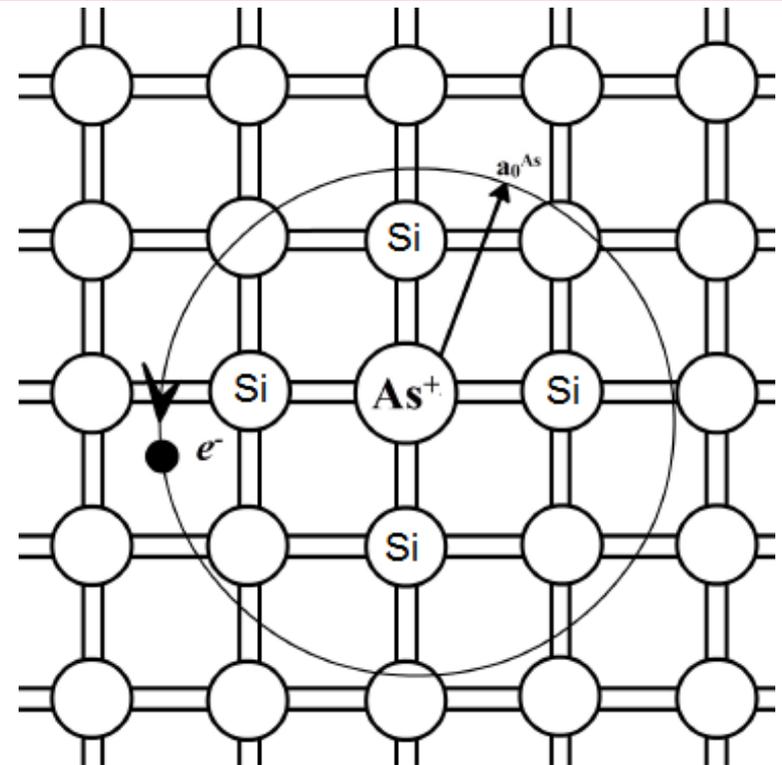
Figure 1: Two dimensional picture of Si. Each Si has 4 sp^3 hybrid electrons which can form a covalent bond with 4 other Si atoms. The arrangement is tetrahedral, which is shown in the figure as a two dimensional array of atoms with 4 bonds each.



A *small* amount of *pentavalent impurity*, like As, is added to Si.

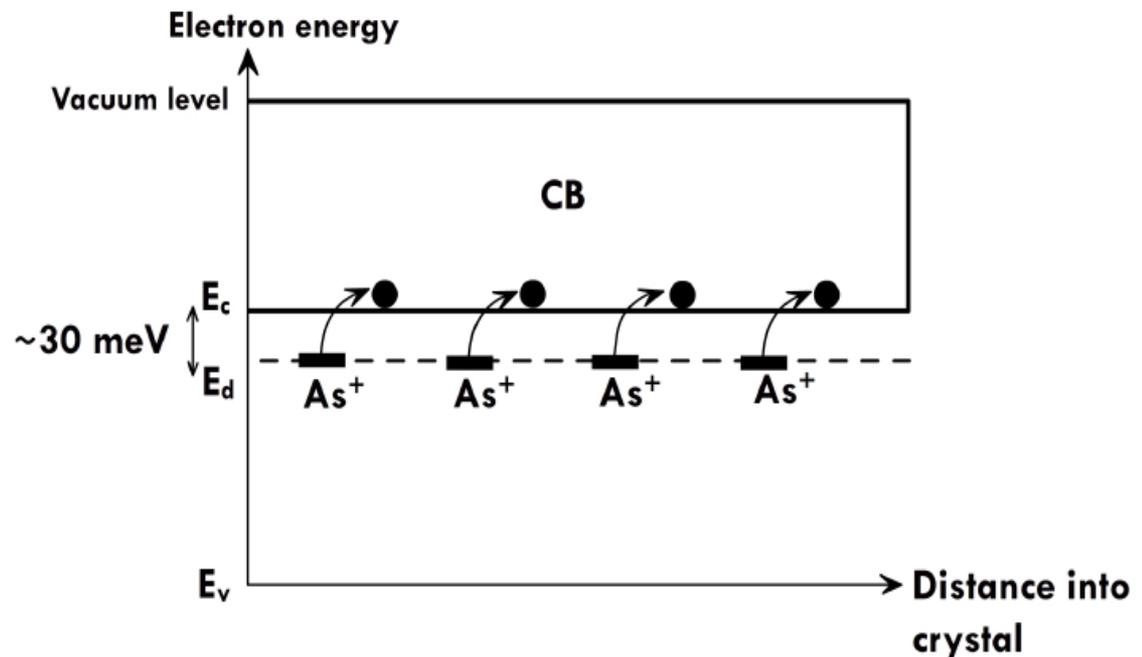
The amount of impurity added is small so that the crystal structure of Si is not disturbed and the impurity behaves like individual atoms and do not form clusters. Later we will quantify the amount of As needed to increase the conductivity and show that our assumption is justified. The As atom can substitute for a Si atom in the lattice, as shown in figure 2. Since, As has 5 electrons, 4 of these are involved in bonding with the Si atom. There is an extra electron in the As atom, and if sufficient energy is supplied it can be delocalized and made available for conduction. This process creates free electrons but immobile As^+ ions

Figure 2: Si lattice with As impurity added. The As atom substitutes for Si in the lattice, As has 5 electrons in the valence shell. Four of these electrons shares in the bonding, and donates one extra electron making it an n-type dopant. By donating one electron, As^+ ion is created.



Pentavalent impurities like P, Sb, and As have an extra electron to ‘*donate*’ to the Si crystal. These impurities are called **donors**. Since the extra electron is delocalized at room temperature and are present in the conduction band the donor energy levels are located close to the conduction band. This is shown schematically in figure 3. The As atoms are localized in the Si lattice, so they are depicted as individual atomic levels in the band gap. The distance between the donor level (E_d) and the conduction band minimum (E_c) is the *donor ionization energy*. This value is of the order of tens of *meV*, which is much smaller than the band gap of Si (1.10 eV).

Figure 3: Si energy band with the As donor levels (E_d) close to the conduction band. The As concentration is low so that its energy levels are localized near E_c .



If N_d is the concentration of the donor atoms in the lattice, there are N_d extra electrons that are available for conduction. At room temperature, these electrons are located in the conduction band so that the concentration of electrons is given by $n = N_d$, when ($N_d \gg n_i$). The concentration of holes is given by equation 1.

$$p = \frac{n_i^2}{N_d} \ll N_d \quad (4)$$

Hence the conductivity of the n -type doped Si sample is given by

$$\sigma = ne\mu_e + pe\mu_e \approx N_de\mu_e \quad (5)$$

In n -type semiconductor, Since $n \gg p$ then:

Electrons are called **majority charge carriers** and Holes are called **minority charge carriers**

3 p-type doping

Consider intrinsic Si where a trivalent impurity like B is added. The concentration of the B atoms is small so that the Si lattice is not changed by individual B atoms substitute for Si atoms in the lattice. This is shown schematically in figure 4. Since a B atom has only 3 electrons it can form 3 bonds with 3 Si atoms. But an extra electron from the valence band of Si can be excited to the B energy level to bond with the fourth Si atom. This leaves behind a hole in the valence band, that is available for conduction.

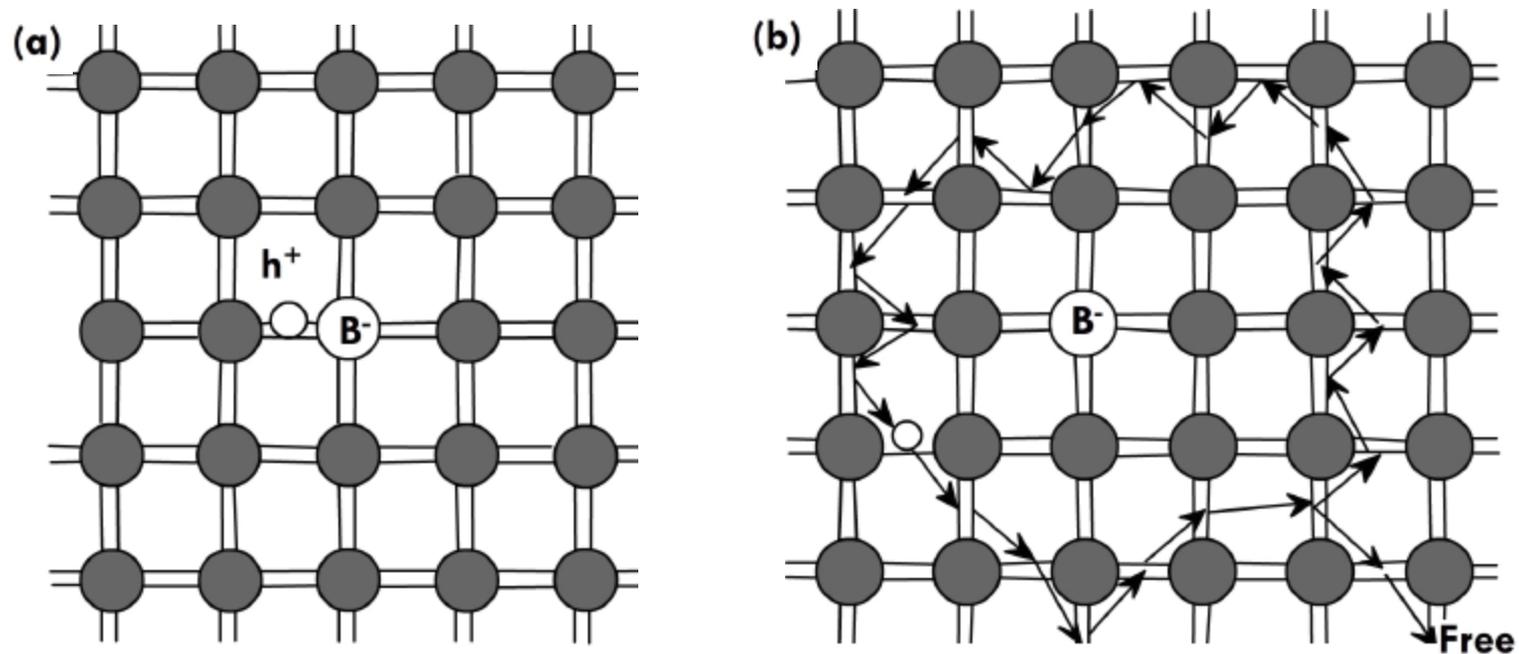
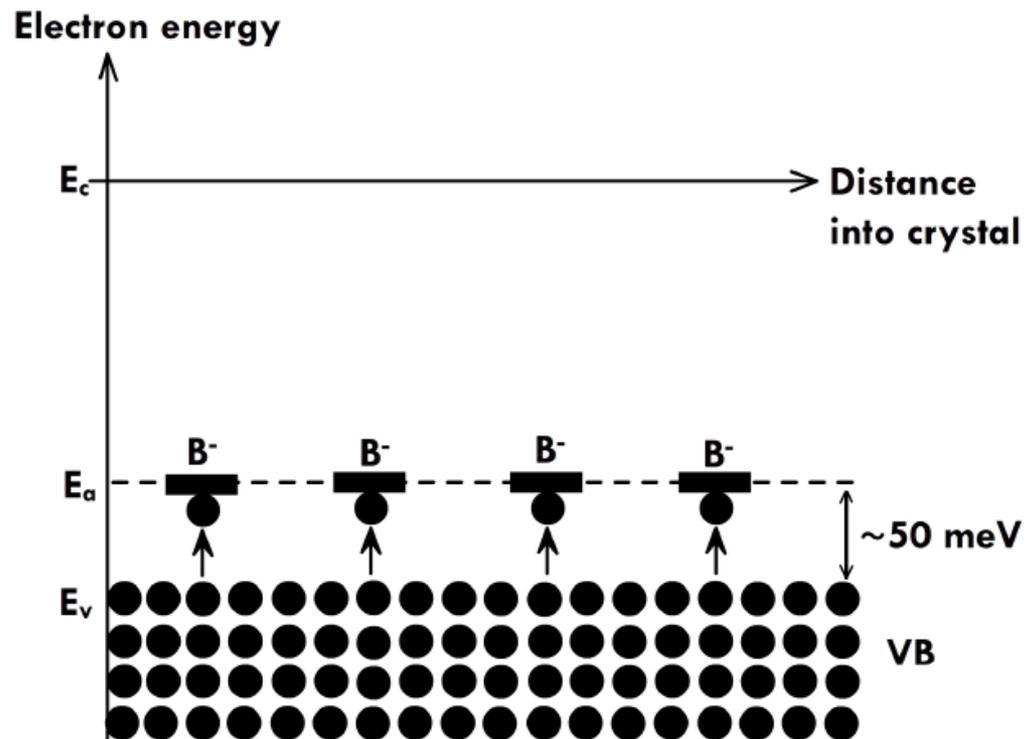


Figure 4: (a) B doping in a Si lattice. (b) The extra hole is delocalized and gets excited to the valence band. This electron is free to move in the Si lattice

There is one hole in the valence band for every B atom doped in the lattice. Since the trivalent atom accepts electrons from the Si, these are called **acceptors**.

Since the acceptor atoms accept electrons from the valence band their energy levels are located close to the valence band. This is shown in figure 5. The distance between the **acceptor level (E_a , localized)** and the valence band maximum (E_v) is the ionization energy.

Figure 5: Acceptor energy levels (E_a) are close to the valence band of the Si. Electrons from the valence band can get promoted to these levels leaving behind holes. These acceptor levels are localized near E_v due to the small concentration.



If N_a is the concentration of the acceptors, then at room temperature, the concentration of holes is given by $p = N_a$, when ($N_a \gg n_i$). The concentration of electrons is given by equation 1.

$$n = \frac{n_i^2}{N_a} \ll N_a \quad (6)$$

Hence the conductivity of the p -type doped Si sample is given by

$$\sigma = ne\mu_e + pe\mu_e \approx N_a e\mu_h \quad (7)$$

In p -type semiconductor, Since $p \gg n$ then:
holes are called **majority charge carriers** and electrons are called **minority charge carriers**

4 Conductivity in extrinsic Si

EXAMPLE RESISTIVITY OF INTRINSIC AND DOPED Si: Find the resistance of a 1 cm³ pure silicon crystal. What is the resistance when the crystal is doped with arsenic if the doping is 1 in 10⁹, that is, 1 part per billion (ppb)?

Given data: Atomic concentration in silicon is 5×10^{22} cm³, $n_i = 1.0 \times 10^{10}$ cm⁻³

SOLUTION $\mu_e = 1350$ cm² V⁻¹ s⁻¹, and $\mu_h = 450$ cm² V⁻¹ s⁻¹.

For the intrinsic case, we apply $\sigma = en\mu_e + ep\mu_h = en(\mu_e + \mu_h)$

$$\text{so } \sigma = (1.6 \times 10^{-19} \text{ C})(1.0 \times 10^{10} \text{ cm}^{-3})(1350 + 450 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}) = 2.88 \times 10^{-6} \Omega^{-1} \text{ cm}^{-1}$$

Since $L = 1$ cm and $A = 1$ cm², the resistance is $R = \frac{L}{\sigma A} = \frac{1}{\sigma} = 3.47 \times 10^5 \Omega$ or 347 k Ω

When the crystal is doped with 1 in 10⁹, then $N_d = \frac{N_{\text{Si}}}{10^9} = \frac{5 \times 10^{22}}{10^9} = 5 \times 10^{13} \text{ cm}^{-3}$

so $n = N_d = 5 \times 10^{13} \text{ cm}^{-3}$

The hole concentration is $p = \frac{n_i^2}{N_d} = \frac{(1.0 \times 10^{10})^2}{(5 \times 10^{13})} = 2.0 \times 10^6 \text{ cm}^{-3} \ll n$

Therefore, $\sigma = en\mu_e = (1.6 \times 10^{-19} \text{ C})(5 \times 10^{13} \text{ cm}^{-3})(1350 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1})$
 $= 1.08 \times 10^{-2} \Omega^{-1} \text{ cm}^{-1}$

Conductivity increase 4 order of magnitude by doping with 5×10^{13} cm⁻³ As (1ppb of Si atoms)

Therefore, $R = \frac{L}{\sigma A} = \frac{1}{\sigma} = 278 \Omega$

5 Compensation doping

In extrinsic doping the semiconductor is doped with either p or n type dopant. It is possible to dope both types of dopant in the same material. This type of doping is called **compensation doping**. Compensation doping is used when junctions are needed to be formed in the case of electronic devices. For forming a pn junction, a n -doped sample is chosen and then compensated doped with p -type dopant or vice versa. If there are both donors and acceptors in a semiconductor then the one with the higher concentration will dominate so that the final material will be either n or p type.

Consider a material with N_d donors and N_a acceptors. Let N_d and N_a be $\gg n_i$. If $N_d > N_a$, then the overall material is n -type with

$$n = (N_d - N_a) \text{ and } p = \frac{n_i^2}{(N_d - N_a)} \quad (8)$$

If $N_a > N_d$, then the overall material is p -type with

$$p = (N_a - N_d) \text{ and } n = \frac{n_i^2}{(N_a - N_d)} \quad (9)$$