COE 360 Principles of VLSI Design
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Lecture#1

Basic Properties of Semiconductor Devices

1. Valence electrons
2. Drift, Diffusion
3. Mobility
4. Conductivity
5. Current Density
6. Semiconductors
7. Concept of a hole
8. Intrinsic & Extrinsic Semiconductors
9. Fermi Energy
10. Mass Action Law
11. Charge Neutrality Law

COE 360 : Lec #1 Dr. Aiman El-Maleh

- An atom has a positive nucleus and inner electronic bands considered as an equivalent positive charge (ionic core) whose magnitude is an integral multiple of the charge on an electron.

- Electrons in the outermost electronic band provide a negative charge to make the atom neutral. These electrons are called valence electrons.

- Electron is a negatively charged particle whose charge or quantity of electricity is 1.6×10^{-19} Coulombs (C).

- Number of electrons per coulomb $= \frac{1}{\text{Charge}} = 6 \times 10^{18}$.

- A current of 1 ampere (A) is the movement of 1 coulomb per second (C/S).

- A current of 1 picoampere (pA or 10^{-12} A) represents the motion of approximately 6 million electrons.

- Drift is the motion of charges due to the application of an electric field.

- Diffusion is the motion of charges resulting from a nonuniform charge distribution.

- Mobility (μ) describes the ease with which charge carriers (e.g. electrons) drift in the material.

- Drift velocity $v_d = \mu \mathcal{E}$ m/s
μ is the mobility of the electron and is given in $[m^2 / V \cdot s]$

- Current I is the total charge passing through any area per unit time

$$I = \frac{qN}{T} = \frac{qN}{T} \cdot \frac{L}{L} = \frac{qN v_d}{L} \quad (A)$$

- Current Density: (J) current per unit area in the conducting medium

$$J = \frac{I}{A} = \left(\frac{A}{m^2}\right)$$

$$\Rightarrow \quad J = \frac{qN v_d}{LA} \quad \left(\frac{A}{m^2}\right)$$

- Volume concentration of electrons $n = \frac{N}{LA}$ (m^{-3})

$$\Rightarrow \quad J = q n v_d = \rho_v \cdot v_d \quad (A/m^2)$$

- $\rho_v = qn$ is the volume charge density (C/m^3)

$$\Rightarrow \quad J = q n \mu \mathcal{E} = \sigma \mathcal{E} \quad (A/m^2)$$

- Conductivity of the material

$$\sigma = q n u \quad (\Omega \cdot m)^{-1}$$

- Applied voltage across a conductor
$V = \mathcal{E} L$

$$\Rightarrow \quad I = JA = \sigma \mathcal{E} A = \sigma \mathcal{E} A \cdot \frac{L}{L}$$

$$= \frac{\sigma A}{L} V$$

$$= \frac{V}{R} \quad (A)$$

$\Rightarrow$ Resistance of the conductor

$$R = \frac{L}{\sigma A} = \rho \frac{L}{A}$$

wher ρ the resistivity is the reciprocal of the conductivity.

<u>Example 1</u> A conducting line on an IC chip is 2.8 mm long and has a rectangular cross section 1×4 μm. A current of 5 mA produces a voltage drop of 100 mV across the line. Determine the electron concentration given that the electron mobility is 500 $(cm^2/V.s)$.

<u>solution</u>

$$n = \frac{\sigma}{q\mu}$$

$$\sigma = \frac{IL}{VA} = \frac{5 \times 10^{-3} \times 2.8 \times 10^{-3}}{0.1 \times (10^{-6} \times 4 \times 10^{-6})}$$

$$= 3.5 \times 10^{7} \ (\Omega . m)^{-1}$$

$$n = \frac{\sigma}{q\mu} = \frac{3.5 \times 10^{7}}{1.6 \times 10^{-19} \times 500 \times 10^{-4}}$$

$$= 4.38 \times 10^{27} \ m^{-3} = 4.38 \times 10^{21} \ cm^{-3}$$

- As seen from the equation, conductivity is proportional to the concentration of charge carriers. The free electron concentration found in the example is a typical value for conductors.

- Few carriers are available in insulators and in the order of 10^7 m^{-3}.

- Semiconductors are a group of materials having conductivities between those of metals and insulators.
  - elementary semiconductors: are those from group (IV) such as silicon (Si) and Germanium (Ge).
  - compound semiconductors: combinations of group (III) and group (V) elements such as Gallium Arsenide (GaAs)

- Silicon, germanium, and gallium arsenide are the three most widely used semiconductors, but silicon is the predominant.

- Silicon has a total of 14 electrons in its atomic structure, four of which are valence electrons, so that the atom is tetravalent. It has a diamond crystal structure, shown below, where every atom has four nearest neighbors.

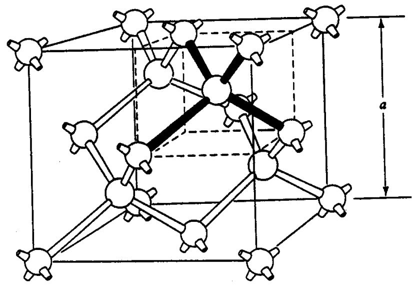
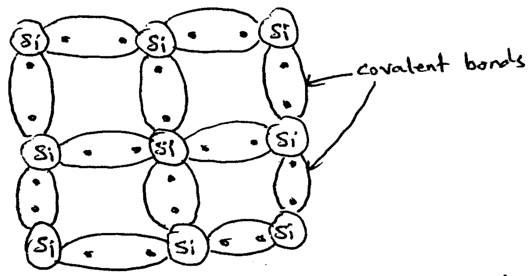


Figure The diamond structure.

- Atoms in group IV of the periodic table, such as silicon and germanium, tend to form covalent bonds. Each of these elements has four valence electrons and needs four more electrons to complete the valence energy shell.

- The silicon atom is formed into an infinite crystal, with each silicon atom having four nearest neighbors, with each neighbor atom contributing one valence electron to be shared, and hence eight shared electrons.



- The valence electrons serve to bind one atom to the next and this results in these electrons being tightly bound to the nucelus. Hence, in spite of the availability of four valence electrons, few of these are free to contribute to conduction.

- The total energy of a system in thermal equilibrium tends to reach a minimum value.

- At T = 0°K, all of the valence electrons are in the valence band. The upper energy band, the conduction band, is completely empty at T = 0°K.

- As the temperature increases above 0°K, a few valence band electrons may gain enough thermal energy to break the covalent bond and jump into the conduction band.

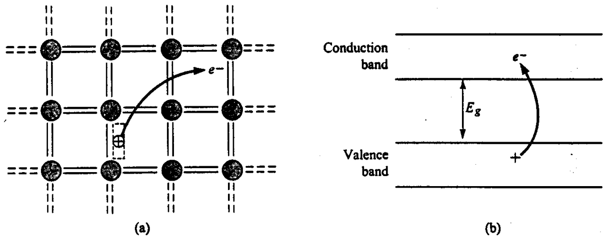


Figure (a) Two-dimensional representation of the breaking of a covalent bond. (b) The corresponding line representation of the energy band and the generation of a negative and positive charge with the breaking of a covalent bond.

- The semiconductor is neutrally charged. This means that as the negatively charged electron breaks away from its covalent bonding position, a positively charged "empty state" is created in the original covalent bonding position in the valence band. As the temperature increases, more covalent bonds are broken, more electrons jump to the conduction band, and more positive "empty states" are created in the valence band.

- <u>Concept of a hole</u>:
  - For $T > 0°K$, all valence electrons may gain thermal energy; if a valence electron gains a small amount of thermal energy, it may hop into the "empty state". The movement of a valence electron into the "empty state" is equivalent to the movement of the positively charged "empty state" itself.
  - The figure below shows the movement of valence electrons in the crystal alternately filling one "empty state" and creating a new "empty state", a motion equivalent to a positive charge moving in the valence band. The crystal now has a second equally important charge carrier that can give rise to a current. This charge carrier is called a <u>hole</u>.

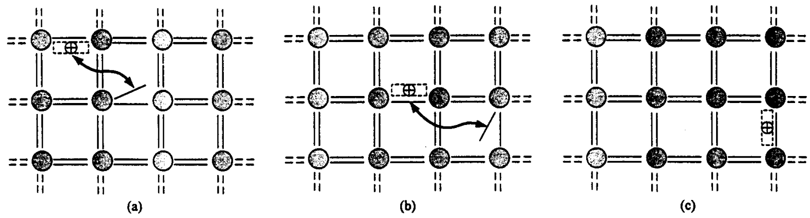


Figure Visualization of the movement of a hole in a semiconductor.

- Intrinsic Semiconductors: are pure crystals that contain no forign atoms or impurities.

- Each crystal has its own energy-band structure. Energy states in silicon are split to form the valence and conduction bands.

- Fermi energy is the energy below which all states are filled with electrons and above which all states are empty at $T = 0°K$.

- For an intrinsic semiconductor, at $T = 0°K$, all energy states in the valence band are filled with electrons and all energy states in the conduction band are empty of electrons. The fermi energy must, therefore, be somewhere between E_c (the energy conduction band) and E_v (the energy valence band).

- As the temperature begins to increase above $0°K$, the valence electrons will gain thermal energy. A few electrons in the valence band may gain sufficient energy to jump to the conduction band. As an electron jumps from the valence band to the conduction band, an empty state or hole is created in the valence band. In an intrinsic semiconductor, then, electrons and holes are created in pairs by the thermal energy so that the number of electrons in the conduction band is equal to the number of holes in the valence band.

- We may denote $\underline{n_i}$ and $\underline{p_i}$ as the electron and hole concentrations, respectively, in the intrinsic semiconductor. However, $\underline{\underline{n_i = p_i}}$, so we simply use the parameter n_i as the intrinsic carrier concentration, which refers to either the intrinsic electron or hole concentration.

- The Fermi energy level for the intrinsic semiconductor is called the intrinsic Fermi energy or $E_F = E_{Fi}$.

- The value of n_i is temperature dependent and increases with temperature.

- Both electrons and holes contribute to the conduction process. Because the mechanisms by which holes and electrons move about in the crystal differ, the mobilities of these charge carriers are different, and the subscripts p and n are used to distinguish hole and electron values. These charge carriers move in opposite directions in an electric field but as they are of opposite sign, the current of each is in the same direction.

- Current density $J = \sigma \mathcal{E} = q\,(n\mu_n + p\mu_p)\,\mathcal{E}$ $\quad (A/m^2)$
- Conductivity $\sigma = q\,(n\mu_n + p\mu_p)$ $\quad (\Omega m)^{-1}$

- For an intrinsic semiconductor $p = n = n_i$

  $\Rightarrow \sigma_i = q\,n_i\,(\mu_n + \mu_p)$ $\quad (\Omega m)^{-1}$

- Silicon has 5×10^{22} atoms$/cm^3$. At room temperature $(300°K)$, $n_i = 10^{10}\ cm^{-3}$. Hence, only 1 atom in about 10^{12} contributes a free electron (and also a hole) to the crystal because of broken covalent bonds.

Example 2 :

An intrinsic silicon bar is 3 mm long and has a rectangular cross section $50 \times 100\ \mu m$. At $300^\circ K$ determine the electric field intensity in the bar and the voltage across the bar when a steady current of $1\mu A$ is measured. Assume that the resistivity at $300^\circ K = 2.3 \times 10^5\ (\Omega.cm)$

Solution

$$\mathcal{E} = \frac{J}{\sigma} = \frac{I}{A} \cdot \frac{1}{\sigma} = \frac{I}{A} \cdot \rho \quad V/m$$

$$= \frac{10^{-6}\ (A)}{50 \times 10^{-6}\ (m) \times 100 \times 10^{-6}\ (m)} \times 2.3 \times 10^5 \times 10^{-2}\ (\Omega.m)$$

$$= 4.6 \times 10^5\ (V/m) = 4.6 \times 10^3\ (V/cm)$$

The voltage across the bar $V = \mathcal{E} L$

$$= 4.6 \times 10^3\ (V/cm) \times 3 \times 10^{-1}\ (cm) = \underline{1380\ V}$$

- The result here indicates that an extremely large voltage is needed to produce a small current ($1\mu A$). This is not surprising since the intrinsic carrier concentration is much closer to an insulator than a conductor.

- **Extrinsic Semiconductor :**

  To increase the number of carriers in an intrinsic semiconductor, a small carefully controlled impurity is added. The addition of impurities most often trivalent or pentavalent atoms forms an extrinsic or doped semiconductor.

- Each type of impurity establishes a semiconductor which has a predominance of one kind of carrier.
- The usual level of doping is in the range of 1 impurity atom for 10^6 to 10^8 silicon atoms. Thus, most physical and chemical properties are essentially those of silicon and only the electrical properties change.
- Pentavalent impurities donate excess electron carriers and are referred to as donor, or n-type impurity. Examples of pentavalent impurities are: phosphorous, arsenic, and antimony.
- Let us consider adding a group V element (pentavalent), such as phosphorous, as a substitutional impurity. A pentavalent atom has <u>five</u> valence electrons. Four of these will contribute to the covalent bonding with atoms of the silicon, leaving the fifth more loosely bound to the phosphorous atom, as shown below.

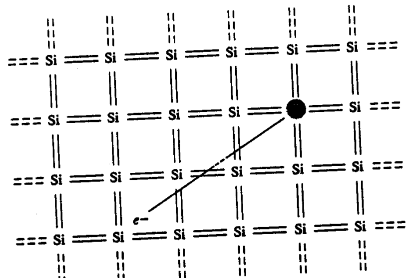


Figure Two-dimensional representation of the silicon lattice doped with a phosphorus atom.

- At very low temperatures, the donor electron is bound to the phosphorus atom. However, by intuition, it should seem clear that the energy required to elevate the donor electron into the conduction band is considerably less than that for the electrons involved in the covalent bonding.

- The energy required to detach this fifth electron from the atom is in the order of only 0.05 ev for silicon.
(1 ev = 1.6 X 10^{-19} J)

- The figure below shows the energy band diagram where the energy level, Ed, is the energy state of the donor electron.

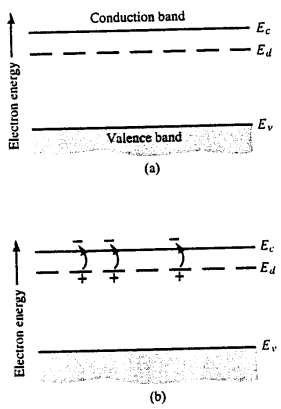


Figure The energy-band diagram showing (a) the discrete donor energy state and (b) the effect of a donor state being ionized.

- If a small amount of energy, such as thermal energy, is added to the donor electron, it can be elevated into the conduction band leaving behind a positively charged phosphorus ion. The electron in the conduction band can now move through the crystal generating current, while the positively charged ion is fixed in the crystal.

- This type of impurity atom donates an electron to the conduction band and so is called a donor impurity atom.

- The donor impurity atoms add electrons to the conduction band without creating holes in the valence band. The resulting material is referred to as an <u>n-type</u> semiconductor (n for the negatively charged electron).

- The majority charge carriers in an n-type semiconductor are electrons and the minority charge carriers are holes.

- <u>Trivalent impurities</u> have three valence electrons and when added to intrinsic semiconductors provide electrons to fill only three covalent bonds. The vacancy that exists in the fourth bond constitutes a hole. Thus, trivalent impurities are called <u>acceptors</u> and form p-type semiconductors in which holes are the predominant carrier. Examples of trivalent atoms are Boron, Gallium, and indium.

- Now consider adding a group III (trivalent) element, such as boron, as a substitutional impurity to silicon. As shown in the figure below, one covalent bonding position appears to be empty. If an electron were to occupy this "empty" position, its energy would have to be greater than that of the valence electrons. However, the electron occupying this "empty" position does not have sufficient energy to be in the conduction band, so its energy is far smaller than the conduction-band energy.

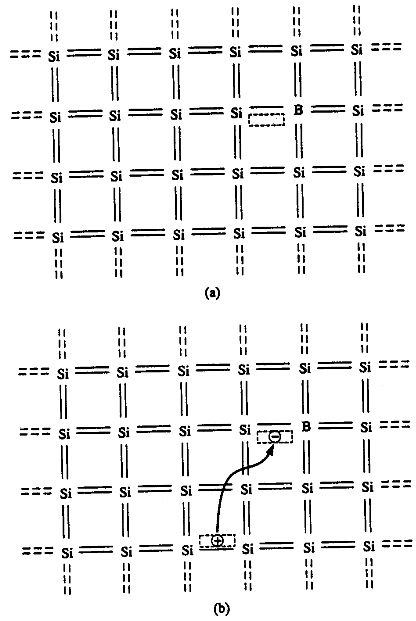


Figure Two-dimensional representation of a silicon lattice (a) doped with a boron atom and (b) showing the ionization of the boron atom resulting in a hole.

- It is shown in the figure how valence electrons may gain a small amount of energy and move about in the crystal. The "empty" position associated with the boron atom becomes occupied, and other valence electron positions become vacated. These other vacated electron positions can be thought of as holes in the semiconductor material.

- The figure below shows the expected energy state of the "empty" position and also the formation of a hole in the valence band. The hole can move through the crystal generating current, while the negatively charged boron atom is fixed in the crystal. The trivalent atom accepts an electron from the valence band and so is referred to as an <u>acceptor</u> impurity atom. The acceptor atom can generate holes in the valence band without generating electrons in the conduction band. This type of semiconductor material is referred to as a p-type material (p for the positively charged hole).

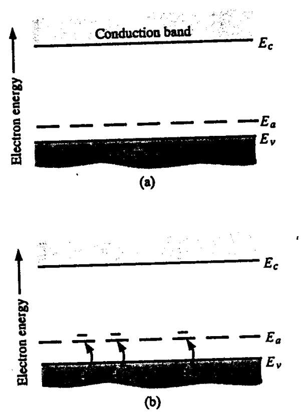


Figure The energy-band diagram showing (a) the discrete acceptor energy state and (b) the effect of an acceptor state being ionized.

- A small amount of energy is needed to ionize the impurity atoms. The temperatures at which electronic devices operate (> 200°K) provide sufficient thermal energy to ionize virtually all impurities. The ionization effect and the creation of electrons and holes in the conduction and valence bands are shown in the figure below.

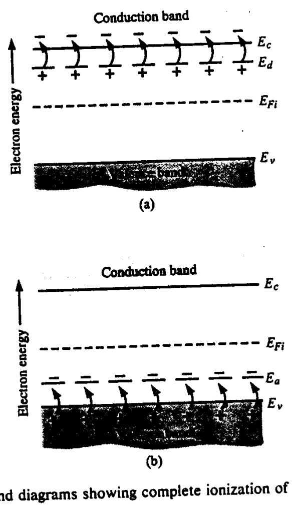


Figure Energy-band diagrams showing complete ionization of (a) donor states and (b) acceptor states.

- Mass action law:

  Under thermal equilibrium, the product of the free negative and positive concentrations is a constant independent of the amount of donor and acceptor impurity doping

$$\boxed{n\,p = n_i^2}$$

- Charge neutrality law:

  Under thermal equilibrium, the semiconductor crystal is electrically neutral. The electrons are distributed among the various energy states creating negative and positive charges, but the net charge density is zero.

- Let n_o and p_o be the thermal-equilibrium concentrations of electrons and holes in the conduction band and valence band, respectively.

- n_d is the concentration of electrons in the donor energy states.

- p_a is the concentration of holes in the acceptor energy states

- N_d and N_a are the concentrations of the donor and acceptor atoms, respectively.

- $N_d^+ = N_d - n_d$ is the concentration of ionized donors (positively charged)

- $N_a^- = N_a - p_a$ is the concentration of ionized acceptors (negatively charged)

- To maintain the electric neutrality of the crystal, the concentration of the positive charges must equal the concentration of the negative charges.

$$\Rightarrow \boxed{n_o + N_a^- = p_o + N_d^+}$$

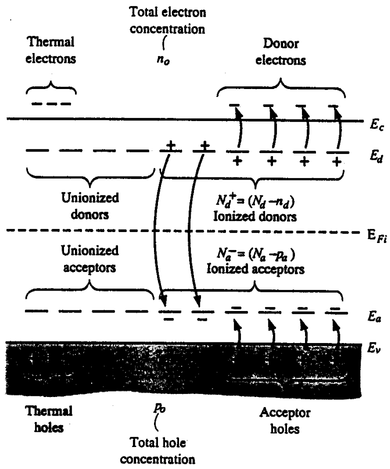


Figure Energy-band diagram of a compensated semiconductor showing ionized and un-ionized donors and acceptors.

$$\Rightarrow \quad n_o + (N_a - p_a) = p_o + (N_d - n_d)$$

if we assume complete ionization, n_d and p_a are both zero, and this leads to

$$\Rightarrow \quad n_o + N_a = p_o + N_d$$

if we express p_o as $\frac{n_i^2}{n_o}$

$$\Rightarrow \quad n_o + N_a = \frac{n_i^2}{n_o} + N_d$$

$$\Rightarrow \quad n_o^2 - (N_d - N_a)\, n_o - n_i^2 = 0$$

$$\Rightarrow \quad n_o = \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}$$

The positive sign in the quadratic formula must be used since in the limit of an intrinsic semiconductor when $N_a = N_d = 0$, the electron concentration must be a positive quantity, or $n_o = n_i$.

- The concentration of electrons in the conduction band increases above the intrinsic carrier concentration as we add impurity atoms. At the same time, the minority carrier hole concentration decreases below the intrinsic carrier concentration as we add donor atoms.

- As we add donor impurity atoms and the correspond. donor electrons, there is a redistribution of electrons among available energy states. A few of the donor electrons will fall into the empty states in the valence band, and in doing so will annihilate some of the intrinsic holes. The minority carrier hole concentration will therefore decrease. At the same time, because of this redistribution, the net electron concentration in the conduction band is not simply equal to the donor concentration plus the intrinsic electron concentration.

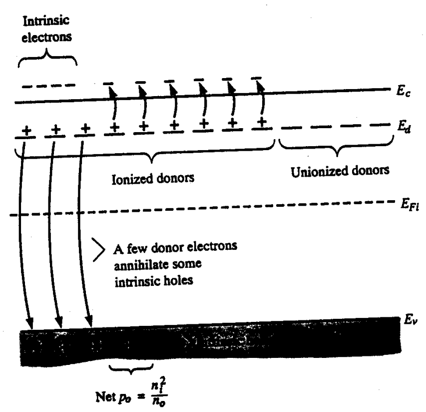


Figure 4–15 Energy-band diagram showing the redistribution of electrons when donors are added.

- Similarly, if we express n_o as $\frac{n_i^2}{p_o}$ in the charge neutrality equation

$$\Rightarrow \frac{n_i^2}{p_o} + N_a = p_o + N_d$$

$$\Rightarrow p_o^2 - (N_a - N_d)\, p_o - n_i^2 = 0$$

$$\Rightarrow p_o = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2}$$

- Note that in an n-type material having $N_A = 0$, since $n_o >> p_o \Rightarrow n_o \simeq N_D$ i.e., free-electron concentration is approximately equal to the density of donor atoms.
  The concentration of holes, p_o, in the n-type semiconductor is $p_o \approx \frac{n_i^2}{N_D}$

- Similarly, in a p-type material having $N_D = 0$, we have $p_o \simeq N_A$ since $p_o >> n_o$, and $n_o \approx \frac{n_i^2}{N_A}$

Example 3

An n-type silicon sample is 3 mm long and has a rectangular cross section 50×100 μm. The donor concentration at $300^\circ K$ is 5×10^{14} cm^{-3} and corresponds to 1 impurity atom for 10^8 silicon atoms. A steady current of 1 μA exists in the bar. Determine the electron and hole concentrations, the conductivity, and the voltage across the bar. Assume that $n_i = 1.45 \times 10^{10}$ (cm^{-3}), $\mu_n = 1500$ $[cm^2/v.s]$.

Solution

- Since the material is n-type, $n \gg p$

$\Rightarrow \quad n \simeq N_D = 5 \times 10^{14} \ cm^{-3}$

$$p = \frac{(n_i)^2}{n} = \frac{(1.45 \times 10^{10})^2}{5 \times 10^{14}} = 4.2 \times 10^{5} \ cm^{-3}$$

- $\sigma = q\,(n\,\mu_n + p\,\mu_p)$

Since $n \gg p \Rightarrow \sigma \simeq q\,n\,\mu_n$

$= 1.6 \times 10^{-19} \times 5 \times 10^{14} \times 1.5 \times 10^{3}$

$= 0.12 \ (\Omega.cm)^{-1}$

- voltage across the bar $= \mathcal{E} L = \frac{J}{\sigma} L$

$$= \frac{I}{A} \cdot \frac{L}{\sigma} = \frac{10^{-6} \times 0.3}{(5 \times 10^{-3}) \times (10^{-12}) \times 0.12} = 0.05\,V$$

- This reduction of voltage exactly equals the decrease in resistivity (from 2.3×10^{5} to $\frac{1}{\sigma} = 8.33 \ \Omega.cm$), Yet the dramatic increase in the number of free electrons (1.45×10^{10} to $5 \times 10^{14} \ cm^{-3}$) occurs when only 1 silicon atom in 100 million is replaced by an impurity atom.

- with increasing temperature, the density of hole-electron pairs increases in an intrinsic semiconductor.

- Mobility, μ, decreases with temperature because more electrons and holes are present and those carriers are more energetic at higher temperatures. This results in an increased number of collisions and μ decreases.

- The conductivity of an intrinsic semiconductor increases with increasing temperature because the increase in hole-electron pairs is greater than the decrease in their mobilities.

- The electron mobility is higher than the hole mobility $\mu_e \simeq 2.5\,\mu_h$