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Semiconductor Physics

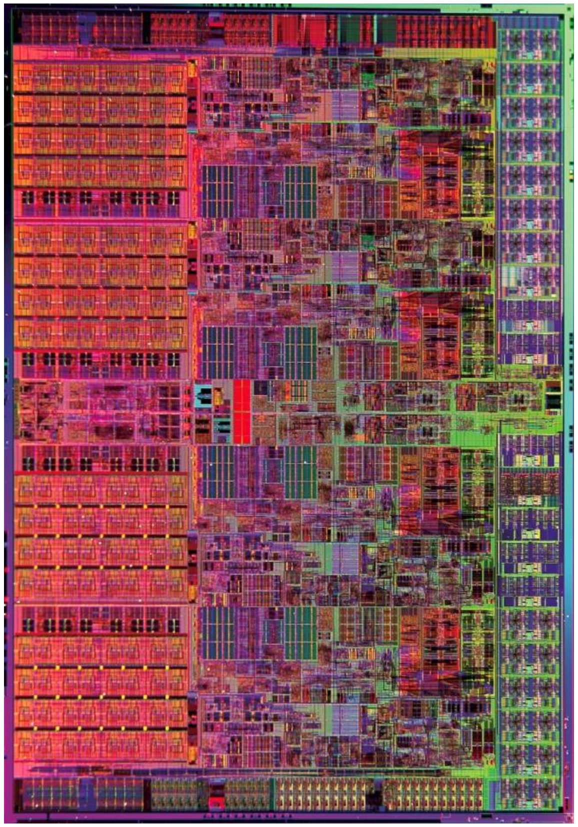
1. Introduction
2. Charge Carriers in Semiconductors
3. Doping of Semiconductors
4. Carrier Transport Phenomena

Reference

- Sedra and Smith, 5th Edition, Oxford University Press, pp. 114 – 120.

1. Introduction

An IC comprises millions of interconnected transistors, resistors, capacitors, etc.



Intel Core i7 Processor
45nm process technology
731 million transistors

Metals – used for interconnects, contacts, and in the transistor structure. *Examples*: aluminium, copper, tungsten, polysilicon, metal silicides.

Dielectrics – for electrical insulation, mechanical support and environmental protection; part of device structure (transistor, capacitor dielectric). *Examples*: silicon dioxide, silicon nitride, various polymers.

Semiconductors – used to make the active device (transistors, LEDs, lasers). *Examples*: silicon, germanium, GaAs in crystalline form.

1.1 Semiconductors

So called because they have electrical conductivities between that of metals (conductors) and insulators*.

	Material	Resistivity (Ω-cm)	Typical carrier concentration (cm^{-3})
Metal	Copper Gold Aluminium Stainless Steel 316	1.69×10^{-6} 2.20×10^{-6} 2.67×10^{-6} $70-78\times10^{-6}$	Around ~10^{23}
Semi-conductor	Germanium Silicon Gallium Arsenide	46 2.3×10^{5} 10^{8}	Wide range up to ~$10^{18\text{-}19}$
Insulator	Silicon nitride Silicon dioxide Polyimide	10^{14} $10^{14}-10^{16}$ 10^{18}	Negligible

Resistivity at room temperature

*Note, however, that semiconductors have unique properties that make them substantially different from metals (conductors) and insulators.

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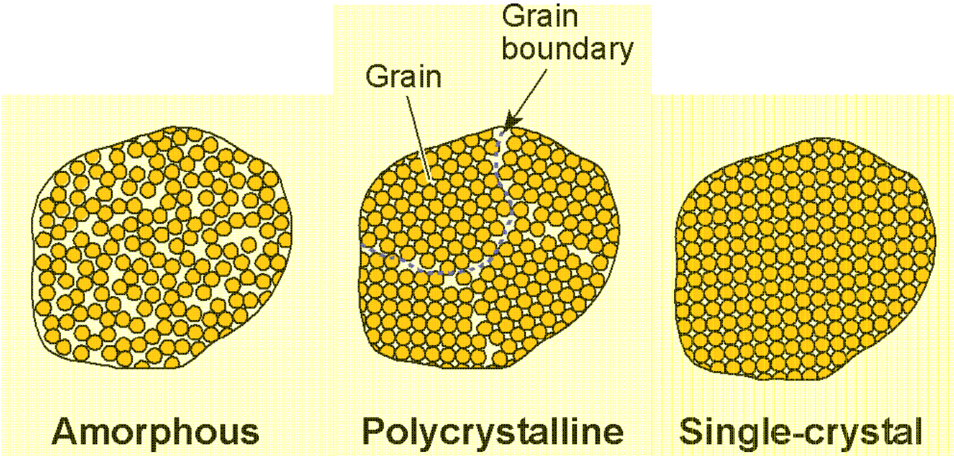
Semiconductor Physics - Introduction

One of the ways solids can be classified is by how orderly their atoms are arranged :

- Amorphous
  Order in the range of a few atoms or on molecular dimensions
- Single-crystal
  One large crystal making up entire volume of material.
  Regularity of atomic arrangement present throughout entire solid.
- Polycrystalline
  High degree of order over many atomic / molecular dimensions.
  Ordered single-crystal regions are called *grains*.
  Grains vary in size and orientation.
  Grains are separated by *grain boundaries*.



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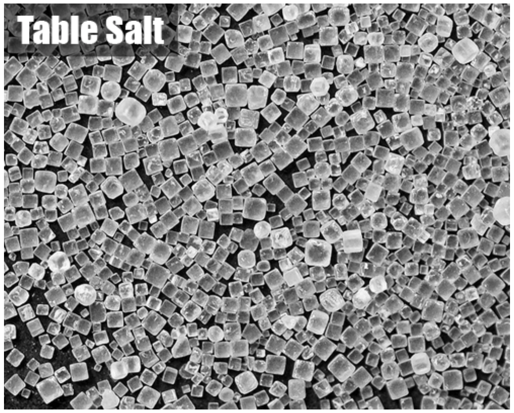
Semiconductor Physics - Introduction

- In our study of semiconductors, we will mainly focus on crystalline solids.
- Examples of crystals are table salt (sodium chloride), diamond (which is a crystalline form of carbon) and crystalline silicon.



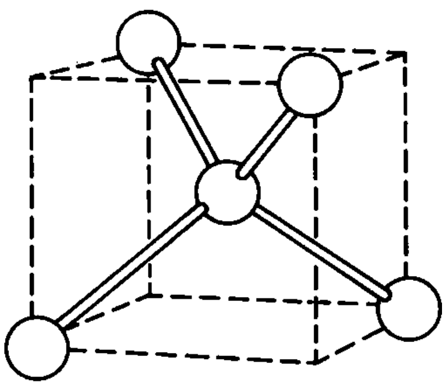
sodium chloride crystals

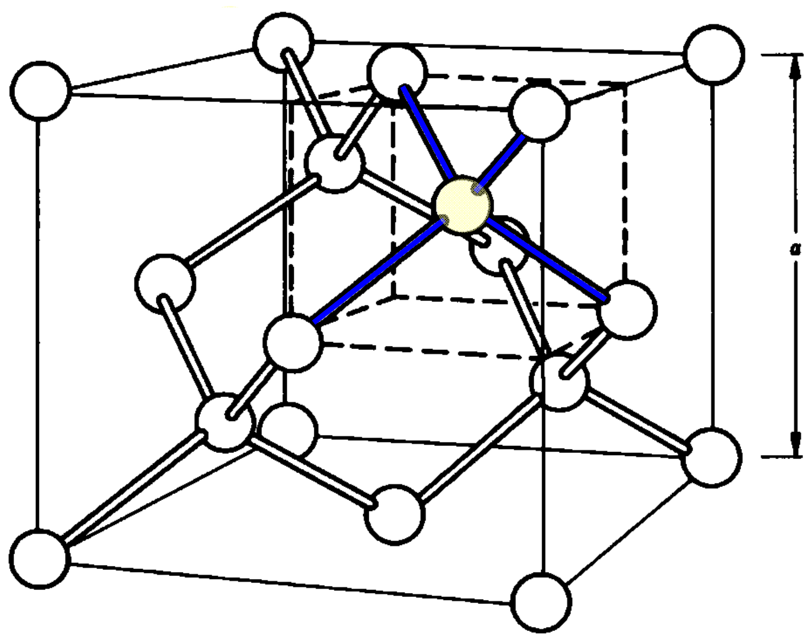
diamond

crystalline silicon
ingots and wafers

1.2 Bond Model of Semiconductors

- In a *crystal*, the atoms form bonds with neighboring atoms, and are arranged in a regular manner, positioned on a periodic array of points in space.
- The silicon atoms are arranged symmetrically in space – the 4 atoms are arranged in a tetrahedron around the central atom.
- If we replicate the arrangement of atoms in a silicon crystal, we end up with the *diamond crystal structure*.





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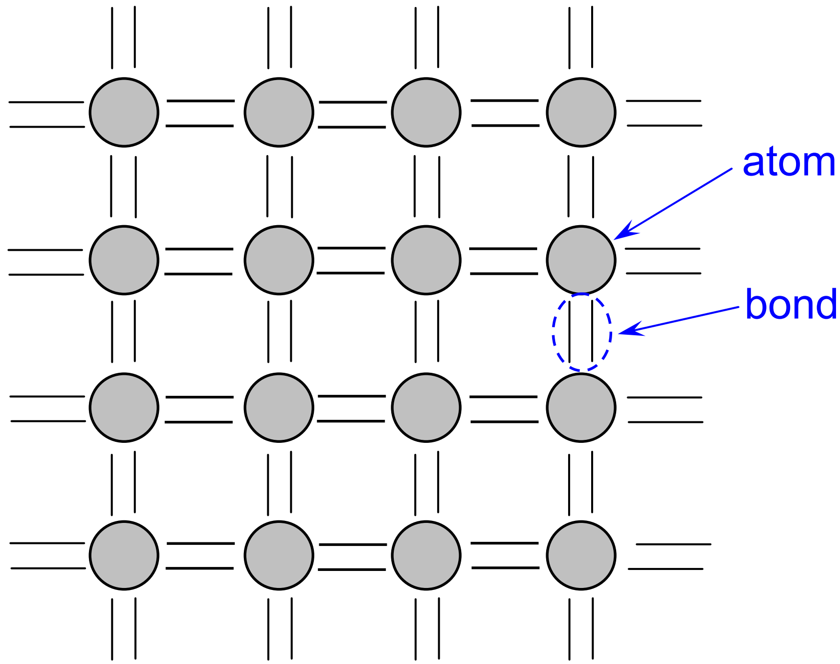
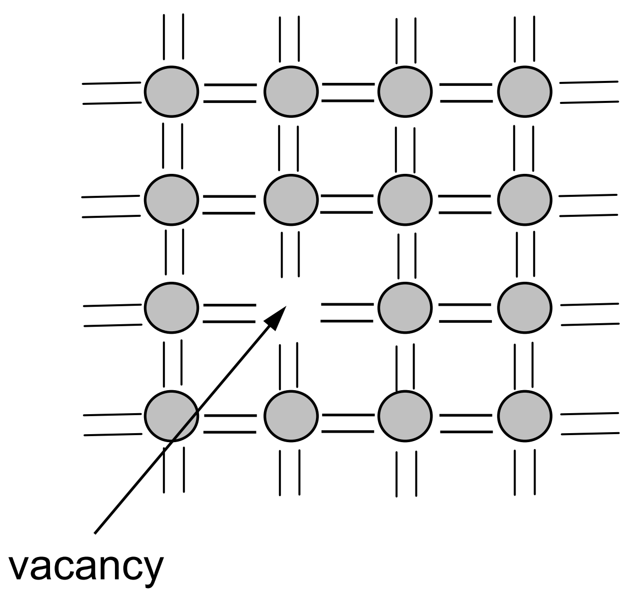
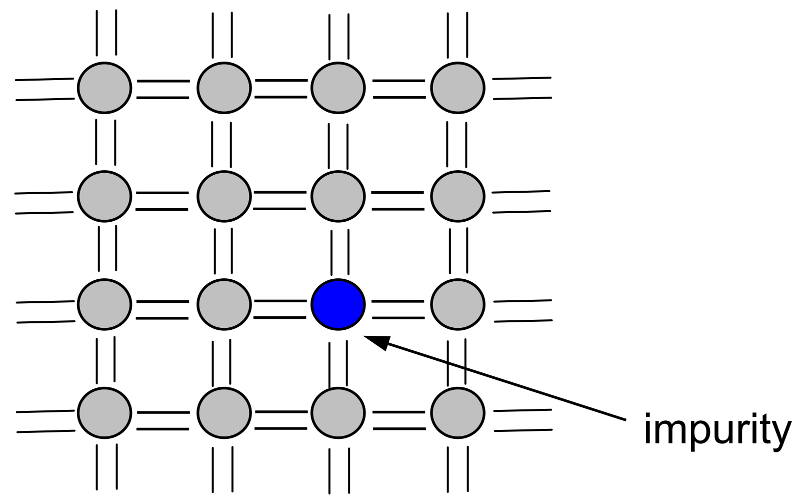
- The 3-dimensional crystals structure is often depicted schematically in a simple, 2-dimensional representation.



Semiconductor Physics - Introduction

- Crystals are seldom perfect. Two examples of imperfections are shown schematically below.





- The properties of the crystal are influenced by the type and amount of imperfections in the crystals.

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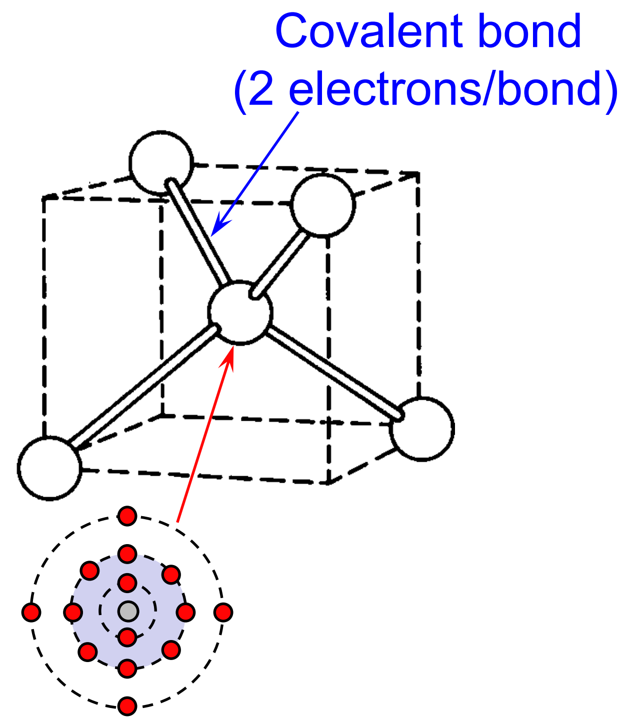
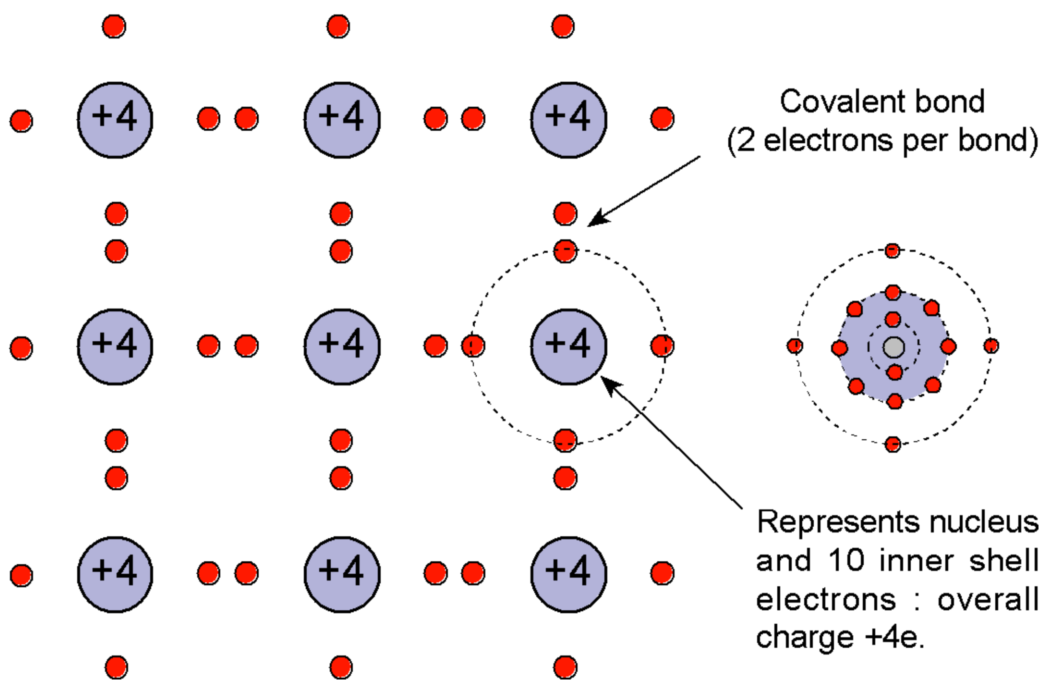
- In a crystal, the atoms are arranged in a regular manner, and they form bonds with other atoms in the crystal.
- Silicon has 4 electrons in its outermost shell. These are called valence electrons.
- In the bond model of silicon, a silicon atom is bonded to 4 other silicon atoms by covalent bonds – each covalent bond involves the sharing of a pair of electrons (one from each atom).



- At T = 0K, all the valence electrons are involved in covalent bonds. There are no free electrons for electrical conduction. (Inner core electrons are tightly bound to the nucleus and are thus not mobile.)

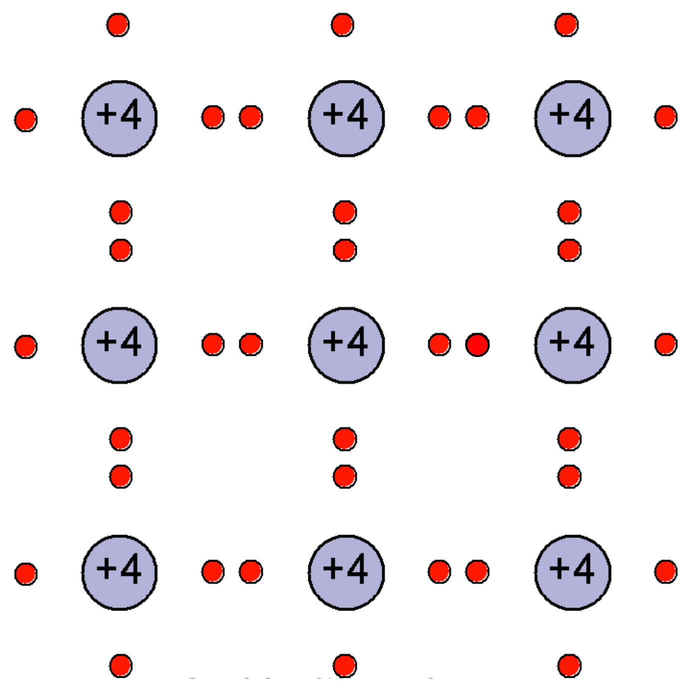
- In 2-dimensional representation:



Silicon at *T* = 0K

Semiconductor Physics – Charge Carriers in Semiconductors

- At temperatures above 0K, some of the electrons have sufficient thermal energy to break free from the covalent bonds.
- The energy required to break the covalent bonds is called the band gap energy, E_g. For silicon E_g = 1.12 eV, where 1 eV = 1.602 x 10^{-19} J.
- The "free" electron are now mobile can take part in electrical conduction. They are thus known as *conduction electrons*.



Conduction Electron

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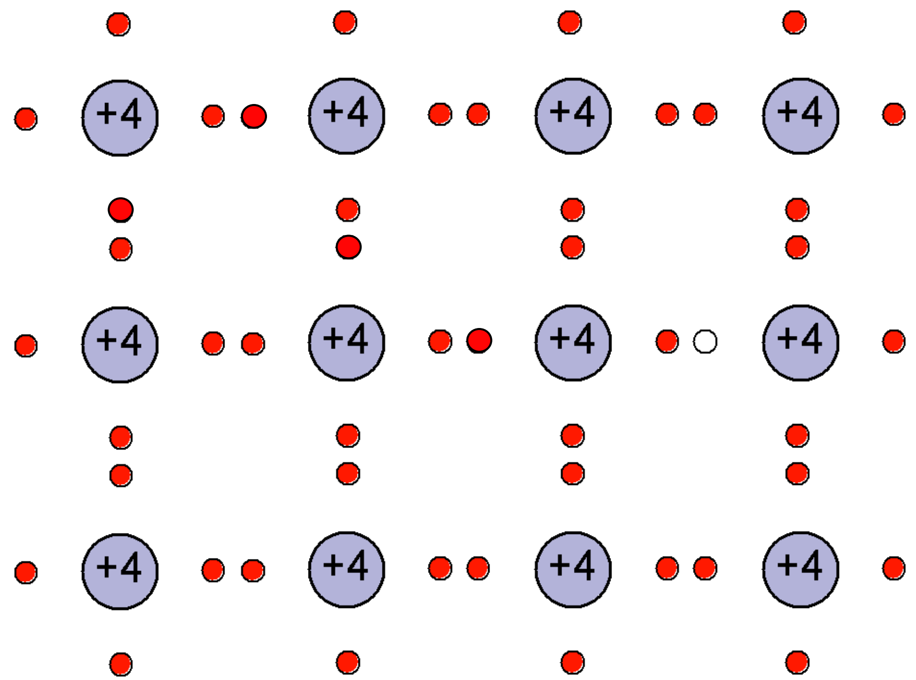
Semiconductor Physics – Charge Carriers in Semiconductors

- The empty state left behind cannot in itself carry current, but it allows other electrons the opportunity of moving without any net input of energy into the system – the energy to break a bond will be "given back" to the system when a new bond is formed.
- As another electron moves into the space, it leaves another behind it, etc.



Successive movement of electrons into spaces left behind

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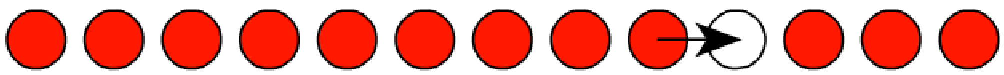
Semiconductor Physics – Charge Carriers in Semiconductors

- Instead of seeing a successive movement of electrons, we can instead consider the motion of the “space” that is left behind.
- The net charge surrounding the “space” is +*q*, where *q* (= 1.602 x 10^{-19}) is the elementary charge.
- The moving space may be treated as if it were a positively charged particle, called a *hole*.



Successive movement of electrons seen as a movement of a hole

- The motion of the hole is independent of the electron that once occupied that state. Holes are thus independent carriers.

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Semiconductor Physics – Charge Carriers in Semiconductors

- There are two types of charge carriers in a piece of semiconductor. They are conductions electrons# and holes.

- Charge of an electron = $-q$ = – 1.602 x 10^{-19} C
- Charge of a hole = $+q$ = + 1.602 x 10^{-19} C

From now on, unless the context indicates otherwise, when we say an "electron" in a piece of semiconductor, we mean a "conduction electron".

- At *thermal equilibrium*, the electron concentration, $n_0\ (\mathrm{cm}^{-3})$, and the hole concentration, $p_0\ (\mathrm{cm}^{-3})$, can be written as:

  $n_0 = p_0 = n_i$ where n_i is known as the *intrinsic carrier concentration.*

  The subscript "$_0$" is used to denote thermal equilibrium conditions.

- Note that $n_0 p_0 = n_i^2$. This is known as the Law of Mass Action.

- The value of n_i is a function of the material and temperature. For silicon, at 300K, $n_i = 1.5\times10^{10}\,\mathrm{cm}^{-3}$.

Thermal Equilibrium

At thermal equilibrium, the energy in a system is everywhere equalized and evenly distributed, and is at equilibrium with its ambient temperature. There is no energy input (or output) from heat, voltage, or optical excitation.

There is no net motion of charge (no net current flow), on a macroscopic scale, even though there may be random fluctuations of the charges or current in a microscopic scale i.e., noise).

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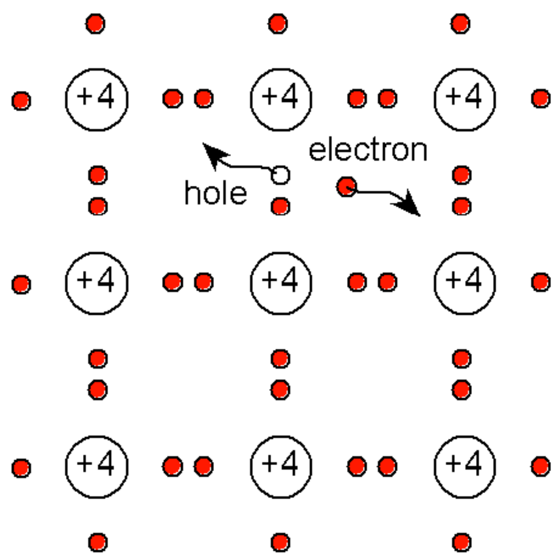
Carrier generation and recombination

- At absolute zero (T = 0K), all the covalent bonds in the semiconductor are intact.

- At finite temperatures, statistically, some of the electrons are able to break out of the covalent bonds, creating (conduction) electrons.

- The vacancies left behind result in the formation of holes This simultaneous creation of an electron-hole pair (EHP) is called a *generation* process.



EHP Generation

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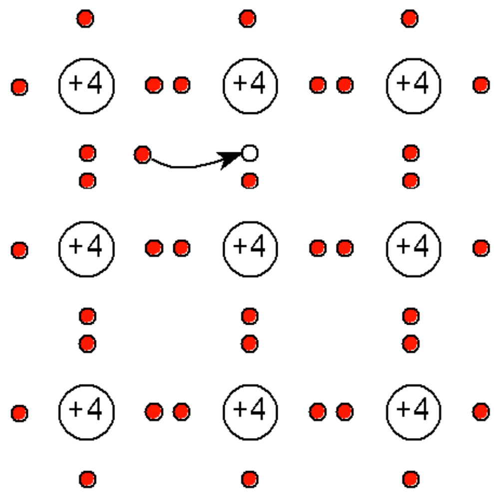
- When an electron, wandering around the crystal, “meets” a hole, it falls into this low-energy empty state and fills it (thus reforming the covalent bond), and an electron-hole pair is annihilated. This process is called recombination.



Recombination leading to annihilation of EHP

- At thermal equilibrium, the generation rate and recombination rate are equal. This dynamic equilibrium establishes a population of electrons and holes in the semiconductor that is constant with time, except for small random fluctuations.

Semiconductor in Non-Thermal Equilibrium Condition

- Non-thermal equilibrium condition can occur when external energy is supplied to the semiconductor. For example, by irradiating the semiconductor with light or some other energetic photons, in a process known as *photogeneration*, additional electron-hole pairs (EHPs) can be created.
- This can only happen provided the photon energy is greater than the energy needed to break the covalent bonds in the semiconductor.
- The additional electrons and holes generated are called *excess electrons* and *excess holes*.
- Under such circumstances, the semiconductor is no longer in thermal equilibrium – there is an input of (light) energy into the semiconductor, and the carrier concentrations are no longer those at thermal equilibrium (TE).

$$n = n_0 + \Delta n$$
$$p = p_0 + \Delta p$$

where

Δn : excess electron concentration

Δp : excess hole concentration

- Quite clearly, under non-thermal equilibrium conditions, $pn \neq p_0 n_0 = n_i^2$
- Excess carrier in a region of the semiconductor can also be supplied from another part of the semiconductor (as we shall see later in pn junctions).

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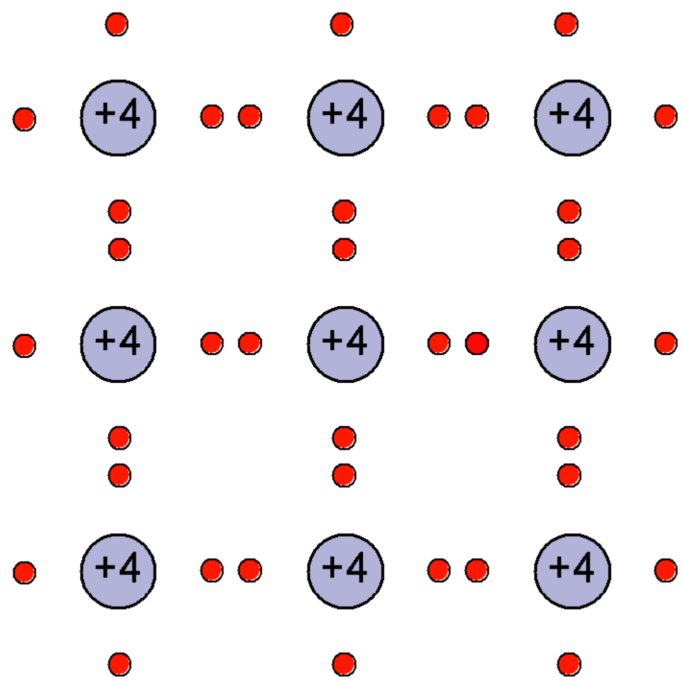
3.1 Undoped Semiconductors

- We have considered pure and ideal semiconductors with *no impurities* so far.
- The properties of the semiconductor are intrinsic to the material, and such semiconductors are said to be *intrinsic semiconductors*.
- In intrinsic semiconductors, the electron and hole concentrations are equal, since every electron that breaks out of a Si bond also results in the formation of a hole.



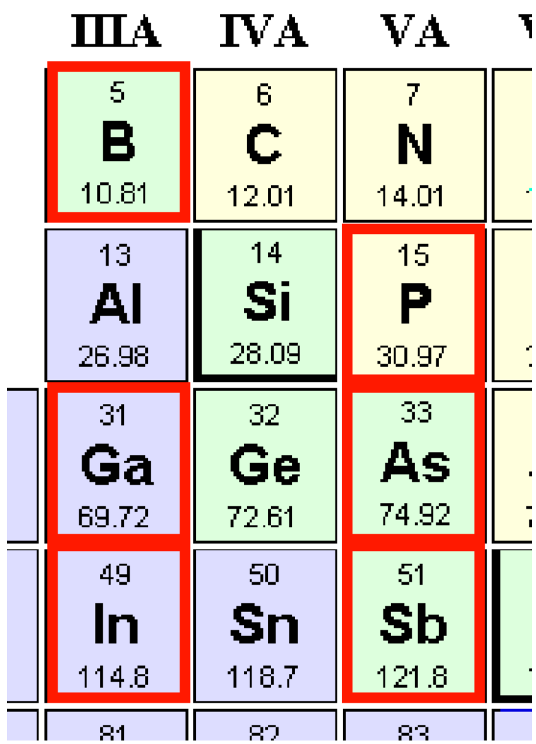
3.2 Doped Semiconductors

- Elements in Groups III & V of the periodic table are incorporated as impurities in Group IV semiconductors such as Ge and Si.

B = Boron

Ga = Gallium

In = Indium



P = Phosphorus

As = Arsenic

Sb = Antimony

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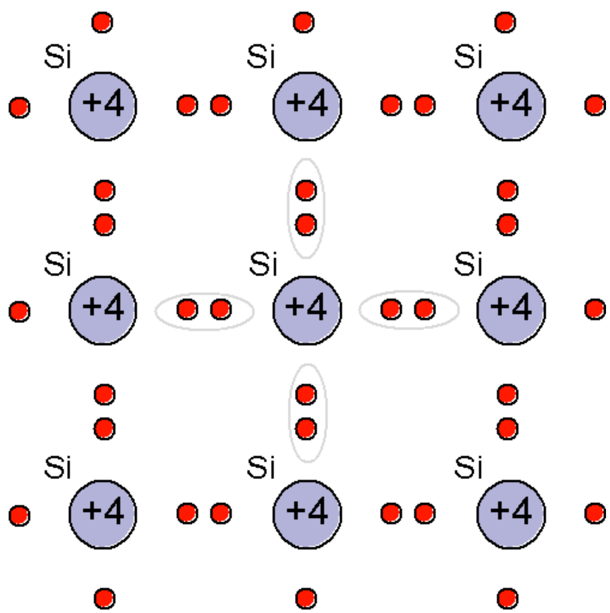
Semiconductor Physics – Doping of Semiconductors

3.2.1 Donors

- *Donors* for silicon (Group IV) come from Group V of the periodic table (e.g. P, As, Sb). Group V elements have 5 valence electrons.
- If an As atom replaces a Si atom (i.e., it forms a *substitutional impurity*) it will form 4 covalent bonds with the 4 surrounding Si atoms. This leaves an unbonded 5th electron.



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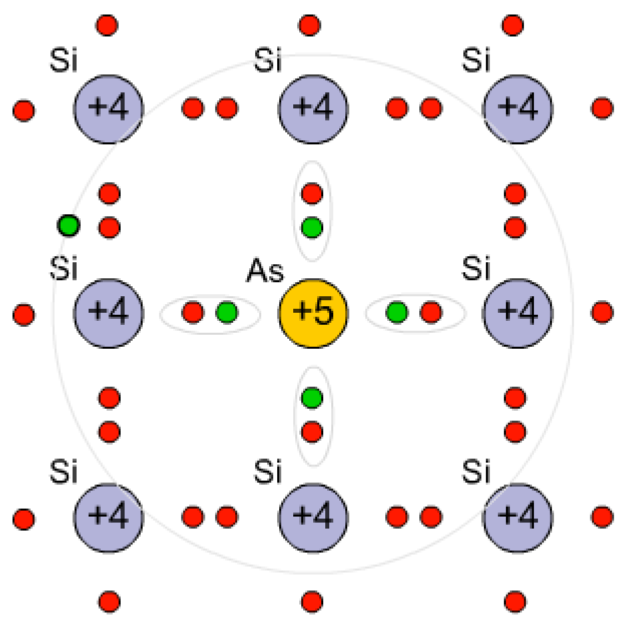
- If an As atom replaces a Si atom (i.e., it forms a *substitutional impurity*) it will form 4 covalent bonds with the 4 surrounding Si atoms. This leaves an unbonded 5th electron.
- The 5th electron is loosely coupled to the parent As atom, and at $T \rightarrow 0$K remains bound to the parent (like an electron orbiting the nucleus).



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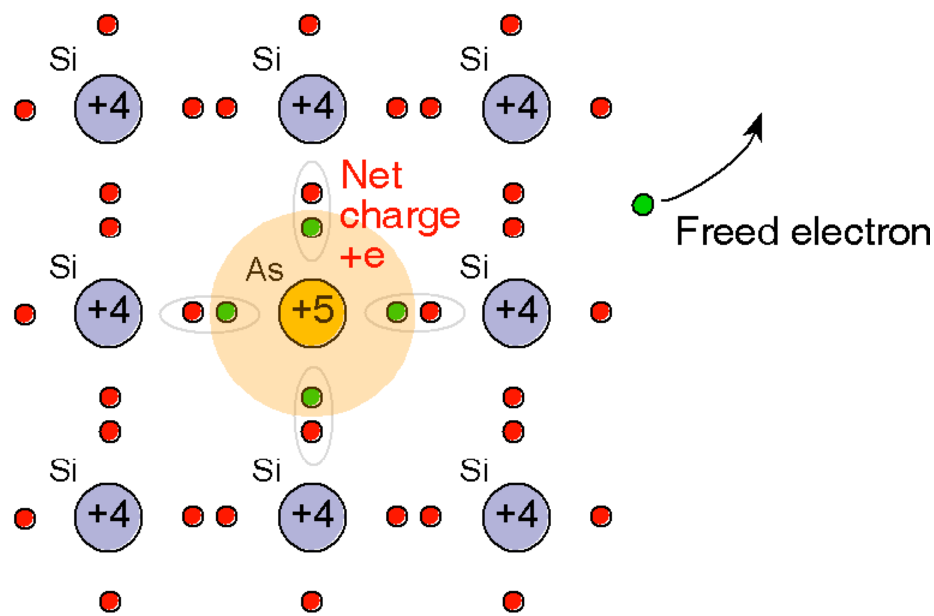
Semiconductor Physics – Doping of Semiconductors

- The amount of energy required to free the loosely-bound electron is of the order of 10s of meV in Silicon. This energy is called the ionization energy.
- As the temperature increases, more and more of the As atoms become ionized. At T > ~150K, practically all the As atoms in Si are ionized.
- The freed electron can now conduct electricity.
- The As atom is now ionized and becomes an As^+ ion, but this ion is covalently bonded to the Si lattice. It is not a charge carrier, but a fixed +ve charge, called an ionised donor.



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Semiconductor Physics – Doping of Semiconductors

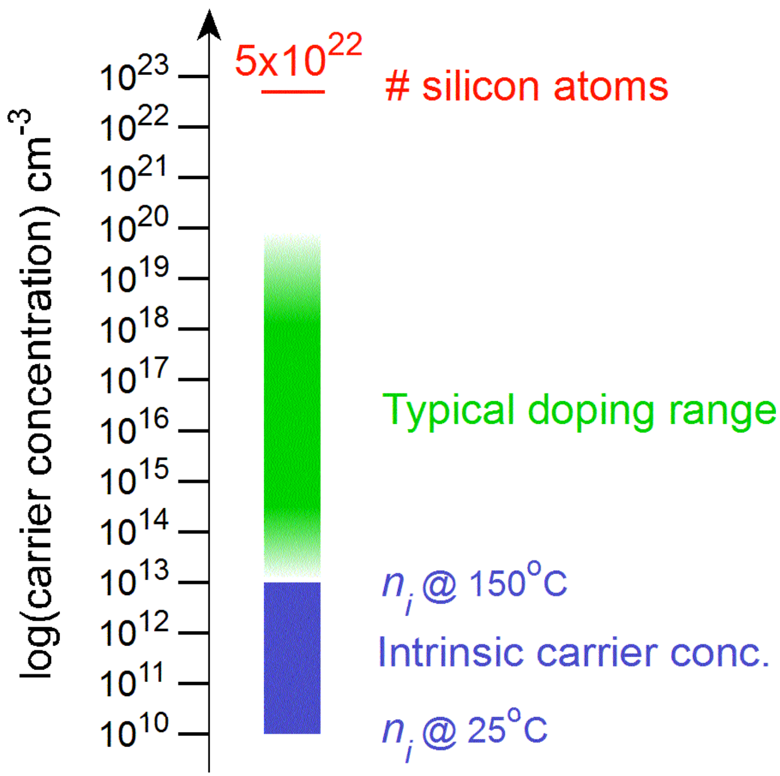
- The As atom is known as a *donor* in the Si lattice since it donates a (conduction) electron when it is ionized.
- Other Group V elements also act as donors in Group IV Si and Ge.
- An otherwise pure semiconductor that has impurities introduced (donors or acceptors) is said to be *doped*. The impurities are called *dopants*.

Semiconductor Physics – Doping of Semiconductors

- If there are N_D (cm^{-3}) donors in the crystal lattice, they will contribute N_D electrons to the semiconductor when they are fully ionized.
- Note that an equal number of positively charged donor ions are left behind, so the *material remains electrically neutral*.

By the way...

- Doping concentrations (10^{13} – 10^{19} cm^{-3}) are LOW compared to the number of silicon atoms (5×10^{22} cm^{-3} for Si).
- The doping concentrations are typically HIGH compared to the intrinsic carrier concentration at typical device operating temperatures (for Si: ~ 10^{10} cm^{-3} at room temperature, ~ 10^{13} cm^{-3} at 150°C).



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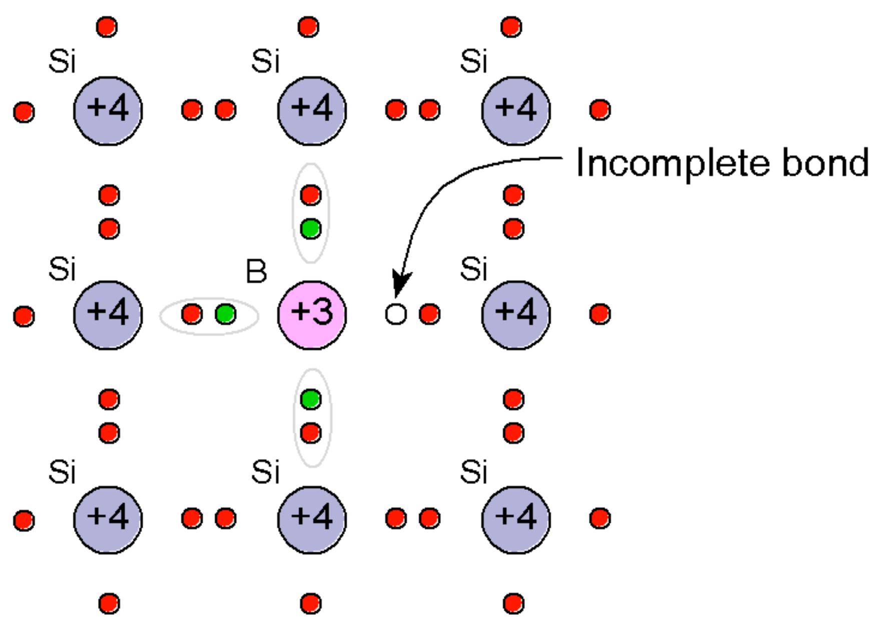
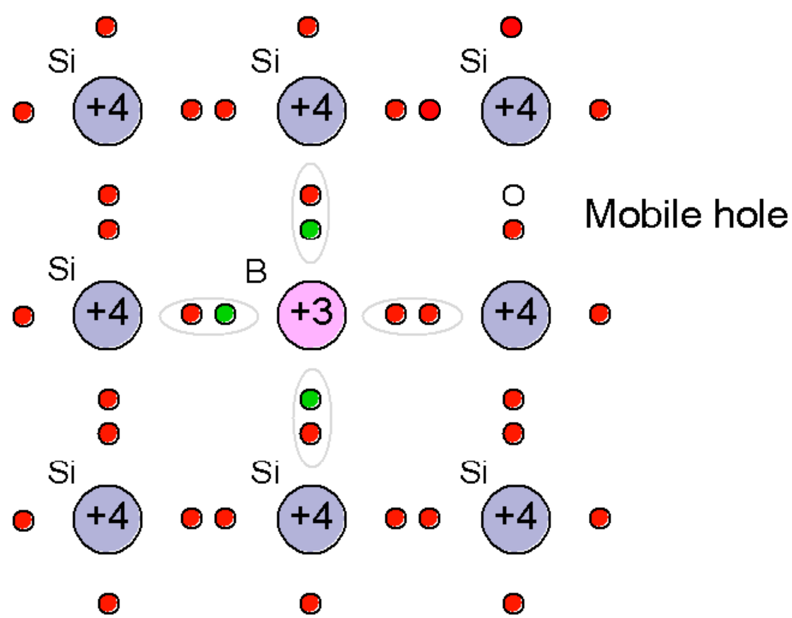
3.2.2 Acceptors

- *Acceptors* for silicon (Group IV) come from Group III of the periodic table (e.g. B, Ga, In). Group III elements have 3 valence electrons.
- They accept electrons from the silicon lattice to create holes.
- If a B atom replaces a Si atom (i.e., it forms a substitutional impurity) it will form 3 covalent bonds with the 3 surrounding Si atoms. This leaves an incomplete 4th bond.



Semiconductor Physics – Doping of Semiconductors

- At T = 0K, the empty state resulting from the incomplete 4th bond is not free to move – it is bound to the parent B atom, and hence it is <u>not</u> a hole.
- You need an ionization energy of ~ 0.05 eV in order to create a (mobile) hole.
- The reason is that a Si-Si bond is stronger than a B-Si bond. To break a Si-Si bond, you need an energy, E_g ~1.12eV. When a B-Si bond is formed, you only get back (1.12 eV - 0.05eV) = 1.07 eV.



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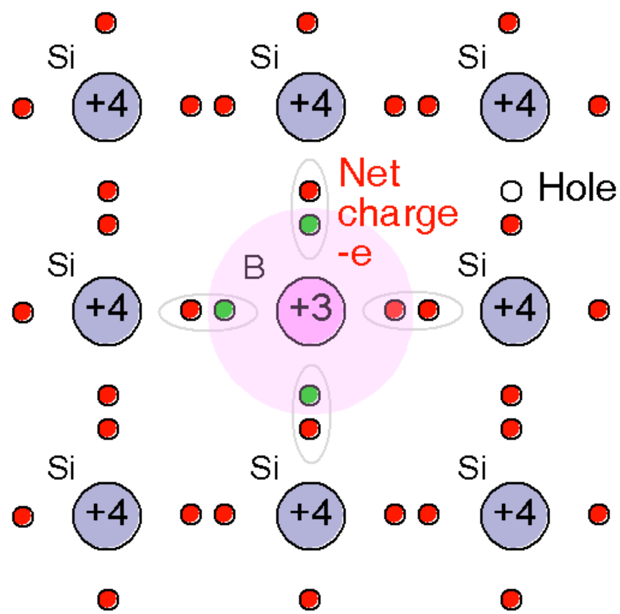
Semiconductor Physics – Doping of Semiconductors

- The amount of energy required to create a hole is of the order of 10s of meV in Silicon.
- As the temperature increases, more and more of the B atoms become ionized. At T > ~150K, practically all the B atoms in Si are ionized.
- The hole created can now conduct electricity.
- The B atom is now ionized and becomes an B^- ion, but this ion is covalently bonded to the Si lattice. It is not a charge carrier, but a fixed –ve charge, called an ionised acceptor.



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Semiconductor Physics – Doping of Semiconductors

- If there are N_A (cm^{-3}) acceptors in the crystal lattice, they will contribute N_A holes to the semiconductor when they are fully ionized. Note that an equal number of negatively charged acceptor ions are left behind, so the material remains electrically neutral.

3.2.3 Extrinsic semiconductors

- Carrier concentrations (electrons or holes) introduced by dopants are usually much higher than the intrinsic carrier concentration of the semiconductor.
- e.g., $n = 10^{15}$ cm^{-3} for Si doped with 10^{15} cm^{-3} donors, compared with $n_i \sim 1.5 \times 10^{10}$ cm^{-3} at T = 300K.
- The electron & hole concentrations of the Si are then no longer controlled by the intrinsic properties of Si, but by the dopants.
- The semiconductor is then said to be an *extrinsic* semiconductor.

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3.2.4 Summary of properties of donors & acceptors

	Donors	Acceptors
Valence electrons	One more valence electron than host semiconductor.	One fewer valence electron than host semiconductor.
For Group IV host	Group V elements	Group III elements
Carrier created	Electrons	Holes
Ionized dopant	Positive, fixed charge	Negative, fixed charge

3.3 Majority and Minority Carriers

- In an undoped semiconductor, electrons and holes are created in pairs.
- At thermal equilibrium, $p_0 = n_0 = n_i$, where n_i = 1.5 x 10^{10} cm^{-3} for Si at 300K.
- Consider donor doping. When you dope a semiconductor with donors, at 300K, each donor will contribute 1 conduction electron.
- Usually the doping levels are such that $N_D >> n_i$, so the electron concentration is $n \approx N_D$.
- Hence if N_D = 10^{15} cm^{-3}, then n = 10^{15} cm^{-3} >> n_i.
- *Q*: What happens to the hole concentration?

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Semiconductor Physics – Doping of Semiconductors

- Consider first a piece of an intrinsic silicon at thermal equilibrium. There are equal number of electrons and holes, with $n_0 = p_0 = n_i$.
- Electron-hole pairs are *generated* by the breaking of covalent bonds, and, for a given semiconductor, the generation rate is a function of temperature. Hence, at a given temperature, the generation rate is constant.
- An electron can also encounter a hole and re-establish the covalent bond. This process is called recombination. The recombination rate is proportional to the concentrations of the electrons and holes.
- At thermal equilibrium, the generation rate and the recombination rate are equal. The concentrations of the electrons and holes therefore do not change with time.
- The system is said to be in dynamic equilibrium in which a process is balanced by its inverse process.

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Semiconductor Physics – Doping of Semiconductors

- Consider now that $N_D = 10^{15}$ cm^{-3} donors are introduced into the piece of silicon. Assuming full ionization, this will produce 10^{15} cm^{-3} additional electrons in the silicon.
- Initially, due to the increased electron concentration, there is an increased recombination rate, which results in a reduction of the hole concentration. The electron concentration is not significantly affected as it is much higher than n_i.
- With reduced hole concentration, the recombination rate will also be reduced. Finally, a new equilibrium is established where the recombination rate is equal to the generation rate once more.
- However, by now, many of the holes have recombined with the (increased number) of electrons. The hole concentration is now much lower than that of the intrinsic silicon, i.e., $p_0 << n_i$.
- Hence, the addition of the donor not only <u>increases</u> the electron concentration, it also leads to a <u>decrease</u> in the hole concentration.
- However, the product $p_0 n_0 = n_i^2$ still holds.

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Semiconductor Physics – Doping of Semiconductors

- Introduction of <u>donors</u> results in:
  - A large concentration of electrons, which become the *majority carriers*.
  - Reduction in the hole concentration, which become the *minority carriers*.
  - Material is said to be *n-type* (n for *negative*, charge of majority electrons).
- Introduction of <u>acceptors</u> results in:
  - A large concentration of holes, which become the *majority carriers*.
  - Reduction in the electron concentration, which become the *minority carriers*.
  - Material is said to be *p-type* (p for *positive*, charge of majority holes).

<u>Summary</u>

Semiconductor doped with:	Donors	Acceptors
Semiconductor type	n-type	p-type
Majority carriers	electrons	holes
Minority carriers	holes	electrons

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Semiconductor Physics – Doping of Semiconductors

3.3.1 Law of mass action

- Under typical doping, conc. of majority carriers >> conc. of minority carriers.
- The *law of mass action* at thermal equilibrium states that:

$$p_0 n_0 = n_i^2 \qquad (1.1)$$

- Obvious for an intrinsic semiconductor where $p_0 = n_0 = n_i$
- Also holds for extrinsic semiconductors. If you increase the electron concentration, then the hole concentration will decrease and *vice versa.*

Example: As (group V, donor) doped Si

If we dope Si with N_D = 10^{16} cm^{-3}, then (to be shown later): $n_0 = N_D^+ \approx N_D = 10^{16}\ \text{cm}^{-3}$

where N_D^+ = conc. of ionized donors (assumed fully ionized at room temp.).

From the law of mass action,

$$p_0 n_0 = n_i^2 \Rightarrow p_0 = \frac{\left(1.5\times10^{10}\right)^2}{10^{16}} = 2.25\times10^4\ \text{cm}^{-3}$$

Only ~22,000 holes per cm^3, or ~12 orders of magnitude fewer holes compared to electrons!

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3.4 Charge Neutrality

- If both donors and acceptors are added to the same crystal, their effects cancel – only the excess of one above the other has an effect on the carrier density.

- To see this, let us consider an electrically neutral region in the semiconductor where both (ionized) donors and acceptors may co-exist.

- *Charge neutrality* simply states that the net charge must be zero, or that the negative charges must balance out the positive charges.

- Since there are 4 types of charges in a semiconductor, for charge neutrality

$$n_0 + N_A^- = p_0 + N_D^+ \qquad (1.2)$$

mobile electrons

fixed ionized acceptors

mobile holes

fixed ionized donors

Note : Unless stated otherwise, we would assume from now on that all the donors and / or acceptors are ionised at 300 K, so that $N_A^- = N_A$, and $N_D^+ = N_D$.

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3.4.1 Compensated semiconductor

- If the concentration of ionized donors and acceptors are equal, i.e., $N_D = N_A$ then their effects cancel out and:

  $n_0 = n_i$ & $p_0 = n_i$

- The semiconductor is then said to be *compensated*.

- If the concentrations of the ionized dopants are not equal, the material is said to be *partially compensated*.

Example

A piece of silicon is initially doped with donors of concentration, N_D = 10^{17} cm^{-3}.

It is n-type, and the electron concentration, $n_0 = N_D$ = 10^{17} cm^{-3}.

Acceptors of concentration, N_A = 4 x 10^{16} cm^{-3} are then added.

As $N_A < N_D$, the silicon remains n-type. However, it is partially compensated, as the acceptors partially cancel out the effect of the donors.

The electron concentration, $n_0 = N_D - N_A$ = 10^{17} - 4 x 10^{16} = 6 x 10^{16} cm^{-3}.

Example

A silicon sample is doped with 2×10^{16} cm^{-3} acceptors and 5×10^{16} cm^{-3} donors. What are electron and hole concentrations at thermal equilibrium at T=300K?

Step 1: Determine if the Si is n- or p- type

- If $N_A > N_D$ -> p-type, majority carriers are holes, minority carriers are electrons.
- If $N_D > N_A$ -> n-type, majority carriers are electrons, minority carriers are holes.
- If $N_D = N_A$ -> Si is fully compensated, intrinsic carrier concentrations.

In this case, $N_D > N_A$, so Si is n-type, & majority carriers are electrons.

Step 2: Calculate majority carrier concentration (if applicable)

- If the material is fully compensated, then $p_0=n_0=n_i$ (nothing else to be done).
- Majority carrier concentration = NET dopant concentration, assuming $|N_A - N_D| >> n_i$.

In this case, the temperature is 300 K and hence we can assume full-ionization of dopants, and $N_D - N_A$ = $(5 \times 10^{16} - 2 \times 10^{16}) = 3 \times 10^{16}$ cm^{-3} >> n_i (= 1.5×10^{10}cm^{-3})
$n_0 = N_D - N_A = (5 \times 10^{16} - 2 \times 10^{16}) = 3 \times 10^{16}$ cm^{-3}

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Step 3: Finally, calculate the minority carrier concentration

- The minority carrier concentration at thermal equilibrium is given by $p_0 n_0 = n_i^2$.
- For n-type, $p_0 = n_i^2/n_0$
- For p-type, $n_0 = n_i^2/p_0$

In this case, since $n_0 = 3\text{x}10^{16}$ cm^{-3}, and using $n_i = 1.5\text{x}10^{10}$ cm^{-3} (at T = 300K), we have,

$$p_0 = \frac{n_i^2}{n_0} = \frac{\left(1.5\times10^{10}\right)^2}{3\times10^{16}} = 7.5\times10^3 \text{ cm}^{-3}$$

Note : If $|N_A - N_D|$ is comparable to n_i (say, within a factor of 5 or so), then we have to calculate n_0 and p_0 by solving the Law of Mass Action equation, eqn (1.1) and the charge neutrality equation, eqn (1.2) simultaneously.*

* For your information, but this is beyond the scope of this module.

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Semiconductor Physics – Doping of Semiconductors

- An important consequence of this compensation is that it is possible to change, for example, a p-type semiconductor into an n-type semiconductor by doping the original p-type semiconductor with more donors than there were original acceptors.
- This "trick" can be repeated several times, so that the n-type semiconductor can be changed back into a p-type semiconductor by adding even more acceptors.
- However, the <u>total</u> concentration of dopants increases each time the material is changed from p-type to n-type and vice versa. This can adversely affect other properties of the semiconductor.

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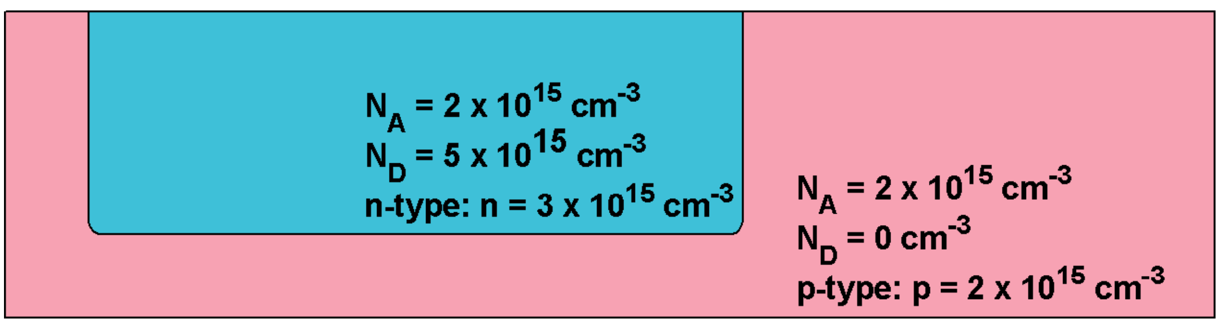
Semiconductor Physics – Doping of Semiconductors

Example

- Consider a silicon substrate with an initial doping of N_A = 2x10^{15} cm^{-3} acceptors. The silicon is thus p-type, with a hole concentration of 2x10^{15} cm^{-3}.
- We now selectively dope a volume with N_D = 5x10^{15} cm^{-3} donors.
- As there are more donors than acceptors, the selected volume is now n-type with an electron concentration of $n = N_D - N_A$ = 3x10^{15} cm^{-3}.
- In this way, we have made a p-n junction.



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3.S Equation Summary

(a) Law of mass action – only applicable under thermal equilibrium conditions:

$$p_0 n_0 = n_i^2 \quad \text{where}$$

p_0 & n_0 are the hole and electron concentrations at thermal equilibrium.

(b) Neutrality – only applicable in an electrically neutral region:

$$n + N_A = p + N_D$$

N_A and N_D are the ionized acceptor and donor concentrations.

(c) Majority carrier concentration

(i) For n-type material, where $N_D > N_A$

$$n_0 \approx N_D - N_A \quad \text{provided} \quad N_D - N_A >> n_i$$

(ii) For p-type material, where $N_A > N_D$

$$p_0 \approx N_A - N_D \quad \text{provided} \quad N_A - N_D >> n_i$$

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Semiconductor Physics

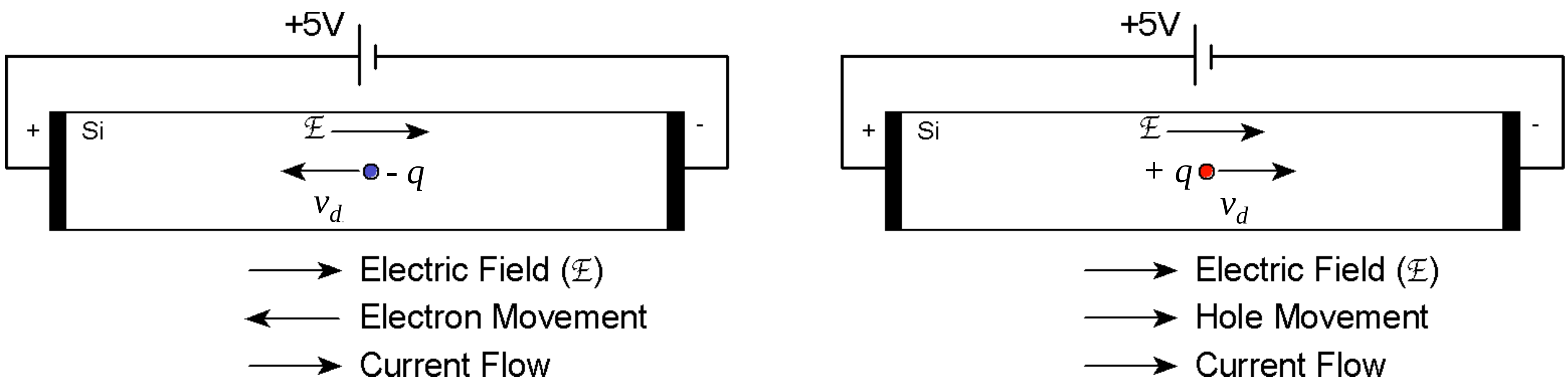
1. Introduction
2. Charge Carriers in Semiconductors
3. Doping of Semiconductors
4. Carrier Transport Phenomena

4.1 Carrier Drift

- There are two mechanisms that cause charges to move in semiconductors: *drift* and *diffusion*.
- *Drift* is the motion of charge carriers due to the presence of an electric field.
- Carriers (i.e., electrons and holes) will move under the influence of an electric field because the field will exert a force on the carriers according to:

$$\vec{\mathbf{F}} = Q \cdot \vec{\mathcal{E}} \qquad (1.3)$$

where Q is the charge of the carrier ($+q$ for holes, $-q$ for electrons).



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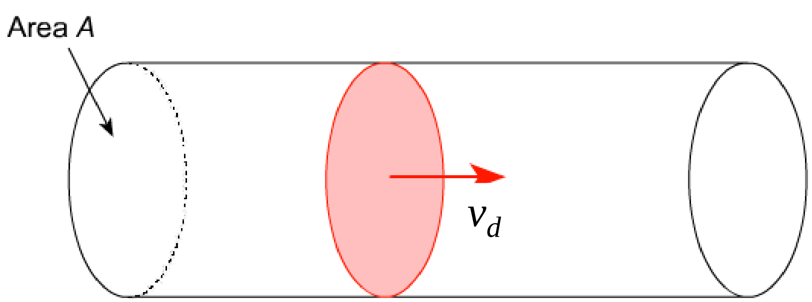
Semiconductor Physics – Carrier Drift

- Current is the rate of flow of charge (C/s). So, for a semiconductor (or conductor) of cross-sectional area A, we have,

$$I_{drift} = NAQv_d \qquad (1.4)$$

where

I_{drift}	=	drift current (A or C/s)
N	=	carrier concentration (cm^{-3})
A	=	conductor area (cm^2)
Q	=	carrier charge (C)
v_d	=	*drift velocity* of carriers (cm/s)



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Semiconductor Physics – Carrier Drift

- With zero applied field, the drift velocity of an electron (or hole) is zero, but this does not mean that the electron (or hole) is stationary.

- An electron (or hole) has *thermal energy* and will bounce randomly to and fro by interacting with the atoms in the lattice such that its average displacement with time is zero. The random *thermal velocity*, is very high – of the order of 10^7 cm/s at room temperature.

- With an electric field, the electron (or hole) will still be scattered by the lattice, but it will experience net motion in the direction of the electric field (in the –ve sense for an electron). The carrier moves with an additional *drift velocity* that is very much lower (e.g. at an E field of 100V/cm, electrons drift at ~10^5 cm/s in Si).

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Semiconductor Physics – Carrier Drift

- The drift velocity, v_d,is the average velocity of all the electrons (or holes) in response to an applied electric field.

- The drift velocity increases linearly with the applied field (at small electric fields**).
- The proportionality factor, μ, is called the *mobility*, of the electrons (or holes).
- As electrons and holes move in opposite directions for the same electric field, the relations between drift velocity and electric fields are:

Electrons: $$\vec{v}_d = -\mu_n \vec{\mathcal{E}} \qquad (1.5)$$

Holes: $$\vec{v}_d = \mu_p \vec{\mathcal{E}} \qquad (1.6)$$

- Mobility is an indicator of how fast electrons (or holes) will drift when driven by an applied field.
- Mobility is not a constant. It is a function of the semiconductor material, temperature, dopant concentration in the semiconductor, electric field, etc.

** at high electric fields, the velocity saturates at ~10^7 cm/s for Si.

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Semiconductor Physics – Carrier Drift

- For convenience we normally deal with current densities (J) rather than current (I), hence, from

$$I_{drift} = NAQv_d$$

Electrons:

$$J_{n,drift} = (-q)nv_d = (-q)n(-\mu_n \mathcal{E}) = qn\mu_n \mathcal{E} \qquad (1.7)$$

Holes:

$$J_{p,drift} = (+q)pv_d = (+q)p(\mu_p \mathcal{E}) = qp\mu_p \mathcal{E} \qquad (1.8)$$

(a) <u>Current density is proportional to electric field</u> – this is generally true for metals, and for semiconductors at low electric fields (< few kV/cm).

(b) Direction of current flow is the same for both electrons & holes.

(c) Current density depends on both mobility AND carrier concentration. Semiconductors have very low carrier concentrations (typ. 10^{13}-10^{18} cm^{-3}) compared to metals (10^{23} cm^{-3}), but higher mobilities in general.

Note : From now on we will consider flow in one-dimension only. Hence the vector notations in the drift velocity, electric field, etc. are omitted.

Semiconductor Physics – Carrier Drift

- The total drift current density in a semiconductor is contributed by both electrons and holes, so

$$\begin{aligned} J_{drift} &= J_{n,drift} + J_{p,drift} \\ &= qn\mu_n \mathcal{E} + qp\mu_p \mathcal{E} \\ &= q(n\mu_n + p\mu_p)\mathcal{E} \end{aligned} \tag{1.9}$$

- From Ohm's law:

$$J = \sigma \mathcal{E} \tag{1.10}$$

where $\sigma = 1/\rho$ is the conductivity (and ρ is the resistivity), we have

$$\sigma = q(n\mu_n + p\mu_p) \tag{1.11}$$

- In most cases, for a doped semiconductor, the majority carrier concentration is much greater than that of the minority carrier in which case:

n-type: $\sigma \cong qn\mu_n$ (1.12)

p-type: $\sigma \cong qp\mu_p$ (1.13)

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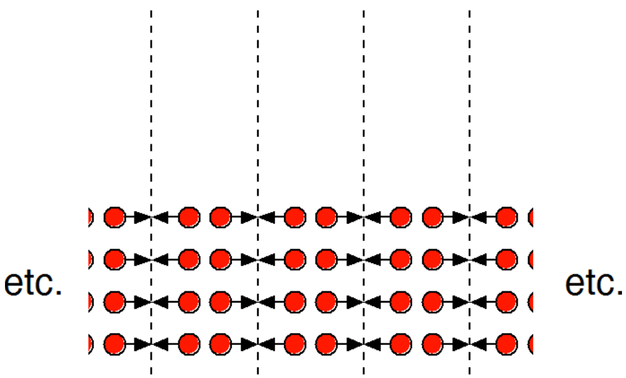
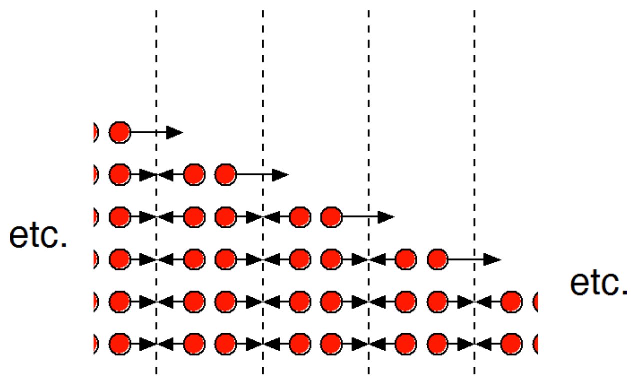
4.2. Carrier Diffusion

- The second mechanism that can give rise to current is *diffusion*.
- Diffusion is a general phenomenon where there is a net transport of particles from a region of higher concentration to a region of lower concentration. The phenomenon is purely statistical.
- For charge carriers, if there is a concentration gradient, diffusion occurs and this leads to net carrier flux and hence current flow.

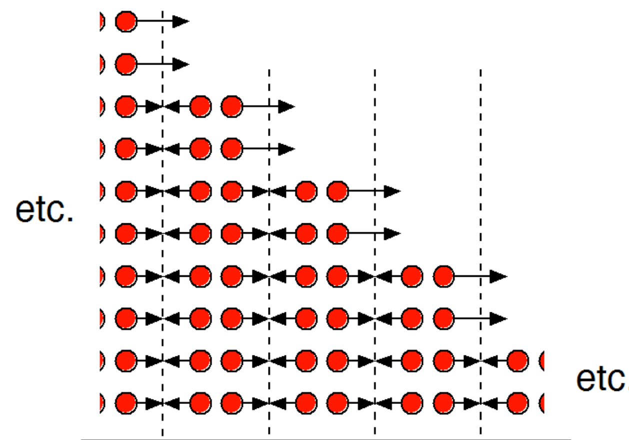
Thought Experiment



No concentration gradient – no diffusion. Does not matter what the actual concentration is.



Net transport in presence of concentration gradient



Doubling of gradient -> doubling of diffusion

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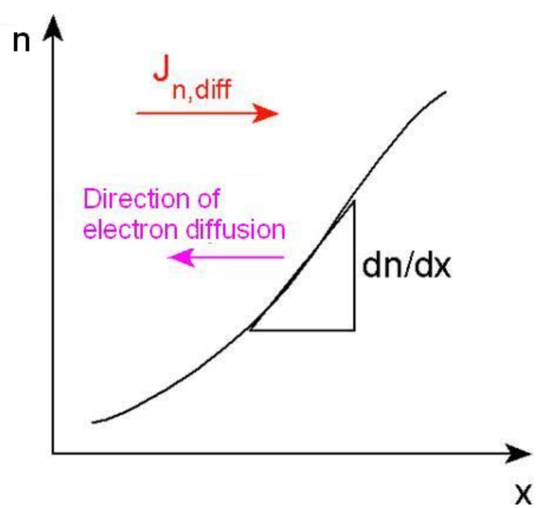
Semiconductor Physics – Carrier Diffusion

- The rate of diffusion is proportional to the concentration gradient.
- For electrons, the diffusion current density:

$$J_{n,diff} = (-q)D_n\left(-\frac{dn}{dx}\right) = qD_n\frac{dn}{dx} \qquad (1.14)$$

- D_n is the *diffusion coefficient* or *diffusivity* for electrons. It is the constant of proportionality that gives a measure of how easy it is for the electron to diffuse.
- The minus sign before the concentration term, dn/dx , indicates that the electrons diffuse from a higher to lower concentration.



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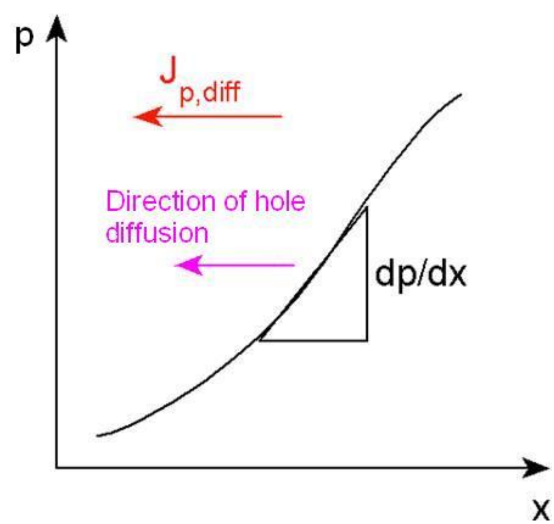
Semiconductor Physics – Carrier Diffusion

- Similarly, for holes, the diffusion current density:

$$J_{p,diff} = (+q)D_p\left(-\frac{dp}{dx}\right) = -qD_p\frac{dp}{dx} \qquad (1.15)$$

where D_p is the diffusion coefficient or diffusivity for holes.

- Note that the diffusion current densities for electrons and holes are in the opposite direction for the same gradient due to the difference in the sign of the charge for electrons and holes.



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4.3. Einstein Relation

- The diffusion coefficient, D_n or D_p is a measure of ease of carrier diffusion motion in a medium, while the mobility, μ_n or μ_p is a measure of the ease of carrier drift in the same medium.
- It is therefore not surprising that the two quantities are related by the *Einstein Relation,*

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{q} = V_T \qquad (1.16)$$

- According to the Einstein Relation, the ratios of the diffusion coefficient to mobility for electrons and holes are equal and depend on the temperature T only. k is the Boltzmann constant ($k = 1.381 \times 10^{-23}$ JK^{-1}).

- The term V_T is known as the thermal voltage. At T = 300 K, $V_T \approx$ 0.025 V.

4.4. Total Current

- In general, if both an electric field and a concentration gradient are present, the carriers will drift and diffuse.
- The equations for the electron current density, J_n, and the hole current density, J_p, are the sum of the drift and diffusion components:

Electron current density

$$J_n = J_{n,drift} + J_{n,diff}$$
$$= qn\mu_n\mathcal{E} + qD_n\frac{dn}{dx}$$

Hole current density

$$J_p = J_{p,drift} + J_{p,diff}$$
$$= qp\mu_p\mathcal{E} - qD_p\frac{dp}{dx}$$

- The total current density, J, in a semiconductor is the sum of contributions from electrons and holes,

$$\begin{aligned} J &= J_n + J_p \\ &= \left(J_{n,drift} + J_{n,diff}\right) + \left(J_{p,drift} + J_{p,diff}\right) \\ &= q\left(n\mu_n + p\mu_p\right)\mathcal{E} + q\left(D_n\frac{dn}{dx} - D_p\frac{dp}{dx}\right) \end{aligned} \qquad (1.17)$$

4.S. Equation Summary

(a) Electron and hole drift current density

$$J_{n,drift} = qn\mu_n \mathcal{E} \quad ; \quad J_{p,drift} = qp\mu_p \mathcal{E}$$

Note: The current density is in the same direction as the $\mathcal{E}$-field for both carriers.

(b) Semiconductor conductivity

$$\sigma = q\left(n\mu_n + p\mu_p\right)$$

(c) Electron and hole diffusion current density

$$J_{n,diff} = qD_n \frac{dn}{dx} \quad ; \quad J_{p,diff} = -qD_p \frac{dp}{dx}$$

Note: The current density is in the same direction as the conc. gradient for electrons, but it is in the opposite direction to the conc. gradient for holes. Carriers diffuse from higher to lower concentrations.

(d) Einstein relation - relates diffusivity to mobility at any given temperature

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{q} = V_T$$