Lecture 2

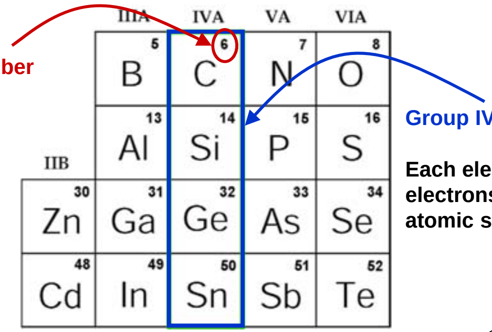
Basic Semiconductor Physics

In this lecture you will learn:

- **What are semiconductors?**
- **Basic crystal structure of semiconductors**
- **Electrons and holes in semiconductors**
- **Intrinsic semiconductors**
- **Extrinsic semiconductors**
  - **n-doped and p-doped semiconductors**

Semiconductors in the Periodic Table

Atomic number

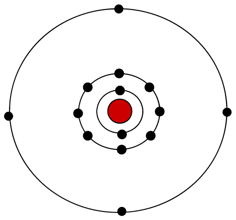


Group IV semiconductors

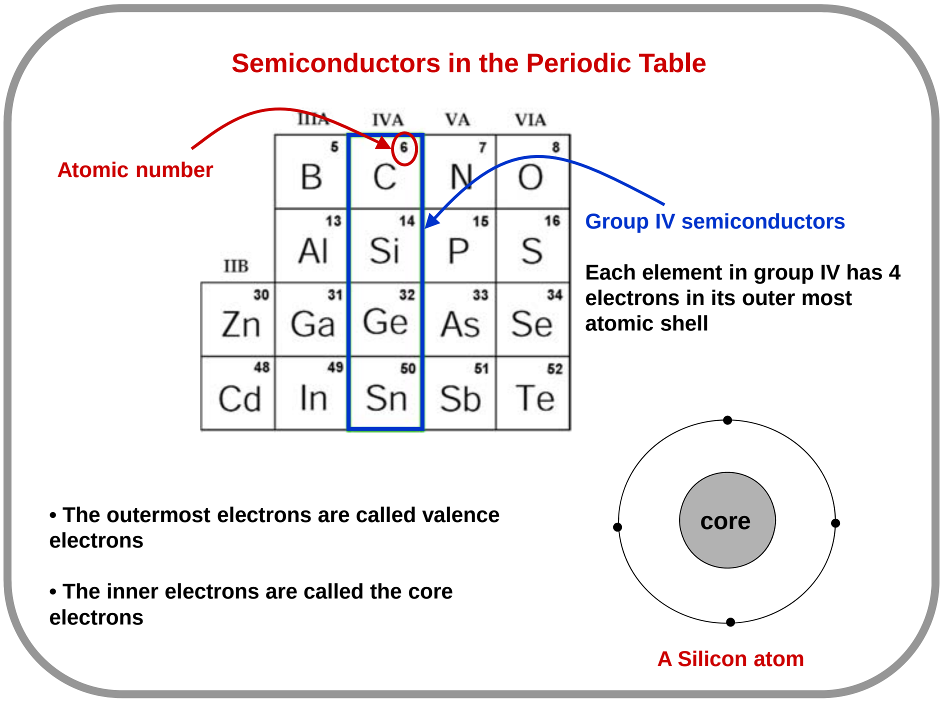
Each element in group IV has 4 electrons in its outer most atomic shell

A Silicon atom has:

2 electrons in the first atomic shell
8 electrons in the second atomic shell
4 electrons in the third outermost atomic shell



A Silicon atom



Semiconductors in the Periodic Table

IIB	IIIA	IVA	VA	VIA
	5 B	6 C	7 N	8 O
	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te

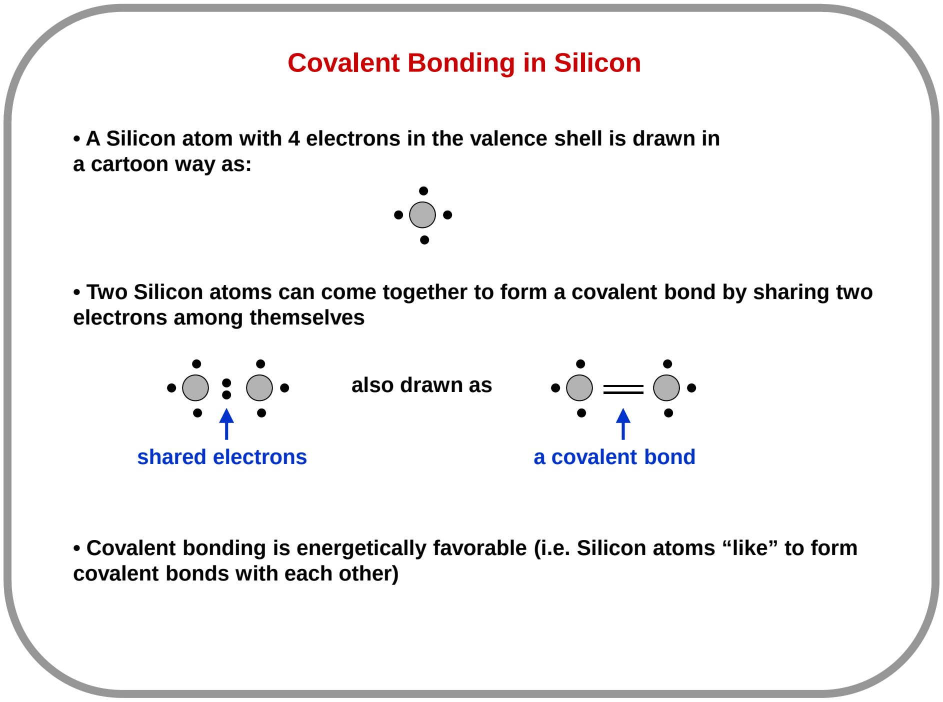
Atomic number

Group IV semiconductors

Each element in group IV has 4 electrons in its outer most atomic shell

- The outermost electrons are called valence electrons
- The inner electrons are called the core electrons

A Silicon atom



Covalent Bonding in Silicon

- A Silicon atom with 4 electrons in the valence shell is drawn in a cartoon way as:
- Two Silicon atoms can come together to form a covalent bond by sharing two electrons among themselves

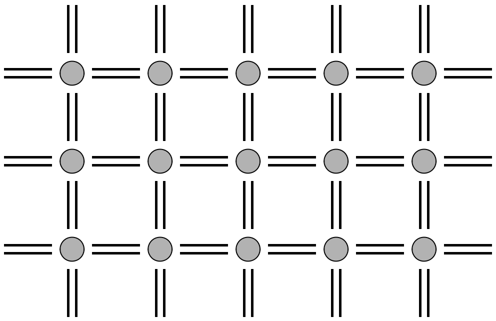
also drawn as

shared electrons

a covalent bond

- Covalent bonding is energetically favorable (i.e. Silicon atoms “like” to form covalent bonds with each other)

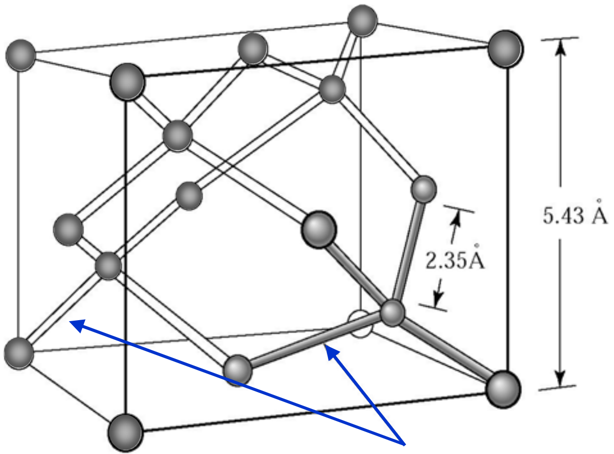
A Silicon Crystal Lattice (A Cartoon View)



In a Silicon crystal:

- Each Silicon atom is surrounded by 4 other Silicon atoms
- Each Silicon atom forms 4 covalent bonds with the neighboring Silicon atoms

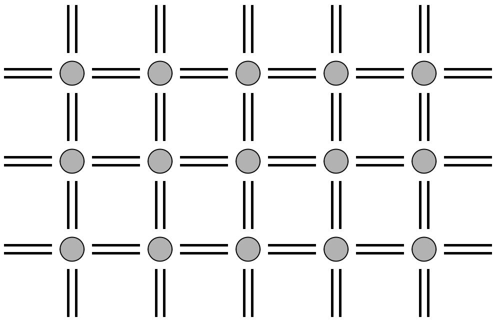
Actual 3D Structure of a Silicon Crystal Lattice



covalent bonds

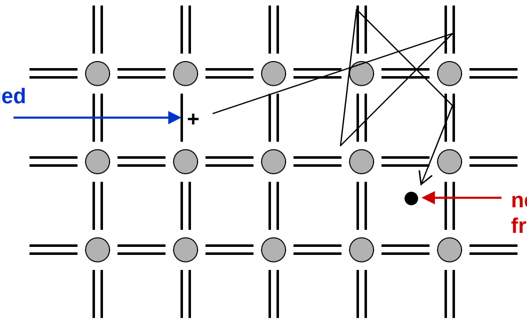
- Each Silicon atom is surrounded by 4 other Silicon atoms in a tetrahedral configuration
- Silicon atomic density = 5×10^{22} cm^{-3}

Electrons and Holes in Semiconductors - I



A perfect Silicon crystal lattice

Electrons and Holes in Semiconductors - II



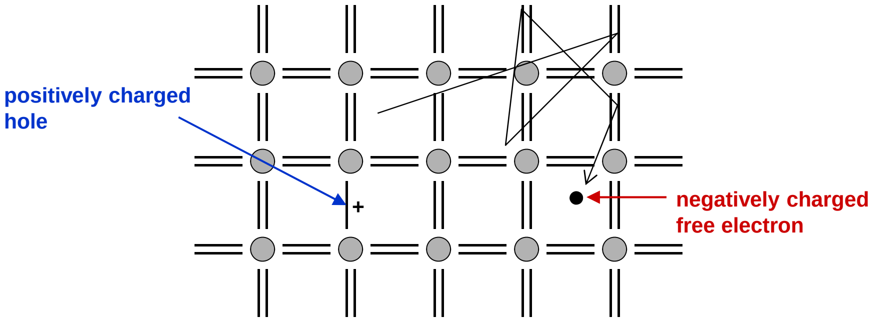
positively charged hole

negatively charged free electron

A Silicon crystal lattice with one broken bond

- It requires energy to break a covalent bond
- The required energy is called the "bandgap" (bandgap of Silicon is ~1.12 eV)
- A broken bond results in one negatively charged "free electron" and one positively charged "hole"
- The "free electron" can freely move around in the crystal

Electrons and Holes in Semiconductors - III



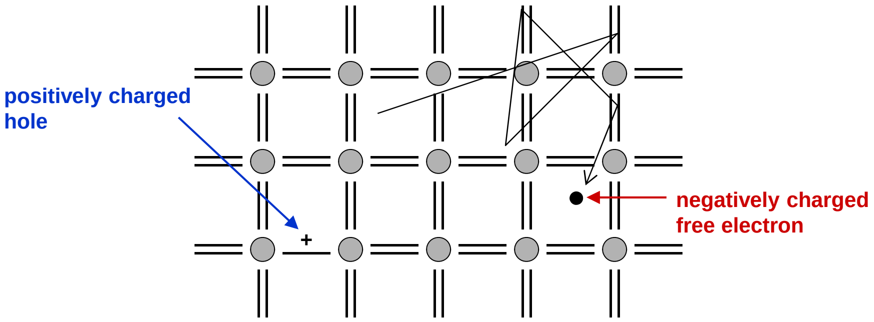
positively charged hole

negatively charged free electron

A Silicon crystal lattice with one broken bond

- A hole can also move through the lattice !!
- A hole moves when an electron from a neighboring bond jumps over to fill that “hole”

Electrons and Holes in Semiconductors - III



positively charged hole

negatively charged free electron

A Silicon crystal lattice with one broken bond

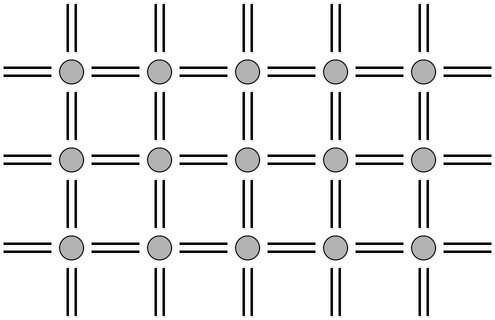
- A hole can also move through the lattice !!
- A hole moves when an electron from a neighboring bond jumps over to fill that “hole”

Definitions and Notations Used in ECE 3150

- The word electron will usually mean a "free electron" (and not an electron forming the covalent bond or a core electron)
- The electron density is denoted by: n (units: $1/\text{cm}^3$)
- The hole density is denoted by: p (units: $1/\text{cm}^3$)
- The charge of an electron is: $-q$
- The charge of a hole is: $+q$

$$\left.\begin{array}{l} -q \\ +q \end{array}\right\} \quad q = 1.6 \times 10^{-19} \text{ Coulombs}$$

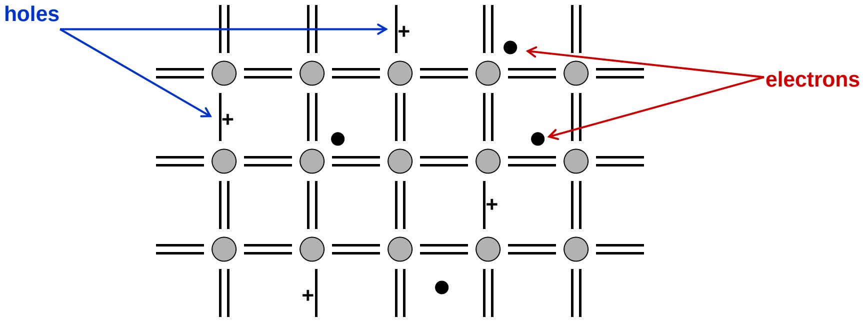
Electrons and Holes at Near Zero Temperature



A perfect Silicon crystal lattice at temperature T≈0 K

- There are no broken bonds and no electrons and holes
  (i.e. $n = p = 0$)

Electrons and Holes at Nonzero Temperature



A Silicon crystal lattice at temperature T>0 K

- Thermal energy breaks the covalent bonds and electron-hole pairs are generated (remember it takes energy to break a covalent bond)

- The number of electrons and holes generated are equal - for every electron generated there is also a hole generated (i.e. $n = p$)

- Question: what is the electron and hole density at room temperature?

Thermal Energy

Thermal energy is typically measured in units of " KT "

"K" is the Boltzmann's constant and equals ~1.38 x 10^{-23} Joules/Kelvin

Temperature "T" is measured in degrees Kelvin

Room temperature corresponds to T = 300 K

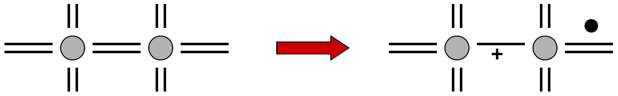
Room temperature corresponds to a "KT " value of 4.14 x 10^{-21} Joules or 25.8 meV

$$\boxed{\text{Energy in eV} = \frac{\text{Energy in Joules}}{\text{Electron charge in Coulombs}}}$$

Generation and Recombination in Semiconductors - I

Generation:

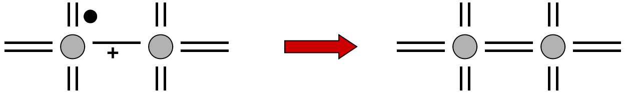
The breaking of a bond to generate an electron-hole pair is called generation



- Generation rate $G(T)$ is a function of temperature
- Units of $G(T)$ are: cm^{-3}-s^{-1}

Recombination:

An electron can also combine with a hole to form a bond. This process is called recombination. It is the reverse of generation.



- Recombination rate $R(T)$ is proportional to the product np

$$R(T) \propto np \quad \Rightarrow \quad R(T) = k(T)\,np$$

(you need electrons as well as holes for recombination to happen)

- Units of $R(T)$ are also: cm^{-3}-s^{-1}

Generation and Recombination in Semiconductors - II

Condition of Thermal Equilibrium:

- In thermal equilibrium a steady state exists in which the rate of electron-hole generation is equal to the rate of electron-hole recombination,

$$\left.\begin{aligned} & R(T) = G(T) \\ \Rightarrow\ & k(T)n_o p_o = G(T) \\ \Rightarrow\ & n_o p_o = \frac{G(T)}{k(T)} \end{aligned}\right\}$$

thermal equilibrium electron and hole densities are usually denoted by n_o and p_o

- By convention, the ratio $\dfrac{G(T)}{k(T)}$ is written as $n_i^2(T)$
- Therefore, in thermal equilibrium, $n_o p_o = n_i^2(T)$
- Since equal number of electrons and holes are present in thermal equilibrium, we have, $n_o = p_o = n_i(T)$
- n_i is called the "intrinsic" carrier density. It equals the number of electrons (or holes) present in a pure semiconductor in equilibrium at a given temperature.
- For Silicon, $n_i \approx 1 \times 10^{10}\,\text{cm}^{-3}$ at room temperature (i.e. at T = 300K)

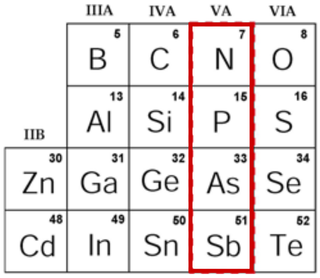
Doping in Semiconductors

Doping:
The introduction of certain impurity atoms in a pure semiconductor to control its electronic properties is called doping

- Doping is done by two kinds of impurity atoms:

a)Donor atoms
b)Acceptor atoms

Donors:
Donor atoms are used to increase the electron density in a semiconductor



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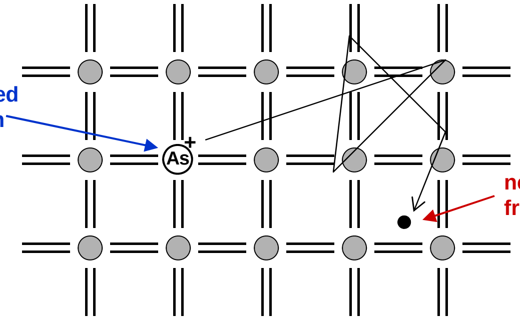
- Group V elements have 5 electrons in their outermost atomic shell (one more than group IV atoms)
- Group V elements can act as electron "donors" in Silicon

Doping by Donors in Silicon (n-doping)



positively charged fixed donor atom

negatively charged free electron

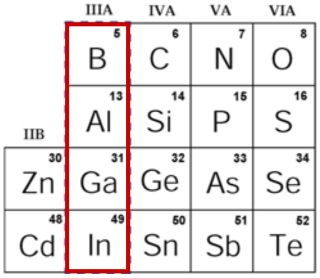
Doping Silicon with Arsenic Atoms

- Donor atom concentration is denoted by: N_d (units: 1/cm^3)
- Each donor atom contributes one free electron to the crystal
- Donor atom after giving off an electron becomes positively charged

Doping in Semiconductors

Acceptors:

Acceptor atoms are used to increase the hole density in a semiconductor



IIB	IIIA	IVA	VA	VIA
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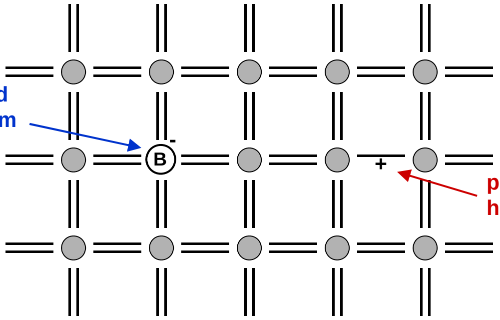
48 Cd	49 In	50 Sn	51 Sb	52 Te

- **Group III elements have 3 electrons in their outermost atomic shell (one less than group IV atoms)**
- **Group III elements can act as electron "Acceptors" in Silicon**

Doping by Acceptors in Silicon (p-doping)



negatively charged fixed acceptor atom

positively charged hole

Doping Silicon with Boron Atoms

- **Acceptor atom concentration is denoted by: N_a (units: 1/cm^3)**
- **Each acceptor atom contributes one hole to the crystal by "accepting" one electron from a neighboring bond**
- **Acceptor atom after giving off a hole (or equivalently, after accepting an electron) becomes negatively charged**

Electron-Hole Density in Doped Semiconductors

Consider a N-doped semiconductor in thermal equilibrium:

Doping density = N_d

- Use condition of charge neutrality: $q\left(+N_d - n_o + p_o\right) = 0$
- Together with the relation: $n_o p_o = n_i^2$
- To obtain:

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

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

- If $N_d >> n_i$, which is usually the case for N-doping, then the above relations simplify:

$$\left.\begin{array}{l} n_o \approx N_d \\ p_o \approx \dfrac{n_i^2}{N_d} \end{array}\right\}$$

n-doping lets one make the electron density much greater than the intrinsic value n_i

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Electron-Hole Density in Doped Semiconductors

Now consider a P-doped semiconductor in thermal equilibrium:

Doping density = N_a

- Use condition of charge neutrality: $q\left(-N_a - n_o + p_o\right) = 0$
- Together with the relation: $n_o p_o = n_i^2$
- To obtain:

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

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

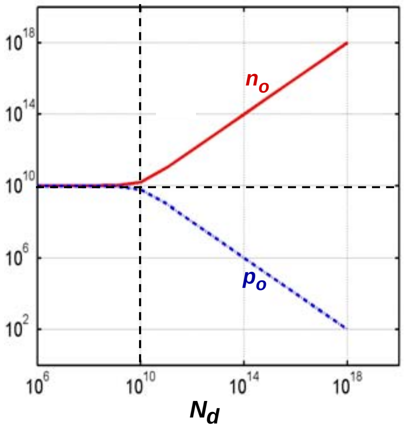
- If $N_a >> n_i$, which is usually the case for P-doping, then the above relations simplify:

$$\left.\begin{array}{l} p_o \approx N_a \\ n_o \approx \dfrac{n_i^2}{N_a} \end{array}\right\}$$

p-doping lets one make the hole density much greater than the intrinsic value n_i

Electron-Hole Density Vs Doping Density

N-doped semiconductors



- **With increasing N-doping the electron density increases above the intrinsic value and the hole density decreases below the intrinsic value**

Example:

Suppose

$$N_d = 10^{17}\,\text{cm}^{-3} \quad \text{and} \quad n_i = 10^{10}\,\text{cm}^{-3}$$

then

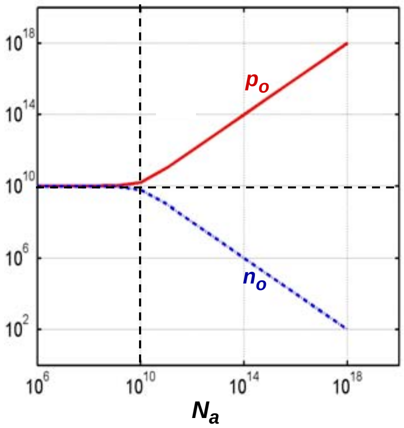
$$n_o \approx 10^{17}\,\text{cm}^{-3} \quad (\text{Since } N_d >> n_i)$$

and

$$p_o = \frac{n_i^2}{n_o} \approx 10^{3}\,\text{cm}^{-3}$$

Electron-Hole Density Vs Doping Density

P-doped semiconductors



- **With increasing P-doping the hole density increases above the intrinsic value and the electron density decreases below the intrinsic value**

Example:

Suppose

$$N_a = 10^{17}\,\text{cm}^{-3} \quad \text{and} \quad n_i = 10^{10}\,\text{cm}^{-3}$$

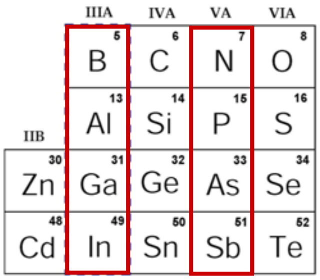
then

$$p_o \approx 10^{17}\,\text{cm}^{-3} \quad (\text{Since } N_a >> n_i)$$

and

$$n_o = \frac{n_i^2}{p_o} \approx 10^{3}\,\text{cm}^{-3}$$

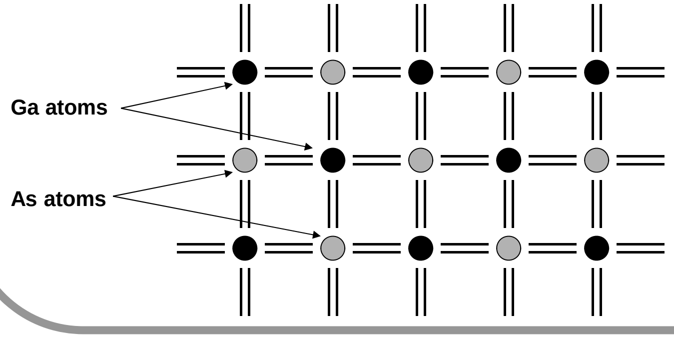
Compound Semiconductors



III-V semiconductors:

Elements in group III can be combined with elements in group V to give compound semiconductors (as opposed to elemental semiconductors of group IV)

***One can also have II-VI semiconductors**



Crystal lattice of the III-V compound semiconductor GaAs