Semiconductor Fundamentals – (II)

2.3 **Energy Bands**

2.4 Doping of Semiconductors

***Gary* Chun Zhao, PhD**

Chun.Zhao@xjtlu.edu.cn

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https://www.xjtlu.edu.cn/en/departments/academic-departments/electrical-and-electronic-engineering/staff/chun-zhao

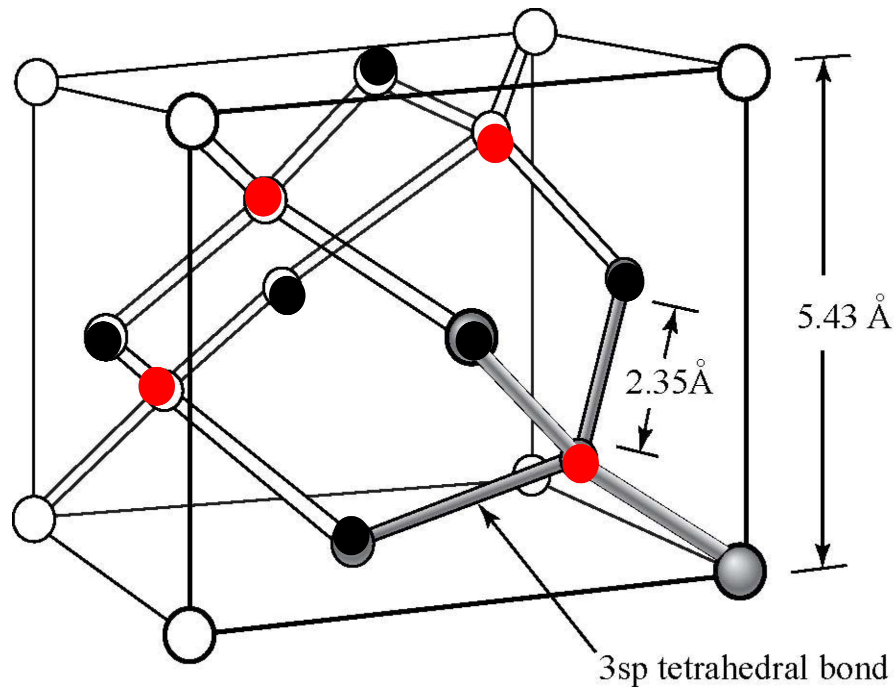
HW-1: solution

- Si atomic density:

$$\frac{\#\,Atoms}{Volume}=\frac{8\times(1/8)+6\times(1/2)+4}{a_0^3}=\frac{8}{(5.43\times10^{-8}\,cm)^3}=5\times10^{22}\,cm^{-3}$$

- **Number of atoms in a unit cell:**
  - **4 atoms** completely inside cell
  - Each of the **8 atoms** on corners are shared among cells → count as **1 atom** inside cell
  - Each of the **6 atoms** on the faces are shared among 2 cells → count as **3 atoms** inside cell

Total number inside the cell = **4 + 1 + 3 = 8**

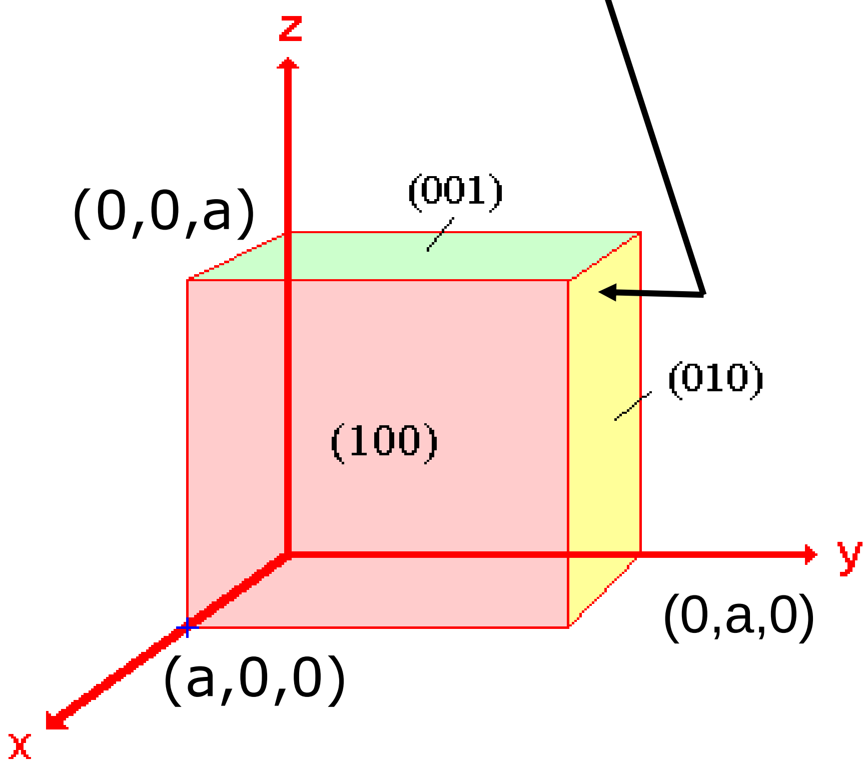


- **Cell volume:**

$(0.543\ nm)^3 = 1.6 \times 10^{-22}\ cm^3$

HW-2: solution

Why the Miller indices of this plane is (010)?

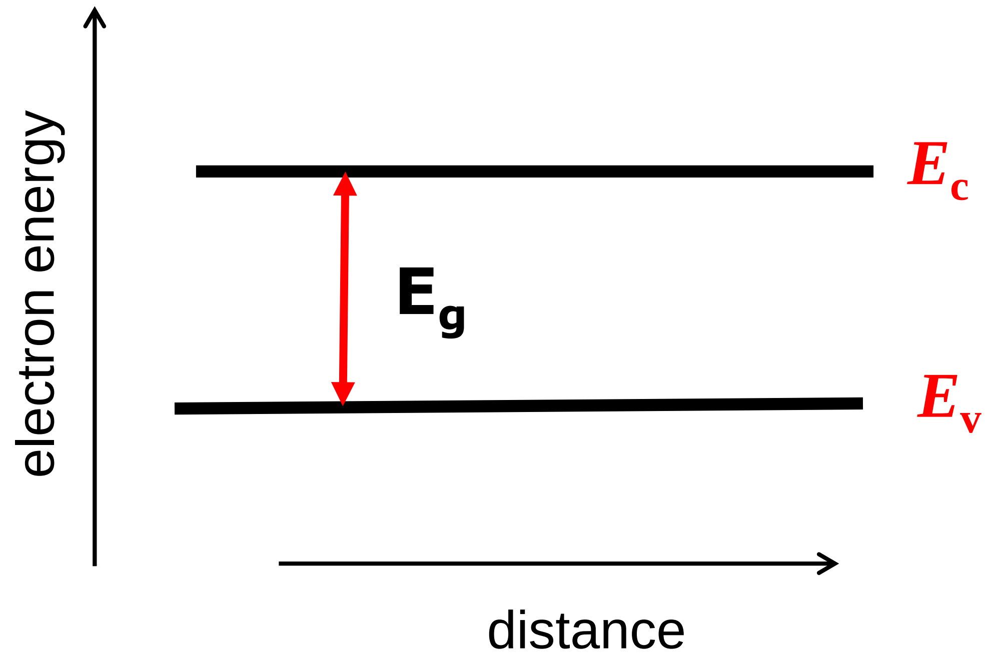


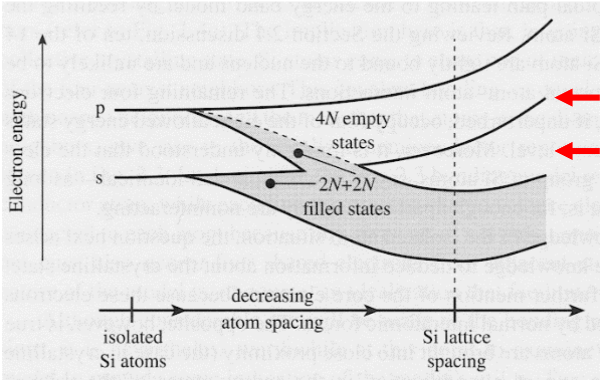
***x*-intercept of plane**
***y*-intercept of plane**
***z*-intercept of plane**

***h*: inverse *x*-intercept of plane**
***k*: inverse *y*-intercept of plane**
***l*: inverse *z*-intercept of plane**

***h, k* and *l* are reduced/enlarged to 3 integers having the same ratio.** **(010)**

Last lecture:





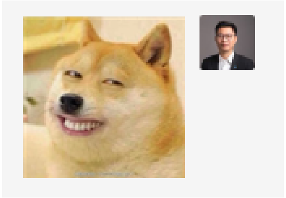
Simplified version of **energy band model**, indicating

- **bottom edge** of the **conduction band** (E_c)
- **top edge** of the **valence band** (E_v)

➢ E_c and E_v are separated by the **band gap energy** E_g

2.3 Energy Bands

- **Band theory**



  - ➢ What's a Semiconductor
  - ➢ Fermi Level
  - ➢ Band model of *e* & *h*
  - ➢ Bond model of *e* & *h*
- Generation and recombination
- Intrinsic semiconductor

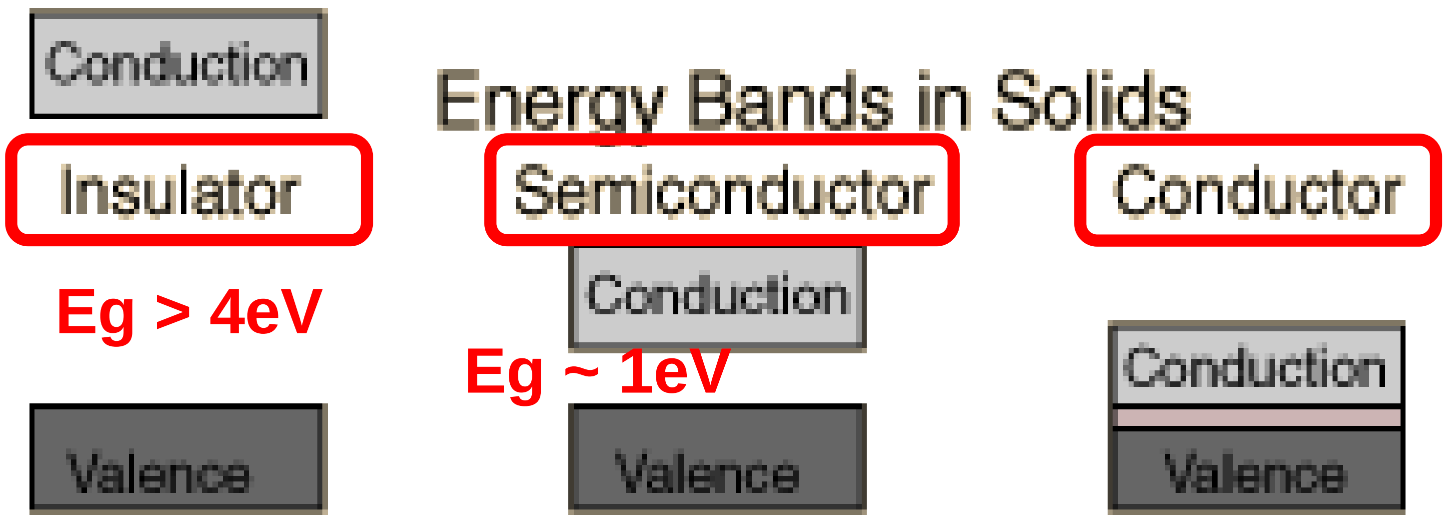
What is a **Semiconductor?**

- Low resistivity => "**conductor**" e.g. Al, Cu
- High resistivity => "**insulator**" e.g. SiO_2
- Intermediate resistivity => "**semiconductor**"

  - **conductivity** lies **between** that of **conductors** and **insulators**

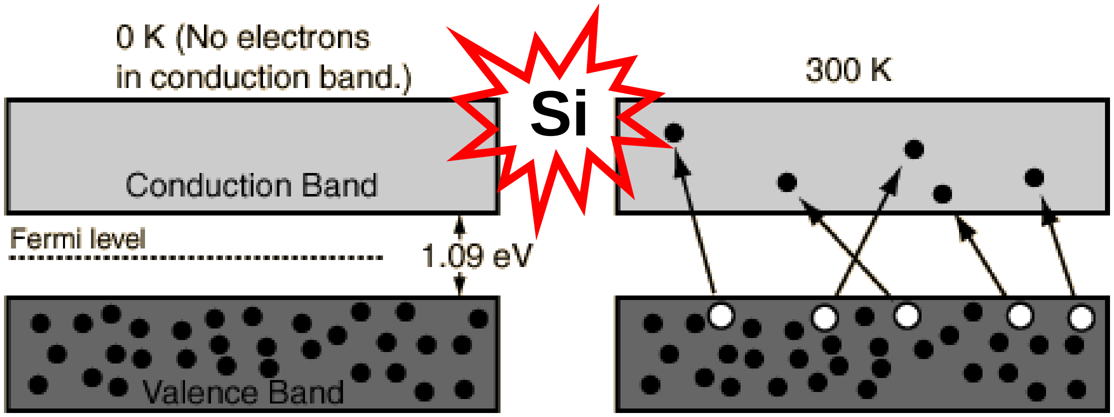
Band Theory of Solids

- A useful way to **visualize** the difference between conductors, insulators and semiconductors is to plot the available energies for electrons in the materials. In **conductors** the **valence band** overlaps the **conduction band**, and in **semiconductors** or **insulator** there is a small or big gap between the **valence** and conduction bands.
- An important **parameter** in the band theory is the Fermi level.



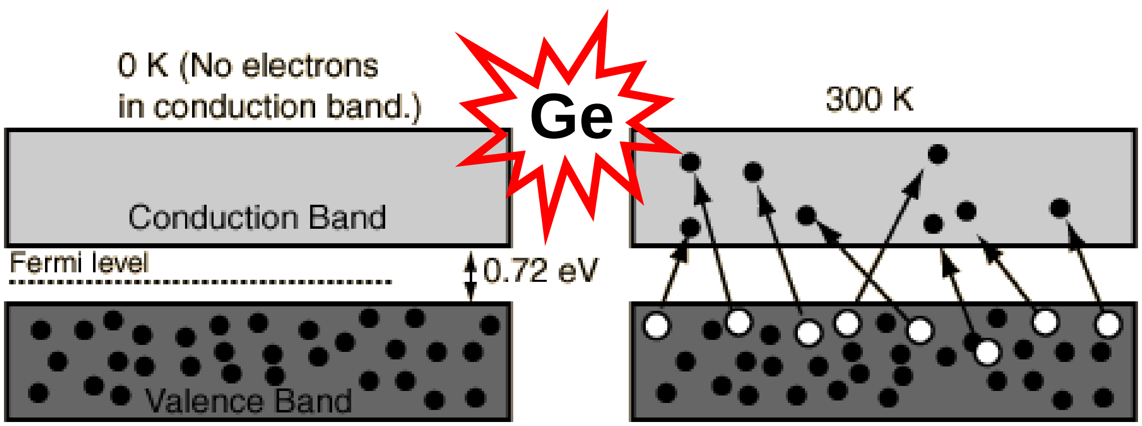
Energy Bands of Silicon & Germanium

- At finite temperatures, **the number of electrons** which reach the **conduction band** and contribute to **current** can be modeled by the **Fermi function**.



1) Fermi level?

2) "holes"?



Fermi function and **Fermi level**

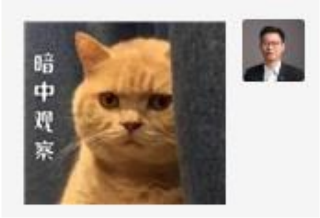
Probability that a **state** at **energy level**, ***E***, is occupied by one electron is,

$$\boxed{f(E)=\frac{1}{1+\exp\left(\frac{E-E_F}{kT}\right)}}$$

Students → electrons

Seat row → energy level, *E*.

Seat → state



Example: Students in a theatre class room.

Every row has different energy level, *E*. For example, for **row 7**, its energy level is *E7*.

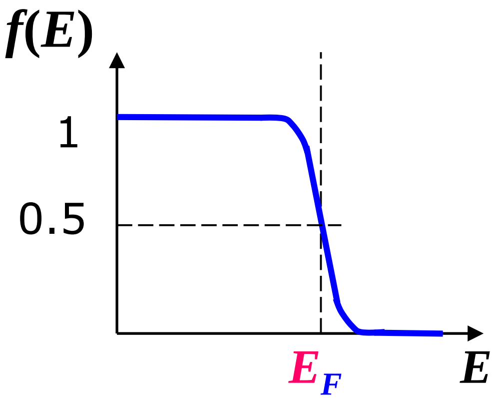
The probability for one student to occupy a seat on **row** 7 can be calculated by *f*(*E7*).

E_F is a energy level at which *f*(*E*) is 50%.

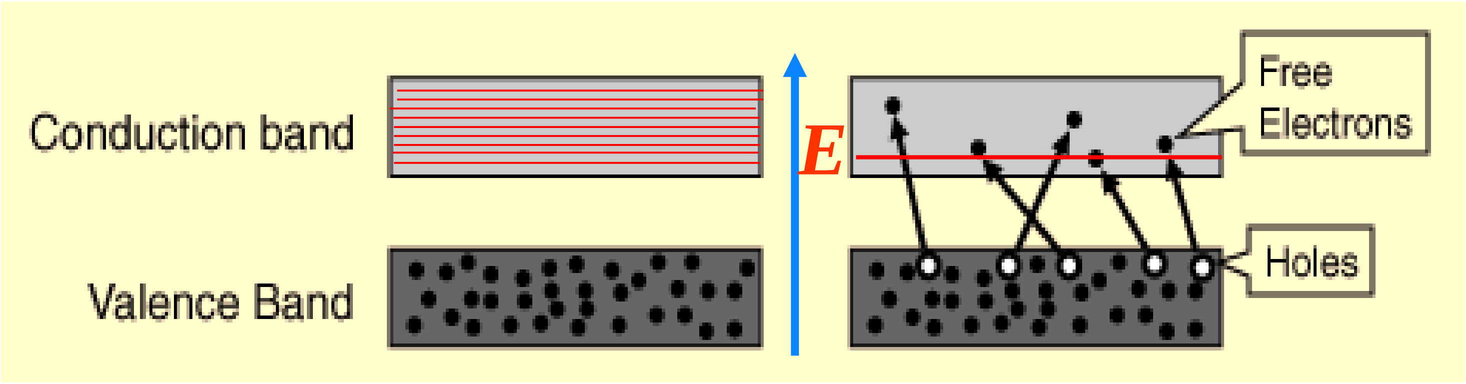
Fermi function and Fermi level

- **Probability** that a **state** at **energy level, *E***, is occupied by one electron is,

$$f(E) = \frac{1}{1+\exp(\frac{E-E_F}{kT})}$$



- $f(E)$: **Fermi**-Dirac **function**
- An increase in E will reduce $f(E)$
- E_F --- **Fermi-level**
  - **When $E = E_F$, $f(E=E_F) = 0.5$.**

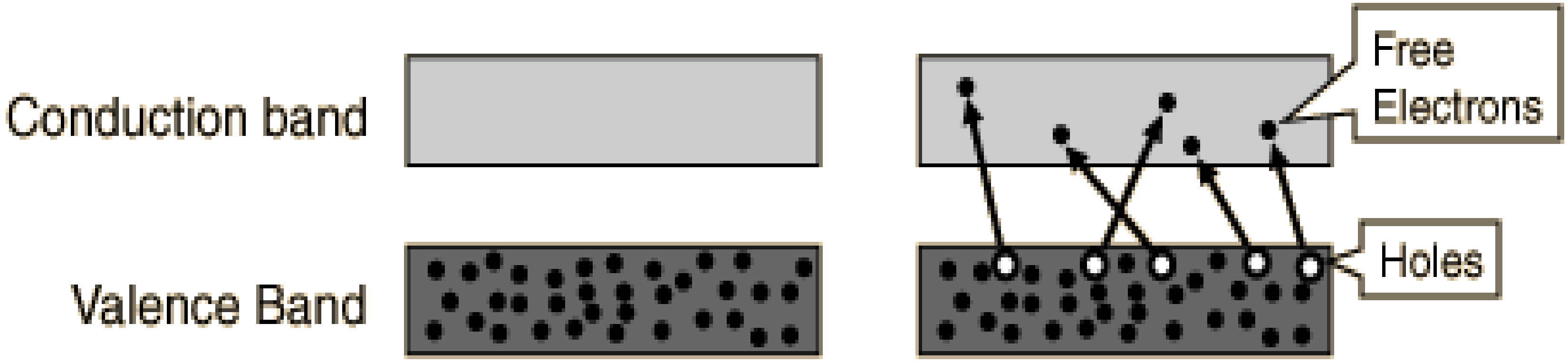


textbook

P.66

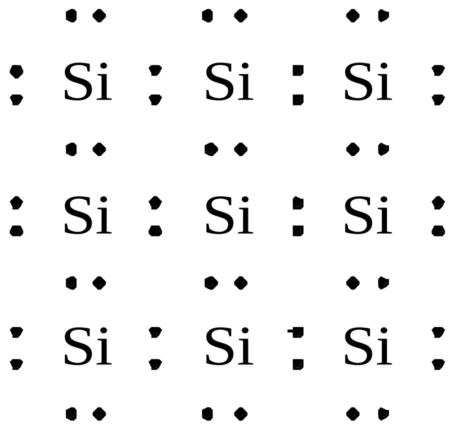
Band Model of Electrons and Holes

- In an pure semiconductor like silicon at temperatures above absolute zero, there will be some electrons which are excited across the band gap into the conduction band and which can produce current.
- When the electron in pure silicon crosses the gap, it leaves behind an **electron vacancy** or "**hole**" in the regular silicon lattice.
- Under the influence of an external voltage, both the electron and the hole can move across the material.

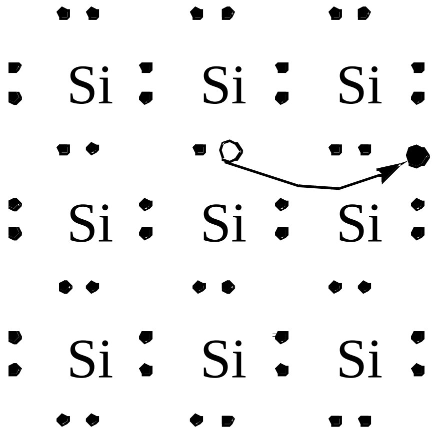


Bond Model of Electrons and Holes

2-D representation:
Covalent Bonds



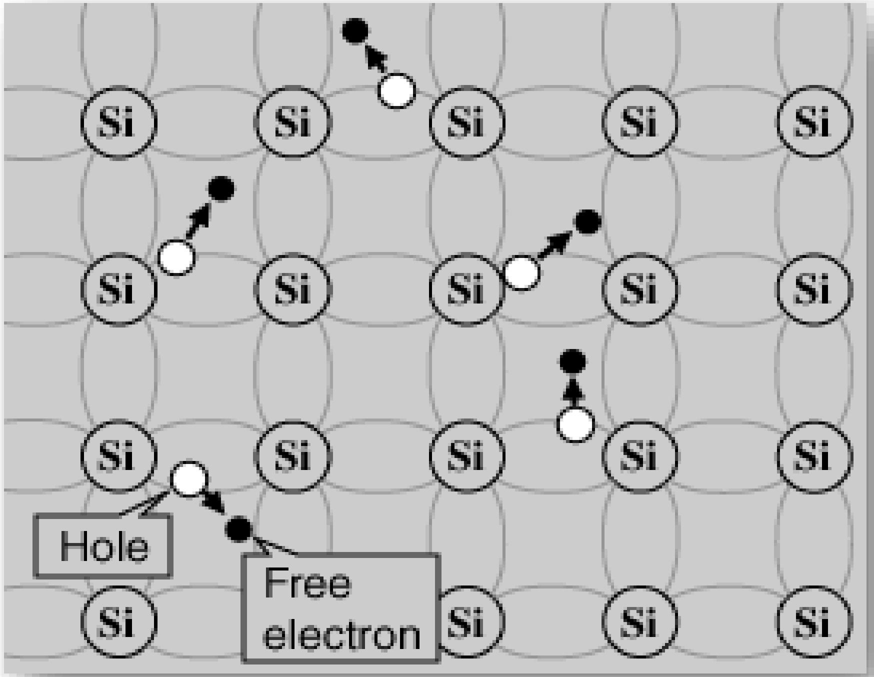
When an electron **breaks loose** and becomes a ***conduction electron***, a ***hole*** is also created.



Bond Model of Electrons and Holes

- When an electron **breaks loose** and becomes a ***conduction electron***, a ***hole*** is also created.
- A hole (along with its associated positive charge) is mobile!
- Hole density **=** electron density in a pure Si.

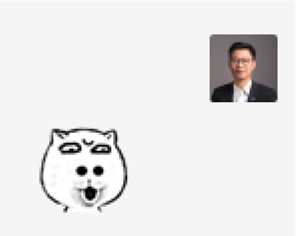
2-D representation:



Pure Si

2.3 Energy Bands

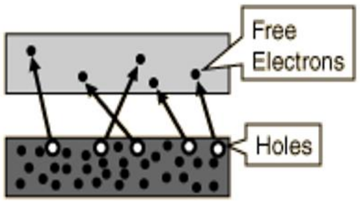
- Band theory
  - ➢ What's a Semiconductor
  - ➢ Fermi Level
  - ➢ Band model of *e* & *h*
  - ➢ Bond model of *e* & *h*

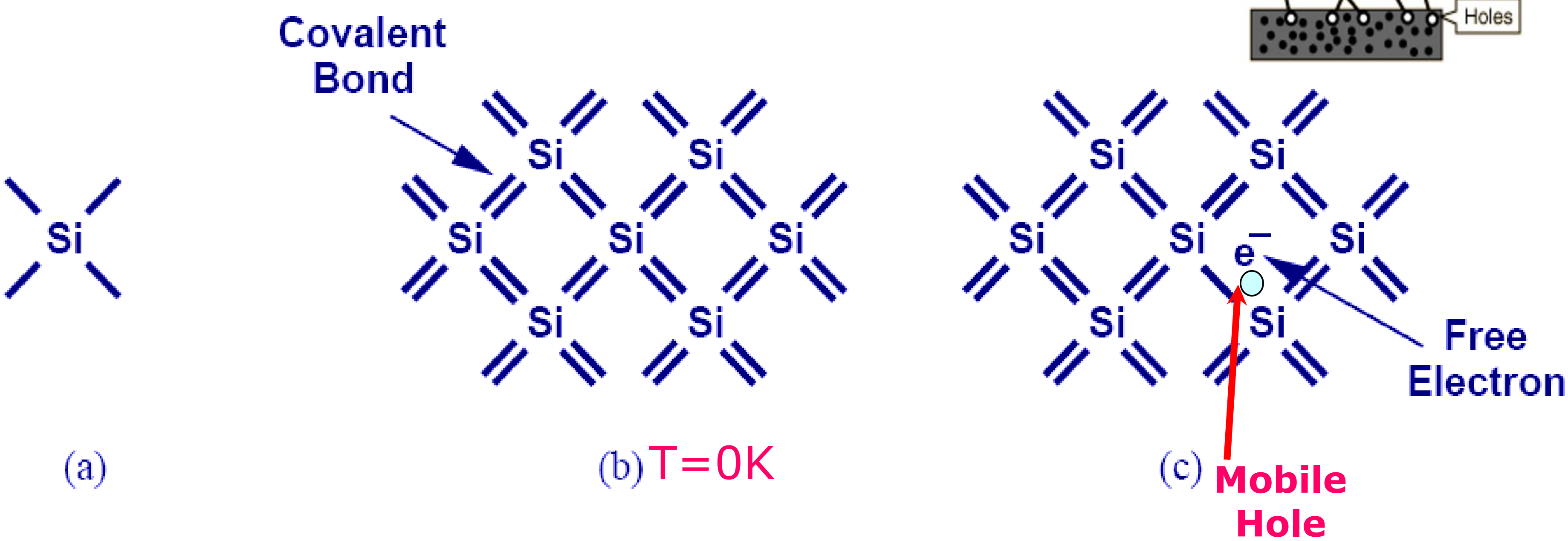


- **Generation and recombination**
- Intrinsic semiconductor

Thermal **Generation**

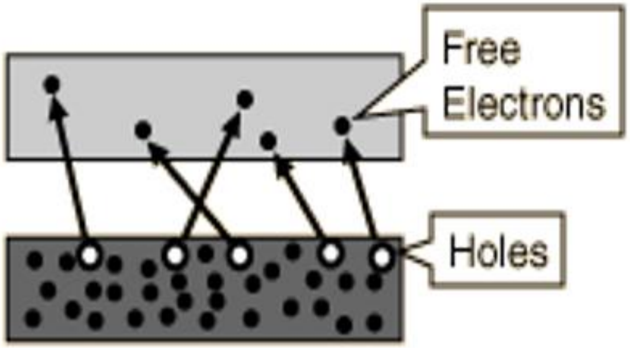
- Inverse process: **recombination**
- Si has four valence electrons. Therefore, it can form covalent bonds with four of its nearest neighbors.
- When temperature goes up, **electrons** can become free to **move** about the **Si lattice**.

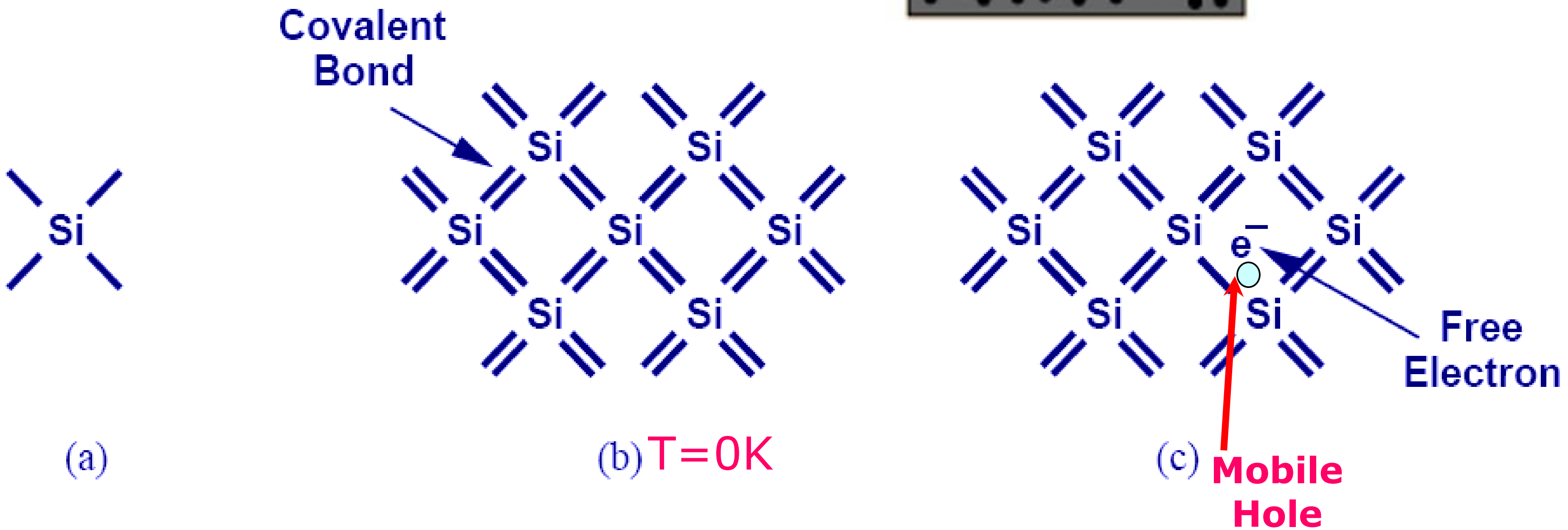




Generation

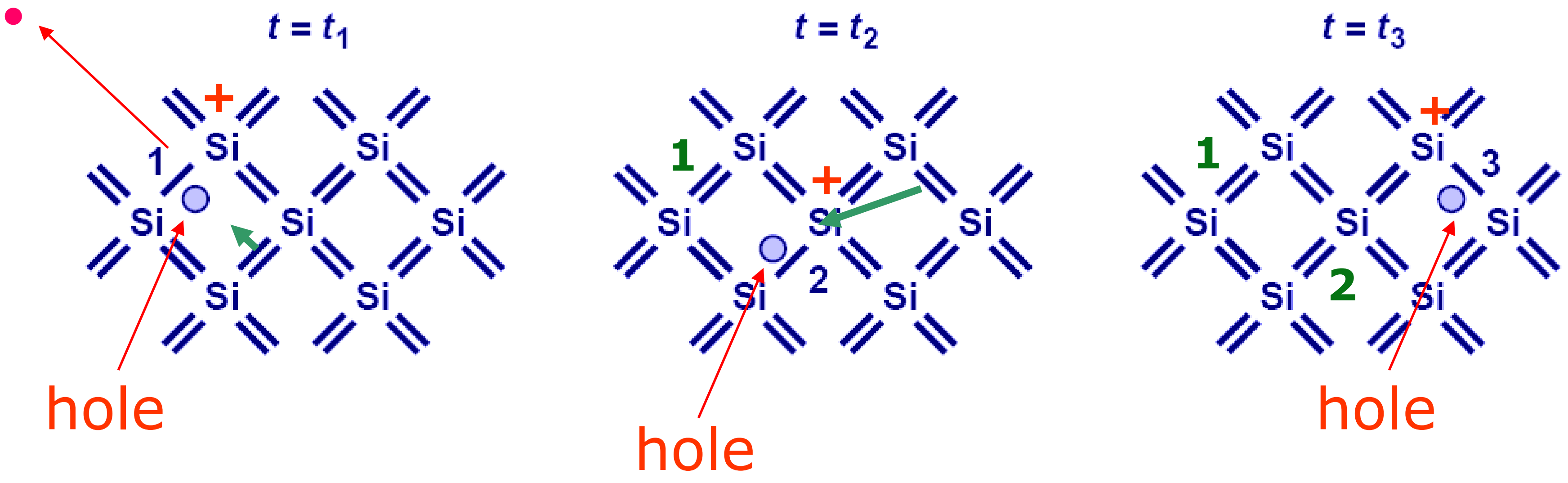
- **Generation: A process to create electron-hole pairs.**





Electron-Hole Pair Generation

- When a conduction electron is thermally generated, a “hole” is also generated.
- A hole is associated with a positive charge, and is free to move about the Si lattice as well.



A hole is **mobile!**

Generation

- We have seen that conduction (mobile) electrons and holes can be created in pure (intrinsic) silicon by **thermal generation**.
  - Thermal generation rate increases exponentially with temperature ***T***

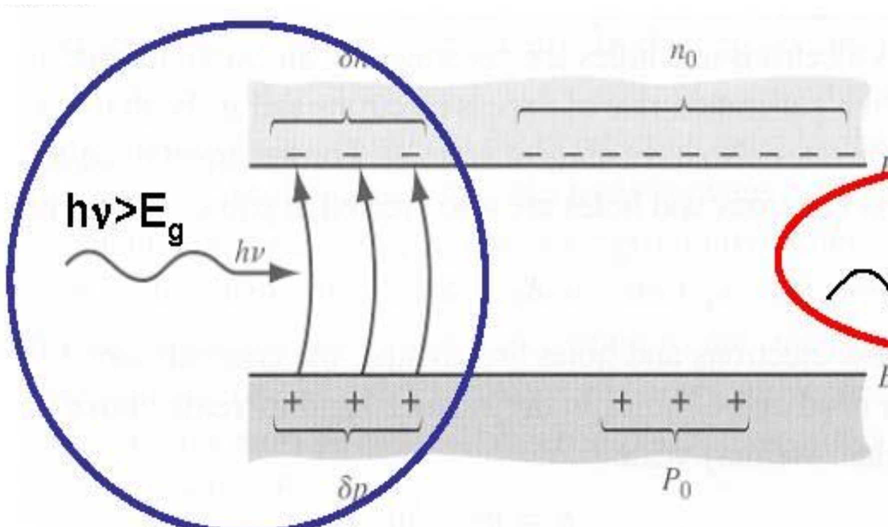
- Another type of generation process which can occur is **optical generation**
  - The energy absorbed from a **photon** frees an **electron** from covalent bond
    - In Si, the minimum energy required is 1.1eV, which corresponds to ~1 μm wavelength (infrared region).
    - 1 eV = energy gained by an electron falling through 1 V potential = $q_eV = 1.6 \times 10^{-19}$ CV = 1.6×10^{-19} J.

- Note that conduction electrons and holes are continuously generated, if $T > 0$

Light interactions with Semiconductors

Absorption of light in a semiconductor:

- For energies of light greater than the bandgap (***hv*** > E_g), light is absorbed
- For energies less than the bandgap ($hv<E_g$), light is out
- **Silicon** is transparent to IR (can see through it with an IR camera)
- **Diamond** is a **wide bandgap (~5.47eV)** semiconductor
- (transparent to **visible light**)



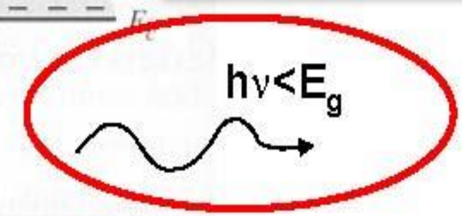
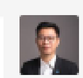


Figure 6.2 | Creation of excess electron and hole densities by photons.

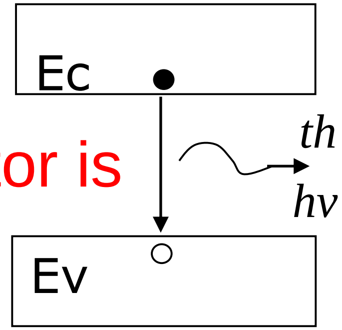


Recombination

- When a conduction **electron** and **hole** meet, each one is eliminated, a process called "**recombination**". The energy lost by the conduction electron (when it "falls" back into the covalent bond) can be released in two ways:

1. to the semiconductor lattice (vibrations)

   "thermal recombination" → semiconductor is **heated**



2. to photon emission

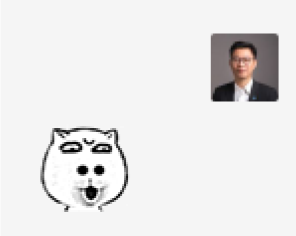
   "optical recombination" → light is **emitted**

   - It is the basis for light-emitting diodes and laser diodes.

LED

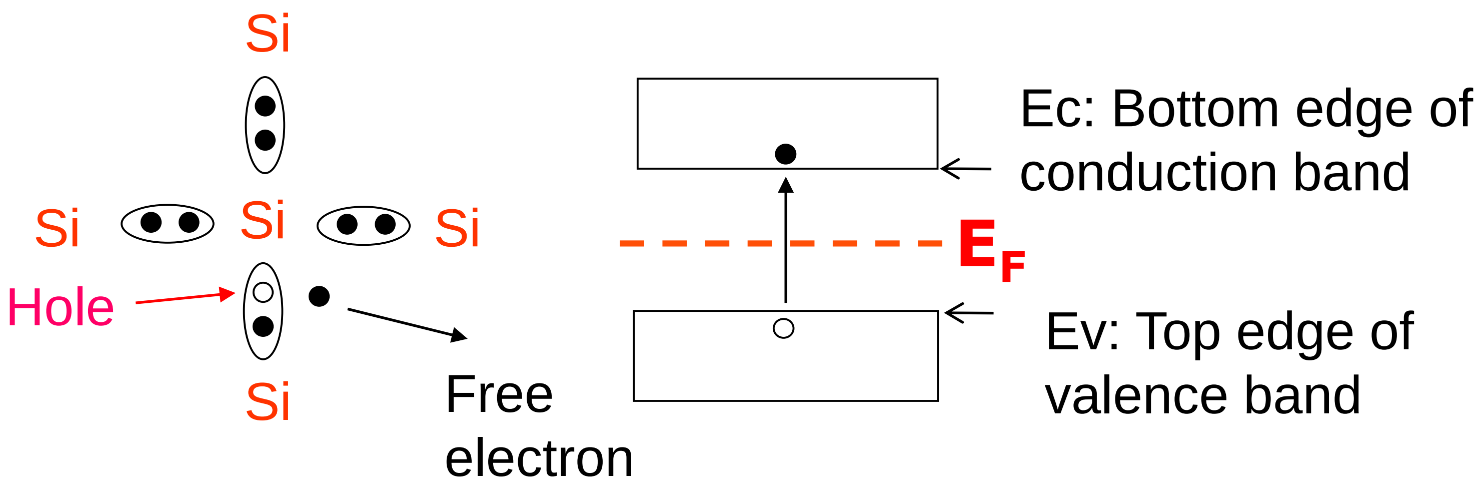
2.3 Energy Bands

- Band theory
  - What's a Semiconductor
  - Fermi Level
  - Band model of *e* & *h*
  - Bond model of *e* & *h*
- Generation and recombination
- **Intrinsic semiconductor**



Intrinsic semiconductors

- **Intrinsic**: **pure semiconductor**
- A **hole** is created simultaneously with a free **electron**
  - ***n***(free electron density) = ***p***(hole density)
- **E_F** is in the **middle** of the **bandgap** ★



Carrier Concentrations in Intrinsic Si

- The "band-gap energy" E_g is the amount of energy needed to remove an electron from a covalent bond.
- The concentration of **conduction electrons** in intrinsic silicon, n_i, depends exponentially on E_g and the absolute **temperature** (T):

E_g=1.12eV

$$n_i = 5.2 \times 10^{15} T^{3/2} \exp \frac{-E_g}{2kT} \quad \text{electrons/cm}^3$$

Boltzmann constant
8.62E-5 eV/K

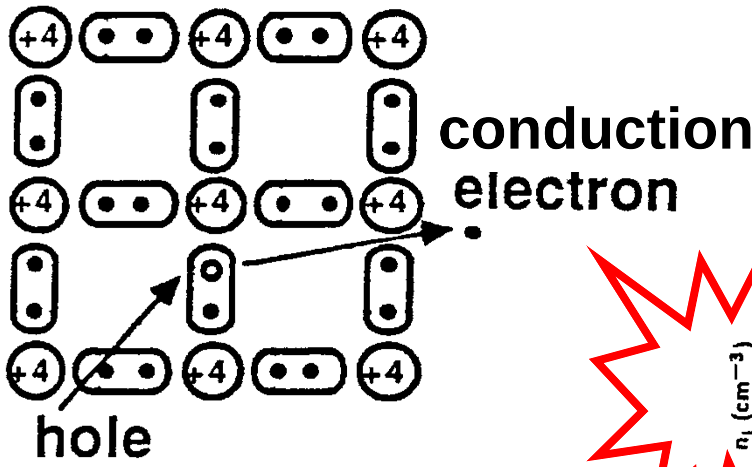
$$n_i \cong 1 \times 10^{10} \text{ electrons/cm}^3 \text{ at } 300\text{K}$$

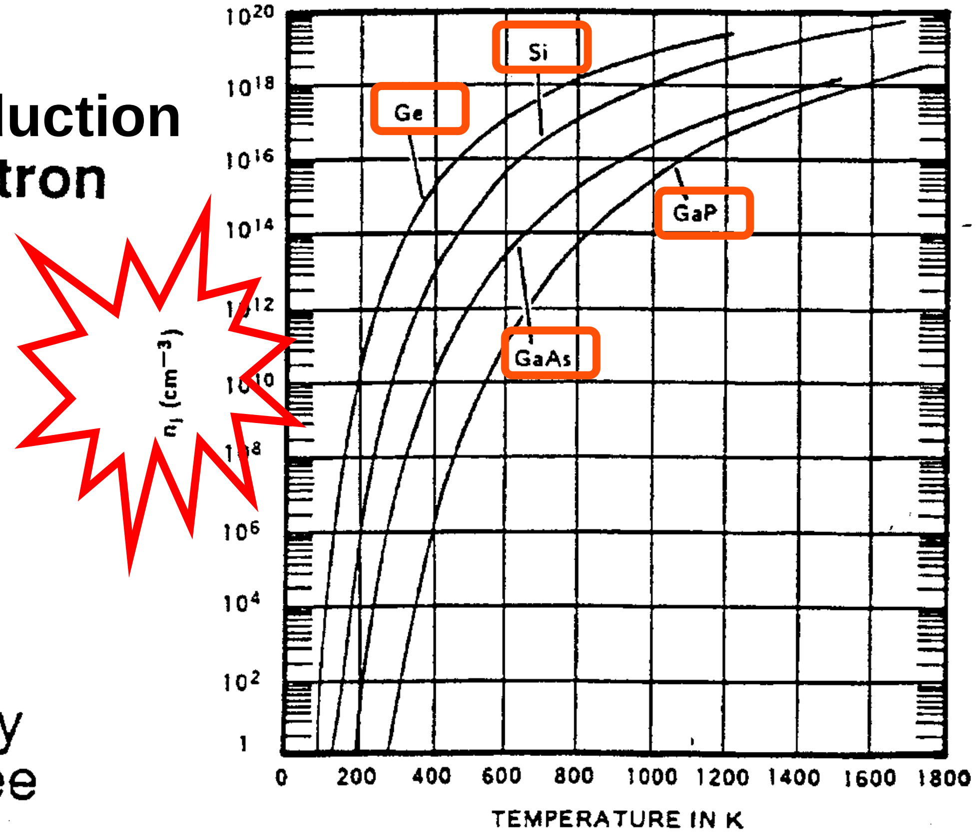
RT

$$n_i \cong 1 \times 10^{15} \text{ electrons/cm}^3 \text{ at } 600\text{K}$$

Pure Si

$$n_i = 5.2\times10^{15} T^{3/2} \exp\frac{-E_g}{2kT} \ \text{electrons/ cm}^3$$





Covalent (shared e⁻) bonds exists between Si atoms in a crystal. Since the e⁻ are loosely bound, some will be free at any T, creating hole electron pairs.

Si:

$$n_i = 3.9 \times 10^{16} T^{3/2} e^{-\frac{0.605\text{eV}}{kT}} /\text{cm}^3$$

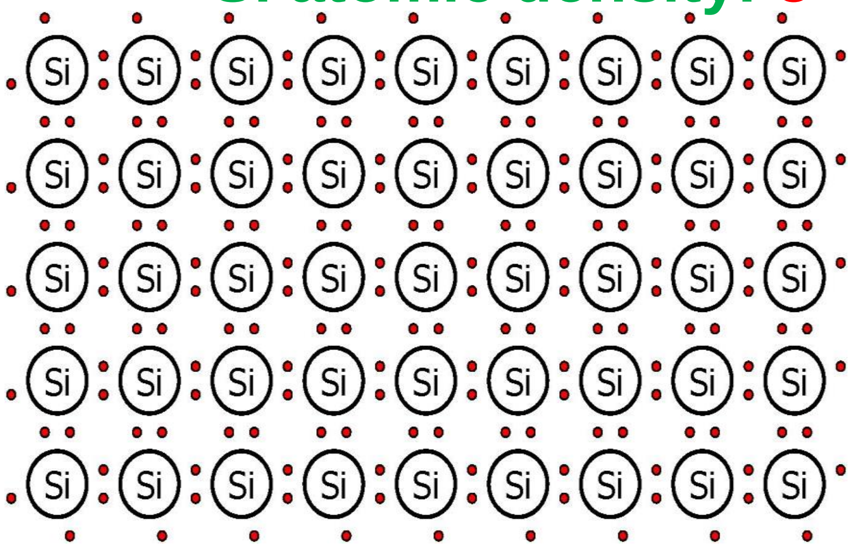
p.75

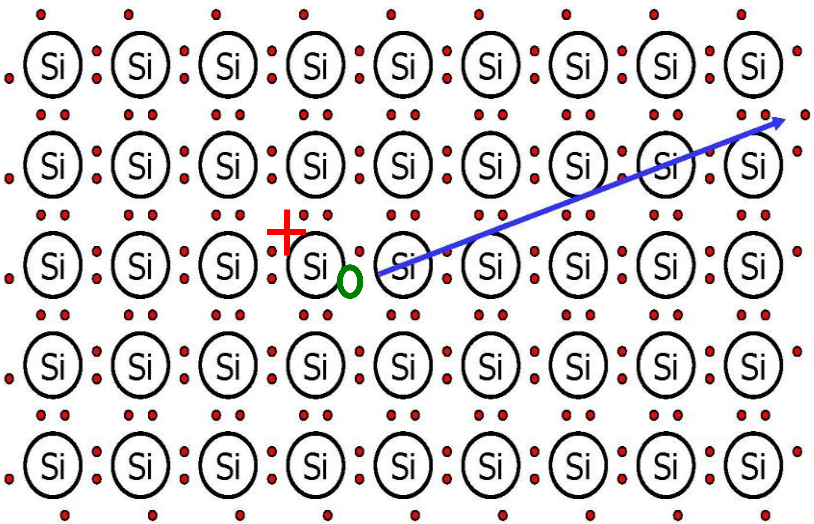
$n_i \cong$ 1$\times 10^{10}$ cm^{-3} at room temperature

Intrinsic Semiconductor

Silicon has four valence electrons

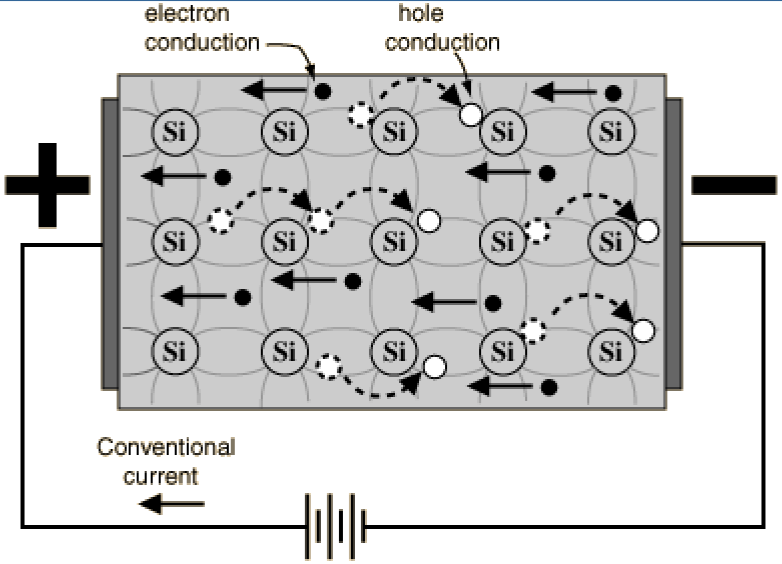
- It covalently bonds with 4 adjacent atoms in the crystal lattice
- Increasing Temperature Causes Creation of Free Carriers. **10^{10}cm^{-3}** free carriers at **23ºC** (out of $2\text{x}10^{23}$cm^{-3}): Intrinsic Conductivity.
- **Si atomic density: 5 $\times 10^{22}$ cm^{-3}**





Semiconductor Current

- Both **electrons and holes** contribute to current flow in an intrinsic semiconductor.



2.4 The doping of semiconductors

- **Doping elements**

- Doping: N type
- Doping: P type
- Counter doping

The Doping

- The addition of a **small percentage** of **foreign atoms** in the regular crystal lattice of silicon or germanium produces **dramatic changes** in their electrical properties, producing **n-type** and **p-type** semiconductors.
- Definition of Terms:

n = number of electrons/cm^3

p = number of holes/cm^3

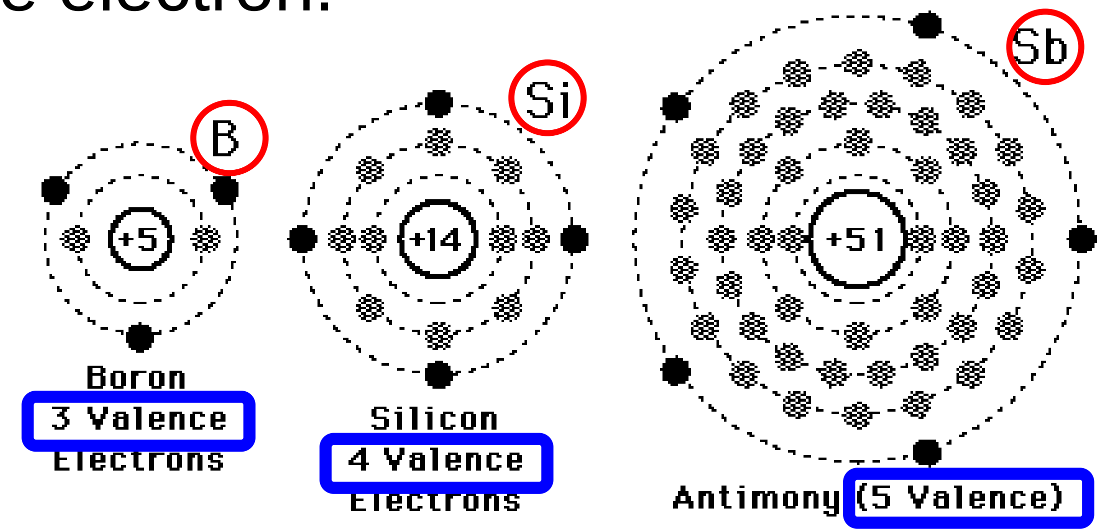
n_i = intrinsic carrier concentration

In a **pure semiconductor**,

$$n = p = n_i$$

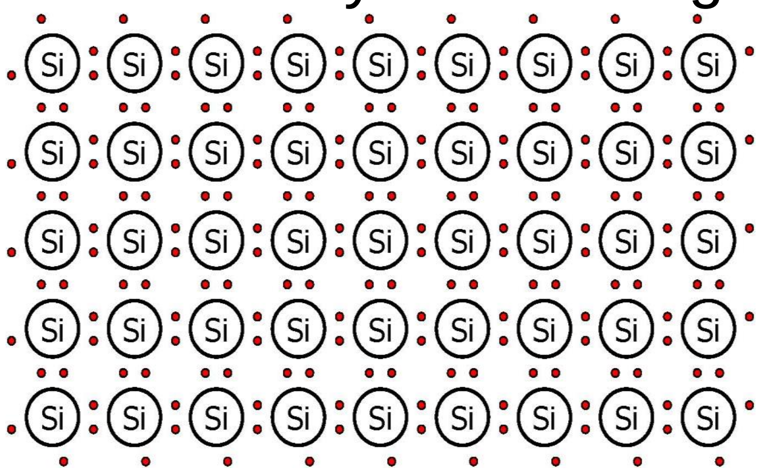
Valence Electrons

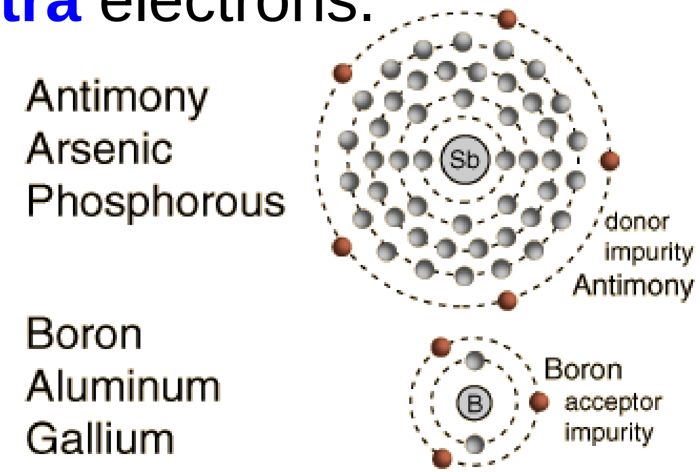
- The electrons in the outermost shell of an atom are called **valence electrons**; they dictate the nature of the **chemical reactions** of the atom and largely determine the **electrical nature** of solid matter. The electrical properties of matter are pictured in the band theory of solids in terms of how much energy it takes to free a valence electron.



The Doping of Semiconductors

Pentavalent impurities (donor impurities = **donors**)
Impurity atom with **5 valence electrons** produce **n-type** semiconductors by contributing **extra** electrons.

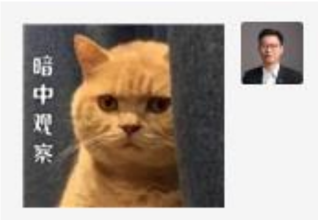




Trivalent impurities (acceptor impurities = **acceptors**)
Impurity atoms with **3 valence electrons** produce **p-type** semiconductors by producing a "**hole**" or **electron deficiency**.

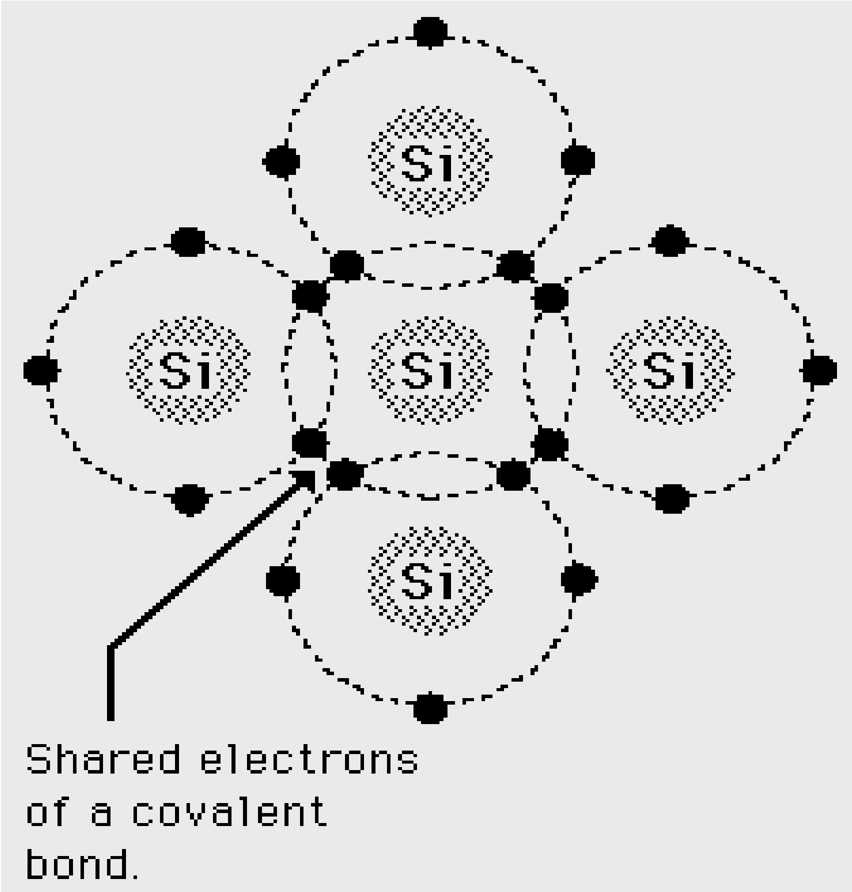
2.4 The doping of semiconductors

- Doping elements
- **Doping: N type**
- Doping: P type
- Counter doping



Doping (N type)

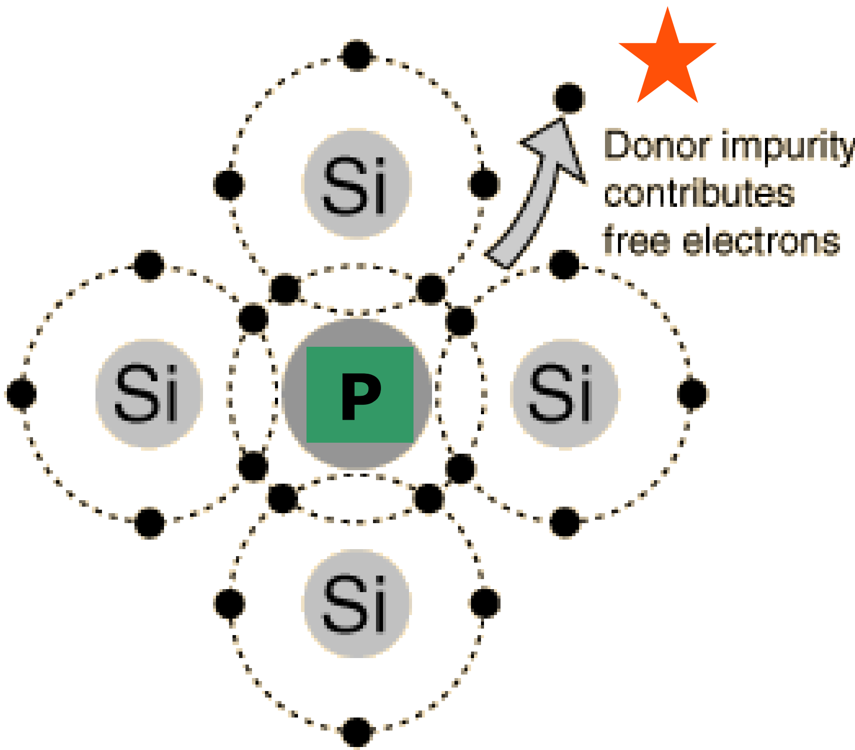
Column **V** elements are **donors**, e.g. P, As, Sb



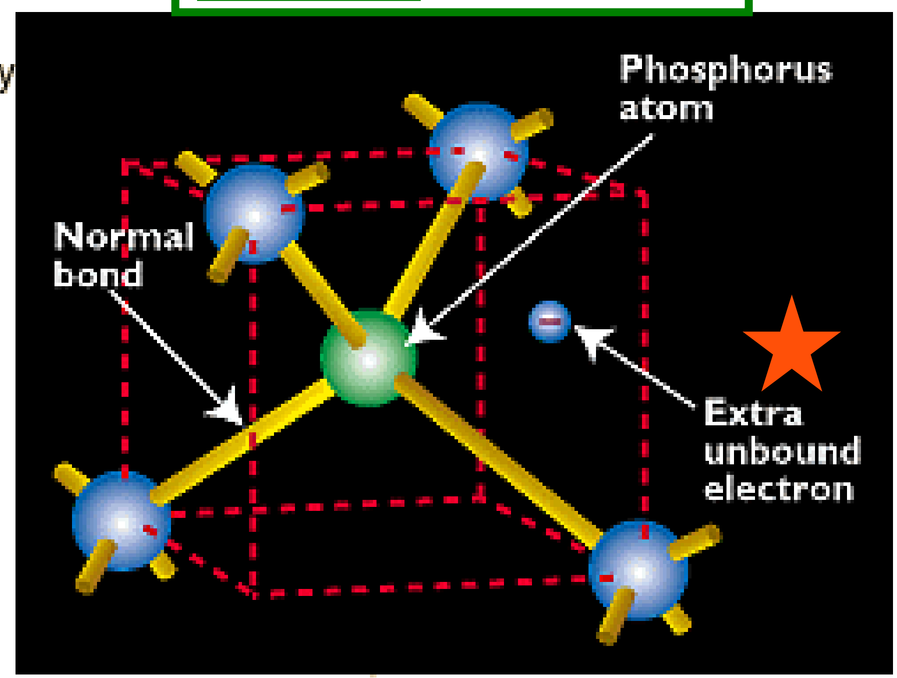
Doping (N type)

Column **V** elements are **donors**, e.g. P, As, Sb

By <u>substituting</u> a Si atom with a special impurity atom (Column V element), a conduction electron is created.

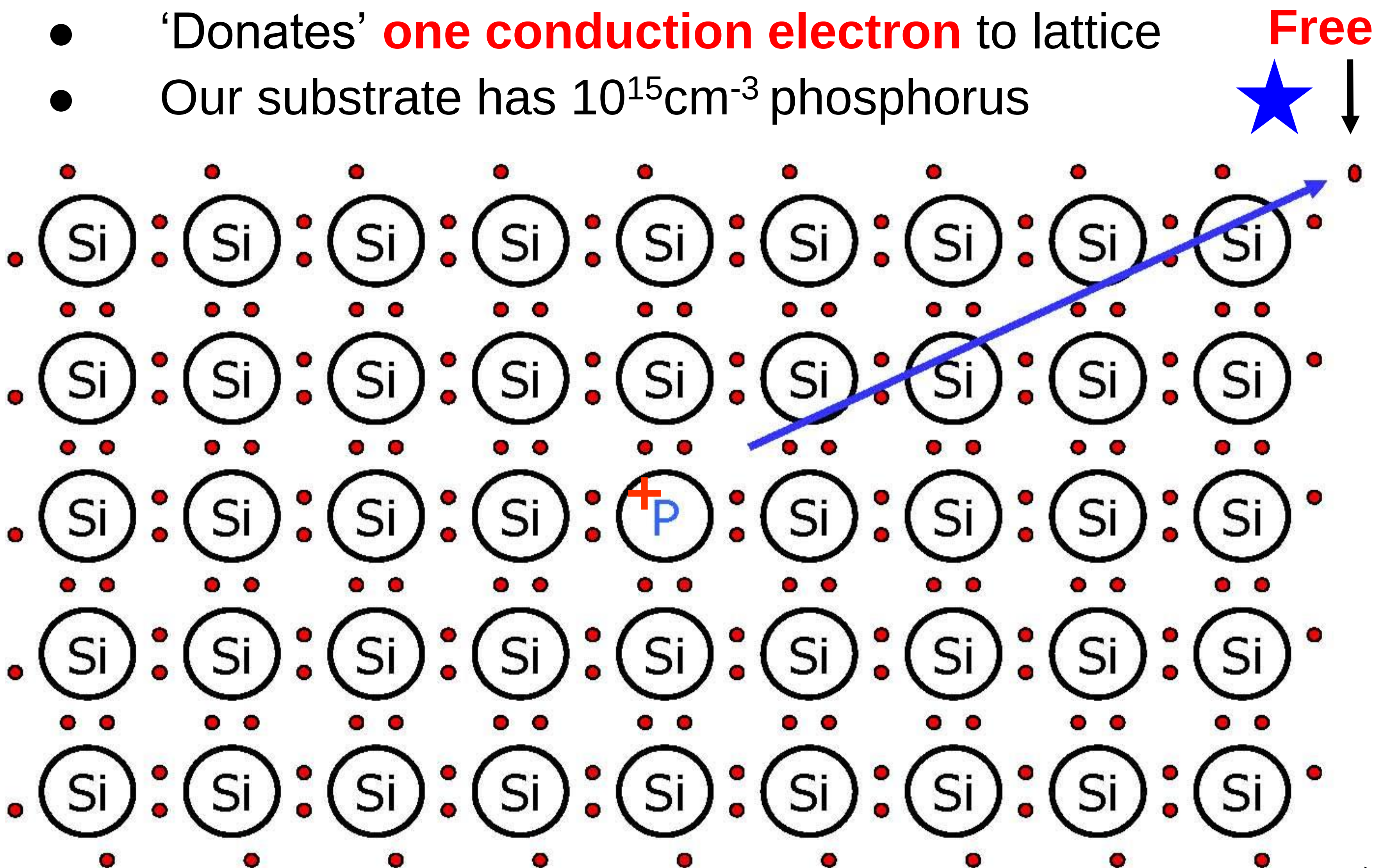


<u>Donors</u>: P, As, Sb



Phosphorus has **5 valence electrons**

- ‘Donates’ **one conduction electron** to lattice
- Our substrate has 10^{15}cm^{-3} phosphorus



Doping (N type)

- If Si is doped with **phosphorus (P)**, each P atom can contribute a conduction **electron**, so that the Si lattice has more electrons than holes, *i.e.* it becomes "**N type**":

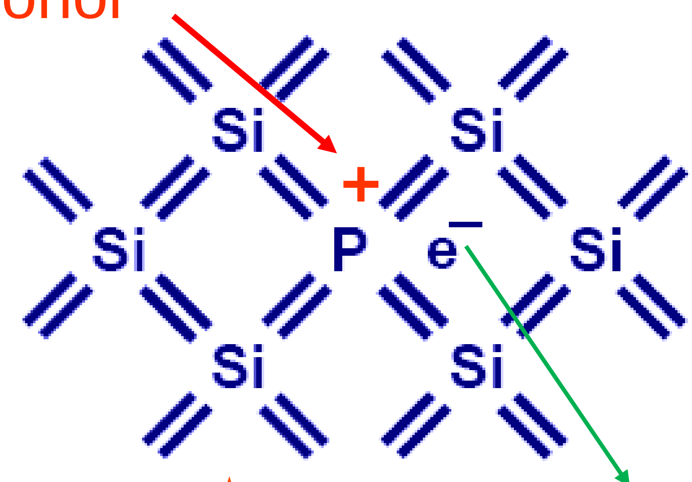
<u>Notation</u>:

N_D = Concentration of donors

n = electron concentration

N_D^+ = Concentration of ionized donors

Immobile ion: N_D^+
Ionized donor



n_{iD} **?**

$$n = N_D^+ + n_{iD}$$

free

Ionization energy < 50meV:

At RT, $N_D \approx N_D^+ >> n_{iD}$

Doping (N type)

- If Si is doped with **phosphorus (P)**, each P atom can contribute a conduction **electron**, so that the Si lattice has more electrons than holes, *i.e.* it becomes "**N type**":

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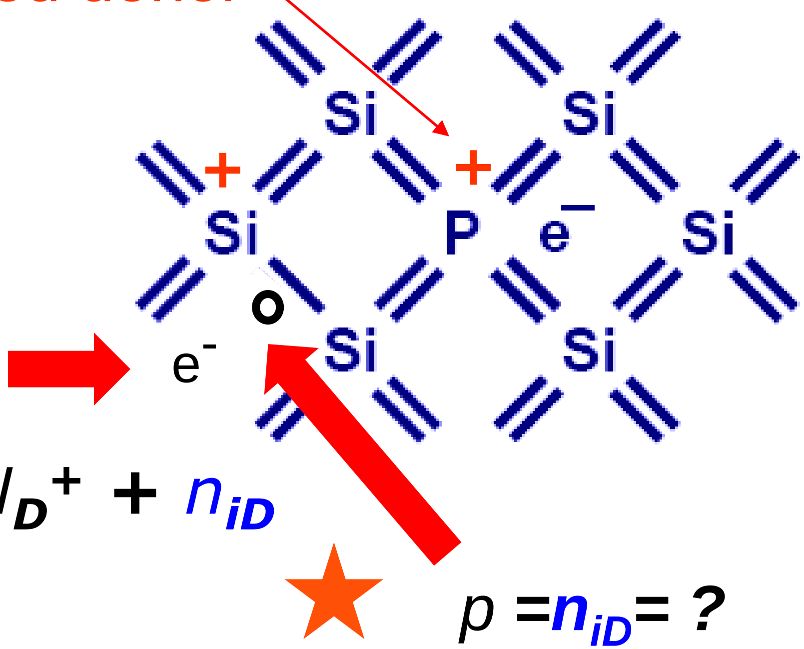


n_{iD} ?

$n = N_D^+ + n_{iD}$

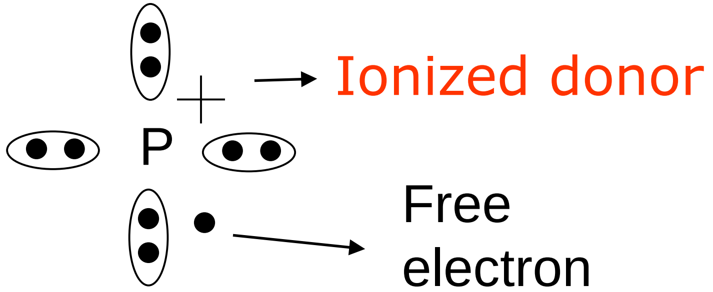
$p = n_{iD} = ?$

Ionization energy < 50meV:

At RT, $N_D \approx N_D^+ >> n_{iD}$

N-type

- Doped by impurities of **5 valence electrons** (**donors**)
- At room temperature, one donor will create one free electron.
- Holes are not created
- $\boxed{\mathbf{n} = n_{iD} + \mathbf{N_D}}$
  - $n_{iD} << n_i$ = density of free electrons in the intrinsic semiconductor
  - $\mathbf{N_D}$ = **density of donors**
- Normally, $\mathbf{N_D} > 10^{14}\ cm^{-3}$ and $n_i \approx 10^{10}\ cm^{-3}$
- Since $\mathbf{N_D} >> n_{iD}$, $\boxed{\mathbf{n \approx N_D}.}$ The density of free electron can be controlled through **doping**.



Electron and Hole Concentrations

No E field, no B field, no light

- Under thermal equilibrium conditions, the product of the conduction-electron density and the hole density is ALWAYS equal to the square of n_i:

★ $\boxed{np = n_i^2 = (10^{10})^2/\text{cm}^3 \textbf{ at RT}}$

N-type material at RT

$$n \approx N_D$$

$$p \approx \frac{n_i^2}{N_D}$$

Example: at RT

$N_D = 10^{15}/\text{cm}^3$

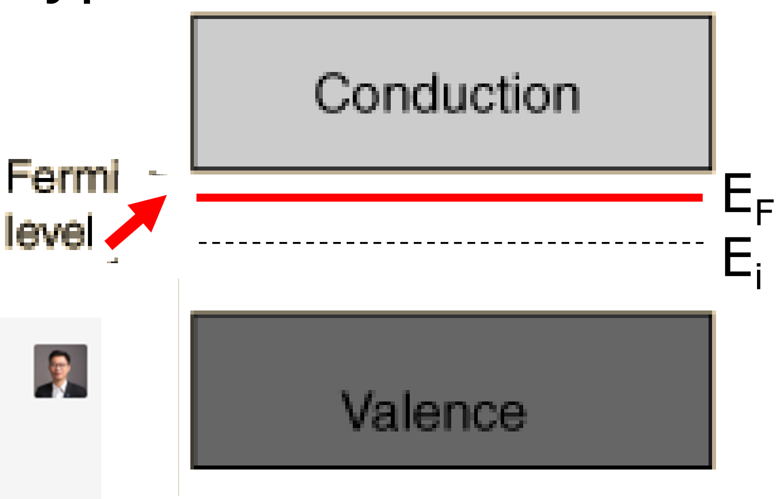
$\boldsymbol{n = 10^{15}/\text{cm}^3}$

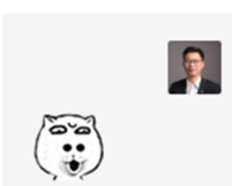
$N_D^+ = 10^{15}/\text{cm}^3$

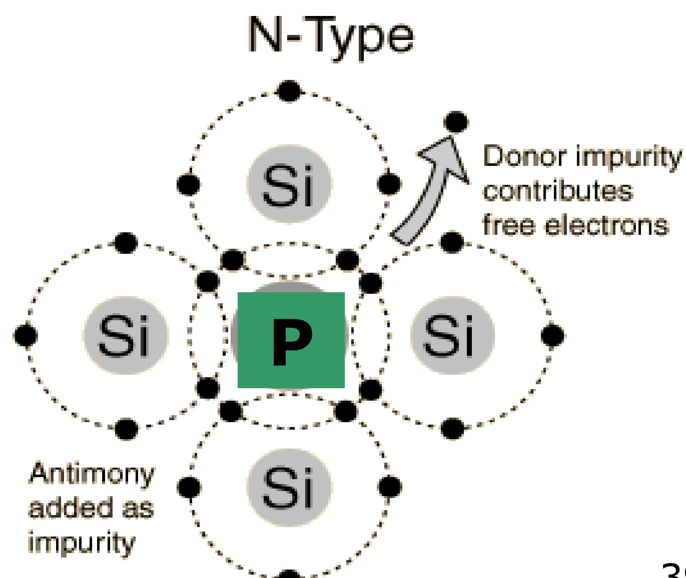
$\boldsymbol{p = 10^5/\text{cm}^3}$

N-Type Semiconductor

- The addition of pentavalent impurities such as Sb, As or P contributes **free electrons**, greatly increasing the **conductivity** of the intrinsic semiconductor.
- **Phosphorus** may be added by diffusion of phosphine gas (PH_3).
- E_F is shifted to the **up-half** of the bandgap for n-type.

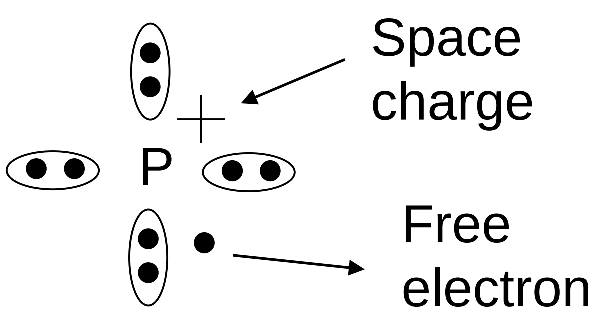


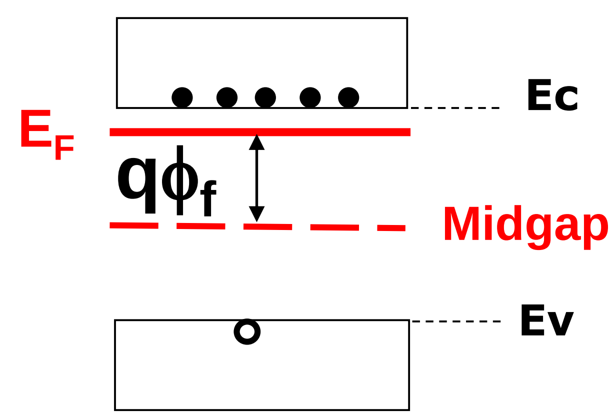




Properties of N-type

- n>>p, so "**n-type**".
- Electrons are '**majority**' charge carriers and holes are '**minority**' charge carriers.
- Space charge: when an electron is freed, it left a positively charged atom behind, which is fixed in space
- **Fermi potential: ϕ_f**
  - How '**strong**' the n-type is





2.4 The doping of semiconductors

- Doping elements
- Doping: N type
- **Doping: P type**

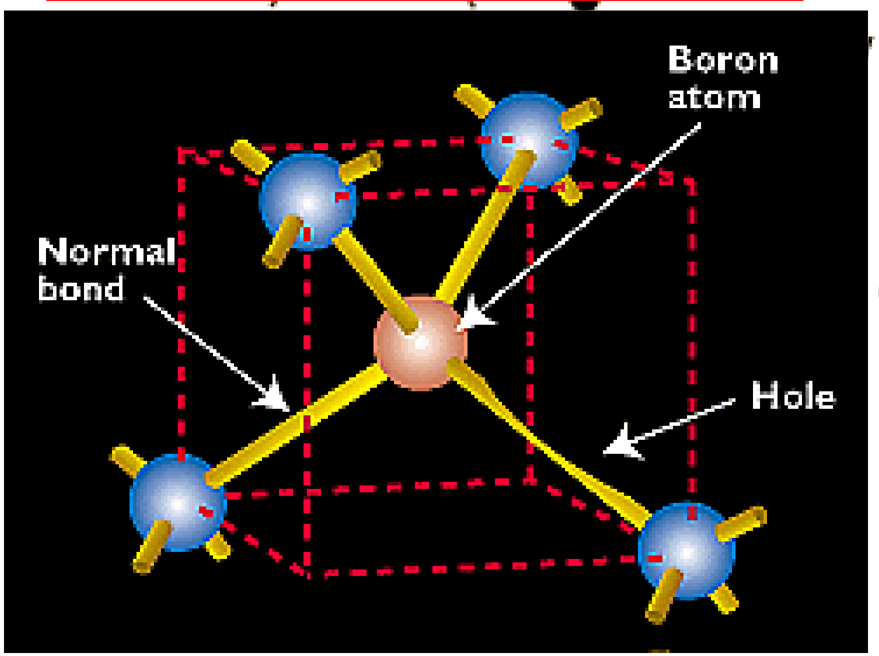
- Counter doping

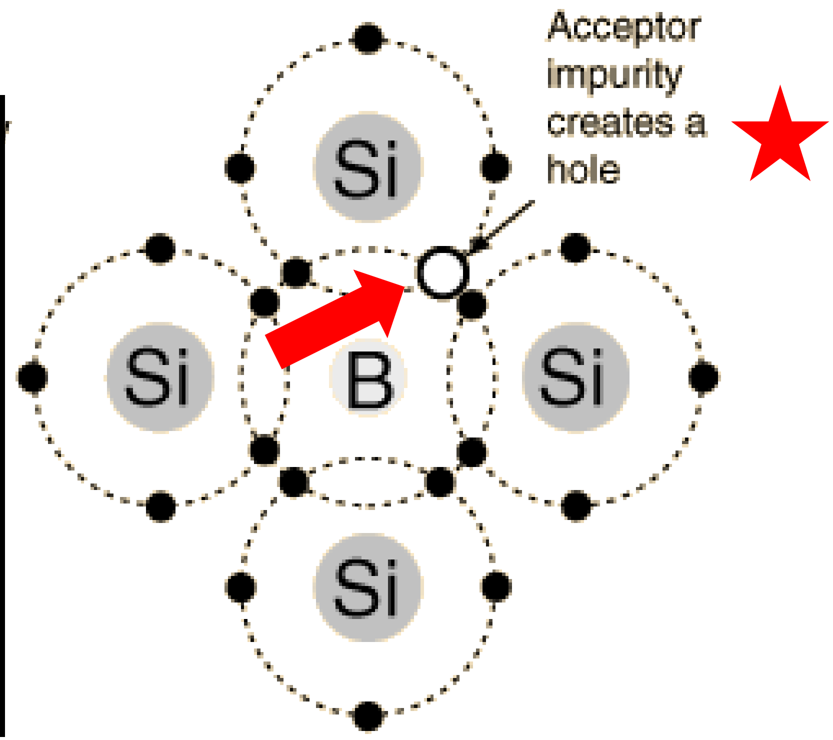
Doping (P type)

Column III elements are **acceptors**, e.g. B, Al, Ga

By <u>substituting</u> a Si atom with a special impurity atom (Column III element), a conduction hole is created.

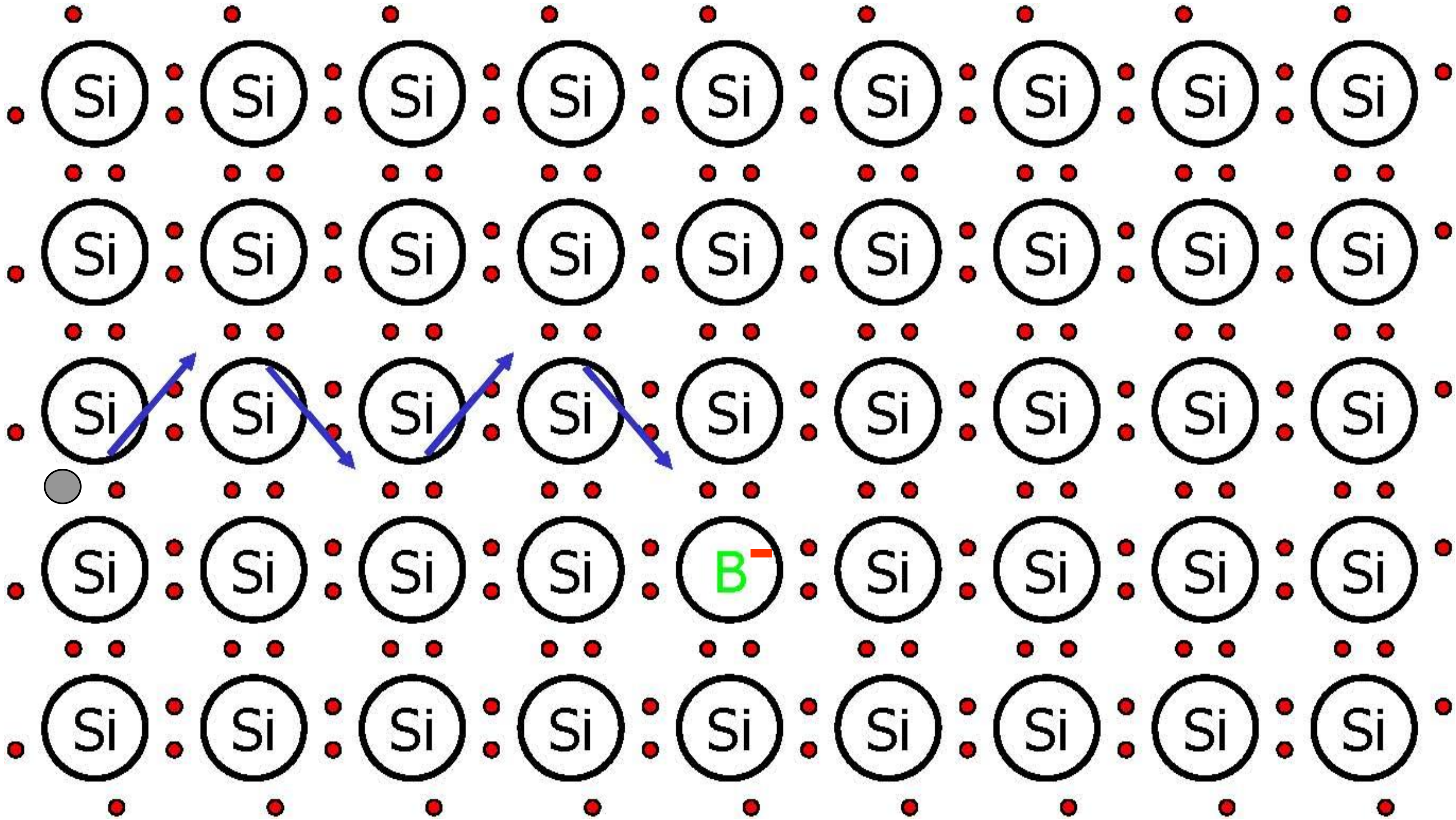
<u>Acceptors</u>: B, Al**,** Ga, **In**





Boron has 3 valence electrons

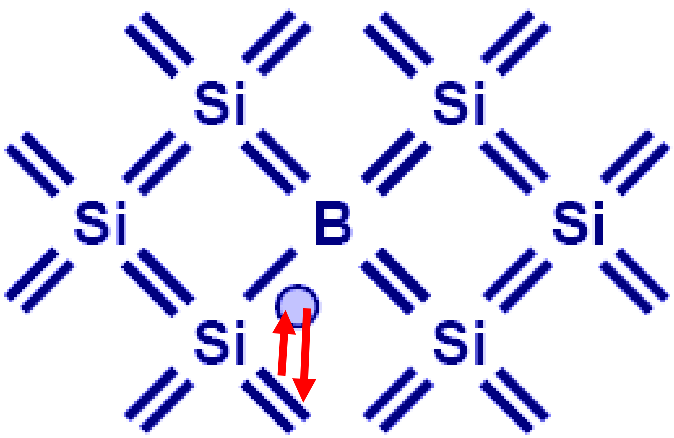
- ‘**Accepts**’ one electron from lattice
- Creates a ‘**hole**’



Doping (P type)

Column III elements are acceptors, e.g. B

- If Si is doped with **Boron (B)**, each B atom can contribute a **hole**, so that the Si lattice has **more holes** than electrons, *i.e.* it becomes "**P type**":



Notation:

N_A = concentration of acceptors

p = hole concentration

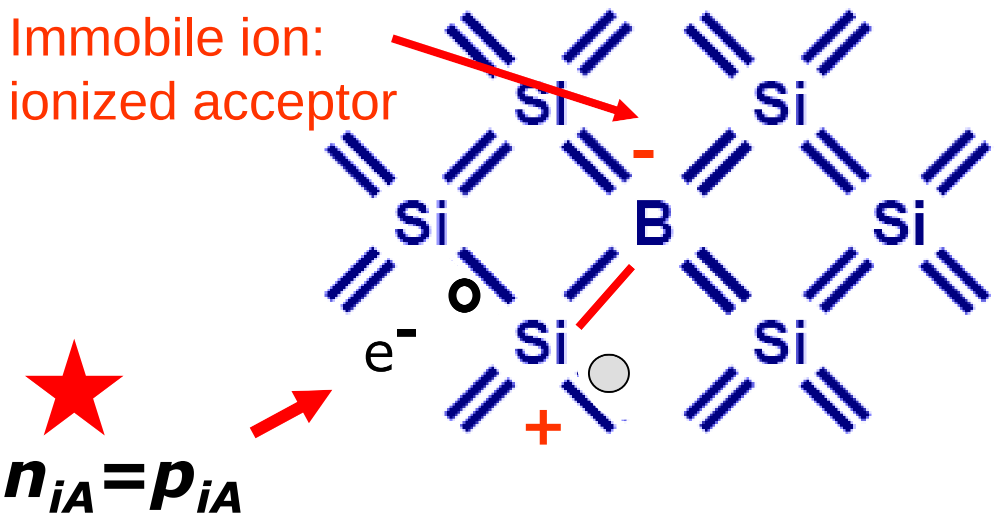
N_A^- = concentration of ionized acceptors

Hole is created when a neighboring valence electron moves to the B atom.

Doping (P type)

Column III elements are acceptors, e.g. B

- If Si is doped with **Boron (B)**, each B atom can contribute a **hole**, so that the Si lattice has **more holes** than electrons, *i.e.* it becomes "**P type**":



Notation:

N_A = concentration of acceptors

p = hole concentration

N_A^- = concentration of ionized acceptors

$$p = N_A^- + p_{iA}$$

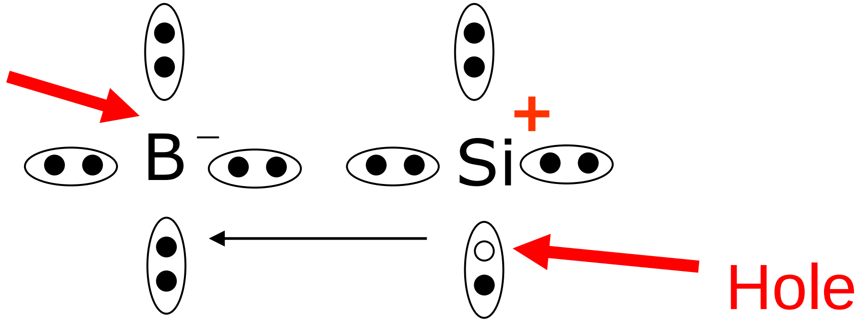
Ionization energy < 50meV:

At RT, $N_A \approx N_A^- >> p_{iA}$

P-type

- Doped by impurities of **3 valence electrons** (acceptors)
- At room temperature, one acceptor will create one hole.
- Free electrons are not created
- $\boxed{\mathbf{p} = p_{iA} + N_A \approx \mathbf{N_A}.}$
  - $p_{iA} << p_i$ = density of holes in the intrinsic semiconductor
  - $\mathbf{N_A}$ = density of acceptors

Immobile ion: N_A^-
ionized acceptor



Electron and Hole Concentrations

- Under thermal equilibrium conditions, the product of the **conduction-electron density** and the **hole density** is ALWAYS equal to the **square of n_i**:

★ $\boxed{np = n_i^2 = (10^{10})^2/\text{cm}^3 \textbf{ at RT}}$

P-type material at RT

$$\boxed{\begin{aligned} p &\approx N_A \\ n &\approx \frac{n_i^2}{N_A} \end{aligned}}$$

Example: at RT

$N_A = 10^{15}/\text{cm}^3$

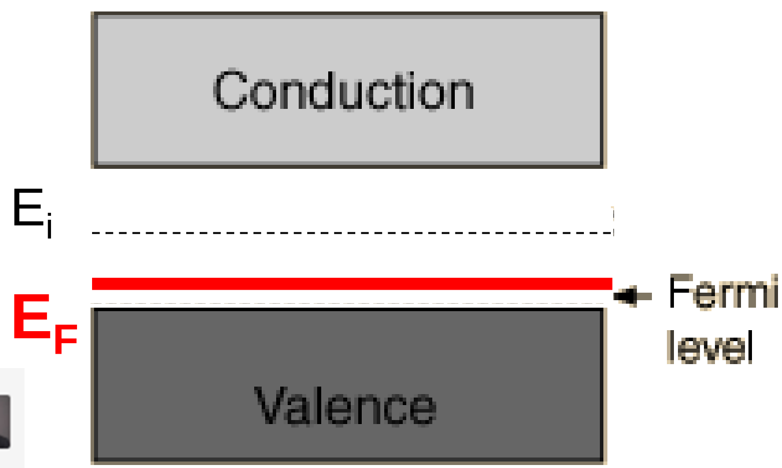
$p = 10^{15}/\text{cm}^3$

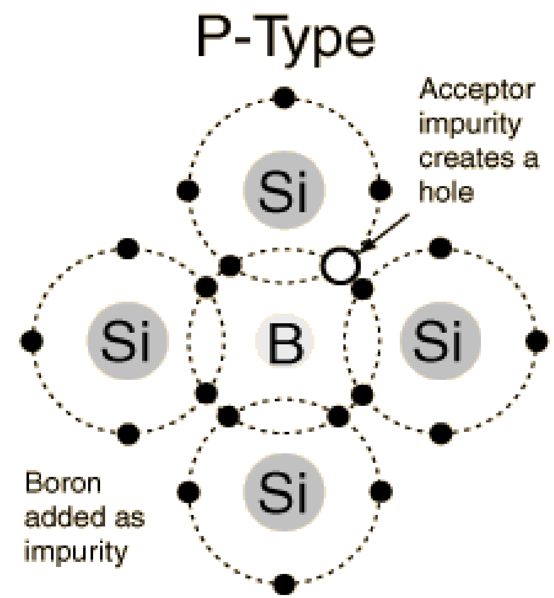
$N_A^- = 10^{15}/\text{cm}^3$

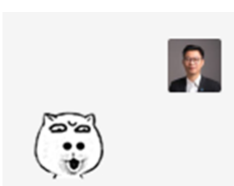
$n = 10^5/\text{cm}^3$

P-Type Semiconductor

- The addition of **trivalent** impurities such as B, Al, or Ga to an intrinsic semiconductor creates deficiencies of valence electrons, called "**holes**".
- It is typical to use B_2H_6 diborane gas to diffuse boron into the silicon material.
- E_F is shifted to the **down-half** of the bandgap for p-type.

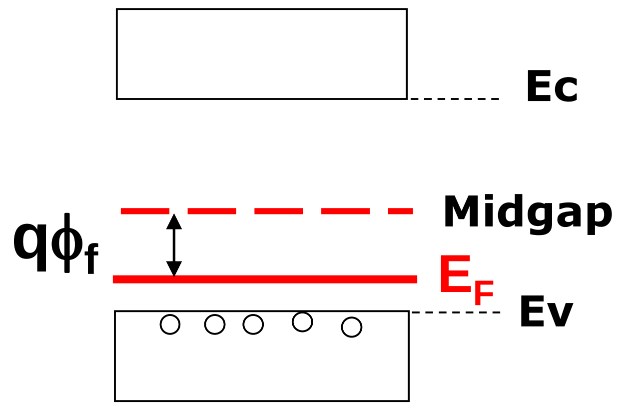






Properties of P-type

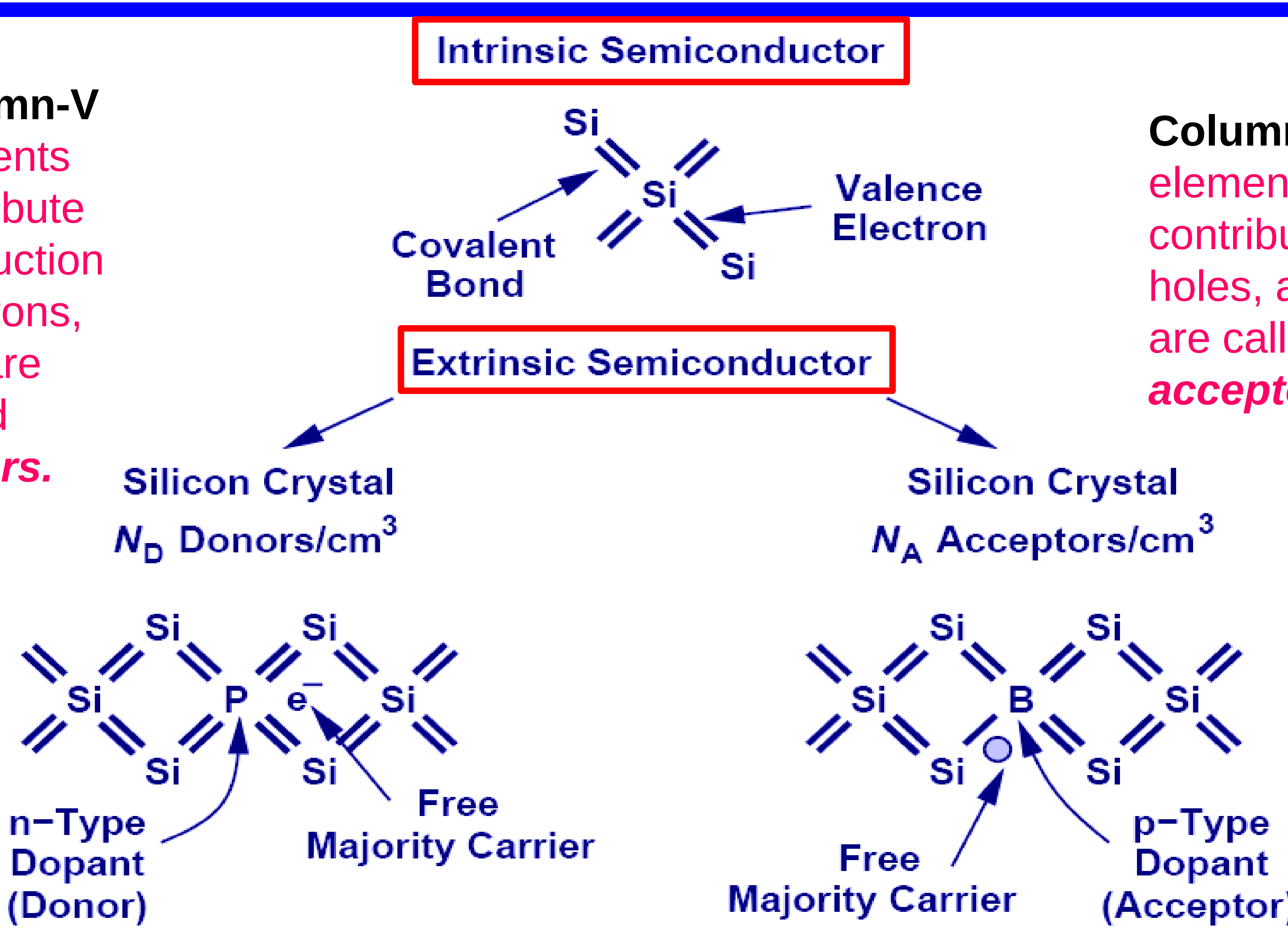
- p>>n, so "**p-type**".
- **Holes are 'majority'** charge carriers and **electrons are 'minority'** charge carriers.
- Space charge: negative charges bonded to Boron atoms
- **Fermi potential: ϕ_f**
  - How '**strong**' the p-type is



Summary of doping

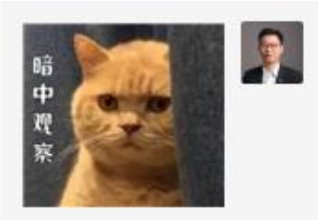
Column-V elements contribute conduction electrons, and are called ***donors.***

Column-III elements contribute holes, and are called ***acceptors***



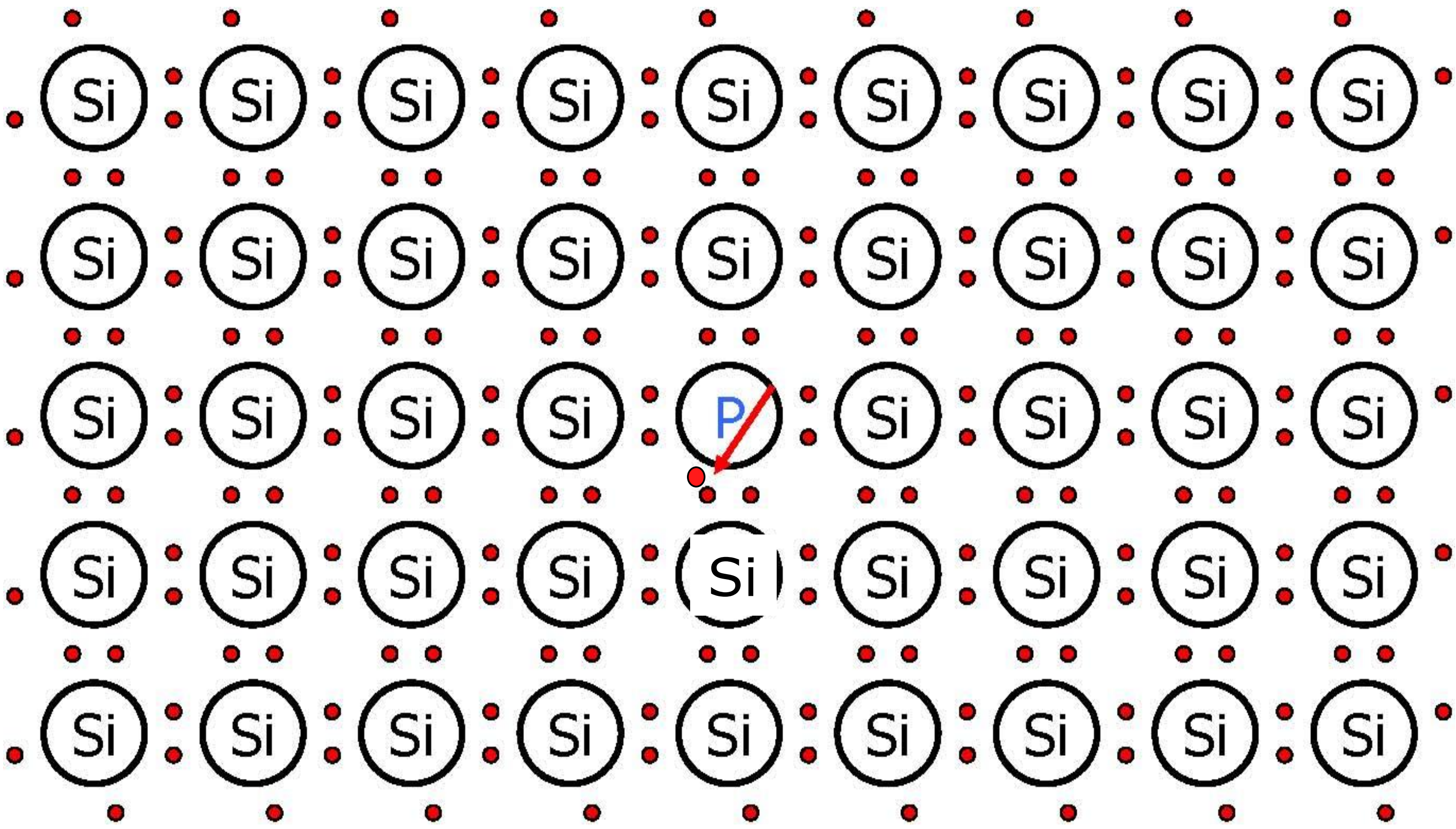
2.4 The doping of semiconductors

- Doping elements
- Doping: N type
- Doping: P type
- **Counter doping**



Counter Doping

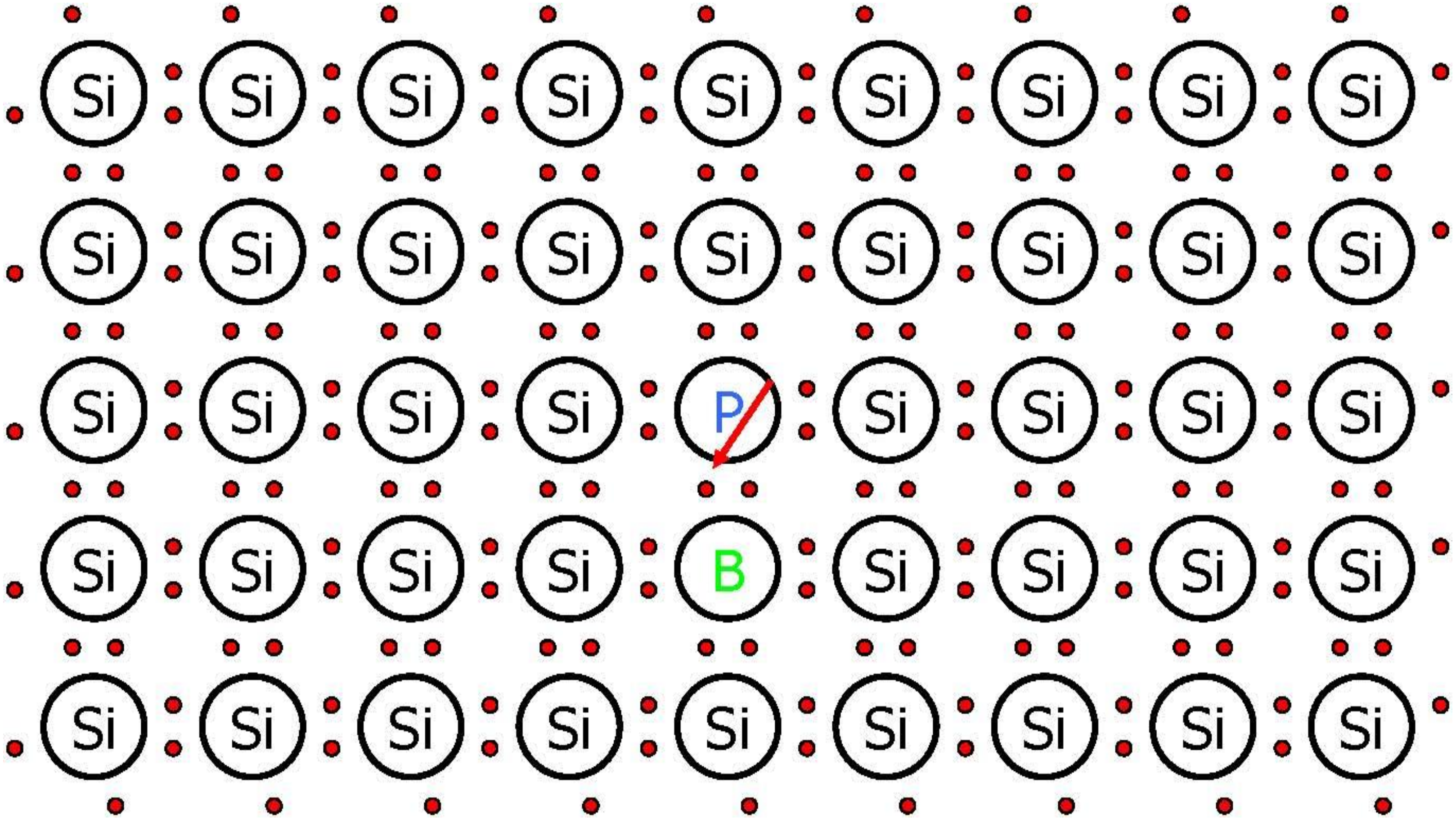
This is a **n-type** Si, $n = N_D + n_i$. Nomally $N_D >> n_i$, so $\boldsymbol{n = N_D}$



Counter Doping

Adding the **same B** as **P** causes the doping type to change.

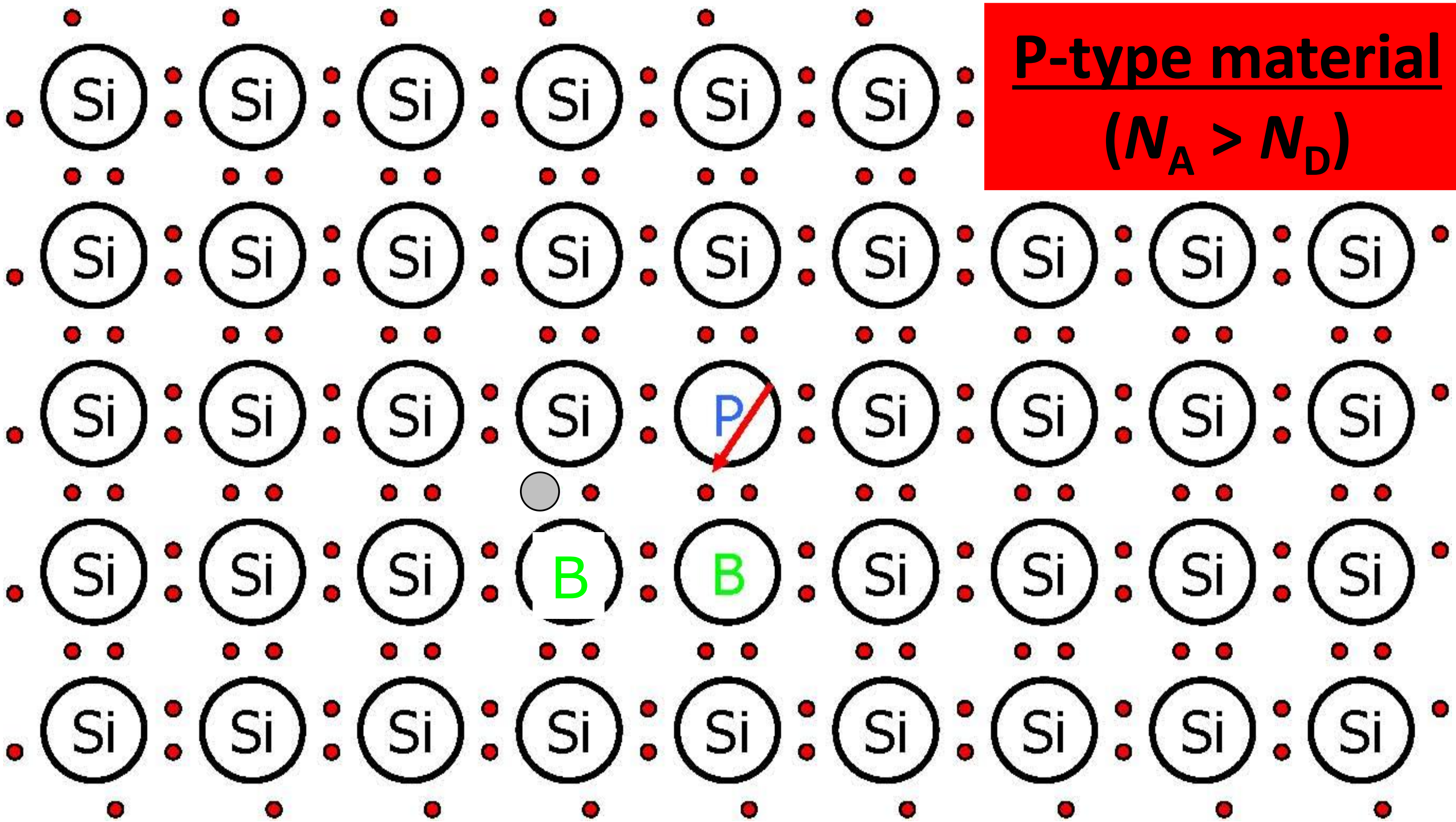
$\boldsymbol{n} = p = N_D - N_A + n_i = \boldsymbol{n_i}$.



Counter Doping

$$p \approx N_A - N_D, \quad n \approx \frac{n_i^2}{N_A - N_D}$$

The addition of **one more B** than **P** causes the doping type to change from n-type to **p-type**



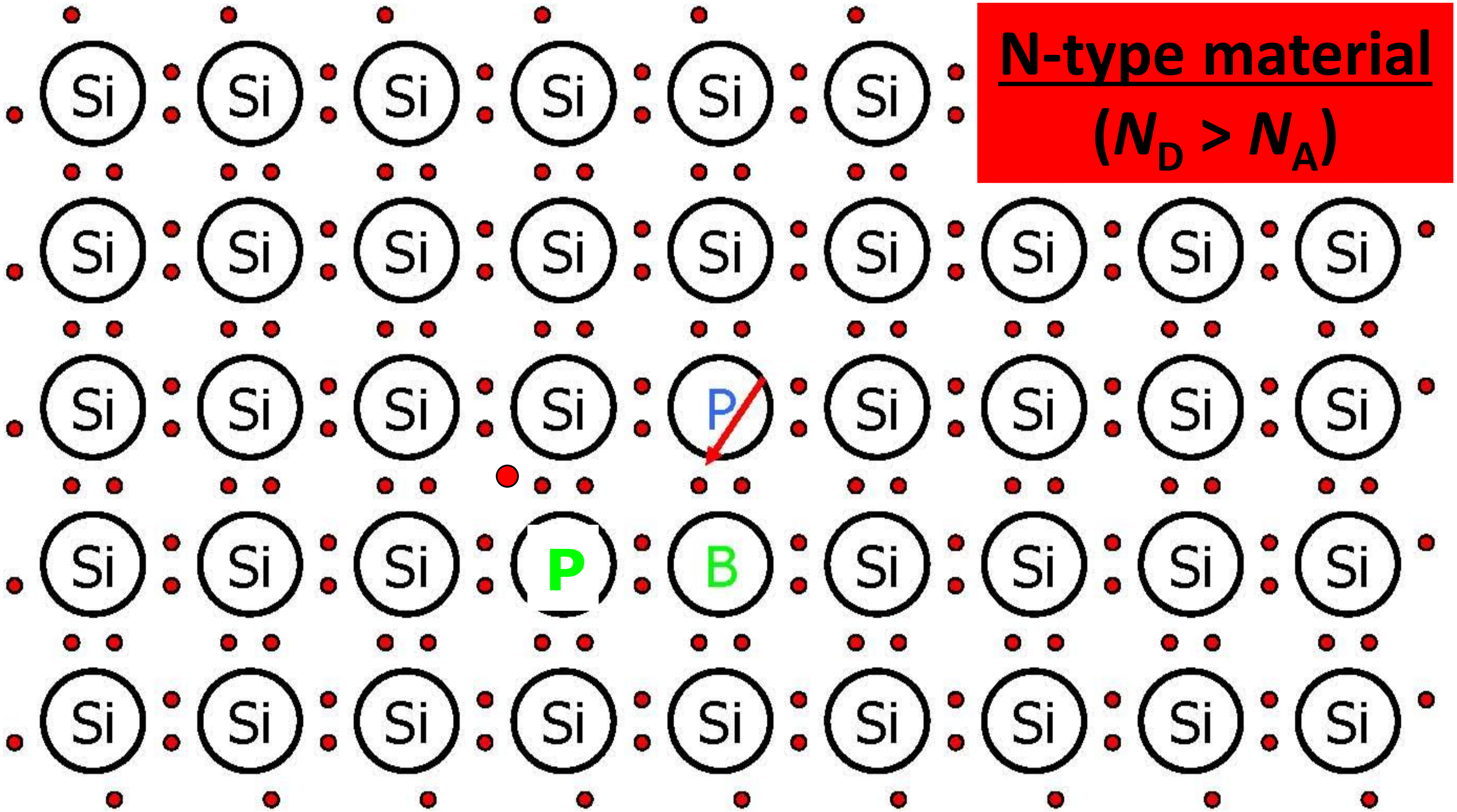
P-type material

($N_A > N_D$)

Counter Doping

$$n \approx N_D - N_A, \;\; p \approx \frac{n_i^2}{N_D - N_A}$$

The addition of **one more P** than **B** causes the doping type to change from p-type to **n-type**



Dopant Compensation

- An **N-type** semiconductor can be **converted** into **P-type** material by **counter-doping** it with acceptors such that $N_A > N_D$.
- A ***compensated semiconductor material*** has both acceptors and donors.

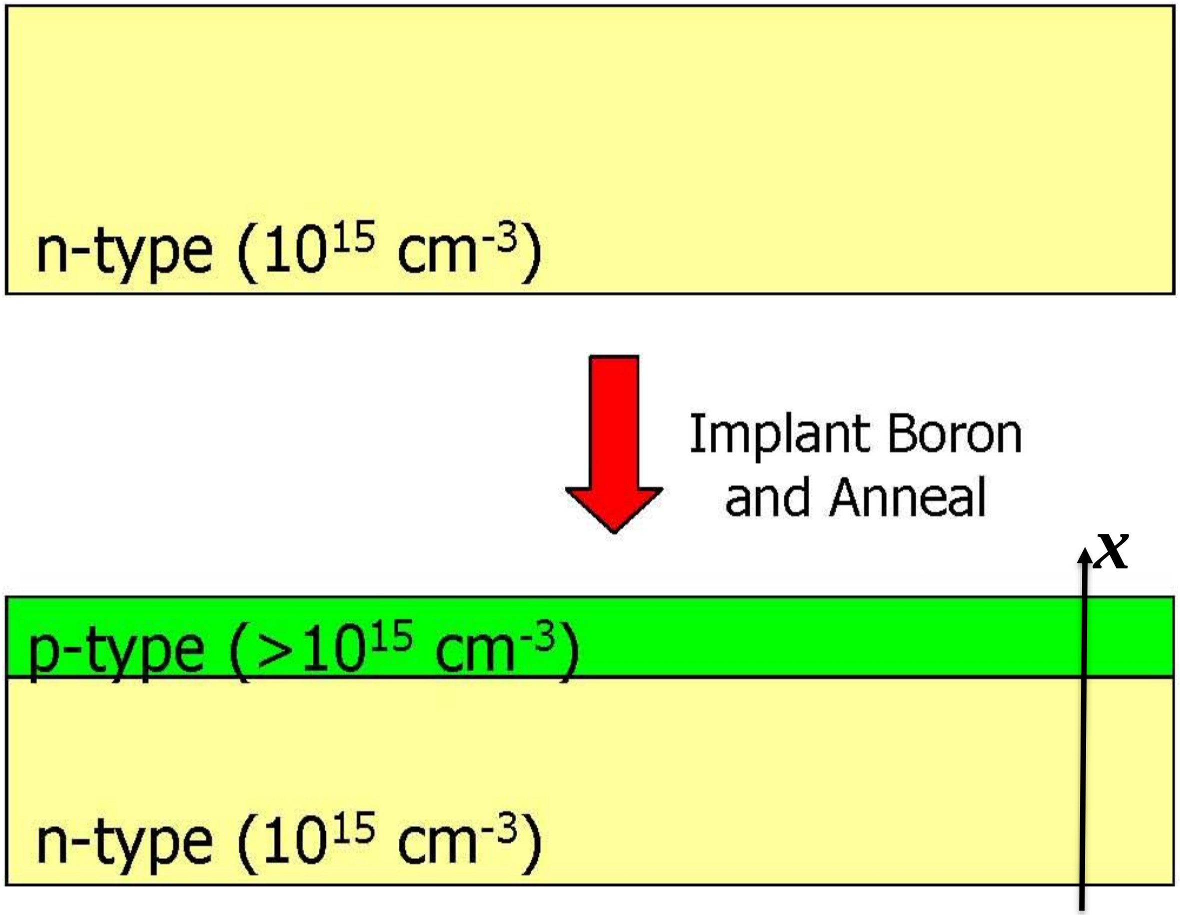
"net doping"

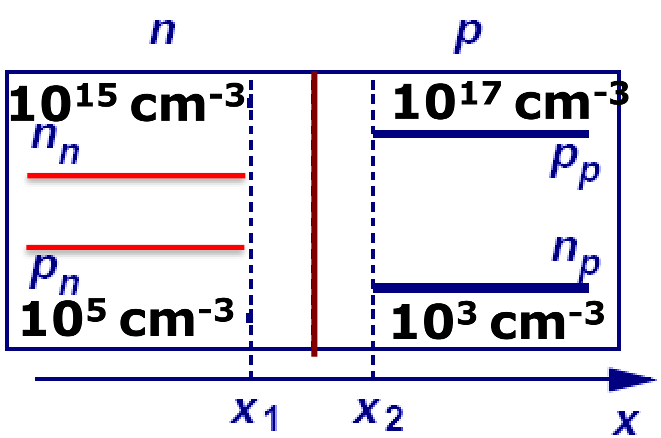
N-type material	P-type material
$(N_D > N_A)$	$(N_A > N_D)$
$n \approx N_D - N_A$	$p \approx N_A - N_D$
$p \approx \dfrac{n_i^2}{N_D - N_A}$	$n \approx \dfrac{n_i^2}{N_A - N_D}$

What is the relationship between E_F and n/p?

Counter Doping Process

- To form pn junction





Next week:

Semiconductor Fundamentals – (III)

2.5 Boltzmann approximation & E_F, n, p

2.6 Carrier drift and diffusion