ELG2316
Physics of the PN (Real) junction diode

Part I

The Intrinsic Silicon as a Semiconductor

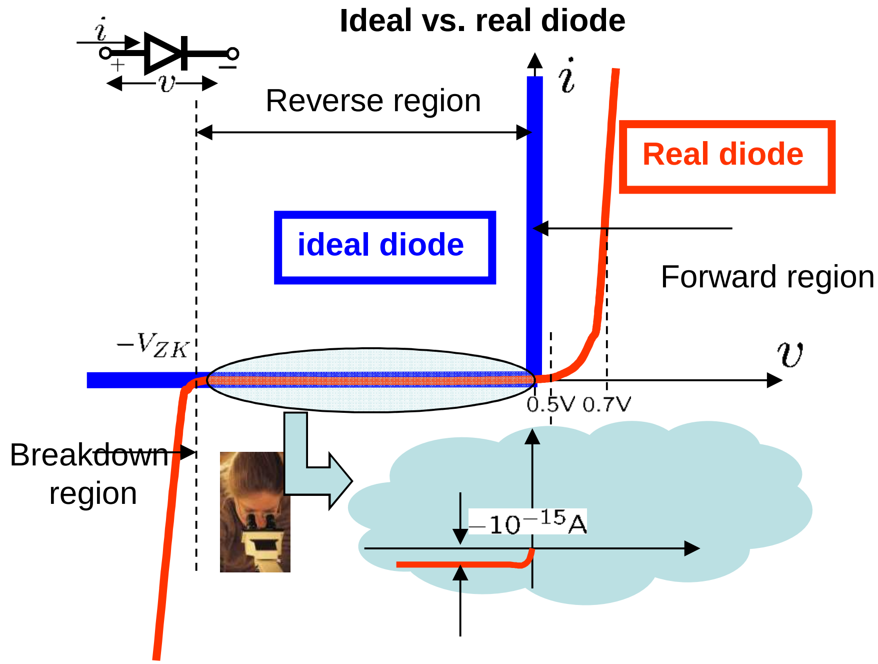
Introduction

- Two kinds of semiconductors:
- Single-element such as silicon and germanium; useful for common diodes; germanium came first in applications; then recently silicon.
- Compound, like gallium arsenide; useful for light-emitting diodes (involves light).

We need to address this question?

Why? **An explanation for the behavior of the real diode.**

We need an explanation for this behavior



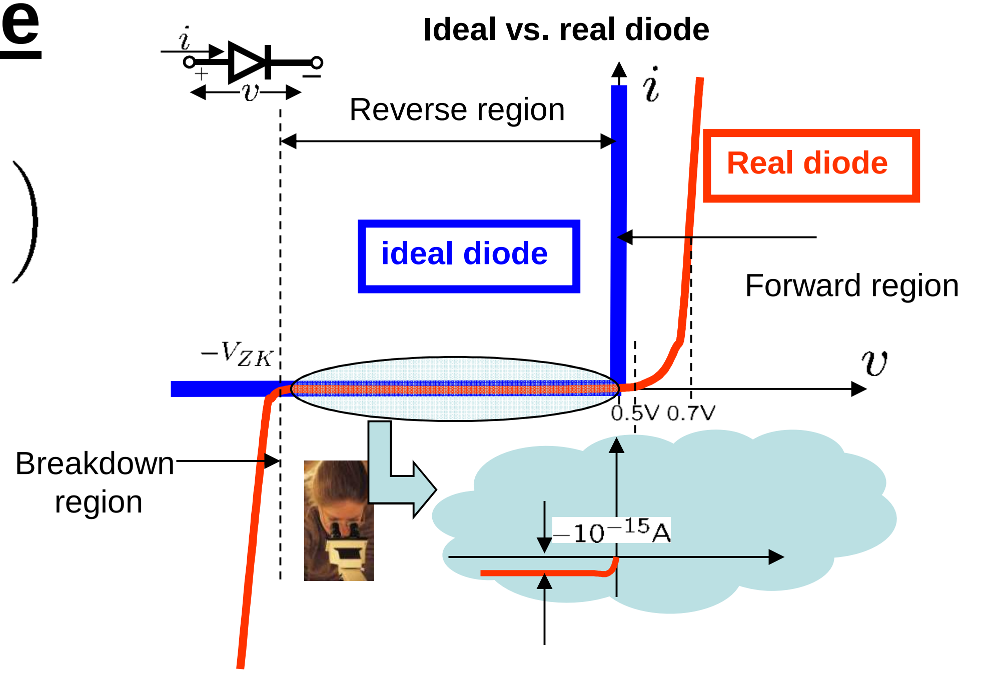
We need to address this question?

Why? An explanation for the behavior of the real diode.

We also need to derive the equation we used before

$$i = I_S\left(\exp\left(\frac{v}{nV_T} - 1\right)\right)$$

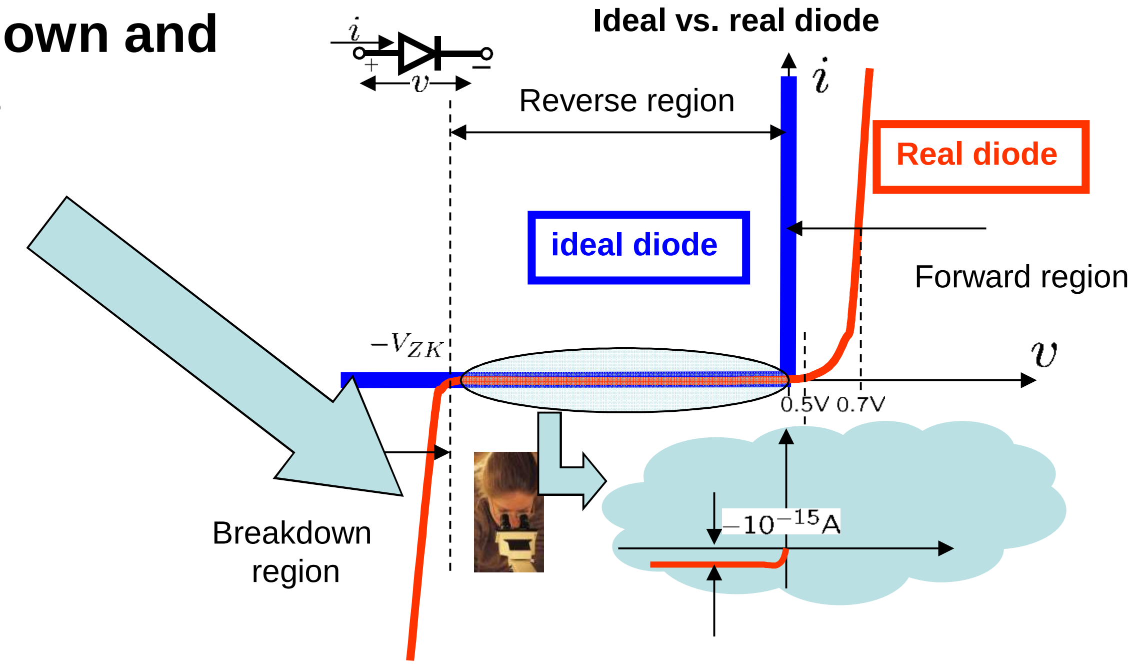
In the forward and reverse regions



We need to address this question?

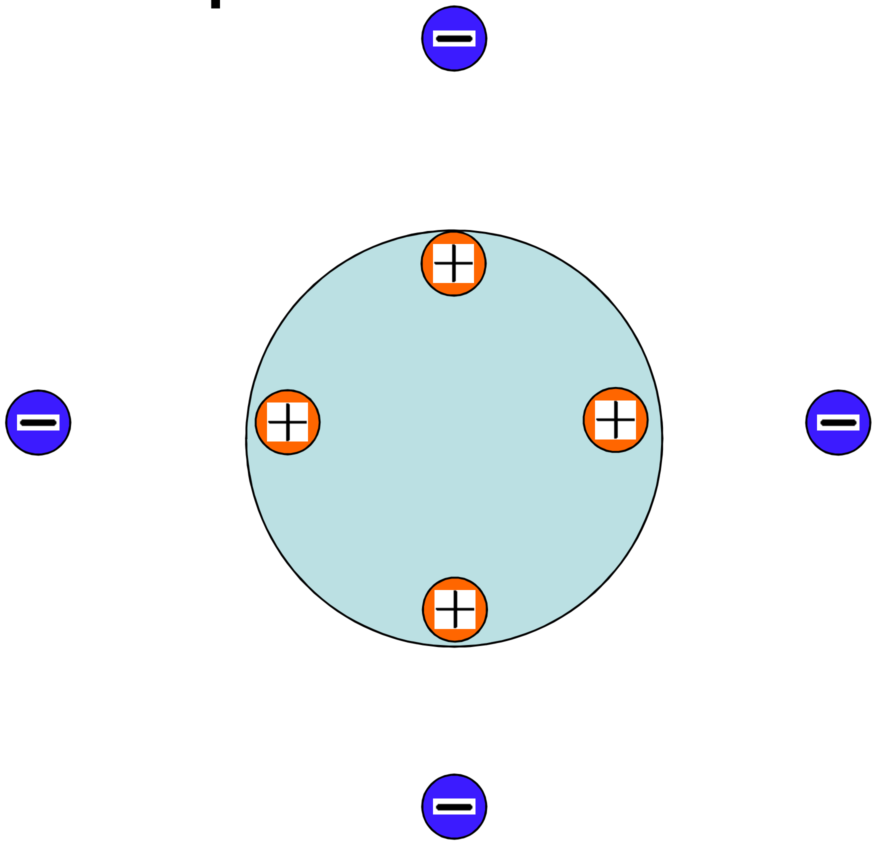
Why? An explanation for the behavior of the real diode.

We also need to an explanation for the phenomenon of break down and how it happens



The Silicon ATOM

Has four electrons in the valence band, and four protons in the nucleus



Covalent Bond

An Important Question

Is the Silicon atom

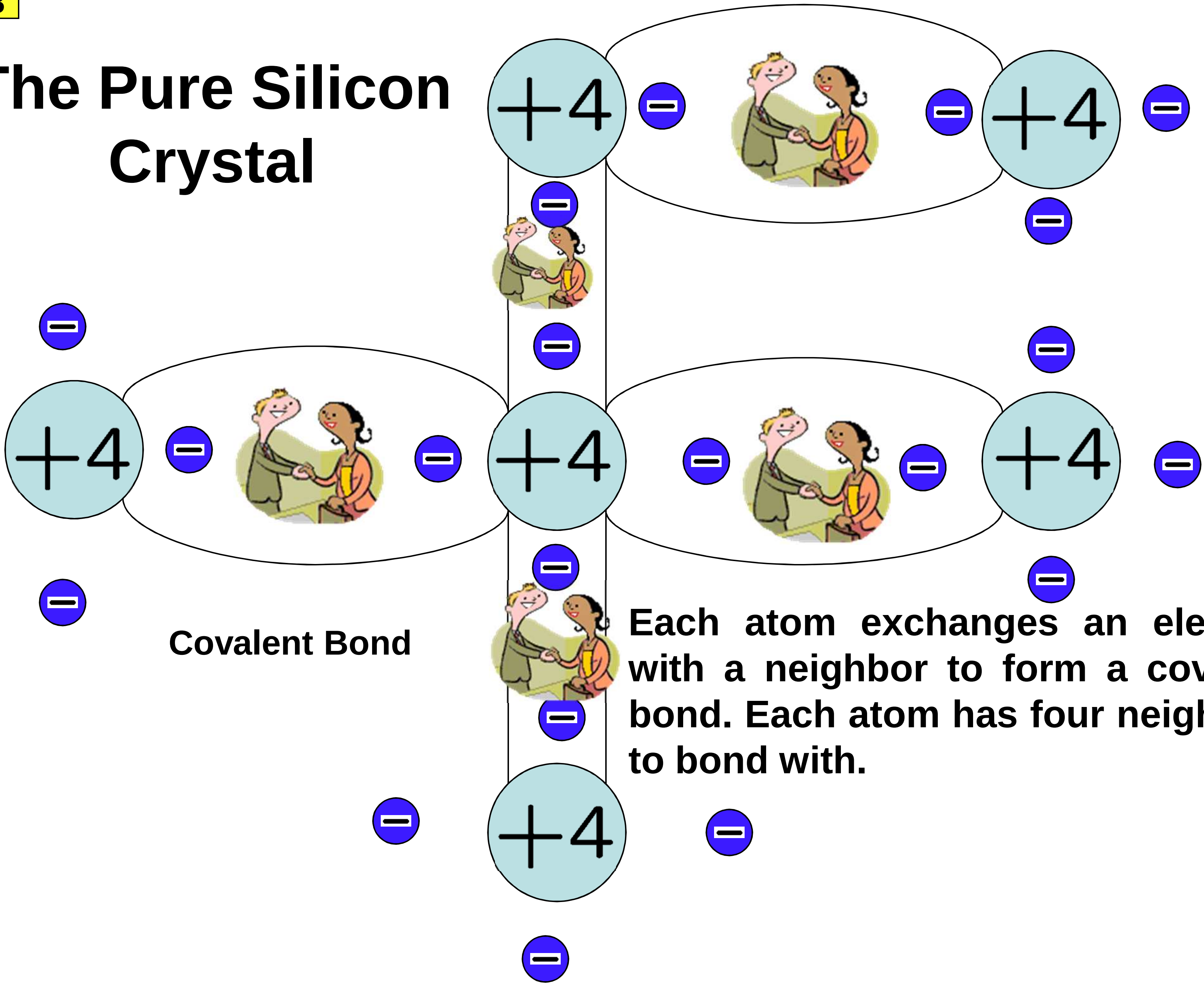
electrically neutral?

Is

(+ve) Charges = (-ve) Charges?

YES

The Pure Silicon Crystal



Each atom exchanges an electron with a neighbor to form a covalent bond. Each atom has four neighbors to bond with.

An Important Question

Is the PURE Silicon Crystal ***electrically*** neutral?

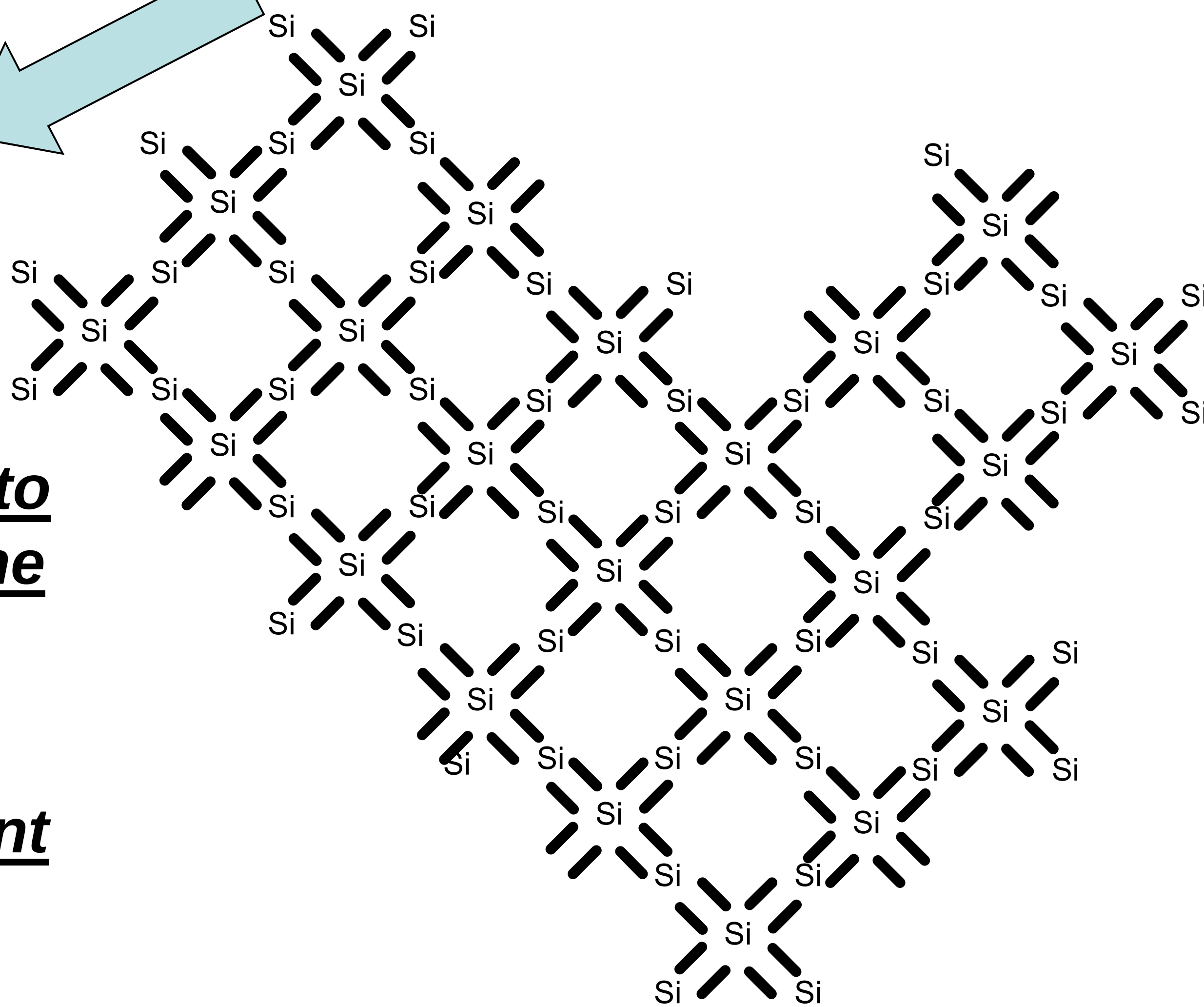
Is

(+ve) Charges = (-ve) Charges?

YES

The Pure Silicon Crystal

At absolute Zero Temperature **0K = -273ºC**

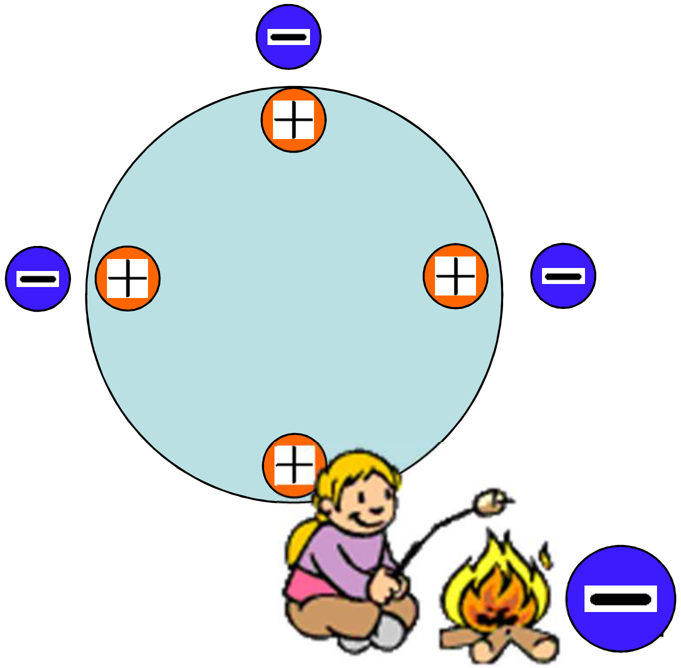


All electrons remain in their covalent bonds.

No free electrons to move around in the crystal

No electric current conduction

Effect of Ionization at high Temp



At higher temperatures, thermal energy can cause an electron to leave its covalent bond

The Pure Silicon Crystal

At higher Temperature

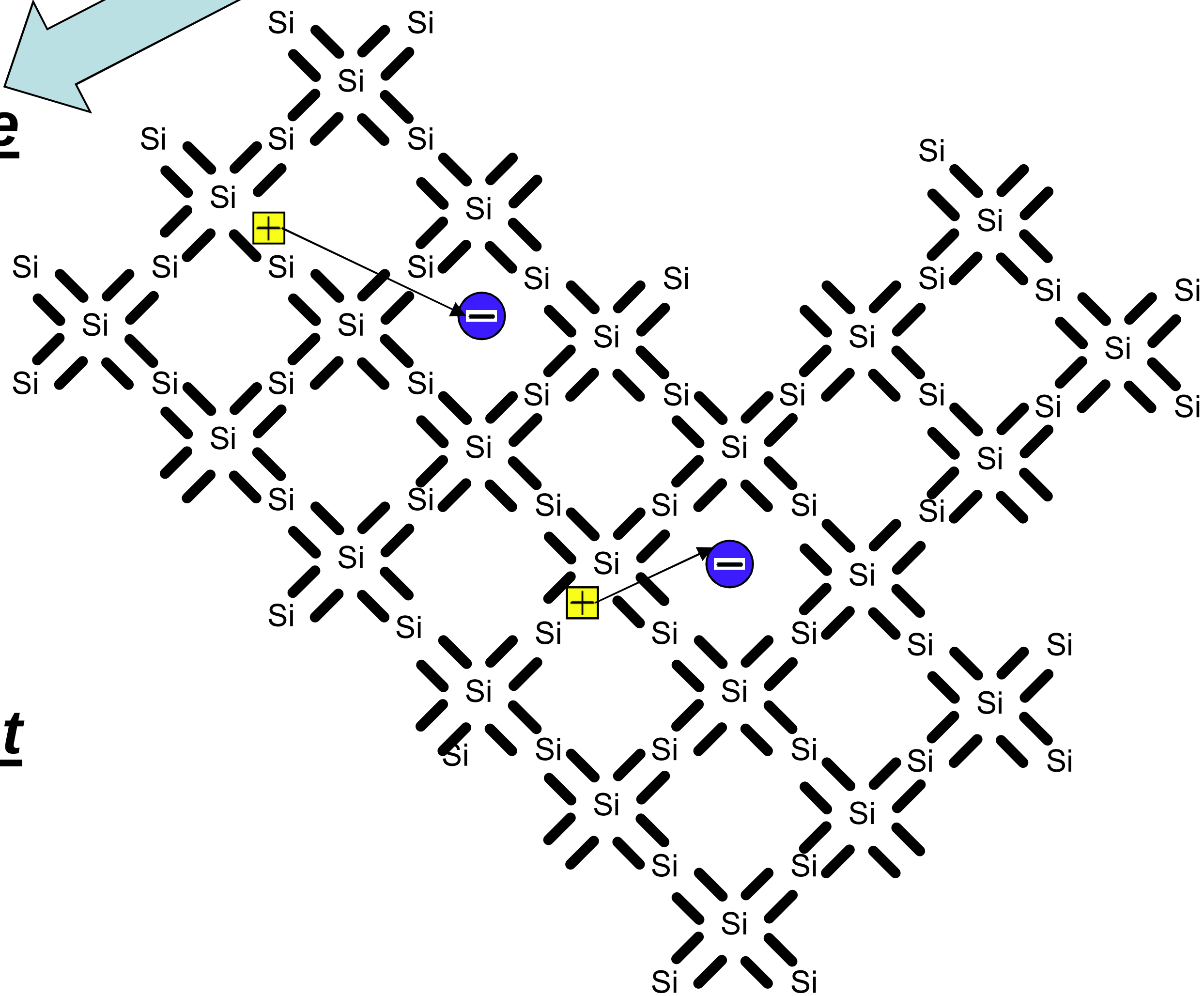
Some Electrons are freed

They leave behind a hole

Conduction Current

MAY

occur



An Important Question

Is the PURE Silicon Crystal

electrically neutral

Under ionization?

Is

(+ve) Charges = (-ve) Charges?

YES

Another Important Question

How many electrons/ holes appear due to ionization?

The Pure Silicon Crystal

At higher Temperature

How many free electrons/holes per unit volume (Density)?

In Pure Silicon (also known as Intrinsic Silicon)

Density of electrons (electrons-per-unit-volume) **=** ***Density of holes (holes-per-unit-volume)***

$$n = p = n_i$$

The Pure Silicon Crystal → **At higher Temperature** → **How many free electrons/holes per unit volume (Density)?** →

In Pure Silicon (also known as Intrinsic Silicon)

n_i **depends on**

- **Minimum Energy required to free an electron** — **"The bandgap energy"** E_g Joules(J)
- **The absolute temperature** T

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

k The Boltzmann constant J/K

The Pure Silicon Crystal

At higher Temperature

How many free electrons/holes per unit volume (Density)?

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

E_g			
High	→	n_i	is a low number **(electric insulators**, e.g. diamond**)**
Moderate	→	n_i	is a moderate number **(semiconductors**, e.g. Silicon**)**
Low	→	n_i	is a high number **(good conductors**, e.g. Cupper**)**

Another Important Question

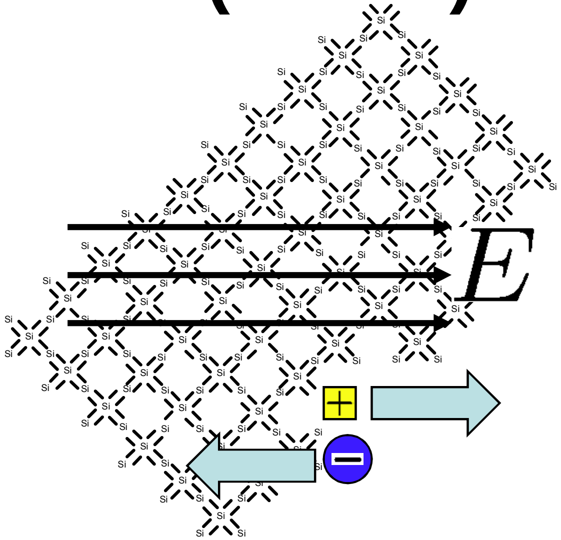
How does electric conduction happen?

There two mechanisms that cause electric conduction due to free charge.

Electric Conduction Mechanisms

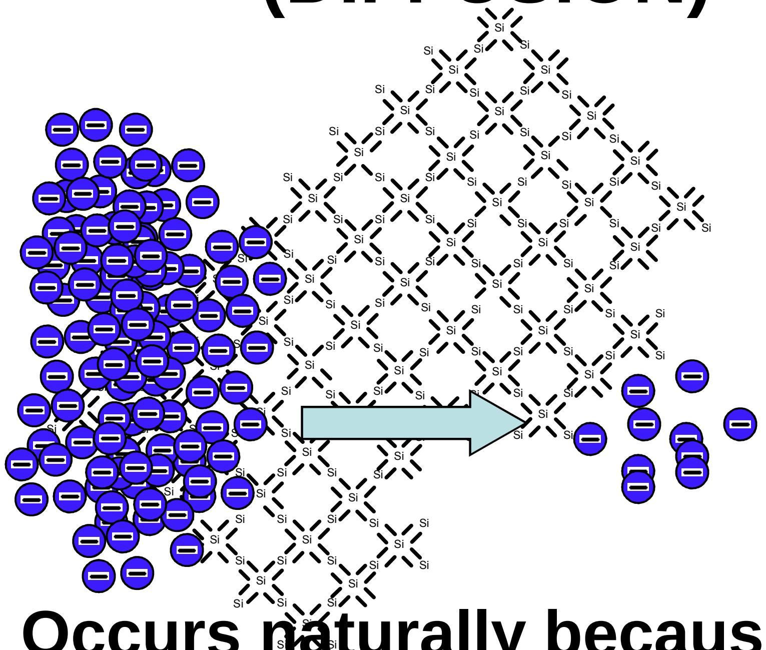
(Two mechanisms for Transport of Carriers in semiconductors)

Forced (DRIFT)



Occurs when an Electric Field is applied. Free charges gets drifted by the field

Natural (DIFFUSION)



Occurs naturally because free charges tend to move from regions with higher concentrations to regions with lower concentrations

Electric Conduction Mechanisms
Transport of Carriers

Forced (DRIFT)

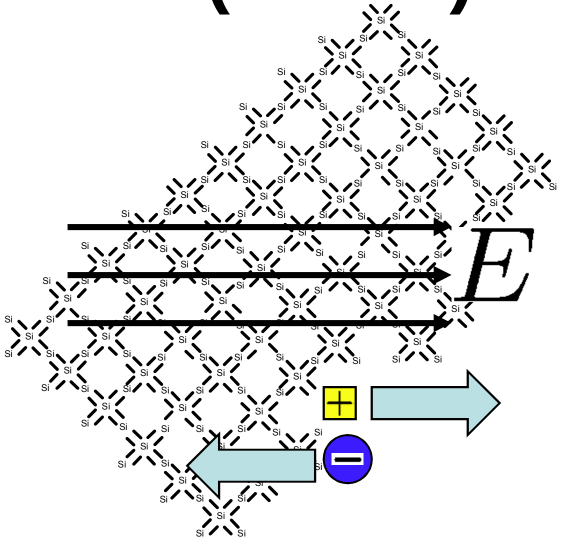
Natural (DIFFUSION)

We need some quantifications

DRIFT First

Electric Conduction Mechanisms
Transport of Carriers

Forced (DRIFT)



Occurs when an Electric Field is applied. Free charges gets drifted by the field

Velocity v of the free charge (electron/hole) is proportional to E

cm/sec $v \propto E$ V/cm

For hole (+) $v_h = \mu_p E$

For electron (−) $v_e = -\mu_n E$

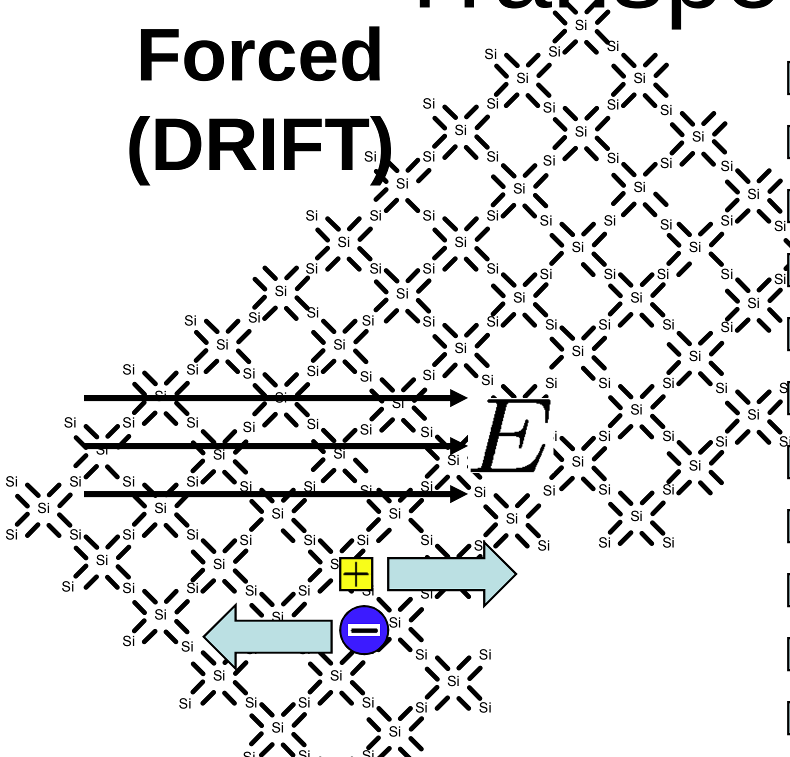
Negative sign is because, the electron moves opposite to the direction field.

μ_n, μ_p

"mobility" constants of electrons and holes in $cm^2/(V.sec)$

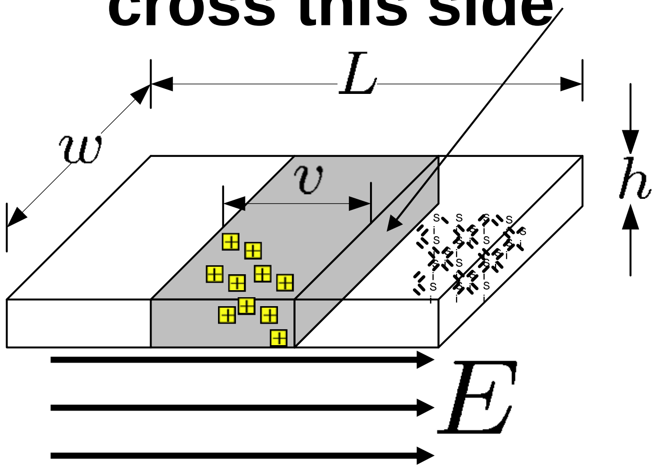
Electric Conduction Mechanisms
Transport of Carriers

Forced (DRIFT)



Occurs when an Electric Field is applied. Free charges gets drifted by the field

In one second, all the free holes in this volume will cross this side

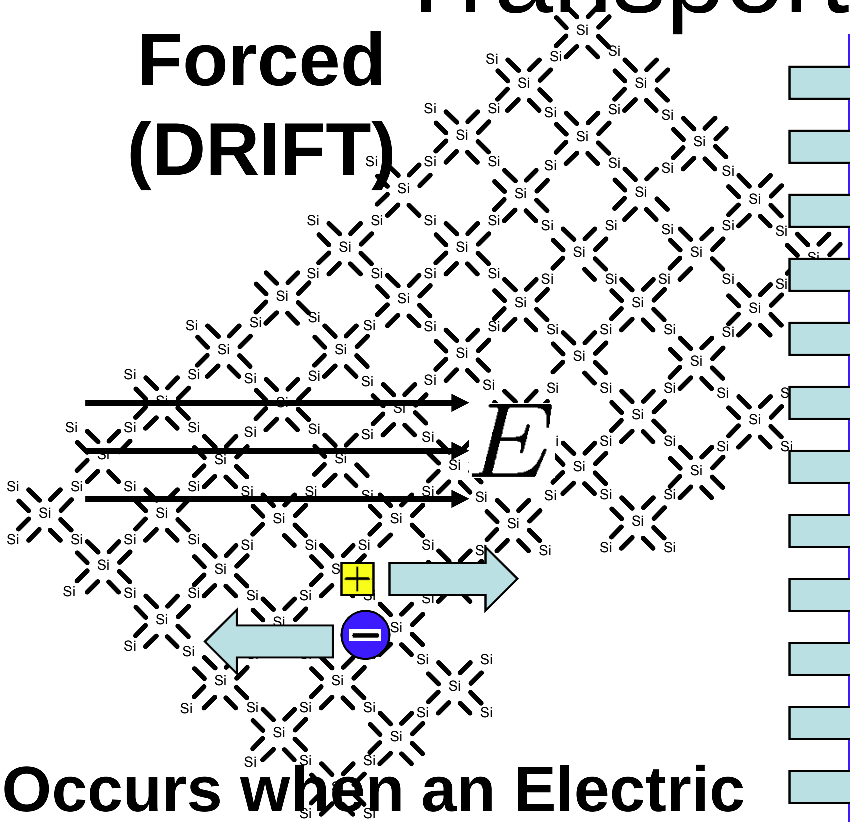


Number of free holes in this shaded volume = Density x Volume =

$$p \times (v \times h \times w)$$

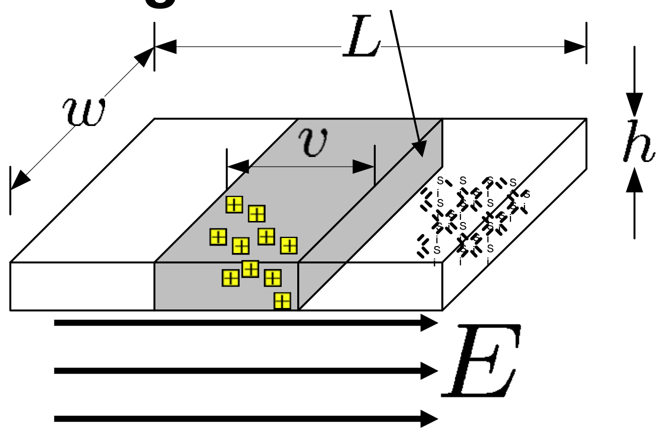
Electric Conduction Mechanisms
Transport of Carriers

Forced (DRIFT)



Occurs when an Electric Field is applied. Free charges gets drifted by the field

Thus, current crossing this side is the total charge crossing this side



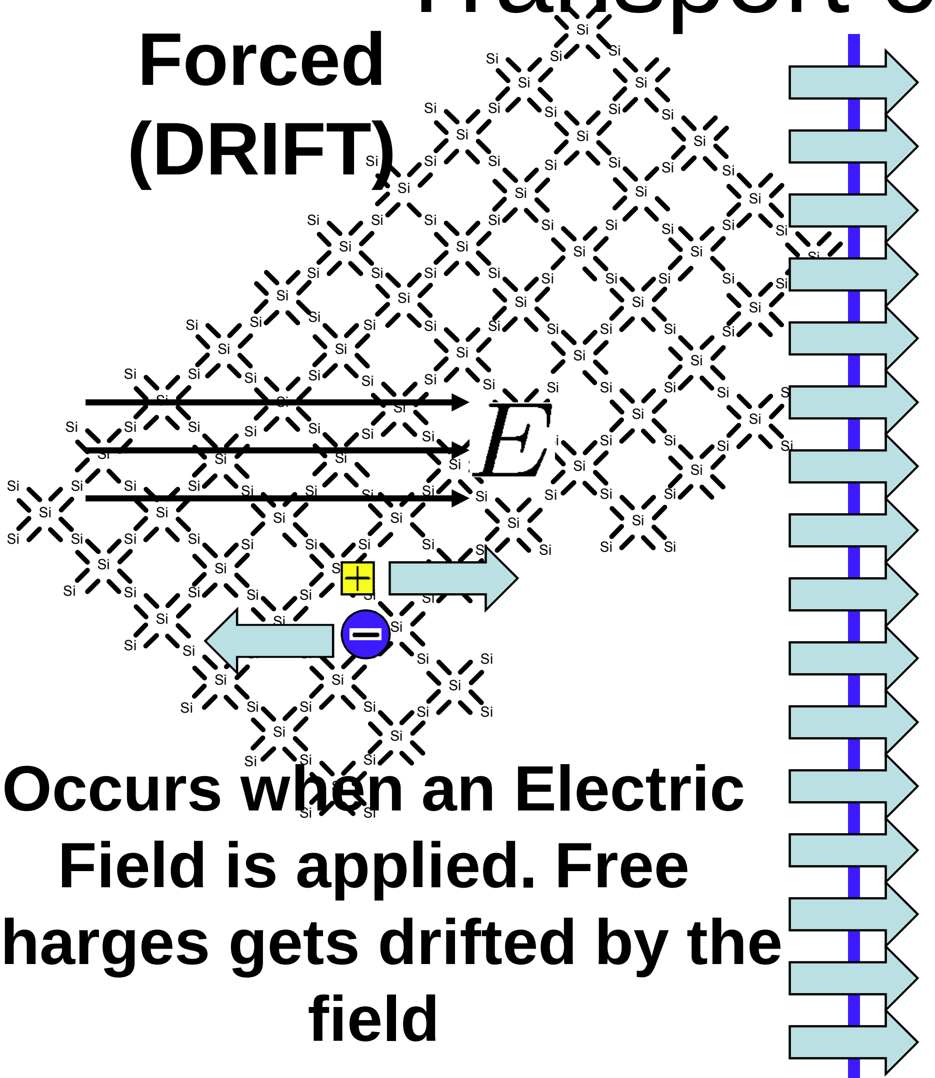
$$I_p$$

$$I_p = q \times p \times (v \times h \times w)$$

The charge of a single electron/hole

Electric Conduction Mechanisms
Transport of Carriers

Forced (DRIFT)



Occurs when an Electric Field is applied. Free charges gets drifted by the field

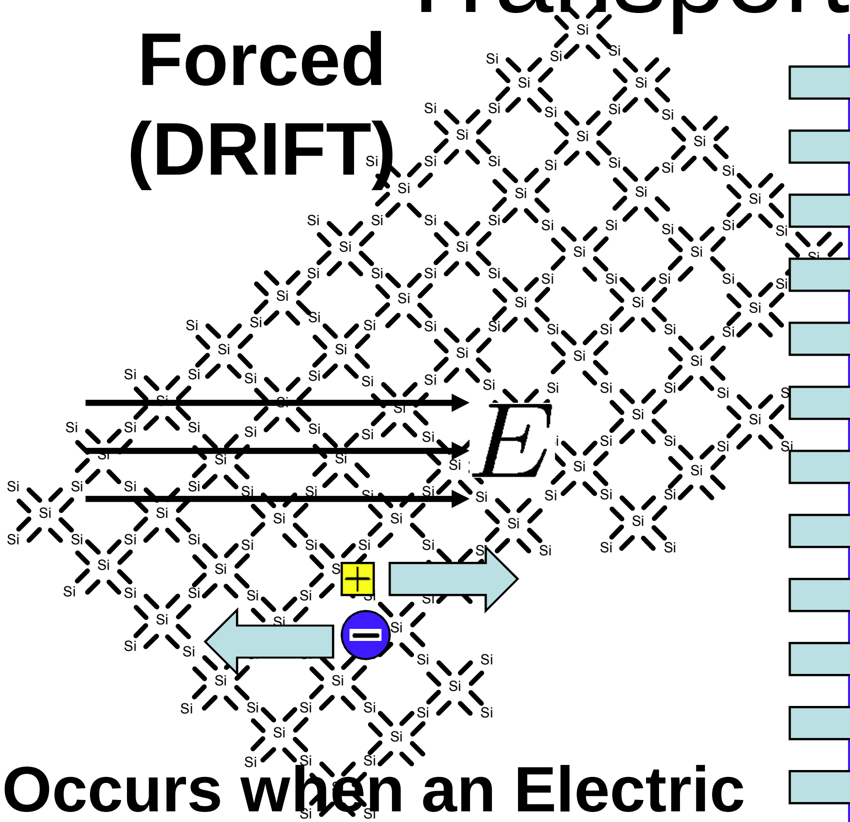
Current density **is better to work with than total current**

The ***current density*** **is the total current per unit area**

$$J = \frac{\text{total current}}{\text{Cross-sectional Area}}$$

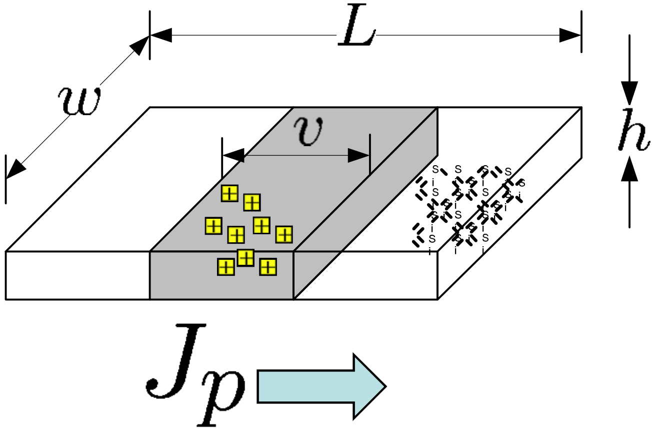
Electric Conduction Mechanisms
Transport of Carriers

Forced (DRIFT)



Occurs when an Electric Field is applied. Free charges gets drifted by the field

$$I_p = q \times p \times (v \times h \times w)$$



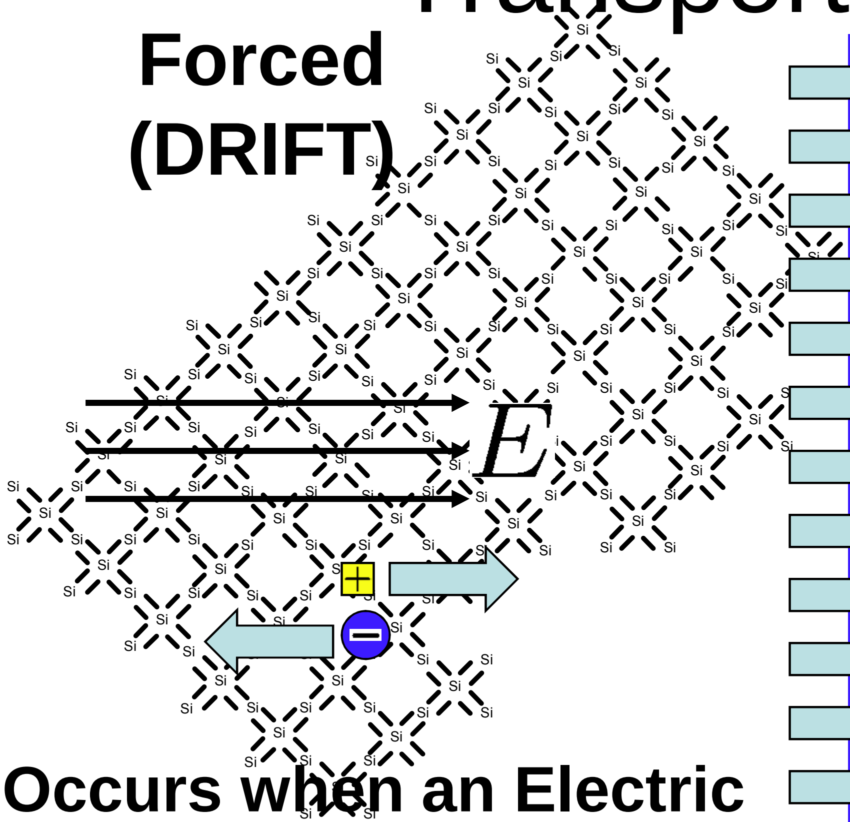
Current density is the current crossing unit area

$$J_p = \frac{I_p}{\text{area}} = \frac{I_p}{hw}$$

$$J_p = qpv = \mu_p E \cdot q \cdot p$$

Electric Conduction Mechanisms Transport of Carriers

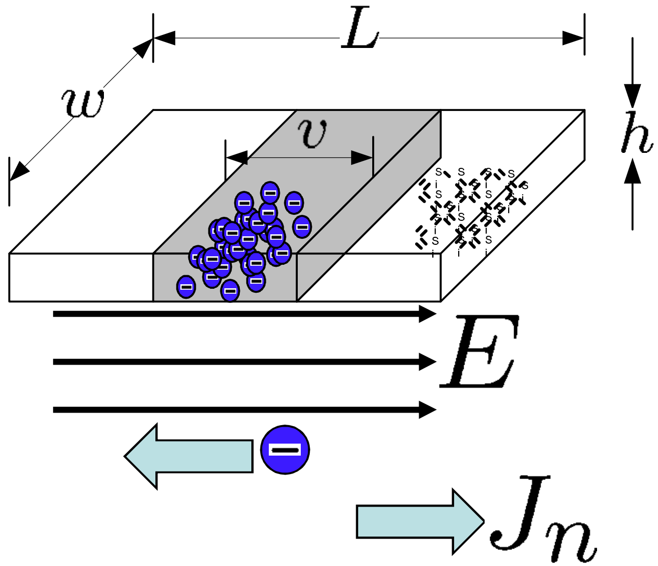
Forced (DRIFT)



Occurs when an Electric Field is applied. Free charges gets drifted by the field

Similarly for electrons,

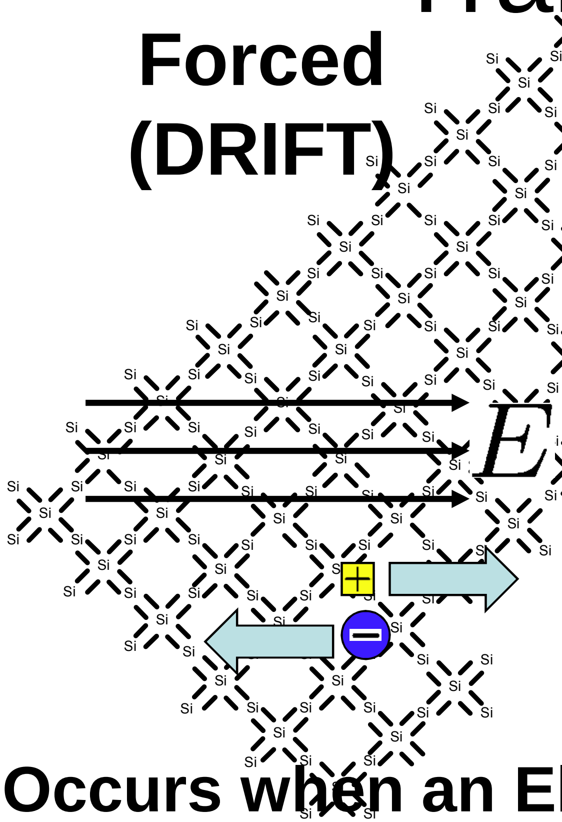
$$I_n = -q \times n \times (v \times h \times w)$$



$$J_n = -qnv = \mu_n E \cdot q \cdot n$$

Electric Conduction Mechanisms
Transport of Carriers

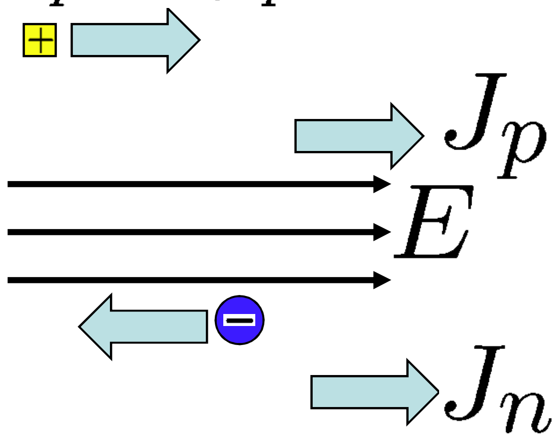
Forced (DRIFT)



Occurs when an Electric Field is applied. Free charges gets drifted by the field

Thus total DRIFT current density

$$J_p = \mu_p E \cdot q \cdot p$$



$$J_n = \mu_n E \cdot q \cdot n$$

$$J_{\text{total}} = J_p + J_n$$

$$J_{\text{drift,tot}} = q\left(\mu_n n + \mu_p p\right) E$$

Electric Conduction Mechanisms
Transport of Carriers

Forced (DRIFT)

Natural (DIFFUSION)

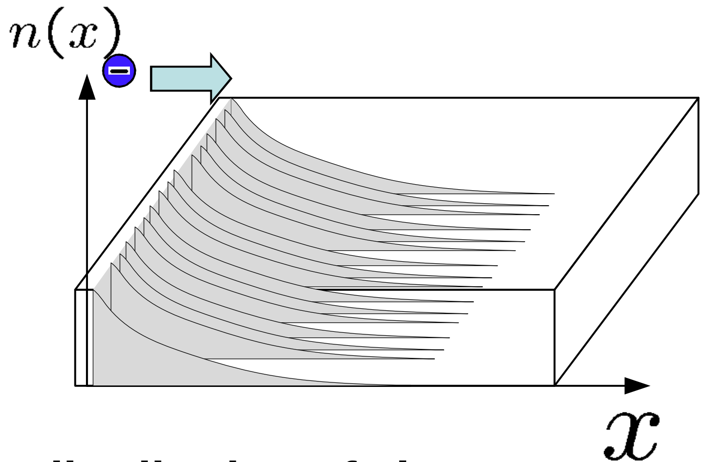
We need some quantifications

$$J_{\text{drift,tot}} = q\left(\mu_n n + \mu_p p\right) E$$

DIFFUSION Second

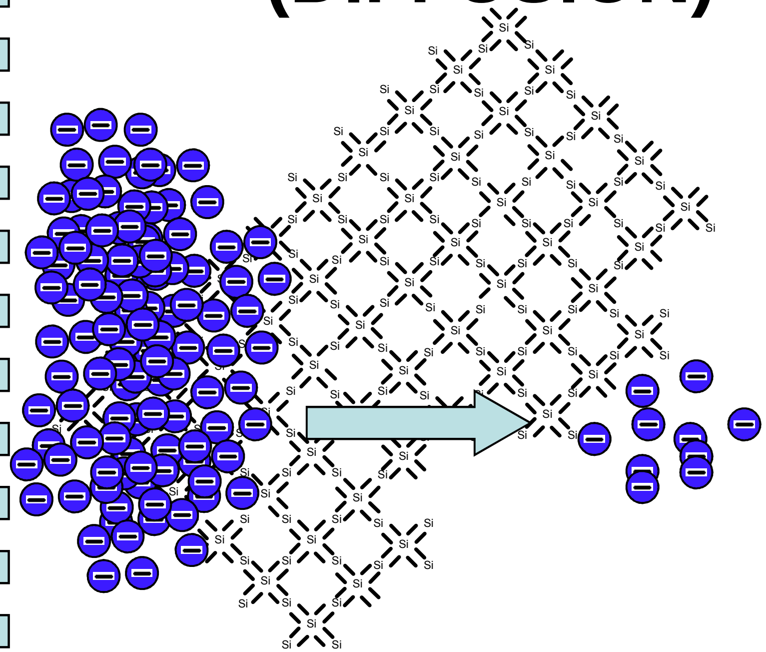
Electric Conduction Mechanisms
Transport of Carriers

Conduction by Diffusion happens when there is a nonuniform distribution of charge density along the spatial dimension of the crystal



The distribution of electrons versus the spatial dimension is nonunifrom

Natural (DIFFUSION)



Occurs naturally because free charges tend to move from regions with higher concentrations to regions with lower concentrations

Electric Conduction Mechanisms
Transport of Carriers

Natural (DIFFUSION)

Similarly for holes

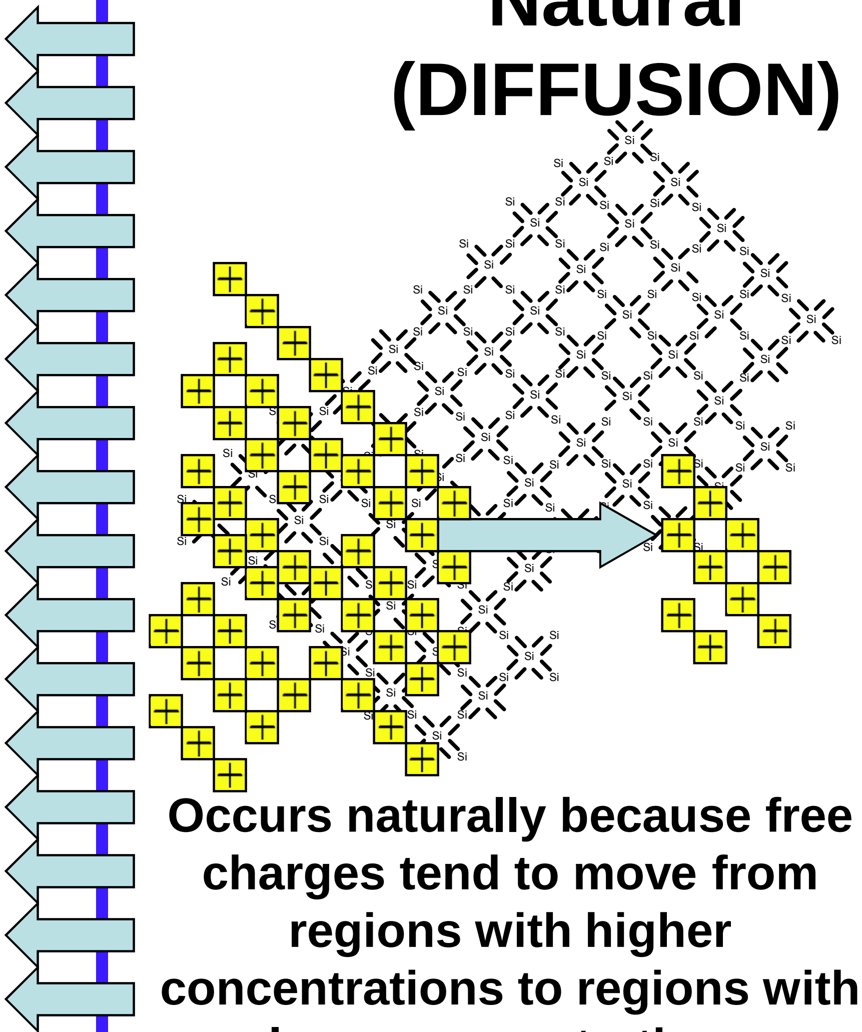
$$I_p$$

Proportionality factor called the "diffusion constant"

$$I_p = D_p A q \frac{dp(x)}{dx}$$

Current Density

$$J_p = D_p q \frac{dp(x)}{dx}$$



Occurs naturally because free charges tend to move from regions with higher concentrations to regions with lower concentrations

Electric Conduction Mechanisms
Transport of Carriers

Total DIFFUSION Current

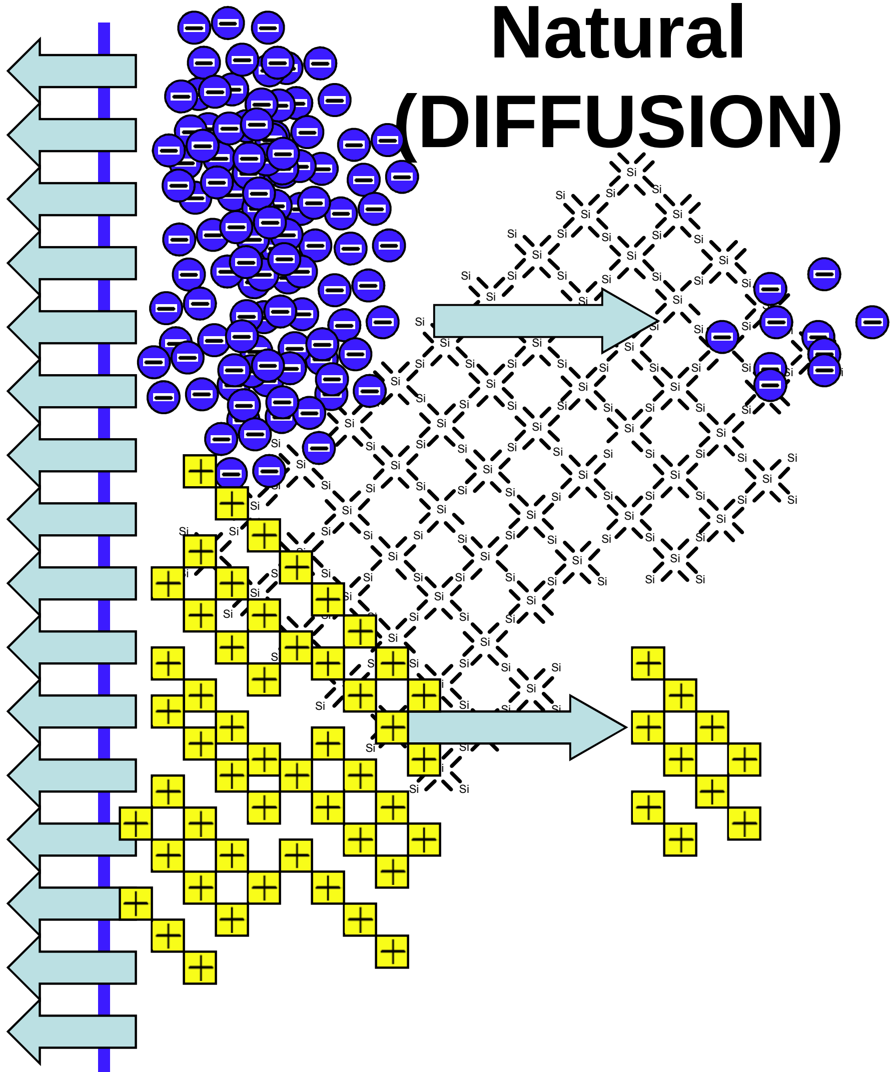
$$\Rightarrow \quad J_p = D_p q \frac{dp(x)}{dx}$$

$$\Leftarrow \quad J_n = D_n(-q)\frac{dn(x)}{dx}$$

$$\Rightarrow \quad J_{\text{total}} = J_p - J_n$$

$$J_{\text{total}} = q\left(D_n \frac{dn}{dx} + D_p \frac{dp}{dx}\right)$$

Natural (DIFFUSION)



Electric Conduction Mechanisms
Transport of Carriers

Forced (DRIFT)

Natural (DIFFUSION)

We need some quantifications

$$J_{\text{drift,tot}} = q\left(\mu_n n + \mu_p p\right) E$$

$$J_{\text{diff,tot}} = q\left(D_n \frac{dn}{dx} + D_p \frac{dp}{dx}\right)$$

Electric Conduction Mechanisms
Transport of Carriers

Forced
(DRIFT)

$$J_{\text{drift,tot}} = q\left(\mu_n n + \mu_p p\right)E$$

Natural
(DIFFUSION)

$$J_{\text{diff,tot}} = q\left(D_n \frac{dn}{dx} + D_p \frac{dp}{dx}\right)$$

The Einstein relation related the two component

$$\frac{D}{\mu} = \frac{kT}{q}$$