Part III. Semiconductors and Semiconductor Devices

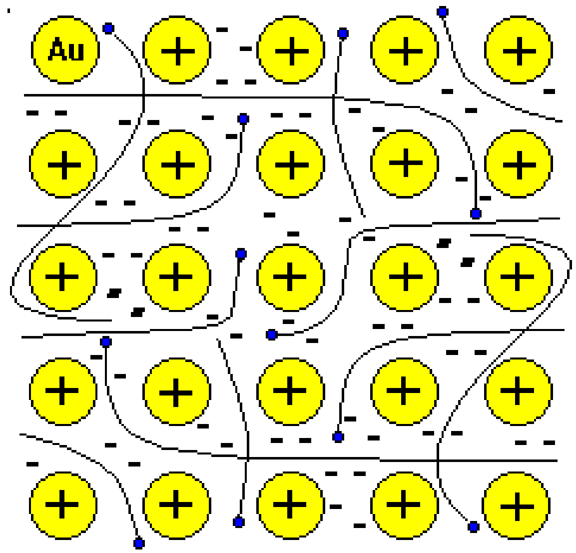
"The Transistor was probably the most important invention of the 20th Century…"

The American Institute of Physics

The Nobel Prize in Physics 1956

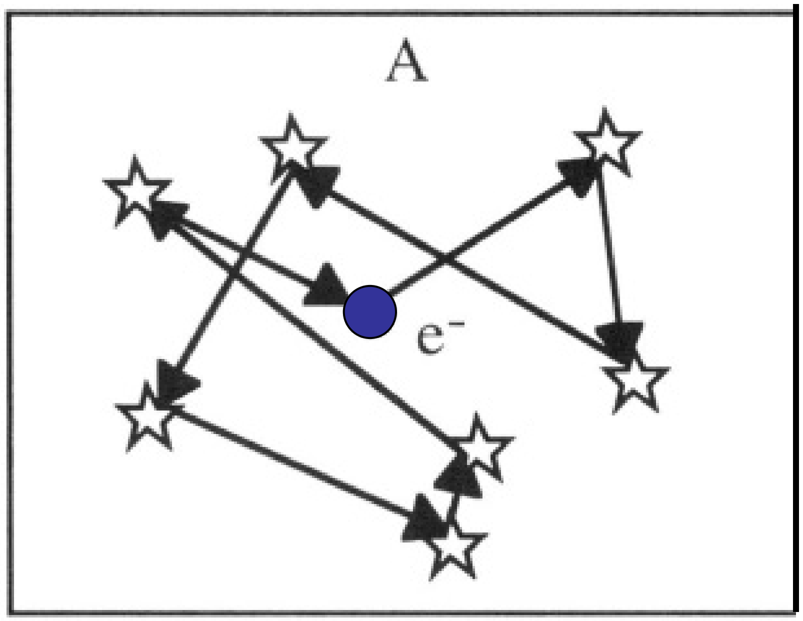
Semiconductors and Semiconductor Devices

The Origin of Electric Conductance



- Free electrons can freely move along the crystal (colliding with the atoms)
- Their kinetic energy comes from the lattice vibrations
- In equilibrium, free electrons move **randomly** inside the crystal.

Electron mobility in crystals



<u>Equilibrium condition, no electric field (voltage) applied</u>

Free electron experiences very frequent collisions with atoms in the metal.

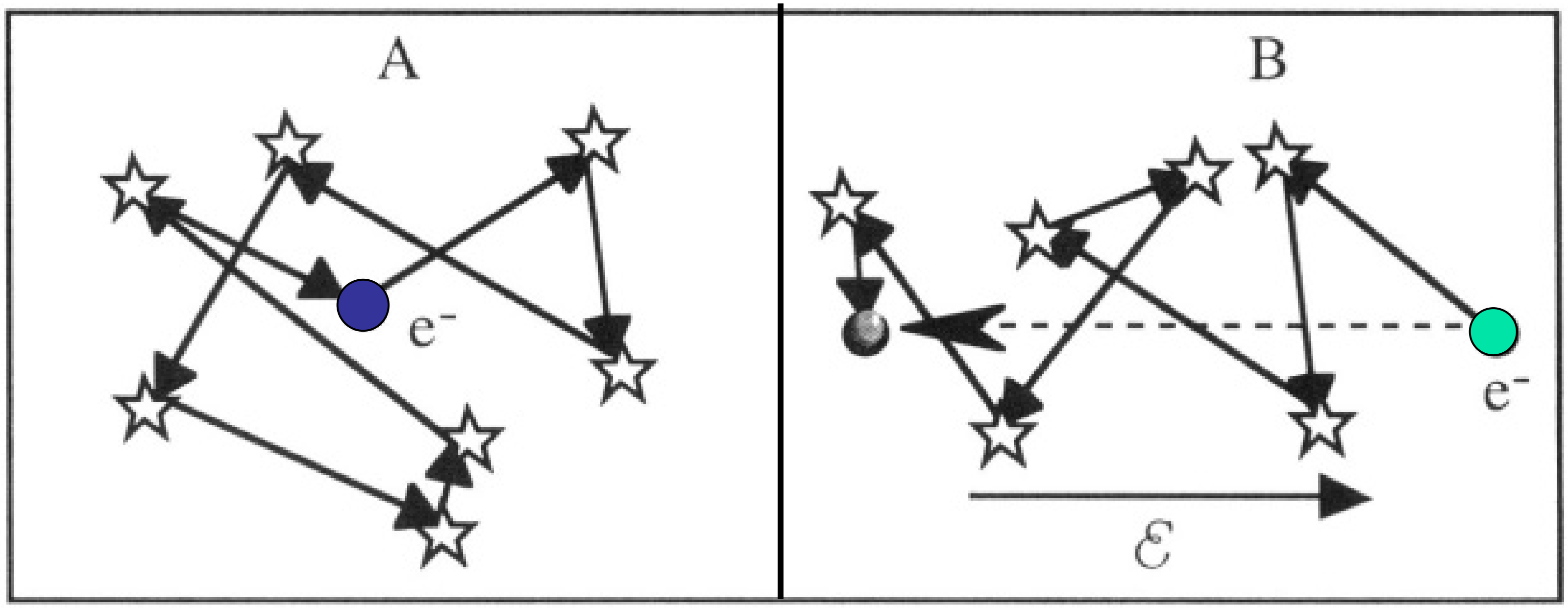
As a result it moves randomly *(with the velocity of around 10^5 m/s)*.

On average, the electron does not go anywhere!

Average electric current is equal to zero

(There is a flicker charge transfer, or the NOISE current though)

Electron mobility in crystals



<u>Electric field applied</u>:

There is an electric force, $\boldsymbol{F = e\,E}$ exerting on any free electron.

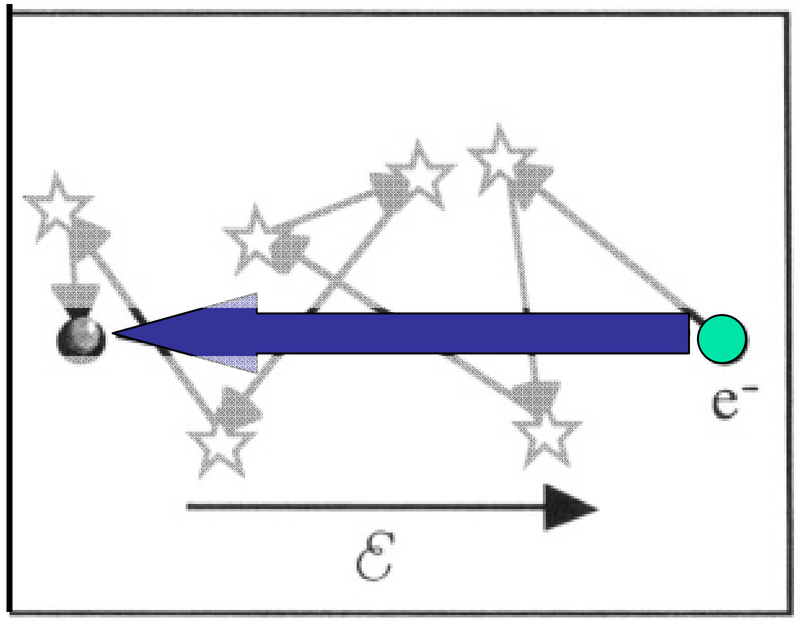
Electron still experiences very frequent random collisions.

However, after each collision the electron's velocity has a component toward the positive electrode (against the field direction)

On average, the electron drifts from negative electrode toward positive.

There is a current flowing through the metal.

Electron mobility in crystals



Let us ignore the random collisions and only monitor the drift in the electric field

Ignoring the collisions, which are completely random, we can say that

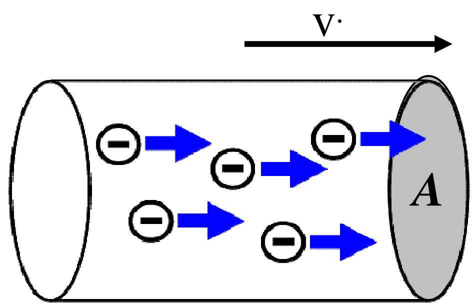
average electron velocity (drift velocity) is proportional to the electric field applied:

$$v \sim E$$

$$v = \mu E$$

μ is called the **electron mobility:** $\mu = v/E$ $[(m/s)/(V/m) = m^2/(V{\cdot}s)]$

Electric current and conductivity



A = wire cross-section area

The electric current is: $I = q\,n\,v\,A$

Electron velocity, $\boldsymbol{v} = \mu\,\mathbf{E}$, where the electric field $\mathbf{E} = \mathbf{V/L}$ (V is the voltage)

the velocity becomes $\boldsymbol{v} = \mu\,\mathbf{V/L}$

the current becomes $\boldsymbol{I} = \mathbf{qn}\mu\,\mathbf{A\,V/L}$

$$\sigma = q \times n \times \mu$$

is the conductivity of the material

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

Conductivity and Resistance

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

$$\sigma = q \times n \times \mu$$ is the conductivity of the material

I-V relationship can be rewritten as $$V = \frac{1}{\sigma}\frac{L}{A} \times I$$

Compare this to the Ohm's law: $$V = R \times I$$

$$R = \frac{1}{\sigma}\frac{L}{A};$$

Resistance, conductivity, resistivity

$$R = \frac{1}{\sigma}\frac{L}{A}$$

The resistance of the sample with conductivity σ, the length L and the cross section area A.

$$\sigma = q \times n \times \mu$$

The conductivity σ [(Ohm ×m)$^{-1}$] is proportional to the free electron concentration in the sample n and the electron mobility μ.

n [m^{-3}] is the free electron concentration

(the number of electrons per unit volume)

μ [m^2/(V×s)] is the electron mobility
defined as the drift velocity - electric field ratio:
$\mu = v / E$, or $v = \mu E$

$$\rho = \frac{1}{\sigma}$$

The resistivity ρ [(Ohm ×m)]; using ρ,

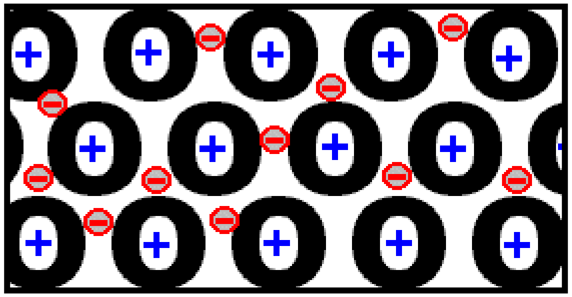
$$R = \rho \frac{L}{A}$$

Conductors, Insulators and Semiconductors

$$\sigma = q n \mu$$

The mobility in different materials differs around **1000** times.

The concentration of free electrons *n* in different materials differs around 10^{23} times!

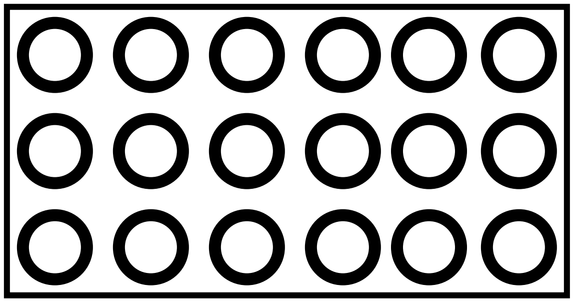


Metal:

~ 10^{23} atoms per 1 cm^3

Every atom donates 1 free electron:

$n \sim 10^{23}\ cm^{-3}$

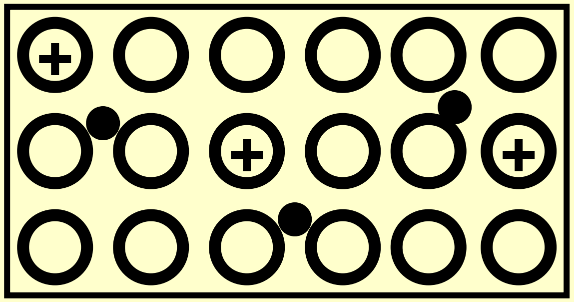


Insulator:

~ 10^{23} atoms per 1 cm^{3};

No free electrons:

$n \sim 0$



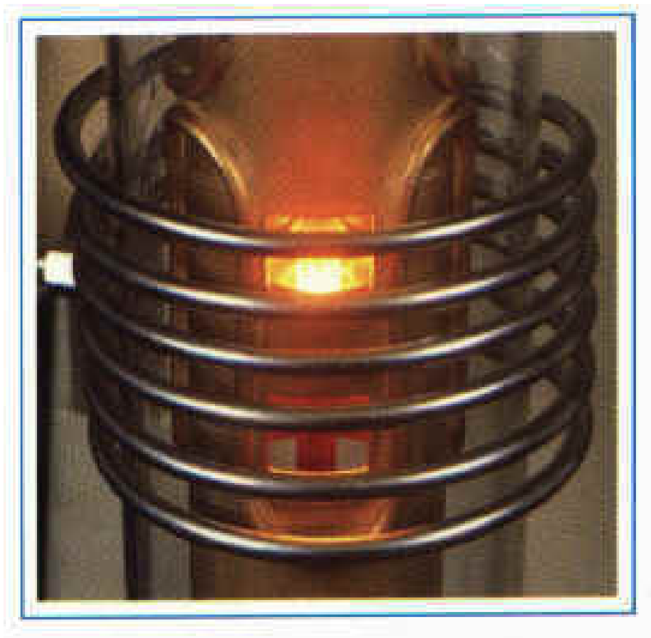
Semiconductor:

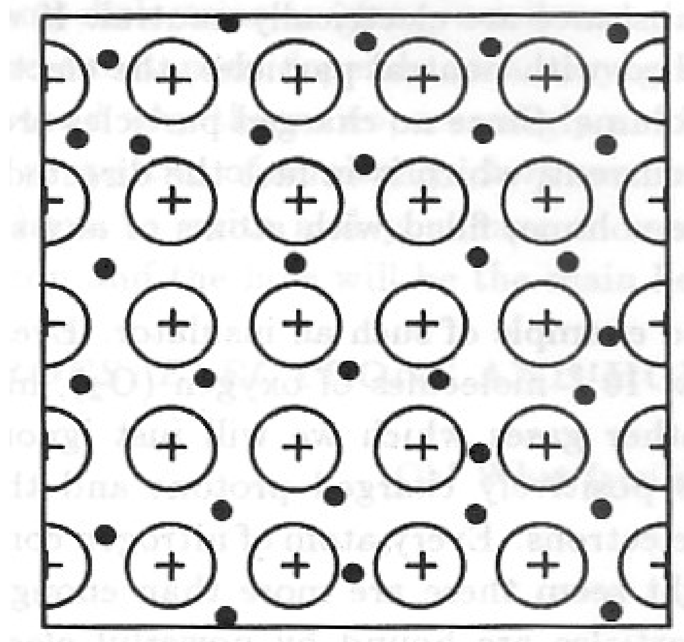
~ 10^{23} atoms per 1 cm^{3};

Some atoms donate free electrons

$n \sim 10^{10} - 10^{19}\ cm^{-3}$

Metals





In metals, the atom-to-atom interactions free up one electron from each atom.

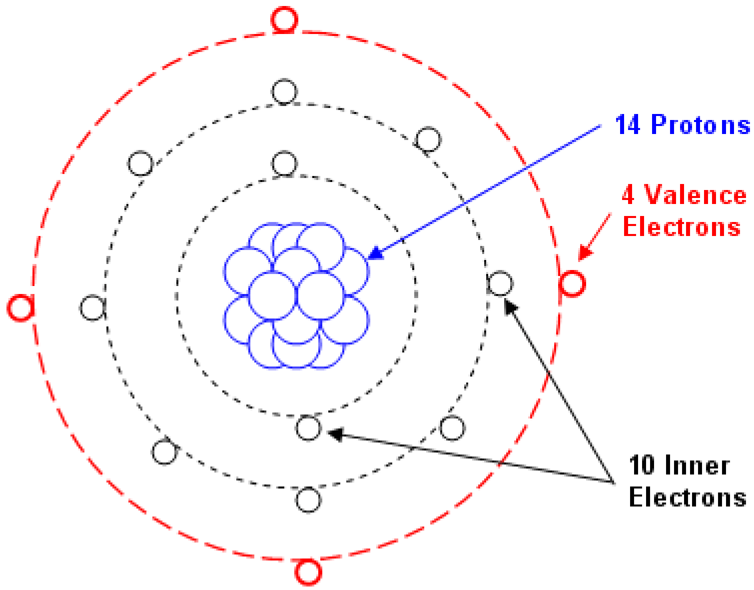
The metal crystals have as many free electrons as they do atoms.

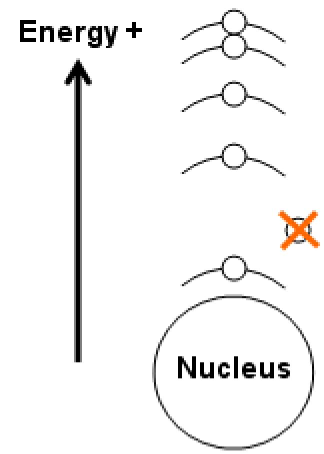
Atom concentration N ~ 10^{23} atoms per 1 cm^3. Free electron concentration, **n ~ 10^{23} cm^{-3}**

The metal conductivity is very high.

Free Electrons in Semiconductors

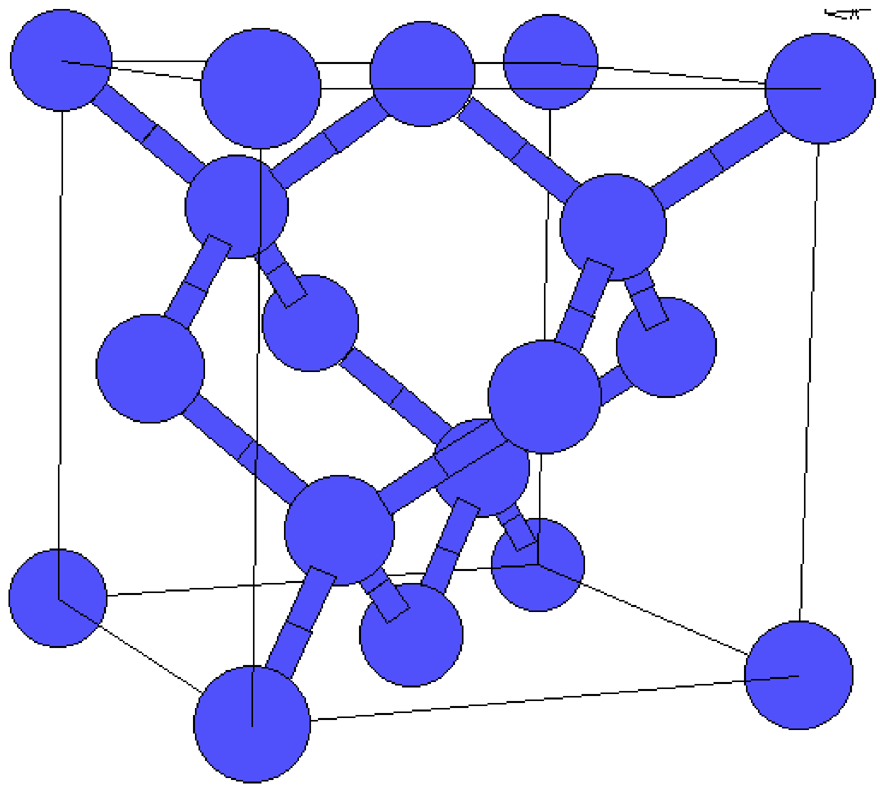
Silicon (Si) is the most important semiconductor material





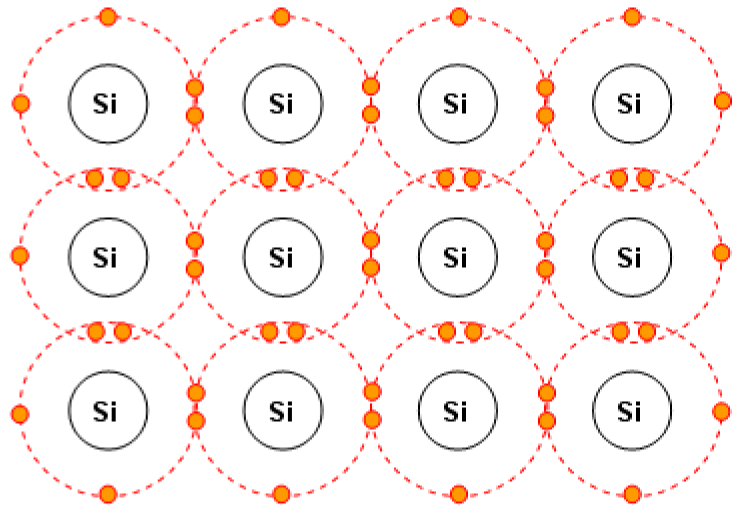
- ***Silicon atom.*** *There are 14 Protons in the nucleus, and 14 electrons orbiting. An electron can exist in any of these orbits, but not outside their confines.*
- *The farthest 4 are known as Valence electrons.*
- *No free electrons: the electrons in the isolated Si atom cannot leave the atom*

Si crystal structure



In Si crystal, each atom is connected to the four neighboring atoms by covalent bonds.

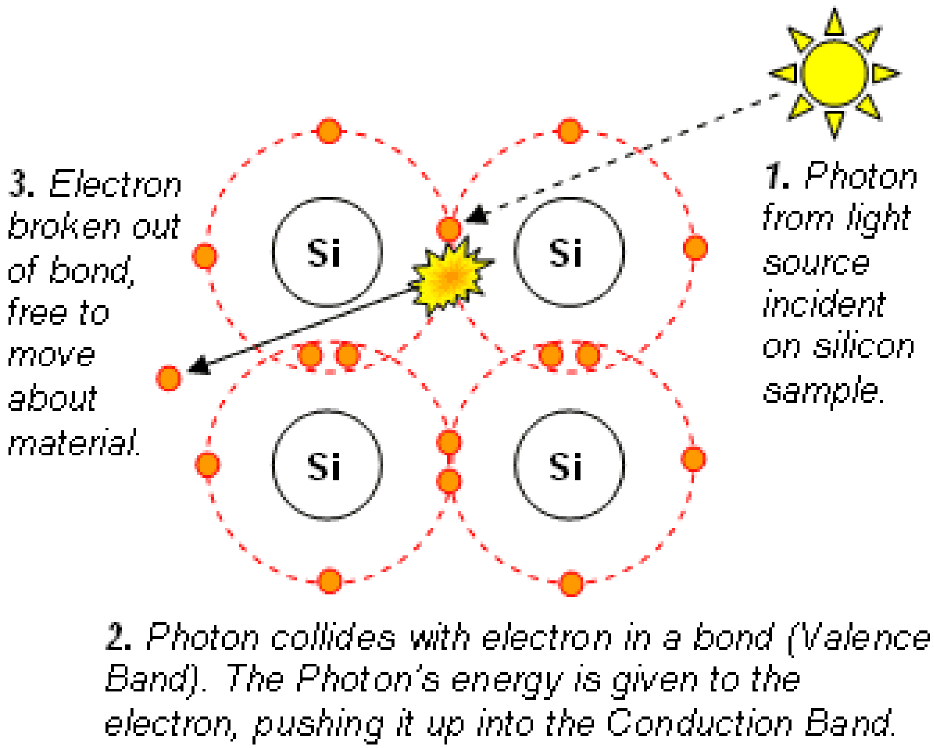
Silicon crystal



Si crystal lattice structure, showing the valence electrons associated with each bond.

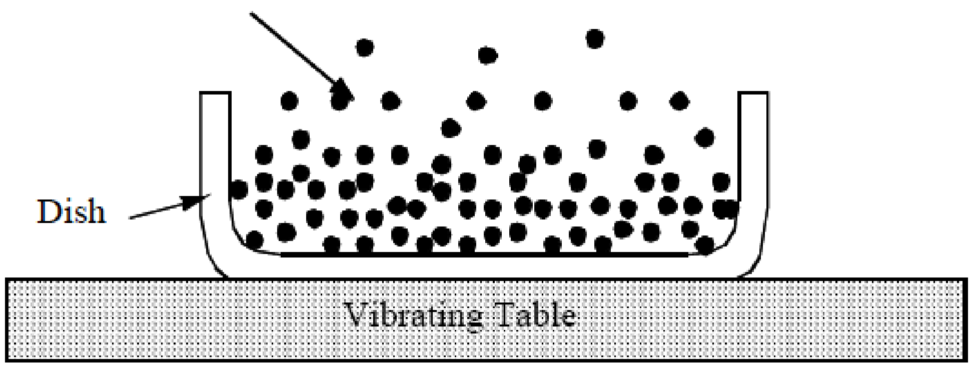
Notice that each silicon atom now has **eight valence electrons**,
but that **they are all shared**, two with each of its four neighbors.
No free electrons!

Silicon crystal under illumination



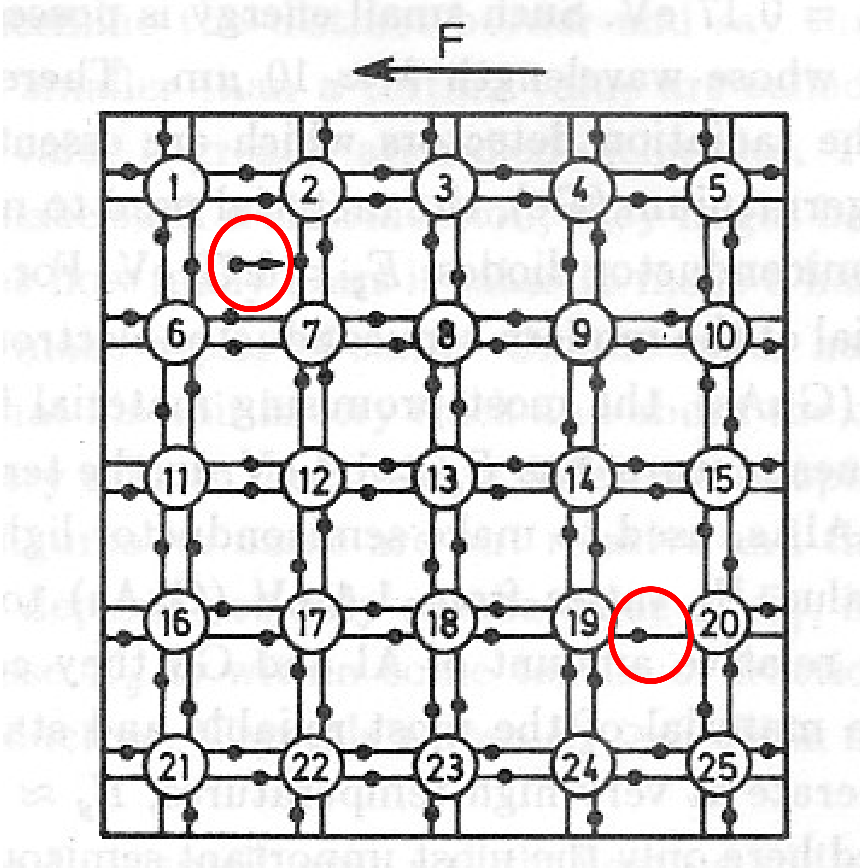
*The **photons** – elementary particles of light can break the bonds and create free electrons in the Si crystal*

Silicon crystal at elevated temperature



If the temperature is high enough the crystal lattice vibrates and delivers extra energy to electrons

Free electrons in semiconductors



The lattice vibrations supply extra energy to the electrons

Some of the electrons acquire high enough energy to become **free electrons.**

The term "free" means that the electrons can move around the crystal

Free electron concentration in semiconductors

- *The probability to acquire an energy high enough to break the atomic bonds is very low*
- *This probability is a very strong function of the temperature (at higher temperatures the lattice vibrations are stronger)*

The energy required to produce a free electron in a crystal is called

the **bandgap energy, ΔE_G**

In the metals, the bandgap energy is equal to zero.

In dielectrics, the bandgap energy is much higher than in semiconductors.

$$n = N_0 \times e^{-\frac{\Delta E_G}{2kT}}$$

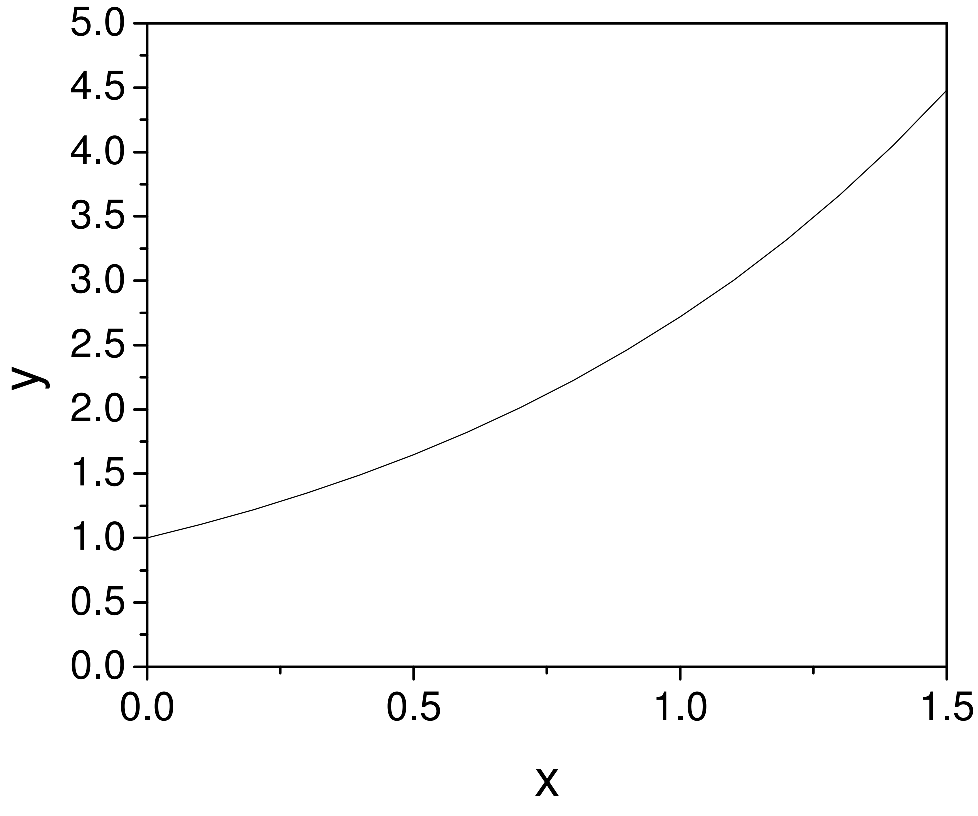
$k = 1.38 \times 10^{-23}$ J/K, is the Boltzmann constant,

T is the crystal temperature, in Kelvin (K)

$N_0 \approx 2\times10^{19}$ cm^{-3} for most semiconductor materials

Free electron concentration in semiconductors

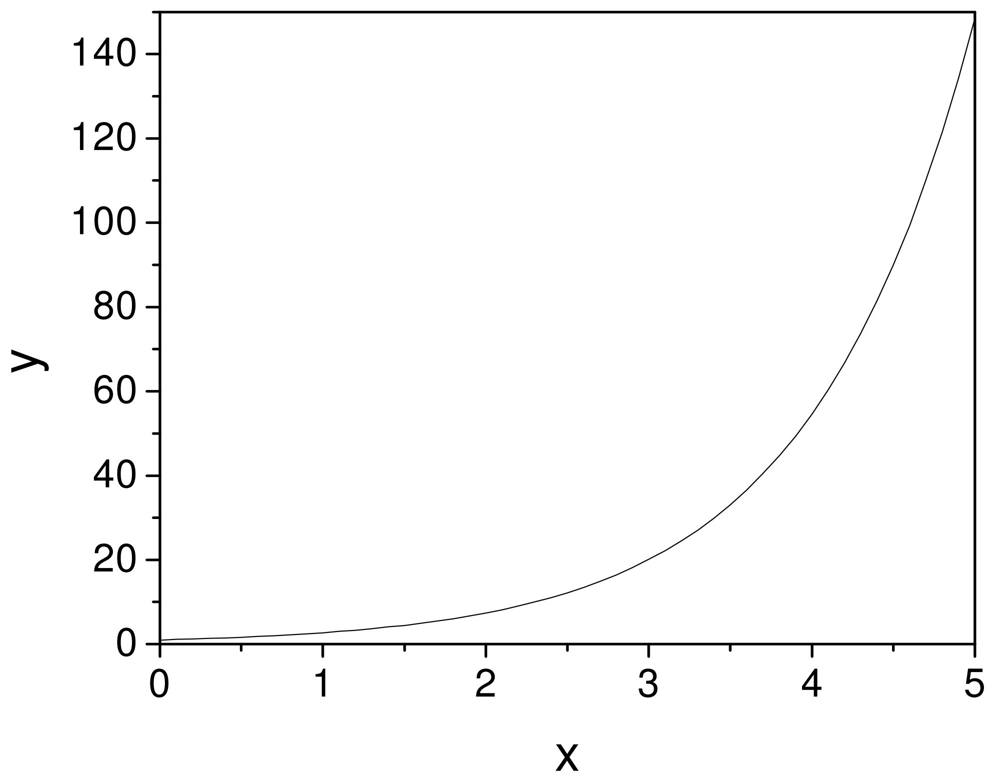
Some properties of the exponential function: $y = e^{x}$



- At x=0, $e^x = 1$;
- Relatively *slow* increase at $x \leq 1$

Free electron concentration in semiconductors

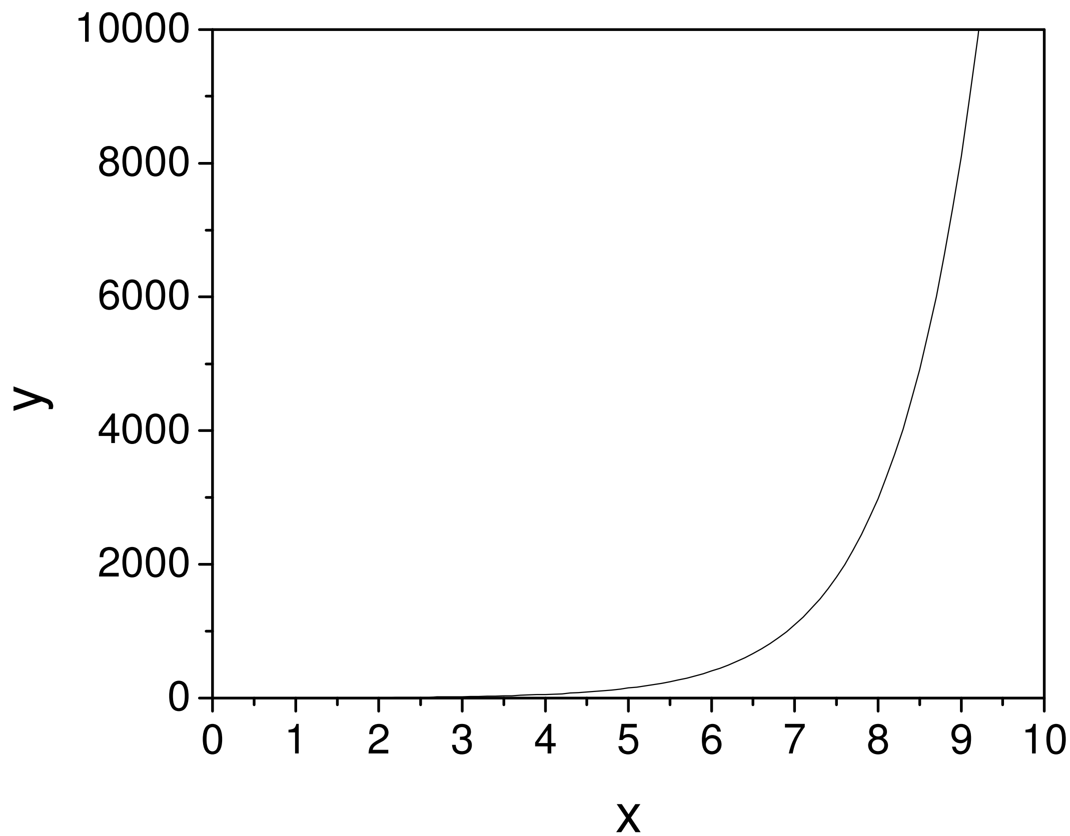
Some properties of the exponential function: $y = e^x$



- ***Steep*** increase at x > 1

Free electron concentration in semiconductors

Some properties of the exponential function: $y = e^{x}$



• **Extremely steep** at $x > 5$

Free electron concentration in semiconductors

$$n = N_0 \times e^{-\frac{\Delta E_G}{2kT}}$$

$k = 1.38 \times 10^{-23}$ J/K, is the Boltzmann constant,

T is the crystal temperature, in Kelvin (K)

$N_0 \approx 2\times10^{19}$ cm^{-3} for most semiconductor materials

$k \times T = 1.38 \times 10^{-23}$ J/K $\times$ 300 K $\approx$

$\approx 4 \times 10^{-21}$ J (at room temperature, T $\approx$300 K)

In most semiconductors,

$E_G \approx (2\ldots10)\times 10^{-19}$ J

Note, $kT << E_G$

- ***Joule is too big unit to describe the electron energy***

Electron - Volt

$$n = N_0 \times e^{-\frac{\Delta E_G}{2kT}}$$

The energy unit in micro-world: Electron-Volt:

$1\ eV = 1.6 \times 10^{-19}\ J$

Using the eV-units,

$k \times T \approx 4 \times 10^{-21}$ J ≈ 0.026 eV (at room temperature, T $\approx$300 K)

In most semiconductors,

$E_G \approx (2\ldots10) \times 10^{-19}$ J = 1 – 3 eV;

In Si, $E_G = 1.1$ eV.

Note, $kT << \Delta E_G$.

The argument $|x| >>1$ in the e^x function!

Free electron concentration in Silicon

$$n = N_0 \times e^{-\frac{\Delta E_G}{2kT}}$$

for Si,

$N_0 \approx 2\times10^{19}$ cm^{-3}

Room temperature: $kT_0 = 0.026$ eV;

$\Delta E_G = 1.1$ eV

$\Delta E_G/(2\times kT) = 21.15$

$e^{-21.15} = 6.5\times 10^{-10}$

$n = 1.3\times10^{10}$ cm^{-3}

Now, consider the temperature of 100 ^{o}C: $kT = kT_0\times(397K/297K)$

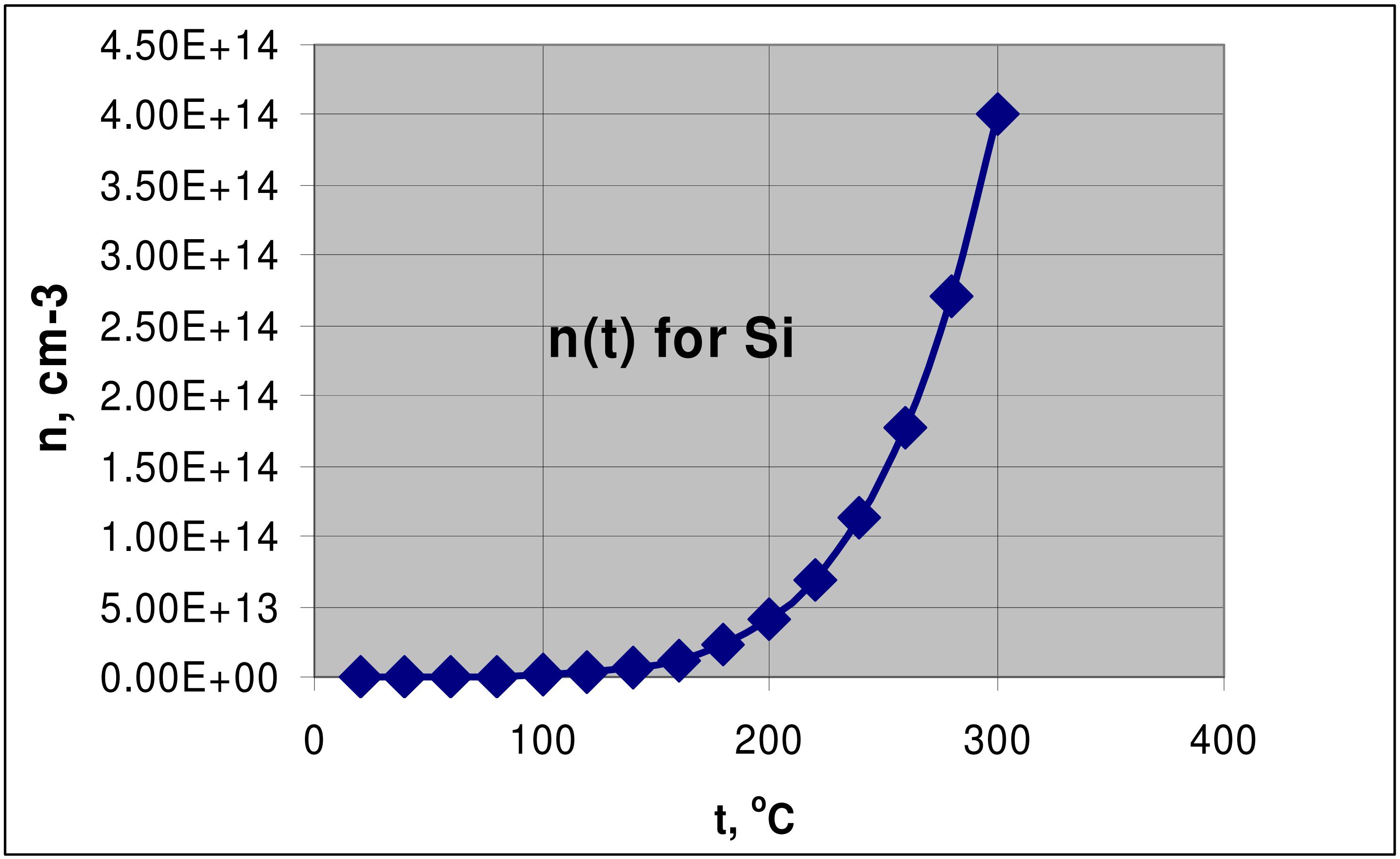
$= 0.026 \times 1.34$ eV $= 0.035$ eV;

$n = 3\times10^{12}$ cm^{-3};

compare this to the Si atom concentration $N_{Si} \approx 10^{23}$ cm^{-3}

Free electron concentration in Silicon

$$n = N_0 \times e^{-\frac{\Delta E_G}{2kT}}$$



Resistance of Silicon sample

How much would be the resistance of the (1 cm×1cm× 1cm) Si sample?

The electron mobility in Si, μ = 1000 $cm^2/(V \times s)$.

Consider room temperature:

$$\sigma = qn\mu;$$

$$R = \rho \frac{L}{A} = \frac{1}{\sigma} \times \frac{L}{A}$$

n = 1.3×10^{10} cm^{-3}

μ = 1000 $cm^2/(V \times s)$

q = 1.6×10^{-19} C

$$\sigma = 1.6 \times 10^{-19}\ C \times 1.3 \times 10^{10}\ cm^{-3} \times 1000\ cm^2/(V \times s)$$

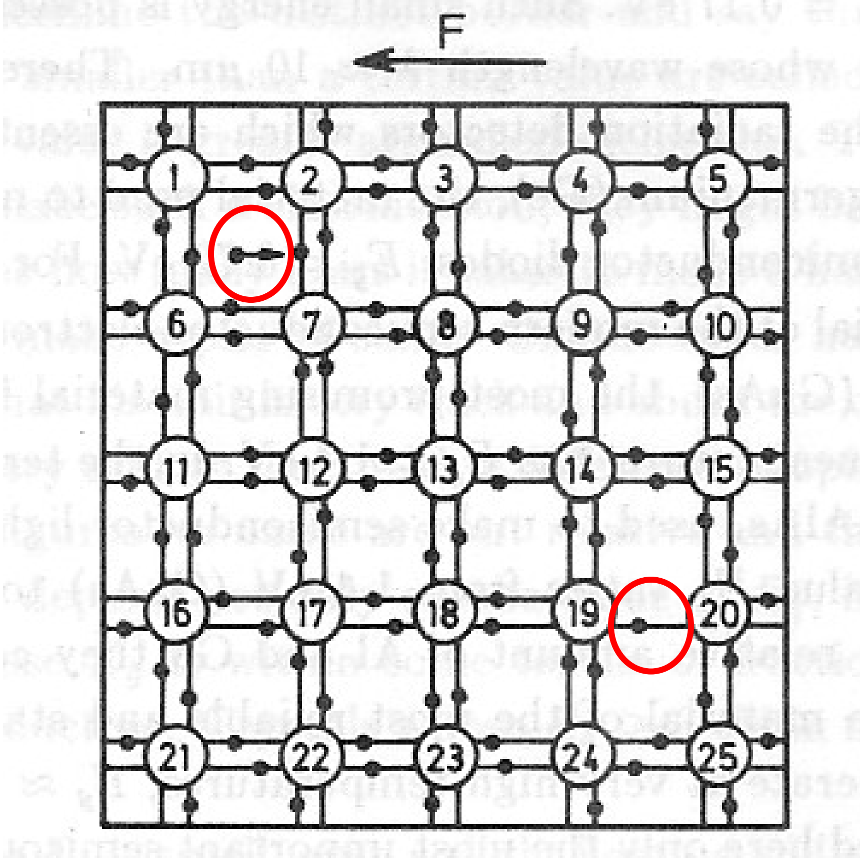
$$\sigma = 2.08 \times 10^{-6}\ (Ohm \times cm)^{-1}$$

$$\rho = 4.8 \times 10^{5}\ Ohm \times cm$$

R = 4.8×10^5 Ohm × cm ×1 cm /(1cm ×1cm) = **4.8×10^5 Ohm**

The resistance is too high for most practical purposes

Electron and Holes in Semiconductors



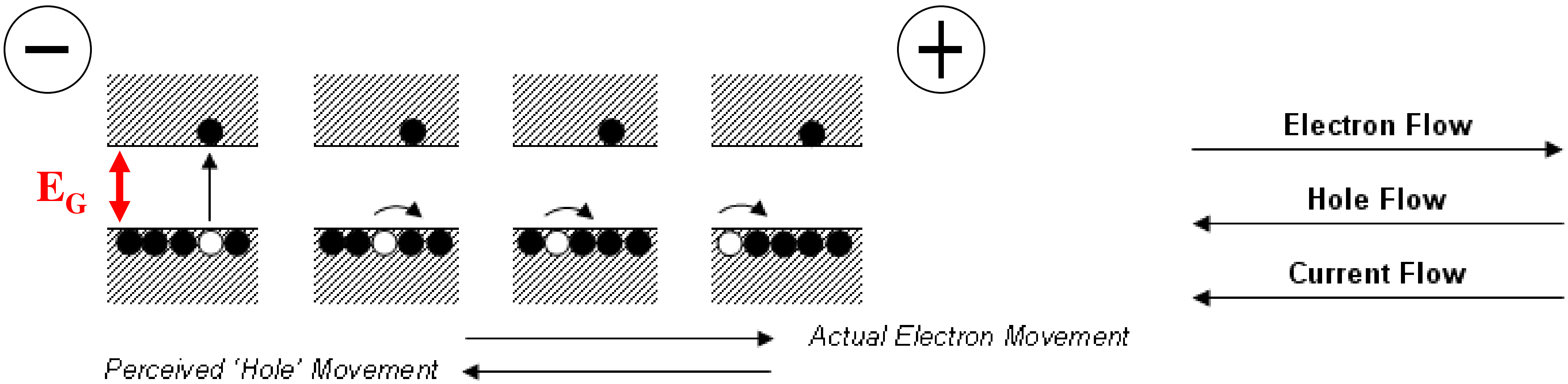
When the electron leaves the Si atom, it is lacking one electron.

The bonds lacking an electron behave as free POSITIVE charges: **holes**

In electric field, the hole "moves" toward negative electrode

Electron and Holes in Semiconductors

In pure (also called *intrinsic*) Si, free electrons and holes appear in PAIRS



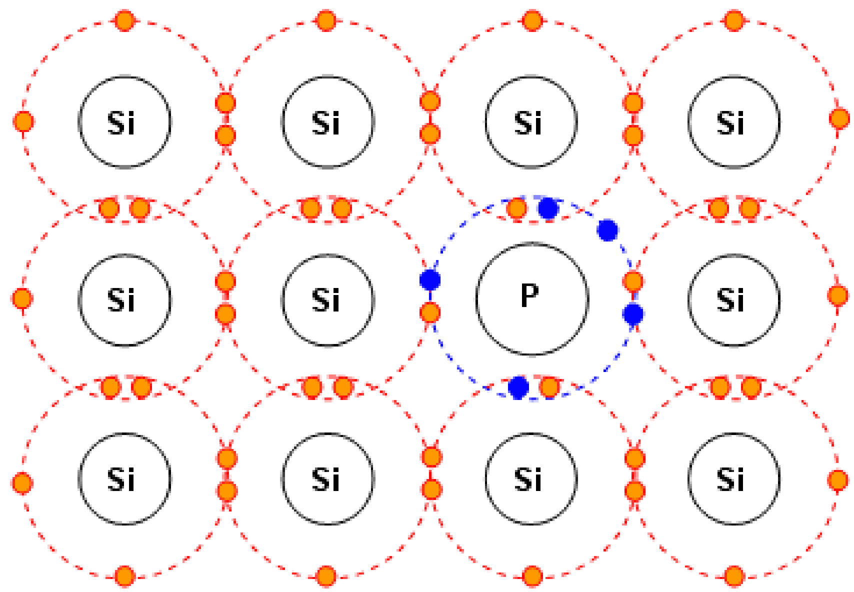
Electrons have negative charge and move toward positive electrode;

Holes have positive charge and "move" toward negative electrode

Any electron that leaves the atom creates a "hole" in the valence orbit.

- *The 'hole' is an abstraction; it has no substance and does not actually move itself, but movement of electrons in the opposite direction is perceived as the hole moving.*
- *In an ideal (intrinsic) semiconductor crystal,* $n_i = p_i$
- *Hole mobility is usually lower than electron mobility.*

Doped semiconductors: donor impurities



A silicon lattice with a single impurity atom (Phosphorus, P) added.

As compared to Si, the Phosphorus has one extra valence electron which, after all bonds are made, has very weak bonding.

Very small energy is required to create a free electron from an impurity atom.

This type of impurity is called donor.

Note, that there is no hole created when a free electron comes from the impurity atom.

Free electron concentration in donor - doped semiconductors

When donor atoms are introduced into the semiconductor material, they are all ionized.

Each donor atom creates one free electron.

If the concentration of donor impurity (e.g. Phosphor) in Si is N_D,
the concentration of free electrons,

$$\mathbf{n \approx N_D}$$

For Si and other semiconductors, the typical doping levels are:

$$N_D = 10^{15}\ cm^{-3} \ldots .10^{18}\ cm^{-3}$$

$n_D = 10^{15}\ cm^{-3} \ldots .10^{18}\ cm^{-3}$ (compare to $n_i = 1.3\times10^{10}\ cm^{-3}$ in intrinsic Si)

$$n_D >> n_i$$

Doping provides a flexible control over semiconductor conductivity.

The vast majority of microelectronic devices are based on doped semiconductors

Resistance of Donor-Doped Silicon sample

How much would be the resistance of the (1 cm×1cm× 1cm) Si sample doped with donor impurities with concentration 2×10^{16} cm^{-3}?

$$\sigma = qn\mu;$$

$$R = \rho\frac{L}{A} = \frac{1}{\sigma}\times\frac{L}{A}$$

$n = 2\times10^{16}$ cm^{-3}
$\mu_n = 1000$ cm^2/(V ×s)
$q = 1.6\times10^{-19}$ C

$$\sigma = 1.6\times10^{-19}\text{ C}\times 2\times10^{16}\text{ cm}^{-3}\times 1000\text{ cm}^2/(\text{V}\times\text{s})$$

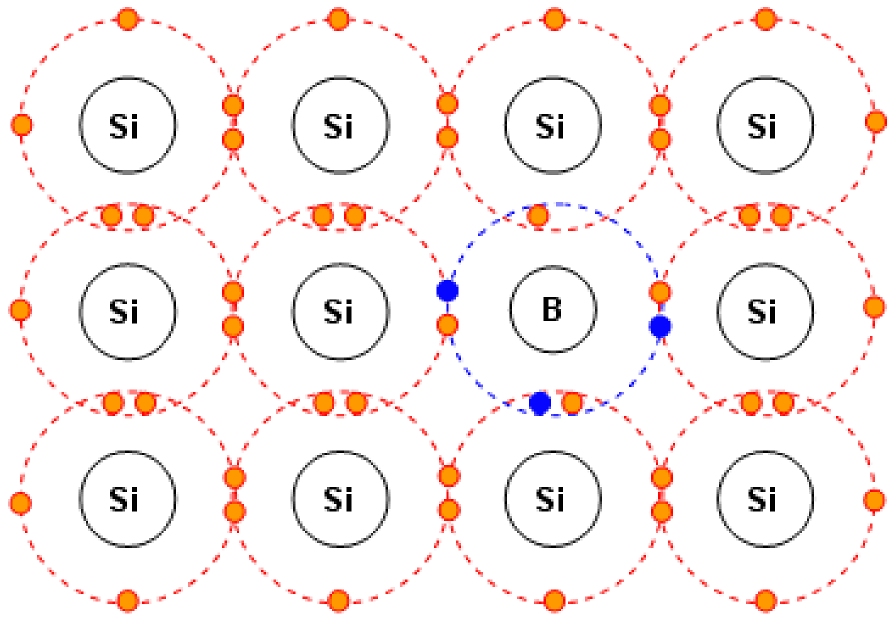
$$\sigma = 3.2\ (\text{Ohm}\times\text{cm})^{-1}$$

$$\rho = 0.325\ \text{Ohm}\times\text{cm}$$

$R = 0.325$ (Ohm × cm) ×1 cm /(1cm ×1cm) = **0.325 Ohm**

The resistance of a doped Si crystal can be significantly lower than that of intrinsic Si

Doped semiconductors: acceptor impurities



A silicon lattice with a single impurity atom (Boron, B) added.
Boron has only three valence electrons, one electron less than the Si atom.
Having only three valence electrons - not enough to fill all four bonds - it creates an **excess hole** that can be used in conduction.

This type of impurity is called acceptor.

There is no corresponding free electron created from acceptor impurity

Hole concentration in acceptor - doped semiconductors

If the concentration of acceptor impurity (B atoms) in Si is N_A, the hole concentration

$$\mathbf{p_A \approx N_A}$$

For Si and other semiconductors, the typical acceptor doping levels are:

$$N_A = 10^{15}\ \text{cm}^{-3} \ldots .10^{18}\ \text{cm}^{-3}$$

$p_A = 10^{15}\ \text{cm}^{-3} \ldots .10^{18}\ \text{cm}^{-3}$ (compare to $n_i = 1.3\times10^{10}\ \text{cm}^{-3}$ in intrinsic Si);

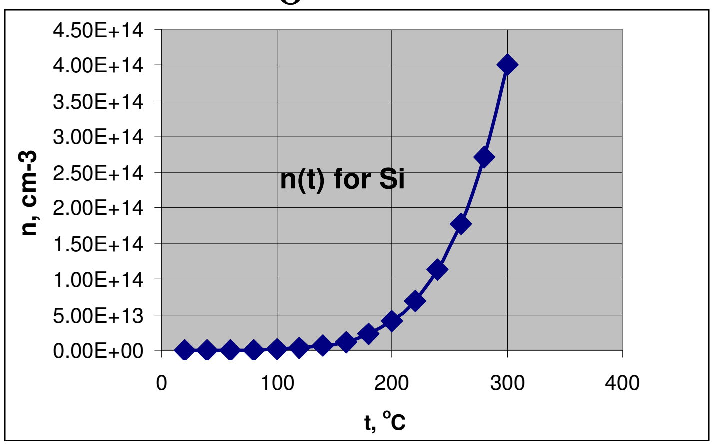
$$p_A >> n_i$$

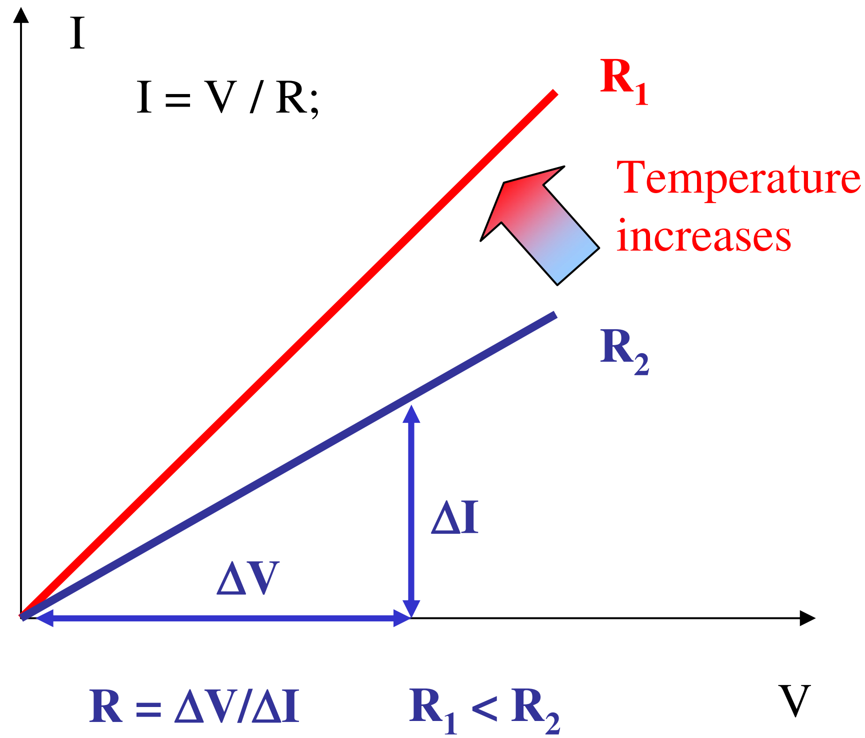
The vast majority of microelectronic devices using hole conductivity, are based on doped semiconductors

In doped semiconductors, the concentration of intrinsic electrons and holes can be neglected as compared to those coming from donor and acceptor impurities.

Thermistor - the semiconductor temperature sensor

$$n = N_0 \times e^{-\frac{\Delta E_G}{2kT}}$$





T increases ⇒ n increases ⇒ R decreases ⇒ Current increases

Thermistor as a temperature gauge

The figure of merit for a resistive temperature gauge is a

"Temperature coefficient of resistance"

$$TCR = \frac{1}{\Delta T} \times \frac{\Delta R}{R}$$

[TCR] = [K^{-1}] or [$^{O}C^{-1}$]

For a semiconductor gauge

$$n = N_D e^{-\frac{\Delta E}{2 \cdot kT}} \Rightarrow R = \frac{1}{q n \mu} \frac{L}{A} = \frac{1}{q N_D \mu} \frac{L}{A} e^{\frac{\Delta E}{2 \cdot kT}} = R_0 e^{\frac{\Delta E}{2 \cdot kT}}$$

$$\frac{\Delta R}{\Delta T} \approx \frac{\partial R}{\partial T} = R_0 e^{\frac{\Delta E}{2 \cdot kT}} \left(\frac{\Delta E}{2 \cdot k} \right) \times \left(\frac{-1}{T^2} \right) = R \times \left(\frac{\Delta E}{2 \cdot k} \right) \times \left(\frac{-1}{T^2} \right)$$

$$TCR = \frac{1}{\Delta T} \frac{\Delta R}{R} \approx -\left(\frac{\Delta E}{2 \cdot kT} \right) \times \left(\frac{1}{T} \right)$$

Example: $\Delta E = 0.7$ eV (Ge) $\Rightarrow$ TCR = - 0.045 $^{O}C^{-1}$ at R.T. (T = 300 K)

Compare to metal gauges: TCR $\cong$ + 0.005

Thermistor as a solid-state switch:
Effect of self-heating on semiconductor thermistor

Initially, the thermistor temperature = room temperature

The voltage applied: the current flows through the thermistor.

$I = V/R$;

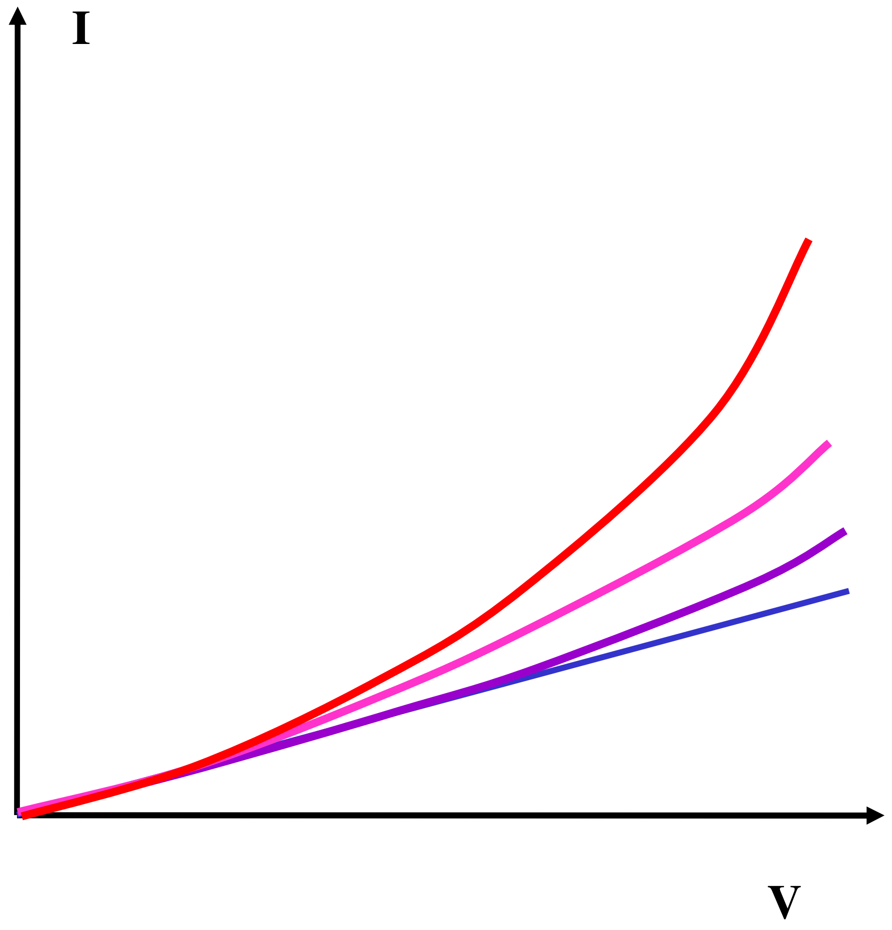
Joule heat **further** increases $P = V \times I = I^2 R$

The device temperature increases even more

The device resistance decreases more

The device current further increases

Effect of self-heating on semiconductor thermistor



Thermistor I- V Characteristics at different temperatures