ELECTRICAL PROPERTIES OF SEMICONDUCTORS

1 Intrinsic Semiconductor
2 Extrinsic Semiconductor
3 Drift and Diffusion
4 Boltzmann's Law

Silicon: our default example and our main focus

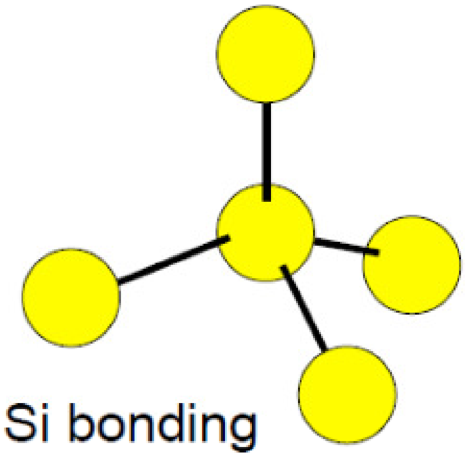
Atomic no. 14

14 electrons in three shells: 2) 8) 4

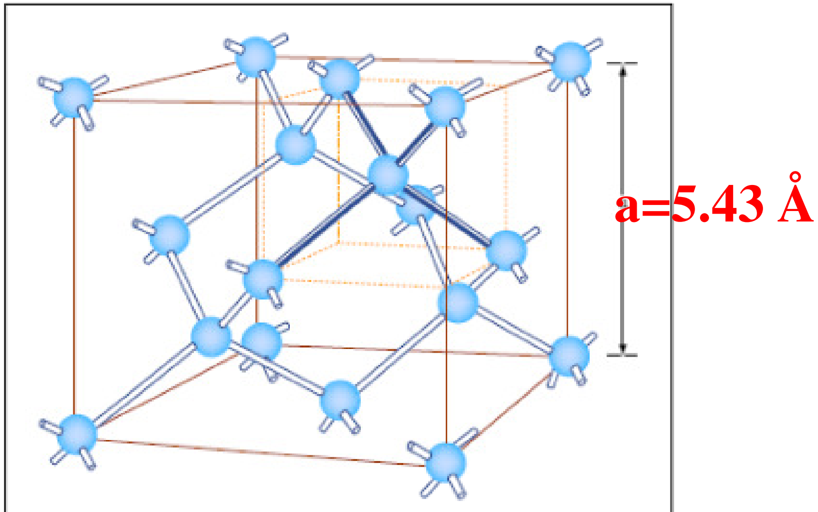
Electrons tightly bound to the nucleus

i.e., 4 electrons in the outer "bonding" shell

Silicon forms strong covalent bonds with 4 neighbors



Si bonding configuration



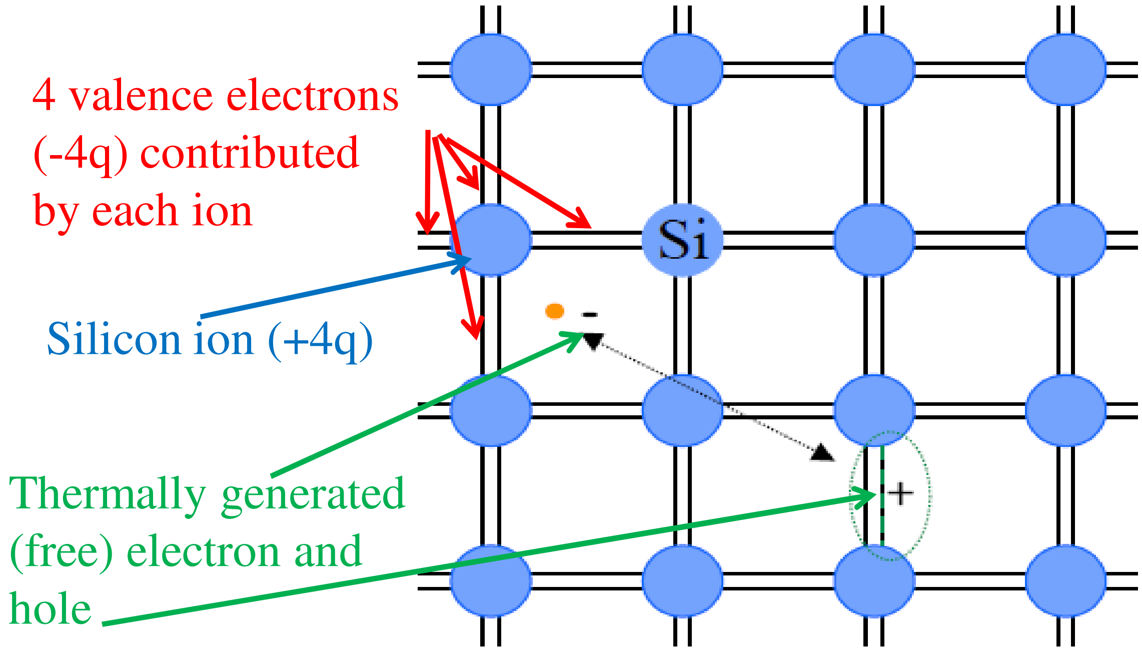
Silicon crystal ("diamond" lattice)

Figure by MIT OpenCourseWare.

Silicon crystal ("diamond" lattice)

Intrinsic silicon - pure, perfect, R.T.:

- All bonds filled at 0 K, $p_o = n_o = 0$

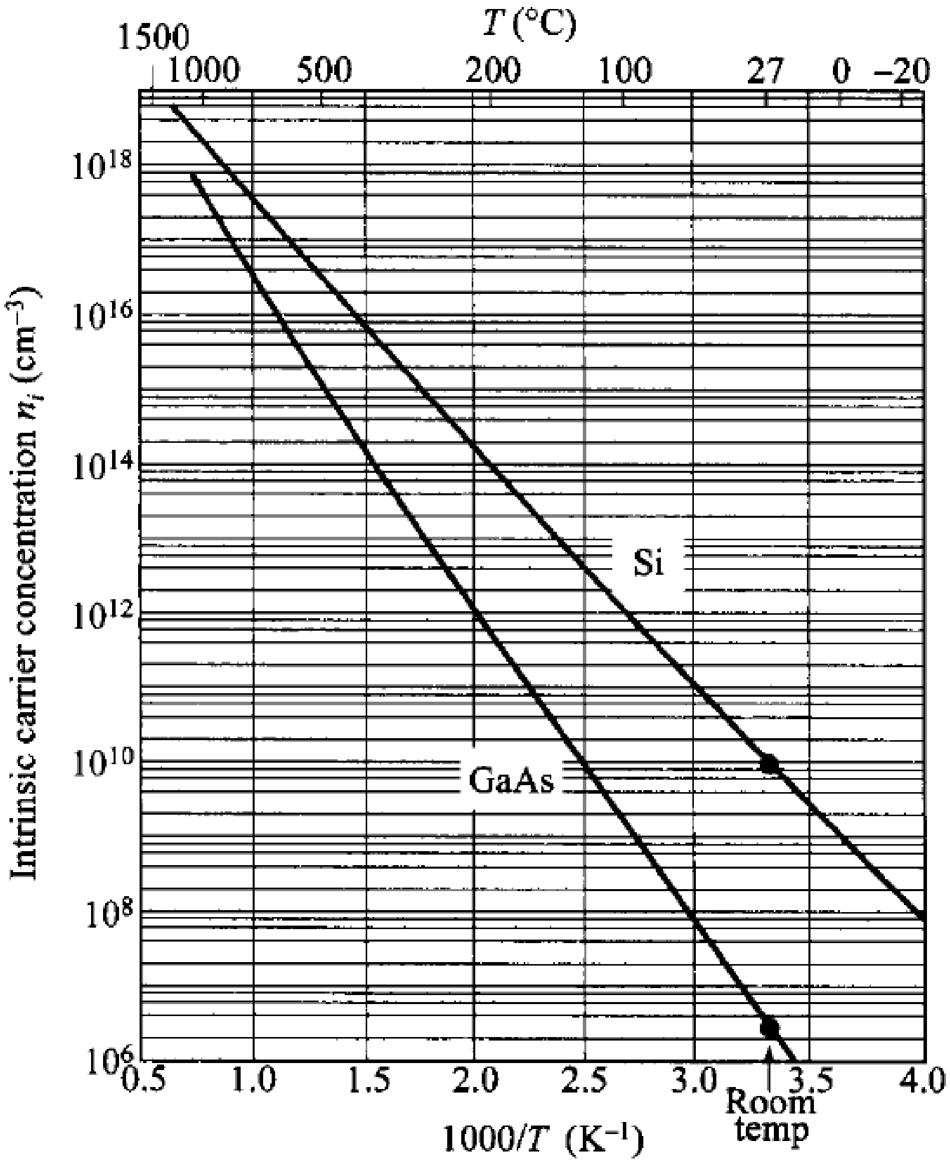


- At R. T., $p_o = n_o = n_i = 10^{10}$ cm^{-3}
- Mobile holes (+) and mobile electrons (-)
- Compare to ≈ 5×10^{22} Si atoms/cm^3

p & n – hole and electron concentrations [cm^{-3}]

$q = 1.6 \times 10^{-19}$ C

R.T.: room temperature



Si : n_i (T = 300K) = 10^{10} cm^{-3}

$$\frac{n_i(T=300K)}{(\text{Si at/cm}^3)} = \frac{10^{10}}{5\times10^{22}} = \frac{1}{5\times10^{12}}$$

$$n_i^2 = BT^3\exp\left(-\frac{E_G}{kT}\right)$$

k : Boltzmann's constant

k=8.62 x10^{-5} eV/K

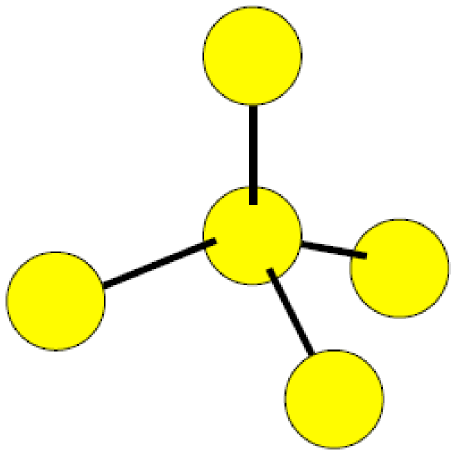
= 1.38 x10^{-23} J/K

E_G (Si) = 1.12 eV @ T=300 K

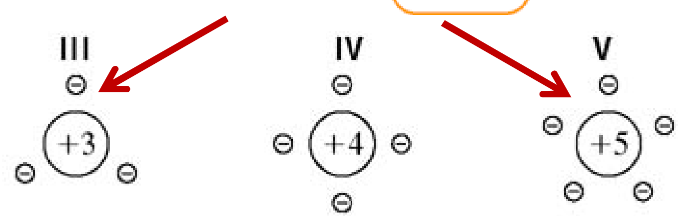
10^{10} cm^{-3} is a very small concentration and intrinsic Si is an insulator; we need to do something

Extrinsic Silicon: carefully chosen impurities (dopants) added

Column IV elements (C, Si, Ge, α-Sn)



II	III	IV	V	VI
	B 5	C 6	N 7	O 8
	Al 13	Si 14	P 15	S 16
Zn 30	Ga 31	Ge 32	As 33	Se 34
Cd 48	In 49	Sn 50	Sb 51	Te 52
Hg 80	Tl 81	Pb 82	Bi 83	Po 84

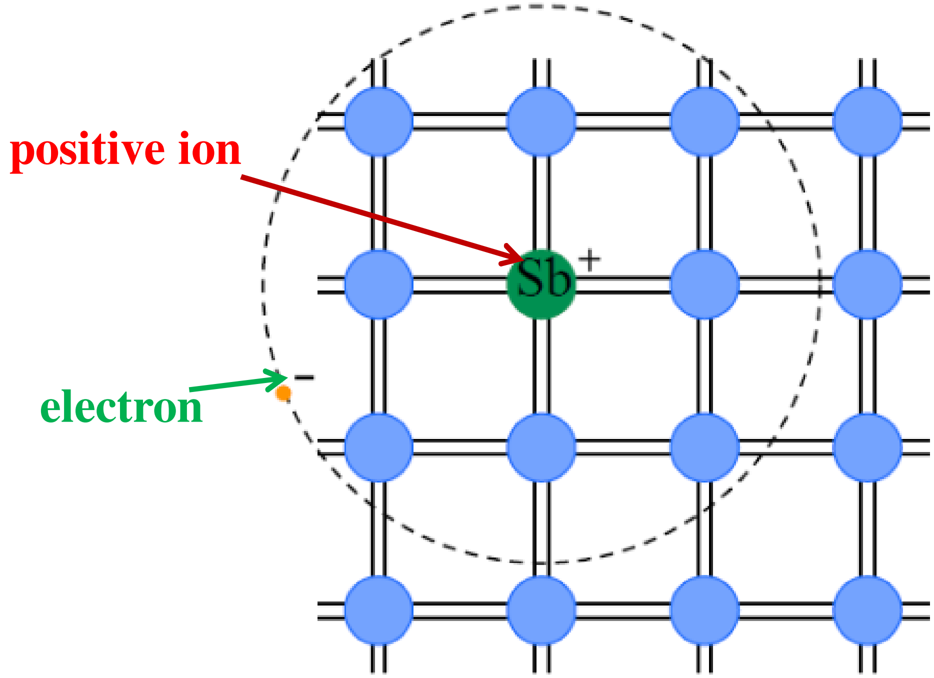


Column V elements (*N*, P, As, Sb):

too many bonding electrons → electrons easily freed to conduct (-q charge)

→ fixed ionized donors created (+q charge)

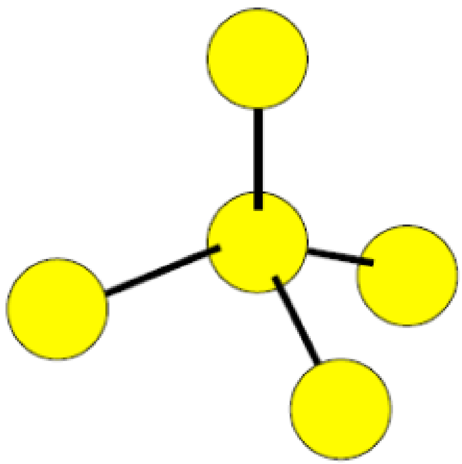
A column V atom replacing a silicon atom in the lattice:



- One more electron than needed for bonding.
- Easily freed to conduct at RT.
- Impurity is an electron "donor."
- Mobile electron (-) and fixed donor (+); $N_d^+ \approx N_d$.

Extrinsic Silicon, cont.: carefully chosen impurities (dopants) added

Column IV elements (<u>C</u>, <u>Si</u>, <u>Ge</u>, α-<u>Sn</u>)



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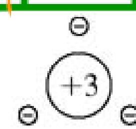
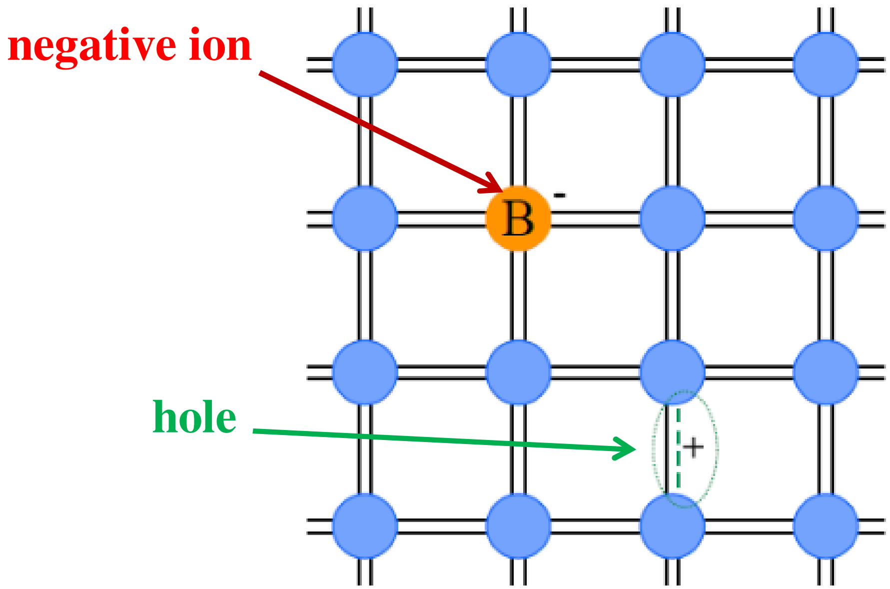


Column III elements (<u>B</u>, *Al*, *Ga*, *In*):

too few bonding electrons → leaves holes that can conduct (+q charge)
→ fixed ionized acceptors created (-q charge)

A column III atom replacing a silicon atom in the lattice:



- One less electron than needed for bonding.
- Bond easily filled leaving mobile hole; at RT.
- Impurity is an electron "acceptor."
- Mobile hole (+) and fixed acceptor (–); $N_a^- \approx N_a$.

Donors : P, As, Sb (Group V)

N-type semiconductor

electrons: majority carriers –

holes: minority carriers +

ionized donors: fixed charges ⊕

$$P \rightarrow P^{\oplus} + e^{-}$$

ion (fixed charge) **electron (mobile charge)**

N_D: donor concentration

$$10^{14}\,cm^{-3} \le N_D \le 10^{20}\,cm^{-3}$$

Acceptors: B, Al (Group III)

P-type semiconductor

holes: majority carries +

electrons: minority carries –

ionized acceptors: fixed charges ⊖

$$B \rightarrow B^{\ominus} + h^{+}$$

N_A : acceptor concentration

$$10^{14}\,cm^{-3} \le N_A \le 10^{20}\,cm^{-3}$$

Heavily doped (degenerate) silicon

GENERATION=break-up of covalent bond to form electron and hole pairs

RECOMBINATION=formation of covalent bond by bringing together electron and hole

Thermal generation/recombination

covalent bond $\rightleftharpoons$ $e^- + h^+$

Both (free) electrons and holes are free to move around the lattice.

Intrinsic Silicon $n = p = n_i\,(T)$

Thermal Equilibrium $G = R$

G (generation rate) ⇒ # covalent bonds broken / cm^3 / s

R (recombination rate) ⇒ # electron-hole pairs eliminated / cm^3 / s

Thermal equilibrium – Isolated (no interactions with environment) semiconductor. Uniform T, no light shining on the device, no applied electric or magnetic field.

Steady-state : **R = G**

In thermal equilibrium we have

Mass-action law:

$$n_0 = \frac{C(material, T)}{p_0}$$

$$\mathbf{n_O \, p_O = n_i^2(T)}$$

Intrinsic semiconductor $n_O = p_O = n_i(T)$

$n_i(T) \approx 10^{10}$ cm^{-3} for silicon at 300 K

http://www.pveducation.org/pvcdrom/pn-junction/equilibrium-carrier-concentration

(Volume) Charge Density ρ

mobile charges (carriers)

$$\rho = q\left(p - n + N_D^+ - N_A^-\right)$$

fixed charges (ions)

<u>Extrinsic semiconductor</u>

N-type

donor concentration : N_D
all donor atoms are ionized
donor $\rightarrow$ ion$^+$ + e$^-$

$\rho = q\,[-n + p + N_D]$
  $-$ $+$ $\oplus$

P-type

acceptor concentration : N_A
all acceptor atoms are ionized
acceptor $\rightarrow$ ion$^-$ + h$^+$

$\rho = q\,[\,p - n - N_A\,]$
  $+$ $-$ $\ominus$

Carrier concentration in doped silicon

N-type

$\rho = 0 \rightarrow n_O = p_O + N_D$

P-type

$\rho = 0 \rightarrow p_O = n_O + N_A$

$$n_O p_O = n_i^2(T)$$

N-type:

$$n_o = \frac{N_D + \sqrt{N_D^2 + 4n_i^2}}{2}$$

$$p_O = n_i^2 / n_O$$

P-type:

$$p_O = \frac{N_A + \sqrt{N_A^2 + 4n_i^2}}{2}$$

$$n_O = n_i^2 / p_O$$

Approximation

N-type:

$N_D >> n_i$

$n_O \approx N_D$

$p_O \approx n_i^2 / N_D$

P-type:

$N_A >> n_i$

$p_O \approx N_A$

$n_O = n_i^2 / N_A$

Example: Si T=300 K $\longrightarrow$ $n_i = 10^{10}$ cm^{-3}

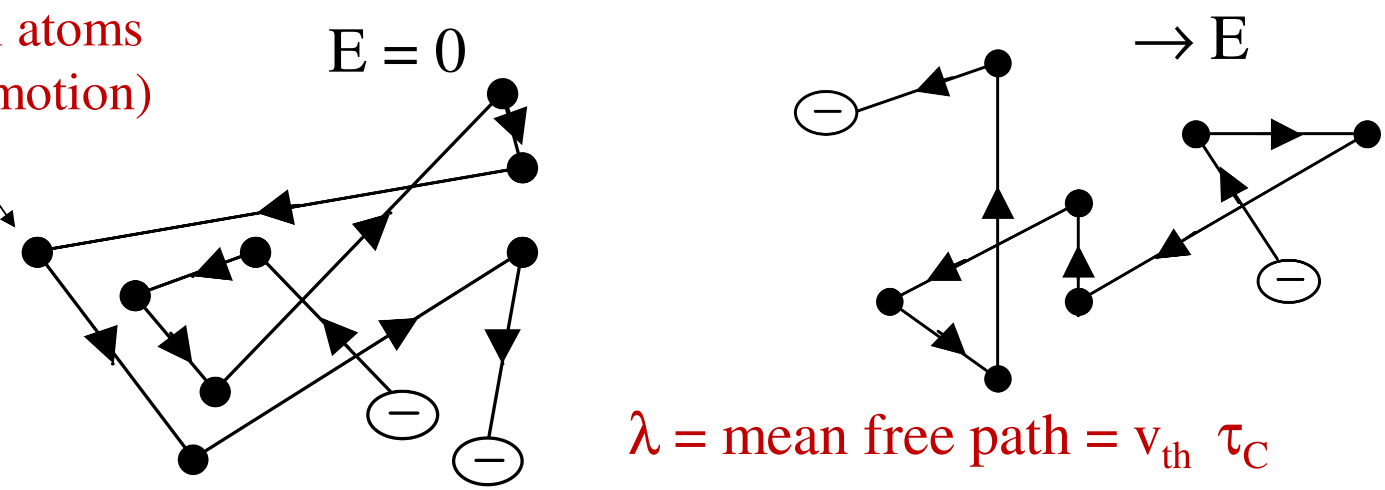
P-type Si	N-type Si
$N_A = 10^{16}$ cm^{-3}	$N_D = 10^{17}$ cm^{-3}

What are p and n in each case?

Carrier transport in semiconductors - Drift

Thermal motion of carriers

Collisions with vibrating Si atoms (Brownian motion)



λ = mean free path = $v_{th}\ \tau_C$

λ = =10^7 cm/s x 0.1 ps 0.01 μm = 100 Å

Kinetic energy of carriers

$\frac{1}{2}\, m^* \, v_{th}^2 = 3/2\ kT$

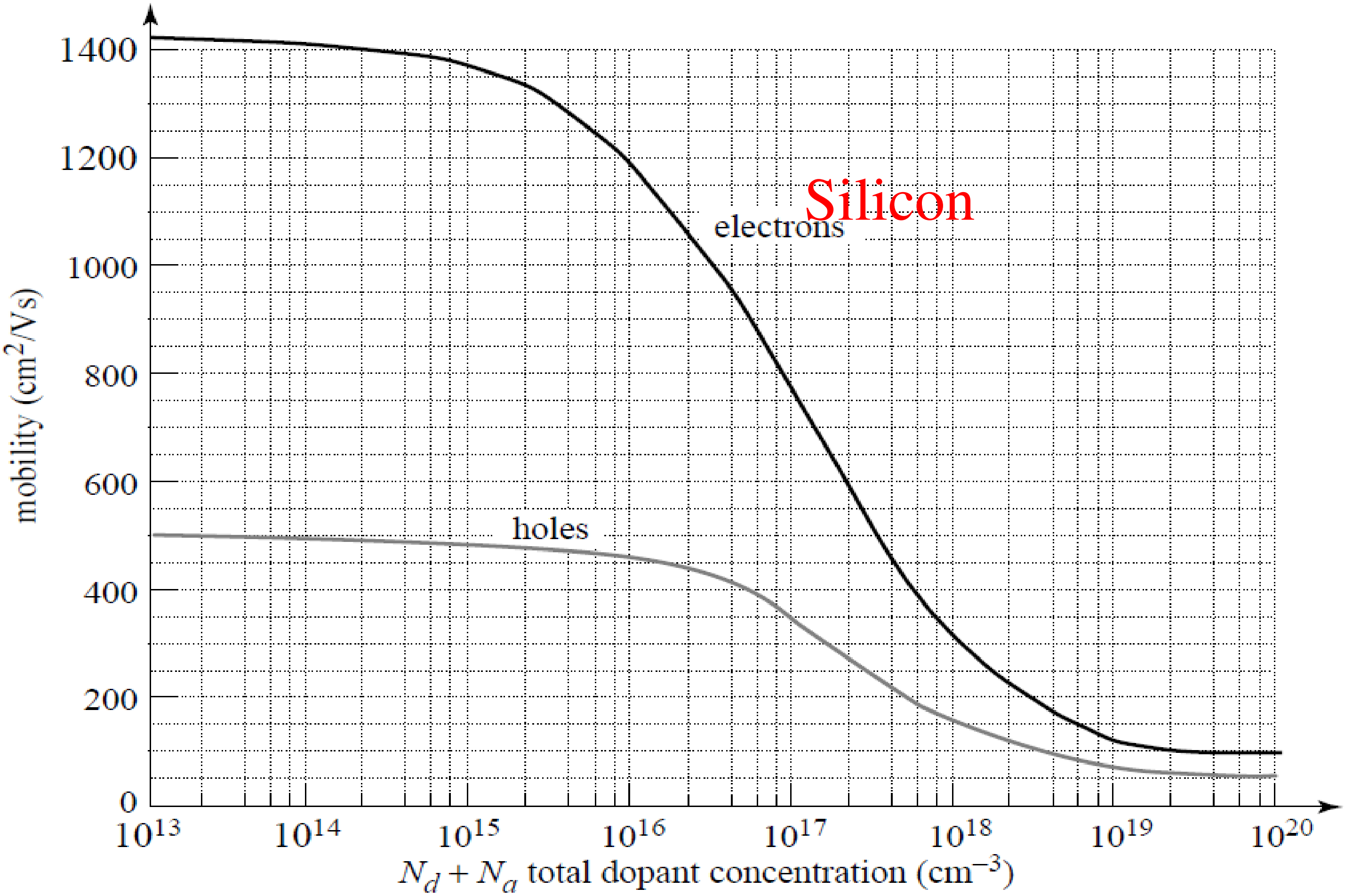
$v_{th} \approx 10^7$ cm/s at 300 K

$\tau_C \approx 0.1$ ps (mean free time = average time between collisions)

Drift velocity [cm s^{-1}] $\bar{v} = \pm \mu_{n,p} \boldsymbol{E}$

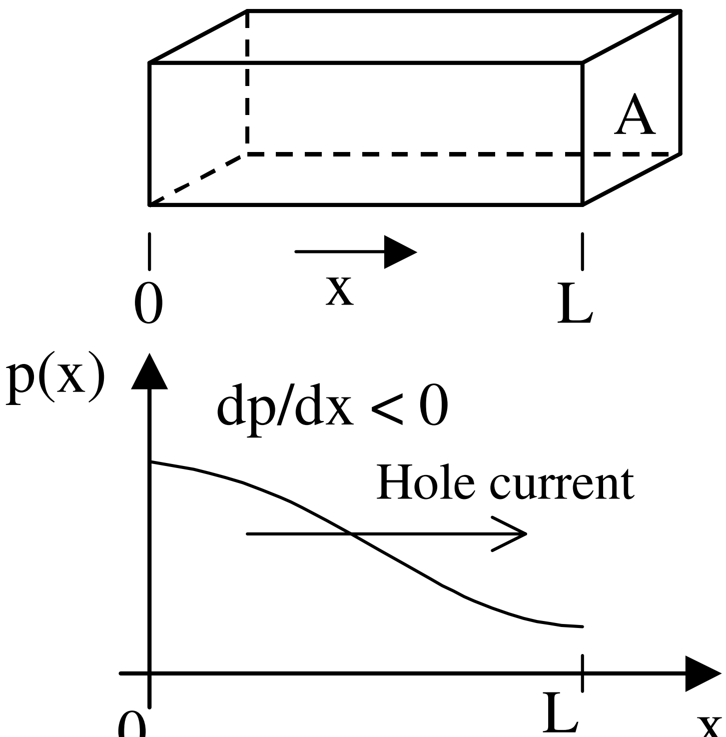
$\mu_{n,p} \equiv$ mobility[cm^{2}V^{-1}s^{-1}]

Mobility - is a measure of *ease of carrier drift*


Silicon
electrons
holes
1400
1200
1000
800
600
400
200
0
mobility (cm^2/Vs)
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
$N_d + N_a$ total dopant concentration (cm^{-3})

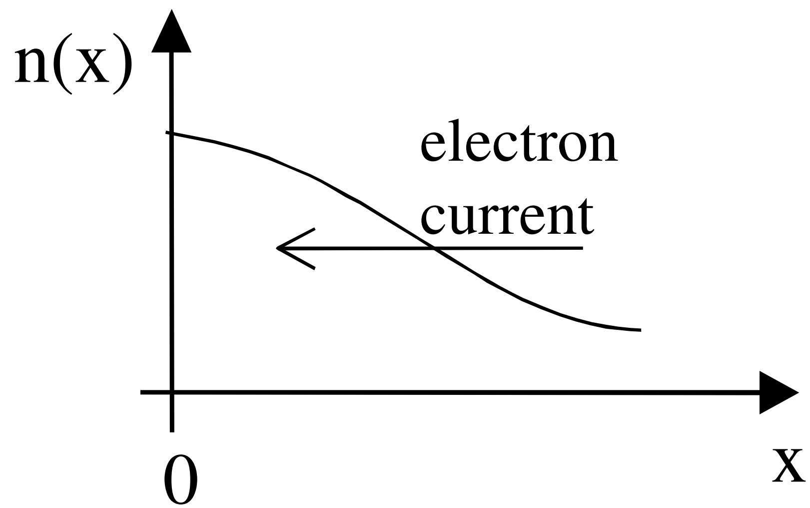
Carrier transport in semiconductors - Diffusion

A spatial variation (gradient) in concentration causes a net transport of particles from regions of higher concentration to regions of lower concentration. Diffusion occurs because more carriers are scattered in the volume of higher concentration than in the volume of lower concentration.



$$J_p\text{diff} = -q\, D_p \frac{dp}{dx}$$

$D_n(D_p)$: electron (hole) diffusion coefficient



$$J_n\text{diff} = q\, D_n \frac{dn}{dx}$$

Einstein Relationship

$$\frac{D}{\mu} = \frac{kT}{q} = \phi_t$$ (for both holes and electrons)

k: Boltzmann's constant
T: absolute temperature
q: electronic charge
ϕ_t: thermal voltage
$\phi_t \approx$ 25 mV (@ 290 K)
26 mV (@ 301.5 K)

$k = 1.38 \times 10^{-23}$ J/K = 86.2×10^{-6} eV/K
$q = 1.6 \times 10^{-19}$ C

T = 290K
$\mu_n = 1000\ cm^2/Vs \rightarrow D_n = 25\ cm^2/s$
$\mu_p = 400\ cm^2/Vs \rightarrow D_p = 10\ cm^2/s$

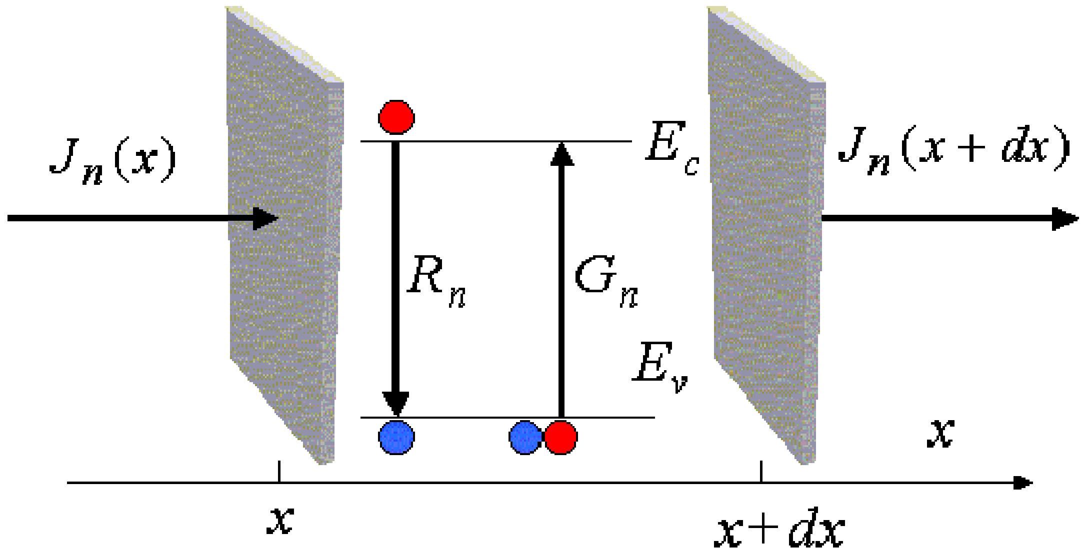
Total current = drift current + diffusion current

$$J_n = qn\mu_n E + qD_n \frac{dn}{dx}$$

$$J_p = qp\mu_p E - qD_p \frac{dp}{dx}$$

$$E = \frac{-d\phi}{dx} \qquad \frac{D}{\mu} = \frac{kT}{q}$$

Continuity 1-D equations for semiconductors



$$\frac{\partial n(x,t)}{\partial t} = \frac{1}{q}\frac{\partial J_n(x,t)}{\partial x} + G_n(x,t) - R_n(x,t)$$

$$\frac{\partial p(x,t)}{\partial t} = -\frac{1}{q}\frac{\partial J_p(x,t)}{\partial x} + G_p(x,t) - R_p(x,t)$$

Principles of

Semiconductor Devices

by

Bart Van Zeghbroeck

http://ecee.colorado.edu/~bart/book/book/title.htm

The Boltzmann's Law

Charge carriers in semiconductor: PE=-qV for electrons

PE= qV for holes

$n = n_O \exp(-PE/kT)$

n_O is the electron concentration for V=0

p_O is the hole concentration for V=0

$$n = n_O \exp(qV/kT) \qquad p = p_O \exp(-qV/kT)$$

k: Boltzmann's constant
T: absolute temperature
q: electronic charge
$\phi_t = kT/q$: thermal voltage
$\phi_t \approx$ 25 mV (@ 290 K)
26 mV (@ 301.5 K)

References

- EEL 7061 Eletrônica Básica
  http://www.lci.ufsc.br/electronics/index7061.htm
  (chapter 2)
- Charles Sodini, “6.012 Microelectronic Devices and Circuits”,OpenCourseWarehttp://ocw.mit.edu
- Sze & Ng, “Physics of semiconductor devices”, 3rd edn. Wiley
- Pierret, “Semiconductor device fundamentals,” Addison-Wesley