Announcements

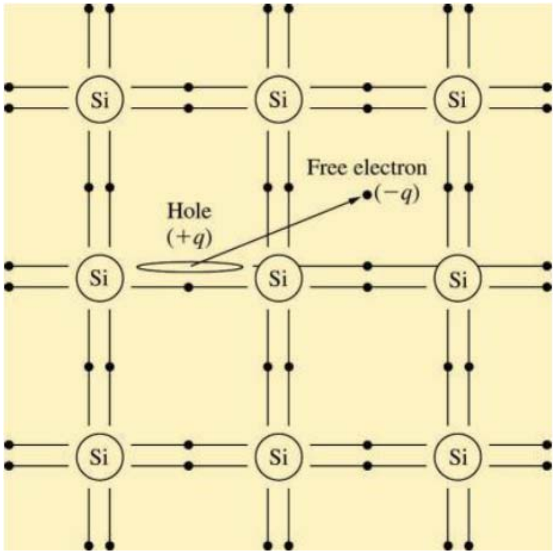
- Readings:
  - Chapter 1
  - Chapter 2 (2.1-2.10)
- Multisim tutorial: if enough interest (GoPost)
- Office Hour after this lecture:
  - Wednesday 2:00-3:00 pm @ EE 218

Intrinsic Carrier Concentration

- Can think of holes and electrons like chemical species.

$$e^- + h^+ \Leftrightarrow \emptyset$$

- In equilibrium, the ratio of the product of the concentrations of the reactants to the product of the concentrations of the products is equal to an equilibrium constant



$$\frac{pn}{4N} = K$$

  – *p* : concentration of holes
  – *n* : concentration of electrons
  – *N* : concentration of atoms

$$pn = 4NK \equiv n_i^2$$

Intrinsic Carrier Concentration

- Intrinsic carrier concentration n_i^2 only depends on temperature (T) and material (B, E_G)

$$n_i^2 = BT^3 \exp\left(-\frac{E_G}{kT}\right) \ \text{cm}^{-6}$$

  - E_G : band gap energy of the material, in eV. E_G is the minimum energy to break the covalent bond and excite a free electron.
  - k : Boltzmann's constant, 8.62×10^{-5} eV / K
  - T : Absolute temperature in K (Kelvin)
  - B : material-dependent parameter

1 eV = 1.6×10^{-19} J
K = °C + 273.15

Intrinsic Carrier Concentration

- Example: Calculate intrinsic carrier concentration of Si at 300 K (RT) and 1200 K .

$$n_i^2 = BT^3 \exp\left(-\frac{E_G}{kT}\right) \ \text{cm}^{-6}$$

- For Si: E_G = 1.12 eV, B_{Si} = 2.23 x 10^{31} K^{-3} cm^{-6}
- At 300 K, $n_i = 1.0 \times 10^{10} \text{cm}^{-3}$
- At 1200 K, $n_i = 1.26 \times 10^{18} \text{cm}^{-3}$

8 orders of magnitude!

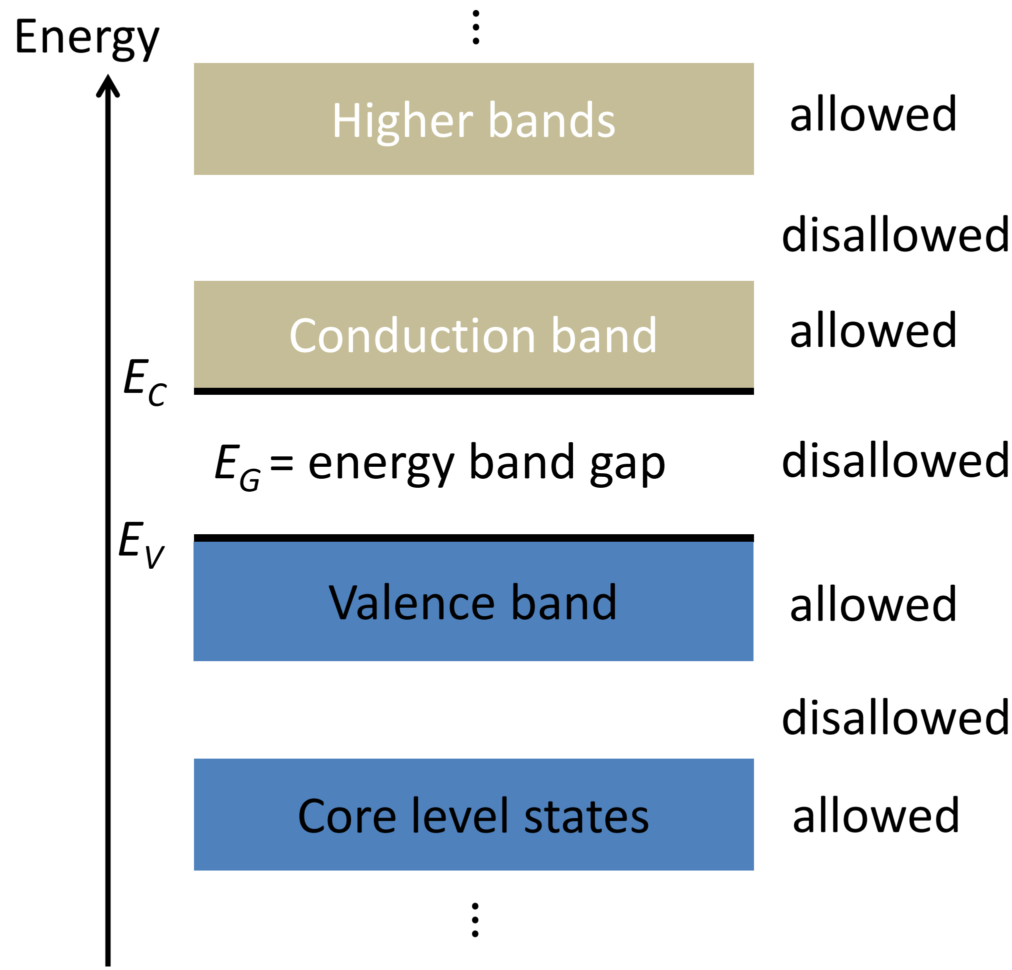
- Silicon valence electron density: $\sim 10^{23} \text{cm}^{-3}$
- Fraction of bonds broken to excite a free electron
  - $\sim 10^{-13}$ for T = 300 K
  - $\sim 10^{-5}$ for T = 1200 K

Small fraction!

Energy Band Model of Semiconductors

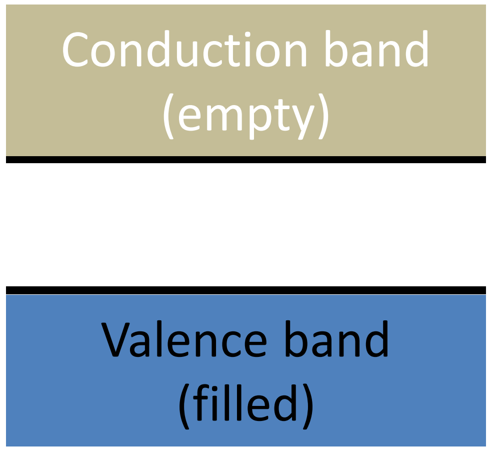
Electron States

- Quantum Physics: 1 electron occupies 1 state
- Crystal Structure of a material produces ranges of allowed and disallowed energy states for electrons.
- Electrons fill allowed states: starting with the lowest energies and filling upwards.

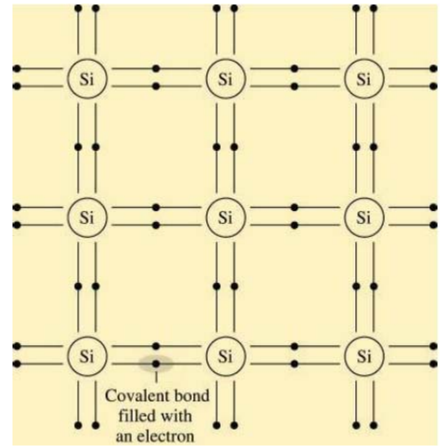


Energy Band Model of Semiconductors

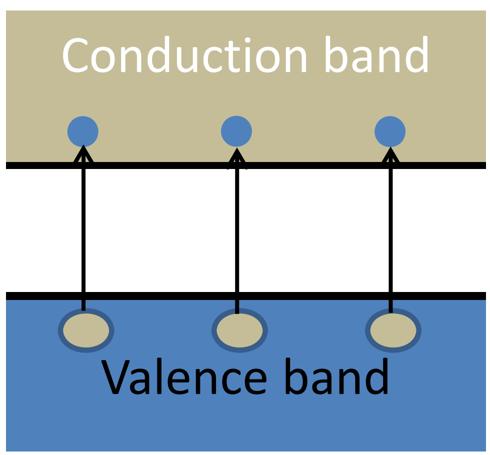
T = 0 K



No free carriers

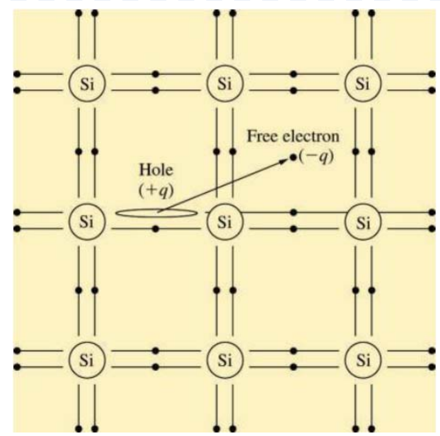


T > 0 K



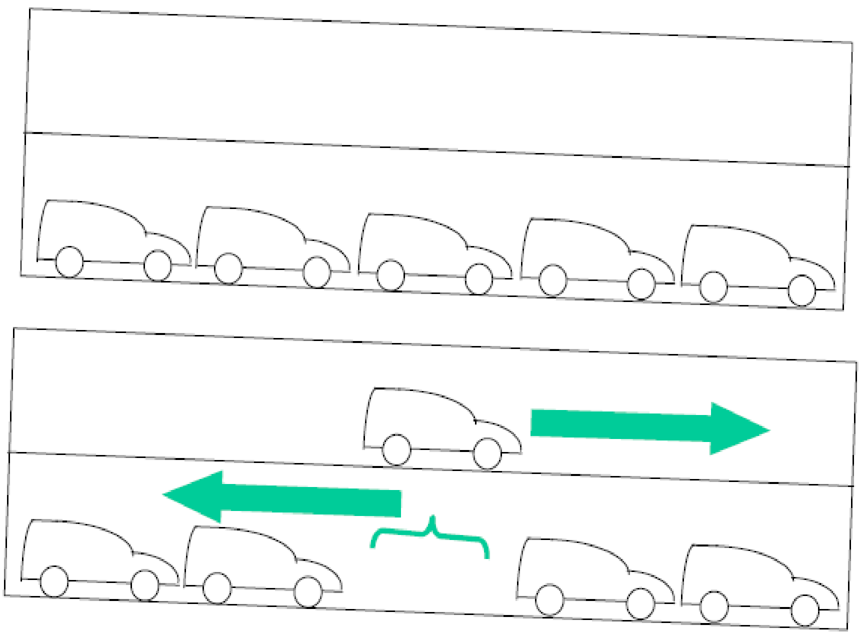
electrons

holes



Conduction – Parking Lot Analogy

- Neither empty bands nor full bands contribute to conduction
- **Conduction arises from partially filled bands** (electrons in conduction band and holes in valence bands)



At T = 0 K

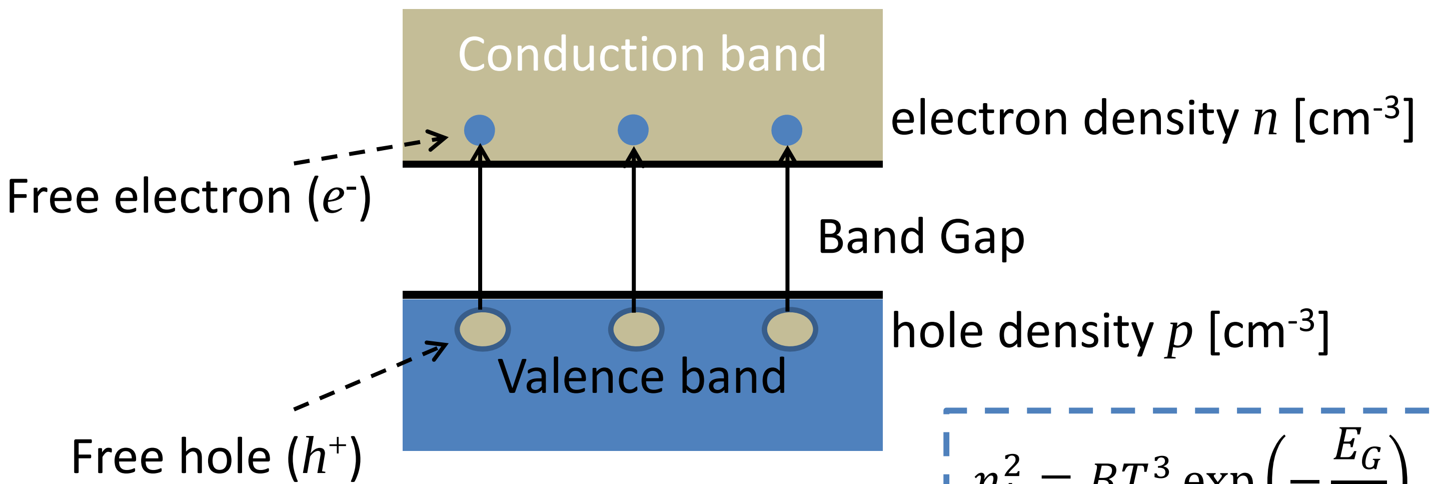
- Upper floor empty – no traffic
- Lower floor full – no traffic

At T > 0 K

- One car move to the top floor; leaves one vacancy in the lower floor
- Both the car and the vacancy can move – traffic

Car – electron; vacancy – hole; traffic – conduction
Upper floor – conduction band; lower floor – valence band

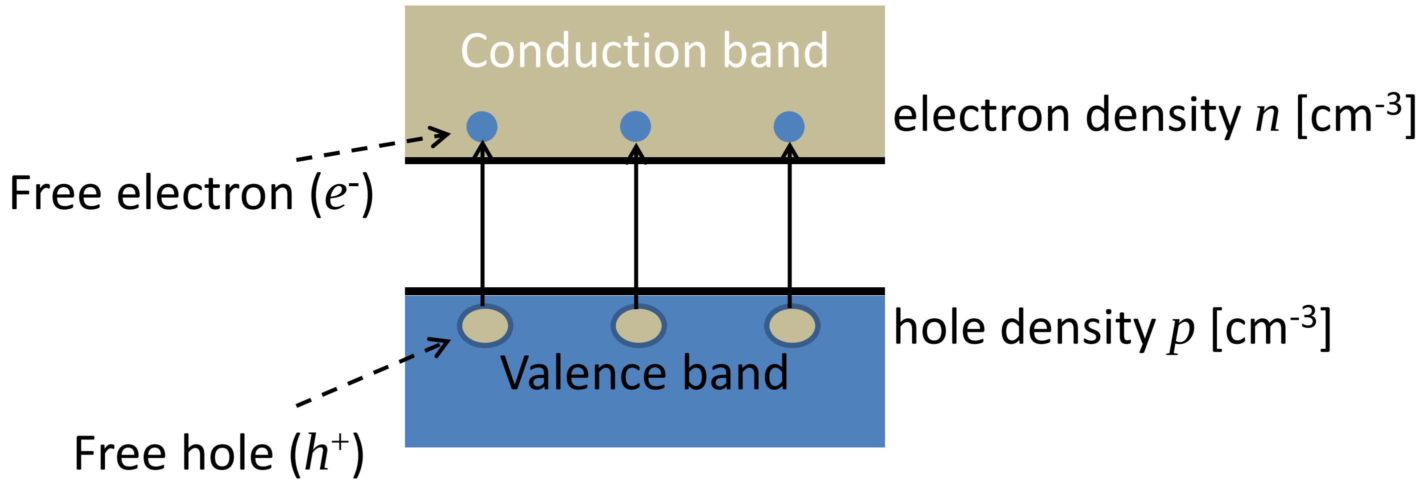
Energy Band Model – Intrinsic Silicon



$$n_i^2 = BT^3 \exp\left(-\frac{E_G}{kT}\right) \text{ cm}^{-6}$$

- In intrinsic silicon, there's one free hole per excited free electron => $n = p$. By definition, $n = p = n_i$ (Intrinsic carrier density)
- n_i depends only on temperature and material
  - Higher T, n_i higher (more thermal energy, easier to excite electrons)
  - Larger Band gap, n_i lower (electrons harder to "jump" to conduction band)

Conduction in Intrinsic Silicon



- Conduction is due to both electrons and holes in a semiconductor

Previously, we had only $\sigma = qn\mu_n$

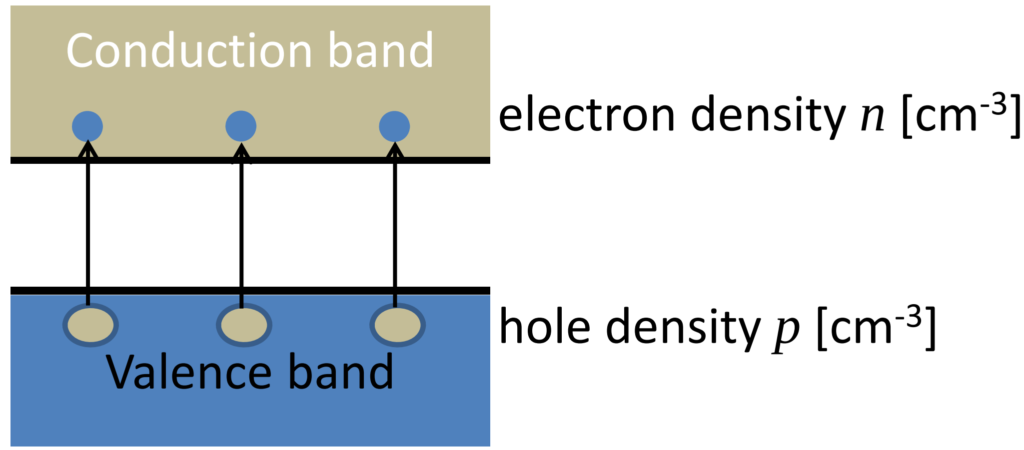
$$\sigma = qn\mu_n + qp\mu_p$$

Electron density (n), Electron mobility (μ_n), Hole density (p), Hole mobility (μ_p)

$\mu_n > \mu_p$

- Intrinsic silicon: $\sigma = q(\mu_n + \mu_p)n_i$

Conduction in Intrinsic Silicon



$J_n = qnu_nE$

$J_p = qpu_pE$

$J = J_n + J_p.$

$J = \sigma E$

$$\sigma = q(\mu_n n + \mu_p p)$$

Intrinsic Si @ RT: $\sigma = q(\mu_n + \mu_p)n_i$

$$= (1.6\text{x}10^{19}\text{C})\left([1000 + 400]\frac{\text{cm}^2}{\text{Vs}}\right)(1\text{x}10^{10}\text{cm}^{-3})$$

$= 2.2\text{x}10^{-6}$ S/cm

Extrinsic Semiconductor

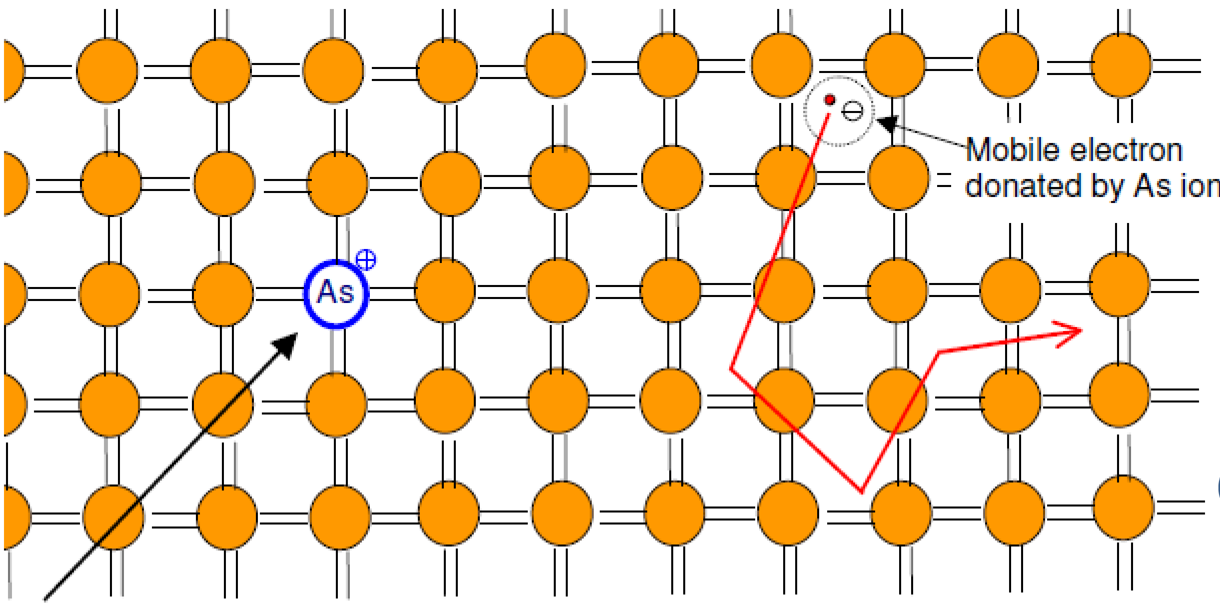
- Conductivity in intrinsic silicon is low in normal conditions (insulator).
- Trace amounts of impurities (dopants) are added to adjust the conductivity.
- Two types of substitutional dopants:
  - Group V elements, P, As, Sb (donor)
  - Group III elements, B, Al, Ga, In (acceptor)

IIB	IIIA	IVA	VA	VIA
	5 B Boron 10.811	6 C Carbon 12.01115	7 N Nitrogen 14.0067	8 O Oxygen 15.9994
	13 Al Aluminum 26.9815	14 Si Silicon 28.086	15 P Phosphorus 30.9738	16 S Sulfur 32.064
30 Zn Zinc 65.37	31 Ga Gallium 69.72	32 Ge Germanium 72.59	33 As Arsenic 74.922	34 Se Selenium 78.96
48 Cd Cadmium 112.40	49 In Indium 114.82	50 Sn Tin 118.69	51 Sb Antimony 121.75	52 Te Tellurium 127.60
80 Hg Mercury 200.59	81 Tl Thallium 204.37	82 Pb Lead 207.19	83 Bi Bismuth 208.980	84 Po Polonium (210)

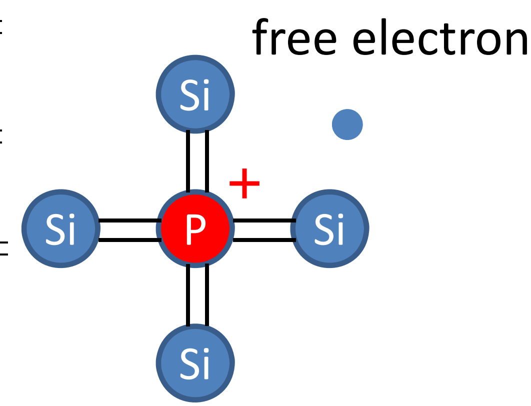
Extrinsic Semiconductor - Donor

- Group V elements (donors)
  - Have one more outer electrons than Si (5 vs. 4)
  - Can donate one free electron, and become positively charged (charge neutrality condition).

N_D = donor density [cm^{-3}] (positive, fixed charge)

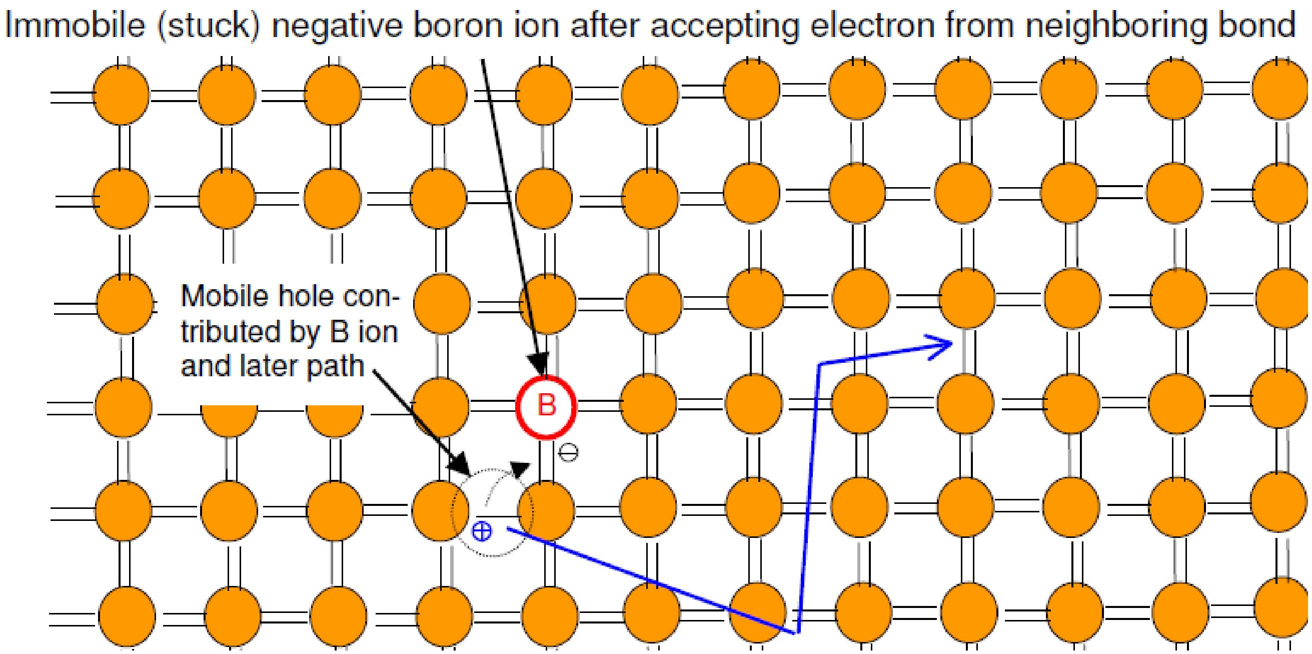


Immobile (stuck) positively charged arsenic ion after 5th electron left

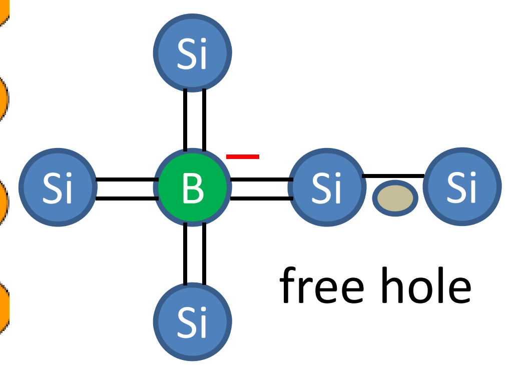


Extrinsic Semiconductor - Acceptor

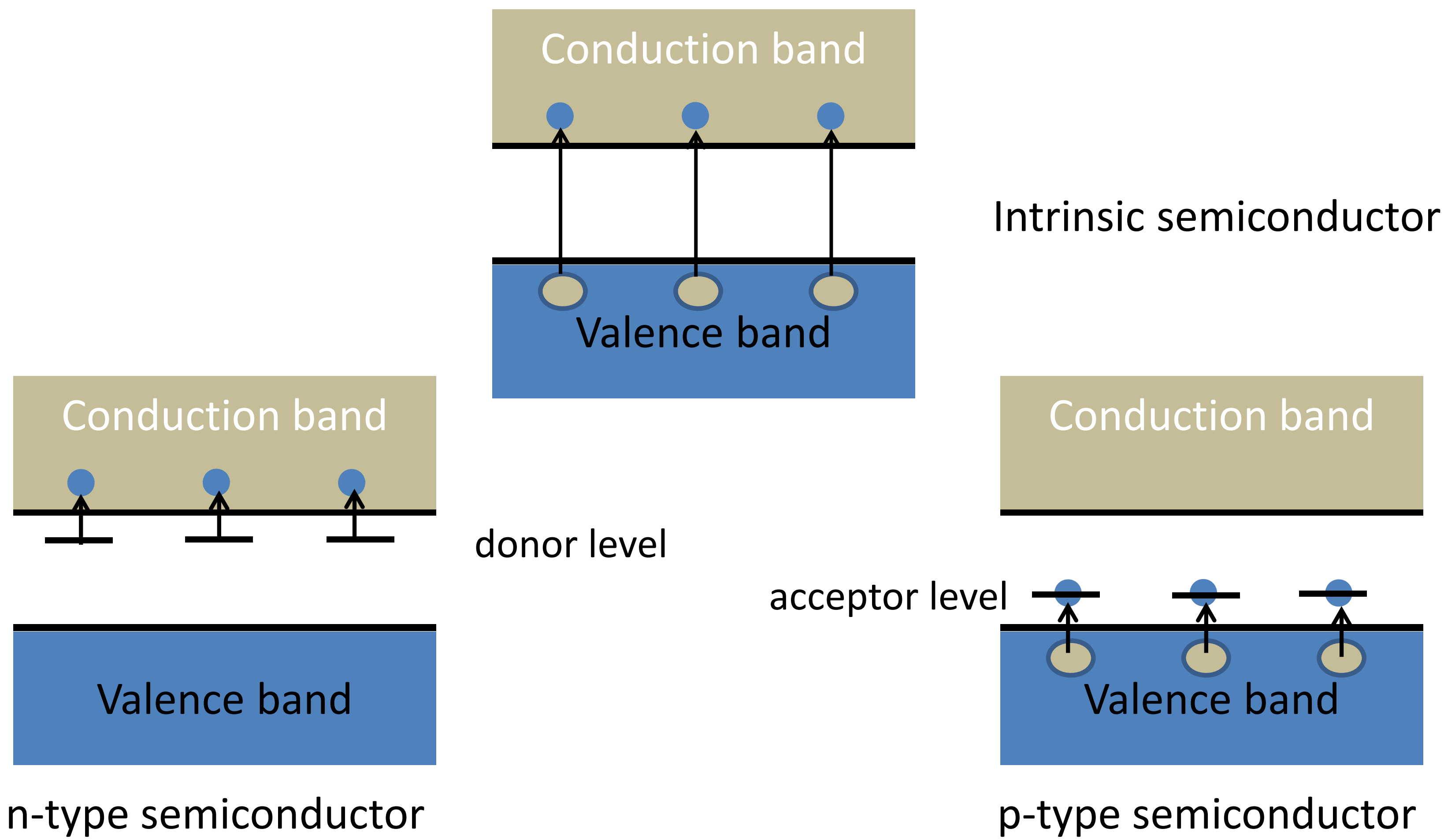
- Group III elements (acceptors)
  - Have one less outer electrons than Si (3 vs. 4)
  - Can accept one electron (donate a hole), and become negatively charged (charge neutrality condition).



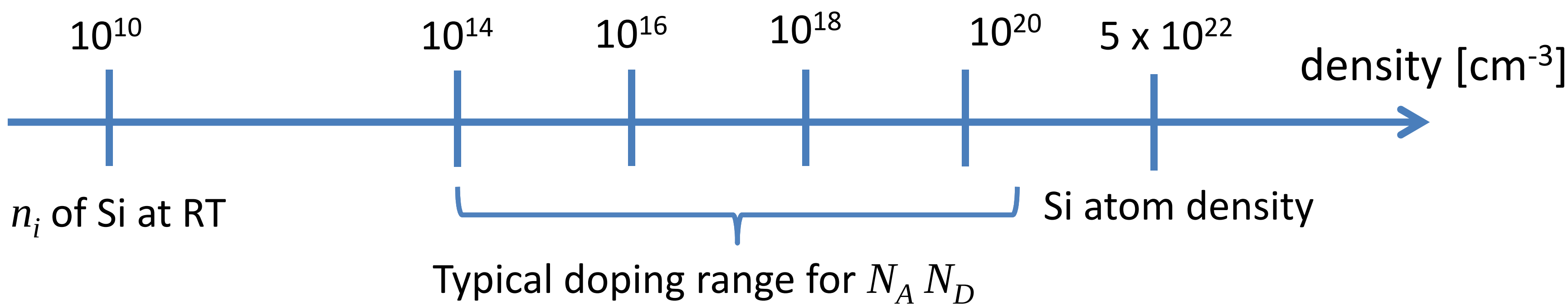
N_A = acceptor density [cm^{-3}] (negative, fixed charge)



Conduction in Intrinsic Silicon



Typical Doping Range



- Typical doping range:
  - Minimal chemical / mechanical changes (trace impurity)
  - Major changes in electrical conductivity

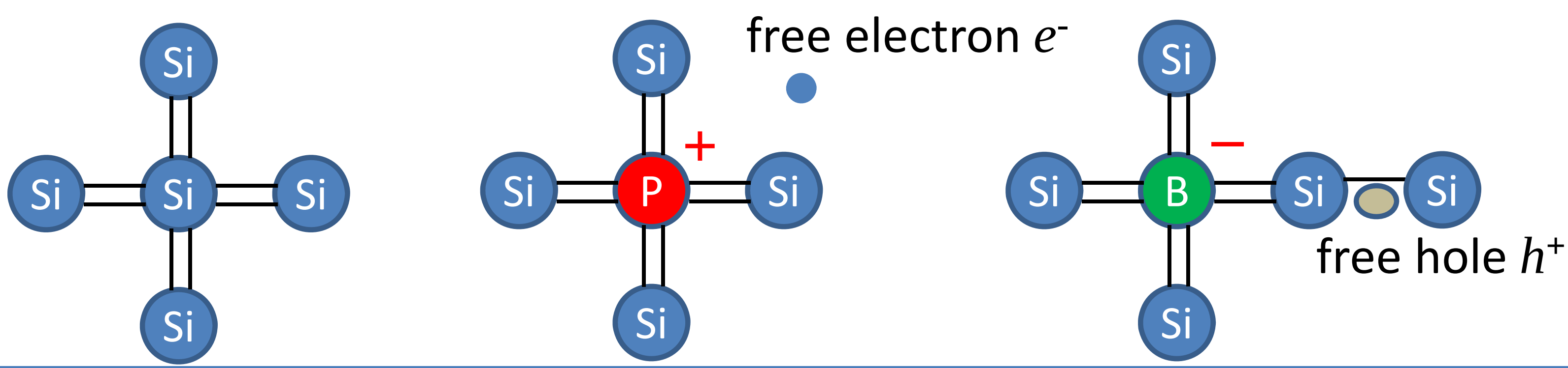
Extrinsic Semiconductors – Carrier Density

- The carrier density (n, p) in extrinsic semiconductors is governed by two laws:
  - Law of Mass Action (equilibrium condition):

$$np = n_i^2$$

  - Charge Neutrality Condition:

$$N_D + p - N_A - n = 0$$



Extrinsic Semiconductors – Carrier Density (*n*-type)

- Silicon doped with donors with density N_D ($N_A = 0$)
  - Solve $np = n_i^2$ and $N_D + p - n = 0$
  - Eliminate p:

$$N_D + \frac{n_i^2}{n} - n = 0 \Longrightarrow n^2 - nN_D - n_i^2 = 0$$

Negative solution tossed out

  - Solve: $n = \frac{N_D + \sqrt{N_D^2 + 4n_i^2}}{2}, p = \frac{n_i^2}{n}$
  - Most of the time: $N_D \gg n_i$, thus $n \cong N_D, p \cong \frac{n_i^2}{N_D} \Rightarrow$ $n \gg n_i \gg p$, the semiconductor is called "*n*-type"
  - Electrons: majority carrier; Holes: minority carrier

Extrinsic Semiconductors – Carrier Density (*p*-type)

- Silicon doped with acceptors with density N_A $(N_D = 0)$
  - Solve $np = n_i^2$ and $p - N_A - n = 0$
  - Eliminate n:

$$p - N_A - \frac{n_i^2}{p} = 0 \Longrightarrow p^2 - pN_A - n_i^2 = 0$$

Negative solution tossed out

  - Solve: $p = \frac{N_A + \sqrt{N_A^2 + 4n_i^2}}{2}, n = \frac{n_i^2}{p}$
  - Most of the time: $N_A \gg n_i$, thus $p \cong N_A, n \cong \frac{n_i^2}{N_A} \Rightarrow$ $p \gg n_i \gg n$, the semiconductor is called "*p*-type"
  - Holes: majority carrier; Electrons: minority carrier