Chapter 1

Semiconductor basics

Basic semiconductor concepts

Outline

- Semiconductor basics
  - Semiconductors, silicon and hole-electron pair
  - Intrinsic silicon properties

- Doped semiconductors
  - n-type and p-type doped semiconductors
  - Doped semiconductor properties

Semiconductor basics

What are semiconductors ?

- Material with properties halfway between a conductor and an insulator

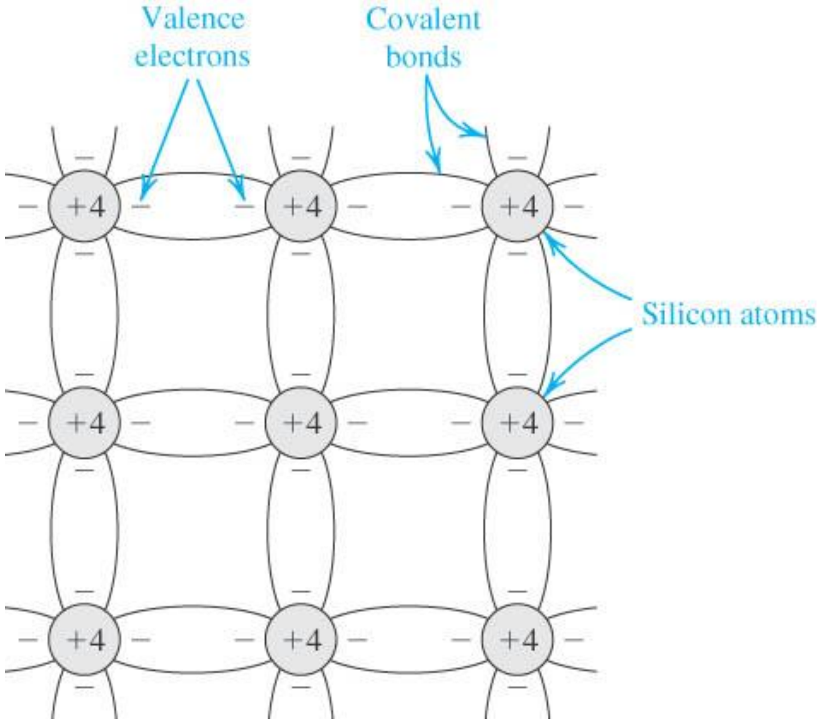
	Metals	Semiconductor	Insulator
Conductivity [$\Omega^{-1}m^{-1}$]	5E+7	1 to 1E+3	1 E-12
Examples	Au, Ag, Cu, Al	Si, Ge, GaAs, SiC, GaN	Glass, ceramic, PVC

- Silicon is by far the most used semiconductor
  - We will use Si throughout this course

Intrinsic silicon

Intrinsic silicon crystal

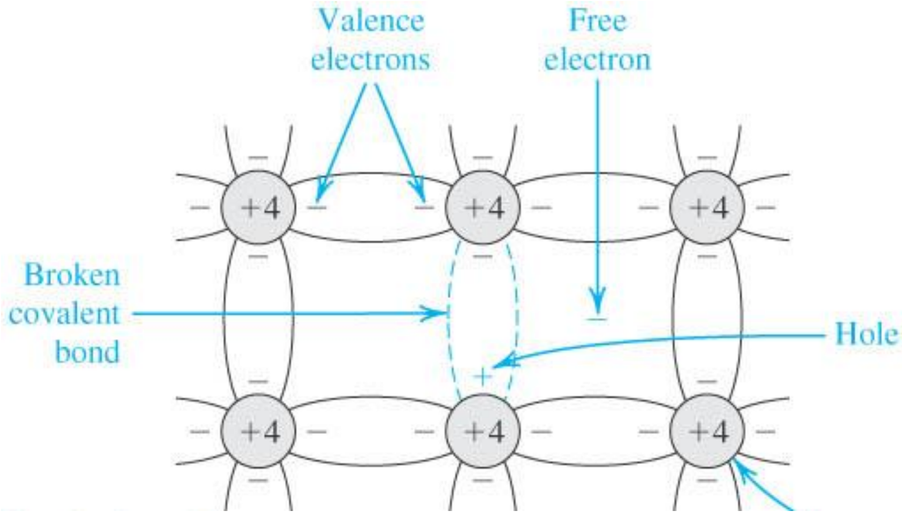
- Crystal has regular lattice structure
- 4 valence electrons / Si atom
- Each atom shares each of its e- with neighbouring atom, creating a covalent bond



Intrinsic silicon

at 300K, thermal ionizations breaks covelent bonds

- Electrons are freed => electron leaves its parent atom
  - Electron will move through the crystal, creating an electric current
- Electron leaves a positive charge, called a ***hole*** ,
  - a hole can be filled by a neighbouring electron
  - neighbouring electron will in turn create a hole
  - the hole will propagate trhough the crystal, creating an electric current



Intrinsic silicon

Bipolar = based on two types of charges

- Thermal ionization creates electron-hole pairs
- Semiconductors have two type of mobile charges carriers
  - Negative: electrons moving throughout the crystal
  - Positive: holes moving throughout the crystal

  => Thermal ionization creates hole-electron pairs

Intrinsic silicon properties

Silicon is neutral

- Concentration of electrons is equal to concentration of holes

  => number of free electrons = number of holes

$$n = p = n_i(T)$$

- Thermal ionization rate is strong function of temperature
  - semiconductor physics shows as that at temperature *T*

$$pn = n_i^2(T) = BT^3 e^{-E_g/kT}$$

Material-dependent parameter
=5.4x 10 E31 for Si

Boltzmann constant = 8.62 x 10E-5 eV/K

Bandgap energy = 1.12 eV for Si

Intrinsic silicon properties

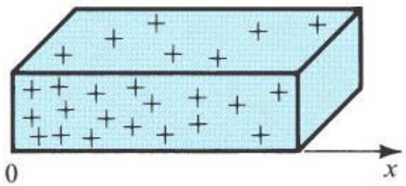
holes and electrons move …

- Two main processes through which electron and holes move: ***diffusion*** and ***drift***
  - Diffusion: random motion of electrons/holes through due to thermal agitation
  - Drift: occurs when electric field is applied accross silicon

Intrinsic silicon properties

Diffusion currents

- Imagine a bar of silicon with non-uniform concentration of holes => generation of an E-field



- Holes will diffuse from left to right => diffusion current

$$J_p = -qD_p \frac{dp}{dx}$$

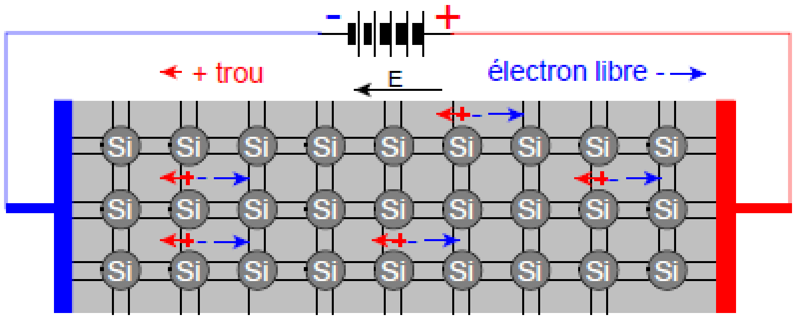
hole diffusion constant
electron charge = 1.6 x 10E-19 C

- Similarly, for electrons: $J_n = -qD_n \frac{dn}{dx}$
- Diffusion constants are nonidentical ! Electrons move about 3x faster than holes: $D_p = 12\ \mathrm{cm}^2/s \quad D_n = 34\ \mathrm{cm}^2/s$
- If Si uniform => random motion does not result in net current

Intrinsic silicon properties

Drift currents

- E-field applied accross piece of silicon



  - holes/electrons will drift in/against direction of E with speed $v_{drift} = \mu_{p/n} E$
  - Current due to holes and electrons

$$J_{p-drift} = qp\mu_p E \qquad J_{n-drift} = qn\mu_n E$$

  - Total drift current: $J_{drift} = q\left(p\mu_p + n\mu_n\right)E$
  - Note that, for intrinsic silicon, mobility of electrons is about 2.5 times higher than the mobility of holes

$$\mu_p = 480\ \mathrm{cm}^2/\mathrm{Vs}$$
$$\mu_n = 1350\ \mathrm{cm}^2/\mathrm{Vs}$$

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  - n-type and p-type doped semiconductors
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Doped semiconductors

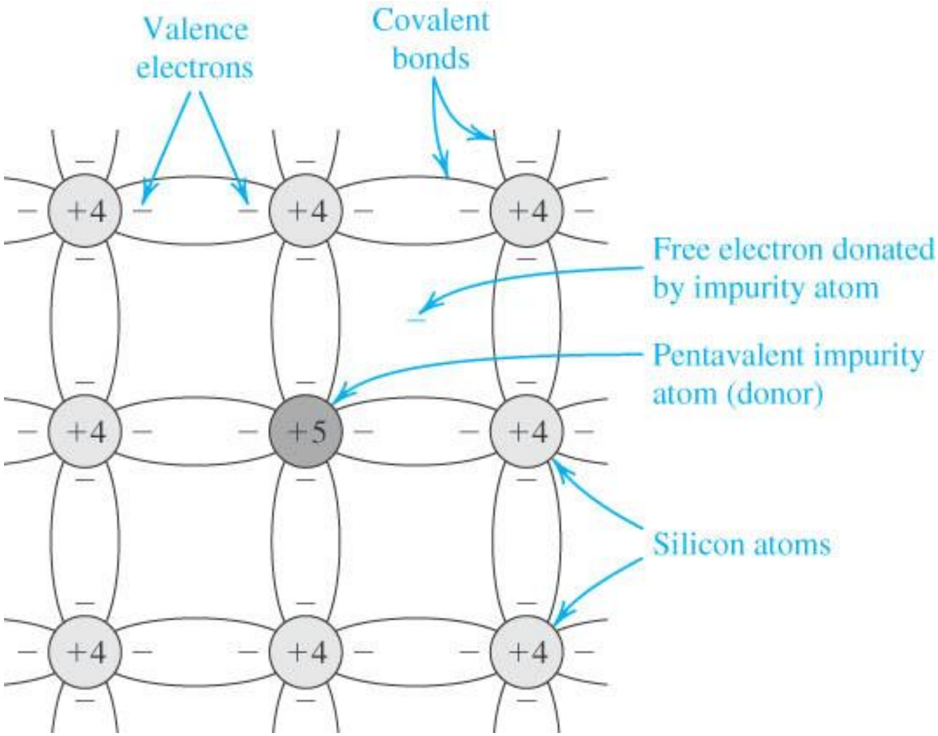
What are doped semiconductors ?

- Intrinsic silicon has equal number of positive and negative carriers
- Doped semiconductors are materials in which one kind of carrier predominate
  - **n-type**: negatively charged electrons are the majority of charge carriers
  - **p-type**: positively charged holes are the majority of charge carriers
- Doping a Si crystal is achieved by introducing a small number of impurity atoms

Doped semiconductors

n-type semiconductor

- Pentavalent atoms are introduced in the Si crystal (P, As, Sb)
  - Five valence electrons => four electrons form covalent bondes, fifth elecron becomes a free electron
  - Each pentavalent atom donates a free electron => ***donor***



Doped semiconductors

n-type semiconductor

- No holes are created in the doping process !
  - Electrons become the majority of charge carriers
  - If number of pentavalent atoms N_d >> number of free electrons in Si

$$n \approx N_d$$

  - Thermal equilibrium relationship is still valid:

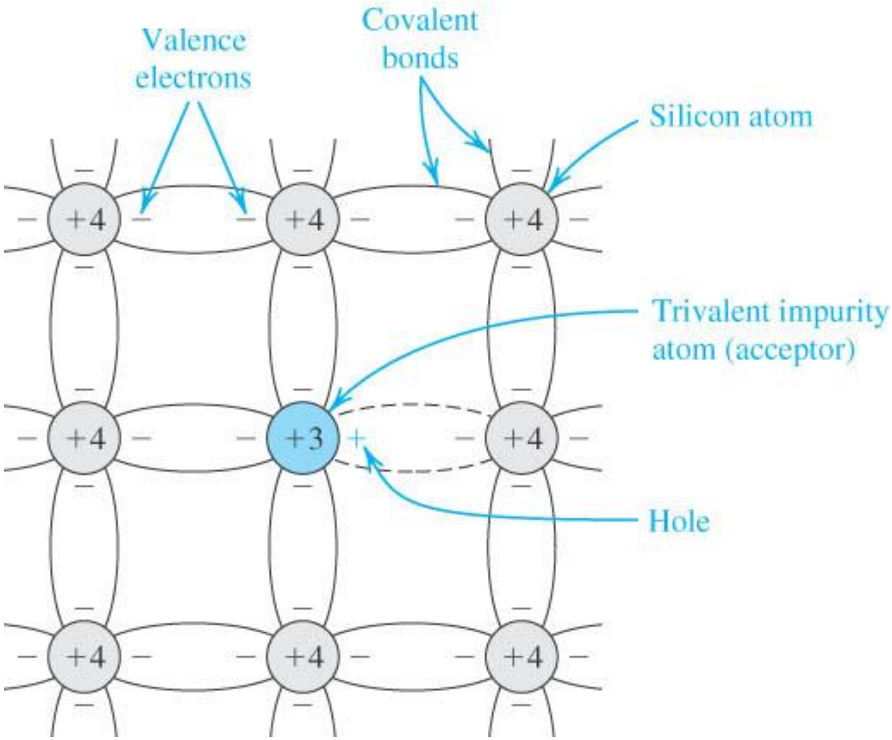
$$pn = n_i^2(T)$$
$$\Leftrightarrow p \approx \frac{n_i^2(T)}{N_d}$$

- Two types of carriers
  - **Majority** of electrons, independent of temperature
  - **Minority** of holes, function of temperature

Doped semiconductors

Similarly, for p-type semiconductors…

- Trivalent impurity introduced in Si cristal (Al, B, Ga)
  - Each trivalent atom accepts an additional electron => ***acceptor***
  - This creates a new hole => majority carriers are the holes
    => minority carriers are the electrons



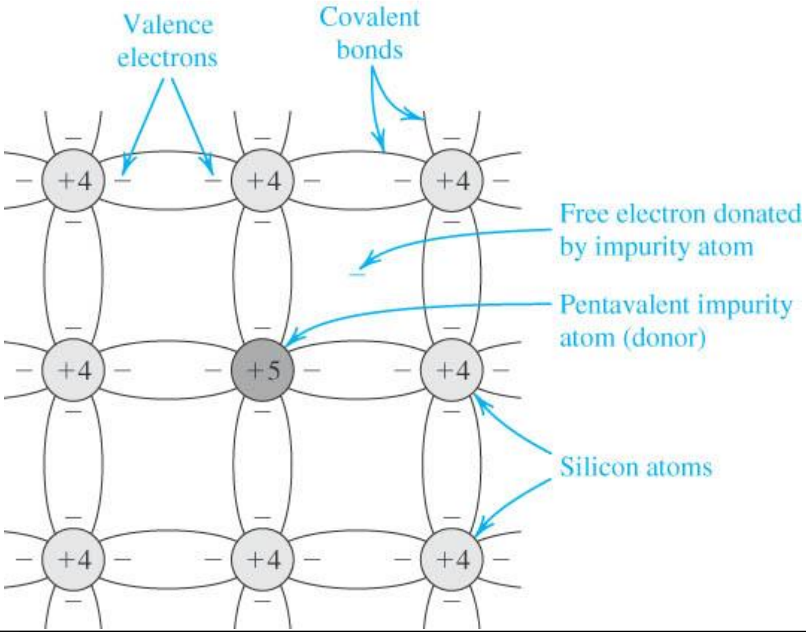
$$p \approx N_a$$
$$pn = n_i^2(T)$$
$$\Leftrightarrow n \approx \frac{n_i^2(T)}{N_a}$$

Doped semiconductors

Both n-type and p-type semiconductors …

… are electrically ***neutral*** !!!

The majority of free carriers (electrons or holes) are neutralized by bound charges (ions) associated with the impurity atoms



=> Extra electron is compensated electrically by the +5 charge of the donor atom

Doped semiconductors

… are limited by temperature

- Above a certain temperature (200°C)
  - n_i becomes larger than N_a or N_d $\boxed{pn = n_i^2(T) = BT^3 e^{-E_g/kT}}$
  - Si becomes intrinsic again, no more n- or p-type doping properties
  - All properties obtained by doping are lost
- At very low temperature, p or n are too low for the semiconductor to be used
- Usual range for components
  - Standard: 0 to 70°C
  - Industrial: -40°C to 85°C
  - Military, spatial: -55°C to 125°C
- Out-of-range temperature might require extra heating or cooling of the circuits and equipment

Conclusions

Summary table

	Intrinsic Si		N-type		P-type	
	Type	Conc.	Type	Conc.	Type	Conc.
dopant	----	-----	Donor	N_d	Acceptor	N_a
+ mob.charges	Holes	$p=n_i$	Holes (min.)	$p=n_i^2/N_d$	Holes (maj.)	$p=N_a$
- mob. charges	Electrons	$n=n_i$	Electr. (maj.)	$n=N_d$	Electr. (min)	$n=n_i^2/N_a$
Fixed charges	----	----	Ions +	N_d	Ions-	N_a

N-type: majority carriers are electrons, but still some minority holes due to thermal ionization. Positive ions appear in the crystal.

P-type: majority carriers are holes, but still some minority electrons due to thermal ionization. Negative ions appear in the crystal.