Lecture 2

of

EEE201

CMOS Digital Integrated Circuits

Department of Electrical & **Electronic Engineering**

Xi'an Jiaotong-Liverpool University (XJTLU)

Monday, 16th September 2024

- **Properties of Silicon**
  - semiconductor crystal
  - energy band diagram
    - **conduction** & **valence bands**
  - doping to make ***n***-type or ***p***-type
  - **charge carriers** & carrier transport

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Digital ICs on Silicon CMOS
(silicon semiconductor)

- Digital ICs are predominantly fabricated on **silicon** wafers, using **CMOS** technology in particular.

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

- Silicon is a group IV element in the Periodic Table (in the 3rd row $\Rightarrow$ what does this tell?)
- Each silicon atom has in its **outmost shell** four **electrons** (or called **valence electrons**).
- Silicon is an ***elemental*** semiconductor.
- $1s^2 2s^2 2p^6 3s^2 3p^2$ & atomic number 14

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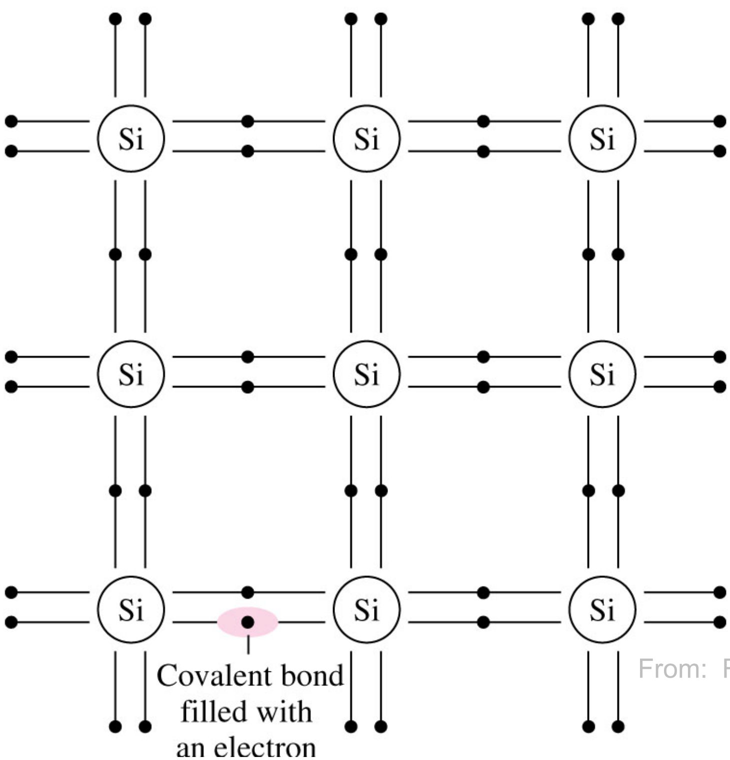
From: R. C. Jaeger & T. N. Blalock, *Microelectronic Circuit Design*, 4e, © 2010 McGraw-Hill, USA.

Silicon Semiconductor
(arrangements of atoms)

- Silicon of very high purity with the almost perfect ***crystalline* structure** is needed for making digital ICs like microprocessors. ⇒ high material cost



- By ***crystalline* structure** or simply called **crystal**, it means that the atoms forms chemical bonds with each other in a ***periodic*** arrangement in **space**.
- In ***crystalline*** silicon, each atom forms covalent bonds with four other neighbouring atoms.

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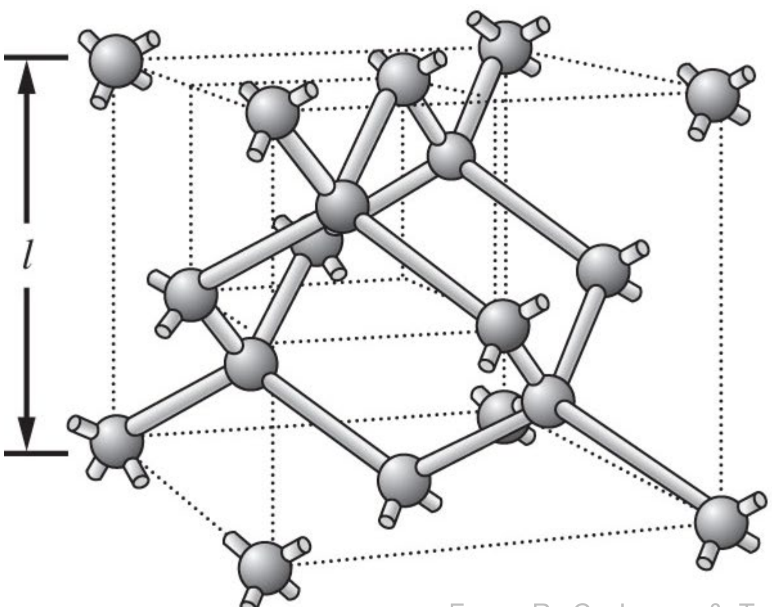
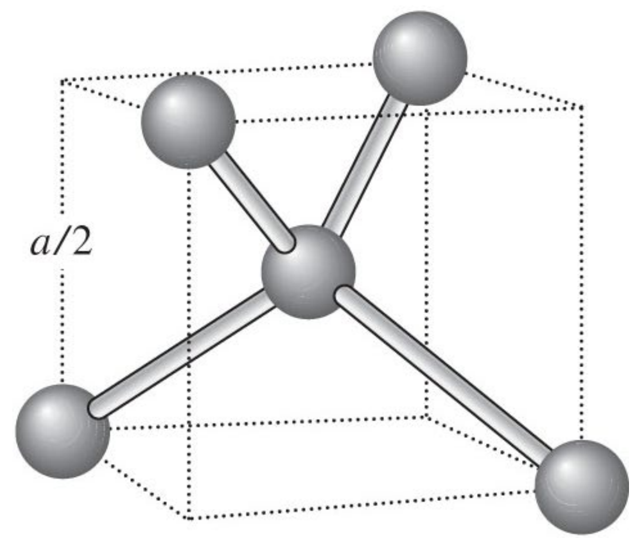
Silicon Semiconductor

(crystal structure)

- ***Crystalline*** silicon semiconductor has a diamond crystal structure.
  - 3-dimensional lattice & representation by a unit cell





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  - **lattice constant *a***

Silicon Semiconductor

(energy levels of single atoms)

- According to **quantum mechanics**, ***discrete* energy levels** exist in an atom for electrons surrounding the nucleus of the atoms.

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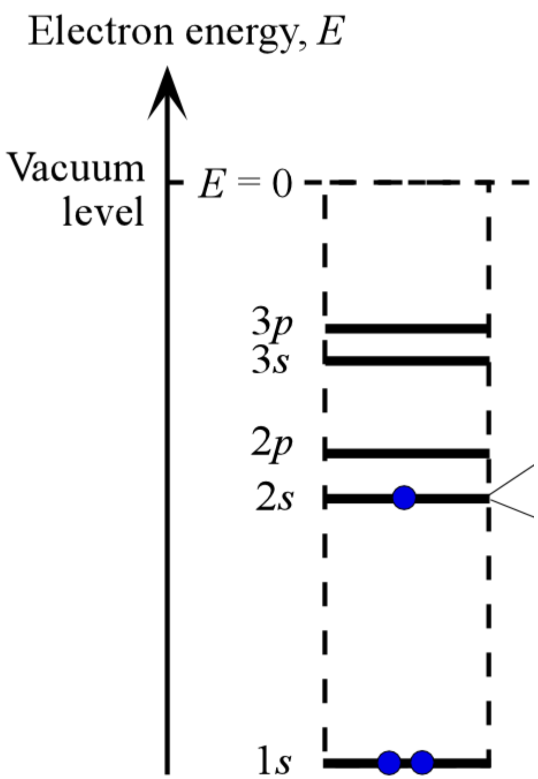

- Electrons tend to occupy the available states of lowest energy levels.
- With the diagram shown here, the state of the lowest energy level is labelled 1s which can allow occupancy of two electrons at most.
- At the energy level of 2p or 3p, only six electrons can be allowed at maximum.
- Silicon's case?

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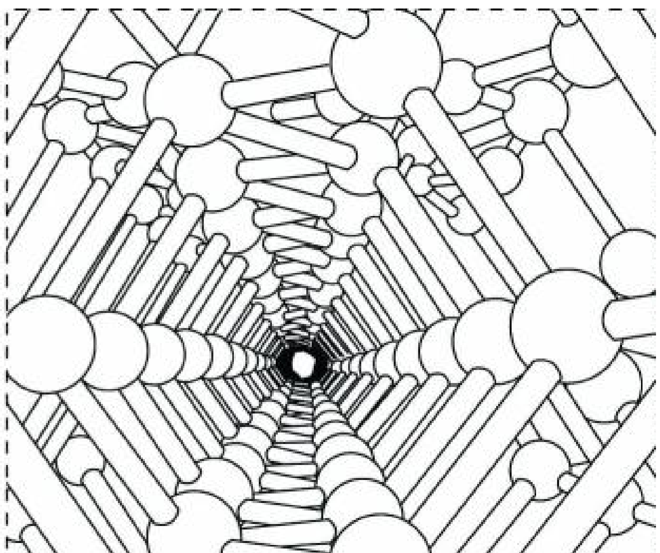
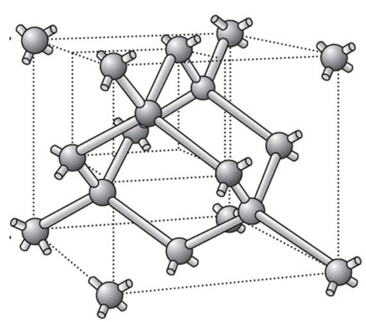
Silicon Semiconductor

(energy levels of atoms in a crystal)

- In a single atom, the energy levels for its electrons are ***discrete***.
- In the case of a large number of atoms but ***isolated*** (i.e. no interaction with each other), the energy levels for the electrons are still ***discrete***.





- What happens to the energy levels when the atoms are brought together as a crystal?

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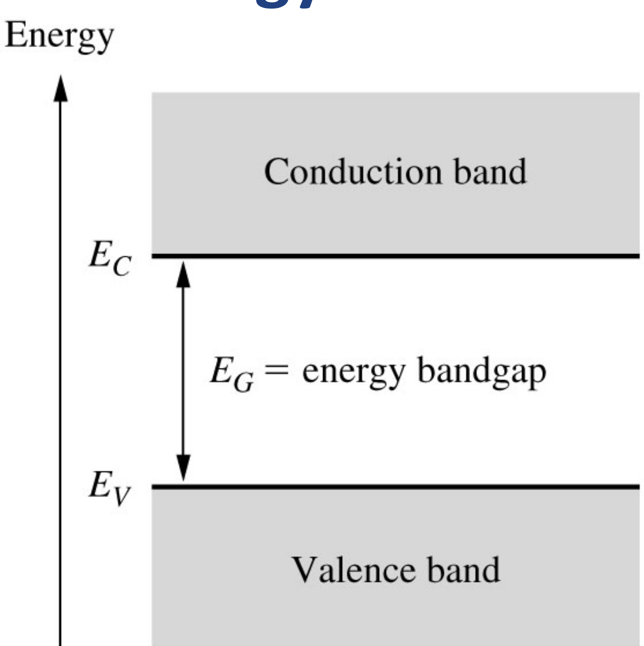
Silicon Semiconductor

(formation of energy bands)

- In a silicon crystal, there are about 10^{23} atoms forming chemical bonds with each other.
- The discrete energy levels are combined to form **energy bands**.



10^{23} atoms in a **crystal**

$\times 10^{23}$

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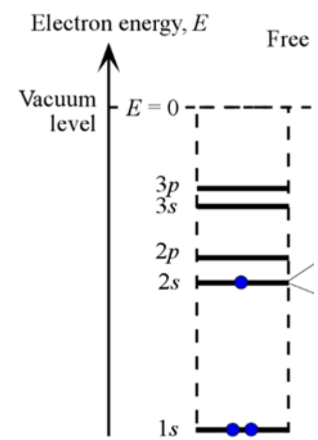

10^{23} isolated atoms

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Silicon Semiconductor
(electron energy & momemtum)

- Note that the **energy bands** are for **electrons** which are *negatively* charged.
  - going up means higher energy for electrons (but lower energy for holes which are positively charged)
- The energy can be a function of space (i.e. position in the semiconductor) and also the **momentum** of the electron.
  - momentum of an electron: $\boldsymbol{p} = hk/(2\pi)$

Planck's constant
$h = 6.63\times10^{-34}$ Js

- In the electronic engineering field, energy bands with position as the horizontal axis are typically used.

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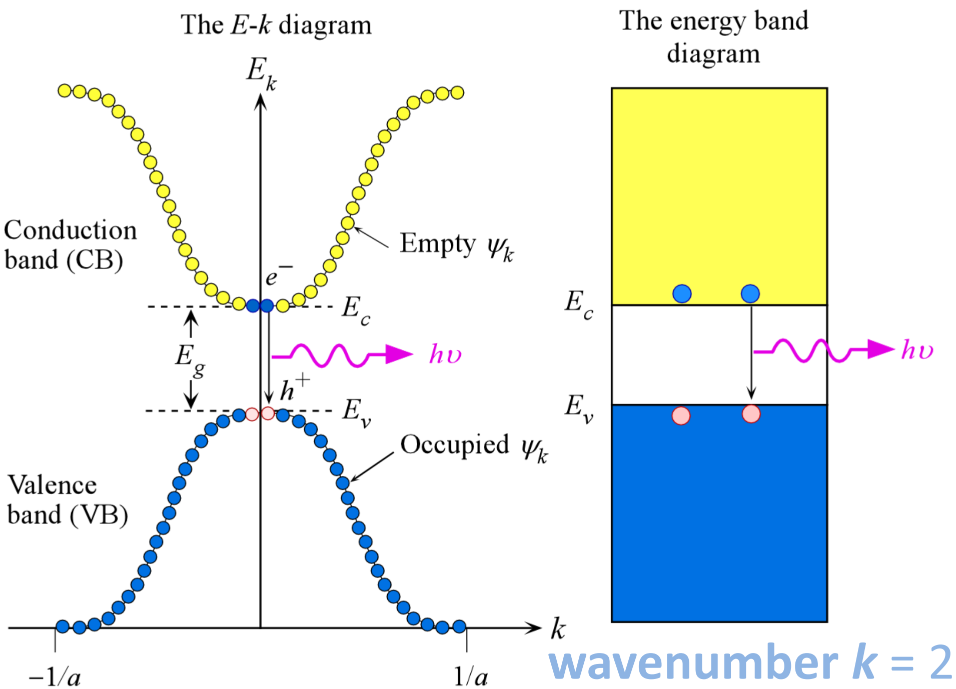
Silicon Semiconductor

(*E*-*k* diagram)

- The variation of the energy as a function of the momentum of electron is not a concern unless there is interaction of light with electrons (in semiconductor).
  - In semiconductor optoelectronics/photonics, electrons can transit between energy bands and the electron momentum would need to be considered.
  - The momentum ***p*** is directly proportional to ***k***. $\Rightarrow$ ***E***-*k* diagram



wavenumber $k = 2\pi/\lambda$

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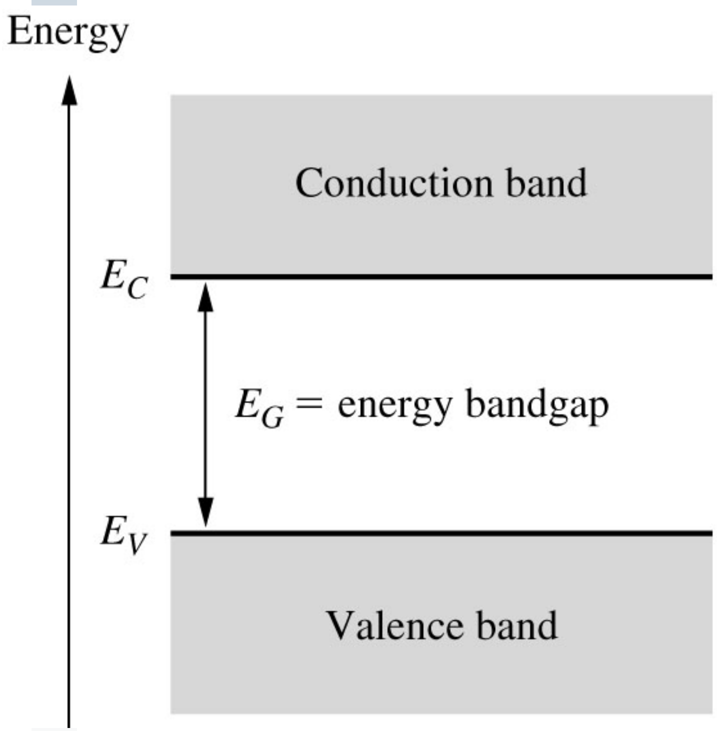
Silicon Semiconductor

(energy band diagram)

- **Energy band diagrams** are essential to understand the electronic properties of semiconductors (including silicon).



- A typical **energy band diagram** for a semiconductor consists of a **conduction band** at the top and a valence band at the bottom with a **band gap** in between the two bands.

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Silicon Semiconductor

(conduction band)

- The **conduction band** has mostly vacant states i.e. the band is only partially occupied by electrons.

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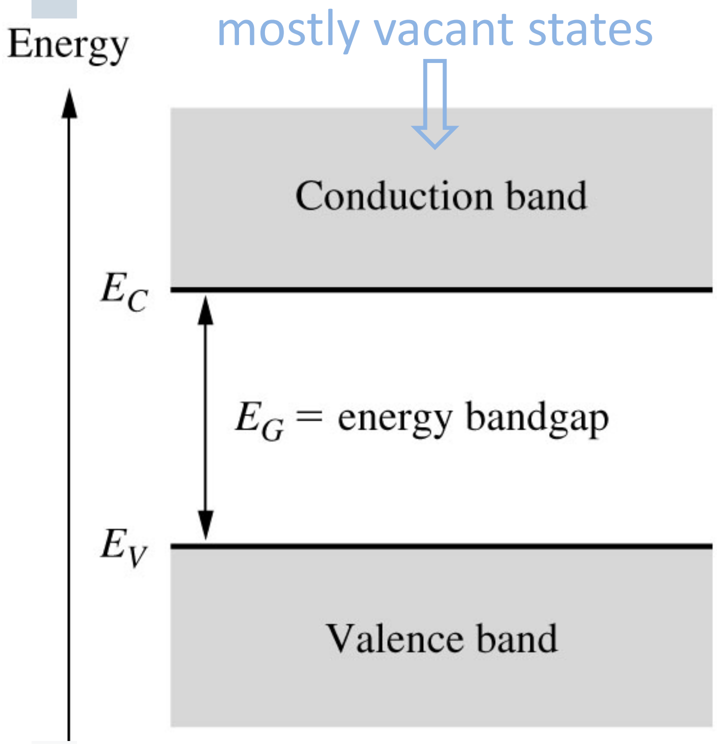

- At temperature above 0 K, **electrons** in the conduction band can freely move around from one vacancy to another.
- Note that the horizontal axis of the energy band diagram here represents position.

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(valence band)

- The **valence band** has almost all the states filled by electrons, with only some vacancies left.

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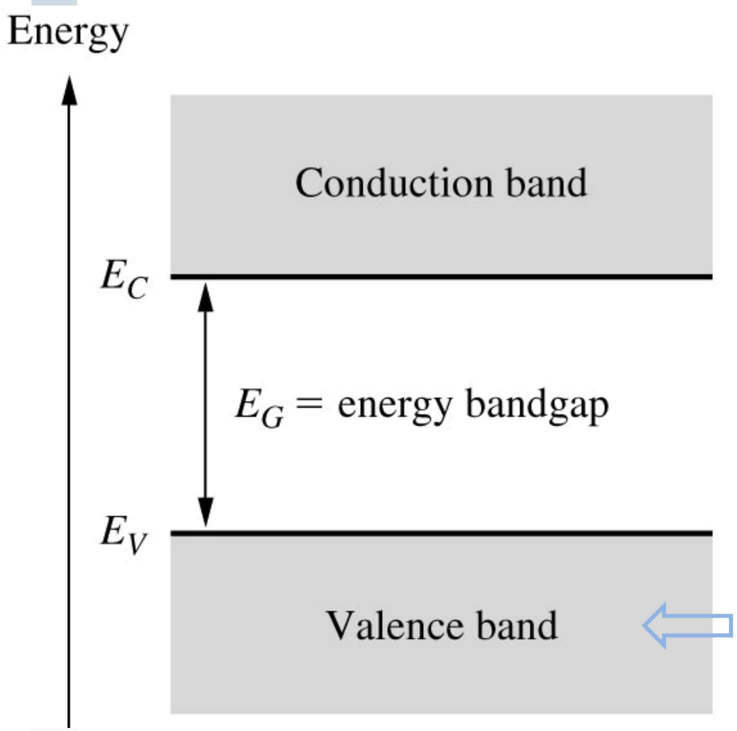


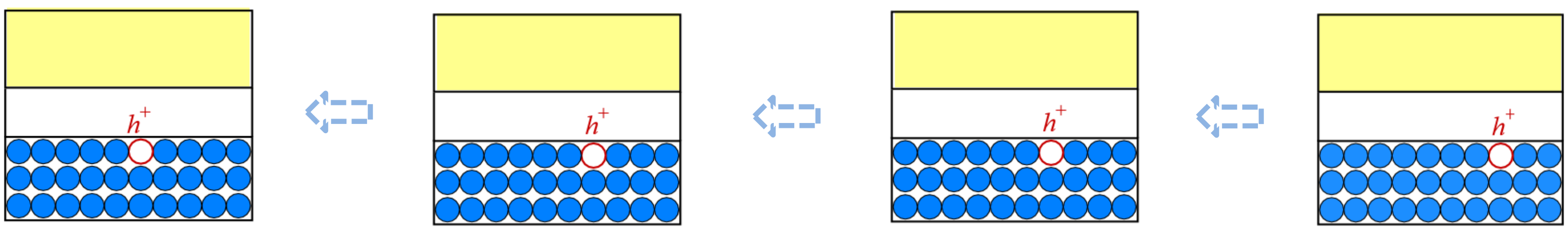
states mostly filled by electrons

- When the **electrons** around the vacancies move to fill up the vacant states, it is as if the vacancies move in position.
- The vacancies in the valence band are called **holes**.

Silicon Semiconductor

(hole motion in valence band)

- While **electrons** carry **negative charge**, the **vacancies** in the **valence band** behave as if electrons are missing at certain positions.



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- As a result, the movement of electrons filling up the small number of **vacancies** in the **valence band** behaves as if vacancies carry positive charge.

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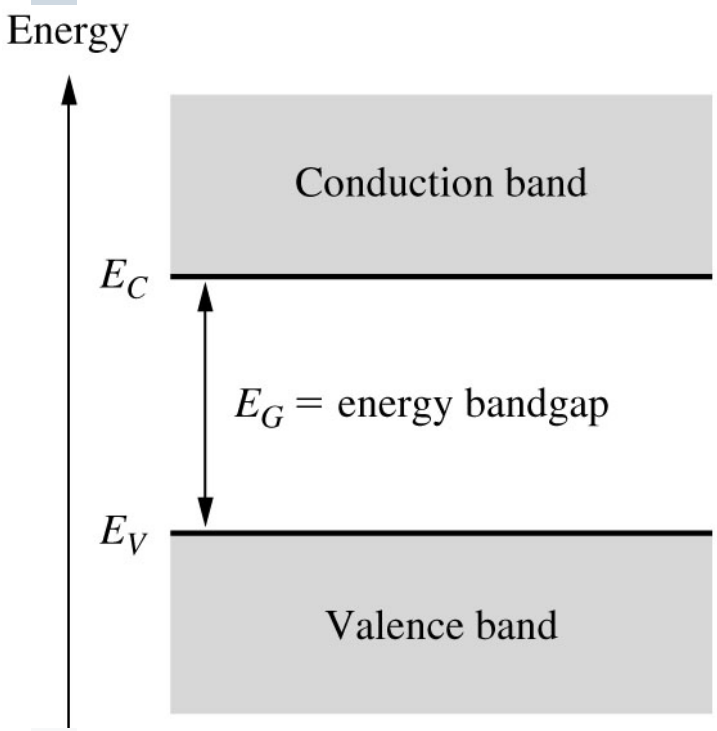
Silicon Semiconductor

(charge carriers)

- The **electrons** are the ***negative* charge carriers** in the **conduction band** while **holes** the ***positive* charge carriers** in the **valence band**.



- Both types of **charge carriers** can contribute to an electrical current in semiconductor.
  - Note that we are not interested in the holes (i.e. vacancies) in the conduction band and electrons in the valence band.

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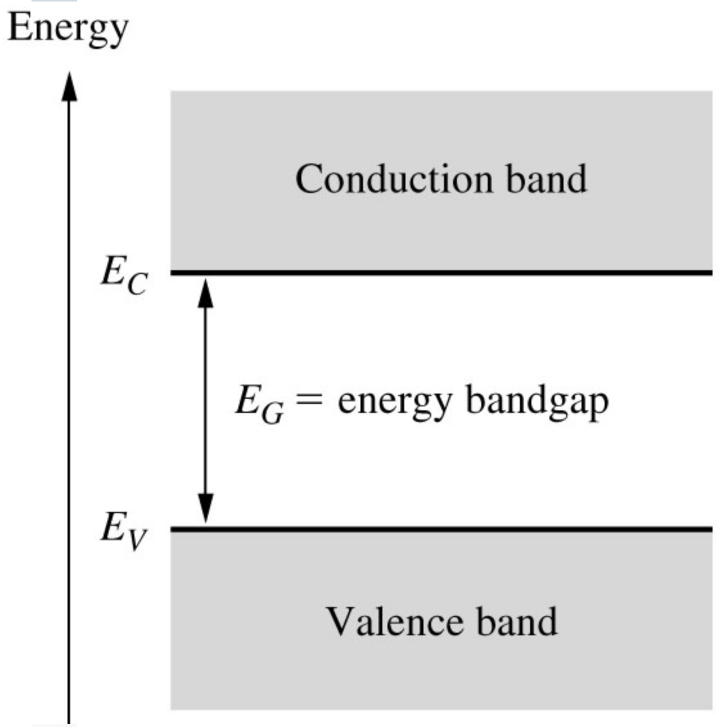
Silicon Semiconductor
(energy bandgap)

- Between the **conduction band** and the **valence band**, there is a span of energy range in which there are no states for electrons.



- It is called the **energy band-gap** of the semiconductor. Usually, no electrons exist in the bandgap.
  - In silicon, the energy bandgap is about 1.1 eV (i.e. 1.76×10^{-19} J) at room temperature.

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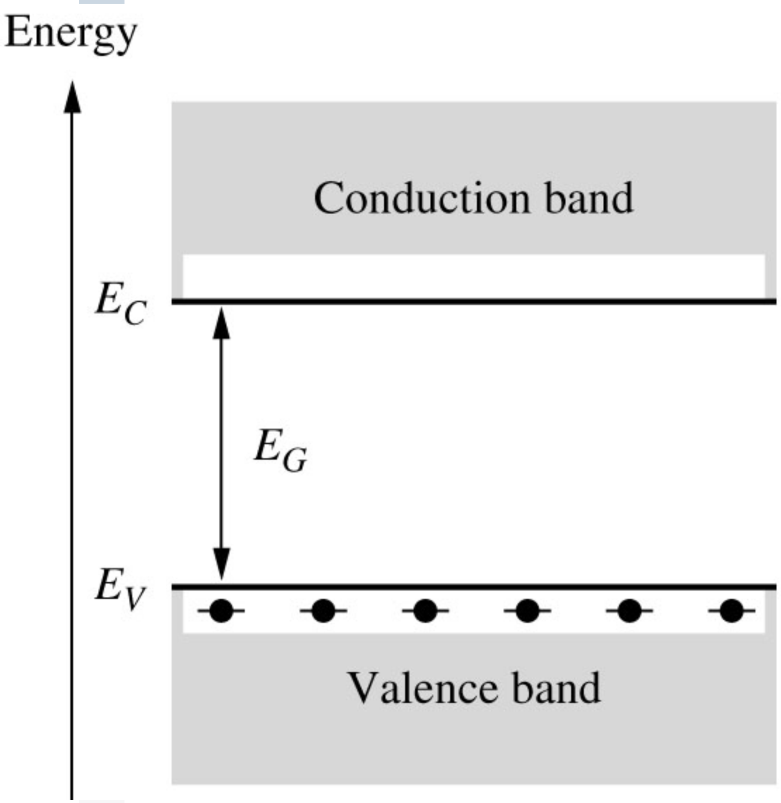
Silicon Semiconductor

(no charge carriers at 0 K)

- At the absolute temperature of 0 K, all electrons will occupy states of the lowest energy state.



- In semiconductor, it means the valence band is completely occupied by electrons and the conduction band has all states vacant.
  - There are neither electrons in the conduction band nor holes in the valence band.
  - implication?

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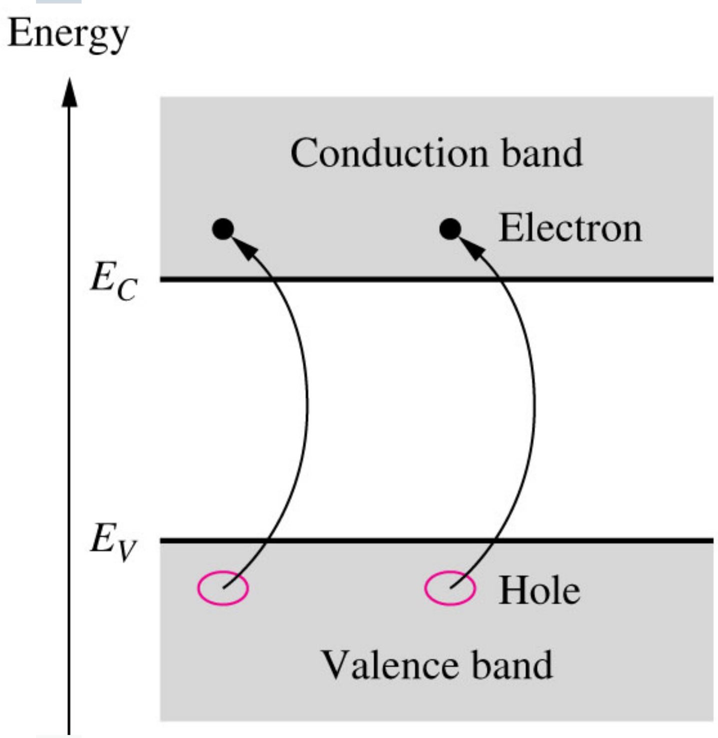
Silicon Semiconductor
(influence of thermal energy)

- At temperature T > 0 K, some electrons in the valence band can gain enough energy to overcome the bandgap and get to the conduction band.



- At T = 300 K (room temperature) for example, some electrons are in the conduction band and some holes in the valence band.
  - Note the equal number of electrons and holes in this case.
  - Why?

Silicon Semiconductor

(electrical conduction)

- The **electrical properties** of semiconductor is determined by the number of electrons and holes as the charge carriers, respectively in the conduction band and valence band.
- The number of ***negative*** **charge carriers** (i.e. electrons) per unit volume is usually denoted by ***n*** while ***positive*** **charge carriers** (i.e. holes) by ***p***.
- If we can control ***n*** and/or ***p***, we can control the electrical properties of semiconductor.
  - control by the temperature?
  - conduction at T = 0 K, 87 K, 300 K?

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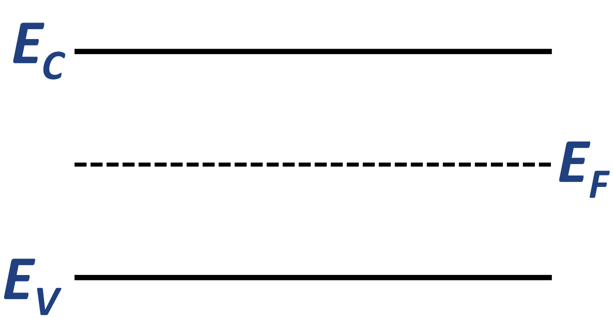
Silicon Semiconductor

(energy band edges)

- In drawing the **energy band diagram**, it can be simplified to a few lines:
  - an upper horizontal straight line labelled E_C which represents the *band edge* of the **conduction band**;
  - a lower horizontal straight line labelled E_V which represents the *band edge* of the **valence band**.
  - Usually, a third horizontal straight line labelled E_F (called **Fermi level**) may be drawn, which is in the bandgap.



  - Its vertical location indirectly indicates the relative number of electrons (in the conduction band) and holes.

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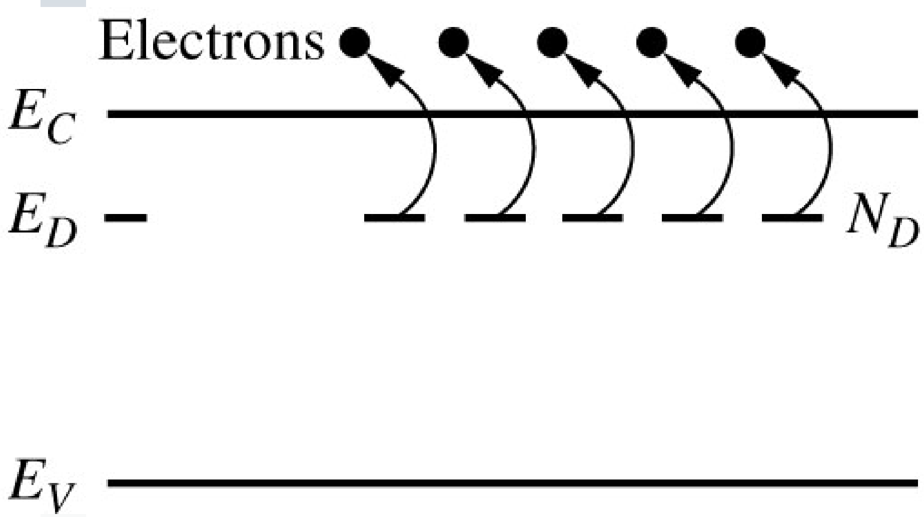
Silicon Semiconductor

(creating states in the bandgap)

- The **charge carrier concentration** (***n*** or ***p***) can be engineered by a process called **doping**.
- By doping a semiconductor, a small amount of a selected impurity element is introduced to the semiconductor.



- With silicon as the group IV element, the impurity elements are usually either from group III or V.
- Examples are phosphorous & boron.

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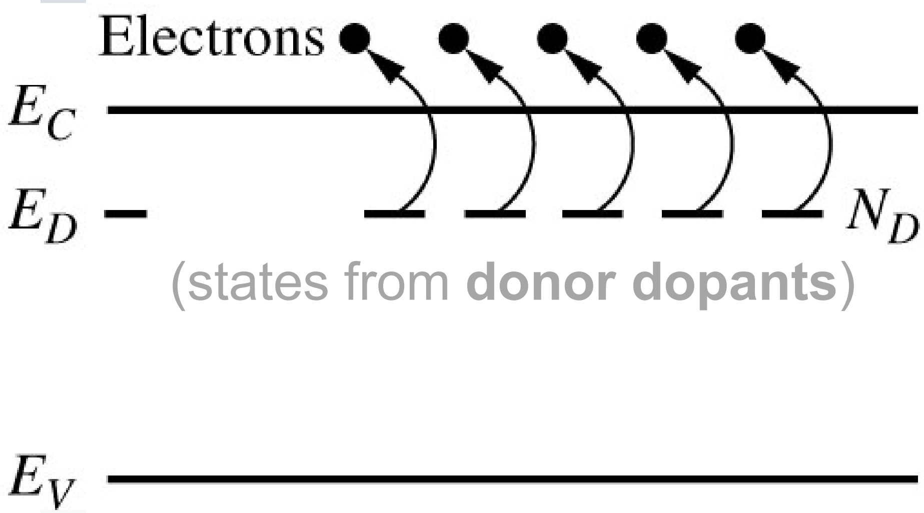
Silicon Semiconductor

(doping by donor dopants)

- By **doping**, it effectively creates some states (with electrons) in the bandgap (in the band diagram).
  - The impurity element used for doping is called the **dopant**.
  - The dopant is usually selected such that that it creates states close to either of the band edges (***E**$_C$* or ***E**$_V$*).



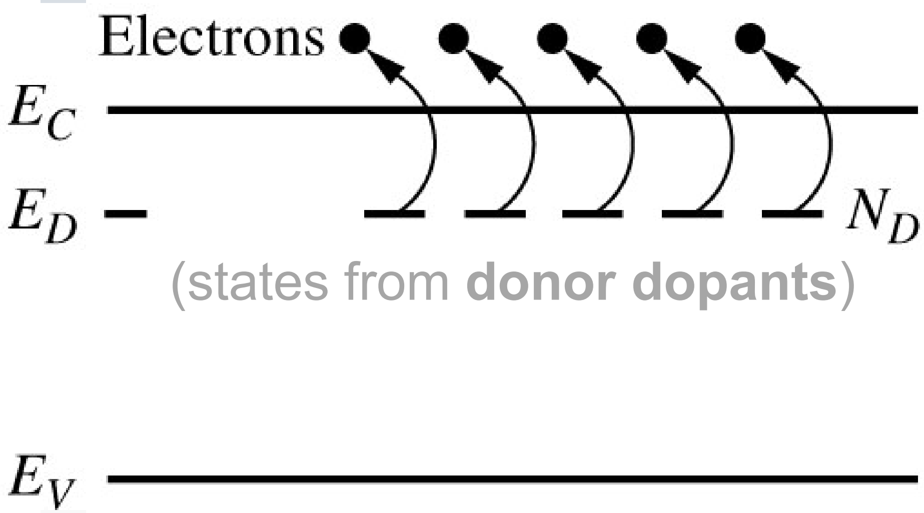
(states from **donor dopants**)

- In silicon, doping with phosphorous (P) will create some states at an energy level close to ***E**$_C$*.

Silicon Semiconductor

(doping by donor dopants)

- With states at energy level E_D close to E_C, electrons in the created states can gain thermal energy and get to the conduction band.
  - Once the excited electrons get to the conduction band, they can move around quite freely.

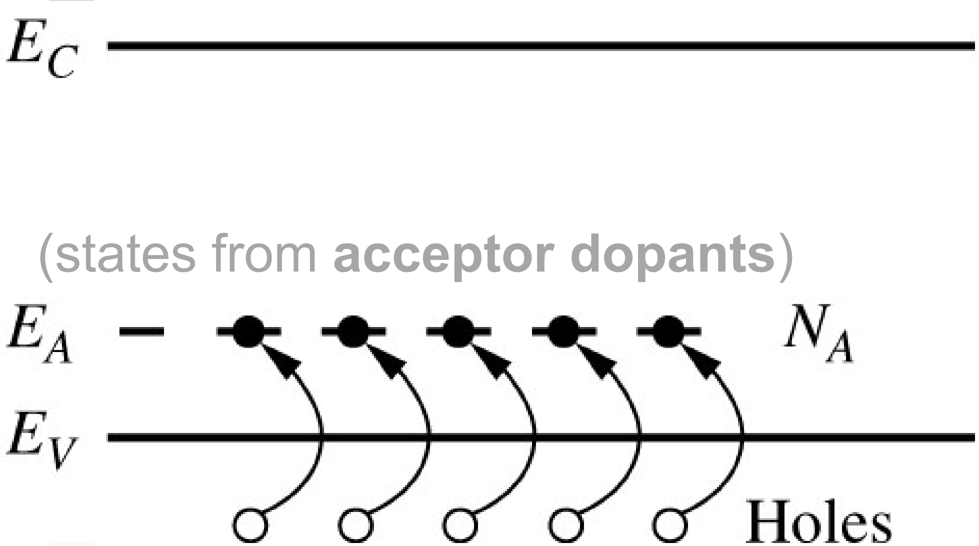


- This increases the number of electrons in the conduction band.
- $\Rightarrow$ ***n*** is made larger (typically 10^5 times or more).

Silicon Semiconductor

(doping by acceptor dopants)

- The electrical conduction can also be improved by doping a small amount of impurity element that creates <u>vacant</u> states at an energy level close to $\boldsymbol{E_V}$.
  - The dopant in this case is called the **acceptor dopant**.
  - Electrons in valence band can gain thermal energy and get to the created states to fill up the vacancies.



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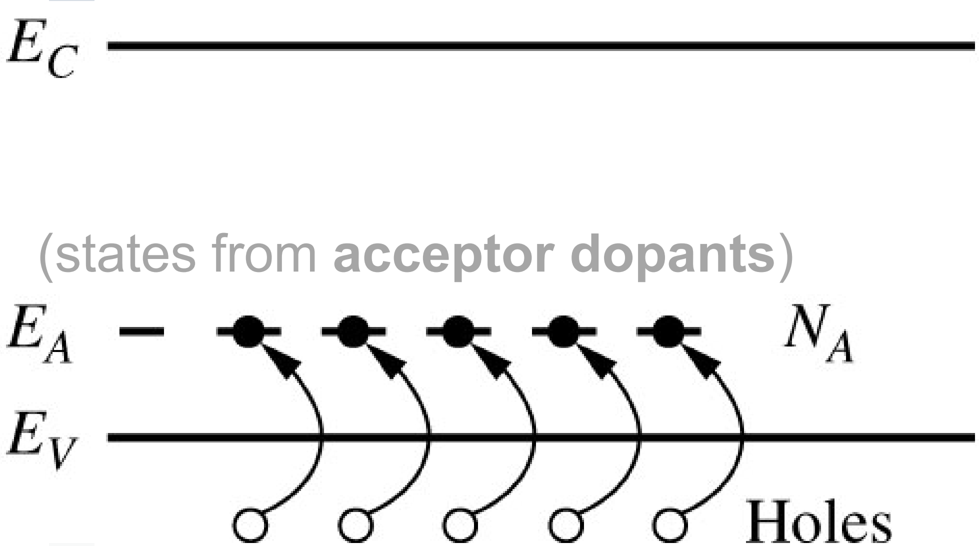
Silicon Semiconductor

(doping by acceptor dopants)

- ❑ As the excited electrons fill up the vacancies in the created states in the bandgap, they cannot move around, because the states are relatively small in number and fixed in space.
- ❑ However, **holes** are created in the **valence band**.



- ➢ The holes can move around in the valence band.
- ➢ $\Rightarrow$ ***p*** is made larger (10^5 times or more).

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Intrinsic & Doped Silicon

(electron & hole concentrations)

- In **intrinsic** semiconductor (i.e. literally without doping), the electrons in the conduction band are equal in number of the holes in the valence band.
  - $\boldsymbol{n = p = n_i}$ (with the subscript *i* for intrinsic)
  - In silicon, $n_i = 10^{10}$ cm^{-3} at room temperature.
  - If silicon is doped by a donor dopant (e.g. phosphorous) with a dopant concentration N_D, $n \approx N_D$ at room temperature.
  - If silicon is doped by an acceptor dopant (e.g. boron) with a dopant concentration N_A, $p \approx N_A$ at room temperature.
  - Typical N_D and N_A can be 10^{15} cm^{-3} up to 10^{20} cm^{-3}.

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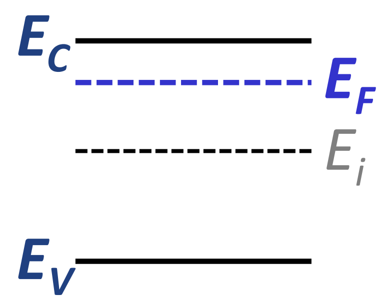
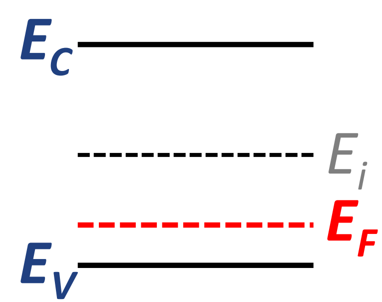
Doped Semiconductor

(relative positions of E_F)

- If silicon is doped by a donor dopant of a concentration N_D, $n \approx N_D$ at room temperature.
  $\Rightarrow$ more electrons in the conduction band
  $\Rightarrow$ E_F is at a vertical position closer to E_C.
  - The doped silicon is called an ***n*-type semiconductor**.



- If silicon is doped by an acceptor dopant of a concentration N_A, $p \approx N_A$ at room temperature.
  $\Rightarrow$ more holes in the valence band
  $\Rightarrow$ E_F is at a vertical position closer to E_V.
  - The doped silicon is called a ***p*-type semiconductor**.



Electron & Hole Concentrations

(mass action law)

$$np = n_i^2 = N_C N_V \exp\left(-\frac{E_g}{k_B T}\right)$$

- The product of electron concentration and hole concentration, ***np***, is a "constant", $\boldsymbol{n_i^2}$, which depends on the material properties $\boldsymbol{N_c}$, $\boldsymbol{N_v}$, $\boldsymbol{E_g}$, and the temperature.
- If somehow ***n*** is increased (e.g. by doping), ***p*** must decrease to keep ***np*** "constant".
- This is known as **mass action law** which applies in **thermal equilibrium** and in the dark (i.e. no illumination).

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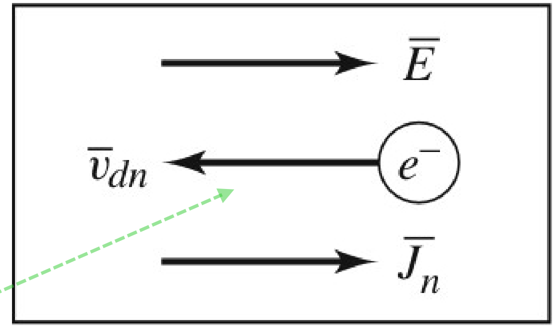
Drift Current

(different drift but same current direction)

- There are two basic processes which cause electrons and holes to move in a semiconductor: **drift** and **diffusion**.
- Electrons and holes flow in opposite directions when under the influence of an **electric field** at different velocities
  - resulting in **drift currents**
- The **drift currents** associated with electrons and holes are in the same direction.

n-type



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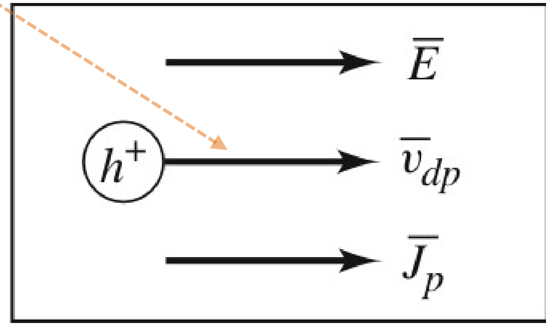
p-type



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Drift Current

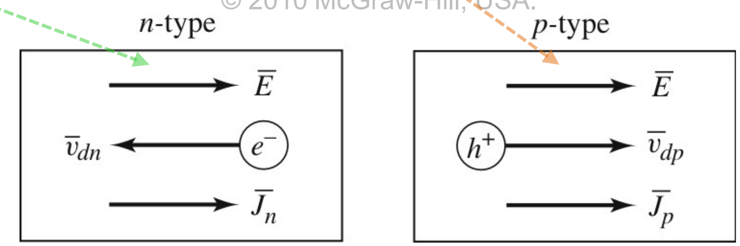
(conductivity & carrier concentration)

$$v_{dn} = -\mu_n E \qquad v_{dp} = \mu_p E$$

v_{dn} = **drift velocity** of the electrons;
μ_n = electron drift mobility;
$\boldsymbol{E}$ = applied electric field;
v_{dp} = drift velocity of holes;
μ_p = hole drift mobility;

$$\boxed{\sigma = en\mu_n + ep\mu_p}$$

From: Donald A. Neamen, *Microelectronics: Circuit Analysis & Design*, 4th edition, © 2010 McGraw-Hill, USA.



(a) (b)

$$J_n = -env_{dn} = en\mu_n E \qquad J_p = epv_{dp} = ep\mu_p E$$

σ = **conductivity**; e = electronic charge (1.60×10^{-19} C);
n = concentration of free electrons;
p = concentration of free holes;

$$\boxed{J = \sigma E = (1/\rho)E}$$

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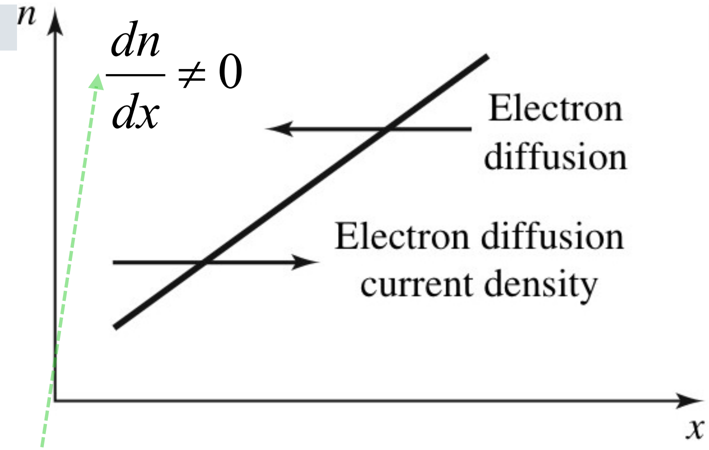
Diffusion Current

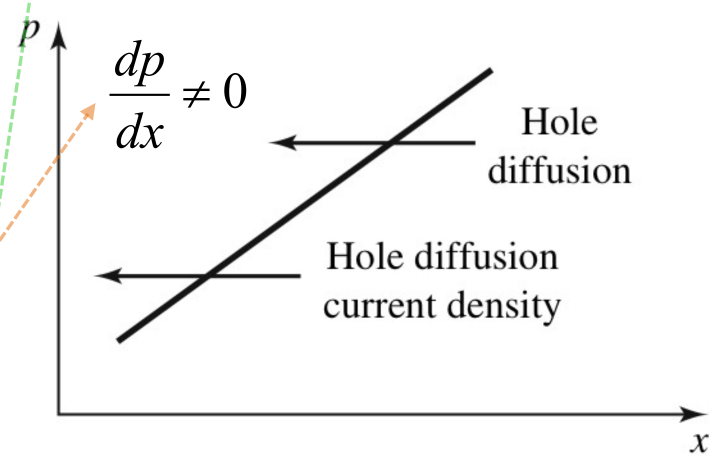
(due to concentration gradient)

- According to kinetic theory, particles flow from a region of high concentration to a region of lower concentration.
  - This is a statistical phenomenon and is known as **diffusion**.
  - Diffusion of electrons and holes occurs when there is a non-zero concentration gradient, resulting in **diffusion currents**:

$$J_n = eD_n \frac{dn}{dx} \qquad J_p = -eD_p \frac{dp}{dx}$$



From: Donald A. Neamen, *Microelectronics: Circuit Analysis & Design*, 4th edition, © 2010 McGraw-Hill, USA.



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Diffusion Current

(relation between diffusion & drift)

- The diffusion current associated with the electrons flows in the opposite direction when compared to that of the holes.
- $\boldsymbol{D_n}$ and $\boldsymbol{D_p}$ are the carrier **diffusion coefficients** respectively for electrons and holes and they are related to the respective **carrier mobility** by the **Einstein relation**:

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{k_B T}{e}$$

$V_T \approx 26\ \mathrm{mV}$
at $T = 300\ \mathrm{K}$

- The ***total*** current density is the sum of the **drift** and **diffusion** components.
  - In most cases, either the diffusion or drift component dominates the current.

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