



2015, Spring Semester

Energy Engineering (Class 458.624)

■ Professor

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- Classroom : 302-720
- Class time : Monday, Wednesday 11:00 ~ 12:15

■ Textbook

- (1) Introduction to Solid State Physics (Charles Kittel)
- (2) Solid State Electronic Devices (Ben G. Streetman, Sanjay Kumar Benerjee)



Chapter 3 .Energy Bands and Charge Carriers in Sem iconductors

We are interested in

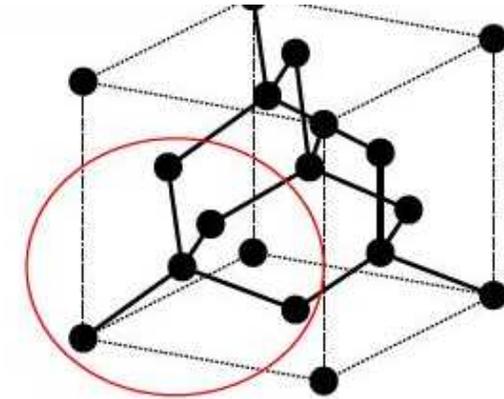
- (1) How to make different charge distribution: use doping, n+ and p+ type regions in p and n type substrate
- (2) How to make carriers(charges) move(transport) from one location to the other in a controlled way (by applying bias - gate bias to form a conducting channel, drain bias to let majority carriers move)

Let's try to understand energy bands, doping, Fermi level, etc., which are fundamental concepts of above issues in solid state electronic devices

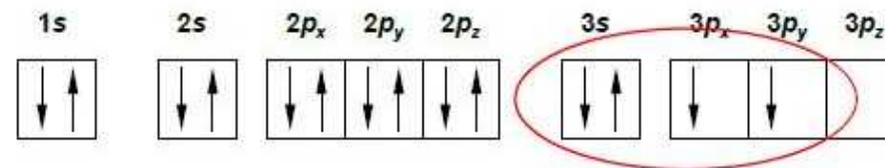
Covalent Bonding

Now we can examine elemental and compound semiconductors.

- Each atom shares bonds with 4 other atoms.
- Silicon bonds are covalent, but compound semiconductors have a mix of ionic and covalent bonds.
 - Depends on separation on periodic table.



DIAMOND CRYSTAL STRUCTURE WITH TETRAHEDRAL BONDING ... EXAMPLES INCLUDE SILICON & GERMANIUM



When silicon atoms **COMBINE** to form a crystal the *s*- and *p*- orbitals **HYBRIDIZE** to form so-called *sp*³ ORBITALS that are mixtures of the *s*- and *p*-orbitals.



s-ORBITAL



p-ORBITAL



*sp*³-ORBITAL

Bands

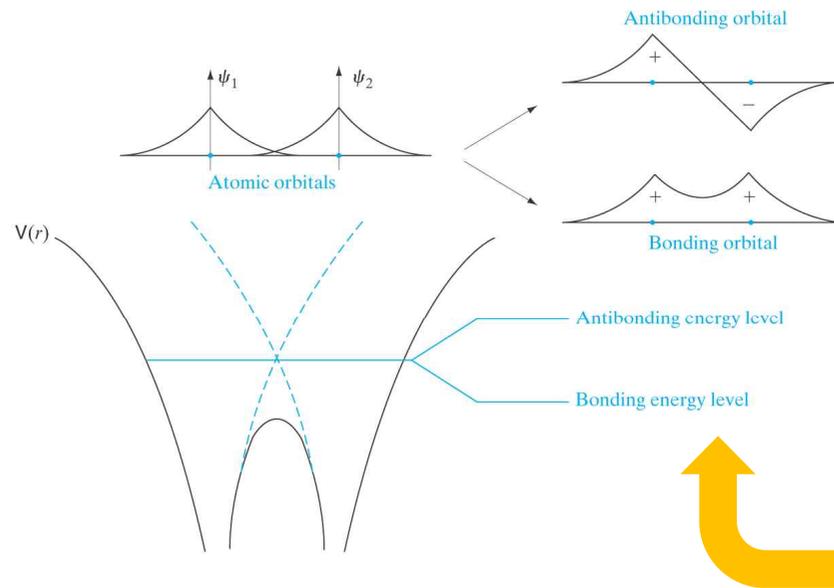
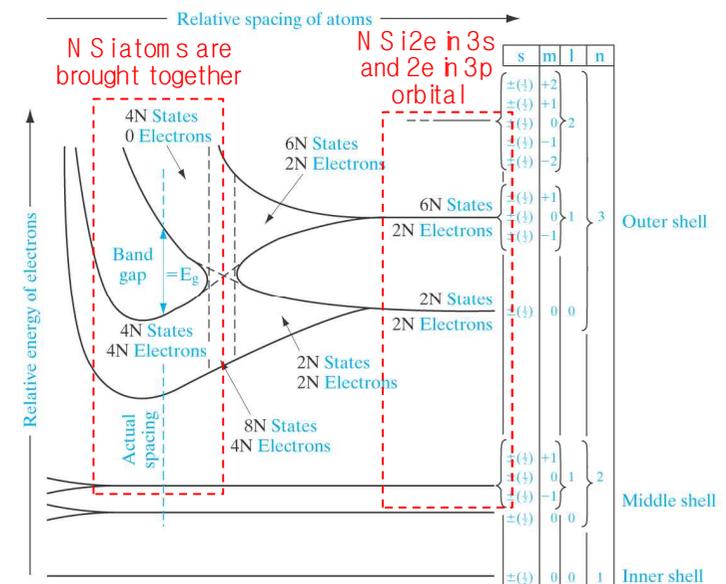


Figure 3.2

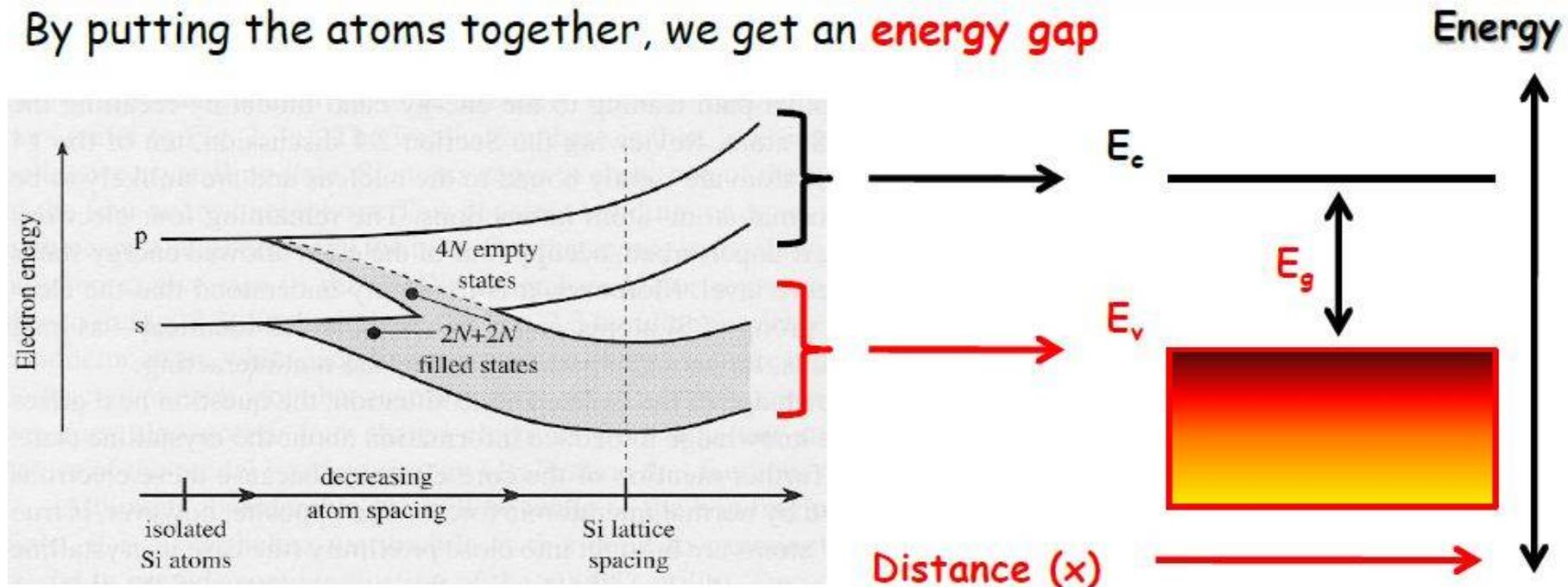
- Figure 3.2 (left) shows schematic Coulombic potential wells of two atoms.
- The composite two-electron wave functions are linear combination of individual atomic orbitals. Antisymmetric combination is antibonding and symmetric combination is bonding orbital.
- Bonding orbital has higher value of wave function (more electron) in between the two nuclei.
- Since electrons in between are attracted by two nuclei, the potential energy of bonding is lower than antibonding.

- The number of distinct energy levels (split by bonding and antibonding) depends on the number of atoms brought together.
- The lowest and highest energy level correspond to entire bonding and entire antibonding.
- In a solid, many atoms are brought together, so that the split energy levels form essentially continuous bands of energy.
- In silicon, the upper band (conduction band) contains $4N$ states (no electron at 0 K) and lower band (valence band) contains $4N$ states ($4N$ electrons at 0 K). There is a forbidden state, called a band gap, between the two bands.



Bands and Band Gap

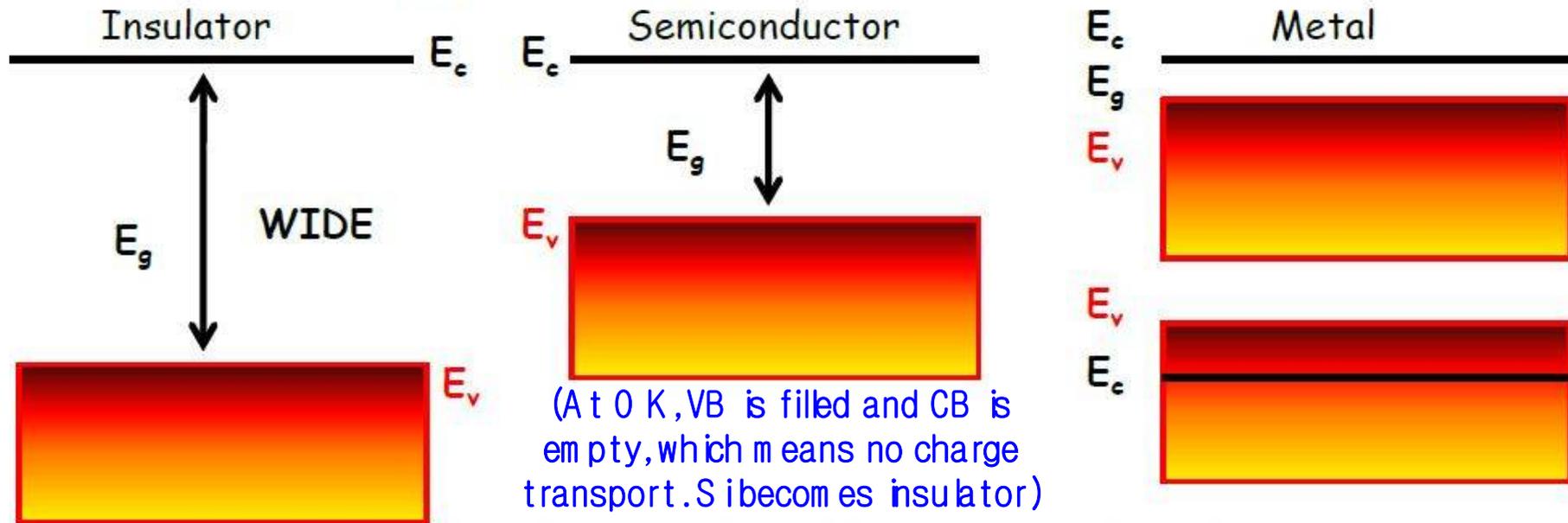
By putting the atoms together, we get an **energy gap**



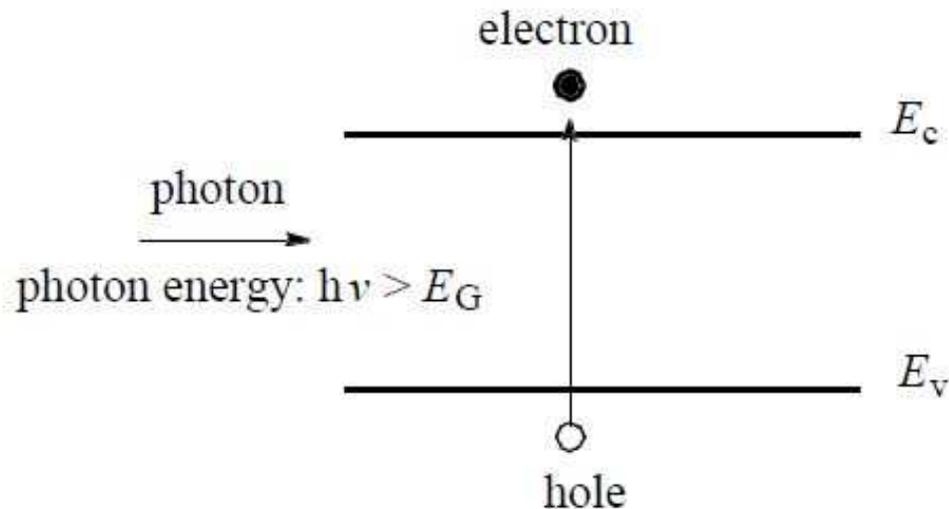
- The top band is referred to as the “conduction” band.
 - At low temperatures it is mostly empty of electrons.
- The bottom band is referred to as the “valence” band.
 - At low temperatures it is almost entirely filled with electrons.

Metal, Insulator and Semiconductor

Let's use the band gap to classify these different classes of materials...



- Insulators are characterized by having a very large band gap.
 - Diamond ($E_g \sim 6 \text{ eV}$)
 - SiO_2 ($E_g \sim 9 \text{ eV}$)
 - Thermal or electrical excitation of carriers is very difficult.
- Metals have either a very small band gap or no gap at all
 - There are always electrons available for conduction.
- Semiconductors are somewhere in-between
 - Silicon ($E_g \sim 1.12 \text{ eV}$)
 - Ge ($E_g \sim 0.66 \text{ eV}$)

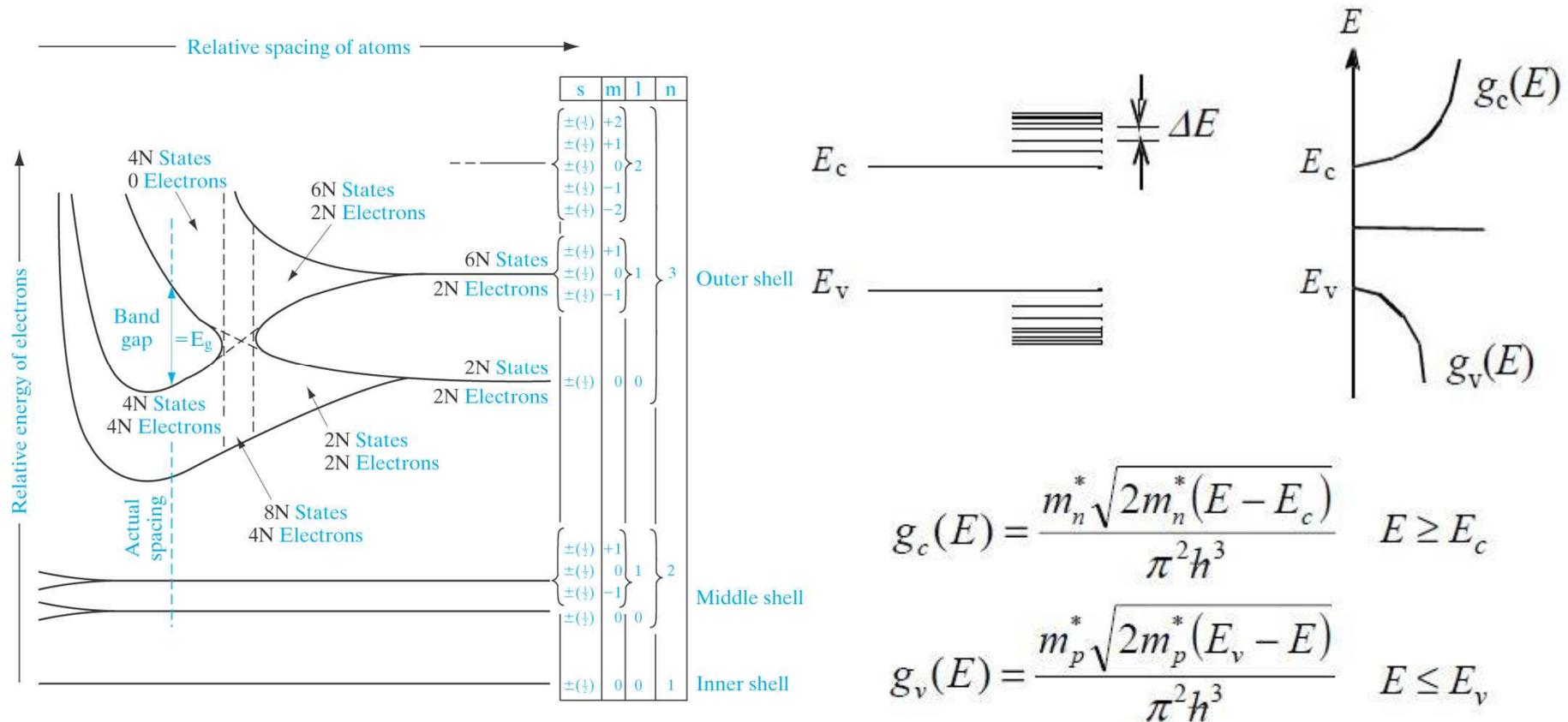


Band gap energies of selected semiconductors

Semiconductor	Ge	Si	GaAs
Band gap (eV)	0.67	1.12	1.42

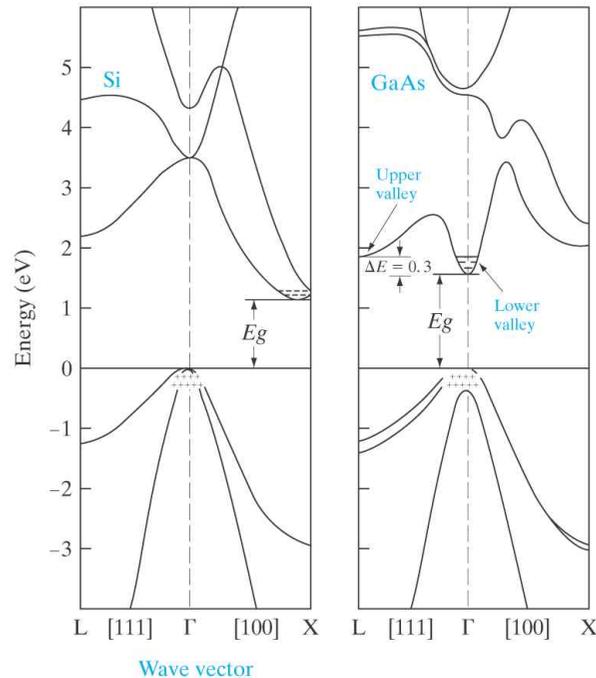
- Band gap energy of a semiconductor material can be measured by photon absorption energy.
- The minimum energy of photons that are absorbed by the semiconductor ($h\nu$) is the band gap energy (E_g).
- Other materials: TiO₂ (3.2), ZnO (3.3), Si₃N₄ (5), SiO₂ (9)

Density of States



- The density of states ($g(E)$) describes the number of states per interval of energy at each energy level that are available to be occupied by electrons.
- i.e. $g(E)dE = \text{number of states/cm}^3$ in the energy range between E and $E+dE$.

Effective Mass



Group	Material	m_n^*	m_p^*
IV	Si (4K)	1.06	0.59
	Si (300K)	1.09	1.15
	Ge	0.55	0.37
III-V	GaAs	0.067	0.45
	InSb	0.013	0.6
II-VI	ZnO	0.29	1.21
	ZnSe	0.17	1.44

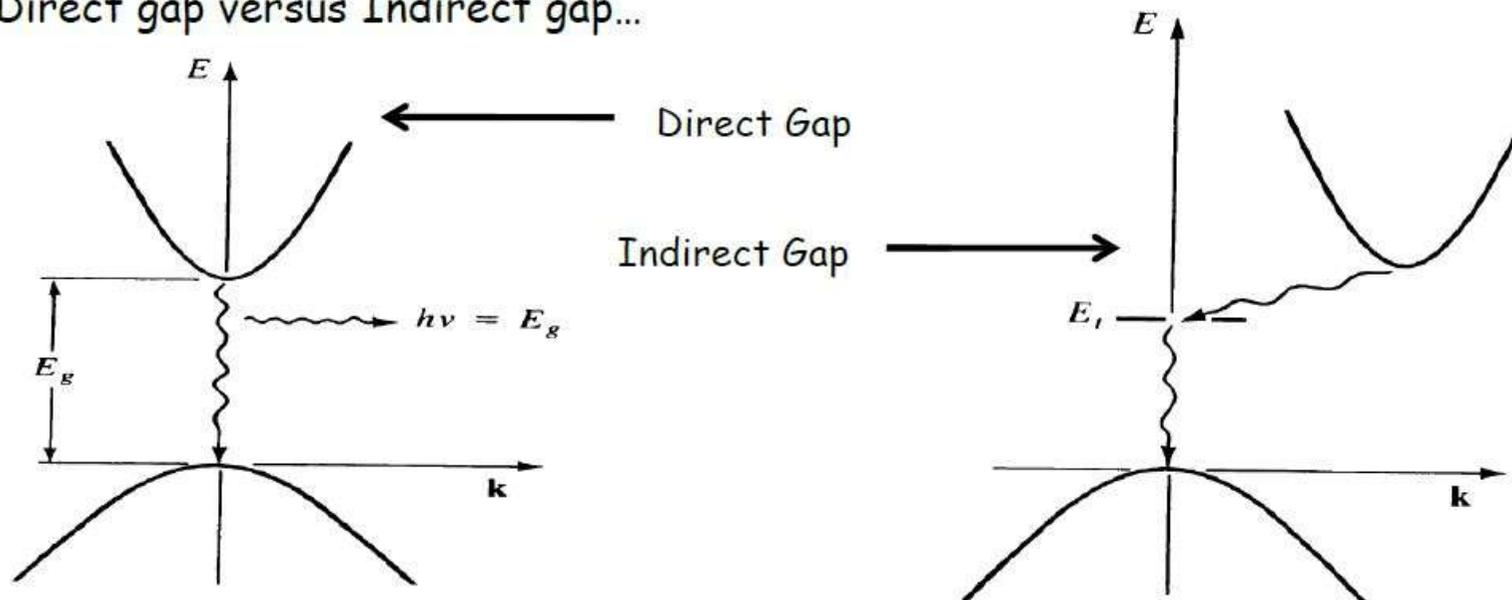
- The electrons in a crystal are not completely free, but instead interact with the periodic potential of the lattice. The interacting force is different in different materials and different directions in one material.
- A particle's effective mass (often denoted m^*) is the mass that it seems to have when responding to forces. (higher interaction \sim heavier effective mass)
- For electrons or holes in a solid, effective mass is usually stated in units of the true mass of the electron m_e , 9.11×10^{-31} kg.

$$m^* = \frac{(\hbar/2\pi)^2}{d^2E/dk^2}$$

high curvature at CB minimum and VB maximum in E-k diagram \sim low effective mass

Direct and Indirect

Direct gap versus Indirect gap...

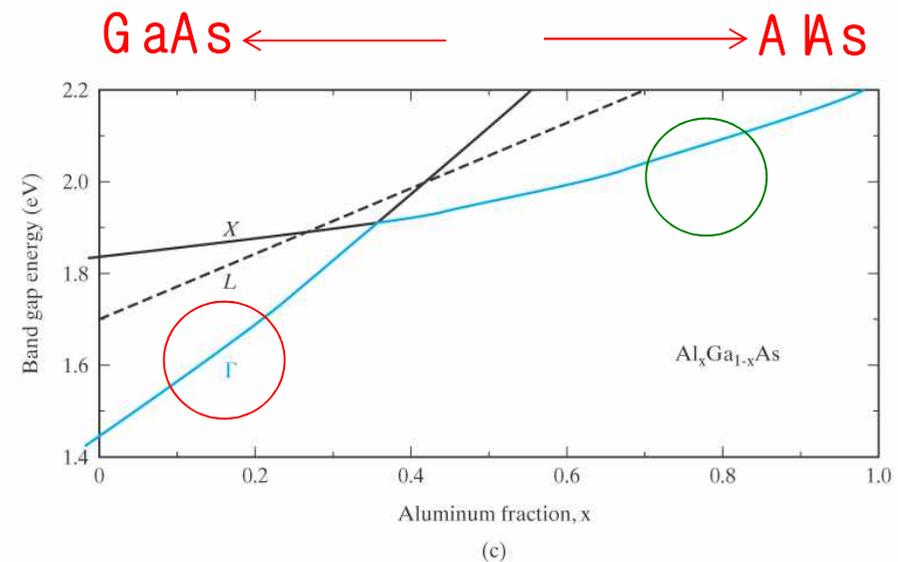
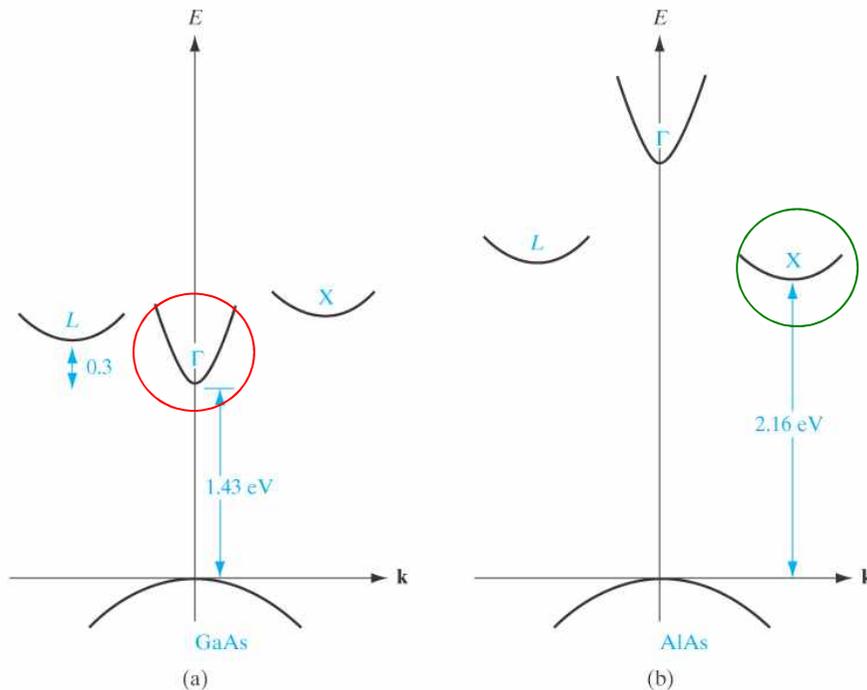
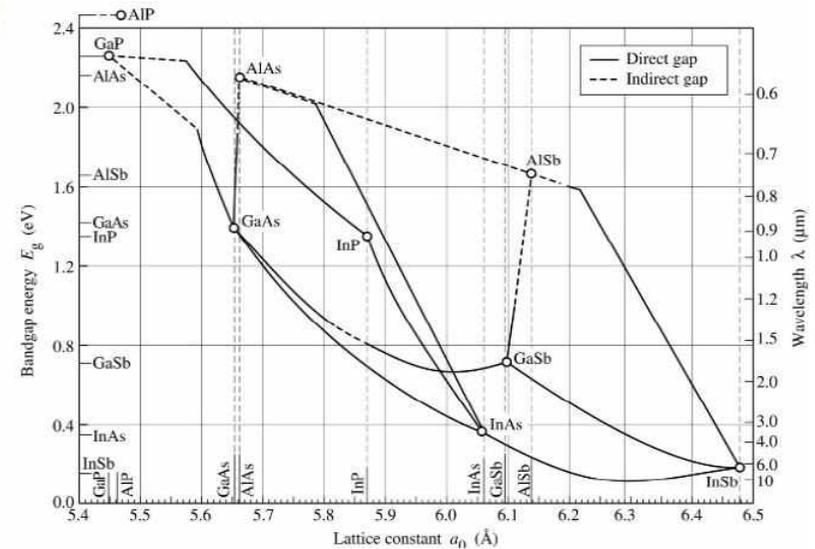


- E-k diagram : Allowed values of E vs k (wave vector, momentum of e^- and h^+) can be plotted.
- Since the periodicity of most crystal lattices is different in various directions of electron movement, relationship between E and k are plotted as above.
- Direct gap material (like GaAs) has the conduction band minimum and valence band maximum at the same k, while indirect gap material (like Si) has them at different k.
- In the case of indirect gap, the electron should change the direction of movement to move between minimum and maximum and thereby involves with momentum change in k.
- In direct gap, an electron in CB falls to an empty space of VB and gives off photons (light).
- In indirect gap, the momentum changes are needed and phonon involves, which emits its energy change as a heat instead of light.
- Generally, optoelectronic devices, like LED, are made of direct gap materials.

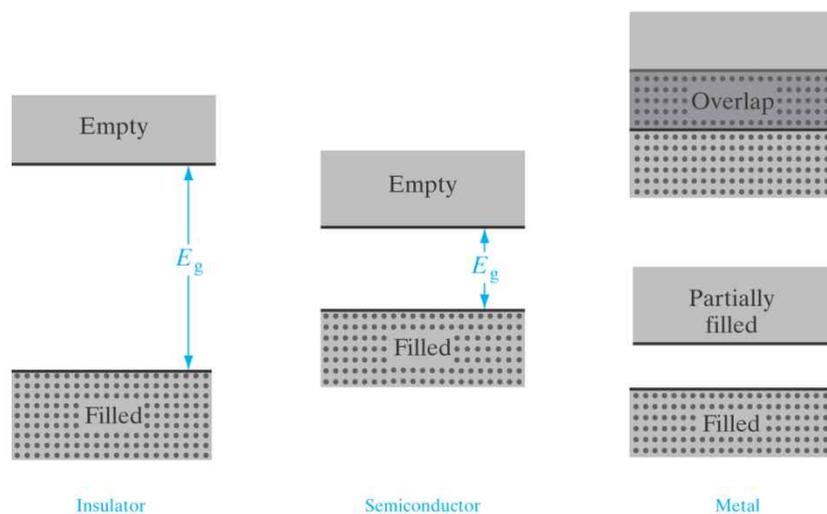
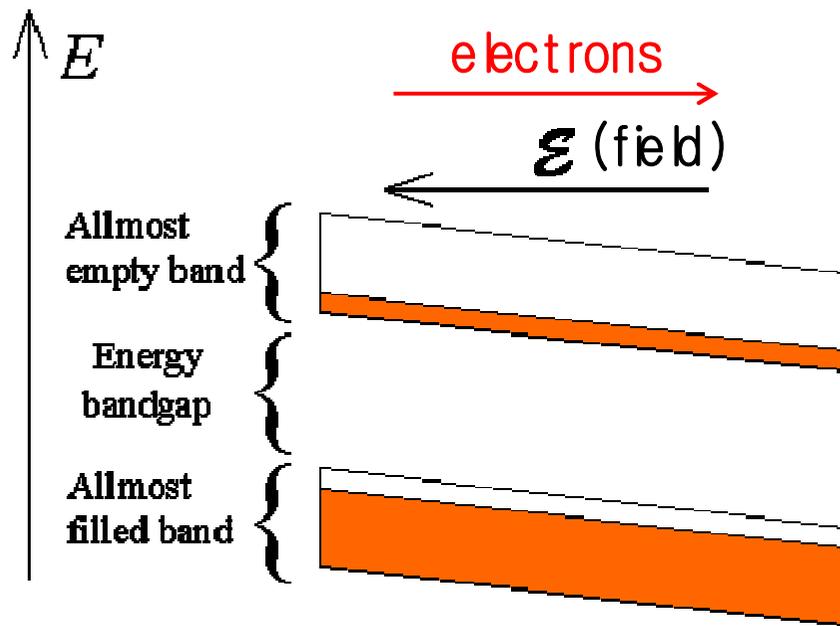
Band Change in Alloy

We can tailor the band gap in compound semiconductors

- Different compound semiconductors have different band structure, which can be tuned by alloying different materials.
- GaAs and AlAs can be alloyed to make $\text{Al}_x\text{Ga}_{1-x}\text{As}$.
- Depending on the Al fraction in alloy the band gap structure changes from indirect gap (AlAs) to direct gap (GaAs), as shown in the following diagrams.

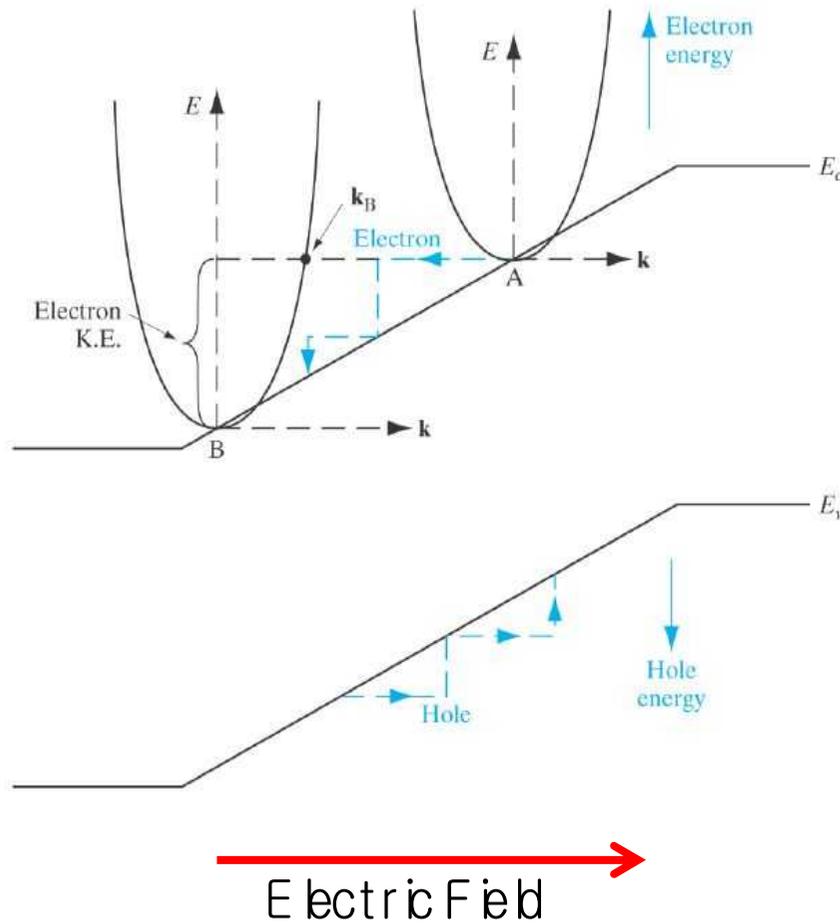


Electrons and Holes



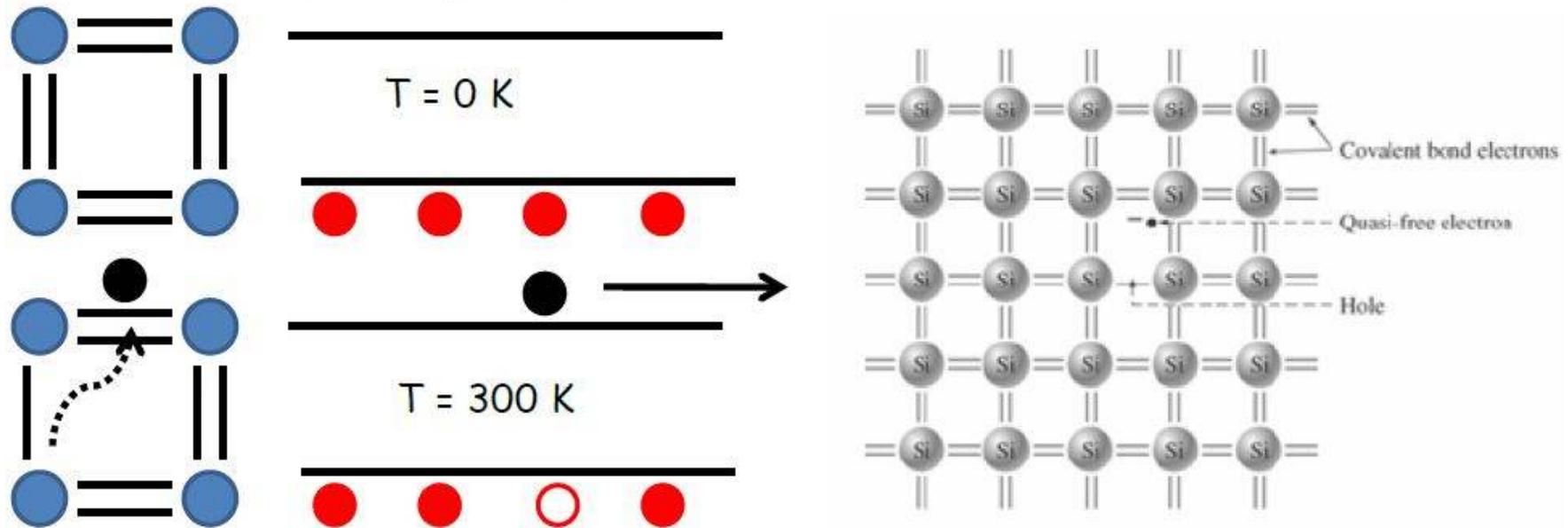
- Semiconductors differ from metals and insulators by the fact that they contain an "almost-empty" conduction band and an "almost-full" valence band ($> 0K$). This also means that we will have to deal with the transport of carriers in both bands.
- To facilitate the discussion of the transport in the almost-full valence band of a semiconductor, we will introduce the concept of holes.
- The concept of holes is introduced in semiconductors since it is easier to keep track of the missing electrons in an "almost-full" band, rather than keeping track of the actual electrons in that band.
- Holes are missing electrons. They behave as particles with the same properties as the electrons would have when occupying the same states except that they carry a positive charge. This definition is illustrated further with next slide, which presents the energy band diagram in the presence of an electric field.

Now put the semiconductor in an electric field...



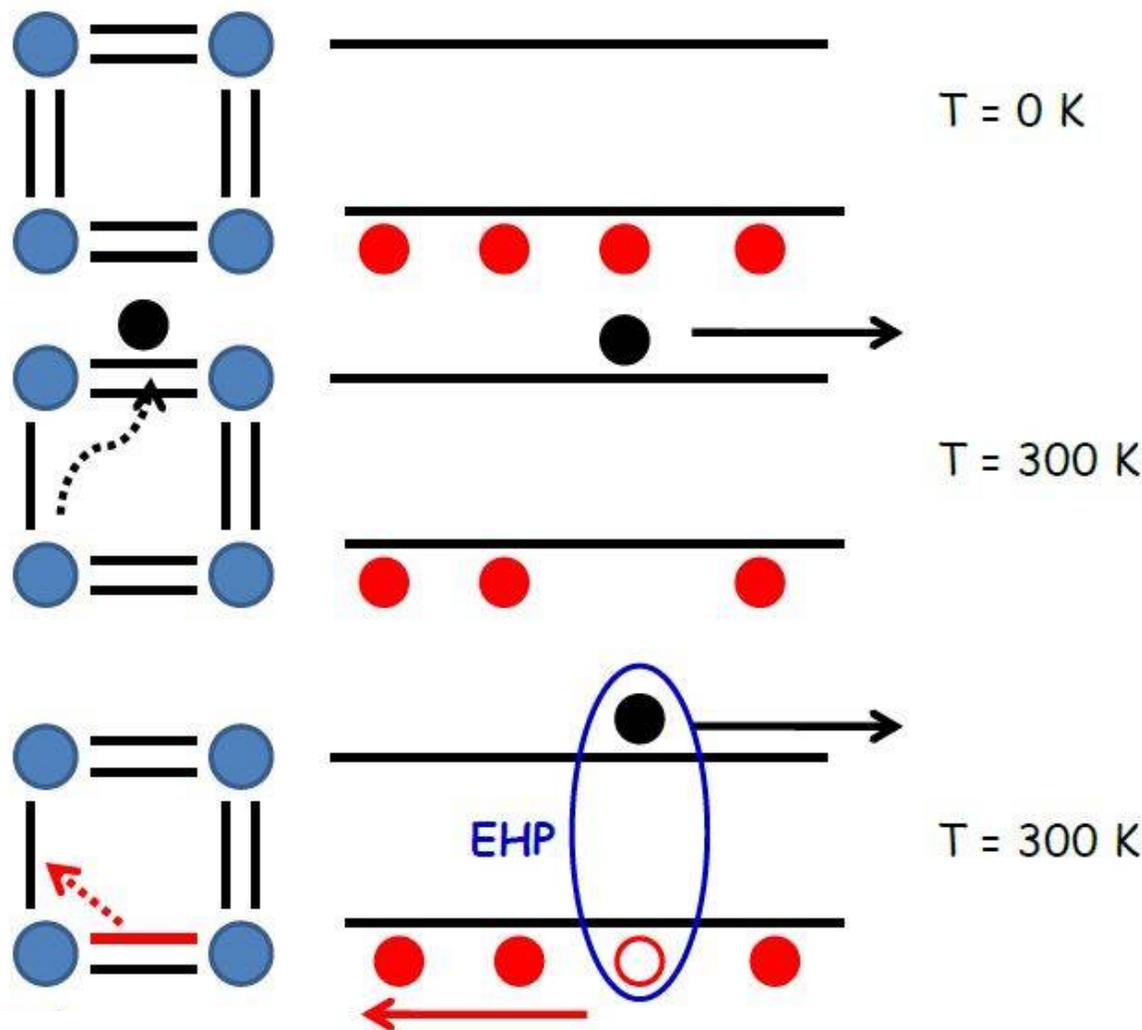
- (E, k) diagram is a plot of the total electron energy (potential + kinetic) as a function of the crystal-direction dependent electron wave vector (k , which is proportional to the momentum).
- Different crystal direction has different $E-k$ diagram
- Therefore the bottom of the conduction band (where $k=0$) corresponds to zero electron velocity or kinetic energy and simply gives the potential energy at that point. (left)
- Energies higher in the band than the minimum k point corresponds to additional kinetic energy of the electron (potential + kinetic E).
- Since the band edge corresponds to the electron potential energy, the variation of the band edge in space is related to the electric field at different points of semiconductor.
- In the left diagram, electron at location A sees an electric field given by the slope of the band edge (potential energy), and gains kinetic energy (at the expense of potential E) by moving to point B (less potential E , more kinetic E).
- The slope of band edge represents local electric field of each point.

Intrinsic Material is pure with no additional contaminants...



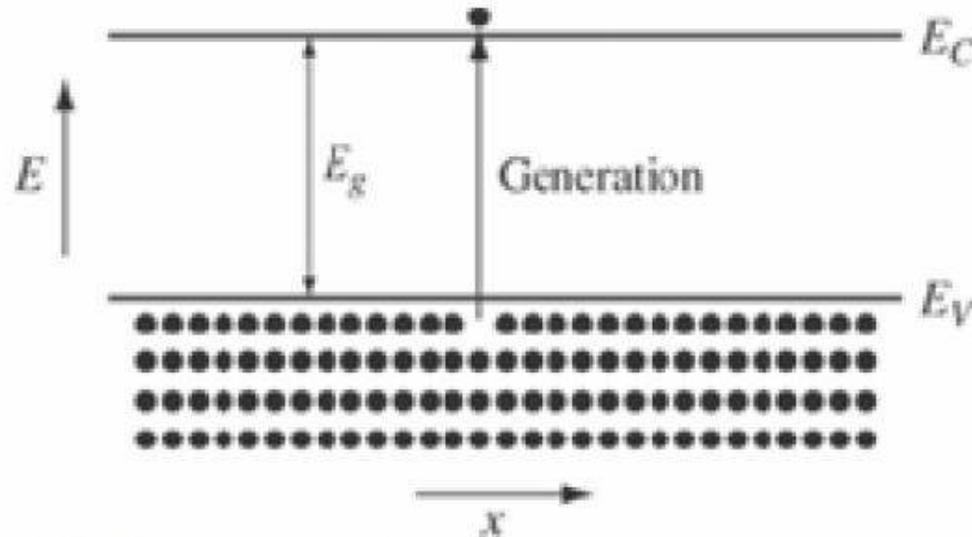
- At $T = 0 \text{ K}$, there is no energy in the system.
 - All of the covalent bonds are satisfied.
 - Valence band is full and conduction band is empty.
- At $T > 0 \text{ K}$, thermal energy breaks bonds apart
 - Crystal lattice begins to vibrate and exchange energy with carriers.
 - Electrons leave the valence band to populate the conduction band.

Putting temperature and band gap together to obtain **carriers**...



- Thermal excitation cause bonds to break
 - At $T = 0$ K there is no energy to break bonds.
 - Valence band is totally full and conduction band is empty.
 - At room temperature, carriers can be excited across the band gap.
 - This liberates electrons and holes.

But there are more processes at work...



Generation Rate:

High temp. Strain

↓ ↓

$$G = G_{th} + G_{opt} + G_{mech} + \dots \left(\frac{1}{cm^3 \cdot s} \right)$$

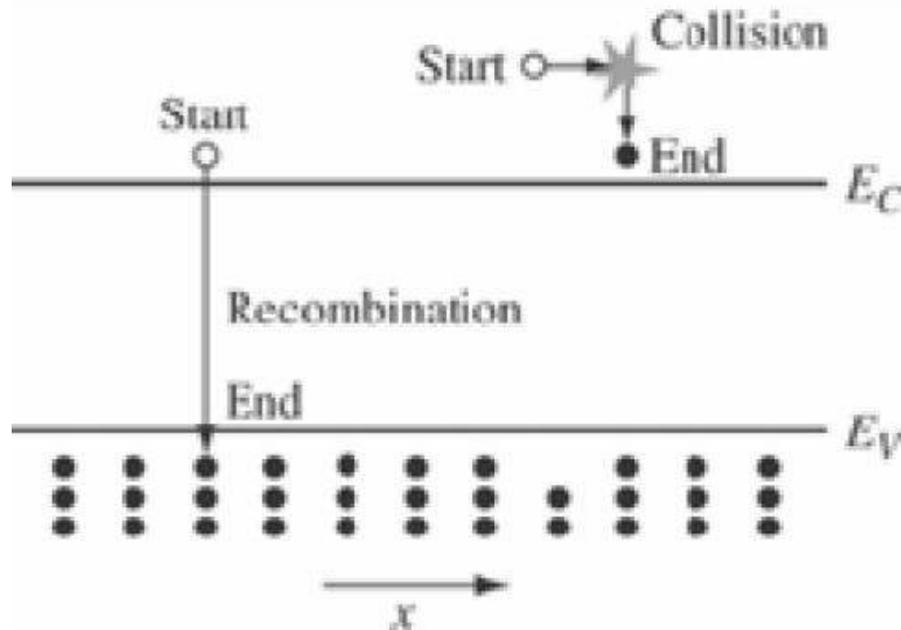
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Irradiation

- **Generation**

- Break up of a covalent bond to form an electron and a hole.
- Requires energy from thermal, optical, mechanical or other external sources.
- Supply of bonds to break is virtually inexhaustible.
 - Atomic density \gg # of electrons or # of holes.

Since we are in thermal equilibrium, there must be an opposite process...



Recombination Rate:

$$R \propto n \cdot p \left(\frac{1}{\text{cm}^3 \cdot \text{s}} \right)$$

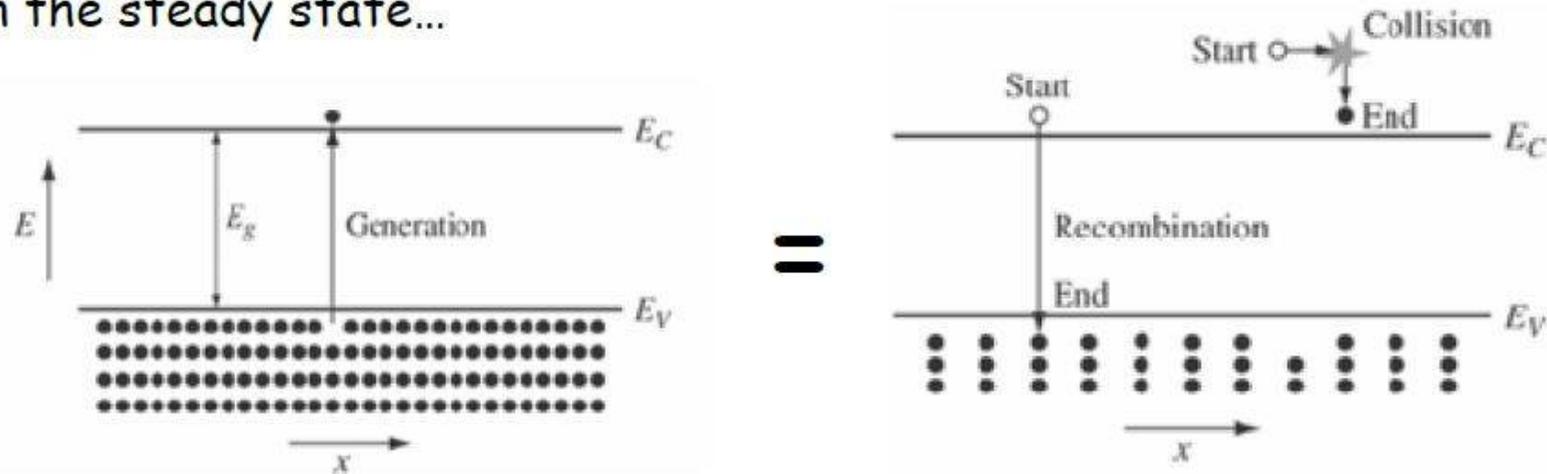
- N - number of electrons
- P - number of holes

- Recombination

- Formation of a bond by bringing together an electron and a hole.
- Releases energy in the form of thermal or optical energy.
- Recombination events require the presence of 1 electron and 1 hole.
- These events are most likely to occur at the surfaces of semiconductors where the crystal periodicity is broken.

(Surface recombination ~ important in photovoltaic devices)

In the steady state...



- The generation rate must be balanced by the recombination rate.

$$G_0 = R_0 \Rightarrow n_0 p_0 = n_i^2 \quad n_0 = p_0 \Rightarrow n_0 = p_0 = n_i$$

- **Important consequence is that for a given semiconductor the np product depends only on the temperature.**



Now, we learned...

- (1) Conduction and Valence Band
- (2) Band Gap
- (3) Electron and Hole, their pair
- (4) Band Bending by External Electric Field
- (5) Thermal Generation and Other Generations
- (6) Recombination, Illuminating and Thermal

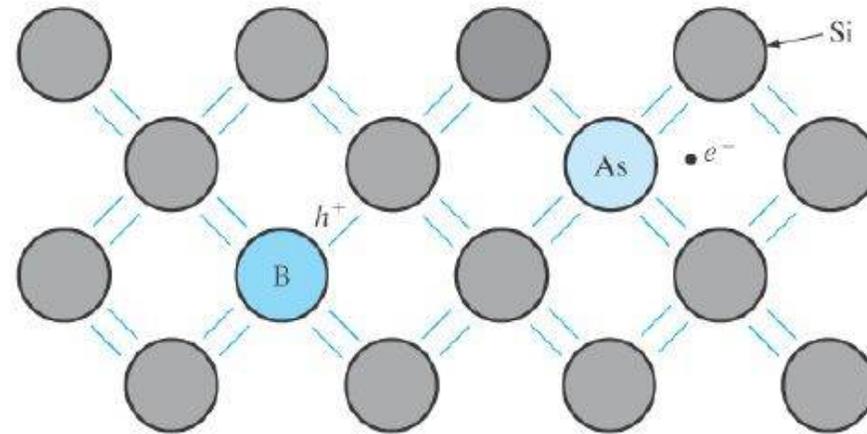
Then How Can We Control Local Carrier Concentrations?
Ex) n^+ , p^+ , n and p

By Doping...

Extrinsic Materials

The great strength of semiconductors...

- We can change their properties many orders of magnitude by **introducing the proper impurity atoms.**
- Which columns add
 - Electrons?
 - Holes?
- What about impurities?
 - Doners and Acceptors

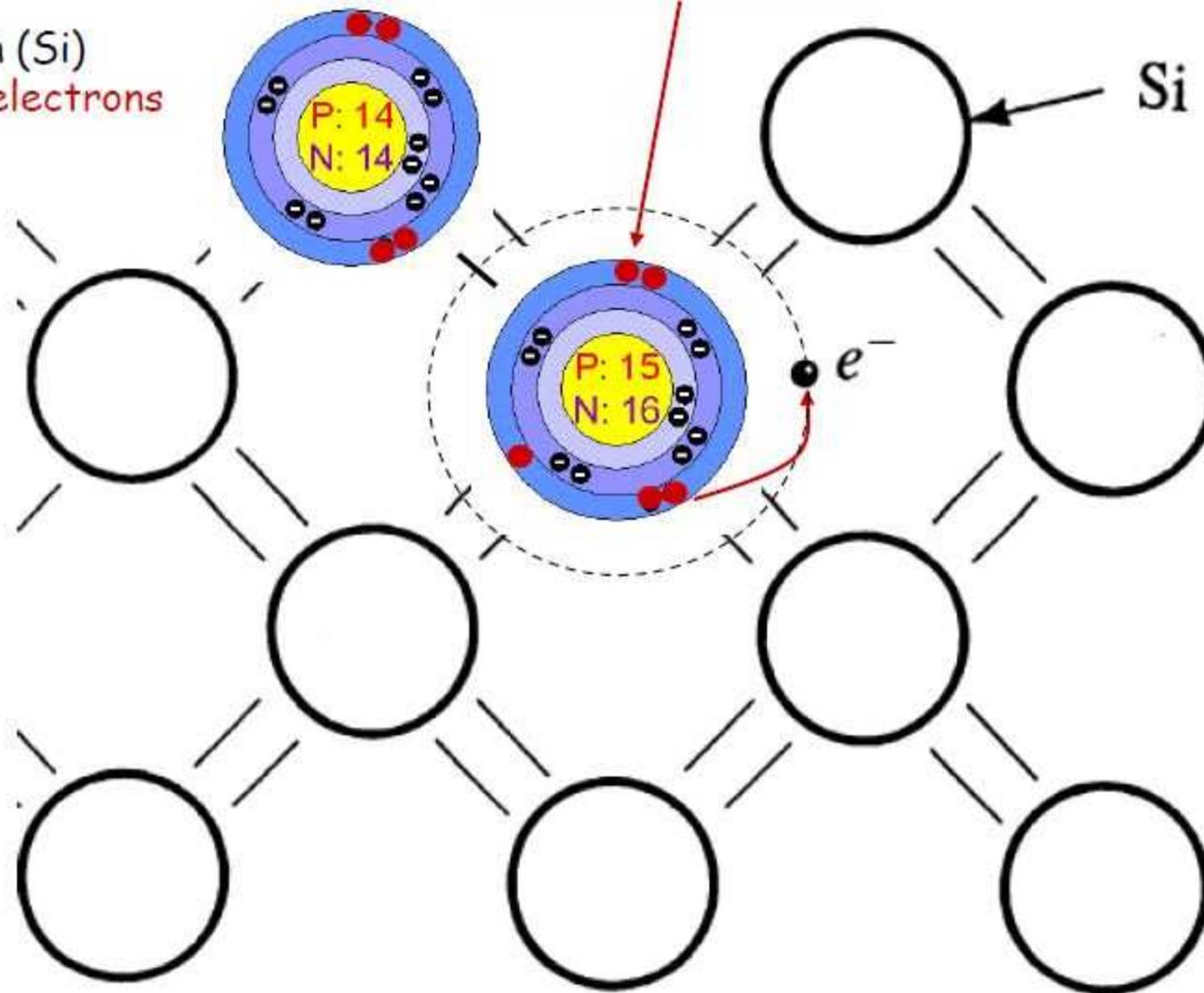


	IIIA	IVA	VA	VIA
	5 B	6 C	7 N	8 O
	13 Al	14 Si	15 P	16 S
IIB	30 Zn	31 Ga	32 Ge	33 As
	48 Cd	49 In	50 Sn	51 Sb
				52 Te

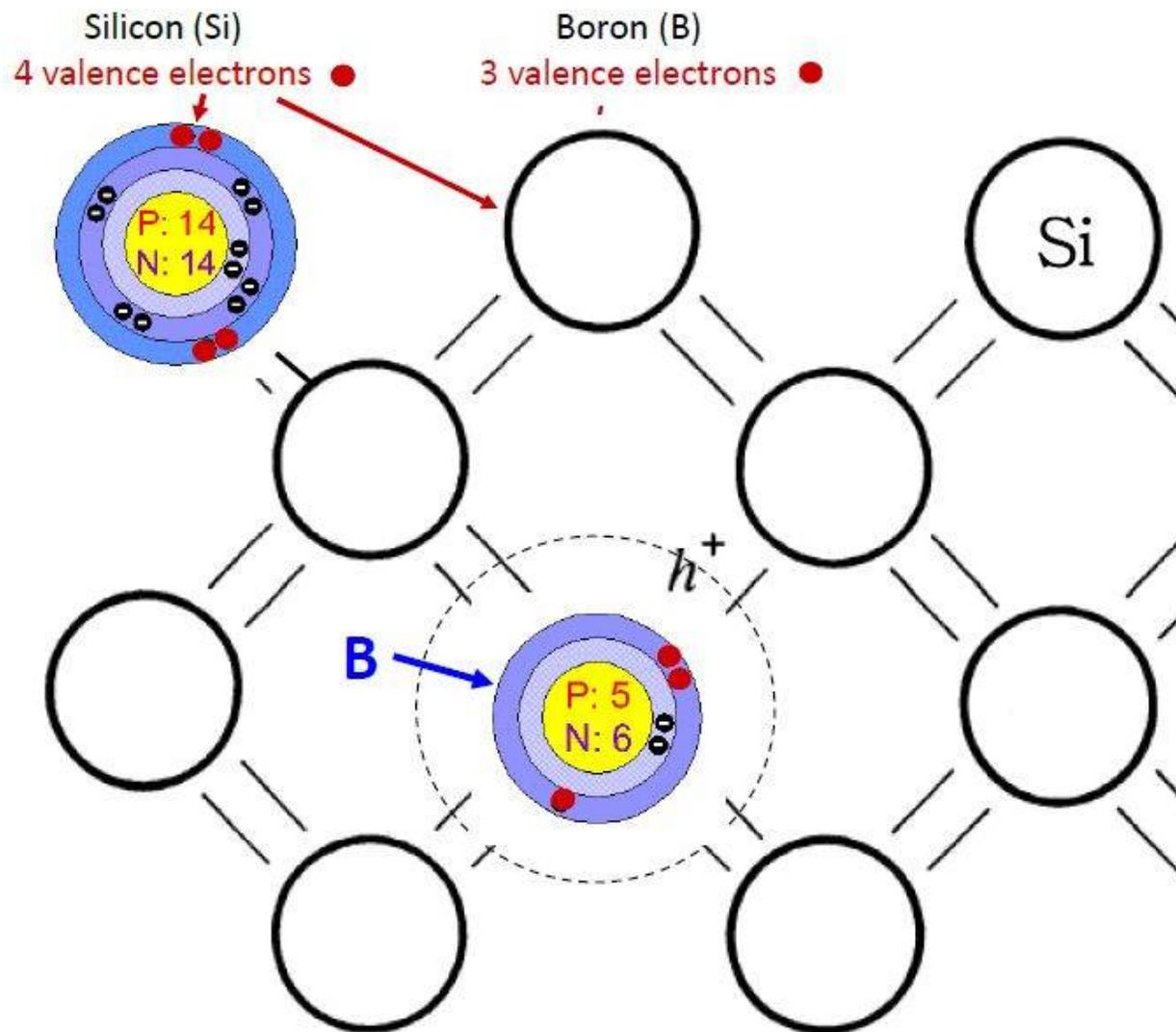
How does a **donor** work?

Silicon (Si)
4 valence electrons

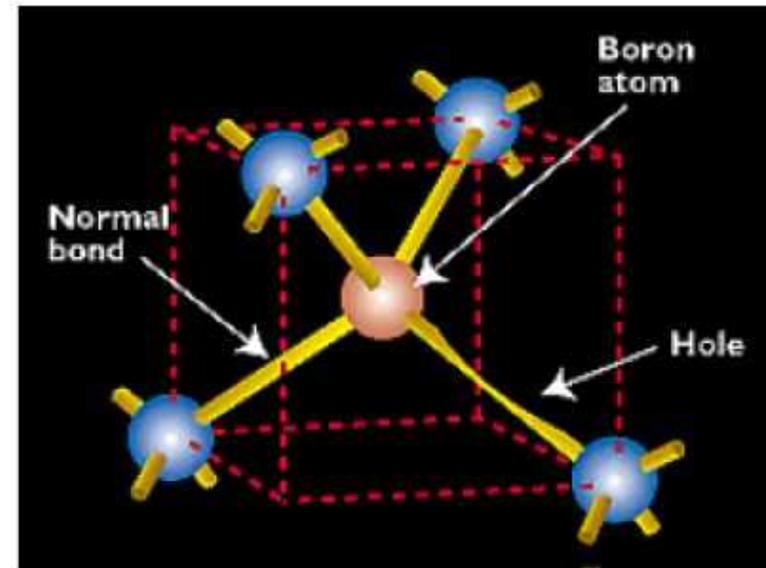
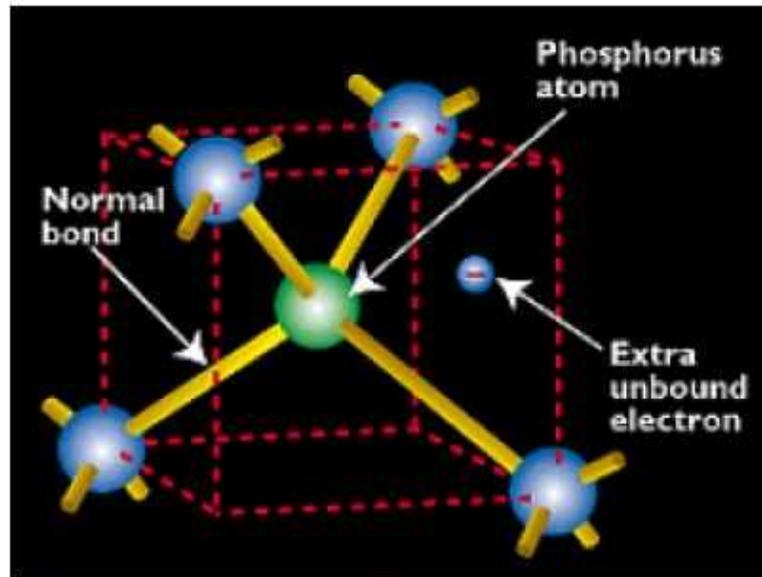
Phosphorous (P)
5 valence electrons



How does an **acceptor** work?



So, let's review doping of elemental semiconductors...



- Dopants in Silicon

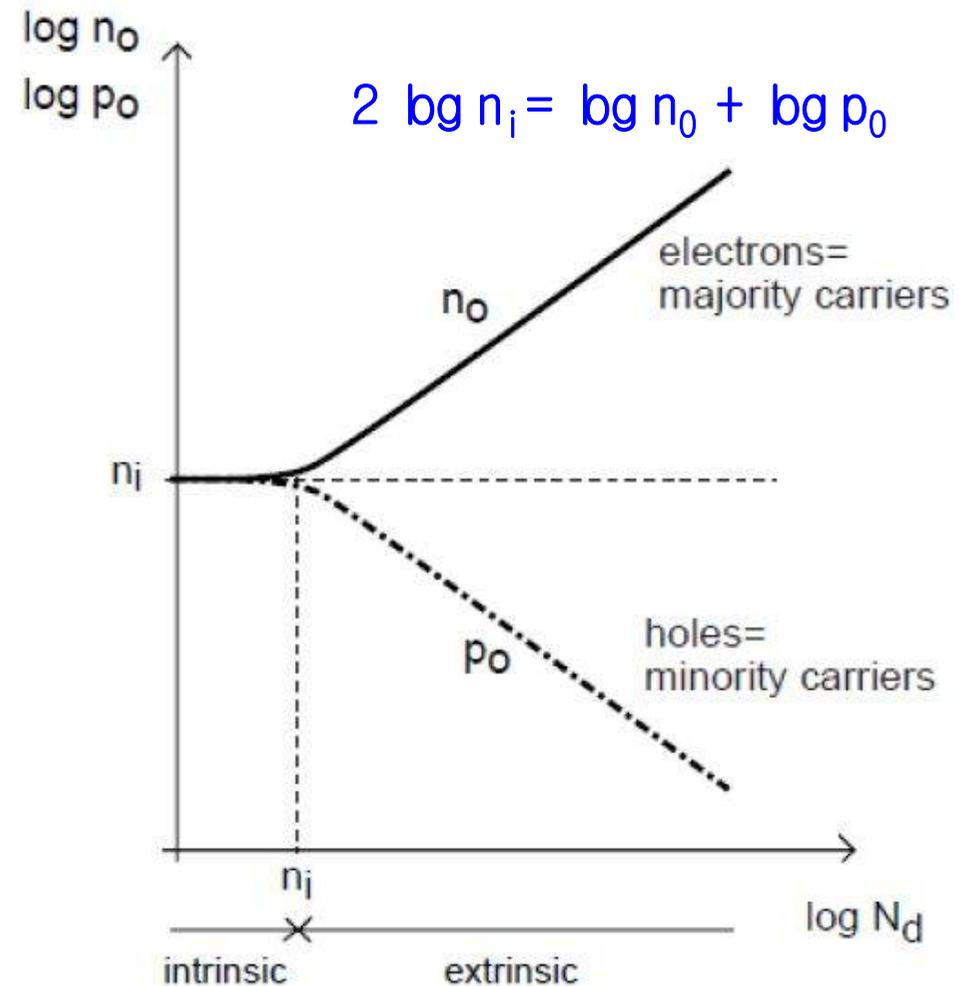
- Reside on the lattice sites.
- Group V elements contribute electrons to the conduction band and are called **donors**.
- Group III elements contribute holes to the valence band and are called **acceptors**.
- These impurities are totally ionized at room temperature.
- Concentrations range from 10^{14} cm^{-3} to 10^{20} cm^{-3} .

Low doping (channel) High doping (contact)

In general, we can modify the materials properties with the introduction of immobile impurity atoms...

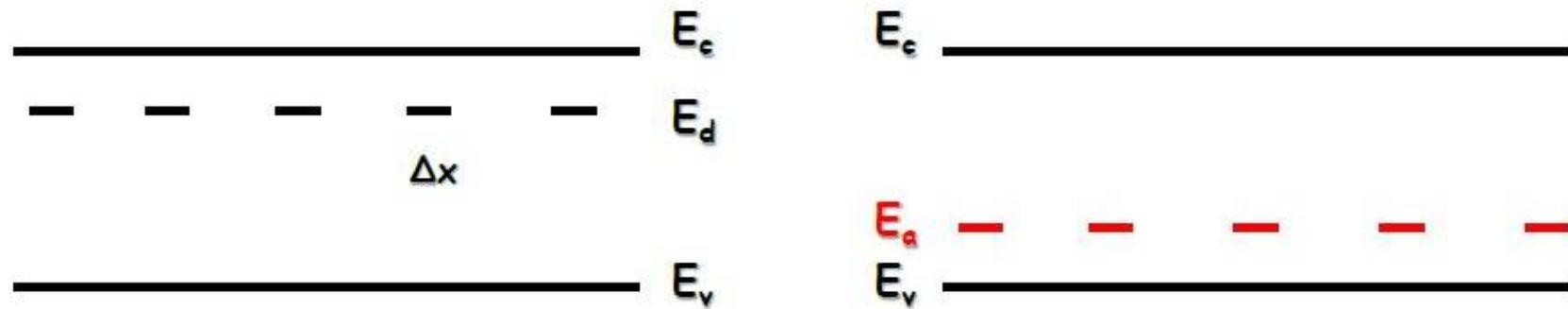
- We can
 - Selectively create regions of n and p .
 - Needed for CMOS.
 - Modify the conductivity over several orders of magnitude.
 - **Manipulate the number of conduction electrons over 5 orders of magnitude.**

(From 10^{14} to 10^{20})

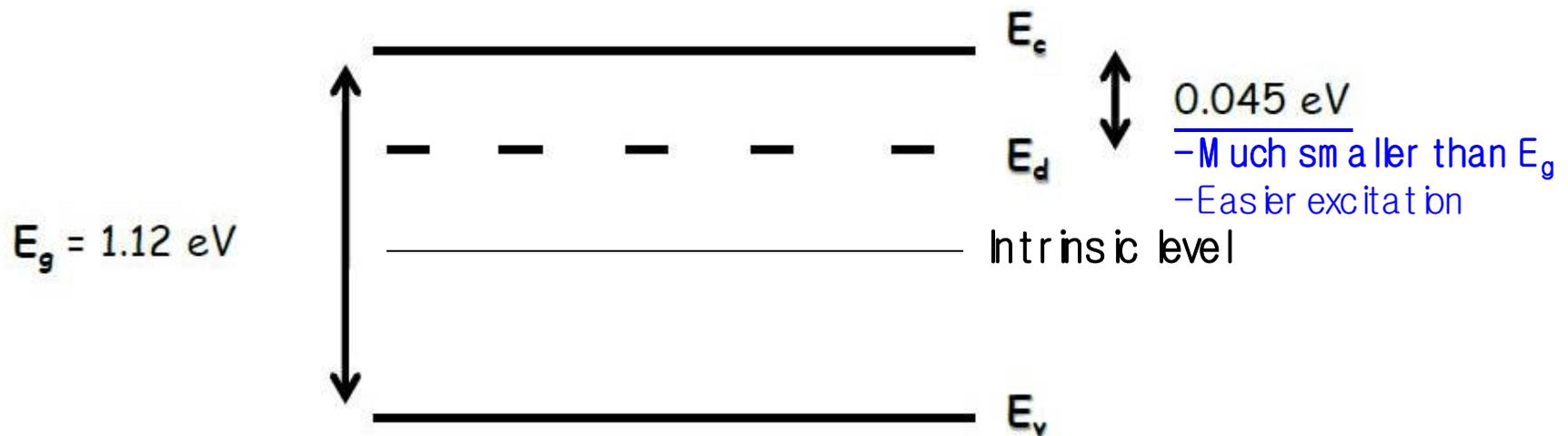


N type material

Band Diagram of Silicon with Donors and Acceptors

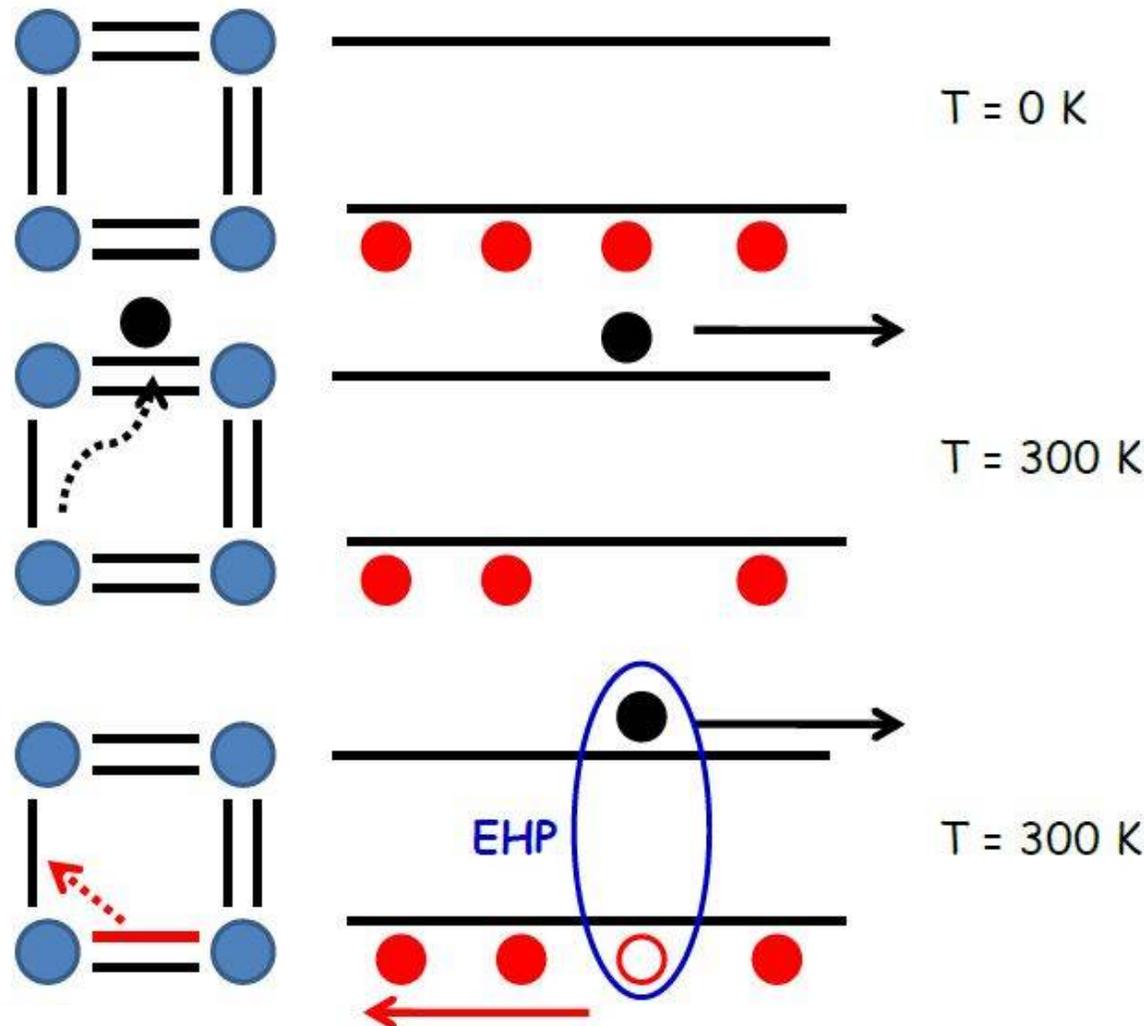


Let's take a look at Silicon with Phosphorus impurity atoms:



Therm a | Excitation of Intrinsic Materials

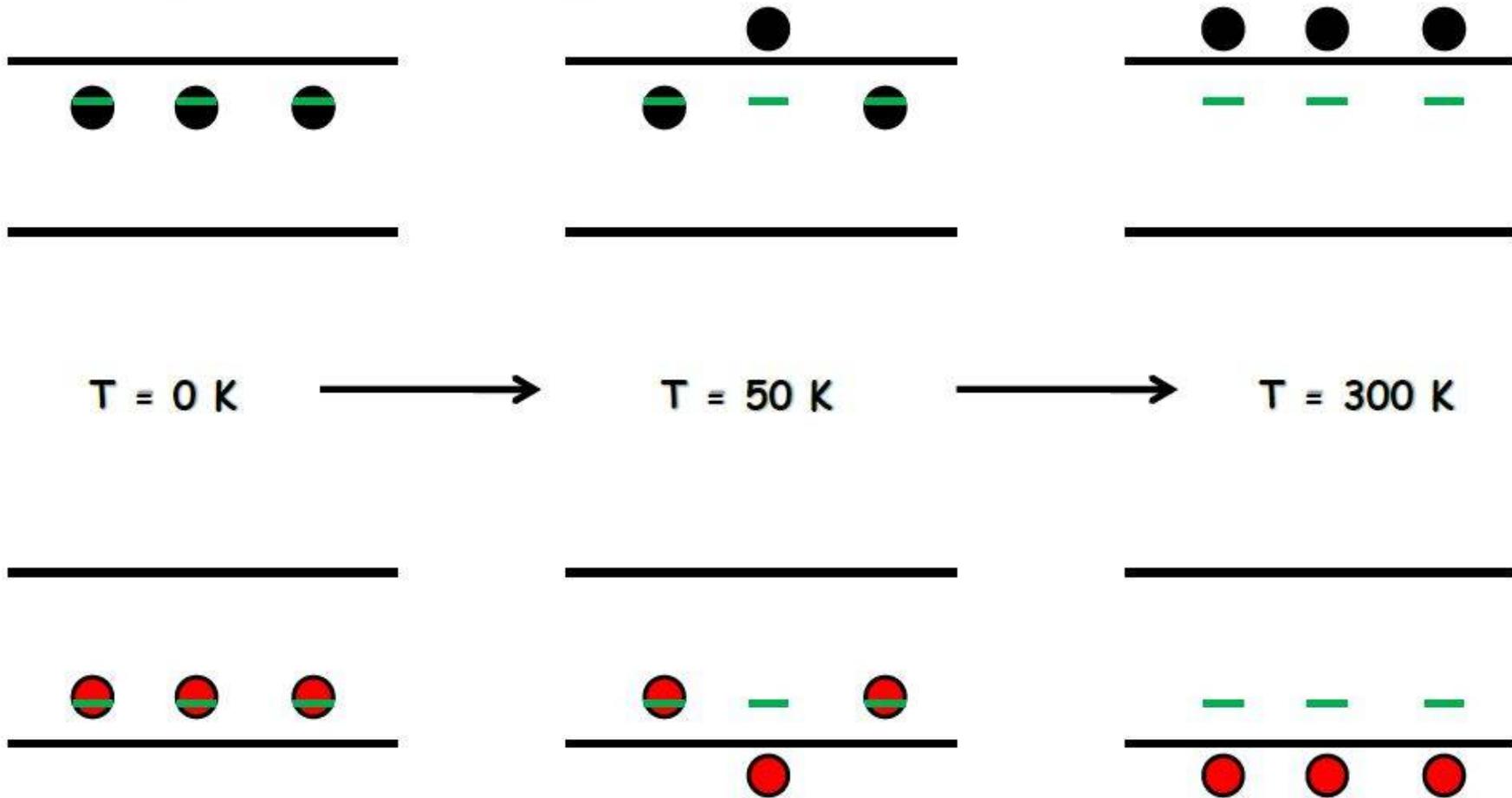
Putting temperature and band gap together to obtain **carriers**...



- Thermal excitation cause bonds to break
 - At $T = 0 \text{ K}$ there is no energy to break bonds.
 - Valence band is totally full and conduction band is empty.
 - At room temperature, carriers can be excited across the band gap.
 - This liberates electrons and holes.

Thermal Excitation of Extrinsic Materials

Revisiting the effect of temperature...



Much easier thermal EHP generation with donors and acceptors !!

Commonly used terms:

- Dopants - specific impurity atoms that are added to semiconductors in controlled amounts for the express purpose of increasing either the electron or hole concentrations.
- Intrinsic semiconductor - undoped semiconductor; extremely pure semiconductor sample containing an insignificant amount of impurity atoms; a semiconductor whose properties are native to the material.
- Extrinsic semiconductor - doped semiconductor; a semiconductor whose properties are controlled by added impurity atoms.
- Donor - impurity atom that increases the electron concentration; *n*-type dopant.
- Acceptor - impurity atom that increases the hole concentration; *p*-type dopant.
- N-type material - a donor doped material; a semiconductor containing more electrons than holes.
- P-type material - an acceptor doped material; a semiconductor containing more holes than electrons.
- Majority carrier - the most abundant carrier in a given semiconductor sample; electrons in *n*-type and holes in *p*-type.
- Minority carrier - the least abundant carrier in a given semiconductor sample; electrons in *p*-type and holes in *n*-type.



Now, we learned...

- (1) Conduction and Valence Band, Band Gap
- (2) Electron and Hole, their pair
- (3) Band Bending by External Electric Field
- (4) Thermal Generation and Other Generations
- (5) Recombination, Illuminating and Thermal
- (6) Control of Local and/or Overall Concentrations of Electrons and Holes by Doping

Then How Can We Express The Amount of Specific Carrier (Either Electron or Hole) in Specific Region?
Ex) n-type and p-type Si have different amount of carriers. How can we tell the difference between these two?

We can use the Fermi Level to express this...

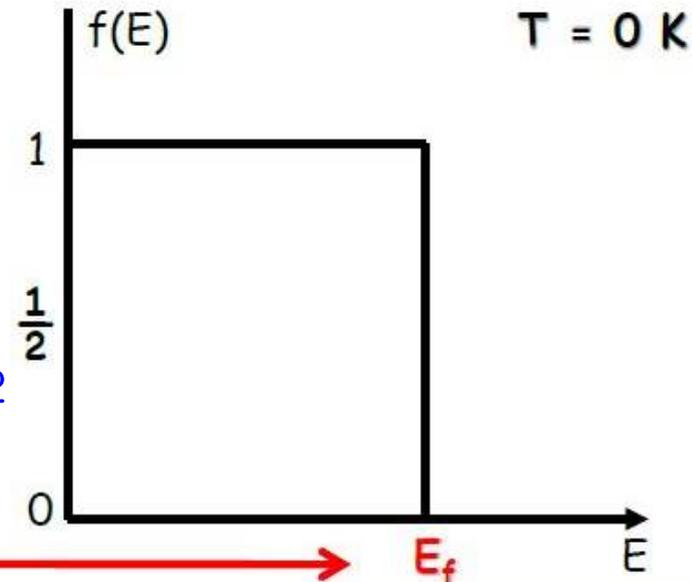
Fermi Level

- The **Fermi function** tells us the **probability** of how many of the existing states at any given energy will be filled with an electron.

Mathematically speaking the end result is a probability distribution function:

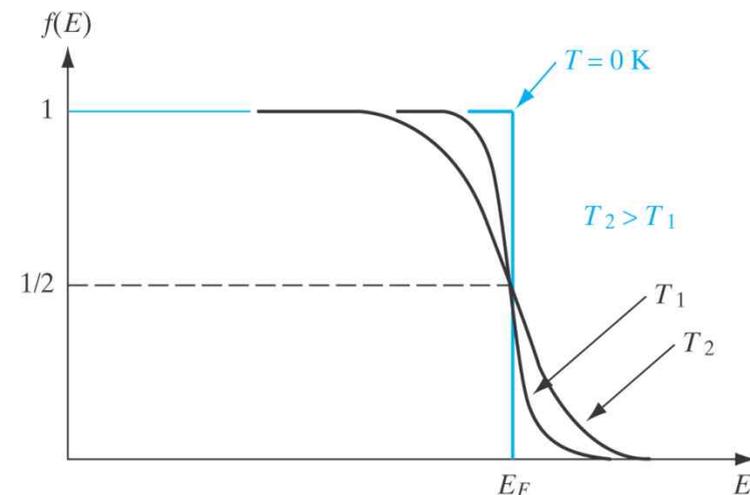
$$f(E) = \frac{1}{1 + e^{\frac{E - E_f}{k_b T}}}$$

i) $E > E_f, T = 0, f = 0$
 ii) $E < E_f, T = 0, f = 1$
 iii) $E = E_f, T > 0, f = 1/2$

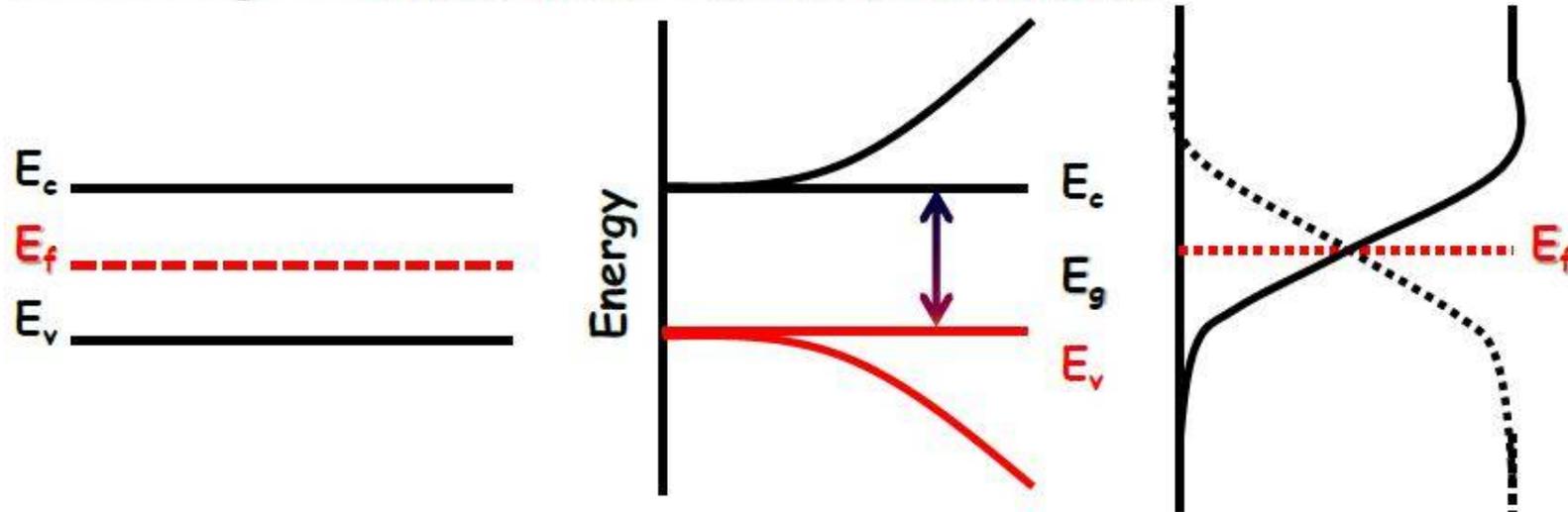


What about the **temperature** dependence?

- At temperatures higher than 0K, some probability exists for states above the Fermi level to be filled.
- In applying Fermi-Dirac distribution, $f(E)$ is the probability of occupancy of an available state at E .
- In intrinsic materials, $f(E_F) = 1/2$, since the number of electrons and holes are same.
- E_F is the energy level where $f(E_F) = 1/2$.



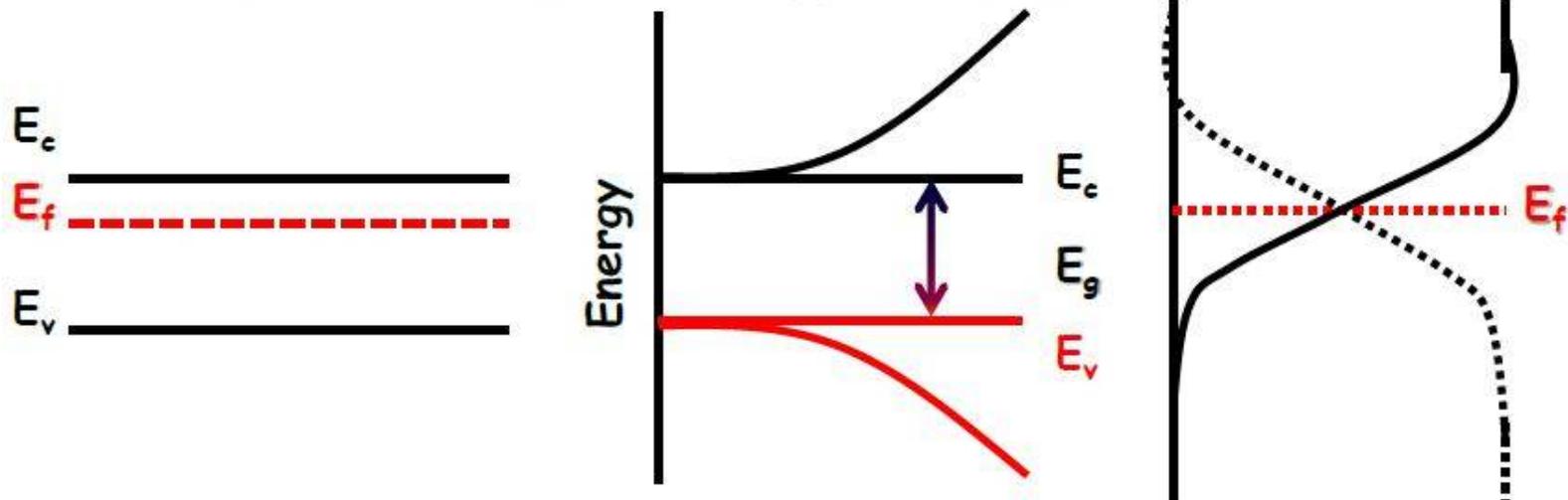
Visualizing the **Fermi level** in **intrinsic material**...



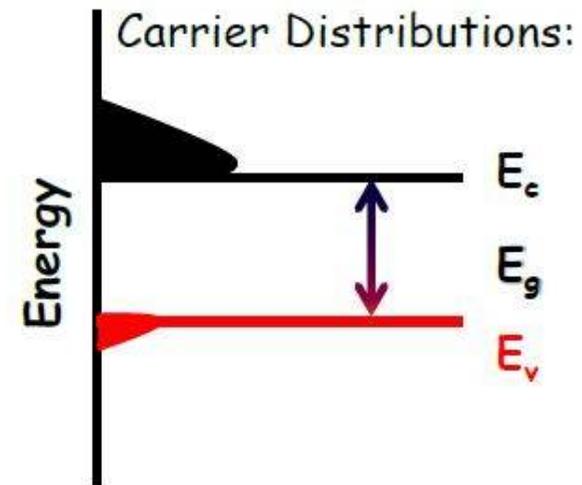
- In **intrinsic material**:

- In intrinsic material, the concentrations of holes in VB and electrons in CB are same. Therefore the Fermi level E_f lies in the middle of band gap.
- The symmetry of the distribution of empty and filled states about E_f makes the Fermi level a natural reference point in calculations of electron and hole concentrations.

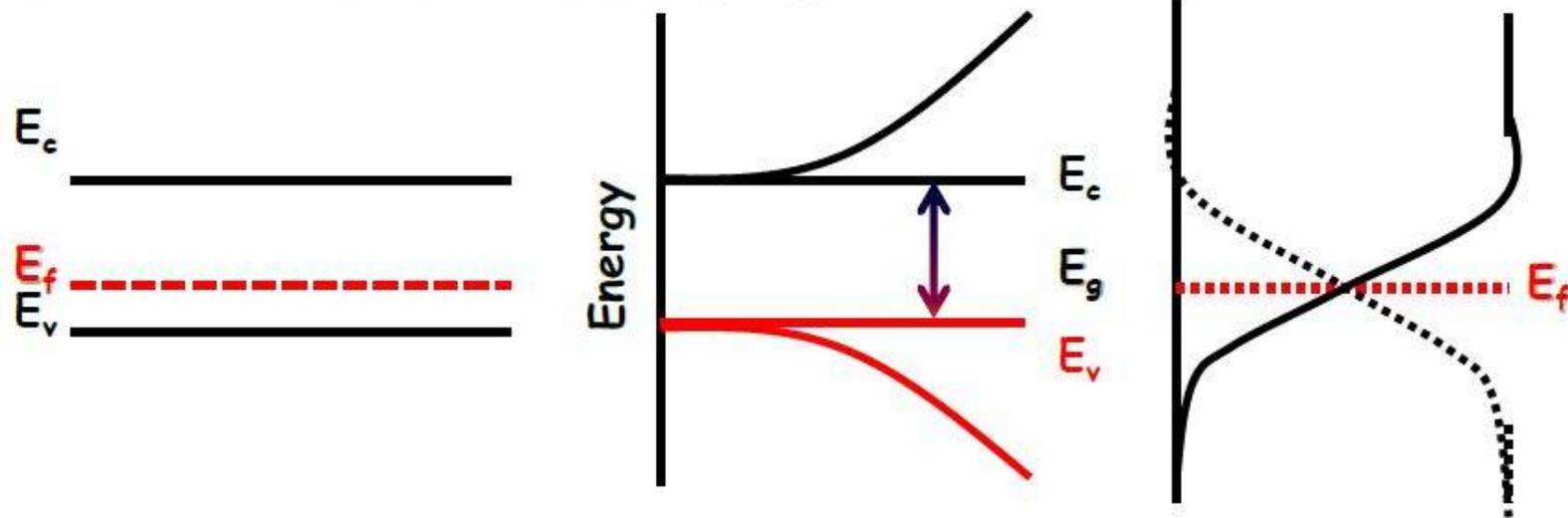
Visualizing the **Fermi level** in **n-type material**...



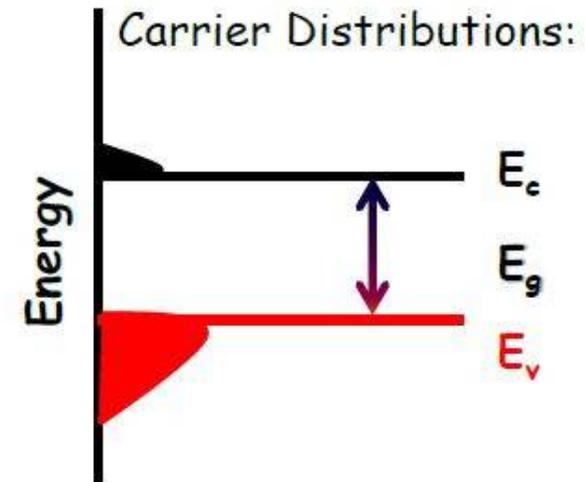
- In **n-type material**:
 - The Fermi level now lies closer to the conduction band.
 - There are many more electrons
 - The difference between E_f and E_v provides a measure of the strength of the doping.



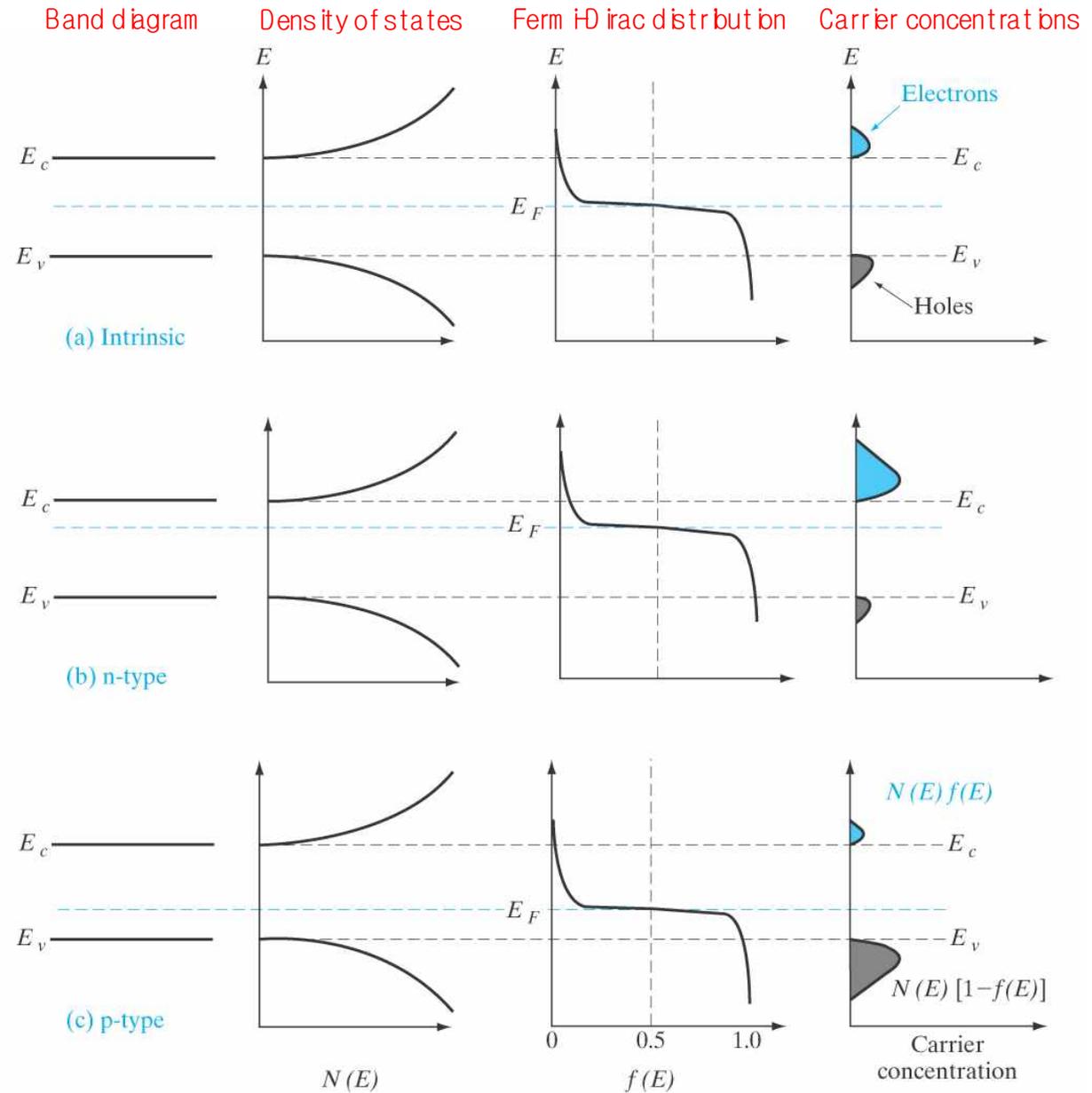
Visualizing the **Fermi level** in **p-type material**...



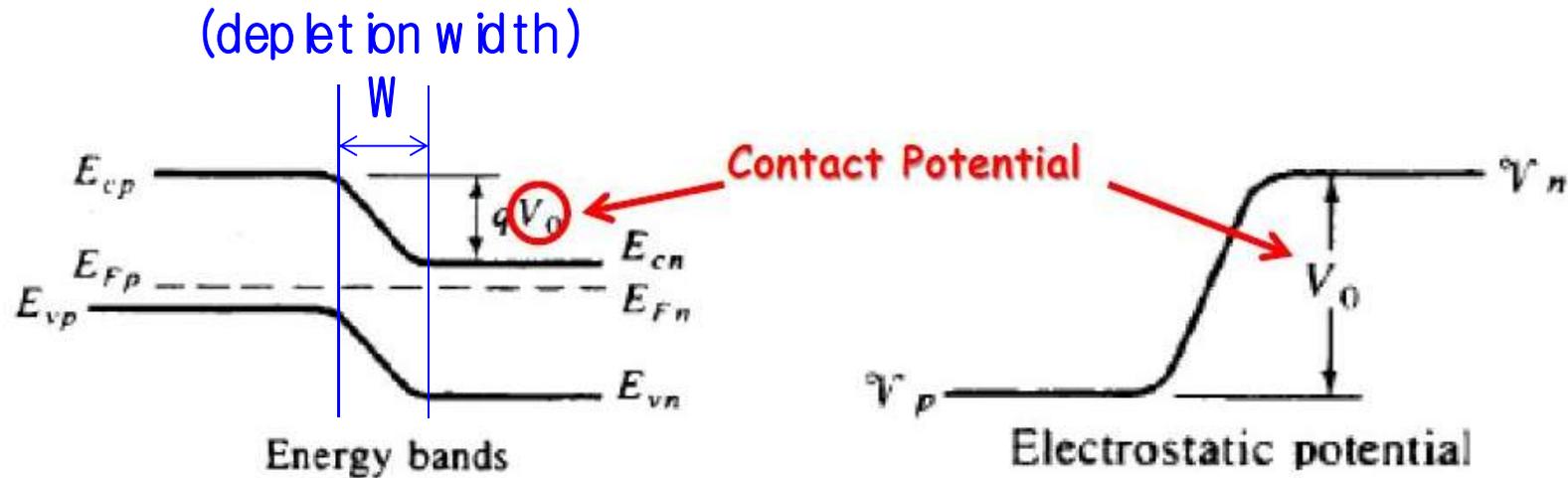
- In **p-type material**:
 - The Fermi level now lies closer to the valence band.
 - There are many more holes



- Compare three cases (intrinsic, n and p type) in one charts
- Band diagram, Density of states, Fermi-Dirac distribution and carrier concentrations for intrinsic, n type and p type materials



Junction under Equilibrium



•The contact potential is the voltage necessary to maintain equilibrium at the junction.

Since there should be no current flowing under equilibrium, the Fermi level of PN junction without external bias should be flat.

⇒ Therefore $E_{cp} > E_{cn}$ & $E_{vp} > E_{vn}$

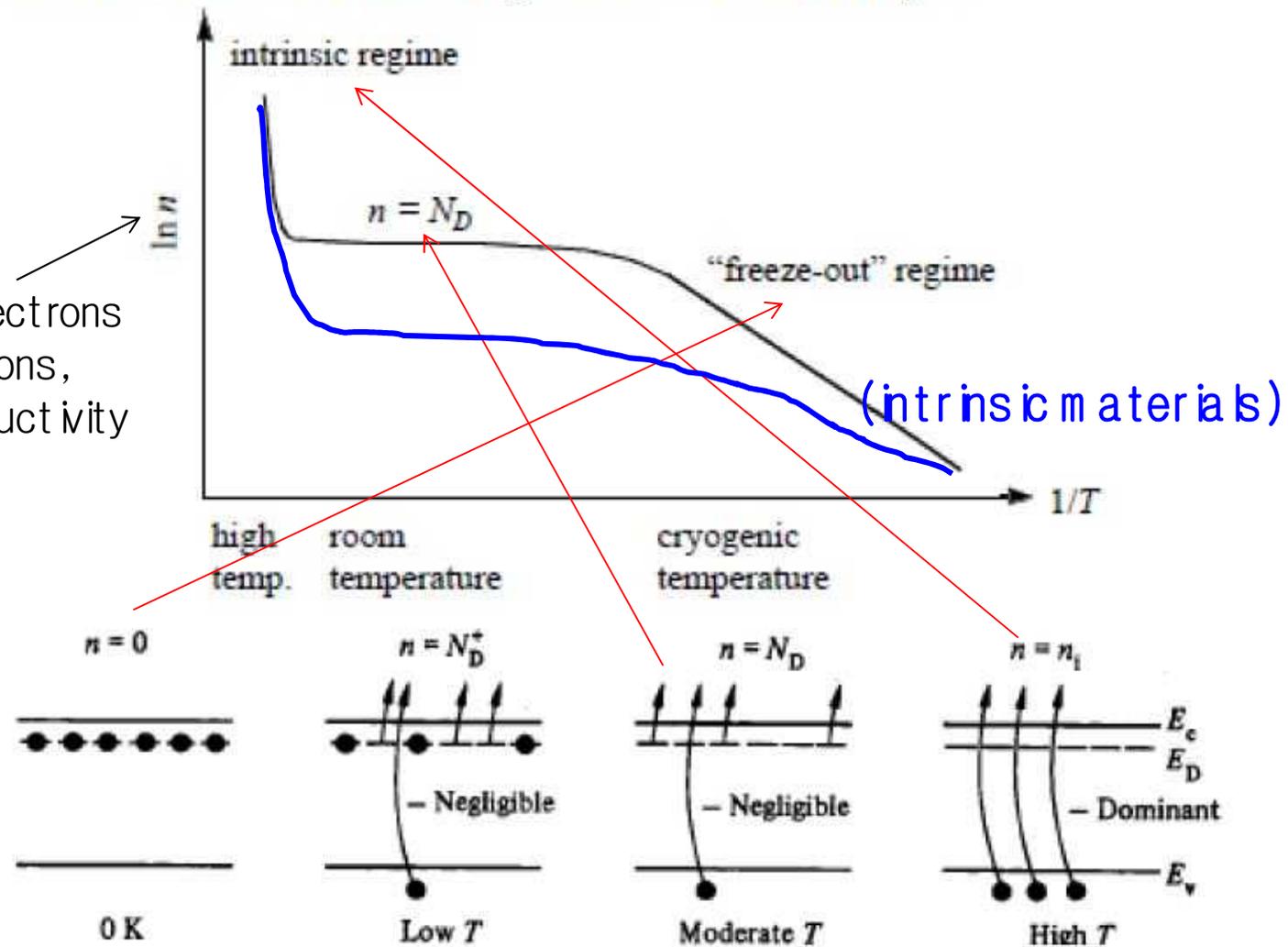
⇒ More about junctions in the next chapter

Temperature Effect

What is the role of temperature?? (n-type materials)

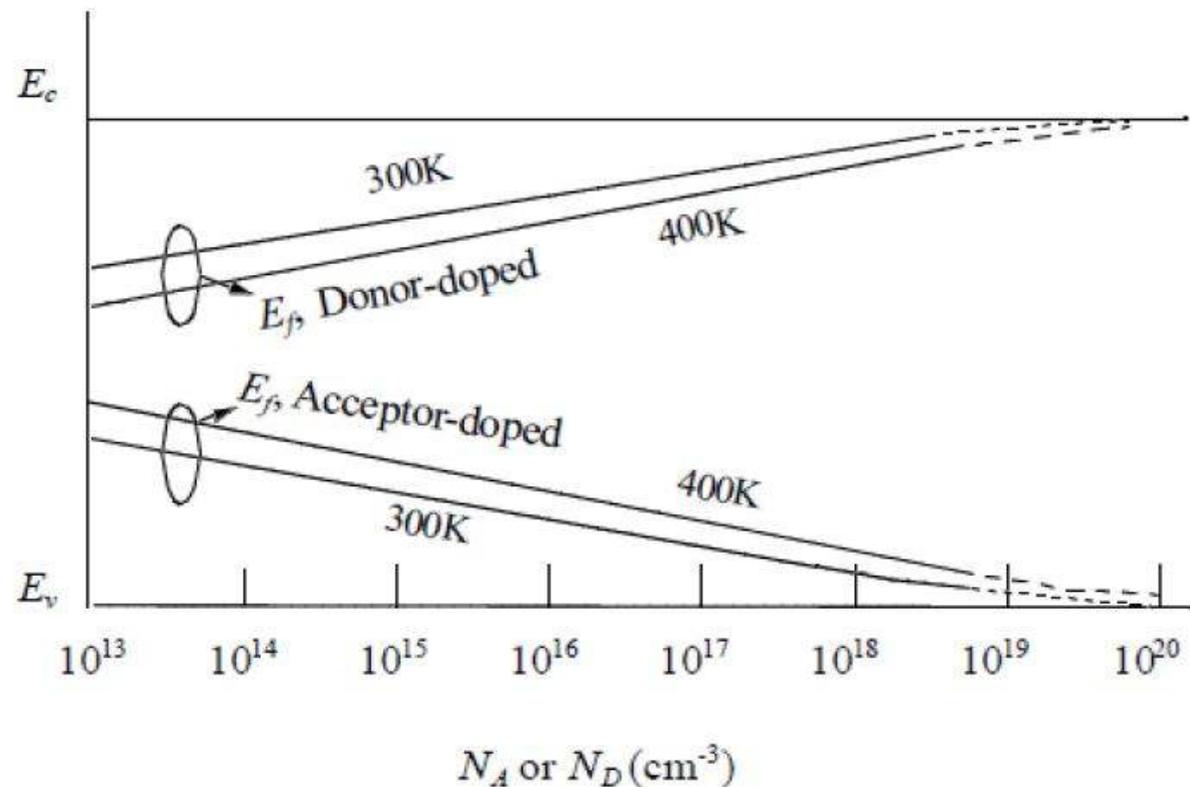
Temperature defines three distinct regions of conductivity...

- Available electrons
- More electrons, higher conductivity



So where does the Fermi level lie for a doped semiconductor??

Fermi level positioning in Si at 300 K as a function of the doping concentration...



- i) At higher doping concentration, E_f approaches E_c (CB) or E_v (VB).
- ii) At higher temperature, thermal contribution to electron hole pairs becomes higher, which leads to more intrinsic property. (N_A and N_D is acceptor and donor concentration)

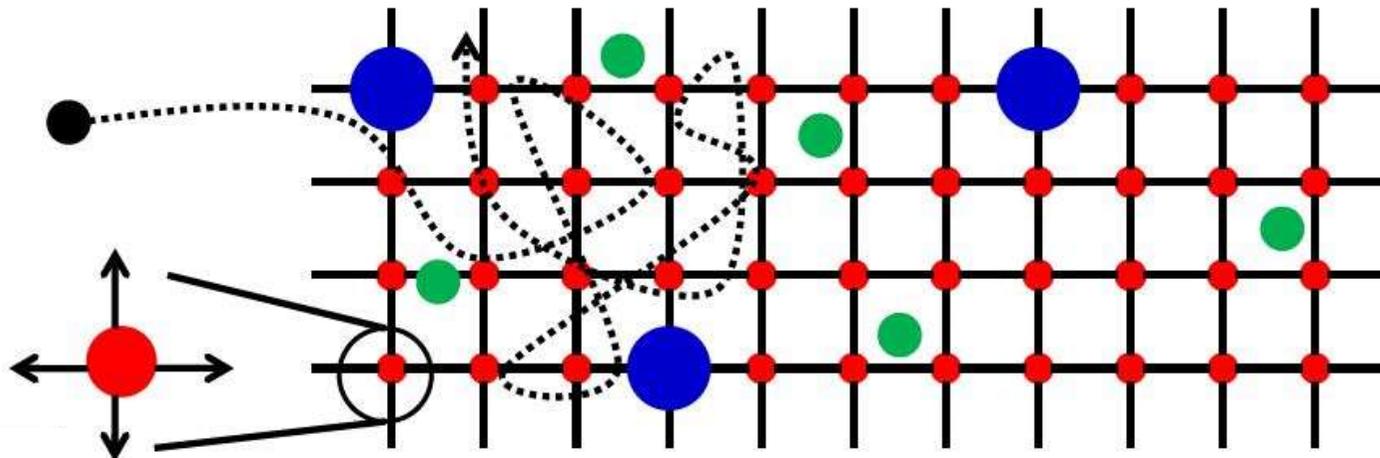
Carrier Scattering

– Three major carrier transport:

i) Random thermal motion, ii) Drift and iii) Diffusion

Carriers are not sitting, what are they doing?

- The carriers are in constant motion!
 - Thermal motion of carriers may be viewed as a random walk.
 - The carriers are interacting with many different things:
 - Lattice vibrations - Increases with temperature
 - Other electrons - Increases with carrier concentrations
 - Impurities - Increases with doping concentrations



So they move quickly, so what?

Let's see how far they go before they scatter...

Define the characteristic time between collisions: τ_c (in seconds)

Define the characteristic length of thermal motion (mean free path): $\lambda \equiv v_{th} \tau_c$ (in meters)

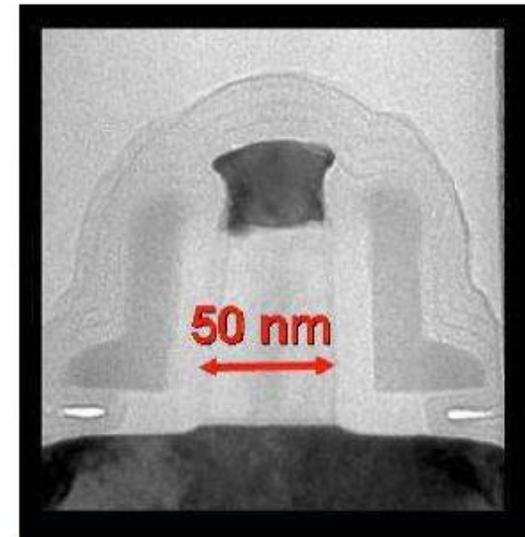
Plug in numbers characteristic of silicon at room temperature:

$$\tau_c \approx 10^{-14} \sim 10^{-13} \text{ s}$$

$$v_{th} \approx 10^5 \frac{\text{m}}{\text{s}}$$

$$\rightarrow \lambda \approx 1 - 10 \text{ nm}$$

Carriers scatter many times in a typical device!!

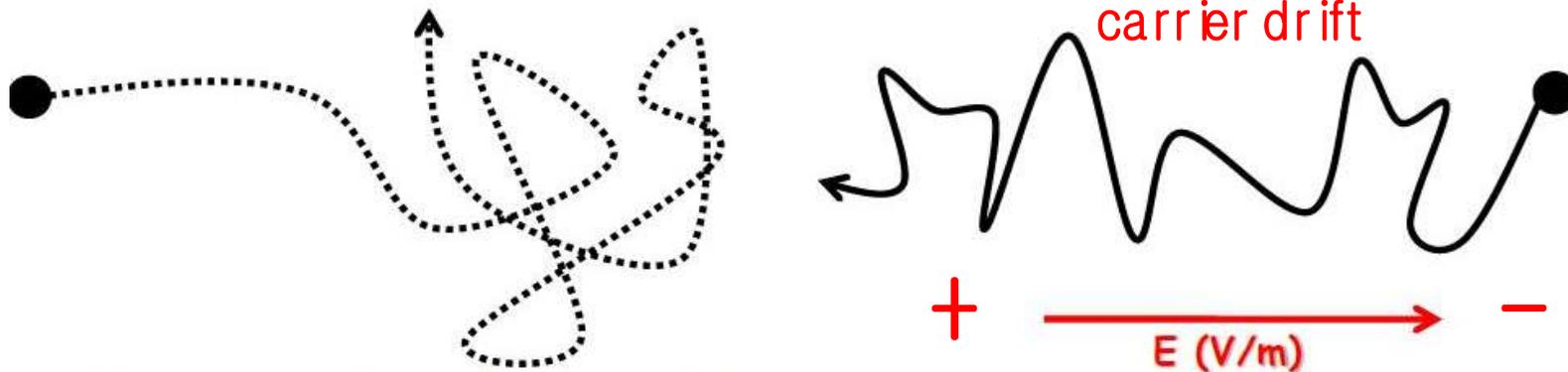


For every ~5nm movement of a carrier in semiconductor, we have collision (scattering). Carrier scattering dramatically increases in polycrystalline and amorphous materials.

Drift of Carriers

We want controlled motion of carriers rather than random motion in our device.

Net current in any direction is zero! So let's **apply an electric field** to our semiconductor...

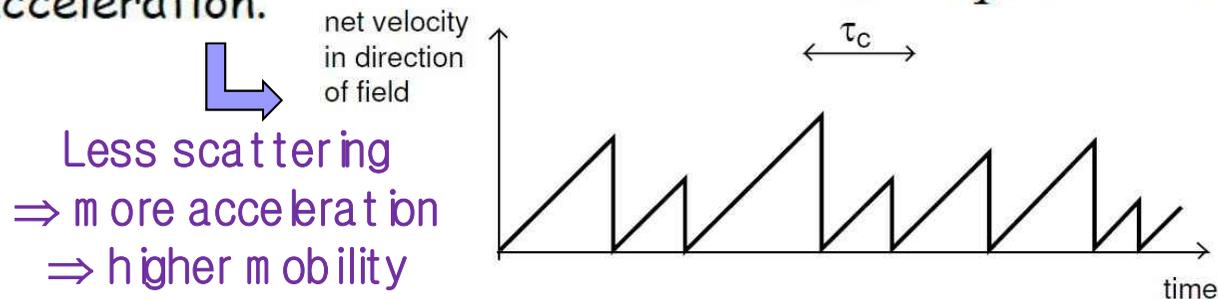


- Now the mobile charges will be accelerated by the electric field.
- This superimposes a direction on the random walk.
- Because of scattering, carriers do not achieve constant acceleration.

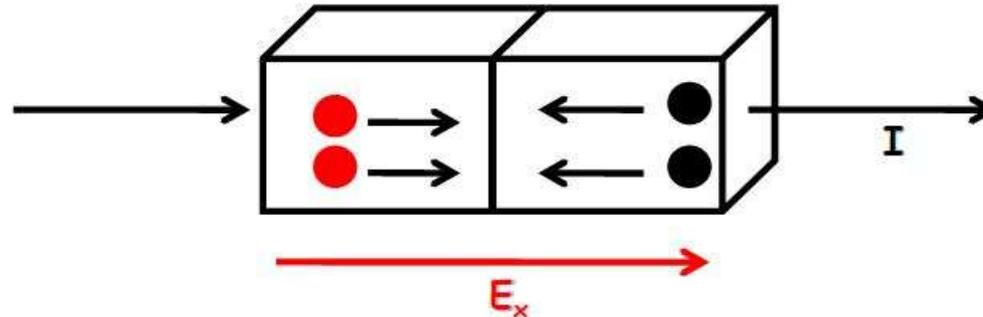
↓ Net force on carriers

$$F = -qE \quad \text{Electrons}$$

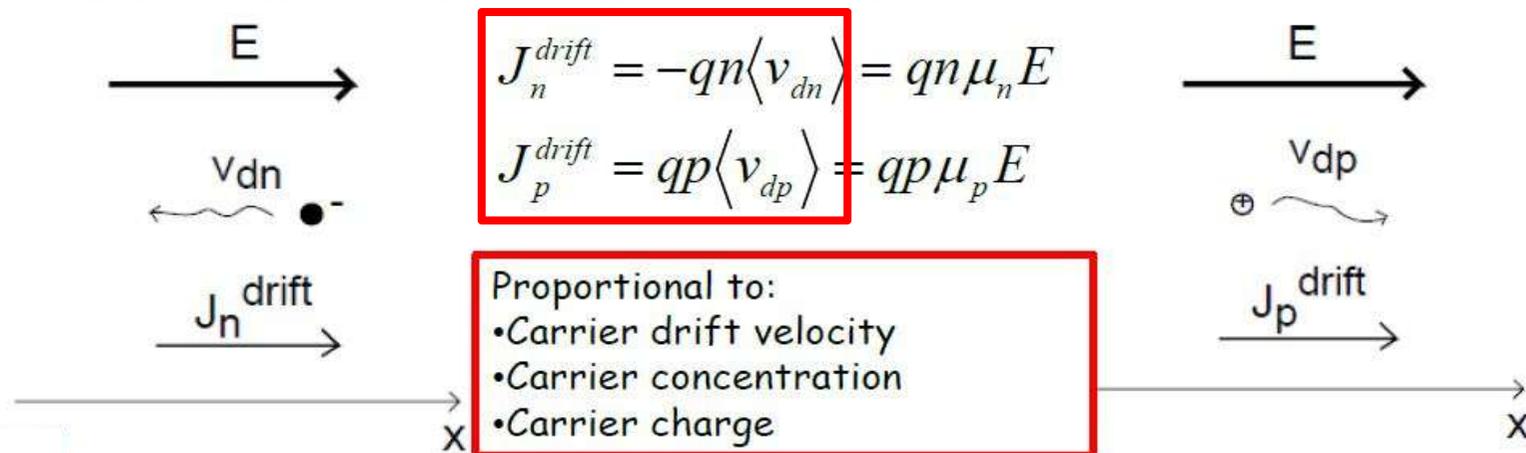
$$F = qE \quad \text{Holes}$$



With this information, we can define the **drift current**...



We want to define a current, or charge per unit time crossing of observation orientated normal to the direction of current flow.



Important equations from carrier drift ($\langle v \rangle = \mu E$, by definition)

Drift current density	form of <i>Ohm's Law</i>	Conductivity and resistivity
$\mathbf{J}^{drift} = \mathbf{J}_n^{drift} + \mathbf{J}_p^{drift} = q(n\mu_n + p\mu_p)\mathbf{E}$	$\mathbf{J} = \sigma\mathbf{E} = \frac{\mathbf{E}}{\rho}$	$\sigma = \frac{1}{\rho} = q(n\mu_n + p\mu_p)$

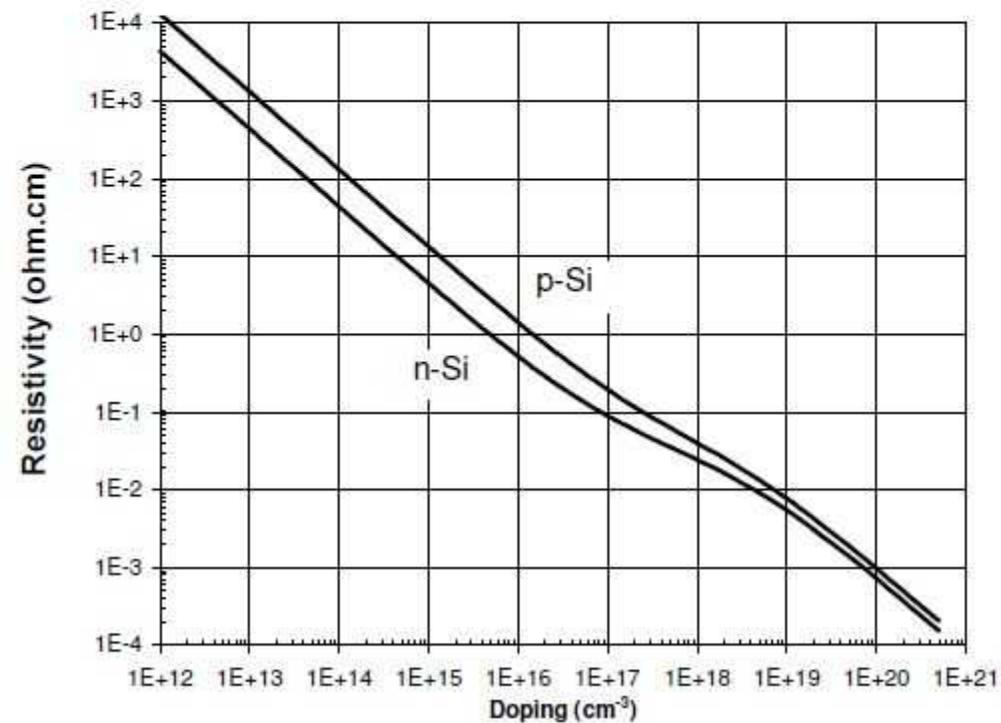
Resistivity - reverse of conductivity

- In n-type semiconductor:

$$\rho_n \approx \frac{1}{qN_d\mu_n}$$

- In p-type semiconductor:

$$\rho_p \approx \frac{1}{qN_a\mu_p}$$



Carrier Mobility

And from the definition of the current, we can define the **mobility**...

Using the definitions for the hole and electron drift currents:

$$J_n^{drift} = -qn\langle v_{dn} \rangle = qn\mu_n E$$

$$J_p^{drift} = qp\langle v_{dp} \rangle = qp\mu_p E$$

The electron and hole mobility then becomes:

$$\mu_n = \frac{q\tau_c}{2m_n^*}$$

collision time
effective mass

Electron Mobility

$$\mu_p = \frac{q\tau_c}{2m_p^*}$$

Hole Mobility

What can we say about the **mobility** in general?

- Refers to the ease with which carriers move through a host crystal.

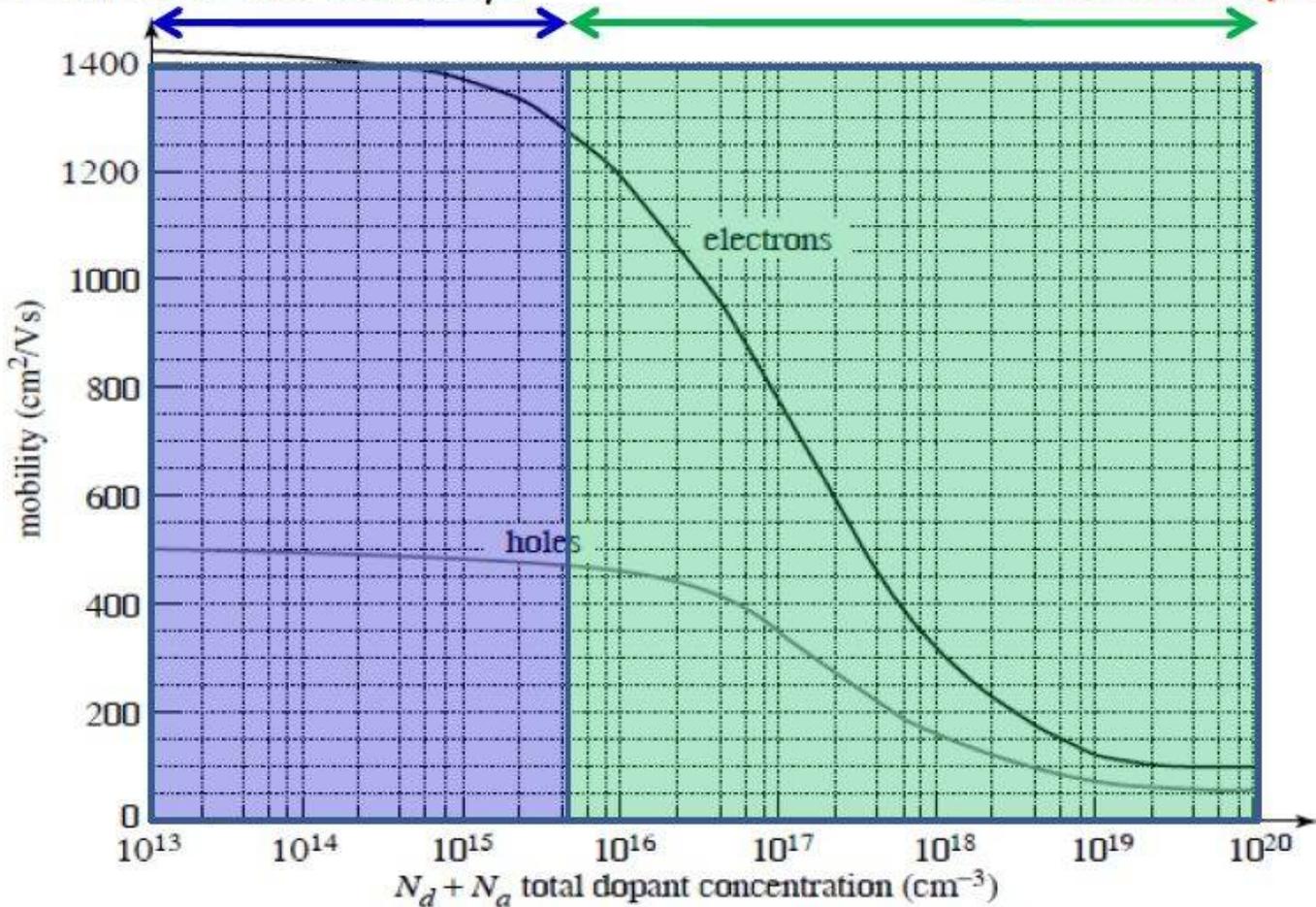
In units of:

$$\frac{cm^2}{V \cdot s}$$

Scattering and Mobility

What else effects the mobility?

Silicon mobility at 300 K



Lattice Scattering

Collision with lattice

Ionized Impurity Scattering

Collision with ionized impurity (dopant)

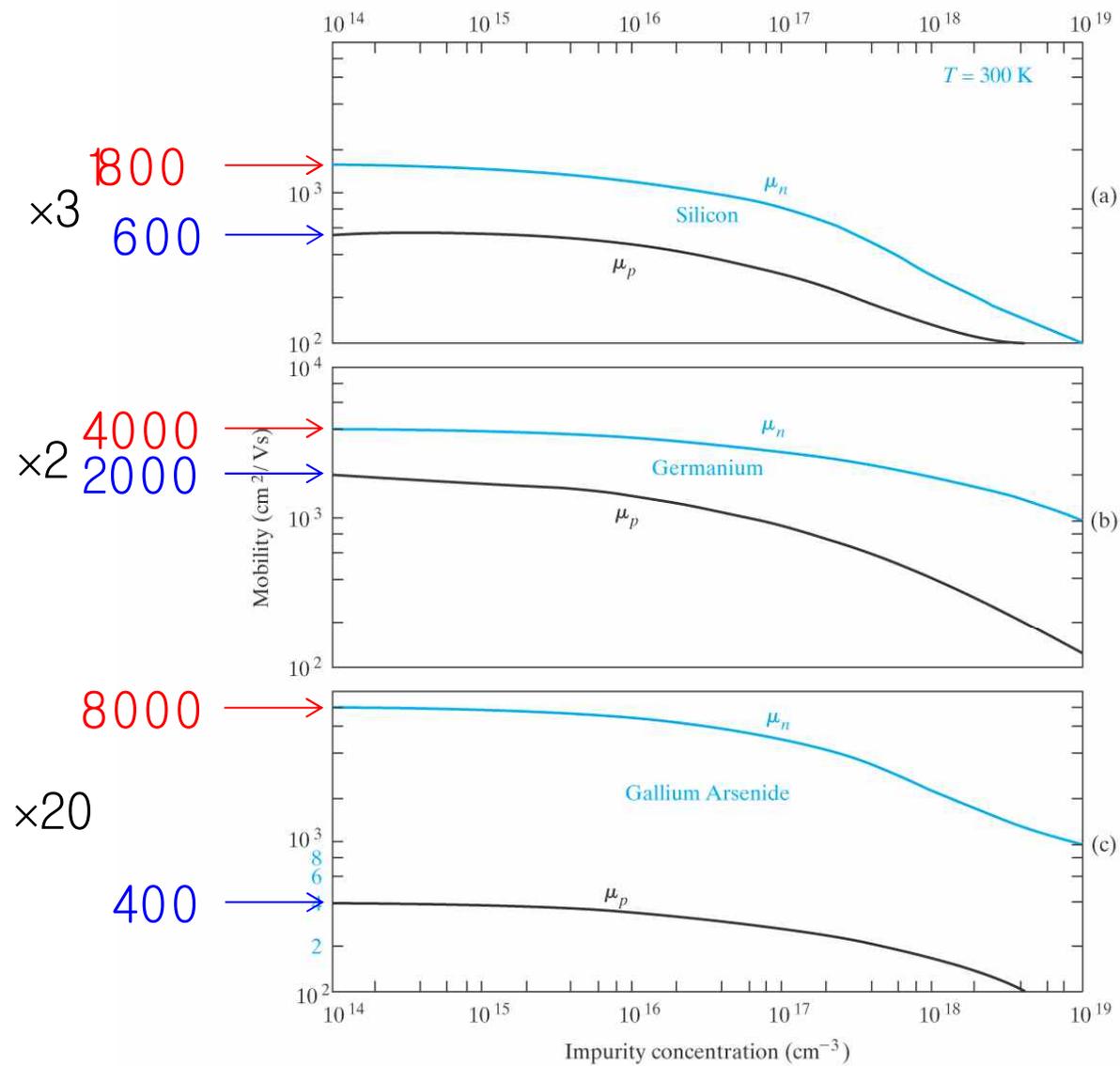
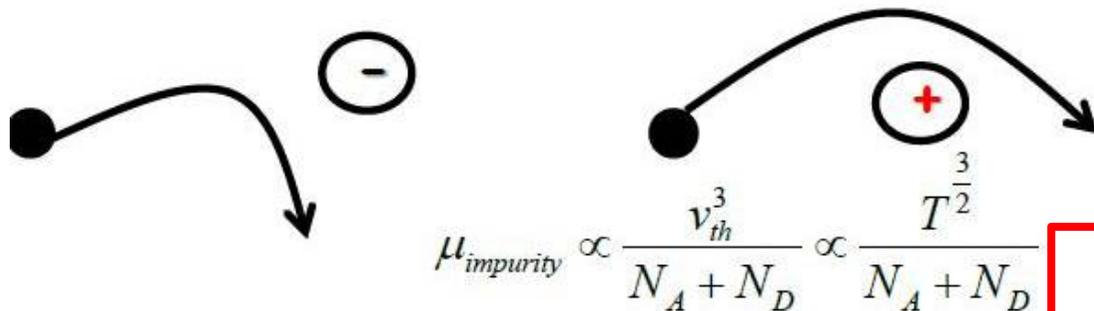


Figure 3.23

Variation of mobility with total doping impurity concentration ($N_a + N_d$) for Ge, Si, and GaAs at 300 K.

Two main competing scattering mechanisms of drifting carriers

Impurity (dopant) Scattering:

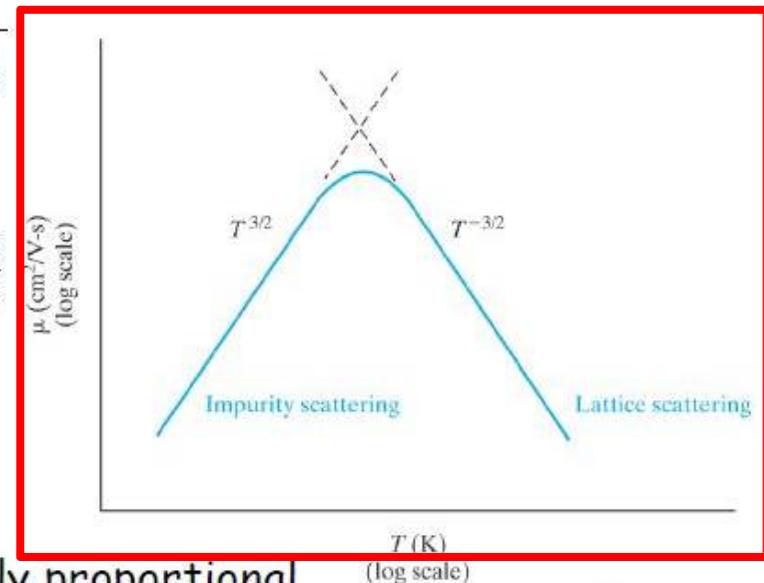


- The force acting on the particles is Coulombic.
- There is less change in the electron's direction of travel the faster it goes.

Phonon (lattice) Scattering:

$$\mu_{phonon} = \frac{q \tau_{phonon}}{m^*} \propto \frac{1}{\#_{phonons} \times v_{th}} \propto \frac{1}{T \times T^{1/2}} \propto T^{-\frac{3}{2}}$$

Phonon scattering mobility decreases as the temperature increases.



Since the scattering probability is inversely proportional to the mean free time and the mobility, we can add individual scattering mechanisms inversely.

(Total scattering probability = \sum individual scattering probability)

$$\frac{1}{\mu} = \frac{1}{\mu_{impurities}} + \frac{1}{\mu_{lattice}} + \frac{1}{\mu_{defects}} + \dots$$

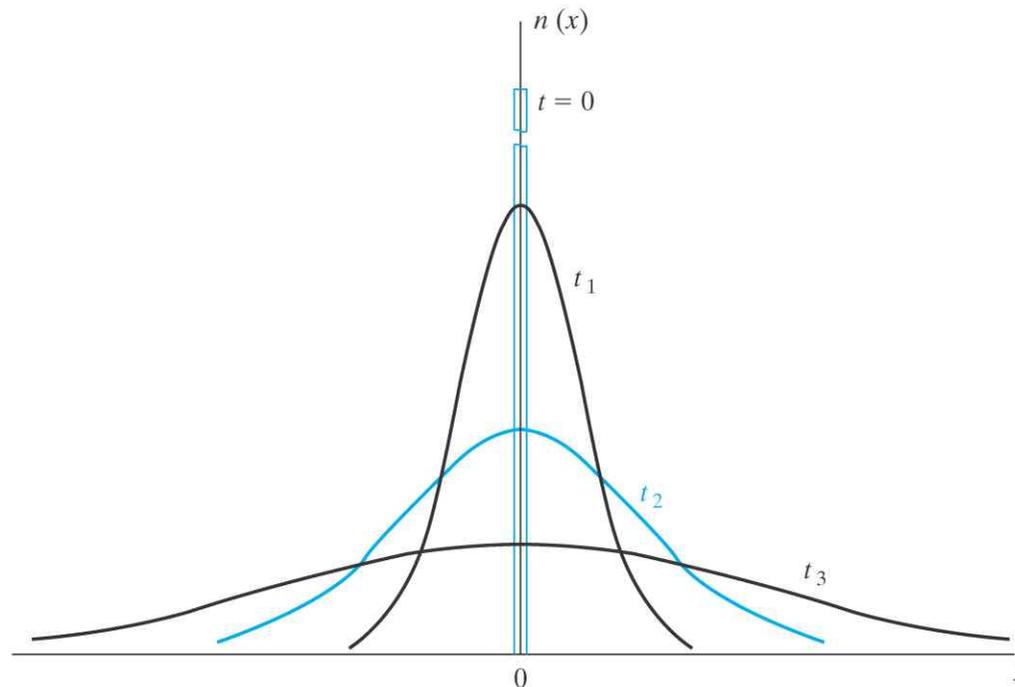
Diffusion of Carriers

- Carriers in a semiconductor diffuse in a carrier gradient by random thermal motion and scattering from the lattice and impurities, from high concentration to low concentration.

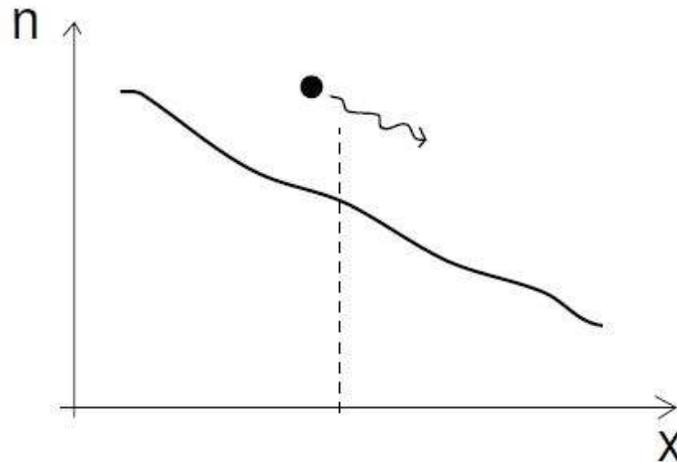
Cf) Drift: driving force - electric field

Diffusion: driving force - concentration difference

- Example: A pulse of excess electrons injected at $x=0$ at time $t=0$ will spread out in time as shown in Fig. 4.12.



Diffusion = particle movement (flux) in response to concentration gradient



Diffusion flux \propto - concentration gradient

Flux \equiv number of particles crossing a unit area per unit time [$\text{cm}^{-2} \cdot \text{s}^{-1}$]

For Electrons:

$$F_n = -D_n \frac{dn}{dx}$$

For Holes:

$$F_p = -D_p \frac{dp}{dx}$$

Diffusion current density = charge \times carrier flux

$$J_n^{diff} = qD_n \frac{dn}{dx}$$

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

- If an electric field is present in addition to the carrier gradient, the current densities will each have a drift component and a diffusion component.
- Therefore the total current density is as follows:

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

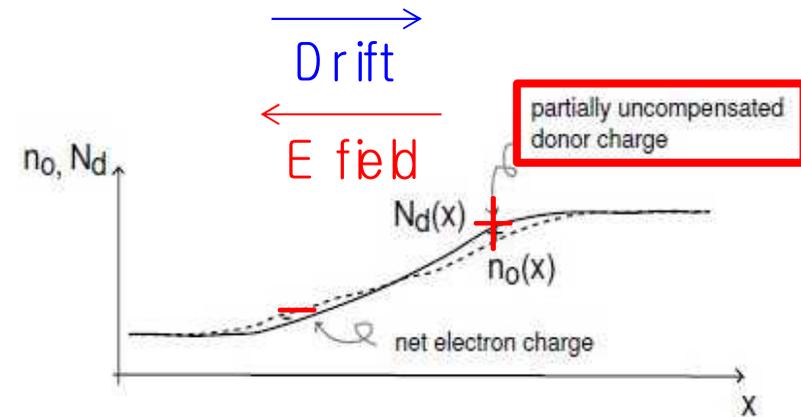
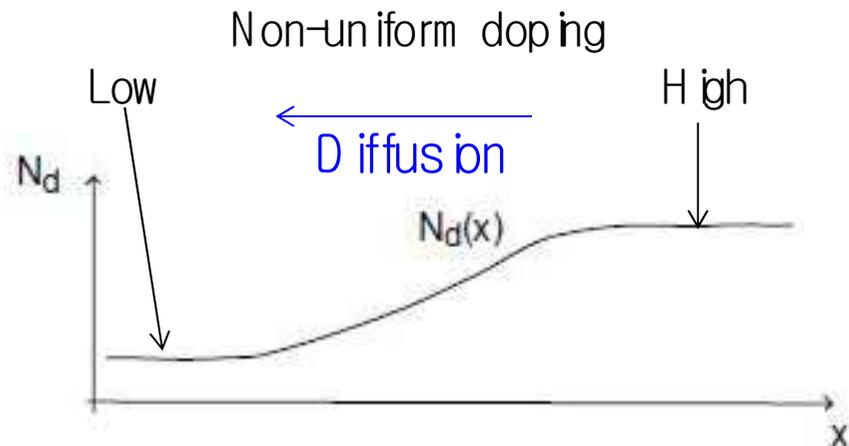
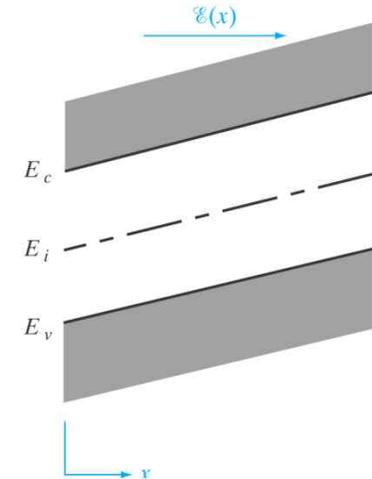
$$J_p = J_p^{drift} + J_p^{diff} = qp\mu_p E - qD_p \frac{dp}{dx}$$

$$J_{total} = J_n + J_p$$

- Majority carriers mainly contribute through drift, while minority carriers contribute through diffusion.
- The concentration of majority current can be much larger than minority current, but the concentration gradient of minority current can be significant.
- Therefore diffusion current by minority carriers sometimes is comparable to drift current by majority carriers (ex. Diode, Drift - transistor)

- It is important to discuss the influence of electric field on the energies of electrons in the band diagrams.
- Let's assume E field $E(x)$ in the x direction, then the energy band bending will be as shown in the right figure (Fig.4.15).
- From the definition of electric field, $E(x)$ is as follow:

$$E(x) = -dV/dx \text{ or } -\Delta V/l$$



- For non-uniform doping in equilibrium (no net current), the carrier concentration gradient (due to non-uniform doping) make a diffusion current, while a built-in electric field (by uncompensated charges) makes a drift current.
- For both electron and hole components, the net current is zero and thus drift and diffusion current are canceled out.

$$J_n(x) = J_n^{\text{drift}}(x) + J_n^{\text{diff}}(x) = 0$$

Summary

In Chapter 3 and 4 (Streetman, Solid State Electronic Devices), we have learned fundamental concepts for electronic device (diodes, transistors, circuits) study.

- (1) bonding, antibonding
 - (2) band structure (conduction, valence band, band gap)
 - (3) direct gap and indirect gap materials
 - (4) electron, hole and their pairs
 - (5) bands in electric field
 - (6) intrinsic and extrinsic materials
- } Fundam ental Concepts
- (7) p type and n type doping
 - (8) Fermi level
 - (9) temperature effect on semiconductor
 - (10) carrier drift
 - (11) mobility, resistivity and scattering
 - (12) carrier diffusion
- } More Applied Concepts

The questions, when we begin these chapters, were...

- (1) How to make different charge distribution: n and p type regions
- (2) How to make carriers (charges) move (transport) from one location to the other in a controlled way (by applying bias or by making carrier concentration gradient)