
Semiconductor Devices (EE336)

Lec. 3: Charge Carriers and Doping

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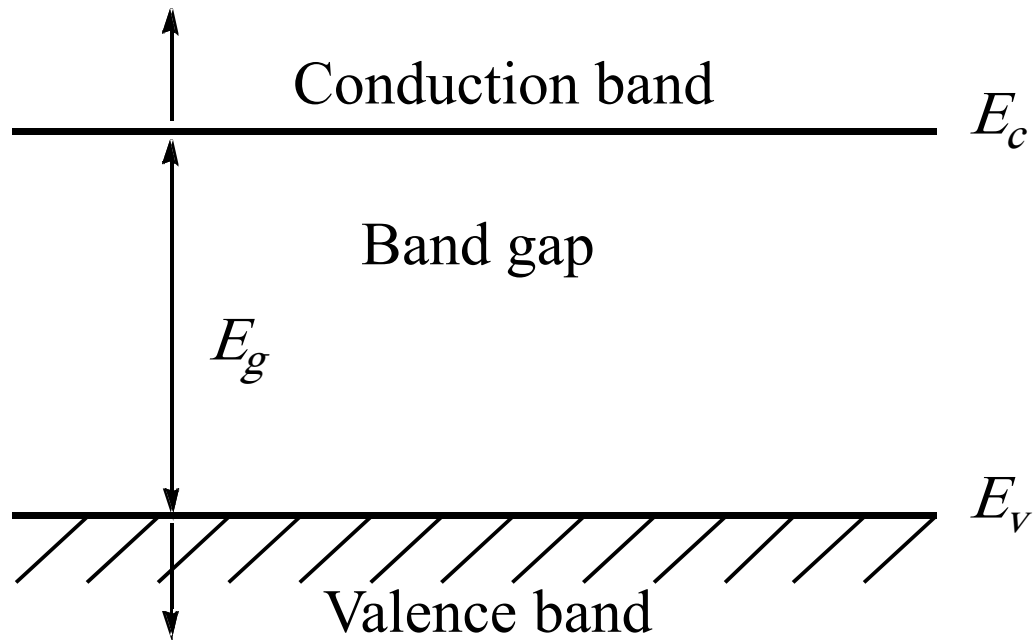
Lecture Outline

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- ❑ Energy band diagram and measurement of energy gap
- ❑ Metals, insulators and semiconductors
- ❑ Band diagrams versus E-k diagrams
- ❑ Direct and indirect bandgap SC materials
- ❑ Effective mass
- ❑ Intrinsic versus extrinsic SCs

Energy band diagram

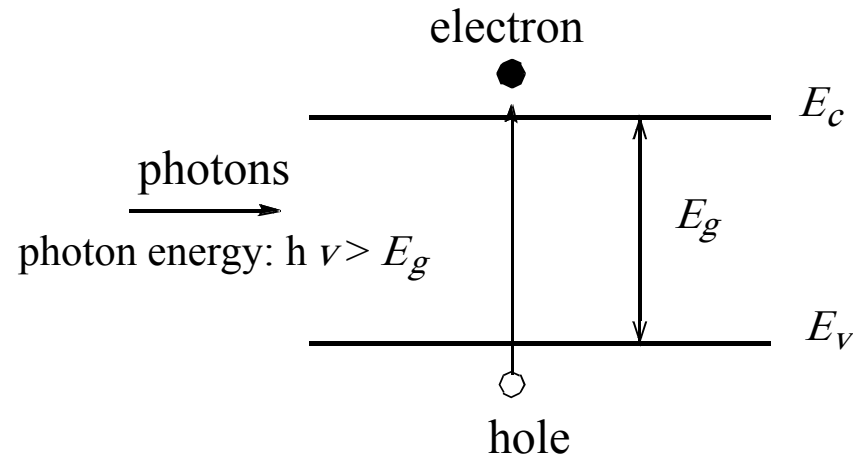
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- **Valence band** is the topmost filled energy band and **Conduction band** is the lowest empty energy band
- **Energy band diagram** shows the bottom edge of conduction band, E_c , and top edge of valence band, E_v .
- E_c and E_v are separated by the **band gap energy**, E_g .

Measuring energy gap by light absorption

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- E_g can be determined from the minimum energy ($h\nu$) of photons that are absorbed by the semiconductor.

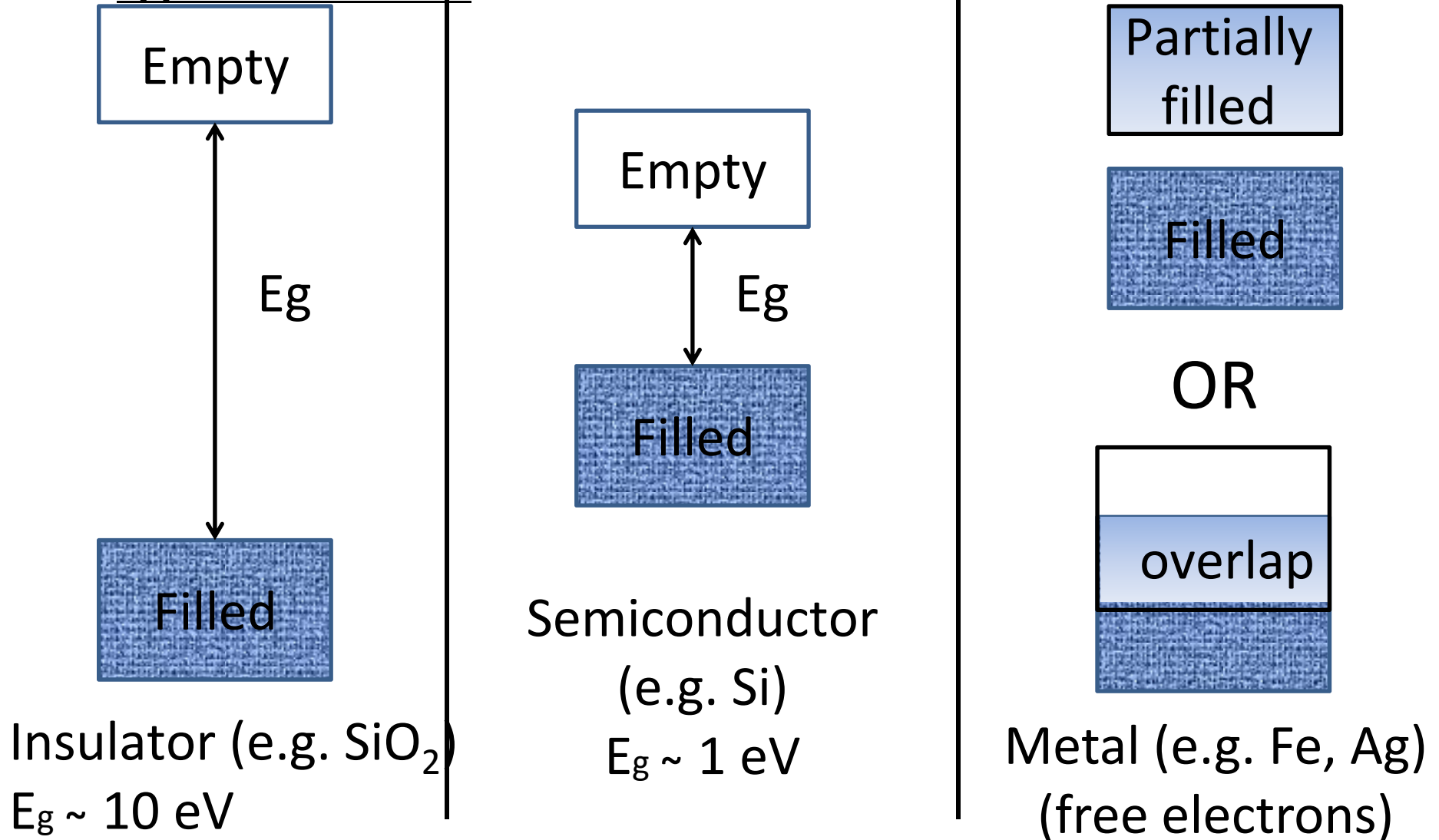
Bandgap energies of selected semiconductors

Semi-conductor	InSb	Ge	Si	GaAs	GaP	ZnSe	Diamond
E_g (eV)	0.18	0.67	1.12	1.42	2.25	2.7	6

Distinction of metals, insulators and semiconductors

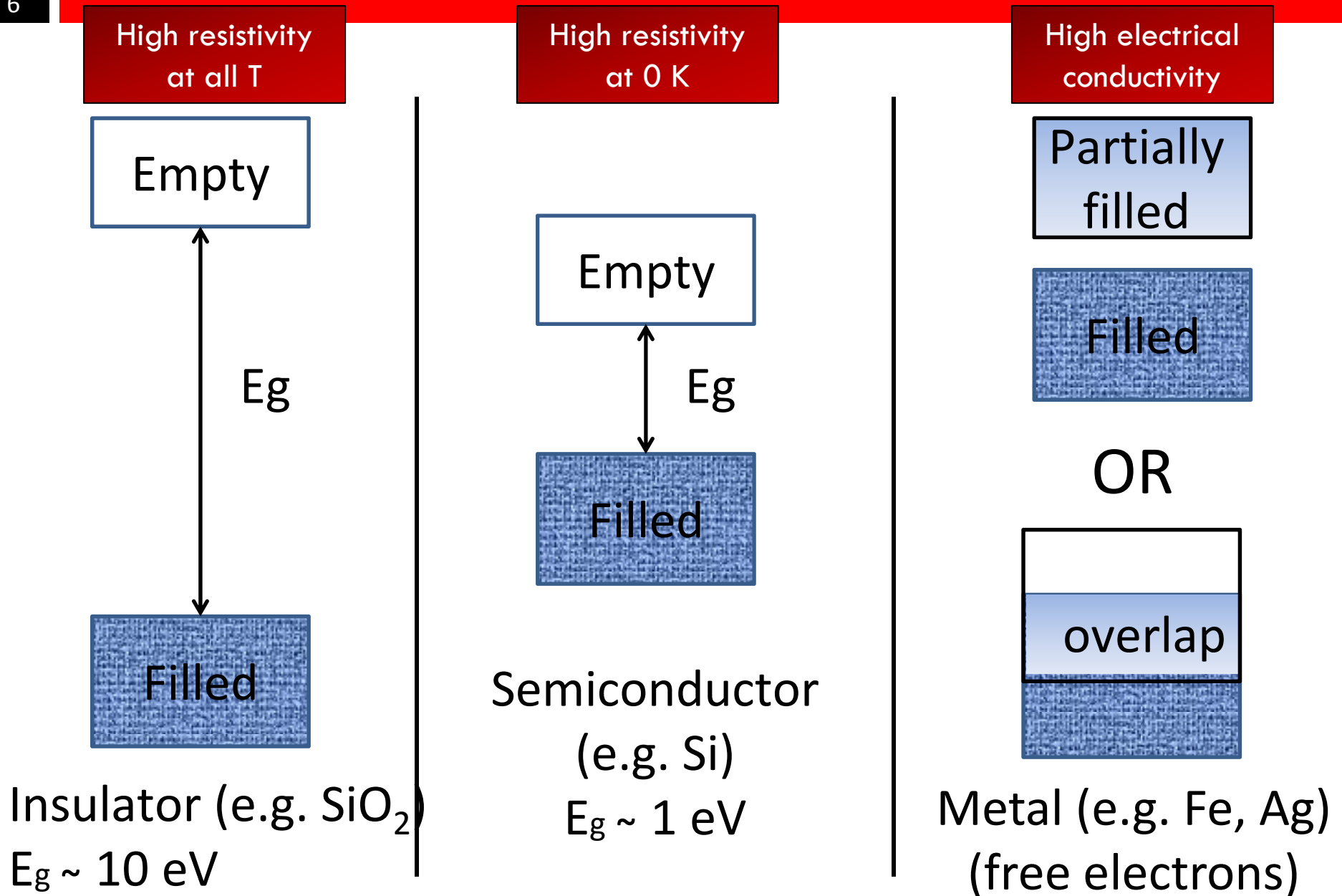
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- Totally filled and totally empty bands do not allow current flow under applied electric field



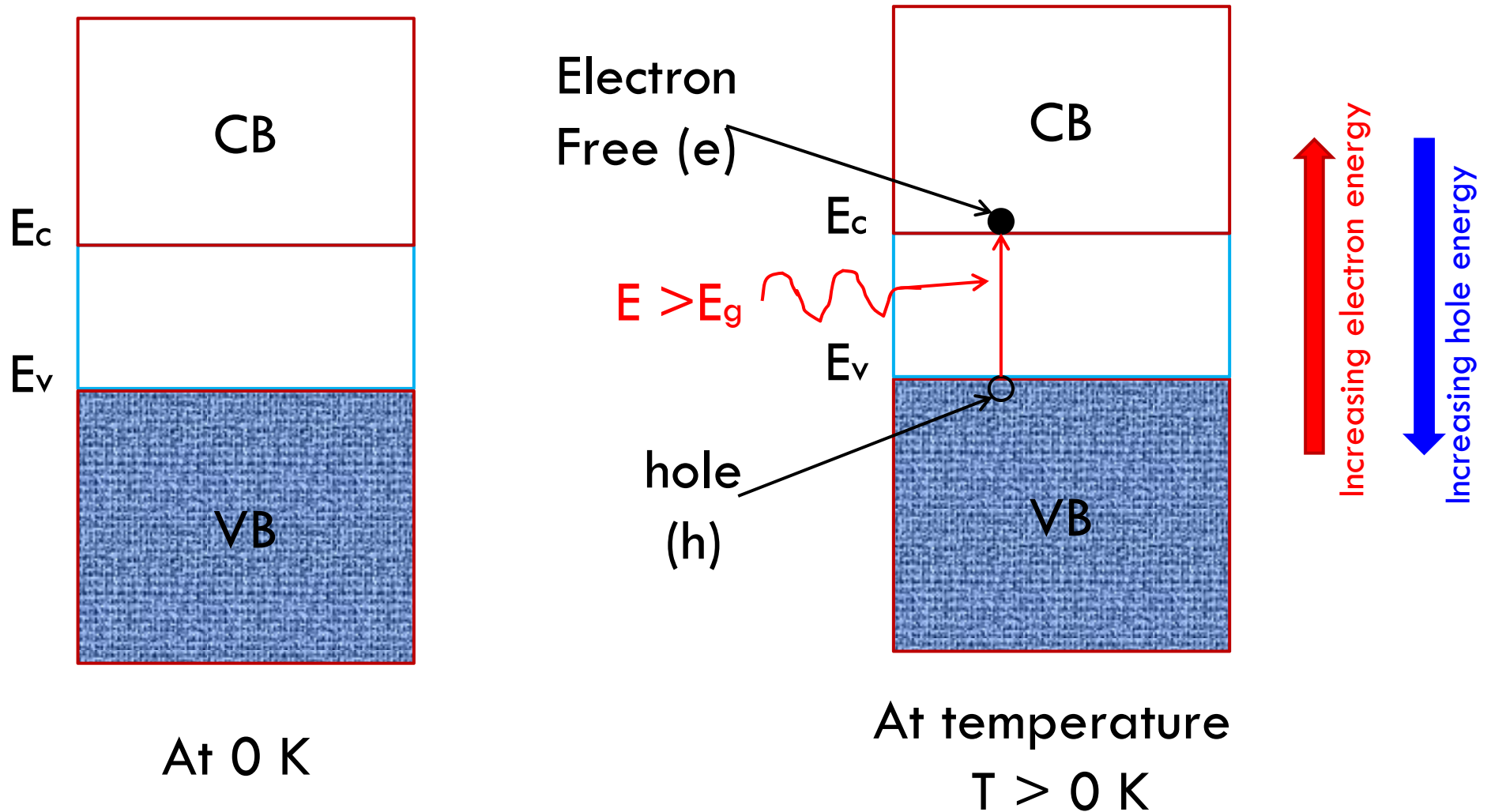
Distinction of metals, insulators and semiconductors

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Electron hole pair (EHP) generation

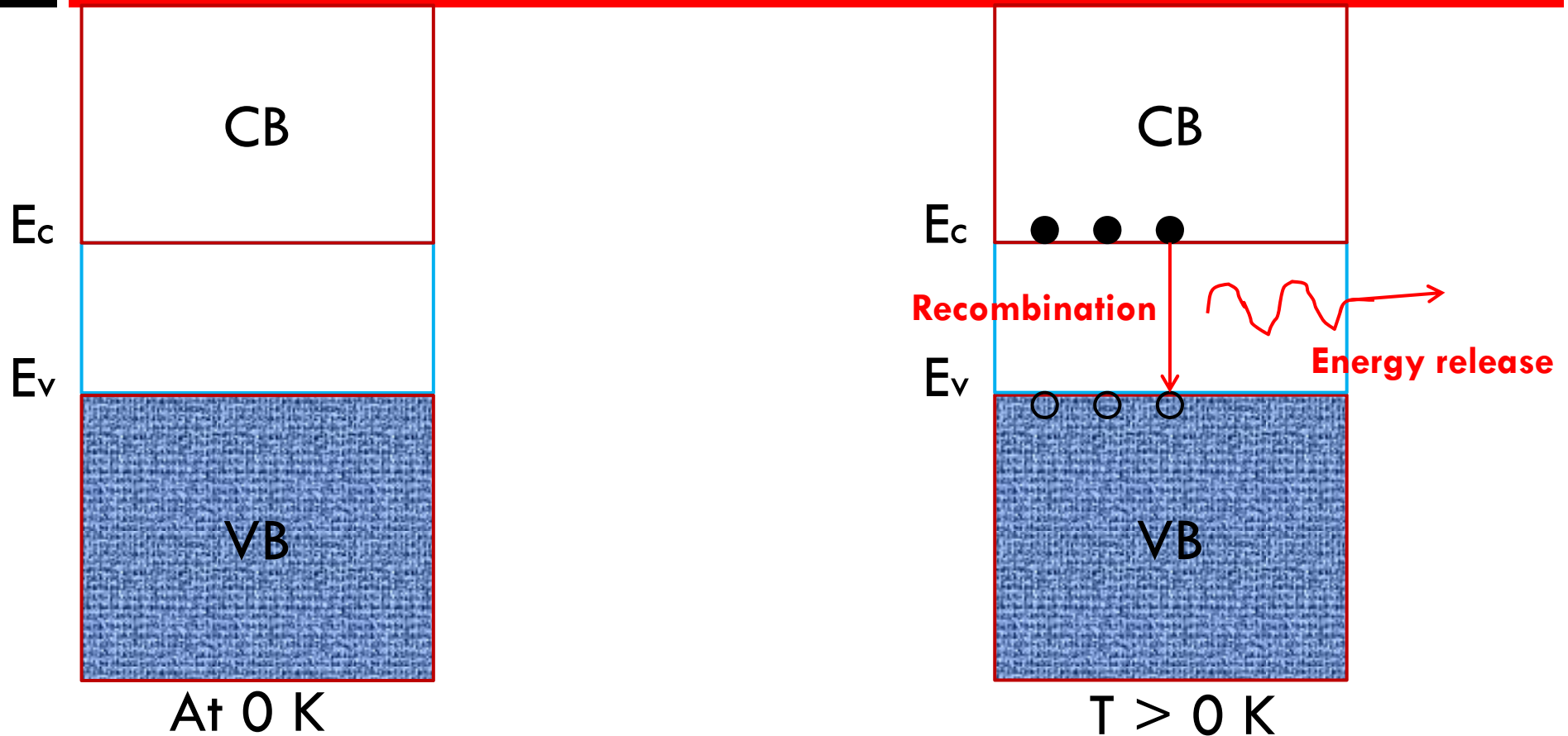
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- Electrons and holes tend to fill their lowest possible energy level
- Electron hole pairs (EHPs) are the charge carriers that are responsible for current conduction

Recombination process

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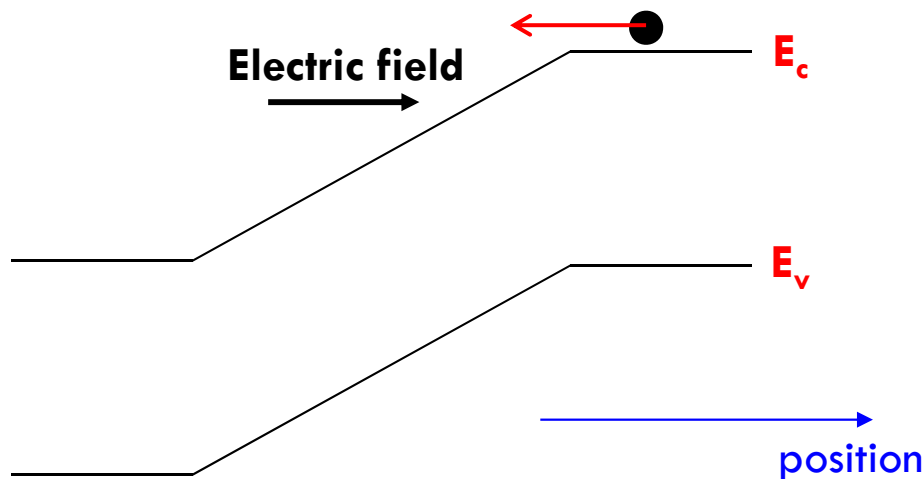


- EHPs are destroyed or cancelled when an electron makes downward transition from CB to VB filling the empty state (hole)
- Recombination rate must equal the EHP generation rate such that the steady state carrier concentration (# of electrons and holes / cm^3) stays constant at a certain temperature
- Energy release sometimes on the form of photon emitted (direct semiconductors) or not (indirect semiconductors)

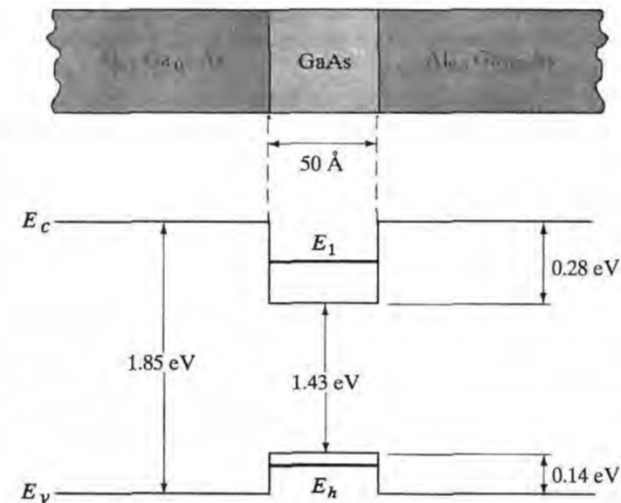
E-K diagrams

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- Band diagrams previously shown are useful for qualitative explanation of SC devices especially when we draw them at different position in the crystal (two examples below)



Linear slope in the energy band diagram with position means a constant electric field is externally applied which will cause an electron to drift in opposite direction



Quantum well created by sandwiching GaAs between two wider bandgap SC materials (AlGaAs)

- On the other hand, E-K diagrams result directly from the solution of Schrodinger's equation in which we plot the total Energy (E) versus the wavevector (k)

E-K diagrams

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- As an example, recall the simple “particle in a box” problem

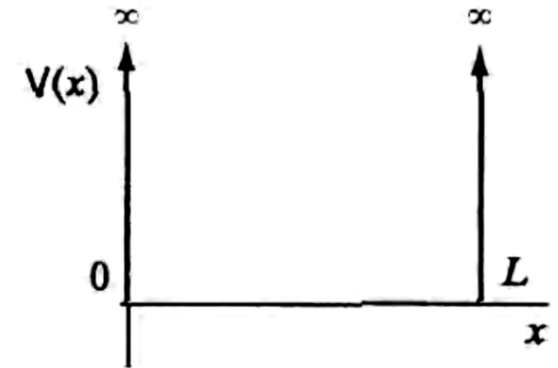
$$-\frac{\hbar^2}{2m} \nabla^2 \psi + V\psi = E\psi$$

$$E_n = \frac{\hbar^2}{2m} k^2 = \frac{\hbar^2 \pi^2}{2mL^2} n^2$$

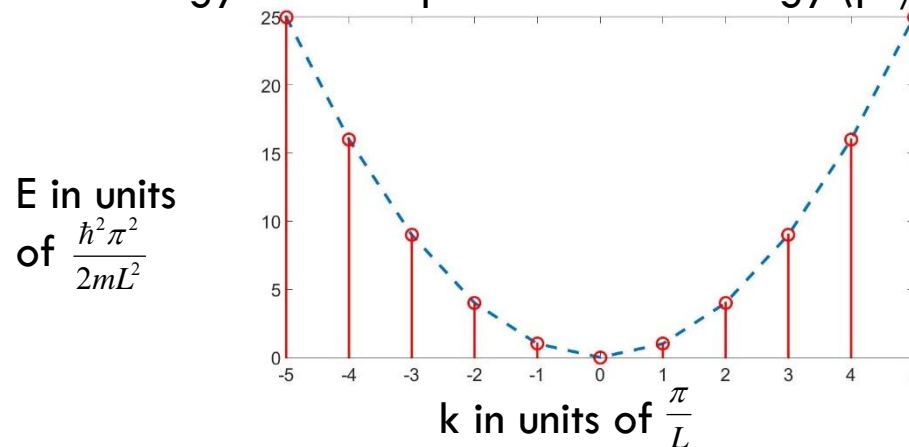
$$-\frac{\hbar^2}{2m} \frac{\partial^2 \psi}{\partial x^2} + V\psi = E\psi \quad (1D)$$

$$V = \begin{cases} \infty & x = 0 \text{ and } L \\ 0 & \text{elsewhere} \end{cases}$$

$$k = \frac{n\pi}{L}$$



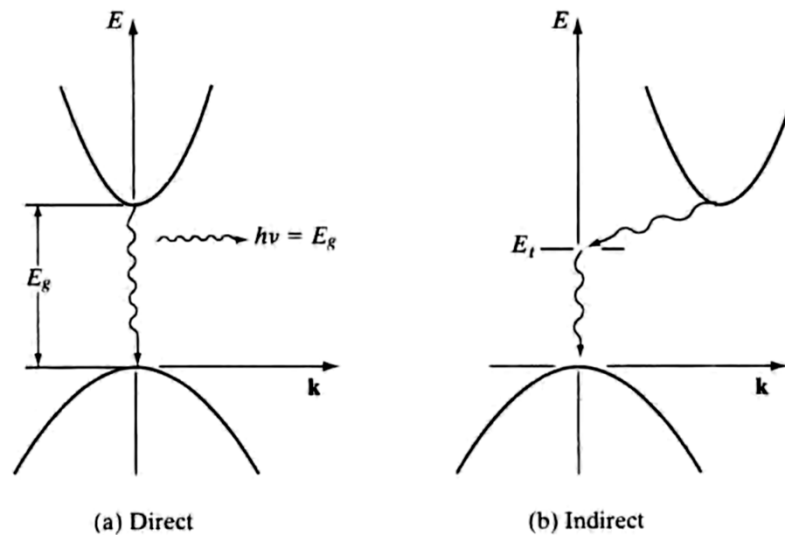
- The E-K relationship is quadratic (or parabolic) where only discrete (quantized) allowed values of k and E are allowed
- The quantization comes from the boundary conditions of the problem
- The result makes total sense since the electron has zero potential energy inside the well (V=0) and its total energy E must equal its Kinetic energy ($p^2/2m$)



E-K diagrams

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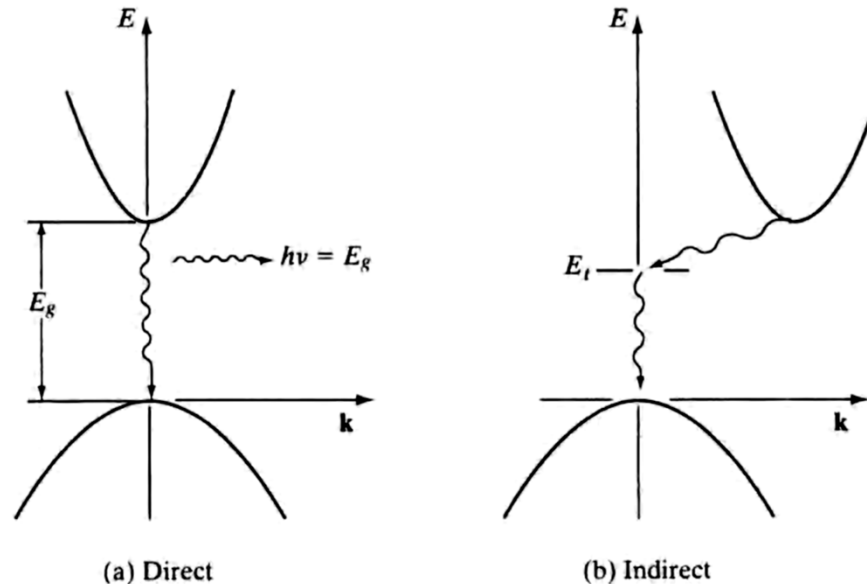
- For particles that are not free (e.g. electrons inside the periodic Coulombic potential well of the lattice), the solution of the Schrodinger equation also gives an E-k diagram
- For a periodic potential barrier, the allowed energy values are no longer discrete however they form bands (allowed intervals of E and corresponding k's)
- Those bands are separated by energy gaps (forbidden bands)
- For some materials the bottom of conduction band and top of valence bands have the same k \rightarrow called **direct bandgap** SCs (e.g. GaAs and InP)
- For some other materials, the bottom of conduction band and top of valence band have different values of k \rightarrow called **indirect bandgap** SCs (e.g. Si and Ge)



E-K diagrams

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- For direct bandgap materials, electron moving from CB minimum to VB maximum can do so without change in k , i.e. in momentum, releasing energy on form of emitted light (photon)
- For indirect bandgap materials, an electron must undergo momentum change first (change in k) before making the downward transition in E results in heat given up to the lattice not photon
- Hence, **Light emitting diodes (LEDs) and lasers are made from direct bandgap materials**

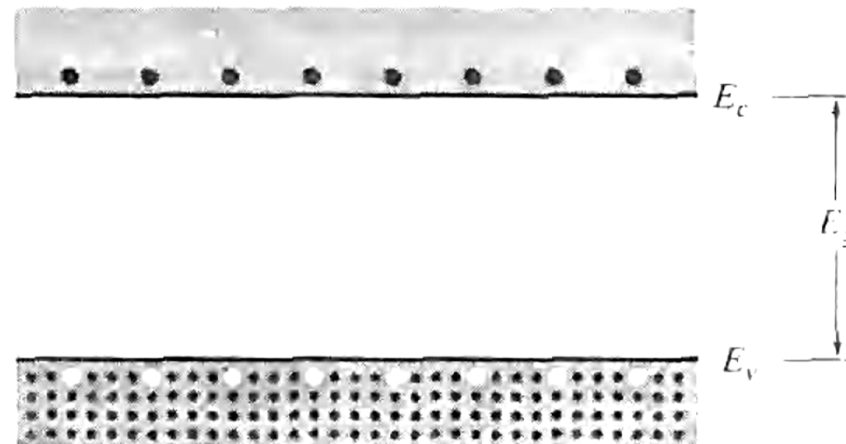


- To relate E-k diagrams to band diagrams, remember that E axis on E-k diagram contains both P.E+K.E whereas the band edges drawn in band diagrams denote the CB minimum and VB maximum where the K.E of the electrons and holes are zero, hence the band edges denote the potential energy change versus position in the crystal

Charge carriers

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- As we previously mentioned, electrons in CB and holes in VB are the charge carriers responsible for current conduction inside a SC
- At $T=0$, CB is empty and VB is completely filled (no conduction)
- For $T>0$, EHP will be generated
- Under an applied electric field, the free electrons in CB will move in opposite direction to E (drift) resulting in current in the same direction as electric field applied
- Also, the holes (+ve) in VB will move in the same direction as electric field contributing current drift in the same direction
- Hence the total drift current will be carried by both electrons and holes
- Of course, the number of carriers per cm^3 is a key parameters that must be derived since it will play an important role in calculation of drift current later on



Effective mass of charge carriers

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True mass (m_0) \leftrightarrow Effective Mass (m^*)

- ❑ Mass of a free electron in vacuum
- ❑ TRUE Mass of an electron is the same in different semiconductors

$$m_0 = 9.1 * 10^{-31} \text{ kg}$$

- Electrons in crystal are not completely free
- Internal forces due to periodic potential of the lattice affect the electrons

$$m^* = \frac{\hbar^2}{d^2 E / dK^2}$$

Effective mass of charge carriers (illustrative example)

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- Calculate the effective mass of a free electron

For a free electron the E - k relationship is

$$E = \frac{\hbar^2}{2m} k^2$$

$$d^2 E / dK^2 = \frac{\hbar^2}{m}$$

$$m^* = \frac{\hbar^2}{d^2 E / dK^2} = m$$

- Hence the effective mass of a free electron is the same as the true mass (makes sense)

Effective mass of charge carriers (qualitative explanation)

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- The true mass of an electron is still the same and can be used to calculate the acceleration of the particles according to Newton's second law as

$$\frac{dp}{dt} = \frac{d(mv)}{dt} = ma = F_{tot} = F_{ext} + F_{int}$$

- F_{int} is the internal force affecting the electron due to the periodic potential barrier inside the lattice structure whereas F_{ext} is the external force due to the applied electric field qE
- The concept of effective mass imbeds the effect of internal forces of the lattice to ease the calculations and only take the effect of the applied external force to calculate the resulting acceleration

$$\frac{d(m^*v)}{dt} = m^*a = F_{ext}$$

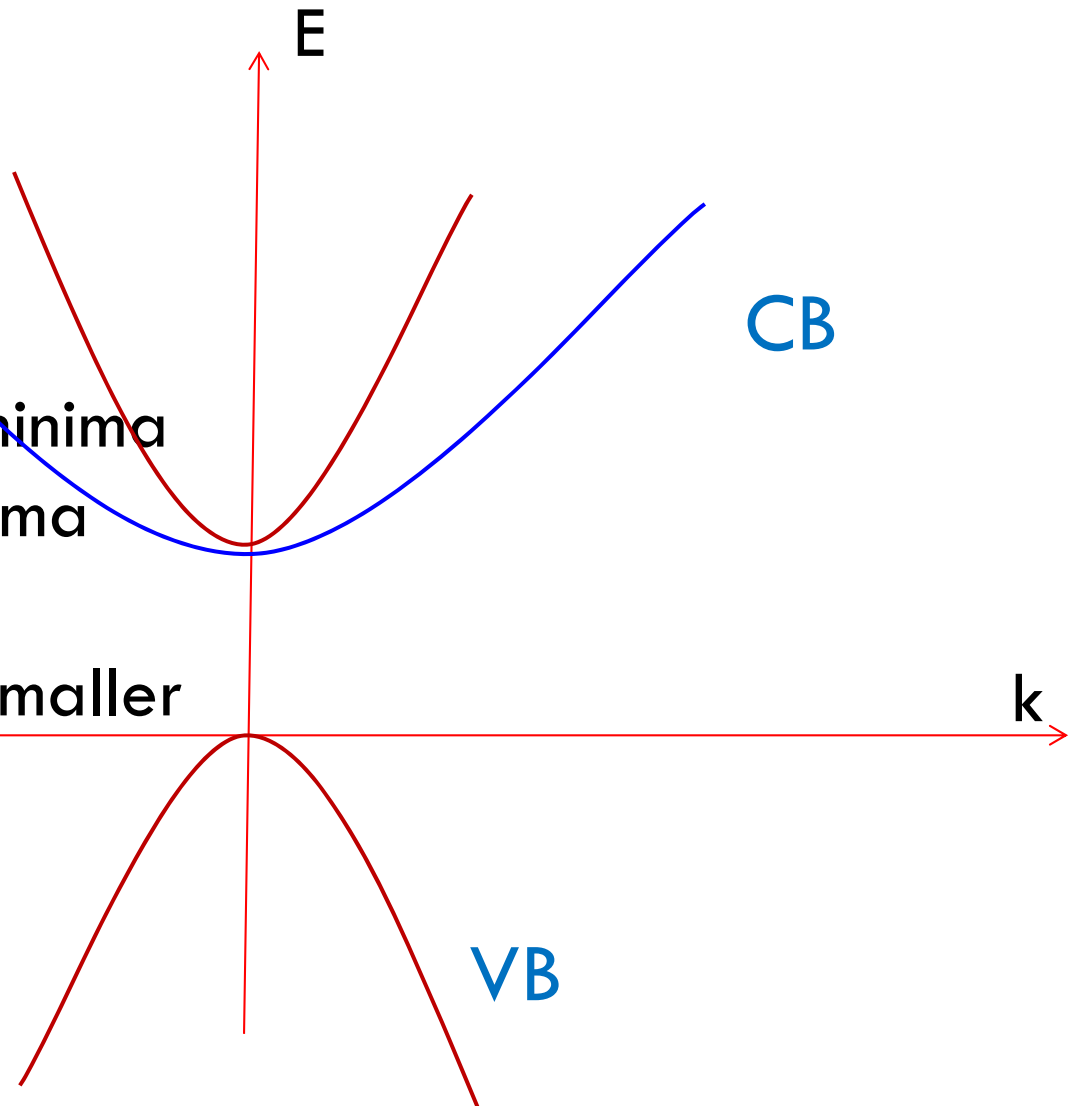
Effective mass of charge carriers (qualitative explanation)

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

- **+ve** at conduction band minima
- **-ve** at valence band maxima

- Sharper curvature means smaller Effective mass



Effective mass of charge carriers (typical values)

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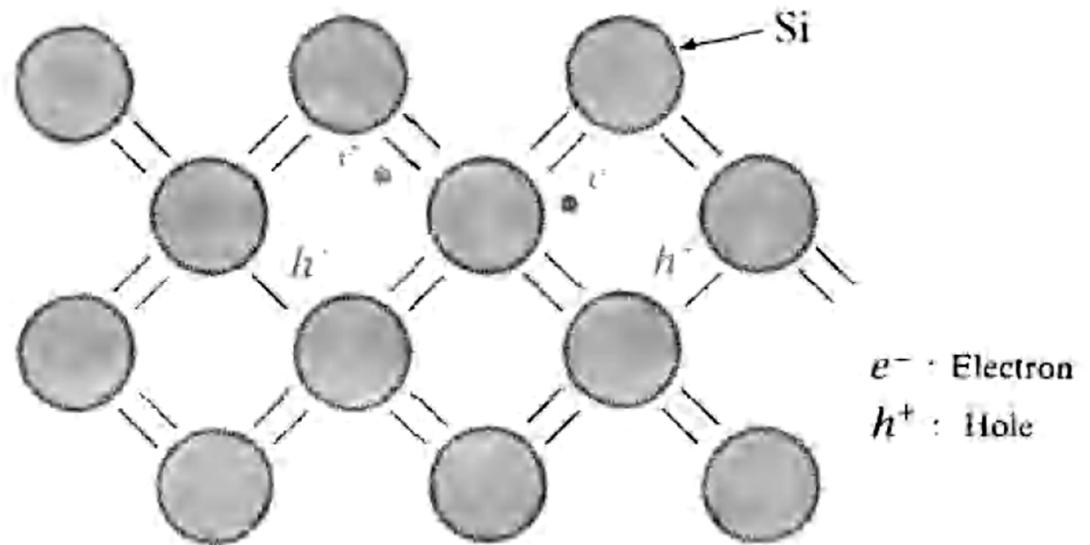
<i>Material</i>	m_n^*/m_0	m_p^*/m_0
Si	1.18	0.81
Ge	0.55	0.36
GaAs	0.066	0.52

**Ge and GaAs have “lighter electrons” than Si
which results in faster devices**

Intrinsic semiconductors

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- Perfect Semiconductor (no impurities, No lattice defects).
- Thermal excitation breaks one covalent bond producing an electron and a hole free to move across the lattice



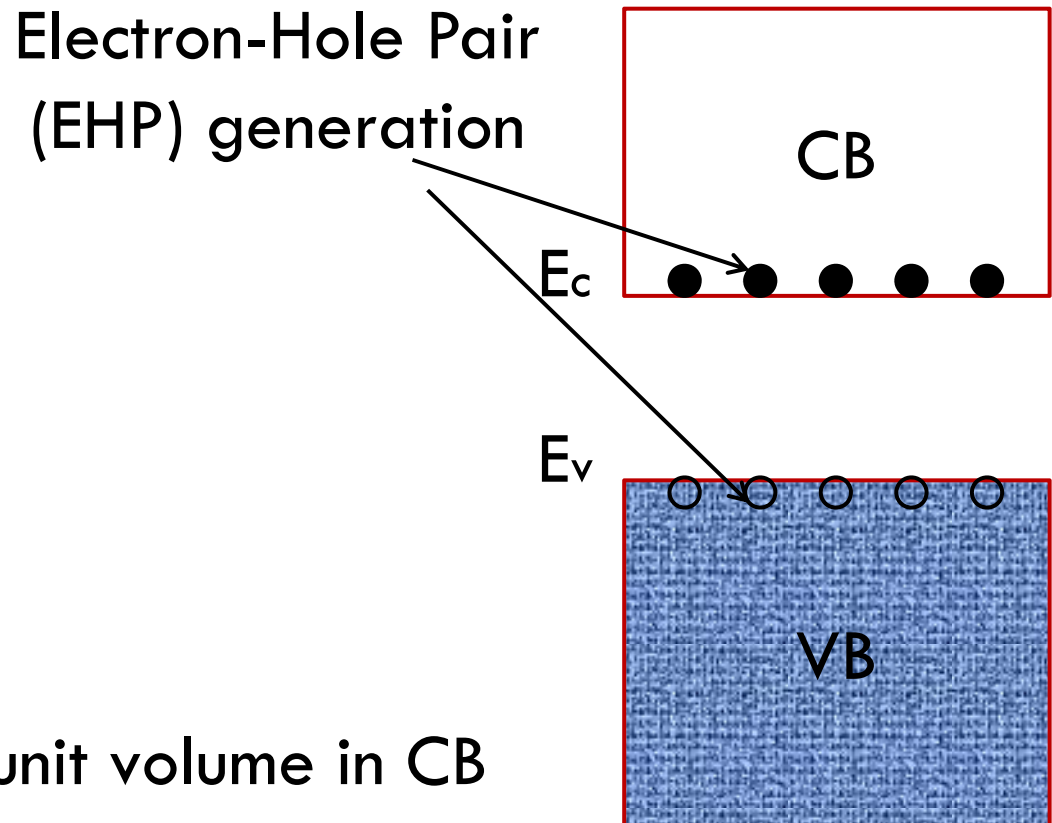
Chemical bond model of intrinsic Si

Intrinsic semiconductors

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- Perfect Semiconductor (no impurities, No lattice defects).

- rate of generation, g_i due to thermal excitation at $T > 0$



n electrons/ unit volume in CB

p holes/unit volume in VB

$$n = p = n_i$$

At temperature
($T > 0$ K)

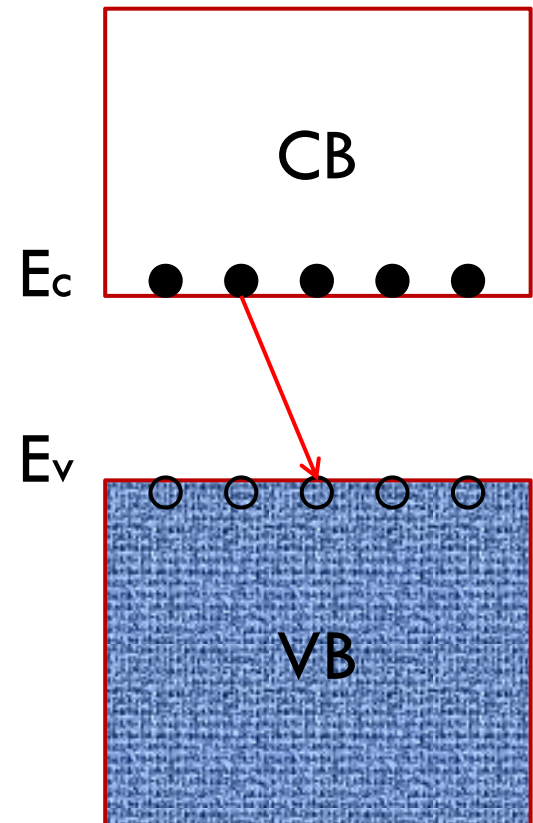
Intrinsic semiconductors

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- Perfect Semiconductor
(no impurities, No lattice defects).

- rate of generation, g_i
due to thermal excitation
at $T > 0$

n electrons/ unit volume in CB
 p holes/unit volume in VB
 $n = p = n_i$



At temperature
($T > 0$ K)

Intrinsic semiconductors

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- Perfect Semiconductor (no impurities, No lattice defects).

- rate of generation, g_i due to thermal excitation at $T > 0$

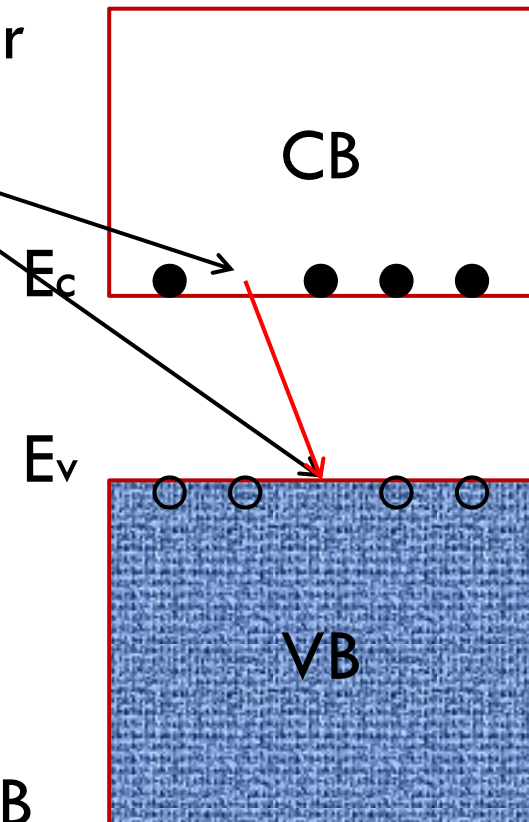
- rate of recombination, r_i must equal g_i to have a constant steady state carrier concentration **(thermal equilibrium)**

n electrons/ unit volume in CB

p holes/unit volume in VB

$$n = p = n_i$$

Electron-Hole Pair (EHP) recombination



At temperature $(T > 0 \text{ K})$

Intrinsic semiconductors

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$$r_i = g_i$$

$$n_o = p_o = n_i$$

$$r_i \propto n_o p_o$$

$$r_i = \alpha_r n_o p_o = g_i = \alpha_r n_i^2$$

α_r : constant

- Of course n_i is temperature dependent and will later be derived
- Also g_i and r_i are temperature dependent
- At room temperature, Si has n_i of about 10^{10} EHP/cm³ which is too small compared to its atomic density of 5×10^{22} atoms/cm³
- Via doping, we can change this carrier density and hence manipulate the conductivity of Si

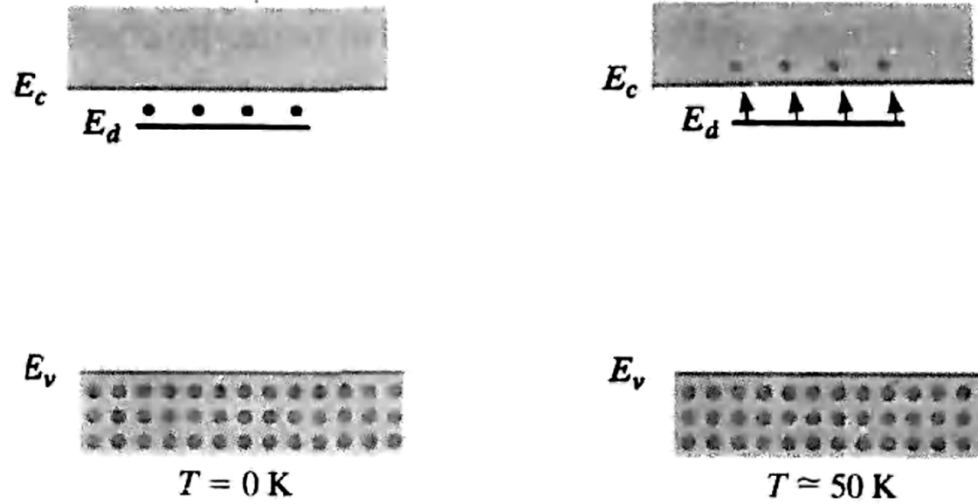
Extrinsic semiconductors

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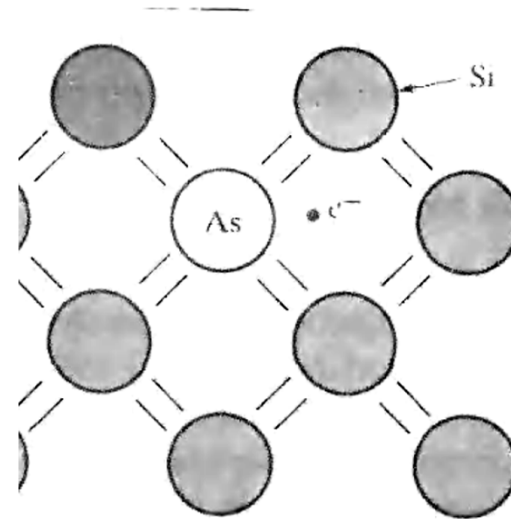
- Impurities introduced via doping process to vary conductivity of SC
- Doping increases the concentration of one type of carrier (either electrons or holes) compared to the intrinsic concentration n_i due to thermal excitation and hence increases the conductivity of SC
- N-type doping by adding pentavalent (valency = 5) atoms such as As and P
- P-type doping by adding trivalent (valency = 3) atoms such as B, Al, Ga
- Introducing impurities creates additional energy levels typically lying within the bandgap of SC either very near its CB (n-type doping) or its VB (p-type doping)

Extrinsic semiconductors (n-type)

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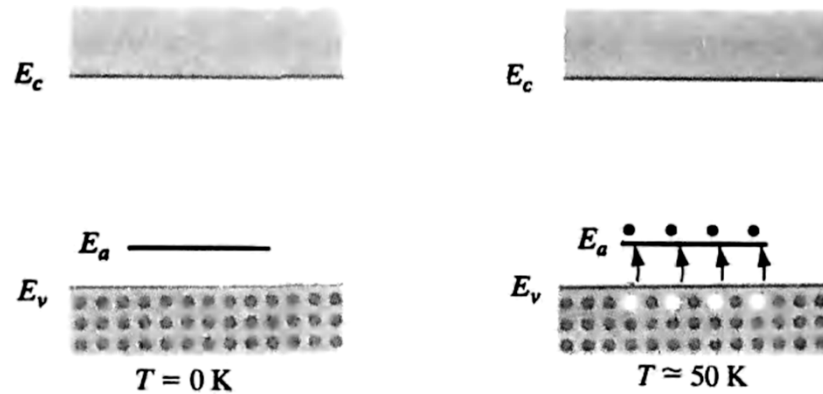


$$n_0 \gg n_i$$
$$n_0 \gg p_0$$

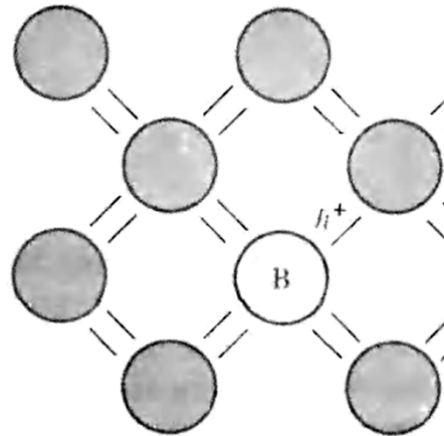


Extrinsic semiconductors (p-type)

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$$p_0 \gg n_i$$
$$p_0 \gg n_0$$



Donor and acceptor ionization energy calculation

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- What we mean by ionization energy E_{ion} is the energy (thermal) required to excite an electron from E_d to E_c , i.e. $E_c - E_d$, or from E_v to E_a , i.e. $E_a - E_v$
- This is typically a very small quantity relative to the bandgap of SC
- The calculation is made by treating the donor atom, which has 5 valence electrons, as a Hydrogen atom and use the Bohr model
- The four tightly bound electrons that contributed to four covalent bonds will be shielded with the nucleus and all core electrons leaving only a single electron in a Hydrogen-like orbit
- We can then use the Bohr's model relationship to calculate the energy to move this electron from $n = 1$ to $n = \infty$ and become a free electron thus ionizing the donor atom as

$$E_{ion} = \frac{mq^4}{2(4\pi\epsilon_0\epsilon_r)^2 \hbar^2} = \frac{mq^4}{8(\epsilon_0\epsilon_r)^2 h^2}$$

Donor and acceptor ionization energy calculation

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Ex: Calculate E_{ion} for n-doped Si crystal

$$E_{ion} = \frac{mq^4}{8(\epsilon_0\epsilon_r)^2 h^2}$$

$$m_n^* = \frac{1}{3}m_0, \epsilon_r = 11.9$$

$$\begin{aligned} E_{ion} &= \frac{9.11 * 10^{-31} * (1.6 * 10^{-19})^4}{3 * 8 * 11.9^2 * (8.85 * 10^{-12})^2 * (6.63 * 10^{-34})^2} \\ &= 0.000005102 * 10^{-15} \text{ J} \\ &= \frac{0.000005102 * 10^{-15}}{1.6 * 10^{-19}} \text{ eV} \\ &= 0.032 \text{ eV} \end{aligned}$$

Donor and acceptor ionization energy actual measured values

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Ionization energy of selected donors and acceptors in silicon

	Donors			Acceptors		
Dopant	Sb	P	As	B	Al	In
Ionization energy, $E_c - E_d$ or $E_a - E_v$ (meV)	39	44	54	45	57	160