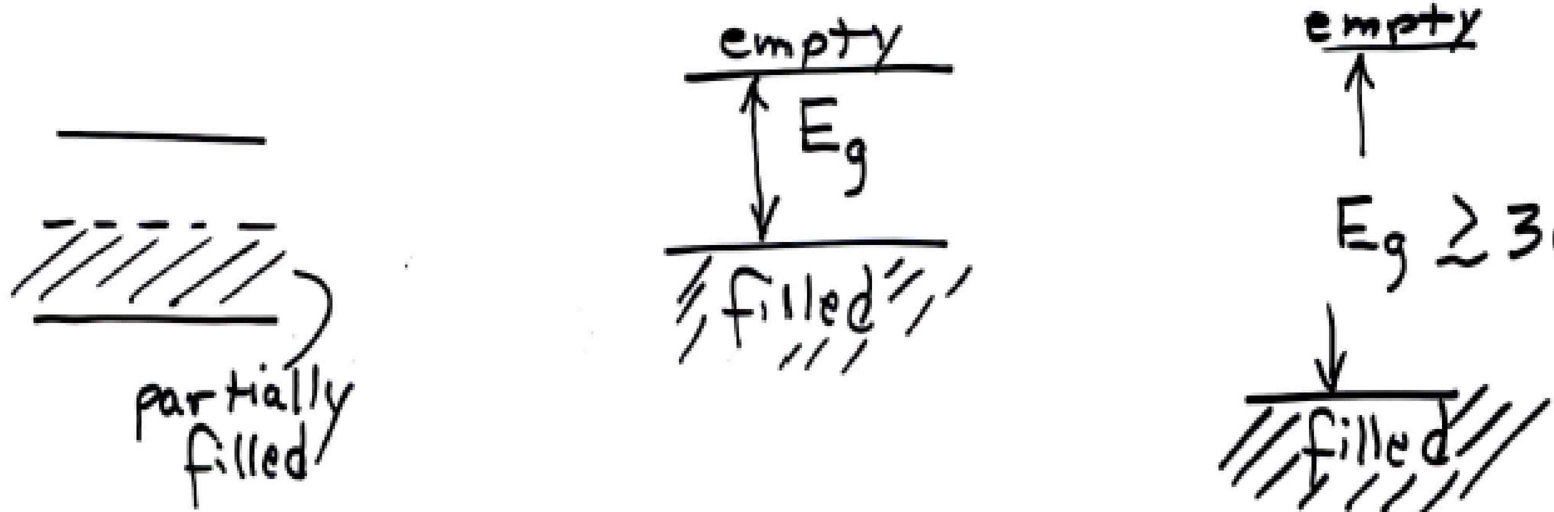
Remember:

$0^\circ K$ Metals Semiconductors Insulators



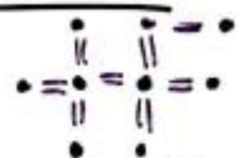
For semiconductors (and insulators), E_g can be "tailored" by changing composition.

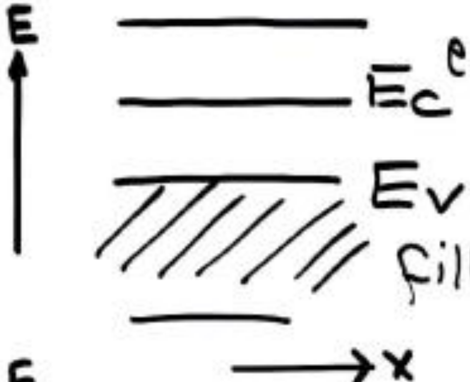
Example: $x(AlAs) + (1-x)(GaAs) \rightarrow Al_x Ga_{1-x} As$

$x(Ge) + (1-x)Si \rightarrow Si_{1-x}Ge_x$

Charge Carriers: Electron and Holes

$T = 0°K$

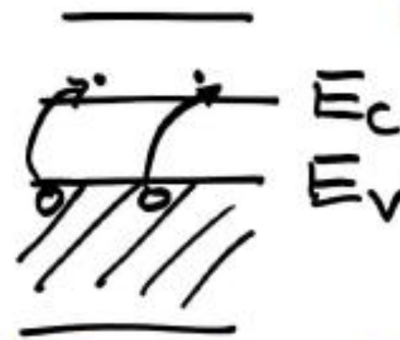




empty (4N states)

filled (4N electrons)

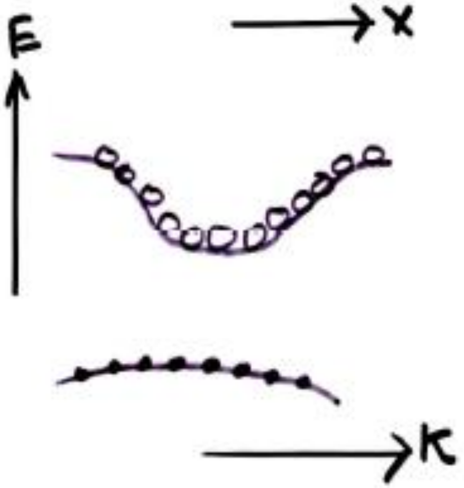
$T > 0°K$



conduction electron

Broken Bonds Due to Thermal Vibration

EHP = "electron-hole Pair"



At $T = 300°K$

equilibrium $\sim 10^{10}$ EHP

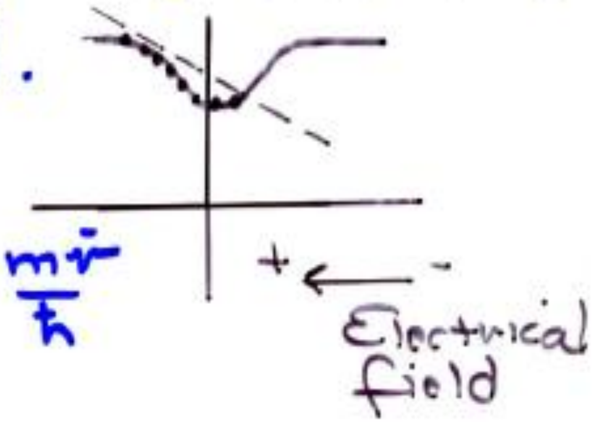
versus 10^{22} atoms/cm^3

So very small number of electrons and holes moving around.

Easy to see how electrons move in conduction band when external force applied.

Here, the k's of all the electrons do not cancel.

$k = \frac{p}{\hbar} = \frac{m\vec{v}}{\hbar}$

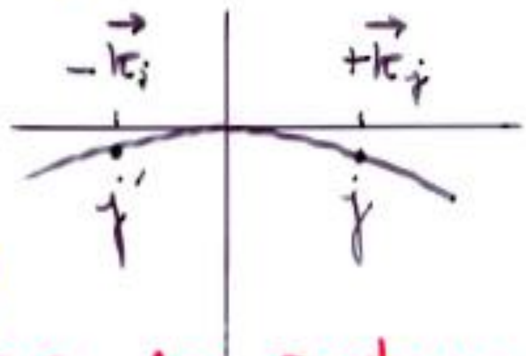


What about valence band?

At T=0°K, valence band is full and all states occupied.

Apply electrical field.

j^{th} electron moves equal and opposite to j'^{th} electron since band filled.



So contributions to net current cancel.

Drift current density $J = -q \sum_{i(\text{filled})} v_i = 0$ for filled band

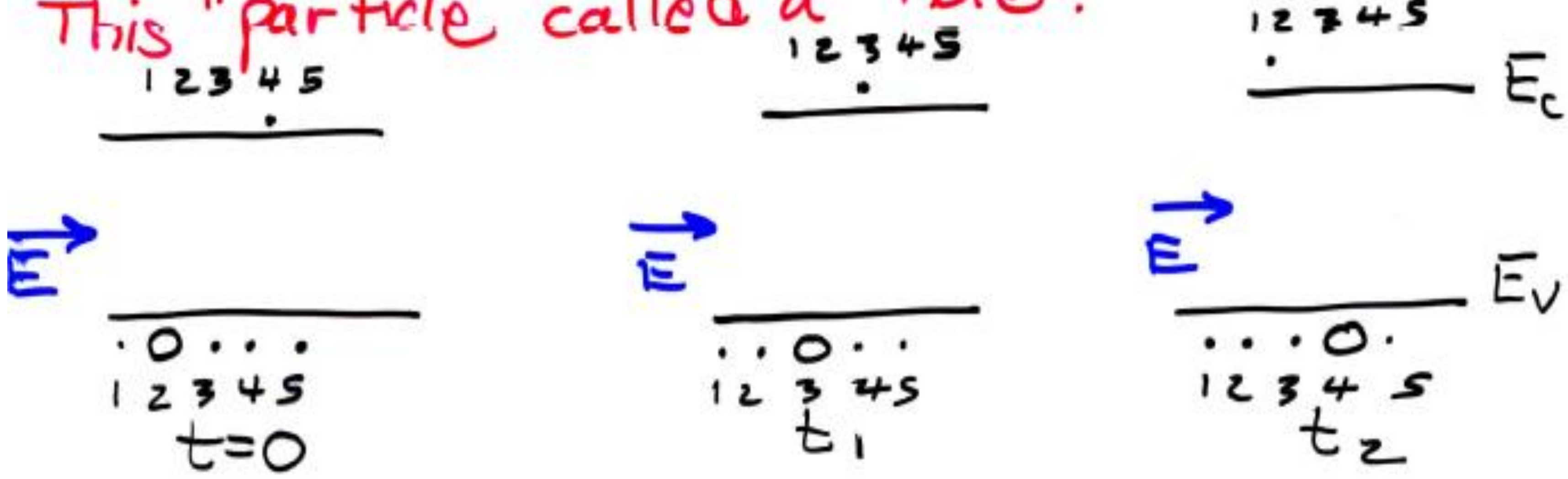
At $T > 0°K$, some electrons excited to conduction band.
Now <u>missing</u> electron at k_j and

$$J = -q\underbrace{\sum_i v_i}_{0} - (-q)v_j = +q v_j$$ → net current!

sign is +, opposite of electron flow.

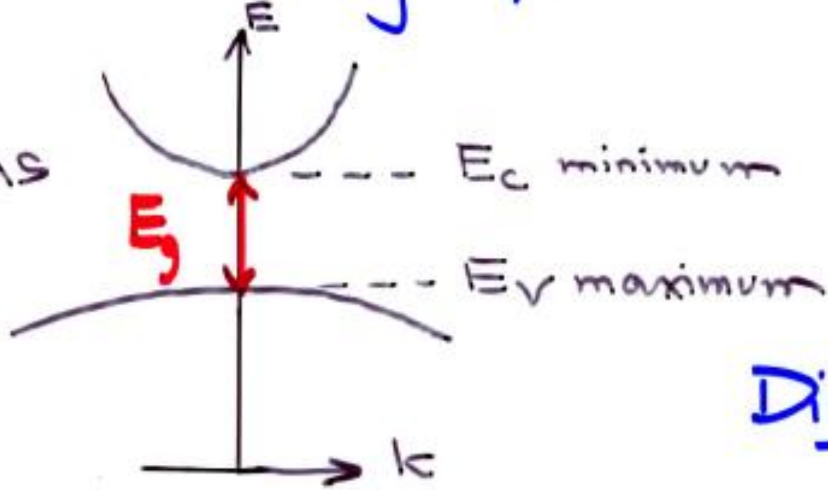
So for <u>nearly</u> filled band, current flows <u>as if</u> a positively charged particle moves with velocity $+v_j$

This "particle" called a "hole".



The relative position of the valence band and conduction band minima are important and make a big difference in crystal properties.

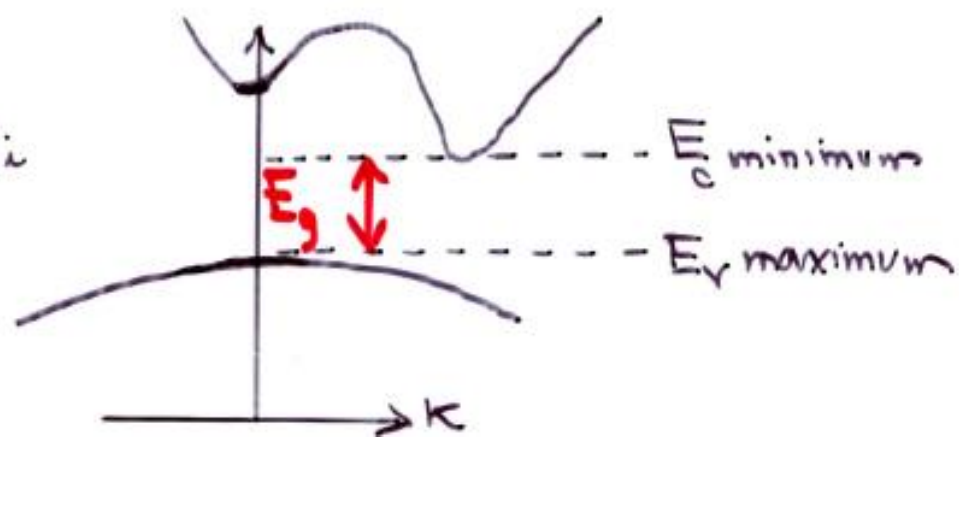
GaAs



If E_c minimum and E_V maximum line up at same k, then

Direct Gap Semiconductor

Si



If they don't line up, then

Indirect Gap Semiconductor

Direct gap semiconductor requires no change in k for electron to be transferred between bands.

Indirect gap semiconductor requires a finite change in k.

This makes a big difference for optical devices: good (direct) versus bad (indirect)

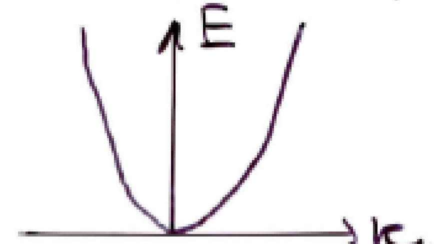
Light emission directly

Need phonon to supply needed Δk: Lower probability

Now, how much do electrons and holes "weigh"?

Nearly-free electron mass NOT the same as rest mass.

How can this be?



Consider free electron E vs. k

E for electron is parabolic in wavevector k: $E = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m}$

Electron Mass related inversely to 2nd derivative with respect to k

$$\frac{d^2E}{dk^2} = \frac{d^2}{dk^2}\left(\frac{\hbar^2 k^2}{2m}\right) = \frac{2\hbar^2}{2m}\frac{dk}{dk} = \frac{\hbar^2}{m}$$

Most bands are close to parabolic near conduction band minima and valence band maxima. So we can approximate mass by:

$m = \boxed{}$

For free electron, d^2E/dk^2 = constant, perfectly parabolic, so m = constant

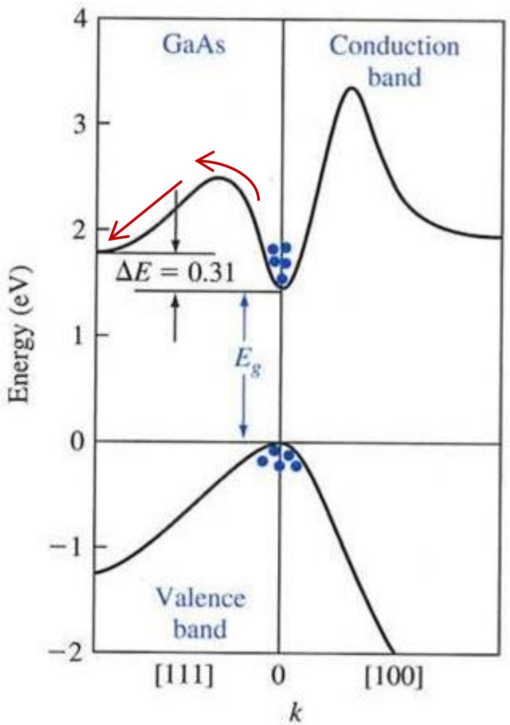
But! We know that bands are <u>NOT</u> parabolic in general.

So m effective = m^* depends on curvature for given E and $\vec{k}$

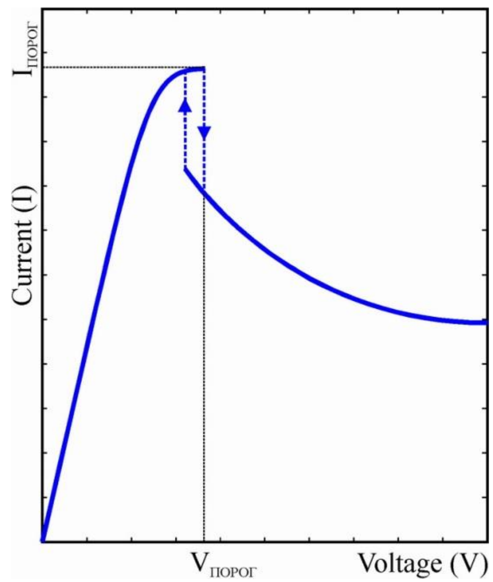
m $\longrightarrow$ $\boxed{}$ Effective Mass

Since $\vec{k} = \alpha \vec{k}_x + \beta \vec{k}_y + \gamma \vec{k}_z$, m^* is a 3×3 matrix which depends on the dielectric medium the particle "sees" in a crystal

Gunn Diode



Lower ↔ Higher μ



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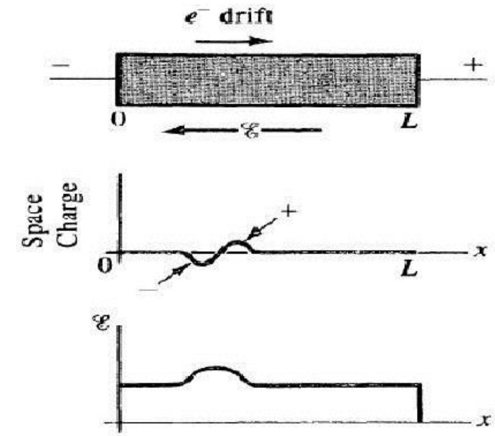
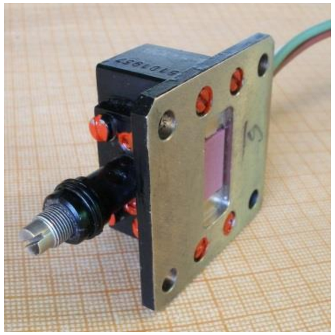
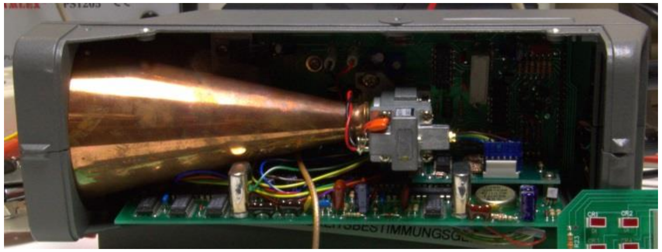


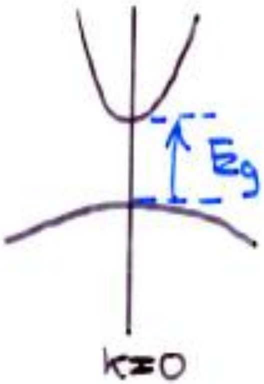




Conduction band mobility changes between two valleys → MHz-GHz oscillations

This dependence on direction makes sense: for example, compare <111> versus <100> Different number of ion cores/cm (line density, ..) → different effect on V and motion.

For conduction band of direct gap semiconductor



Direct gap semiconductor

For conduction band, $E(k) \simeq \frac{\hbar^2 k^2}{2m^*} + E_g$

Near k=0, assume parabolic so curvature and m^* = constants

For valence band, $\frac{d^2E}{dk^2} < 0$ (negative curvature) so m^* for electrons is negative near valence band max.

So electron in valence band has negative m^* and negative q and moves like positive m^* with positive q in E-field.
"missing electron"

So we treat the missing electron in the valence band as electron-like particle with $+m^*$ and $+q$ → HOLE

$m_n^* \equiv$ electron, m^* in conduction band (CB)

$m_p^* \equiv$ hole, m^* in valence band (VB)

---

rest mass

Examples: $m_n^* = 1.1\,m_0$, $m_p^* = 0.56\,m_0$ for Si

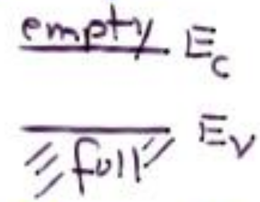
$m_n^* = 0.067\,m_0$, $m_p^* = 0.48\,m_0$ for GaAs

Can get an average m^* by lumping all equivalent bands at different k together. (e.g., density of states calculations)
(you'll see this very soon!) :-)

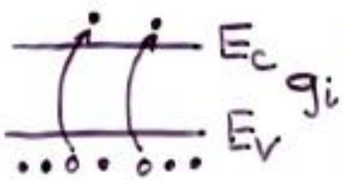
End Note: Big dispersion, moving fast; no dispersion — $\frac{d^2E}{dk^2} = 0$, $m^* = \infty$

Intrinsic Semiconductors

In Perfect crystal, (so no impurities or defects)
no free e^- or holes at $T = 0°K$



As T increases, bonds break → create free e^-s and holes.



Thermal generation of electron-hole pairs EHP's
Need energy E_g to generate.

g_i = generation rate

$n = \#$ of e^-/cm^3 and $p = \#$ of holes$/cm^3$

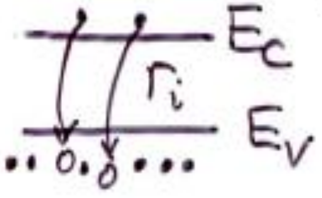
$\underline{n = p}$ since created in pairs

For intrinsic semiconductor, n_i = intrinsic carrier concentration

At higher T, n_i increases.

At constant T, n_i is constant. Therefore steady-state.

Intrinsic generation <u>balance</u>d by intrinsic recombination.



r_i = recombination rate

$$\underline{r_i = g_i} \quad \left(\frac{\#}{cm^3\text{-}sec}\right)$$

At a given temperature, equilibrium e^- concentration $= n_o$

" hole " $= p_o$

Recombination rate $r_i \propto$ available e-h pairs

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

True even if extra carriers added.

Intrinsic n and p not very useful to us.

For example, in Si, $n_i = p_i = 1.5 \times 10^{10}\,cm^{-3}$

versus $10^{19}\,cm^{-3}$ density of states.

Need to add more carriers to affect conductivity

Make it more (+) or (−). How?

Add selected impurities called dopants

Extrinsic Si = Intrinsic Si + dopant impurities

n-type Si : Conductivity controlled by e^- : Add $\boxed{}$

p-type Si : " " " holes : Add $\boxed{}$

Donors: $\boxed{}$-type dopant atoms → Increase $\boxed{}$

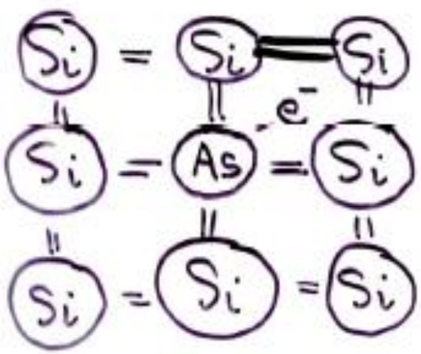
Acceptors: $\boxed{}$-type dopant atoms → Increase $\boxed{}$

n-type semiconductor: $n_o \gg n_i$, $n_o \gg p_o$

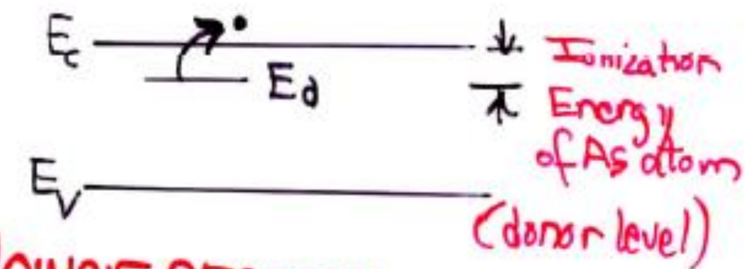
"majority" carrier → n_o; "minority" carrier → p_o

p-type semiconductor: $p_o \gg n_i$, $p_o \gg n_o$

Donors in Si: Group V elements, e.g., As, Sb, P substituted on Si site



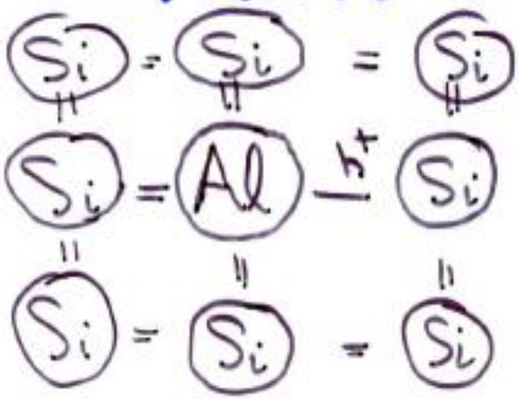
e^- weakly bound to As atom in Si lattice



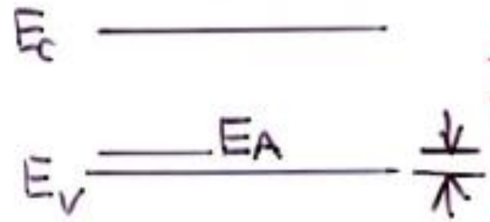
Much lower energy needed to get e^- up to E_c

→ Electron "donated" to conduction band

Impurities for donors and acceptors selected for shallow depth (low ionization E) and valence (column in Periodic Table.



h^+ weakly bound to Al atom



Ionization Energy for Al atom

Much lower energy needed to get h^+ into valence band

To satisfy missing bond, an electron is accepted from the host crystal, leaving a hole behind in valence band.

For both cases, no donor or acceptor ionization at $T = 0°K$. So no extrinsic carriers.

→ Need to "dope" semiconductors!

Here, dopant levels close to band edges E_c and E_v.
Other impurities deeper (called "traps").

How many charge carriers do we have or can we generate?

Consider how many of all energy states in a band have electrons. → Too many to count!

Consider distribution of carriers over all available states. → Fermi-Dirac Statistics

Electrons obey Fermi-Dirac Statistics:

(Fact without proof)

1) Pauli Exclusion Principle holds

2) All e^- particles are indistinguishable

3) Wave Nature

Distribution of electrons over a range of allowed energy levels at thermal equilibrium is:

$f(E) =$

Probability function between 0 and 1

Absolute temperature T

E_F = Fermi level

k_B = Boltzmann's constant $= 1.38 \times 10^{-23}$ J/K atom $= 8.62 \times 10^{-5}$ eV/atom·K

VERY IMPORTANT QUANTITY