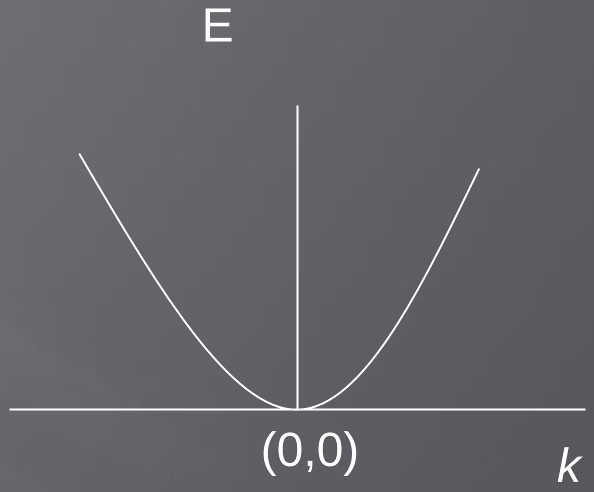
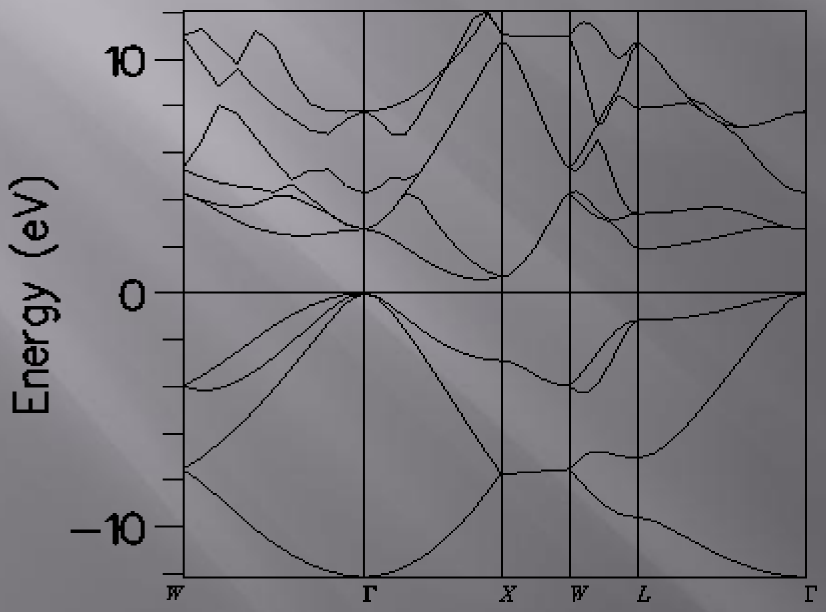
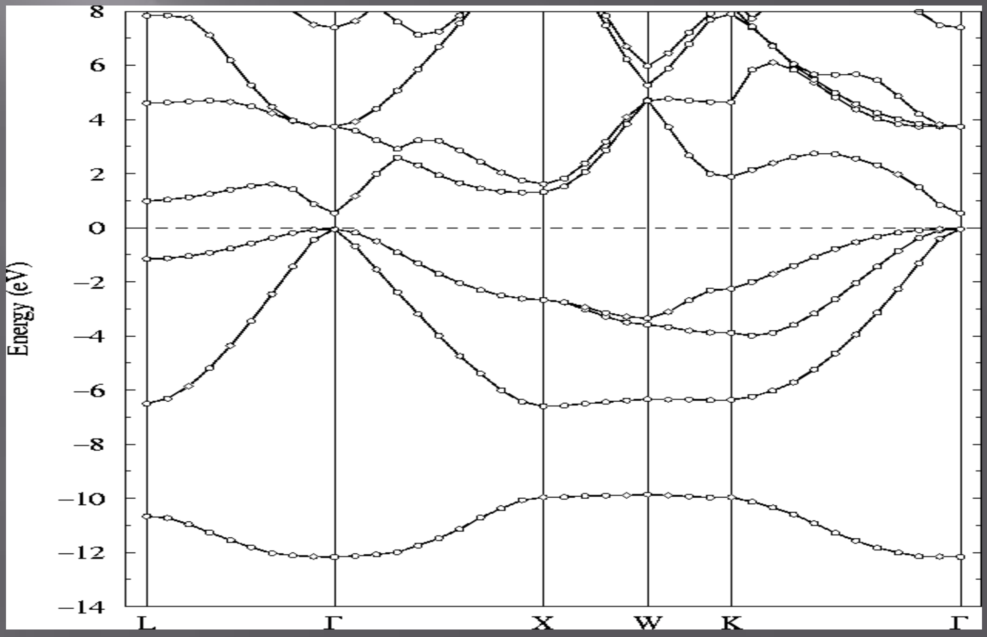
- Most important semiconductors are crystals
- Crystals have periodic arrangement of atoms or molecules
- They also have a periodic potential
- A periodic potential results in energy bands, with allowed and forbidden values of energy
- Energy bands are relationships between electron energy and *k* vector.

- For a free electron, E vs. *k* is parabolic
- For real semiconductors the bandstructure is more complicated





Bulk Silicon Band structure (from cmt.dur.ac.uk)



Bulk GaAs Band structure (from fhi-berlin.mpg.de)

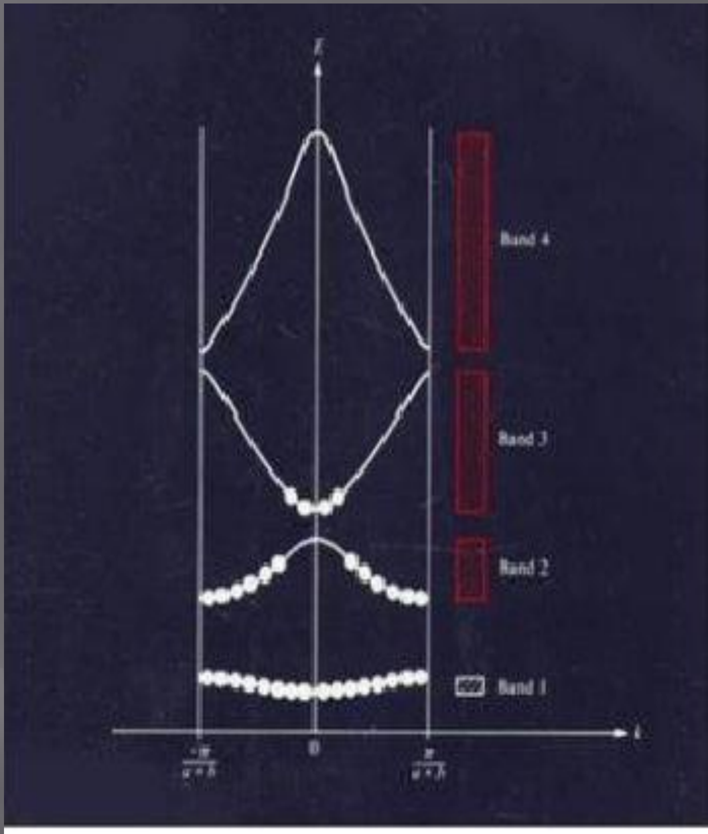
- Different letters represent different directions in the crystal
- Properties of electrons in a semiconductor are determined from the band structure
- The bands near the band edge are nearly parabolic to a good approximation. Therefore effective mass in those regions is nearly constant

$$v = \frac{1}{\hbar}\frac{\partial E}{\partial k} \quad electron \quad velocity$$

$$\frac{1}{m^*} = \frac{1}{\hbar^2}\frac{\partial^2 E}{\partial^2 k} \quad electron \quad effective \quad mass$$

- At 0K, electrons occupy all available k states below an energy called Fermi Energy.
- These states are called valence bands.
- All available states above Fermi Energy are unoccupied by electrons at 0K. They are called conduction bands.
- Above 0K, some electrons gain energy and move to the conduction bands. These electrons result in electron current when a voltage is applied across the semiconductor

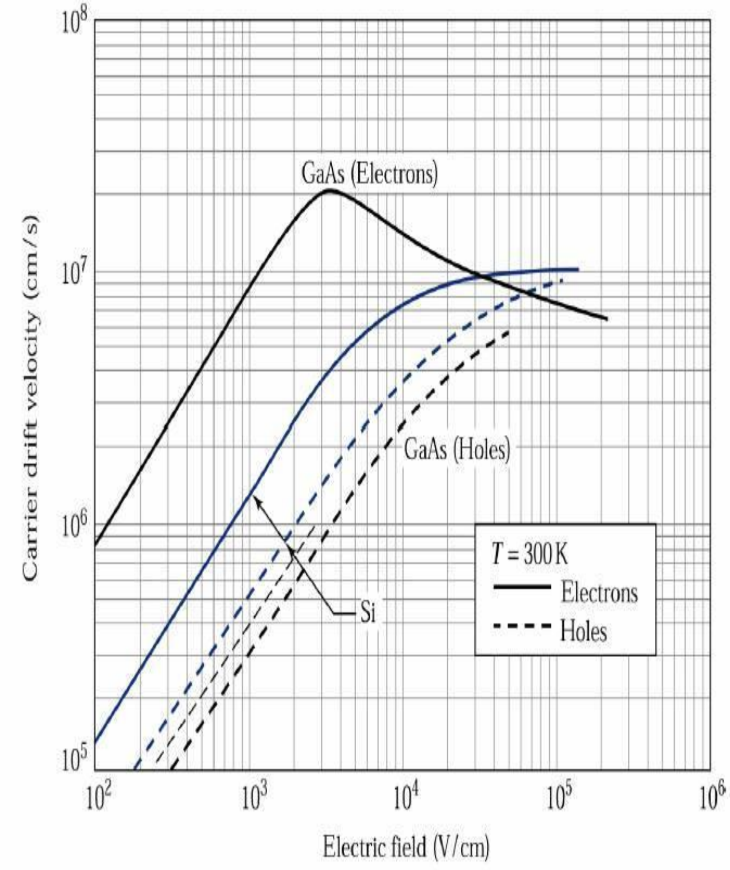
- When some electrons move to the conduction band, they leave behind vacancies.
- These vacancies may be treated as positive charged particles. These pseudo-particles are called holes.
- Under an applied voltage, these holes result in a hole current. Holes will move in the opposite direction to that of electrons under an applied voltage



From Advanced semiconductor fundamentals ,Robert F. Pierret. Published 1987 by Addison-Wesley Pub. Co.

- At low electric fields, the electron average drift velocity v is proportional to the applied electric field $\mathcal{E}$ → $v = \mu \mathcal{E}$
- μ is called the mobility and is a measure of how fast an electron can move in a semiconductor
- Mobility is determined by various scattering mechanisms. Some are intrinsic, such as phonons (i.e. crystal atom vibrations)
- Some factors are extrinsic, such as ionized impurity atoms added to dope a semiconductor to make it p- or n-type

- At higher electric fields the behavior is different
- In silicon the velocity saturates at high electric fields. This has important implications for device size reduction, since it shows that device speed will not simply increase, since mobility decreases
- In GaAs, the velocity decreases, and then increases. This results in a negative differential resistance (NDR), which is useful for microwave applications.



Drift velocity versus electric field in Si and GaAs. Note that for *n*-type GaAs, there is a region of negative differential mobility.

From http://www.globalsino.com/micro/1/1micro9939.html

- Electron and hole motion in a semiconductor device can be described by the Continuity Equation. It is simply a statement on charge conservation, and in its basic form is given by:

$$\frac{\partial n}{\partial t} = \left.\frac{\partial n}{\partial t}\right|_{drift} + \left.\frac{\partial n}{\partial t}\right|_{diffusion} + \left.\frac{\partial n}{\partial t}\right|_{thermal\ G-R} + \left.\frac{\partial n}{\partial t}\right|_{other\ G-R}$$

for electrons, and:

$$\frac{\partial p}{\partial t} = \left.\frac{\partial p}{\partial t}\right|_{drift} + \left.\frac{\partial p}{\partial t}\right|_{diffusion} + \left.\frac{\partial p}{\partial t}\right|_{thermal\ G-R} + \left.\frac{\partial p}{\partial t}\right|_{other\ G-R}$$

for holes

- Let us look at individual terms in the equation:
- Drift: Under an applied electric field, Ohm's Law requires that $J = \sigma \mathcal{E}$, where σ is the conductivity.
- Under steady state, $\sigma = qn\mu_n$, where n is the electron density, and q is the fundamental charge
- Therefore drift current density is:

$J_n = qn\mu_n \mathcal{E}$; for electrons, and

$J_p = qp\mu_p \mathcal{E}$; for holes

- Diffusion: Electron or hole diffuse from a region of high concentration to a region of low concentration, resulting in a current.
- The current is proportional to the gradient of the concentration.
- For electrons:

$$\vec{J}_n = q D_n \vec{\nabla} n$$

- For holes :

$$\vec{J}_p = -q D_p \vec{\nabla} p$$

where D is called the diffusion coefficient. Under equilibrium, *D* and *μ* are related by Einstein relationship:

$$\frac{D}{\mu} = \frac{kT}{q}$$

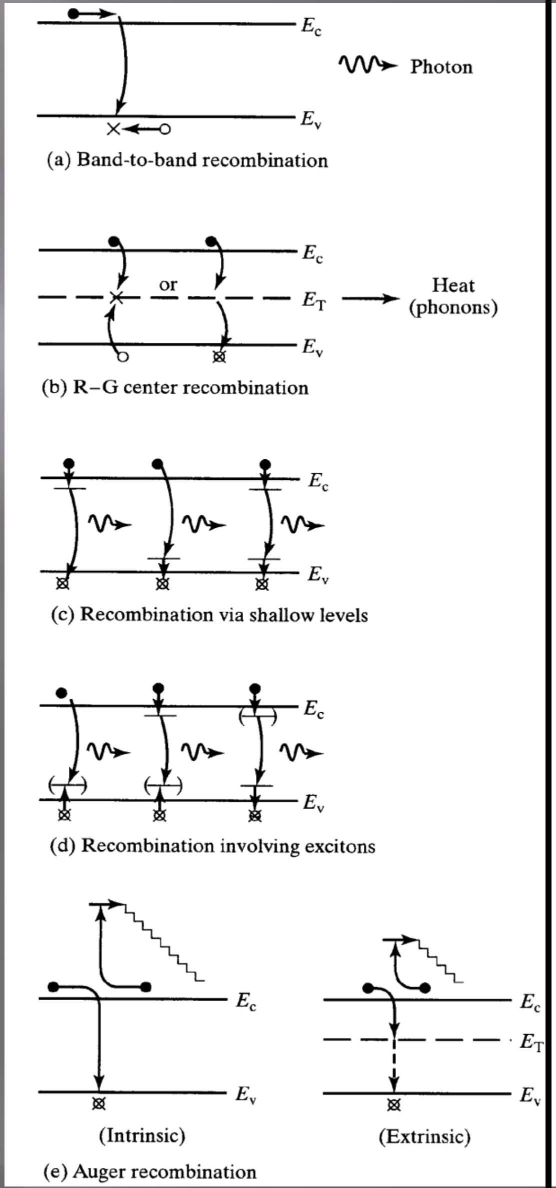
- Total electron and hole current density become:

$$\vec{J}_n = qn\mu_n\vec{\varepsilon} + qD_n\vec{\nabla}n$$

$$\vec{J}_p = qp\mu_p\vec{\varepsilon} - qD_p\vec{\nabla}p$$

- At any given instant of time, electrons and holes are being generated, or are recombining.
- There are several RG processes, such as thermal, photon assisted, impurity state assisted
- When charge carrier (electron or hole) concentration is greater than equilibrium, recombination dominates. If concentration is lower than equilibrium, generation dominates

Recombination



(a) Band-to-band recombination

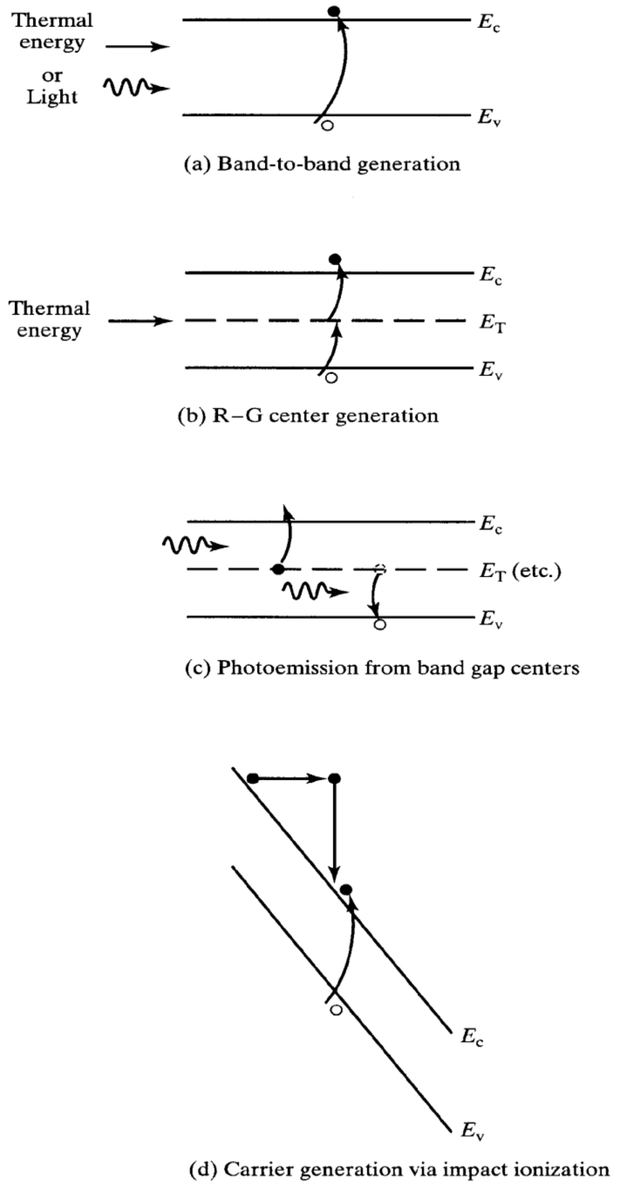
(b) R–G center recombination

(c) Recombination via shallow levels

(d) Recombination involving excitons

(e) Auger recombination

Generation



(a) Band-to-band generation

(b) R–G center generation

(c) Photoemission from band gap centers

(d) Carrier generation via impact ionization

Figures from Advanced semiconductor fundamentals ,Robert F. Pierret. Published 1987 by Addison-Wesley Pub. Co.

- Now we can recast the continuity equation by noting the following: $\vec{\nabla}.\vec{J} = -\frac{\partial \rho}{\partial t}$

- Therefore,

$$\frac{1}{q}\vec{\nabla}.\vec{J}_n = \left.\frac{\partial n}{\partial t}\right|_{drift} + \left.\frac{\partial n}{\partial t}\right|_{diffusion} \quad and$$

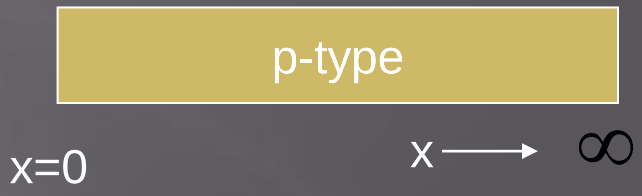
$$-\frac{1}{q}\vec{\nabla}.\vec{J}_p = \left.\frac{\partial p}{\partial t}\right|_{drift} + \left.\frac{\partial p}{\partial t}\right|_{diffusion}$$

- And so we obtain,

$$\frac{\partial n}{\partial t} = \frac{1}{q}\vec{\nabla}.\vec{J}_n + \left.\frac{\partial n}{\partial t}\right|_{thermal\ G-R} + \left.\frac{\partial n}{\partial t}\right|_{other\ G-R}$$

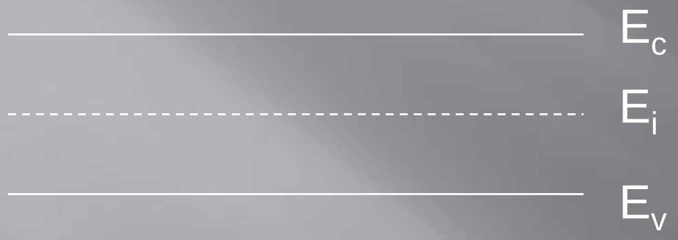
$$\frac{\partial p}{\partial t} = -\frac{1}{q}\vec{\nabla}.\vec{J}_p + \left.\frac{\partial p}{\partial t}\right|_{thermal\ G-R} + \left.\frac{\partial p}{\partial t}\right|_{other\ G-R}$$

- Solving the continuity equation is not easy.
- Fortunately it can be approximately solved for important practical cases
- Solve the continuity equation to determine the electron current in an infinitely long, square cross-section p-type semiconductor as shown in figure, under steady-state, no electric field, where electrons with a density of n_o are injected into the semiconductor at x=0 (i.e. minority carrier injection),.
- We will assume that the only GR process is thermal recombination

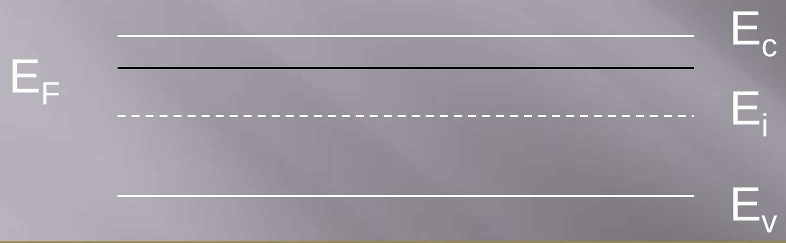


- A diode works in a similar way to the previous example
- The dominant current in a diode is electrons diffusing into the p-side, and holes diffusing into the n-side
- Amount of minority carrier injection into the p- or n-side is determined by the applied voltage.
- Applied voltage lowers or raises the potential barrier, which in turn controls the amount of diffusion.

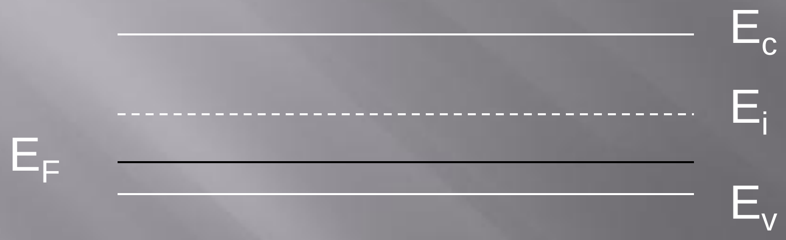
- The operation of a pn junction, and in turn, semiconductor devices, can be qualitatively understood through the use of a band diagram.
- A band diagram depicts energy versus distance, i.e. it is a depiction of the behavior of the potential within a semiconductor
- Band diagrams provide a visual aid to understanding the operation of semiconductors



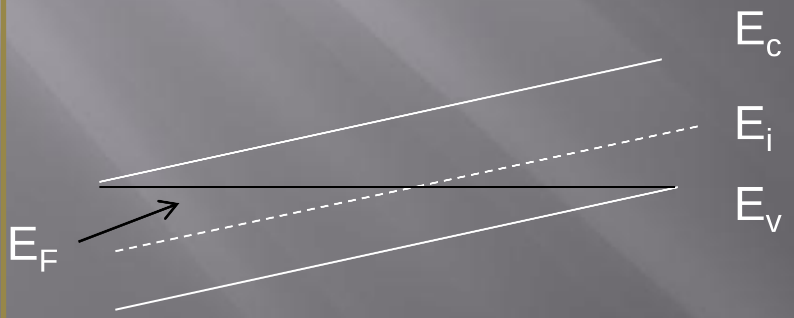
Intrinsic semiconductor, n=p
$E_F = E_i$, and near the center of the bandgap



n-type extrinsic semiconductor
E_F is above E_i



p-type extrinsic semiconductor
E_F is below E_i



Band bending in a semiconductor because of potential difference

To draw a band diagram for a pn junction, the following rules are followed:

- Under equilibrium the Fermi energy level is constant throughout the system
- Away from a junction, the band diagram attains its bulk value
- The band diagram is continuous for junctions among the same material

- Band diagrams for the following:

1. pn junction diode
2. npn Bipolar Junction Transistor
3. Schottkey diode
4. Metal-semiconductor Ohmic junction

- Traditional metal-oxide-semiconductor field effect transistors (MOSFETs) work differently than diodes and BJTs
- Drift component of the current is dominant

sketch of MOSFET

operation of MIS system from band diagram

operation of MOSFET from band diagram, including linear, pinchoff, and saturation