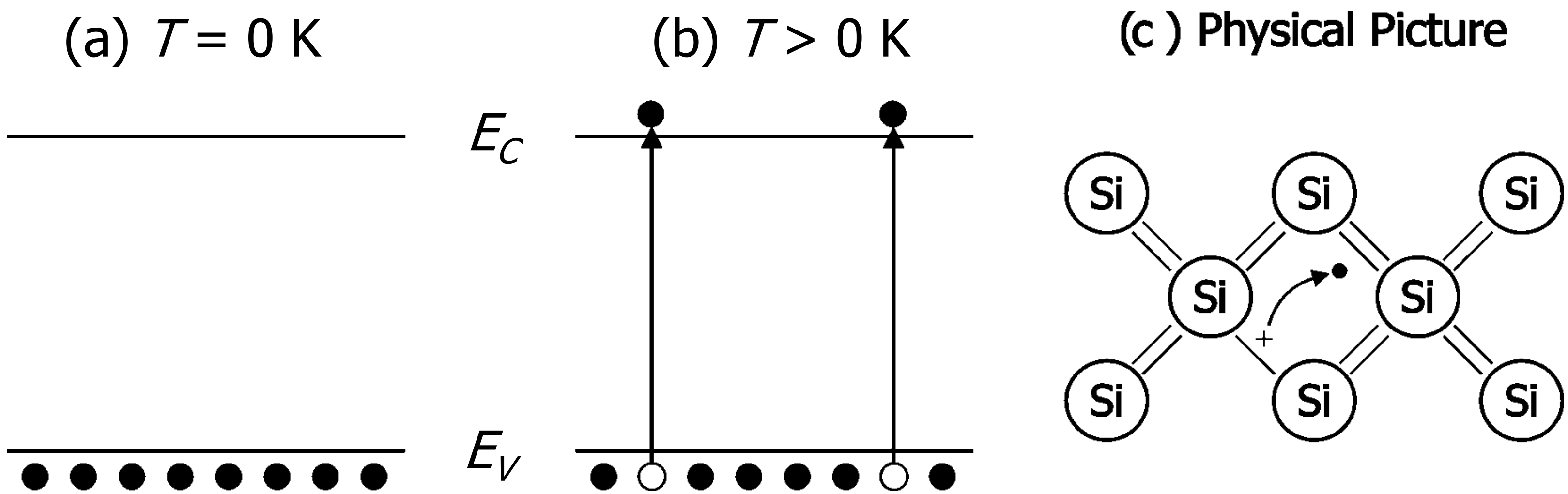
EE2003 Semiconductor Fundamentals

Carrier Generation/Recombination

Electron-Hole Pair Generation



Schematic illustration of band-to-band or direct electron-hole pair (EHP) generation. (a) At T= 0 K, the conduction band is entirely empty and the valence band is fully filled with electrons. (b) When T > 0 K, electrons gaining enough thermal energy are excited onto the conduction band, leaving behind positively charged holes in the valence band. (c) Physically, the generation of an electron-hole pair is a bond breaking process.

Electron-Hole Pair Generation

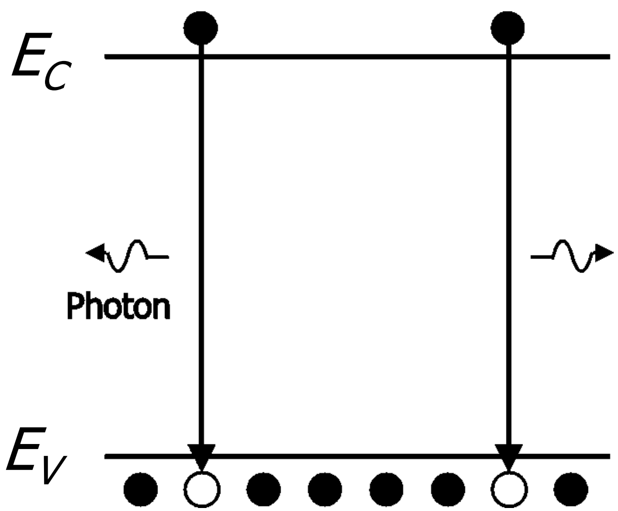
- **Generation** refers to the process whereby an electron-hole pair (EHP) is created.
  - Physically, this means a covalent bond between a Si atom and its neighbor is broken.
  - From an energy point of view, this refers to the excitation of an electron from the valence band to the conduction band.
- The generation process shown is known as ***band-to-band*** or ***direct generation***, i.e. the electron makes a direct transition from the valence band to the conduction band.
- Band-to-band generation always involves the creation of an **equal number** of electrons and holes.

Electron-Hole Pair Generation

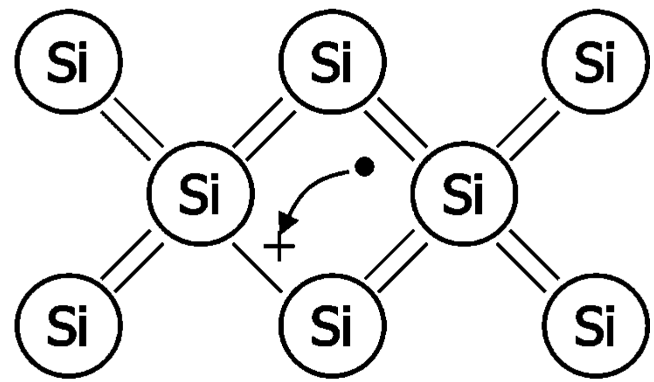
- Energy must be provided in order for generation to occur. Two means by which energy can be provided:
  - Changing the temperature – **Thermal generation**
  - Exposing the semiconductor to light – **Photo generation**
- In order for photo generation to occur, the photons must have energy at least equal or greater than the semiconductor band gap.
  - Recall: Photon energy, $E_{ph} = hf$, where h - Planck's constant; f ($= c/\lambda$) – frequency; c - speed of light; λ - wavelength

Electron-Hole Pair Recombination

(a) Energy Band Perspective



(b) Physical Picture



Schematic illustration of band-to-band or direct recombination. (a) Energy band perspective and (b) physical picture showing the reformation of a broken bond.

Electron-Hole Pair Recombination

- **Recombination** refers to the process whereby an electron-hole pair is annihilated.
  - Physically, this means the covalent bond between a Si atom and its neighbour is reformed.
  - From an energy point of view, it refers to the case where an electron in the conduction band falls back onto an empty electron state in the valence band.
- The recombination process shown is called **band-to-band** or **direct recombination**, i.e. the electron makes a direct transition from the conduction to the valence band.
- Band-to-band recombination always involves the annihilation or removal of an **equal number** of electrons and holes.

Electron-Hole Pair Recombination

- Energy is released during recombination.
- Depending on the type of semiconductor bandgap (direct/indirect), energy can be released in the form of electromagnetic radiation or heat.

Recombination Rate

- For band-to-band or direct recombination, one expects the rate at which electrons and holes recombine to be directly proportional to the electron (*n*) and hole (*p*) concentration in the respective conduction and valence band.
- A general expression for the **recombination rate *R*** may be expressed as

$$R = \alpha_r \cdot n \cdot p$$

– α_r (cm^3s^{-1}) is some constant of proportionality

Thermal Equilibrium

- Under thermal equilibrium (i.e. absence of an external excitation), the recombination rate equals the **thermal generation rate *G_{th}*** such that the electron and hole concentrations are constant and independent of time.

$$\boxed{\sim exp\left(-\frac{E_g}{k_B T}\right)}$$

$$G_{th} = R = \alpha_r \cdot n \cdot p$$

$$G_{th} = \alpha_r \cdot n_0 \cdot p_0 = \alpha_r n_i^2$$

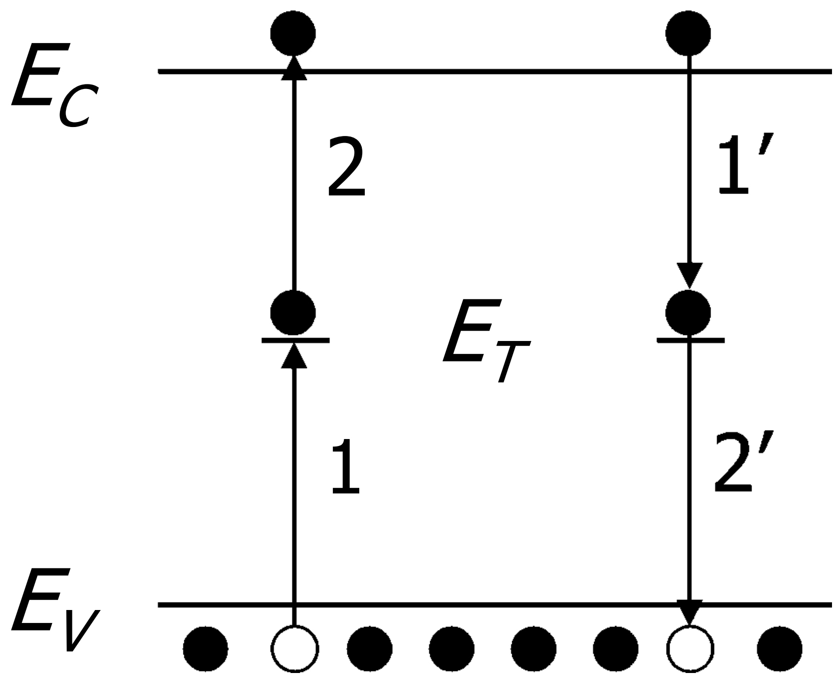
  – Recall: $n_0 p_0 = n_i^2$ under thermal equilibrium

Non-Equilibrium

- When the **generation rate *G*** is **greater** than the **recombination rate *R*** (e.g. exposing the semiconductor to light), the concentrations of electrons and holes in the system increase with time, i.e. $\partial n/\partial t, \partial p/\partial t > 0$.
- On the other hand, when $\boldsymbol{R > G_{th}}$ (e.g. switching off the light after some time), the concentrations of electrons and holes in the system **decrease** with time, i.e. $\partial n/\partial t, \partial p/\partial t < 0$.

More on this later!

Indirect Processes



An energy band diagram illustrating the indirect transitions between the conduction and valence bands via an intermediate defect or trap level E_T.

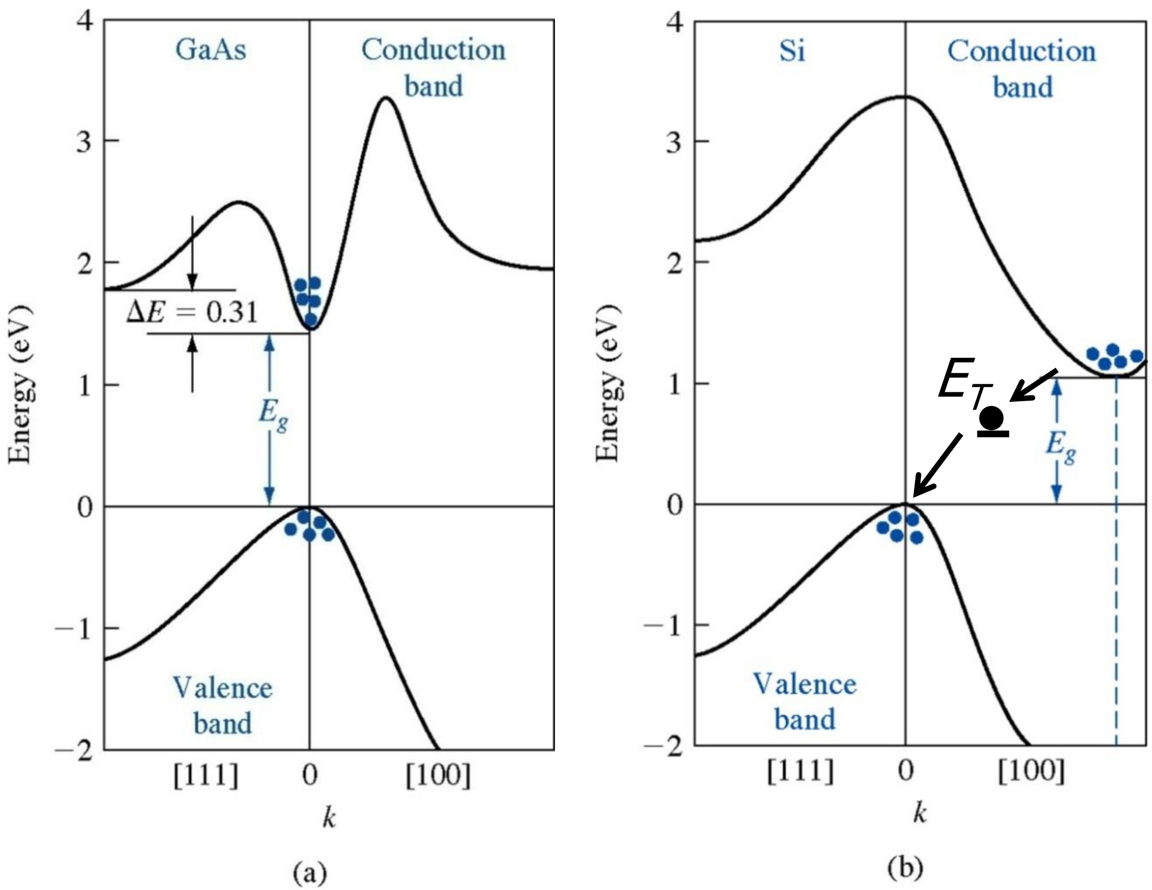
Indirect Processes

- When a valence/conduction band electron makes a transition to an **intermediate energy level E_T** within the bandgap, before proceeding to the conduction/valence band, the process is known as **indirect transition**.
- The energy level E_T is commonly known as the **generation-recombination (G–R) center**. It arises from crystallographic defects or impurity atoms present in a semiconductor crystal.
- Only energy levels situated near the **middle** of the band gap are **efficient** generation-recombination centers.

Indirect Processes

- The transition rate increases with the defect or trap (present in all practical semiconductors) density.
- Indirect transitions are the main mechanism for electron-hole pair recombination in an indirect bandgap semiconductor such as **silicon** (Si).

Direct/Indirect Bandgap Semiconductor



The requirement for momentum conservation makes direct transition between the conduction and valence bands **difficult** in an indirect bandgap semiconductor (e.g. Si).

In an indirect bandgap semiconductor, transitions take place via an intermediate defect state E_T, such as that shown in the diagram.

Energy band structure of (a) GaAs & (b) Si

Summary

- You should now be quite familiar with the following concepts:
  - Meanings of carrier generation and recombination in the context of semiconductors.
  - What do they mean physically and how to represent them in an energy band diagram.
  - Thermal equilibrium is a special case where the carrier generation rate equals the recombination rate, in the absence of an external excitation.
  - Differences between direct and indirect recombination.