Announcements

- HW4 due: 2/21, Friday 5 pm
- Mid-term exam 2: 2/25, Tuesday
  - Chapters 9 and 10
  - Open textbook, notes, and slides
- Review session schedule

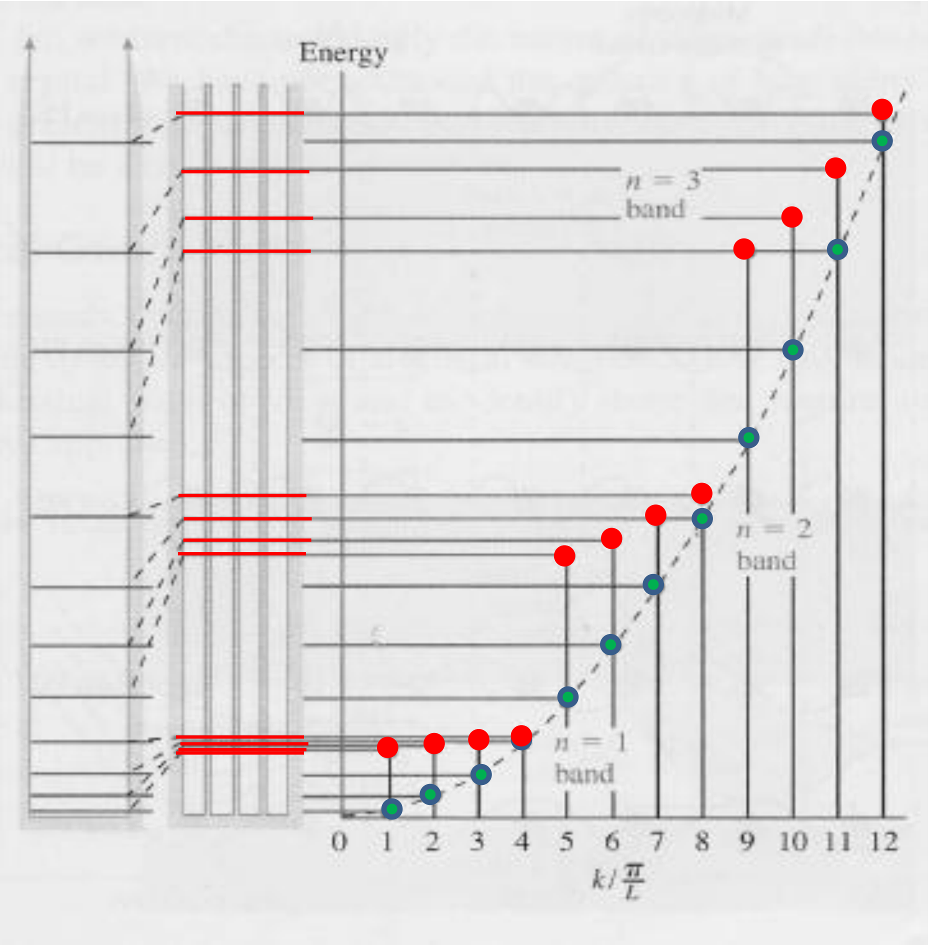
Lecture 14 Topics

- Extrinsic semiconductors
  - n-type
  - p-type
- Semiconductor devices
  - Diode
  - Transistor
- Superconductivity
  - Characteristics: Perfect conductivity and perfect diamagnetism
  - Type 1, Type 2, and High Tc Superconductors
  - BCS Theory and Cooper Pairs

Comparing energy bands vs. free particle solution

Free particle solution:

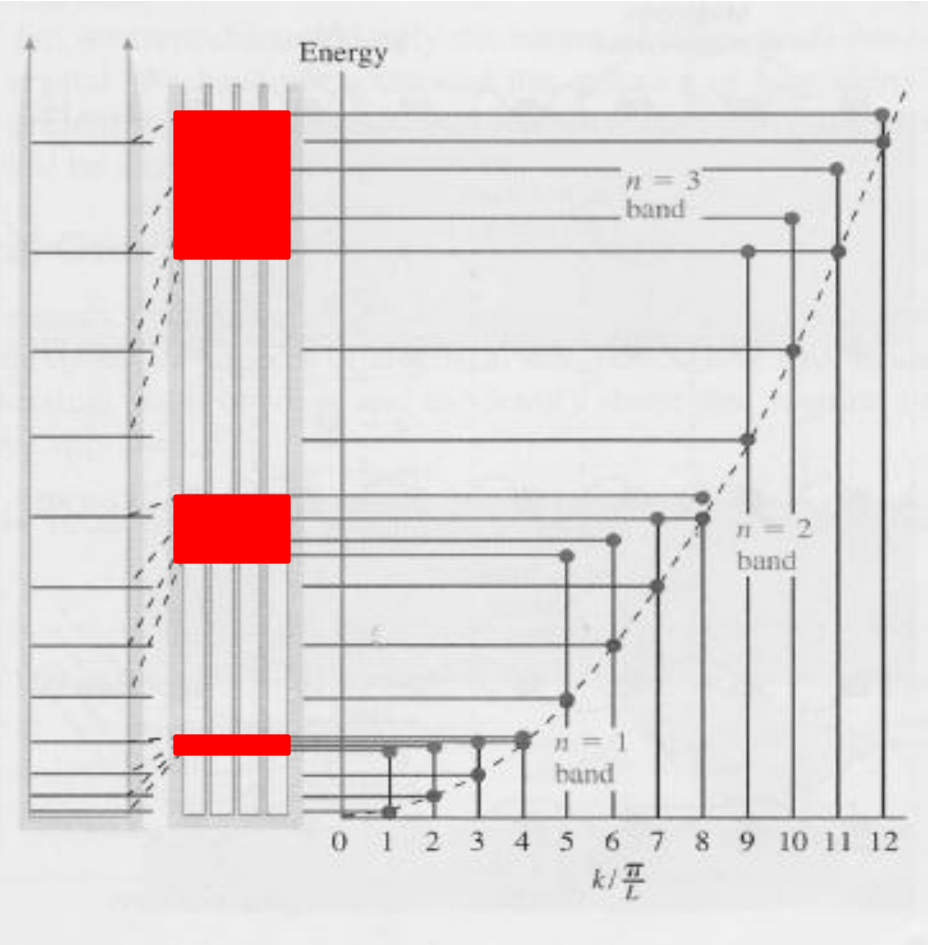
$$E = \frac{\hbar^2}{2m} k^2$$



Large well 4-atom well

Comparing energy bands vs. free particle solution

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



Large well 4-atom well

Energy band gap

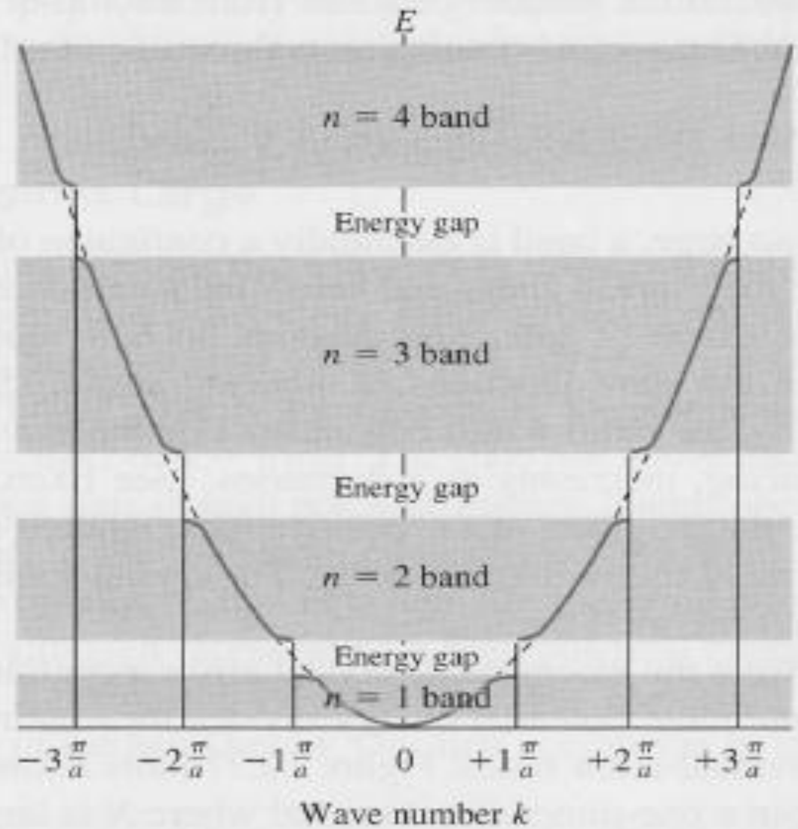
Three differences between free particle and electron in crystal:

1. Energy level continuity

2. Energy band existence

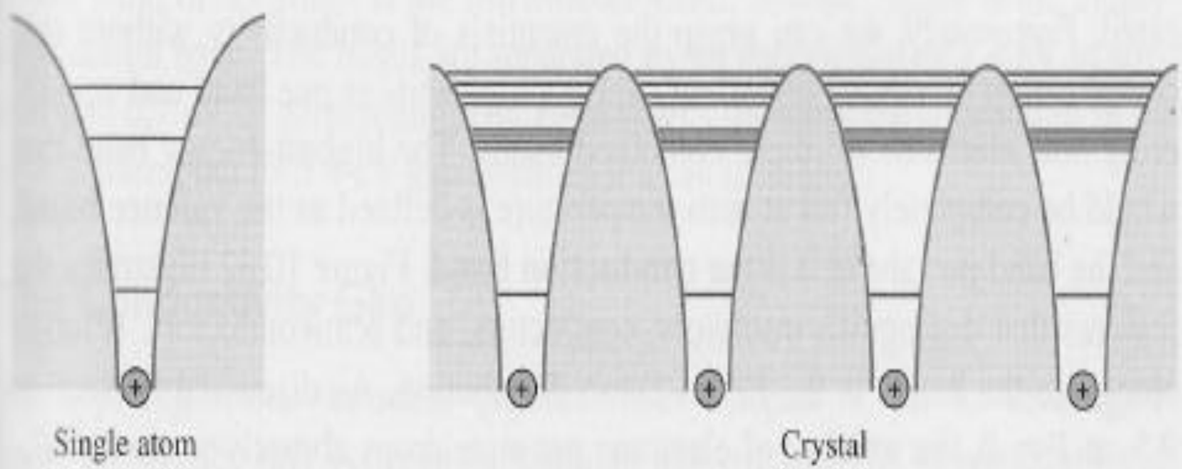
3. The curvature of energy values allowed in the system

Figure 10.27 Bands and gaps in a one-dimensional crystal.



Conductors, Insulators, and Semiconductors

Figure 10.29 When atoms form a crystal, low-lying nonvalance levels still belong to each atom, while higher levels become bands.



Band structure

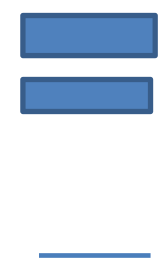
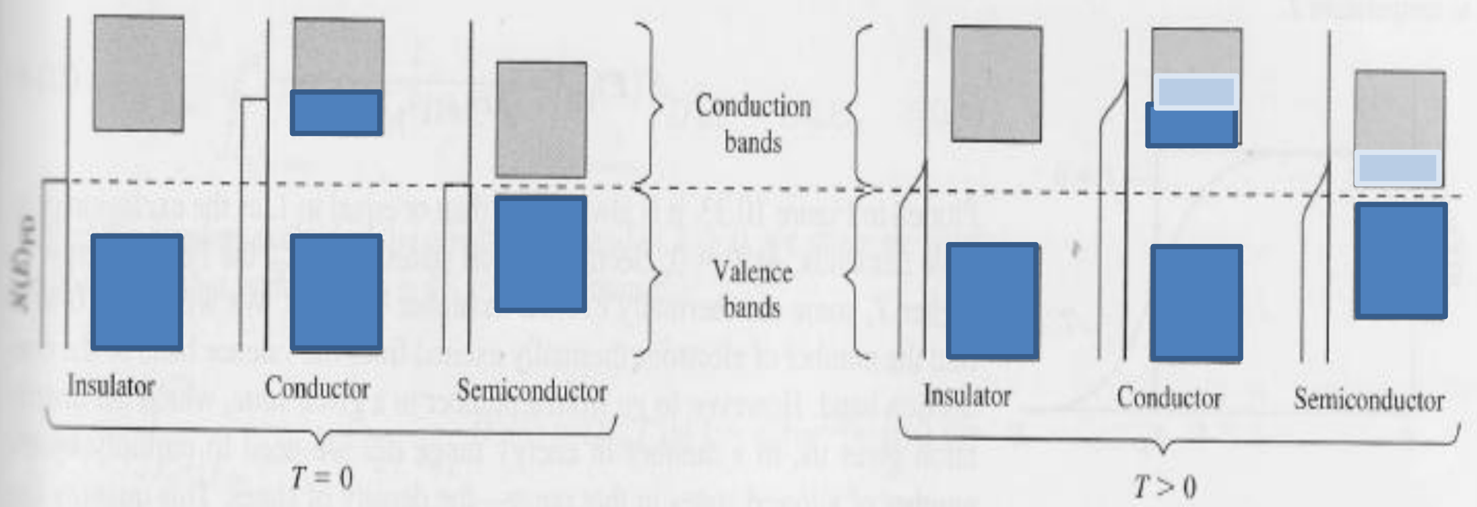


Figure 10.32 Band filling for an insulator, a conductor, and a semiconductor at zero and nonzero temperature. When $T > 0$, a semiconductor will have some electrons in the conduction band.



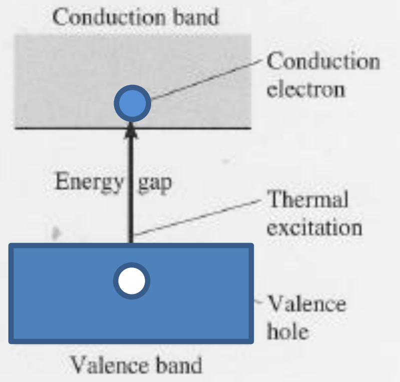
Two types of charge carriers

Conduction band electrons

Valence band holes

- created by electrons left the valence band at $T > 0$
- Behave like positive charge carriers
- Are free to move in the valence band
- Are always found near the top of the valence band

Figure 10.35 Thermal excitation creating a pair of charge carriers.



Current in an E field

Figure 10.38 In a semiconductor at $T > 0$, both holes and electrons contribute to current in the direction of an applied electric field.

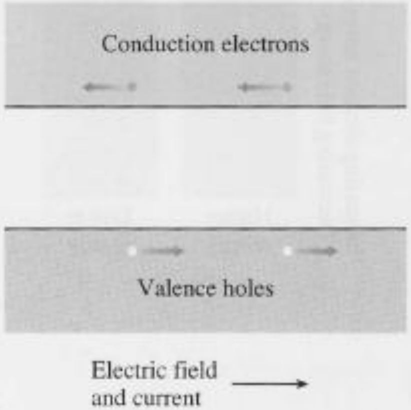
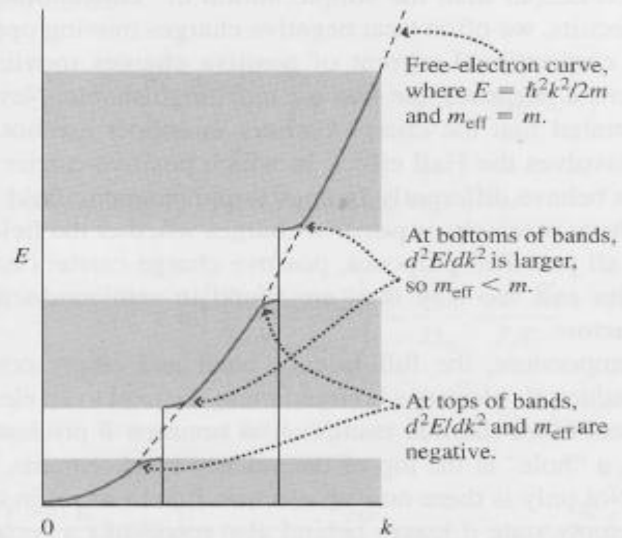
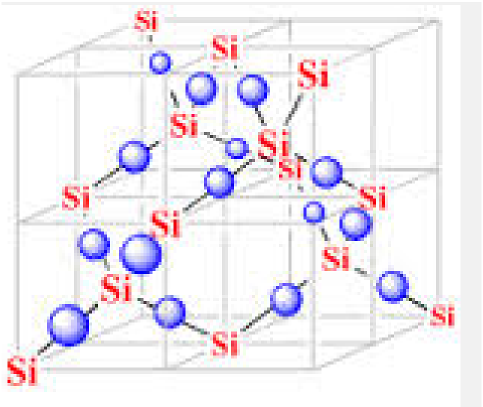


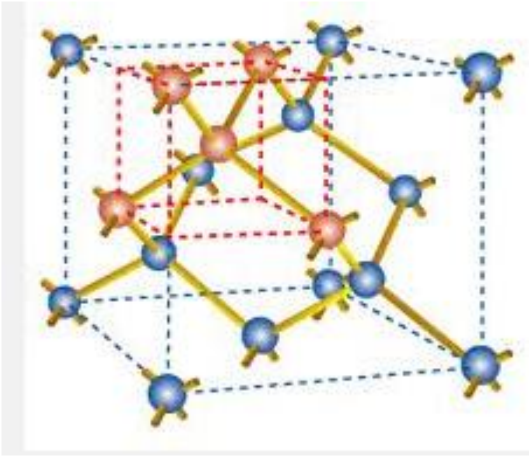
Figure 10.37 Energy versus wave number for electrons in a one-dimensional crystal. An electron's effective mass depends on what state it occupies.

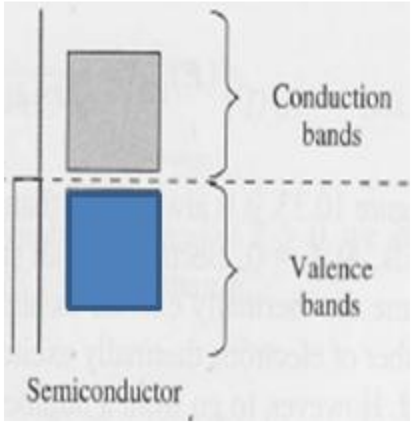


Doping

- Intrinsic semiconductors





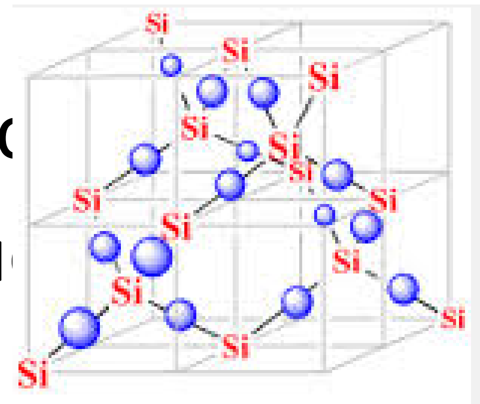


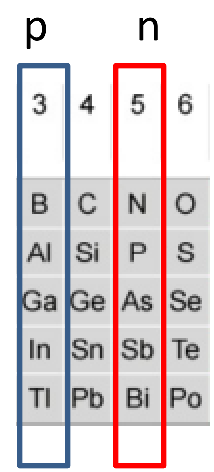
Doping

3	4	5	6
B	C	N	O
Al	Si	P	S
Ga	Ge	As	Se
In	Sn	Sb	Te
Tl	Pb	Bi	Po

- Intrinsic semiconductors
- Extrinsic semiconductors:
  - n-type:
    - Use elements with 5 valence electrons as impurities
    - Extra electron per impurity atom
  - p-type:
    - Use elements with 3 valence electrons as impurities
    - A hole per impurity atom

Doping





- Intrinsic semiconduc
- Extrinsic semicondu
  - n-type:
    - Use elements with 5 valence electrons as impurities
    - Extra electron per impurity atom
  - p-type:
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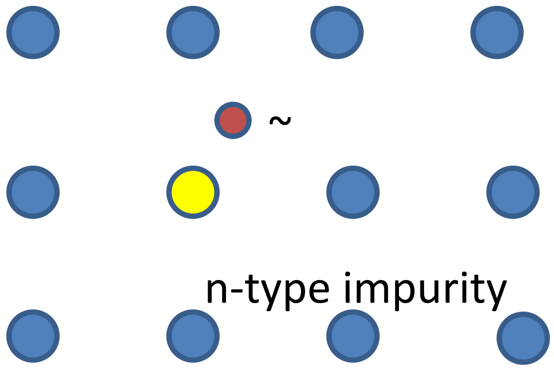
    - A hole per impurity atom

n-type semiconductor

Si: Semiconductor



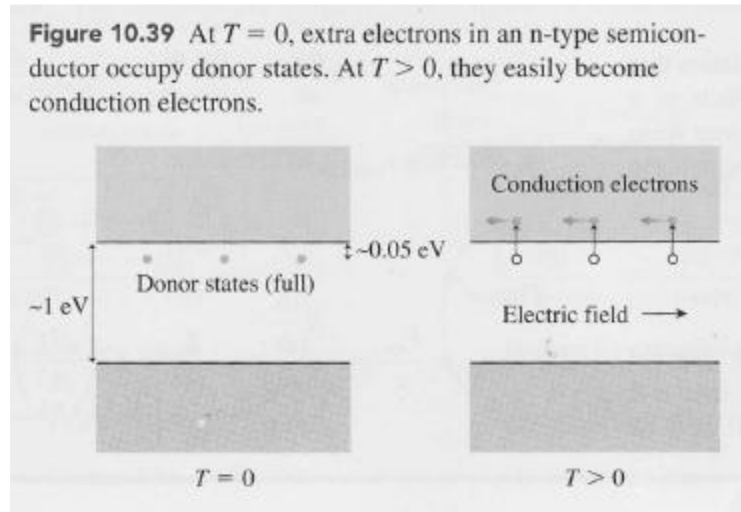
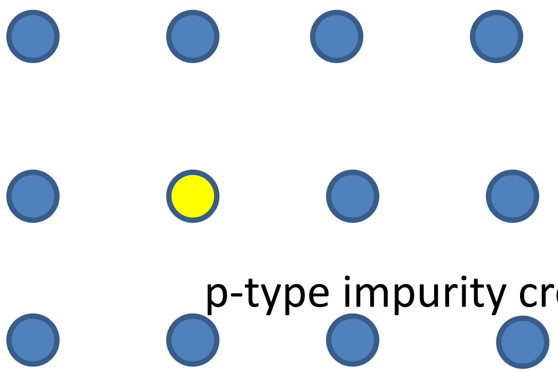


Figure 10.39 At $T = 0$, extra electrons in an n-type semiconductor occupy donor states. At $T > 0$, they easily become conduction electrons.

-create donor states below the conduction band.
-electrons in the donor states can be easily excited to be in the conduction band.
-since impurities are sparse, the donor states do not form energy bands and do not harbor holes.
-in the conduction band, electrons from the donor states are more abundant than those from the valence band
-majority carrier in n-type → conduction band electrons
-minority carrier in n-type → holes in valence band

p-type semiconductor

Si: Semiconductor



p-type impurity creates hole

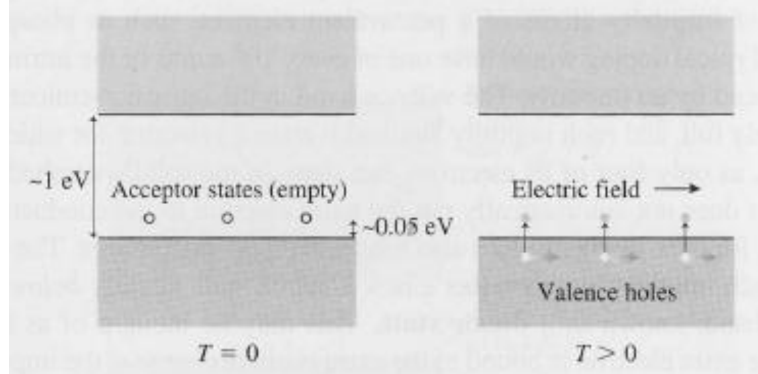
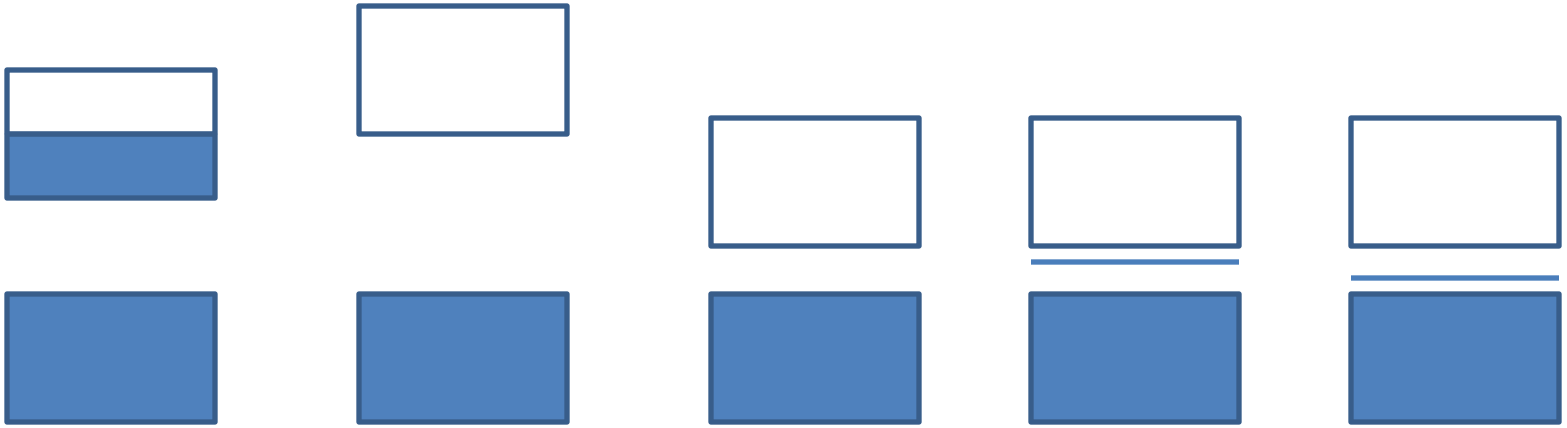


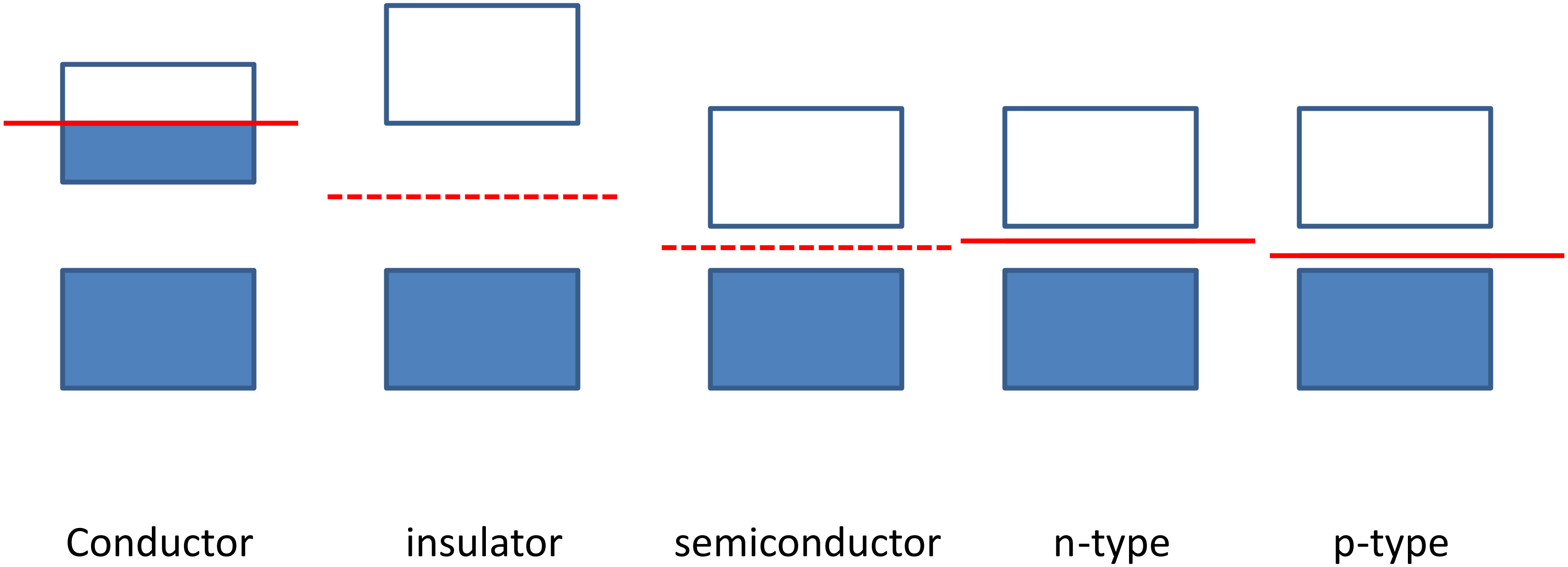
Figure 10.40 At $T = 0$, a p-type semiconductor has empty acceptor states, which at $T > 0$ are filled by electrons from the valence band, freeing holes.

-create acceptor states above the valence band.
-electrons in the valence band can be easily excited to be in the acceptor states, creating holes in the valence band.
-majority carrier in p-type → valence band holes
-minority carrier in p-type → conduction band electrons

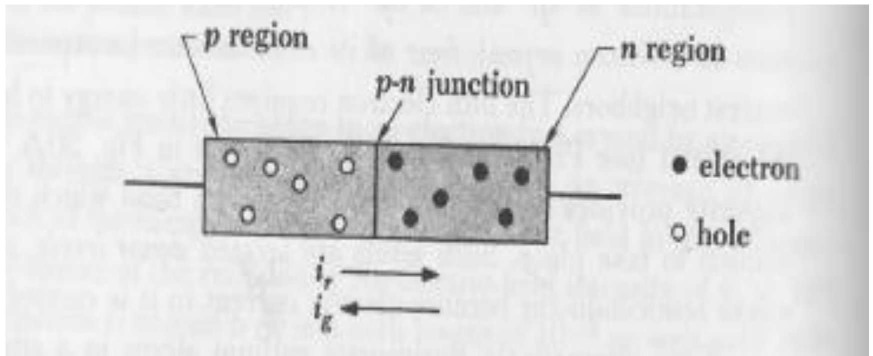
Energy Bands

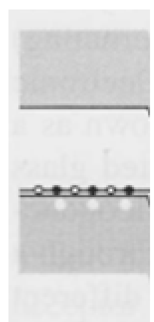


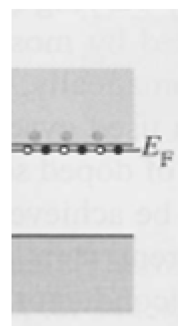
Fermi Energy



Unbiased Diode (p-n)



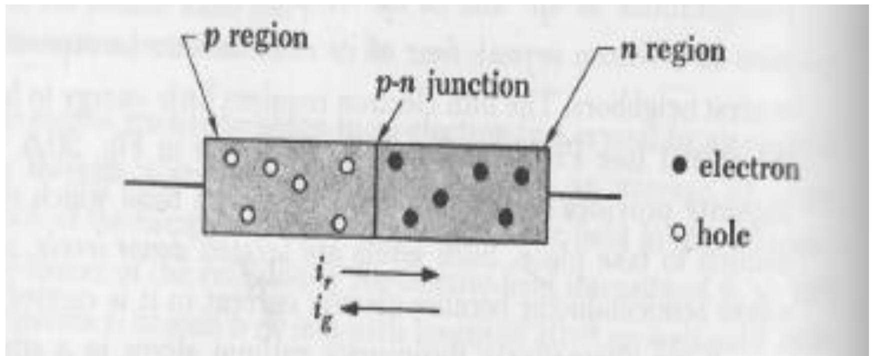


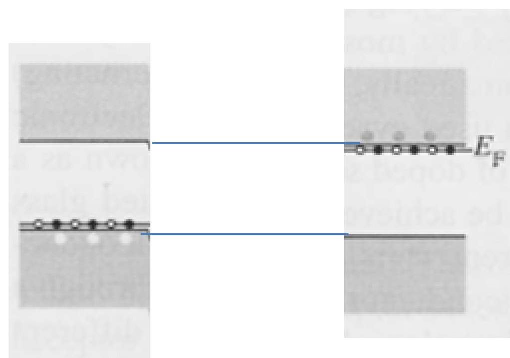


p-type

n-type

Unbiased Diode (p-n)

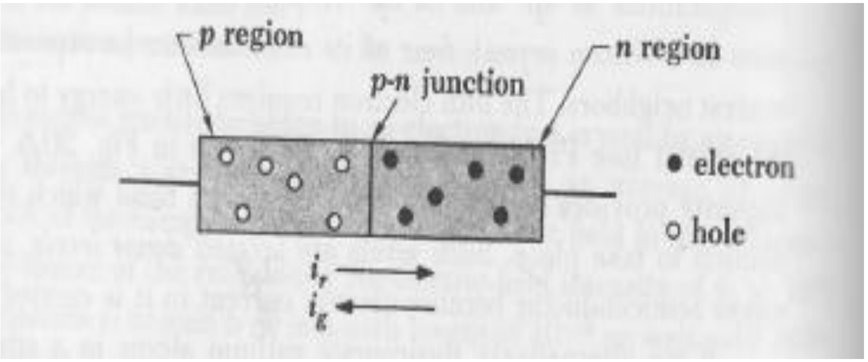


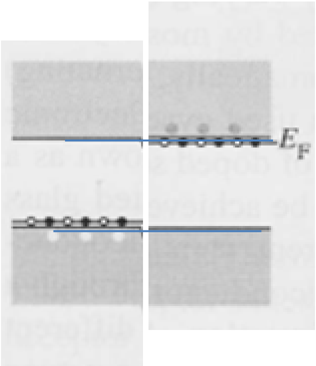


What happens when put together?

p-type n-type

Unbiased Diode (p-n)

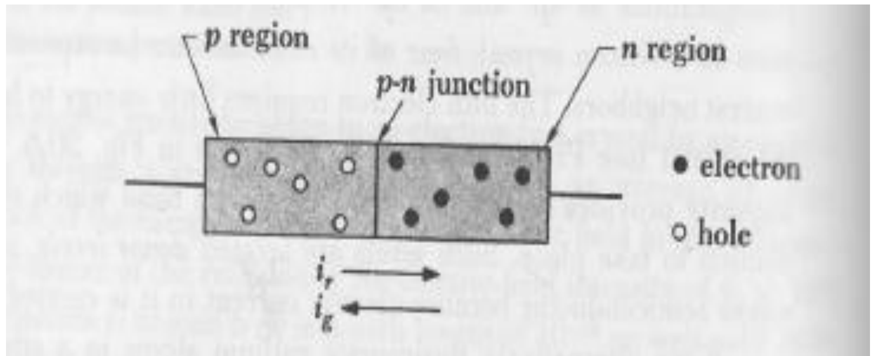


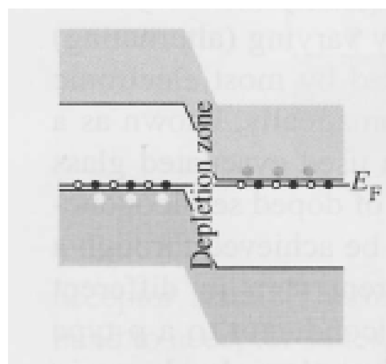


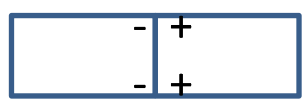
What happens when put together?

p-type n-type

Unbiased Diode (p-n)





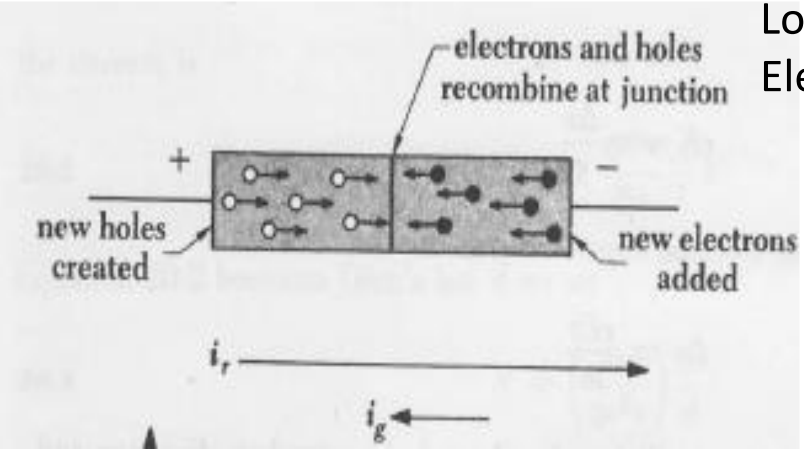


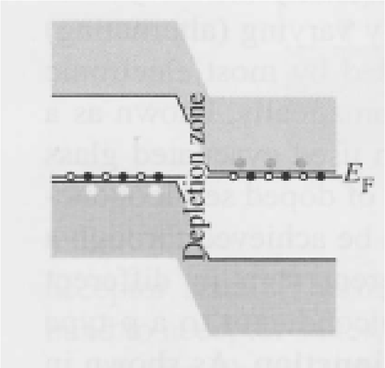
p-type n-type

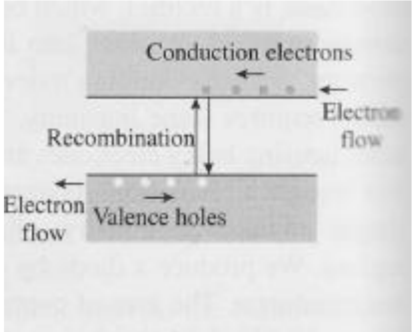
-Diffusion of excessive electrons/holes
-Coulomb interactions between new charge distributions resulting from diffusion of electrons and holes
-Depletion zone

Forward biased

Higher potential at p end
Lower potential at n-end
Electrons are supplied at n-end



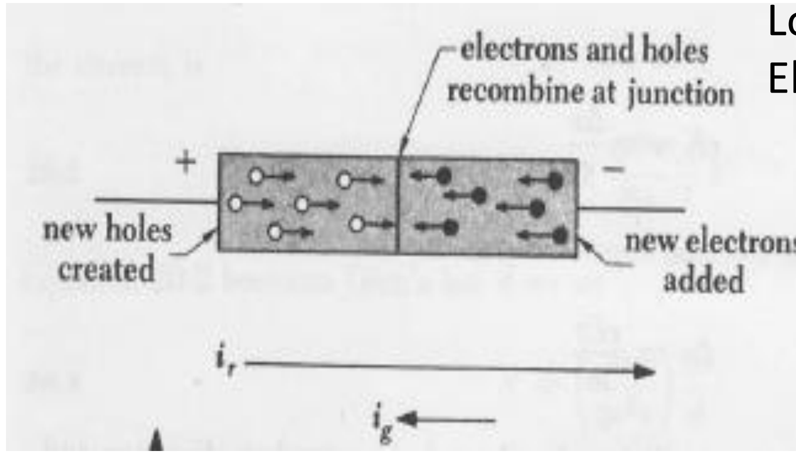


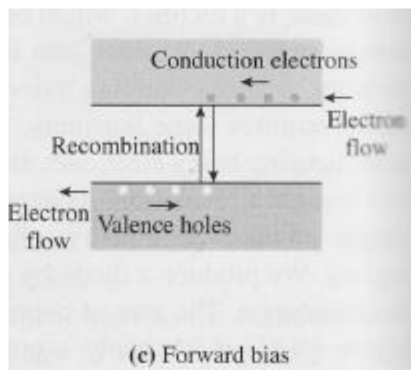


(c) Forward bias

Forward biased

Higher potential at p end
Lower potential at n-end
Electrons are supplied at n-end

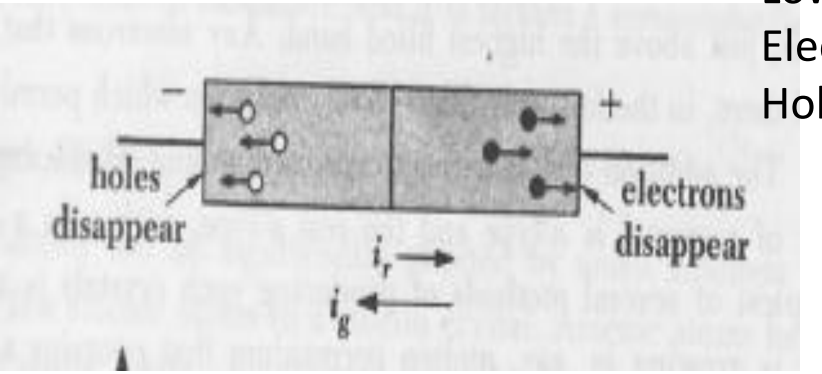


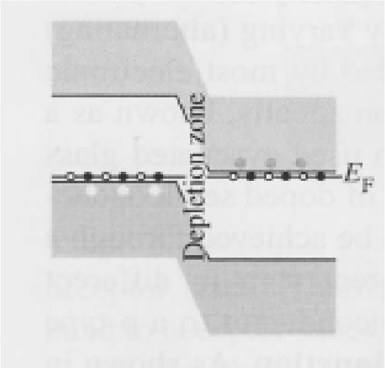


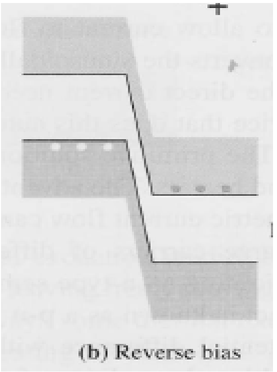
-electrons and holes recombine when they meet
-current flows continuously
-forward-biasing shifts the n-type conduction band upward, allowing higher energy conduction electrons to fill lower energy valence holes. Energy is lost to heat/light

Reverse Biased Diode

Higher potential at n- end
Lower potential at p-end
Electrons disappear at n-end
Holes disappear at p-end







Reverse Biased Diode

Higher potential at n- end
Lower potential at p-end
Electrons disappear at n-end
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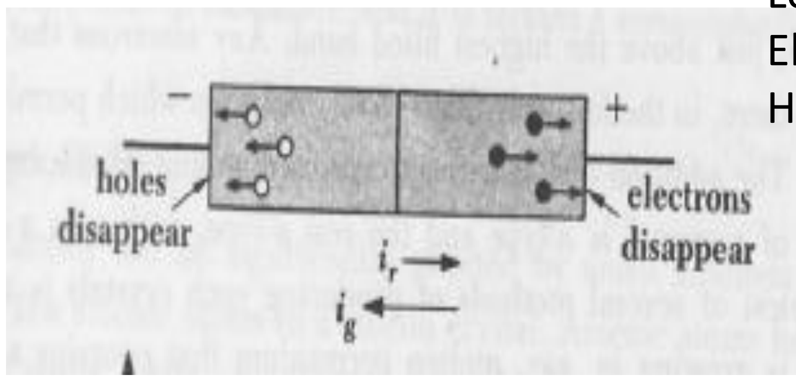
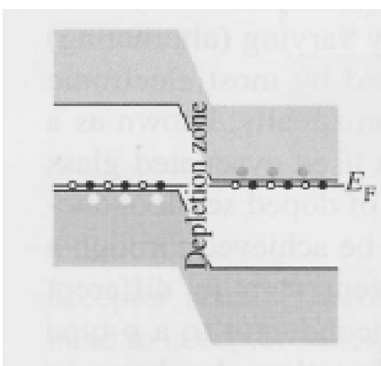
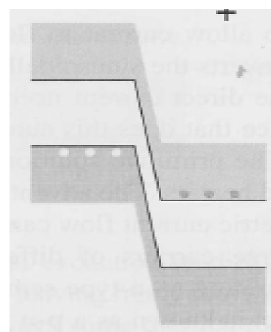
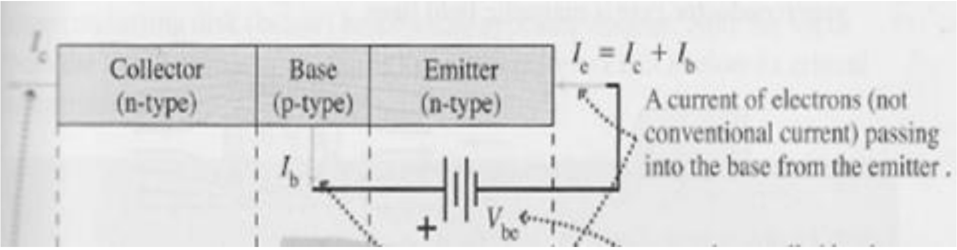




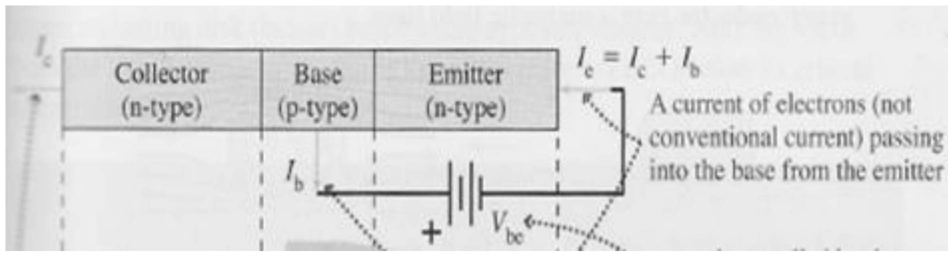

(b) Reverse bias

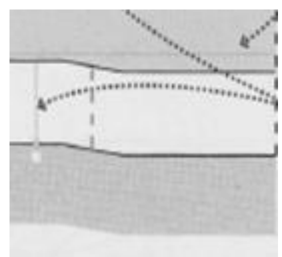
-depletion region (no free charge carriers)
-current stops immediately
-reverse-biasing makes the potential difference more pronounced
-minor charge carriers (conduction electrons in p and valence holes in n) can recombine at a negligible rate

Transistor (npn)

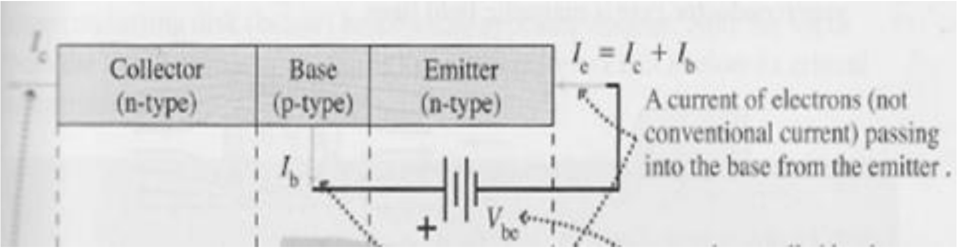


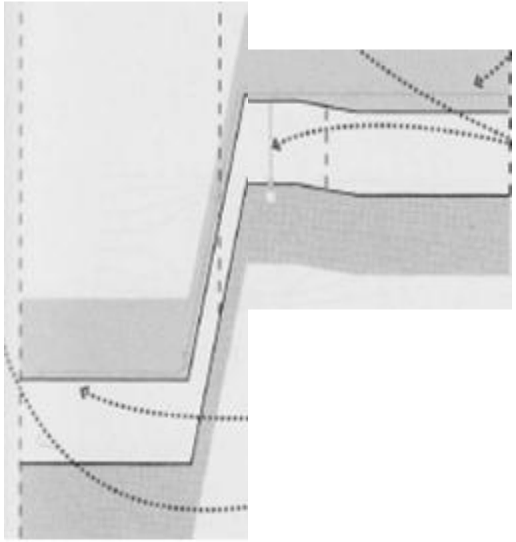
Transistor (npn)





Transistor (npn)





Transistor (npn)

Figure 10.44 Bands and charge flow in a npn transistor.

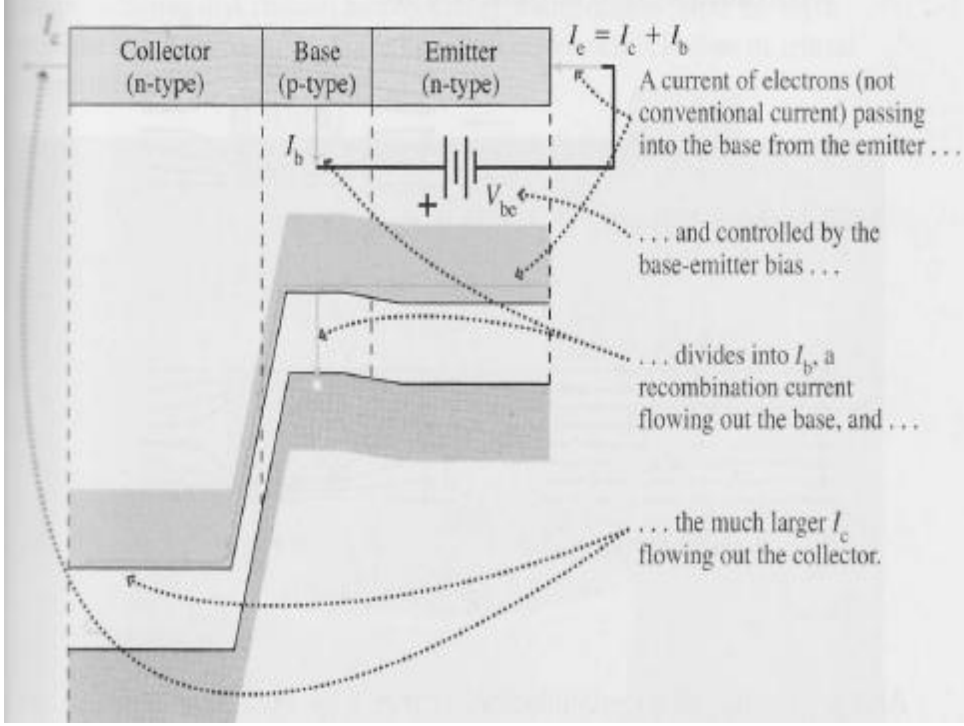


Figure 10.45 The elements of a transistor amplifier.