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EEE105 "Electronic Devices"

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Lecture 7

- Statistical mechanics and the Boltzmann function
  →Application in gases & band-gaps in semiconductors
- Formalisation of transitions between states
- Recombination and generation of carriers
- Magnitudes of n_i, σ for intrinsic semiconductors

Boltzmann Function

- Free electrons in a solid are similar to charged atoms in a gas
- Statistical mechanics of quantum theory is required
- Boltzmann's law – probability of finding molecules in a given spatial arrangement varies exponentially with the negative of potential energy of the arrangement divided by KT

$$n = (\text{constant}) \exp\left(-\frac{\text{P.E.}}{K_B T} \right)$$

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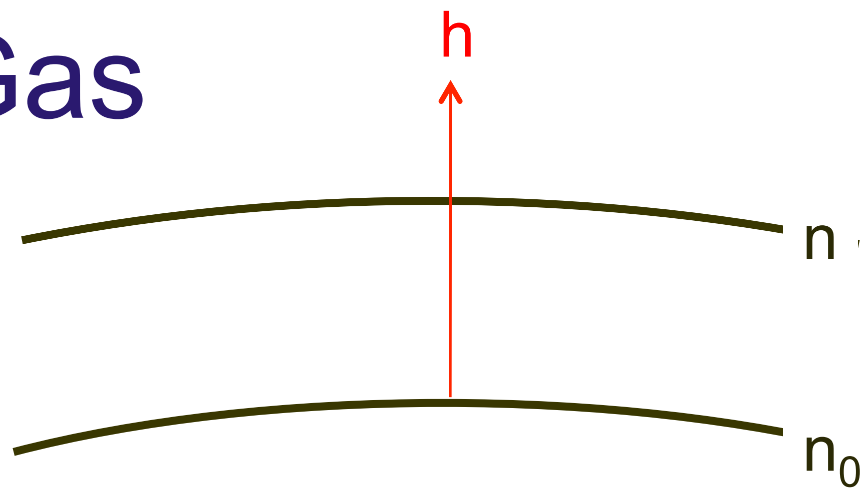
Applications – Gas



In atmosphere P.E. = mgh

$$n = n_0 \exp\left(-\frac{mgh}{k_B T}\right)$$

m=mass
g=acceleration due to gravity
h=height
n=particle density at height h
n_0=particle density at height h=0

Exponential decrease in density with height in the atmosphere

Applications – Electrons

Semiconductor P.E. = Band-gap

We therefore expect something like -

$$n_i = (\text{constant})\exp\left(-\frac{E_g}{k_B T}\right)$$

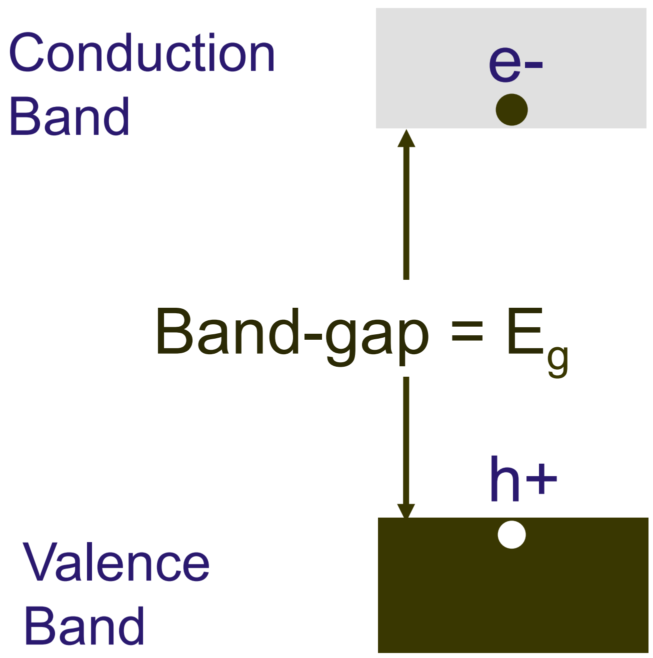
In reality

$$n_i = (\text{constant})\exp\left(-\frac{E_g}{2k_B T}\right)$$

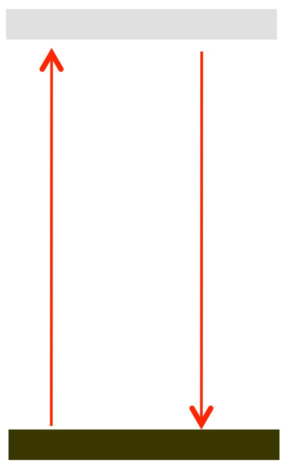
n_i shows exponential;

Increase with temperature

Decrease with band-gap



Transition Between States



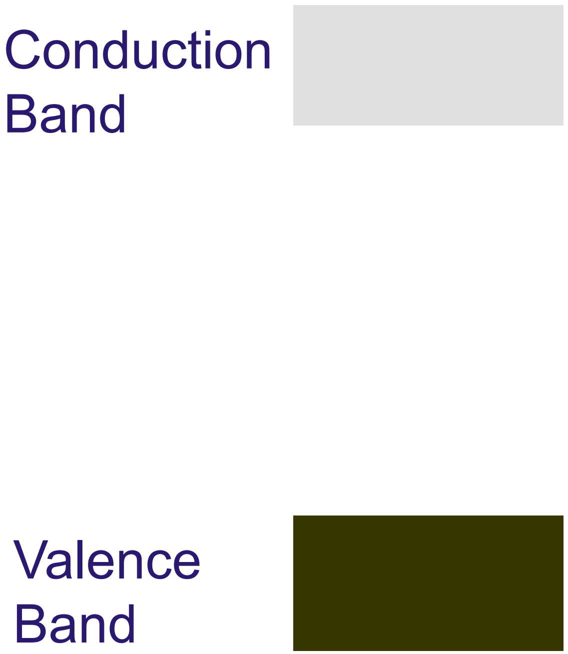
General Principle

Transition rate, R, between two states is number of transitions per second

(We usually think of this as being per unit volume)

$$R \propto (\#\,\text{candidates with enough energy}) \times (\#\,\text{empty final states})$$

Thermal Generation



candidates with sufficient energy = #initial states x Boltzmann factor

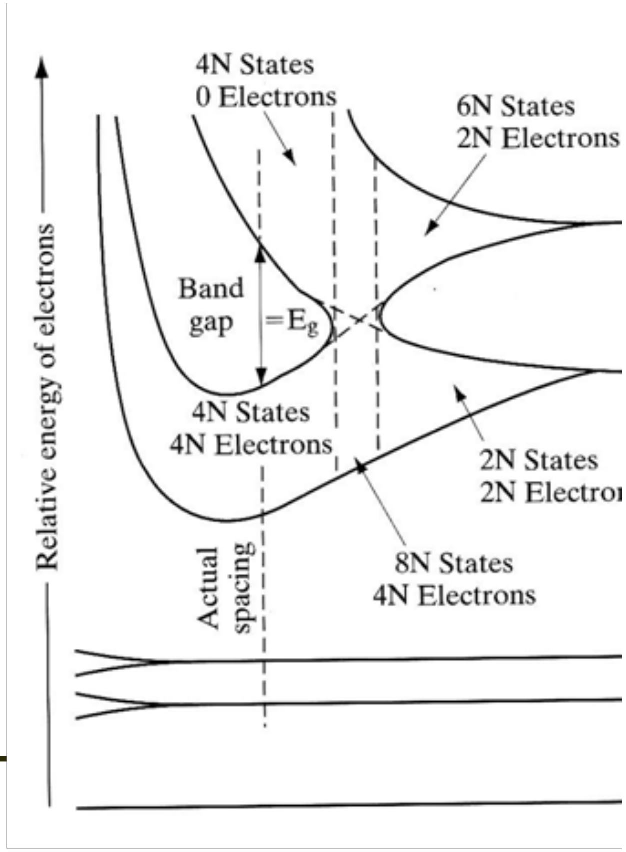
Boltzmann factor is related to Fermi – levels not band edge

Density of electrons and holes related to $E_g/2$

$$G \propto (\#\text{initial states}) \text{ x } \exp\left(-\frac{E_g}{2K_BT}\right) \text{ x } (\#\text{final states})$$

Full n_i equation

$$n_i = C\, T^{3/2} \exp\left(-\frac{E_g}{2K_B T}\right)$$



A new term - $T^{3/2}$ appeared !

Due to density of states changing with T

$$G \propto (\#\text{initial states}) \text{ x } \exp\left(-\frac{E_g}{2K_B T}\right) \text{ x } (\#\text{final states})$$

However, main temperature effect is the exponential part

Recombination

- From slide 7 – for recombination of electrons and hole

$$R \propto (\#\,\text{candidates with enough energy}) \times (\#\,\text{empty final states})$$

$$R \propto n\,p \qquad\qquad R = B\,n\,p$$

- Where B is the (Einstein) recombination constant
  - Characteristic of different semiconductors
  - Independent of doping, n, p

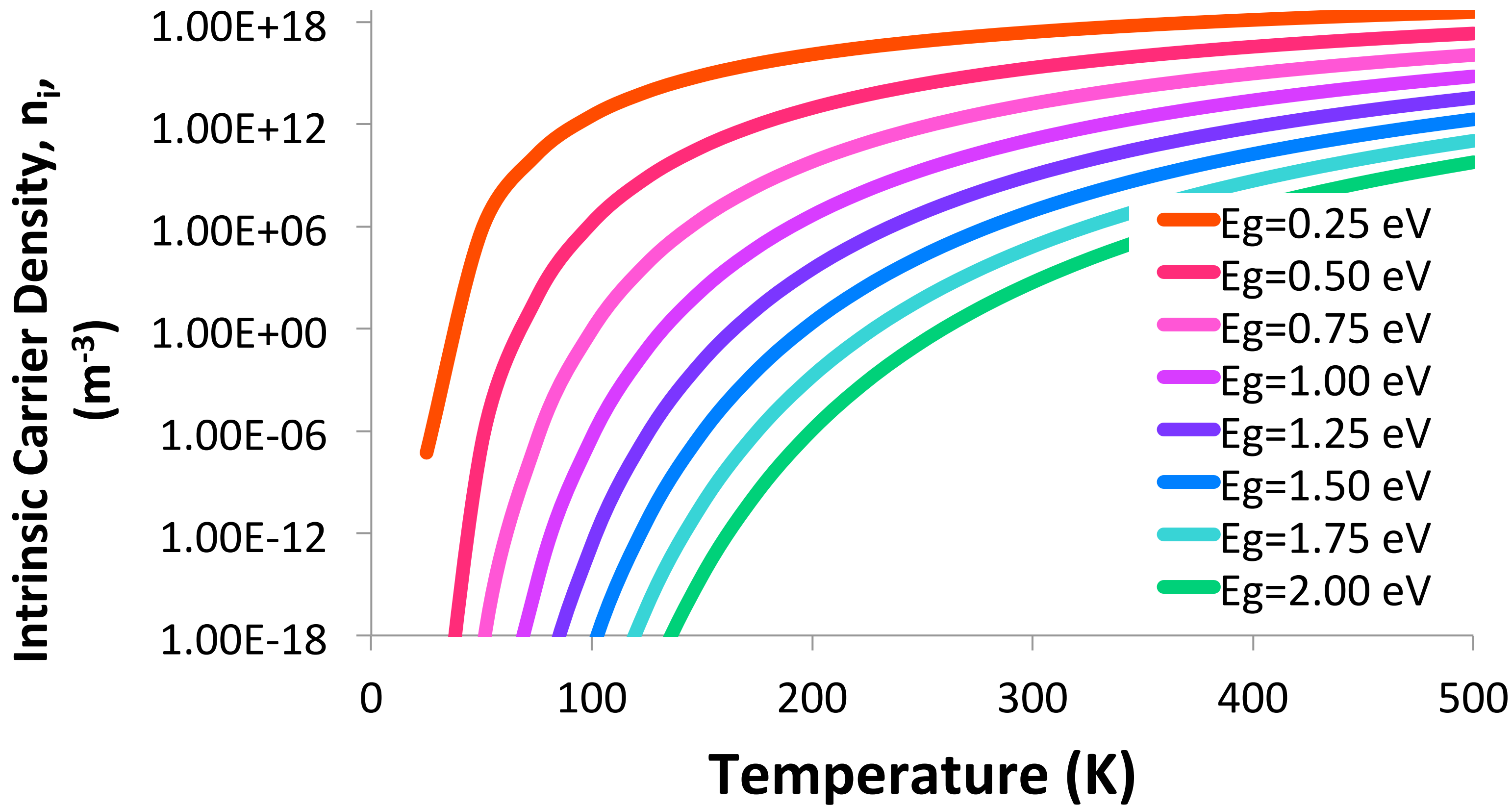
Equilibrium (G=R)

- Intrinsic Semiconductor

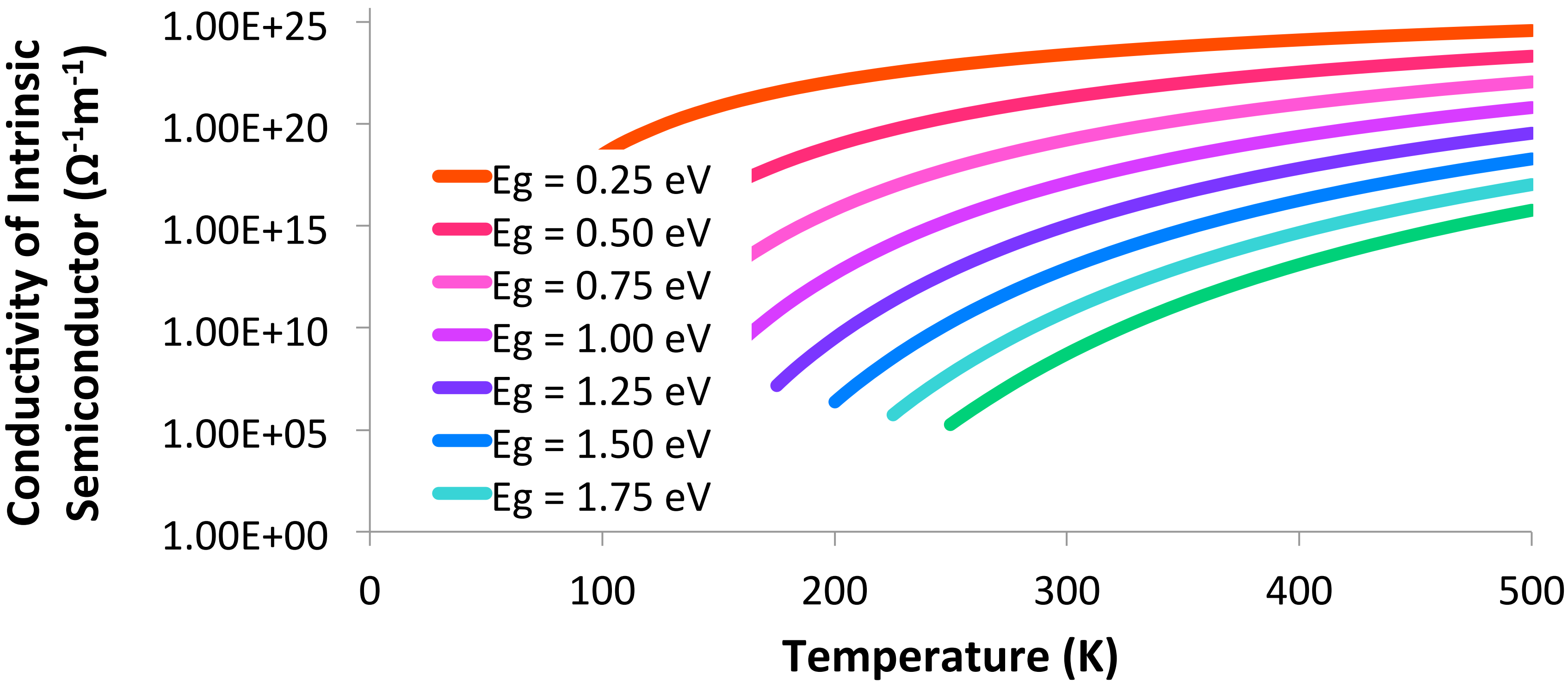
$$G = R = Bn_i p_i = B\,n_i^{\,2} \qquad \text{As} \quad n_i = p_i$$

This will be very useful later - when we dope our semiconductors

How big is n_i?


1.00E+18
1.00E+12
1.00E+06
1.00E+00
1.00E-06
1.00E-12
1.00E-18
0
100
200
300
400
500
Temperature (K)
Intrinsic Carrier Density, n_i, (m^{-3})
Eg=0.25 eV
Eg=0.50 eV
Eg=0.75 eV
Eg=1.00 eV
Eg=1.25 eV
Eg=1.50 eV
Eg=1.75 eV
Eg=2.00 eV

σ - Intrinsic Semiconductors



Summary

- The Boltzmann function has been introduced and applied to a semiconductor - intrinsic carrier density can be determined
- The transition between states is governed by the number of candidates with sufficient energy and the number of empty states
- Using this we can develop a fuller description for the intrinsic carrier density has been discussed
- Recombination of carriers is proportional to the electron density and hole density
- At equilibrium thermal generation and recombination rates are equal
- The effect of temperature and band-gap on intrinsic carrier density and conductivity has been explored – huge variations can be obtained through band-gap and temperature changes of intrinsic semiconductors

