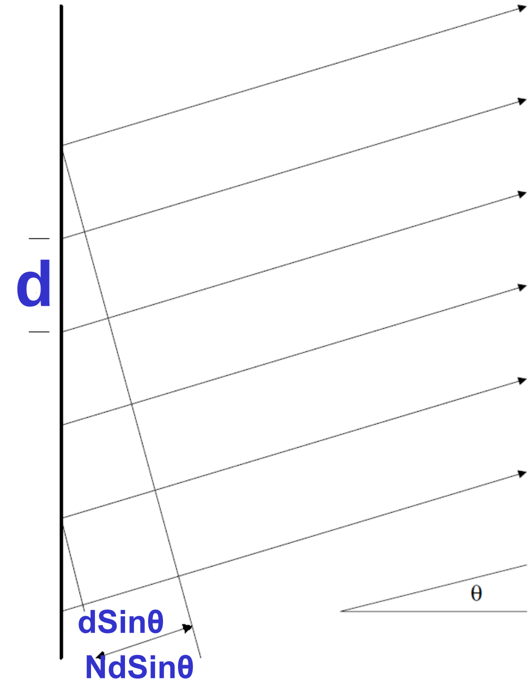
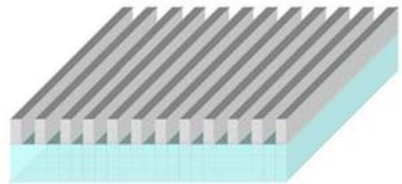
Topic 13

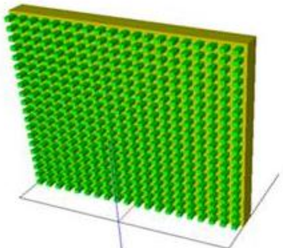
13 Review on semiconductor physics

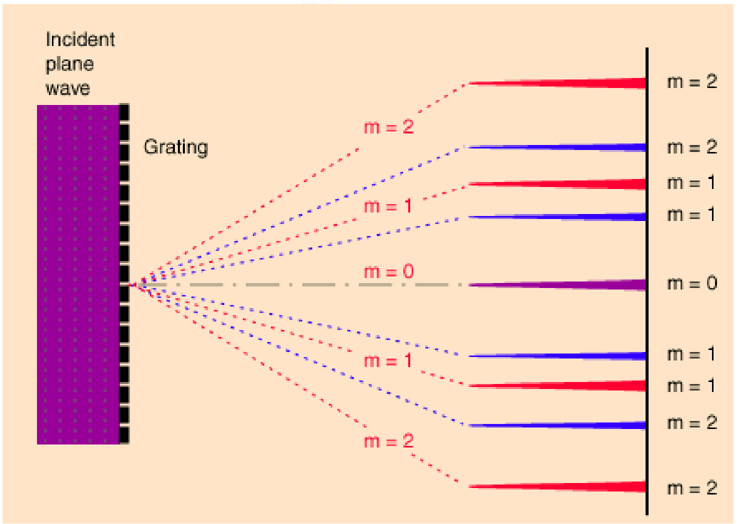
- 13.1 Introduction
- 13.2 Energy Band
- 13.3 Effective-mass Approximation
- 13.4 Indirect and Direct Bandgap
- 13.5 Density of States
- 13.6 Hetero-structures

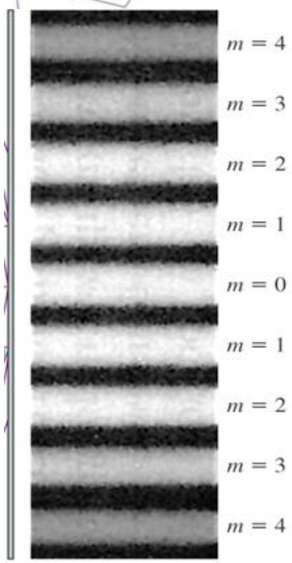
Introduction (1)











$\sin\theta_m = m\lambda/d$, (d: period of grating): **$\sin\theta_m - \sin\theta_{m+1} \sim 1/d$ for a fixed λ**

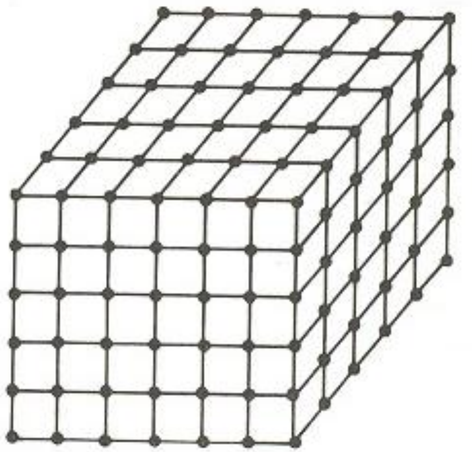
The interaction between light and a **periodic structure**:

- Only certain angles (**discrete**) are allowed for observing light
- The angles between these "**allowed**" angles: "**forbidden**" for the light

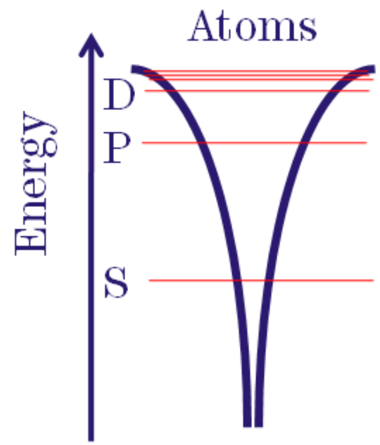
Conclusion:

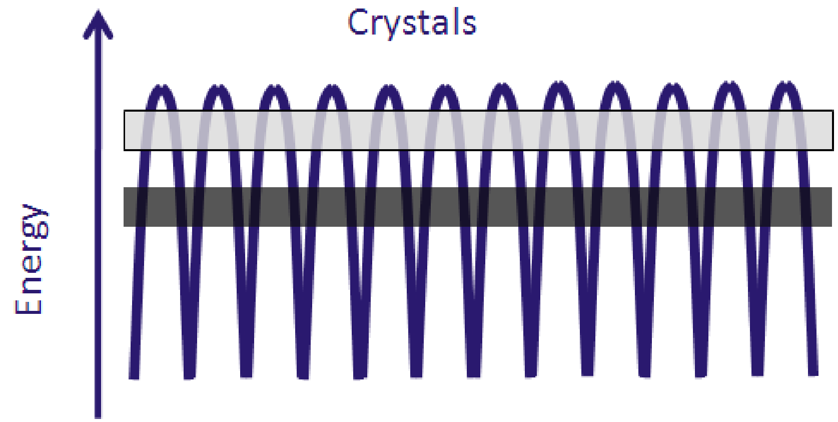
- Generate **a series of discrete "allowed" angles**, and "**forbidden**" **angles**
- The angle separation is determined by **the period of grating (1/d)**

Introduction (2)



Crystalline





Crystalline: Similar to "grating structure", **a periodic structure** (period parameter: lattice constant)

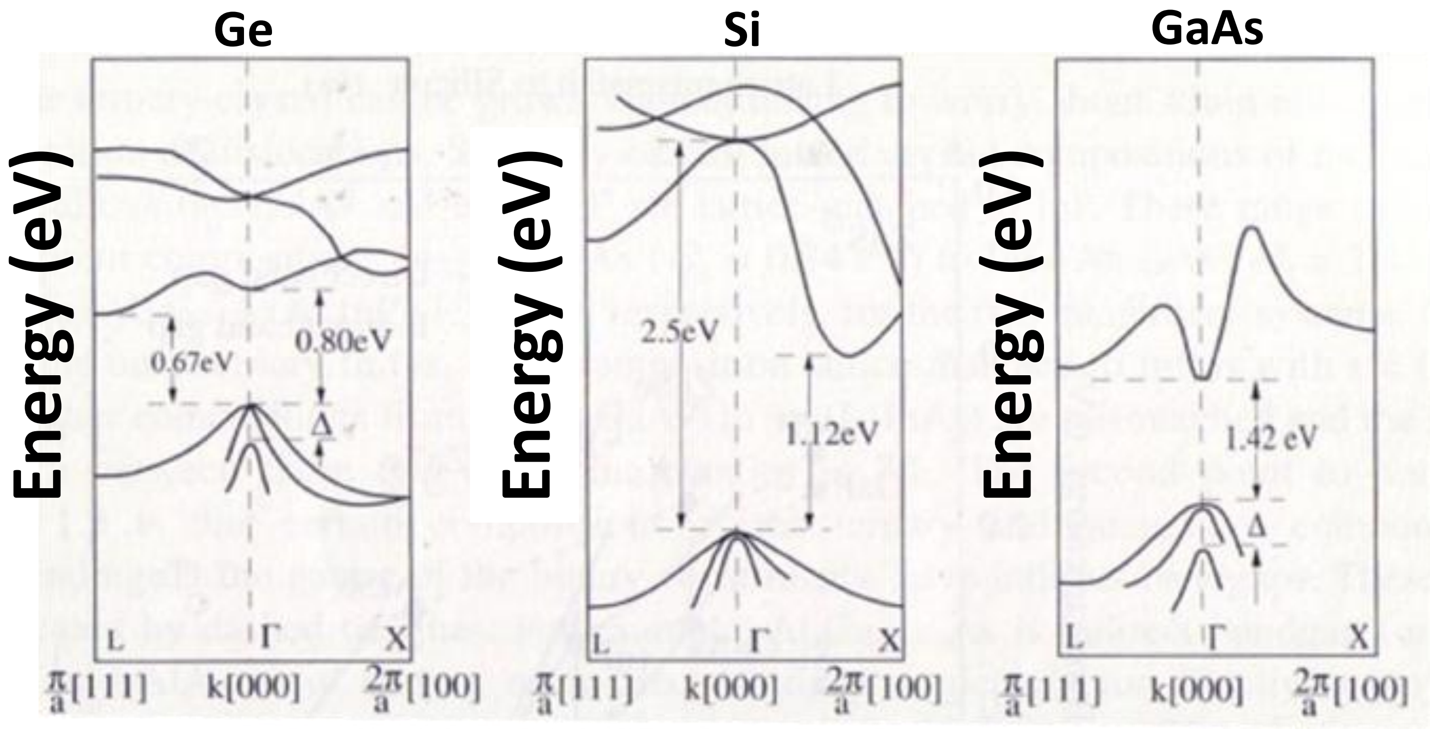
Semiconductor: electrons of the outermost shell are "free" within it (RT)

The interaction between these "free" electrons and the periodic structure:

(1) A series of discrete energy levels, allowing electrons to stay; and the energy gaps between them do not allow electrons to stay

(2) Conduction and valence band: **the two highest energy levels**, allowing electrons to stay. The energy gap between them: "forbidden gap", which is called the **bandgap**.

Band Structure



- **Energy distribution depends strongly on interatomic distance, and also relies on crystallographic direction**
- **Valence band: existence of subbands due to spin-orbit interaction**
- **Minimum of conduction band and maximum of valence band:**
  - **(i) Ge and Si: along different directions**
  - **(ii) GaAs: along the same direction**

Effective-mass Approximation

- It is extremely difficult to describe the motion of electrons, as it contains **10^{22}-10^{23} electrons cm^{-3}**

- We need to know all forces that any electrons receive:
  (i) Its **kinetic energy**; (ii) interaction between the **electron and any other of 10^{22}-10^{23} electrons cm^{-3}**; (iii) interaction between **the electron and all positively charged ions (nucleus)**
  It is almost impossible. An approximation is necessary.

An very useful model which can simplify the issue

Effective-mass Approximation

Key points:

(1) Electron or hole is treated as a **free particle**,

(2) Electron or hole is with an **effective mass**

(3) The effective mass:
All forces that any electrons receive from all the ions and all the other electrons.

Effective-mass

III-nitrides:

	AlN	GaN	InN
Band gap (eV)	5.96	3.42	0.7
Effective Mass of m_e	0.48	0.20	0.11

III-As:

	AlAs	GaAs	InAs
Band gap (eV)	2.15	1.424	0.36
Effective Mass of m_e	0.1	0.067	0.027

III-Sb:

	AlSb	GaSb	InSb
Band gap (eV)	1.615	0.75	0.17
Effective Mass of m_e	0.12	0.042	0.027

III-P:

	AlP	GaP	InP
Band gap (eV)	2.45	2.272	1.344
Effective Mass of m_e	?	?	0.073

In general

Bandgap ↑
Effective mass ↑

Effective mass plays an important role in device design

Temp. Dependent Bandgap and Refractive Index

- Temperature

(1) increase temperature and the lattice expands
reducing the bandgap energy

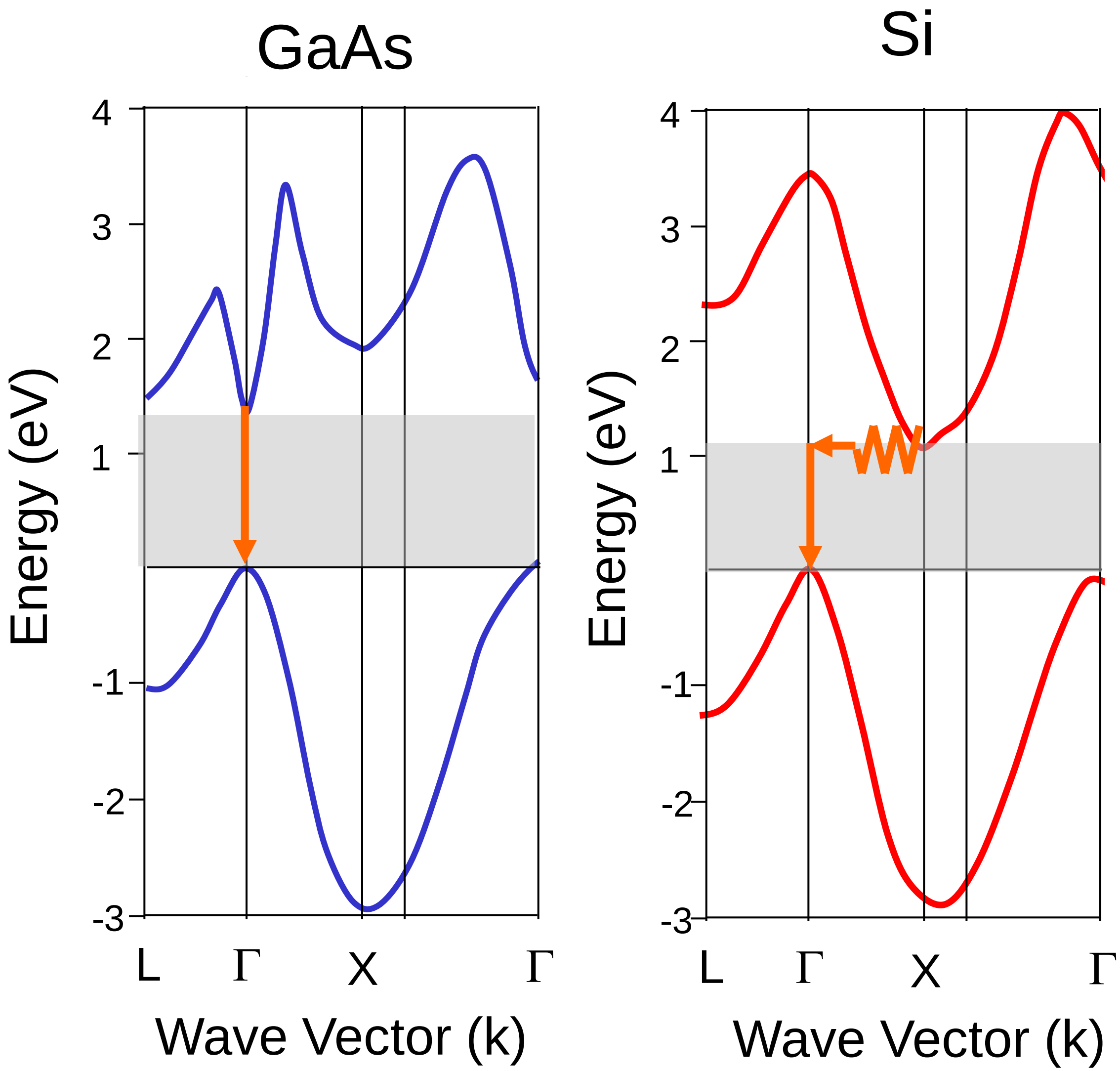
(2) reduce temperature and the lattice shrinks
increasing the bandgap energy

$$\boxed{E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta}}$$

(3) $n^4 E_{gap}$=constant

Bandgap energy (E) increases; refractive index (n) decreases

Direct and indirect Semiconductors



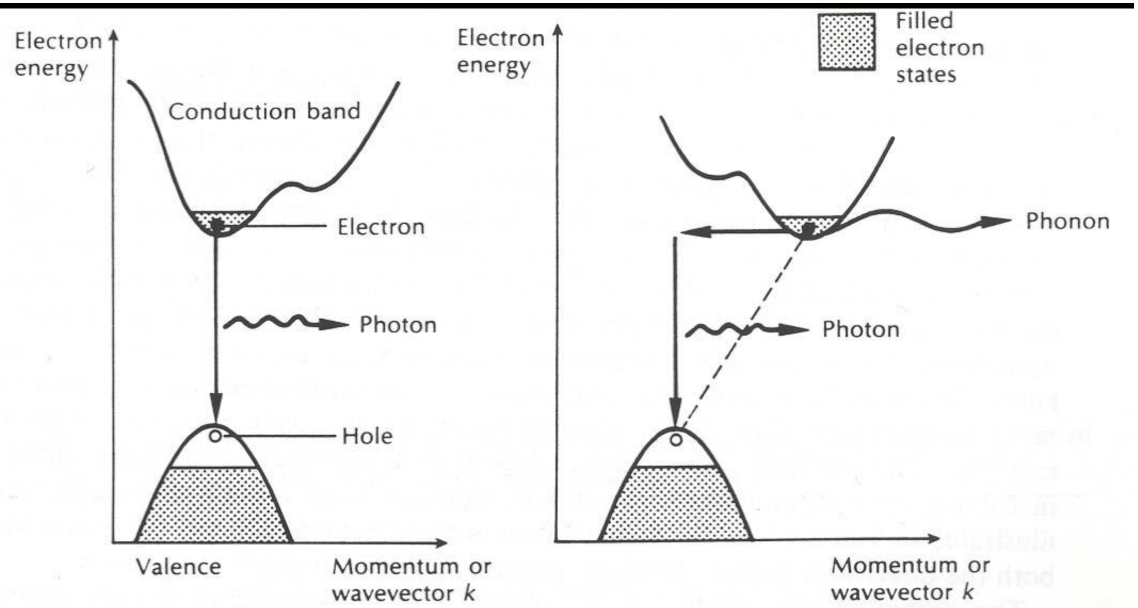
Conduction Band

Valence Band

$\Gamma \; k_x = k_y = k_z = 0$

$L \; k_x = k_y = k_z = \pm \boldsymbol{\pi/a}$

Radiative Recombination Process



Radiative recombination: an electron recombines with a hole, releasing the energy as a photon.

Direct bandgap: This process is easy to occur, thus efficiency is high.
The radiative lifetime is short. **(Good for emitters)**

Indirect bandgap: Due to the conservation of crystal momentum, the process must involve the absorption of a **phonon** (the **phonon** momentum= momentum difference between electron and hole)
The efficiency is low.
The radiative lifetime is long. **(not Good for emitters)**

"Bulk" Semiconductor Density of States

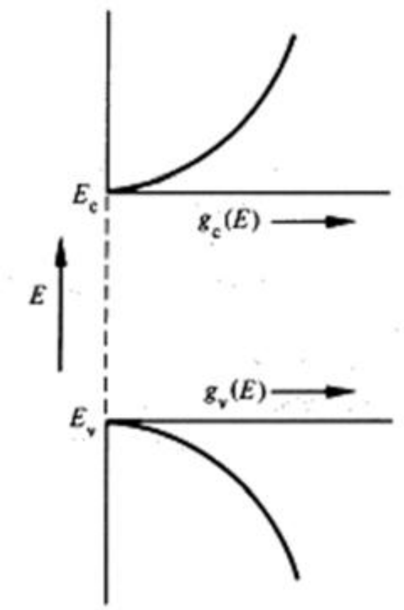
Definition: g(E) dE, the number of quantum states per unit volume of the crystal between E and E + dE (**DOS**)

Following Fermi-Dirac statistics and **Pauli exclusion principle: start from low energy states;** prevents **more than one electron** occupying an identical state

Calculate the number of carriers and carrier distribution (**electrical & optical properties**)

$$g(E)dE = \left[N(E+dE) - N(E)\right]/V$$

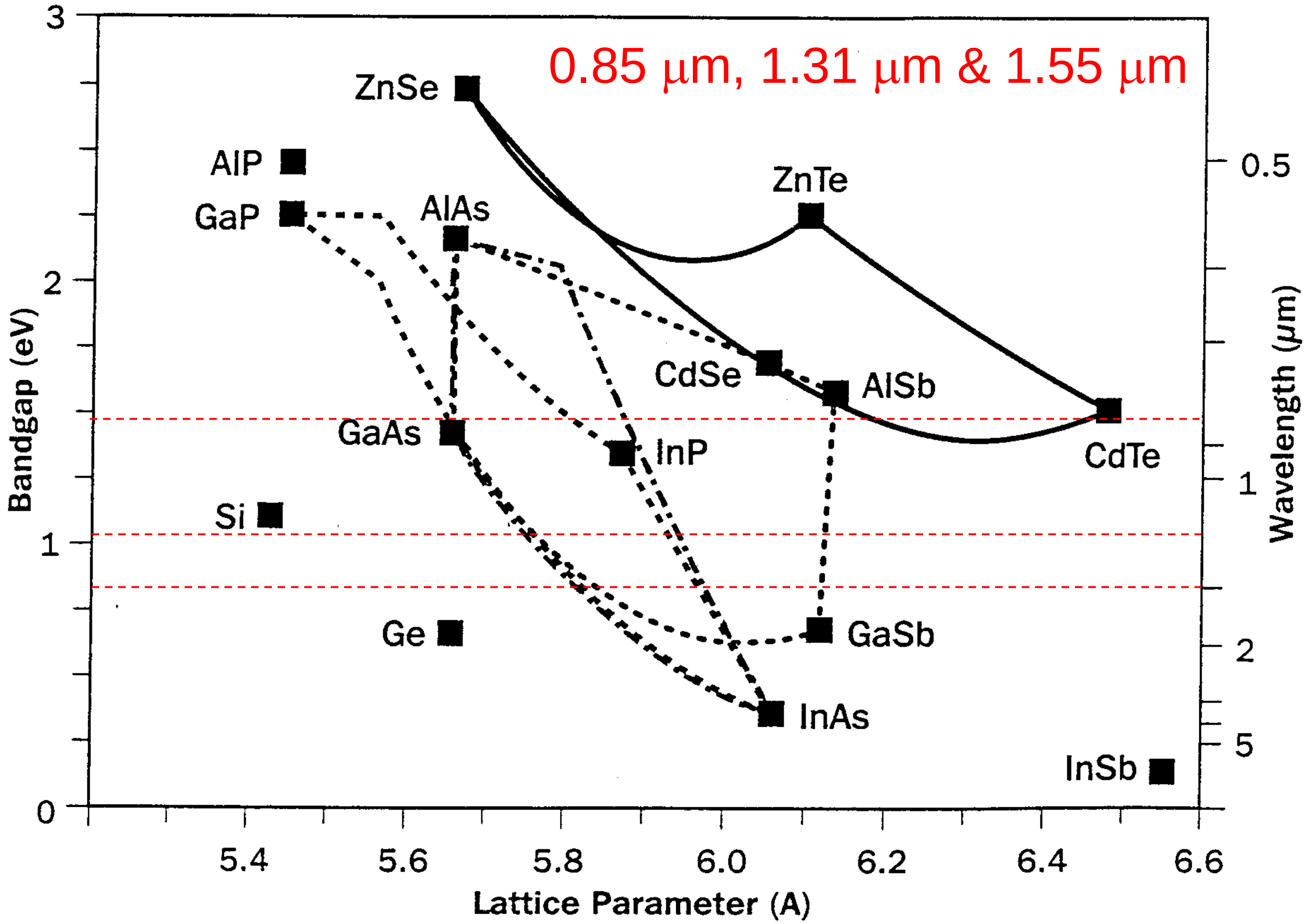
$$g(E) = \left(\frac{4\pi}{h^3}\right)(2m)^{3/2} E^{1/2}$$



DOS:

- **Strongly depends on dimension**
- **3D (bulk semiconductor): ∝ E$^{1/2}$**

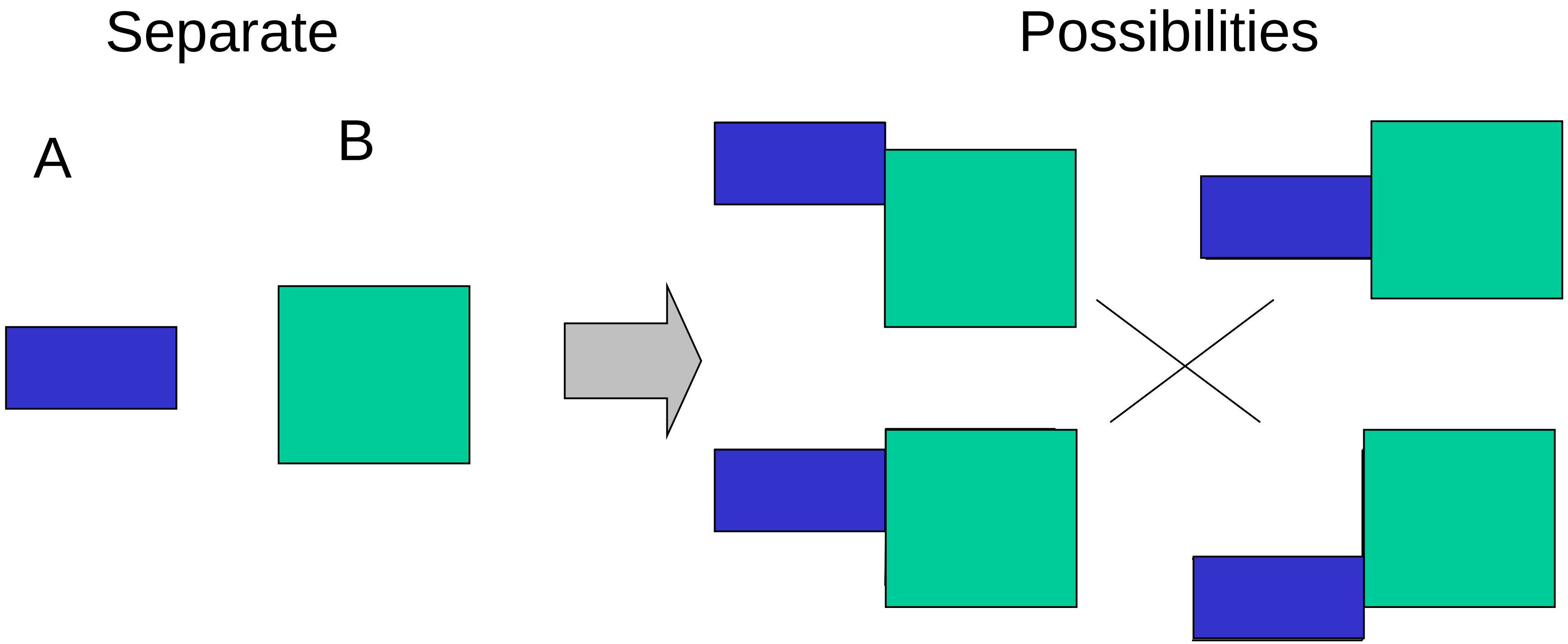
Materials For Optical Communications



0.85 μm – GaAs Based,
1.31 μm & 1.55 μm – Traditionally InP Based – But current research on GaAs based long wavelength materials – Dilute Nitrides and QDs

Band-Structure Engineering

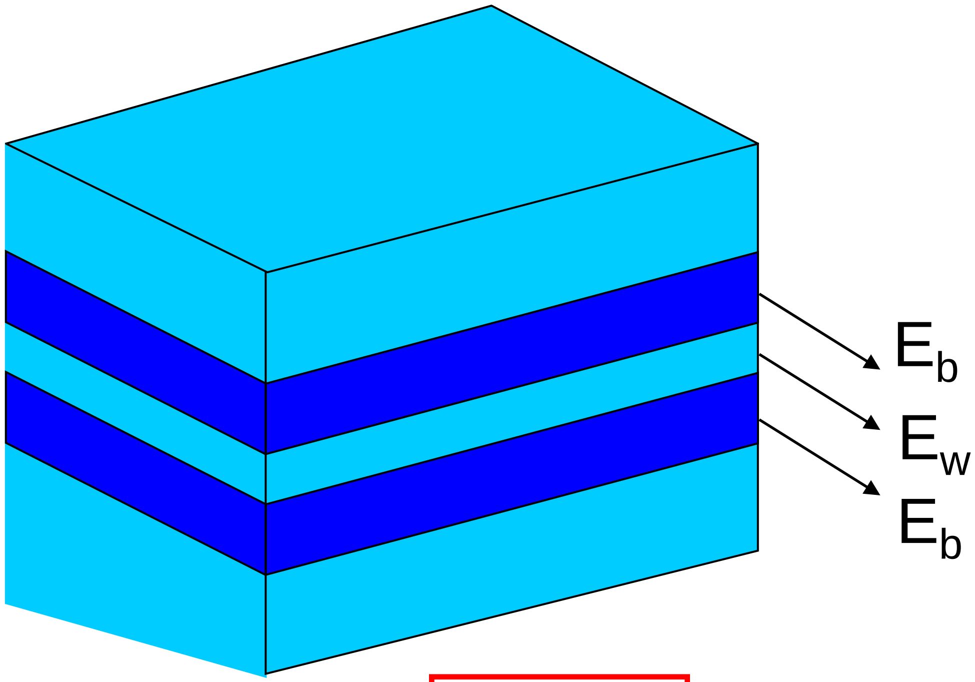
The offsets of the valence-band and conduction bands are different for different materials – need to refer to common datum line (**vacuum level**)

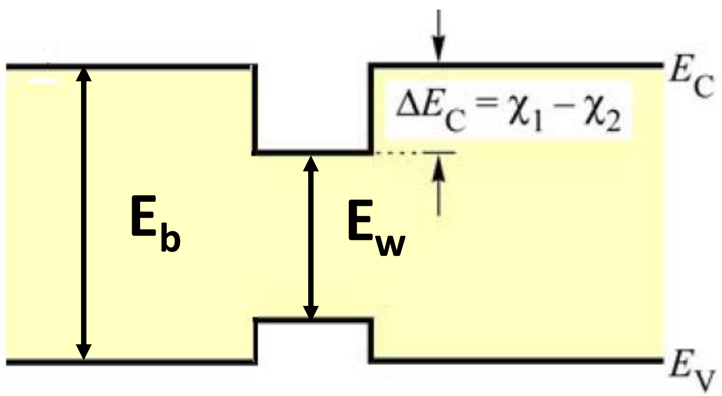


Schematic of Heterostructure

Carrier Confinement

Double heterostructure:
two large bandgap materials sandwich a narrow band-gap material, generating carrier confinement due to the energy barrier



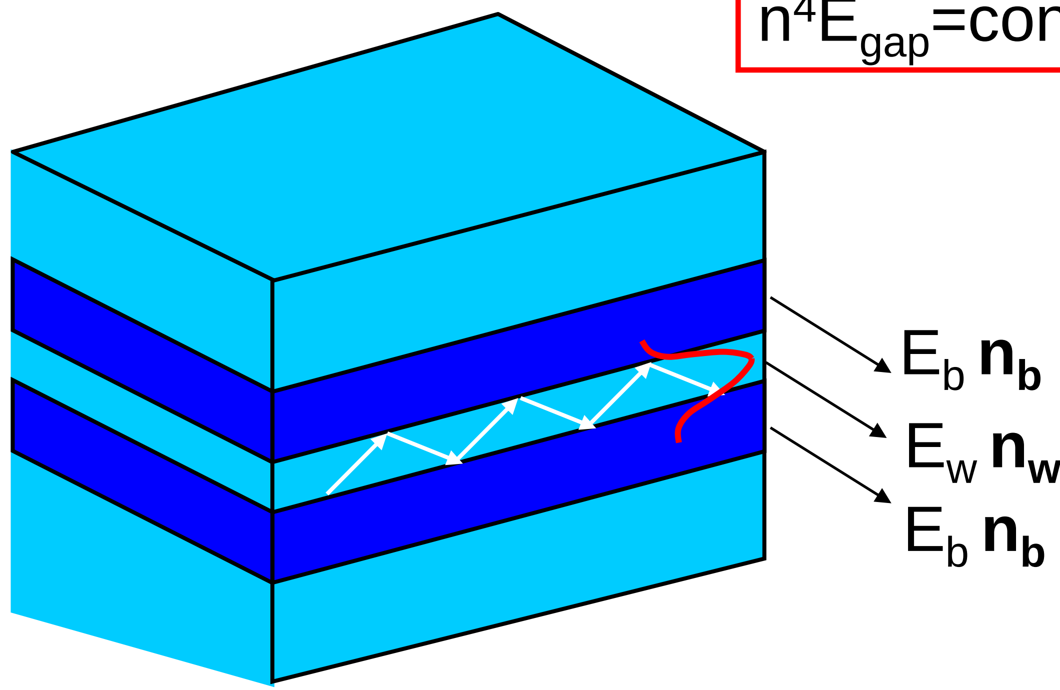


$E_w < E_b$

Optical Confinement

A heterostructure:
two large bandgap semiconductors with small refractive indices sandwich a narrow bandgap material with a large refractive index, generating confinement for both the carriers and photons

$n^4 E_{gap} = \text{constant}$



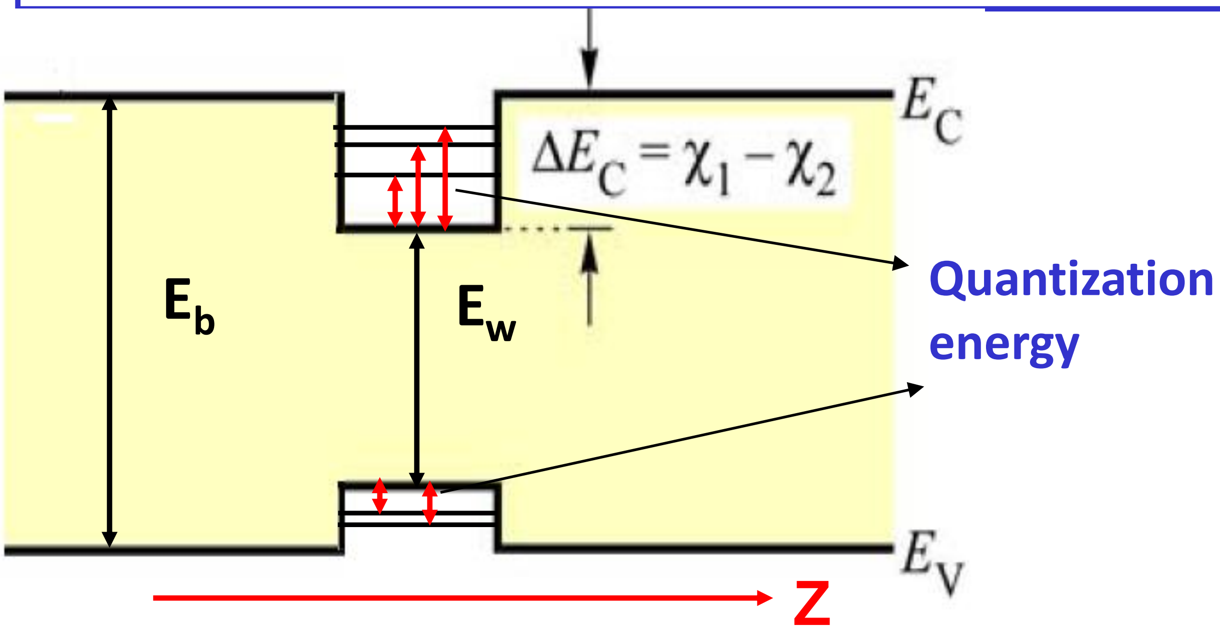
$E_w < E_b$ and $n_w > n_w$

Low dimensional semiconductors

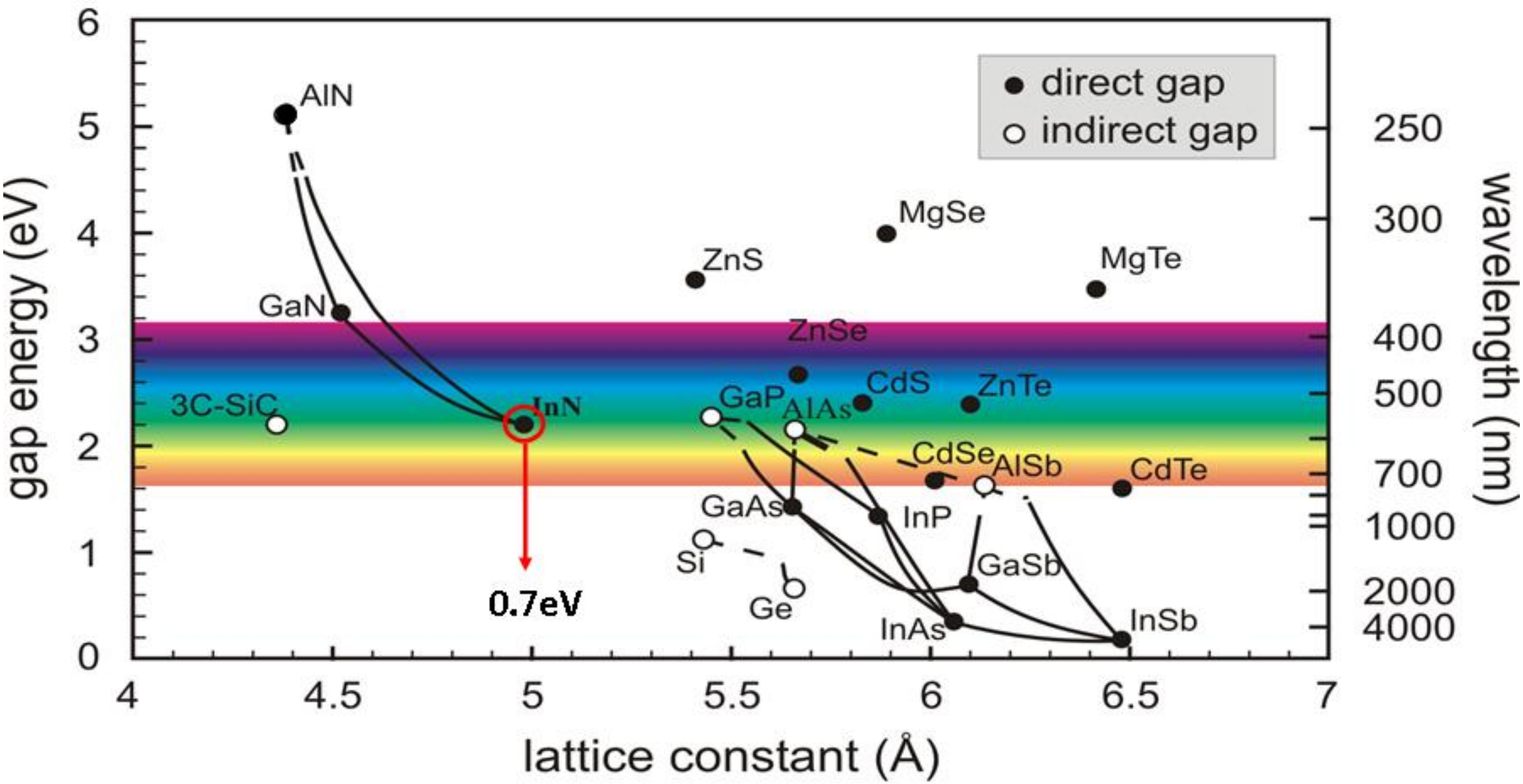
Double heterostructure: two layers with large E_g sandwich a layer with low E_g

If the low E_g layer is on a nanometer scale, electrons/holes will have extra energy generated due to quantum confinement. (The carriers can not move along z direction). This is **quantum well structure.**

DOS and Energy: will be changed, (significantly affect optical & electrical properties)



Provide **more chances to tune optical energy** for the fabrication of optoelectronics



III-V: III-N (**all direct band gap,** covering from **infrared to deep UV**)

III-As & III-Sb (infrared, direct or indirect), III-P (indirect except In-P)

II-VI: **Visible or UV, but with mechanical problems**

Others: SiC (visible; indirect); Si and Ge (infrared, indirect)

Tutorial Questions

T13.1 What is a direct and indirect bandgap semiconductor?

T13.2 Sketch the band structure of a "bulk" semiconductor in the region of k=0, and the density of states, labelling and describing the band-gap, and form of the conduction and valence bands. Sketch the relative hole and electron density at a "high" and "low" temperature.