Topic 11

11 Review on semiconductor physics

     11.1 Introduction

     11.2 Energy Band
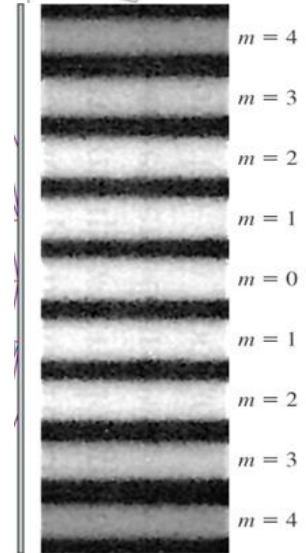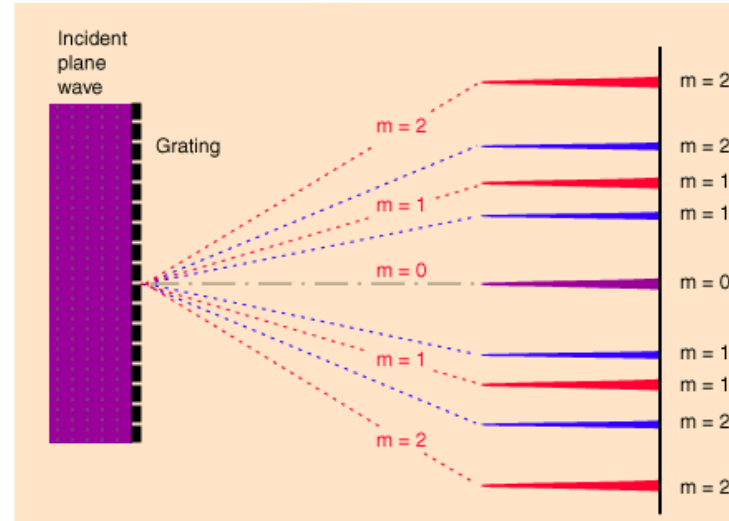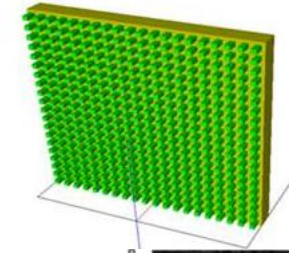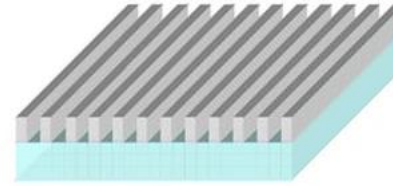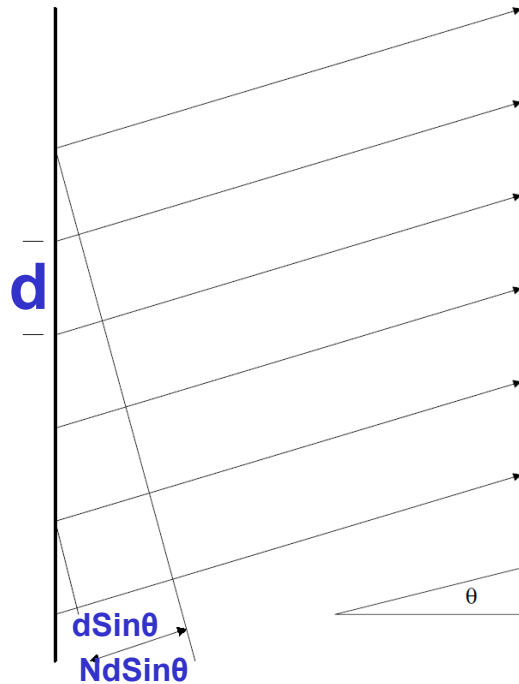
     11.3 Effective-mass Approximation

     11.4 Indirect and Direct Bandgap

     11.5 Density of State

     11.6 Hetero-structures

Introduction (1)

$\text{Sin}\theta_m = m\lambda/d$, (d: period of grating): $\text{Sin}\theta_m - Sin\ \theta_{m+1} \sim 1/d$ **for a fixed λ**
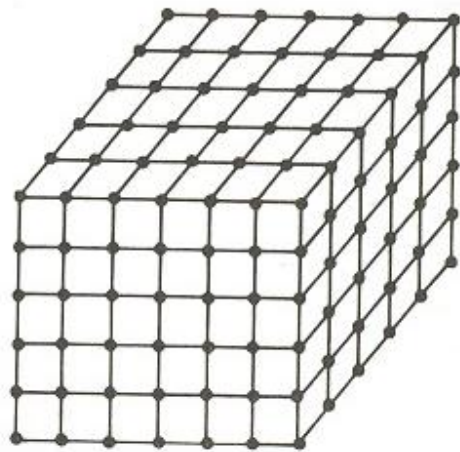
The interaction between light and a **periodic structure**:
- Only certain angles (**discrete**) are allowed for observing light
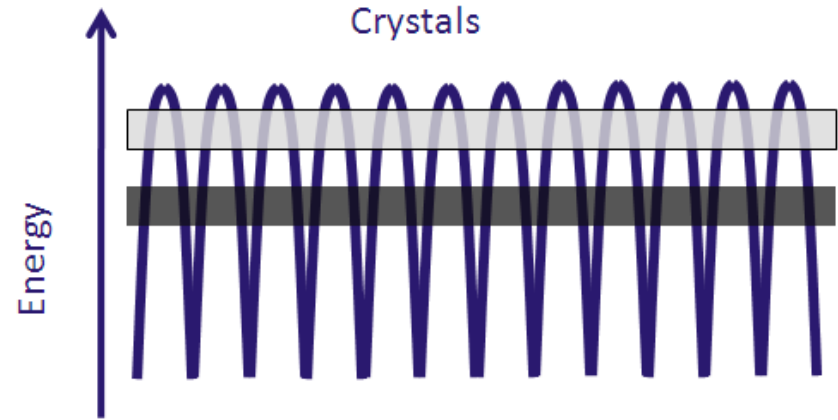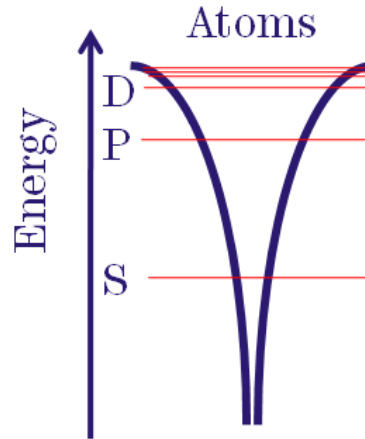- The angles between these "**allowed**" angles: "**forbidden**" for the light

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

2

Introduction (2)

Crystalline

Atoms

Crystals

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
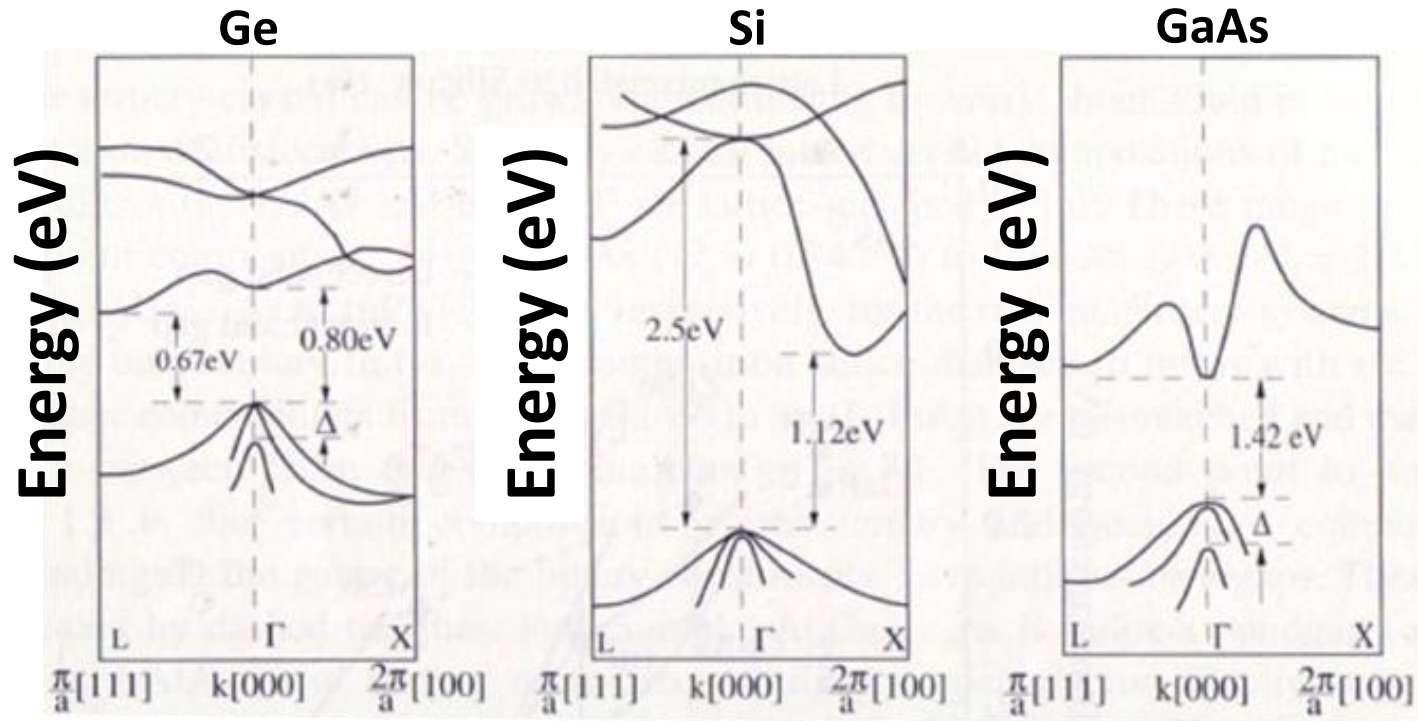
- **Energy distribution depends strongly on interatomic distance, relying on crystallographic direction**

- **Valence band: existence of subbands due to spin-orbit intercation**

- **Minimum of conduction band and maximum of valence band:**
  - **(i) Ge and Si:** along **different directions**
  - **(ii) GaAs:** along the **same direction**

4

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
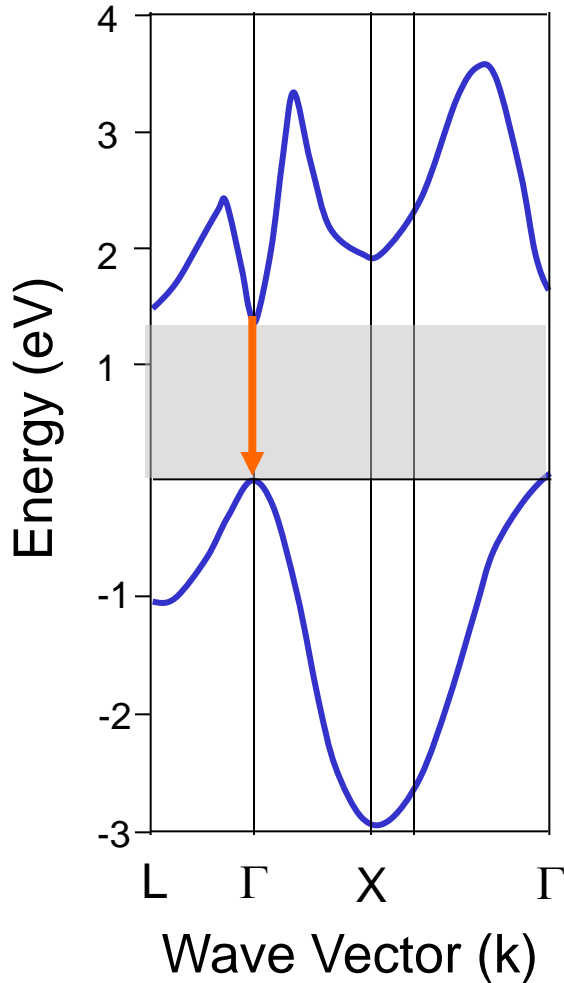   increasing the bandgap energy

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

(3) $n^4 E_{gap}$=constant
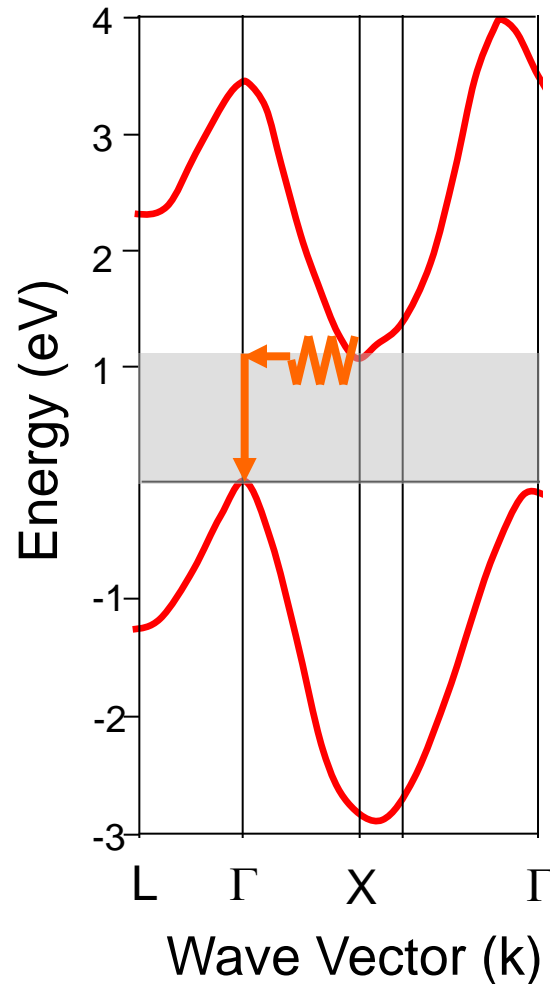
Bandgap energy (E) increases, refractive index (n) decreases

Direct and indirect Semiconductors

GaAs

Si

Conduction Band

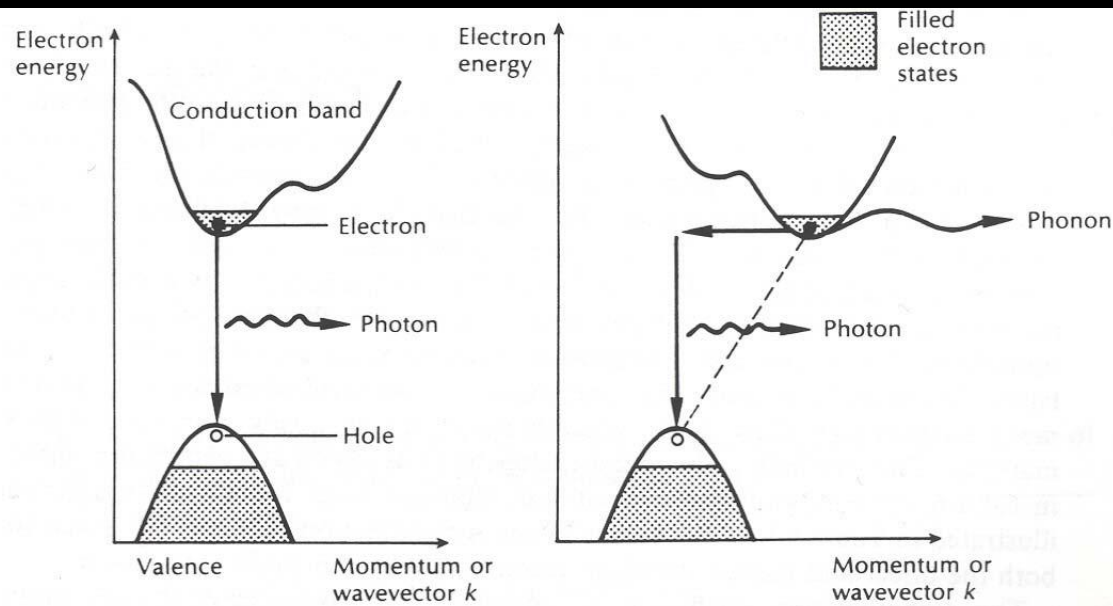Valence Band

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

$L\ k_x = k_y = k_z = \pm\pi/a$

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
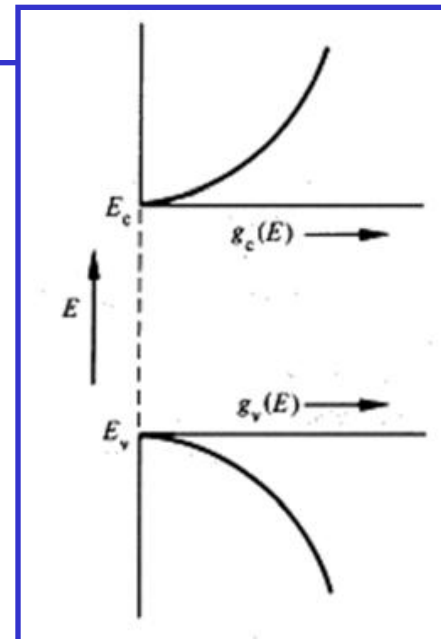
Calculate the number of carriers and carrier distribution (**electrical & optical properties**)
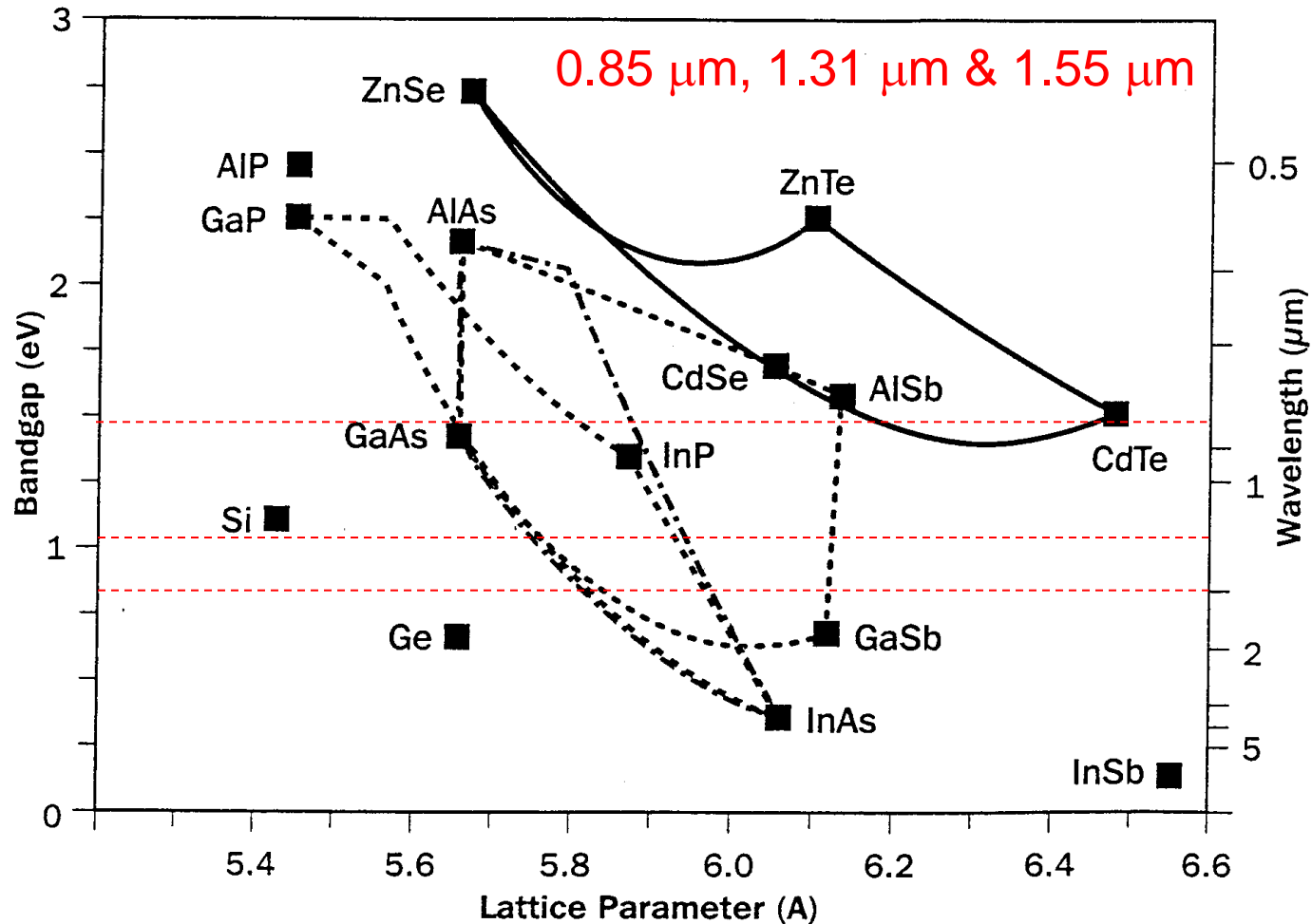
$$g(E)dE = \left[N(E + dE) - N(E) \right] / V$$

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

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

Materials For Optical Communications

0.85 μm, 1.31 μm & 1.55 μm

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

11

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**)

Separate   Possibilities

A

B
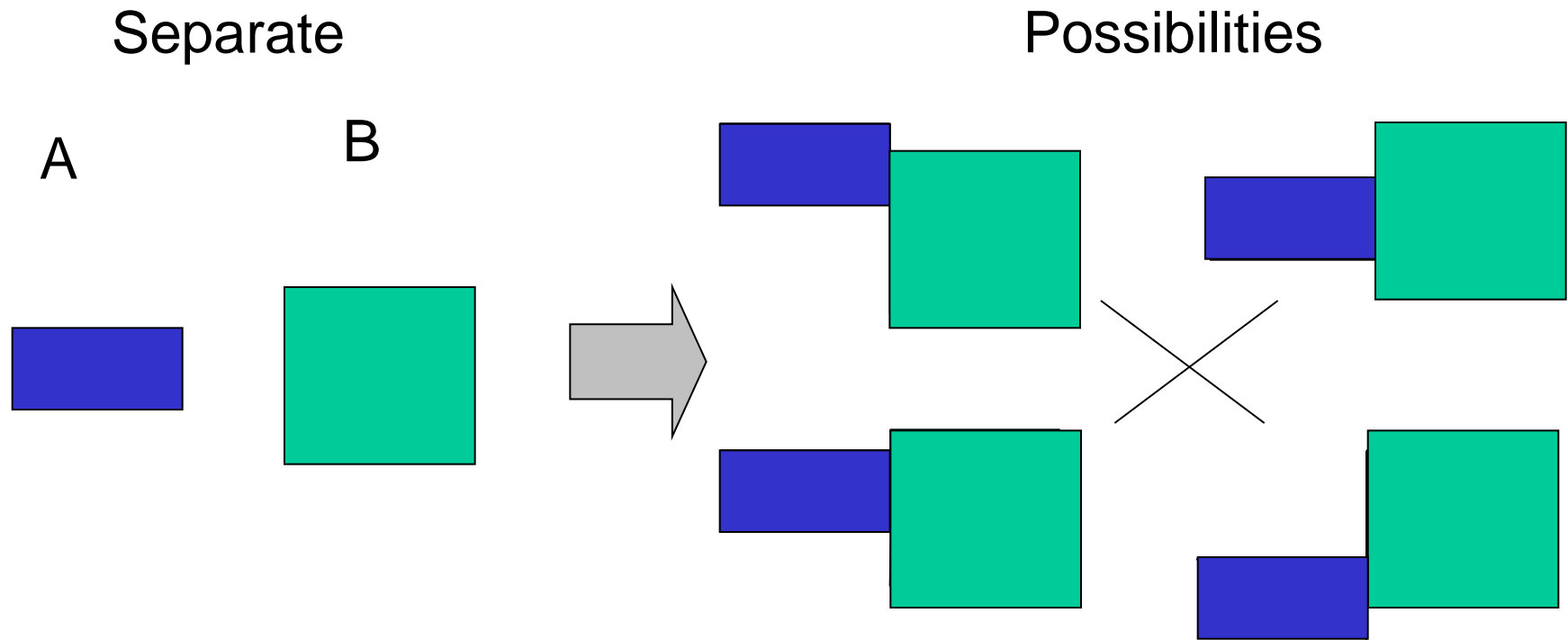
Schematic of Heterostructure

Carrier Confinement

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

E_b

E_w

E_b

E_b

E_w

$\Delta E_C = \chi_1 - \chi_2$

E_C

E_V

$E_w < E_b$

13
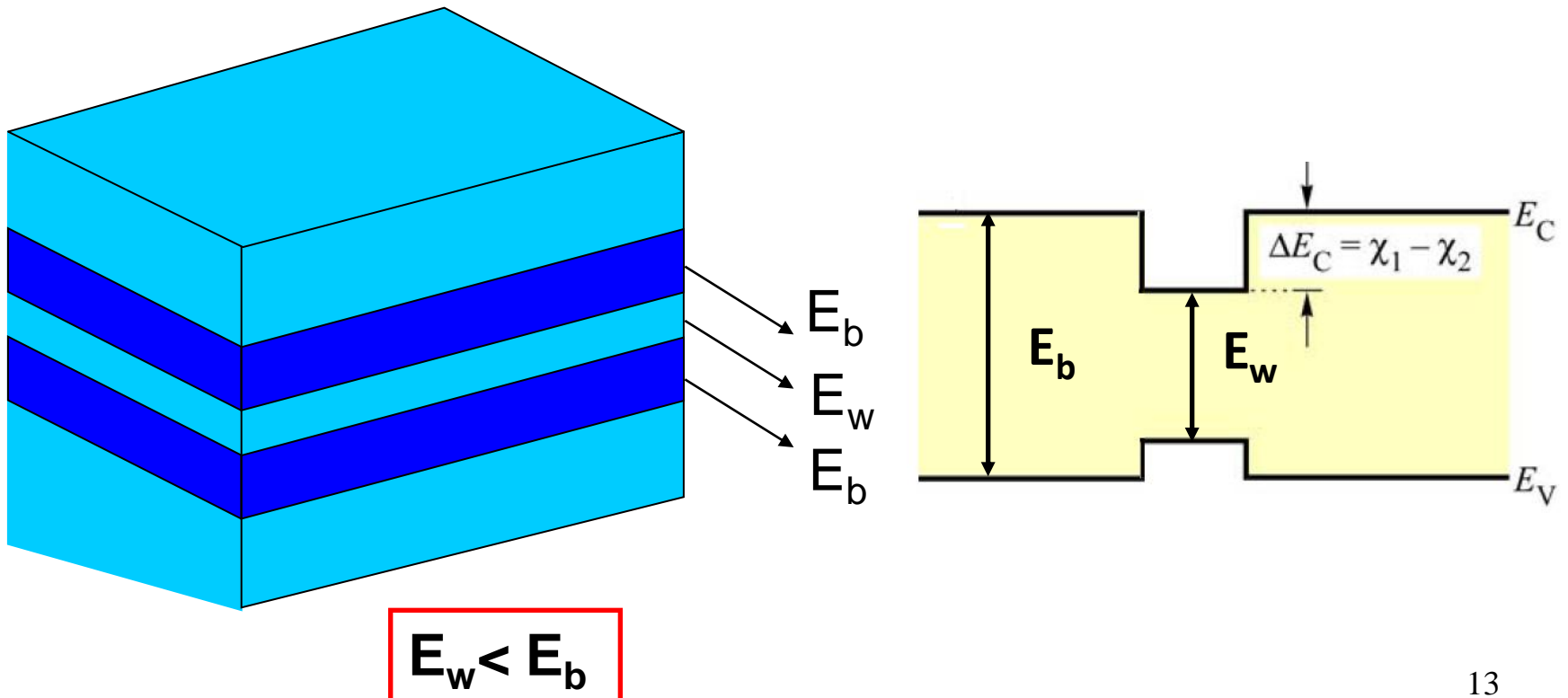
Optical Confinement

A heterostructure:

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

$n^4 E_{gap} = constant$

E_b **n_b**

E_w **n_w**

E_b **n_b**
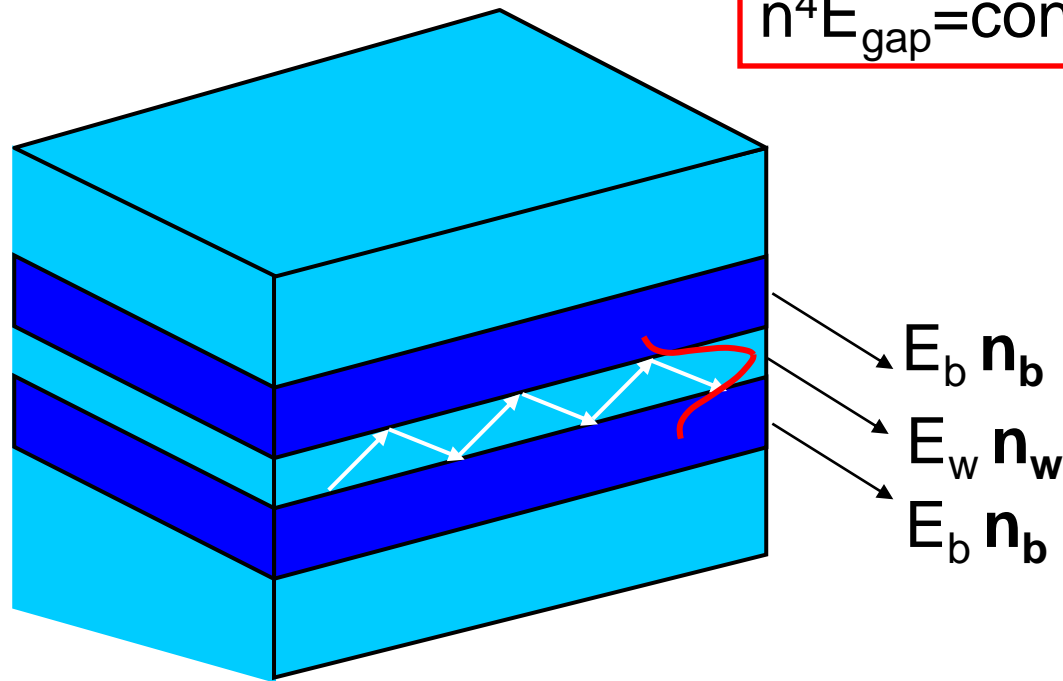
$E_w < E_b$ and $n_w > n_w$

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 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)

$$\Delta E_C = \chi_1 - \chi_2$$

E_C

E_b

E_w

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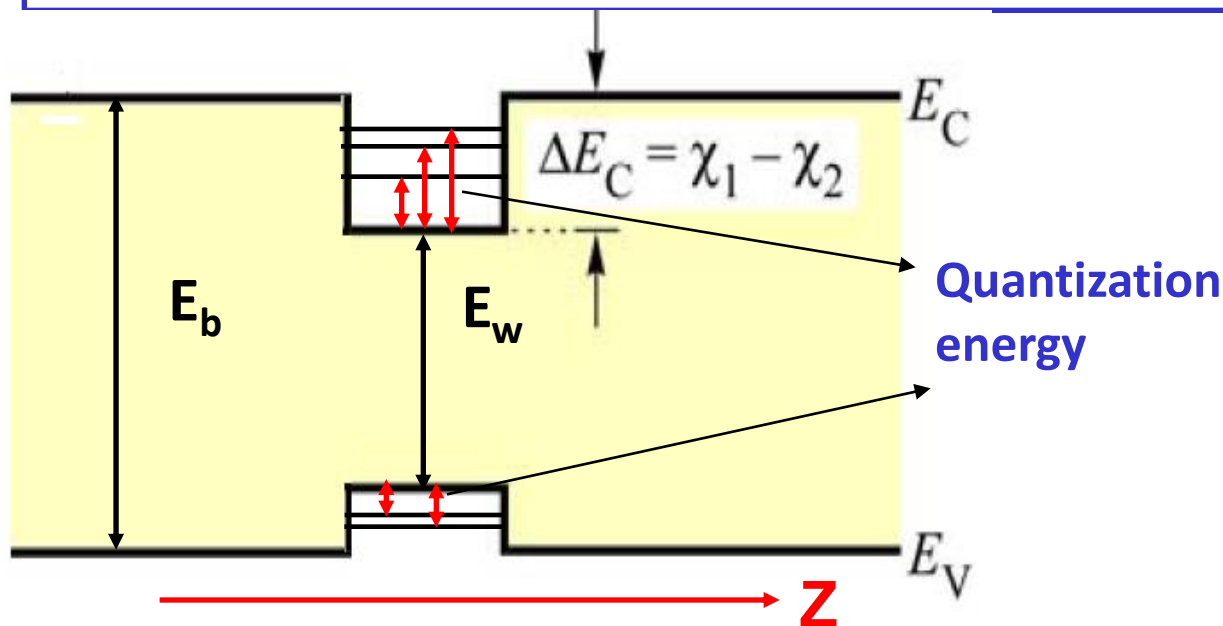
Provide **more chances to tune optical energy** for the fabrication of optoelectronics

E_V

Z

15
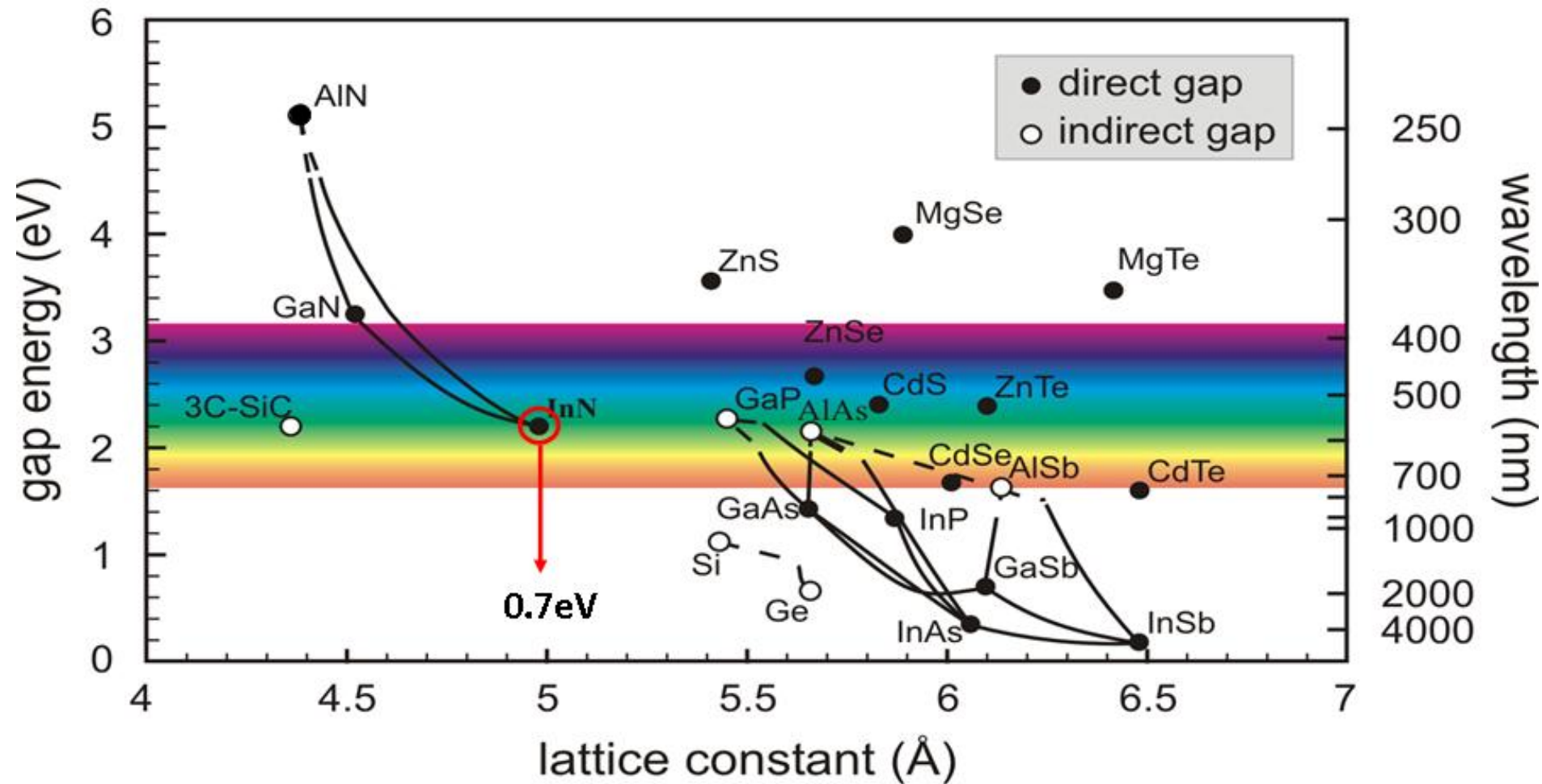
III-V: III-N (**all direct band gap,** covering from **infrared to deep UV**)
III-As & III-Sb (infrared, direct or indirect), III-P (indirect except In-P)
II-VI: Visible or UV, but with mechanical problems
Others: SiC (visible; indirect); Si and Ge (infrared, indirect)

Tutorial Questions

T11.1 What is a direct and indirect bandgap semiconductor?

T11.2 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.