

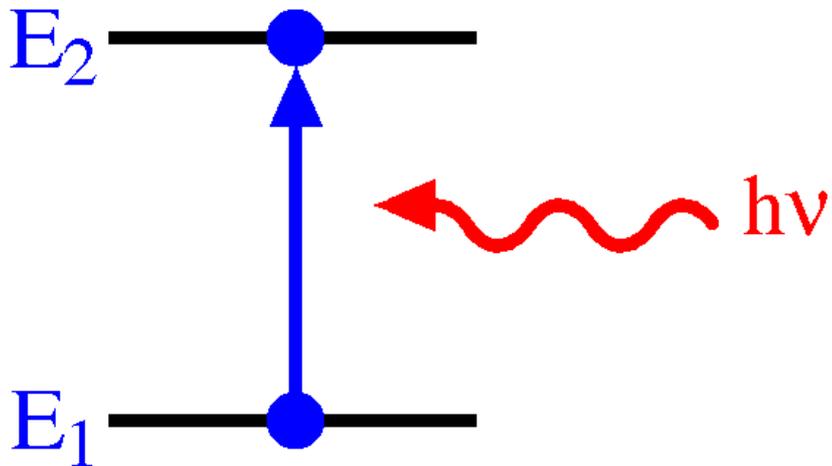
# UNIT - III Light-Semiconductor Interaction

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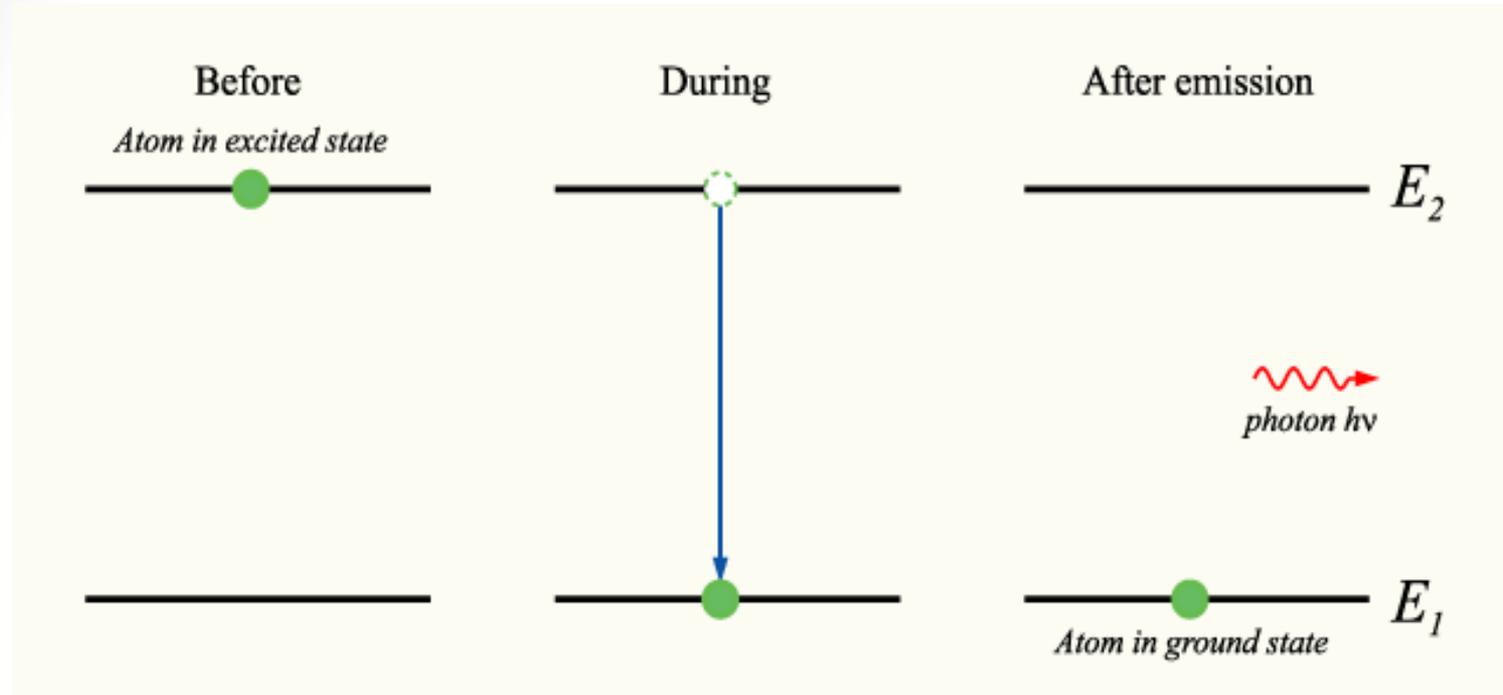
# Optical transitions in bulk semiconductors

## Absorption



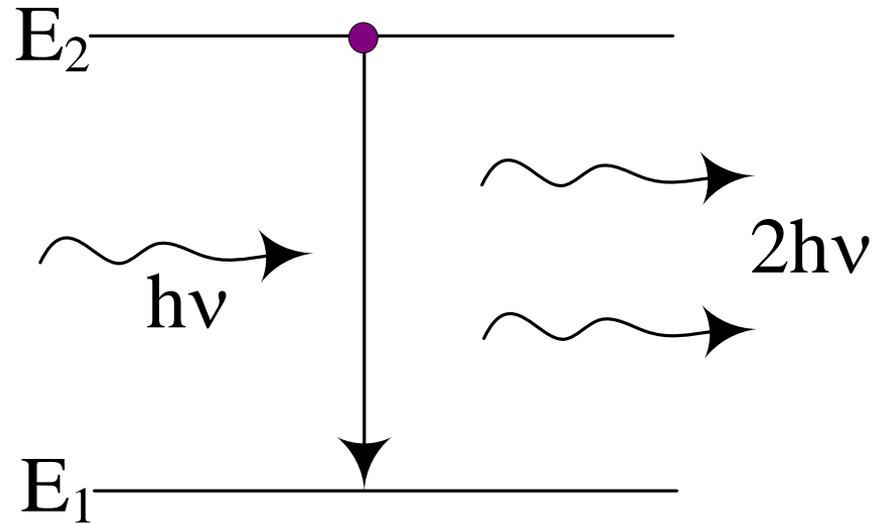
- Spontaneous event in which an atom or molecule absorbs a photon from an incident optical field
- The absorption of the photon causes the atom or molecule to transition to an excited state

# Spontaneous Emission



- Statistical process (random phase) – emission by an isolated atom or molecule
- Emission into  $4\pi$  steradians

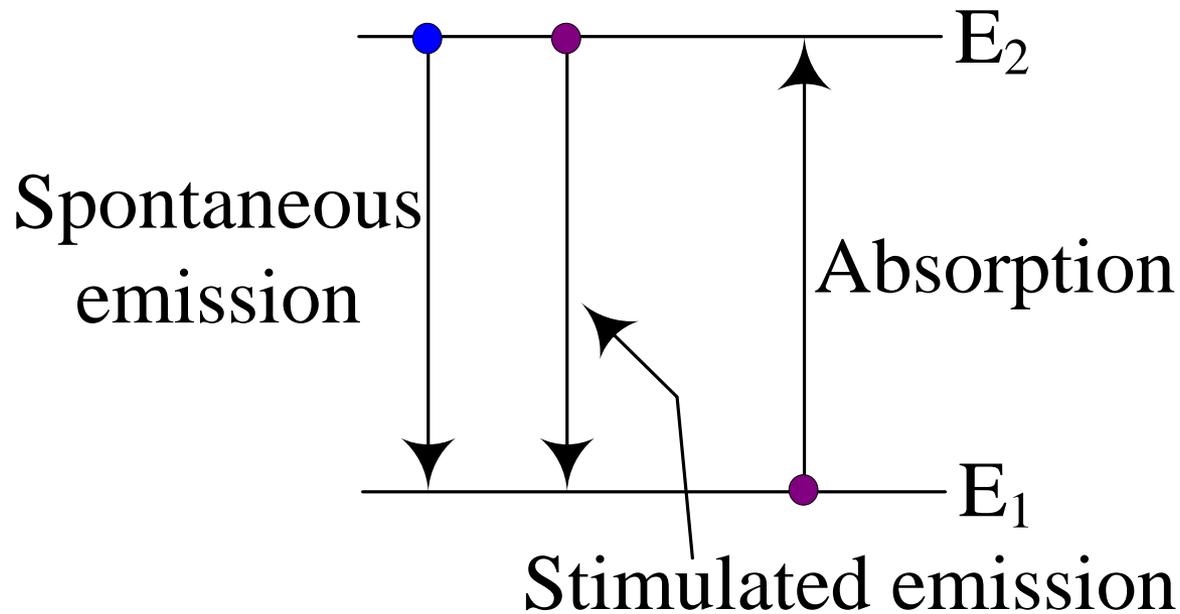
# Stimulated Emission



- Same phase as “stimulating” optical field
- Same polarization
- Same direction of propagation

# Putting it all together...

- Assume that we have a two state system in equilibrium with a blackbody radiation field.



# Joint Density of States

The frequency dependence (or dispersion) of  $\varepsilon_i(\omega)$  results mainly from the summation over both initial and final states satisfying energy and momentum conservation:

$$\sum_k \delta(E_c(k) - E_v(k) - \hbar\omega)$$

This summation over  $k$  can be converted into integration over the interband energy difference  $E_{cv} = E_c(k) - E_v(k)$  by defining the **Joint Density of States** (JDOS)  $D_j(E_{cv})$  as:

$$D_j(E_{cv}) = \frac{1}{4\pi^3} \int \frac{dS_k}{|\nabla_k(E_{cv})|},$$

# Fermi's Golden Rule

In order to determine the *probability* or *amplitude of the absorption* we must find the *overlap* of the initial and final wavefunctions.

$$\left| \int \psi_f^* H \psi_i dr \right|^2 \equiv \left| \langle \psi_f | H | \psi_i \rangle \right|^2.$$

Instead of *single* initial and *final* states in *single-particle* picture, we have in principle a large *density of final states* -  $\rho(\mathbf{k})$

$$W_{abs} = \frac{2\pi}{\hbar} |\langle f | H_{int} | i \rangle|^2 \delta(E_f - E_i - \hbar\omega)$$

The probability of absorption or emission will depend on the *overlap* and *energy difference* of the initial and final state, and the *density of these states*.

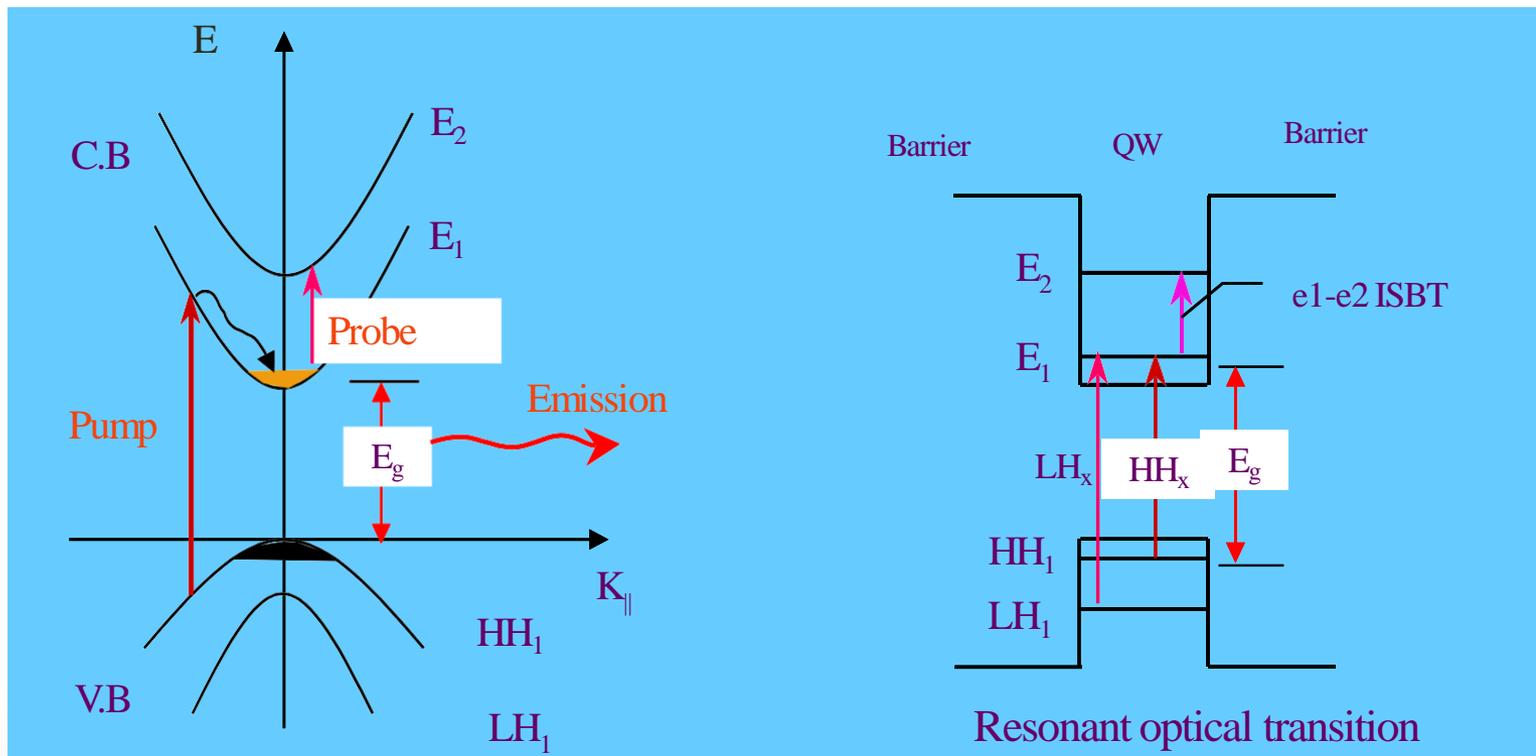
# In quantum structures case

Choice of the *wavefunctions* for the *initial* and *final* states

*Two different* kinds of possibilities in quantum structure

Transitions between the *valence* and *conduction* bands

Transitions between the quantum-confined states *within a given band*, so-called "*intersubband*" transitions



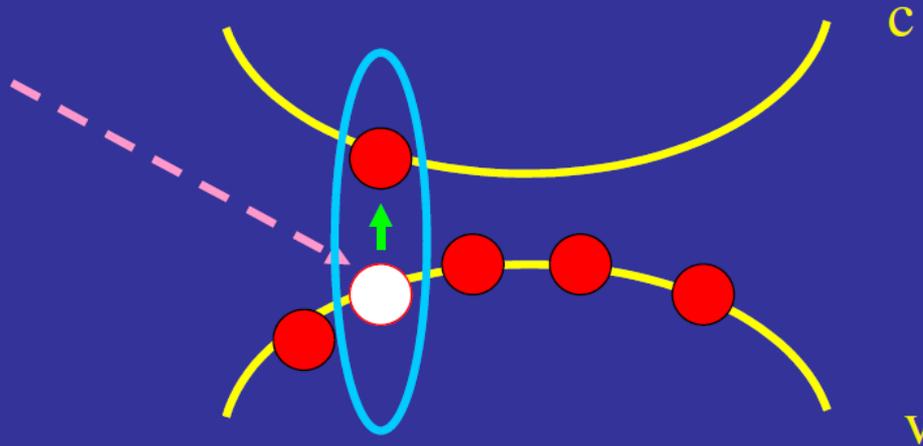
# Photovoltaic effect

The photovoltaic effect is the creation of voltage and electric current in a material upon exposure to light and is a physical and chemical phenomenon.

The photovoltaic effect is closely related to the photoelectric effect. In either case, light is absorbed, causing excitation of an electron or other charge carrier to a higher-energy state. The main distinction is that the term photoelectric effect is now usually used when the electron is ejected out of the material (usually into a vacuum) and photovoltaic effect used when the excited charge carrier is still contained within the material. In either case, an electric potential (or voltage) is produced by the separation of charges, and the light has to have a sufficient energy to overcome the potential barrier for excitation. The physical essence of the difference is usually that photoelectric emission separates the charges by ballistic conduction and photovoltaic emission separates them by diffusion, but some "hot carrier" photovoltaic device concepts blur this distinction.

# Excitonic Effect : Two particle (e-h) interaction

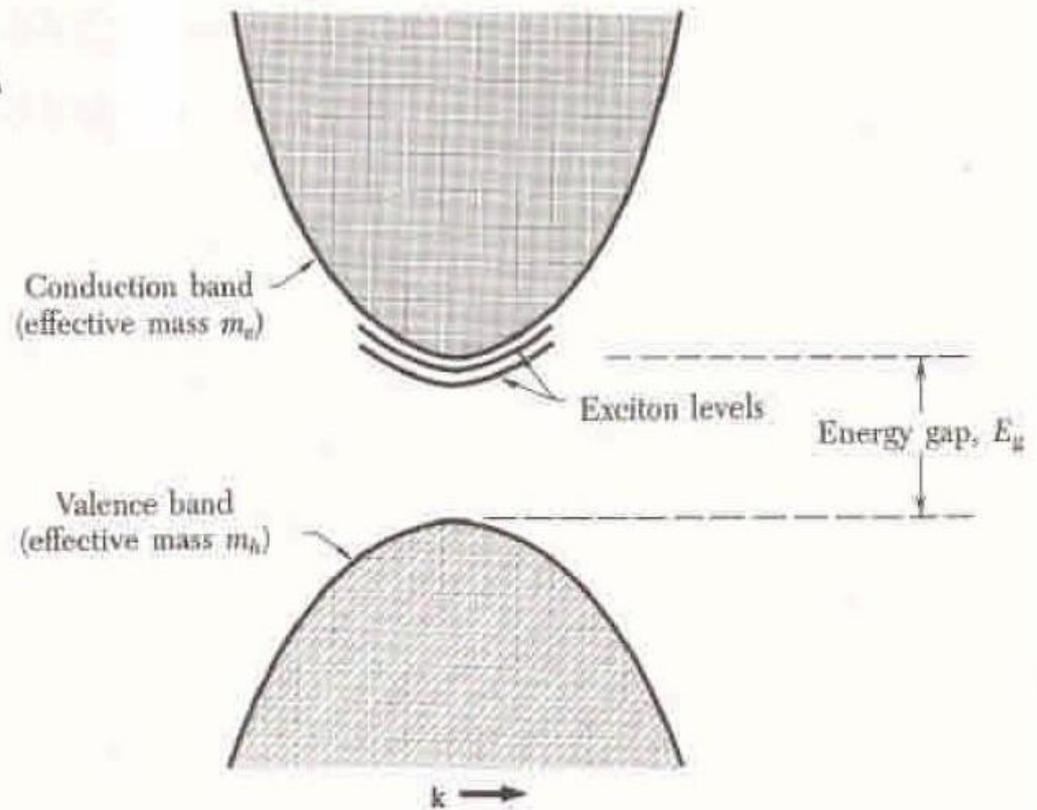
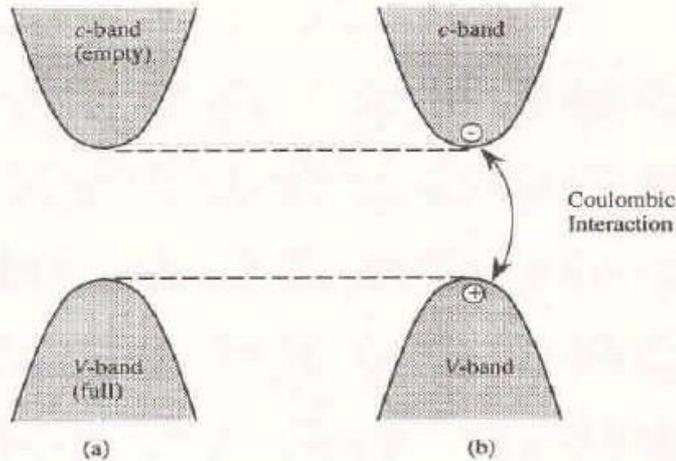
Absorption ?



Electron-hole interaction

Excitonic effects

# Absorption via Excitons



## Electron-Hole interaction: Excitons

The annihilation of a photon in exciting an electron from the valence band to the conduction band in a semiconductor can be written as an equation:  $\hbar\omega \Rightarrow e+h$ .

Since there is a *Coulomb attraction* between the electron and hole, the photon energy required is lowered than the band gap by this attraction

To correctly calculate the absorption coefficient we have to introduce a **two-particle state** consisting of an electron attracted to a hole known as an **exciton**

# Classical Electron Model ( Lorentz Model)

Let the electric field of optical wave in an atom be

$$\mathbf{E} = \mathbf{E}_0 e^{-i\omega t}$$

the electron obeys the following equation of motion

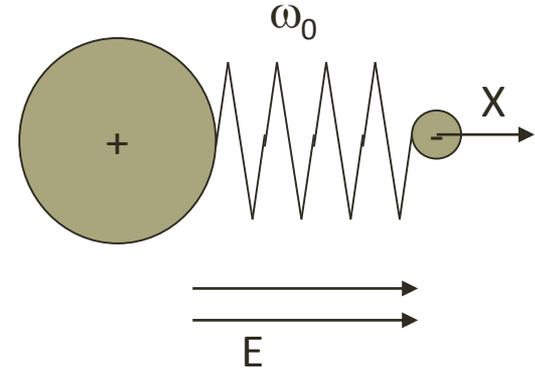
$$m \frac{d^2}{dt^2} \mathbf{X} + m\gamma \frac{d}{dt} \mathbf{X} + m\omega_0^2 \mathbf{X} = -e\mathbf{E}$$

$\mathbf{X}$  is the position of the electron relative to the atom

$m$  is the mass of the electron

$\omega_0$  is the resonant frequency of the electron motion

$\gamma$  is the damping coefficient



# Classical Electron Model ( Lorentz Model)

The solution is 
$$\mathbf{X} = \frac{-e\mathbf{E}_0}{m(\omega_0^2 - \omega^2 - i\omega\gamma)} e^{-i\omega t}$$

The induced dipole moment is

$$\mathbf{p} = -e\mathbf{X} = \frac{e^2}{m(\omega_0^2 - \omega^2 - i\omega\gamma)} \mathbf{E} = \alpha\mathbf{E}$$

$\alpha$  is atomic polarizability

$$\alpha = \frac{e^2}{m(\omega_0^2 - \omega^2 - i\omega\gamma)}$$

The dielectric constant of a medium depends on the manner in which the atoms are assembled. Let  $N$  be the number of atoms per unit volume. Then the polarization can be written approximately as

$$\mathbf{P} = N \mathbf{p} = N \alpha \mathbf{E} = \epsilon_0 c \mathbf{E}$$

# Classical Electron Model ( Lorentz Model)

The dielectric constant of the medium is given by

$$\varepsilon = \varepsilon_0 (1 + \chi) = \varepsilon_0 (1 + N\alpha / \varepsilon_0)$$

If the medium is nonmagnetic, the index of refraction is

$$n = (\varepsilon / \varepsilon_0)^{1/2} = (1 + N\alpha / \varepsilon_0)^{1/2}$$

$$n^2 = \frac{\varepsilon}{\varepsilon_0} = 1 + \frac{Ne^2}{\varepsilon_0 m(\omega_0^2 - \omega^2 - i\omega\gamma)}$$

If the second term is small enough then

$$n = 1 + \frac{Ne^2}{2\varepsilon_0 m(\omega_0^2 - \omega^2 - i\omega\gamma)}$$

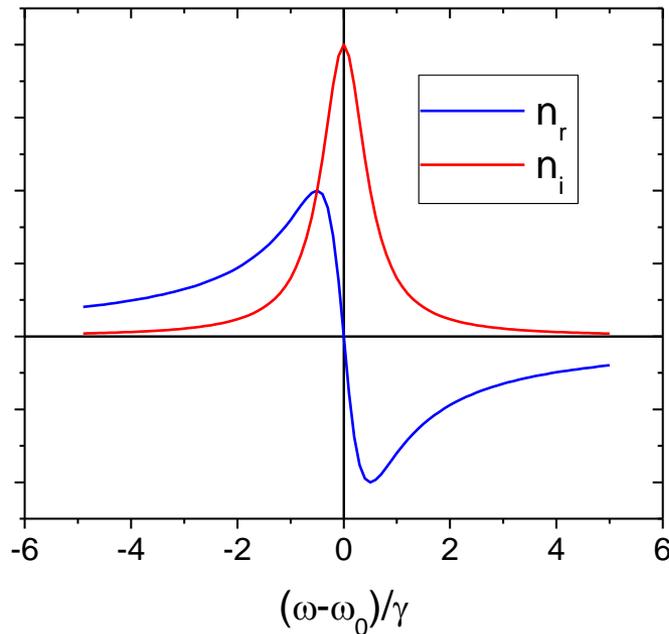
# Classical Electron Model ( Lorentz Model)

The complex refractive index is

$$n \rightarrow n_r + in_i = 1 + \frac{Ne^2(\omega_0^2 - \omega^2)}{2\varepsilon_0 m[(\omega_0^2 - \omega^2)^2 + \omega^2\gamma^2]} + i \frac{Ne^2\gamma\omega}{2\varepsilon_0 m[(\omega_0^2 - \omega^2)^2 + \omega^2\gamma^2]}$$

at  $\omega \sim \omega_0$ ,

$$n_r + in_i = 1 + \frac{Ne^2(\omega_0 - \omega)}{4\varepsilon_0 m\omega_0[(\omega_0 - \omega)^2 + (\gamma/2)^2]} + i \frac{Ne^2\gamma}{8\varepsilon_0 m\omega_0[(\omega_0 - \omega)^2 + (\gamma/2)^2]}$$



Normalized plot of  $n-1$  and  $k$  versus  $\omega-\omega_0$

For more than one resonance frequencies for each atom,

$$n^2 = 1 + \frac{Ne^2}{\epsilon_0 m} \sum_j \frac{f_j}{(\omega_j^2 - \omega^2 - i\omega\gamma_j)} \quad \sum_j f_j = Z$$

### Classical Electron Model ( Drude model)

If we set  $\omega_0=0$ , the Lorentz model become Drude model. This model can be used in free electron metals

$$n^2 = 1 - \frac{Ne^2}{\epsilon_0 m(\omega^2 + i\omega\gamma)}$$

# Relation Between Dielectric Constant and Refractive Index

By definition,

$$n^2 = \frac{\epsilon}{\epsilon_0}$$

$$n = n_r + in_i$$

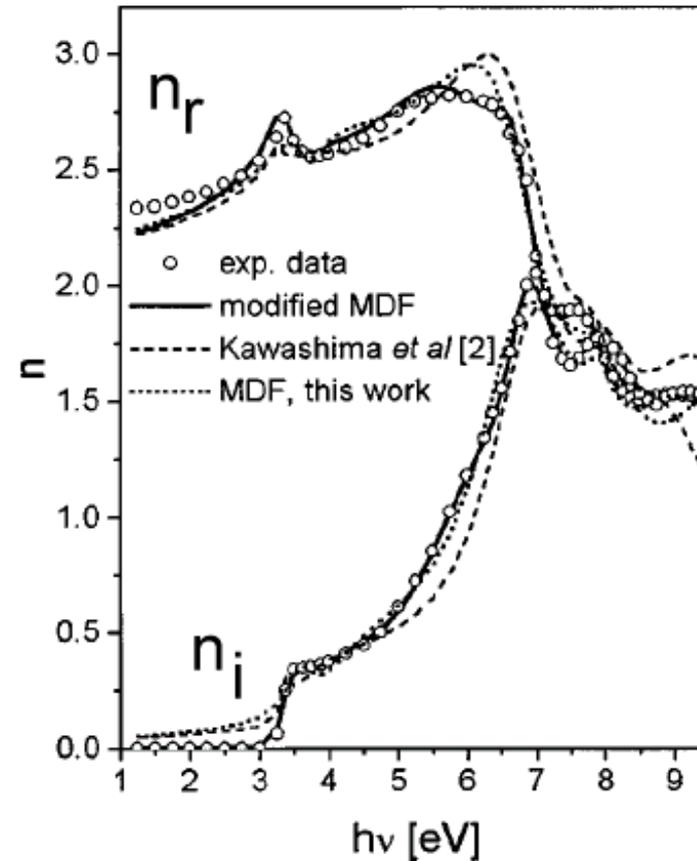
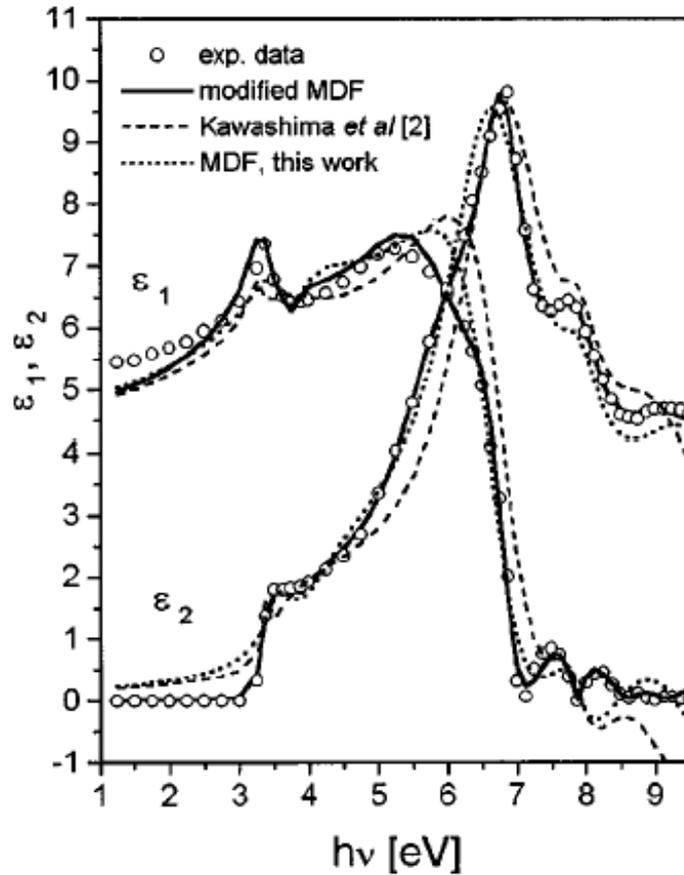
$$\epsilon = \epsilon_1 + i\epsilon_2$$

We can easily get:

$$n_r = \left\{ \frac{1}{2} [(\epsilon_1^2 + \epsilon_2^2)^{1/2} + \epsilon_1] \right\}^{1/2} / \epsilon_0$$

$$n_i = \left\{ \frac{1}{2} [(\epsilon_1^2 + \epsilon_2^2)^{1/2} - \epsilon_1] \right\}^{1/2} / \epsilon_0$$

# An Example to Calculate Optical Constants



$$\epsilon(E) = \sum_{\alpha=A,B,C} \left( \sum_{n=1}^{\infty} \frac{A_{0\alpha}^{\text{ex}}}{n^3} \frac{1}{E_{0\alpha} - (G_{0\alpha}^{3D}/n^2) - E - i\Gamma} \right)$$

Real and imaginary part of the index of refraction of GaN vs. energy;

# Kramers-Kronig Relation

The real part and imaginary part of the complex dielectric function  $\epsilon(\omega)$  are not independent. they can be connected by Kramers-Kronig relations:

$$\epsilon_1(\omega) = \epsilon_0 + \frac{2}{\pi} P \int_0^{\infty} \frac{\epsilon_2(\omega') \omega'}{\omega'^2 - \omega^2} d\omega'$$

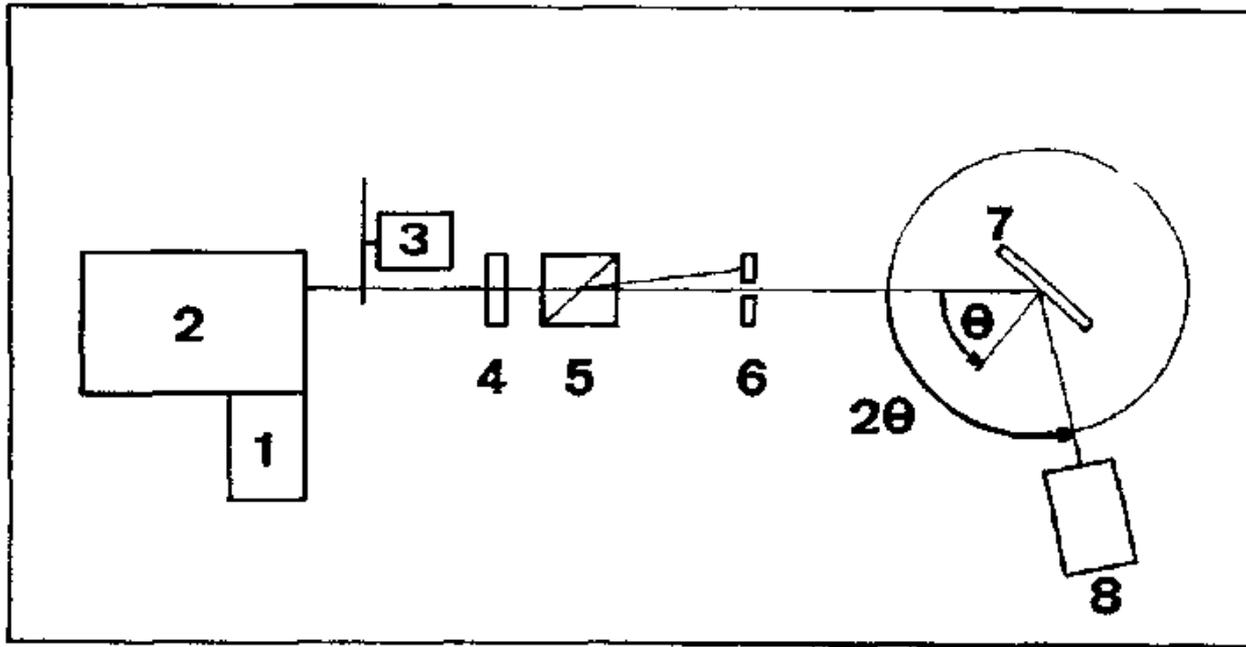
$$\epsilon_2(\omega) = \frac{2\omega}{\pi} P \int_0^{\infty} \frac{\epsilon_1(\omega') - \epsilon_0}{\omega'^2 - \omega^2} d\omega'$$

P indicates that the integral is a principal value integral.

K-K relation can also be written in other form, like

$$n(\lambda) = \frac{1}{\pi} P \int_0^{\infty} \frac{\alpha(\lambda')}{1 - (\lambda'/\lambda)^2} d\lambda'$$

# A Method Based on Reflection



Typical experimental setup

( 1) halogen lamp;

(2) mono-chromator; (3) chopper; (4) filter;

(5) polarizer (get p-polarized light); (6) hole diaphragm;

(7) sample on rotating support ( $\theta$ ); (8) PbS detector( $2\theta$ )

# Calculation

In this case,  $n_1=1$ , and  $n_2=n_r+i n_i$

Snell Law become:

$$k_{1z} = k_{2z} = \frac{2\pi}{\lambda} \sin \theta \equiv \beta$$

Reflection coefficient:

$$r_p = \frac{n_1^2 k_{2x} - n_2^2 k_{1x}}{n_1^2 k_{2x} + n_2^2 k_{1x}} = \frac{k_{2x} - (n_r + i n_i)^2 k_{1x}}{k_{2x} + (n_r + i n_i)^2 k_{1x}}$$

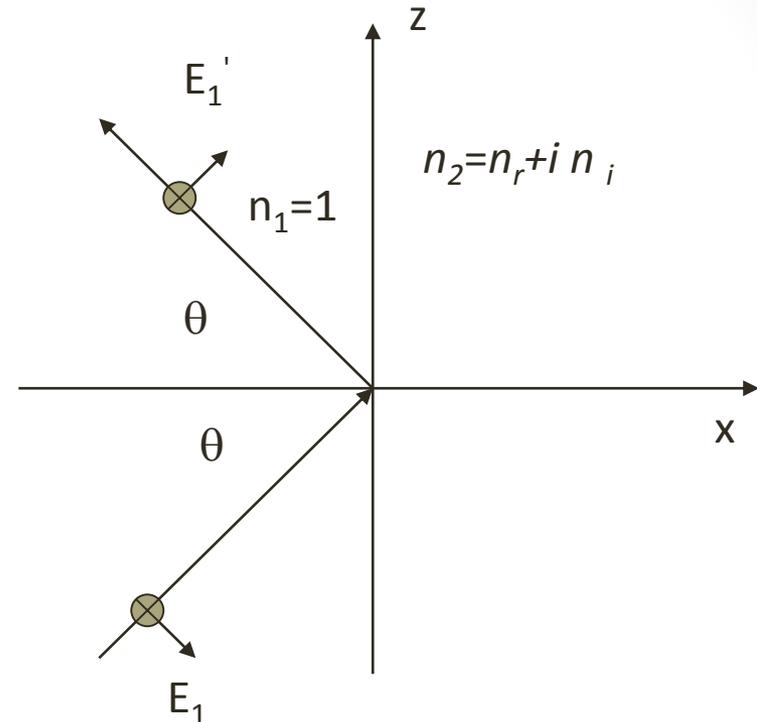
$$k_{1x} = \left[ \left( \frac{2\pi}{\lambda} \right)^2 - \beta^2 \right]^{1/2}$$

$$k_{2x} = \left[ \left( \frac{2\pi}{\lambda} \right)^2 (n_r - i n_i)^2 - \beta^2 \right]^{1/2}$$

Reflectance:

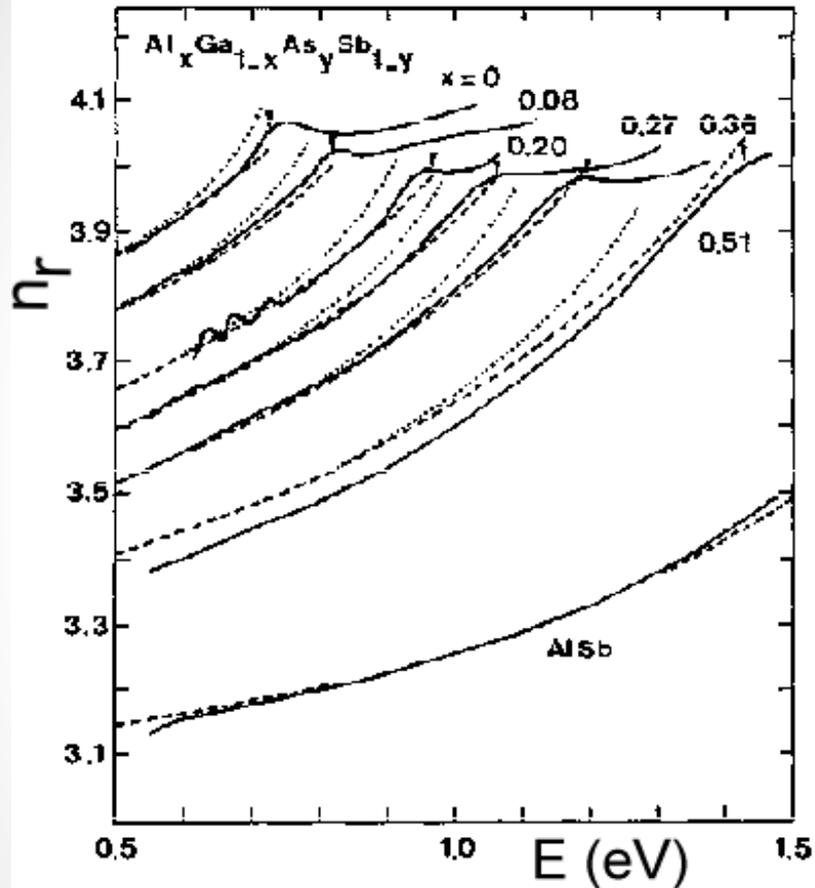
$$R(\theta, \lambda, n_r, n_i) = |r_p|^2$$

From this measurement, they got  $R$ ,  $\theta$  for each wavelength  $\lambda$ , Fitting the experimental curve, they can get  $n_r$  and  $n_i$ .



Reflection of p-polarized light

# Results Based on Reflection Measurement



Single effective oscillator model

$$n_r^2 - 1 = \frac{E_0 E_d}{E_0^2 - E^2} \quad (\text{Eq. 1})$$

$$n_r^2 - 1 = \frac{E_d}{E_0} + \frac{E^2 E_d}{E_0^3} + \frac{\eta E^4}{\pi} \ln\left(\frac{E_f^2 - E}{E_\Gamma^2 - E^2}\right) \quad (\text{Eq. 2})$$

$$E_f^2 = 2E_0^2 - E_\Gamma^2$$

$$\eta = \frac{\pi E_d}{2E_0^3 (E_0^2 - E_\Gamma^2)}$$

$E_0$ : oscillator energy

$E_d$ : dispersion energy

$E_\Gamma$ : lowest direct band gap energy

FIG. 2. Measured refractive indices at 300 K vs. photon energy of AlSb and  $\text{Al}_x\text{Ga}_{1-x}\text{As}_y\text{Sb}_{1-y}$  layers lattice matched to GaSb ( $y \sim 0.085x$ ).

Dashed lines: calculated curves from Eq. (1);

Dotted lines: calculated curves from Eq. (2)