Lecture 15 - Optical Processes - Outline

- **Absorption processes**

    Band-to-band (bulk): indirect gap, direct gap, excitons

    Quantum well: inter-band, intra-band: selection rules

    Impurity level absorption

    Free carrier absorption

- **Light emission** **(producing light from bulk semiconductors)**

    Recombination processes

    - **Band-to-band (direct vs. indirect)**
    - **Via mid-gap levels**
    - **Auger**
    - **Stimulated**

    Radiative vs. non-radiative transitions **(radiative efficiency)**

    Spontaneous vs. Stimulated Emission

- **Refraction and diffraction**

    Directing and guiding light **(focus of Lecture 16)**

<u>Absorption in semiconductors</u>: reflection and absorption coefficients

Light normally incident on a solid will be partially reflected at the air (or vacuum) and solid interface, and the remaining light will enter the solid. If it is absorbed by the solid, its intensity will decrease exponentially with distance as $e^{-\alpha(\lambda)x}$, where $\alpha(\lambda)$ is the absorption coefficient.

$$I(\lambda,x) = \left[1 - R(\lambda)\right] I_o(\lambda)\, e^{-\alpha(\lambda)x}$$

where $R(\lambda)$ is the reflection coefficient at the interface. We will say more about $R(\lambda)$ shortly, but first discuss $\alpha(\lambda)$.

Absorption in semiconductors - energy level systems

- We will look at energy transitions in bulk and quantum well systems

Absorption in semiconductors: processes

Within these energy level systems we can have a variety of mechanisms by which electrons (and holes) absorb optical energy. Most of these processes can occur in quantum wells, wires, and dots, as well as in bulk material. :

Band-to-band: an electron in the valence band absorbs a photon with enough energy to be excited to the conduction band, leaving a hole behind.

Band-to-exciton: an electron in the valence band absorbs almost enough energy to be excited to the conduction band. The electron and hole it leaves behind remain electrically "bound" together, much like the electron and proton of a hydrogen atom.

Band-to-impurity or impurity to band: an electron absorbs a photon that excites it from the valence band to an empty impurity atom, or from an occupied impurity atom to the conduction band.

Cont. next foil

<u>Absorption in semiconductors</u>: processes cont.

<u>Free carrier</u>: an electron in the conduction band, or hole in the valence band, absorbs a photon an is excited to a higher energy level within the same set of bands (i.e, conduction or valence).

In quantum structures there can be photon absorption due to carriers being excited between the quantum levels within the same band (termed "intra-band"), as well as between the various quantum levels in one band and those in another "(inter-band"):

<u>Intra-band</u>: these transitions can occur only between even and odd index levels and are only operative for light polarized parallel to the direction of quantization. That is, in a quantum well the light must be polarized normal to the well itself, and in the direction of the composition variation.

<u>Inter-band</u>: inter-band transitions can occur between conduction and valence bands, or between different valence bands (light-hole, heavy-hole, and spin-off). There are transitions can be active for either polarization of the light, depending on the symmetries of the respective bands.

Absorption in semiconductors - band-to-band

- **Comparing direct and indirect band gap absorption**

	Direct gap	Indirect gap
Transitions	(Image deleted)	(Image deleted)
Absorption Edges	(Image deleted)	(Image deleted)

See Fig. 5.1: Swaminathan, V. and Macrander, A.T., Materials Aspects of GaAs and InP Based Structures. Englewood Cliffs, N.J.: Prentice-Hall, 1991.

(Swaminathan and Macrander, Fig. 5.1)

Absorption in semiconductors: band-to-band

Direct-gap: Direct-gap absorption involves only a single electron and a photon. Single electron theory (which ignors the possibility of excitons) tells us that the absorption coefficient for direct-gap absorption varies as the square-root of energy above the band edge:

$$\alpha_{\substack{direct\\gap}}(h\nu) = A_{\substack{direct\\gap}}\left[h\nu - E_g\right]^{1/2} u_1\left(h\nu - E_g\right)$$

Indirect-gap: Indirect-gap absorption requires the absorption or emission of a phonon, as well of a photon. In this case single electron theory tells us that the absorption coefficient for direct-gap absorption varies as the square of energy above onset:

$$\alpha_{\substack{indirct\\gap}}(h\nu) = A_{\substack{phonon\\absorption}}\left[h\nu - \left(E_g - E_{ph}\right)\right]^2 u_1\left(h\nu - E_g + E_{ph}\right)$$

$$+ A_{\substack{phonon\\absorption}}\left[h\nu - \left(E_g + E_{ph}\right)\right]^2 u_1\left(h\nu - E_g - E_{ph}\right)$$

Bottom line: Direct-gap absorption is more abrupt, and more intense than indirect-gap absorption.

Absorption in semiconductors - bulk band-to-band

- Comparison of the absorption edge of several direct- and indirect-gap semi-conductors

Notice the abruptness of the absorption edge, and the difference in the strength of the absorption just above the band-edge.

Absorption in semiconductors - band-edge tail

- **Sub-gap absortpion**

Note: Some sub-gap absorption is due to impurities and some is due to polar optical phonons.

In this high purity sample it is due to the later, an effect termed the Franz-Keldysh Effect.

(Image deleted)

GaAs sample
R.T.

See Fig. 5.2: Swaminathan, V. and Macrander, A.T., Materials Aspects of GaAs and InP Based Structures. Englewood Cliffs, N.J.: Prentice-Hall, 1991.

Absorption in semiconductors - excitonic absorption near 0 K

- **Structure seen at very low temperatures**

The sharpest spectra are obtained at very low temperatures where the photon population is low.

Note the sharp rise in absorption in the exciton continuum, and compare it to the bulk theory ignoring excitons (dashed line)

(Image deleted)

See Fig. 5.24: Swaminathan, V. and Macrander, A.T., Materials Aspects of GaAs and InP Based Structures. Englewood Cliffs, N.J.: Prentice-Hall, 1991.

Absorption in semiconductors - exciton absorption vs. T

- Spectra for GaAs and InP at various temperatures

GaAs

(Image deleted)

InP

(Image deleted)

See Fig. 5.5, 5.6: Swaminathan, V. and Macrander, A.T., Materials Aspects of GaAs and InP Based Structures. Englewood Cliffs, N.J.: Prentice-Hall, 1991.

<u>Absorption in semiconductors</u> - free carrier (hole) absorption

- **Valence band free carrier absorption**

Note: The free carrier absorption spectum for electrons has a simple $\square^2$ variation, but there are multiple valence bands and as a consequence the hole free carrier spectrum is more complex, with peaks at valence band to valence band resonances.

(Image deleted)

See Fig. 5.10: Swaminathan, V. and Macrander, A.T., Materials Aspects of GaAs and InP Based Structures. Englewood Cliffs, N.J.: Prentice-Hall, 1991.

Absorption in semiconductors - quantum well spectra

- **Theory and experiment**

Theorectical curve:

(Image deleted)

Data:

(Image deleted)

Note the excitons at each sub-band step edge.

See Fig. 8.B.3: Rosencher, E. and Vinter B., Optoelectronics Cambridge, UK; New York NY: Cambridge University Press, 2002.

Absorption in semiconductors - quantum well excitons with an applied electric field

- Changing with a field: the basis for a device

(Image deleted)

We shall see that this can be used to make a light modulator.

See Fig.52: Weisbuch, C. and Vinter B., Quantum Semiconductor Structures: fundamentals and applications Boston: Academic Press, 1991.

Recombination in semiconductors - various processes

- **Hole-electron recombination**

The processes that occur in any semiconductor. Some are radiative, many are not.

(Images deleted)

See Fig. 5.16: Swaminathan, V. and Macrander, A.T., Materials Aspects of GaAs and InP Based Structures. Englewood Cliffs, N.J.: Prentice-Hall, 1991

Band-to-band recombination is radiative, but it is very slow in indirect semiconductors, and it cannot compete with non-radiative processes.