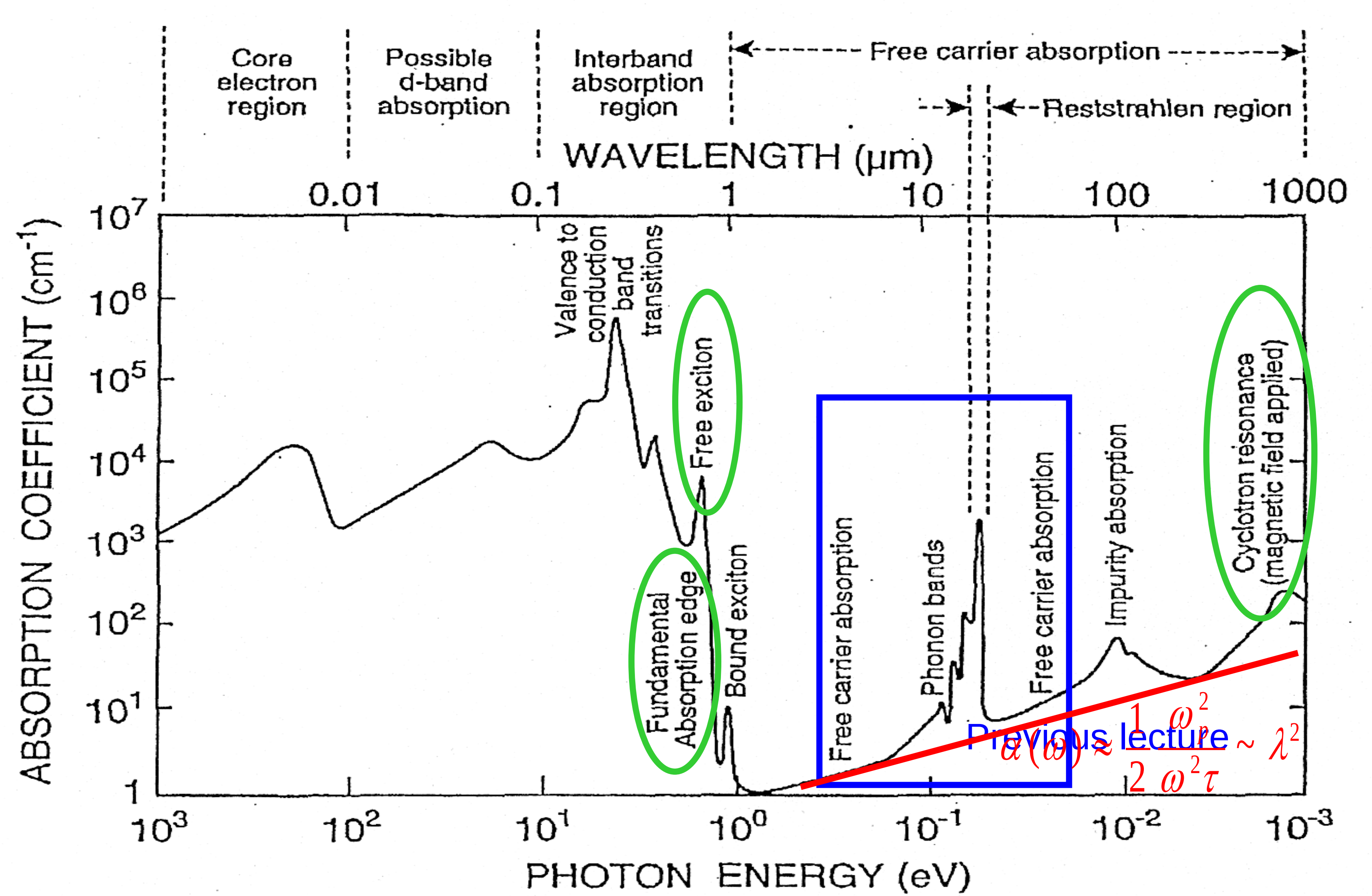
Overview

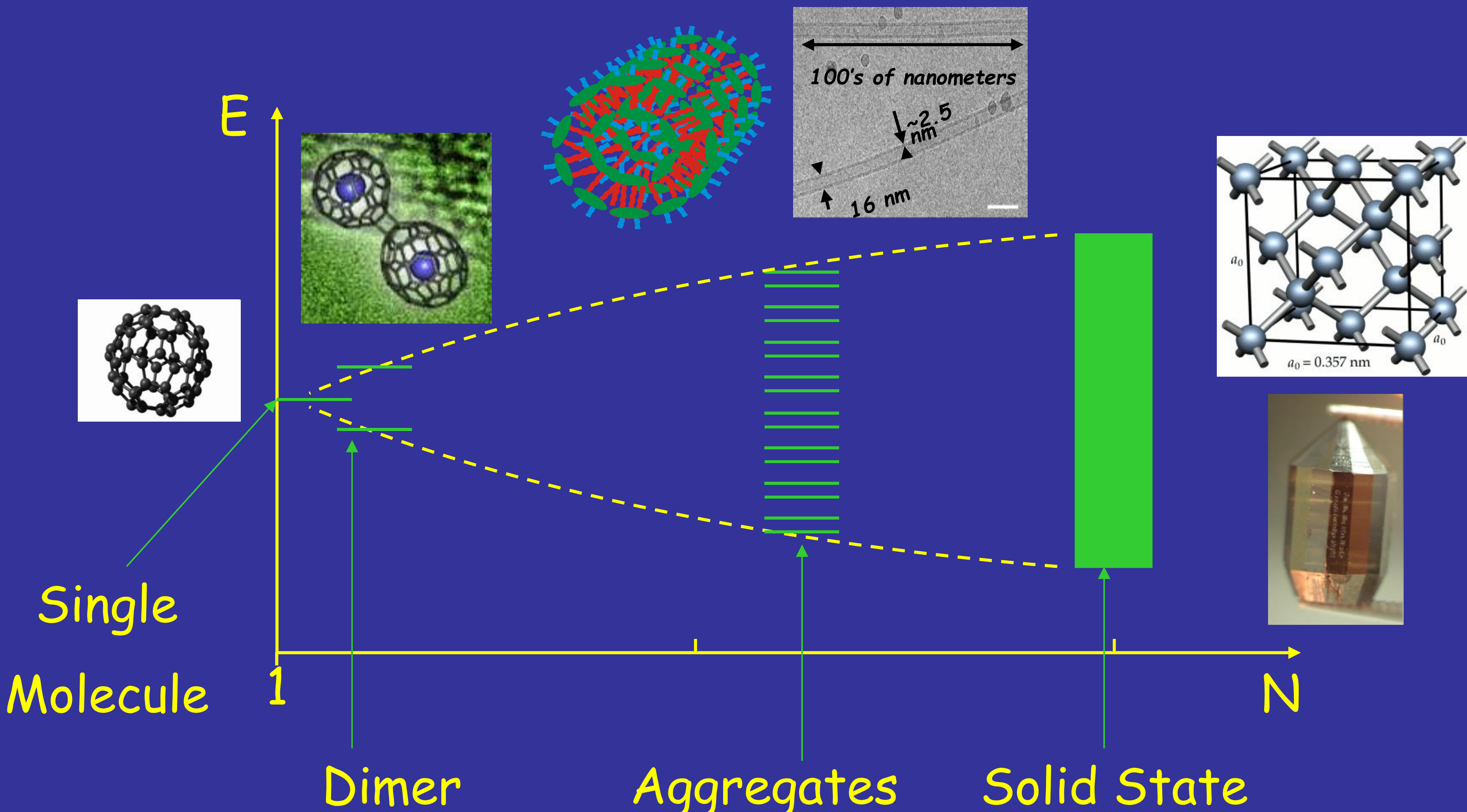
- Introduction (Fox-Ch1)
  - Response function
  - Optical processes
  - Optical constants
- Waves in solids (Fox-Appendix A)
  - Maxwell equations and wave equation
- Models (Fox-Ch2,3,7)
  - Lorentz model
  - Drude-Lorentz model
  - Transition rates, QM treatment
- Magneto-optical effects, XMCD
- Inelastic light scattering
- Non-linear optics
- Time resolved optics
- Optical modification of matter

Semiconductors (Fox 3)

Absorption in semiconductors

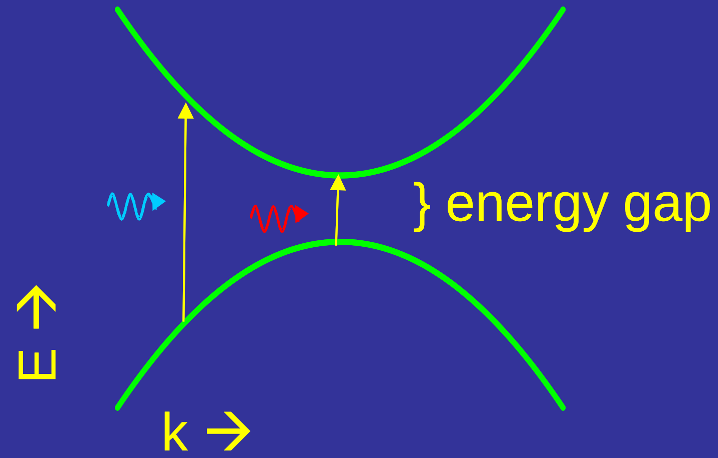


Energy bands in solids



Fundamental absorption edge

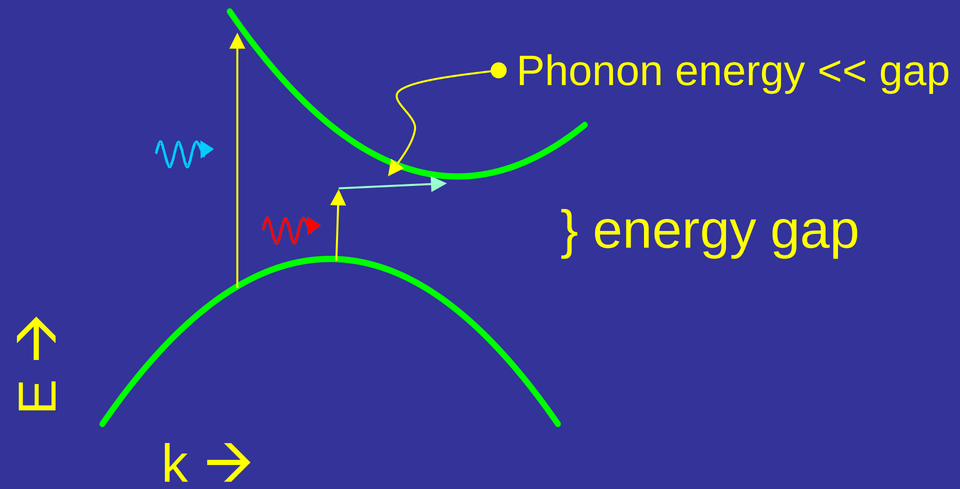
- Direct semiconductors
  'vertical' transitions



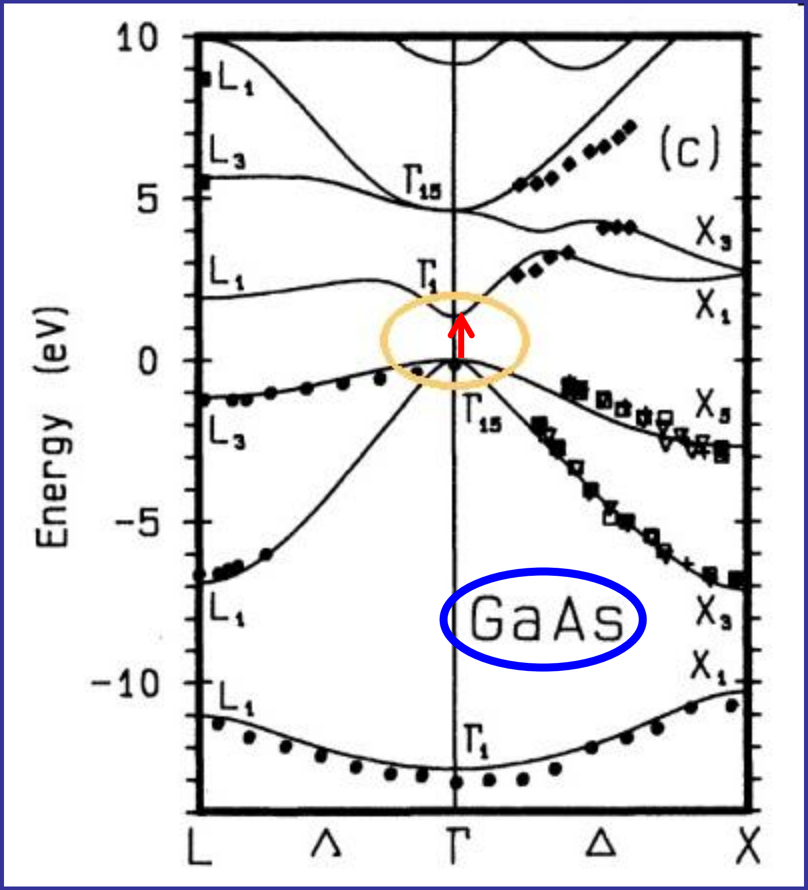
- Indirect semiconductors

  Phonon assisted
  (takes up momentum)

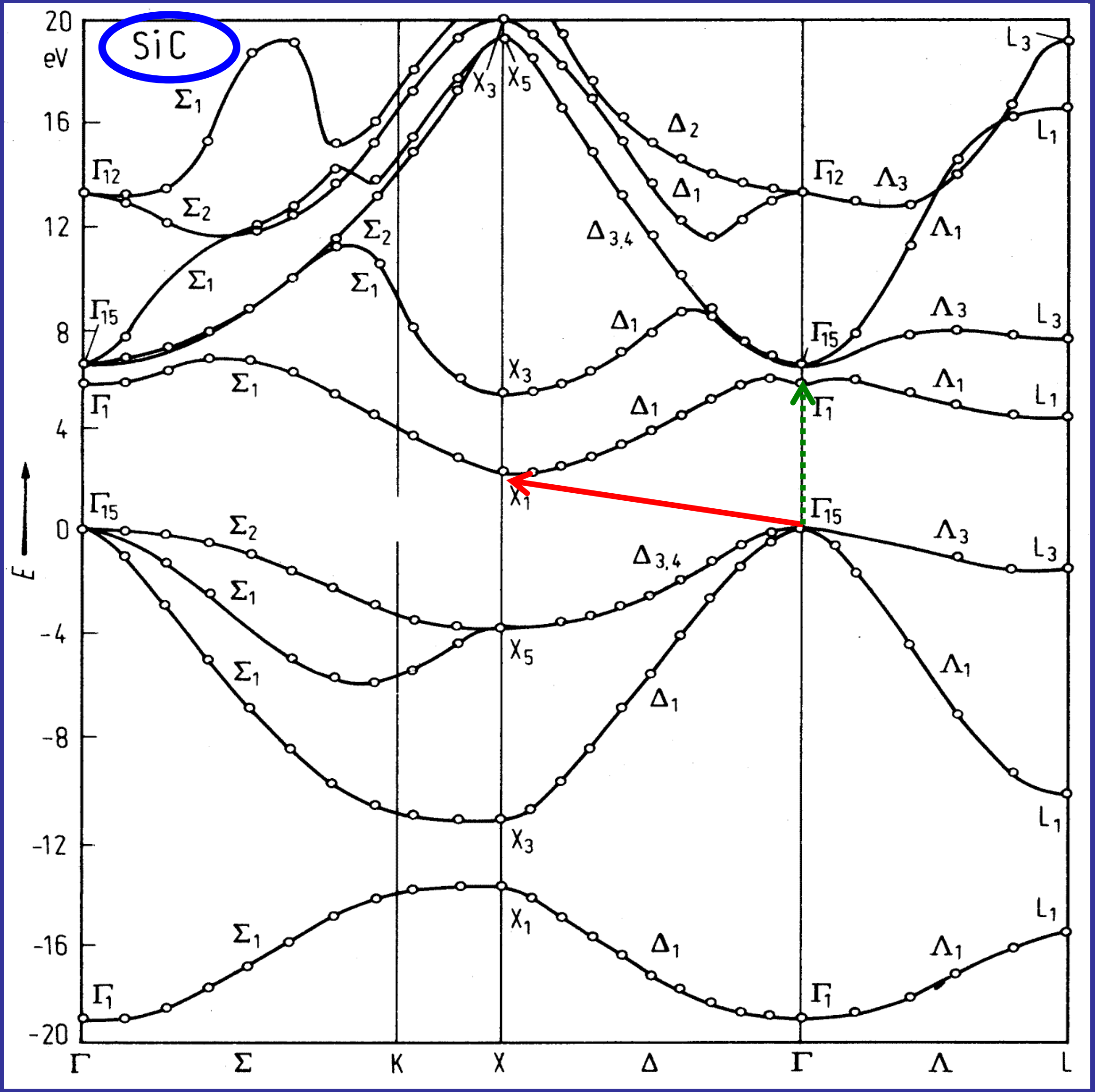
  Vertical transitions
  for higher E



GaAs and SiC



Energy (eV)
10
5
0
-5
-10
(c)
GaAs
L
Λ
Γ
Δ
X



SiC
20 eV
16
12
8
4
0
-4
-8
-12
-16
-20
E
Γ
Σ
K
X
Δ
Γ
Λ
L

Transition rates

$$\text{Absorption coefficient}: \alpha = \frac{\Delta I / I}{\Delta z} = \frac{\text{Rate of E loss/volume}}{\text{incoming E/area}} = \frac{\hbar\omega \cdot P_{fi} / V}{\hbar\omega / A}$$

Once α is known, rest of optical functions can be calculated

Task is to calculate the transition rate $P_{fi} \Rightarrow$ Fermi Golden Rule

Optical transitions

- Conservation of energy and momentum

$$E_f = E_i + \hbar\omega$$

$$k_f = k_i + q$$

- Fermi golden rule: transition rate

$$W_{i\to f} = \frac{2\pi}{\hbar}\left|\left\langle \phi_f \left| P \right| \phi_i \right\rangle\right|^2 \delta\left(E_f - E_i - \hbar\omega\right)\delta\left(k_f - k_i - q\right)$$

- Photon momentum ~0, many combinations of states with $E_f - E_i = \hbar\omega$

$$W_{i\to f} = \frac{2\pi}{\hbar}\left|M\right|^2 g\left(\hbar\omega\right)$$

- $g\left(\hbar\omega\right)$: joint density of states

Density of states

How many states are there in a given interval dk ? Or in an interval dE ?

Volume of a sphere in k-space: $4/3\ \pi\ k^3$

Volume one state occupies in k-space: $(2\pi/a)^3$

Number of spin degenerate states within the sphere: $N(k) = 2\frac{\frac{4}{3}\pi k^3}{\left(\frac{2\pi}{a}\right)^3} = \frac{k^3 a^3}{3\pi^2}$

Density of states: $D(k) = \frac{1}{V}\frac{dN(k)}{dk} = \frac{k^2}{\pi^2}$

In energy space $D(E)dE = D(k)\frac{dk}{dE}dE$

For free electrons:

$$D(E) = D(k)\frac{dk}{dE} = \frac{k^2}{\pi^2}\frac{m}{\hbar^2 k} = \frac{m}{\pi^2\hbar^2}k = \frac{m}{\pi^2\hbar^2}\frac{\sqrt{2mE}}{\hbar} = \frac{\sqrt{2}m^{3/2}}{\pi^2\hbar^3}\sqrt{E}$$

Bandgap absorption by direct semiconductors

- Transition rate proportional to available initial *and* final states
- Initial states: Valence band $E_v(k) = -\frac{\hbar^2 k_v^2}{2m_v}$
- Final states: Conduction band $E_c(k) = E_g + \frac{\hbar^2 k_c^2}{2m_c}$

$$\hbar\omega = E_g + \frac{\hbar^2 k_c^2}{2m_c} + \frac{\hbar^2 k_v^2}{2m_v} = E_g + \frac{\hbar^2 k^2}{2\mu} \text{ using } k = k_v = k_c \text{ and } \frac{1}{\mu} = \frac{1}{m_v} + \frac{1}{m_c}$$

- JDOS:

$$\text{For } \hbar\omega < E_g : \quad g(\hbar\omega) = 0$$

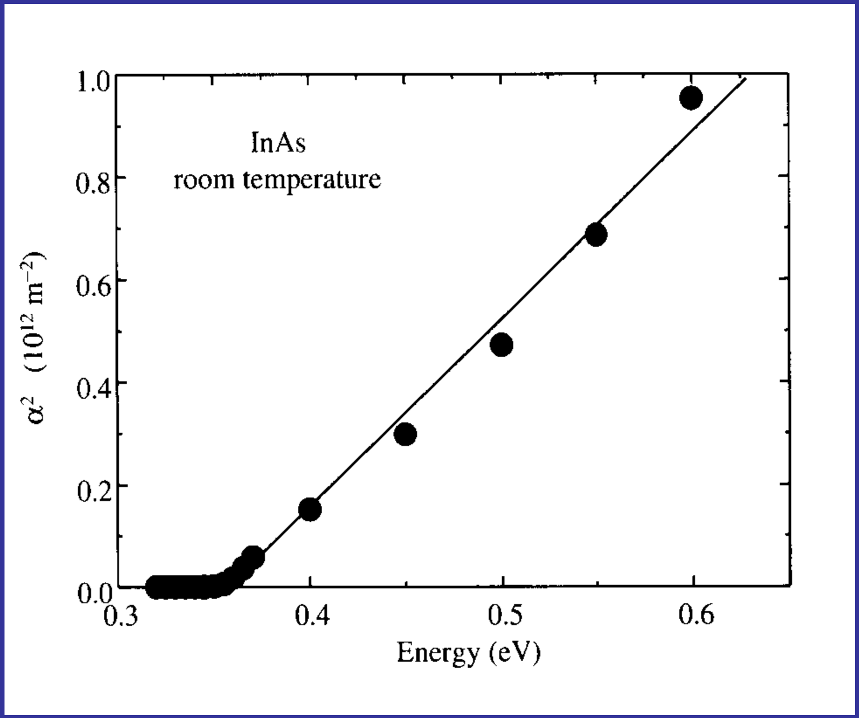
$$\text{For } \hbar\omega > E_g : \quad g(\hbar\omega) = \frac{\sqrt{2}\mu^{3/2}}{\pi^2 \hbar^3} \sqrt{\hbar\omega - E_g}$$

Direct transitions

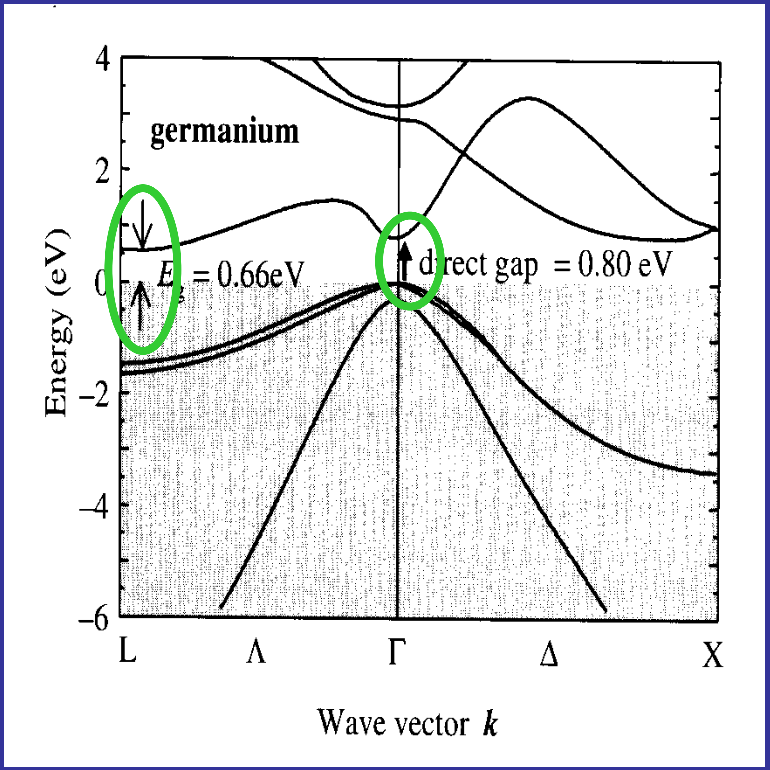
- Absorption coefficient proportional to transition rate $\alpha = -\frac{1}{I}\frac{dI}{dz} \propto W_{i \to f}$ (beer's law: $dI=-\alpha z I(z) \rightarrow I(z)=I_0 e^{-\alpha z}$)

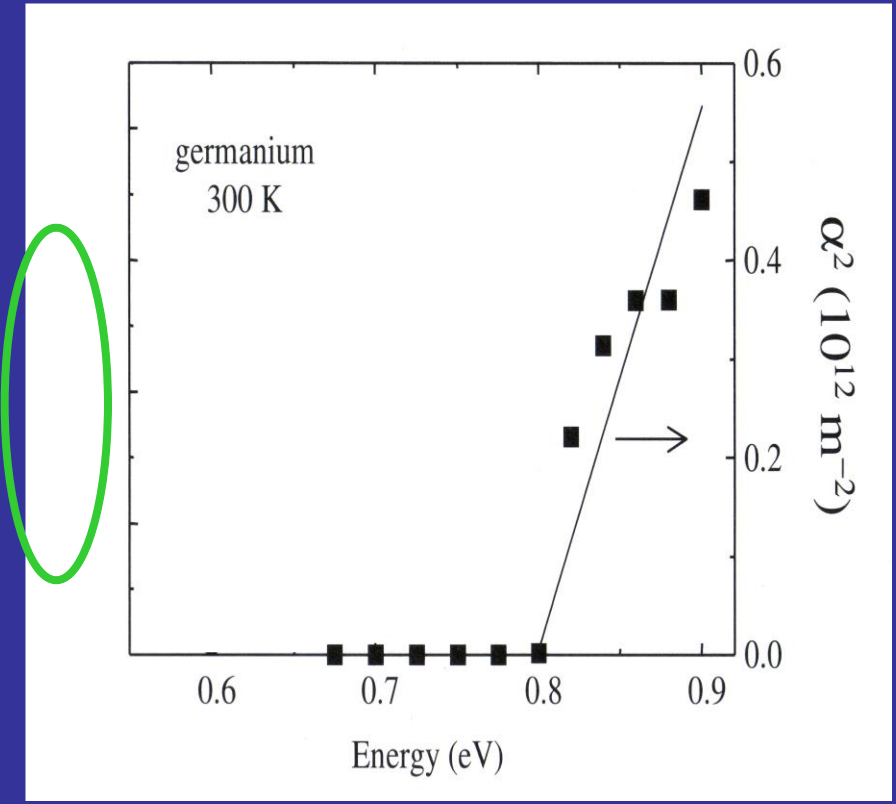
$$\text{For } \hbar\omega < E_g : \quad \alpha(\hbar\omega) = 0$$

$$\text{For } \hbar\omega > E_g : \quad \alpha(\hbar\omega) \propto \mu^{3/2} \sqrt{\hbar\omega - E_g}$$



Germanium

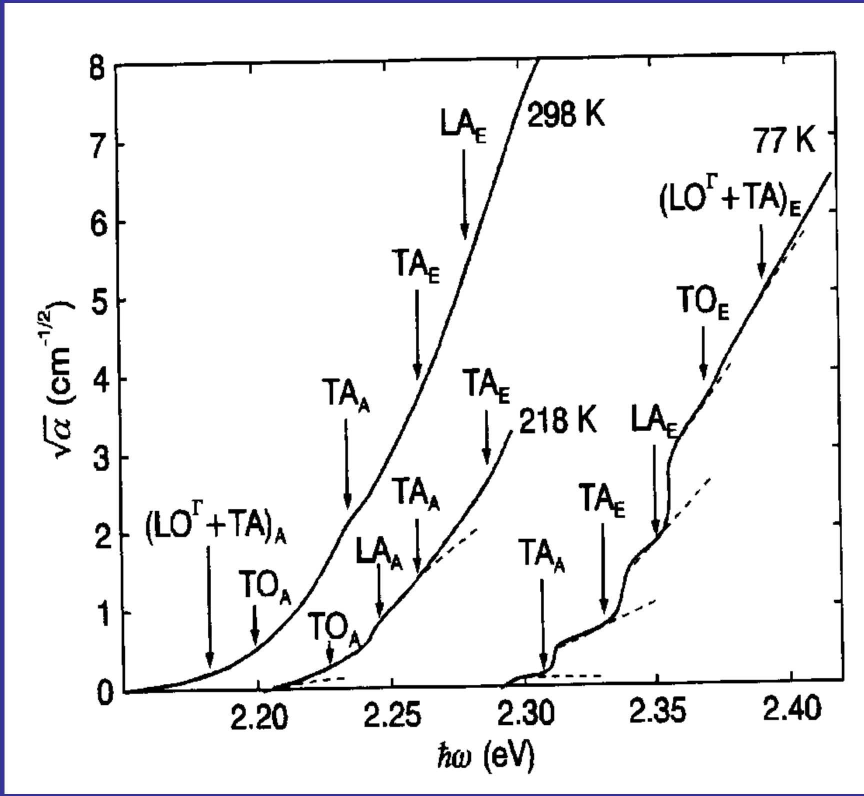


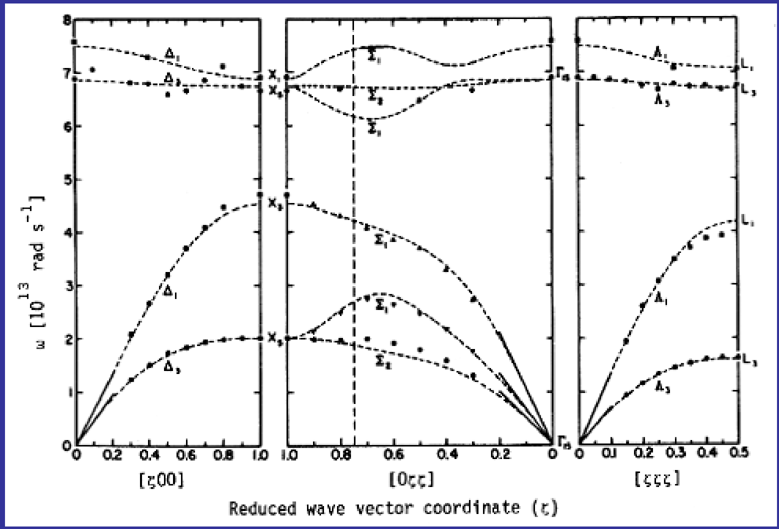


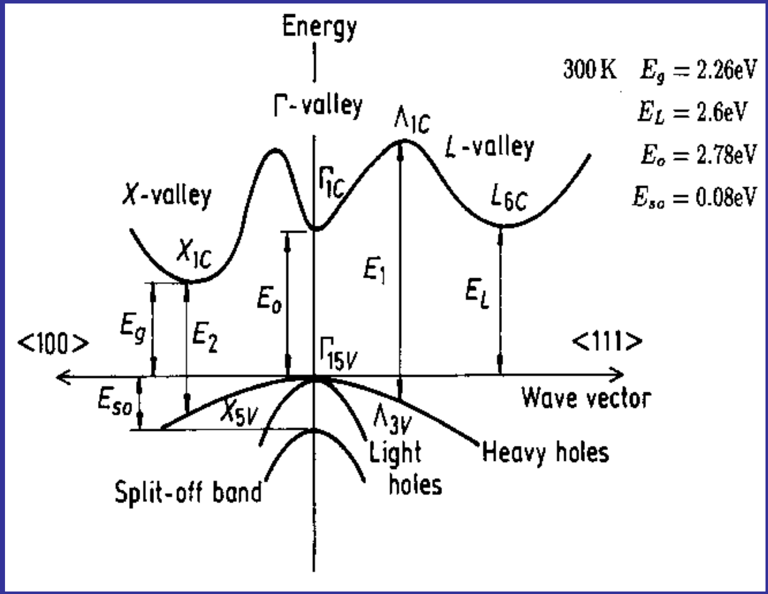
Direct gap : $\alpha(\hbar\omega) \propto \sqrt{\hbar\omega - E_g}$

Indirect gap (not derived here) : $\alpha(\hbar\omega) \propto \left(\hbar\omega - E_g \mp \hbar\Omega\right)^2$

GaP phonon structure







Indirect gap : $\alpha(\hbar\omega) \propto \left(\hbar\omega - E_g \mp \hbar\Omega\right)^2$

Semiconductors in a magnetic field

- At high enough fields: quantization of orbits and energy

$$E_n = \left(n + \frac{1}{2}\right)\hbar\omega_c$$

- For $B=B_z$: $E_n^v(k_z) = -\left(n + \frac{1}{2}\right)\hbar\frac{eB}{m_h^*} - \frac{\hbar^2 k_z^{v\,2}}{2m_h^*}$

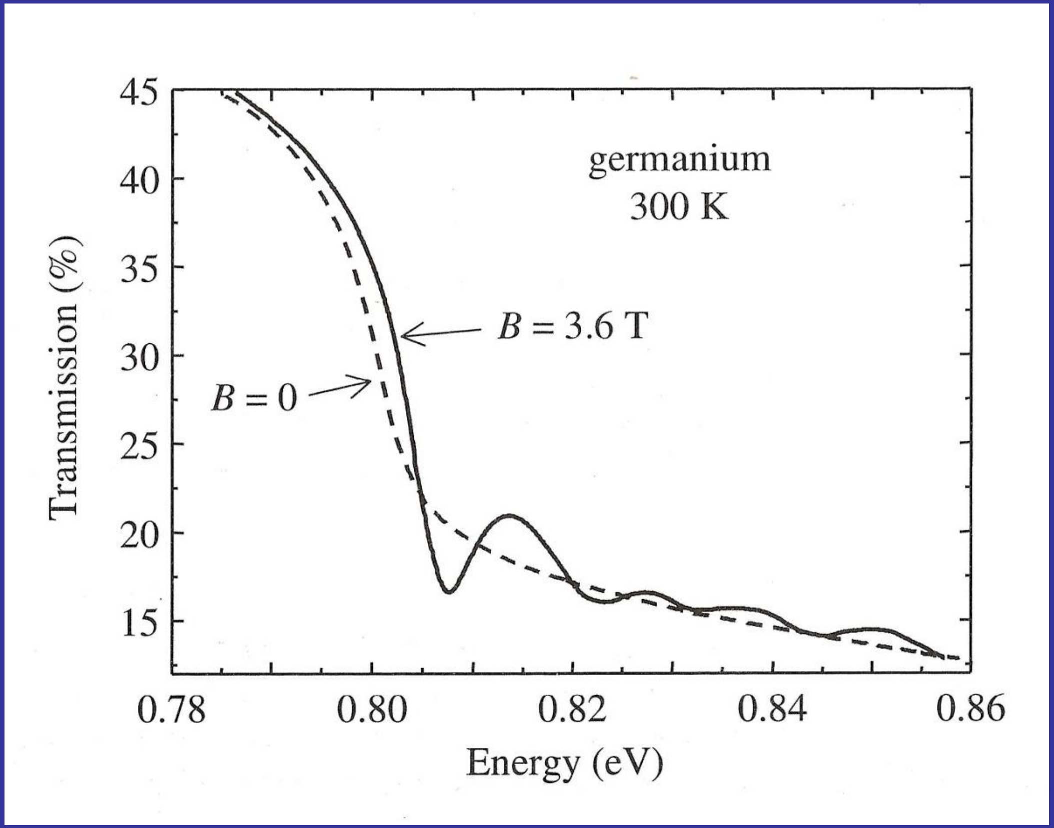
$$E_n^c(k_z) = E_g + \left(n + \frac{1}{2}\right)\hbar\frac{eB}{m_e^*} + \frac{\hbar^2 k_z^{c\,2}}{2m_e^*}$$

$$\hbar\omega = E_g + \left(n + \frac{1}{2}\right)\hbar\frac{eB}{\mu} + \frac{\hbar^2 k_z^2}{2\mu}$$

- Strong absorption for $k_z=0$
  ➔ equidistant peaks in absorption spectrum $\hbar\omega = E_g + \left(n + \frac{1}{2}\right)\hbar\frac{eB}{\mu}$

- Absorption edge shift in magnetic field $\Delta = \hbar\frac{eB}{2\mu}$

Ge in a magnetic field



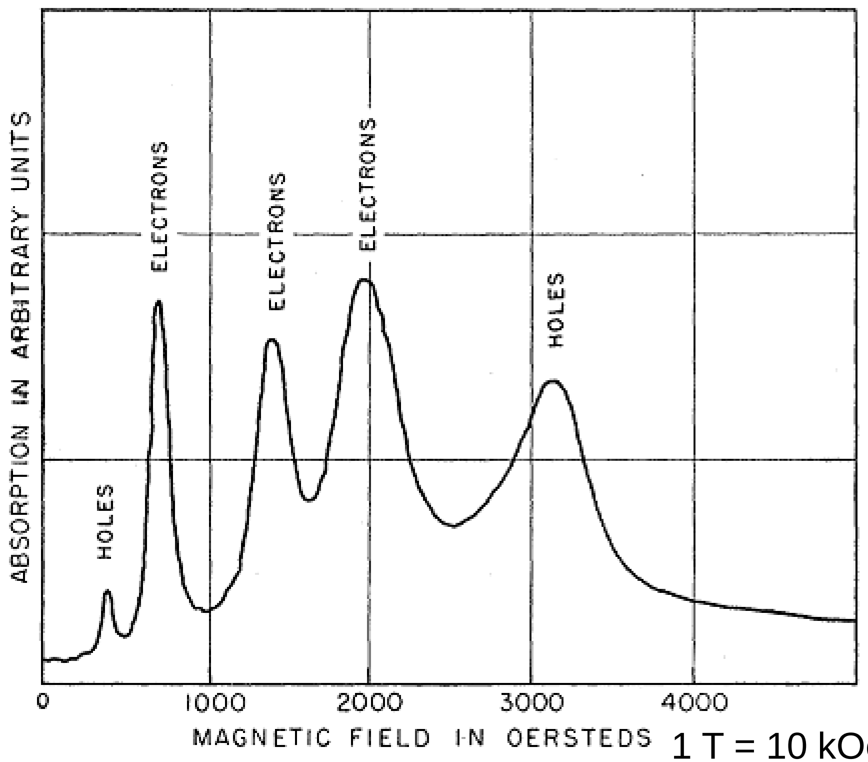
PHYSICAL REVIEW VOLUME 108, NUMBER 6 DECEMBER 15, 1957

Oscillatory Magneto-Absorption in Semiconductors*

SOLOMON ZWERDLING, BENJAMIN LAX, AND LAURA M. ROTH
Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts

(Received August 30, 1957)

Cyclotron resonance



1 T = 10 kOe

FIG. 2. Typical cyclotron resonance results in germanium near 24 000 Mc/sec and 4°K: direct copy from a recorder trace of power absorption *vs* static magnetic field in an orientation in a (110) plane at 60° from a [100] axis.

- Transitions with $\Delta n = 1$
- 24000 Mc/sec ~ 1 meV
- Energy fixed, scan B

$$\omega_c = \frac{eB}{m^*} \Rightarrow \text{ determine effective mass}$$

Cyclotron Resonance of Electrons and Holes in Silicon and Germanium Crystals

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Department of Physics, University of California, Berkeley, California
(Received December 16, 1954)

Wannier-Mott Excitons

- Conduction band: electrons with mass m_e^*
- Valence band: holes with mass m_h^*
- Hydrogen problem with very light ‘proton’ in a screened environment
  - Screening: $e^2 \rightarrow e^2 / \varepsilon_r$
  - Reduced mass: $m_e \rightarrow \mu = \left[\frac{1}{m_e} + \frac{1}{m_h}\right]^{-1}$

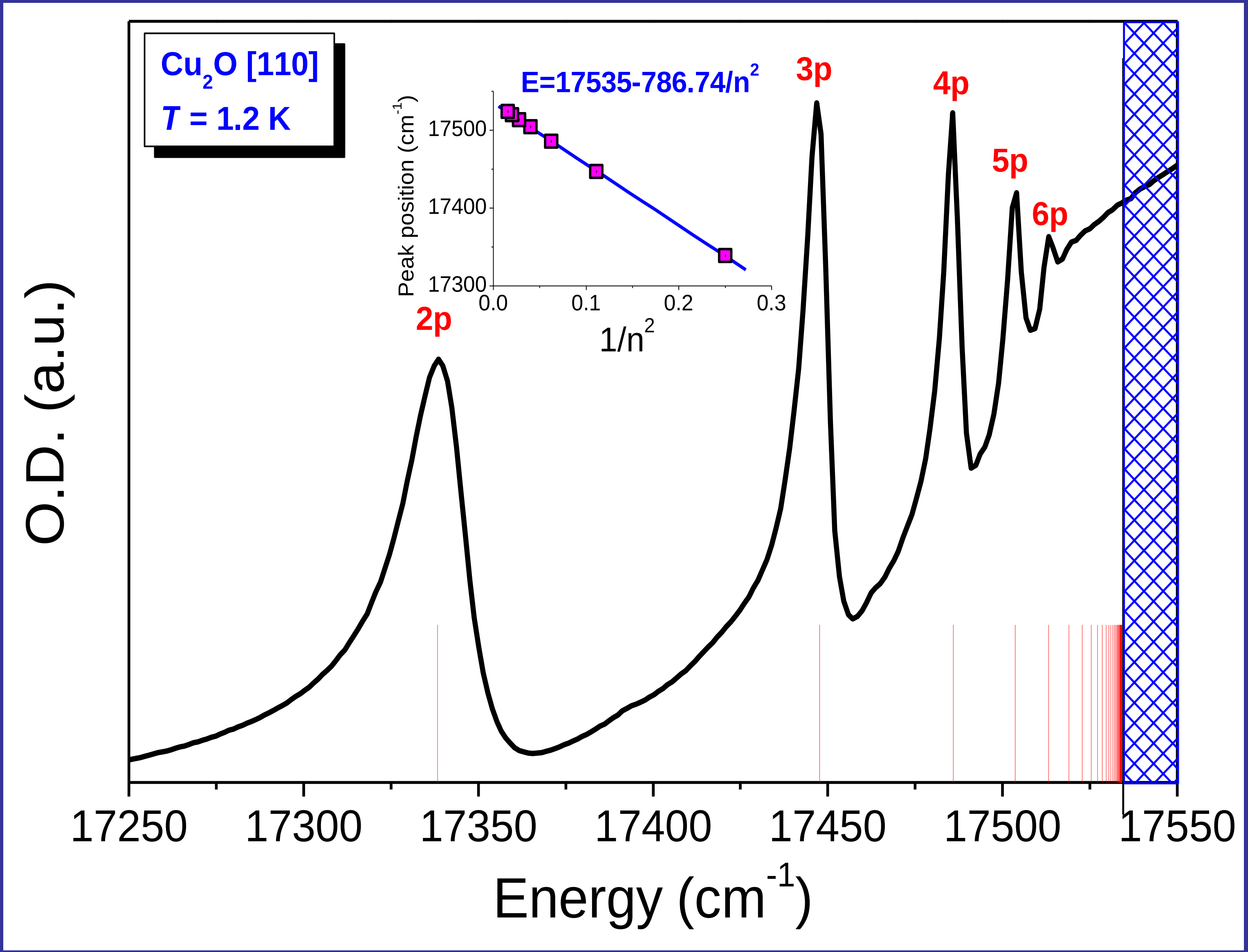
$$H = \frac{p_e^2}{2m_e} + \frac{p_p^2}{2m_p} - \frac{e^2}{|r_e - r_p|} \quad \Rightarrow \quad H = \frac{p_e^2}{2m_e^*} + \frac{p_h^2}{2m_h^*} - \frac{e^2}{\varepsilon_r |r_e - r_h|}$$

$$a_{ex} / a_H = \frac{m_e}{\mu} \varepsilon_r \approx 20$$

$$E_{ex} / E_H = \frac{\mu}{m_e} \frac{1}{\varepsilon_r^2} \approx \frac{1}{144}$$

	Hydrogen	Cu_2O
Bohr radius	0.53 Å	10.6 Å
Binding E_1	13.6 eV	94 meV

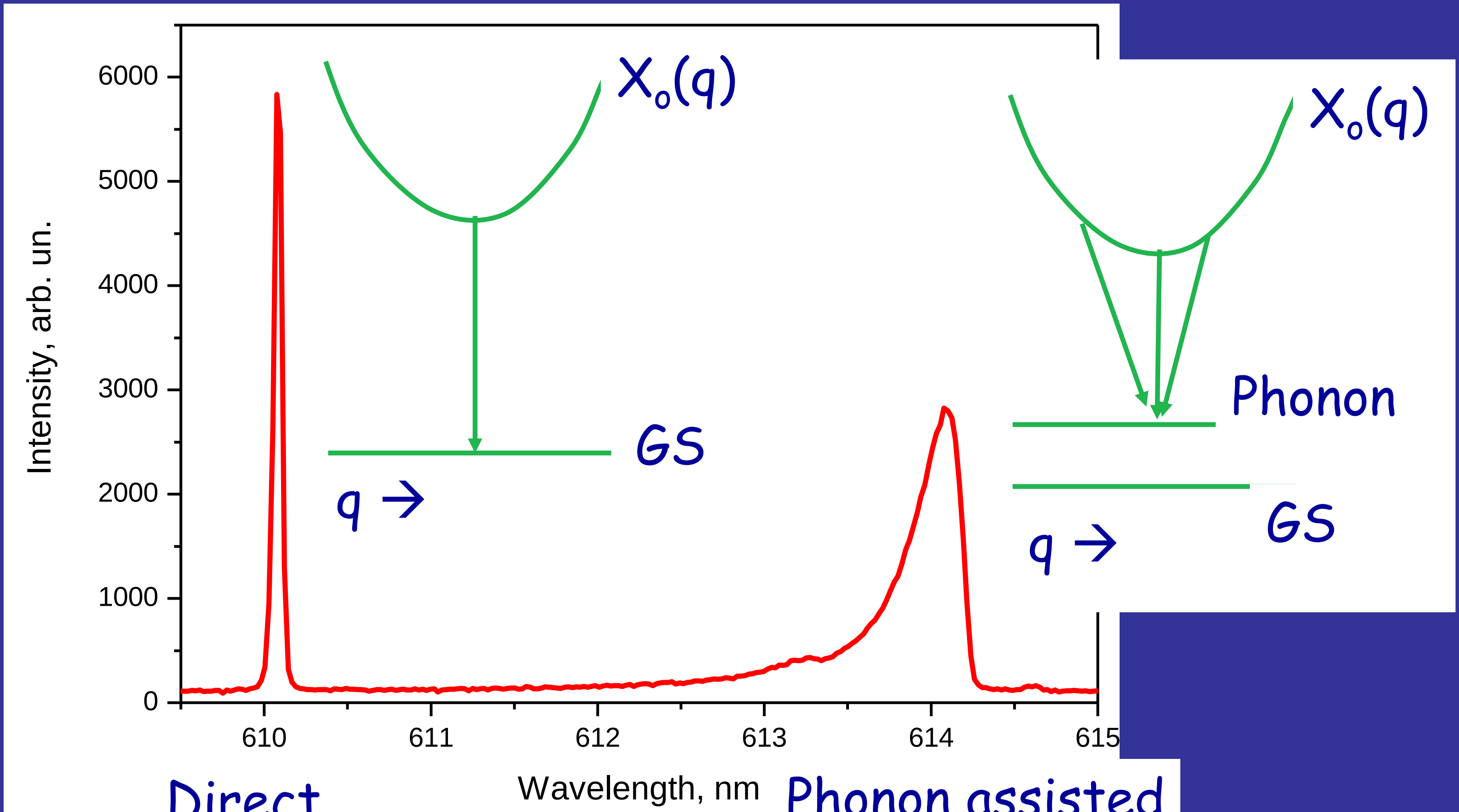
Excitons in Cu_2O (absorption)



Lyman series

$$E(n) = \frac{E_0}{n^2}$$

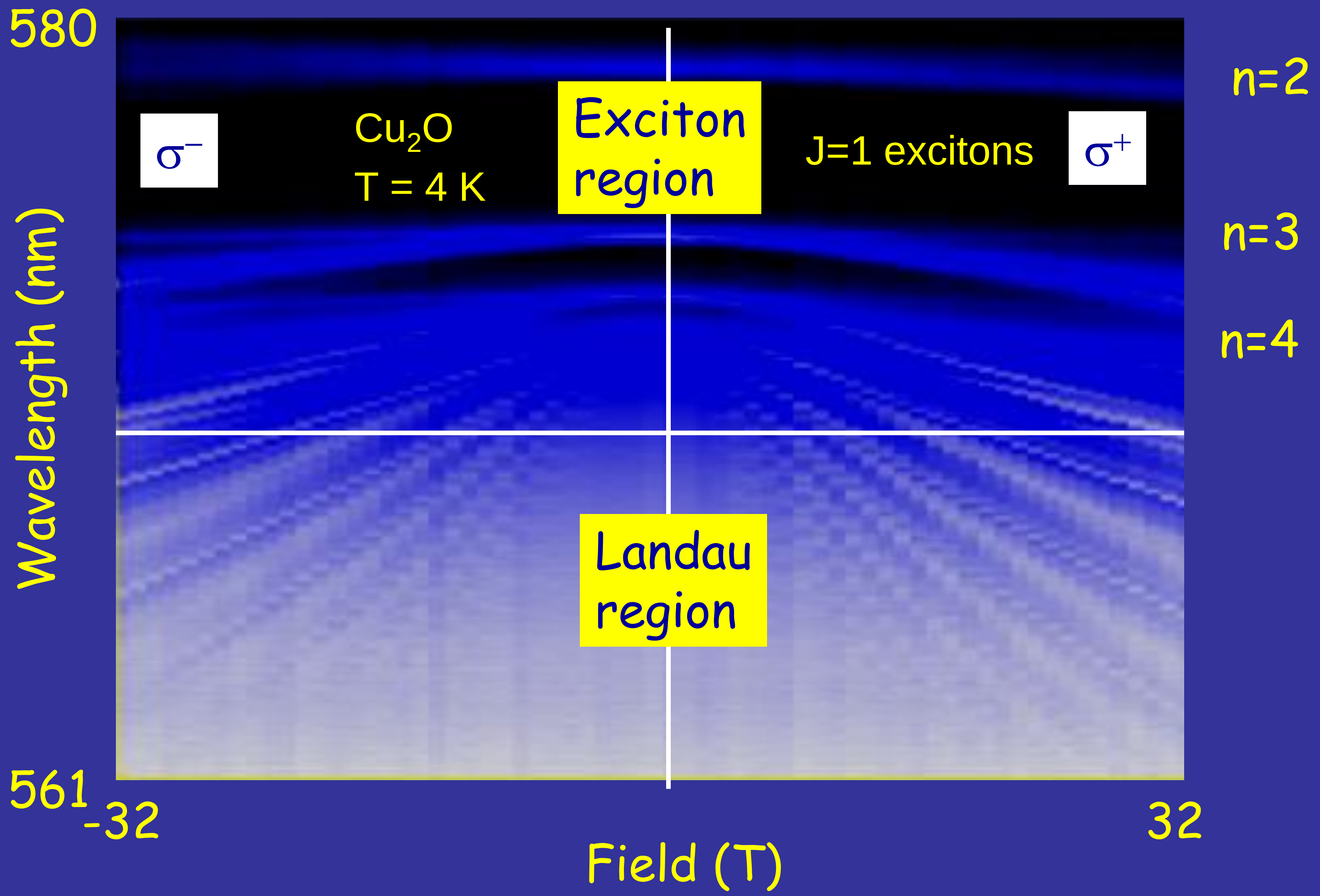
Cu_2O Emission



Direct Emission

Phonon assisted Emission

Magneto-absorption of excitons



Excitons in KBr

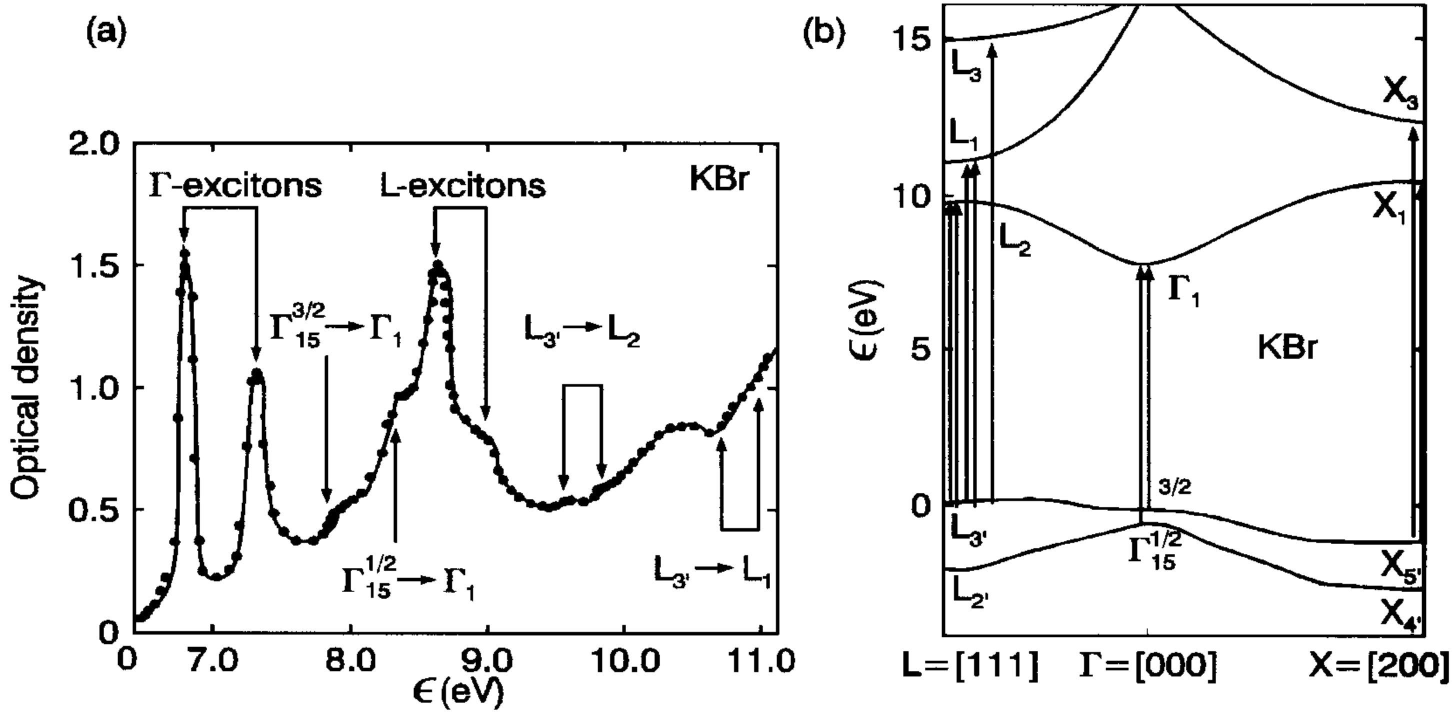


Fig. 7.7. Optical density for KBr measured at 80 K (**a**) and band structure for the corresponding lattice (**b**); after [7.11].

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Ultraviolet Absorption of Alkali Halides*

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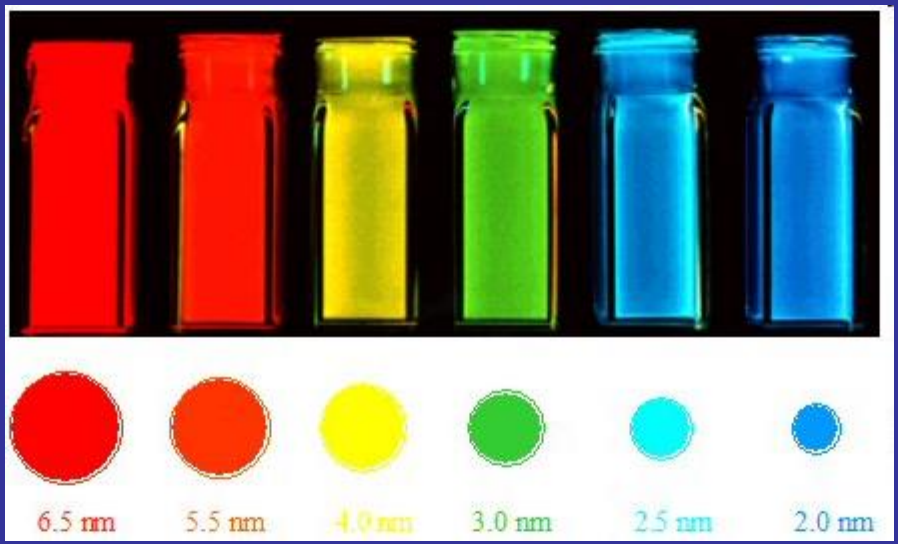
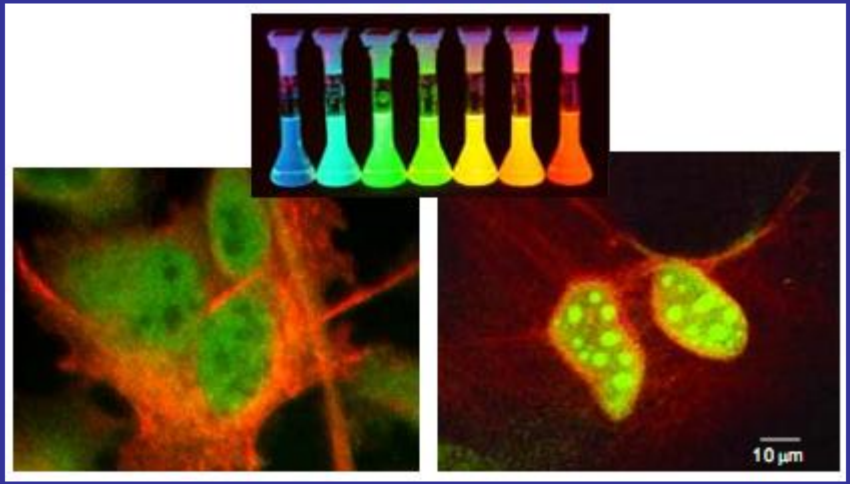
(Received May 27, 1959; revised manuscript received August 19, 1959)

Nano Crystals

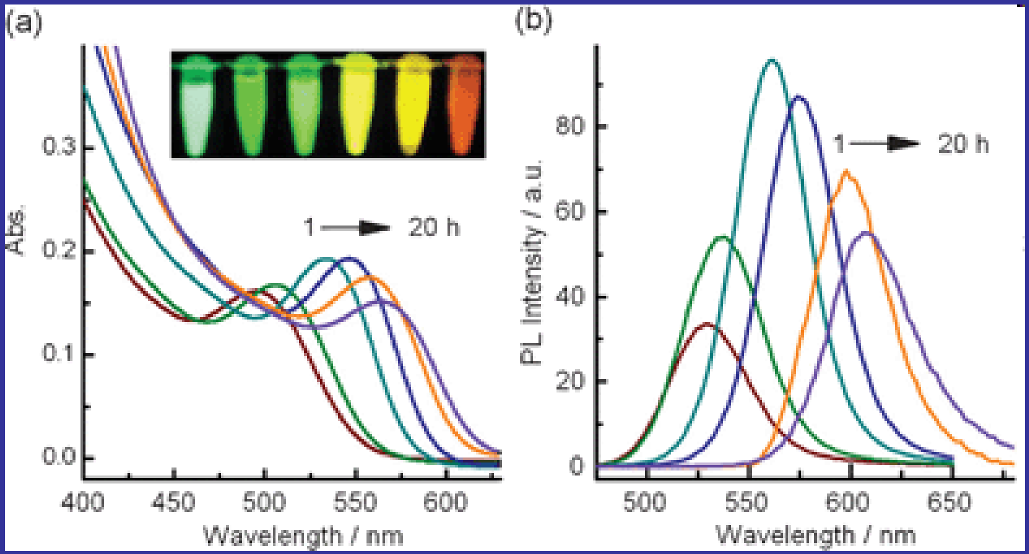
CdSe nanocrystals



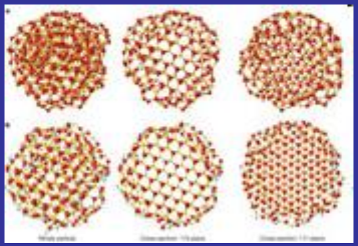


CdTe nanocrystals

- Bio labeling
- Displays
- Solar cells
- Photonic crystals
- MRI enhancement
- …



Nano Crystals



Bandgap CdTe: 1.56 eV (direct)

Bulk → emission at 795 nm

Small particle: confinement energy (particle in a box)

$$E = E_g + \frac{\hbar^2 \pi^2}{2\mu R^2}$$

CdTe: $m_e^* \approx 0.1\, m_0$, $m_h^* \approx 0.44\, m_0$ } $\mu \approx 0.08\, m_0$

2 nm particles: Confinement 1.15 eV

E = 1.56 + 1.15 = 2.71 eV Corresponds to 475 nm

For 3 nm: 600 nm