Lecture 8 – Light-Matter Interaction Part 2 Basic excitation and coupling

EECS 598-002 Winter 2006

Nanophotonics and Nano-scale Fabrication

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Schedule for the rest of the semester

- Introduction to light-matter interaction (1/26):
  - How to determine ε(r)?
  - The relationship to basic excitations.
- **Basic excitations and measurement of ε(r). (1/31)**
- Structure dependence of ε(r) overview (2/2)
- Surface effects (2/7 & 2/9):
  - Surface EM wave
  - Surface polaritons
  - Size dependence
- Case studies (2/14 – 2/21):
  - Quantum wells, wires, and dots
  - Nanophotonics in microscopy
  - Nanophotonics in plasmonics
- Dispersion engineering (2/23 – 3/9):
  - Material dispersion
  - Waveguide dispersion (photonic crystals)

Last time

- We learned:
  - To determine $\varepsilon(r)$, we need to study how the microscopic interaction between atoms/electrons with the light.
  - This interaction is similar to coupling of two SHO's.
  - The only details we need to know are the interaction near resonances of basic excitations.
  - The rest of the information needed to complete the calculation of $\varepsilon(r)$ is through the Kramers-Kronig relation.

Today

- Basic excitations by photons → polaritons
  - Plasmons (last time)
  - Phonons
  - Excitons, biexcitons, etc.
- Measurement of $\varepsilon(r)$

Ref: D. L. Mills and E. Burstein, “Polaritons,” *Rep. Prog. Phys.*, **37** (1974) 817.
P. Y. Yu and M. Cardona, *Fundamentals of Semiconductors*, 2nd ed., Springer-Verlag (1999) chapters 6 and 7.

Review of the concept of polaritons

- In a dielectric medium:

$$\varepsilon(\omega) = \varepsilon_0 \left[1 - \sum_{\substack{n \text{ basic} \\ \text{excitations} \\ \text{or oscillators}}} \frac{\omega_{pn}^2}{(\omega^2 - \omega_{0n}^2) + i\gamma_n \omega} \right] \quad \text{where} \quad \omega_{pn}^2 \equiv \frac{N_n q_n^2}{m_n \varepsilon_0}$$

$$= \varepsilon_\infty - \varepsilon_0 \frac{\omega_p^2}{(\omega^2 - \omega_0^2) + i\gamma\omega}$$

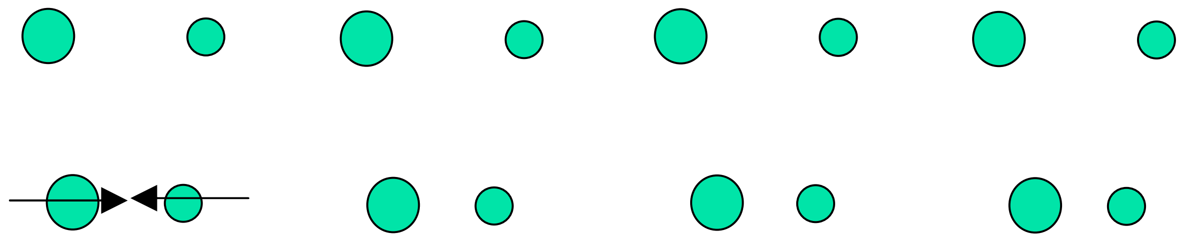
where the index denotes the n-th kind of basic excitation or SHO.

- QM analogue:

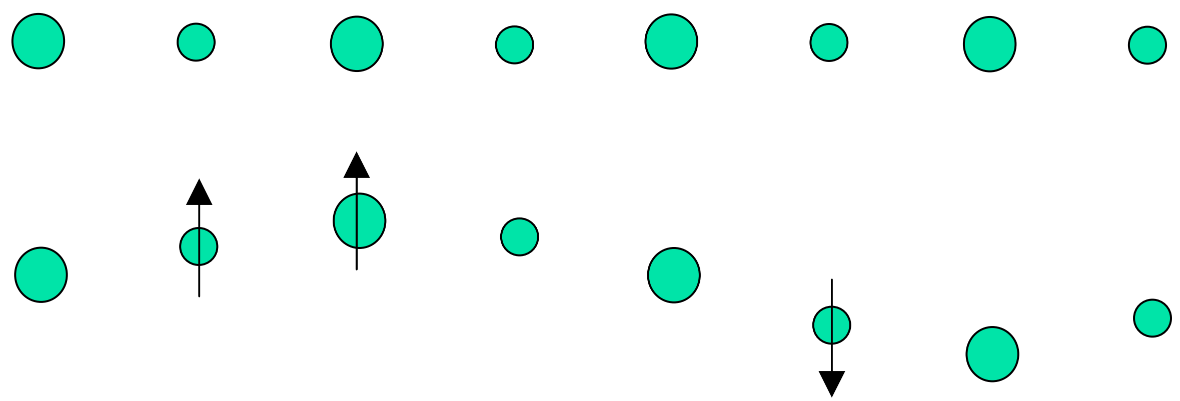
$$\omega_p^2 = \frac{nq^2}{\varepsilon_0 m} \rightarrow \frac{|e\hat{x}|^2}{\varepsilon_0}$$

Transverse and longitudinal vibrations

Longitudinally vibrated SHO's



Vertically vibrated SHO's



Transverse and longitudinal polaritons

For homogeneous media:

$$\nabla \cdot \vec{D} = 0$$

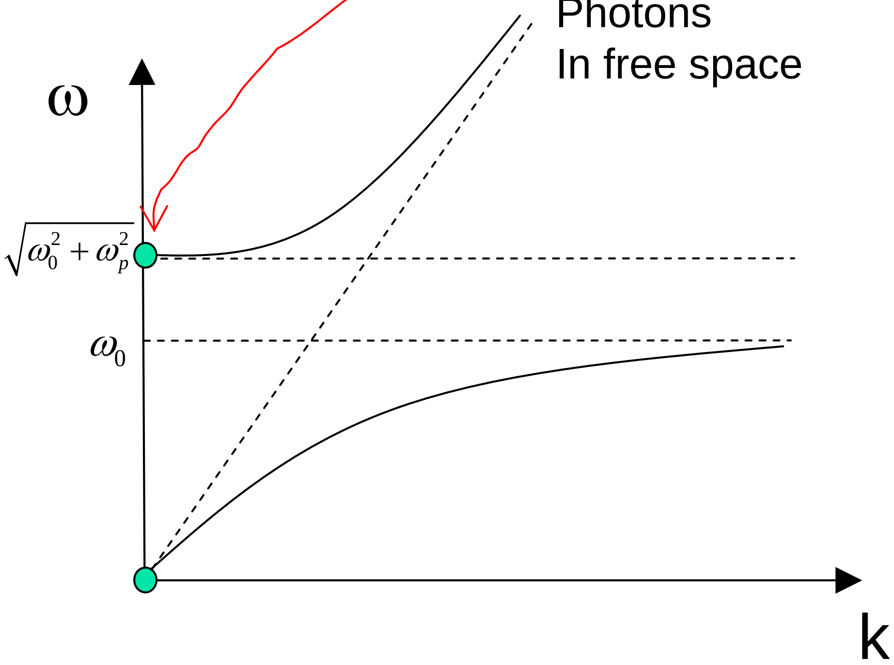
$$\Rightarrow \nabla \cdot \left(\varepsilon \vec{E} \right) = 0 \Rightarrow \varepsilon \vec{k} \cdot \vec{E} = 0$$

$$\Rightarrow \vec{k} \cdot \vec{E} = 0 \quad \text{or} \quad \varepsilon = 0$$

Normally EM wave couples only to transverse SHO's unless the dielectric constant vanishes.

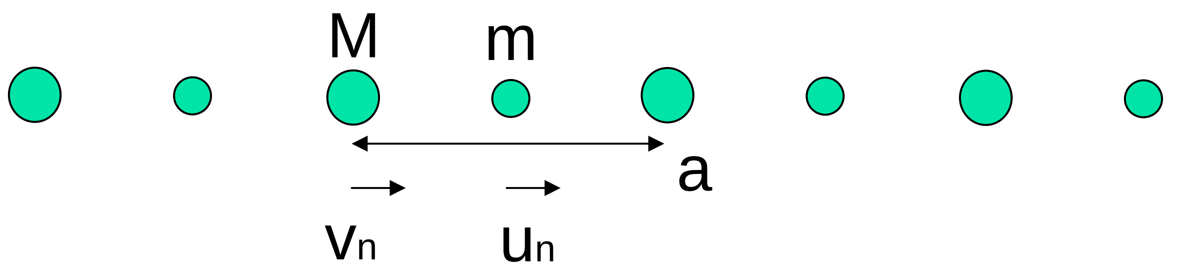
Longitudinal polaritons

$$\varepsilon = \frac{k^2}{\omega^2 \mu_0} = 0$$



EM wave can couple to the longitudinal vibration.

Phonons



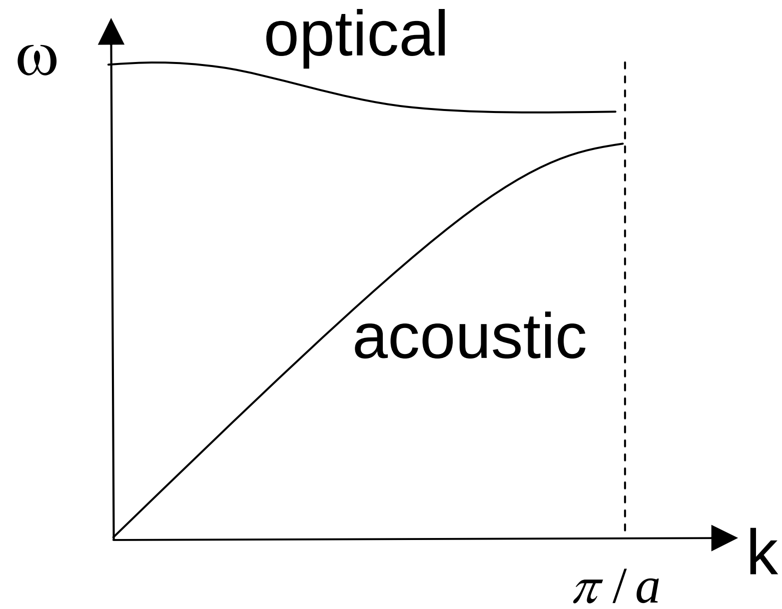
$$\begin{cases} m\ddot{u}_n = -\alpha(u_n - v_{n-1}) - \alpha(u_n - v_{n+1}) \\ M\ddot{v}_n = -\alpha(v_n - u_{n-1}) - \alpha(v_n - u_{n+1}) \end{cases}$$

By periodicity:

$$\begin{cases} u_n = u \exp\left[i(2nka - \omega t)\right] \\ v_n = v \exp\left[i(2(n+1)ka - \omega t)\right] \end{cases}$$

$$\Rightarrow \begin{cases} -m\omega^2 u = \alpha\left[v\left(e^{ika} + e^{-ika}\right) - 2u\right] \\ -M\omega^2 v = \alpha\left[u\left(e^{ika} + e^{-ika}\right) - 2v\right] \end{cases}$$

$$\Rightarrow \omega^2 = \alpha\left(\frac{m+M}{mM}\right) \pm \alpha\left[\left(\frac{m+M}{mM}\right)^2 - \frac{2(1-\cos ka)}{mM}\right]^{1/2}$$



Orders of magnitude

- At optical frequencies, $k=\omega/c\sim10^7$.
- For typical crystal lattice, $\pi/a\sim10^{10}$.
- Only optical phonons couple to the light.

$$k \approx 0$$

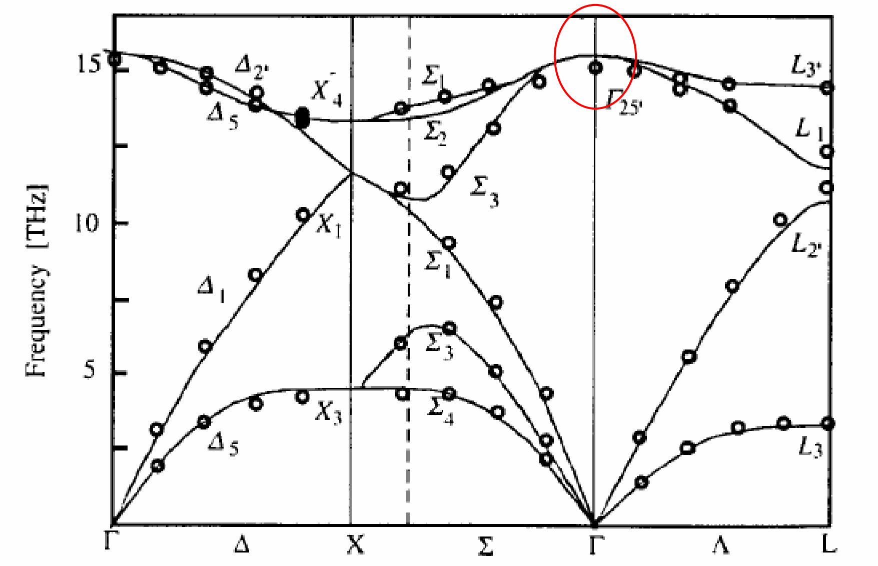
For optical branch:

$$\frac{\mathrm{u}}{\mathrm{v}} \approx -\frac{M}{m} \longrightarrow \text{Can generate the dipole moment}$$

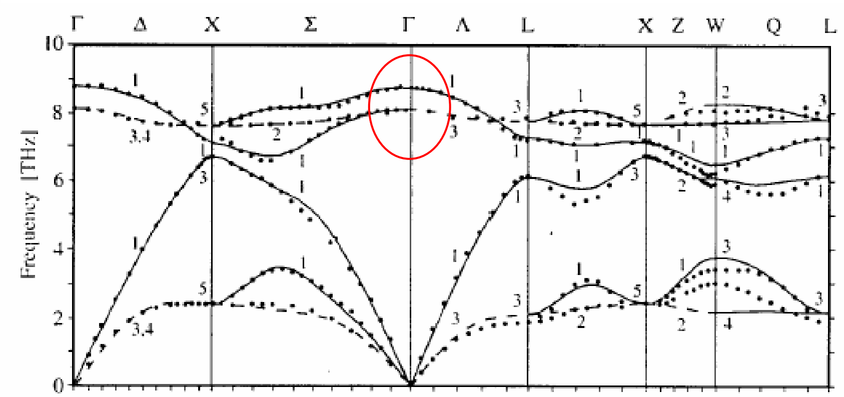
For acoustic branch:

$$\frac{\mathrm{u}}{\mathrm{v}} \approx 1$$

Examples of phonon dispersion curves



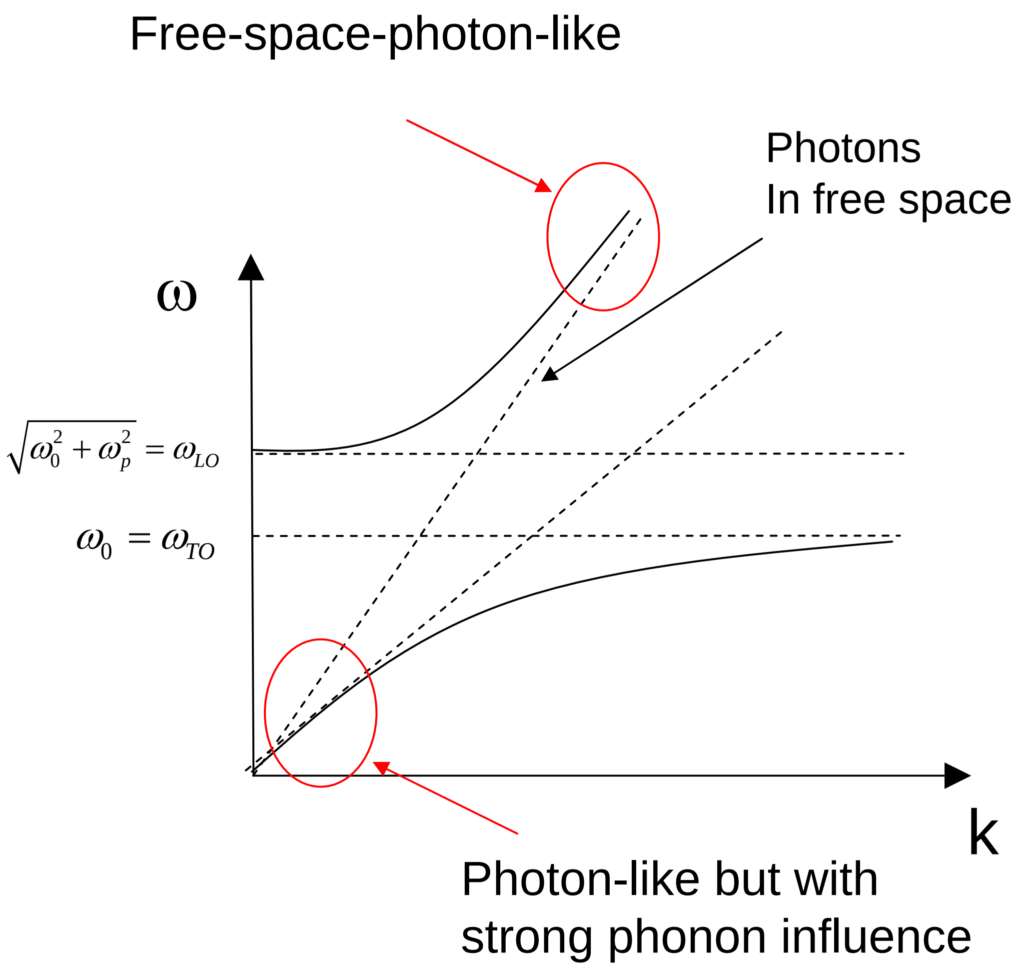
silicon



GaAs

Taken from P. Yu and M. Cardona.

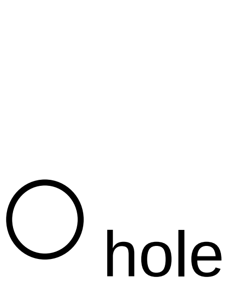
Dispersion curve for phonon polaritons



Raman processes

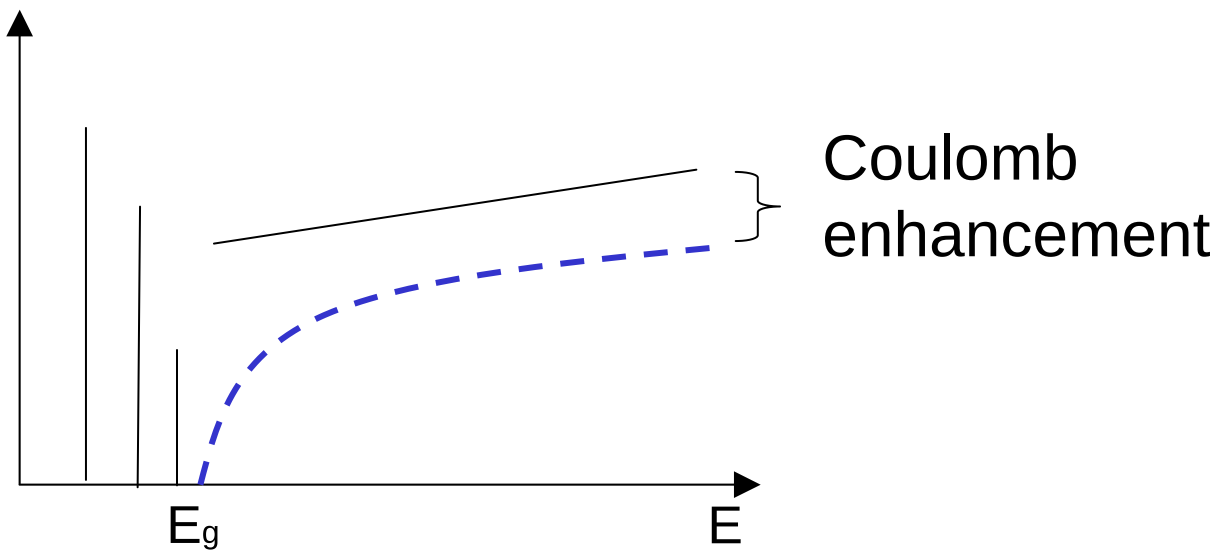
- When light is not at the infrared frequency, phonons can still participate in the inelastic processes with light → Raman processes.
- The scattered light has a frequency shift w.r.t to the incident light due to its energy lost (or gain) to phonons.
- Energy lost: Stokes process
  Energy gain: Anti-Stokes process

Excitons (two-level system)

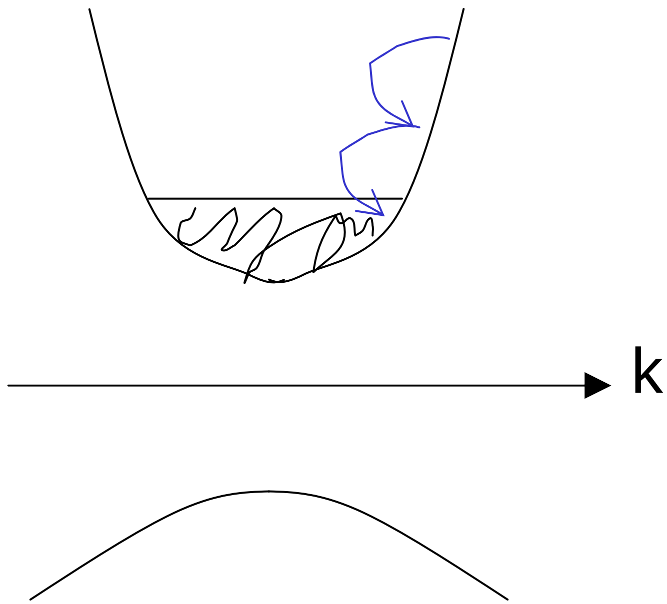


The Coulomb interaction b/w electron and hole makes the exciton. Exciton is like a hydrogen atom.

Exciton absorption



Hot carriers relaxation processes



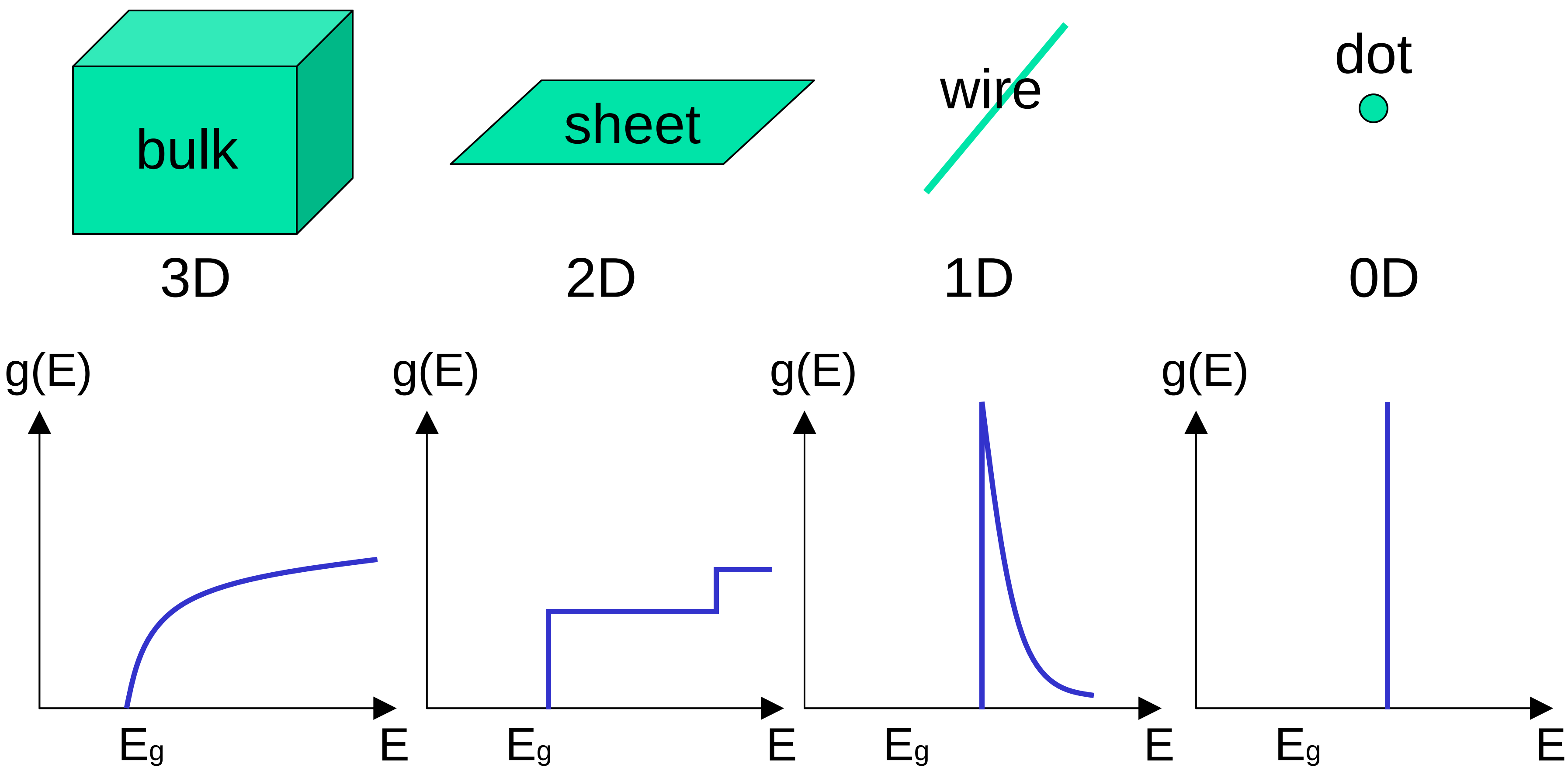
Carrier capture

Phase relaxation
Thermalization
} T_2~100fs - ps

Recombination (T_1~ns)

Size dependence (quantum confinement)

g(E) = Density of states

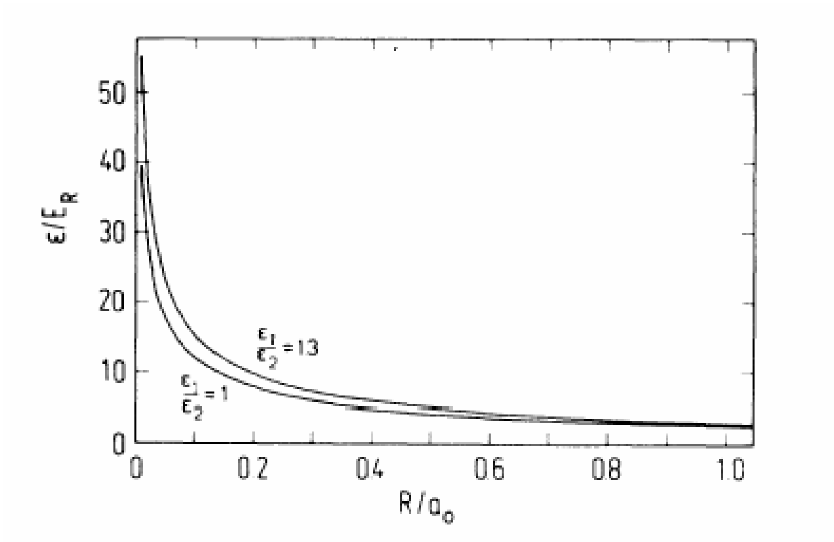


Exciton absorption in low-dim structures

Exciton binding energy:

2D: $$E^{2d}_{B,n=1} = 4E^{3d}_{B,n=1}$$

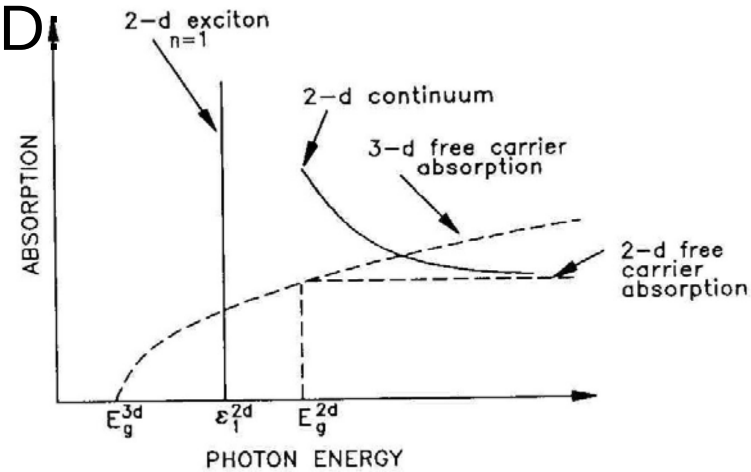
1D:



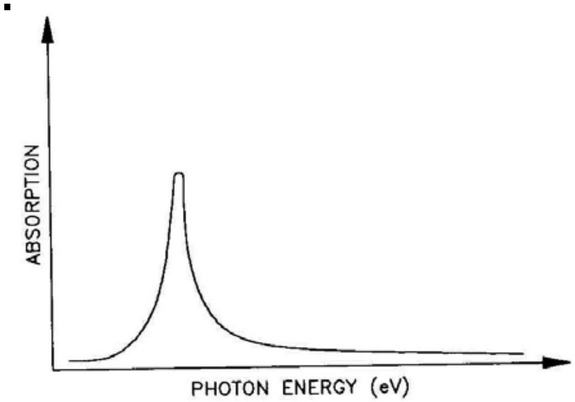
a0=exciton Bohr radius~100A

Exciton absorption:

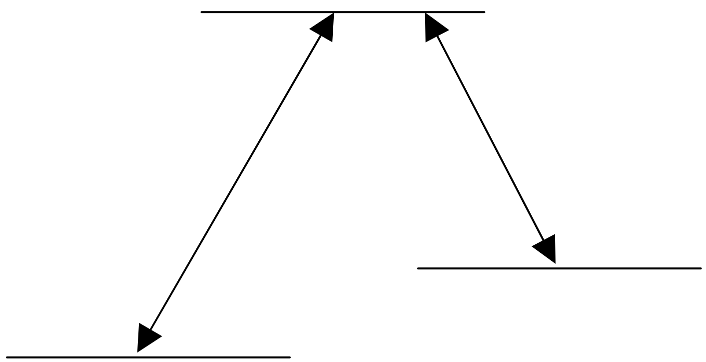
2D:



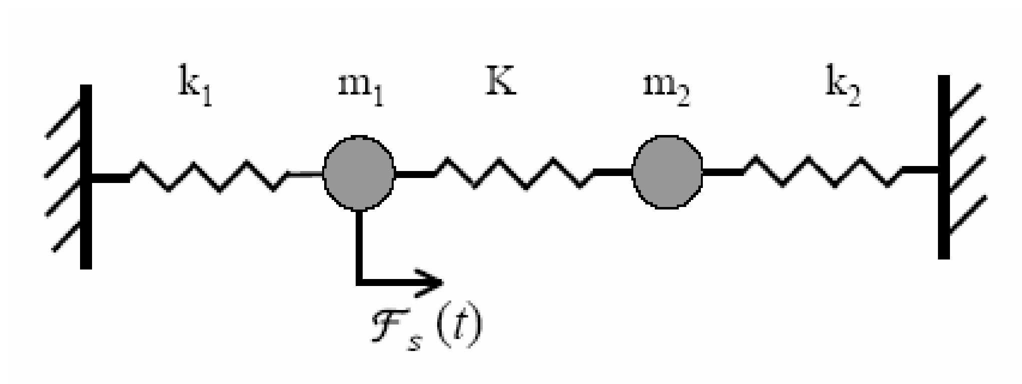
1D:



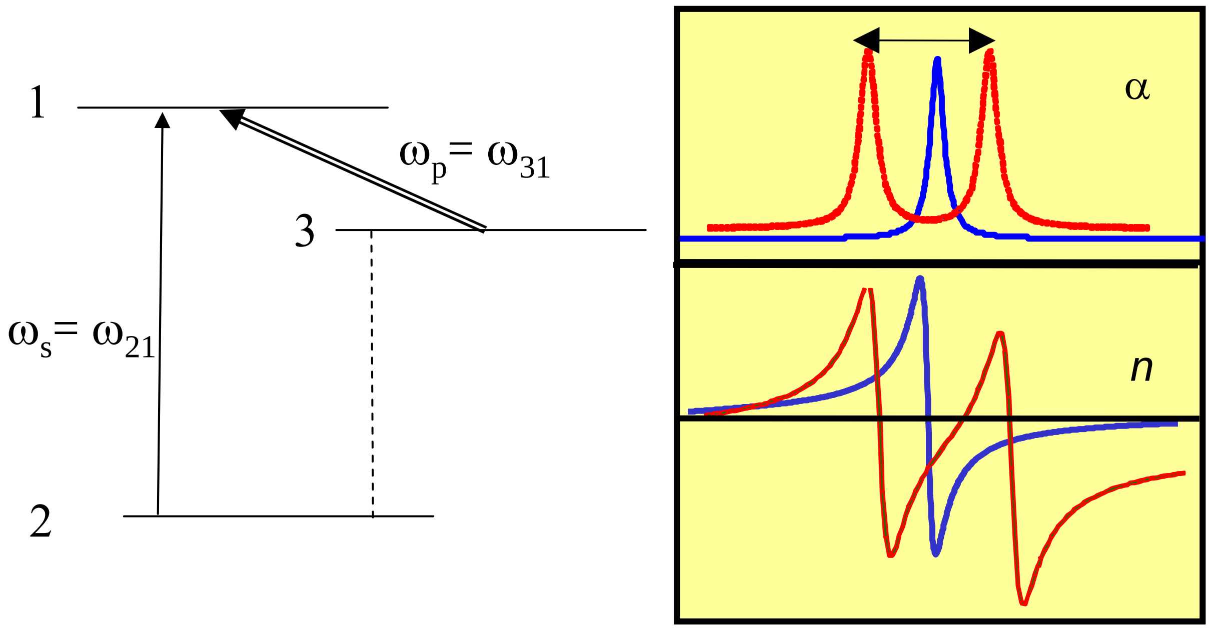
Excitons (three-level system)



If we consider the polariton corresponding to exciton 1:

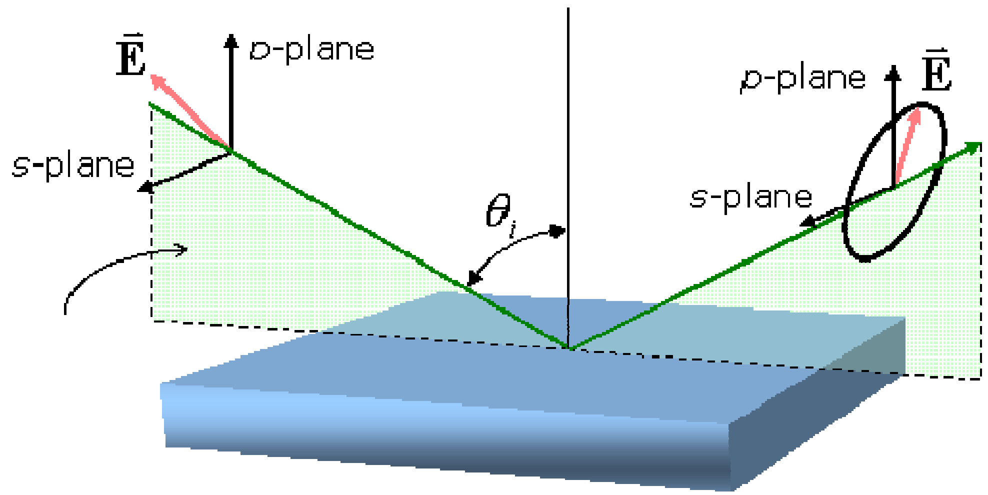


Electromagnetically induced transparency



Measurement of ε(r) - ellipsometry

ellipsometry



Sensitive to:

1. Film thickness
2. Surface roughness
3. Anisotropy

Need to know underlying composition of materials.