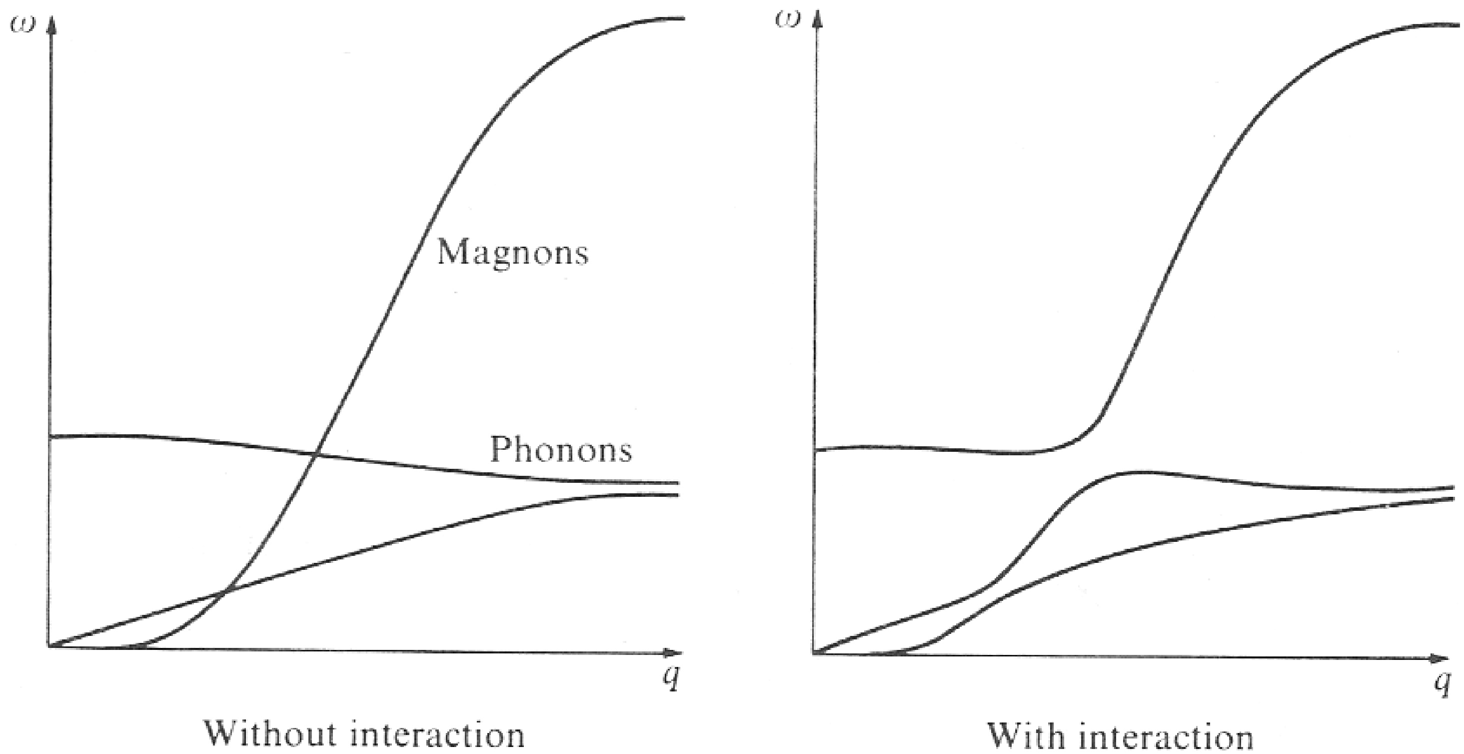
Fig. 5.7 Schematic magnon and phonon dispersion curves. The magnon curve has been compressed by a factor of order 10 for illustrative purposes.



From: *Solid State Theory*, Harrison

Longitudinal plasma waves

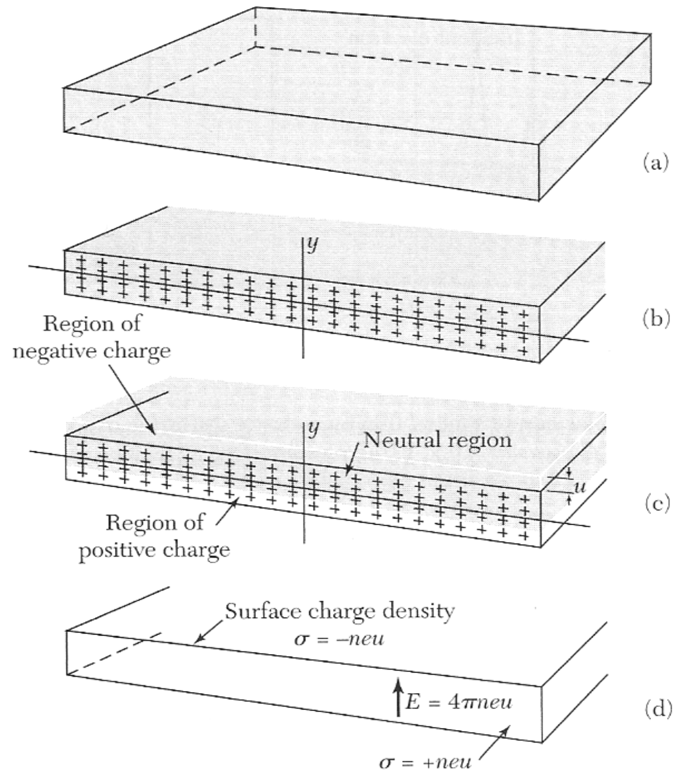
$$nm\frac{d^2y}{dt^2} = -neE$$

$$E = \frac{ney}{\varepsilon_0}$$

$$nm\frac{d^2y}{dt^2} = -\frac{n^2e^2y}{\varepsilon_0}$$

$$\frac{d^2y}{dt^2} + \omega_p^2 y = 0$$

Plasma frequency $$\omega_p = \sqrt{\frac{ne^2}{m\varepsilon_0}}$$

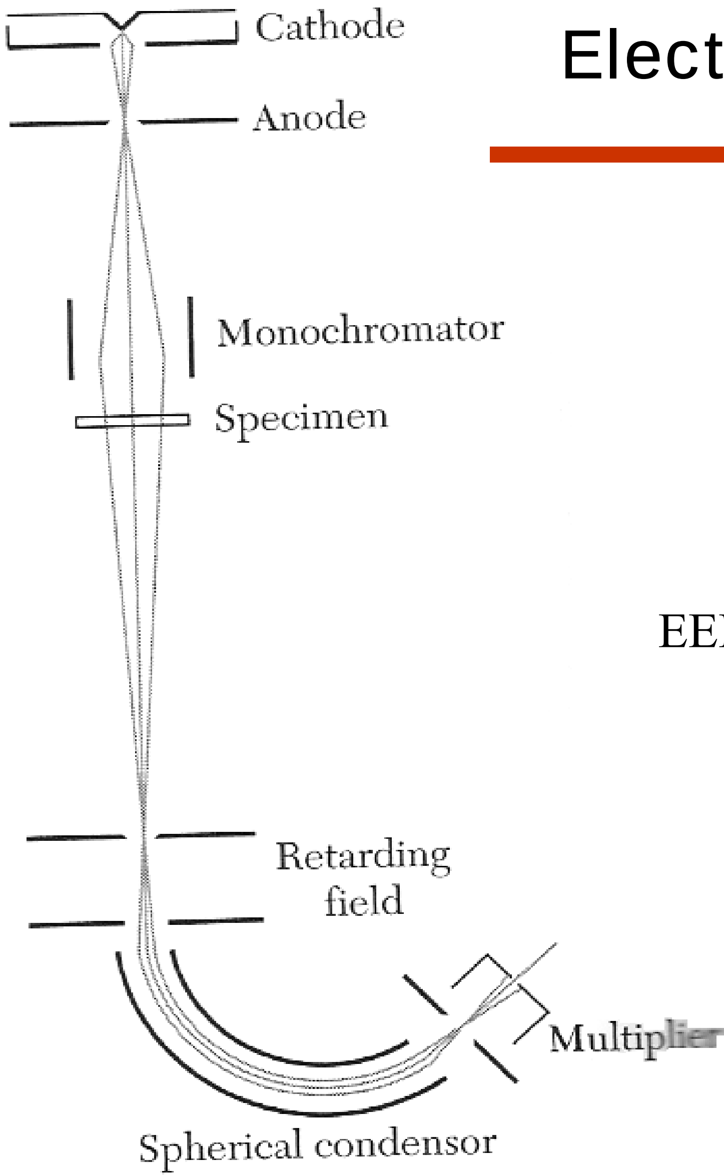


Kittel

There is no magnetic component of the wave.

Plasma waves can be quantized like any other wave

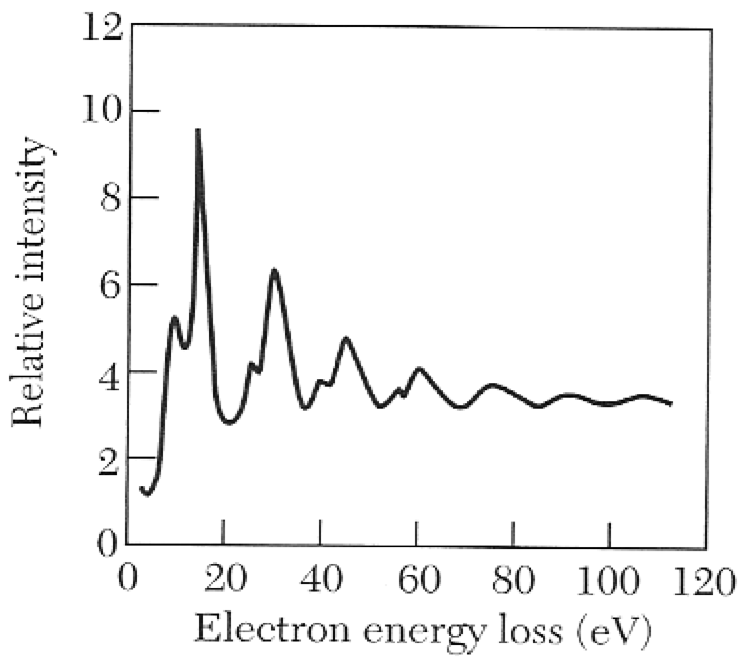
Electron energy loss spectroscopy



$$\Delta E = n\hbar\omega_p$$

EELS is often used to measure phonons

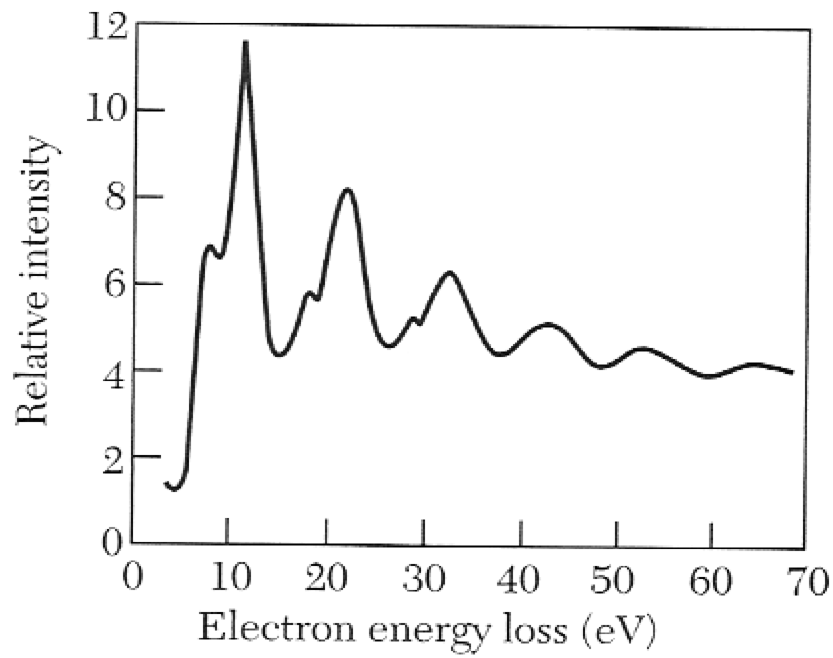
Electron energy loss spectroscopy



Aluminum

Plasmons 15.3 eV

Surface plasmons 10.3 eV



Magnesium

Plasmons 10.6 eV

Surface plasmons 7.1 eV

Transverse optical plasma waves

The dispersion relation for light

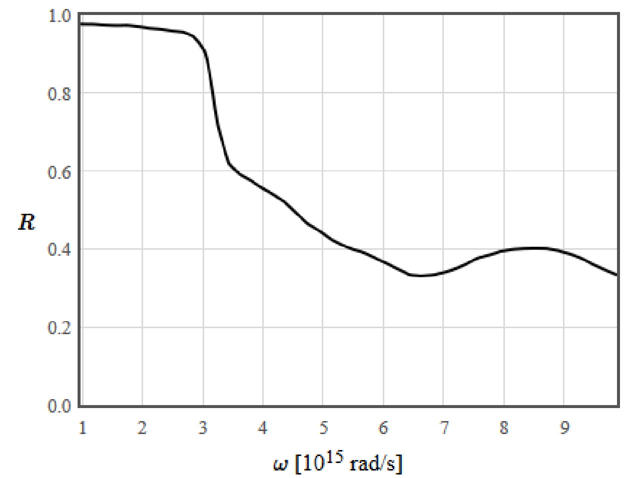
$$\varepsilon\varepsilon_0\mu_0\omega^2 = \frac{\varepsilon\omega^2}{c^2} = k^2$$

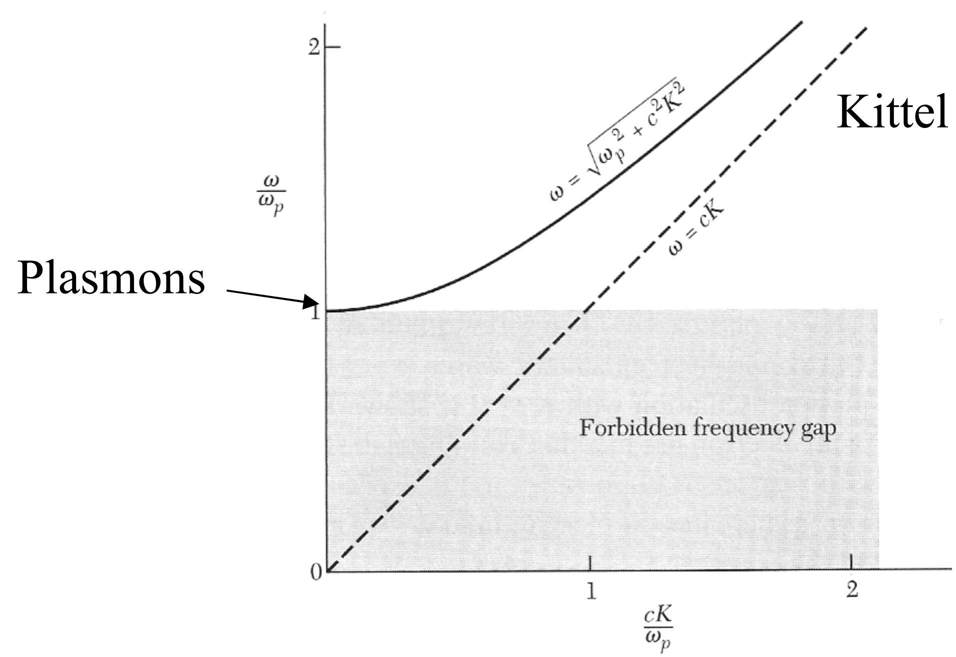
For a free electron gas

$$\varepsilon = 1 - \frac{\omega_p^2}{\omega^2}$$

$$\left(1 - \frac{\omega_p^2}{\omega^2}\right)\omega^2 = c^2k^2$$

$$\omega^2 = \omega_p^2 + c^2k^2$$

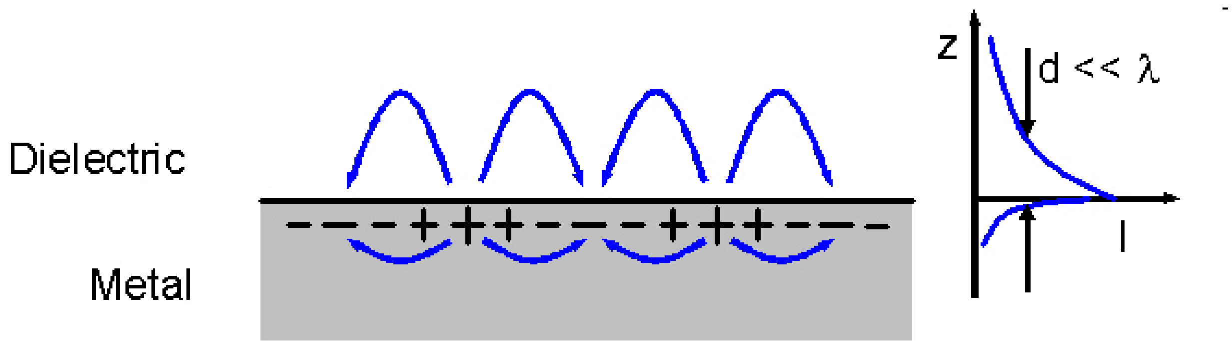




Surface Plasmons

Waves in the electron density at the boundary of two materials.

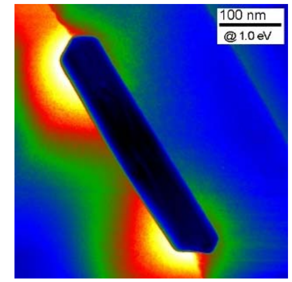
Surface plasmons have a lower frequency that bulk plasmons. This confines them to the interface.



Surface Plasmons

High-resolution surface plasmon imaging of gold nanoparticles by energy-filtered transmission electron microscopy

PHYSICAL REVIEW B 79, 041401 R 2009



Surface plasmons on nanoparticles are efficient at scattering light.

Green and blue require different sized particles.

Nature Photonics

LETTERS

Organic plasmon-emitting diode

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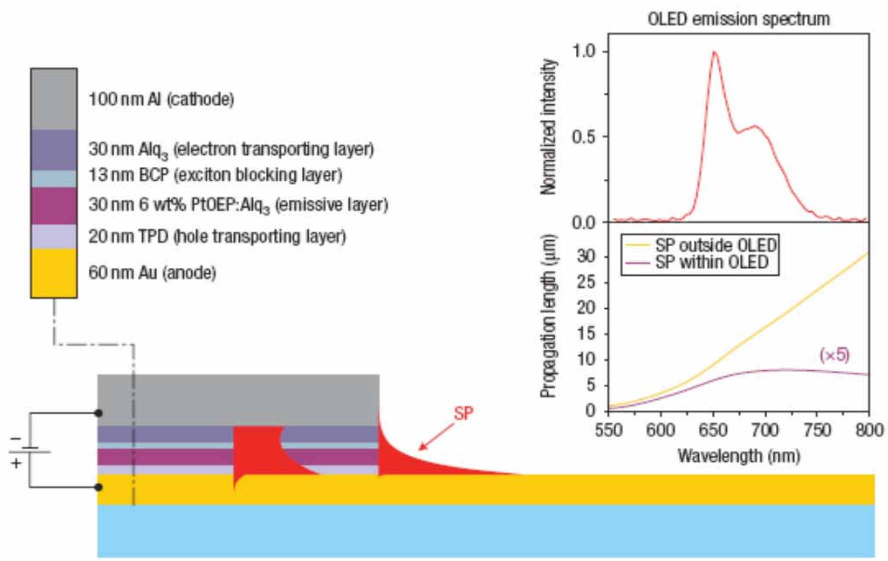
Published online: 28 September 2008; doi:10.1038/nphoton.2008.200

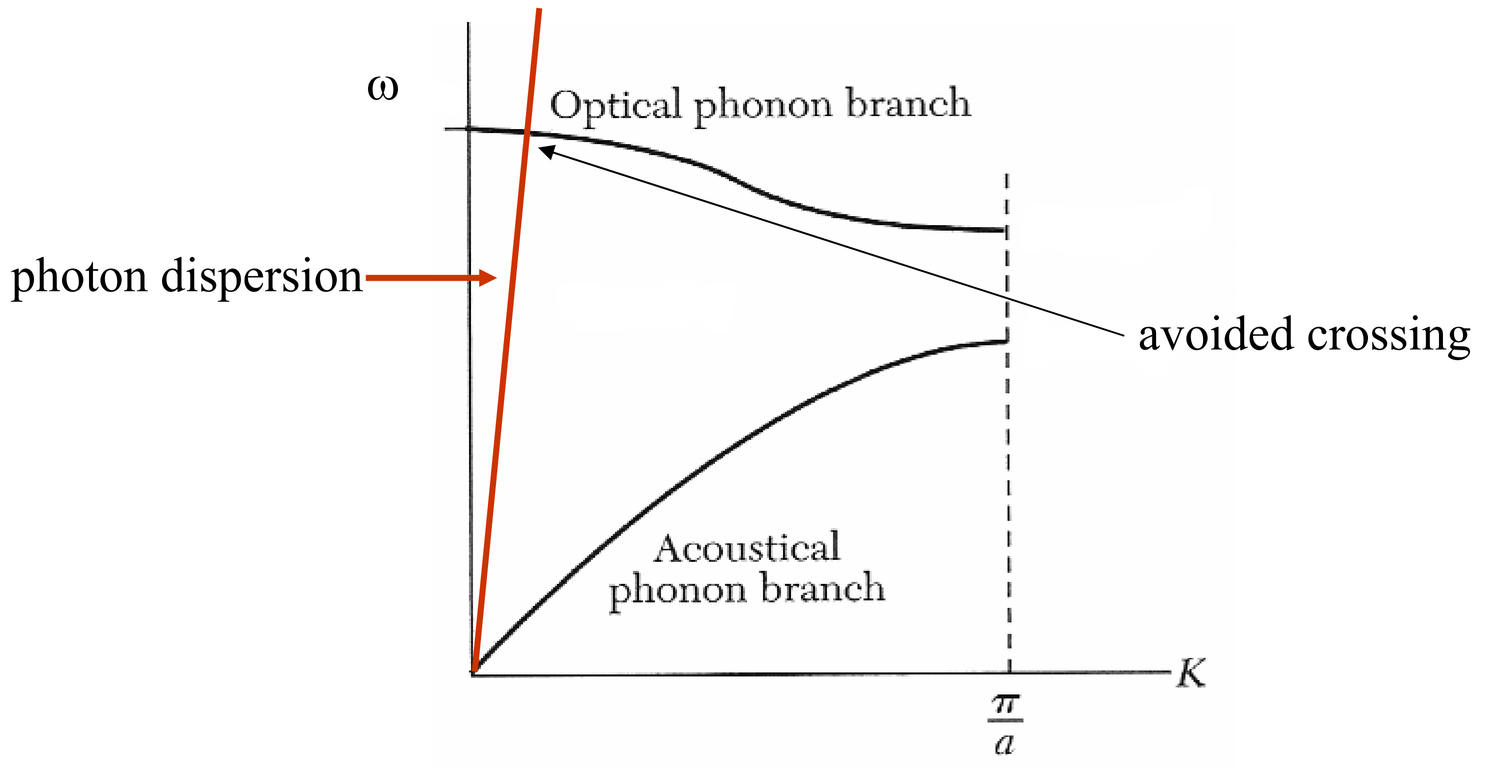
Surface plasmons are hybrid modes of longitudinal electron oscillations and light fields at the interface of a metal and a dielectric[1,2]. Driven by advances in nanofabrication, imaging and numerical methods[3,4], a wide range of plasmonic elements such as waveguides[5,6], Bragg mirrors[7], beamsplitters[8], optical modulators[9] and surface plasmon detectors[10] have recently been reported. For introducing dynamic functionality to plasmonics, the rapidly growing field of organic optoelectronics[11] holds strong promise due to its ease of fabrication and integration opportunities. Here, we introduce an electrically switchable



Surface plasmons are used for biosensors.

Polaritons

Transverse optical phonons will couple to photons with the same ω and *k*.



Light Bragg reflects off the sound wave; sound Bragg reflects off the light wave.

Polaritons

Newton: $$m\frac{d^2x}{dt^2} = -eE - Cx$$

Optical phonons are modelled by a 1-D mass-spring system.

$$\omega_T = \sqrt{\frac{C}{m}}$$

polarization: $$P = -Nex$$

$$\frac{\omega^2 mP}{Ne} = -eE + \frac{m\omega_T^2 P}{Ne}$$

$$-\omega^2 P + \omega_T^2 P = \frac{Ne^2 E}{m}$$

Component of E-field parallel to mass-spring motion.

$$k^2 E = \mu_0 \omega^2 \left(\varepsilon_0 E + P\right)$$

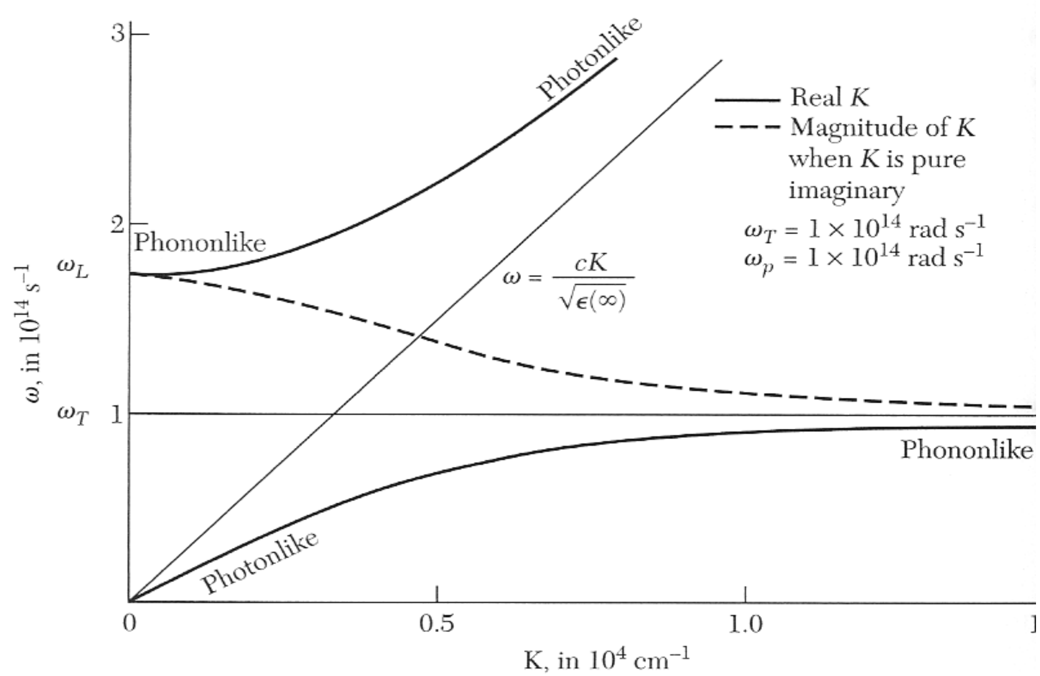
$$\begin{vmatrix} \mu_0\varepsilon_0\omega^2 - k^2 & \mu_0\omega^2 \\ Ne^2/m & \omega^2 - \omega_T^2 \end{vmatrix} = 0$$

Polaritons

$$-\omega^2 P + \omega_T^2 P = \frac{Ne^2 E}{m}$$

$$k^2 E = \mu_0 \omega^2 \left(\varepsilon_0 E + P \right)$$

$$\begin{vmatrix} \mu_0 \varepsilon_0 \omega^2 - k^2 & \mu_0 \omega^2 \\ Ne^2 / m & \omega^2 - \omega_T^2 \end{vmatrix} = 0$$

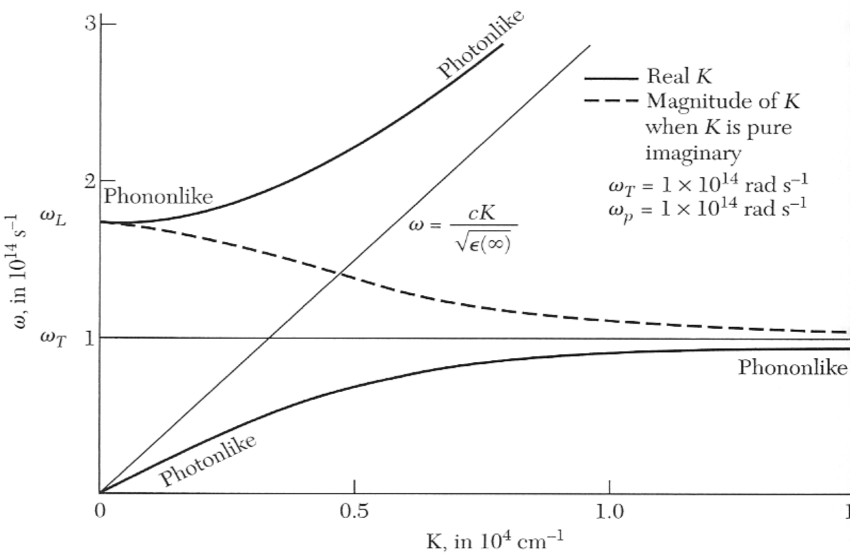


There are two solutions for every k, one for the upper branch and one for the lower branch.

A gap exists in frequency.

Polaritons are the normal modes near the avoided crossing.

Polaritons allow us to study the properties of phonons using optical measurements



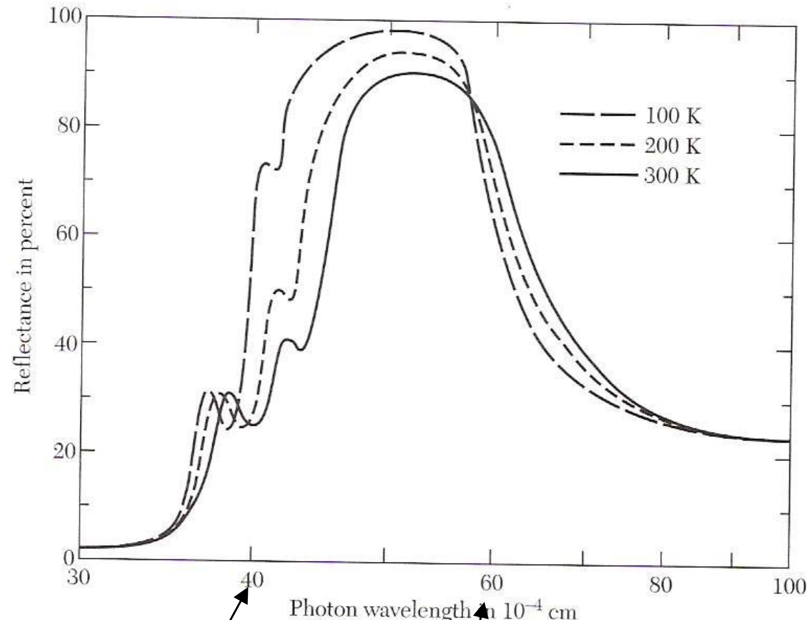


Figure 15 Reflectance of a crystal of NaCl at several temperatures, versus wavelength. The nominal values of ω_L and ω_T at room temperature correspond to wavelengths of 38 and 61 × 10^{-4} cm, respectively. (After A. Mitsuishi et al.)

ω = 4.7E13

ω = 3.1E13

Kittel

By looking at the reflectance in different crystal directions, you can determine the frequencies of the transverse optical phonons.

Polaritons and optical properties

Print version

Advanced Solid State Physics

Optical properties of insulators and semiconductors

In an insulator, all charges are bound. By applying an electric field, the electrons and ions can be pulled out of their equilibrium positions. When this electric field is turned off, the charges oscillate as they return to their equilibrium positions. A simple model for an insulator can be constructed by describing the motion of the charge as a damped mass-spring system. The differential equation that describes the motion of a charge is,

$$m\frac{d^2x}{dt^2}+b\frac{dx}{dt}+kx=-qE.$$

Rewriting above equation using $\omega_0=\sqrt{\frac{k}{m}}$ and the damping constant $\gamma=\frac{b}{m}$ yields,

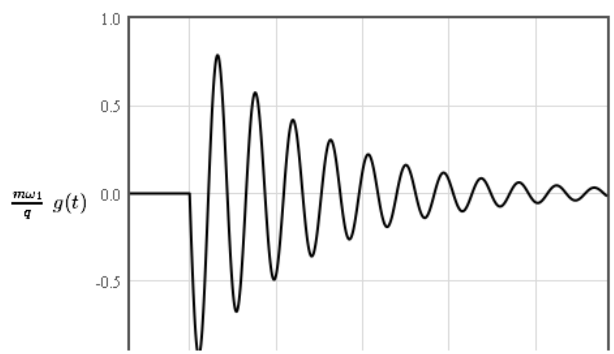
$$\frac{d^2x}{dt^2}+\gamma\frac{dx}{dt}+\omega_0^2x=-\frac{qE}{m}.$$

If the electric field is pulsed on, the response of the charges is described by the **impulse response function** $g(t)$. The impulse response function satisfies the equation,

$$\frac{d^2g}{dt^2}+\gamma\frac{dg}{dt}+\omega_0^2g=-\frac{q}{m}\delta(t).$$

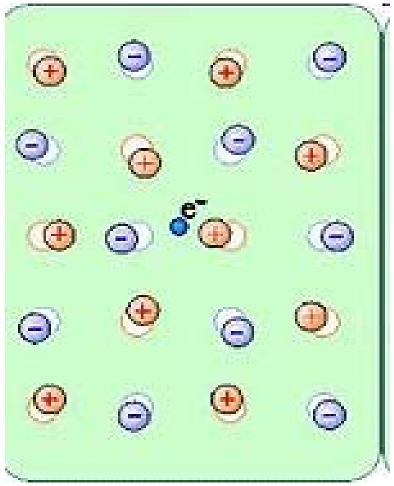
The solution to this equation is zero before the electric field is pulsed on and at the time of the pulse the charges suddenly start oscillating with the frequency $\omega_1=\sqrt{\omega_0^2-\frac{\gamma^2}{4}}$. The amplitude of the oscillation decays exponentially to zero in a characteristic time $\frac{2}{\gamma}$.

$$g(t)=-\frac{q}{m\omega_1}\exp\left(-\frac{\gamma}{2}t\right)\sin(\omega_1 t).$$



Polarons

A polaron is a quasiparticle consisting of an electron and an ionic polarization field. The electron density is low so the screening by electrons can be neglected.

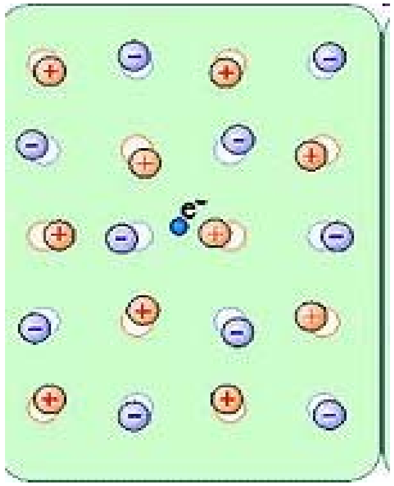


Electronic charge is partially screened by lattice ions. This is a charge - phonon coupling.

Large polaron (Fröhlich polaron)

The spatial extent of the polaron is much larger than the lattice constant.

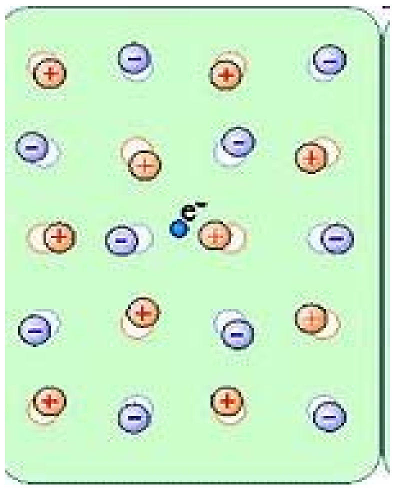
Large polarons typically form bands.



Electrons move in bands with a large effective mass (432 m_e for NaCl)

Small polaron (Holstein polaron)

For a small polaron, the polarization is about the size of the lattice contant.



Small polaron - Holstein Hamiltonian - electrons are localized and hop (thermally activated or tunneling). Small polarons often form in organic material. In soft materials the energy for making a distortion is smaller.

Bipolarons

Two polarons can bind together to form a bipolaron (a quasiparticle).

Elastic strain energy is reduced by sharing the polarization field.

Bipolarons have integral spin -> they are bosons.

It is possible that the condensation of bipolarons into the same ground state could lead to superconductivity.

Bipolarons

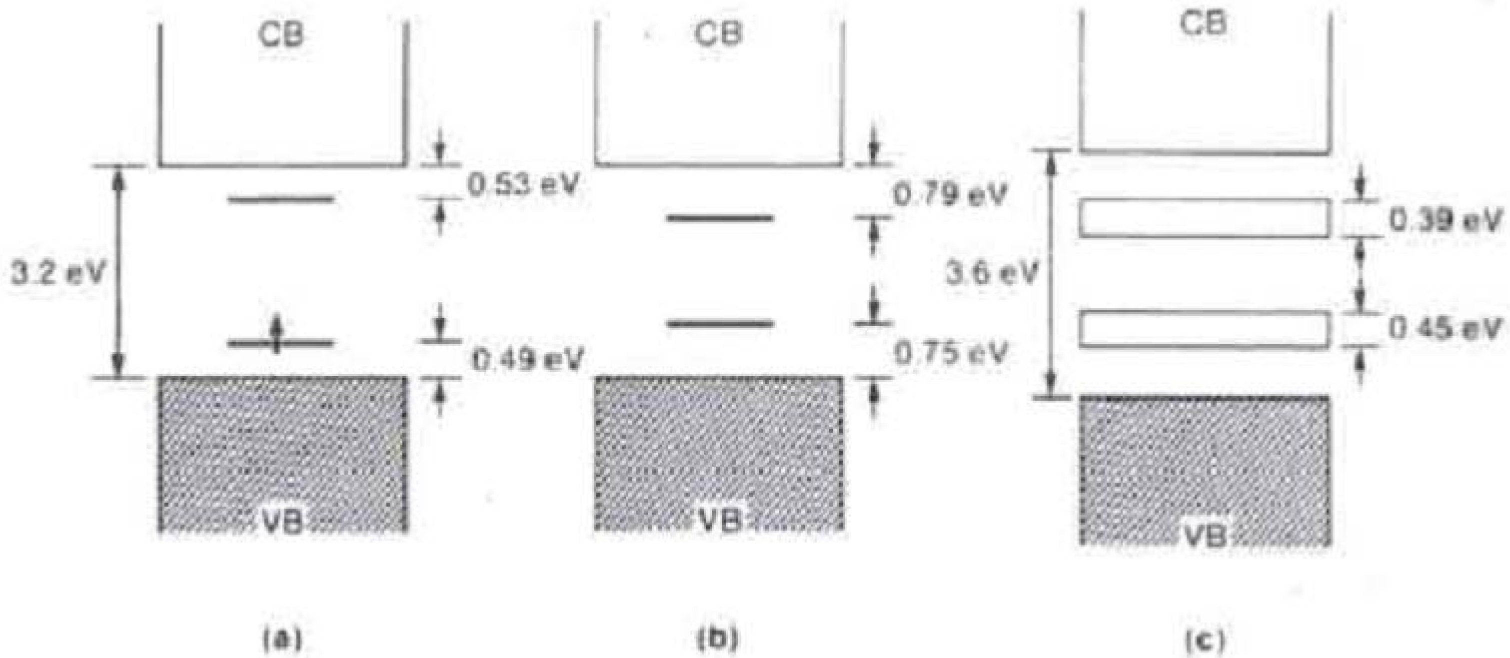


Figure 10. Evolution of the polypyrrole band structure upon doping: (a) low doping level, polaron formation; (b) moderate doping level, bipolaron formation; (c) high (33 mol %) doping level, formation of bipolaron bands.

J. L. Breda and G. B. Street, Acc. Chem. Res. 1985, 18, 309-315.