How about semiconductor?

Electrical conductivity and Ohm's law

equation of motion
Newton's law

$$m\frac{d\mathbf{v}}{dt} = \hbar\frac{d\mathbf{k}}{dt} = -e\mathbf{E}$$

$$\frac{d\mathbf{p}(t)}{dt} = -\frac{\mathbf{p}(t)}{\tau} + \mathbf{f}(t) = 0$$
$$\mathbf{p} = \mathbf{f}\tau = -e\mathbf{E}\tau$$

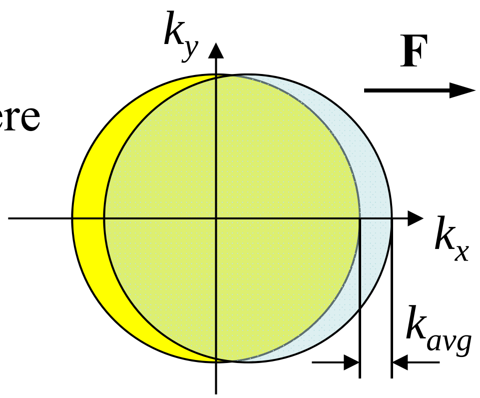
in the absence of collisions the Fermi sphere in k-space is displaced as a whole at a uniform rate by a constant applied electric field

$$\mathbf{k}(t) - \mathbf{k}(0) = -\frac{e\mathbf{E}}{\hbar}t$$

because of collisions the displaced Fermi sphere is maintained in a steady state in an electric field

$$\mathbf{k}_{avg} = -\frac{e\mathbf{E}}{\hbar}\tau$$

Fermi sphere



$$\mathbf{v}_{avg} = \frac{\hbar\mathbf{k}_{avg}}{m} = -\frac{e\mathbf{E}}{m}\tau$$

$$\mathbf{j} = -ne\mathbf{v}_{avg}$$

Ohm's law

$$\mathbf{j} = \left(\frac{ne^2\tau}{m}\right)\mathbf{E}$$

$$\sigma = \frac{ne^2\tau}{m}$$

$$\rho = \frac{1}{\sigma} = \frac{m}{ne^2\tau}$$

$$\mathbf{v}_{avg} = \frac{\hbar\mathbf{k}_{avg}}{m} = -\frac{e\mathbf{E}}{m}\tau$$

Define μ=eτ/m as mobility

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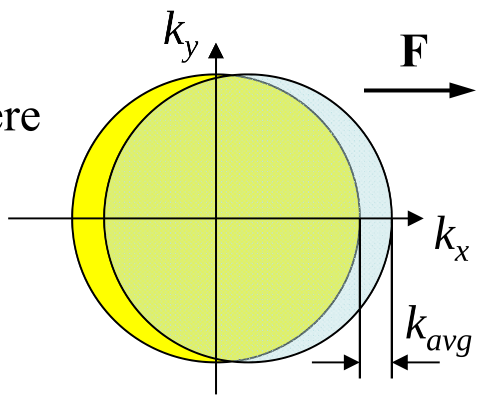

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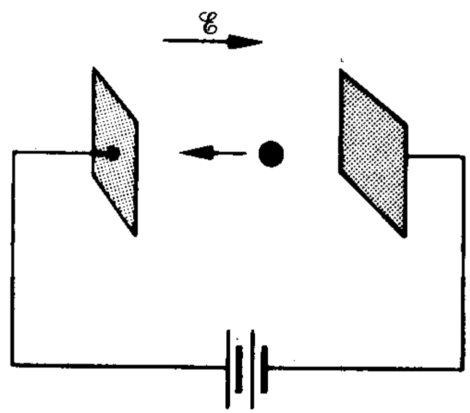
Define μ=eτ/m as mobility

$\mu = e\tau/m$

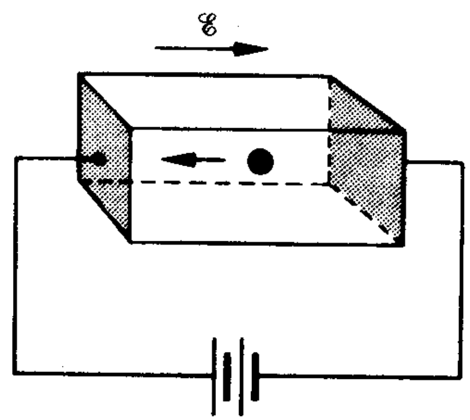
Electrons as Moving Particles

In vacuum



$$F = (-q)\mathbf{E} = m_o a$$

In semiconductor



$$F = (-q)\mathbf{E} = m_n{}^* a$$

where $m_n{}^*$ is the ***conductivity effective mass***

Conductivity Effective Mass, *m**

Under the influence of an electric field (E-field), an electron or a hole is accelerated:

$$a = \frac{-q\mathcal{E}}{m_n^*} \quad \text{electrons}$$

$$a = \frac{q\mathcal{E}}{m_p^*} \quad \text{holes}$$

Electron and hole conductivity effective masses

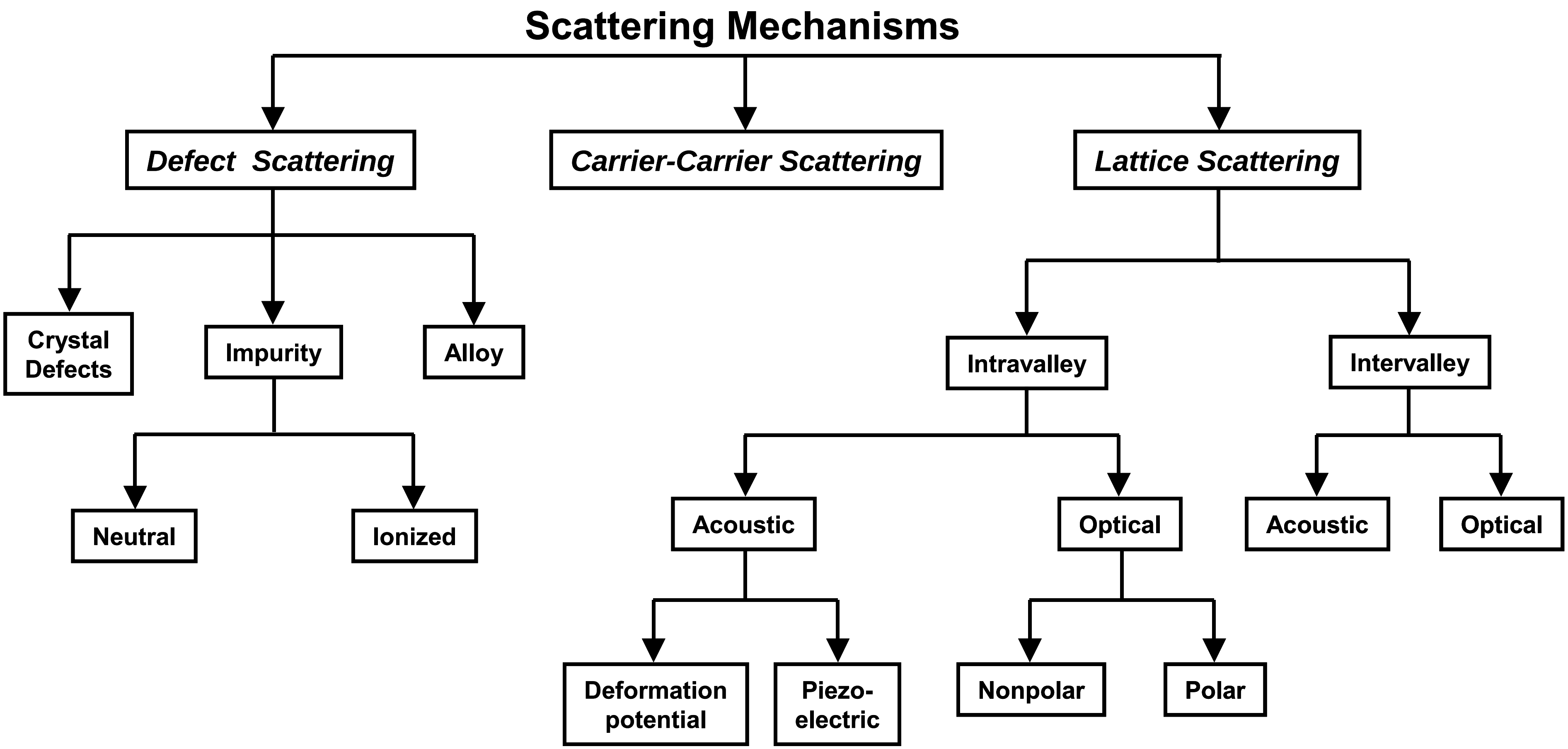
	Si	Ge	GaAs
m_n^*/m_o	**0.26**	0.12	0.068
m_p^*/m_o	**0.39**	0.30	0.50

$m_o = 9.1\times10^{-31}$ **kg**

Carrier Scattering

- Mobile electrons and atoms in the Si lattice are always in random thermal motion.
  - Electrons make frequent collisions with the vibrating atoms
    "lattice scattering" or **"phonon scattering"** – increases with increasing T

- Other scattering mechanisms:
  - deflection by ionized impurity atoms
  - deflection due to Coulombic force between carriers
    "carrier-carrier scattering" – only significant at high carrier concentrations


Scattering Mechanisms
Defect Scattering
Carrier-Carrier Scattering
Lattice Scattering
Crystal Defects
Impurity
Alloy
Intravalley
Intervalley
Neutral
Ionized
Acoustic
Optical
Acoustic
Optical
Deformation potential
Piezo-electric
Nonpolar
Polar

Mechanisms of Carrier Scattering

Dominant scattering mechanisms:

1. Phonon scattering (lattice scattering)
2. Impurity (dopant) ion scattering

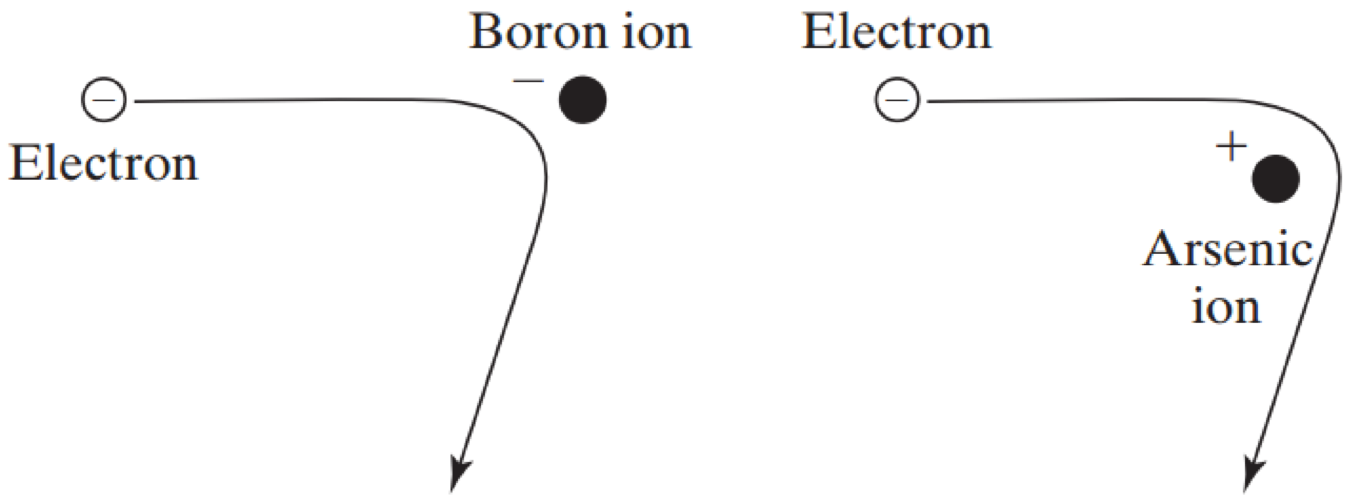
Phonon scattering limited mobility decreases with increasing *T*:

$$\mu_{phonon} \propto \tau_{phonon} \propto \frac{1}{\text{phonon density} \times \text{carrier thermal velocity}} \propto \frac{1}{T \times T^{1/2}} \propto T^{-3/2}$$

$$\mu = q\tau / m$$

$$v_{th} \propto \sqrt{T}$$

Impurity Ion Scattering



There is less change in the electron's direction if the electron travels by the ion at a higher speed.

Ion scattering limited mobility increases **with increasing *T*:**

$$\mu_{impurity} \propto \frac{v_{th}^{3}}{N_A + N_D} \propto \frac{T^{3/2}}{N_A + N_D}$$

Matthiessen's Rule

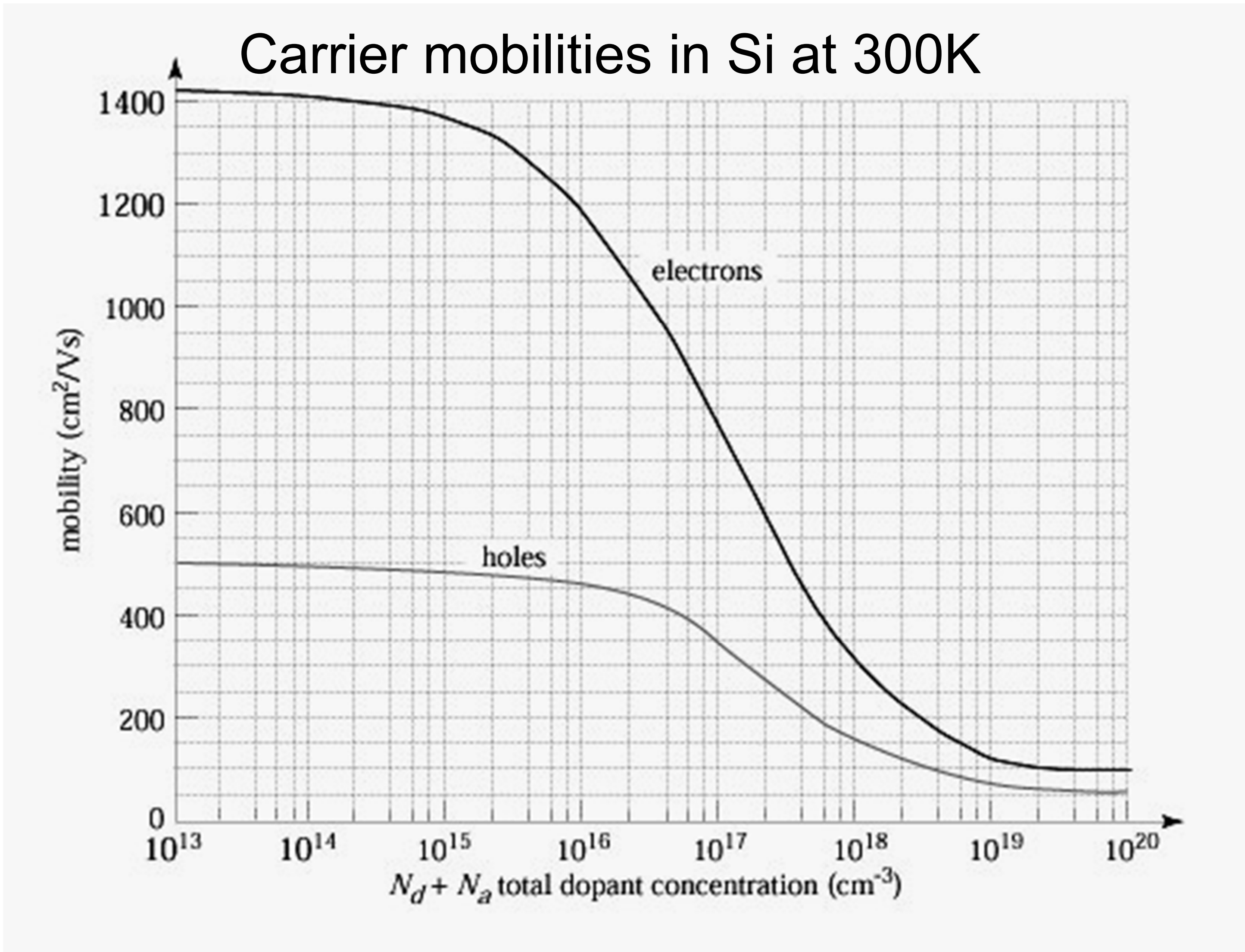
- The probability that a carrier will be scattered by mechanism *i* within a time period *dt* is dt/τ_i

  t_i ≡ mean time between scattering events due to mechanism *i*

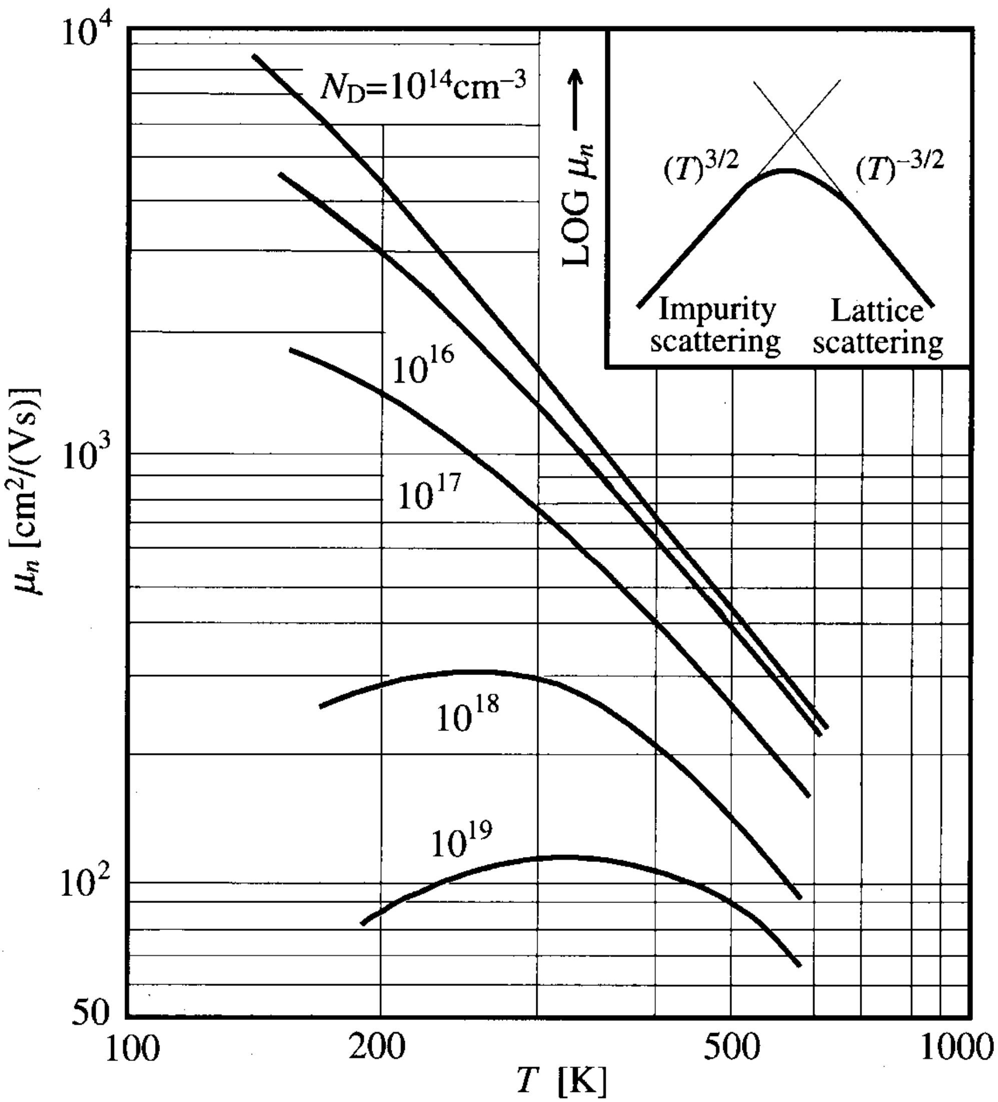
→ Probability that a carrier will be scattered by any mechanism within a time period *dt* is $\sum_i dt/\tau_i$

$$\boxed{\frac{1}{\tau} = \frac{1}{\tau_{phonon}} + \frac{1}{\tau_{impurity}} \quad \Rightarrow \quad \frac{1}{\mu} = \frac{1}{\mu_{phonon}} + \frac{1}{\mu_{impurity}}}$$

Mobility Dependence on Doping



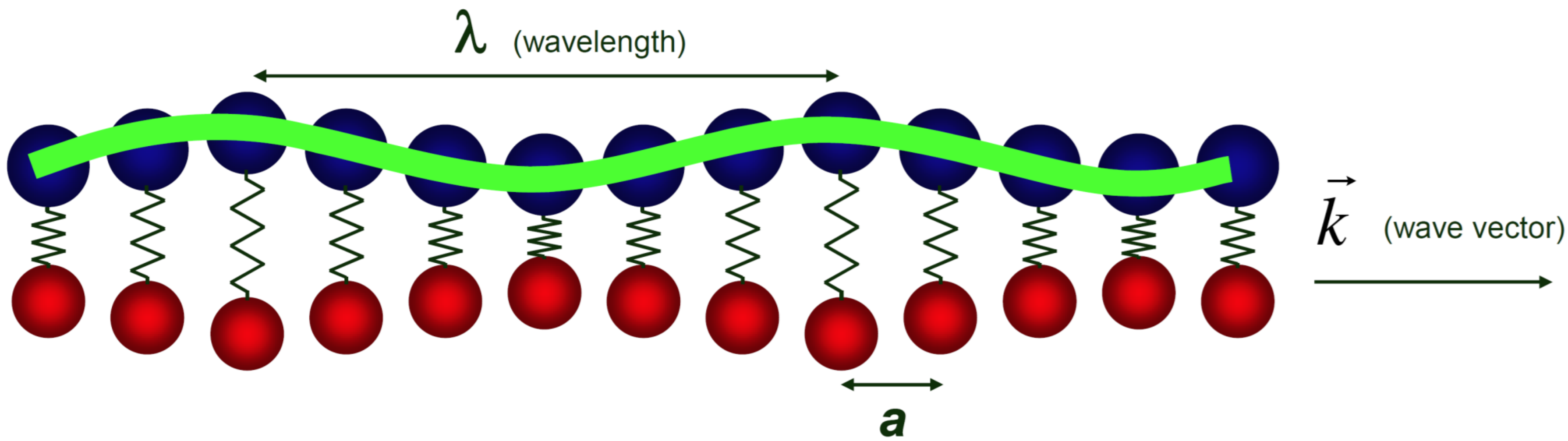
Mobility Dependence on Temperature



$$\frac{1}{\mu} = \frac{1}{\mu_{phonon}} + \frac{1}{\mu_{impurity}}$$

Phonon

Vibrations and phonons ...

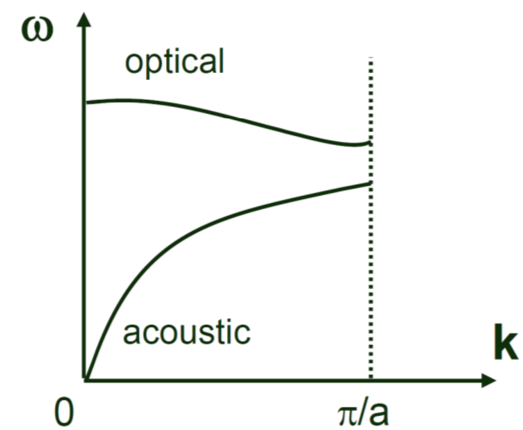


A vibrational wave can be described by a *quasi*-particle: **A phonon**

(in analogy with a photon for an electromagnetic wave)

$$\omega = \omega(k)$$

(Phonon dispersion)

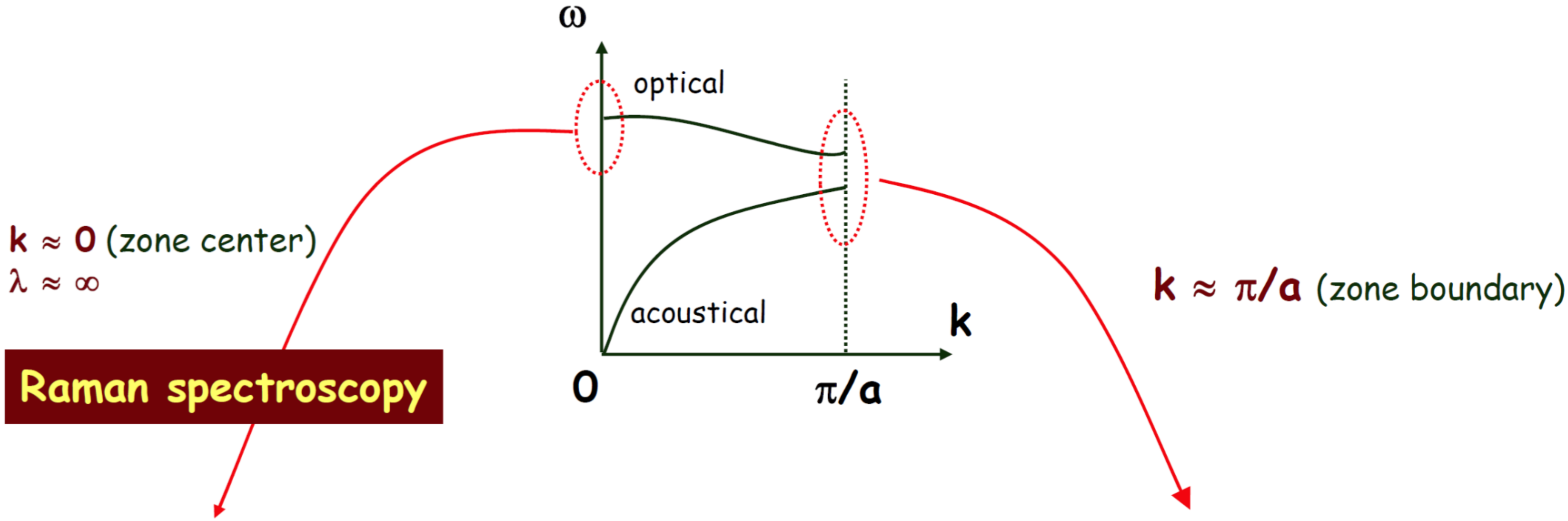


Dispersion curve

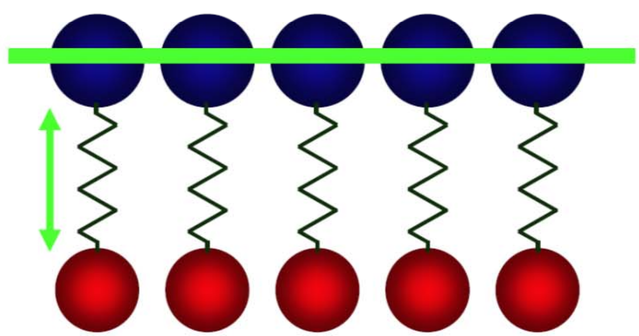
Phonons and Raman spectroscopy

- Optical photons: small wave-vector
- Wave-vector conservation

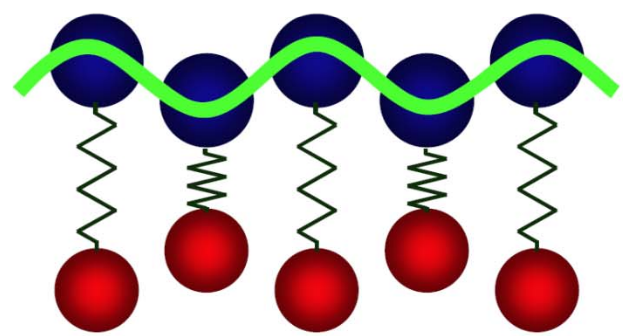
➔ Raman phonons: very small momentum transfer



all unit cell vibrate in phase



all unit cells vibrate in anti-phase



Raman scattering, a bit of history ...

1923 Theoretical prediction by the Austrian physicist A.Smekal

"The quantum theory of dispersion" (*Naturwissenschaften* **11**, p. 873, 1923)

1928 Experimental discovery

- by the Indians C.V. Raman and K.S. Krishnan in Kalkutta

"The optical analog of the Compton effect" (*Nature* **121**, p.711, 1928)

- by the Russians G. Landsberg et L. Mandelstam à Moscou

"A novel effect of light scattering in crystals" (*Naturwissenschaften* **16**, p.557, 1928)

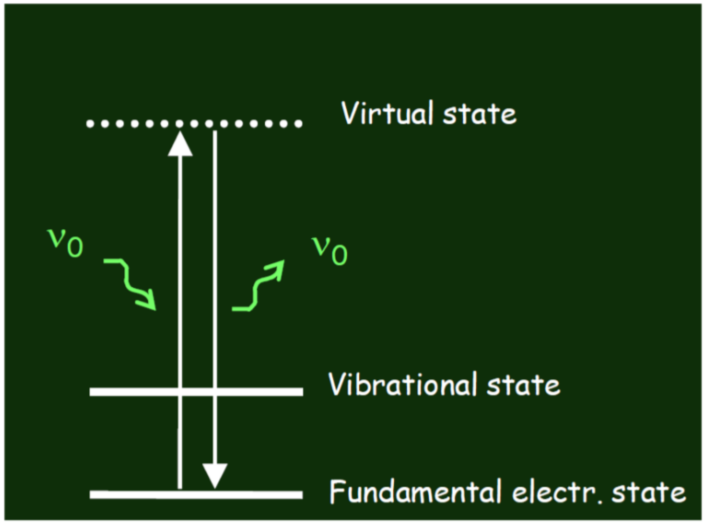
1930 Nobel price: Sir C.V. Raman (* 1888, † 1970)

"… for is work on light scattering and the discovery of the later called Raman effect ..."

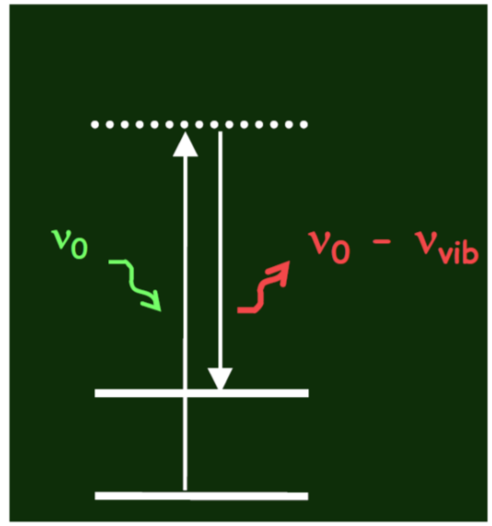
≈ 10.000 published articles using Raman scattering in the year 2011 [source WoS]

Energy transfer model ...

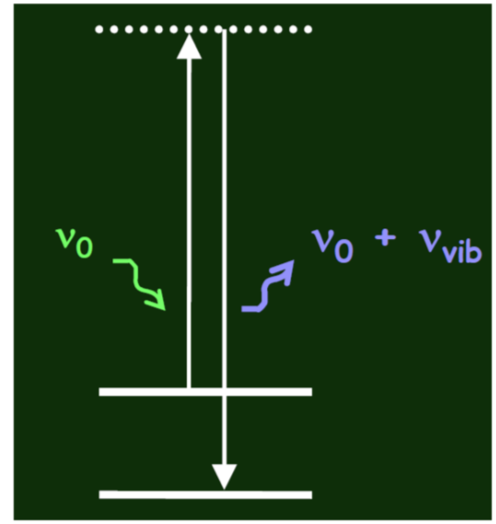
Raleigh scattering (elastic)

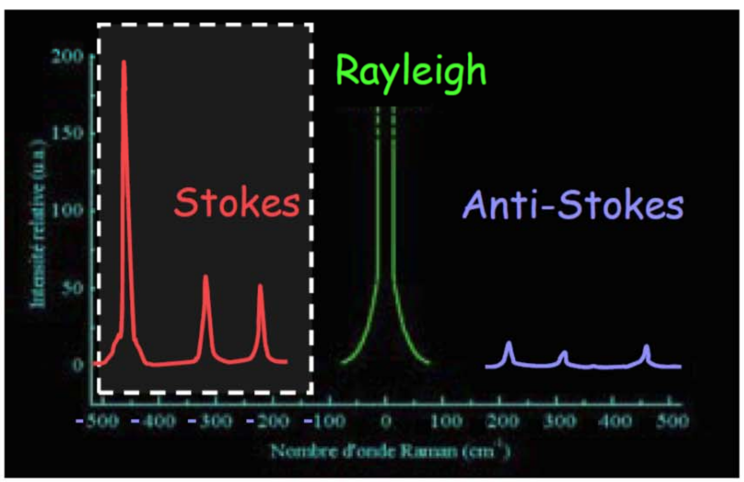


Stokes Scattering



Anti-Stokes scattering





optical mode → Raman scattering

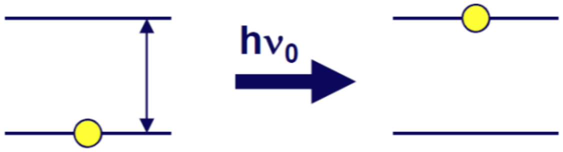
acoustic mode → Brillouin scattering

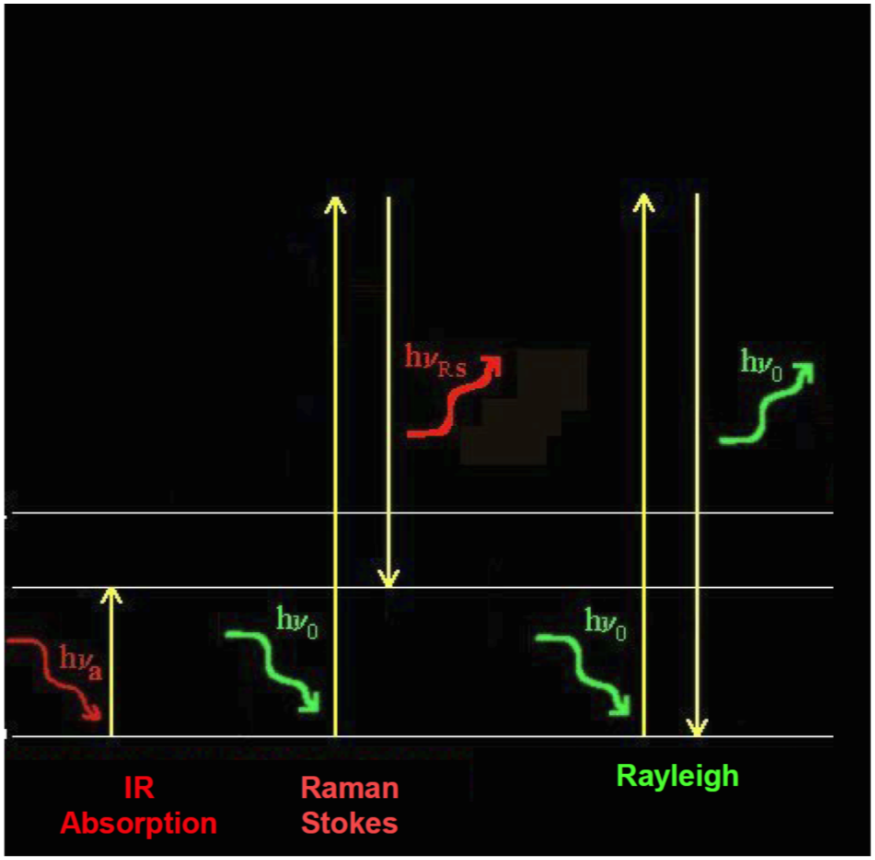
In principle, we can also study:

- rotational states
- magnetic states (→ magnons)
- electronic states (→ polarons)
- magneto-electric states (→ electromagnons)
- etc ...

Raman scattering $\leftrightarrow$ Infrared absorption

Infrared absorption spectroscopy

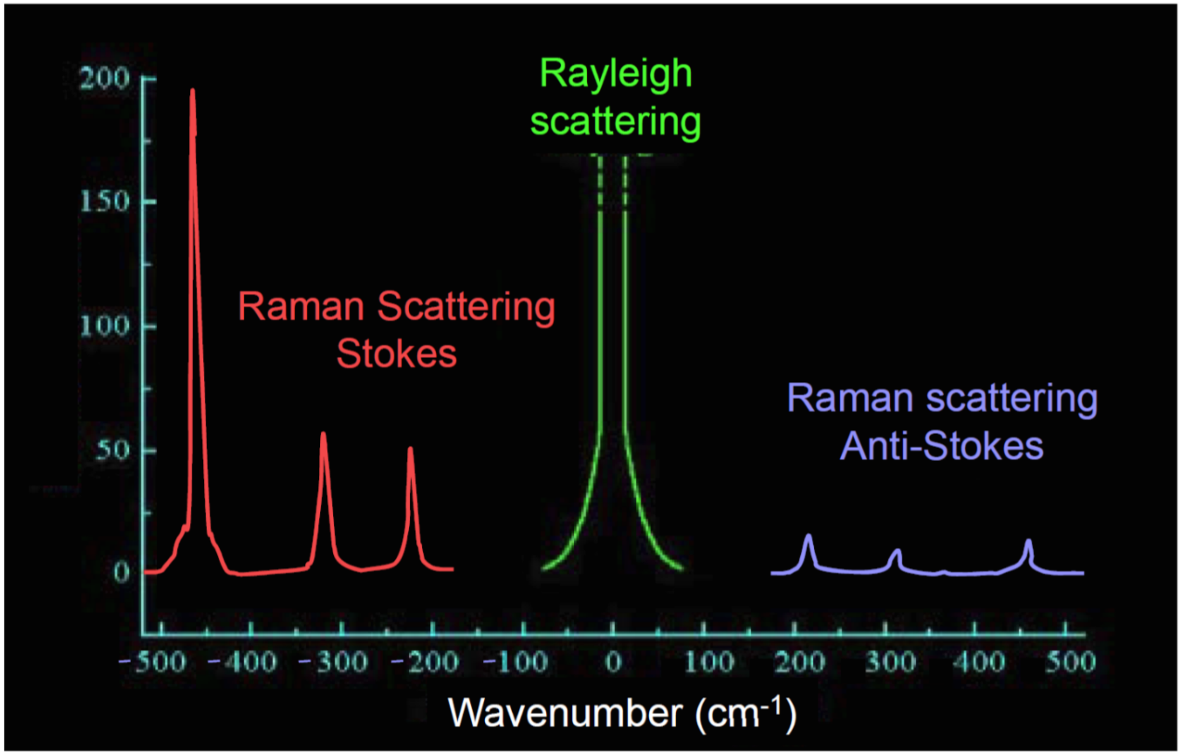




IR absorption and Raman scattering are both vibrational spectroscopies

but involve different interactions (and thus selection rules)

Example of a Raman spectrum



The unit of « spectroscopists », the wavenumber (cm^{-1}):

$$\tilde{\nu} = \frac{1}{\lambda} = \frac{\nu}{c}$$

Conversions: 1 meV= 8.051 cm^{-1} 1 THz = 33 cm^{-1} 1THz = 4.136 meV