Lecture contents

- Other scattering mechanisms
  - Piezoelectric
  - Optical non-polar phonons
  - Optical polar phonons
  - Ionized impurities
  - Neutral impurities
  - Alloy

Scattering mechanisms: Piezoelectric scattering

- Compound semiconductors with lack of inversion symmetry
- Interaction through polarization [electromechanical tensor times strain tensor]:

$$\mathcal{E}_{pz} = -\frac{4\pi}{\varepsilon} P_{pz} = -\frac{4\pi}{\varepsilon}\left[\hat{e}_m \cdot \hat{\varepsilon}\right]$$

- Acoustic phonon scattering: almost elastic
- Interaction increases at low *q*-vectors (due to electrostatic interaction:

$$H_{pz} = e\frac{\mathcal{E}_{pz}}{q}$$

- Scattering time:

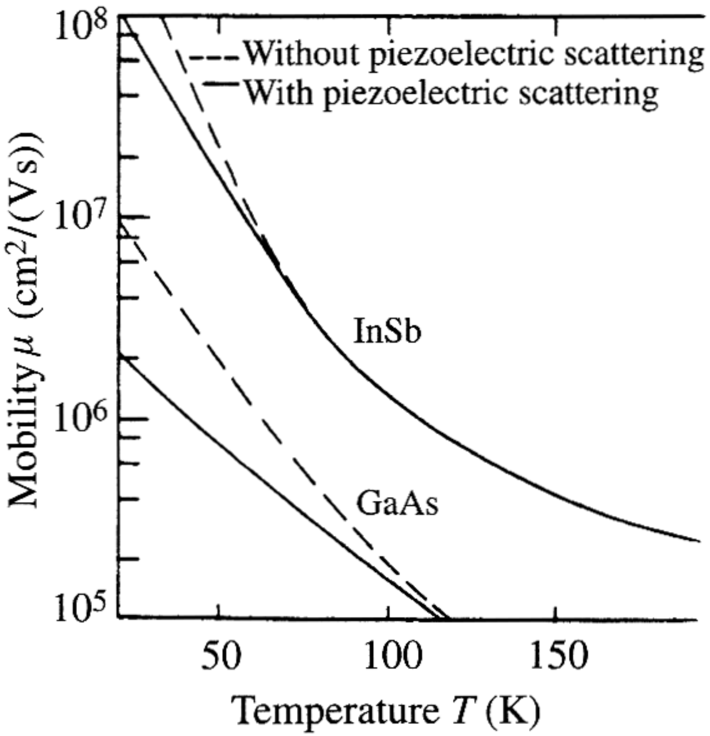
$$\tau_k \propto E^{1/2}$$

- Mobility will be affected by phonon density:

$$\mu \propto (kT)^{-1/2}$$

Table 8.2 Piezoelectric coefficients e_{14} in C/m^2 for cubic III–V and II–VI semiconductors (after Ridley 1988)

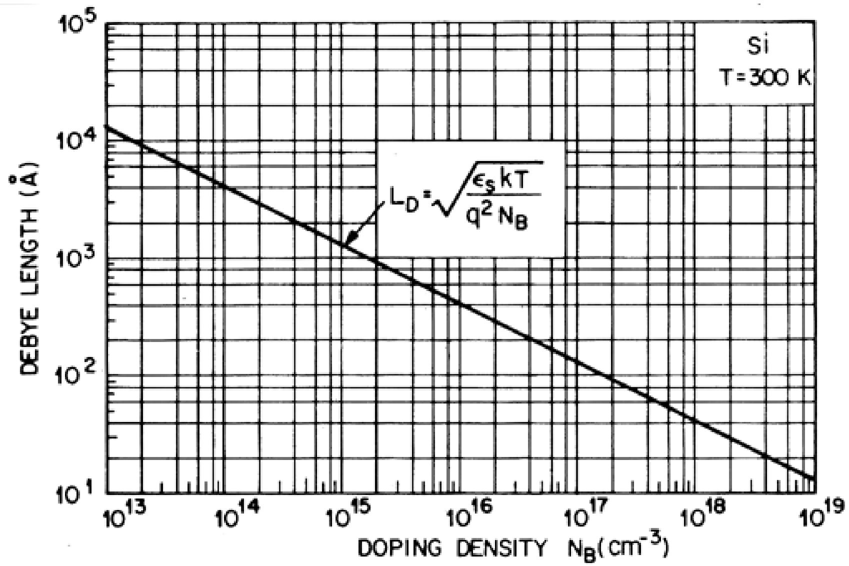
III–V	e_{14}	II–VI	e_{14}
GaAs	0.160	ZnS	0.17
GaSb	0.126	ZnSe	0.045
InAs	0.045	ZnTe	0.027
InSb	0.071	CdTe	0.034



From Balkanski and Wallis, 2003

Debye screening length

Range of long wavelengths of phonons which scatter carriers is determined by Debye screening length L_D



Debye length in Si as a function of doping density.

- Continuity equation without sources:

$$\frac{\partial \Delta n}{\partial t} + \frac{1}{e}\nabla \sigma \mathcal{E} = 0$$

- Poisson equation (field divergence due to uncompensated charges)

$$\nabla \mathcal{E} = \frac{4\pi e}{\varepsilon}\Delta n$$

$$\frac{\partial \Delta n}{\partial t} = -\frac{4\pi\sigma}{\varepsilon}\Delta n$$

$$\Delta n = n(t=0)e^{-t/\tau_D}$$

- Debye or dielectric relaxation time:

$$\tau_D = \frac{\varepsilon}{4\pi\sigma} = \frac{\varepsilon}{4\pi e n\mu}$$ using $\sigma = en\mu$

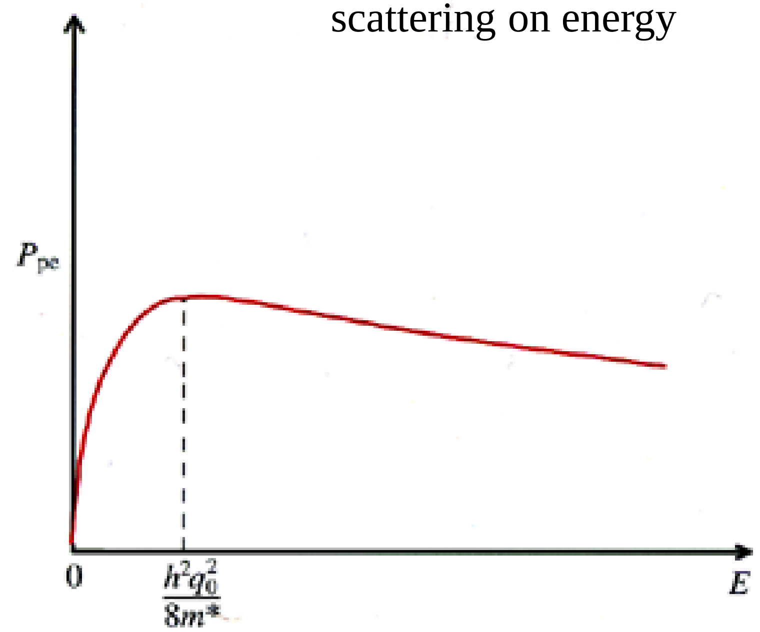
- Debye screening length (diffusion during τ_D)

$$L_D = \sqrt{D\tau_D} = \left(\frac{\varepsilon kT}{4\pi e^2 n}\right)^{1/2}$$ using $D = \frac{k_B T}{e}\mu$

Piezoelectric scattering by long-wavelength acoustic phonons

- Piezoelectric acoustic phonon scattering rate decreases with electron energy (small q-vector of phonons involved)
- Due to screening of long-range field by carriers, very long-wavelength phonons are ineffective for scattering
- Range ($2/q_0$) is determined by Debye screening length L_D

Rate of piezoelectric acoustic phonon scattering on energy



From Yu and Cordona, 2003

Scattering mechanisms: Optical phonons

- Inelastic = scattering with significant energy transfer
- Different scattering rate of events with absorption and emission of phonons
- Two mechanisms: deformation potential and Frohlich (polar optical)
- <u>Nonpolar optical phonons: Deformation potential scattering</u>
- Though no long-range (macroscopic) distortions are generated as in acoustical phonons, the “microscopic distortions” within a unit cell affect the band structure.
- Interaction via “optical deformation potential”

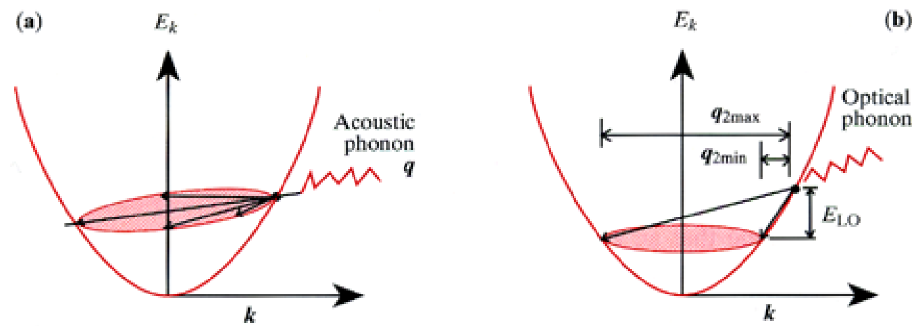
$$H^{opt} \propto D^{opt} u \propto D^{opt} e^{iqr}$$

- Very similar to acoustic deformation potential with different parameters

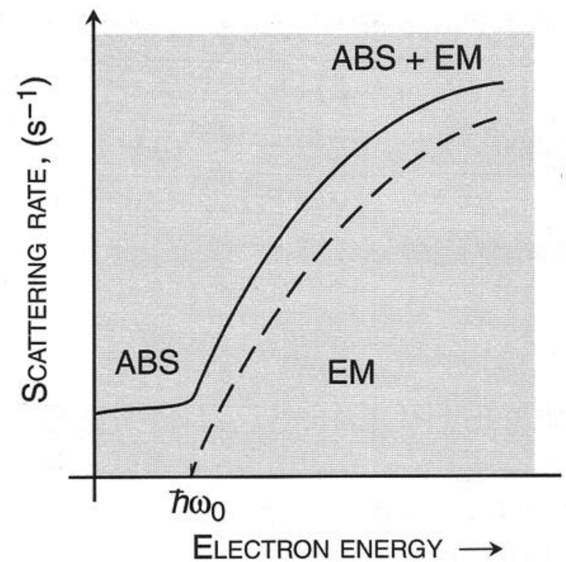
$$\tau_k \propto E^{-1/2}$$

- In case $k_B T >> \hbar\omega_{ph}$

$$\mu \propto (kT)^{-3/2}$$



From Yu and Cordona, 2003



From Singh, 2003

Scattering mechanisms: polar optical phonons

- Polar optical phonon scattering is due to scattering by polarization field generated by optical phonons (Frölich interaction)

$$H_{pol} \propto e_{eff} u \propto e_{eff} e^{iqr}$$

- Similar to piezoelectric acoustic phonon scattering:

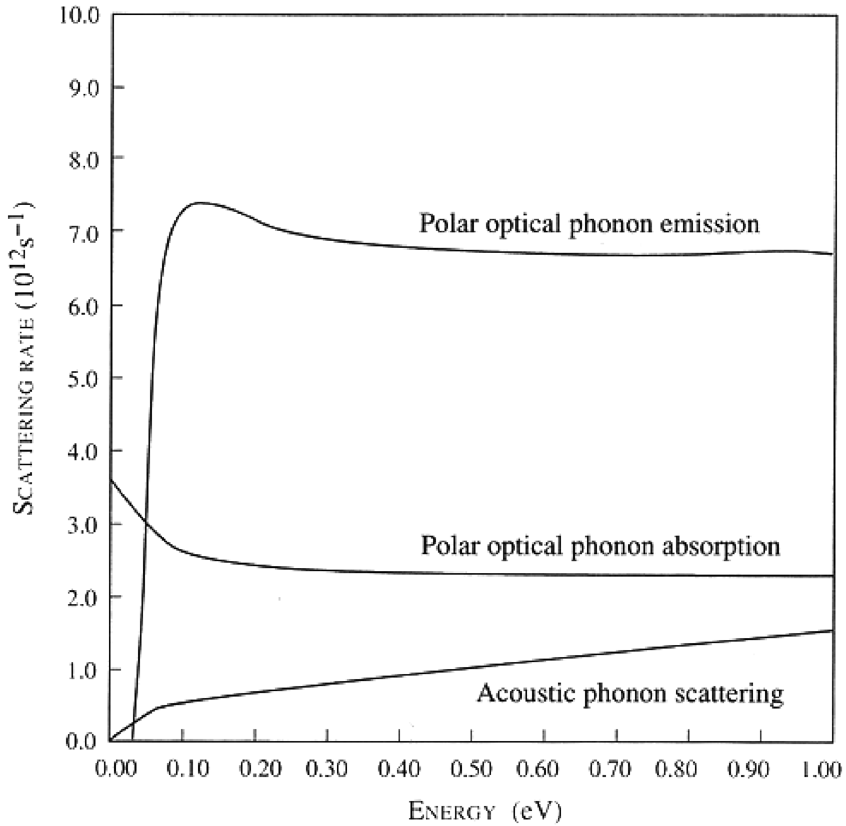
$$H_{pol} \propto \frac{1}{q}$$

$$\tau_k \propto E^{1/2}$$

- At high temperatures

$$k_B T \gg \hbar\omega_{ph} \qquad \mu \propto (kT)^{-1/2}$$

Scattering rates of polar optical and acoustic phonons in GaAs at room temperature



From Singh, 2003

Scattering mechanisms: polar optical phonons

- Polar optical phonon scattering is dominant at room temperature in high-purity III-V's

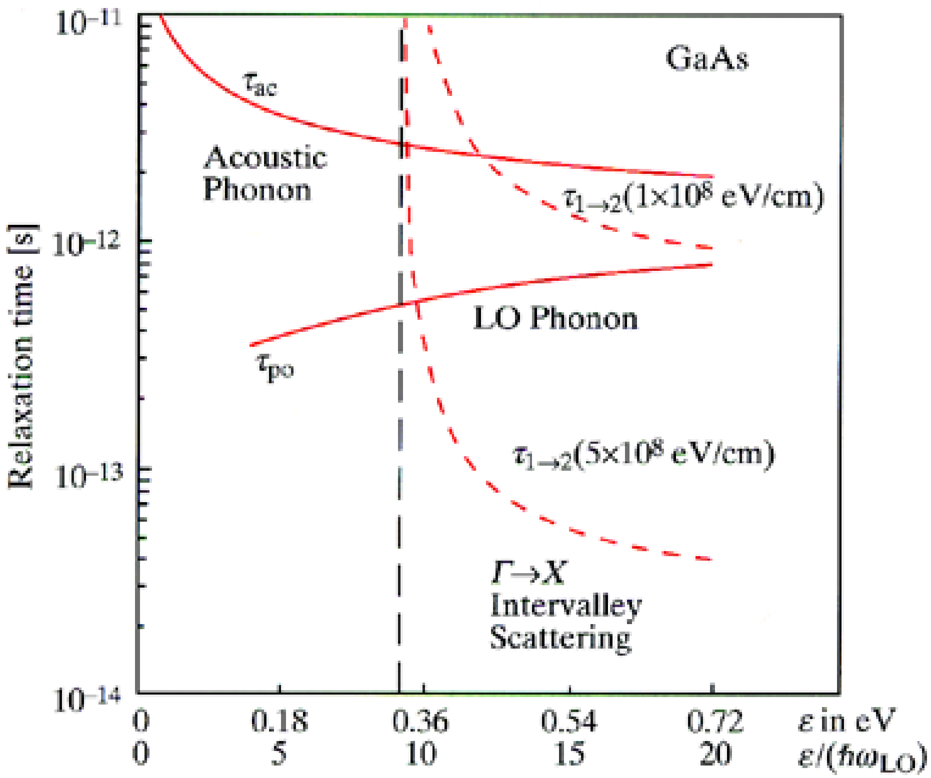
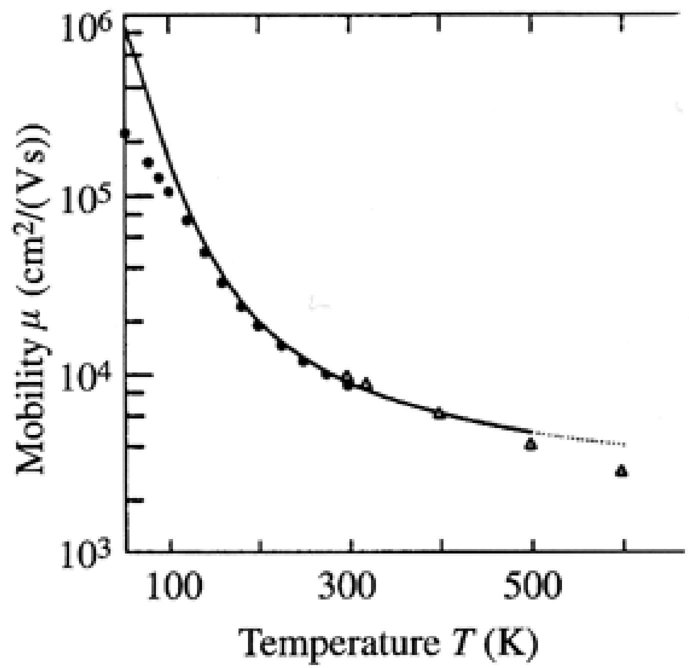


Fig. 5.3. Momentum relaxation times of a conduction electron in the Γ valley of GaAs as a function of electron energy. Scattering by: small wave vector LA phonons (τ_{ac}) via the deformation potential interaction; small wave vector optical phonons (τ_{po}) via the Fröhlich interaction and via zone-edge phonons from Γ to the X valleys ($\tau_{1\to 2}$) calculated by *Conwell* and *Vassel* [5.8]. Notice that the deformation potential for the Γ to X intervalley scattering has been assumed to be either 1×10^8 or 5×10^8 eV/cm. These values are smaller than the now accepted value of 10^9 eV/cm [5.9]

From Yu and Cordona, 2003

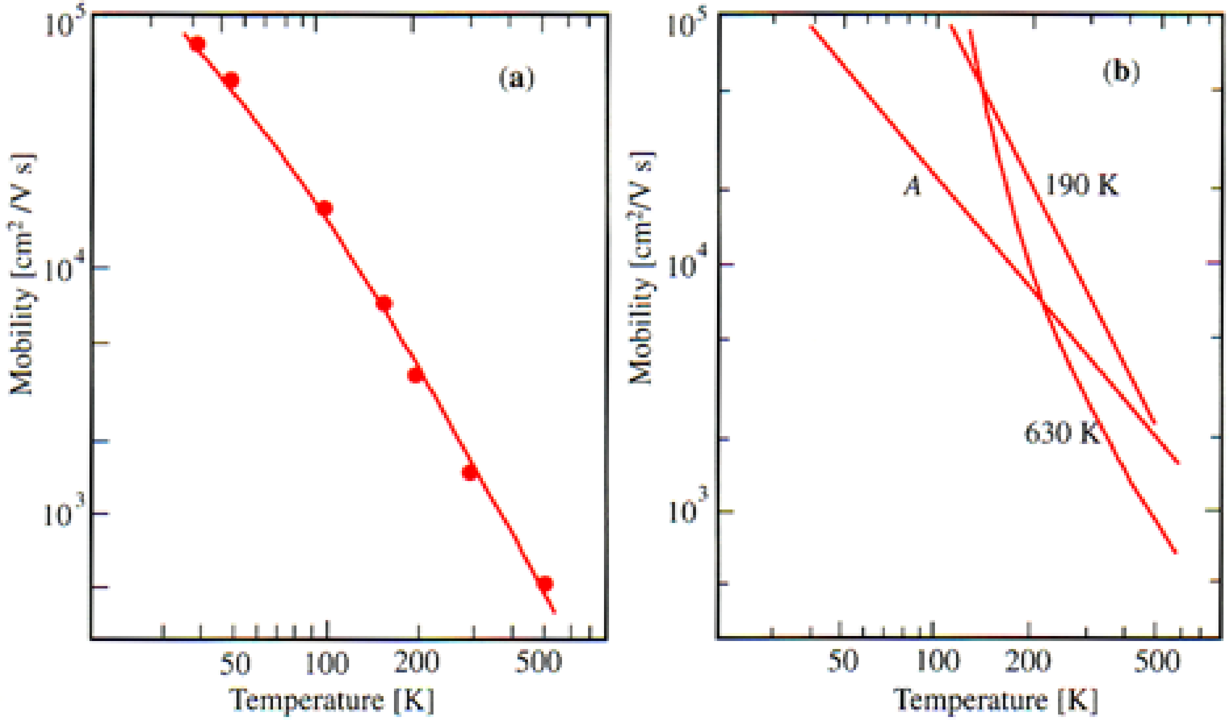
Experimental and theoretical (polar optical phonon scattering) results on ultrapure GaAs mobility



From Balkanski and Wallis, 2000

Intervalley carrier scattering

Temperature dependence of mobility in n-type Si.
Experimental and theoretical results.

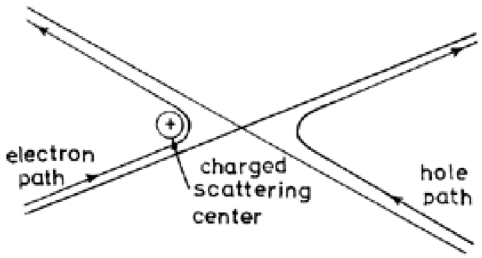


A - intravalley acoustic phonon scattering
190K intervalley scattering by 2x 16mev TA phonons
630K intervalley scattering by 54mev LO phonons

From Yu and Cordona, 2003

Scattering mechanisms: ionized impurities

Ionized impurity scattering: elastic (no energy change in the scattering event)

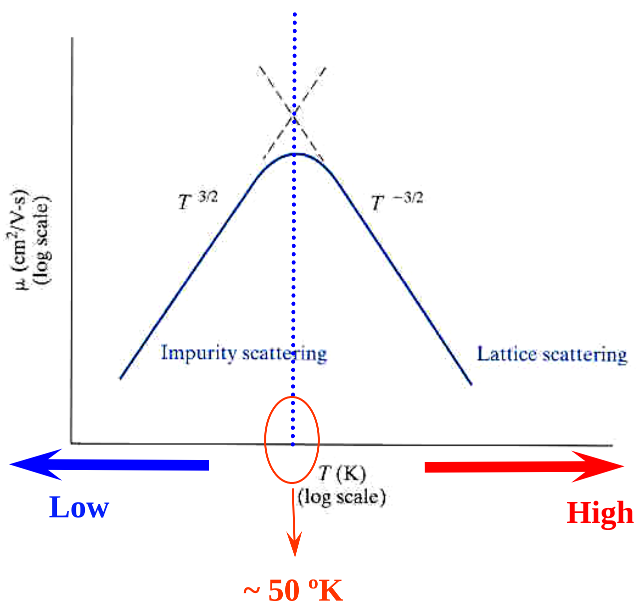


Carriers with lower energy are scattered stronger

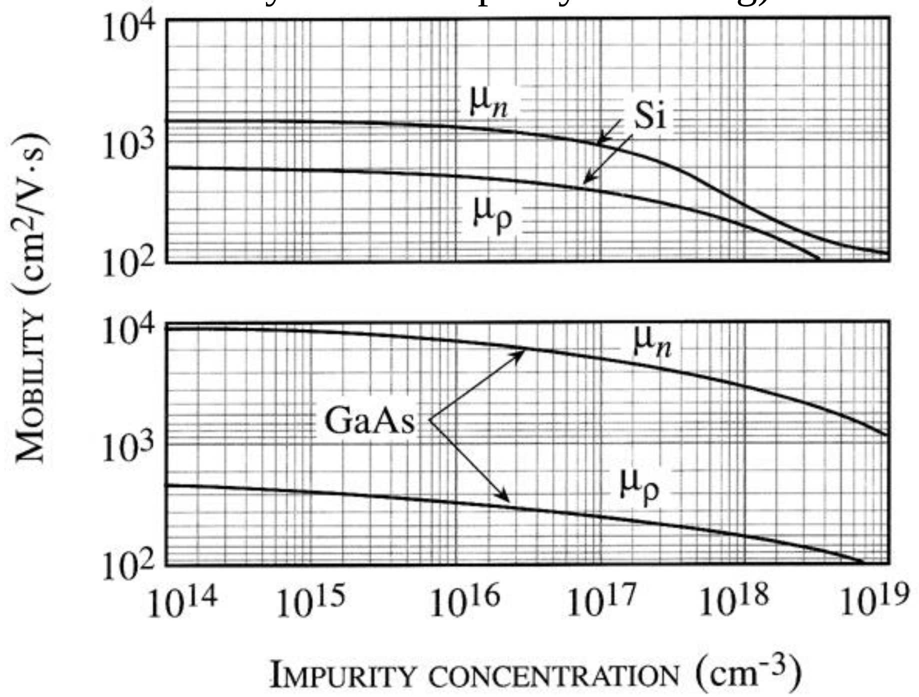
$$\tau \propto E^{3/2}$$

$$\mu \propto (kT)^{3/2}$$

Ionized impurity scattering is usually the dominant mechanism at low temperatures



Mobility of carriers in Si and GaAs at room temperature (slope is determined by ionized impurity scattering)



From Singh, 2003

Scattering mechanisms: neutral impurities

Scattering rate can be derived from "collisions of carriers with defect centers" :

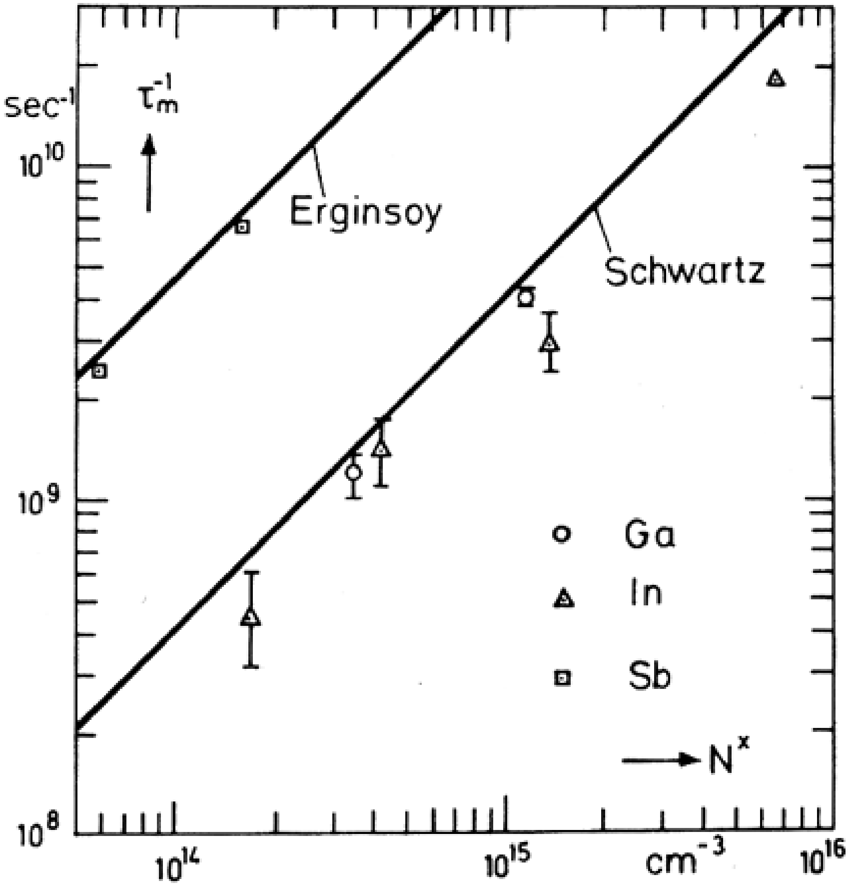
$$\frac{1}{\tau} = N\sigma v$$

Relaxation time does not depend on energy and averaging procedure is not needed.

$$\mu = \frac{e\tau}{m^*} \propto (kT)^0$$

Scattering of electrons and holes can be different .

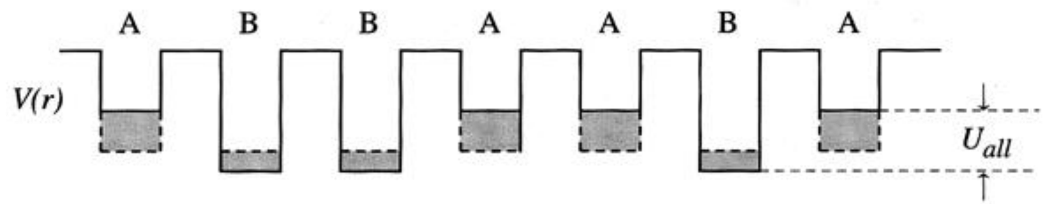
Inverse cyclotron relaxation time in Ge at low temperature



From Seeger, 1973

Scattering mechanisms: alloy scattering

- Interaction with field generated due to fluctuations of atomic potential



Scattering probability does not depend on *k*-vectors and therefore, on electron energy (*x* is a composition of alloy)

$$\frac{1}{\tau} \propto (1-x)xU_{alloy}^2$$

The strongest scattering at $x = 0.5$

Averaging over the density of states :

$$\mu \propto (kT)^{-1/2}$$

EXAMPLE 5.2 Calculate the alloy scattering limited mobility in $Al_{0.3}Ga_{0.7}As$ at 77 K and at 300 K. Assume that the alloy scattering potential is 1.0 eV. The relaxation time at 300 K is ($m^* = 0.07\ m_0$).

$$\frac{1}{\langle\langle r \rangle\rangle} = \frac{3\pi V_0 (U_{all})^2 x(1-x) m^{*3/2} (k_B T)^{1/2}}{8\sqrt{2}\hbar^4 (0.75)}$$

$$= 2.1 \times 10^{12}\ \mathrm{s}$$

Here we have used $x = 0.3$, $V_0 = a^3/4$ with $a = 5.65$ Å.

The value of $\langle\langle r \rangle\rangle$ is 4.77×10^{-13} s. The mobility is then

$$\mu_{all}(300\ \mathrm{K}) = 1.2 \times 10^4\ \mathrm{cm^2/V \cdot s}$$

The mobility goes as $T^{-1/2}$ which gives

$$\mu_{all}(77\ \mathrm{K}) = 2.36 \times 10^4\ \mathrm{cm^2/V \cdot s}$$

From Singh, 2003

Mechanisms of carrier scattering

Temperature dependence of drift mobility

Scattering process	$\mu = A(kT)^p$		Hall factor
	A	p	
Acoustic phonons, deformation potential	$\frac{4e\pi^{1/2}Mc_s^2\hbar^4}{3(2m^5)^{1/2}E_1^2k^{3/2}V_0}$	$-3/2$	$\frac{3\pi}{8}=1,18$
Acoustic phonons, piezoelectric scattering	$\frac{5\varepsilon^2Mc_s^2\hbar^2}{2\beta^2eV_0(2k\pi^3m^3)^{1/2}}$	$-1/2$	$\frac{45\pi}{128}=1,105$
Nonpolar optical phonons, $kT \gg \hbar\omega_0$	$\frac{4e\pi^{1/2}M\hbar^4\omega_0^2}{3V_0E_0^2(2m^5k^3)^{1/2}}$	$-3/2$	$\frac{3\pi}{8}=1,18$
Polar optical phonons $kT \gg \hbar\omega_0$	$\frac{eV_0M_1M_2\hbar^2\omega_0^2\sqrt{2}}{3(Ze^2)^2(M_1+M_2)} \times (\pi^3km^3)^{-1/2}$	$-1/2$	$\frac{45\pi}{128}=1,105$
Ionized impurities	$\frac{8\varepsilon^2(2k^3)^{1/2}(m\pi^3)^{-1/2}}{e^3N_t\ln\left(\frac{24mkT}{\hbar^2}r_0^2\right)}$	$3/2$	$\frac{315\pi}{512}=1,93$
Neutral impurities	$\frac{me^3}{20\varepsilon\hbar^3N_0}$	0	1

From Kalashnikov, 1977

Plasma waves (plasmons)

Field due to displacement in electron plasma (relative to ions)

$$\mathcal{E} = \frac{4\pi neu}{\varepsilon}$$

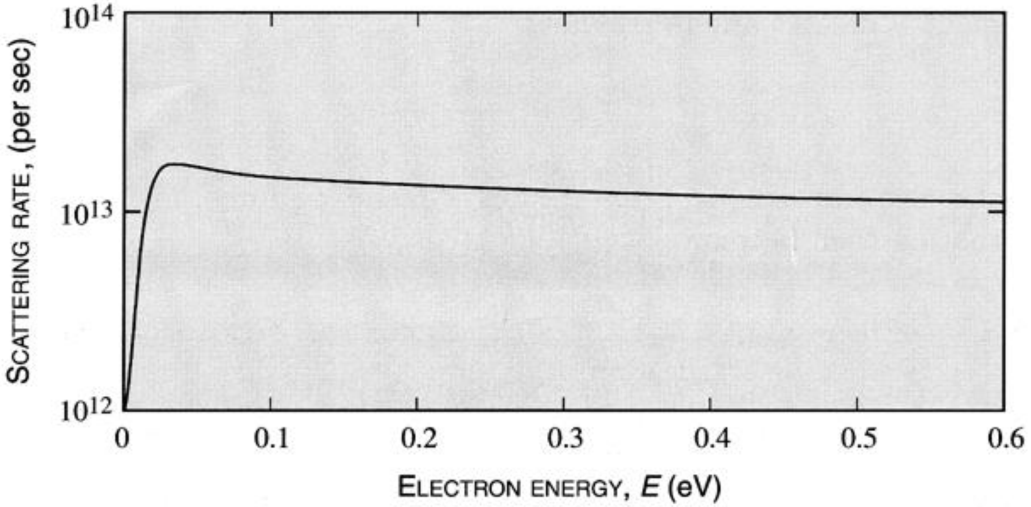
Motion equation:

$$m^* \frac{d^2u}{dt^2} = -e\mathcal{E}$$

Solution: Oscillations with plasma frequency

$$\omega_p^2 = \frac{4\pi e^2 n}{\varepsilon m^*}$$

Electron-plasmon scattering rate for GaAs
at room temperature for n=1x10^{17} cm^{-3}



From Singh, 2003