Review: Debye model used $\omega = vk$

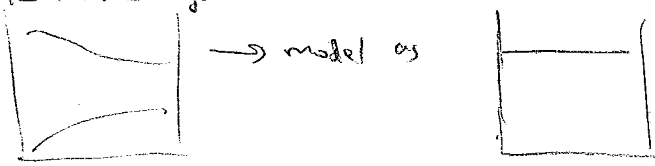
OK for acoustic branch.

horrible for optical branch.

mention ×3 for 3 acoustic branches

New model: Einstein model (for optical branches)

diatomic lattice again



$$D(\omega) = N\delta(\omega - \omega_0)$$

↳ Dirac delta

$$U = \int D(\omega) \frac{\hbar\omega}{e^{\hbar\omega/kT} - 1} \, d\omega$$

trivial!

$$U = \frac{N\hbar\omega_0}{e^{\hbar\omega_0/kT} - 1}$$

ω_0 = characteristic (optical phonon) frequency

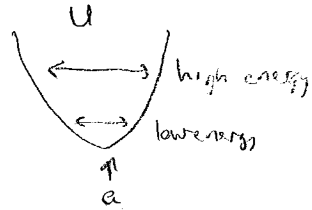
define Θ_E : $\hbar\omega_0 = k_B \Theta_E$ (can use as fit parameter)

$$C_V = \frac{\partial U}{\partial T} = N k_B \left(\frac{\hbar\omega_0}{kT}\right)^2 \frac{e^{\hbar\omega_0/kT}}{\left(e^{\hbar\omega_0/kT} - 1\right)^2}$$

Fig 11 pg 117

Beyond the Harmonic Approximation

Some big problems: 1)



No change in lattice constant as energy is added!

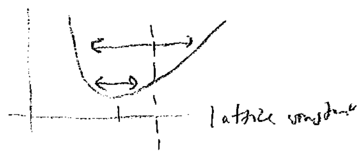
2). No way for phonons to interact.
(like light – if not nonlinear crystal, can't get 800 nm → 400 nm conversion in pulsed Ti sapph)

$\omega_3 = \omega_1 + \omega_2$ → present w/ phonons like in photons

Actuality: if phonon present, produces some strain, which modulates in space + time the elastic constants

Full nonlinear ("anharmonic") theory very complicated.

For us:

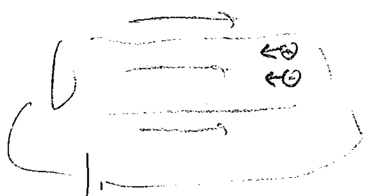


increases when more energy!

Kittel: $x_{ave} = \frac{3}{4} kT \cdot \frac{g}{c^2}$ → cubic coefficient; c^2 → quadratic coefficient

Thermal Conductivity

first: electrical conductivity (really in Ch 6, pg 147-148)



Do electrons accelerate all the way down the wire?

$F = qE$, $E = \frac{V}{l}$

No! Why not? → scattering

electron accelerates for a bit, but then scaters in some random direction (resetting velocity)

Net effect: some overall "drift velocity", $V_{drift} \sim E$

$$\frac{\text{current}}{\text{area}} = \left(\frac{\text{electrons}}{\text{volume}}\right)\left(\frac{\text{charge}}{\text{electron}}\right)\left(\frac{\text{length}}{\text{time}}\right)$$

$$J = n q V_{drift}$$

(V_{drift} → $\sim E$)

so $J \sim E$

$$J = \sigma E$$

(σ → electrical conductivity)

Back to thermal conductivity

Back in Ph 123: $\frac{Q}{t} = \frac{k A \Delta T}{\text{length}}$ (k → thermal conductivity)

Kittel: $\frac{Q}{A t} = -k \frac{dT}{dx}$

($\frac{Q}{At}$: " " ju, flux of thermal energy; $-$: so flow is in right direction)

Where does it come from? Same thing: phonon scattering

if no scattering, get "ballistic transport," leads to very different situation

Scattering:

τ = ave scattering time (assume it exists)

λ = mean free path (distance between scattering events)

$$V_{rms} = \frac{\lambda}{\tau}$$

Assume τ = independent of phonon energy