Phonons

Longitudinal Lattice Wave (phonon)

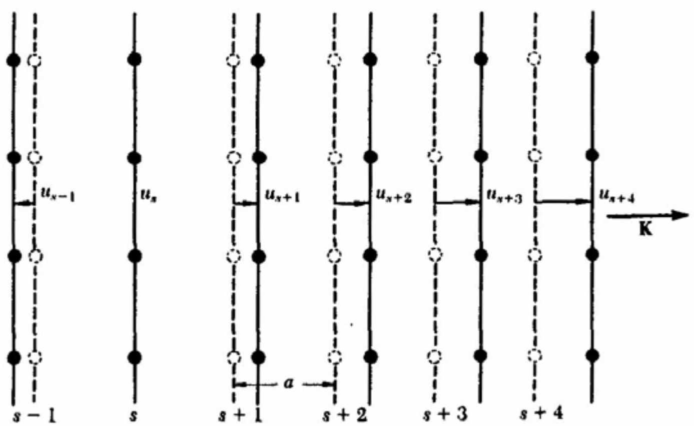

Figure 2 (Dashed lines) Planes of atoms when in equilibrium. (Solid lines) Planes of atoms when displaced as for a longitudinal wave. The coordinate u measures the displacement of the planes.

$s+p$ = specific plane
u_{s+p} = displacement

p = whole number

Phonons

Phonon Dispersion Relation for a monatomic lattice

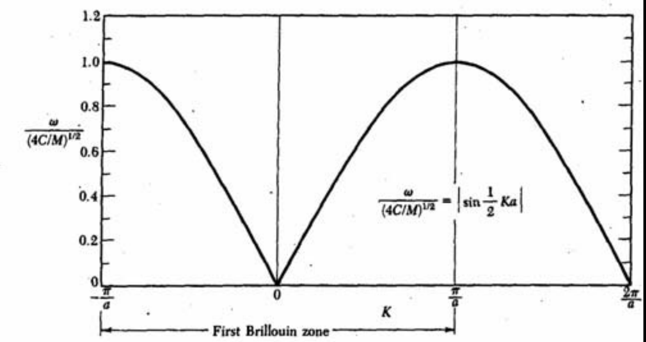

Figure 4 Plot of ω versus K. The region of $K \ll 1/a$ or $\lambda \gg a$ corresponds to the continuum approximation; here ω is directly proportional to K.

$$v_g = \frac{\partial \omega}{\partial k} = 0 \text{ at the Brillouin zone boundaries.}$$

Phonons

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Phonon Dispersion Relation for 2 Atoms per Basis

- Assume the 2 atoms have different mass, m_1 & m_2
- Displacements are:

  u for m_1

  v for m_2

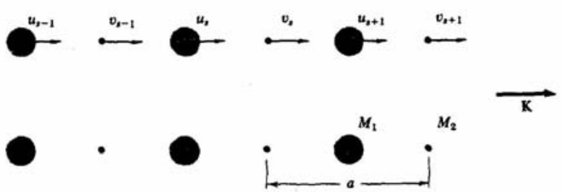


Figure 9 A diatomic crystal structure with masses M_1, M_2 connected by force constant C between adjacent planes. The displacements of atoms M_1 are denoted by $u_{s-1}, u_s, u_{s+1}, \ldots$, and of atoms M_2 by v_{s-1}, v_s, v_{s+1}. The repeat distance is a in the direction of the wavevector K. The atoms are shown in their undisplaced positions.

 Kittel, *Introduction to Solid State Physics*, 6th Ed (Wiley, 1986) Ch. 4

Phonons

Phonon Dispersion Relation for Diatomic Linear Lattice

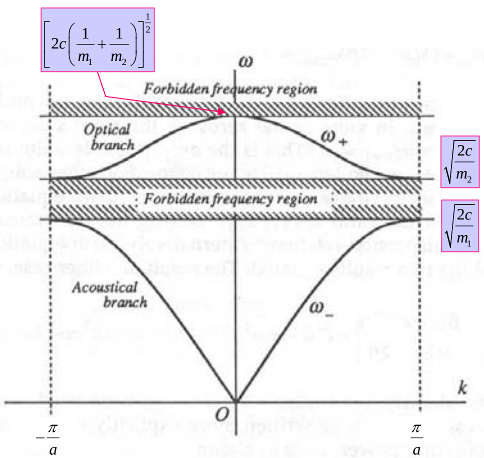
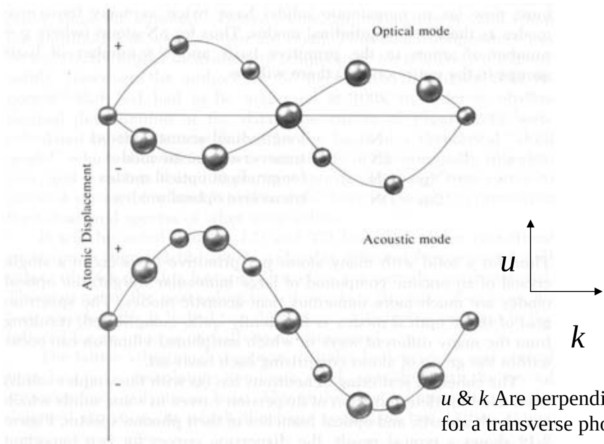


Figure 3.23 Dispersion curve for the diatomic linear lattice with nearest neighbor Hooke's law forces.

McKelvey, *Solid State Physics for Engineering & Materials Science*, (Krieger, 1993) Ch. 3

Phonons



u & *k* Are perpendicular for a transverse phonon

Figure 2-11 The sequence of atomic displacements involved in the transmission of a transverse wave along a diatomic chain. The difference between the acoustic and optical modes can be seen more clearly when transverse displacements are sketched rather than a longitudinal wave.

Blakemore, *Solid State Physics*, 2nd Ed (Cambridge, 1985) Ch. 2

- Whether a vibrational mode is longitudinal or transverse, a given atomic amplitude of motion requires much more energy for a long wave optical than acoustic mode.
- Why? B/c optical modes minimize changes in 2nd n.n. separation by maximizing separation between n.n.'s.
- N.n. interaction greater than any other n.n. interaction, therefore, energy required for n.n. separation greater than any other separation.
- $U = dF/dx$ integrate under curves to get energy.

Phonons

- When the masses of n.n. differ, then their charge density differs so a dipole exists.
- When a phonon ~~will~~ (oscillating EM wave) interacts with the lattice, the interaction is primarily with the dipoles.
- The dipoles will oscillate at the frequency of the photon. The rapidly changing dipole can then emit EM radiation.
- Even when the mass of a solid do not differ, such as for non-ionic ~~m~~ solids that are covalently bonded, optical phonons exist.
- This is true of polyatomic bases (a basis that has more than 1 atom).

Phonons Dispersion Curves

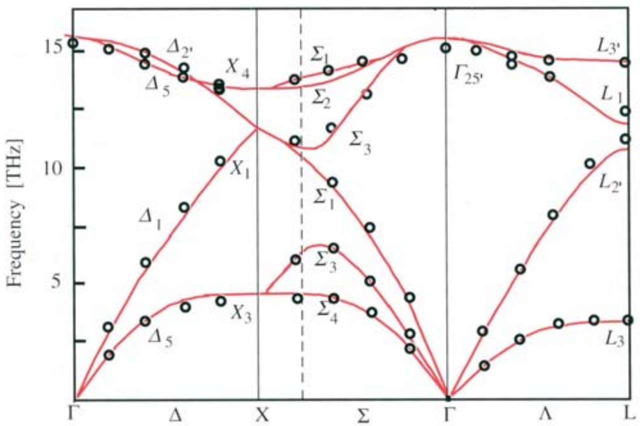


Fig. 3.1. Phonon dispersion curves in Si along high-symmetry axes.

P.Y. Yu & M. Cardona, *Fundamentals of Semiconductors*, (Springer, 1996) Ch. 3

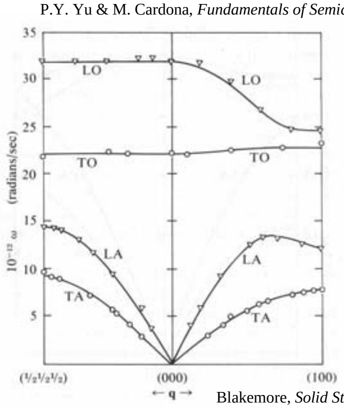


Figure 2–12 Dispersion curves for lattice vibrations in sodium iodide, plotted for reduced wave-vector along two important directions away from the center of the zone. The letters L, T, O, and A signify longitudinal, transverse, optical branch, and acoustic branch respectively. The data were taken at 100K by A. D. B. Woods et al., Phys. Rev., 131, 1025 (1963).

Blakemore, *Solid State Physics*, 2nd Ed (Cambridge, 1985) Ch. 2

Phonons

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Quantization of Lattice Vibrations

- Lattice vibrations are quantized into phonons.
- A thermal vibration is a number of thermally excited phonons.
- The energy of an elastic mode of angular frequency ω is:

$$E = (n+\tfrac{1}{2})\hbar\omega$$

where n = the # of phonons in a mode

$\frac{1}{2}\hbar\omega$ = the zero point energy of the mode – a consequence of quantum mechanics.

- Phonons carry crystal momentum, but no real mechanical momentum.
- If you think about a vibrating harmonic oscillator or O_2 molecule, the average displacement is zero. So the center of gravity is the equilibrium position. Hence $p = mv = 0$, $\Delta x = 0$.
- But the crystal momentum is: $p = \hbar \underline{\underline{k}}$

Phonons

Phonon Combination Bands
(two phonon overtone bands)

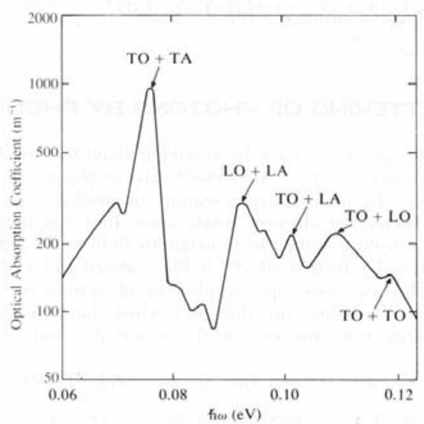
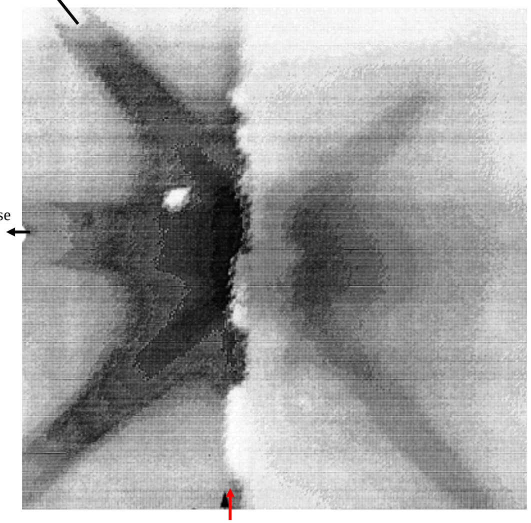


Figure 2-17 Infrared optical absorption of silicon, showing the various phonon combination bands, and the TO overtone band. After F. A. Johnson, Proc. Phys. Soc. 73, 265 (1959).

Blakemore, *Solid State Physics*, 2nd Ed (Cambridge, 1985) Ch. 2

Phonon Imaging

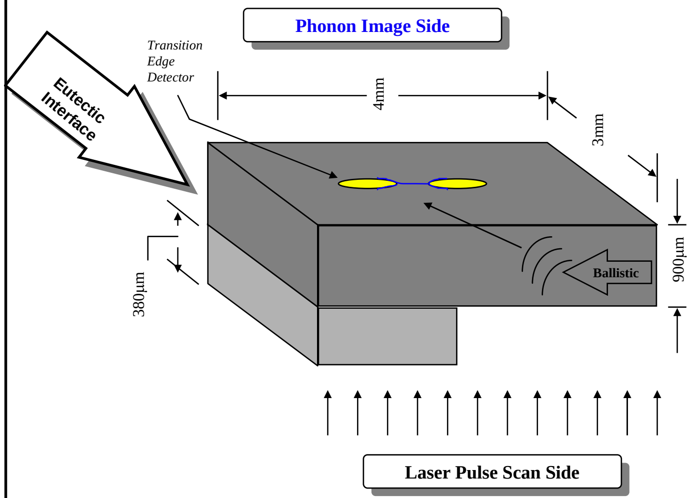
- ❑ Phonon Transmission study:
  - ✓ 65% transmission of ballistic phonons



Dark Matter Detector Sensing Phonon Using Ge:Au:Ge Eutectic Bonding

Phonon Imaging

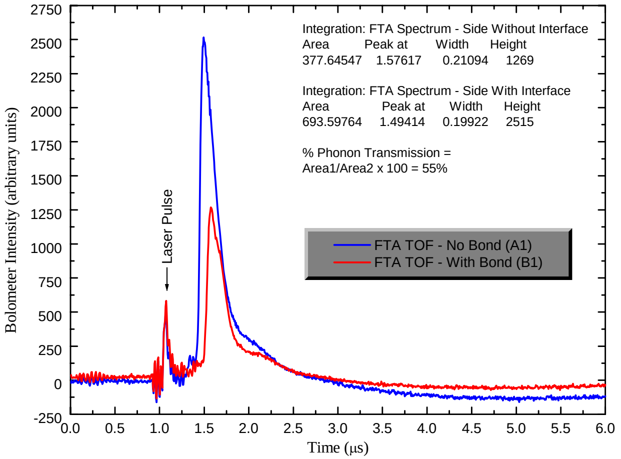
- Phonon Transmission study:
  - ✓ Sample configuration



Dark Matter Detector Sensing Phonon Using
Ge:Au:Ge Eutectic Bonding

Phonon Imaging

- Phonon Transmission study:
  - ✓ Time of flight

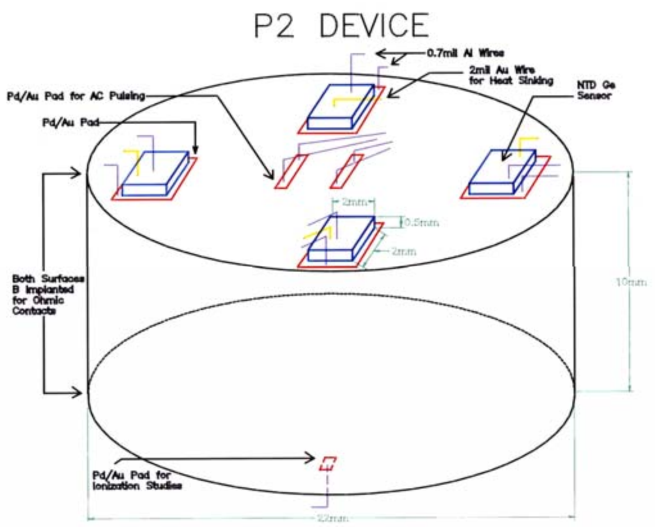


- Fast tranverse optical phonon
- Slow transverse optical phonon
- If we examine TOF data from phonon imaging study
- Notice that time at peak max is no more than 1 μs

Dark Matter Detector Sensing Phonon Using
Ge:Au:Ge Eutectic Bonding

Phonon Imaging

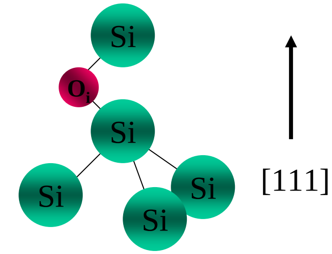
- Phonon Transmission study:
  - ✓ Prototype Dark Matter Detector
  - ✓ Really a phonon detector

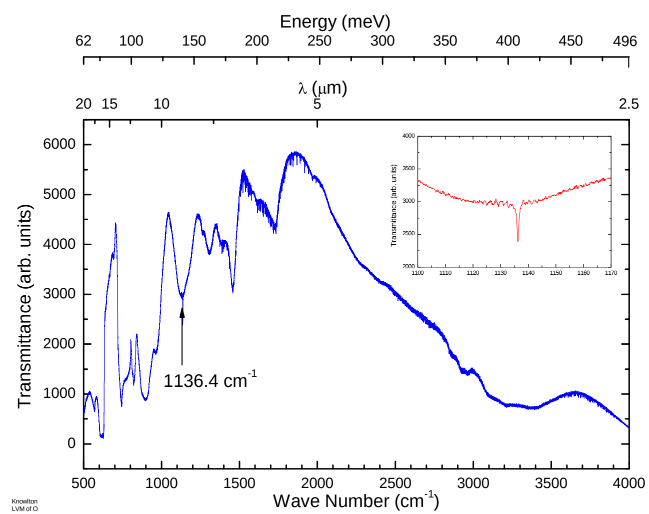


Dark Matter Detector Sensing Phonon Using
Ge:Au:Ge Eutectic Bonding

Phonons – Local Vibrational Modes

O interstitial





Knowlton, *U.C. Berkeley*, ~1995