

Fermi's golden rule



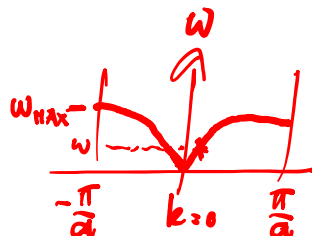
MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Last week:

$$\int_{-\infty}^{\infty} g_c(\epsilon) f_F(\epsilon - \mu) d\epsilon$$

$\mu = 0$

- Intrinsic carriers and chemical potential
- Impurity levels
- Temperature dependence of majority carriers
- Carrier densities and chemical potentials in doped semiconductors
- p-n junction and built-in voltage
- Vibrational states of one-dimensional monoatomic chain
- (remember – do in-depth evaluations)

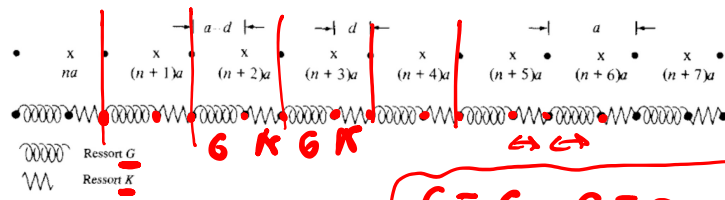


$$u_s = u e^{i\mathbf{k} \cdot \mathbf{r}} e^{-i\omega t}$$

$\omega = \omega(k)$

MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

1-dimensional diatomic chain



III. Equations of motion

$$M \frac{d^2 u_{1s}}{dt^2} = K(u_{2s} - u_{1s}) + G(u_{2s-1} - u_{1s})$$

$$M \frac{d^2 u_{2s}}{dt^2} = K(u_{1s} - u_{2s}) + G(u_{1s+1} - u_{2s})$$

IV. Solutions

$$u_{1s} = u_1 e^{iksa} e^{-i\omega t}, \quad u_{2s} = u_2 e^{iksa} e^{-i\omega t}$$

V. Dispersion relations

$$\begin{cases} (M\omega^2 - (K+G))u_1 + (K + Ge^{-ika})u_2 = 0 \\ (K + Ge^{ika})u_1 + (M\omega^2 - (K+G))u_2 = 0 \end{cases}$$

The homogenous linear equations have a solution only if the determinant of the coefficients is zero:

$$\begin{vmatrix} (M\omega^2 - (K+G)) & (K + Ge^{-ika}) \\ (K + Ge^{ika}) & (M\omega^2 - (K+G)) \end{vmatrix} = 0$$

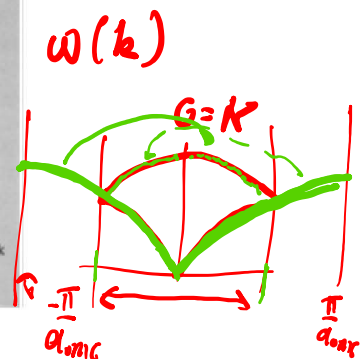
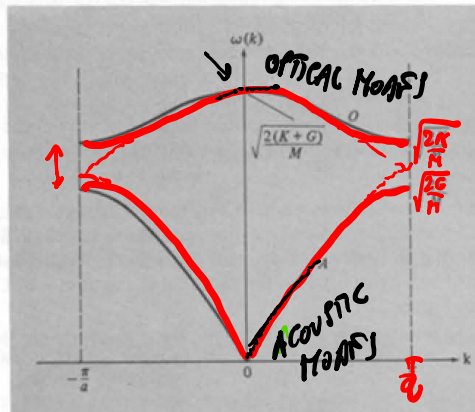
with solutions:

$$\omega^2 = \frac{K+G}{M} \pm \frac{1}{M} \sqrt{K^2 + G^2 + 2KG \cos ka}$$

$$\frac{u_1}{u_2} = \mp \frac{K + Ge^{-ika}}{K + Ge^{ika}}$$

for each k there are two solutions which are called the two branches of the dispersion curves.

Figure 22.10
Dispersion relation for the diatomic linear chain. The lower branch is the acoustic branch and has the same structure as the single branch present in the monatomic case (Figure 22.8). In addition, there is now an optical branch (upper branch).



The perfectly harmonic crystal

Phonon: lattice vibration of wave-vector $\mathbf{q}$ and frequency $\omega_j(\mathbf{q})$ (j : band index). Frequencies are calculated from the second derivatives of the energy (**interatomic force constants**) versus atomic displacements:

$$C_{\alpha i, \beta j}(\mathbf{R}_L, \mathbf{R}_{L'}) = \left. \frac{\partial^2 E}{\partial u_{\alpha i, L} \partial u_{\beta j, L'}} \right|_{\text{equilibrium}} = C_{\alpha i, \beta j}(\mathbf{R}_L - \mathbf{R}_{L'})$$

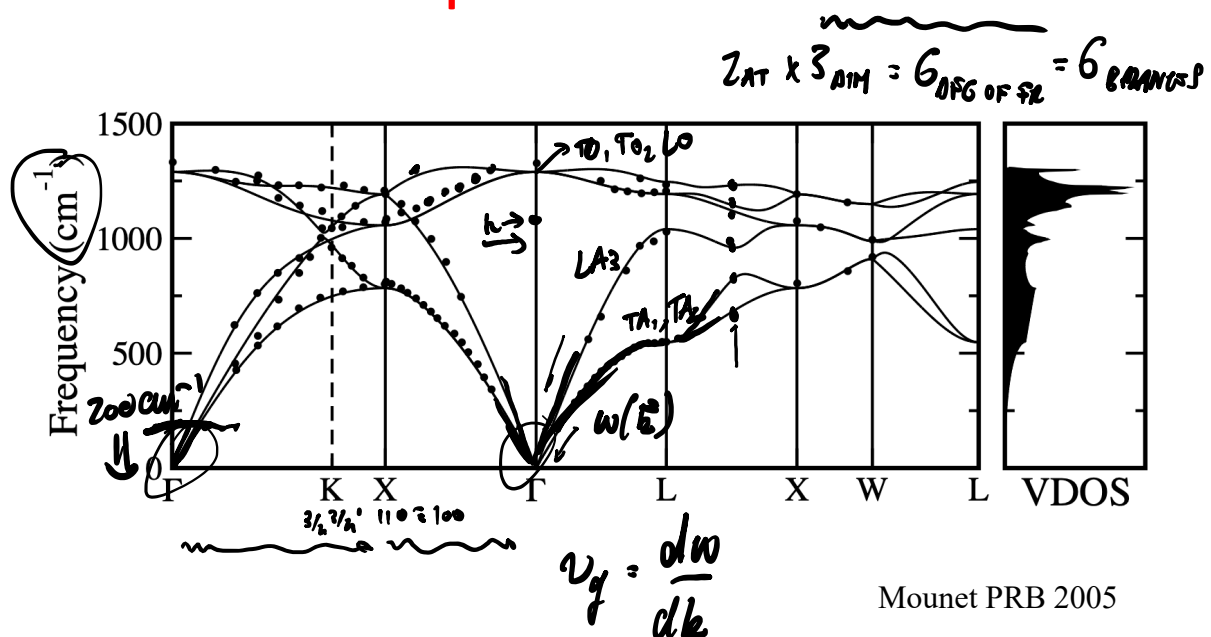
Precisely, phonon frequencies are the eigenvalues of the **dynamical matrix** $\tilde{D}_{\alpha i, \beta j}(\mathbf{q})$, Fourier transform of $C_{\alpha i, \beta j}(\mathbf{R}_L)$:

$$\tilde{D}_{\alpha i, \beta j}(\mathbf{q}) = \sum_L C_{\alpha i, \beta j}(\mathbf{R}_L) e^{-i\mathbf{q} \cdot \mathbf{R}_L}$$

$$\omega^2 u_{\alpha i} = \sum_{\beta j} u_{\beta j} \tilde{D}_{\alpha i, \beta j}(\mathbf{q})$$

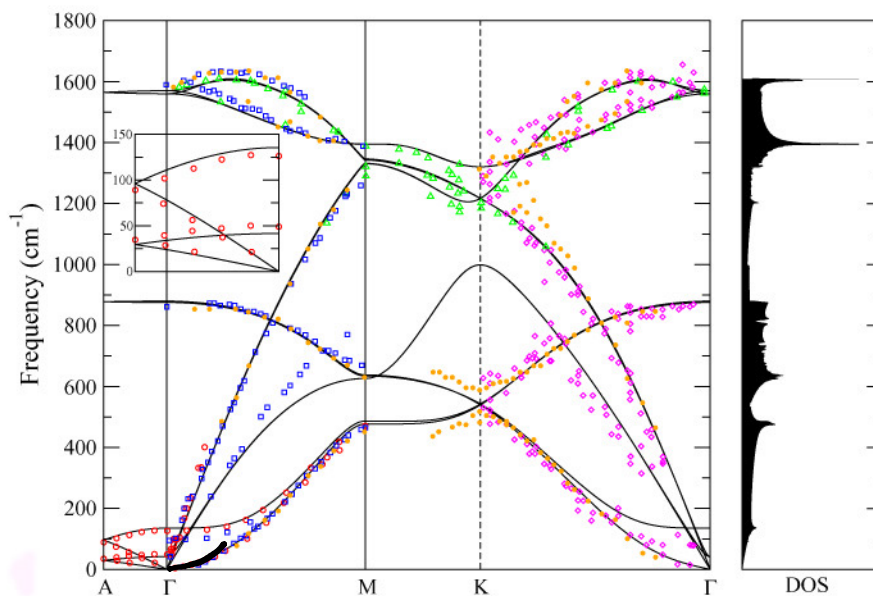
MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Phonon dispersions in diamond



MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Phonon dispersions in graphite



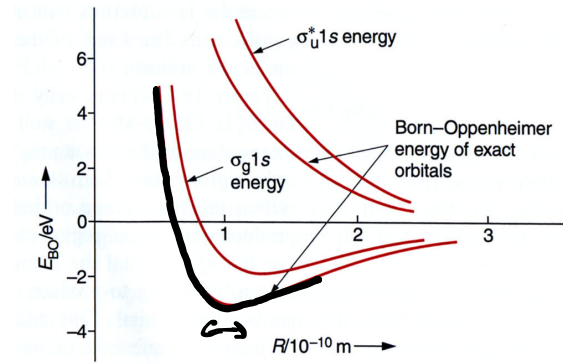
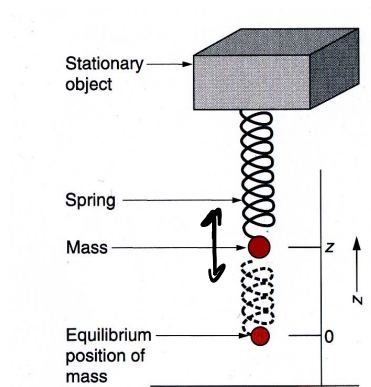
MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

The quantization of vibrations

- Electrons are much lighter than nuclei ($m_{\text{proton}}/m_{\text{electron}} \sim 1800$)
- Electronic wave-functions always rearrange themselves to be in the ground state (lowest energy possible for the electrons), even if the ions are moving around
- Born-Oppenheimer approximation: electrons in the instantaneous potential of the ions (so, electrons can not be excited – FALSE in general)

MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Nuclei have some quantum action...



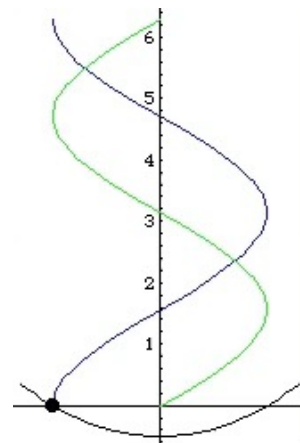
MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

$$\mathcal{P} \approx K z^2$$

The quantum harmonic oscillator (I)

$$\left[\underbrace{-\frac{\hbar^2}{2M} \frac{d^2}{dz^2}}_{\text{KINETIC}} + \underbrace{\frac{1}{2} K z^2}_{\text{POTENTIAL}} \right] \varphi(z) = E \varphi(z)$$

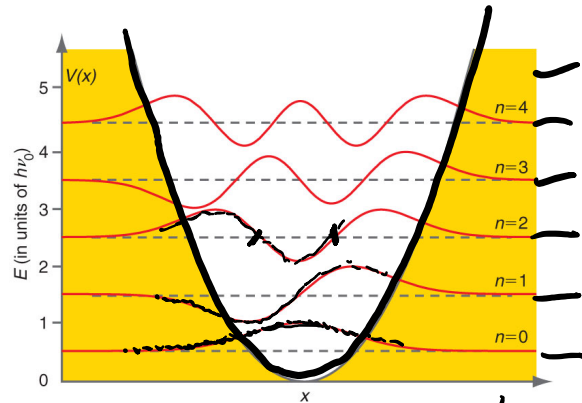
$$\omega = \sqrt{\frac{K}{M}} \quad a = \frac{\sqrt{KM}}{\hbar}$$



MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

The quantum harmonic oscillator (II)

$$\left[\begin{aligned} \psi_0 &= \left(\frac{a}{\pi}\right)^{1/4} e^{-az^2/2} \\ \psi_1 &= \left(\frac{4a^3}{\pi}\right)^{1/4} z e^{-az^2/2} \\ \psi_2 &= \left(\frac{a}{4\pi}\right)^{1/4} (2az^2 - 1) e^{-az^2/2} \end{aligned} \right]$$

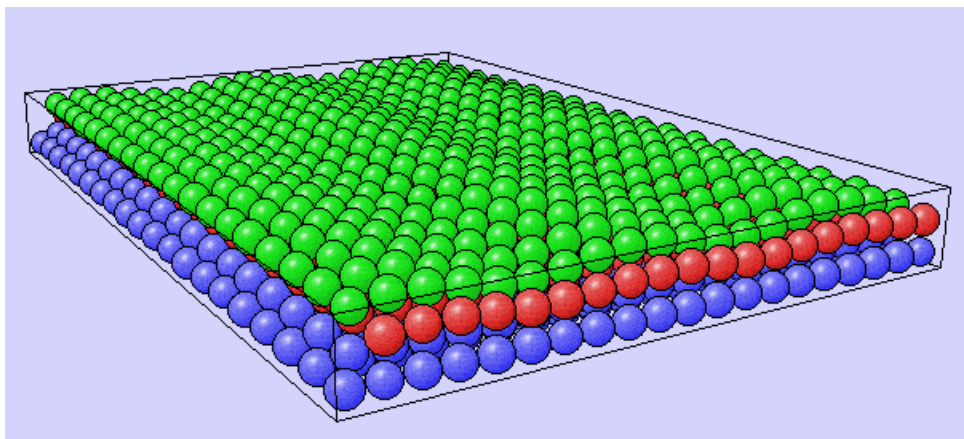
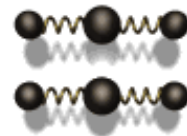


$$E = \hbar\omega_0 \left(n + \frac{1}{2} \right)$$

→ ZERO-POINT MOTION
 $n = 0, 1, 2, 3, \dots$
 $\omega_0 = \sqrt{\frac{\kappa}{M}}$

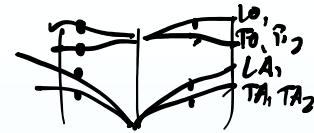
MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Quantized atomic vibrations



MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Harmonic crystal's free energy



Quantization of phonons' energy:

For Si $j=1, \dots, 6$ ($N_{Ac} \times N_{TA}$) $E_j(\mathbf{q}) = \hbar \omega_j(\mathbf{q}) (n + \frac{1}{2})$

Partition function of one phonon (microcanonical ensemble - T & V constant):

$$Z_{\mathbf{q},j} = \sum_n \exp\left(-\frac{\hbar \omega_j(\mathbf{q})}{k_B T} (n + \frac{1}{2})\right) = \frac{1}{2 \sinh \frac{\hbar \omega_j(\mathbf{q})}{k_B T}}$$

Total partition function:

$$Z_{total} = \prod_{\mathbf{q},j} Z_{\mathbf{q},j} = \frac{1}{\prod_{\mathbf{q},j} 2 \sinh \frac{\hbar \omega_j(\mathbf{q})}{k_B T}}$$

Free energy: ($\{a_i\}$ = lattice parameters)

$$\begin{aligned} F(\{a_i\}, T) &= E(\{a_i\}) + F_{vib} \\ &= E(\{a_i\}) - k_B T \ln Z_{total} \\ &= E(\{a_i\}) + \sum_{\mathbf{q},j} \frac{\hbar \omega_{\mathbf{q},j}}{2} + k_B T \sum_{\mathbf{q},j} \ln(1 - \exp(-\frac{\hbar \omega_{\mathbf{q},j}}{k_B T})) \end{aligned}$$

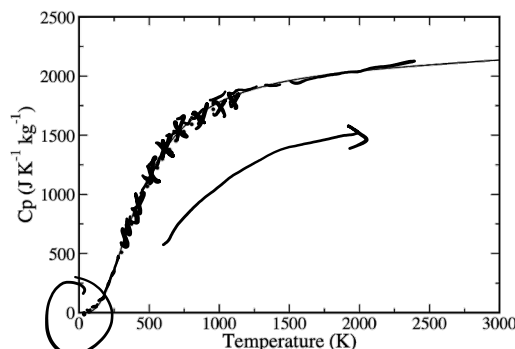
Handwritten notes:
 - $F = -\frac{1}{k} \ln Z$
 - $\sum_{\mathbf{q},j} \frac{\hbar \omega_{\mathbf{q},j}}{2}$ is labeled "CLASSICAL ELAST"
 - $k_B T \sum_{\mathbf{q},j} \ln(1 - \exp(-\frac{\hbar \omega_{\mathbf{q},j}}{k_B T}))$ is labeled "VIBRATIONAL ENTROPY"
 - An arrow points from the classical elastic term to the text "TOWARD ZERO POINT MOTION"

MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Heat capacity

Constant volume heat capacity given by:

$$\begin{aligned} C_v &= -T \frac{\partial^2 F}{\partial T^2} \\ &= \sum_{\mathbf{q},j} c_v(\mathbf{q},j) = k_B \sum_{\mathbf{q},j} \left(\frac{\hbar \omega_{\mathbf{q},j}}{2k_B T} \right) \frac{1}{\sinh^2 \left(\frac{\hbar \omega_{\mathbf{q},j}}{2k_B T} \right)} \end{aligned}$$



$$C_p - C_v = TV_0 B_0 \alpha_V^2$$

MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

The quasi-harmonic approximation: principle

$$F(\{a_i\}, T) = \underbrace{E(\{a_i\})}_{\text{CLASS.}} + \underbrace{\sum_{\mathbf{q},j} \frac{\hbar \omega_{\mathbf{q},j}}{2} + k_B T \sum_{\mathbf{q},j} \ln(1 - \exp(-\frac{\hbar \omega_{\mathbf{q},j}}{k_B T}))}_{\text{E.P. MECHAN VIBR. ENT.}} \quad \text{IF } \omega_{\mathbf{q},j} \text{ DOES NOT DEPEND ON } \{a_i\}$$

If phonon frequencies assumed constant (harmonic crystal), no dependence of the vibrational free energy on structure

→ no thermal expansion, no temperature dependence of elastic constants, heat capacity reaching a limit at high temperature, i.e. **no anharmonic effects**.

Quasi-harmonic approximation: use harmonic expression of the free energy but add additional dependence of the phonon frequencies on the **lattice parameters** $\{a_i\}$.

Thermal expansion

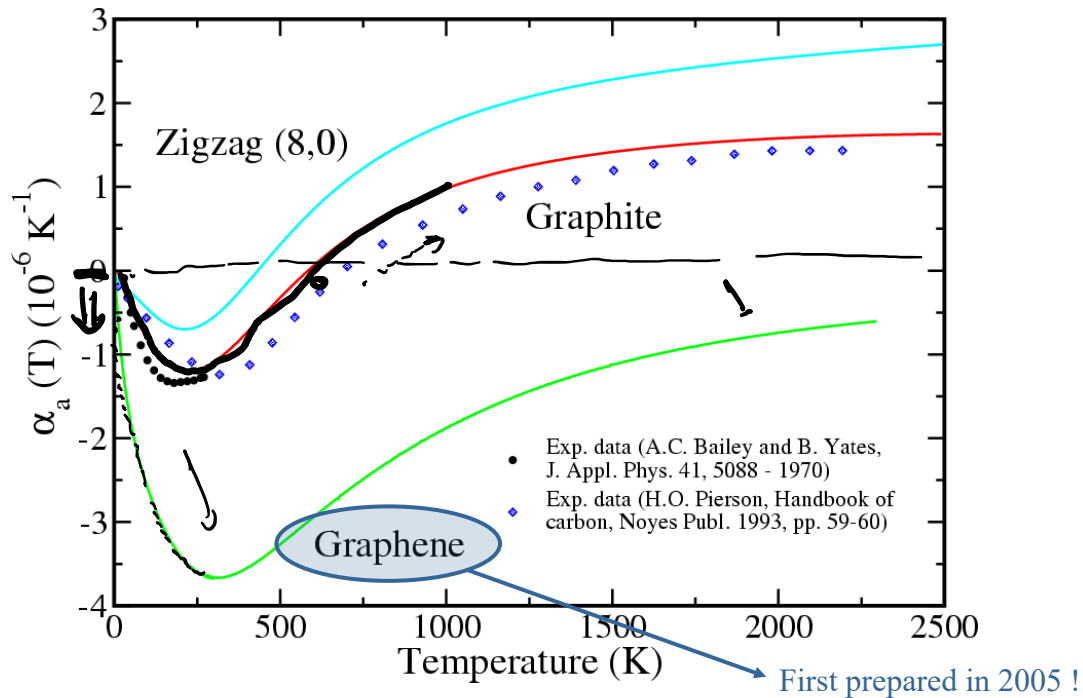
Minimization of quasi-harmonic free energy vs. lattice parameters $\{a_i\}$:

$$F(\{a_i\}, T) = \underbrace{E(\{a_i\})}_{\text{CLASSICAL}} + \underbrace{\sum_{\mathbf{q},j} \frac{\hbar \omega_{\mathbf{q},j}(\{a_i\})}{2}}_{\text{E.P.M.}} + \underbrace{k_B T \sum_{\mathbf{q},j} \ln(1 - \exp(-\frac{\hbar \omega_{\mathbf{q},j}(\{a_i\})}{k_B T}))}_{\text{VIBR. ENT.}}$$

Equilibrium lattice parameters given by that minimization change with temperature → **Thermal expansion** (or contraction):

$$\alpha_i = \frac{1}{a_i} \frac{\partial a_i}{\partial T}$$

Thermal Contraction in 2-d and 1-d Carbon

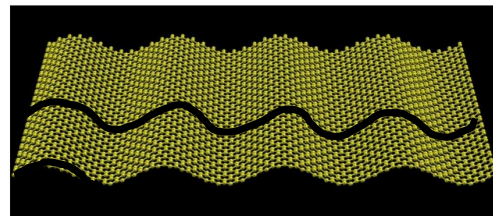
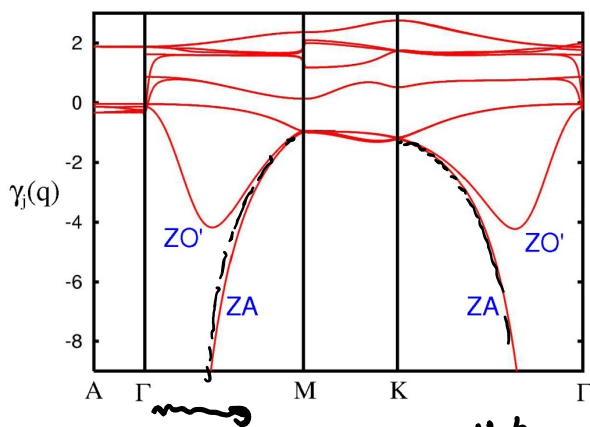


MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Grüneisen parameters for graphene

Grüneisen parameters

$$\gamma_k(\mathbf{q}, j) = \frac{-a_{0,k}}{\omega_{0,\mathbf{q},j}} \left. \frac{\partial \omega_{\mathbf{q},j}}{\partial a_k} \right|_0$$



ZA bending mode

Handwritten notes:

Normal process

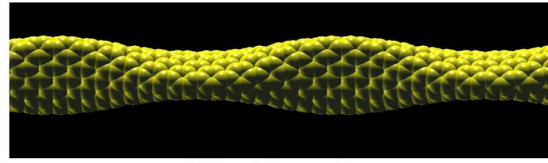
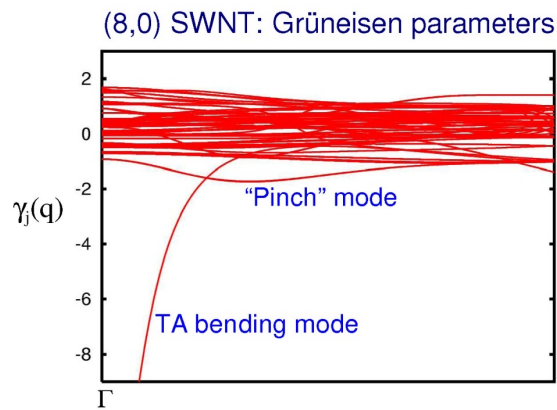
$$\omega_1 = \omega_2 + \omega_3$$

$$\vec{k}_1 = \vec{k}_2 + \vec{k}_3 + \vec{G}$$

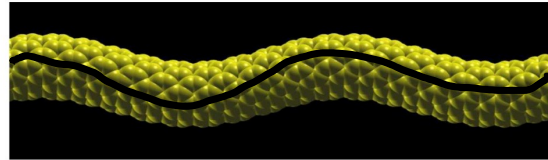
UMKLAUF

MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Grüneisen parameters for SWNT

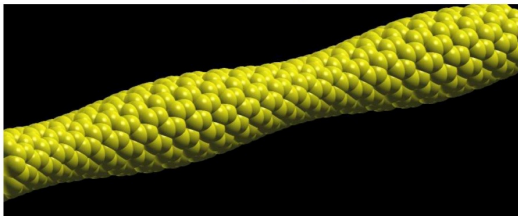


"Pinch" mode

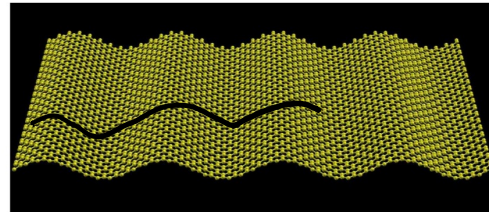


TA bending mode

Radial breathing mode



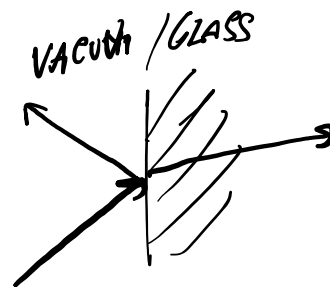
ZA bending mode of graphite



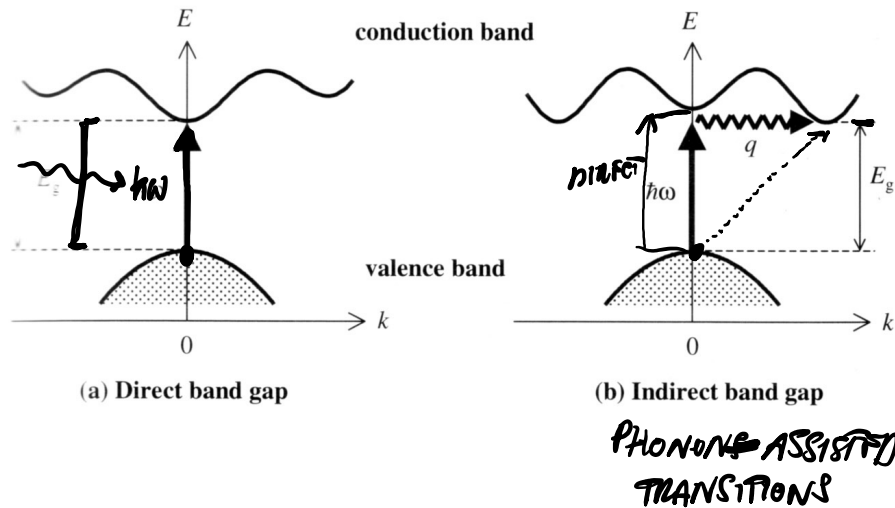
MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Optical processes

- Reflection and refraction
 - Absorption
 - Luminescence
 - Scattering
- CLASSICAL OPTICS
- QUANTUM OPTICS

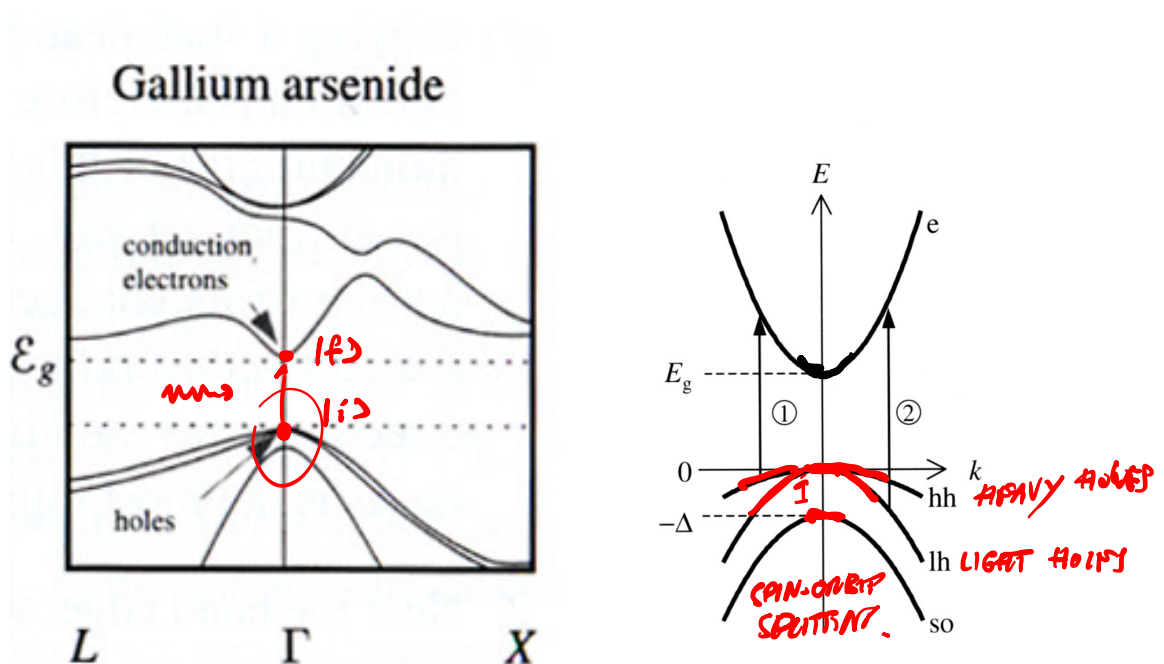


Direct and indirect transitions



MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Transition rate for direct absorption



MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Dipole-allowed selection rules

These are for atoms...

- Parity of initial and final state are opposite
- $\Delta m = -1, 0$ or 1
- $\Delta l = -1$ or 1

PROB. FOR $|i\rangle \rightarrow |f\rangle = \frac{2\pi}{\hbar} \|\langle f | \vec{r} | i \rangle\|^2$

$\cdot \delta(E_f - E_i - \hbar\omega)$
 $\cdot \delta(k_f - k_i + G)$

PERTURBATION:

IF I USE LIGHT, IT'S AN ELECTRIC FIELD $\sim \vec{V}$

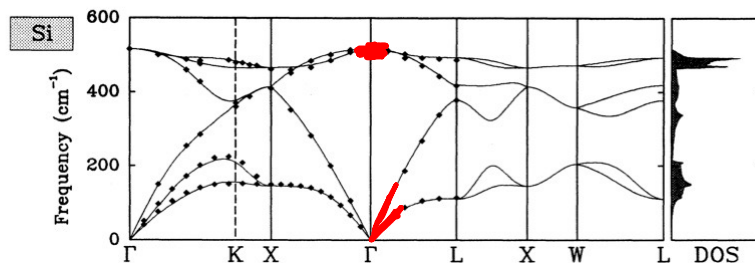
E.g. phosphorescence involves dipole-forbidden transitions that are mediated by higher order terms (magnetic dipole, electronic quadrupole)

IS
LINEAR
 $\vec{r}$

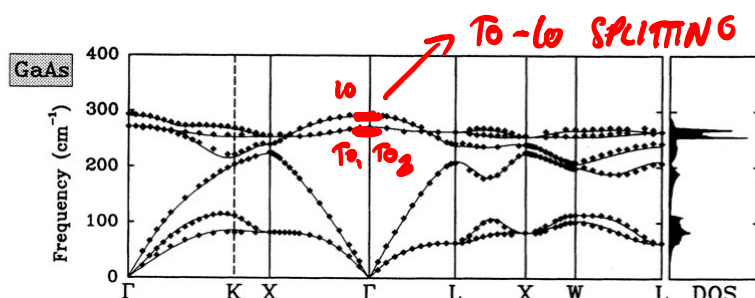
$\langle 2s | \vec{r} | 1s \rangle = 0$



Infrared active modes

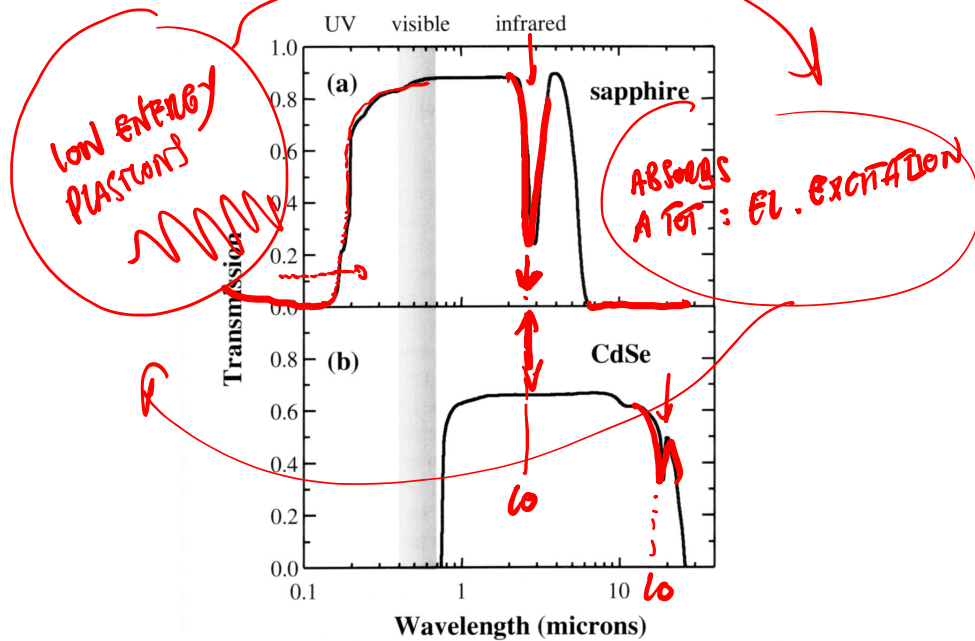


NON POLAR



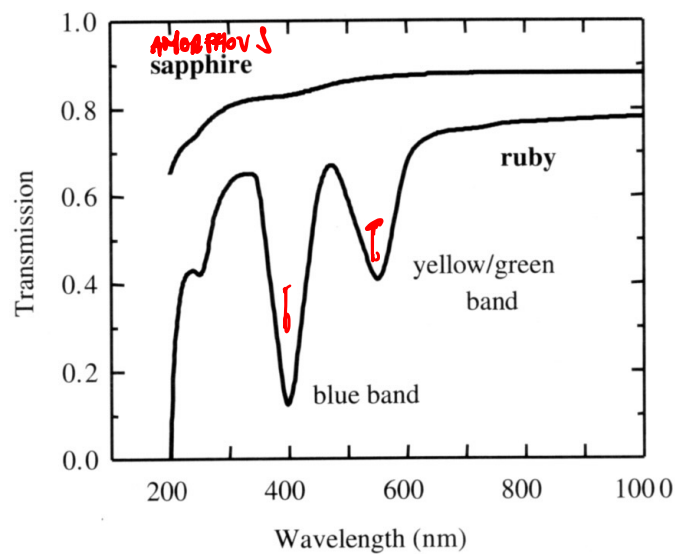
POLAR

Transmission coefficient



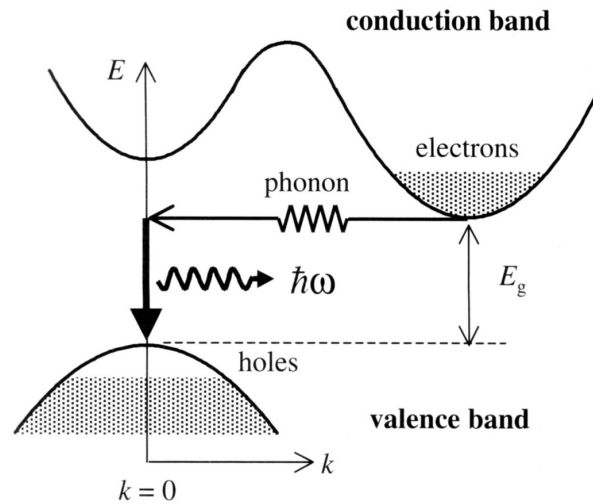
MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Transmission: amorphous vs optical



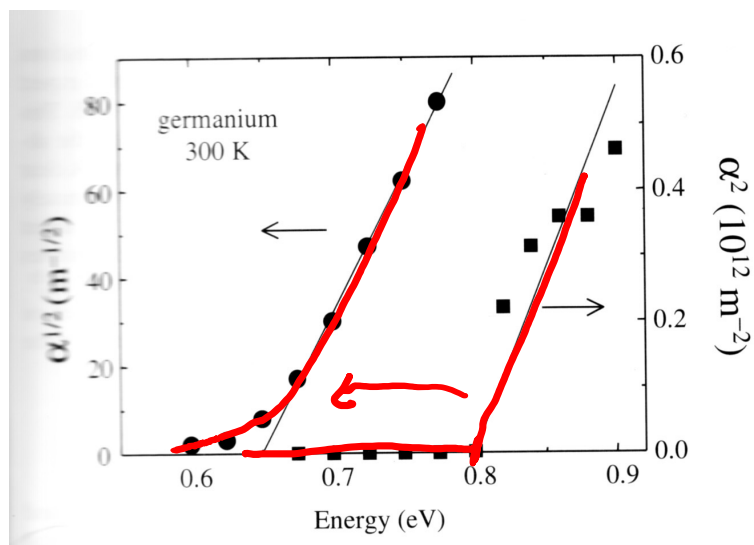
MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Indirect band gap materials



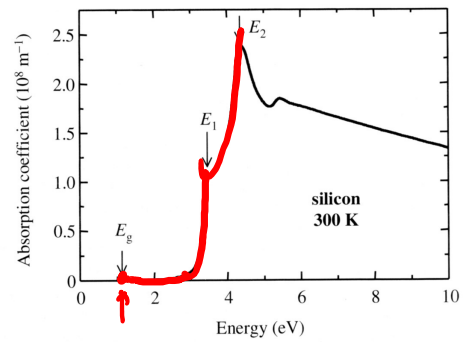
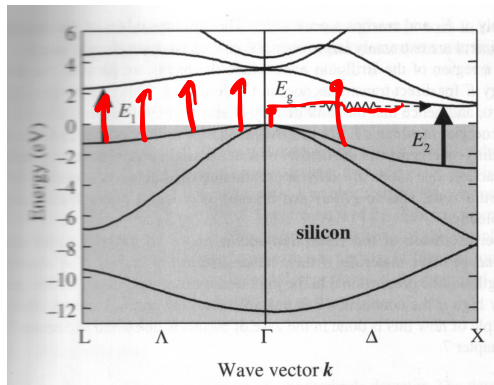
MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Indirect gap semiconductors



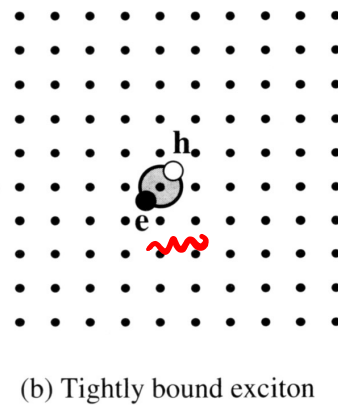
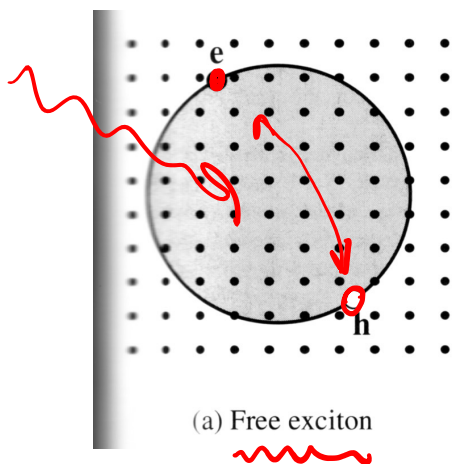
MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Absorption above the band edge



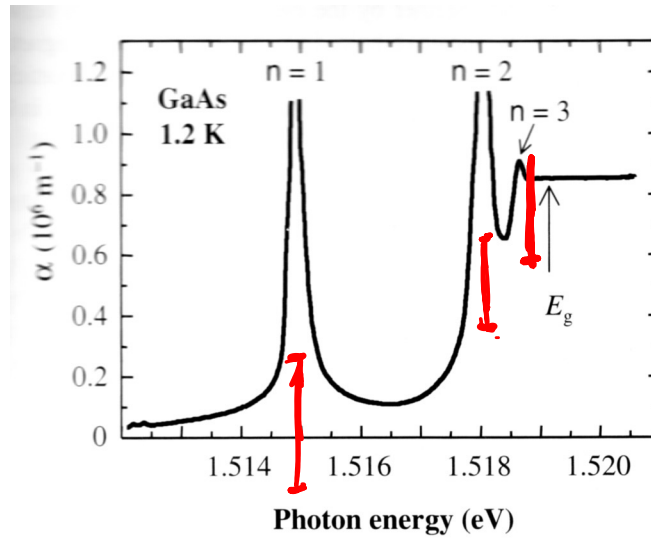
MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Excitons



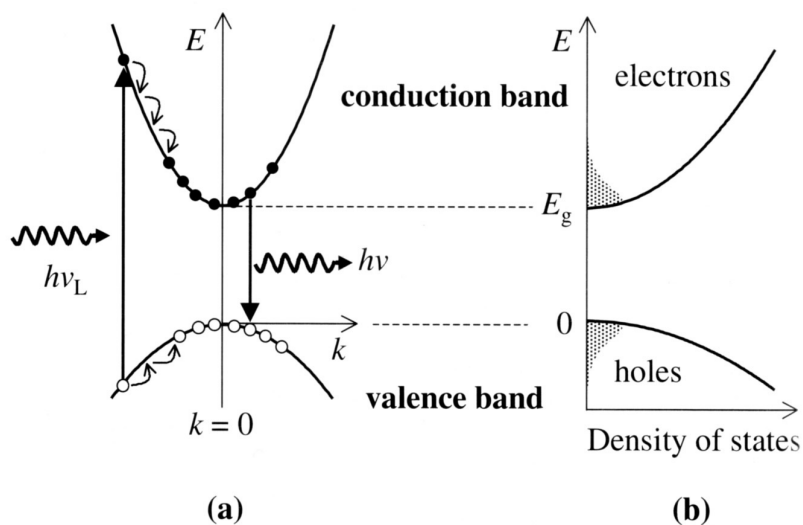
MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Excitons absorption



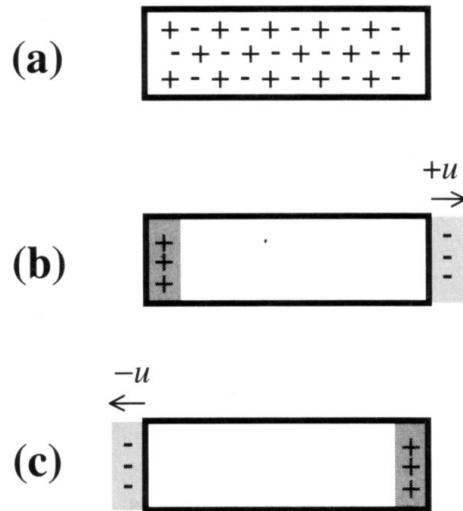
MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Photoluminescence: excitation, relaxation



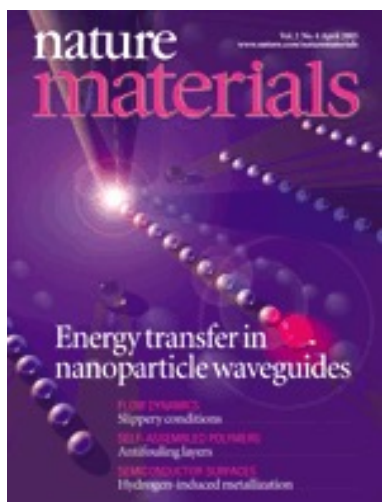
MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Plasmons



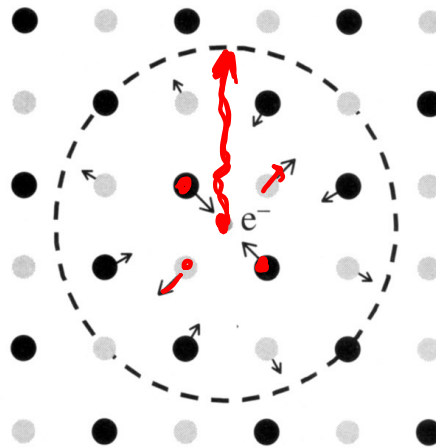
MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Plasmonics



MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

Polarons



MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

~~Monday~~
Exam: ~~Friday~~ 20 Jan 2025
15h15 to 18h15 (in room AAC231)

We will have a written exam: 3 hours, 4 questions. Two theory questions, and two exercises. **Closed book, you cannot have any material with you – at most a basic calculator. Bring pen/pencil, we'll bring paper. No cell phones, not even as a watch (we'll announce time every 1h).** In the next slide you find a list of the theory questions that could be asked (in part or in full). The exercises will closely follow the ones you did during the semester.

MSE 423 Fundamentals of Solid-state Materials - Nicola Marzari (EPFL, Fall 2024)

MSE 423 F23: Questions for the oral exam

- Schrodinger equation (time dependent, stationary); solutions for a free particle, for square wells in 1, 2 and 3 dimensions, for a potential barrier (graphical)
- Dirac notation, operators (Hermiticity, commutators), proof of the variational principle
- Five postulates of quantum mechanics
- Solving a differential equation as a diagonalization in a basis
- Angular momentum, spherical coordinates and Laplacian, spherical harmonics, Hamiltonian in a central potential
- Radial wavefunctions and nodal surfaces for the hydrogen atom, and the 3 quantum numbers n , l , m ; spin; emission and absorption lines
- 2- and many-electron wavefunctions; Hartree equations, connection to spin-statistics, Hartree-Fock concepts; atomic energy levels and the periodic table
- Schrodinger equation for molecules; molecular states and energy levels (diatomic homonuclear molecules); potential energy surfaces (energy vs distance).
- The method of Linear Combination of Atomic Orbitals (LCAO), sp^n hybridization, Huckel approach (by diagonalization)
- Symmetry operations – point group symmetries, and translational symmetries; Bravais lattices and reciprocal lattices; Wigner-Seitz cells and Brillouin zones
- Hamiltonian in a periodic potential; Bloch theorem and Bloch wavefunctions
- Band structure of the free electron gas, relation with the empirical pseudopotential method; band structures of semiconductors (Si, Ge, GaAs, and their conduction band pockets), of metals, of perovskites
- Bloch eigenstates of an atomic (exploded) crystal as Bloch sums of atomic orbitals; Bloch eigenstates of a real crystal as Bloch sums of linear-combinations of atomic orbitals; tight binding method – from levels to bands.
- Filling the bands: Fermi energy and Fermi surfaces; Fermi-Dirac statistics and Fermi-Dirac distribution; group velocity, effective mass; density of states in different cases.
- Homogeneous semiconductors: number of carriers at thermal equilibrium; density of available states; law of mass action; temp. dependence of the chemical potential on temperature.
- Impurity levels, temperature dependence of majority carriers; p-n junction; charge/field/voltage; built-in voltage
- 1-dimensional monoatomic and diatomic chain; dispersion relations for monoatomic/diatomic chain; phonons; vibration free energy and thermomechanical properties.
- Optical properties; direct and indirect transitions, absorption; excitons, plasmons, polarons.