

Review of Semiconductor Physics

Solid-state physics

The daunting task of solid state physics

- Quantum mechanics gives us the fundamental equation
- The equation is only analytically solvable for a handful of special cases
- One cannot solve the equations for more than two bodies!
- Solid-state physics is about many-body problems

There are 5×10^{22} atoms/cm³ in Si

Si atom: $1s^2 2s^2 2p^6 3s^2 3p^2$

Core: Nucleus + $1s^2 2s^2 2p^6$, Valence electrons: $3s^2 3p^2$

We'll come back to this later

Each particle is in the potential of all the other particles, which depends on their positions, which must be solved from the equation...

You have an equation with $\sim 10^{23}$ unknowns to solve. Mission impossible!

- Solid state physics is all about approximations.

Solid state Physics is about many-body problems.

The equation for 3 particles:

$$\psi = \psi(\vec{r}_1, \vec{r}_2, \vec{r}_3)$$

$$\vec{r}_i = x\hat{x} + y\hat{y} + z\hat{z}$$

$$-\frac{\hbar^2}{2m} (\nabla_1^2 + \nabla_2^2 + \nabla_3^2) \psi$$

$$+ \frac{1}{4\pi\epsilon_0} \left(\frac{q_1 q_2}{|\vec{r}_1 - \vec{r}_2|} + \frac{q_2 q_3}{|\vec{r}_2 - \vec{r}_3|} + \frac{q_3 q_1}{|\vec{r}_3 - \vec{r}_1|} \right) \psi$$

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Crystal structures

If we assume the atomic cores have known and fixed positions, we only need to solve the equation for the valence electrons. Life much easier!

Static lattice approximation

- Justification
- Related/similar approximation: Born-Oppenheimer

Crystal structures

If you shine X-ray on a piece of solid, very likely you'll have a diffraction pattern.

That means **periodicity** in the structure.

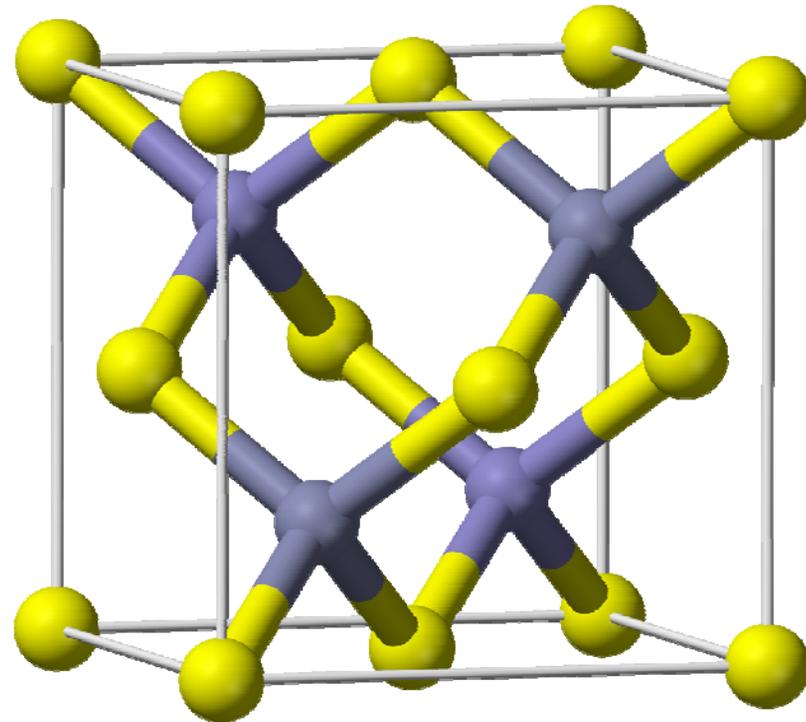
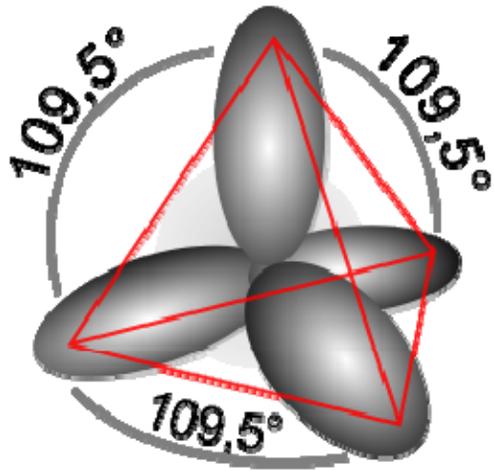
There may be a way in which we only need to study the several valence electrons.

“valence electrons” \neq “valence band electrons”

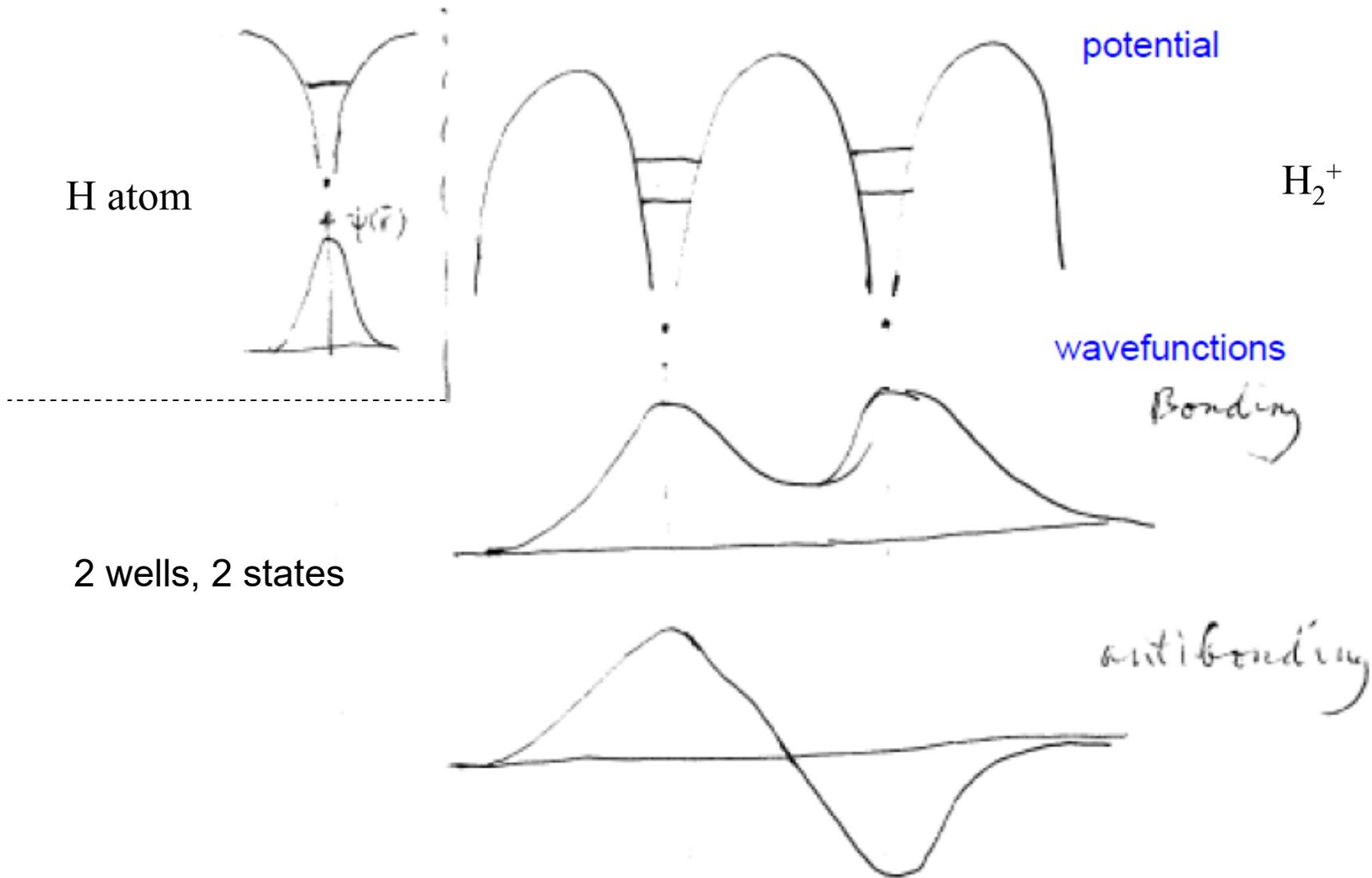
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Energy bands

- Bonding types – classroom discussion
- The bond picture vs. the band picture



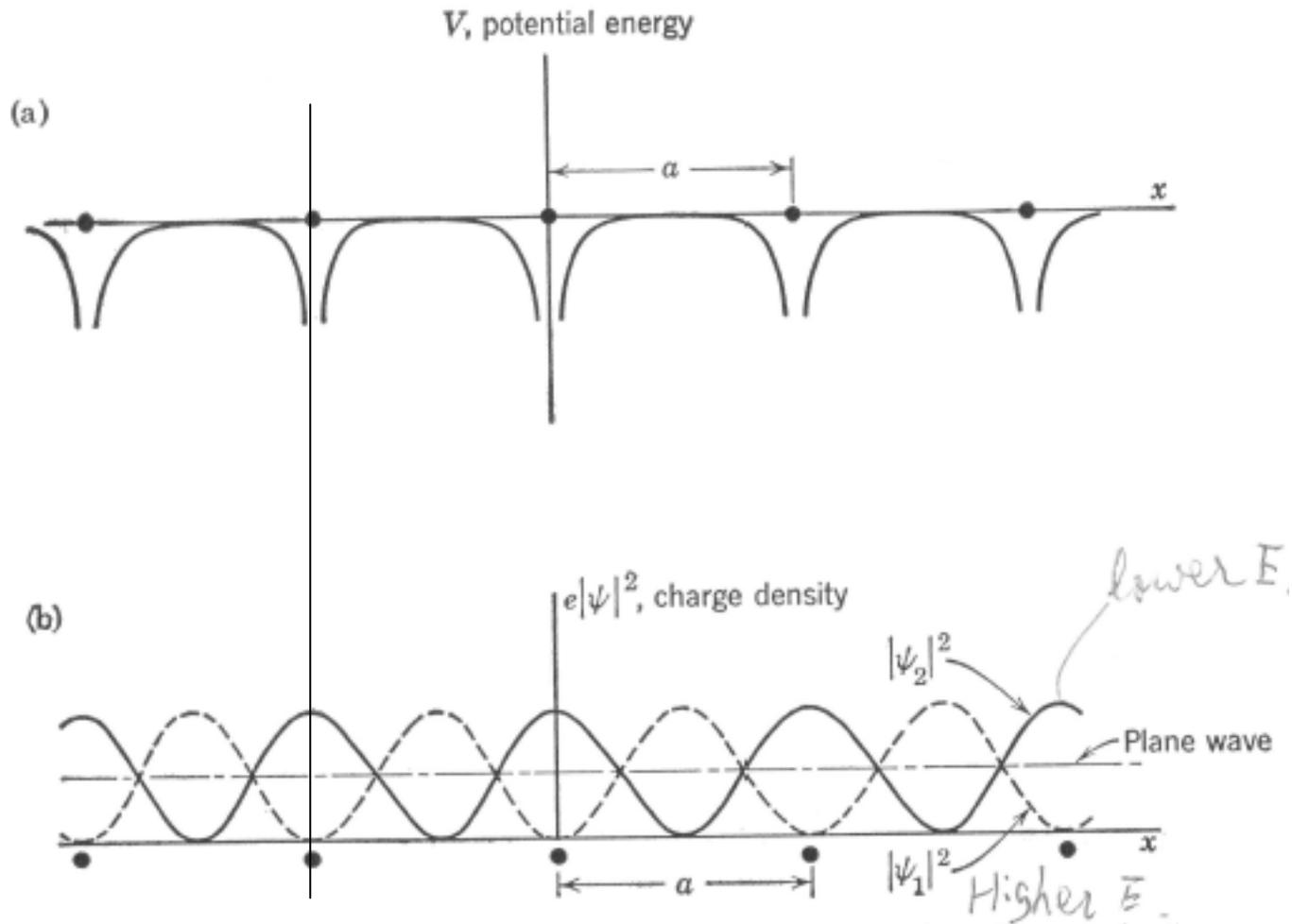
Bonding and antibonding
Conduction band and valence band

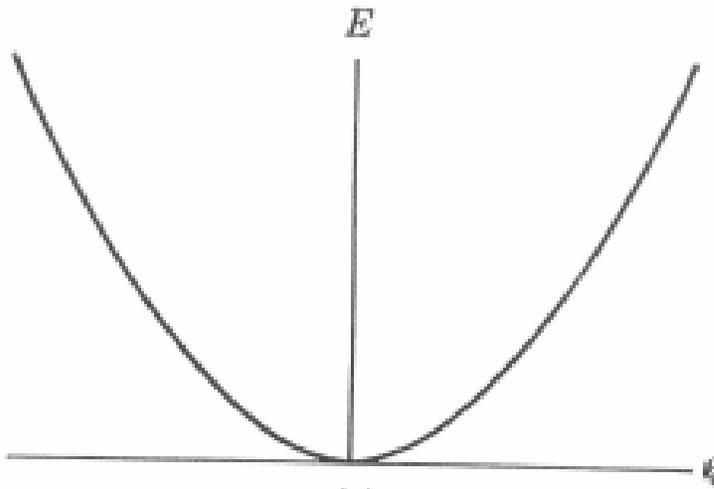


Now imagine N wells. N states. $N/2$ in a lower band, $N/2$ in a upper band.

The bond picture is important if you work with not-so-conventional semiconductors, e.g. a-Si:H, sp^2 carbon based stuff, etc.

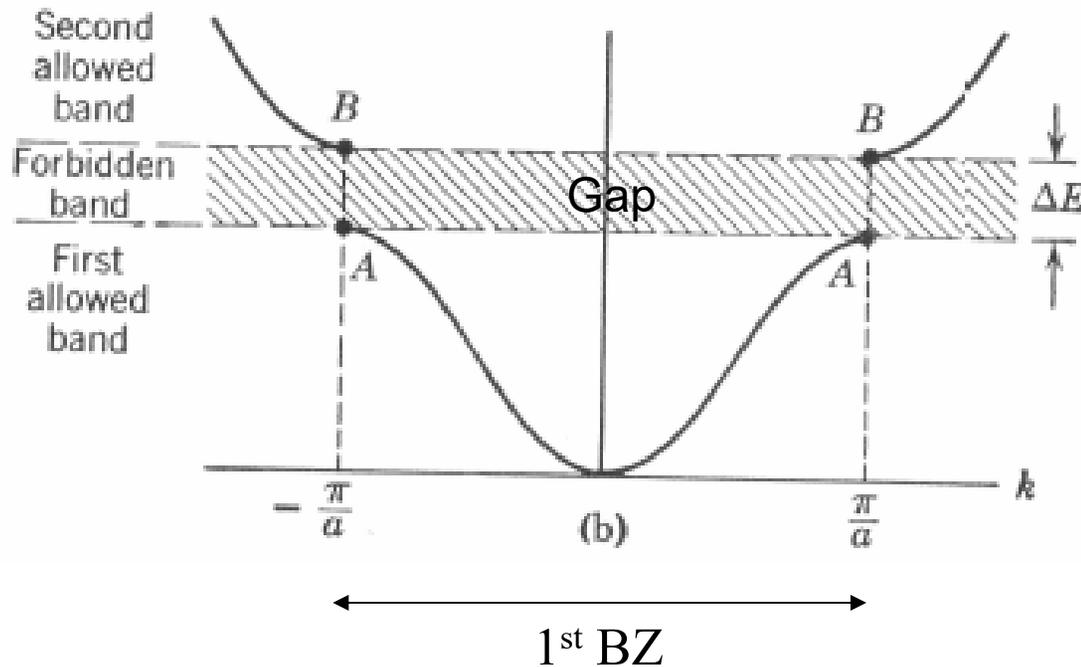
In the band picture, the band gap is the consequence of Bragg diffraction:
 Two plane waves $e^{\pm ikx}$ form standing waves
 - one peaks near the atoms and the other between them





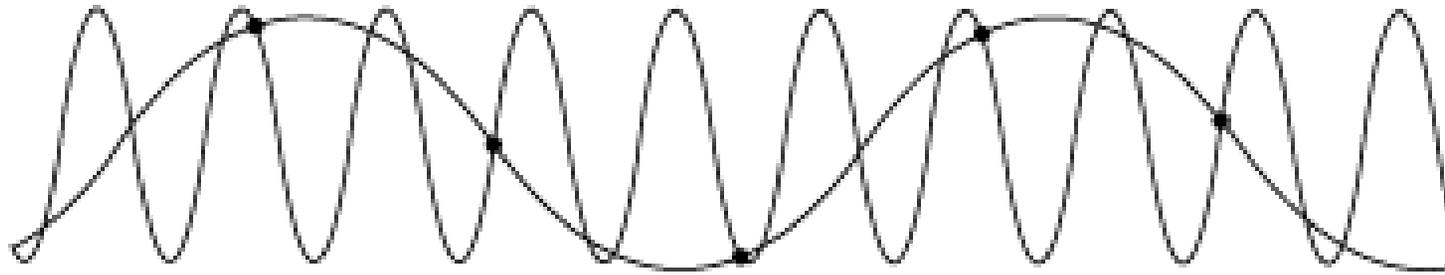
The k (vector) of the plane wave is changed upon reflection by

$$|\Delta k| = |k_f - k_i| = 2 \left(n \frac{2\pi}{2a} \right) = n \frac{2\pi}{a}$$



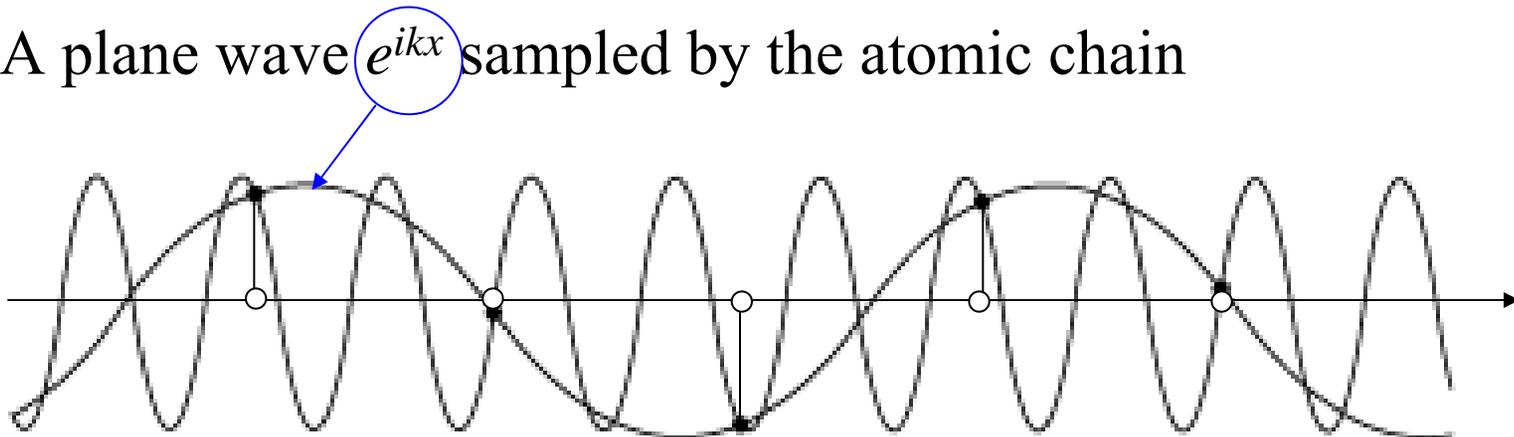
In the 1D case, those $k = \Delta k/2 = n\pi/a$ correspond to constructive interference, i.e., standing waves.

You can draw the E-k just in the 1st BZ. Over-/under-sampling of a plane wave.



Aliased Signal Due to Undersampling

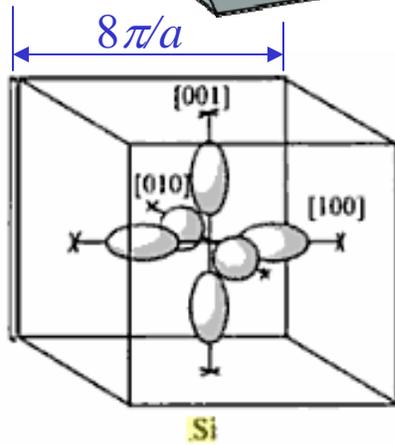
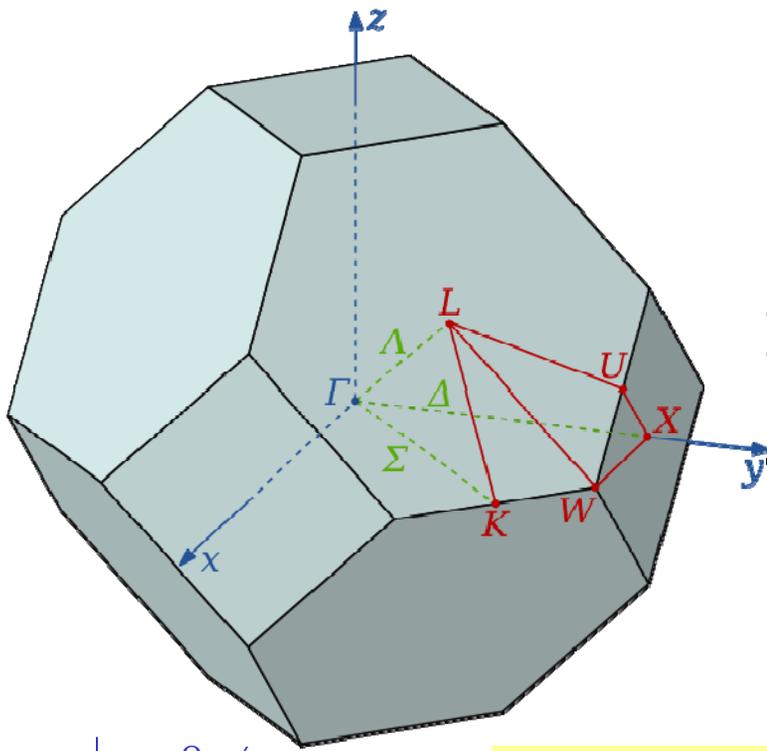
A plane wave e^{ikx} sampled by the atomic chain



You can draw the $E-k$ just in the 1st BZ.
 Over-/under-sampling of a plane wave.
 The concept is extended to 3D space.

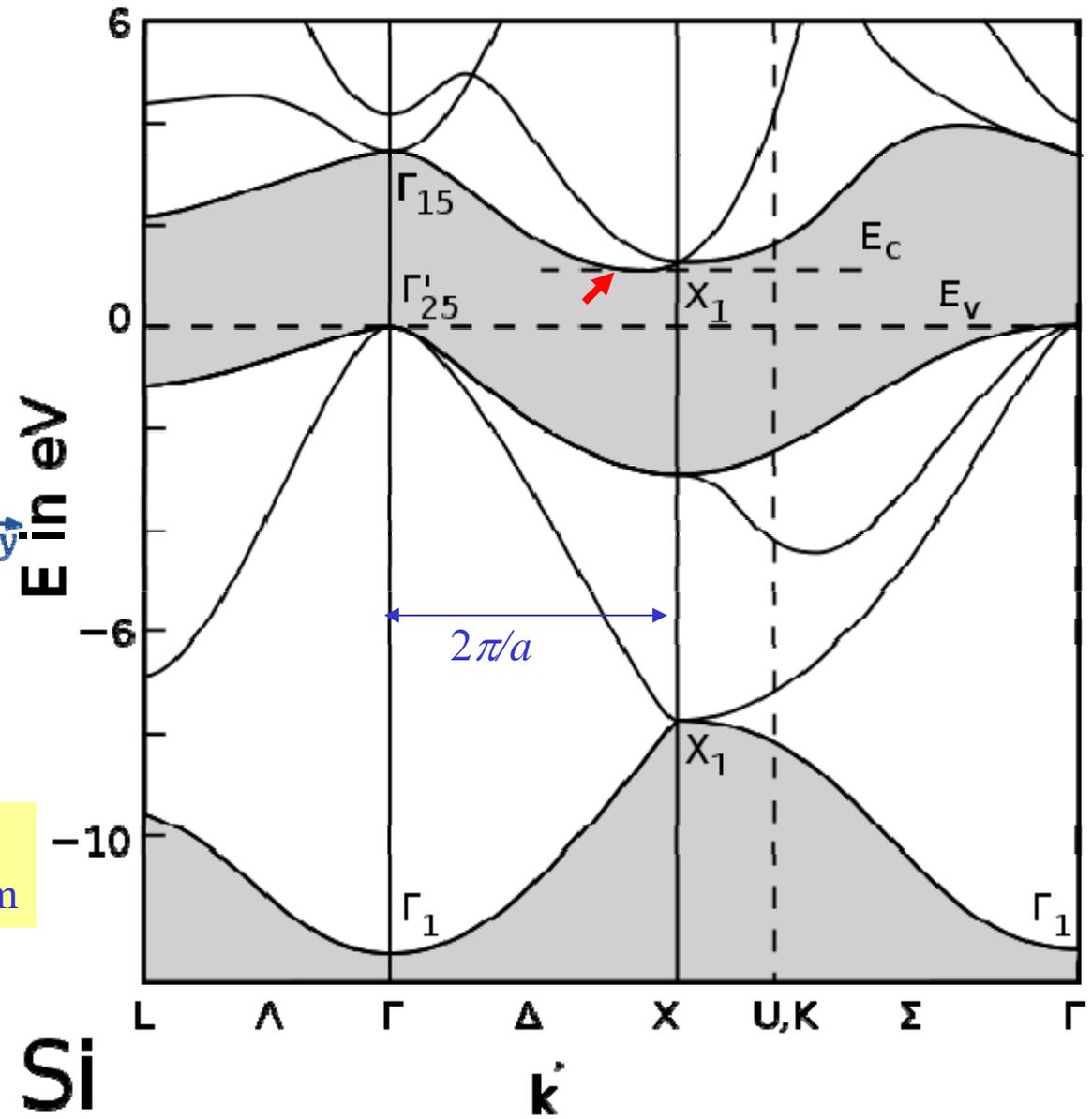
- Band structure
3D case

Only need to show 1st BZ.

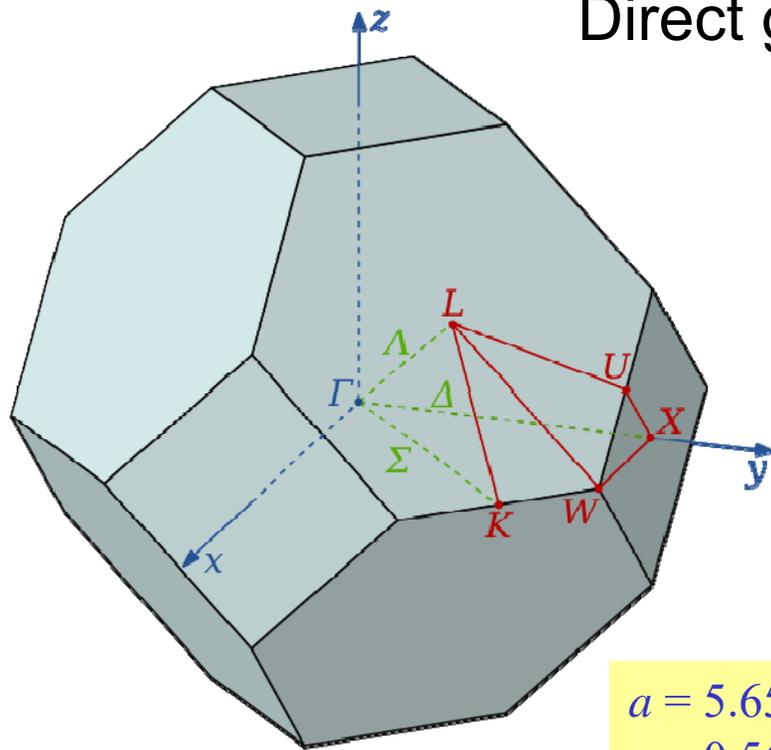


$a = 5.43 \text{ \AA}$
 $= 0.543 \text{ nm}$

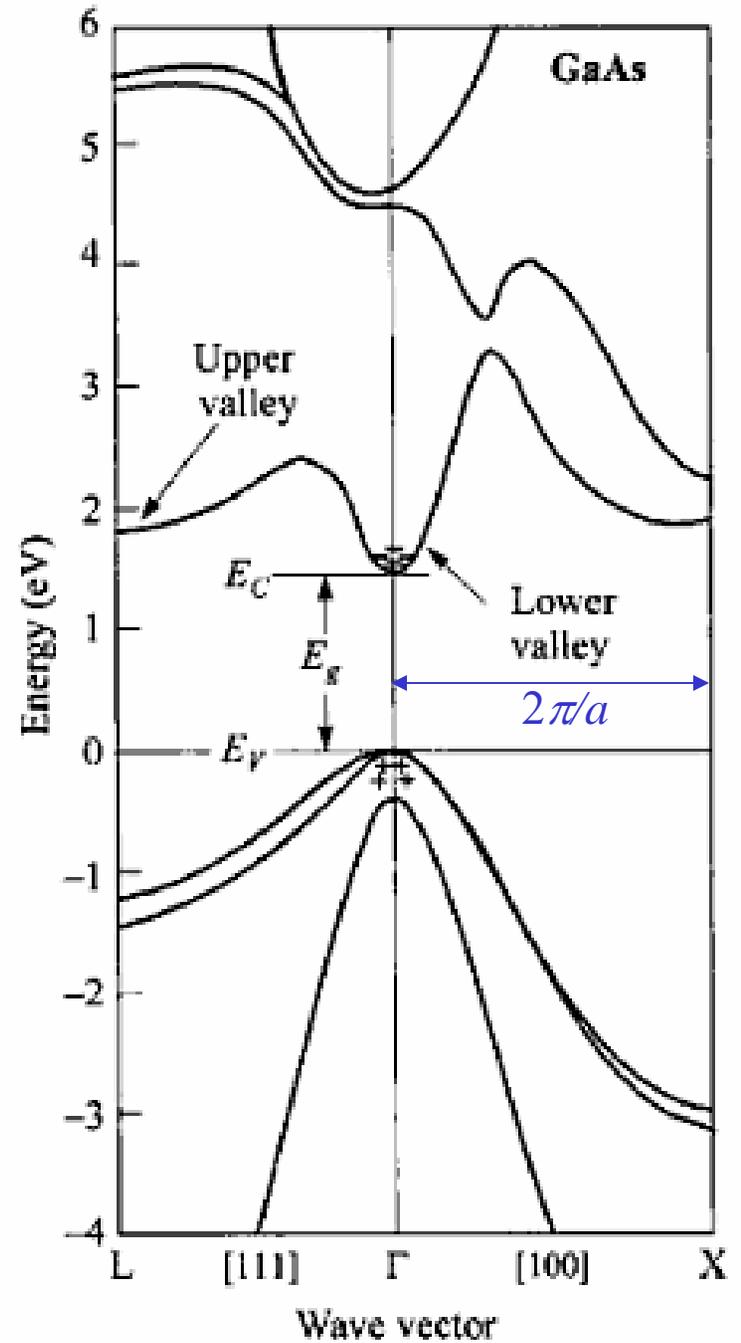
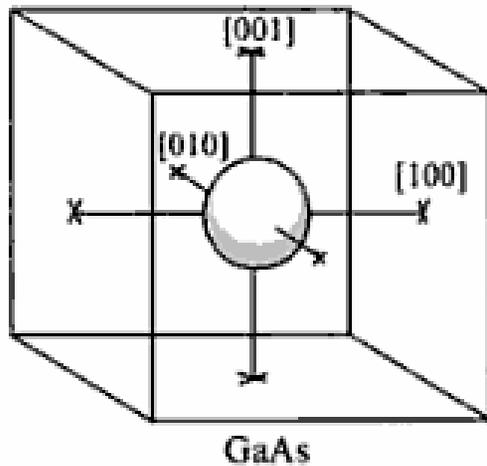
Indirect gap



Direct gap



$a = 5.65 \text{ \AA}$
 $= 0.565 \text{ nm}$



- The band picture – Bloch's Theorem

Notice it's a theorem, not a law. Mathematically derived.

The theorem:

The eigenstates $\psi(\mathbf{r})$ of the one-electron Hamiltonian

$$\hat{H} = -\frac{\hbar^2}{2m} \nabla^2 + \underbrace{V(\mathbf{r})}_{\text{including contributions from all other e's}}$$

← lattice vectors

where $V(\mathbf{r} + \mathbf{R}) = V(\mathbf{r})$ for all \mathbf{R} in a Bravais lattice can be chosen to have the form of a plane wave times a function with the periodicity of the Bravais lattice:

$$\psi_{n,\mathbf{k}}(\mathbf{r}) = e^{i\mathbf{k}\cdot\mathbf{r}} u_{n,\mathbf{k}}(\mathbf{r})$$

where $u_{n,\mathbf{k}}(\mathbf{r} + \mathbf{R}) = u_{n,\mathbf{k}}(\mathbf{r})$.

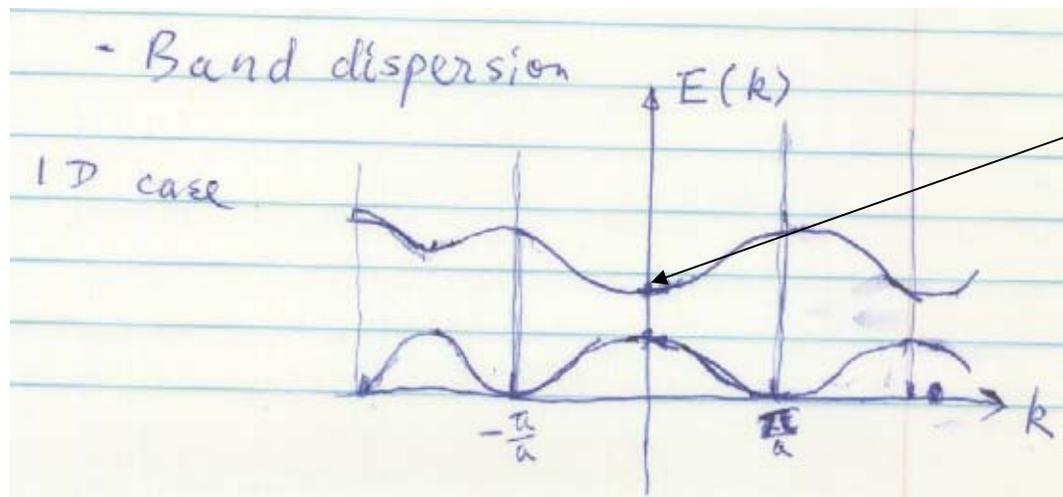
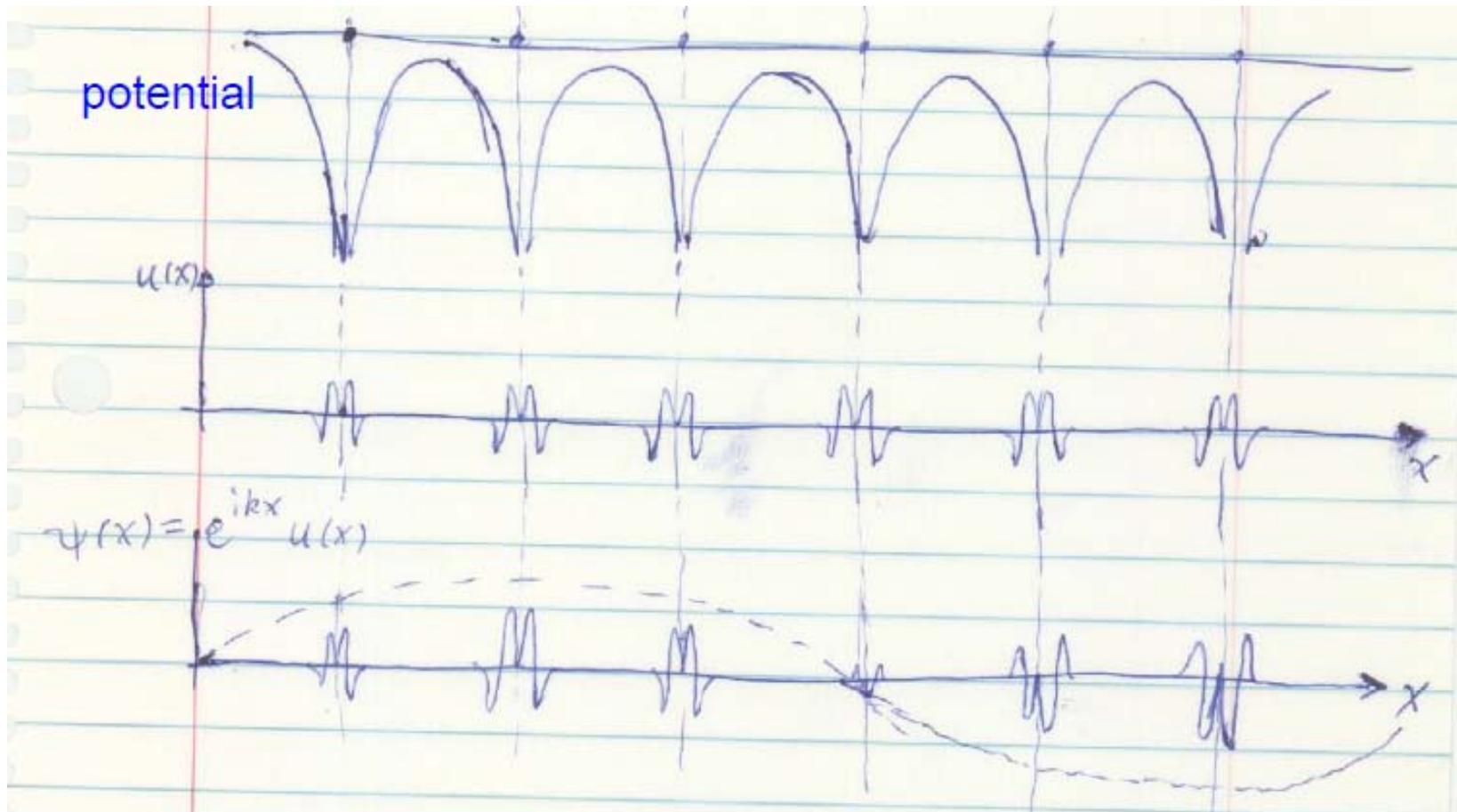
Equivalently,

$$\psi_{n,\mathbf{k}}(\mathbf{r} + \mathbf{R}) = e^{i\mathbf{k}\cdot\mathbf{R}} \psi_{n,\mathbf{k}}(\mathbf{r})$$

A periodic function $u(\mathbf{r})$ is a solution, but the Bloch function is general.

Physical picture

- Wave function



$$v_n = \frac{\hbar(k - k_0)}{m^*} = \frac{1}{\hbar} \frac{dE_n}{dk}$$

Limitations of the band theory

Static lattice: Will introduce phonons

Perfect lattice: Will introduce defects

One-electron Schrödinger Eq: We in this class will live with this

Justification: the effect of other electrons can be regarded as a kind of background.

Semi-classical theory

Free electron	Bloch electron
$\hbar\mathbf{k}$ <u>is</u> the momentum.	$\hbar\mathbf{k}$ is the crystal momentum, which is <u>not</u> a momentum, but is <u>treated as</u> momentum in the semiclassical theory. n is the band index.
$E(\mathbf{k}) = \frac{\hbar^2 k^2}{2m}$	$E(\mathbf{k}) = \frac{\hbar^2 \mathbf{k} - \mathbf{k}_0 ^2}{2m^*} \quad E_n(\mathbf{k}) = E_n(\mathbf{k} + \mathbf{K})$
<div style="display: flex; justify-content: space-around;"> <div style="text-align: center;"> <p>1D</p> $v = \frac{\hbar k}{m} = \frac{1}{\hbar} \frac{dE}{dk}$ <p>(group velocity)</p> </div> <div style="text-align: center;"> <p>3D</p> $\mathbf{v} = \frac{\hbar \mathbf{k}}{m} = \frac{1}{\hbar} \nabla_{\mathbf{k}} E(\mathbf{k})$ </div> </div>	<div style="display: flex; justify-content: space-around;"> <div style="text-align: center;"> <p>1D</p> $v_n = \frac{\hbar(k - k_0)}{m^*} = \frac{1}{\hbar} \frac{dE_n}{dk}$ </div> <div style="text-align: center;"> <p>3D</p> $\mathbf{v}_n(\mathbf{k}) = \frac{\hbar \mathbf{k} - \mathbf{k}_0 }{m^*} = \frac{1}{\hbar} \nabla_{\mathbf{k}} E_n(\mathbf{k})$ </div> </div>
$\psi_{\mathbf{k}}(\mathbf{r}) = e^{i\mathbf{k} \cdot \mathbf{r}}$	$\psi_{n,\mathbf{k}}(\mathbf{r}) = e^{i\mathbf{k} \cdot \mathbf{r}} u_{n,\mathbf{k}}(\mathbf{r})$ $u_{n,\mathbf{k}}(\mathbf{r} + \mathbf{R}) = u_{n,\mathbf{k}}(\mathbf{r})$

If you want to really understand the semiclassical theory and why **you can treat the band edges as potentials**, read (how?) James, Physical Review **76**, 1611 (1949).

The Bloch (i.e. semiclassical) electron behaves as a particle following Newton's laws.

(We are back in the familiar territory.)

- With a mass m^* (meaningful near band extrema)
- Emerging from the other side of the first Brillouin zone upon hitting a boundary

Newton's 1st law: the Bloch electron moves forever

Can get a current w/o applying a voltage?

What is that constant speed if there's no applied voltage (field/force)?

Newton's 2nd law:

$$F = dp/dt = \hbar dk/dt$$

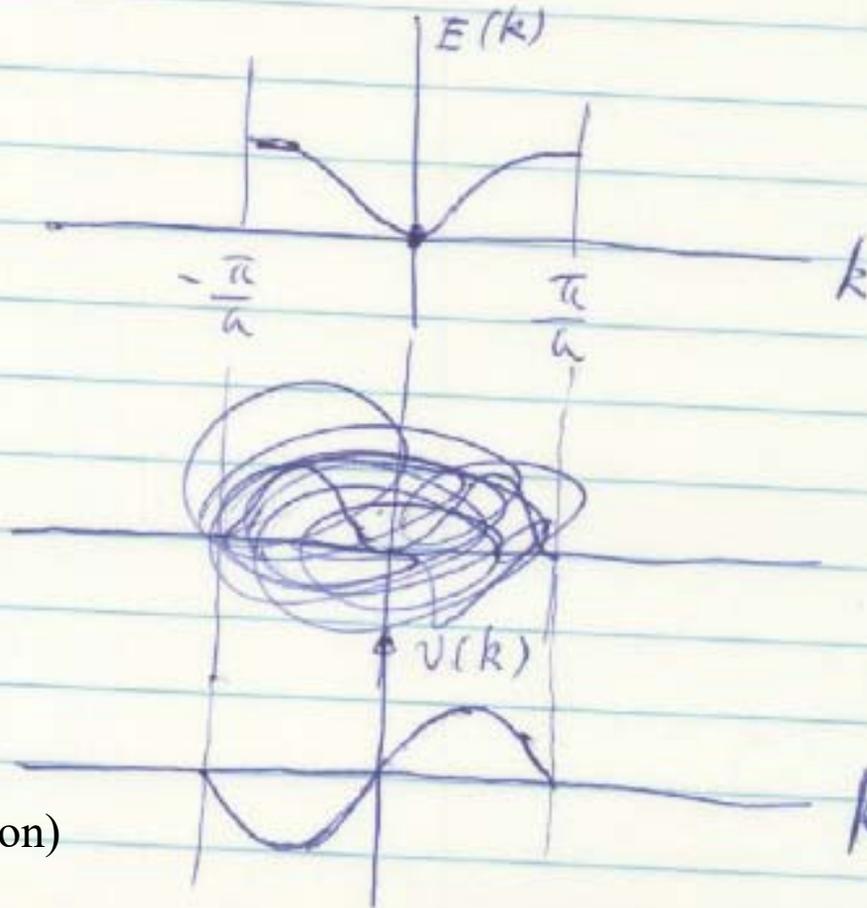
Consider one electron, a full band of e's, and a partial band of e's

Oscillation in dc field for a partially filled band. So far not observed yet. Why?

Compare the free e & the Bloch e.
The free e:

The quantum view (wave packet); the classical view; the semiclassical view

The Bloch e follows Newton's laws
with a mass m^*



“Newton’s 2nd law”

$$\frac{dk}{dt} = \frac{F}{\hbar}$$

translation
in k space.
oscillation in
real space.

$$v_n = \frac{1}{\hbar} \frac{dE_n}{dk}$$

(group velocity;
not an approximation)

The concept of the hole

A FULL BAND of electrons do NOT conduct!

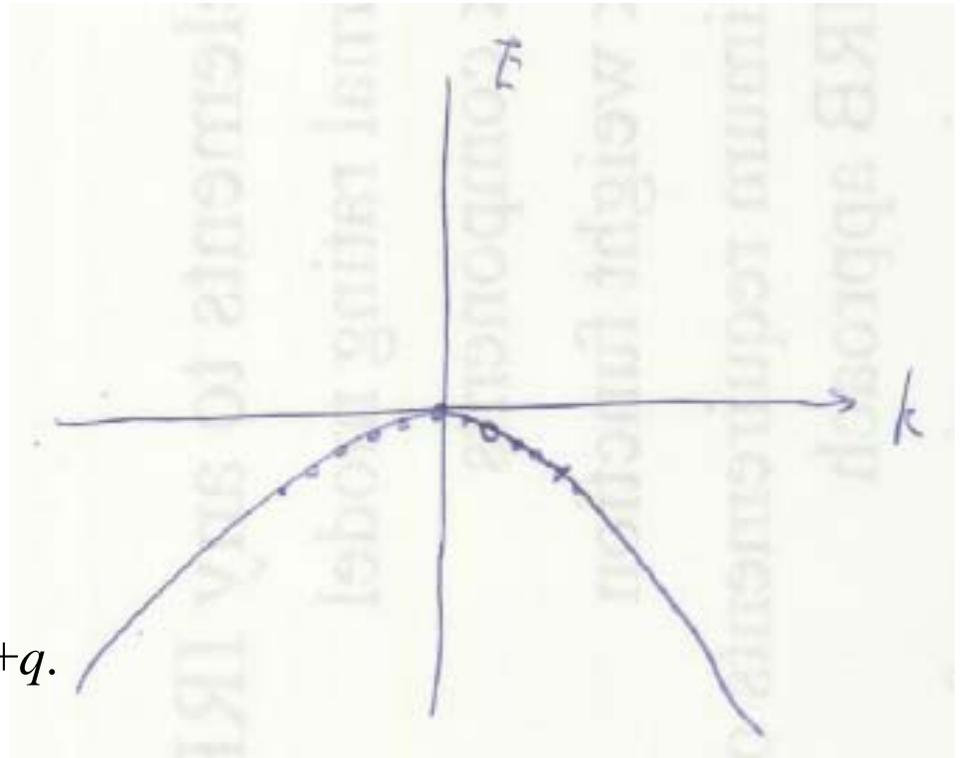
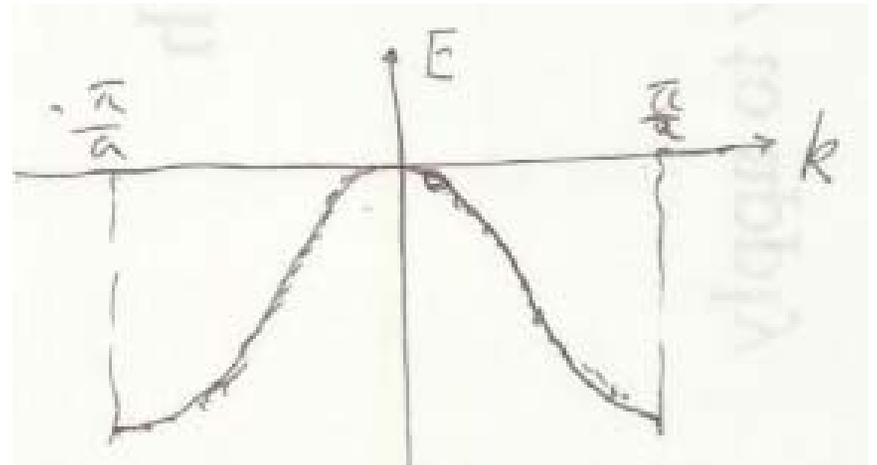
$$\sum_{\mathbf{k}} \mathbf{v}(\mathbf{k}) = 0$$

$$\mathbf{v}(\mathbf{k}_h) + \sum_{\mathbf{k} \neq \mathbf{k}_h} \mathbf{v}(\mathbf{k}) = 0$$

$$\mathbf{v}(\mathbf{k}_h) = - \sum_{\mathbf{k} \neq \mathbf{k}_h} \mathbf{v}(\mathbf{k})$$

$$q\mathbf{v}(\mathbf{k}_h) = -q \sum_{\mathbf{k} \neq \mathbf{k}_h} \mathbf{v}(\mathbf{k})$$

As if the “hole” carries positive charge $+q$.



Real crystals are not perfect. Defects scatter electrons.

On average, the electron is scattered once every time period τ . Upon scattering, the electron forgets its previous velocity, and is “thermalized.”

$$v_d = \frac{F\tau}{m^*} = \frac{q\mathcal{E}}{m^*}\tau \equiv \mu\mathcal{E} \quad \Rightarrow \quad \mu = \frac{q\tau}{m^*} \quad \text{Mobility}$$

$$J = \sigma\mathcal{E} = qnv_d = qn\mu\mathcal{E} \quad \Rightarrow \quad \sigma = qn\mu = \frac{q^2 n \tau}{m^*}$$

Note:

It's the defects, **not** the atoms (ions), that are scattering the electrons!
How can we ignore the atoms (ions)?!

The Drude (or crude?) model

For a metal, you know n from its valence and atom density, so you know μ by measuring conductivity.

$$\tau = m\mu / q \rightarrow \text{The mean free path } l = v_{th}\tau = v_{th}m\mu / q \gg a$$

There are other scattering mechanisms, e.g., phonons.

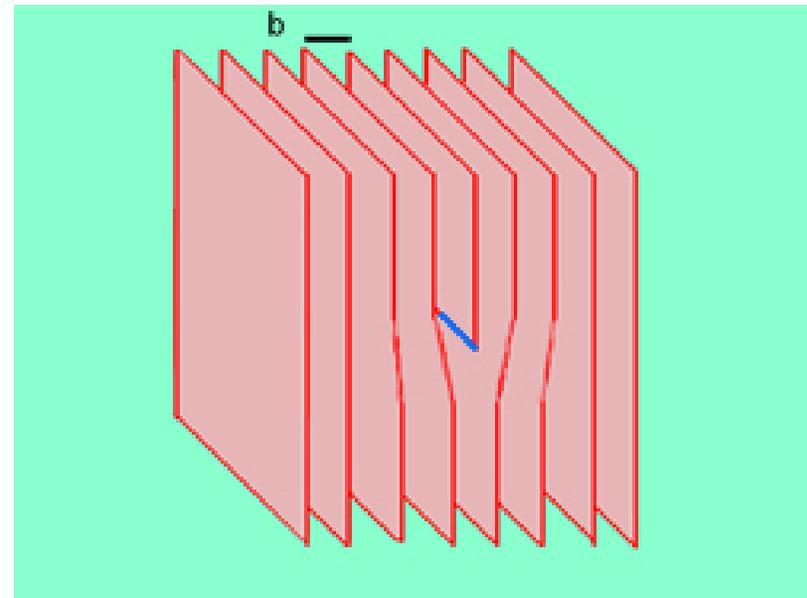
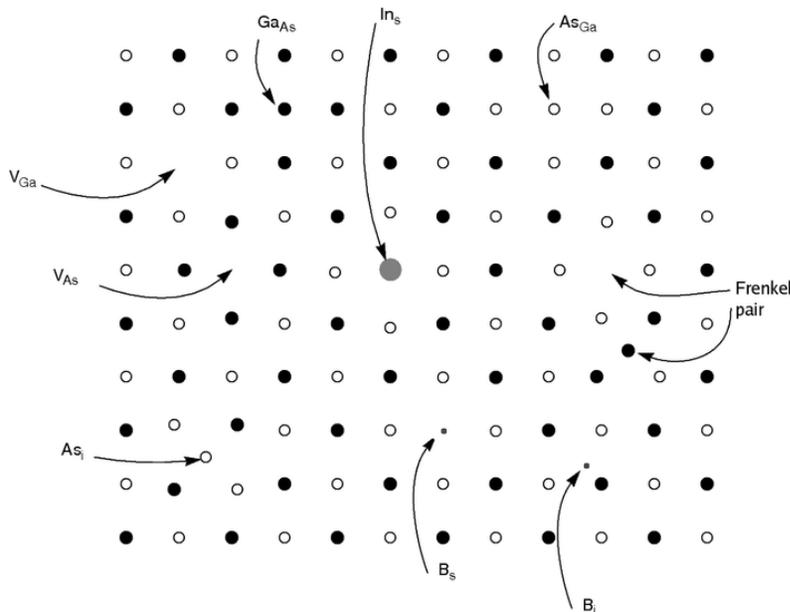
We have mentioned defect scattering:

Real crystals are not perfect. Defects scatter electrons.

On average, the electron is scattered once every time period τ . Upon scattering, the electron forgets its previous velocity, and is “thermalized.”

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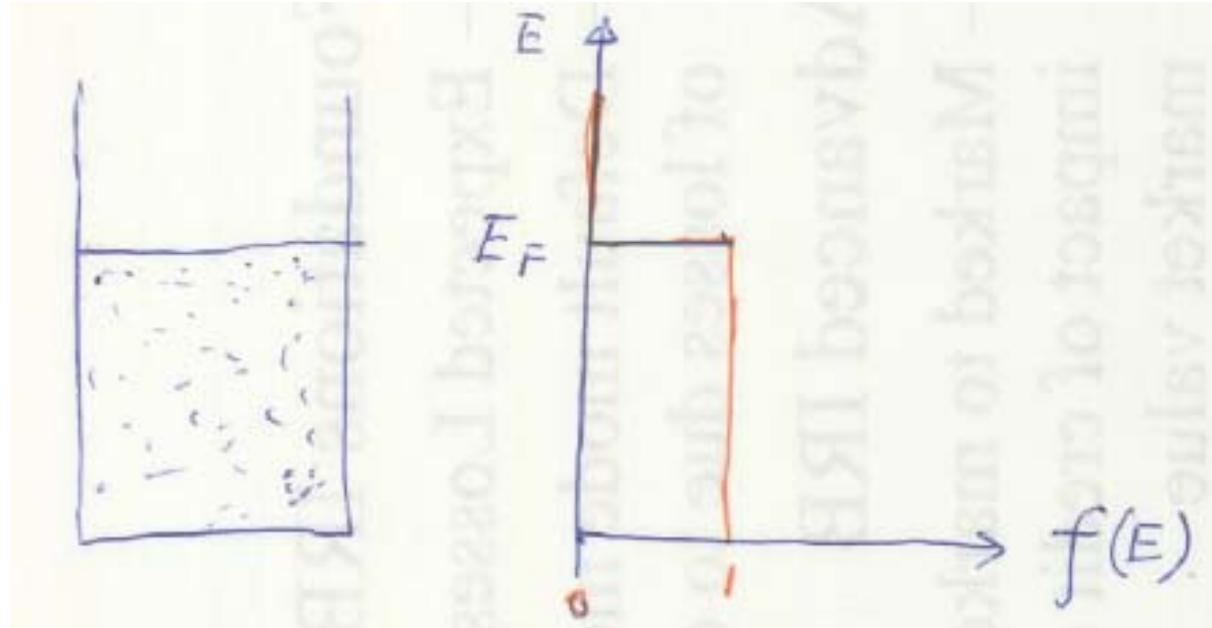
$$J = \sigma\mathcal{E} = qnv_d = qn\mu\mathcal{E} \quad \Rightarrow \quad \sigma = qn\mu = \frac{q^2n\tau}{m^*}$$



Any deviation from perfect periodicity is a defect. A perfect surface is a defect.

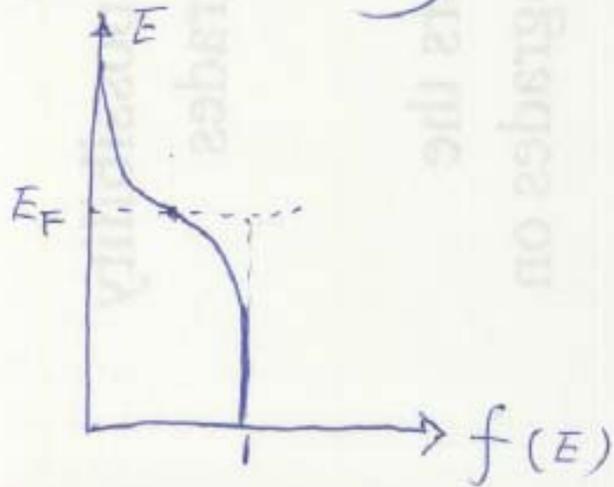
Carrier Statistics

- Fermi-Dirac distribution



$f(E)$ is the probability of a state at energy E being occupied.

Now, imagine each particle is energetic, bouncing around



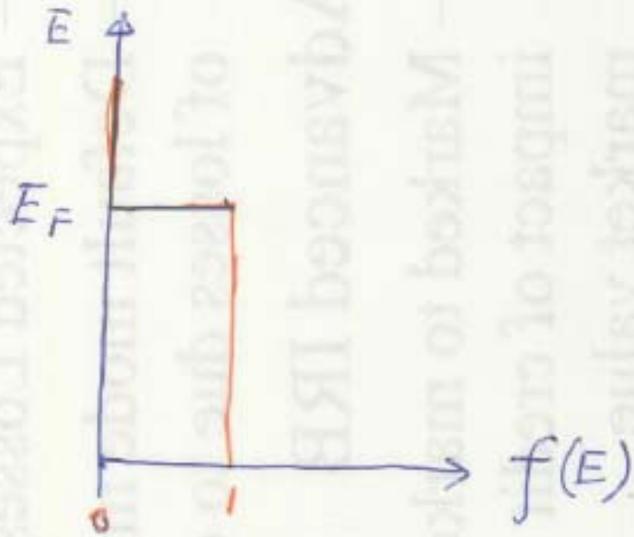
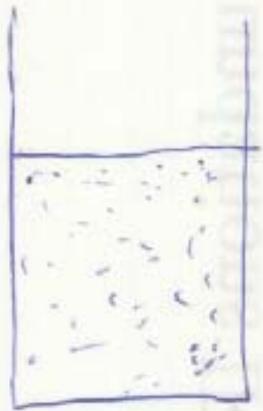
$$f(E) = \frac{1}{e^{\frac{E - E_F}{k_B T}} + 1}$$

Features to notice.

- $f(E_F) = \frac{1}{2}$ for any T .

- When $T = 0$.

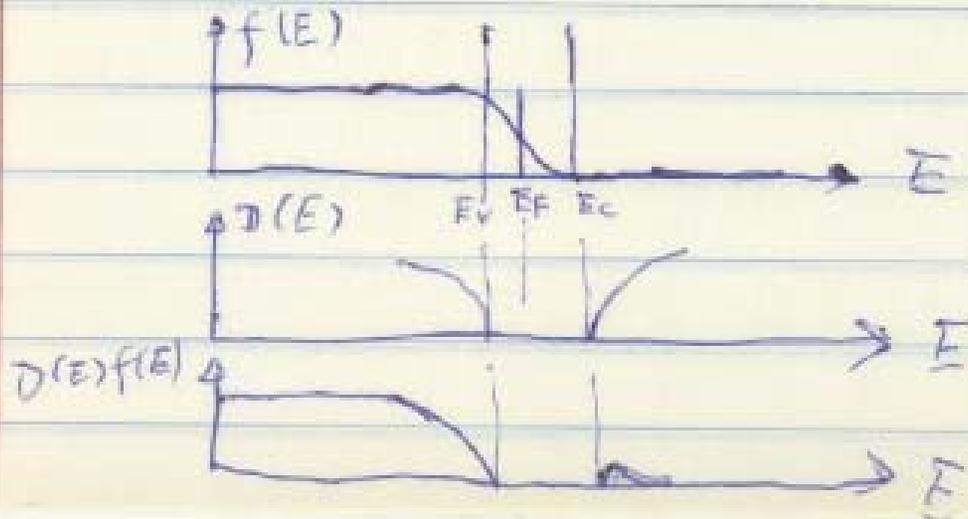
$$f(E) = \begin{cases} 0 & \text{for } E > E_F \\ \frac{1}{2} & \text{for } E = E_F \\ 1 & \text{for } E < E_F \end{cases}$$



Density of States

How many states are there in the energy interval dE at E ? (per volume)

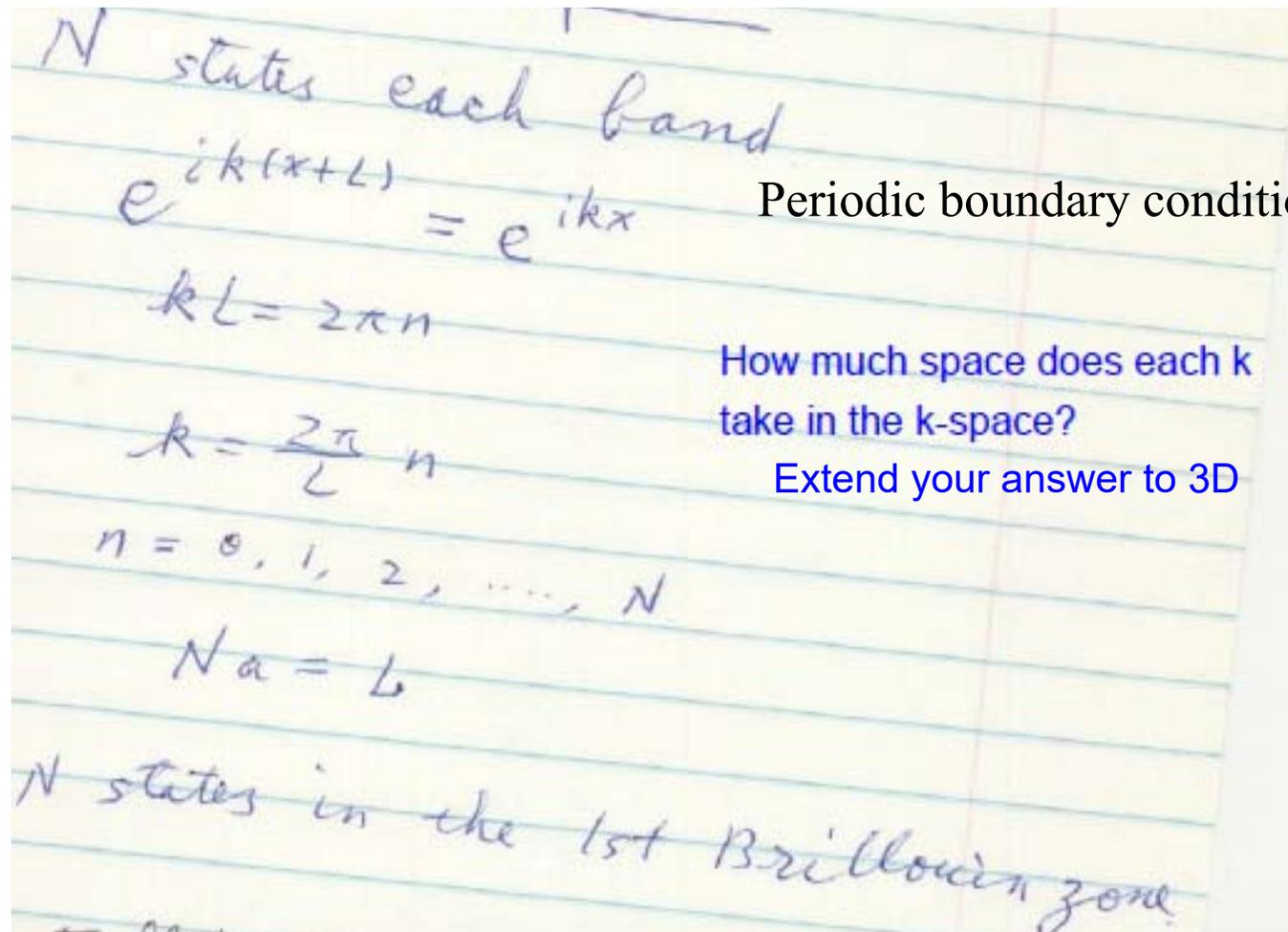
$$D(E) dE$$



Possible values of k

$$k = 2\pi n/L, n = 1, 2, 3, \dots, N$$
$$L = Na$$

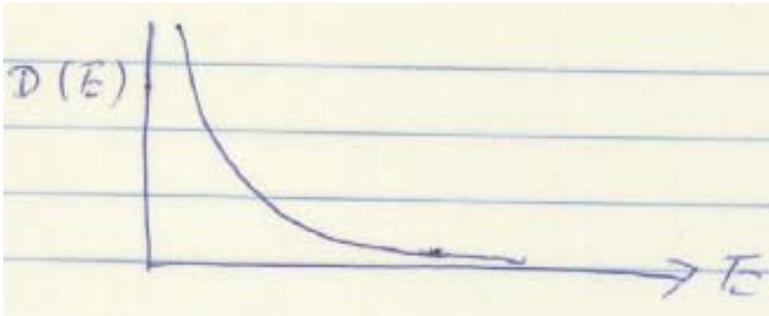
Discrete but quasi-continuous



How to find $D(E)$

1D case:

Each k occupies $2\pi/L$ in k -space.



In the interval dk , there are

$$\frac{dk}{2\pi/L} = \frac{L}{2\pi} dk \text{ states}$$

Then translate $D(k)dk$ to $D(E)dE$

$$E = \frac{\hbar^2 k^2}{2m^*}$$
$$dE = \frac{\hbar^2}{2m^*} 2k dk$$
$$= \frac{\hbar^2 k}{m^*} dk$$
$$k = \frac{\sqrt{2m^*E}}{\hbar}$$

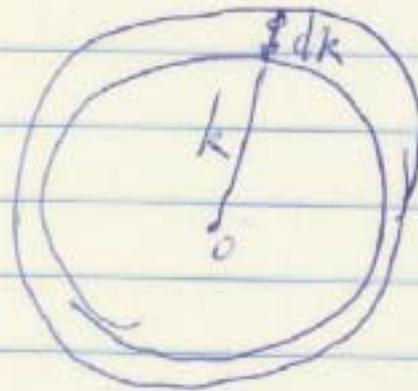
$$D(E)dE = \frac{L}{2\pi} \frac{m^*}{\hbar^2 k} dE$$
$$= \frac{L}{2\pi} \frac{m^* dE}{\hbar^2 \frac{\sqrt{2m^*E}}{\hbar}} = \frac{L}{2\pi\hbar} \sqrt{\frac{m^*}{2E}} dE$$

The take-home message is $D(E) \propto E^{-1/2}$

2D case:

Each k occupies $(2\pi)^2/L^2$ in k -space.

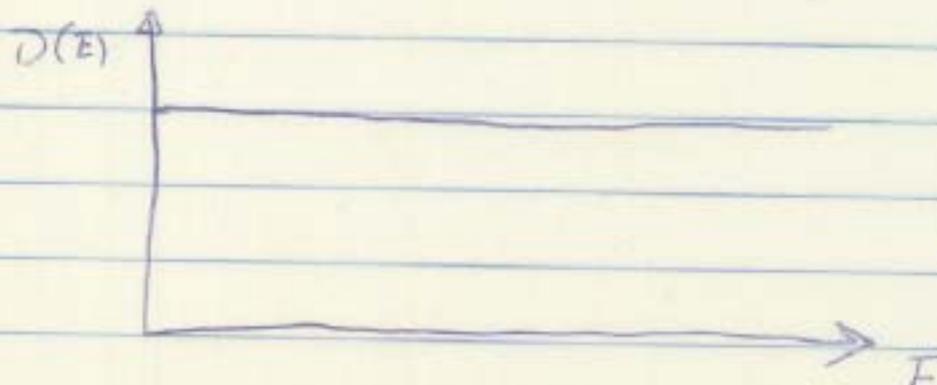
Hint — Count $\mathcal{D}(k) dk$



$$dA = 2\pi k dk$$

$$\frac{2\pi k dk}{4\pi/L^2}$$

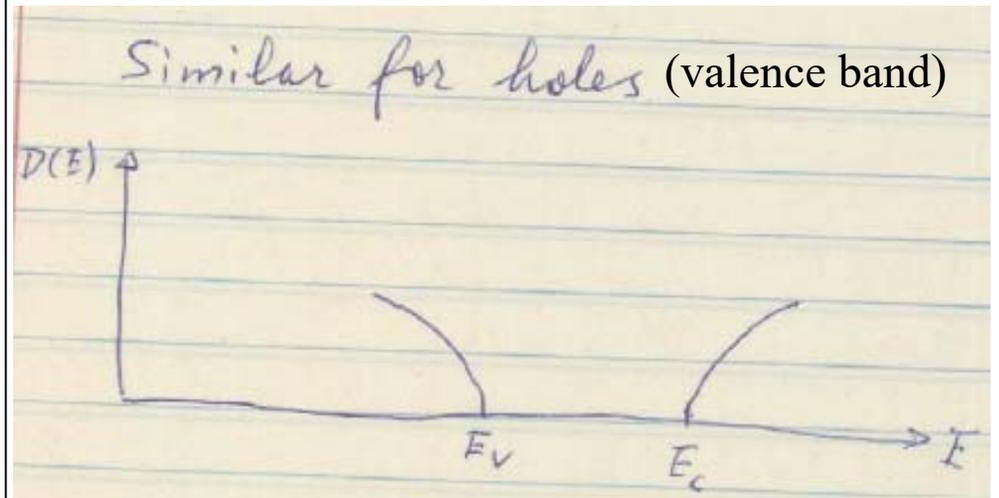
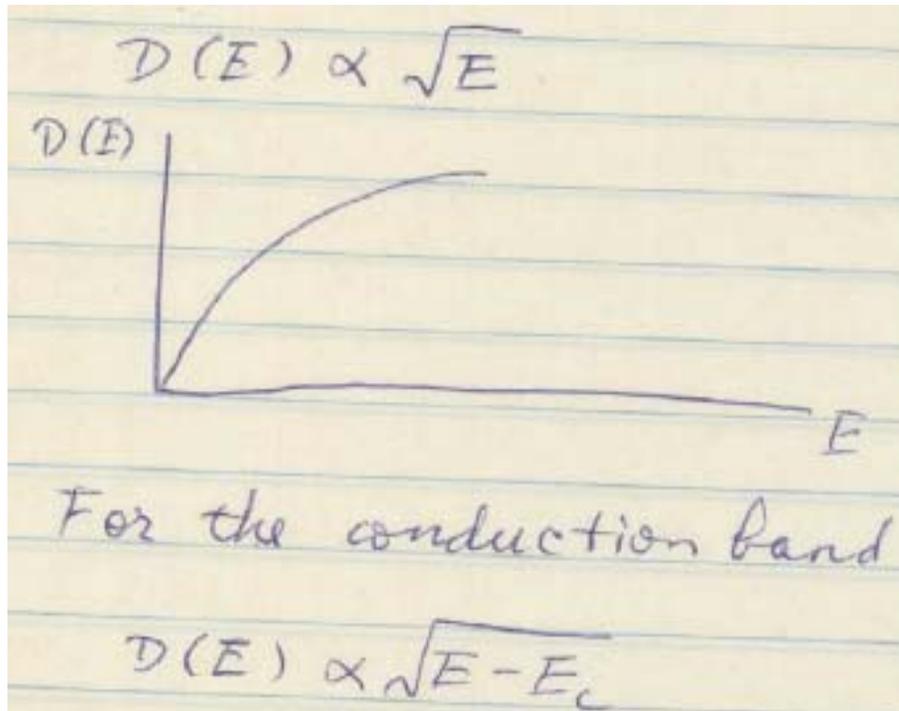
The take-home message $\mathcal{D}(E) = \text{const.}$



3D case:

Each k occupies $(2\pi)^3/L^3$ in k -space.

Run the extra mile, derive this on your own:



2D case

Run the extra mile

Derive $D(E)$ in 2D.

Hint: count number of \mathbf{k} 's in 2D.

The answer: $D(E) = \frac{L^2 m^*}{2\pi \hbar^2}$ Or, for unit area $D(E) = \frac{1}{2\pi} \frac{m^*}{\hbar^2}$

The take-home message: $D(E) = \text{constant}$

3D case

Run the extra mile

Derive $D(E)$ in 3D.

Hint: count number of \mathbf{k} 's in 2D.

For unit volume, $D(E) = \frac{\sqrt{2}}{2\pi^2} \frac{(m^*)^{3/2}}{\hbar^3} \sqrt{E}$

The take-home message: $D(E) \propto E^{1/2}$

Things we have ignored so far:

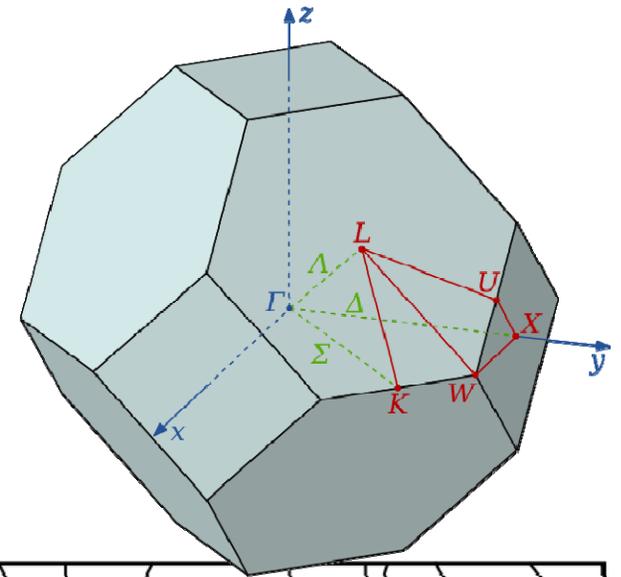
Degeneracies.

explain what degeneracy means

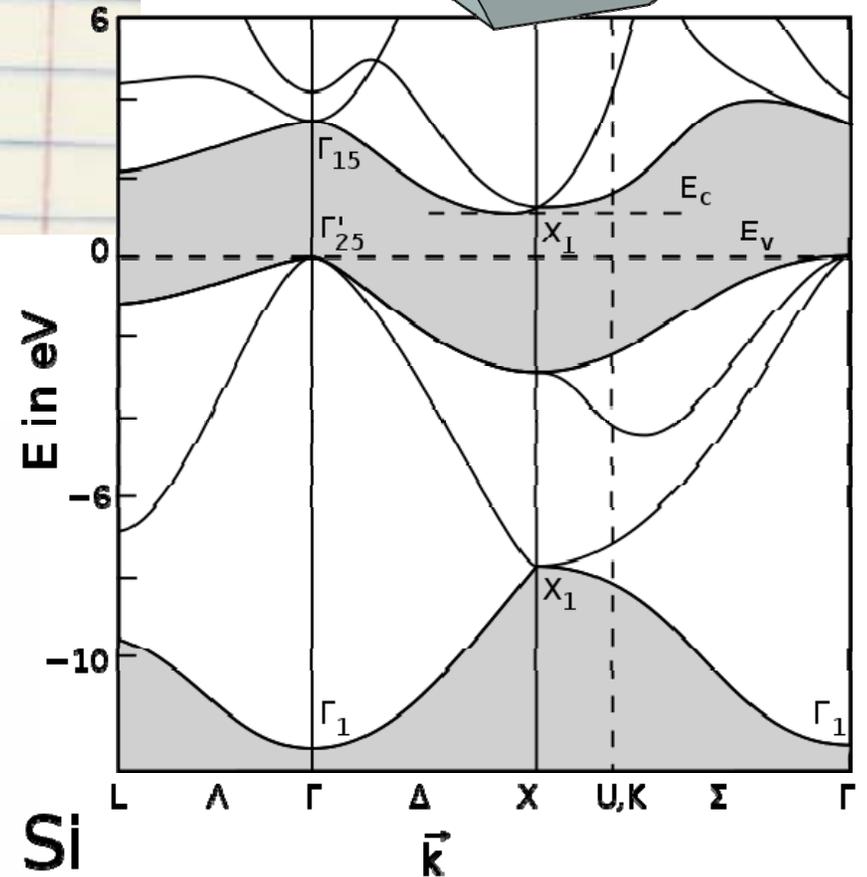
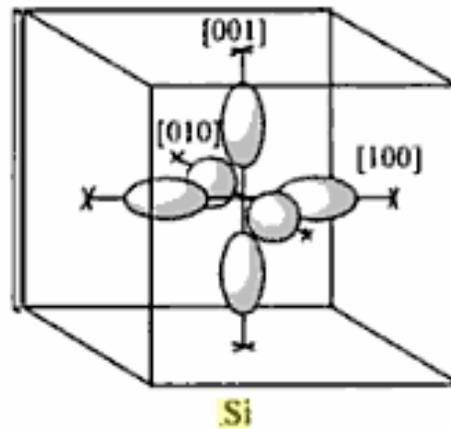
Spin degeneracy 2

Valley degeneracy M_c

$M_c = 6$ for Si



$$D(E) = 2M_c \frac{\sqrt{2}}{2\pi^2} \frac{(m^*)^{3/2}}{\hbar^3} \sqrt{E}$$

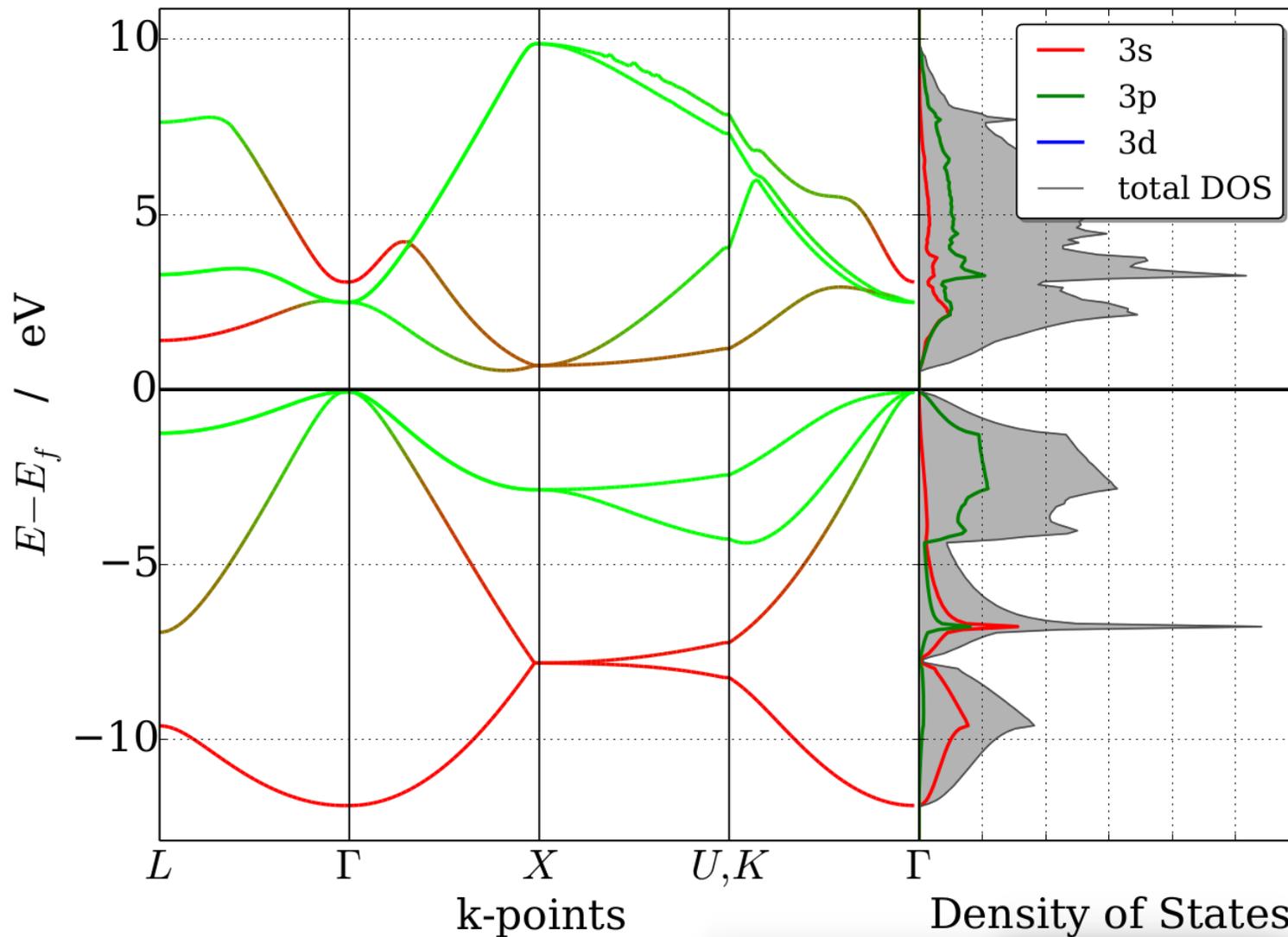


Holes more complicated.
Light, heavy...

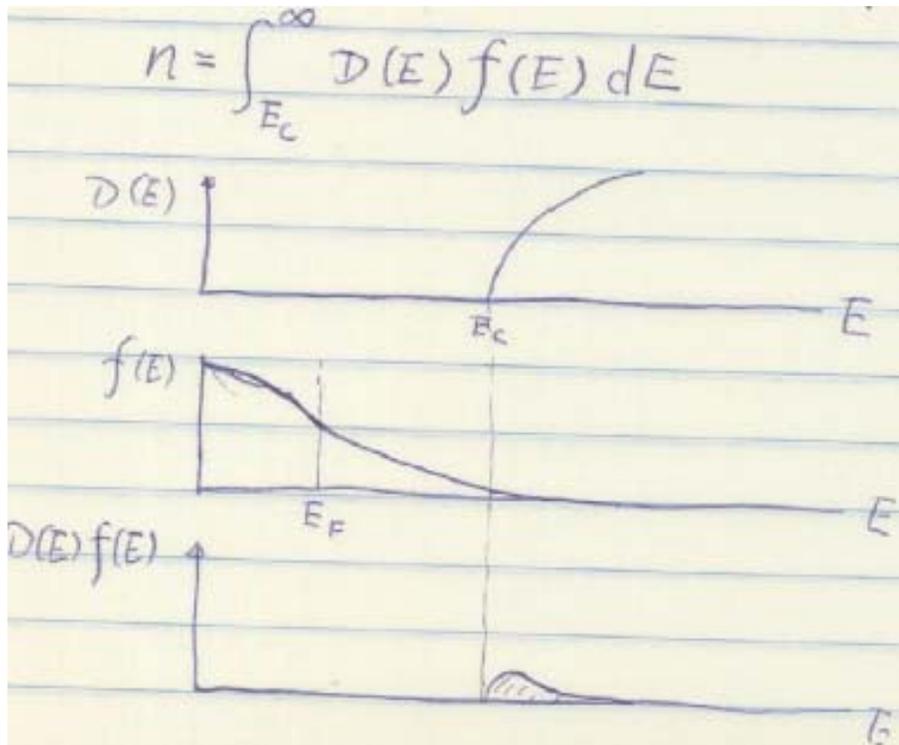
Disclaimer

Those $D(E)$ expressions only apply around the band extrema, because $E \propto k^2$ only there.

Bands diagram of silicon



Density or concentration of electrons/holes



We only care about the tail of $f(E)$

$$f(E) = \frac{1}{e^{\frac{E-E_F}{k_B T}} + 1} \approx e^{-\frac{E-E_F}{k_B T}}$$

So, the integral becomes much easier

$$n = N_c e^{-\frac{E_c - E_F}{k_B T}}$$

$$N_c = 2M_c \left(\frac{2\pi m^* k_B T}{h^2} \right)^{\frac{3}{2}}$$

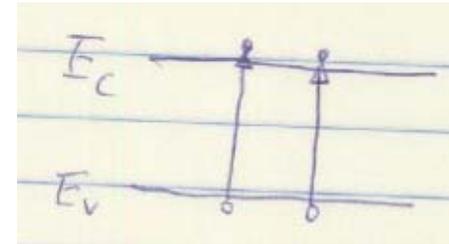
Similarly, for holes

$$p = N_v e^{-\frac{E_F - E_v}{k_B T}}$$

Doping

For intrinsic (i.e., pure) Si, all valence electrons are in the valence band, which is full, at $T = 0$ K.

There are some conduction electrons and holes by thermal excitation at finite T .



What about doped Si (at 0 K and finite T)?

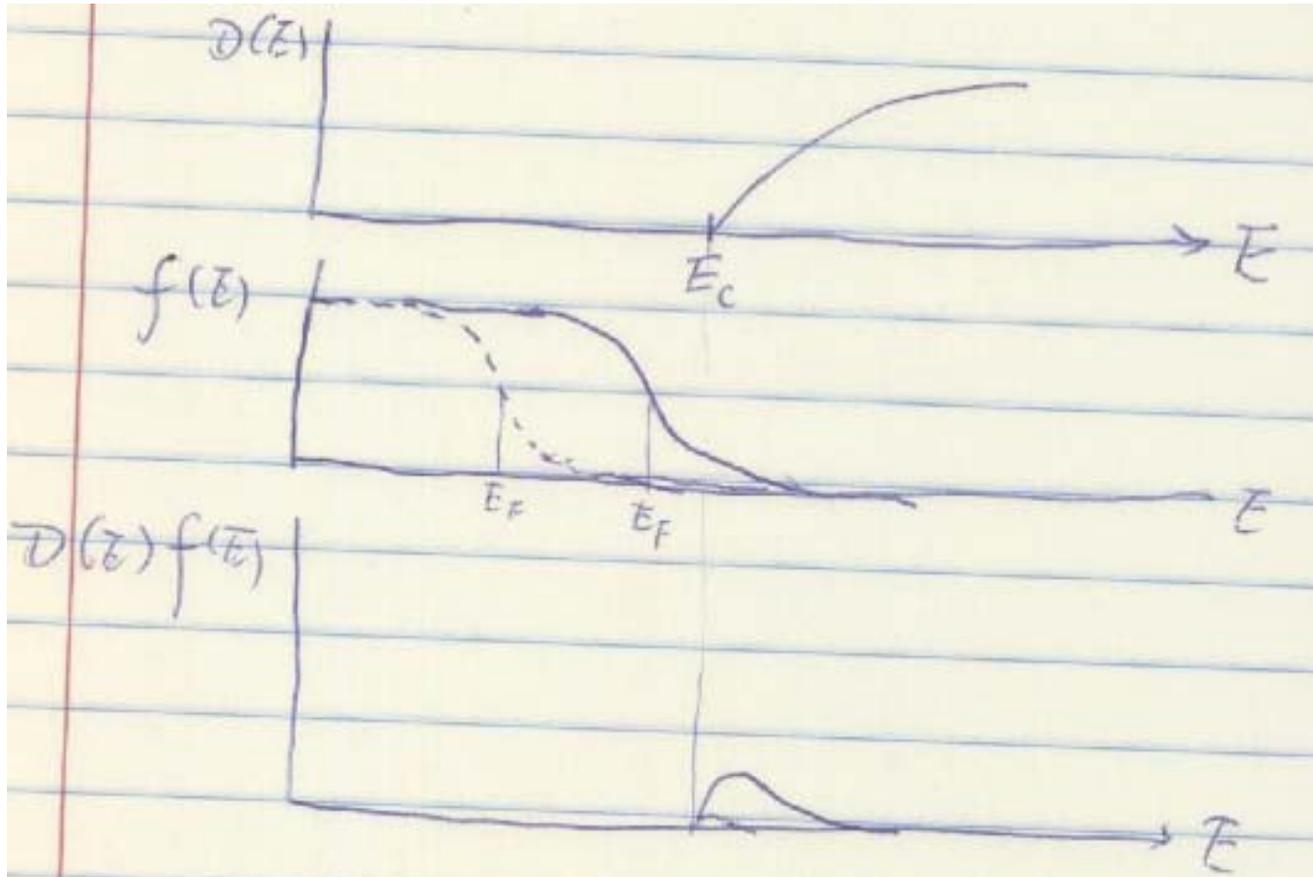
$$n = p = n_i$$

Si is valence 4.

Donors: valence 5: P, As, Sb (antimony, [**an**-tuh-moh-nee])

Acceptors: valence 3: B,

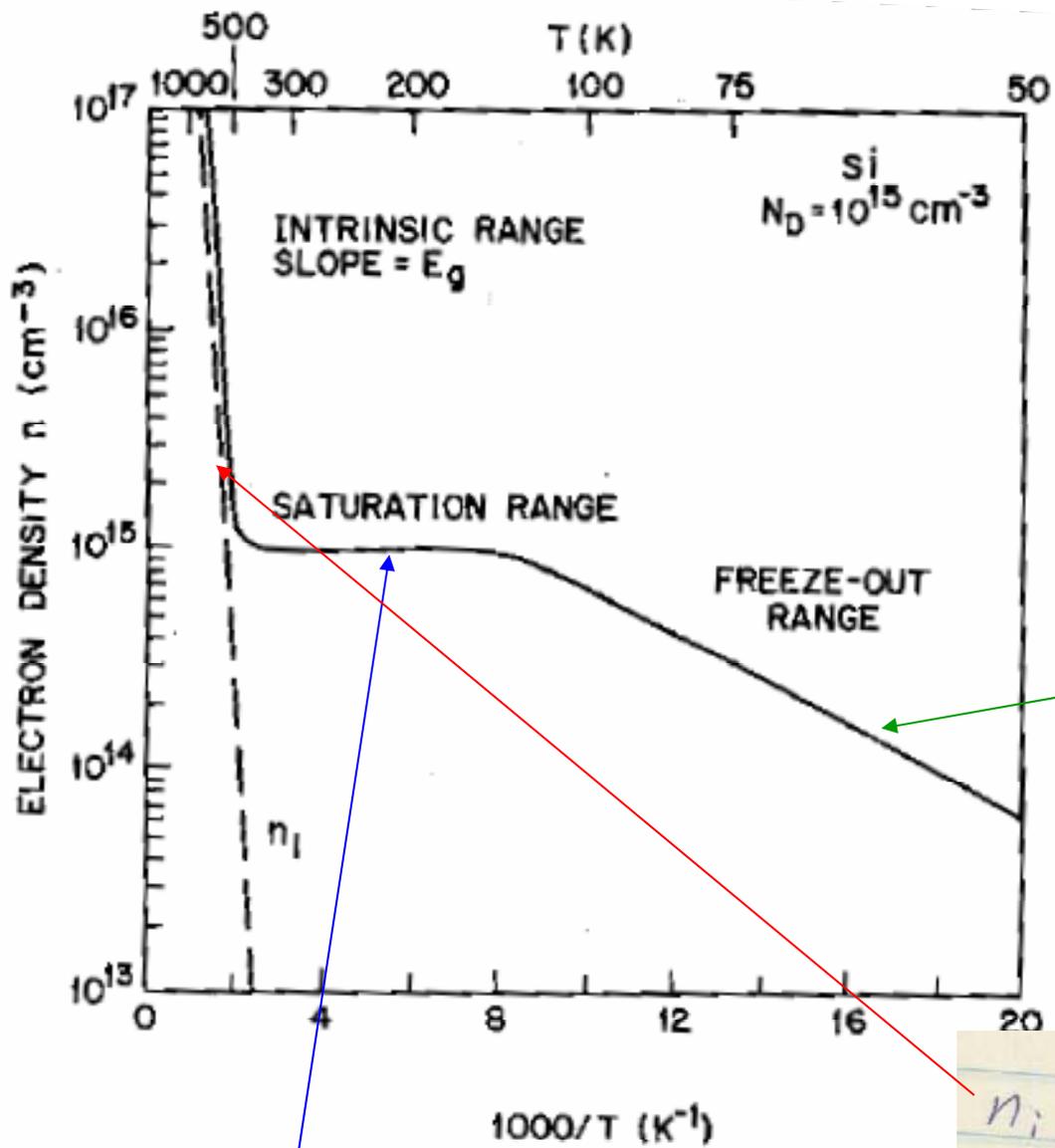
What happens to E_F when you dope Si?



Doping shifts E_F

AT room temperature, all dopants are active: $n = N_D$, or $p = N_A$
Compensation: $n = N_D - N_A$, or
 $p = N_A - N_D$

$$n = N_c e^{-\frac{E_c - E_F}{k_B T}}$$
$$p = N_v e^{-\frac{E_F - E_v}{k_B T}}$$



$$n = N_c e^{-\frac{E_c - E_F}{k_B T}}$$

$$p = N_v e^{-\frac{E_F - E_v}{k_B T}}$$

What is this shallow slope?

$$n_i = \sqrt{N_c N_v} e^{-\frac{E_g}{2k_B T}}$$

Fig. 16 Electron density as a function of temperature for a Si sample with donor impurity concentration of 10^{15} cm^{-3} (After Smith, Ref. 5.)

N_D

$$n = N_c e^{-\frac{E_c - F_F}{k_B T}}$$

$$p = N_v e^{-\frac{F_F - E_v}{k_B T}}$$

$$np = N_c N_v e^{-\frac{E_c - E_v}{k_B T}} \equiv n_i^2$$

$$= N_c N_v e^{-\frac{E_g}{k_B T}}$$

$$n_i = \sqrt{N_c N_v} e^{-\frac{E_g}{2k_B T}}$$

For Si, @ $T = 300 \text{ K}$

$$n_i = 1.45 \times 10^{10} / \text{cm}^3$$

$$N_c = 2.8 \times 10^{19} / \text{cm}^3$$

$$N_v = 1.04 \times 10^{19} / \text{cm}^3$$

$$\left\{ \begin{array}{l} n = N_c e^{-\frac{E_c - E_F}{k_B T}} \quad (1) \\ n_i = \sqrt{N_c N_v} e^{-\frac{E_g}{2k_B T}} \quad (2) \end{array} \right.$$

$$(1) \div (2) \Rightarrow$$

$$\frac{n}{n_i} = \sqrt{\frac{N_c}{N_v}} e^{-\frac{E_c - E_F - \frac{1}{2}E_g}{k_B T}}$$

$$= e^{\ln \sqrt{\frac{N_c}{N_v}}} e^{-\frac{E_c - E_F - \frac{1}{2}E_g}{k_B T}}$$

$$= e^{-\frac{E_c - E_F - \frac{1}{2}E_g - k_B T \ln \sqrt{\frac{N_c}{N_v}}}{k_B T}}$$

$$n = n_i e^{-\frac{E_F - (E_c - \frac{1}{2}E_g - k_B T \ln \sqrt{\frac{N_c}{N_v}})}{k_B T}}$$

$$= n_i e^{-\frac{E_F - E_i}{k_B T}}$$

(By setting $n = n_i$, you know E_i is the Fermi level of intrinsic Si)

$$n = n_i e^{\frac{E_F - (E_c - \frac{1}{2}E_g - kT \ln \sqrt{\frac{N_c}{N_v}})}{k_B T}}$$

$$= n_i e^{\frac{E_F - E_i}{kT}}$$

$$E_i \equiv E_c - \frac{1}{2} E_g - kT \ln \sqrt{\frac{N_c}{N_v}} \quad \text{Intrinsic Fermi level}$$

$\therefore N_c \approx N_v$ Really?

$kT = ? \text{ eV}$

$$N_c = 2.8 \times 10^{19} / \text{cm}^3$$

$$N_v = 1.04 \times 10^{19} / \text{cm}^3$$

$$\therefore E_i = E_c - \frac{1}{2} E_g \quad \text{Intrinsic Fermi level}$$

When $E_F = E_i$, $n = n_i$

Similarly

$$p = n_i e^{\frac{E_i - E_F}{k_B T}}$$

Again, $np = n_i^2$

$E_F > E_i \rightarrow n \text{ type}$
 $E_F < E_i \rightarrow p \text{ type}$



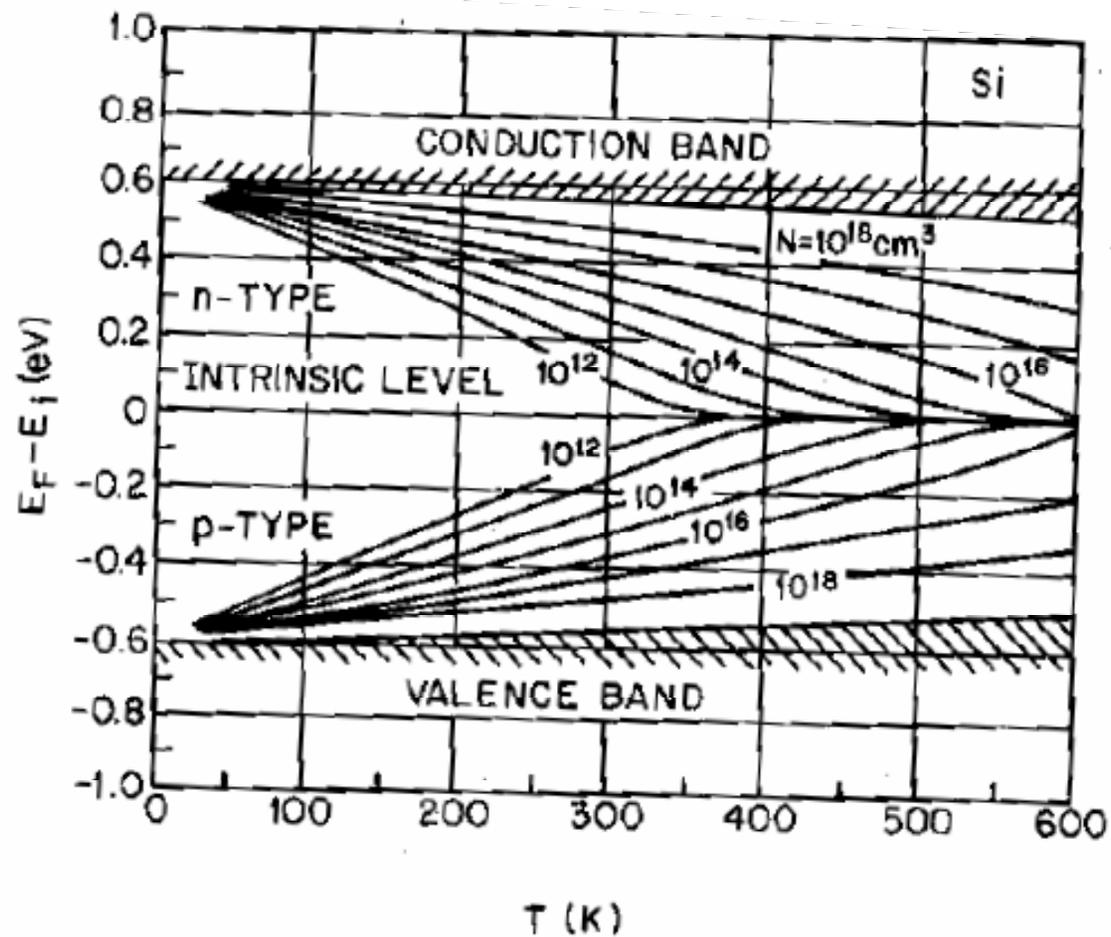
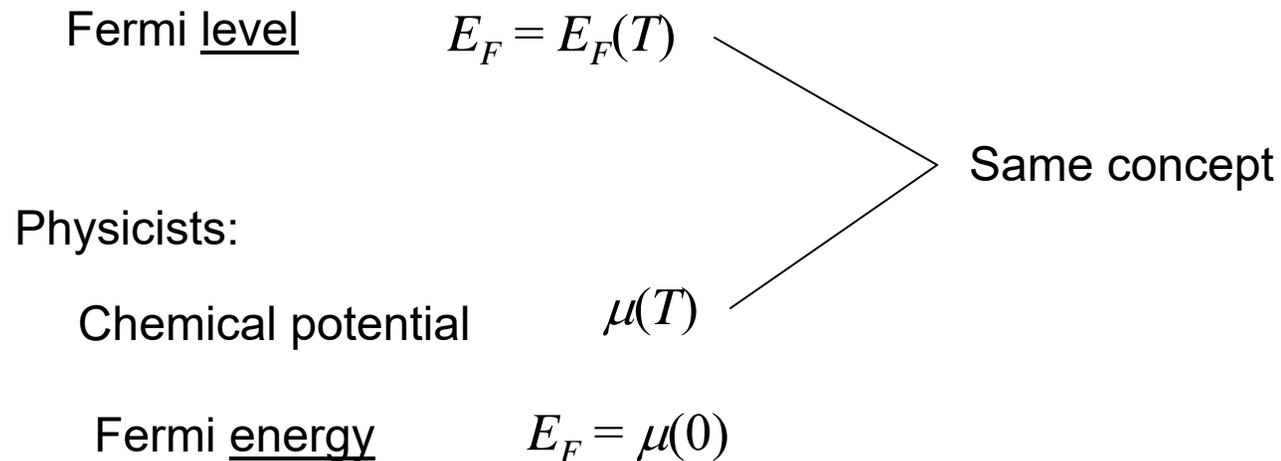


Fig. 17 Fermi level for Si as a function of temperature and impurity concentration. The dependence of the bandgap on temperature is also incorporated in the figure. (After Grove, Ref. 32.)

One small thing to keep in mind:
Subtle difference in jargons used by EEs and physicists

We use the EE terminology, of course.



We already used μ for mobility.

Before we talk about devices, what are semiconductors anyway?

Classroom discussion

Na, K, ... are metals

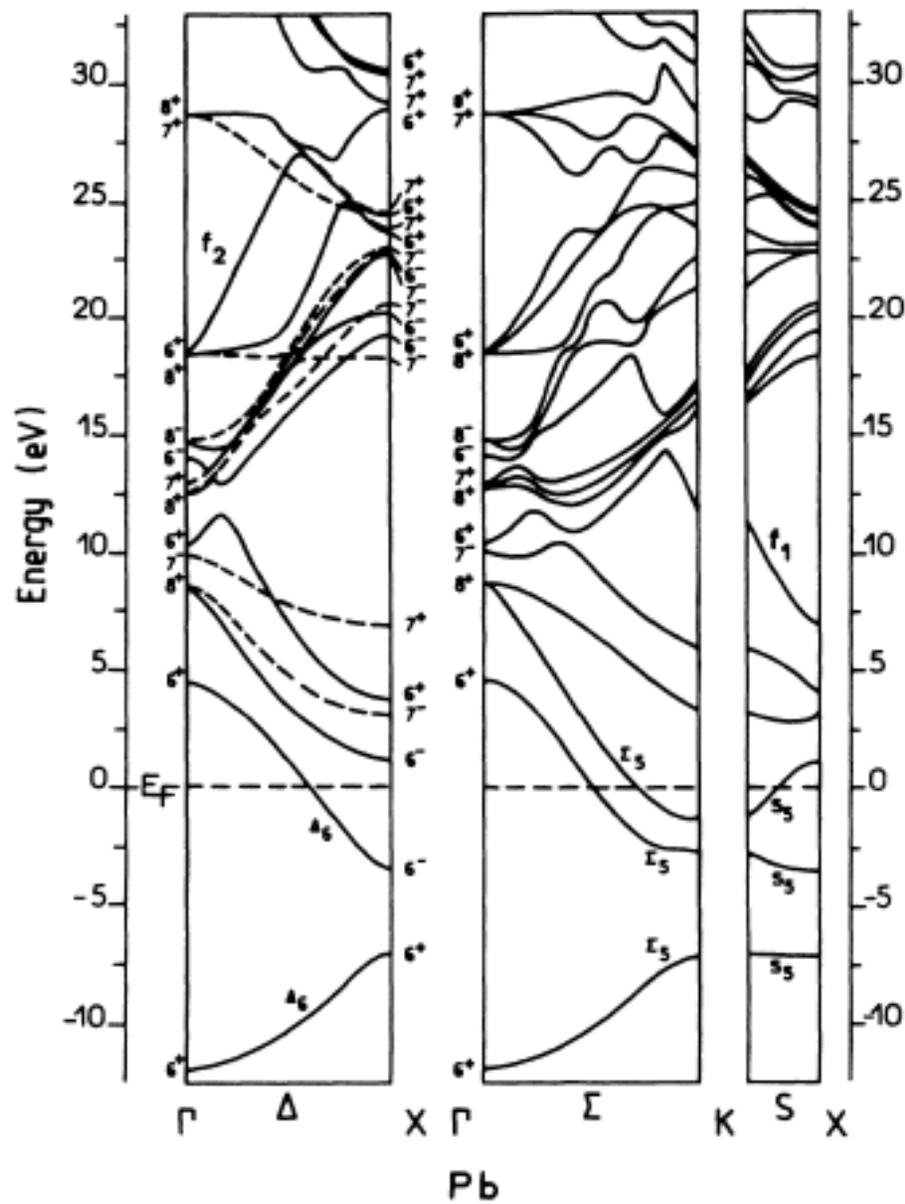
Mg, Ca, ... are also metals. Why?

Si (gap 1.1 eV) and Ge (gap 0.66 eV) are semiconductors.

Pb is a metal.

Why can we modulate their properties by orders of magnitude?

Classroom discussion



Jezequel & Pollini, Phys Rev B **41**, 1327 (1990)

Phonons

Static lattice approximation

Atoms vibrate

Harmonic approximation: springs

Vibration quantized

Each quantum is a phonon.

Similar to the photon:

$$E = \hbar\omega, \quad p = \hbar k$$

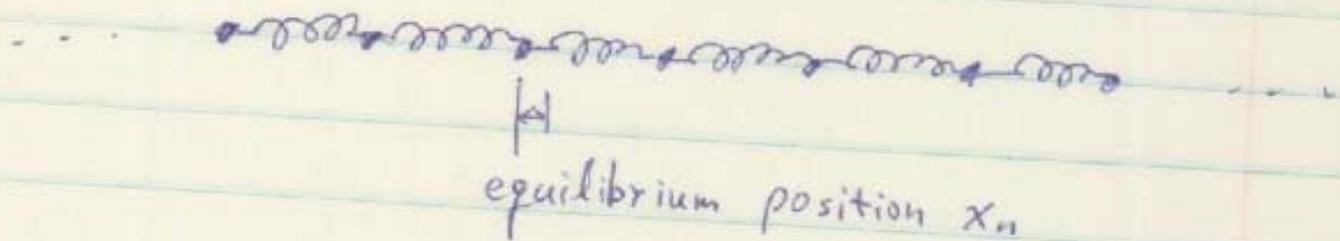
Phonons scatter carriers, too.

The higher the temperature, the worse phonon scattering becomes.

You can use the temperature dependence of conductivity or mobility to determine the contributions of various scattering mechanisms.

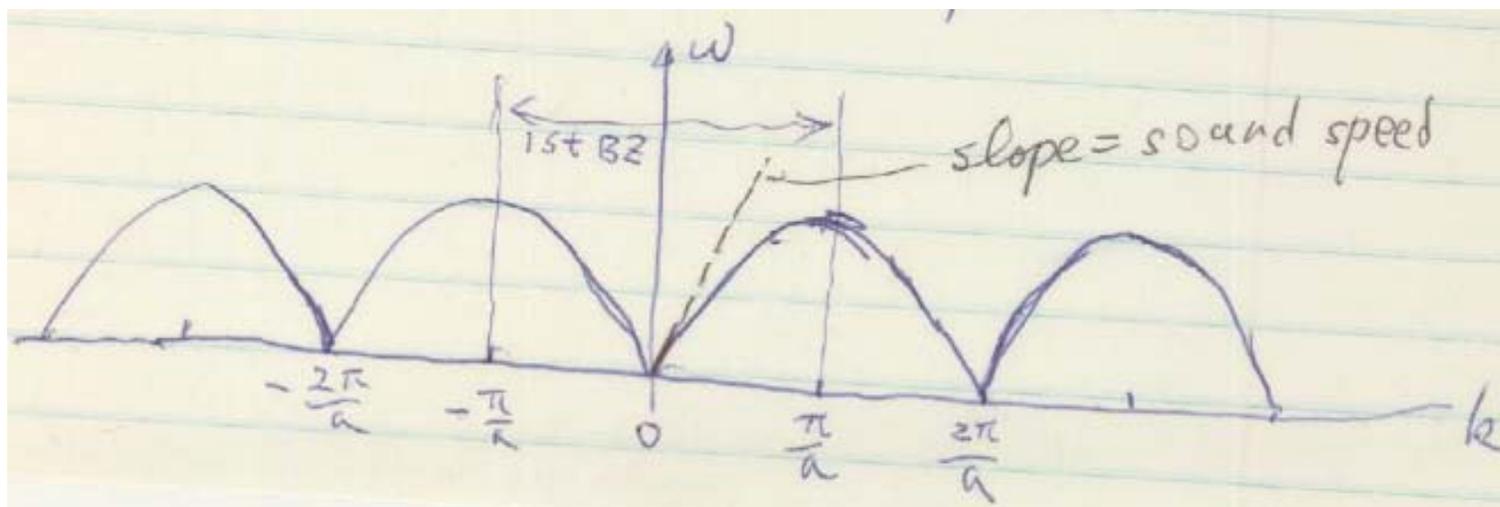
Phonons

The solid is discrete on the atomic scale.



The displacement from the equilibrium position of n th atom

$$u_n = A e^{i(kx_n - \omega t)}$$



Phonons

Sound wave in continuous media $\omega = vk$

Microscopically, the solid is discrete.

Phonon dispersion

Wave vector folding, first Brillouin zone.

Watch animation at http://en.wikipedia.org/wiki/File:Phonon_k_3k.gif

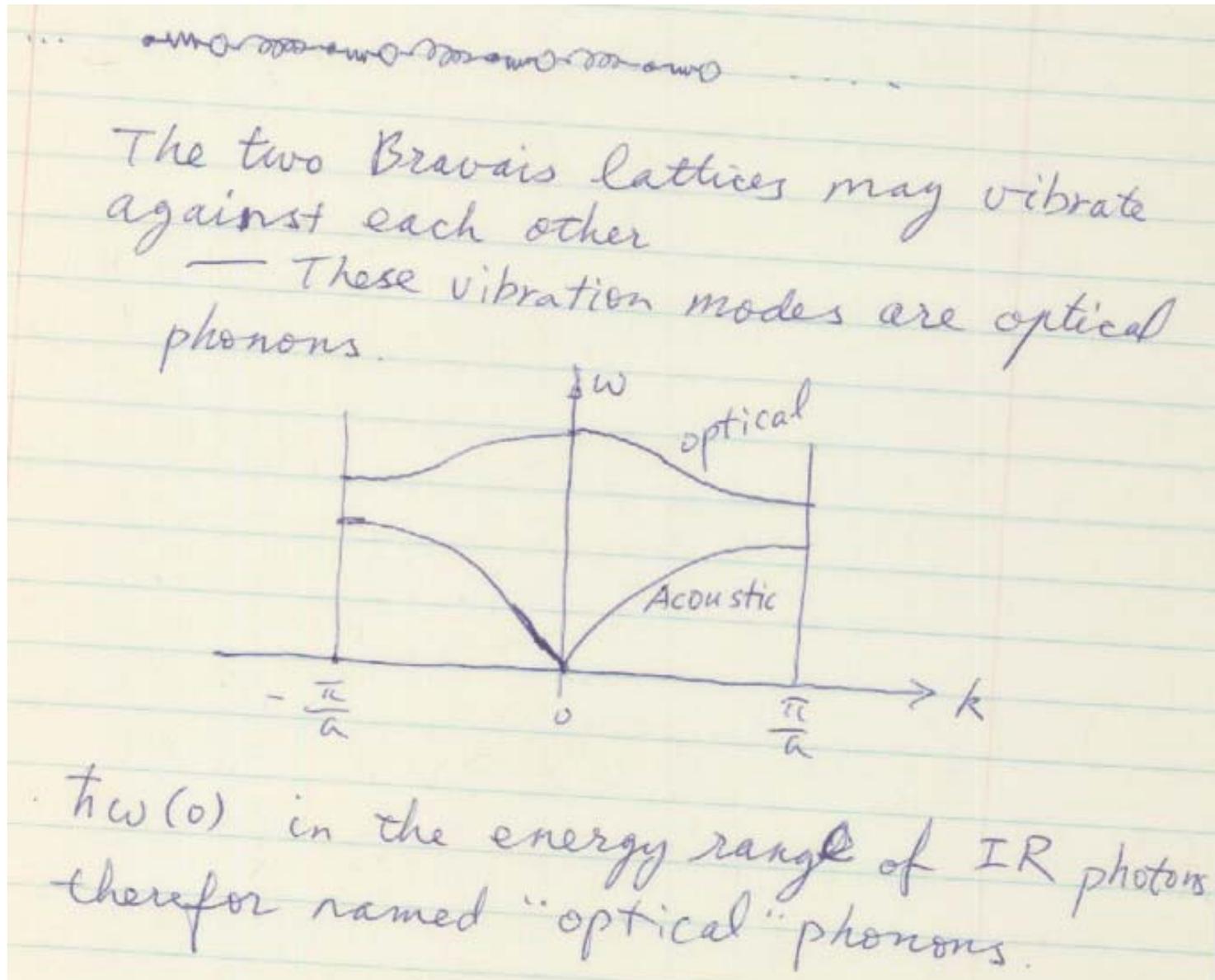
Recall that

Crystal structure = Bravais lattice + basis

If there are more than 1 atom in the basis, optical phonons

If you are serious and curious about photons, read
Kittel, Introduction to Solid State Physics

If there are more than 1 atom in the basis, optical phonons

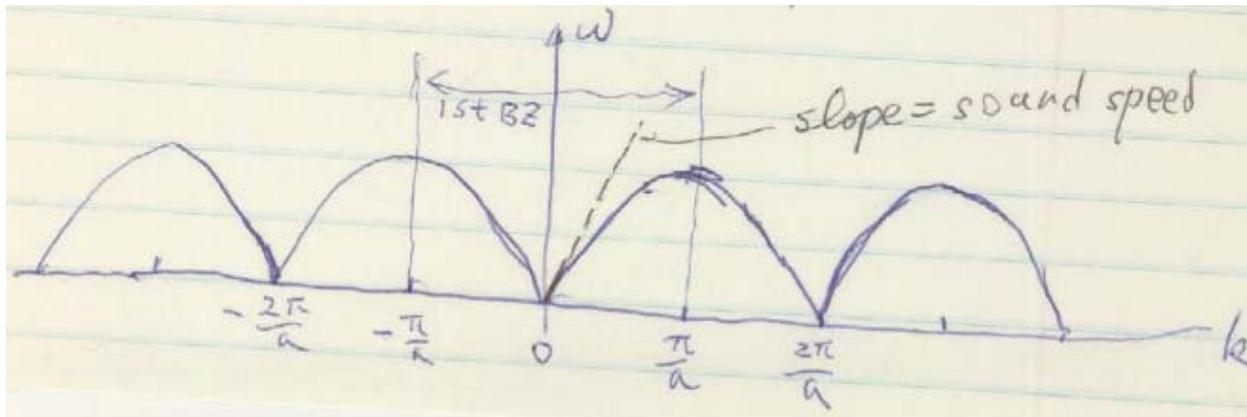


One atom in the unit cell.

$$\omega = 2 \sqrt{\frac{K}{M}} \left| \sin \frac{ka}{2} \right|$$

K : spring constant (in Hooke's law)

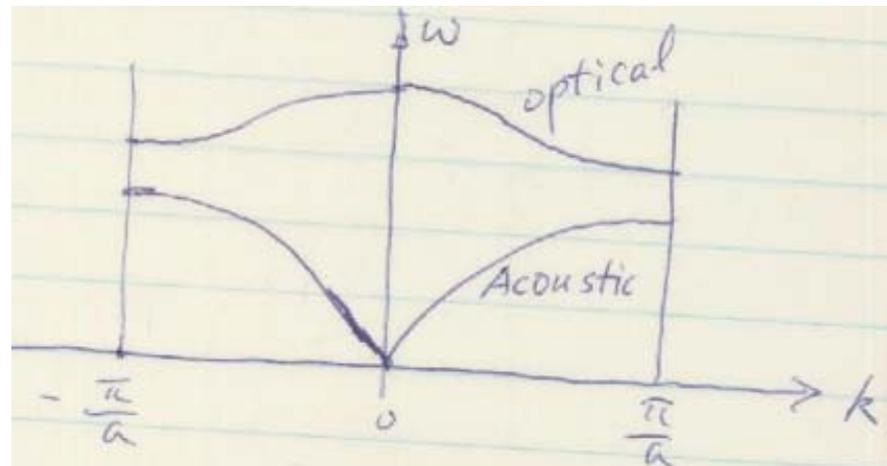
M : mass



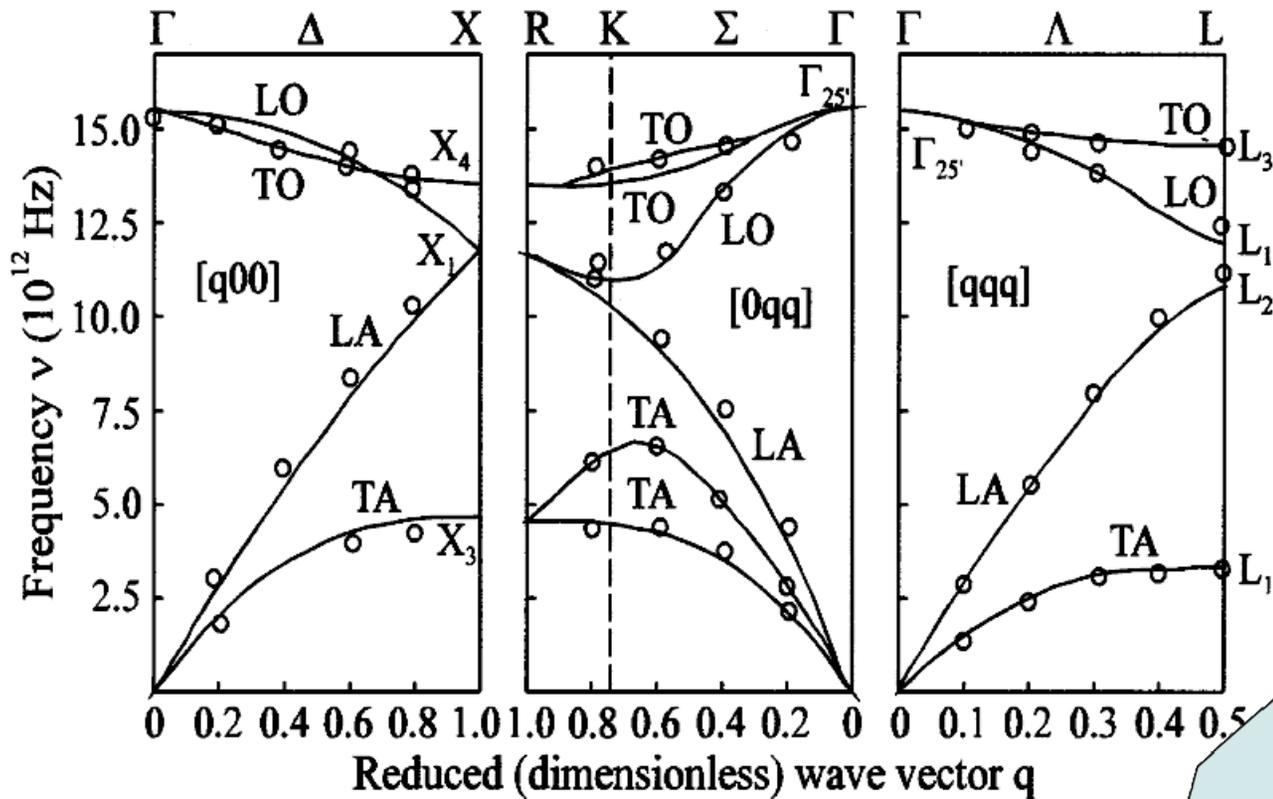
Two atoms in the unit cell (same mass, different springs)

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

K and G



Phonons in the 3D world -- Si

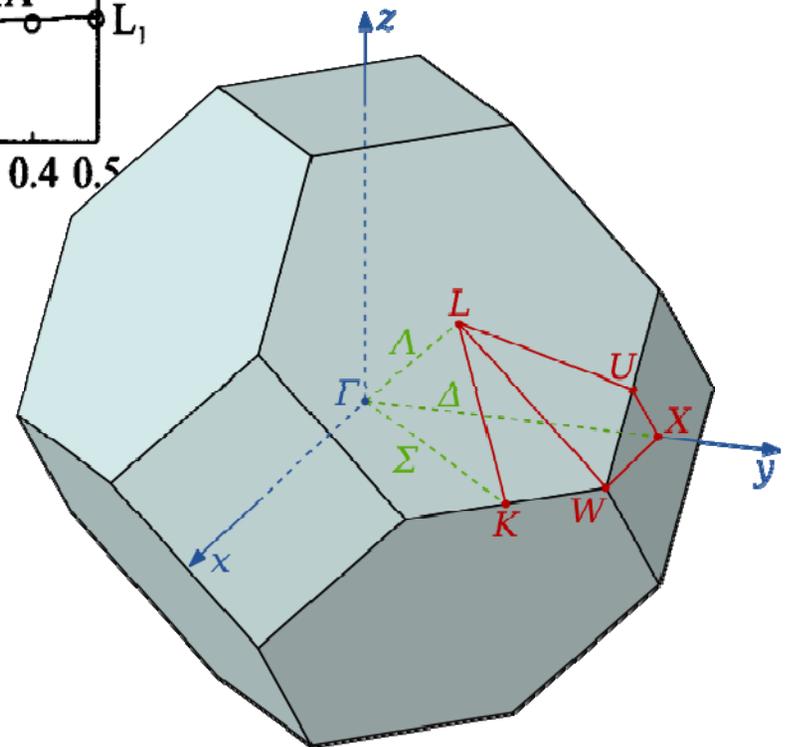


In 3D, there are transverse and longitudinal waves.

$$E = h\nu = \hbar\omega$$

15 THz \longrightarrow 62 meV

When electron energy is low, the electron only interacts with acoustic phonons,

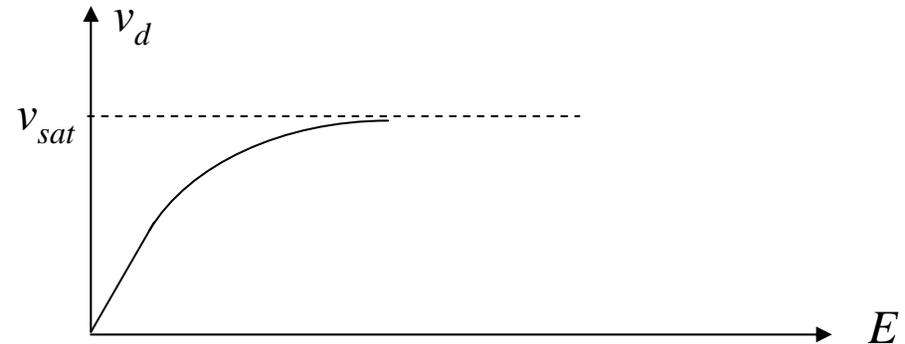


Optical phonons and transport

At low fields, $v_d = \mu \mathcal{E} \ll v_{th}$

$$\frac{1}{2} m^* v_{th}^2 = \frac{3}{2} k_B T = 38 \text{ meV}$$

For Si, $v_{th} = 2.3 \times 10^7 \text{ cm/s}$



At high fields, v_d comparable to v_{th}

Electrons get energy from the field, hotter than the lattice – hot electrons

When the energy of hot electrons becomes comparable to that of optical phonons, energy is transferred to the lattice via optical phonons.



Velocity saturation

For Si, $v_{sat} \sim 10^7 \text{ cm/s}$

Alloys

Compounds, alloys, heterostructures

InP, GaAs, ..., SiC

$\text{In}_x\text{Ga}_{1-x}\text{As}_y\text{P}_{1-y}$, ..., $\text{Si}_x\text{Ge}_{1-x}$

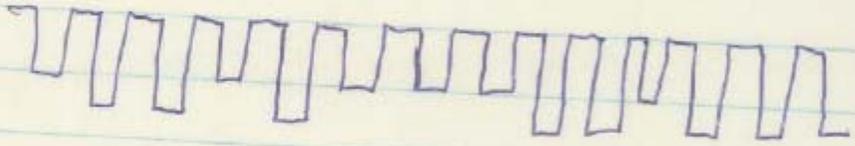
Epitaxy

Band structure of alloys

For an alloy A_xB_{1-x} , the lattice constant

$$a_{\text{alloy}} = xa_A + (1-x)a_B \quad (1)$$

The alloy is crystalline, but the potential is NOT even periodic!



But we still have bands.

$$E_{g,\text{alloy}} = xE_{g,A} + (1-x)E_{g,B} \quad (2)$$

(2) is NOT as good an approximation as (1).

$$\frac{1}{m^*_{\text{alloy}}} = \frac{x}{m^*_A} + \frac{1-x}{m^*_B}$$

Remember $E = \frac{\hbar^2}{2m^*} k^2$?

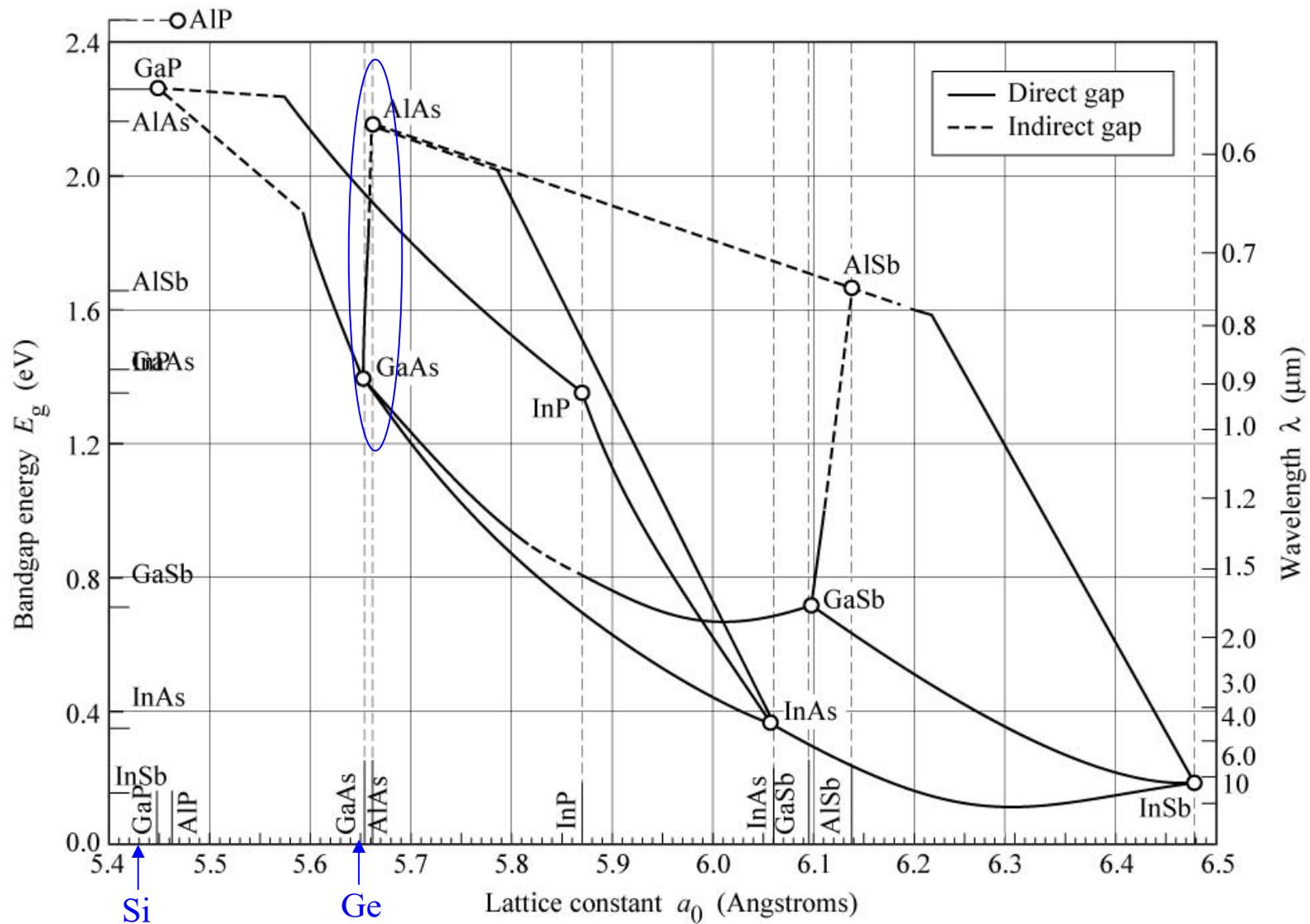


Fig. 12.6. Bandgap energy and lattice constant of various III–V semiconductors at room temperature (adopted from Tien, 1988).

Topics

- Review of Semiconductor physics
 - Crystal structure, band structures, band structure modification by alloys, **heterostructures, and strain**
 - Carrier statistics
 - Scattering, defects, phonons, mobility
- Device concepts
 - MOSFETs, MESFETs, MODFETs, TFTs
 - Heterojunction bipolar transistors (HBT)
 - Semiconductor processing
 - Photodiodes, LEDs, semiconductor lasers
 - (optional) resonant tunneling devices, quantum interference devices, single electron transistors, quantum dot computing, ...
 - Introduction to nanoelectronics

We will discuss heterostructures in the context of devices.

More discussions on semiconductor physics will be embedded in the device context.