Solids

• Solids are everywhere. Looking around, we see solids.

• Most of our electronics is solid state.

• Composite materials make airplanes and cars lighter, golf clubs more powerful, …

• In addition to “hard matter” there is “soft matter”, such as polymers (plastics) and biological matter.
Crystals

- A solid can be represented by a crystal, a regular array of atoms.

- A crystal is described by a unit cell that is repeated in all directions.

- Real materials are polycrystalline. They consist of small crystallites.

(Ch. 2.3)
Instead of calculating an infinite crystal, one just needs to calculate one unit cell and its connections with neighbor cells.
Quantum numbers of electrons in a solid

• The quantum numbers are: Energy $E$ and momentum $\mathbf{p} = (p_x, p_y, p_z)$

• They reflect symmetries and thus are conserved (Lect. 6, Slide 12):
  - The energy $E$ is related to translation symmetry in time $t$.
  - Momentum $\mathbf{p}$ is related to translation symmetry in space $\mathbf{x} = (x, y, z)$.

• Translation in time allows $\Delta t = \infty \Rightarrow \Delta E = 0$ (zero uncertainty in $E$).
  Translation in space allows $\Delta x = \infty \Rightarrow \Delta p = 0$ (zero uncertainty in $p$).

• We keep encountering the same four variables:
  $t, x$ in real space and $E, p$ in reciprocal space

• Since the quantum numbers $E, p$ live in reciprocal space, one needs to think in reciprocal space when describing solids. As we saw in diffraction (Lect. 9, Slides 11, 12), large and small are inverted in reciprocal space.
Measuring the quantum numbers of electrons

The quantum numbers $E$ and $p$ can be measured by angle-resolved photoemission. This is an elaborate use of the photoelectric effect, which was explained as quantum phenomenon by Einstein:

Measure $E, p$ of the emitted photoelectron. Subtract $E, p$ of the photon to obtain $E, p$ of the electron inside the solid.

$$\text{Electron energy outside the solid} - \text{Photon energy} = \text{Electron energy inside the solid}$$
Momentum $p$ from angle-resolved photoemission
The many-particle problem

- A typical piece of a solid (≈ cm$^3$) contains ≈10$^{24}$ electrons (Avogadro’s number). How do we deal with all of these electrons?
- Make $10^{24} = \text{infinity}$. That actually simplifies the problem, because one can use an infinite crystal and consider only atoms inside one unit cell.
- With so many electrons the energy levels are very dense and become continuous ‘bands’.
- Solids are good examples demonstrating strange concepts in particle physics, such as antiparticles. These correspond to holes (= missing electrons) in semiconductors.
Two types of solids

To conduct electricity, electrons need to move into an empty level.

**Metals**
- The energy levels are *continuous*.
- Electrons need very little energy to move ⇒ electrical conductor

**Semiconductors / Insulators**
- Filled and empty energy levels are separated by an energy *gap*.
- Electrons need the gap energy to move ⇒ poor conductor.
Holes = missing electrons

A photon with an energy larger than the band gap can move an electron from a filled level to an empty level. The missing electron corresponds to a hole. The missing negative charge gives the hole a positive charge. The result is an electron-hole pair. There is a close analogy in particle physics: Antiparticles are missing particles, like holes. A Gamma photon with 1 MeV energy can create an electron-positron pair with a mass of \((\frac{1}{2}+\frac{1}{2})\) MeV/c\(^2\). The vacuum of particle theory is a semiconductor with a 1 MeV band gap.
Doping of semiconductors

To make semiconductors conductive, one introduces extra energy levels by adding a small number of different atoms. Being able to control the conductivity over a wide range by doping makes semiconductors so appealing for electronics.

**p-type doping**

Holes in a filled level carry electric current.

**n-type doping**

Electrons in an empty level carry electric current.
A light-emitting diode combines negative electrons (from a n-doped region) with positive holes (from a p-doped region). An applied voltage pushes the electrons from right to left, where they fill the holes. The energy drop of an electron is converted to a photon.

In a LED, electrons fall into holes and emit light.
A quantum well laser is an improved LED. Electrons and holes are kept together inside the semiconductor at the center, which has a smaller gap. That makes it easier for electrons to find holes.
A solar cell is an LED in reverse: Photons are absorbed instead of emitted. They generate electrons and holes which are pulled towards front and back contacts. Voltage is generated instead of applied.

**In a solar cell, a photon creates an electron-hole pair.**
Energy diagram of a solar cell

Electron and hole are **pulled in opposite directions** by the opposite charges at the n- and p-type doping atoms (Slide 11).

It is important to make sure that electrons and holes make it to the contacts without getting trapped or losing energy. Using a single crystal of a semiconductor helps, but is expensive.
Applying a positive voltage to the gate draws negative electrons into the channel, and thereby **closes a switch** between source and drain.
Semiconductor electronics

- **Semiconductors** conduct electricity poorly, but they can be made conducting either by doping (LED, solar cell) or by attracting electrons via a gate voltage (transistor).
- **Computers** use silicon transistors, which act as switches.
- **Optoelectronics** converts electron-hole pairs to photons and vice versa. Photons are used for long-distance data transfer in fiber-optic cables.
- **LEDs** provide energy-efficient and long-lasting lighting.
- **Solar cells** produce renewable energy free of pollution.