Emergent Phenomena

The Physics of Many-Body Systems

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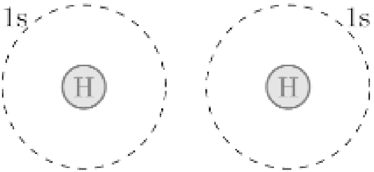
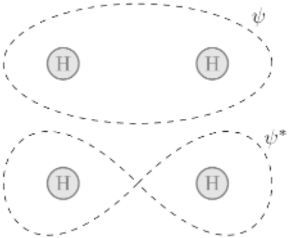
Outline

Molecular Orbitals

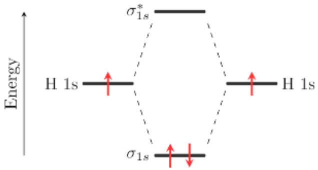
- Schrödinger's equation – the quantum equation of motion – is linear
- Solutions can be formed by adding other solutions





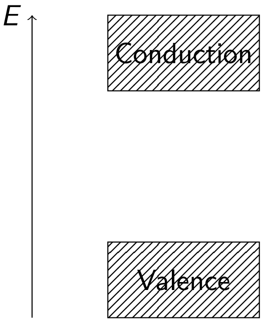
Energy Levels

- Equal energy atomic orbitals split into bonding and antibonding orbitals
- Atoms bond if more bonding orbitals are filled than antibonding



Crystal Bands

- In a crystal, with $\sim 10^{23}$ atoms, orbitals form energy "bands"
- Electrons fill low energy (valence) bands first
- Occupation of conduction band depends on electron content of crystal



Insulators and Conductors

- Pauli exclusion principle: at most one electon occupies a given state
- Filled bands do not conduct
- Example: diamond

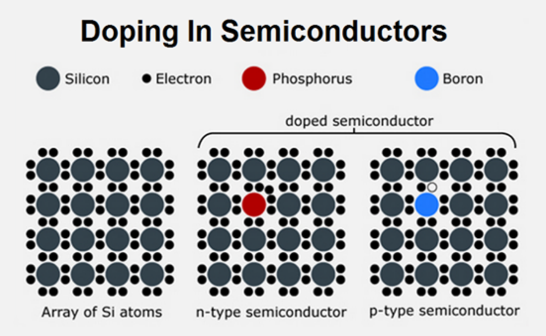
Insulators and Conductors

Band Gaps

- Between the valence and conduction bands is some energy difference ΔE
- Statistical physics gives an occupation probability of $e^{-\Delta E / k_B T}$
- Thermal energy $k_B T \approx 0.025\,\text{eV}$
- Silicon band gap $\Delta E \approx 1.14\,\text{eV}$
- Pure silicon is an excellent insulator

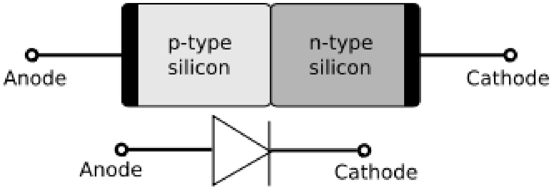
Doping

- Boron: 3 electrons; Silicon: 4 electrons; Phosphorus: 5 electrons
- Adding an atom of phosphorus to silicon will put an electron in the conduction band
- Small concentration of phosphorus makes silicon a conductor



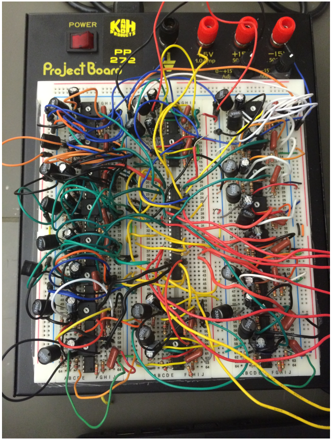
p–n junction

- Excess of electrons in *n*-type semiconductor
- Electrons flow *n* to *p* (current *p* to *n*)



Transistors

- Transistors have three semiconductor wafers, either pnp or npn
- Extremely useful in electronics; replaced vacuum tubes
- Enables construction of more complex circuit elements



Solar Cells

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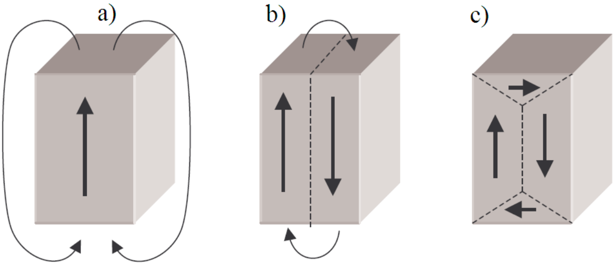
- $E = 2.1$ eV, more than enough for silicon band gap

Electron Magnetic Moment

- Quantum mechanics requires electrons to have an intrinsic spin
- Electron spin acts like current loop – creates magnetic field
- Magnetism of electrons in materials is stronger than magnetism of current loops

Magnetic Domains

- Magnetic fields store energy; at low temperatures, systems tend towards low energy states
- Quantum mechanical effect: magnetic domains

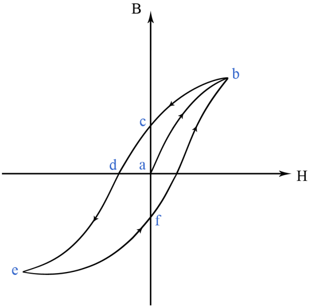


Ising Model

- Domain formation can be modeled statistically
- Electrons relax with a preference to match their neighbors

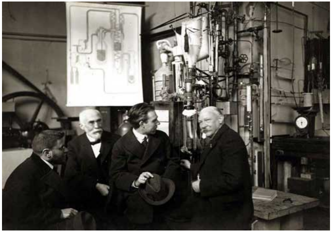
Ferromagnetism

- Below the Curie temperature, certain materials form domains which can be realigned
- Applying an external magnetic field lines up domains
- Histeresis effect leaves permanent magnetization



Superconductivity

- Superconductivity: zero electrical resistance occuring in some materials
- Discovered in 1911 by Heike Kamerlingh Onnes



Cooper Pairing

- Quantum statistics: if electrons form pairs, they can form intense currents ("electron lasers")
- At low enough temperatures, Cooper pairs of electrons become energetically favored
- Mediated by lattice vibrations – confirmed by isotope effect

Meissner Effect

- Minimum energy for a superconductor results from expelled magnetic field
- Leads to magnetic “trapping” of superconductors

Magnetic Levitation