Temperature Dependence of Superconductivity and Band Gap

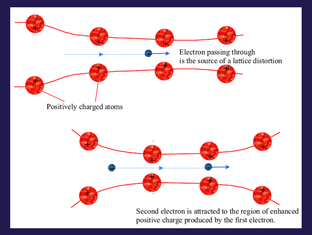
Anna Burns, David Fang, Kelly Guo, Julie Tang, Miranda Wang, Vivian Zhang, Aria Jin, Angela Ge
Mentor: Elizabeth Park, Harvard

This work was completed as part of the Quantum Engineering Research and You (QuERY) program at Bellaire High School, supported by the Harvard Quantum Initiative and MIT through the Research Laboratory for Electronics and CQE-iQuISE (Center for Quantum Engineering, Interdisciplinary Quantum Information Science and Engineering program).

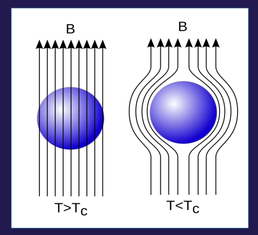
Superconductivity properties

Superconductivity is the property of certain materials to conduct direct current (DC) electricity without energy loss. This phenomenon is characterized by:

- Cooling of all materials below a critical temperature (T_c)
- Loss of all electrical resistance, which can expel magnetic fields, seen in the **Meissner effect**
- Formation of Cooper pairs of electrons, causing energy gap and macroscopic quantum coherence (BCS theory)



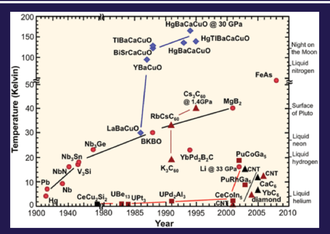
Fermions → "Bosons"

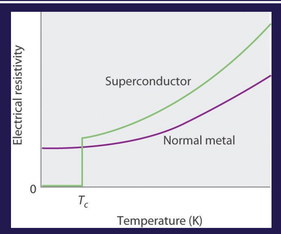


Meissner Effect

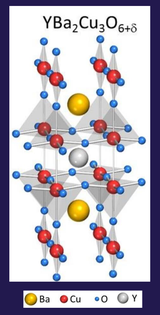
- Type 1 (Doesn't allow vortex) vs. Type 2 (allows vortex)
- There are many kinds of pairing symmetry : s-wave (isotropic, e.g., BCS superconductors), d-wave (anisotropic, with gap nodes and high T_c cuprates), etc.

High temperature SC and YBCO





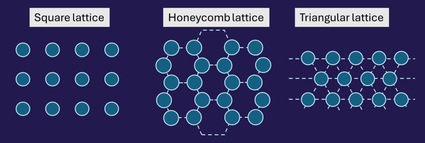
- YBCO (Yttrium Barium Copper Oxide or $YBa_2Cu_3O_{7-d}$) , d < 0.7
- Transition temperature : 93 K or -180 C
  Comparing to liquid nitrogen temperature = 77 K or -196 C
- Material is saturated with Oxygen
  But some vacancies only in CO portion gives rise to oxidation state of copper atoms => leads to superconducting behavior (mystery how?)
- Research towards room temperature SC :
  Powerful medical scanners, faster and less heating computers, Efficient levitating trains



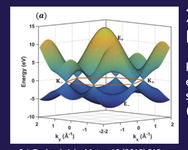
Structure of YBCO and CuO_2 layers

Band structure of LEDs

Crystal structure of materials example (2D)



Band structure



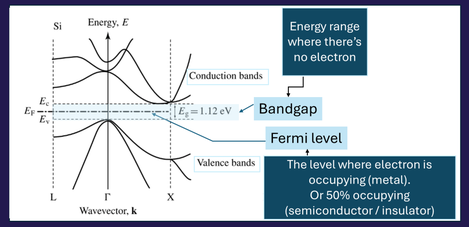
2D honeycomb lattice

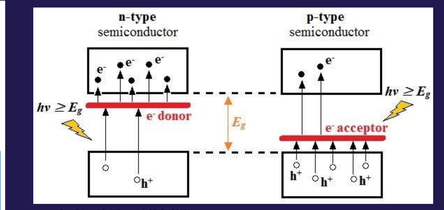
Possible energy states that electron can have at a specific momentum (direction of velocity)

Sci. Technol. Adv. Mater. 19 (2018) 618

https://www.fiberoptics4sale.com/blogs/wave-optics/semiconductors

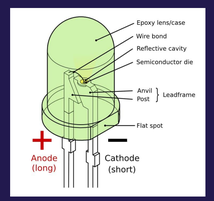
Features of band structures

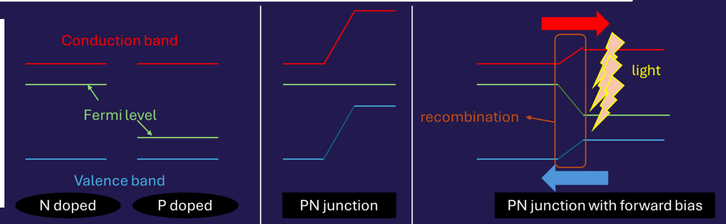




Env. Sci. and Poll. Research 25 (3) (2018)

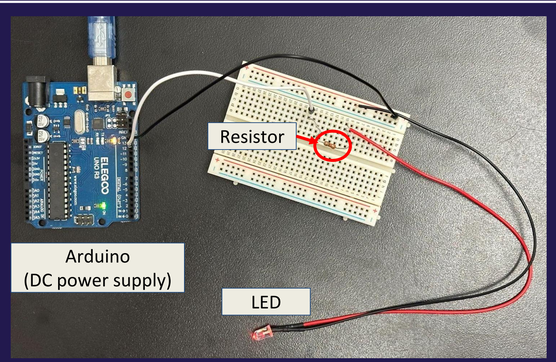
Light emitting diode (LED)





Doping: Method of increasing conductivity by mixing impurities into a substance

Picture of the LED circuit



Temperature dependence of band gap and Superconductivity

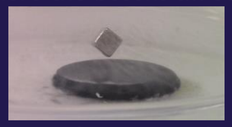
Band gap is the minimum energy required to excite an electron from the highest to the lowest energy shell.
As temperature decreases:

- Rapid cooling changes lattice spacing and vibration energy
- Increased band gap in the semiconductor of the light emitting diode (LED)
- Emission of higher energy photons, leading to shorter wavelengths and blue-shift
  - $E = hc/\lambda$

In this experiment, LEDs of different colors were submerged in liquid nitrogen with a boiling point of -196°C (-321°F) for 1-2 minutes. Color change was most visibly observed with red and orange LEDs.

Before (orange) **After (yellow)**

At temperature below T_c, cooper pairs act as **bosons** to create a **superconducting** condensate where the bosons all occupy the lowest available energy state.



WHY LEVITATE? Form screening currents when external magnet is applied, upward force cancelling out gravity

References

- https://chem.libretexts.org/Bookshelves/Inorganic_Chemistry/Inorganic_Chemistry_(LibreTexts)/07%3A_The_Crystalline_Solid_State/7.03%3A_Superconductivity/7.3.01%3A_Superconductors
- N. Mermin, N. Ashcroft. Solid State Physics (1976)
- Sci. Technol. Adv. Mater. 19 (2018) 618
- https://www.ch.ic.ac.uk/rzepa/mim/century/html/ybco_text.htm