Modern Physics (PHY 3305) Lecture Notes

Solid-State Physics: Superconductivity (Ch. 10.9)

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Review

no tags

- We applied our model of conductors and insulators to understand semiconductors
- We learned that semiconductors have two kinds of current: electron and hole current
    - holes are vacancies in quantum states in the valence band, which can move around under the influence of an electric field
- We discussed intrinsic semiconductors, and then how those can be "doped" to create more useful and flexible extrinsic semiconductors
    - doping adds impurities to the intrinsic semiconductor, creating either donor or acceptor states near the conduction or valence bands (respectively) and promote more current flow (either electron or hole)
- We discussed applications of extrinsic semiconductor: the diode
    - allows current to flow in one direction but not in the other

Example: The Transistor

A double sandwich of n-p-n doped semiconductor. The p-type is the base, the n-types are the emitter and the collection (they typically have different doping). The sandwich causes the emitter-base junction to be forward biased while the base-collector junction is reverse-biased. While the electrons entering the base are minority carriers there, and a small current leaves the bias output, the majority of electrons slide down into the conduction band of the collector, resulting in a huge current out the collector. emitter-collector current can be 100 times larger than the emitter-base current. This is the amplification, then. A small input signal (emitter-base) can be amplified into a large emitter-collector signal. (see slides)

For their 1948 discovery of the transistor, John Bardeen, Walter Brattain, and William Shockley were awarded the 1956 Nobel prize in physics.

Superconductivity

Some materials lose all electrical resistance at low temperature.

- reminder discussion of resistance: what are the causes of resistance in a solid?
    - thermal motion of ions (high-temperature dominant)
    - missing ions (low-temperature dominant)
    - impurity ions (low-temperature dominant)

Comparison:

- copper retains resistance down to the lowest measurable temperature
- tin's resistivity plummets to zero at its **CRITICAL TEMPERATURE**

The critical temperature is a characteristic of a material. Below this temperature, in a state of zero resistivity, the material is called a "superconductor". About 40% of natural elements are known to become superconducting at low temperature.

Features of Superconductors

Superconductivity really is super.

- With no resistance, an electric current established in a superconducting material should persist indefinitely, without an applied voltage. Experiments testing this prediction have suggested that minimum "wind down" times of 100,000 years can be achieved.
- Superconductors also "expel" magnetic fields. A superconductor below T_c, which is then exposed to a magnetic field, will not be permeated by the field lines. Similarly, a superconductor initially about T_c and already immersed in a magnetic field will expel the field as the temperature goes below T_c.

The latter property is not explained only by perfect conduction (and thus response of electrons in the conductor to magnetic fields, creating opposing magnetic fields by flowing). IN addition, perfect

DIAMAGNETISM is required to expel magnetic fields. Superconductors are able to create perfect opposing magnetic dipole moments that cancel out the external magnetic field and expel it from the solid. As such, a superconductor always repels a magnet, regardless of pole.

(see slides - the black disc is Yttrium Barium Copper Oxide (YBCO), a man-made superconductor. It rests on copper, a very good conductor, which itself sits in liquid nitrogen. The copper draws heat out of the YBCO. A magnet rests above the disc and can be spun freely. This video and accompanying information come from http://www.physics.umd.edu/deptinfo/facilities/lecdem/outreach/QOTW/active/q355.htm)

Another cool video:
http://www.bing.com/videos/watch/video/cool-superconductor-presentation/3d8371b5d207e3d6f7b03d8371b5d207e3d6f7b0-1470111220160

A line of magnets are arranged into "tracks" with one rail arrange *N-S*, the middle *S-N*, and the last *N-S*. A material that can become superconducting when cooled is cooled by exposing it to liquid nitrogen (likely YBCO) - a conducting cup rests atop the YBCO and holds the liquid nitrogen for cooling. A small piece of plastic is placed between the YBCO and the magnetic rail, the YBCO is driven superconducting, and the plastic is removed. Any motion of the YBCO in the gravitational field causes eddy currents in the superconductor, and that coupled with perfect diamagnetism creates a opposing magnetic field that RESISTS VERTICAL MOTION. Forward-back motion is resisted because the magnetic poles change sign on the outer rails, causing more eddy currents to oppose motion. The only allowed motion is horizontal, where the field strength is not changing. Not only can the YBCO levitate, it can remain fixed above the track EVEN UPSIDE DOWN.

Strong Magnetic Fields

With a strong enough magnetic field (the critical field), you can overcome the expulsion and destroy superconductivity. The reaction of a material to strong fields is important, as it helps you to decide which superconductor to use in different current-carrying situation (large currents can set up magnetic fields, which in turn are large enough to end the superconductivity). There are two classes of superconductor, based on their magnetic properties:

The discovery of superconductivity was awarded the 1913 Nobel Prize (Heike *Kamerligh-Onnes*).

- *Type-I* Superconductor:
    - characterized by a sharp transition as the external magnetic field increases (from field-excluding superconduction to field-penetrating normal conduction). Superconducting atomic elements tend to be *Type-I*. Their critical fields and temperatures are typically low, 0.01-0.1 T and 1-9K. Their usefulness is limited.
- *Type-II* Superconductor
    - characterized by the ability to form VORTICES, superconducting regions of circulating current surrounding "tubes," known as "normal cores," of normal-conducting material. Magnetic field lines pass normally through the normal cores. As the external field is strengthened, the vortices become more dense. More magnetic field can pass through the material.
    - there are two critical fields: below the first one, the material behaves like a *Type-I* superconductor. Above it the vortices form (a "vortex state"). The second critical field occurs when the vortices are densely packed enough that all external field lines pass through, and the entire sample is normal.
    - metallic compounds and alloys tend to be *Type-II*. They are marked by critical temperatures that are twice as high as in type-I, in the 20K range, and critical fields 2-3 orders of magnitude higher than type-I. They are much more practical for applications.

***Bardeen-Cooper-Schrieffer* (BCS) Theory**

But what IS superconductivity?

Although there are differences in properties of type-II and type-I superconductors, they both work by the same underlying mechanism: COOPER PAIRS. The ordered motion of pairs of electrons (COOPER PAIRS) is responsible for superconductivity. The motion of all pairs is so strongly correlated and ordered that they respond to all electric fields as a single unit. They are thus unable to scatter individually in ways that ordinarily result in electrical resistance.

Where do COOPER PAIRS come from? Consider two pieces of information:

1. a given material's critical temperature T_c varies with the average mass of the positive ions according to $T_c \propto M^{-1/2}$. This is known as the ISOTOPE EFFECT.
2. atomic elements that superconduct at low T tend be be bad conductors

at room T, and vice versa. Examples are lead (electrical resistivity = (20 °C) 208 nΩ·m) and aluminum (resistivity = (20 °C) 28.2 nΩ·m), as compared to a good room T conductor like copper ((20 °C) 16.78 nΩ·m)

DISCUSSION

- what can make something like aluminum and lead (which do have conduction electrons) bad conductors?
- what does the answer to the first question imply about the nature of superconductivity? That is, upon what property of bad conductors might superconductivity rely?

The answer is: interactions between the lattice ions and the electrons PROMOTES superconductivity. It's counterintuitive, but here's how.

- How can the electron-lattice interaction form a bound pair of electrons?
    - Electrons repel by the Coulomb force, but interaction with the lattice promotes ATTRACTION.
    - QUESTION: how can attraction to the lattice promote attraction between two pairs of electrons?
    - DISCUSSION: consider and electron passing through an arrangement of ions (a square, for instance). There is a small deformation of the lattice in the locality of the electron, as it attracts the ions to it. That deformation propagates through the lattice - one displaced ion pulling on the next. Another electron, possibly very far away in the solid, will also be tugged by this distortion. Overall, it appears as though over a long range one electron has attracted another. This was Cooper's big revelation. And even bigger was the following: any attractive force, regardless of HOW WEAK it might be, allows for the formation of BOUND STATES. Thus, Cooper Pairs are bound states of electrons attracted to one another by lattice deformation. This deformation is called a "Phonon" - a quantum of lattice deformation (like a sound wave) emitted by the electron and attracting another electron.

Under the proper conditions, this attraction is stronger than the Coulomb Repulsion. Even so, the binding energy is small (typically 0.001 eV) and the electron separation is large, typically $1\mu\mathrm{m}$. Because this is larger than atomic spacing, a great many Cooper Pairs overlap one another.

BCS Theory of Superconductivity involves not just the binding of pairs of electrons, but their correlations among ALL Cooper Pairs.

According to BCS Theory:

- the overall state of lowest energy occurs when the most energetic conduction electrons - those at the Fermi Energy - form opposite-spin Cooper pairs with ALL pairs having the same net momentum.
- in a state of zero current, that net momentum is zero and is common to all pairs. The result is a very ordered state. Although members of a pair experience changes in their relative momentum (as during a current), the momentum of their center of mass is all the same.
- random vibrations in the lattice when it is cooled below T_c (where Cooper Pairs can form) cannot break the pairs, which is the only way to disrupt the ordered state.
- What differentiates type-I and type-II pairs is the mean free path of the electrons in the lattice. Long mean-free-paths result in cooper pairs bound over long distances, acting collectively over the entire material to expel magnetic fields. Short mean-free paths mean that cooper pairs are bound over short regions, which allows the formation of vortices.

High T_c Superconductors

As an example of how this is a vibrant area of research, consider the phenomenon of High T_c superconductivity, discovered in 1986. These were compounds of copper and oxygen with other elements (and qualified as ceramics - excellent INSULATORS at normal temperatures) . The discovery earned a 1987 Nobel Prize. The first compound discovered had a critical temperature of 30K, and the race was one to find more exotic ones. A milestone was the creation of YBCO in 1987, with a critical temperature of 92K - well in excess of the boiling point of liquid nitrogen (77K).

Why is this important? Previous superconductors required liquid helium for cooling - a precious commodity. High T_c superconductors required only liquid nitrogen, much cheaper and plentiful! The record holder was discovered in 2006, with a critical temperature of 150K.

Explanations of high T_c superconductivity have eluded theoretical physicists. BCS theory does not alone explain the phenomenon, and no comprehensive theory has emerged. There has been some recent work that is promising, but the jury is out. Of course, the experimental holy grail is a superconductor at room temperature.

Next Time

- Nuclear Physics: Chapters 11.1-11.3