Superconductivity

A short introduction

By: Dr. Werner Prusseit

The following compilation is intended to give – in simple word and without in depth theory - a short introduction into the phenomenon of superconductivity and the related effects.

This short manuscript does not claim completeness. Analogies and simplifying pictures are intended to facilitate the understanding but should not be taken too far to go into details.

For further reading we recommend:

M. Tinkham

Introduction to Superconductivity, 2. Edition

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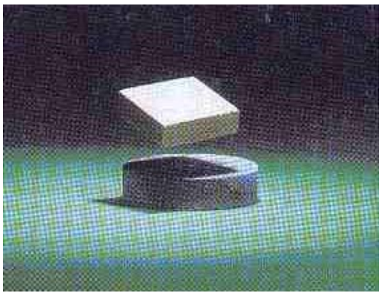
Superconductivity

Superconductivity, i.e. the absence of electrical resistance, is a quantum mechanical phenomenon at low temperature.



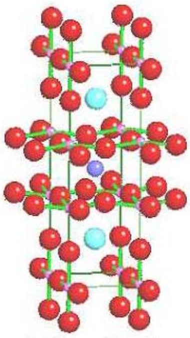
It can be observed in conventional metals (Hg, Pb, Nb ...), alloys (Nb_3Sn ...), oxides, and other inorganic and organic molecules close to absolute zero of the temperature scale (-273.15 °C) or at least around the boiling point of liquid Helium (4.2 K).

High temperature superconductors (HTS) discovered in the late 1980ies are complex oxide compounds which get superconducting above the boiling point of liquid nitrogen ($\approx$ 77K). The record transition temperature set by a mercury compound is at 134 K.

THEVA is producing thin film coatings of a certain class of these materials, namely 123-HTS or $REBa_2Cu_3O_7$.

HTS

High temperature superconductors are very complex oxide compounds derived from the so called Perovskite lattice. The crystal structure of $REBa_2Cu_3O_7$ (so-called 123-structure) where RE stands for a rare earth like element is depicted in the figure.



$RBa_2Cu_3O_7$

In these compounds superconductivity is essentially confined to double planes of CuO_2 (Cu = small pink spheres) as shown in the figure in the middle of the unit cell. The adjacent building blocks act as charge reservoirs for doping carriers into the CuO_2 planes. This planar arrangement results in a strong anisotropy. Supercurrent flow along the planes can exceed the flow across by several orders of magnitude.

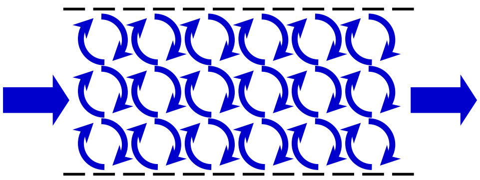
Another important feature of HTS is that the size of the charge carriers, the so called Cooper pairs, is very small – usually only a few atomic distances. Hence, boundaries between misaligned crystal grains interrupting the CuO_2 – planes are serious obstacles for the supercurrents.

So the crystal grains must be well aligned to achieve maximum current carrying capacity. This imposes new challenges for the fabrication of high quality HTS films and wires in contrast to conventional metals which can be highly disordered.

Mechanism

In a conventional metal wire conduction electrons move independently from one another, transporting charge from end to end. As they move along, they feel friction by defects and lattice vibrations. Therefore, an electric voltage is required to keep them going.

In superconductors electrons are bound together in pairs, the “Cooper” pairs named after L.N.Cooper, who first proposed this concept in 1956. This is surprising because the electrons would repel each other in vacuum, carrying equally negative charge. In a solid, the electrons move amid positively charged atoms, or ions, and these can attract both of the electrons, so binding them effectively together. In HTS it is thought that magnetic forces are even more important than the electric attraction.

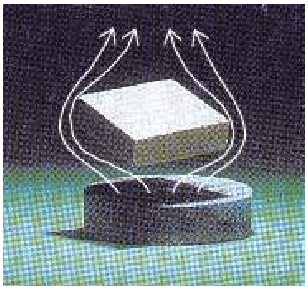


The Cooper pairs cannot exist unless they all move with the same pace. Within in the framework of quantum mechanics this means that all pairs together form a coherent wave, like a sound wave or a radio wave. If a pair is scattered out of this wave, its binding force vanishes, and the pair breaks up into two single electrons. The singles may stop for a while, but they are not lost. After some time they will find new partners to condense back into the bound state. But again, binding requires to take up newly the same pace as all the other pairs. So the newly bound pairs again contribute to the current as if they were never scattered.

More simply, we can view the Cooper pairs as a route column marching in step with arms linked together. If one member stumbles, it may stop for a moment, but then it is dragged along by its mates.

This way the current made up by moving pairs can never stop – it is a true supercurrent – and no voltage is required to keep it going.

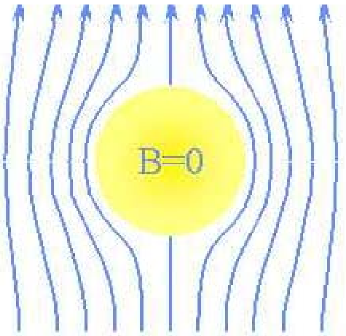
Meissner effect



The Meissner – Ochsenfeld effect is a very fundamental feature of superconductivity. It means that a magnetic field is expelled from the interior of a superconductor. This is most strikingly demonstrated when a superconductor is levitating on a magnet, i.e. sitting on a cushion of expelled magnetic field lines. This effect can be used directly for magnetic bearings.

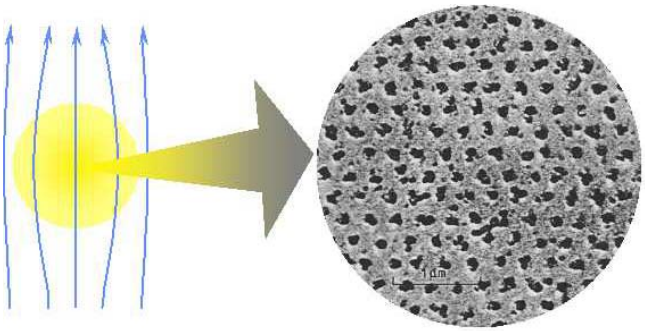
The Meissner effect is based on the quantum mechanical nature of the coherent pair wave. The wave has a certain stiffness and can form only when it has a very long wave length. A magnetic field would make the wave curly, but the pairs can avoid this by setting themselves into motion. So the pairs can only condense if they move, thus forming a current. This current has a magnetic field of its own which is opposite to the external field and shields it from the interior of the sample.

Type I SC



The first superconductors that had been discovered exhibited the Meissner effect just in the simple form as described above. Most of the pure element superconductors fall into this category which is named type I superconductivity. They were of limited use because they could not sustain any significant fields before they returned into the normal state. The reason is, that the expulsion of the field as shown in the figure costs energy, the more the larger the field. So the cost exceeds the gain at a certain critical field H_c which is relatively low.

Type II SC



There was a first break-through of superconductivity when a second type of superconductors was discovered that did not strictly expel the field. Having less energy to pay, these superconductors can sustain much higher magnetic fields. Most metal alloys and all HTS are of this type II.

In these materials the pair wave is not as stiff as in type I superconductors, so that the magnetic field can penetrate into the material in the form of flux lines which carry a smallest unit of magnetic flux – a so called flux quantum. Each flux line consists of a normal conducting core and a surrounding vortex of supercurrent.

The flux lines have been made visible by some experimental trick in the above picture. They form a triangular, regular lattice. This is the so called mixed state of type II superconductors

The core of the flux lines can be “pinned” by normal conducting defects or at locations where superconductivity is degraded. Such pinning centers are essential for the technical use of type II superconductors.

DC - resistivity

Type I superconductors can carry currents up to a level when the magnetic field produced by the current exceeds the critical field. Then superconductivity breaks down.

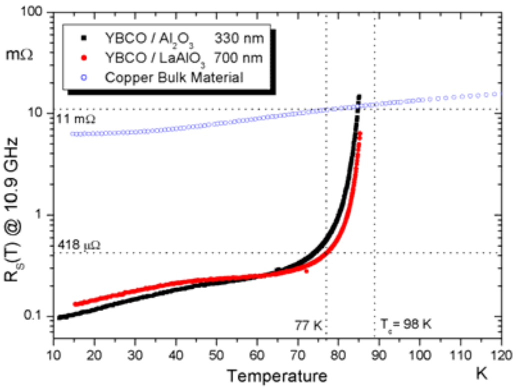
In type II superconductors the situation is better, because the fields they can stand are so much higher. However, there is another source of trouble. The flux lines threading the superconductor can move under the Lorentz force produced by the external field and the transport current. This motion causes a finite resistance in the material so that it no longer superconducts. Fortunately it is possible to pin down the flux lines by defects and inhomogeneities.

Pinning is particularly effective in the case of thin films made of REBCO due to segregations and also surface roughness. Very high critical currents in excess of several millions of amps/cm^2 can therefore be realized even at liquid nitrogen temperature (77 K). For example: a 10 mm wide and only 1 μm (1/100 of a human hair) thin REBCO film can carry 300 A of DC current. Conventionally, one would need a 15 mm thick copper cable for such a high current.

This property makes REBCO films very attractive for power applications such as fault current limiters or high power switches.

RF resistance

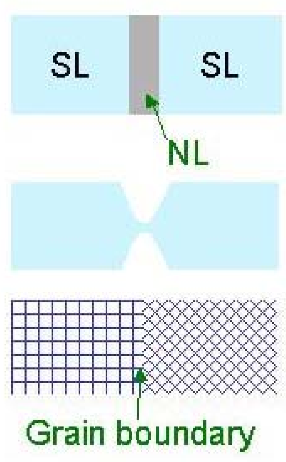
Strictly superconductors are lossless only for DC. In AC there are losses which increase with the second power of frequency. But still in the GHz range the losses remain moderate, some orders of magnitude less than in copper.



The diagram compares the surface resistance at 10 GHz vs. temperature of two REBCO films (different thickness) to copper. At 77K the gain is about a factor of 20.

Hence, RF – resonators made from REBCO offer significantly better performance than those made from conventional “good” conductors. Used for antennas (MRI or NMR) or filters in communications technology such superconducting resonators exhibit a drastically reduced noise level and higher sensitivity even at moderate cooling (around 77 K).

Josephson effects



The Josephson effects are the most striking manifestation of the pair wave. They occur when two superconducors are in weak contact, e.g. by a constriction, an insulating tunneling barrier or a normal conducting barrier for the pairs. In HTS junctions can be made by a grain boundary (cf. figure) and there are intrinsic Josephson effects (IJE) when a current is forced normal to the CuO_2-layers.

There are two cases to be distinguished:

The DC Josephson effect, when there is no voltage drop across the contact. This effect can be used to build a SQUID.

AC Josephson effect, when a voltage drop is maintained across the weak contact.

DC Josephson effect

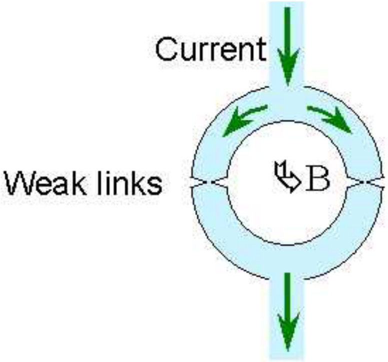
While the pair wave is generally "stiff" in the sense that its wave length is very long, the Josephson junction makes it curl easily because the contact is only weak. The wave curls whenever a supercurrent is flowing over the junction. The curling implies that there is a phase difference between both superconductors in contact. The larger the supercurrent the bigger becomes the phase difference. The actual relationship was first discovered by B. Josephson:

$$I = I_0 \sin \varphi$$

where I is the supercurrent and φ is the phase difference. I_0 is the maximum supercurrent which corresponds to $\varphi = 90°$. At this point the junction turns into a resisitive state exhibiting the AC Josephson effect.

Interesting interference phenomena arise when two Josephson junctions are connected in parallel. These can be used for a very sensitive magnetic field sensor, the SQUID.

SQUID



A Superconducting Quantum Interference Device (SQUID) is the most sensitive sensor known to science. There are several ways to build a SQUID, but here we restrict ourselves to the so called DC-SQUID which has two equal Josephson junctions connected in parallel, as indicated in the figure.

As already mentioned, each of them carries a current depending on the phase difference it feels. If the phase differences are the same, their currents add up and the total current has a maximum (constructive interference). However, if the phase differences are opposite to each other, the currents cancel each other and the total current is zero (destructive interference)

The interference can be controlled by curling the pair wave of the superconductors in between the junctions. This can be done by a small magnetic flux inside the ring. Tiny changes in the flux can already change the interference from constructive to destructive, and this is readily observable by total current flowing through the device. This makes this device the most sensitive sensor known. As an example, the SQUID can be used to detect fields generated by brain signals which are less than a billionth of the earth's field.

Such SQUID sensors are used whenever tiny signals have to be measured, e.g. in medicine technology, non destructive testing or basic research.

AC Josephson effect

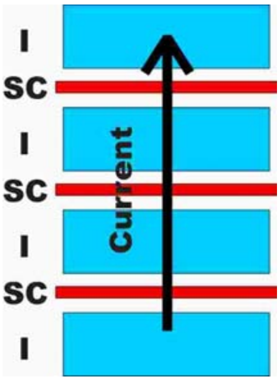
At low currents a Josephson junction behaves like an ordinary superconductor. It carries a lossless current while its phase difference is constant in time. However, when the critical current I_0 is exceeded, a resistive state occurs. Then the phase difference φ is no longer stationary but it increases with time: $\varphi = \omega t$. In view of the fact that the supercurrent is proportional to sin φ , (see the DC Josephson effect) we expect an AC current varying in time as $\sin \omega t$ This is the famous AC Josephson effect.

In the language of quantum physics the generation of an AC current corresponds to the emission of photons, and the angular frequency of the current corresponds to the photon energy according to Planck's formula $E = \hbar\omega$. This energy quantum has to be provided by a Cooper pair passing the junction. In other words, the AC Josephson current implies an energy difference or voltage drop between both superconductors in contact, so that the energy gained by a pair on passing is equal to the energy needed to emit the photon, or

$$2eU = \hbar\omega.$$

This is the second Josephson equation, where 2e denotes the charge of one pair. Hence, when a DC voltage is applied to the junction the current will acquire an AC component and can emit electromagnetic radiation. This has been observed experimentally. For typical voltages of a few mV this radiation is in the microwave regime.

Intrinsic Josephson effect



HTS consist of a periodic sequence of strongly superconducting layers separated by weakly superconducting blocks acting as charge reservoirs. Due to this layered structure they are anisotropic and can be viewed as stacks of intrinsic Josephson junctions. When driving a current perpendicular to the superconducting layers even the bulk material behaves like a series array of junctions and Josephson effects can be observed. The intriguing feature is that these Josephson junctions are not artificial but natural and occur on a microscopic scale with spacing of less than a nanometer.