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Review Article

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A Review on Cuprate Based Superconducting Materials

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Abstract

When Bednorz and Müller discovered the superconductivity in a compound La-Ba-Cu-O in 1986, it was considered as a breakthrough in the research of the superconductivity. This leads to the discovery of the other cuprate superconductors, and immediately the transition temperature of the synthesized materials reached to the liquid nitrogen temperature. Today the maximum transition temperature of the cuprate superconductors changes from 35 K for $La_2{-}xSr_xCuO_4$ to 138 K for $Hg_{1-x}Tl_xBa_2Ca_2Cu_3Oy$ (the highest record under normal pressure, which extends to ~160K at high pressure). High-temperature superconductivity in the Non-stoichiometric cuprate lanthanum barium copper oxide . The T_c for this material was 35 K, well above the previous record of 23K. Thousands of publications examine the superconductivity in cuprates between 1986 and 2001, and Bednorz and Müller were awarded the Nobel Prize in Physics only a year after their discovery. From 1986 to 2008, many cuprate superconductors were identified, the most famous being yttrium barium copper oxide ($YBa_2Cu_3O_7$, "YBCO" or "1-2-3"). Another example is bismuth strontium calcium copper oxide (BSCCO or $Bi_2Sr_2Ca_nCu_{n+1}O_{2n+6-d}$) with T_c = 95–107 K depending on the n value. Thallium barium calcium copper oxide (TBCCO, $Tl_mBa_2Ca_{n-1}Cu_nO_{2n+m+2+\delta}$) was the next class of high-T_c cuprate superconductors with T_c = 127 K observed in $Tl_2Ba_2Ca_2Cu_3O_{10}$ (TBCCO-2223) in 1988. The highest confirmed, ambient-pressure, T_c is 135 K, achieved in 1993 with the layered cuprate $HgBa_2Ca_2Cu_3O_{8+x}$. few months later, another team measured superconductivity above 150K in the same compound under applied pressure (153 K at 150 k bar).

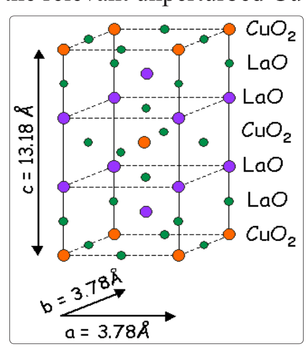
Introduction

Superconducting Cuprates

There are three main families of hole-doped cuprate high temperature superconductors studied today. However, much of the confusion in the study of HTSC results from the fact that each material is accessible to different experimental techniques. For example, it is easy to measure the electronic density of states of $Bi_2Sr_2CaCu_2O_{8+x}$, but harder to measure its magnetic properties. In the quest to find a unifying theory for all HTSC, it is tempting to treat these three as one material, and combine the experimental results from all families. Because of this common practice, the field of high-Tc research is rife with conflict and apparent contradictions.

$La_{2-x}Sr_xCuO_2$

The lanthanum family of high-Tc was the first family of materials to be discovered, by Bednorz and Muller in 1986. The structure of LSCO is shown to the right (with no Sr content). LSCO is physically the hardest of the three materials, and with stronger bonds it is easier to grow large (> 1 cm!) single crystals. Neutron scattering experiments, which probe the magnetic structure of the material, are typically limited to studying LSCO because of their requirement for large single crystals. But LSCO has not been successfully studied with an STM, because so far there has been no successful recipe to obtain an atomically flat surface with tunnel access through an insulating layer to the relevant unperturbed CuO_2 plane.



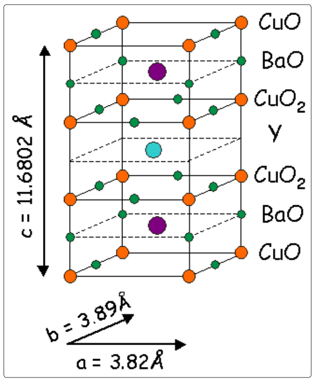
LSCO structure

$YBa_2Cu_3O_{7-x}$

YBCO structure

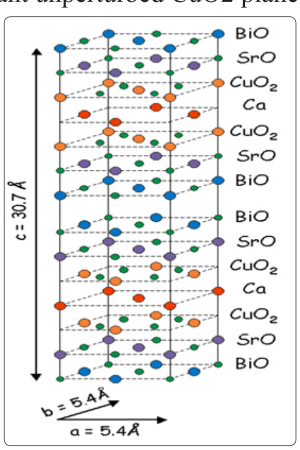
The discovery of YBCO followed that of LSCO within a year. YBCO was the first material to break the 77 K (liquid nitrogen) temperature boundary. The optimal Tc is now >90 K. The structure of YBCO is shown to the left. YBCO has perhaps been the most highly studied because it is the cleanest and most ordered crystal. But studies of YBCO can also be quite confusing because there are two CuO planes: the square plane and the chain plane. By analogy with the other HTSC families, it is thought that the superconductivity originates in the square plane, but it is hard to isolate the behaviors of the planes. YBCO is not an ideal material for STM studies, because it typically cleaves on the chain plane. STM studies of the chain planes have been made by Derro et al, but this is not usually thought to access the intrinsic superconducting properties of the material.

YBCO has typically been used in nuclear magnetic resonance (NMR) studies, which probe the spatial distribution of magnetic field. This is because YBCO is so well ordered that all atoms of a particular species will live in the same electronic environment (not true for BSCCO or LSCO). More recently, very clean YBCO has been used for quantum oscillation experiments, to map out the size of the Fermi pockets.



$Bi_2Sr_2CaCu_2O_{8+x}$

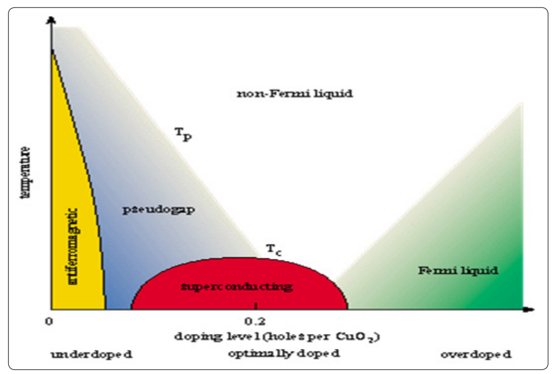
Finally we come to BSCCO, the favorite material for STM and ARPES. BSCCO was discovered in 1988. BSCCO itself can have 1, 2, or 3 CuO planes, with Tc increasing with the number of planes. Bismuth can also be replaced with thallium or mercury, which results in the highest Tc material known (~135K). BSCCO competes with YBCO as the most technologically useful material. YBCO has been used in magnetic field applications because it is easier to pin flux. YBCO can be used to grow high-Tc SQUIDS with grain-boundary Josephson junctions. Their higher operating temperature makes it easier to study living biological materials. BSCCO has been formed into superconducting wires (with silver) and placed into the Detroit power grid but problems in maintaining vacuum have delayed the success of this operation. The structure of BSCCO is shown to the right. Surface sensitive techniques such as STM and ARPES can study BSCCO because it cleaves easily between layers, leaving an atomically flat surface for study, and, it is thought, direct tunnel access to the relevant unperturbed CuO2 plane.



BSCCO structure

Phase Diagram

Phase diagram of the cuprate superconductors can be divided into two as the electron doped and the hole doped side. Inphase diagram of the hole doped and electron doped cuprate superconductors had been shown. The electron doped case is not the topic of this thesis; therefore, the hole doped side of the phase diagram will be explained in more detail. The so-called parent compound in cuprates (for instance non-doped $YBa_2Cu_3O_6$ for YBa_2Cu_3Oy, hole concentration is zero) is an antiferromagnetic Mott insulator. The Néel temperature is around 350 K. With hole doping to the system, the antiferromagnetic insulator state is rapidly suppressed and around 5% doping superconductivity starts to be observed. The superconducting dome is another common behavior among the cuprate families, even though the transition temperature differs greatly from around 35–138 K. The maximum Tc will be observed around 16% doping level that is referred as the optimally doped region. The doping region between 5 and 16% is called the under doped region. The normal state of this region is the strange metal region, which is characterized by the pseudo gap. Although this region is metallic in the normal state, it cannot be defined as the conventional Fermi liquid region; hence it is referred as the strange metal region



The generic phase diagram of the cuprates shows a wide variety of different behavior at different temperatures and levels of doping. All the compounds investigated so far show characteristic changes in almost all their thermodynamic and transport properties as either the temperature, T, or the number of holes per unit cell of CuO_2 is varied. The number of holes per CuO_2 unit, x, is a convenient parameter that can be used to compare the different cuprates.

The physical properties of the cuprates change abruptly at the superconducting transition (and also at the antiferromagnetic transition – see below). In the other regions of the phase diagram, however, the properties change gradually and there is a “cross-over” region rather than a well defined phase transition. Understanding the phase diagram in figure 1 is tantamount to understanding the cuprates and all their puzzling behaviors, including high-temperature superconductivity.

Condensed-matter physicists are interested in all of the thermodynamic, magnetic and transport properties of these materials. The challenge is to develop a microscopic theory that will predict all these properties. Here we will focus on a few key properties, including the specific heat capacity and the magnetic susceptibility, which is governed by excitations of the magnetic degrees of freedom.

The antiferromagnetic region is the best understood region in the phase diagram. At zero doping the cuprates are all insulators, and below a few hundred kelvin they are also antiferromagnets (i.e. the electron spins on neighboring copper ions point in opposite directions).

However, when the doping is increased above a critical value (about 5%, although this varies from compound to compound), the antiferromagnetic state disappears and we enter the so-called pseudo gap or under doped region. It is called under doped because the level of doping is less than the level that maximizes the superconducting transition temperature. Some of the most interesting behavior observed in the cuprates is observed in this region and we will return to it – along with an explanation of what a pseudo gap is – later

The Fermi-liquid region of the phase diagram is also well understood. One of the central concepts in condensed-matter physics, introduced by Lev Landau, is the "quasi particle". In a so-called Landau-Fermi liquid the properties of single electrons are changed or "renormalized" by interactions with other electrons to form "quasi particles". The properties of the material can then be understood in terms of the weak residual interactions between the quasi particles and their excitations. A key feature of the quasi particle concept is that low-energy single-particle excitations have very narrow line widths: $Dw \sim w^2$ where w is the energy of the excitation. When the quasi particle approach is valid, there is a well defined boundary between particles and holes in both energy and momentum space at zero temperature. This boundary occurs at the Fermi energy and defines the "Fermi surface" in momentum space. However, the Landau quasi particle model can only explain part of the phase diagram of the cuprates. The best known characteristic of the superconducting region is the fact that the resistivity is zero. However, condensed-matter physicists measure many other properties of superconductors, such as the energy needed to split the Cooper pairs. This is the superconducting energy gap, 2D. The pairing process means that there are no single-particle excitations with energies of less than D in the superconducting state (hence the name gap).

Normal metals and Fermi liquids do not exhibit such gaps. Energy gaps show up clearly when the single-particle density of states is plotted – that is when the number of electronic states with a given energy is plotted as a function of energy. Energy gaps are also responsible for semi conductivity, but the mechanism that leads to the formation of the gap is completely different.

The part of the phase diagram between the under doped and Fermi-liquid regions, and above the area with the highest superconducting transition temperatures, is called the non-Fermi-liquid region. The thermodynamic properties in this region are unexceptional and, within experimental uncertainties, are in fact similar to the behavior of a Fermi liquid. However, this region is characterized by exceptionally simple but unusual power laws in all of its transport properties as a function of temperature. These transport properties include the resistivity, the optical conductivity, the electronic Raman-scattering intensity, the thermal conductivity, various nuclear relaxation rates, the Hall conductivity and the magneto resistance. These unusual transport properties are why this part of the phase diagram is called the non-Fermi-liquid region. The exceptional transport properties of the non-Fermi-liquid region led Phil Anderson of Princeton University to suggest in the late 1980s that radically new physics was – and still is – required to understand the cuprates. One of us and collaborators suggested that the non-Fermi-liquid region of the phase diagram is well described by the so-called marginal-Fermi-liquid hypothesis. Here the line width of a single-particle excitation is proportional to its energy, which means that the quasi particles are not well defined, and there is no clear boundary between particles and holes at zero temperature.

This point was reinforced by angle-resolved photoemission spectroscopy measurements, which found no evidence for quasi particles. On the other hand, the first derivative of the occupied density of states with respect to momentum is discontinuous, and this can be used to define a Fermi surface. But in the under doped region, as we shall see, the concept of the Fermi surface itself is lost. For condensed-matter physicists.

Conclusion

The discovery of high temperature one of the most brilliant events to the wider physical concept electron system". This system because, the physics of high-temperature not thoroughly understood yet. Temperature superconducting properties within many types of materials. Tried to discuss about cuprate materials. We have studied diagram, characteristics and different based superconductors.

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