Fabrication and characterization of a High-Tc $YBa_2Cu_3O_{7-x}$ ceramic superconductor.

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A high Tc $YBa_2Cu_3O_7$ ceramic superconductor was fabricated and tested to work based on the Meissner effect. A qualitative description of the temperature dependence of resistivity is given, and the critical temperature, T_c was found to be approximately 78.3 K. This could be increased by increasing the oxygen content of the superconductor.

INTRODUCTION

In all metals and alloys, resistance decreases with decreasing temperature. It was expected that no sample of metal could be perfectly pure, and that there would always be a"residual resistivity" that persisted at the lowest of temperatures, due to crystal imperfections.[1] For some materials however, once the temperature reaches a critical value T_c, the resistivity drops dramatically to practically zero. This phenomenon is called superconductivity. It was first discovered by H. Kamerleigh Onnes in 1911[2], shortly after he managed to produce liquified helium, which was necessary to achieve the low temperatures required for superconductivity. The other hallmark of a superconductor is perfect diamagnetism: the magnetic field is expelled from the interior of the superconductor.[3] This effect is known as the Meissner effect, which will be dealt with in greater detail later in the paper. Bednorz and Müller discovered the first high-T_c ceramic superconductor in 1986.[4] Since then, there has been much research into discovering materials that superconduct at progressively higher temperatures. An ideal that researchers are working towards is a material that superconducts at room temperature, or slightly below it. This would eliminate the expense required to refrigirate the superconductor, which can often outweigh the benefits of reduced energy loss through resistive heating. However, at present, we are far from that goal.

THEORY

The behavior of classical superconductors has been fairly well explained by the theory put forward by Bardeen, Cooper, and Schrieffer (BCS)[5]. However, there is still disagreement about the theory of high temperature superconductors (HTSCs), so we will not delve too deeply into it. (A good review of probable theories of HTSCs is given in chapter 12 of Thomas P. Sheahen's "Introduction to High-Temerature Superconductivity"[6]We will, however, briefly deal with the structure of Yttrium barium copper oxide (YBCO), the superconductor that we will fabricate, as well as the Meissner effect, which we employ in testing whether our sample superconducts.

Structure of YBCO

The unit cell structure of YBCO is given in figure 1.[6].

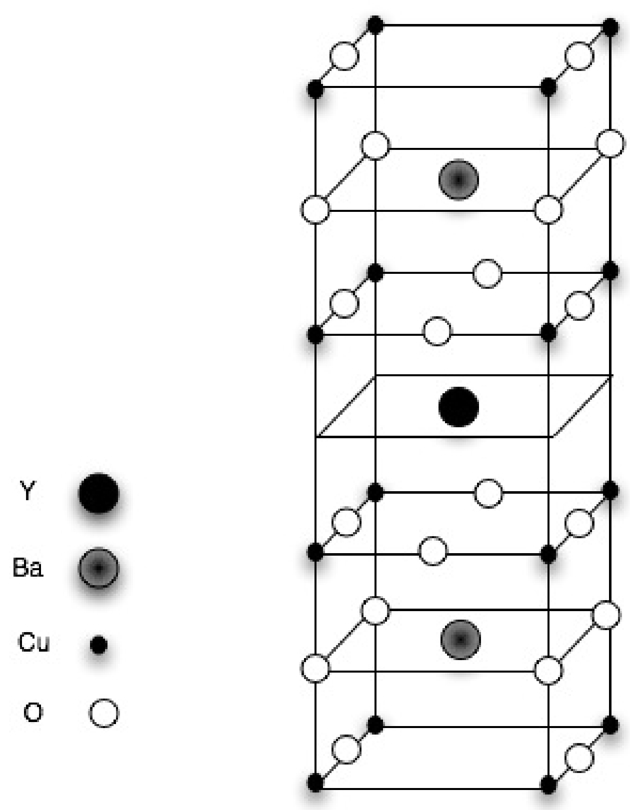

FIG. 1: Unit-cell structure of YBaCuO superconductor[6]

Ceramic superconductors like YBCO are often very anisotropic, that is, they have different properties in different crystalline directions. The superconducting current flows entirely in the planes of copper oxide in the crystal. YBCO has been found to be superconducting up to 92 K. This is important because then liquid helium is not required to cool the material, liquid nitrogen will suffice, which is much cheaper.

Meissner effect

The Meissner effect is the name given to the phenomenon in which a superconducting material, when cooled through T_c expels any applied magnetic field inside it, up to a certain field strength known as the critical magnetic field $H_c(T)$. A field greater than this will overcome the Meissner effect and the material ceases to superconduct (it resumes superconduction once the field is removed). In any material, the applied magnetic field $\mathbf{H}$ and the magnetization $\mathbf{M}$ are related as follows:

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}) \tag{1}$$

In a perfect diamagnet such as a superconductor, $\mathbf{M} = -\mathbf{H}$, and $\mathbf{B}$=0 as a result. The Meissner effect can be explained using the theory proposed by F. and H. London in 1935[7]. The London equation is as follows:

$$\mathbf{j} = -\frac{1}{\mu_0 \lambda_L^2}\mathbf{A} \tag{2}$$

where $\mathbf{j}$ is the current density, and $\mathbf{A}$ is the magnetic vector potential, related to magnetic field $\mathbf{B}$ as follows:

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{3}$$

In the London gauge, $\nabla \cdot \mathbf{A} = 0$. We take the curl of both sides of (2) to get:

$$\nabla \times \mathbf{j} = \frac{-1}{\mu_0 \lambda_L^2}\mathbf{B} \tag{4}$$

We know the Maxwell equation:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} \tag{5}$$

Taking the curl of both sides, we have:

$$\nabla \times \nabla \times \mathbf{B} = \mu_0 \nabla \times \mathbf{j} \tag{6}$$

Another Maxwell's equation gives us the divergence of $\mathbf{B}$:

$$\nabla \cdot \mathbf{B} = 0 \tag{7}$$

Therefore, (6) reduces to

$$-\nabla^2 \mathbf{B} = \mu_0 \nabla \times \mathbf{j} \tag{8}$$

Combining this with (4), we obtain, for a superconductor:

$$\nabla^2 \mathbf{B} = \frac{\mathbf{B}}{\lambda_L^2} \tag{9}$$

This equation implies that a uniform magnetic field cannot exist within a superconductor.[6],[8]. From the above equation, $\mathbf{B} = B_0 e^{\frac{-z}{\lambda_L}}$, where z is the distance from the surface to the point inside the semiconductor where the magnetic field is being measured. Thus we see that the magnetic field within a superconductor is expelled. $\lambda_L$is the London penetration depth, which indicates the depth of penetration of the magnetic field through the surface of the superconductor.

EXPERIMENTAL SETUP

Fabrication

The method we used for fabricating our superconductor sample is adapted from the procedure laid out by Colin Greaves in "Structural, Electrical and Magnetic Properties of Perovskite Ceramics"[9]. The reagents used were dried Y_2O_3, CuO, and $BaCO_3$. The reagents were weighed out to give a Y:Ba:Cu ratio of 1:2:3, then ground together with a mortar and pestle until no white streaks were observable on grinding. The mixture was loaded into a circular die with a radius of approximately one inch, and then pressed at 5000 Kg in a hydraulic press to form a pellet approximately 3 mm in thickness. The pellet was then placed in a furnace programmed with the following sequence:

1. Heat to 930^{o}C and hold for 12 hours
2. Cool to 500^{o}C and hold for 1 hour
3. Cool to 400^{o}C at 50^{o}C h^{-1}
4. Cool to room temperature.

Once the furnace temperature was below 400^{o}C, the sample was removed from from the furnace and cooled. The sample, which was previously gray and shimmery and brittle, turned black and hard upon this treatment. To test whether our sample did in fact superconduct, we took it to a magnetic rail after cooling it in liquid nitrogen, and tested whether it levitated above the magnets due to the Meissner effect. It did in fact levitate (though not very high, due to its large size), so we concluded that we were successful in fabricating the $YBa_2Cu_3O_7$ ceramic superconductor.

Characterization

After fabrication, we proceeded to characterize the superconductor, that is, observe how its resistance changed with change in temperature. To do this, we adapted the simple procedure laid out by L. M. León-Rossano[10]. A 'T' type copper-constantan thermocouple was attached to the bottom of the sample with adhesive. The sample was placed in a metal sample holder, whose insides we covered with duct tape to provide insulation. Electric leads were then attached to the sample in the manner shown figure 2, with thin copper wires. The sample in the sample holder was then lowered into a wide-based cylindrical styrofoam container. The leads from the thermocouple, and the two middle leads on the sample were connected to multimeters, and the two outer leads were connected to a constant current source of 0.3 A. We constructed a LabVIEW program to measure the multimeter readings from both multimeters simultaneously, convert the thermocouple multimeter voltage reading into a linearized temperature value, and then input a 2D array of

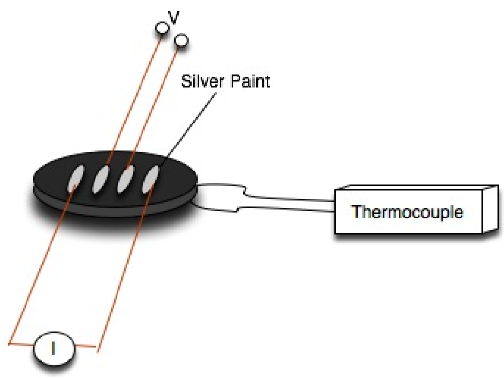

FIG. 2: Sample setup.

these values into a spreadsheet. The last step in our experimental setup/procedure was to pour liquid nitrogen into the container, and then place a styrofoam lid on it, to slow down the temperature increase rate of the sample (so that we could take more data). The data obtained is presented in the next section.

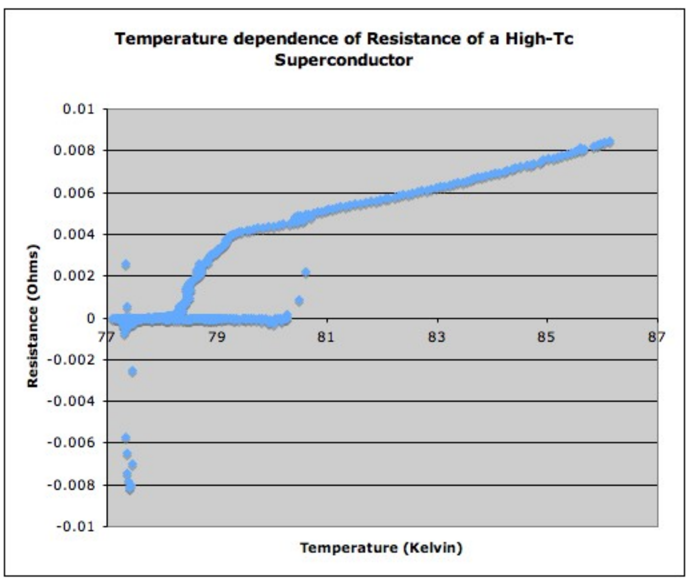

FIG. 3: Plot of resistance of $YBa_2Cu_3O_7$ versus temperature. We see that there is a drastic drop in resistance once the temperature reaches 79 K, with it reaching zero at $T_c = 78$K

RESULTS AND ANALYSIS

Figure 3 gives a plot of the change in resistance of the superconductor with temperature. From the graph we can observe that above approximately 79.4 K, there is a linear dependence of resistance on temperature. However, there is a drastic drop in resistance below this temperature, signifying a phase transition to superconductivity. At approximately 78.3 K, the resistance of the sample drops to zero. There are some spurious data points on the graph. These were caused by the leads becoming detached from the sample (they were notoriously tough to affix). These points appear as a horizontal line segment along the x-axis from 77 K to 80 K, and other outliers on the left hand side of the graph, and should be ignored. The critical temperature of 78.3 K is well below the ideal T_c of 93 K. This can be attributed to insufficient oxygen content[9], or crystal impurities and defects.

CONCLUSION

We successfully fabricated and characterized a high temperature $YBa_2Cu_3O_7$ ceramic superconductor sample. Further care and caution while preparing the sample will result in a higher T_c, closer to 93 K. Superconductors already have application in industry and in hospitals where they are used in the electromagnets for magnetic resonance imaging. High temperature superconductors would further reduce the refrigeration costs associated with normal superconductors. However, one as-yet unsurmounted practical setback is that it is extremely difficult to fashion ceramic superconductors into wires.[6]

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