

Experimental Setup for Understanding the Superconductor to Insulator Transition in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ Thin Films

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Abstract. We refine a technique used by B. Boyce to change the carrier concentration level of thin $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) films. The purpose of this is to eventually study the superconductor to insulator transition that takes place in YBCO as carrier concentration level decreases.

Introduction. For high carrier densities, YBCO is a d-wave superconductor, and its superfluid density has either a linear or a quadratic temperature dependence near zero temperature. However, for lower carrier densities ($\delta \sim 0.5$ or lower), YBCO is an antiferromagnet. To understand how this material changes between these two states, a process to alter quickly the carrier concentration of YBCO is needed. This process must also yield a uniform carrier density throughout the crystal; else different regions of the film make transition at different average carrier concentration levels, resulting in a blur in the transition over several concentration levels.

In YBCO crystals, there are both copper oxide chains and copper oxide planes. It is believed that conduction in YBCO takes place predominately within the copper oxide

planes. The oxygen atoms in the copper oxide chains are more mobile, and changing the number of such atoms in a crystal alters the number of carriers available for conduction. In thin films these chain oxygens are more easily removed due to their proximity to the surface.

Thin films are thus a good type of sample to study to investigate this transition. To tell if a film is homogeneous, we look at its behavior around T_c . For a uniform film, the superfluid density graph should always retain its downward curvature; in an inhomogeneous film, there will be a noticeable “foot” over a range of a few K as the superfluid density goes to zero at T_c . This is due to a breadth in the transition of the film, which is likely due to differing local carrier concentrations. A transition for a homogeneous film will be spread out over a temperature range of less than 1K. Superfluid density varies as $1/\lambda^2$, so measuring the penetration depth not only gives us a means of characterizing the type of superconductor the film is, but a means of telling if the film is homogeneous or not.

Experiment. To measure the penetration depth of a film, a two-coil method is used (see Figure 3). The film is fixed between two coils. Typical coils are 2mm in diameter and have from 20 to 80 turns of wire. Through the so-called drive coil is run an AC current I with angular frequency ω , and the voltage V induced in the other coil is measured. The complex mutual inductance of the system is then given by $M = V/\omega I$. The coils are attached to the end of a probe placed inside a glass dewar. The film is then cooled to 4.2K by vapor from liquid helium transferred to the bottom of the dewar. Heat leaks then

warm the film, and the mutual inductance is recorded as a function of temperature. A technique by Turneure et al. [1] is then applied to the recorded data to extract the penetration depth of the film as a function of temperature. This gives the penetration depth to an absolute accuracy of 10%, the largest source of error being the determination of film thickness. However between measurements on the same film the thickness remains constant, so the relative uncertainty between measurements on a film is 1%, the greatest source of error being the centering of the film in the probe.

Oxygenation Procedure. The oxygenation procedure detailed below is an improvement over the technique of Boyce [2] in that the films thus processed are much more homogeneous.

The film is processed by exposure to a mixture of argon, oxygen, and ozone at an elevated temperature. The furnace is first ramped up to 300°C to 500°C after which the sample is sealed in a cool part of the furnace. The sealed furnace is evacuated to a pressure of about 2 torr, and then flushed with either argon, oxygen, or some chosen gas mixture. This flushing is done to eliminate any gaseous contaminants that could potentially damage the film. Preferably the gas mixture used for flushing is the one to be used for processing; if not the gas system is set to give the correct mixture and everything is left to stabilize for about ten minutes. The sample is then pushed to the center of the furnace with a bent metal rod inserted through a small hole at the exhaust end of the furnace. The sample then sits in the furnace for 40 minutes while the flow rates are

monitored. It is then removed from the furnace and set onto a copper block to quench it to room temperature. The sample is typically at room temperature in under a minute.

It is assumed that for each gas mixture and temperature there is some equilibrium state for the sample, and that 40 minutes is long enough for the sample to attain this state. If this were not true, the attainment of uniformly oxygenated films would be impossible. Quenching is necessary to minimize shifts from this equilibrium state during cool down.

The greatest challenge of this method is choosing parameters that yield a homogeneous film in a reasonable amount of time while minimizing the damage done to the film.

There are at least ten different settings that the user of this system has control over, including the ozone generator setting, the temperature of the furnace during processing, the flow rates (oxygen and argon), and the degree of oxygen-argon mixing that occurs before the oxygen reaches the ozone generator. In order to simplify matters, I decided to leave most of these parameters fixed while altering only oxygen flow rate and temperature, and keeping the ozone generator either set to its highest setting or turned off.

At higher temperatures, more atoms in the film are mobile, and the chain oxygen atoms are easier to add and remove. This makes the resulting film more homogeneous, but can result in permanent damage to the film as atoms other than oxygen atoms in the copper oxide chains may move. Lower temperatures alleviate this danger, but do not always produce uniformly oxygenated films.

My solution is to use a lower temperature when a higher T_c is desired, and a higher temperature when a lower T_c is desired. This allows me to preserve the samples to the greatest extent possible while still getting useful information from them.

Results. Two films A and B were studied using this oxygenation procedure, with good results obtained to a T_c of 30K for one of the films. Difficulties dealing with possible contaminations and minor equipment failure prevented a more in depth study. Both films are coevaporated YBCO on SrTiO_3 substrates; film A is 700Å thick and film B is 1000Å thick (both thicknesses $\pm 100\text{Å}$). Optimal T_c for both films were around 90K. As shown, homogeneity was retained for film A to a T_c of 29K. Processing after that point damaged the film. Figures 4-6 show data taken for different film states.

Conclusion. Although much work still remains to be done, this technique looks to be a valuable tool in the study of the superconductor to insulator transition. Further work will involve the use of the different gas mixing settings available and

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References.

[1] S. J. Turneaure, A. A. Pesetski, and T. R. Lemberger, *J. Appl. Phys.* 83, 4334 (1998)

[2] B. R. Boyce, Ph.D. Thesis, The Ohio State University (2000)

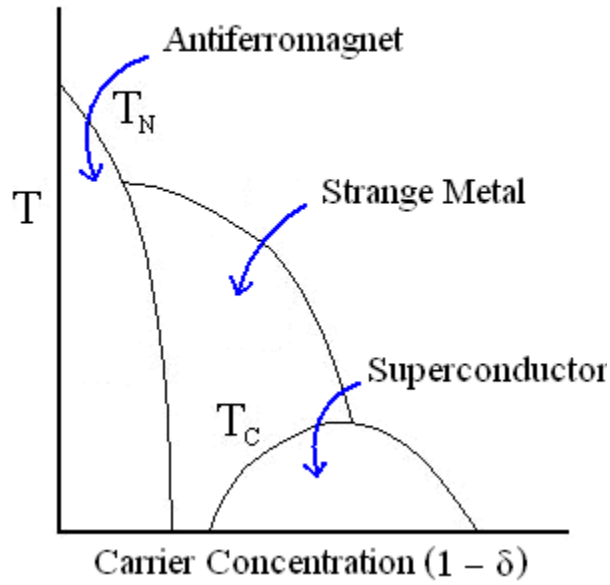


Figure 1. An approximate temperature vs. carrier concentration phase diagram for YBCO. Altered from a diagram in [2].

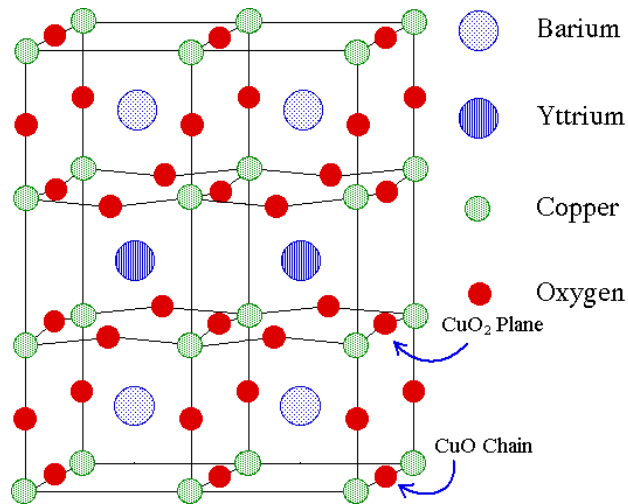


Figure 2. A schematic drawing of two YBCO unit cells, $\delta = 0$. Shown are segments of copper oxide planes and copper oxide chains. Altered from a diagram in [2].

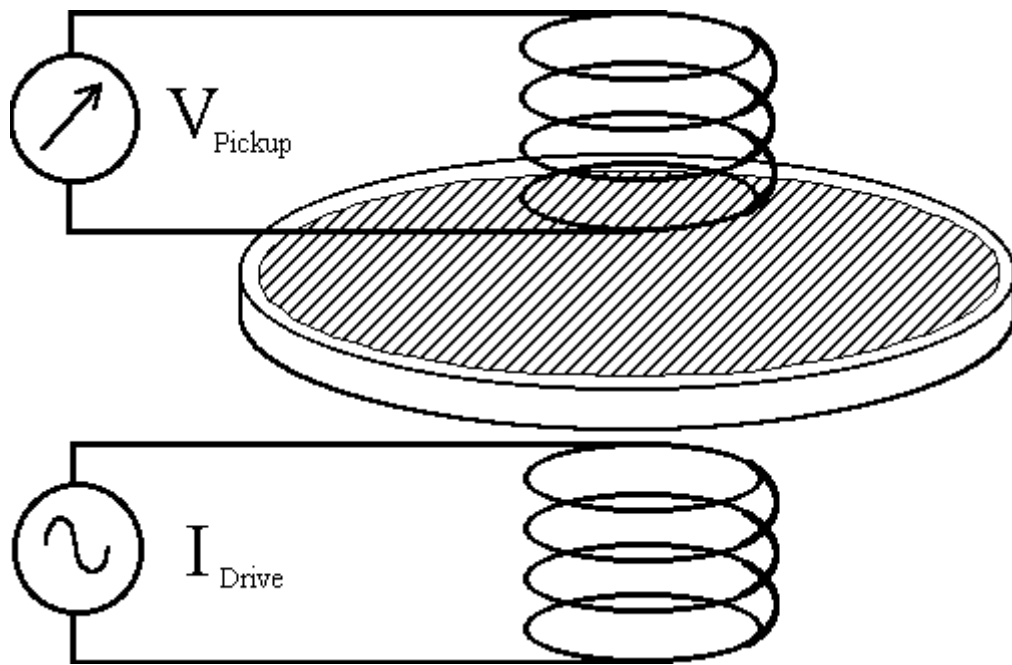


Figure 3. A schematic drawing of the two-coil apparatus. Typical coils are 2mm in diameter and 2 mm long. Counter wound quadrupole coils were used in all of my measurements.

Film A

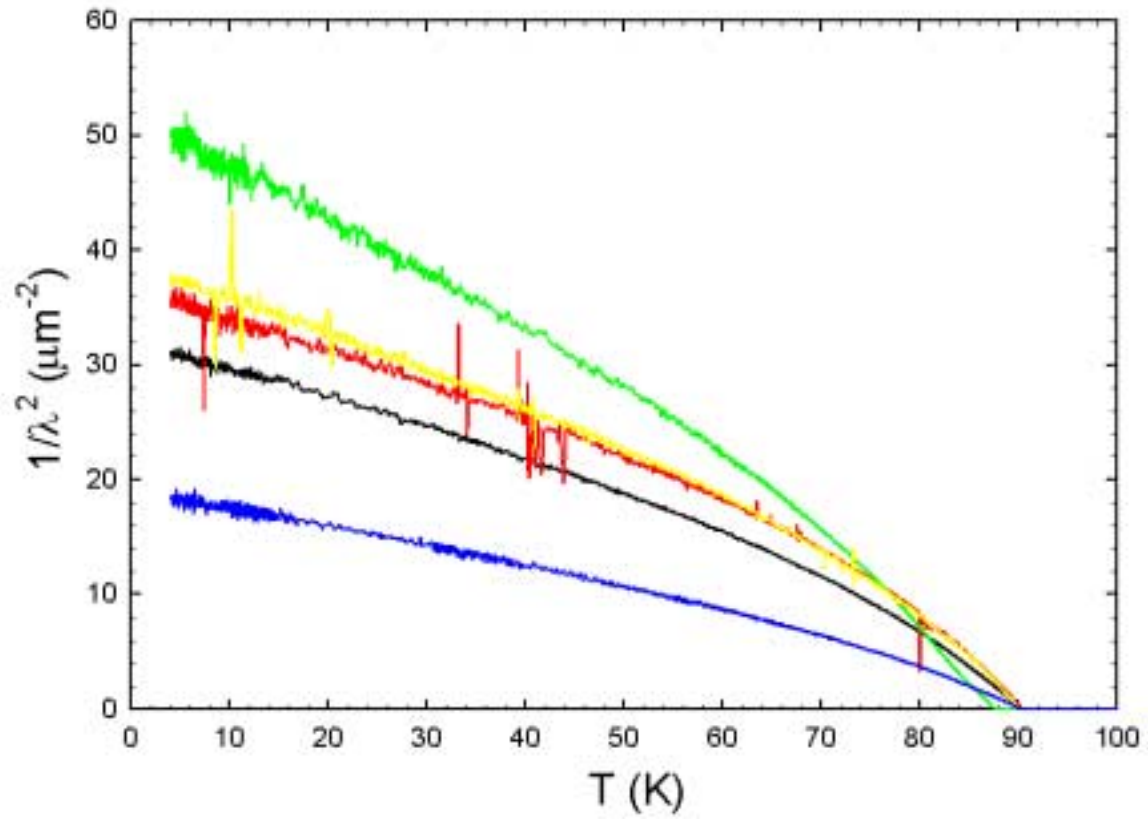


Figure 4. A graph of $1/\lambda^2$ vs. temperature for film A at higher oxygen concentrations. The oxygenation process yielded a homogeneous film for these measurements.

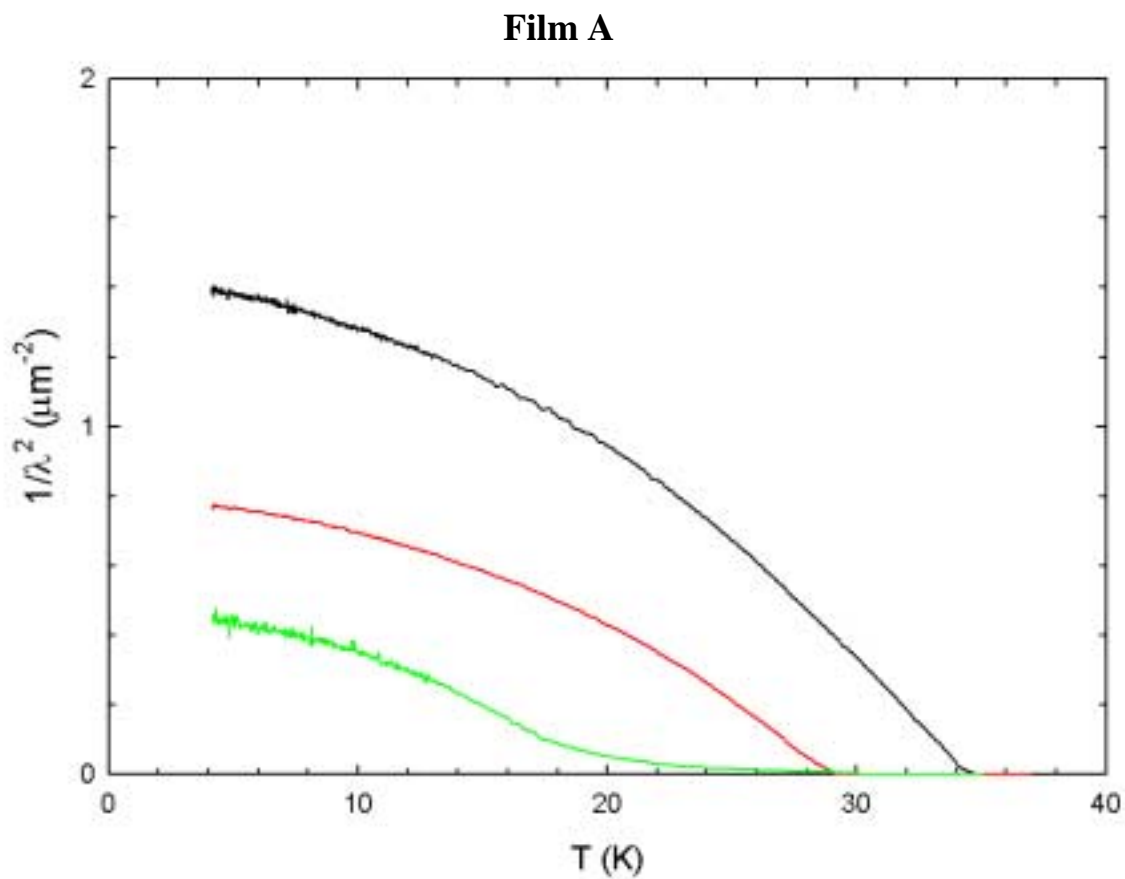


Figure 5. A graph of $1/\lambda^2$ vs. temperature for film A at lower oxygen concentrations. Of note is the upward curvature in the green (lowest) graph which the other two curves lack. This is indicative of film inhomogeneity. Processing destroyed the film shortly after that measurement was taken.

Film B

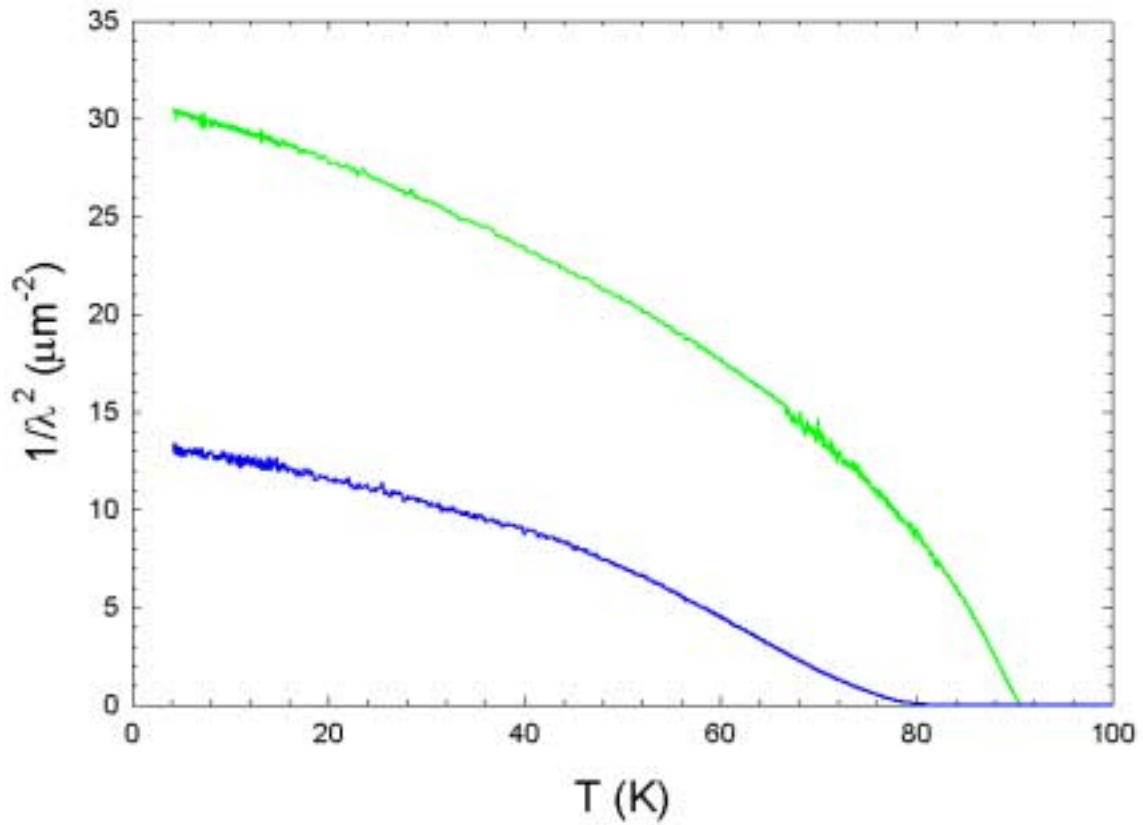


Figure 6. A graph of $1/\lambda^2$ vs. temperature for film B. The blue curve again has the upward curvature indicative of film inhomogeneity. In this case, the inhomogeneity was due to setting the temperature too low during processing.