FYSZ 460 Advanced laboratory work:
Superconductivity and high $T_C$
superconductor $Y_1Ba_2Cu_3O_{6+y}$

Laboratory Instructions

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1 Introduction

The main goal of this advanced laboratory work is to provide a general picture about superconductivity and demonstrate the basic properties of superconductors by simple and easy experiments. The main part of the experiments are performed with high T\textsubscript{C} superconductor Y\textsubscript{1}Ba\textsubscript{2}Cu\textsubscript{3}O\textsubscript{6+y} (YBCO). Superconductivity of YBCO can be easily verified by e.g. Meissner effect, where the pellet of superconducting material is levitating on top of a permanent magnet. The high T\textsubscript{C} superconductor is cooled below its T\textsubscript{C} (92 K) with liquid nitrogen, which boiling temperature is 77 K. In addition to the experiments with HTC superconductor, the measurement of transition temperature of a thin film sample made of niobium nitride (NbN) will be performed.

Students should return written laboratory report, which should contain information about basic phenomena and theory of superconductivity: Students should present briefly the basics of the theoretical background of superconductivity. In addition, the report should contain description of the experiments and experimental setups. Each member of the group should write 1-2 pages about their own specific subject, which is given by the laboratory work instructor. Grades (scale 1-5) will be given based on working in the laboratory and on written reports.

2 Fabrication of Y\textsubscript{1}Ba\textsubscript{2}Cu\textsubscript{3}O\textsubscript{6+y} HTC superconductor

YBCO High T\textsubscript{C} superconductor is fabricated by using Yttrium oxide (Y\textsubscript{2}O\textsubscript{3}), barium carbonate (BaCO\textsubscript{3}) and copper oxide (CuO). First one needs to calculate the mixture ratios for fabrication of superconducting pellet with mass of 3g. Ratios for different substances can be calculated by knowing the reaction equation

\begin{equation}
2Y\textsubscript{2}O\textsubscript{3} + 8BaCO\textsubscript{3} + 12CuO + O\textsubscript{2} \rightarrow 4YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7} + 8CO\textsubscript{2}.
\end{equation}

After measuring the mixture ratios for different components, they need to be mixed very well, until mixture is gray, fine-coarse powder. After mixing the components, mixture is put into ceramic crucible for annealing.

Mixture is heated up to 950°C (close to melting point of the mixture) in two hours, and held in this temperature for next 10 hours. After heating up the mixture is cooled down very slowly (for about 10 hours) back to room temperature. During the heating procedure the excess oxygen atoms evaporate out from the sample, the crucial point in the fabrication is to achieve a correct ratio for yttrium, barium and copper atoms. If the mixture is black after
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the whole procedure, it is superconducting. If the color of the mixture is e.g. green, something has gone wrong in the annealing procedure and mixture is not superconducting.

After first annealing cycle mixture has correct crystal structure and it is superconducting. For experiments one has to grind the mixture again to fine-coarse powder and press it into pellets with weights of 0.5-1.0g in the pressure of 15-20 MPa. Fragile pellets are heated up again into temperature of 950°C, held in high tempreature for ten hours and cooled down slowly. Both annealing procedures should be done in the oxygen athmosphere, to ensure high enough concentration of oxygen while annealing and the transition form tetragonal into orthorhombic crystal structure.

3 Measurements

Safety precautions: **NOTE!** Be careful when handling of liquid nitrogen ($LN_2$): Do not spill $LN_2$ to skin or clothing. Liquid nitrogen may cause serious frost bites. Handle YBCO pellets with care, they are extremely fragile. Use always gloves and plastic tweezers, when handling YBCO pellets and do not put pellets into water. Pellets will dissolve into water and form bariumhydroxide.

3.1 Measurements with HTC superconductor

1. Meissner effect. Cool down YBCO pellet with liquid nitrogen and perform levitation experiment. Measure the levitation height.

2. Define the density of the superconducting pellet. Compare measured value with ideal value (6.37 g/cm$^3$).

3. Measurement of the inductance of the coil. Build RCL-circuit (Fig. 2) on bimboard. Use coil, which has YBCO pellet as a core, 200 turns and width is 29.06 mm and diameter is 14.76 mm. Other components for RCL circuit are resistor ($R=150 \, \Omega$) and capacitor ($C=1 \, \mu F$). Use sinusoidal signal from the signal generator and measure the resonance frequency of the circuit at room temperature (superconductor is in normal state) and 77 K (superconducting state). Measurement for the resonance frequency is performed with help of an oscilloscope. Determine the inductance of the coil from the resonance frequency at both room and liquid nitrogen temperature. Why there is a change in the resonance frequency? What is the relative permeability (and magnetic susceptibility) of the core of the coil before and after cooling down?
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You can check the measured inductance value by measuring it directly with LCR meter. Schematic of setup is shown in Fig. 1.

4. Mean-free path of electrons in copper wire. Measure the dimensions of the copper wire. Measure the resistance at room T and 77K. How does resistance change as a function of temperature? What is the corresponding mean-free path in both cases?

5. Perform your own experiments (OPTIONAL).

3.2 Measurement of transition temperature of NbN thin film sample

In this section the transition temperature is measured for a thin NbN film. Dimensions of the sample are width 1.5 $\mu$m, thickness 200 nm and length 285 $\mu$m. The resistance of the sample is performed as a four probe measurement with AC technique in liquid helium dewar. Temperature is measured with help of a calibrated thermometer mounted on the sample stage. Temperature of the sample is controlled by adjusting the sample distance from the surface of the liquid helium (T=4.2K). Use bias current of 50 nA at low (<100 Hz) frequency. Schematic picture of measurement setup is shown in figure 2.

Determine transition temperature from the experimental data. Compare with literature values, do you observe differences? What might be the cause of differences?
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Figure 2: Four-probe setup for resistance measurements of Nb thin film.

4 Homeworiks

4.1 Before laboratory

Recall the equations for RCL circuit and derive the equation for the impedance of the circuit at resonance frequency. Derive the relation between the inductance of the coil and the resonance frequency. Calculate the theoretical inductance of the coil, which is used in the experiments.

4.2 Homeworks for written report

Do the following homeworks with help of literature.

1. Write down the equation for mean free path of electrons expressed in terms of resistivity. Determine resistivity and mean free path for Cu and Nb from your experiments. Compare to the literature value.

2. What advantages and disadvantages HTC superconductors have compared to conventional superconductors?

3. What kind of a crystal structure YBCO has?

4. Show with help of Maxwell and London equations, what is the difference between perfect (classical) conductor and superconductor.
5. Starting from London’s equations, show that in superconductor the current flows only at the surface. Show also, that the magnetic field penetrating in the superconductor decays exponentially.

6. Draw a sketch, which shows how eddy currents are flowing in the superconducting pellet, when it is levitating on top of a permanent magnet (a) horizontally and (b) vertically. Hint: Resultant field in zero inside the superconductor.

7. Estimate the magnitude of the eddy current, which is created on superconductor in the levitation experiment. Magnetic field is $\sim 0.3\text{T}$ on the surface of the superconducting pellet.

8. Derive the expression for levitation height (in terms of magnet thickness, magnetic field and mass density of the superconductor) of YBCO pellet above the permanent magnet. Hint: Magnetic potential energy is

\[ U_{\text{mag}} = \frac{B^2(a) a^2}{2\mu_0 z^2} V, \]  

where $B$ is the applied field, $a$ the thickness of the magnet in the $z$-direction (levitation direction), $z$ is the levitation height and $V$ is the volume of the superconducting pellet. Total potential energy is the sum of gravitational potential energy and magnetic energy.

9. Why transition temperature is measured with four probe technique? Explain the principles of four probe technique.

10. Tunneling conductance of SIS junction is shown in Fig. 10 ($dI/dV$ vs. applied voltage), electrodes are aluminum and tunneling barrier aluminum oxide. Determine the energy gap of aluminum from the figure. Explain the physical meaning of the constant conductance at higher voltages.
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![Graph showing tunneling conductance of SIS junction at 60 mK.](image)

Figure 3: Tunneling conductance of SIS junction at 60 mK.

References


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