Studies of YBaCuO superconductor electrical properties (T5)

Superconductivity is an intriguing state of matter, which lacks electrical resistivity (see Fig. 2) and exhibits strong diamagnetism. Discovered in 1911 by Heike Kamerlingh Onnes in Leiden University it initiated intensive research on the electron interactions. The discovery of high temperature superconductors in 1986 allowed for the observation of superconductivity in more accessible temperatures than before (above nitrogen boiling temperature).

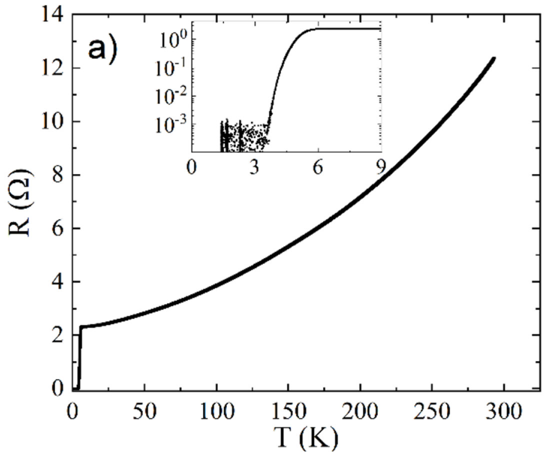

Figure 1: Resistance drop for PbTe/SnTe transition into the superconducting state at around $T = 3\,\mathrm{K}$ (from P. Sidorczak - MSc thesis, FUW).

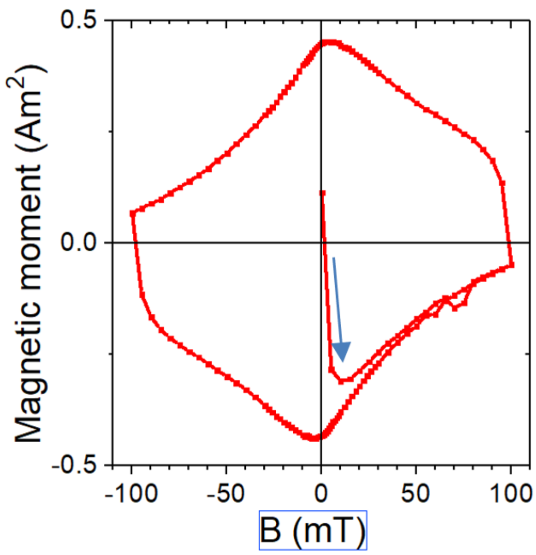

Figure 2: An exemplary hysteresis loop in magnetic measurements for FeSe superconductor at $T = 5\,\mathrm{K}$ (from T. Werner-Malento - PhD thesis, IFPAN).

The aim of the project is the investigation of the electrical properties of $YBa_2Cu_3O_{6+x}$ compound in the normal and superconducting phase, determination of the critical temperature and critical current values in for different magnetic fields. Moreover, superconducting levitation (due to the Meissner-Ochsenfeld effect) and flux pinning in the inhomogeneous magnetic field will be observed.

Basic parameters describing superconductor are critical temperature T_C, critical magnetic field H_c and critical current j_c. If a chosen factor (e.g. temperature or current magnitude) overcomes the critical value, a material experience a phase change from superconducting to normal phase. For type-II superconductors there are two critical fields (H_{c1} and H_{c2}). Between them, a material is in the mixed state. Critical current is determined by pinning force of the vortices that exist in the mixed state. This effect is also responsible for the magnetic hysteresis loop observed in type-II superconductors (Fig. 1).

1 What should you know before undertaking the project?

General facts related to the solid-state physics and metals:

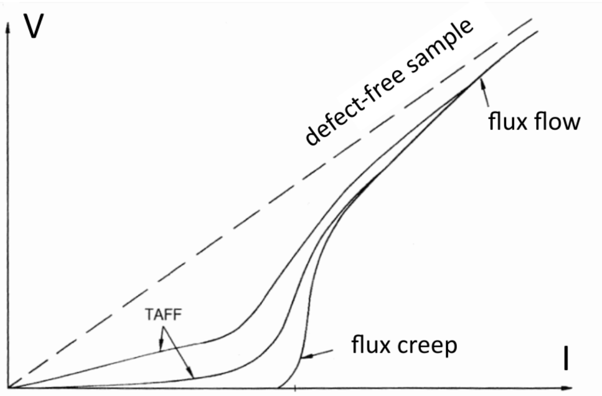

Figure 3: I-V (current-voltage) curves for type-II superconductors (high-temperature) for different temperatures. Figure based on [1].

a. Physical properties of metals: quantum mechanical description of an electron in a periodic potential, energy dependence on wavevector, density of states, occupation probability, Fermi energy. Conductivity of metals, Drude model, scattering mechanisms and their dependence on temperature, resistivity dependence on temperature, mobility, concentration.
b. Superconductivity: electrical and magnetic properties of superconductors, type-I and II superconductors, London equations, behaviour of superconductor in the magnetic field, flux flow and flux creep and flux pinning.
c. Measurements of low-resistance samples.

You are expected to refer not only to this instruction but also to the literature (you will find suggested literature at the end).

2 Sample investigated

The investigated sample is yttrium barium copper oxide. It is a crystalline chemical compound exhibiting superconductivity. The actual stechiometry of the material can differ among samples. The sample originates from Can Superconductors https://www.can-superconductors.com/. The picture of the sample can be seen in Fig. 4. The sample dimensions are the following: $b = 3\,\text{mm}$, $d = 2\,\text{mm}$, $l_1 = 20\,\text{mm}$ and $l_2 = 12\,\text{mm}$.

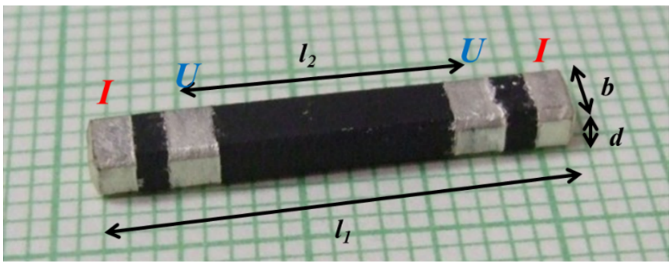

Figure 4: Studied sample with metallization. Electrical contacts for current application are marked in red (I) and voltage contacts are marked by blue (U).

3 Experimental procedures

1. Familiarizing with the experimental setup.

(a) Multichannel voltmeter Keithley 2000 is equipped with so-called scanner card, which allows for a measurement of 10 distinct voltages. A proper input should be chosen (FRONT/REAR) and then the voltage can be read by pressing OPEN/CLOSE.
(b) Power supplies for the sample and the magnet. Both of them can either stabilize voltage or current.

2. Calibration of the electromagnet $\rightarrow$ determination of the magnetic field ($\mathbf{B}$, measured by a teslameter) on the current magnitude ($\mathbf{I_B}$) flowing through the coil. The $\mathbf{H}$ field is proportional to the current. The current is measured by the voltage drop accross the standarized resistor in series with the coil. Since $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$, where μ_0 is free space permeability equal to $\mu_0 = 4\pi \cdot 10^{-7}\,\text{N/A}^2$, the contribution to $\mathbf{B}$-field may also come from electromagnetic pole pieces (remanence). You should determine how strong is the effect. The maximum current for electromagnet is $I_{\text{Bmax}} = 10\,\text{A}$.
3. Measurements of YBaCuO samples.
   (a) Two-point resistance check of the sample (between contacts 7-8, 4-5). Subsequent 4-point measurement (current applied between 7 and 8, voltage measurement between 4 and 5.)
   (b) A cable resistance determination in a 4 point measurement as a training.
   (c) Measurement of I-V (current-voltage) curves at room temperature $\rightarrow$ determination of the sample resistivity and the study of its evolution upon magnetic field application (several values). The maximum sample current $I_{\text{max}} = 1\,\text{A}$.
   (d) Measurement of I-V (current-voltage) curves at liquid nitrogen temperature. Observation of its evolution upon magnetic field application (several values). Collection of data to $\rightarrow$ determine critical current for different field values. $\rightarrow$ Determination of the critical current dependence on the field. The maximum sample current $I_{\text{max}} = 1\,\text{A}$.
   (e) Measurement of the voltage drop on the sample as a function of applied magnetic field and for a constant current applied to the sample at liquid nitrogen temperature $\rightarrow$ determination of the critical current at the given field. For each magnetic field magnitude, voltage measurement is conducted for two opposite current direction (implemented in the software).
   (f) Measurement of the voltage drop on the sample as a function of temperature (during sample heating, dynamically, i.e. without temperature stabilization) for several field magnitudes (at a specific current) or for several current magnitudes (at a specific field) $\rightarrow$ determination of the resistance change AND parasitic voltage as well as their dependence on temperature. T_C determination. The temperature sensor is a thermocouple, whose one end is located near the sample and the other one should be placed in a reference liquid nitrogen container. For each temperature, the voltage measurement should be performed for two orientations of current through sample (implemented in the software).
   (g) Observation of the superconductor levitation - having several permanent magnets (containing rare-earth metals) and a metallic plate construct an experimental setup. Magnetic field magnitude can be determined with the teslameter. Place a superconducting sample in the magnetic field to observe levitation. Find arguments supporting the fact the the superconductor is of type-II.

4 What should you include in the report?

The report must include the following parts:

1. Abstract - here you summarize what has been done in a concise manner.
2. Theoretical introduction - where you briefly recall fundamentals relevant to the achieved results, studied effects and the material.
3. Description of the methodology - it answers the question how the experiment was done, what was the setup and the sample as if someone else wanted to reproduce the result.
4. Results and analysis - where you present obtained data in a clear way, describe the observations (do not treat anything as obvious), determined parameters and comment on them and interpret it.
   To recalculate thermocouple voltage to temperature the following dependence is suggested: $T(K) = 100 \cdot \sqrt{0.034x^2 + 1.07x + 0.58}$ K, where x is a thermocouple voltage expressed in mV with a reference in liquid nitrogen temperature.
5. Summary and conclusions - where you recap the most important results and draw conclusions.

The report should have a form of a scientific publication. During report writing remember about enumerating all the equations and figures. When using external resources or citing, please provide references in the bibliography at the end. Refer to the supervisor of the project in case of doubts.

References

[1] M. Cyrot, D. Pavuna, *Introduction to superconductivity and high-Tc materials.* Singapore: World Scientific, 1992.

[2] J. Singleton, *Band theory and electronic properties of solids.* Oxford University Press, 2001.

[3] Stephen J. Blundell, *Superconductivity: A Very Short Introduction.* Oxford University Press, 2009, [Online - BUW resources].

[4] J. V. Yakhmi, *Superconducting Materials and Their Applications*, ser. 2053-2563. IOP Publishing, 2021. [Online]. Available: https://dx.doi.org/10.1088/978-0-7503-2256-0

[5] "Low Level Measurements Handbook," sec. 3.3. [Online]. Available: http://www.helmar.com.pl/helmar/plik/linki-low_level_handbook_nn551.pdf