TEL-390 YBCO Superconductor 4 Point Probe

Introduction

Superconductivity is the property of a substance to allow electric current to flow with absolutely zero resistance. Many materials are superconductors at very low temperatures, but only a few materials retain their superconducting property as they are warmed. Materials that are superconducting at temperatures over the temperature of liquid nitrogen, 77K, are known as high temperature superconductors (HTS). Nearly all of the known HTS are Cuprate based ceramics. Ceramics are hard, brittle materials, and few practical applications of HTS have been developed due to the difficulty of fabrication and the frequency of breakage.

In the early 2010s, the process of creating HTS 2nd generation wire was developed and became commercially viable. 2G HTS wire has a steel substrate on which a yttria stabilized zirconia thin film is deposited. A thin layer of superconductor (usually Yittrium Barium Copper Oxide (YBCO)) is then grown on top of the zirconia. The entire assembly is then coated in copper. These wires are have several desirable features:

- flexible (minimum bend radius ~ 25cm)
- easy to solder to
- manufactured in large quantities (maximum length > 1km)
- Can carry large currents (>100 amp)
- Have a high critical magnetic field (>10T at liquid helium temperatures)

Clearly HTS wire will be an important product in the future for a variety of engineering applications. Because we expect it to be so useful, TEL-Atomic has decided to use 2G HTS wire for our superconducting four point probe.

TEL-Atomic has also introduced the TEL-391 Non-Superconducting 4 Point Probe to allow students to compare the conductivity of a similarly sized piece of copper to the 2G HTS wire. The construction is exactly the same, but students should not observe a superconducting transition.
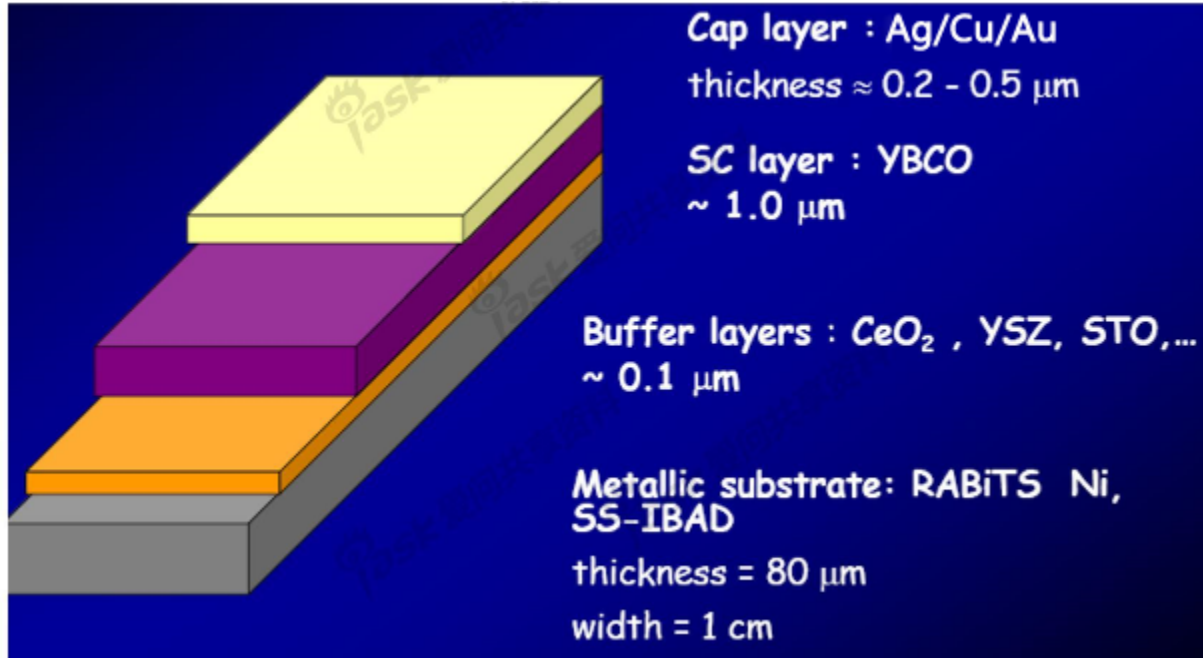
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Construction

HTS wire

The layers of the HTS wire are listed below.

Cap layer : Ag/Cu/Au
thickness ≈ 0.2 - 0.5 μm

SC layer : YBCO
~ 1.0 μm

Buffer layers : CeO_2 , YSZ, STO,...
~ 0.1 μm

Metallic substrate: RABiTS Ni, SS-IBAD
thickness = 80 μm
width = 1 cm

Four Point Probe

The four point probe is a design for making precise measurements of resistance. A constant current source supplies power to the item to be tested. The voltage across the sample is measured via two separate leads. Because the voltmeter has very high impedance, essentially no current flows across the voltage leads allowing for a very accurate measurement of the voltage drop. The TEL-390 uses red leads for the current and green leads for the voltage measurement.

The TEL-390 also has an integrated temperature sensor with white leads. The PT1000 temperature sensor is a thin film platinum sensor with a predictable and stable relationship between resistance and temperature. The resistance of the sensor depends on the temperature based on the following formula:

For T>0C: $R(T) = R_0(1 + AT + BT^2)$

For T<0C: $R(T) = R_0(1 + AT + BT^2 + C(T - 100)T^3$

Where   A = 3.9083E-03

B = -5.775E-07
C = -4.183E-12

This equation does have an algebraic solution for T, but it has so many terms that it is not useful. Values for the sensor resistance at various temperatures are provided in appendix A.

TEL-390 Diagram
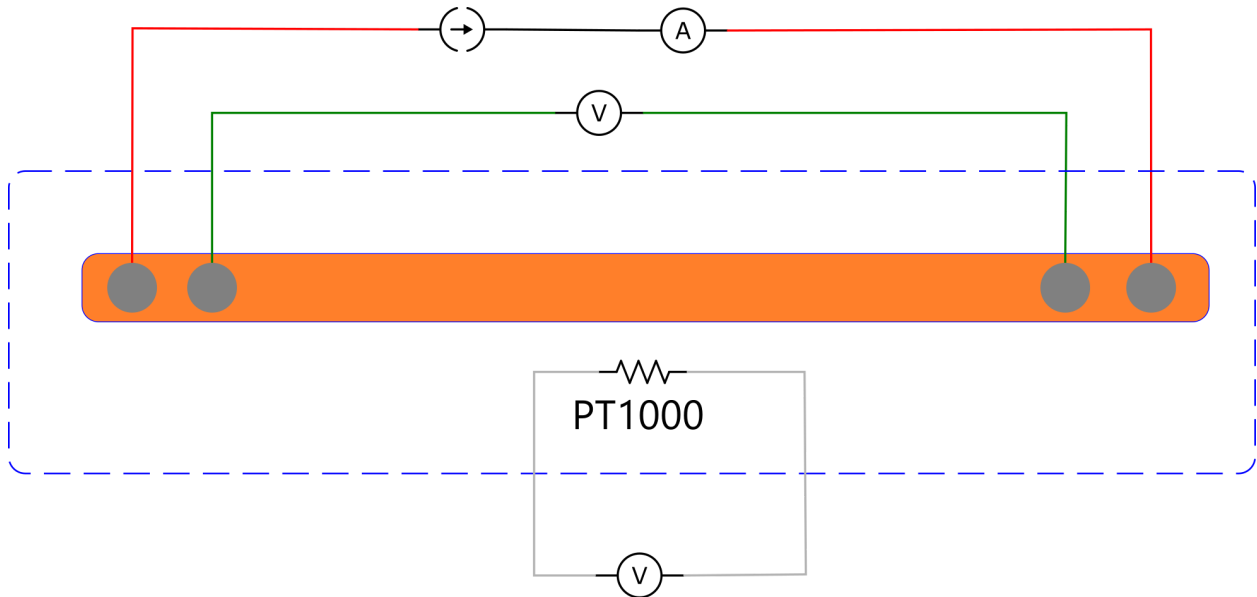
TEL-390 4 Point Probe

TEL-CRYO

TEL-Atomic recommends using the TEL-CRYO sand cryostat with the TEL-390 and TEL-391. The TEL-CRYO is a well insulated vacuum flask filled with glass beads. The glass beads create a large thermal mass. When the 4 point probe is immersed in the glass beads, the temperature will be more uniform throughout the probe, and the temperature will change slowly. During the superconducting transition, a small change in temperature creates a large change in conductivity, so collecting data points at small temperature intervals is important.

Experiments

Superconducting Transition Temperature Measurement

YBCO was the first superconductor with a superconducting transition temperature (T_c higher than the temperature of liquid nitrogen (77K). Measuring T_c is a good introduction to superconductors.

Part 1: Calibrate the temperature probe

Simple method:

1. Measure the ambient temperature in your room and measure the resistance of the temperature probe
2. Place the TEL-390 inside the TEL-CRYO and bury it under the glass beads. Gradually add liquid nitrogen to the TEL-CRYO until the glass beads are immersed and the nitrogen stops boiling violently. Check that the resistance of the temperature probe is constant, and record it. The temperature is 77K.
3. Using the lookup table, determine the high and low measured temperatures (T_{high} and T_{low}), and the difference between those temperatures and the actual temperature at each point. Let these points be ΔT_{high} and ΔT_{low}.
4. Using the temperatures and resistances recorded, create a formula to correct the temperature.

$$T_{corrected} = T_{measured} - \frac{\Delta T_{High} - \Delta T_{Low}}{T_{High} - T_{Low}}(T_{measured} - 77) - \Delta T_{low}$$

Advanced method:

For a more accurate calibration, prepare an ice bath as described in https://www.ic.gc.ca/eic/site/mc-mc.nsf/eng/lm00557.html. Place the four point probe in a plastic bag and use the ice bath to calibrate the temperature. For even more detailed information, read the Nathion Bureau of Standards monograph at https://www.govinfo.gov/content/pkg/GOVPUB-C13-60efd69bc3a0fd9aebde95def5c94bdb/pdf/GOVPUB-C13-60efd69bc3a0fd9aebde95def5c94bdb.pdf

For accurately converting resistance to temperature, a basic approach is to linearly interpolate between temperature values on the data table in appendix A. A convenient python library is also avaliable at https://github.com/ulikoehler/UliEngineering. A basic project would be for students to write a program to convert resistance to temperature. A more advanced program could include the calibration described above. The most advanced project would use a microcontroller or labview to measure and calibrate the temperature sensor.

Part 2: Measuring the Superconducting Transition Temperature

After completing the temperature calibration at 77K, it is easy to proceed directly to measuring the superconducting transition temperature.

1. Wait for all of the liquid nitrogen to evaporate. The temperature should remain stable during this time.
2. Attach a voltmeter to the green leads, and your power supply to the red leads.
3. Replace the foam plug at the top of the sand cryostat.
4. Choose and apply a target current. If you do not have high precision meters, you may want to use a relatively higher current (1A) to increase the voltages you will measure. If you have high precision meters, you may choose a lower current. The room temperature resistance of the four point probe is about 50 mΩ.
5. Record the temperature probe resistance, voltage drop, and current. You may want to choose a temperature probe resistance interval to help space your measurements evenly. It is also possible to measure the temperature at regular time intervals. With either method, be sure to collect a higher density of data points near the transition temperature. At that temperature (93K) the temperature probe has a resistance of about 271 Ω.
6. Record data until the temperature reaches about 110K. The temperature probe will read about 343 Ω.
7. Using appendix A and the temperature sensor calibration, create a graph of the voltage drop as a function of temperature.
8. Estimate the superconducting transition temperature. Superconductors have a maximum current capacity after which they become regular conductors. The maximum current (critical current) varies with temperature and external magnetic field. The superconducting transition temperature is the temperature at which the critical current is 0 A in no magnetic field. Because the four point probe requires current to flow, it cannot measure the actual transition temperature. Instead, we will measure the transition temperature at a given current.
   The simplest method is to print the graph and draw a line through the points of the superconducting transition. Find the temperature where the line intersects the 0V axis and use that as the transition temperature. A more advanced method is to use a computer to perform a least squares fit on the same section of data and solve the resulting equation for 0V.

Appendix A: PT1000 Resistance in kΩ

°C	0	1	2	3	4	5	6	7	8	9
-200	0.185	0.19	0.194	0.198	0.202	0.207	0.211	0.215	0.22	0.224
-190	0.228	0.233	0.237	0.241	0.245	0.25	0.254	0.258	0.262	0.267
-180	0.271	0.275	0.279	0.284	0.288	0.292	0.296	0.301	0.305	0.309
-170	0.313	0.318	0.322	0.326	0.33	0.334	0.339	0.343	0.347	0.351
-160	0.355	0.36	0.364	0.368	0.372	0.376	0.381	0.385	0.389	0.393
-150	0.397	0.401	0.406	0.41	0.414	0.418	0.422	0.426	0.43	0.435
-140	0.439	0.443	0.447	0.451	0.455	0.459	0.464	0.468	0.472	0.476
-130	0.48	0.484	0.488	0.492	0.496	0.501	0.505	0.509	0.513	0.517
-120	0.521	0.525	0.529	0.533	0.537	0.542	0.546	0.55	0.554	0.558
-110	0.562	0.566	0.57	0.574	0.578	0.582	0.586	0.59	0.594	0.599
-100	0.603	0.607	0.611	0.615	0.619	0.623	0.627	0.631	0.635	0.639
-90	0.643	0.647	0.651	0.655	0.659	0.663	0.667	0.671	0.675	0.679
-80	0.683	0.687	0.691	0.695	0.699	0.703	0.707	0.711	0.715	0.719
-70	0.723	0.727	0.731	0.735	0.739	0.743	0.747	0.751	0.755	0.759
-60	0.763	0.767	0.771	0.775	0.779	0.783	0.787	0.791	0.795	0.799
–50	0.803	0.807	0.811	0.815	0.819	0.823	0.827	0.831	0.835	0.839
–40	0.843	0.847	0.851	0.855	0.859	0.862	0.866	0.87	0.874	0.878
–30	0.882	0.886	0.89	0.894	0.898	0.902	0.906	0.91	0.914	0.918
–20	0.922	0.926	0.929	0.933	0.937	0.941	0.945	0.949	0.953	0.957
–10	0.961	0.965	0.969	0.973	0.977	0.98	0.984	0.988	0.992	0.996
0	1	1.004	1.008	1.012	1.016	1.02	1.023	1.027	1.031	1.035
10	1.039	1.043	1.047	1.051	1.055	1.058	1.062	1.066	1.07	1.074
20	1.078	1.082	1.086	1.09	1.093	1.097	1.101	1.105	1.109	1.113
30	1.117	1.121	1.124	1.128	1.132	1.136	1.14	1.144	1.148	1.152
40	1.155	1.159	1.163	1.167	1.171	1.175	1.179	1.182	1.186	1.19

Note: to use this table, add the number from the first column to the number from the first row. For instance, to find the resistance for -196C, start at -200C and move four columns to the right.