# Precision Measurements of BISCO Transition point with Current Source and Amplifier

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**Abstract**

We observed the temperature effects on a BISCO (Bismuth Strontium Calcium Copper Oxide) high-temperature superconductor (HTS) from our current source and amplifier circuit. We measured the point of superconductivity at 90.3 K with a resistance of $(1.90 \cdot 10^{-3} \pm 1.43 \cdot 10^{-3})$ $\Omega$ which suggests our sample is a Bi-2212 superconductor. However, we obtained strange negative voltage readings between the superconductivity transition and room temperature. We also observed the lowest resistance at room temperature and could not measure this again due to limited time. We believe these issues arose from some mix of measurement scale error, Seebeck effect, and contact resistances.

## 1 Introduction

### 1.1 Physics Motivation

Bismuth-based superconductors (BISCO) are a family of HTS discovered in 1988 [1]. $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) is notable for its critical temperature ($T_c$) around 85–90 K, making it a key material for practical applications like power cables and electronic devices [2][3]. The transition to superconductivity occurs when the sample is cooled below $T_c$ and is characterized by zero resistance and the Meissner effect [4]. The superconducting properties are highly sensitive to doping levels where optimal oxygen doping maximizes $T_c$, while under or overdoping diminishes it [4].

While measurements the transition temperature for superconductivity can be measured with a simple DC voltage source and measurement device (voltmeter or oscilloscope), the data may not be precise and voltage drops from the source need to be handled. Since the resistance of the circuit changes, the voltage drops across the circuit change, causing readings across the superconductor to be unreliable since the current across the HTS will change unless the required care is taken. A three-terminal regulator can be used to create a stable current source to provide accurate voltage drop readings across the superconductor. Since the current will be constant, any resistance changes will not make voltage measurements ambiguous, but rather they will make voltage and resistance directly proportional to each other. Thus, knowing the voltage the exact resistance can be calculated because of the constant current.

A current source is made using the three-pin regulator with a resistor across the regulated output voltage; thus producing a constant current as shown in **Equation 1**. With regulators like the LM317 or LT3080, a high current output is possible with an input voltage of 1-10V [5]. With this, the current variation issue would be solved.

$$I_{\mathrm{R}} = \frac{V_{\mathrm{reg}}}{R} \tag{1}$$

To increase the precision of the voltage measurements across the superconductor, a voltage amplifier component would be helpful. Referencing Horowitz & Hill, *The Art of Electronics*, a simple yet common circuit is the three op-amp amplifier [6]. This circuit utilized three operational amplifiers to produce an amplified voltage output with a configurable gain. The gain can be found by

$$G_{\mathrm{diff}} = 1 + \frac{2R_{\mathrm{f}}}{R_{\mathrm{g}}} \tag{2}$$

where $R_{\mathrm{f}}$ and $R_{\mathrm{g}}$ are two configurable resistances. With this circuit, small voltages from the HTS will be amplified by the gain so it is readable on common measuring equipment like voltmeters and oscilloscopes. Thus, greater precision is achieved without adding much noise to the amplification.

### 1.2 Experimental Setup

As mentioned above, we will utilize a constant current source component and a current amplifier component to pass a constant current through the BISCO HTS and read the voltage on an oscilloscope from the classic three op-amp amplifier. Despite using a DC source, we use the oscilloscope to gather better readings as compared to the multimeter. We noticed that the multimeter was unable to read the low voltages from the amplifier.

We initially utilized the LT3080 voltage regulator for our current source but had to switch to the LM7805 component after it burnt out. We were attempting to troubleshoot the circuit to understand why our current-setting resistor was not changing the output current and pulled out the resistor while the voltage was being supplied. This most likely burnt out our LT3080.

We used three OPA277PA-ND op-amps to construct our voltage amplifier circuit. We attached the current source to the HTS load using the four-probe method and connected both terminals of the voltage output from the superconductor to the voltage amplifier. The BISCO was placed inside a large styrofoam box and we cooled it down using liquid nitrogen since the $T_c$ transition point was above the boiling point of liquid nitrogen (77 K).

# 2 Circuit Theory and Construction

Let's discuss how each component in this circuit works. In this experiment, we highlight three components: the current source, the superconductor, and the voltage amplifier. We briefly discussed on what each component is and why we use it but here we will explore these more in depth.

## 2.1 Constant Current Source

As mentioned in the first section (**Physics Motivation**), a constant current source can be built using a voltage regulator with a resistor across the output current voltage. The output current is determined by **Equation 1**. We initially utilized the LT3080 package and found the circuit in the figure below to best suit our needs.

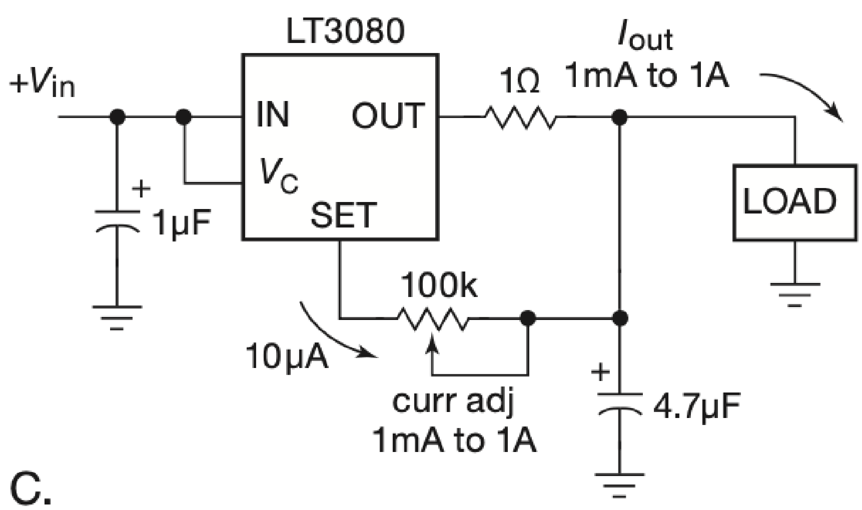


Figure 1: LT3080 Current Source Circuit from Horowitz & Hill [5]

The LT3080 has a fixed 10 4 $\mu$A **SET**-pin current reference which allowed us to set the voltage across the current-setting resistor to low voltages (less than 1.25 V). This allowed a wide range of 1 mA to 1 A for our current source. The $V_{\text{CONTROL}}$, or $V_C$, is used to drive the output current from the regulator. However, after this component was damaged, we had to switch to an alternative current source circuit using the LM7805 regulator.

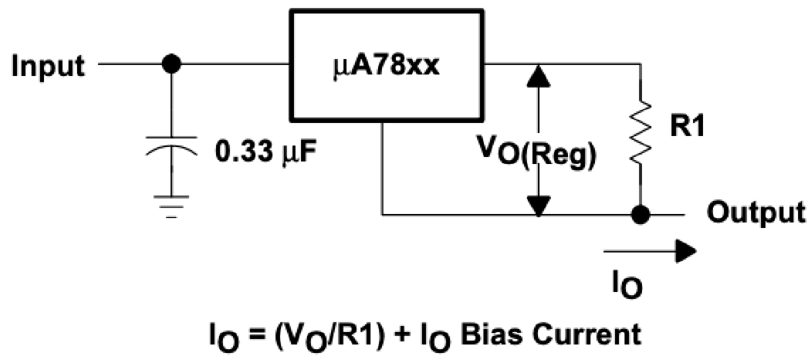


Figure 2: Current regulator circuit taken from the LM7805 data sheet

This circuit is much more simplified compared to the circuit in **Figure 1**. We fed 10 V into the LM7805 regulator and used a 50 Ω resistor to output a 0.1 A current. We measured the current using a multimeter and were able to find the reverse bias current as -0.1 A, although this value is not crucial. This circuit works by taking the sum of the voltage difference from the regulated and output currents and sending it to the load. The output current is adjusted with **R1**. Thus, this circuit produced a steady 0.1 A current for our BISCO superconductor.

## 2.2 BISCO Superconductor

Luckily for us, this component was already prepared for us and ready to use. The sample allowed for connections via the 4-point electrical probe method.

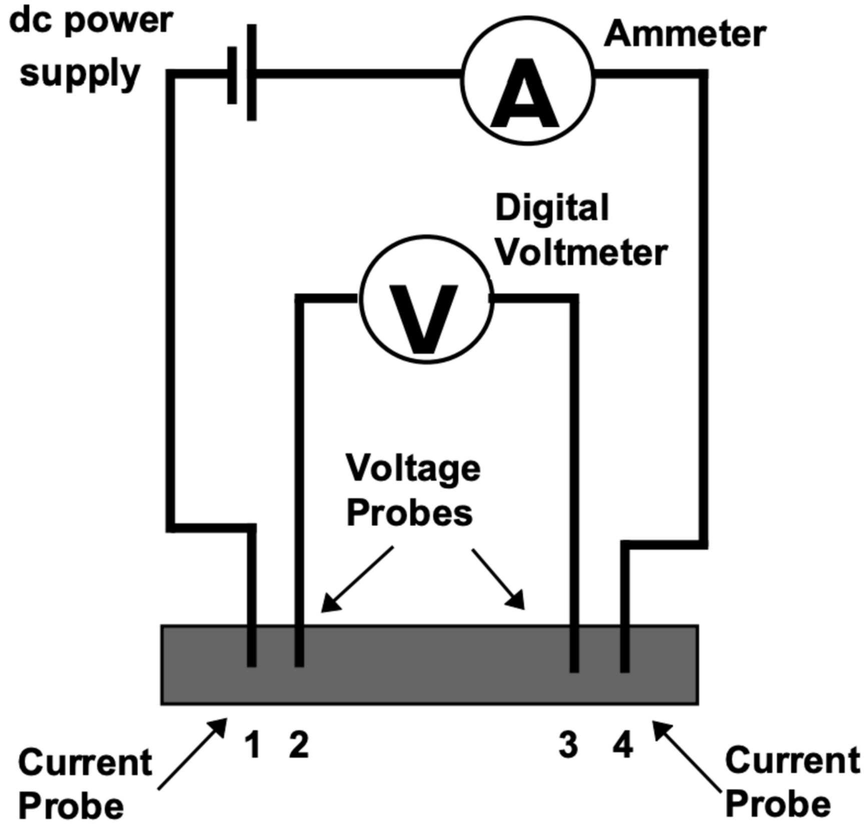


Figure 3: Schematic of Four-point probe [8]

The above schematic shows a demonstration of how to connect a DC power supply to a superconductor and measure the voltage difference across the sample. Note that our implementation is quite different than this but this figure demonstrates the essence of the 4-point probes. The two outer probes are current probes that supply current to the superconductor. The two inner probes are voltage probes that measure the voltage across the sample. In our setup, instead of a DC supply, we have our LM7805 constant current supply that feeds current into the superconductor. Our superconductor is placed inside of a large styrofoam box with extremely thin wires coming from it. Two of them are soldered to a current BNC connection and another two are soldered to a voltage BNC connection. There are two more BNC connections which we will discuss shortly.

To connect our current source to the superconductor, we connect the **Output** in **Figure 2** to the inner pin of the BNC input, and the outer sleeve is

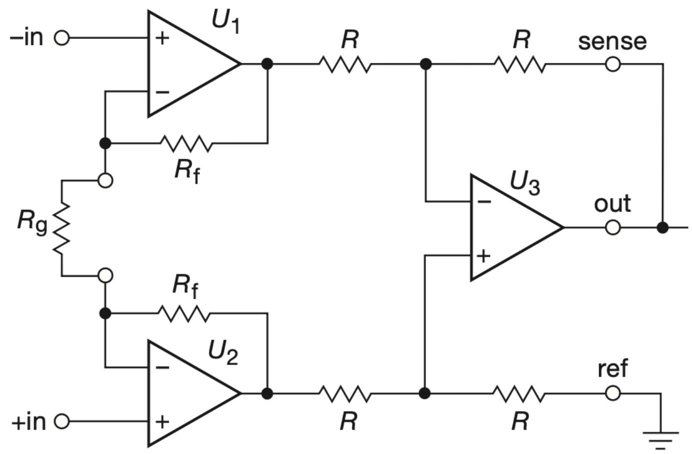


Figure 4: Classic three op-amp amplifier [6]

connected to ground to complete the circuit. The voltage BNC input is connected similarly, except that the inner pin and outer shell connect to the two inputs of the voltage amplifier.

As for the other two BNC connections, one is the thermocouple DC source and the other is the RTD resistance probe. We do not use the thermocouple DC source because it makes for unnecessary overhead and measurements directly from the RTD are sufficient for our purpose. We connect the RTD BNC to a multimeter and measure the RTD resistance. With the RTD resistance, we can calculate the temperature of the superconductor. Keep in mind that the superconductor is on top of a thermocouple plate.

$$T = \frac{R_{\mathrm{RTD}} - R_{\mathrm{ref}}}{\alpha R_{\mathrm{ref}}} \tag{3}$$

The above equation calculates the temperature, in Celsius, based on the measured RTD resistance and reference resistance. For our calculations, we took our reference resistance to be 100 $\Omega$ from 0 °C and $\alpha$ to be 0.00392 °C$^{-1}$ [9].

## 2.3 Classic Three Op-Amp Amplifier

This component utilizes three OPA277PA-ND op-amps with particular resistors to create a voltage gain of 21.

In **Figure 4**, we see two op-amps on the left and one op-amp on the right. The two op-amps on the left we denote as the input stage and the third on the right is the differential stage. In the input stage, the two op-amps are configured to the non-inverting amplifiers. Each op-amp amplifies one of the input voltages (-in and +in) while maintaining a high input impedance. The resistor network between the inverting inputs sets the circuit gain as shown in **Equation 2**. We used $R_\mathrm{f} = 10$ kΩ and $R_\mathrm{g} = 1$ kΩ to get our gain of 21. We used 10 kΩ for the other resistors $R$.

In the differential stage, the third op-amp takes the difference between the first and second op-amps as

$$V_\mathrm{out} = G \cdot (V_2 - V_1) \tag{4}$$

where $G$ is the gain. This subtraction amplifies the voltage while also canceling out any noise or interference common to both inputs. This common noise is referred to as Common-Mode Rejection. Since this circuit cancels out much noise, the Common-Mode Rejection Ratio (CMRR) is high (which can also be inferred when analyzing the differential and common-mode gain ratio since the CMRR is directly dependent on it). Thus, the higher the gain, the better the noise reduction. We limited our circuit to a gain of 21 to avoid railing the op-amps since we supplied them with ±15 V.

# 3 Experimental Collection and Results

## 3.1 Data Collection

The data collection was quite straightforward as we only used an oscilloscope to gather the maximum observed voltages. We also used a multimeter to note down the RTD resistance to see the temperature of the BISCO sample.

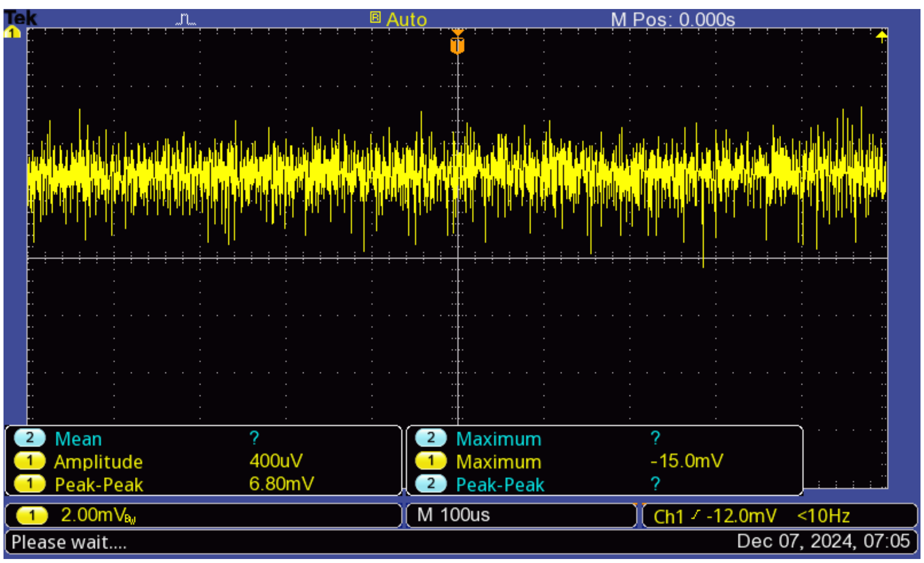


Figure 5: Voltage reading at -156 °C

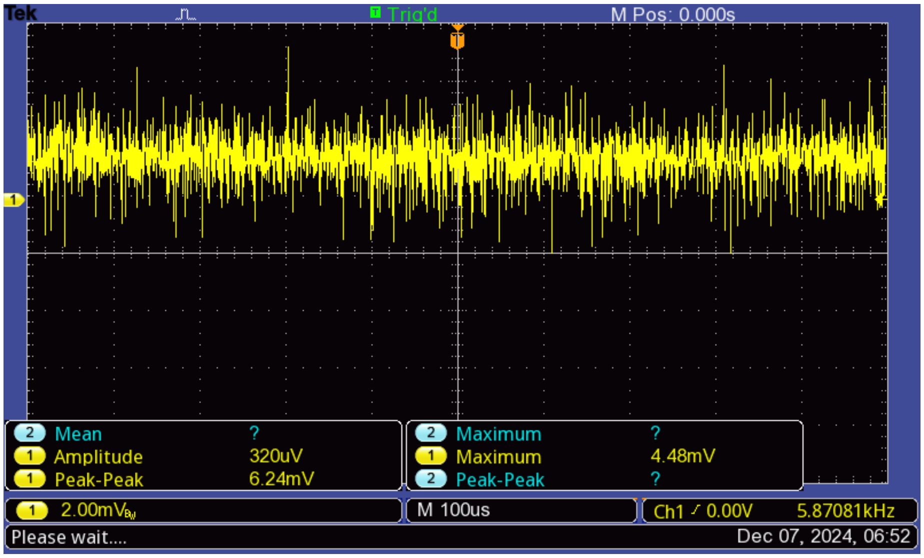


Figure 6: Voltage reading at -182 °C (near transition point)

The two figures above show the waveform taken at two different temperatures. We noticed that each waveform had roughly a $\pm 3$ mV variation which could be attributed to noise since the scale was quite small. Our CMRR was not too high because of our smaller difference gain which could have allowed more noise to slip into our measurements. Note that Channel 1 (the yellow waveform) is our measured voltage and Channel 2 (the blue waveform) is not measuring anything.

## 3.2 Data Analysis

After collecting our data, we noticed some strange negative voltage values and an abnormal room temperature resistance measurement. We noticed that for measurements between room temperature and the transition point, the voltages were negative, despite being connected to the amplifier circuit correctly. We knew this since the room temperature and transition point voltages were non-negative. We believe that our initial method of measurement was faulty as we did not understand which values to read on the oscilloscope and what an appropriate scale to gather accurate measurements would be. We found out that our scope was not zoomed in all the way, causing us to read faulty measurements initially. We also may have caused the liquid nitrogen to make contact with the BISCO sample, causing a temperature gradient that may have influenced the Seebeck effect [7].

As for the room temperature measurement, in a rush to gather measurements as the sample was cooling, we failed to notice the abnormally low voltage reading for the sample. We should have expected roughly 1-3 Ω but instead, we got

$9.52 \cdot 10^{-5}$ Ω. This turned out to be the lowest resistance we calculated which is quite strange. We are unsure why the resistance was so low and suspect it to be a scaling issue on the oscilloscope. We may have been too zoomed out, causing the **Measure** feature to assume much smaller voltage values than it is.

After sifting through our data, we found a good trend (excluding the room temperature measurement) that demonstrated when the sample started superconducting.

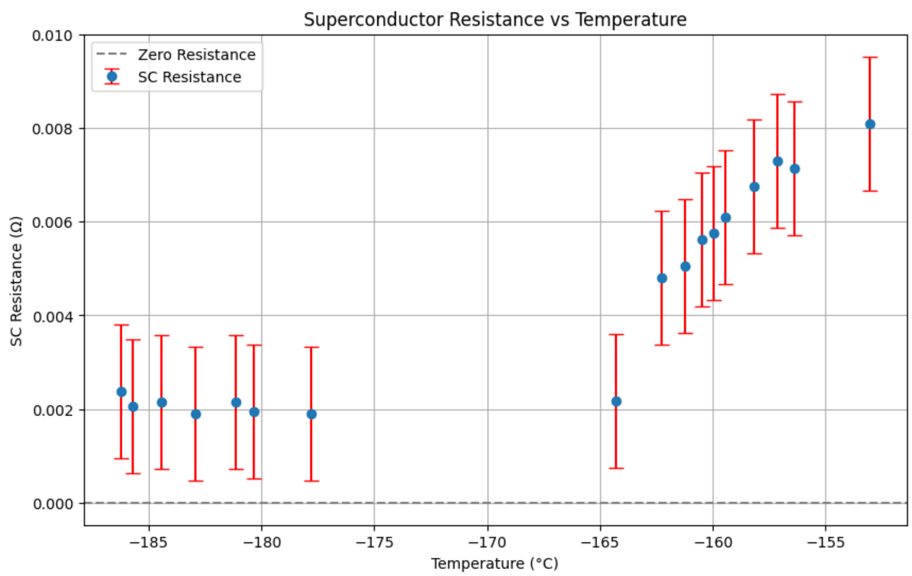


Figure 7: Temperature vs Corrected Resistance. The error bars indicate a $\pm 1.43 \cdot 10^{-3}$ Ω uncertainty propagated from the ±3 mV error discussed in the previous section.

The figure above has a corrected resistance (nonnegative resistance). We see that the lowest resistance is at the lowest temperature.

# 4 Results

We were able to measure the lowest resistance of $(1.90 \cdot 10^{-3} \pm 1.43 \cdot 10^{-3})$ Ω at 90.3 K. The error is quite high which we suspect is from our low CMRR. We were successfully able to produce a steady 0.1 A current and amplify the HTS voltage difference by a factor of 21.

## 5 Summary and conclusions

The experiment was not too theoretically rigorous but had quite a few technical challenges such as troubleshooting the LT3080 package and replacing components. Although, initially, we had trouble seeing good data, we eventually observed some interesting data showing the transition point of the Bi-2212 sample into superconductivity. Some further improvements, if time permits, would be to compare measurements to the raw output of the superconductor to see the noise reduction between the raw and amplified signals. Another change would be to increase the gain up to around 101 to increase the CMRR and obtain finer results. Our results were limited to $10^{-3}$ which indicates that a gain of 101 would be within the bounds of the op-amps and not cause any railing.

I would like to thank my partner Aryan Dhanaraj for his teamwork and insights while completing this experiment. I would also like to thank Dr. Heinzen and Ilya Beskin for their invaluable insights and assistance as we set up and conducted our experiments. I would also like to thank Dr. Sitz and the Modern Laboratory for loaning the BISCO superconductor sample as well as the liquid nitrogen. Finally, I would like to acknowledge Horowitz and Hill, *The Art of Electronics*, for providing the circuit designs for our current source and voltage amplifier.

## References

[1] Bednorz, J. G., & Müller, K. A. (1986). "Possible high $T_c$ superconductivity in the Ba-La-Cu-O system." *Zeitschrift für Physik B Condensed Matter*, 64(2), 189–193.

[2] Maeda, H., Tanaka, Y., Fukutomi, M., & Asano, T. (1988). "A new high-$T_c$ oxide superconductor without a rare earth element." *Japanese Journal of Applied Physics*, 27(2A), L209–L210.

[3] Cava, R. J., et al. (1988). "Superconductivity near 110 K in the Bi-Sr-Ca-Cu-O system." *Nature*, 332(6163), 814–816

[4] Chmaissen, G., et al. (1992). "Phase diagram of Bi-2212." *Physical Review Letters*, 68(23), 3458–3461.

[5] Horowitz, P., & Hill, W. (2015). *The Art of Electronics* (3rd ed., pp. 620–621). Cambridge University Press.

[6] Horowitz, P., & Hill, W. (2015). *The Art of Electronics* (3rd ed., pp. 357–358). Cambridge University Press.

[7] ScienceDirect. (n.d.). Seebeck effect. *In Encyclopedia of Materials: Science and Technology*

[8] Colorado Superconductor Inc. *Experiment Guide for Superconductor Demonstrations*. Colorado Superconductor Inc., 2007, p. 21.

[9] Omega Engineering. *RTD Temperature vs. Resistance Table*. Omega Engineering, n.d.