Detection of Meissner Effect in YBCO using Giant Magnetoresistors

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1 Introduction

During this project we tried to observe the Meissner effect associated with the transition of a material from normal conducting state to superconductive state using Giant Magnetoresistors (GMR). So let us first give us an overview of superconductivity and briefly explain how the Giant Magnetoresistors work.

1.1 Superconductivity

Superconductivity was first discovered around 1913 by Heike Kamerlingh-Onnes as a result of his systematic study of conductivity at very low temperatures using liquid Helium. He discovered that the resistance of Mercury suddenly dropped to zero at 4.2 Kelvin. Thus at 4.2K mercury makes a transition from normal conducting state to superconductive state. This temperature at which a material's resistance suddenly drops to zero is called critical temperature denoted by T_c.[1]

But this sudden drop in resistance is not the only feature of superconductivity, along with electrical properties, the magnetic properties of the material also change.

1.1.1 Meissner Effect

In 1933 Meissner and Ochsenfeld, discovered that if a sample is cooled below T_c in the presence of a small magnetic field, the field is expelled from the interior of the sample at T_c, except for a very thin layer at the surface of the sample. The thickness of this layer is called the penetration depth. This effect is called Meissner-Ochsenfeld effect or Meissner effect.[1]

However the behavior of all superconductors is not same in this regard and they can be divided into two classes on the basis of this effect.

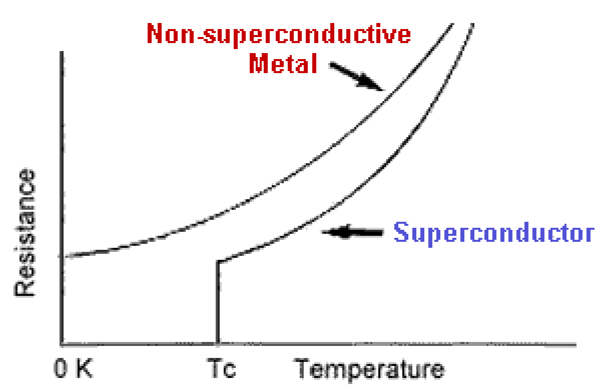


Figure 1: Resistance vs Temperature for a Super-conductor and non-superconductive metal[2]

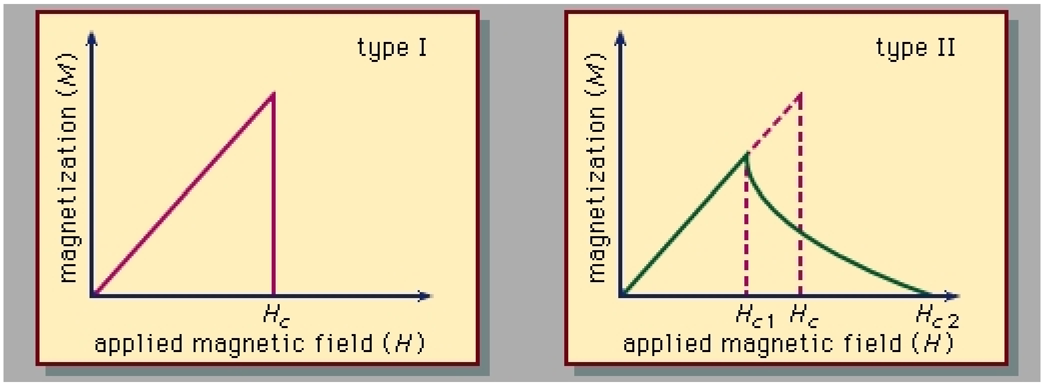


Figure 2: Magnetization vs Magnetic field for type I and II superconductors[3]

1.1.2 Type-I superconductors

For this type of superconductors, if the magnetic field in which they are placed is increased, they expel it completely up to maximum value, which is called critical field and we will denote it by B_c. Above this value, superconductivity breaks down, no field is expelled and the sample behaves as normal conductor. This value of critical field is temperature-dependent and reaches zero at the critical temperature T_c.[1]

1.1.3 Type-II superconductors

This type of superconductors expel magnetic field completely up to a lower critical field B_{c1}. Above this strength of magnetic field, it is only partially expelled, although the resistance remains zero and the sample remains a superconductor. For such superconductors, the superconductivity breaks down above the upper critical field B_{c2} above which no field is expelled. Both upper and lower critical fields become zero at the critical temperature.[1]

1.1.4 High Temperature Superconductors

Most of the early superconductors discovered had very low critical temperatures and liquid helium was required to achieve these temperatures. Elements like mercury and tin which exhibit superconductivity are examples of such superconductors. However during 1970's and afterwards many superconductive alloys and compounds have been discovered, whose critical temperatures are greater than the boiling point of nitrogen i.e. 77K. Due to this they can be studied using liquid nitrogen, which is both inexpensive and readily available as compared to liquid helium. These superconductors are called high temperature superconductors.

$YBa_2Cu_3O_{7-\delta}$, which will be used in this experiment is such a type-II superconductor with critical temperature of around 90K.

1.2 Giant Magnetoresistance

Despite its name Giant Magnetoresistance is really a nanoscale phenomena. The materials exhibiting this phenomena show a large (and hence the name 'giant') change in resistance when they are placed in a magnetic field. This phenomena was discovered independently by Peter Grnberg and Albert Fert in 1988. They received the 2007 Nobel Prize in Physics for this discovery.

1.2.1 Structure of GMRs

Simple GMR's have layered structure, in which two magnetic layers are separated by a very thin (few nanometers) non-magnetic layers. Examples of such layers are Fe-Cr-Fe layers. In the absence of any externally applied magnetic field the magnetic moments of two layers are antiparallel to each other. This is known as anti-ferromagnetic coupling and the resistance is maximum in this state. When a small external magnetic field is applied, the magnetic moments of two magnetic layers, become partially aligned which results in a decrease in resistance. Increasing the magnetic magnetic field results in a better alignment which further decreases the resistance. This happens till the magnetic moments of two layers become completely aligned and increasing the magnetic field further will result in no appreciable change in resistance. GMR of such a layer is defined as the maximum fractional change in resistance.[4]

$$GMR = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}} \tag{1}$$

1.2.2 NVE AA002-02

In this project we used NVE AA002-02 chip. This chip has 4 GMRs connected in the form of Wheatstone bridge. Two of these are shielded from the external magnetic fields by means of flux concentrators, while the other two are sensitive to external magnetic field. This arrangement allows the sensor to give its output as potential difference across its out-terminals. This voltage varies linearly with magnetic field in the range of 1.5×10^{-4}T to 10.5×10^{-4}T. This makes it useful for low magnetic field sensing.[5]

2 Experimental Activity

2.1 Details of Experimental apparatus

2.1.1 Magnetic Field Measurement

During this project the magnetic field was measured by NVE-AA002-02 chip, the details of which have already been provided above.

2.1.2 Temperature Measurement

Thorough out this project, the temperature was measured by silicon diode. The diode was operated on a constant current of 10μA and the potential difference across its terminals was measured. The diode was calibrated by measuring potential difference across its terminals first at room temperature and then at the boiling point of liquid nitrogen.

2.1.3 Resistance Measurement

Resistance measurement was done by using a four-probe device which was made to stay in its place on the superconductor using silver paint and teflon tape. A constant current source was used to supply current to it.

2.1.4 Data Acquisition

The data was acquired through a National Instruments DAQ module using LabView. The LabView took samples at the rate of 10000 per second. It was programmed to average every 1000 signals. So on the whole it generated 10 readings per second.

2.2 Observing the transition of Resistance

To observe the transition in resistance, the current-terminals of the four-probe device were supplied a constant current of 15mA through the constant current source. Teflon tape was wound around the four-probe and diode to keep them in place. The sample was then immersed in liquid nitrogen and and the potential difference across the voltage terminals was recorded as the liquid nitrogen evaporated.

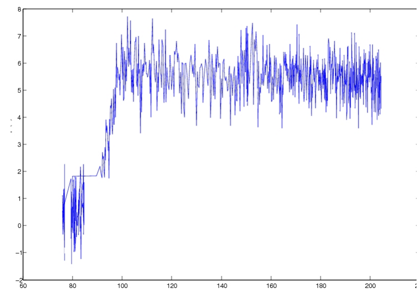


Figure 3: Resistivity Measurement, On y-axis is potential difference in mV and on x-axis temperature in K

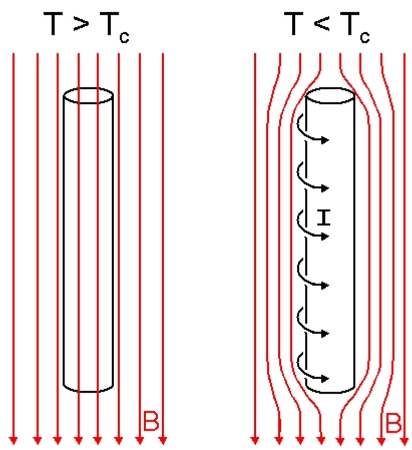


Figure 4: The Idea behind 1st approach[6]

The resulting data showed that the potential difference did drop to zero at around 95K which confirmed that the sample was indeed a super-conductor.

2.3 Observing the Meissner Effect

Two different approaches were used in trying to observe the meissner effect.

2.3.1 First Approach

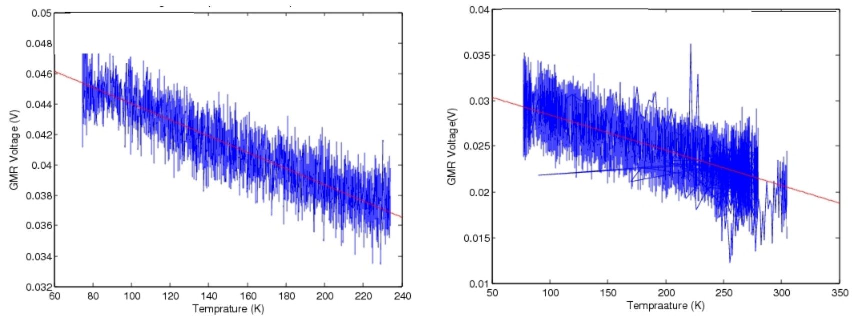
Meissner effect means the expulsion of magnetic flux from the interior of the superconductor. This expulsion may result in an increase in the magnetic field outside the superconductor.

To observe this the super-conductor with diode attached to it was placed in a plastic jacket which was mounted on top of the GMR sensor inside a solenoid. The solenoid was provided current through a resistor with the same power supply which was used to power GMR sensor.

The solenoid was then immersed in the liquid nitrogen and output voltage of the sensor and temperature were recorded as the liquid nitrogen evaporated. The same process was repeated many times with different amount of current passing through the solenoid. This process was also repeated without the superconductor, to check the temperature dependence of GMR sensor.

The results showed no transition in magnetic field around the superconductor and the only change in output of GMR sensor observed was due the temperature dependence of its own output.

This failure to observe the Meissner effect may have been due to following reasons:



(a) With Superconductor

(b) Without Superconductor

Figure 5: Results of the 1st approach: Temperature vs Output Voltage of GMR sensor

1) The thickness of the superconductor disc was smaller than the chip size. This might have prevented the sensor from resolving the change in magnetic field confined to a very small region.

2) The effect can be more easily observed using cylindrical samples rather than disc shaped ones because for cylindrical sample the field around the sample near its center will be uniform and completely axial. While in the case of a thin disc the magnetic field around the sample will not be uniform and will also have a considerable tangential component which will not be detected by the GMR sensor.

3) There was considerable noise present in the readings obtained which could have obfuscated a small change.

2.3.2 The Second Approach

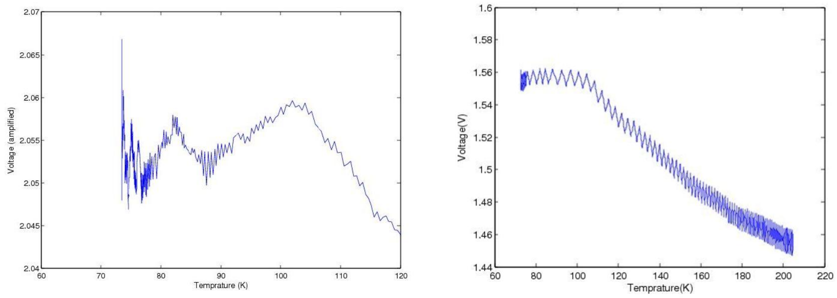
If the superconductor is placed between the solenoid and the GMR sensor, then all the magnetic field will reach the sensor above the critical temperature, but below the critical temperature, the superconductor will shield some of the magnetic field from reaching the sensor, which will result in a decrease in the potential difference across the out-terminals of the GMR.

To try this approach, a small solenoid was wound around a lead pencil, and the superconductor was glued to its bottom. Unfortunately, the super-conductor had broken during the time we were trying the first approach, and so instead of the disc, two pieces of it were glued to the bottom of the solenoid.

To reduce the noise a simple non-inverting amplifier was made using u-571 op-amp with a gain of 100. This reduced the noise somewhat, but it was still considerable. Then we realized that much of the noise was due to the resistor which was in series with the solenoid. The resistor got heated up during its operation, which resulted in the fluctuations in current through the solenoid. So, the solenoid was from then on powered by a separate power supply, which was operated in constant current mode. This step significantly reduced the noise.

The GMR sensor was fixed to the bottom of the dewar, by gently pressing it against the superconductor pieces glued to the solenoid, to which the diode was also attached for sensing temperature. Then liquid nitrogen was poured in the dewar, and data about temperature and magnetic field was acquired as it evaporated.

This approach yielded results, which although encouraging are far from decisive.From room temperature to a temperature of about 100K, the sensor shows an increase in the potential difference across its out-terminals with decrease in temperature, which is consistent with its expected behavior. However at about 100K a reversal in the trend is seen, which shows a some shielding from magnetic field, but this reversal is somewhat gradual and does not look like a transition. Also a second peak is also seen, origins of which are difficult to explain. But it may have arisen due to the fact that two pieces were used to cover the solenoid and there was no thermal contact between two pieces, so the their temperatures might not have been same. Without the superconductor, the curve of voltage across out-terminals of sensor



(a) With Superconductor (b) Without Superconductor

Figure 6: Second Approach: Temperature vs Output Voltage of GMR sensor

flattened out but no reversal in trend was observed.

3 The conclusions so far

As has been said in the preceding section, the results obtained until now are very ambiguous and no definite conclusions can be drawn from them and the project has not been a success.

We still need to verify that the reversal of trend in voltage output of GMR sensor was indeed a transition and give a more satisfactory answer about the second peak observed, only then we can draw some definite conclusion from our experiments.

References

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