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Determination of YBCO Superconductor Critical Temperature and its Voltage-Current Characteristics using Four-Point Probe Method

Abba Alhaji Bala[1*], Mukhtar Lawan Adam[2], Sabiu Said Abdullahi[3], Ibrahim Murtala Musa[4] & Bala Ismail Adamu[5]

[1, 3, 4, 5] Department of Physics,
Federal University Dutse,
P.M.B.7156 Jigawa State Nigeria
Email: abkabuga@yahoo.com

[2]Department of Physics,
Bayero University Kano,
P.M.B. 3011 Kano State Nigeria

Abstract

The IV characteristics of $YBa_2Cu_3O_{7-\delta}$ (YBCO) superconductor was studied at different temperatures. The power law $V = I^{\beta\ (T,\ B)}$ was employed as a model to fit the data. The parameter β was found to be directly proportional to the temperature which indicated the dissipation mechanism of the superconductor. The critical current (I_c) of the sample is observed to be inversely proportional to the magnetic field and temperature with a current density of $9.90Acm^{-2}$ at 80K, which thus shows the transport property of the material. Using the four-point probe and thermocouple to pass current through the superconductor, the resistance was analyzed to obtain a critical temperature value of 93K which is the approximate temperature of the superconductor to make transition to another phase by dropping the electrical resistivity to zero.

Keywords: Voltage, Current, temperature, YBCO superconductor, and Four-point Probe.

INTRODUCTION

High temperature superconductors (HTS) are essential to construction of magnetic system in fusion reactors that are resistant to thermal leads and high neutron. However, in recent researches, the most widely used HTS material is $YBa_2Cu_3O_{7-\delta}$ (Yttrium Barium Copper Oxide; YBCO). This superconductor has high magnetic field, critical current and yielding temperature (Veterníková et al, 2012; Li et al, 2005). HTS coils and tapes are used in power devices and transformers (Friedman et al, 2012; Lécrevisse et al, 2012). Using YBCO wires for power applications, there are factors to be put in to consideration; (1) Changes in the resistance of the material that is, changing from superconducting state to metallic/semiconducting state and (2) the recovery tendency phase change, which is conversion from metallic/semiconducting to superconducting state (Seung-Gyu et al, 2013).

*Author for Correspondence

Voltage-Current (*V-I*) characteristics are attached with emission of heat and self-heating which can change the resulting *V-I* curve. Velocity dependence on the *V-I* curve and heat hystereses are indications of self-heating. Moreover, the elimination/reduction of self-heating is a vital phenomenon in transport studies of HTS due to their sensitivity with temperature. Changing the cross sectional area of the bulk sample, the *V-I* plot can be measured at the fixed range of the current density of the measuring current, small values of current and self-heating is seen to decrease (Gokhfeld et al, 2007).

If *V-I* characteristics distinctively obey the scale for a varied range of currents and voltages, then the *V-I* characteristics gives a very significant evidence for phase transition and failure to obey shows the otherwise (Strachan et al, 2003). The voltage-current characteristics of YBCO superconductor is been used to study the dissipation mechanism and its potential application. The Voltage-Current plots follow the power law;

$$V = \mathrm{I}^{\beta(\mathrm{T,B})} \quad (1)$$

Where the experimental parameter β is almost uniform with increasing temperature (Ozkan et al, 2000).
This study presents *V-I* plot of YBCO superconductor and the role of temperature and magnetic field on the transport properties of the material.

THEORITICAL BACKGROUND
This study presents some of the remarkable superconductivity phenomena; which is a property that certain materials like mercury, lead, tin exhibit when they are cooled to a very low temperature. Liquid Nitrogen or helium is used as the cooling agent that boils at 77K or 4.2K respectively. The temperature of the sample can be controlled in the range above these boiling temperatures by suitable operation of the equipment (MIT 2011).

Superconductivity and BCS Theory
Superconductivity is a quantum mechanical phenomenon in which a material exhibits zero electrical resistance and the magnetic field expulsion. It occurs in certain materials at a lower temperature. Superconductivity is a process by which electrical resistance of a material as a function of temperature is studied and on cooling the material, the resistance abruptly vanishes. Superconductivity is greatly applied for magnetic bending of particle accelerators and Magnetic Resonance Imaging (MRI) (MIT 2011).

A theory expressing superconductivity was proposed by Bardeen, Cooper and Schrieffer in 1957. The BCS theory assumes that Cooper pairs are formed by electrons. The ions contain in the material are at rest at absolute zero. When an electron moves through a lattice of positive charges, the attractive force between opposite charges causes a slight disturbance in the lattice which results to achieving higher concentration of positive charges. A pair of electrons at same speed moving in opposite direction is created with energy lower than the normal conduction electrons. The formation of this Cooper pairs allows electron to move freely thereby making superconductivity possible (Nicolae 2014).

The superconducting properties of materials depends on magnetic field strength, B, temperature, T and current density, J. The critical magnetic field strength with no current flowing at T = 0K is symbolized as B_c, the critical temperature in the absence of an external magnetic field with no current flowing is represented by T_c, and the critical current density at T = 0K with no external magnetic field is denoted by J_c.

The Meissner effect

The Meissner effect is a unique behavior of superconductor in magnetic fields and a phenomenon in quantum physics in which a superconductor ejects all magnetic fields inside the material. This process is done by creating small currents along the surface of the superconductor, which has the effect of removing out all magnetic fields that would come in contact with the material. In the superconducting state, Meissner effect exhibit perfect diamagnetism or super-diamagnetism in which the total magnetic field is very close to zero deep inside them. This means that their magnetic susceptibility is minus one (-1) (Nicolae 2014). One of the most interesting aspects of the Meissner effect is the phenomenon called quantum levitation as shown in Fig.1

Fig. 1: A magnet levitating above a YBCO superconductor

Fig. 2: The Four-Point probe

EXPERIMENTAL METHODS

Sample Preparation

The pure YBCO material used was prepared using solid-state reaction conventional method. High quality powders of Y_2O_3, BaCO3 and CuO are mixed according to the stoichiometry ratios of 1:2:3 respectively. Which are then crushed for 2h in a mortar. The powder was then heated in a furnace at 500^{o}C for 1h at the rate of 20^{o}C per min to air out the CO_2 gas. At the same rate, the temperature was increased to 850^{o}C and the powder was heated for 10 h, then cooled down to room temperature for 1h and reground. The sample was pressed into pellets under a pressure of 10 torr. Then mould at 950^{o}C for 10 h with radius of 4.5mm. At this juncture, the structure ($YBa_2Cu_3O_{7-\delta}$) is formed by ions inter diffusion with oxygen deficiency content. The sample was then cooled to 550^{o}C and annealed in oxygen flow for 6 h.

The Four-Point Probe and Data Collection

The resistance with respect to the temperature across the YBCO superconductor was measured using a standard D.C. four-point probe with its diagram presented in figure 2. A Keithley 2182 sensitive nano-voltmeter with accuracy 0.0001V was used to measure the potential difference between probes 2 and 3 in the four point probe at a constant current supply across probes 1 and 4 from a Keithley 2425 current source with accuracy of 0.001µA.The circuit diagram of the four-

point probe (Nicolae 2014) is shown in Fig.3 which indicates that as the probes flow through the superconductor, the contact resistance can therefore be neglected.
Liquid nitrogen of boiling temperature 77K was employed to cool the YBCO superconductor. The coolant was poured into a highly insulated Dewar flask cryostat with the superconductor fully submerged until equilibrium is reached thermally. The sample superconductor was then moved up above the liquid nitrogen surface and allowed to warm thereby controlling resistance and temperature of the superconductor. With the sample in the cryostat and setting up the current values in mA on the I-V meter source, respective voltage measurements were recorded in mV.

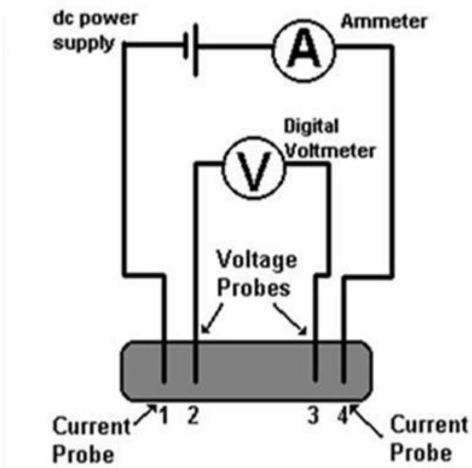

Fig. 3 Circuit diagram of Four-Point Probe [10]

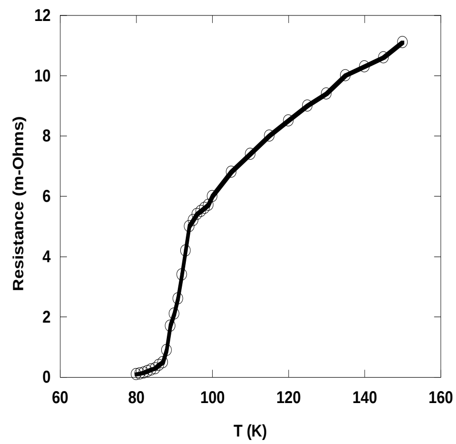

Fig. 4 Resistance versus Temperature

The measured temperature was obtained using thermocouple. In the measurements, the sample was initially cooled down to zero-field around 80K, and then the temperature was raised slowly using temperature controller to the required temperature thereby taking its respective resistance value. From these measurements, *V-I* and *R-T* characteristic curves were plotted to obtain the critical current density.

The electrical resistance versus temperature graph for YBCO near T_c is shown in Fig. 4, and is superconducting above the boiling point of Liquid Nitrogen 77K with critical temperature 93K; the transition width of the sample is about 8–10K. These data agree well with the corresponding literature of Albiss et al (2010); Benjamin et al (2011); Pickett (2006). The V-I data were collected at an interval of 1.0K between 80 to 150K.

RESULTS AND DISCUSSION
The V-I Plots for YBCO at temperature 80-150K are shown in Fig.5 The data display a line plot which indicates that, this data can also be presented by power law (Eq.1). The magnetic field relative to the current as applied to the YBCO sample is expressed as;

$$B = \frac{\mu_o I}{2\pi r} \qquad (2)$$

For which r is the radius of the YBCO sample and μ_0 is the permeability constant.

Fig.6 is a plot of β versus T which reveals β to be constant as the temperature increases and behaves ohmically at high magnetic field. The result also shows that, the YBCO sample is more sensitive to magnetic field which may be caused by the short annealing time and phase purity.

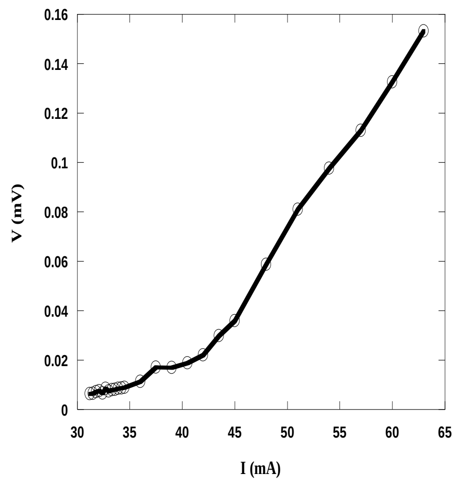

Fig. 5 Graph of Voltage versus Current

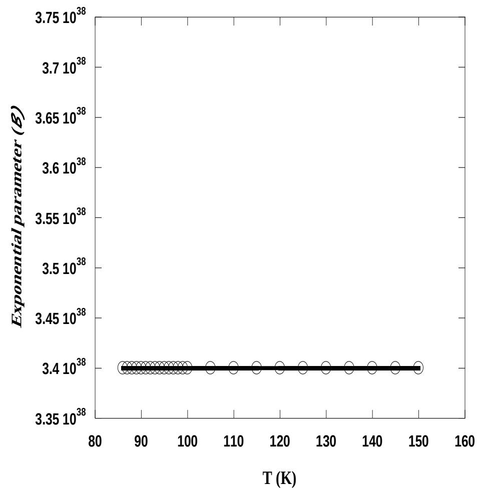

Fig. 6 Graph of β versus Temperature

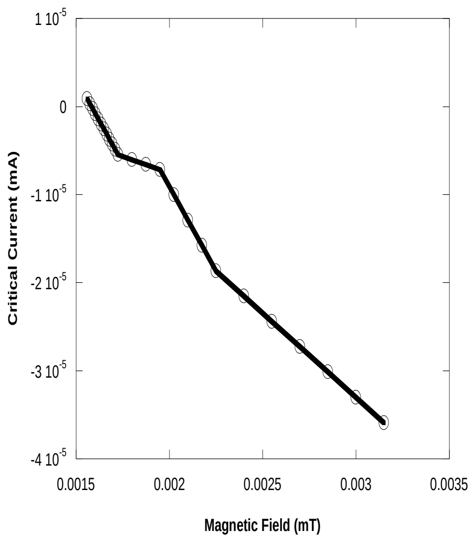

Fig. 7 Graph of Critical Current Vs Magnetic Field

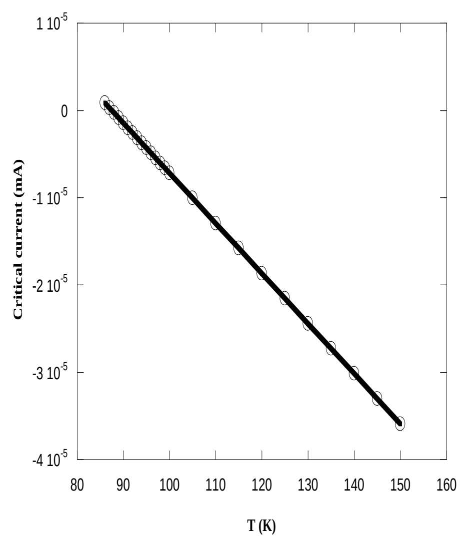

Fig. 8 Graph of Critical Current Vs Temp.

It is observed from Fig.7 that, the increase in critical current (I_c) results to the decrease in magnetic field which reveals the capability of generating a magnetic field using a solenoid wire as also reported by Shoji (2006) and Friedman et al (2005) using BSCCO tape carrying current. Similar results were also observed in Albiss et al (2010) and Ozkan et al (2000) using Thallium-Based ceramic superconductor.

The critical current density of the present YBCO sample is about 9.90Acm^{-2} at 80K obtained using Eq. 3. A value close to this was reported by Ozkan et al (2000) at 85K.

$$j_c = \frac{I_c}{A} \quad (3)$$

The behavior of critical current and temperature in Fig. 8 shows an increase in temperature with decrease in critical current which is due to the consistent change of the resistance of the sample with temperature. This kind of behavior is also reported by Yi et al (2013) using amorphous tungsten superconducting nanostrips. The result also indicates a temperature dependence of critical temperature which came abreast with the work of Chu & McHenry (2000); Zhixian et al (2007) using $NbSO_2$ superconducting nanowires and Qianqian et al (2014).
The grain boundary is the micro-structural phenomena that limit the critical current density J_c. For pure YBCO sample, J_c depends on strong field due to grain boundary random arrangement, inhomogeneous current distribution of the intragrain and the weak links between the grains.

CONCLUSION

High temperature superconductors (HTS) are materials of high potentials used in many applications and can also be used in magnetic systems of fusion reactors. In view of its high critical temperature, YBCO is one of the essential materials. The V-I data of the YBCO sample near its transition temperature obey the power law equation for which the parameter β is uniform with increasing temperature. It was observed that I_c variation with temperature and magnetic field for the YBCO sample is quite similar using a BSCCO tape carrying current [15] and using $NbSO_2$ superconducting nanowires [18] respectively. Using the four-point probe and thermocouple to pass current through the superconductor, the resistance as a function of temperature of the material was analyzed to obtain a critical temperature value of 93K. Further studies need to be performed to investigate the phase purity, the condition of processing of this material and studying the resistance behavior at lower current values.

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