Abstract

In this paper a novel method to measure the critical current density of superconductor bulks through a small point contact to the surface of the samples has been presented. Based on the proposed method a localized current is applied to the superconductor at the center of its surface in the absence of magnetic field where there is a second ring shape electrode in the outer area of the surface of the superconductor bulk. By increasing the pulse current through the central electrode beyond the critical current density of the material, normal zones develop in the superconductor. Theoretical results anticipate semi oblate spheroid normal zones as also confirmed by the obtained experimental data. Based on the used theoretical model, the form of the voltage-current relation is obtained as also verified by the measurements. Considering the area of the central electrode and the voltage current relation, a model is proposed to obtain critical current density of the bulk material, while the used electrical approach and technique avoid heat generation in the sample.

Keywords: Critical current density, Superconductor bulk, Joule heating.

1. Introduction

The critical current density, \( J_c \), is one of the most important parameters for characterizing a superconductor bulk material, to measure the conductor’s current carrying capacity [1]. As well known this parameter is depended on the temperature and the applied magnetic field [2]. Number of problems associated with critical current density measurement have been aroused and different solutions have developed which each have different aspects [3]. The two most commonly used methods to extract the critical current density are: 1- currents are induced in the superconductor by the application of an ac magnetic field and a voltage proportional to the electric field is generated in a pickup coil surrounding the sample, 2- current is driven in the sample and the resulting longitudinal voltage is measured with electrical leads attached to the sample [4]. Among various methods based on voltage current characterization, the four probe method is more often employed [6]. Besides, one of the widely used nondestructive and contactless methods for characterizing HTS superconductors is an inductive method [7] which uses the width of the magnetic hysteresis loop of superconductor [3].
In this paper a new method for critical current density measurement has been proposed. This new approach is based on a current distribution in HTS bulk samples and our-derived voltage current relationship leads to a formula for derivation of the critical current density. In section two general analysis of the work has been illustrated; Theoretical aspects of the work has been investigated in part three. Section four has been devoted to experimental setup, and section five depicts results of the work.

2. General Analysis

The proposed method makes use of the fact that if the cross section of arrival current in superconductors would have been minimized, the required current for phase transition will be decreased as well. Furthermore, the used pulsed current approach reduces heat generation caused by Joule heating in resistance of normal zones and avoids unfailing data acquisition.

Considering an electrode in the center of a disk of YBCO bulk, the current would go through the bulk via a circular cross section at its center where there would be a conductive ring around the sample. Under this circumstances the current will distribute uniformly in semi oblate spheroid normal zone as theoretically investigated. In the mentioned normal zone minor axis of oblate spheroid is the penetration depth of the normal current inside the bulk and major axis is the radius of circular cross section. When the current would exceed its critical value in semi oblate spheroid zone, normal zone will develop in the superconductor contributing to the voltage drop across the probes due to its resistance. The normal zone distributes in semi oblate spheroid forms since any other distribution means that there is a zero resistance path for the current to flow. Fig. 1 illustrates the contact point and how the normal zone is distributed in the superconducting bulk. The produced voltage due to the normal zone leads to voltage-current curve which inherently presents the critical current density of the material to be found in the following sections.

![Fig. 1. Schematic of point contact: 1- HTS bulk, 2- Central electrode, 3- Conductive ring electrode](image)

3. Theoretical approach

By considering the semi oblate spheroid current distribution in the normalized regions, the voltage-current relationship in the normal zone can be obtained. It is clear from electromagnetic fundamentals,

$$V = \int_0^r J \rho dr$$ (1)
where $\rho$ is the specific electrical resistance of the normal zone and $J$ is current density. Therefore,

$$V = \rho \int_0^1 \frac{1}{A_{\text{SemiOblate}}} dr,$$

in which $A_{\text{SemiOblate}}$ is the surface area of the semi oblate spheroid normal zone. Then,

$$A_{\text{SemiOblate}}(r) = \frac{\pi}{2\sqrt{a^2 - r^2}} \left[ 2a^2 \sqrt{a^2 - r^2} + ar^2 \ln \left( \frac{a + \sqrt{a^2 - r^2}}{a - \sqrt{a^2 - r^2}} \right) \right]$$

In this equation, $a$ is the radius of central circular electrode and $r$ is the penetration depth of current in normal zone. Fig. 2 shows $A_{\text{SemiOblate}}(r)$ versus $r$ for $r=0$ to $r=a$ when $a=0.05$ (cm).

A power equation could be fit for $A_{\text{SemiOblate}}(r)$ by power curve fitting in MATLAB as follows.

$$A_{\text{SemiOblate}}(r) = \frac{I}{J} = 0.5r^{1.38} + 0.0077$$

therefore the penetration depth is obtainable via equation (4).

$$r = \frac{2^{1.38}}{\sqrt{\frac{I}{J}}} - 0.0077$$

All coefficients in equation (4) are depended on the radius of the circular cross section of the central electrode. Equation (5) is a relationship between penetration depth and the distributed current. It is observable that the penetration depth is meaningful for a specific value of current, i.e. $I > 0.0077 I_c$, and should lead to a positive voltage. This amount of current after which superconductor transforms to normal phase is particular regional critical current; it depends on the critical current density of the bulk and the radius of the central electrode. Using the polynomial curve fitting contributes to another equation for $A_{\text{SemiOblate}}$.

$$A_{\text{SemiOblate}}(r) = -26.83r^3 + 3.43r^2 + 0.053r + 0.0077$$

By substituting equation (6) in equation (2) and taking an integral from 0 to $r$, the voltage current expression is obtainable as follows, where $r$ has been illustrated in equation (5).

$$V = \rho I [5.2 \arctan(0.3 + 24.4r) - 1.28 \ln(0.15 - r) + 0.64 \ln(r^2 + 0.025r + 0.0018) + 0.1008]$$
Fig. 3 displays voltage current curve in equation (7) for $a=0.05 \text{ cm}$, $\rho=1.7 \times 10^{-6}\Omega \text{ cm}$ and $J_c=400 \text{ A/cm}^2$. It is obvious that for currents above 3.08 $A$ for the given conditions, there is a positive voltage and it implies that the superconductor has been adjusted to normal in semi oblate spheroid zones. For currents lower than 3.08 $A$, there is no normal zone and consequently no resistance and no voltage.

![Voltage current curve](image)

**Fig. 3. Voltage current curve for $a=0.05 \text{ cm}, \rho=1.7 \times 10^{-6}\Omega \text{ cm} \text{ and } J_c=400 \text{ A/cm}^2$**

4. Experimental Setup

The YBCO bulk disk with a diameter of 0.7 cm was selected as a sample to do the test. Prior to test, the surface of the disk was polished to eliminate any surface crack or flaw and cleaned in an ultrasonic bath with Propanol. In order to avoid heat generation, the sample was test using a designed 200 $\mu$s width pulse current source.

To employ a holder for the contacts, a conductive rod was placed on the Nitrogen dewar and then a rectangular-shaped plate of copper was implemented on the rod to act as a hinge, where the hinge can rotate freely around the rod. Since the bulk is placed in the boiling liquid Nitrogen while being characterized, it is wobbled and the contact may be cracked or disconnected. In order to avoid these failures, a repelling force should be used to push the rod down onto the surface of the disk firmly. To achieve this goal, a small piece of magnet was glued on the other side of the copper plate using glue. Then another magnet was mounted exactly above the magnet on the copper plate using a clamp so that the two magnets repelled each other. This repelling force guarantees that the probe is fixed exactly where it has been pasted; moreover it prevents any wobbling movement of the disk.

Then the disk was placed in a plastic cylindrical holder, which prevents undesirable movements of disk during the test. In order to minimize the Ohmic contact resistance and providing a fixed position for the probe while the disk is being tested, the probe was attached to the disk using silver paint. In order to cancel the effect of the contact resistance on the measurement results, the contact is circumvented using the four-probe technique. A copper ring with periphery of 3.7 cm was cut and placed around the bulk using silver paint, where the ring shape leads to uniform current distribution since there is no priority for internal current at the center of the bulk. Current pulses have been generated using a circuit based on a MOS differential pair which is connected to a rectangular wave generator with adjustable duty cycle. The rectangular wave is responsible for switching one of the MOS transistors on and off and therefore
producing current pulses with desired duty cycle. Current is generated using MOS transistors and the current amplitude can be set by the circuit, where this current is mirrored into the differential pair.

5. Result and Discussion

Current and voltage values were measured during the test. In order to extract the superconductor bulk V-I curve; the effect of linear Ohmic contacts should be eliminated. Since the Ohmic resistance originates mainly from the copper ring, its Ohmic resistance was evaluated at the liquid Nitrogen temperature using four-probe technique before the test. Linear curve fitting of resulting values was performed to obtain the Ohmic resistance of the ring at the liquid Nitrogen temperature. To evaluate the V-I curve of superconductor bulk, current values were substituted in the linear equation obtained from the resistance measurement of the copper ring and the resulting voltage was subtracted from the voltage values on the V-I curve resulted from test. The resulting V-I curve is illustrated in Fig. 5. The HTS bulk shows nearly zero resistance in the current values smaller than \(2.1A\), while in the greater currents it gradually loses its superconductivity beneath the central electrode and the voltage across the bulk increases drastically to values above zero.
This leap can be seen by investigating Fig. 5; consequently, 2.1 $A$ could be considered as the critical current. Regarding $I> 0.0077 \ J_c$, the critical current density equals to $272.7 \ A/cm^2$.

6. Conclusion

A new method for critical current density measurement has been introduced in this work. Current has been applied at the center of HTS bulk in a small circular cross section in one end. At the other end a conductive ring around the bulk is used, which guarantees symmetrical current distribution inside the bulk. Theoretical approach predicts semi oblate spheroidal normal current distribution beneath the central electrode. When the current exceeds a particular regional critical value, the semi oblate spheroid normal zone develops inside the bulk. A voltage current relationship in the developed normal zones inside the bulk is obtained and introduced, in which there is a positive voltage after a specific value of the current and no voltage before it. As obtained, this particular critical current and the critical current density of the bulk material relate to each other by a coefficient pertaining to the surface area of the central contact. Since the critical current could be obtainable from the voltage current curve, the critical current density can be acquired by the theoretically obtained specific relationship. Experimental work has been done and measurements confirm the theoretical approach.

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