



The Determination of the Specific Capacitance of Mercury Based Copper Oxide Layered Superconductor at Superconducting State

Özden ASLAN ÇATALTEPE

İstanbul Gedik University, Engineering Faculty, İstanbul, TURKEY

Received: 25.05.2018; Accepted: 10.07.2018

<http://dx.doi.org/10.17776/cs.j.427219>

Abstract. Mercury based copper oxide layered high temperature superconductor, which consists of superconductor–insulator–superconductor (SIS) layers, can be considered as a stack of nearly ideal, intrinsic Josephson junctions (IJJ). The SIS junction, where the electrical field is confined, topologically resembles a parallel-plate capacitor. As is known, the coupling between junctions in superconductors is capacitive. Hence, the determination of the specific capacitance (C_s) of the IJJ at the superconducting state has a crucial importance in order to give information about superconductivity mechanism. In this study, the C_s values of the investigated sample have been calculated by means of the critical current density, J_c and plasma frequency, ω_p that have been obtained from magnetic measurements taken at the below temperatures than the critical transition temperature, T_c . Moreover, C_s values at superconducting temperature have been compared to that of the normal temperature.

Keywords: Specific capacitance, intrinsic Josephson junctions, copper oxide layer.

Süperiletken Durumda Cıva Bazlı Bakır Oksit Katmanlı Süperiletkenin Özgül Kapasitanslarının Tespiti

Özet. Süperiletken-yalıtkan-süperiletken (SYS) katmanlardan oluşan cıva bazlı bakır oksit katmanlı yüksek sıcaklık süperiletkenleri neredeyse ideal, asli Josephson kavşakları dizisi olarak göz önüne alınabilir. Elektrik alanı hapseden bir SYS kavşağı, topolojik olarak paralel plakalı bir kapasitöre benzer. Bilindiği üzere, süperiletkenlerdeki kavşaklar arasındaki kuplaj kapasitiftir. Bundan dolayı, süperiletken durumda özgül kapasitans, C_s 'nin tespiti süperiletkenlik mekanizması hakkında bilgi elde etmek için çok büyük bir öneme sahiptir. Bu çalışmada, incelenen örneğin C_s değerleri kritik geçiş sıcaklığı olan T_c 'den daha düşük sıcaklıklarda yapılan manyetik ölçümlerden elde edilen kritik akım yoğunluğu, J_c ve plazma frekansı ω_p değerleri aracılığıyla elde edildi. Ayrıca süperiletken sıcaklıkta C_s değerleri normal durumdaki C_s değerleriyle de karşılaştırılmıştır.

Anahtar Kelimeler: Özgül kapasitans, asli Josephson kavşakları, bakır oksit katmanları.

1. INTRODUCTION

Copper oxide layered high-temperature superconductors have a common structure in which superconducting copper oxide layers are separated by a thin insulating layer. Copper oxide layers are coupled together by Josephson

tunnelling between adjacent layers. According to the experimental evidences, cuprates (copper oxide layered samples) such as Bi-Sr-Ca-Cu-O, Y-Ba-Cu-O, Tl-Ba-Ca-Cu-O and Hg-Ba-Ca-Cu-O behave like stacks of superconductor–insulator–superconductor (SIS) intrinsic Josephson

junctions (IJJ) [1,2]. Because of this property, the Josephson junctions topologically resemble a parallel plate capacitor. SIS junctions are used as SIS mixer for radio astronomical spectroscopy in millimeter and sub-millimeter range, and environmental science. [3,4]. In order to determine the specific capacitance (C_s) of the IJJ at superconducting state, the most used experimental method is direct microwave experiment [5]. In this context, the determination of the specific capacitance of the superconducting sample has a crucial importance in order to understand the superconducting mechanism. In this study, the C_s values of the $\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_{8+x}$ (Hg-1223) superconductor have been investigated both at superconducting and non-superconducting states for the first time. C_s value at superconducting state has been calculated by means of the critical current density, J_c and plasma frequency, ω_p that have been obtained by the magnetic measurements. At non-superconducting state, C_s values have been obtained by dielectric measurements. At superconducting state, it has been determined that the specific capacitance values of the samples are independent from both oxygen doping ratio and temperature. Also, it has been determined that the specific capacitance value of the Josephson junction at the non-superconducting state is much bigger than that of the superconducting state. Moreover, the oxygen doping procedure affects the specific capacitance value at room temperature. From this point of view, determination of the specific capacitance of the Josephson junction of the Hg-based cuprate sample has a key role for capacitor and memory device applications.

2. SYNTHESIS OF HG-1223 SAMPLES

The Hg-1223 samples have been synthesized by using the two-step solid state reaction technique. In the technique the precursor material with the same nominal composition of $\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_x$ (reactant material) has been prepared with four nine purity compounds of BaO, CaO and CuO, and then heating them at 1340 °C for 10 h in oxygen environment. The reactant material and

the high-purity HgO, which has been put in a smaller diameter test tube, have been both placed in the first tube, which has been finally evacuated and sealed. In the second step, the sealed quartz tube has been placed horizontally in a furnace and heated at a rate of 1.5 °C/min to 940 °C for 3 h. At the end of the preparation method, the “under-doped mercury based sample” has been obtained. In order to obtain the optimally oxygen doped Hg-1223 superconducting material, the sample has been annealed in oxygen atmosphere at 300°C, well below the decomposition temperature of HgO, for 10 h. It has been determined that the result of oxygen annealing process, holes are doped to the superconducting system which causes a change in the electronic excitations. The process, by which the optimum oxygen doped sample has been synthesized, has been relatively decided to the specimen response to magnetization measurements such as magnetic susceptibility versus temperature and magnetic hysteresis. Hence, the critical parameters, i.e. the critical transition temperature (T_c), the critical current density (J_c) and the critical magnetic field (H_c), which are important indicator in order to determine optimum oxygen level, are higher values than under-doped sample. For example, the critical transition temperatures for optimally and under-oxygen-doped $\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_{8+x}$ superconductors have been determined as 137.3 K and 123 K, respectively [6].

3. THEORETICAL BACKGROUND

The primitive cell of the Hg-based cuprate superconductor contains three superconducting copper oxide planes separated by insulating layers. Hence, this structure is considered as an IJJ array (Figure 1). The main Josephson plasma excitation modes in weakly Josephson coupled layered superconductors are the longitudinal along the c-axis and transversal plasma modes in the ab-plane. [7]. In high temperature cuprate superconductors, Bose -Einstein Condensation (BEC) occurs in copper oxide layers (i.e. ab planes). At superconducting state, BEC of Cooper pairs in the CuO_2 layers extends through the all copper oxide layers with the plasma resonance frequency. In other words, superconductivity

occurs in connection with a crossover from two-dimensional (2D) to 3D transport below the critical transition temperature, T_c [8-12]. So that, the perfectly coupled layered mercury-based superconducting material has been proposed to serve as an example of exhibition of 3D-spatial BEC [6]. It means that the longitudinal (Josephson) plasma frequency (ω_j) along the c-axis equals to the transversal plasma frequency, (ω_p) in ab-plane, $\omega_j = \omega_p$ [13].

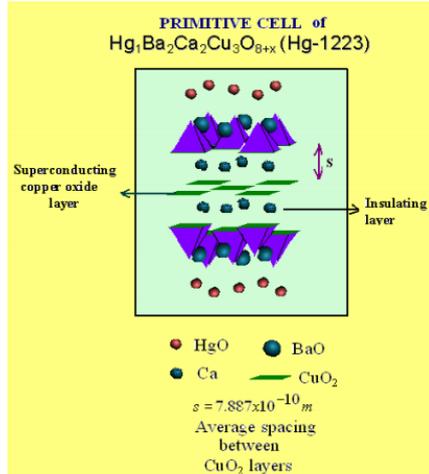


Figure 1. The primitive cell of mercury based (Hg-1223) superconductor [14].

Superconducting Josephson junctions, which exhibit solitonic behavior, can be described by Sine-Gordon equation. As is known that in superconducting state, solitons are quantum of magnetic flux. The production and storage of the solitons give very important knowledge about the investigated systems. The solution of the Sine-Gordon equation give us the information about the Josephson plasma frequency, ω_j [15-19].

$$\omega_j = \sqrt{2eJ_c / (C_s \hbar)} \quad (1)$$

where J_c , C_s , \hbar , and e are the critical current density, specific capacitance of the IJJ, Planck constant and the charge of the electron, respectively. In order to calculate the specific capacitance of IJJ, the plasma frequency, ω_p and

the critical current density, J_c values are needed. ω_p and J_c values for optimum and under oxygen doped samples have been obtained from magnetic hysteresis curves. The dynamic hysteresis measurements of mercury cuprates been performed by the Quantum Design SQUID susceptometer, model MPMS-5S. The measurements of magnetic hysteresis have been made around the lower critical magnetic field, H_{c1} [6].

4. RESULTS

The C_s values of the IJJ have been calculated by means of Equation 1. The related ω_p , J_c and C_s values of the samples have been given Table 1.

Table 1. ω_p , J_c and C_s values of the under and optimally oxygen doped samples.

$T(K)$	$\omega_p(Hz)$	$J_c(A/m^2)$	$C_s(mF/m^2)$
4.2(opt.)	5.217×10^{14}	10^{12}	11.15
27(opt.)	2.09×10^{14}	1.62×10^{11}	11.26
77(opt.)	5.217×10^{13}	10^{10}	11.15
7(und.)	31.4×10^{12}	1.43×10^{11}	11.15

The capacitance values of the optimally and under oxygen doped samples at room temperature values, which have been calculated by means of the capacitive reactance, X_c and frequency, f ($C = 1/2\pi f X_c$), have been performed by Hewlett Packard 4192A impedance analyzer [20]. The area of the copper oxide layers (ab-plane), which is necessary for calculating the C_s value, has been calculated by the lattice parameter. The lattice parameters of both the optimally and under doped Hg-based superconductors, which have been calculated by means of XRD data, have been found as $a=b=3.8684 \times 10^{-10}$ m and $a=b=3.8328 \times 10^{-10}$ m, respectively [14]. The variation of the capacitance and specific capacitance values with frequency of the under and optimally oxygen doped samples at room temperature has been listed in Table 2.

Table 2. Capacitance and specific capacitance value of the under and optimally doped sample the at room temperature.

<i>Under doped sample</i>			<i>Optimally doped sample</i>		
<i>f(kHz)</i>	<i>C(F)</i>	<i>C_s(F/m²)</i>	<i>f(kHz)</i>	<i>C(F)</i>	<i>C_s(F/m²)</i>
5	5.502x10 ⁻⁹	0.375 x10 ¹¹	5	1.639x10 ⁻¹⁰	0.109x10 ¹⁰
40	2.199x10 ⁻¹⁰	0.149x10 ¹⁰	40	9.411x10 ⁻¹²	0.629x10 ⁸
80	6.478x10 ⁻¹¹	0.441 x10 ⁹	80	5.225x10 ⁻¹²	0.349x10 ⁸
500	3.58x10 ⁻¹²	0.244x10 ⁸	800	2.88x10 ⁻¹²	0.193x10 ⁸
3x10 ³	8.464x10 ⁻¹³	0.576x10 ⁷	3x10 ³	2.702x10 ⁻¹²	0.181x10 ⁸
1x10 ⁴	5.168x10 ⁻¹³	0.352x10 ⁷	1x10 ⁴	2.567x10 ⁻¹²	0.172x10 ⁸

5. DISCUSSION AND CONCLUSIONS

As is known, the design restrictions for high frequency devices and SQUIDs depend on the properties of the specific capacitance of the IJJ. Hence, the study has been devoted to the specific capacitance values of the various oxygen doped mercury based samples which have been investigated at superconducting and non-superconducting state for the first time. It has been found that the specific capacitance quantities of the samples at superconducting state, which are independent from oxygen doping ratio and temperature, have approximately same value as 11 mF/m^2 . This result is consistent with the study on small-capacitance Josephson junctions in literature where the specific capacitance, C_s is on the order of 20-100 $fF/\mu m^2$ (i.e. 20-100 mF/m^2) [21,22,23]. Also, it has been determined that the specific capacitance values of the Josephson junctions at the non-superconducting state are much bigger than that of the superconducting state. Moreover, the oxygen doping procedure affects the specific capacitance values at room temperature. From this point of view, the determination of the specific capacitance of the intrinsic Josephson junction of the Hg-based copper oxide layered has a key role for capacitor, memory device applications, single electron transistors and high frequency devices.

ACKNOWLEDGEMENT

This research has been supported by İstanbul Gedik University Scientific Research Projects Coordination Department with the Project No. GDK201702-BA004

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