The effect of potassium substitution on the properties of HgBa$_2$Ca$_2$Cu$_3$O$_{8+\delta}$ compound

Kassim Mahdi Wadi$^1$, Riyadh Kamil Chillab$^1$, Aqeel N. Abdulateef$^1$, Kareem A. Jasim$^2$, Auday H. Shaban$^3$, Maher A. Hassan$^4$, Sarab Saadi Jahil$^2$

$^1$Al-Ma'amoun University College, Electrical Engineering Techniques Department, Iraq
$^2$Department of physics, College of Education for pure Sciences Ibn AlHaitham, University of Baghdad, Baghdad, Iraq.
$^3$College of Science, University of Baghdad, Baghdad, Iraq.
$^4$Department of Physics, College of Education for Pure Science, University of Tikrit, Tikrit, Iraq

E-mail: kareem.a.j@ihcoedu.uobaghdad.edu.iq

Abstract. This article reported investigations the effect of partial substitution potassium at calcium site for HgBa$_2$Ca$_2$Cu$_3$O$_{8+\delta}$ system with x from 0 to 0.2. All samples were prepared using solid state reaction technique. The samples were subjected to gross structural characterization by X-ray diffraction. The XRD data for the prepared samples are consistent with the Hg-1223 phases, and the analysis showed that the structures are tetragonal. Increasing potassium level results in decreasing the mass density (from 1.53 to 1.51), volume fraction (from 76.4 to 71.9), lattice parameters c, c/a length of c. Electrical resistance was testing by four-probe technique to determine the critical temperature, and it is noticed that the non-potassium HgBa$_2$Ca$_2$Cu$_3$O$_{8+\delta}$ compound has a critical temperature around 118 K, while introducing potassium in HgBa$_2$Ca$_2$$_x$K$_x$Cu$_3$O$_{8+\delta}$ compound with x=0.1 and 0.2 led to decrease the critical temperature to 110 K and 93 K, respectively.

Keywords: partial substitution, Tetragonal structure, Potassium, Electrical Resistance, X-ray diffraction.

1. Introduction

The large variation in the layered structure of High Temperature Superconducting Compounds (HTSC) leads to important changes in physical, mechanical and structural properties such as magnetic field, electrical conductivity, current density, dielectric constant [1,4], hardness[5], tensile strength, elasticity, grain size and crystal size depending on the type of superconducting compound[6], the proportions of the elements and their partial substitution in the compound [4-8]. The difference in the stratigraphic composition of the high temperature superconducting compounds leads to important changes in the magnetic field depending on its movement that is relative to the axes of the crystal lattice. For superconducting planes, the direction of the magnetic field varies. The results of the measurements of the critical magnetic field and its critical temperature depend on the angle between the magnetic fields.
and the surface (a – b). Generally, it showed that the dissipation in the electric magnetic field strongly decreases when the field tends towards the superconducting layers away from the c axis [9, 10]. Measurements in oblique fields were commonly analyzed in terms of the approach based on the anisotropic of mass. Anisotropy reduces the effective electric and magnetic field component in the same direction and parallel to the superconducting layers [11]. The electric and magnetic field component along the c-axis is the only active component within highly anisotropic materials, because it has been found already experimentally at BSCCO system [4, 12]. For moderate contrast materials, such as Y-B-C-O, field scale has been shown to be valid in the flow region [13], and for Hg-Ba-Ca-O compounds families have anisotropy between those of YBCO and BSCCO. Regarding -2212 phase [14], only few investigations were reported on the angle dependence for the transmission characteristics. The resistance of (Hg, Re) Ba2CaCu4O10 was recently studied under different directions of magnetic field with respect to c-axis, and the dependence of the dissipation field on the angle of inclination has been inferred [15]. The physical properties of many superconducting materials, such as high phase formation, temperature transition and the isolation of the superconducting compound Hg-1223 have been improved by means of cation substitutions and doping with highly valued pb, Re or other elements [16, 17]. The electrical resistance is one of the most important characteristics of material, and it is mostly a common method to determine the transition temperature of a superconductor.

The aim of this research is to study the effect of partial sedimentation of calcium with potassium, in HgBa2Ca2-KCu3O8+δ compound with different x values. Important measurements were carried out to determine the structural and electrical properties of the samples.

2. Experimental

The pure powders of HgO, CaO, CuO, BaO and K2O were weighted by a sensitive balance to form the chemical formula HgBa2Ca2-xKxCu3O8+δ, with x = 0, 0.1 and 0.2. The samples were synthesized by solid state reaction method. The chemical formulas listed below are the general guide for starting materials.

\[
\text{HgO} + \text{2BaO} + \text{(2-x)CaO} + \text{xK}_2\text{O} + \text{3CuO} \rightarrow \text{HgBa}_2\text{Ca}_2-x\text{K}_x\text{Cu}_3\text{O}_{8+\delta}
\]

The powders were mixed together using an agate mortar to produce a homogenous mixture, and the grinding process took a period of time between 30-50 minutes. The powders were shaped as a disc-pellets with a diameter of 15 mm and a thickness of 3 mm using a hydraulic press with 5 MPa pressure for 1 min. The pellets were pre-sintered at (850°C) for one day using a Carbolite furnace with increasing the temperature rate by 7 °C/min, then cooled down to 25°C with same heating rate. The crystal structures of HgBa2Ca2-xKxCu3O8+δ compounds were obtained using X-Ray diffractometer type Shimadzu with the following features: Source: Cu Kα, Wavelength: 1.5405, Current: 30 mA, Voltage: 40 KV. The scanning speed is 8 degree/min in a 2θ range of (10-80)°. The computerized calculations for (a, b, and c) were based on Full Prof Suite toolbar [18]. The intensities of the X-ray diffraction peaks have been used in equation (1) to estimate the phase’s volume fraction [19]:

\[
V_{ph} = \frac{\sum I_i}{\sum I_0 + \sum I_i + \sum I_2 + \sum I_{other(peak)}} \times 100\%
\]

Where \( I_i \) = XRD phase peak intensity that determined, \( I_0 \), \( I_2 \), ... \( I_n \) represented the peaks intensities of all XRD. The densities (d0) of the samples were determined using this equation [12].

\[
d_0 = \frac{W_m}{N_A V} \times (2)
\]

where: \( W_m \) = the molecular weight in (amu) 
\( N_A \) = Avogadro’s number (particles/gm ml) 
V = the volume of the unit cell in (cm³).

The superconductor’s critical temperature was determined by measuring the electrical resistivity as a function of the temperature. Four-point probe technique was used to measure the electrical resistivity within a temperature range of (77-300 K).
The samples were tested under vacuum of $6 \times 10^{-2}$ mbar prepared by a rotary pump. The cryostat was connected to the rotary pump, and a digital thermometer sensor was attached near the sample. Four copper wires were also connected to the sample through oven-dried silver paste, which served as two wires for the current and the others for the electric voltage. The sample was prepared with a current of 5 mA by means of a constant current source, and the voltage drop in the sample was measured using the nanometer as a function of its cooling. Resistivity ($\rho$) was measured as the temperature of the sample changed using the relationship:

$$\rho = \frac{V \omega t}{I L}$$  \hspace{1cm} (2)

where: the current passing through the sample $I$, voltage drop between the electrodes $V$, $\omega$ is the sample width, $L$ is the effective length passing through electrodes, and $t$ is the sample thickness.

3. Result and Discussions

Figure 1 shows the XRD pattern of HgBa$_2$Ca$_{2-x}$K$_x$Cu$_3$O$_{6+\delta}$ compound with $x=(0, 0.1, \text{ and } 0.2)$. The figure illustrated that the potassium substitution has produced changing in the high (H-phase) and low phases (L-phase). It is also noted that the partial replacement leads to a displacement of the peaks and a change in their intensities. This confirms the interaction between the elements and components of the superconducting compound.

Table 1 shows the values of the crystal lattice constants and the mass density that calculated from the X-ray diffraction plot after applying Brack's law to each partial substitution value of $x$. This table shows that the mass density, lattice parameters, and volume fraction decrease with increasing potassium substitution. This is due to the substitution of calcium by potassium and the difference in the sizes of the atoms replaced the elements since the ionic radius of potassium is longer than that for calcium. This is because the expansion at the base structure of HgO results in decreasing in mass density, volume fraction, $c/a$ and the length of $c$. 
Figure 1. XRD of HgBa2Ca2-xKxCu3O8+δ with x=0, 0.1 and 0.2

Figure 2. Temperature dependence of resistivity for HgBa2Ca2-xKxCu3O8+δ

Figure 3. Temperature dependence of Potassium concentration for HgBa2Ca2-xKxCu3O8+δ

Table 1. Critical temperature $T_c$(OFF, $T_c$(ON)), lattice parameters $c$, $a$, $c/a$, volume fraction and mass density for HgBa2Ca2-xKxCu3O8+δ system for x=0, 0.1 and 0.2.

| X  | $T_c$(OFF)(K) | $T_c$(ON)(K) | $a$(Å)  | $c$(Å)  | $c/a$ | $\rho_M$ (g/cm³) | $V_{Ph-1223}$% |
|----|----------------|--------------|---------|---------|-------|-----------------|-----------------|
| 0  | 135            | 118          |         |         |       |                 |                 |
| 0.1| 131            | 113          |         |         |       |                 |                 |
| 0.2| 110            | 93           |         |         |       |                 |                 |
In this study, we synthesized HgBa$_2$Ca$_{2-x}$K$_x$Cu$_3$O$_{8+\delta}$ system with $x=0$, 0.1 and 0.2. The samples were prepared by solid state reaction process. The partial substitution of calcium with potassium in the Ca-O$_2$ layer of HgBa$_2$Ca$_2$Cu$_3$O$_{8+\delta}$ has been studied with special emphasis on the effect of this partial substitution on superconductivity and microstructure properties. The XRD data collected from various samples show that all the samples are polycrystalline correspond to Hg-1223 phase. The critical transition temperature $T_c(\text{offset})$ decreases from 118 to 93 when increasing potassium concentration. The results conclude that the substitutions of potassium lead to change in the volume fraction, lattice parameter and mass density.

4. Conclusions

In this study, we synthesized HgBa$_2$Ca$_{2-x}$K$_x$Cu$_3$O$_{8+\delta}$ system with $x=0$, 0.1 and 0.2. The samples were prepared by solid state reaction process. The partial substitution of calcium with potassium in the Ca-O$_2$ layer of HgBa$_2$Ca$_2$Cu$_3$O$_{8+\delta}$ has been studied with special emphasis on the effect of this partial substitution on superconductivity and microstructure properties. The XRD data collected from various samples show that all the samples are polycrystalline correspond to Hg-1223 phase. The critical transition temperature $T_c(\text{offset})$ decreases from 118 to 93 when increasing potassium concentration. The results conclude that the substitutions of potassium lead to change in the volume fraction, lattice parameter and mass density.

References

[1] Richter H Puica I Lang W Peruzzi M Durrell J H Sturm H Pedarnig J D and Bauerle D 2006 Journal of Physics: Conf. Series 43 706.
[2] Kadhim B B Khaleel I M Hussein B H Jasim K A Shaban A H ALMaiyaly B K H and Mahdi Sh M 2018 AIP Conf. Proc. 1968 030054-(1-4).
[3] Jasim K A 2012 Turk J. Phys 36 245.
[4] Jasim K A and Alwan T J 2009 Journal of superconductivity and novel magnetism springer 22 861.
[5] Wadi K M Abdulateef A N Shaban A H and Jasim K A 2019 Energy Procedia 157 222.
[6] Jasim K A 2012 Journal of superconductivity and novel magnetism 25 1713.
[7] Kadhim B B Risan R H Shaban A H and Jasim K A 2019 AIP Conf. Proc 2123 1.
[8] Jasim K A and Alwan T J 2017 J Supercond Nov Magn 30 451.
[9] Iye Y Nakamura S and Tamegai T 1989 Physica C 159 433.
[10] Amirfeiz M Cimberle M R Ferdeghini C Giannini E Grassano G Marr’e D Putti M and Siri A S 1997 Physica C 288 37.
[11] Blatter G Geshkenbein V B and Larkin A I 1992 Phys. Rev. Lett. 68 875.
[12] Mohammed L A and Jasim K A 2018 Ibn Al-Haitham Jour. for Pure & Appl. Sci. 31 26.
[13] Aleabi S H Watan A W Salman E M.-T Jasim K A Shaban A H and AlSaadi T M 2018 AIP Conf. Proc. 1968 020019-(1-5).
[14] Ibrahim Z H Ibrahim S A Shaban A H Jasim K A and Mohammed M K 2017 Energy Procedia 119 709.
[15] Jasim K A Thejeel M A and Al-Khafaji R S 2017 Ibn Al-Haitham Journal for Pure and Applied Science 27 170.
[16] Passos C A C Orlando M T D Oliveira F C da Cruz P C M Passamai Jr J L Orlando C G P Eloi N A Correa H P S and Martinez L G 2002 Effect of oxygen content on the properties of the Hg0.82Re0.18Ba2Ca2Cu3O8+\delta superconductors.
[17] Tian W Shao H M Zhu J S and Wang Y N 2006 Physica Status Solidi.
[18] Carvajal J R 2000 An Introduction to the ProgramFullprof (Leon France).
[19] BIJU A 2007 Structural and Transport Properties of Rare Earth Modified (Bi, Pb)-2212 Superconductors Ph.D. Thesis, University of Kerala: 52