INFLUENCE OF $BiFeO_3$ NANOPARTICLE ON THE PROPERTIES OF $YBa_2Cu_3O_{7-\delta}$ SUPERCONDUCTOR FOR POSSIBLE ENHANCEMENT OF CURRENT DENSITY

By

NUR ATHIRAH BINTI CHE DZUL-KIFLI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

December 2021

FS 2021 66

DEDICATION

This thesis is specifically dedicated to my parent, my husband, my daughter and my siblings who have been such a great supporter and my true inspiration along this master journey.

CHE DZUL-KIFLI BIN ABDULLAH
RAHIMAH BINTI AB.LLAH
MUHAMMAD ABDUL SHAKIR BIN HASRI
MARYAM JAMEELA BINTI MUHAMMAD ABDUL SHAKIR

And to my dearest family for the never-ending encouragement.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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December 2021

Chair : Mohd Mustafa Awang Kechik, PhD
Faculty : Science

Superconductivity is a phenomenon where the superconductor's resistance abruptly turns zero ohm as the material meets the superconductor properties. In this work, the bulk superconductor of $YBa_2Cu_3O_{7-\delta}$ (Y-123) added with $BiFeO_3$ (BFO) nanoparticle in different weight percentage (x = 0.0 wt.%, 0.2 wt.%, 1.0 wt.%, 1.5 wt.% and 2.0 wt.%), is synthesized by using thermal treatment method. Further studies were made upon the bulk sample in order to determine the characteristics and properties of the samples. The samples were characterized by using X-Ray Diffraction (XRD), Alternating Current Susceptibility (ACS), Field emission scanning electron microscopy (FESEM) and Energy Dispersive X-ray spectroscopy (EDX).

For the first part, the effect of oxygen flow during the sintering process of Y-123 bulk superconductor is studied. This part found that the results obtained for the sample with the oxygen flow are much better than the Y-123 with no oxygen flow. Further study was made regarding the addition of Y-123 (with oxygen flow) with BFO nanoparticle. Based on XRD results, all samples with BFO addition show a *Pmmm* space group with orthorhombic crystal structure. The weight percentage for x = 1.0 wt.% gives the highest value of Y-123, and the value is decreasing as higher amount of BFO is added. The higher amount of BFO added had degrades the samples' crystallite size, which shows that the addition does not promote the grain growth of Y-123, while the lattice strain increases with higher addition of BFO. As for the ACS, the value of the $T_{c\text{-onset}}$ is enhanced with the addition of BFO nanoparticle, where the x = 1.5 wt.% give the highest T_c value with 91.91 K. The sample with 1.5 wt.% also shows a high value of T_p with the value of 89.15 K. In terms of microstructure properties, the FESEM analysis shows that the average grain size of the samples is decreases as BFO is introduced. This

result is as expected as the crystallite size value mentioned in XRD also shows the same trend. However, the small grain size is expected to fill in the boundary and thus can help in enhancing the grains connectivity. All in all, the addition of BFO nanoparticle in Y-123 does help to improve the superconducting properties mainly for x = 1.5 wt.%.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENGARUH NANOPARTIKEL $BiFeO_3$ TERHADAP SIFAT-SIFAT SUPERKONDUKTOR $YBa_2Cu_3O_{7-\delta}$ UNTUK MEMUNGKINKAN PENINGKATAN KETUMPATAN ARUS

Oleh

NUR ATHIRAH BINTI CHE DZUL-KIFLI

Disember 2021

Pengerusi : Mohd Mustafa Awang Kechik, PhD
Fakulti : Sains

Superkonduktor pukal $YBa_2Cu_3O_{7-\delta}$ (Y-123) dengan penambahan nanopartikel $BiFeO_3$ (BFO) dalam peratusan berat yang berbeza (x = 0.0 wt.%, 0.2 wt.%, 1.0 wt.%, 1.5 wt.% dan 2.0 wt.%) telah dihasilkan dengan menggunakan kaedah rawatan termal. Kajian lebih lanjut telah dibuat bagi menentukan ciri-ciri dan sifat sampel. Sampel dicirikan dengan menggunakan pembelauan sinar-X (XRD), kerentanan arus bergantian (ACS), mikroskop elektron imbasan pancaran medan (FESEM) dan spektroskopi serakan tenaga sinar-X (EDX). Terdahulu, kajian mengenai superkonduktor pukal Y-123 mengenai kesan aliran oksigen semasa proses pensinteran telah dikaji. Hasil dari bahagian ini, didapati bahawa hasil yang diperoleh untuk sampel dengan aliran oksigen jauh lebih baik daripada sampel Y-123 tanpa aliran oksigen. Kajian selanjutnya mengenai penambahan nanopartikel BFO pada superkonduktor Y-123 (dengan aliran oksigen) telah dilaksanakan. Berdasarkan hasil XRD, semua sampel dengan penambahan BFO menunjukkan kumpulan ruang *Pmmm* dengan struktur kristal ortorombik. Peratusan berat untuk x = 1.0 wt.% memberikan nilai tertinggi Y-123, dan nilainya menurun apabila jumlah BFO yang lebih tinggi ditambahkan. Penampbahan BFO pada superkonduktor Y-123 telah menurunkan nilai ukuran kristal, yang menunjukkan bahawa penambahan tersebut tidak mendorong pertumbuhan ukuran kristal Y-123. Bagi ACS, nilai $T_{c\text{-onset}}$ meningkatkan dengan penambahan nanopartikel BFO, di mana x = 1.5 wt.% memberikan nilai T_c tertinggi dengan 91.91 K. Sampel dengan 1.5 wt.% juga menunjukkan nilai T_p yang tinggi dengan nilai 89.15 K. Dari segi sifat struktur mikro, analisis FESEM menunjukkan bahawa ukuran butiran purata sampel semakin berkurang ketika BFO diperkenalkan. Hasil ini adalah seperti yang dijangkakan kerana nilai ukuran kristal yang disebutkan dalam XRD juga menunjukkan tren yang sama.

Walau bagaimanapun, ukuran butiran kecil diharapkan dapat memenuhi ruang dan dengan demikian dapat membantu merapatkan ruang-ruang antara bijirin. Secara keseluruhan, penambahan nanopartikel BFO dalam Y-123 membantu meningkatkan sifat superkonduktor terutamanya untuk x = 1.5 wt.%.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Mohd. Mustafa Awang Kecik, PhD
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Chairman)

Abdul Halim Shaari, PhD
Professor
Faculty of Science
Universiti Putra Malaysia
(Member)

Chen Soo Kien, PhD
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Member)

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ZALILAH MOHD SHARIFF, PhD
Dean & Professor
School of Graduate Studies
Universiti Putra Malaysia

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LIST OF ABBREVIATIONS AND SYMBOLS

A	Ampere
Å	Angstrom
a-	Lattice parameter a
ACS	Alternating current susceptibility
b-	Lattice parameter b
B	Magnetic flux density
BCS	Bardeen-Cooper-Schrieffer Theory
$BiFeO_3$	Bismuth ferrite
c-	Lattice parameter c
CuO	Copper (II) oxide
DTA	Derivative Thermal Analysis
DTG	Derivative Thermogravimetric Analysis
EDX	Energy dispersive X-ray spectroscopy
FESEM	Field emission scanning electron microscope
FWHM	Full width half maximum
h	hour
H_a	Applied magnetic field
H_c	Coercivity
H_{c1}	Lower critical field
H_{c2}	Upper critical field
HTS	High Temperature Superconductor
ICSD	Inorganic Crystal Structure Database

I_o	Critical Josephson current
J_c	Critical current density
J_{cm}	Intergranular critical current density
K	Kelvin
Kbar	kilobar
km/h	Kilometre per hour
LH_2	Liquid helium
LN_2	Liquid nitrogen
LTS	Low Temperature Superconductor
M_r	remanence magnetization
M_s	Saturation magnetization
MRI	Magnetic Resonance Imaging
Nb	Niobium
Oe	Oersted (unit of magnetic field)
Pb	Lead
PVP	Polyvinyl Pyrrolidone
rpm	Rotation per minute
R-T	Resistance-temperature measurement
RE-211	$REBa_2CuO_5$
T	Tesla (Standard unit of magnetic flux density)
T_c	Critical temperature

CHAPTER 1

INTRODUCTION

1.1 Introduction

In recent years, the development of a technology has start to incline into a more environmentally friendly technology. The green technology refers to the technology that involve the energy efficiency, recycling, renewable resources and health. Green technology and renewable energy come together with the same mission: to conserve energy and improve the energy efficiency for the future human race. For instance, the solar cell is the best-known example in this technology. The solar cell helps to generate electricity by converting light energy into electrical energy through photovoltaic cells. This technology helps in minimizing the consumption of fossil fuels and hence reduces pollution and greenhouse emissions.

Despite of the great energy conversion, the electrical resistance issue that comes together with the heat waste problem has become a massive issue in this technology. As a consequence, this complication of the electrical resistivity may have distorted the idea to have a more conserving energy, mainly in energy efficiency. In this aspect, superconductivity comes as the best solution to tackle these issues.

Superconductivity is a phenomenon where a superconductor material's resistance drops abruptly to zero ohm without releasing any other form of energy. To become superconductive, the materials need to possess two important requirements. First and foremost, the superconductor materials need to be cooled down below its critical temperature (T_c). The critical temperature or transition temperature is a temperature where the superconductor starts to lose its resistance. The material becomes superconductive once it reaches its critical temperature, T_c (Van & Kes, 2010). Secondly, the magnetic flux's repulsion took placed inside the superconductor, resulting in the zero magnetic induction, $B = 0$. A superconductor which placed in a magnetic field and cooled down through the critical temperature expels magnetic flux. This phenomenon is called as the Meissner effect (Geim *et al*., 1998).

1.2 History of Superconductivity

Superconductivity was discovered by a Dutch physicist, Heike Kamerling Onnes in the year of 1911. The superconductivity was first discovered in mercury wire in his laboratory in Leiden University, Holland. Onnes was the first person to discover and find the right method to liquefy helium gas. Onnes managed to do the experiment on materials immersed in liquid helium, which the experiment has never done by other researchers before. Onnes carried out an experiment to measure the electrical resistance on mercury and found a nobility when the mercury's resistance disappeared as it is cooled to the liquid helium of temperature lower than 4.2 K. The current even continues to flow in months and years. This unusual behavior gave a big attraction to other researchers on giving hypothesis on the reasons of the behavior. Unfortunately, the discoveries did not make any clear results until Walther Meissner and Robert Ochsenfeld discovered about the Meissner effect in the year of 1933. This is the phenomenon where the superconductor expels the magnetic flux in the superconducting material and it is actually one of the superconductor properties. This exclusion of the magnetic flux in a superconductor can give a better understanding in superconductivity. Later in the year of 1957, the American physicist John Bardeen, Leon Cooper and John Schrieffer introduced the theory on the superconductivity phenomenon in which this theory are currently being widely accepted as Bardenn, Cooper and Scrieffer Theory (BCS Theory). This theory won the Nobel Prize in 1972. The BCS theory explained how the vibrating atoms in a lattice caused the electrons to form bound pairs called as Copper pairs (Frank & Charles, 2002).

After the first finding of the superconductor material back in 1911, the progress in developing the superconductor materials moved up very slowly. However, in the year of 1986, the number of new superconductor materials found started to arise progressively. As of 1986, $Ba_xLa_{5-x}Cu_5O_9$ was found with the T_c of 30 – 35 K. Later in February 1987, a scientist in University of Houston, Paul Chu together with Wu made an announcement of their great discovery in finding a high temperature superconductor (HTS) material above 90 K. Paul Chu found that the resistivity of $YBa_2Cu_3O_{7\sim\delta}$ material started to drop at 93 K and went to zero at 80 K (Chu, 1988). The extensive research on the YBCO is being proceeds up until now. Back in 1964, Bill Little from Stanford University has also made some research on the superconductivity. In his research, he manages to set a theory about the possibility of organic superconductors which is also part of the organic conductor family. The organic conductor is included the molecular salts, polymer and pure carbon systems. The molecular salts have large organic molecules that exhibit superconductive properties at a very low temperature (Burchell, 2018). The first organic superconductor which is $(TMTSF)_2PF_6$ where TMTSF denotes tetramethyl-tetraselenafulvalene, is synthesized in 1980 by a Danish researcher, Klaus Bechgaard from University of Copenhagen together with the French team members Jerome, Mazaud and Ribalut. $(TMTSF)_2PF_6$ needs to be cooled down to 0.9 K and subjected to high pressure of 12 kbar to exhibit as a superconductor (Jeremy, 2007). This organic superconductor received subsequent innovation and development which led to higher critical temperature materials, resulting to an assortment of novel electronic and superconducting properties (Jérome *et al*., 1980).

1.3 Application of Superconductor

The advancement and revolution is taking place in the superconductivity field since 1911 and since then many possible applications have been explored primarily such as in medical and transportation. The applications of the superconductor are as discussed below:

1.3.1 Superconducting Magnetic Energy Storage, SMES

A superconductor is well established and are applied in many fields including in the energy storage system. The Superconductor Magnetic Energy Storage (SMES) is among the best applications of the superconductor as it has an ability to store large amount of energy and is well-known for its efficient energy storage device. In 1969, the SMES was being introduced by Ferrier in effort to tackle the power demands issue (Ferrier, 1970). The earliest SMES devices used was commissioned by US Bonneville Power Administration in 1980s, with storage capacity of 30 MJ and a power rating of 10 MW. Nowadays, the small commercial of SMES which known as micro-SMES system was commercialize with the capacities of 100 kW to 100 MW to be established (Breeze, 2018). Basically, the SMES store the energy in a magnetic field, which is generated by a direct current through a superconducting coil. The wire in SMES is made of a superconducting material that has been cooled down below its critical temperature, T_c. As a consequence, the electric current can pass through the superconducting wire with almost zero resistance and achieve higher efficiency. As compared to normal wire, some energy is lost to heat because of the electric resistance (Johnson *et al*., 2019). The energy stored in the device however can be discharged in a short time, making it suitable to be used in power quality applications. Figure 1.1 below shows the schematic diagram of SMES, which consists of three components comprise of superconducting coil (SC), power conditioning system (PCS) and cryogenic system (CS). The energy stored in the system is determined by the size of the coils and the properties of the conductor. The size of the coils influence the inductance of the coil whereas the property of the conductor controls the maximum current applied (Abdin & Khalilpour, 2019).

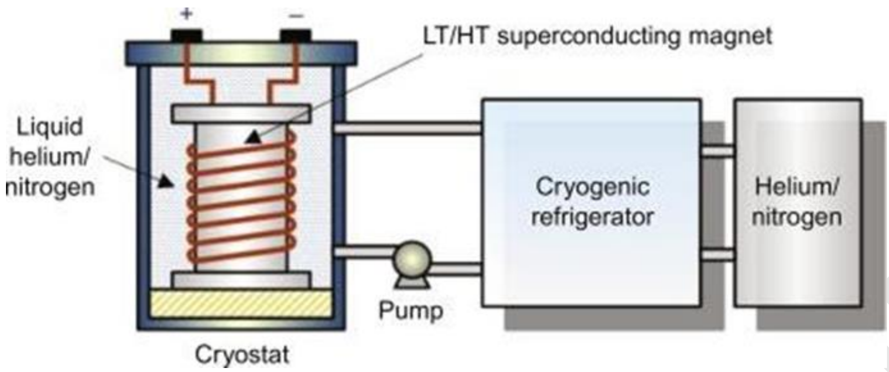

Figure 1.1: The schematic diagram of the SMES
(Chen *et al*., 2009)

1.3.2 Magnetic Resonance Imaging, MRI

The technology of a superconductor is well established and continues to evolve even in medical field. The best application of the superconductor is Magnetic Resonance Imaging, MRI. This technology took placed and became one of the best medical technologies in scanning human structures. Magnetic Resonance Imaging is a medical imaging technique used in radiology in forming human anatomy and physiological process in the body. In 2003, Paul Christian Lauterbur and Peter Mansfield shared the Nobel Prize in Physiology or Medicine. These two researchers are the one who made the MRI becomes possible. The first human to be scanned using this technology is John Francis Bovell in Southampton General Hospital, United Kingdom. Superconductor is said to be the heart of this powerful technology. The superconducting electromagnets used in MRI could align the weak magnetic moment of the protons in the human body with magnetic field of 0.5 to 1.5 Tesla (Aarnink & Overweg, 2012). The protons then absorbs the energy from the magnetic field and flip the spin. The protons' return process to the normal spin once the field is turned off produce a radio signal and received in the scanner as an image (Lewis, 2017). The image results help the doctors identify the patients' conditions in a huge range of clinical applications such as in clinical neurology, cardiology, and cancer. This powerful process can only be achieved using superconducting electromagnets.

1.3.3 Magnetic Levitation Train

The invention of train transportation proved the critical times in history of human development. Steam train is the first train developed by Richard Trevithick back in 19th century. In 1980, the majority steam locomotives were retired and has been replaced by electric and diesel locomotives. Superconductor technology also took a special place in this transportation expansion. Maglev Train or Magnetic Levitation Train is an advanced-speed train that levitates just above the track by using the superconducting magnet. The superconducting magnet will increase the power of magnetic field once it is cooled to extreme temperature. Maglev train does not use wheels just like other conventional trains. The train levitated and propelled from the tracks along the guide way using repelling magnet by using the principle of magnetic repulsion. The acceleration and braking system of this train does not depend on the friction of the track. The train travels along the guide way without any wheels and thereby reducing the friction. This resulting to a very high speeds train that can run more than 500 km/h (Lee *et al*., 2006). Thus, the maglev train is claimed to be a superfast train with a cheap travel cost. Referring to Figure 1.2, the diagram shows how the maglev train moves. As the direction of the current changes back and forth on the propulsion coils in the wall on the guide way, the north and south poles reverse repeatedly. The alternating forces and attractions which produced between the coils and superconducting magnets on the train then propels the train. While in Figure 1.3, the diagram shows how the maglev train levitates. The electric current is induced in the coils along the guide way, as the train passes. The train is levitated by the attraction force, which pull up the magnet below the train body, as well as by repulsion, which pushes up the train (Kurokawa, 2014). Figure 1.4 is a prototype of a maglev train that was launched in southwest China's city of Chengdu, Sichuan, in January 2021. On the same day, 165 meter track was launched to test the train with 21 meter long locomotive was also seen floating along the track. The train's designer from Southwest Jiatong University said that the designed maglev train can runs up to 620 km/h. On the other hand, the first maglev train of that country was already put into operation in 2003 in Shanghai (Ho, 2021).

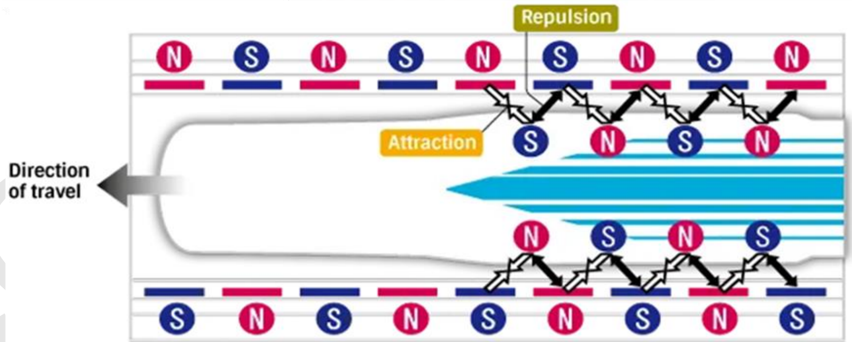

Figure 1.2: An illustration of how the maglev train moves (Kurokawa, 2014)

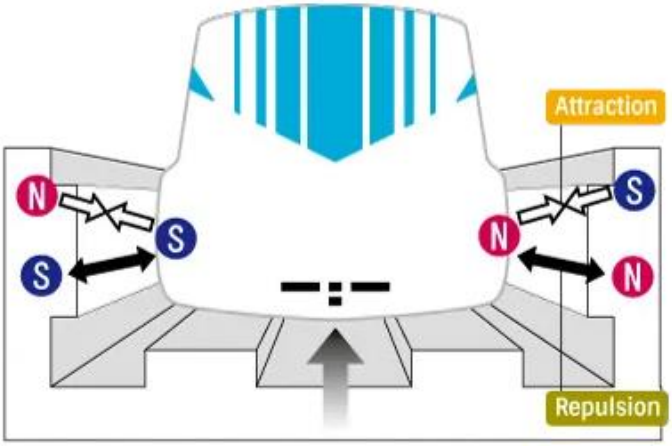

Figure 1.3: An illustration of how the maglev train levitates (Kurokawa, 2014)

Figure 1.4: A prototype of maglev train was launched in Changdu, China on 13 January 2021 (Ho, 2021)

1.4 Research Problem

High temperature superconductor (HTS) of Yttrium Barium Copper Oxide ($YBa_2Cu_3O_{7-\delta}$) together with Bismuth Ferrite ($BiFeO_3$) nanoparticle were synthesized by using the thermal treatment method. The limitations faced by the superconductor is that it is made from brittle materials consisted of non-connected grains. This impacts the flow of the supercurrent among the grains that leads to the limitation of current-carrying capacity or the critical current density, J_c (Lehndorff, 2001). The thermal treatment method has been chosen among other methods like solid state and co-precipitation method because it was found that the thermal treatment can produce more homogeneous and finer powders besides of its low cost, quicker and simpler steps preparation (Dihom *et a*l., 2017). Nanoparticles are good addition material as it will get easily dissolved through the high temperature processing thus helping to enhance the superconducting properties as it can act as strong pinning centers compared to micro-particles materials. Thus, the research was conducted to improve the properties of the superconductor without significantly decreasing the T_c.

1.5 Research Objective

The main objectives of this research are:

1. To synthesize $BiFeO_3$ nanoparticle by using thermal treatment method.
2. To synthesize the good quality of Y-123 bulk superconductor with $BiFeO_3$ nanoparticle additions via the thermal treatment method.
3. To study the effect of $BiFeO_3$ nanoparticle additions on $YBa_2Cu_3O_{7-\delta}$ bulk superconductors in term of its morphology and superconducting properties.

1.6 Thesis Overview

This thesis consists of five chapters. The first chapter explains the introductions of the superconductor. This chapter helps the readers understand more about the superconductor as the superconductor's history and applications are also provided in this section. The research objectives and problem statement are stated here too. Chapter 2 will be focusing on the literature review and briefly explains the theory of the superconductor. While in Chapter 3 the methodology of the work research will be explained one by one, starting with the synthesize of pure superconductor YBa2Cu3O7, $BiFeO_3$ nanoparticle, followed by the addition of these two materials. The explanations about the characterization instruments used also will be stated here in this chapter. The results from the research will be analyzed and discussed further in chapter 4. The last chapter which is Chapter 5 will conclude the results obtained from this research. The recommendation for future work will be given here as well for the purpose of a better study afterwards.

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