View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Research Online

University of Wollongong

Research Online

University of Wollongong Thesis Collection 1954-2016

University of Wollongong Thesis Collections

2010

Multilayering approach to enhance current carrying capability of YBa2Cu3O7 films

Serhiy V. Pysarenko
University of Wollongong, serhiy@uow.edu.au

Follow this and additional works at: https://ro.uow.edu.au/theses

University of Wollongong

Copyright Warning

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site.

You are reminded of the following: This work is copyright. Apart from any use permitted under the Copyright Act 1968, no part of this work may be reproduced by any process, nor may any other exclusive right be exercised, without the permission of the author. Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Unless otherwise indicated, the views expressed in this thesis are those of the author and do not necessarily represent the views of the University of Wollongong.

Recommended Citation

Pysarenko, Serhiy V., Multilayering approach to enhance current carrying capability of YBa2Cu3O7 films, Doctor of Philosophy thesis, Institute for Superconducting and Electronic Materials - Faculty of Engineering, University of Wollongong, 2010. https://ro.uow.edu.au/theses/3150

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

NOTE

This online version of the thesis may have different page formatting and pagination from the paper copy held in the University of Wollongong Library.

UNIVERSITY OF WOLLONGONG

COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Multilayering approach to enhance current carrying capability of $YBa_2Cu_3O_7$ films

A thesis submitted in fulfilment of the requirements for the award of
the degree of
Doctor of Philosophy of
UNIVERSITY OF WOLLONGONG
by

Serhiy Pysarenko

Faculty of Engineering
Institute for Superconducting and Electronic Materials

January 2010

Declaration

I, Serhiy Pysarenko, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Faculty of Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Serhiy Pysarenko
Wollongong
January 2010

Acknowledgements

I would like to thank my supervisors, Professor Shi Xue Dou and Associate Professor Alexey Pan for opening to me the possibility to do this work in their institute and for their financial and academic support as well as for the numerous fruitful discussions I had with them during the course of my PhD.

I also would like to thank Ron Kinnell and all technical staff of the Faculty of Engineering for their technical support and their invaluable work in manufacturing and repairing parts for the PLD system as was required on many occasions during this work.

Special thanks also go to Doctor David Wexler and Greg Tillman for their time and efforts spent in train me in the use of XRD, TEM and AFM, respectively.

I would like to express my gratitude to Doctor Germanas Peleckis and Doctor Ivan Nevirkovets for dedicating their time and participating in fruitful discussions of various aspects of Chapters 3, 5, 6, 7.

I also wish to acknowledge the help I received from the ISEM academic staff members and PhD students, especially Doctor Joseph Horvat, for their helpful explanations about how to use of some equipment and Doctor Tania Silver for correcting some parts of my thesis.

Finally I would like to thank my family members here in Australia as well as in Ukraine and on the other side of the world; they have constantly been encouraging me to complete the work; and it would have been really difficult to finish this work without their support.

Abstract

High temperature superconducting (HTS) thin films deposited onto metallic substrates are known as coated conductors (CC) and are currently the most promising HTS candidates for wide-scale industrial applications. These films are fabricated from $ReBa_2Cu_3O_7$ (where Re is a rare earth element) ceramics and have very specific requirements with regard to their manufacturing and maintenance, due to their complex stoichiometry and large anisotropy. One of the most important problems studied by many researchers around the world is the improvement of critical current capability in such superconducting films. Structures consisting, for example, of both $YBa_2Cu_3O_7$ (YBCO) layers and layers of different superconductive or non-superconductive materials having a similar crystal structure are likely to have enhanced microstructural properties, and they are able to carry larger critical currents as compared to their monolayer counterparts. Such sandwich-like films are called multilayer structures.

Usually, in order to increase the amount of electrical current being transported through a coated conductor, one needs to make necessary adjustments to the superconducting layer. An "obvious" way to enhance transport electrical current is to increase the thickness of the superconducting film. However, this approach has one very significant flaw: the fact that critical current density degrades with increasing thickness of the film. This phenomenon is widely observed in coated conductors, which are already used for transmission of electricity in electric motors and high-field magnets around the globe.

The present work involves fundamental studies of the fabrication of multilayered

structures on single crystal and metallic substrates with the emphasis on improvement of the critical current density and understanding the mechanisms responsible for the behaviour of the critical current in such superconducting multilayer thin films. Enhancement of the critical current density has been achieved, reaching 3.4 MAcm^{-2} at 77 K in $YBa_2Cu_3O_7/NdBa_2Cu_3O_7$ based multilayers about 1 μm thick. This critical current density is higher than that for the best quality and optimal thickness $YBa_2Cu_3O_7$ monolayer films.

Investigation of the crystal structure and electromagnetic properties of mono- and sandwich-like structures has been performed to clarify the origin of the critical current enhancement in the multilayer structures. It was found that, from the structural point of view, the multilayer films have much better microstructure and surface quality (i.e. the smoothness of the surface) than is the case for monolayer films. This is due to the increased filling factor in the multilayered structures, because the holes which are usually observed in the film, have been successfully eliminated. With one of the critical problems being solved, which is degradation of critical current due to thickness of the superconducting film, multilayer structures offer great potential to be utilized not only for electrical power transmission, but also, for example, in fabrication of superconducting electronic components, such as magnetic detectors, superconducting quantum interference devices, etc.

Enhancement of the critical current capability of multilayer structures was investigated using a newly developed theoretical model. Mathematical modelling of critical current behaviour in thin superconducting films is one of the most complicated tasks of modern solid state physics. Theoretical investigation of multilayering is crucial for understanding the superconductivity and for further improvement of the superconducting properties of such structures. The qualitative analysis of electric current properties in superconductors can uncover the nature of the coexistence and interaction of two states: the solid state and the field state of the matter. The existing theory of vortex lattice behaviour in superconducting thin films in the field state of matter is an intriguing part of the research, as parameters controlling such a lattice are controllable. By changing these parameters, a variety of structural defects and crystal characteristics on macroscopic and microscopic scales can be investigated.

One of the major objectives of this PhD project was to develop a theoretical model that would allow modelling of critical current behaviour in superconducting films. The constraints and applicability of the model are discussed in accordance with experimental data and fitting procedures. Calculation results, obtained within reasonable approximations, can well describe various properties of the crystal structures of monolayer and multilayer thin films. An automated computer program was successfully designed on the basis of the statistical theory for the quantification of the crystal structure parameters in superconducting thin films. Observed data showed that multilayering is crucial to enhance the quality of the upper layers of the films and to increase the amount of dislocations that act as effective pinning centres, resulting in improved critical current carrying capability.

During this work, a few additional related research problems have been addressed. An emphasis was put onto development of the pulsed laser deposition method (to prepare thin film samples of the highest quality) and investigation of the effect of Ag doping, which has a positive influence on the critical current carrying capability of YBCO superconducting films.

Fabrication of high quality YBCO thin films implies usage of very reactive oxygen atmosphere and high temperature. These peculiarities make the process very sensitive to a number of various deposition parameters. Optimal deposition conditions were verified and, as a consequence, a new heater was designed and fabricated. As a result of this work, the amount of time required to be spent on optimization of deposition conditions has been considerably reduced. This, in fact, significantly increased the productivity of the pulsed laser deposition system. A comprehensive study of one deposition parameter, the target to substrate distance was performed. The obtained results showed that the target to substrate distance plays a crucial role in pulsed laser deposition of monolayer and multilayer structures.

Special efforts were also dedicated to the investigation of Ag doping of the YBCO

superconducting thin films. It was found that doping strongly improves critical current at low applied magnetic fields. Research was directed towards uncovering the nature of advanced critical current carrying capabilities in Ag doped films. Microstructural analysis revealed that Ag doping leads to the enhancement of transparency for electrical current flow in the films. This is achieved in the process of deposition of the $YBa_2Cu_3O_7$ films, in which silver particles transfer extra energy to the $YBa_2Cu_3O_7$ ablated adatoms, thus ordering the microstructure during growth of the film. Moreover, the amount of silver which remains in the intergrain boundaries increases the transparency of films to the supercurrent flow and presumably plays a role as a barrier against oxygen depletion.

Contents

Declaration i

Acknowledgements ii

Abstract v

List of figures xii

List of tables xx

1 Introduction to superconductivity and literature review 1

1.1 Historical overview of superconductivity 1

1.2 Two types of superconductivity 4

1.3 Critical current and Bean's critical state model 8

1.4 Structural and physical parameters of YBCO 10

1.5 Properties of YBCO thin films 12

1.6 Applications of superconductors 20

1.7 HTSC for Coated Conductors (CC) 23

2 Characterization methods and techniques 29

2.1 Characterization of the thin film microstructure 29

2.1.1 X-ray diffraction analysis 29

2.1.2 Atomic force microscopy (AFM) 31

2.1.3 Optical microscopy 33

2.1.4 Scanning Electron Microscopy (SEM) 34

2.1.5 Transmission electron microscopy (TEM) 36

2.1.6 Profilometry 38

2.2 Electromagnetic characterization 39
2.2.1 Magnetic measurements of critical current densities 39
2.2.2 Magnetic measurements of critical temperatures 44
2.2.3 Magneto optic imaging (MOI) 45

3 Development and optimization of the pulsed laser deposition process 49

3.1 Thin film growth technique 49
3.1.1 Introduction to the growth of YBCO thin films 49
3.1.2 Pulsed Laser Deposition (PLD) technique 52
3.1.3 PLD system setup in the Institute for Superconducting and Electronic Materials 54
3.1.4 Deposition procedure 56
3.1.5 Development of PLD system in ISEM 59
3.1.6 Study of “optimal” deposition conditions 63
3.2 Study of target-to-substrate distance parameter. 70
3.3 Conclusion 79

4 Critical current and pinning mechanisms in single-crystalline epitaxially-grown YBCO thin films 81

4.1 Outline 81
4.2 Introduction 81
4.3 Strong pinning considerations in YBCO films 88
4.4 J_c behaviour at different applied magnetic fields 90
4.5 Model of critical current vs. applied magnetic field 93
4.6 Development of the model of the critical current vs. applied magnetic field dependence 104
4.7 Results and discussion 110
4.8 Conclusion 116

5 Multilayer technique as an effective method to enlarge the critical current in YBCO films 119
5.1 Outline 119
5.2 Introduction and literature review 120
5.3 Investigation of thin film current carrying capability as a function of film thickness 124
5.4 YBCO/NdBCO multilayers 131
  5.4.1 Structural characterization of multilayer films 132
  5.4.2 Electromagnetic properties of multilayer films 136
  5.4.3 Multilayer YBCO/YBCO films 139
5.5 Conclusion 143

6 Multilayering for Coated Conductors 145
6.1 Outline 145
6.2 Introduction 145
6.3 Optimization of Deposition Parameters 149
6.4 Results and discussion 153
  6.4.1 Structural characterization of ISD-MgO templates 153
  6.4.2 Structural and electromagnetic characterization of CC 155
6.5 Conclusion 165

7 Silver doping of YBCO films 167
7.1 Outline 167
7.2 Introduction and literature review 167
7.3 Sample preparation technique 169
7.4 Structural characterization of doped and undoped films 170
7.5 Electromagnetic properties of Ag doped and undoped films 174
7.6 Conclusion 180

8 Conclusions 183

References 211

Publications 211

A Appendix A 213

List of Figures

1.1 Phase diagram of Type-I (a) and Type-II (b) superconductors. 5

1.2 Magnetic flux penetration and current distribution in Type - II superconductor in according to the Bean critical state model. 9

1.3 Crystallographic structure of YBCO 11

1.4 Schematic representation of YBCO quasi crystal 13

1.5 Grain boundary created by rotation around an axis in the plane of the grain boundary. 14

1.6 Schematic view of various defects in thin films that can act as effective flux pinning sites [53]. 16

1.7 Schematic view of grain variety in YBCO film (quasi crystal). Misoriented grains form the network of ab-plane (also called in-plane) grain boundaries. 17

1.8 Schematic representation of Coated Conductor. 27

2.1 Schematic layout of the Bragg-Brentano geometry. 29

2.2 Schematic layout of the atomic force microscope 31

2.3 Schematic layout of the optical microscope 34

2.4 Schematic view of the scanning electron microscope. 35

2.5 Schematic view of the transmission electron microscope. 37

2.6 Schematic view of the stylus profilometer. 38

2.7 Schematic view of the MPMS 40

2.8 Magnetic moment as a function of the external applied magnetic field for the determination of critical current density $J_c(B_a)$. 41
2.9 Magnetic moment as a function of the temperature for the determination of critical temperature and transition width. 44
2.10 Schematic diagram of the Magneto Optic Imaging (MOI) principle used to obtain high quality MO images. 46

3.1 Schematic of the basic processes occurring in epitaxial growth. . . . 50
3.2 Ambient oxygen pressure v.s. temperature phase diagram for YBCO according to Bormann and Nolting [115]. 52
3.3 Schematic view of the PLD system installed in the ISEM. 55
3.4 Schematic view of the deposition setup. During the deposition process this configuration makes it possible to switch targets without stopping the laser shoot. 58
3.5 The construction of the heater parts. 61
3.6 The positioning of the thermocouple on the surface of the removable plate. 62
3.7 Schematic presentation of the concepts of reproducible thin film deposition. 64
3.8 Normalized dependence of the magnetization on the oxygen pressure during deposition of the YBCO film. 68
3.9 Normalized magnetization versus deposition temperature of the YBCO film. 69
3.10 Dependence of the normalized magnetization on the substrate material. 70
3.11 Schematic representation of the arrangement of the target, substrate and ablated plume. 72
3.12 Normalized magnetization curves as a function of temperature for the YBCO films with 300 nm thickness deposited at different D_{TS}. 73

3.13 SEM images (a), (b), (c) of the surface morphology for YBCO films deposited at D_{TS}=37 mm, 41 mm, and 46 mm; the film thickness is 450 nm in each case. 74

3.14 SEM images of the surface morphology for YBCO films deposited at D_{TS}=37 mm (a) and 46 mm (b) with thickness of 1.6 μm and 1.3 μm respectively. 75

3.15 Critical current density (J_c) as a function of the applied magnetic field (B_a) for YBCO films with thickness of 300 nm. 76

3.16 TEM images of the inner structure of films deposited at D_{TS}=37 mm(a) and 46 mm(b), respectively. 77

4.1 FESEM images (a) and (b) of the surface morphology for YBCO films taken at high resolution. A few grain boundaries within trenches are marked by white lines in the image at higher magnification (a). . . . 88

4.2 Schematic view of low-angle grain boundaries (a) and vortices pinned along them (b). 89

4.3 STM image of YBCO film surface deposited on CeO_2/Al_2O_3 substrate [206]. 90

4.4 Typical experimental $J_c(T, B_a)$ curves (b) and the rate of $J_c(T)$ degradation as a function of temperature encoded in parameter s: $J_c = J_{co}(0)(1 - T/T_c)^s$. Four different vortex modes are observed. 92

4.5 Out-of-plane edge dislocations in a LAB. Supercurrent **J** is flowing across the boundary and Abrikosov vortices are pinned at dislocations. 94

4.6 Schematic illustration of the theoretical model of J_c behaviour on applied magnetic field in accordance with Ref. [205]. Free energy loss due to the elastic distortion of the VLL in the presence of linear defects as compared with the energy gain due to vortex pinning. 96

4.7 Calculated of dependencies $J_c(B_a, \tau)/J_c(0, \tau)$ on the dimensionless parameter $b = (\nu/(2\mu\delta_c))^2$ at different ν values according to the Equation 4.16. 99

4.8 Probability function of grain sizes according to Equation 4.13. 100

4.9 Typical normalized critical current dependencies versus parameter b for different space-filling domain shapes: squares, rectangles and hexagons. 101

4.10 Typical normalized experimental critical current data versus magnetic field: (a) presents $J_c(B_a)$ curves normalized to $J_c(10K)$ on the vertical axis at different temperatures: 20 K, 30 K, 40 K, and 60 K, respectively; (b) presents $J_c(B_a)$ curves normalized to $J_c(10K)$ on the horizontal axis at different temperatures: 20 K, 30 K, and 40 K, respectively. The regions indicated by letters in (b) are the vortex pinning regimes: single vortex (A), small vortex bundle (B), large vortex bundle (C), and vortex creep (D). 102

4.11 (a) Normalized experimental data of critical current dependencies versus magnetic field fitted by old model of equation 4.16. (b) and (c) show the discrepancy between experimental and modelled data in low and high magnetic field regions, respectively. 103

4.12 (a) Original model [205] pinning potential. (b) Modified, pinning potential (see Equation 4.17). 105

4.13 The approximation which was derived to simplify expression 4.17 in the in-plane projection. 106

4.14 Normalized experimental data of critical current dependencies versus magnetic field fitted by old model of Equation 4.16 and newly developed model of Equation 4.20. The inset shows an enlargement of the higher critical current region. 109

4.15 Normalized experimental data on critical current dependencies versus magnetic field fitted by Equation 4.20. 111

4.16 (a) Statistical domain size distribution. (b) Critical current densities fitted by Equation 4.20. 114

4.17 SEM micrographs of the surface morphology of MS deposited film (a), and PLD film (b). 115

5.1 SEM images of the surface morphology for YBCO films deposited at 2 Hz with the thicknesses: (a) 100 nm, (b) 345 nm, (c) 1820 nm, and at 6 Hz with thicknesses: (d) 50 nm, (e) 480 nm, (f) 1000 nm. 125
5.2 $J_c(d)$ dependencies at different fields and temperatures for YBCO films deposited at 2 Hz. 126
5.3 $J_c(d)$ dependencies at different fields and temperatures for YBCO films deposited at 6 Hz. 127
5.4 $J_c(T, B_a)$ dependencies for two samples deposited at 2 Hz and 6 Hz. . 128
5.5 $J_c(T, B_a)$ dependencies for two samples deposited at 2 Hz and 6 Hz. . 129
5.6 Normalized experimental data on critical current versus magnetic field for F(1000) and F(300) samples, fitted by equation 4.20. The inset contains the domain size distribution functions. 130
5.7 Schematic view of the multilayer sandwich-type YBCO/NdBCO film structure. 132
5.8 SEM micrographs of the surface morphology of multilayer YBCO/NdBCO film (a,b) and an YBCO monolayer film (c,d). 133
5.9 TEM images of the YBCO/NdBCO film multilayer: (a) extra amount of defects produced by the interfaces. Circled areas have denser defect structure, (b) and (c) formation of dislocations can be interrupted or initiated by the interfaces as well. 134
5.10 XRD $\theta - 2\theta$ scan data for the monolayer and multilayer films. 135
5.11 Critical current density as a function of applied magnetic field in double-logarithmic scales at 77 K. YBCO monolayer films with different thicknesses and two YBCO/NdBCO multilayers are shown for comparison. 136
5.12 Critical current density as a function of applied magnetic field in double-logarithmic scales at 10 K and 40 K. YBCO monolayer films with different thicknesses and two YBCO/NdBCO multilayers grown at different temperatures are shown for comparison. 137

5.13 Critical current density as a function of applied magnetic field in semi-logarithmic scales with simulated curves (red colour). Inset demonstrates sufficient domain size distribution functions. 138

5.14 Critical current density as a function of applied magnetic field in semi-logarithmic scales for YBCO/NdBCO multilayer films deposited at temperatures of 780°C and 800°C. 140

5.15 Schematic view of the multilayer YBCO/YBCO film structure. 141

5.16 SEM images of YBCO/YBCO multilayer (a) and YBCO/NdBCO multilayer (b) films deposited at D_{TS}=41 mm. 141

5.17 Critical current density as a function of applied magnetic field in semi-logarithmic scales for YBCO/YBCO multilayer, YBCO/NdBCO multilayer, and YBCO monolayer films. 142

6.1 Schematic view of the coated conductor configuration mastered within this work. 146

6.2 Comparison of transition curves of two samples deposited at different post-annealing conditions. 150

6.3 Comparison of transition curves obtained from AC magnetic susceptibility from PPMS measurements of two samples deposited under the same deposition conditions but on different substrate material. 151

6.4 Comparison of transition curves of two samples deposited under the "optimal" deposition conditions on different buffer layers. 152

6.5 Optical images of the ISD metallic surface before deposition at lower (a) and higher (b) magnification. 154

6.6 3D surface obtained using AFM: (a) surface scan obtained from 5 μm × 5 μm spot of single crystal $SrTiO_3$ substrate; (b) surface scan of 5 μm × 5 μm area of metallic substrate (ISD-MgO template). 155

6.7 SEM scan showing slightly tilted view of the metallic Hastelloy C276 substrate with ISD-MgO deposited buffer layer (see text for more details).156

6.8 XRD scan results for two YBCO films of the same thickness, deposited on different substrates: $SrTiO_3$ and Hastelloy/ISD/CeO_2. 157

6.9 SEM images of the surface of the 0.5 μm thick (a,b), 1.7 μm thick (c,d), and 3.7 μm thick (e,f) YBCO films, respectively. Cracks appeared as a result of manipulation related to taking the images. Circled areas show holes in the structure. 158

6.10 Critical current density as a function of the thickness of YBCO films. 159

6.11 SEM images of the cross-section of two films deposited on the STO/ISD-MgO template: (a) monolayer film with the a thickness of about 3.7 μm, and (b) multilayer film with a thickness of about 3.5 μm. . . 160

6.12 Magneto-optical images of flux behaviour in 0.5 μm thick monolayer YBCO film deposited on ISD-Mg metallic template. (See detailed description in the text) 161

6.13 Typical data of the normalized experimental critical current versus magnetic field. 163

7.1 XRD pattern of 2% Ag doped and undoped YBCO films. Two insets of Figure 7.1 visualise the two peaks (005) and (007). 171

7.2 SEM images of undoped (a) and 2% Ag doped(b) YBCO thin films. . 172

7.3 TEM images of 2% Ag doped (a,b) and of undoped (c) YBCO thin films. The circles enclose precipitates and second phases. 173

7.4 Normalized magnetization versus temperature dependencies for doped and undoped YBCO films. 175

7.5 Critical current density of doped and undoped YBCO thin films as a function of applied magnetic field at 10 K and 77 K. 175

7.6 Critical current density as a function of the YBCO film thickness. Asterisks mark the 2% Ag-doped film. 177

7.7 Normalized critical current density for pure and Ag-doped YBCO film. 177

7.8 DC normalized magnetization versus temperature and differential of this function is presented for Ag-doped YBCO film. 179

7.9 DC normalized magnetization versus temperature and differential of this function for pure YBCO film. 180

List of Tables

3.1 Deposition parameters which are constant during target-to-substrate distance study. The thickness of the films investigated varied from 0.3 μm to 1.6 μm. 72

5.1 Structural parameters which were obtained during model fitting procedure. 139

6.1 Optimal deposition parameters which were used for multilayering CC study. 152

6.2 XRD FWHM values of the (005) peak, critical temperatures, and J_c values measured at 77 K in self field for YBCO films deposited under optimal conditions. 155

7.1 Optimal deposition parameters which were used for silver doping study. 170