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Gianluca Ghigo · Daniele Torsello

Microwave Analysis of Unconventional Superconductors with Coplanar-Resonator Techniques

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Preface

Since the discovery of superconductivity more than a century ago—a milestone in condensed matter physics—a large variety of superconducting materials have been studied. Besides conventional superconductors, materials well described by the Bardeen–Cooper–Schrieffer (BCS) theory, the so-called unconventional superconductors, came into play starting from the 80s. These are materials characterized by at least one feature among multiband superconductivity, triplet spin state and non-phononic coupling. If the coupling mechanism is non-phononic, Cooper pairs are bound together by the exchange of a different boson with respect to phonons (as for the BCS model). A typical example is spin fluctuations in superconductors contiguous to a magnetic phase or even with a coexisting magnetic order. The category of unconventional superconductors includes a number of compounds, such as the cuprates, magnesium diboride and the recently discovered iron-based superconductors, that raised great interest for both their peculiar fundamental properties and their potential for practical applications. All experimental methods meeting the need for a complete characterization of such materials are useful to reach new insights and a comprehensive understanding of their properties. Within this context, microwave methods, and in particular resonant techniques, were revealed to be particularly valuable and provided the motivation for this work.

The idea to write this book stems from the research work of Dr. D. Torsello within his Ph.D. in Physics, started in 2017 at the Politecnico di Torino under the supervision of Prof. G. Ghigo. The Ph.D. project focused on the influence of disorder on the fundamental properties of Iron-Based Superconductors (IBS), investigated by means of a microwave Coplanar-Waveguide Resonator (CPWR) technique. Indeed, CPWR techniques have been used in our research group at Politecnico since the early 2000s, to study also other classes of superconductors, i.e. cuprates and magnesium diboride (MgB_2). Thus, we decided to extend the subject of this book to cover the whole research activity on the study of unconventional superconductors by CPWR methods. Not only do the experimental microwave techniques underlie all these studies, but also some common physical aspects lead to similar modeling approaches, e.g. both MgB_2 and IBS are multiband superconductors.

The book is structured starting with a brief state of the art of methods and approaches to the microwave characterization of superconductors, with a short review of techniques. Then, a detailed description of the adopted CPWR microwave methods is given. Basically, the approach to study superconducting thin films is to pattern them in the shape of coplanar resonators and to analyze their behavior as a function of temperature, rf (radiofrequency) and dc field. To analyze single crystals, instead, we adopted a perturbative approach, measuring the modifications of the transmission parameters of a coplanar resonator to which the crystal under study is coupled. In a second part, several cases of study are described, which comprehensively cover a large spectrum of materials and issues. Particular emphasis is given to hot topics about iron-based superconductors.

This work is intended for a broad audience, from Ph.D. students to senior scientists. The authors believe that the book will serve as a comprehensive guide, providing inspiring examples of the use of CPWR techniques to address key topics in the field of unconventional superconductivity.

The authors warmly acknowledge their colleagues from Politecnico di Torino, Profs. Roberto Gerbaldo, Laura Gozzelino, Francesco Laviano and Giovanni Alberto Ummarino, for providing them with support in the research work over the years and with useful comments to write the book. The authors also acknowledge researchers providing them with high-quality samples of the most interesting and recently discovered materials, namely Prof. T. Tamegai and his group at the University of Tokyo, Japan; Prof. P. Canfield and his group at the Iowa State University, USA; and Dr. E. Monticone and his group at INRIM, Italy. The results presented here were achieved also through other precious collaborations, with R. Prozorov, M.A. Tanatar, V.S. Stolyarov, D. Roditchev, the INFN-LNL staff, to name a few.

Turin, Italy
September 2021

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Daniele Torsello

Contents

Acronyms and Symbols

ARPES	Angle Resolved Photoemission Spectroscopy
BCS	Bardeen–Cooper–Schrieffer
CPW	CoPlanar Waveguide
CPWR	CoPlanar Waveguide Resonator
dpa	Displacements per atom
e	Elementary charge
ε	Complex permittivity
f_0	Resonance frequency
ϕ_0	Magnetic flux quantum
Φ	Ion-irradiation fluence
GB	Grain Boundary
GBN	Grain Boundary Network
Γ_f, Γ_Q	Geometrical factors
Γ_{ij}	Interband scattering rate
H_{c1}	Lower critical magnetic field
H_{c2}	Upper critical magnetic field
H_{rf}	rf magnetic field
HTS	High critical Temperature Superconductors
IBS	Iron-Based Superconductor
I_{rf}	rf current
j	Imaginary unit $\sqrt{-1}$
j_c	Critical current density
j_{dp}	Depairing current density
j_{rf}	rf current density
LAO	$LaAlO_3$
λ_L, λ	London penetration depth
MOI	Magneto-Optical Imaging
μ	Complex magnetic permeability
NFMM	Near-Field Microwave Microscope
NMR	Nuclear Magnetic Resonance
QCP	Quantum Critical Point

Q_L	Loaded quality factor
Q_0	Unloaded quality factor
rf	Radio Frequency
R_s	Surface resistance
S_{ij}	S-parameter matrix
σ	Complex conductivity
T_c, T_{sc}	Superconducting critical temperature
τ	Quasiparticle scattering time
VNA	Vector Network Analyzer
WL	Weak Link
X_s	Surface reactance
YBCO	$YBa_2Cu_3O_{7-x}$
Z_s	Surface impedance