Preface

Starting with the success in liquefying He and the surprising discovery of the superconductivity of Hg by the group in Leiden led by H. Kammerling-Onnes, the last century provided us with the conceptual framework to understand and handle macroscopic quantum coherence: “superconductivity” in the case of existence of charge carriers, or “superfluidity” in the absence of charge carriers. No less than nine Nobel Prizes have been awarded for breakthrough discoveries and theories relating to superconductivity and superfluidity, from Kammerling-Onnes’s initial 1913 prize, to the 2016 prize awarded to Thouless, Haldane and Kosterlitz for their theoretical discoveries of topological phases of matter and topological phase transitions, including topologically driven superconductivity.

Superconductivity is now an established (although, in some cases, not yet fully understood) form of macroscopic quantum coherence that regularly impacts the scientific community with new surprises, such as the discovery of high-temperature superconductivity in cuprates (Bednorz and Müller, IBM Zürich, Nobel Prize in 1987) followed rapidly by the discovery of superconductivity above the boiling point of nitrogen in $YBa_2Cu_3O_{7-x}$ by the Houston group of P. Chu; the discovery of superconductivity at 40 K in MgB_2; and later on, superconductivity in chalcogenides and pnictides, the last examples also being multi-component (multi-gap) superconductors. Superconductivity is a solid-state phenomenon that possesses the advantages that made electronic and semiconductor technology so successful: scalability and large-scale production. At the same time, radically different functionalities emerge due to macroscopic quantum coherence, from large-scale, energy-efficient applications due to electric current transportation without losses, to quantum computing and rapid single flux quantum electronics.

In this context, magnetic flux quanta in superconductors, also named “vortices” due to the circulating supercurrent supporting them, play crucial roles in both cases: (i) in superconducting electronics, they are the “carriers” of information instead of electrons; and (ii) in large-scale power applications, their mobility due to the Lorentz force leads to unwanted energy dissipation. So, for significant market penetration of such large-scale applications of superconductors, “pinning” of vortices by nanoscale engineered defects is crucial.

This book provides expert coverage of some modern and novel aspects of the study of vortex matter, dynamics, and pinning in nanostructured and multi-component superconductors. Vortex matter in superconducting materials is a field of enormous beauty and intellectual challenge, which began with the theoretical prediction of vortices by A. Abrikosov (Nobel Laureate for Physics in 2003, sadly deceased on March 23, 2017, age 88). Vortices, vortex dynamics, and pinning are key features in many of today's human endeavors: from the huge superconducting accelerating magnets and detectors at the Large Hadron Collider at CERN Geneva, which opened new windows of knowledge on the universe, to the Tokamak fusion magnets that will be utilized at the International Thermonuclear Energy Reactor in Cadarache, to the tiny superconducting transceivers using rapid single flux quanta, which have opened a revolutionary means of communication.

In this book, leading researchers survey the most exciting and important recent developments. The book offers something for almost everybody interested in the field: experimental techniques to visualize vortices and study their dynamics, nanotechnologies for improving current-carrying capabilities in high applied magnetic fields, current anisotropy, second magnetization peak, and intuitive and theoretical aspects concerning the novelty and beauty of multi-component superconductivity.

Chapter 1 presents unpublished data regarding the detailed evolution of a vortex approaching pinning centers. Using scanning Hall probe microscopy, the authors have directly visualized, at a microscopic level, the interaction of a single quantum vortex with pinning centers. When few adjacent pinning centers are present, the vortex can be trapped by one of them, while the interaction of the vortex with the adjacent pinning centers can be tuned by varying superconducting characteristic lengths with temperature. It was found that when the vortex size is comparable to the distance between two pinning centers, the vortex deforms along the line connecting the pinning centers and the magnetic flux spreads by embracing both pinning centers, thus generating a magnetic dipole. In contrast, a vortex located on an isolated pinning center preserves its round shape up to temperatures close to the critical temperature. The experimental data are in a good agreement with theoretical simulations based on the time-dependent Ginzburg–Landau approach.

Thirty years after the discovery of high critical temperature superconductors, the large-scale application of second-generation superconducting coated conductors based on rare-earth cuprates ($RE\mathrm{Ba_2Cu_3O_{7-x}}$) is still waiting for a lower price in terms of $/kA m. This can be achieved by increasing the critical current. For high-field applications, this is even more crucial because of very large Lorentz forces. Fortunately, nano-engineered artificial pinning centers can provide large pinning forces to counteract Lorentz forces. Chapter 2 is a comprehensive review of various materials and architectures used for nanostructured $RE\mathrm{Ba_2Cu_3O_{7-x}}$ films with artificial pinning centers (APCs). Several categories of APCs are described in terms of their dimensionality (nanorods, nanoparticles, nanolayers, segmented nanorods, and more), and experimental results are discussed under the framework of Ginzburg–Landau theory. Various results obtained by many groups worldwide are presented and analyzed, with emphasis on outstanding pinning performance in a wide range of temperatures (4.2–77 K) and magnetic fields (1–30 T).

Energy resources are now a major issue in the global economy. It is obvious that fossil fuels will not last forever. In addition, changes to the climate due to increasing CO_2 emissions are now obvious. Fortunately, we are witnessing the first, tentative steps toward a clean, sustainable "hydrogen economy," so in the not-so-distant future we would expect that liquid hydrogen with its boiling point of 20.3 K will be a common, abundant, and cheap liquid. In these circumstances, energy-efficient cryo-magnetic devices and equipment (transformers, magnets, motors, induction furnaces, superconducting-magnet energy storage, fault-current limiters, etc.) based on MgB_2 (a cheap and abundant superconductor with critical temperature of 40 K) cooled by liquid H will have a performance/price ratio much better than similar equipment based on copper wires, will require much less energy to operate, and will be more environmentally friendly. Tuning electronic structure and nanostructure is the critical issue for engineering an MgB_2 superconductor toward applications. In Chap. 3, a variety of chemical and microstructural control techniques that have been developed to artificially enhance flux pinning strength in the material are presented. The influence of chemical additives and oxygen doping on the formation of nanoprecipitates and superconducting properties, carbon doping effects, and methods of introducing carbon using different sources and microstructural control via ball-milling and mechanical alloying techniques are reviewed and summarized.

As shown in Chaps. 2 and 3, with creative materials nano-engineering, researchers have been successful in improving critical currents over the field and temperature ranges relevant to applications. Intrinsic thermodynamic properties and the interaction between the magnetic vortices and the pinning landscape combine to determine how much current is supported. Due to both factors, the resultant critical currents generally vary with the angle of the imposed external field. Chapter 4 explores what is known about this current anisotropy, very important in superconducting devices in which various parts are exposed to magnetic fields of various orientations. The difficulty of this problem stems partially from having two sources of anisotropy: the anisotropy in the vortex cross section, arising from the intrinsic mass anisotropy of the carriers of the vortex current; and the anisotropy of the pinning centers themselves. The effects of these two factors are not easily separated. It is never possible to have a fully isotropic pinning landscape in an anisotropic superconductor. If the critical current (I_c) varies strongly with angle, this presents challenges for coil designers who must keep the coil within safe operating margins of I/I_c everywhere within the coil. An unpredictable or only weakly predictable I_c with field, field orientation, and temperature means exploiting the full capacity of these materials is compromised. The chapter summarizes the common methods to analyze the critical current anisotropy. Firstly, there are scaling methods, such as the Blatter scaling and other scaling approaches which are a modification of this approach. Secondly, there are more direct methods of calculating the expected response from defects, which examine the pinning forces on vortices from defects under certain assumptions, and finally, the author presents the vortex path model or maximum entropy method, which is an information theory or statistical approach for extracting information from the field orientation dependence of critical current.

The strong nonlinear relation between the current density and the electric field, along with nonlocal interactions, determines the complex behavior of vortex matter, which also includes "catastrophic" phenomena like vortex avalanches. Chapter 5 presents a brief review of the experimental studies devoted to these unstable vortex patterns, starting from historical findings up to recent works, and focusing on the analysis of vortex avalanches by means of magneto-optical imaging (MOI). The MOI technique, based on either Kerr (in reflection) or Faraday (in transmission) effects, is a powerful tool for the visualization of magnetic field distribution and enables the observation of magnetic field distribution in real time, on the whole surface of the superconductor, with microscopic resolution. The dynamics and morphology of the vortex avalanches are reported in detail, along with theoretical efforts for understanding and modeling this complex phenomenon. It is shown that vortex avalanches are ubiquitously occurring in superconductors if certain conditions are satisfied; in particular, temperature, applied magnetic field, and applied field rate are of paramount importance for observing/avoiding these phenomena. Together with the interest in the fundamental behavior of vortex matter, the understanding of vortex avalanches is instrumental for assessing the limits of superconductor usage in power applications.

Chapter 6 is devoted to the change of magnetic hysteresis curves and of vortex dynamics in "self-nanostructured" $La_{2-x}Sr_xCuO_4$ single crystals (with charge and spin stripes), offering useful information about the nature of the second magnetization peak occurring for single crystal specimens with random pinning. By decreasing x, with the external magnetic field oriented perpendicular to the stripe plane, the second magnetization peak completely disappears in the doping domain of a well-developed static stripe structure ($x \sim 1/8$) and reappears for $x \leq 0.10$. This behavior follows the instability of the quasi-ordered vortex solid (the Bragg vortex glass, stable against dislocation formation) in the presence of static stripe order (as revealed using small-angle neutron scattering experiments), which is confirmed by the determined temperature variation of the normalized vortex-creep activation energy. The results support the scenario in which the second magnetization peak is generated by the pinning-induced disordering of the Bragg vortex glass in the dynamic conditions of magnetic measurements.

The last two chapters are devoted to multi-component superconductivity, which is a rather new and very "fashionable" quantum phenomenon in various superconducting materials: multi-band superconductors in which different superconducting gaps open in different Fermi surfaces, films engineered at the atomic scale to enter the quantum confined regime, multilayer, two-dimensional electron gases at oxide interfaces, and complex materials in which different electronic orbitals or different carriers participate in the formation of the superconducting condensate. The increased number of degrees of freedom of the multi-component superconducting wave function allows for quantum effects that are otherwise unattainable in single-component superconductors. Chapter 7 focuses on inter-band phase difference soliton, the fractionalization of the unit magnetic flux quantum, and frustration between quantum phases of multiple components. Taking into account the fluctuations in the inter-band phase difference provides a bridge between superconducting multiband condensates and other multicomponent macroscopic quantum systems such as Bose–Einstein condensates with multiple components and particle physics systems governed by a non-Abelian gauge field. Chapter 8 is theory-focused, investigating various excitation modes in multi-gap superconductors. In particular, the Nambu–Goldstone mode, Leggett mode, and Higgs mode are important and play a key role in multi-gap superconductors. The multiple-phase invariance in a multi-gap system is partially or totally spontaneously broken in a superconductor. The dispersion relation and the mass formulas of these modes are evaluated by using the functional integral method. The broken multiple-phase invariance leads to a new quantum phase such as time-reversal symmetry breaking, the emergence of massless modes, and fractionally quantized-flux vortices.

Finally, apart from the colleagues, friends, and collaborators who contributed to this book, I am grateful to my many friends from the Vortex community (VORTEX 10th Jubilee Conference is held in September 2017 in Rhodes together with the 65th anniversary of its initiator, Prof. V.V. Moshchalkov). The birth and title of this book are related to the International Conference on Superconductivity and Magnetism organized by Prof. Ali Gencer (Ankara University) every even year since 2008. Together with my friend, Prof. M. Milosevic (Antwerpen University), I chaired and co-organized a session entitled "Vortices and Nanostructured Superconductors," which provided excellent, world-class contributions and vivid discussions among the very best people in the field. And last, but not least, my special thanks to Sara Kate Heukerott from Springer who proposed this endeavor to me.

Financial support from the Romanian Ministry of Research and Innovation through POC (European Regional Development Fund, Operational Fund Competitiveness) Project P-37_697 number 28/01.09.2016 is gratefully acknowledged. Various funding agencies supporting the research activities which led to the results reported are mentioned in each chapter.

Bucharest, Magurele, Romania Adrian Crisan

Springer

http://www.springer.com/978-3-319-59353-1

Vortices and Nanostructured Superconductors
Crisan, A. (Ed.)
2017, XIV, 259 p. 121 illus., 63 illus. in color., Hardcover
ISBN: 978-3-319-59353-1