Vortices and non-equilibrium phenomena in superconductors

The selection of works included in this special issue "Vortices and non-equilibrium phenomena in superconductors" is immediately related to the research activity of Valerij Alexandrovich Shklovskij and reflects a "cross-section" of some of his research interests. V.A. Shklovskij, who celebrated his 80th anniversary on August 24, 2019, is a prominent scientist whose theoretical works in the field of electronic and magneto-transport properties of conducting and superconducting systems are very well known in the scientific community. Currently, V.A. Shklovskij is professor of the I.M. Lifshitz Department of Theoretical Physics in the School of Physics of the V.N. Karazin Kharkiv National University, where he keeps on conducting active research work.

V.A. Shklovskij graduated from the School of Physics of the Kharkiv State University (now V.N. Karazin Kharkiv National University (KhNU), Ukraine) in 1966. Working as a scientist in the Theoretical Department of the Kharkiv Institute of Physics and Technology (now National Science Center — Kharkiv Institute for Physics and Technology of the NAS of Ukraine), V.A. Shklovskij began his scientific activity under the supervision of prominent theorist A.M. Kosevich and defended his PhD thesis "Phase transformations in non-ideal crystals based on an Izing model" in 1972. Since then, as a recognition of his scientific maturity, V.A. Shklovskij was offered much room to work independently and, in 1989, defended his higher doctoral thesis "Non-isotermic macrokinetics of heterogenous phase transformations in condensed media".

The early research activity of V.A. Shklovskij was chiefly concerned with electronic and magneto-transport properties of normal metals and superconductors. Extensively interacting with the group of experimentalists headed by I.M. Dmitrenko at the Institute for Low Temperature Physics and Engineering (now B.I. Verkin Institute for Low Temperature Physics and Engineering of the NAS of Ukraine), V.A. Shklovskij was the first who elaborated the theory of hot electrons in superconducting films. This theory, in conjunction with the elucidation of the nature of the size effect in thermal resistivity of a metal-insulator boundary, has allowed for the first-time explanation of the critical current hysteresis in superconducting constrictions and for the prediction of a series of new effects in metallic films at low temperatures. Later on, most of these effects have been experimentally confirmed worldwide.

The interest in the dynamics of vortices governing the resistive response of superconductors motivated V.A. Shklovskij to further extend the theory of hot electrons for the strong-current-driven vortex state. This resulted in a substantial generalization of the theory of flux-flow instability originally elaborated by A.I. Larkin and Yu.N. Ovchinnikov and allowed him to explain a series of pioneering experiments in this topical area. Furthermore, a deep understanding of the involved physics has allowed V.A. Shklovskij to successfully solve an extensive range of problems in the non-linear anisotropic vortex dynamics in superconductors in the presence of periodic pinning landscapes and point disorder. Many of his theoretical predictions have been experimentally confirmed in a number of groups. Among these are the groups headed by M.A. Obolenskii in the Department of Low Temperature Physics (KhNU, Ukraine), H. Adrian (Johannes Gutenberg-Universität Mainz, Germany), and M. Huth (Goethe-Universität Frankfurt am Main).

V.A. Shklovskij is a broad-minded person whose high workability and healthy lifestyle are combined with a striking scientific longevity. The success of his 50-year research work should likely be attributed to a rare self-critically and a close interaction with experimentalists. V.A. Shklovskij has published more than 100 research articles and supervised several generations of researches, among which are D.T.B. Hop, V.V. Mezinova, A.P. Nazipova, J.T. Seo, A.A. Soroka, A.K. Soroka, V.V. Sosedkin, and the editors of this special issue.

This special issue contains 3 reviews and 14 research papers organized in three topical sections. Since the entire field cannot be covered in a single issue, either an original research paper with extended introduction or a review is placed at the beginning of each topical section.

The first section "Pinning and vortices in superconductors" is devoted to the magneto-transport properties of superconductors at moderately strong dc currents. C. Reichhardt and C.J.O. Reichhardt present on molecular dynamics simulations of vortices interacting with pinning arrays where a portion of the pinning sites have been removed in order to create coexisting regions of strong and weak pinning. The authors analyze the vortex guiding effect in channeled pinning arrays and build a dynamic diagram of the different vortex phases. Lara *et al.* and Smirnova *et al.* report simulations of the dynamics of the order parameter in nanostructured superconductors on the basis of the timedependent Ginzburg–Landau (TDGL) equation. Lara *et al.* consider the problem of discretization of the TDGL equations when passing from two to three dimensions and exemplify their simulation procedure by the evolution of tilted vortices in inclined magnetic fields and the *ratchet* (rectification) effects in superconducting stripes with notches along edges. Smirnova *et al.* evaluate quantitatively the effect of magnetic field renormalization in 3D superconducting nanostructures, revealing an about 10% increase of the average voltage in *C*-shaped structures with thicknesses equal to about a doubled penetration depth.

The papers by Aichner *et al.* and Kasatkin and Tsvetkovskii are concerned with the critical current in YBCO. Aichner *et al.* study the angular dependence of magnetic-field commensurability effects in YBCO thin films with artificial pinning sites produced by either the focused ion beam in a helium ion microscope or the wide-field helium ion beam of an ion implanter through a stencil mask. The authors conclude that both irradiation methods are suitable for the creation of well-defined tailored pinning landscapes, which are important for vortex manipulation in fast and low-dissipative fluxonic devices. Kasatkin and Tsvetkovskii study the dependence of the critical current density on the misorientation angle in YBCO bicrystals. Their theoretical results reveal a good agreement with experimental data on YBCO bicrystals with [001]-tilt low-angle grain boundaries.

The second section “Superconductors at microwave frequencies and flux flow instabilities” is devoted to high-frequency and non-equilibrium effects occurring at large biasing currents and microwave ac frequencies. The review by Pompeo *et al.* introduces a series of physical parameters which can be deduced from microwave surface impedance measurements in the vortex state, illustrating the main aspects of the involved physical models by sample measurements. The review by Malyshev *et al.* gives an overview of the microwave properties of surface electromagnetic wave resonators made from superconducting films and possible applications of such resonators. Melnyk *et al.* investigate the avalanche-like dc-bias-induced transition of microwave transmission lines to a strongly dissipative state and reveal a qualitative agreement of the experimental data with a phenomenological description of the avalanche effect relying upon the catastrophe theory. Pinheiro *et al.* visualize magnetic flux avalanches in Nb/NbN thin films by magneto-optical imaging, identify flux instability regimes and reveal a series of interesting features of the dendritic flux avalanches in this bi-layer system, including halo-like patterns and crossing avalanches.

The works of Vodolazov, Leo *et al.*, and Cirillo *et al.* are concerned with the flux-flow instability (FFI) occurring at high vortex velocities in superconductors. Vodolazov discusses two possible FFI mechanisms in terms of a spatially uniform instability (the Larkin–Ovchinnikov mechanism) without changes in the vortex lattice in comparison with the spatially non-uniform FFI occurring due to changes in the vortex lattice and leading to the formation of vortex rivers. Leo *et al.* study experimentally the pinning effects on FFI at lower temperatures and report on a perfect correspondence between the experiment and the phenomenological approach developed by Shklovskij for the hot-electron FFI. Cirillo *et al.* study the current-voltage characteristics of NbRe films in order to test their suitability for superconducting single-photon detectors, concluding that NbRe is a promising candidate material.

The third section “Vortices and quasiparticles interactions in superconducting systems and beyond” comprises a series of works concerned with various systems in which either vortex states occur or quasiparticles interactions are pivotal for the system response. The review by Bozhko *et al.* is devoted to the interaction between phonon and magnon subsystems in magnetic media, outlining some recent advances in the fields of spin-caloritronics and magnon spintronics. The review covers a wide range of phenomena ranging from the interaction of coherent magnons with surface acoustic waves to the formation of magnon supercurrents in thermal gradients. Ekino *et al.* study the current–voltage characteristics of tunnel break junctions made of BSCCO crystals. The authors theoretically calculate the tunnel current in the *ab* plane of the break junctions in the framework of the model of inhomogeneous *d*-wave superconductor partially gapped by charge density waves and qualitatively reproduce the behavior of experimental curves.

An overview of theoretical models for the description of relaxation processes in metals excited by short laser pulses is given by Kabanov. The author discusses the applicability of the widely used two-temperature model and the possibility to deduce the electron-phonon coupling constant from experiments. The work of Fil and Shevchenko is devoted to the vortex generation in a superfluid gas of dipolar chains in crossed electric and magnetic fields. The authors theoretically demonstrate that the density of vortices is proportional to the number of particles in the chain and argue that this can be used for monitoring the formation and destruction of chains in multilayer dipolar gases. The magnetic and transport properties of a superconducting closed loop with a thin film quantum interferometer are investigated by Bondarenko *et al*. The authors measure the loop current as a function of the transport current and external magnetic field applied to both, the loop and the interferometer, and discuss the differences between the observed dependences in comparison with those measured for loops where the interferometer is formed as a pressed point contact.

We cordially thank all the authors for their contributions to the issue!

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