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Foreword

Superconductivity and functional oxides

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Functional oxides exhibit a very wide set of physical phenomena across the whole spectrum of electrical, magnetic, and optical properties from insulating to superconducting, implying that this class of materials has enormous potential applications and could revolutionize electronics and energy devices and storage. On the other hand, thermodynamic and electronic-transport studies of correlated electron systems as manifested in cuprates, iron-based superconductors, and in doped topological insulators is a growing field of investigation. Moreover, there are a plenty of important open problems in the field of complex multi-orbital electronic systems with a strong interplay between charge, spin and orbital degrees of freedom, and geometric frustration.

The present Special Topics issue addresses and covers this range of subjects both from the phenomenological/experimental side and by means of microscopic theories. Within this frame, the present volume would like to testify the state of the art of the research in these fields of research, covering a brief overview of the materials relevant for the novel superconductivity and for technological applications, also including issues concerning functional oxides materials and theoretical models.
Nowadays, the theoretical prediction and experimental outcomes on the role played by spin-orbit coupling on superconductors as well as on topological insulators have enriched the scenario of phases of matter which can be obtained by suitably designing quantum materials.

In this framework, Autieri et al. [1] analyze the effect of the spin-orbit coupling on the electronic and symmetry properties of a recently discovered superconducting material, i.e. the CrAs. This compound exhibits superconductivity when an external pressure is applied. Interestingly, this is the first chromium-based superconductor. In this paper, considering both the Cr $3d$ and the As $4p$ origin for the spin-orbit coupling, the authors use a method that combining the tight-binding approximation and the Löwdin down-folding procedure, allows calculating and making predictions on the energy spectra. In this way, they find that the main effect of this interaction on the energy spectrum is the removal of the degeneration of the bands along the high symmetry line k_y of the orthorhombic Brillouin zone. They are able to estimate the splitting of the bands produced by this coupling, and also show that the Fermi surface sheets are reduced from four to three.

Furthermore, there has been a significant expansion towards topologically protected gapless phases, e.g. metals and semimetals, boosting the discovery of novel

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materials with non-trivial band crossing points in the momentum space as well as quantum materials that combine topological and conventional forms of ordering. In this respect, Forte et al. investigate two-dimensional trilayer quantum systems with multi-orbital conduction bands, by focusing on the role played by the layer degree of freedom in setting the character of nodal line semimetals [2]. They demonstrate that both the atomic spin-orbit coupling and the removal of local orbital degeneracy can lead to different types of electronic transitions with nodal lines that undergo a changeover from a loop structure enclosing the center of the Brillouin zone to pockets winding around multiple high symmetry points. Interestingly, they introduce a criterion to find the nodal lines transitions and establish the structure of the nodal loops and the resulting topological transitions.

It is widely accepted that the study of strongly correlated electronic systems is very relevant being one of the most intriguing open challenge in theoretical condensed matter physics. Indeed, strongly correlated materials exhibit a rich variety of unconventional features with very promising technological applications. Even though apparently simple, the t-J model seems able to address puzzling phenomena such as the Mott-Hubbard metal-insulator transition, exotic charge, spin and/or orbital ordering, non-Fermi-liquid normal phases as well as high-temperature superconductivity. However, the solution of this correlated model is a difficult task, so that may result very useful the application of new methods especially non-perturbative ones. To manage a consistent solution, in paper [3] it is reported a mean-field approximation obtained in the framework of the composite operator method, within the so-called one-pole approximation. The properties of the model have been investigated as a function of the filling and the temperature and compared with well-established numerical results in order to gauge the reliability of the approximated solution.

Nucara et al. [4] use grazing-angle infrared spectroscopy to detect the Berreman effect in the two-dimensional electron systems (2DES), spontaneously formed at the $LaAlO_3/SrTiO_3$ (LAO/STO) interface and at the surface of the topological insulator Bi_2Se_3. From the outcomes of the Berreman effect they study longitudinal optical excitations in ultrathin films in both systems and are able to deduce the thickness of the two-dimensional system, as function of the temperature, as well as the plasma frequency, the scattering rate, the density, and the mobility of the carriers.

Another interesting study of 2DES comes from Mauro et al. [5] who investigate the photoconductivity on the amorphous-$LaGaO_3$/STO system. The discovery of a two-dimensional electron gas (2DEG) with properties very similar to the prototypical LAO/STO system in interfaces with an amorphous rather than a crystalline overlayer was considered as a highly disconcerting result but is now generally accepted. Mauro et al. investigate the light response of this system in a wide temperature range and find a substantial modulation of the surface resistivity, exhibiting also a strong temperature dependence. Moreover, the transport properties manifest a characteristic response to light, well reproduced by a simple model, and a persistent photoconductivity effect. This experimental information can be precious for a deeper understanding of the metastable excited state forming in oxide 2DEGs under light.

Concerning the functional materials, the magneto-optical response exhibited by ferromagnetic Co-doped ZnO films upon hydrogen ions irradiation, is investigated by Varvaro et al. [6] who also addresses the role of hydrogen in the improvement of the magneto-optical properties. Likewise, they study the magnetic circular dichroism spectra of these H-irradiated ZnCoO films. The results suggest an intrinsic nature of the ferromagnetism in this class of materials as arising from the spin polarized carriers magnetically coupled to Co ions. Remarkably, they propose the use of magneto-optical thin film materials with high ratio of Faraday rotation per unit length to the optical loss per unit length, as a probe to pave the way for development of new integrated on-chip non-reciprocal photonic devices.

Superconductivity in boron-doped diamond has been widely studied in the last decade. To overcome the limit in boron concentration which can be chemically incorporated in the lattice, a pure charge doping by means of the electrochemical gating technique has been proposed. Romanin et al. [7] address this issue by studying the possible superconductive phase transition of the hydrogenated diamond [111] surface by means of ab initio density functional theory computations within the pseudo-potential plane-wave approximation. The superconducting critical temperature is then computed using McMillan's semi-empirical model starting from ab initio electron–phonon matrix elements. The results are compared with experimental measurements on slightly B-doped nanocrystalline diamond films under electrochemical gating.

Granular aluminum oxide (G-AlO_x), which consists in a three-dimensional network of nanosized Al grains having their surface covered by a thin aluminum oxide layer, has recently raised a lot of interest among functional materials. Indeed, its transport properties are quite different from aluminum and possibly relevant for applications in quantum circuits. However, several issues regarding its normal state transport properties are still open. Barone et al. [8] have performed detailed DC and noise transport measurements on thin films of G-AlO_x. The results evidence the presence of a Kondo-type resistivity increases at low temperatures, where specific excess 1/f noise is observed. The excess noise is reduced by the application of an external magnetic field with intensity close to 1500 gauss, revealing the possible magnetic origin and strengthening the connection to the Kondo mechanism.

Among multiferroic materials, those showing at the same time ferroelectricity and ferromagnetism, such as $Ba_2CuGe_2O_7$ (BCGO), are very important and useful for many technological applications. Granata et al. [9] report experimental details of growth of large defect-free BCGO crystals by the floating zone method employing two different routes: 3 bars of pure oxygen or 5.5 bars of dried air. The quality of the crystals depends on many experimental parameters. Among the others, the nature of atmosphere (i.e. its composition and pressure), where the crystal growth process is performed, plays an important role. Very often, even slight modification of the atmosphere leads to drastically changes in their physical properties. Some of the crystals grown under oxygen show inclusions, formed by $BaCu_2Ge_2O_7$ phase, in the first 300 μm from the external border, likely due to the evaporation of barium. Crystals grown in oxygen without inclusions have a dark color and they show crystalline structure and magnetic properties comparable with the measurements in literature.

Another material aspect is related to production of high brightness electron beams. Single crystalline photocathodes with small electron effective mass are supposed to enable ultra-low emittance beams, by taking advantage of the conservation of transverse crystal momentum. This has been heavily studied on crystalline metals, but the goal now is to develop new materials (or artificial heterostructures) with small effective mass and a band structure specifically engineered towards minimizing the transverse momentum spread of the photoelectrons. Galdi et al. [10] report the first evaluation of La-doped $BaSnO_3$ compound as a photocathode and discuss perspectives for future studies aimed at producing high brightness electron beams.

On the application of superconductivity side, the irradiation of superconducting or magnetic materials deserves special attention because this procedure may give rise to interesting phenomenology.

Torsello et al. [11] describe microwave measurements of London penetration depth and superconducting transition temperature in $Ba(Fe_{1-x}Rh_x)_2As_2$ single crystals, in the presence of defects generated by proton irradiation. They look for the experimental signatures of a transition to a state where the sign of the gaps is preserved, this transition being expected in the presence of high levels of disorder, and detectable as a discontinuity in the low-temperature values of the London penetration depth. They hypothesize that this behavior can be described by multi-band Eliashberg calculations where disorder is suitably accounted for, and show that self-consistent calculations exactly reproduced the experimental critical temperatures and semi-quantitatively the superfluid densities.

The structure of Fe-SCs affects its transport properties, such as critical current density and critical magnetic field that are important for applications. Galluzzi et al. [12] have investigated Fe(Se,Te), fabricated by means of the Bridgman technique, using DC magnetic measurements as a function of temperature and magnetic field (H). The critical density versus applied magnetic field curves show the presence of a second magnetization peak effect that causes an anomalous increase in the field dependence of the critical current density. The triggering of this phenomenon has been explained by a crossover from a weak pinning regime to a strong pinning regime and it has been linked to the presence of the twin boundaries inside the sample. The irreversibility field and upper critical field have been compared with simple models, obtaining a value for the upper critical field at $T = 0\,\mathrm{K}$ that is very close to the maximum value reported in literature for the 11 family of F-SCs.

An aspect that is of great important for applications of superconductivity, in particular for high critical temperature superconductors, is the goodness of the material surface in terms of structural and electrical properties. In hole-doped cuprate materials it is well known that a degraded surface layer can form quite rapidly after the sample fabrication, due to the possible evaporation of the loosely bound oxygen or contamination of the layer exposed to the air. Avitabile et al. [13] have investigated the surface properties and the stability in the less studies electron-doped cuprate materials, namely, the $\mathrm{Nd}_{2-x}\mathrm{Ce}_x\mathrm{CuO}_{4\pm\delta}$ here studied in the form of thin films grown by DC sputtering by means of point contact measurements.

The interaction of superconductors with magnetic materials allows the investigation of a large number of phenomena where the interplay of superconductivity and magnetism is of paramount importance, both for the basic physics involved and for the possible applications. In this context, Cirillo et al. [14] have proposed a new superconducting spin-valve (SSV) based on NbPy trilayer. In their work the influence of the magnetic configuration of thick Py layers on the critical temperature Tc of Py/Nb/Py trilayers was systematically investigated as a function of the Py thickness, spanning from the homogenous magnetization to the magnetic stripe domains (SD) regime. The main goal is to understand if it is possible to control the Tc in the emerging and in the stable SD regimes, by tuning the magnetic configuration of the Py layer. The presence of ordered SD in thick Py layers is shown to determine an enhancement of Tc in Nb/Py/Nb trilayers with respect to the case in which magnetic stripes are absent. The effect is maximum when the dimensions of the stripes, and their walls, are optimized with respect to the other characteristic microscopic lengths. By tuning the domain wall dimensions, NbPy-based hybrids can be promising candidates to realize SSVs based both on conventional as well as on long range triplet (LRT) pairing, or possibly to switch between singlet and LRT states.

The planned future high energy colliders bring to a new level the demand of performance of all the involved technologies. In particular, there is an open problem in properly absorbing the synchrotron radiation emitted by the beams during their circling in the collider. A proposal of using high temperature superconductors as a shield has been put forward. Vaglio and Calatroni [15] address this issue by a proper modeling of the surface resistance of these superconductors in high magnetic field and at low frequency. The possible "thermal runaway" problems arising using YBCO tapes, is also discussed, as well as the strategies for an accurate determination of the "depinning frequency" that represent the crucial material parameter for this application.

These topics were discussed, and the articles were collected from a selection of papers presented at the SuperFOx conference held in Salerno (Italy) in September 2018.

We close this Editorial hoping that scientists working on fundamental aspects and novel functionalities of superconductivity and functional oxides will enjoy reading the selected papers of this volume, and we express our pleasure to have been able to present them in The *European Physical Journal Special Topics*.

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