REPORT

April 26, 2013

PREFACE

This document is intended for the SPIN International Advisory Board and describes in synthesis the background and expertise, the present research activity and projects as well as the possible future trends in SPIN of the researchers listed below who will be affiliated to SPIN in the framework of the CNR re-organization process.

List of researchers: Carlo Camerlingo, Roberto Cristiano, Mikkel Ejrnaes, Ciro Nappi and Ettore Sarnelli.

It is worth to mention that the research activities benefit of the fundamental contribution of two post-doc researchers:

Maria Adamo (presently with a post-doc contract supported by the IRON-SEA Project).
Alessandro Casaburi (presently at the Glasgow University with a Marie Curie Fellowship).

In order to help the identification of the researchers with the different research topics, in the list of references (which, far from being complete, reports only the main publications) the authors involved in the passage to SPIN are written in bold. We have also indicated in green the authors with SPIN affiliation in order to outline the links and collaborations with SPIN.

BACKGROUND AND EXPERTISE

Our background is in the experimental physics and theoretical modelling of superconducting thin films and Josephson devices, with particular emphasis on electronic transport properties and tunnelling phenomena, Josephson electrodynamics of junctions and arrays, quantum coherent phenomena, vortex dynamics, non-equilibrium phenomena, detection and sensing. Devices are investigated and developed both for fundamental studies and for practical applications.

A non exhaustive list of our technical expertise includes:

- Technologies for micro and nanofabrication of thin-film-based superconducting electronic advanced devices. We have 4 UHV systems for the deposition of low-temperature (Nb, NbN, Al, Ta, WSi) and hight temperature (YBCO) superconducting materials and for the growth of oxides interlayers.
- Technologies for micro and nanolithography based on UV mask aligners and laser pattern generator and EBL, reactive ion etching and ion milling systems.
- Electronic low-noise measurements at low temperatures for complete characterization of superconducting and Josephson devices. We have liquid and closed-cycle nitrogen and helium cryostats, a ^{3}He insert, an ADR system able to cover a wide temperature range from 77 K to 70 mK.
- Measurements at low temperatures to investigate the radiation (photons, ions and molecules) induced response of superconducting devices produced by laser and nuclear X-ray sources.
- micro-characterisation techniques: SEM and optical microscopy, high-resolution EDS, Raman spectroscopy, FTIR microscopy and spectroscopy, magnetic SQUID microscopy.

PRESENT RESEARCH ACTIVITY AND PROJECTS

In the period from 2001 to 2011 the research activities described here have been funded by several regional, national and European projects (5 EU projects, 7 national projects and a large number of regional projects) where we often had the leading role. Presently, the active projects are Progetto Premiale CNR-INRIM that will be funded by MIUR, and the joint European-Japanese Project Iron-SEA.

Superconducting Quantum Detectors

The research activities and projects on this topic concern the investigation of superconducting quantum detectors of photons, ions and molecules.

We are active in the field of superconducting detectors since long time. In the last two decades the research in this area was supported by national and European projects where we have had a leading role. We have a well established expertise in detectors based on superconducting tunnel and Josephson junctions and in non-equilibrium phenomena involved in. Since 2007 we moved to the investigation of superconducting nanowires single photon detectors (SNSPD). In this field our main achievement was the proposal and realization of a novel configuration that exploits the "cascade switching" due to an internal avalanche mechanism able to switch the nanowires from the superconducting to the resistive state. The new *parallel nanowire* configuration allows a reduction of the detector kinetic inductance with the positive effects of making the detector faster, the signal amplitude larger and the nanowire device scalable in order to achieve the demanding requisite of a large coverage area for a more efficient radiation collection. The principal articles that report our efforts in this direction are listed in references [1-10].

Research on SNSPD is presently a hot topic in the Applied Superconductivity Community and is attracting a wide general interest since SNSPD can become the detector-of-choice in the region of wavelengths from the visible to the near infrared (1550 nm is the telecom wavelength in optical fibers). This is by virtue of the excellent performance like speed, sensitivity, dark counts, all elements This is by virtue of the excellent performances like speed, sensitivity, dark counts all elements relevant for fundamental quantum optics studies, for applications in quantum information and cryptography, for quantum metrology beyond the classical limits [For an overview see Natarajan C M, Tanner MG and Hadfield RH *Supercond. Sci. Technol.* **25** (2012) 063001 (16pp) and Hadfield R H 2009 *Nature Photon*. **3** (2009) 696–705].

In details we are presently interested: i) in improving the detector configuration; ii) in using advanced materials like WSi, YBCO and Fe-based superconductors as well as hybrid superconducting /ferromagnetic structures, that for different reasons may constitute appealing alternatives to NbN (the present material of choice for SNSPD); iii) in the very challenging task of improving the system detection efficiency beyond the present limit of 90%. The last issue could represent a true cornerstone in the more general field of the single photon detection.

The research activity on SNSPD is presently carried out in collaboration with the groups of prof. R. Hadfield (Glasgow University), prof. F. Lombardi (Chalmers University), prof. H. Myoren (Saitama University).

The research activity and projects on quantum detectors for ions and molecules again deals with the investigation of superconducting nanowires as ultra-fast and efficient detectors of very-high-mass ions (beyond 10^5 amu) for applications in time-of-flight mass spectroscopy of biomolecules (proteins and DNA fragments). In this case we are interested in improving the detector configuration to increase the detector area without speed degradation. We have obtained impressing results in this kind of improvement [11-14] and we are presently pursuing the objectives of enabling charge-state discrimination to eliminate charge/mass ambiguity and realize a "true" mass spectrometry as well as of using advanced materials like Fe-based micro-stripes and MgB_2.

The activity on molecule detection is made in strong collaboration with the group of Masataka Ohkubo (AIST-RIIF Tsukuba) which has the unique experimental facility for testing low temperature devices under molecular radiation.

The activity on SNSPD has recently received awards and recognitions. We mention here the ones for 2012: the Barone Prize of the Italian Physical Society (SIF) to Alessandro Casaburi for his doctorate thesis on "Superconducting strip-line detectors for mass spectrometry"; the prize to Mikkel Ejrnaes for the best presentation of the Applied Physics Section of the last SIF conference; the press release on May 18, 2012 of the Japanese AIST (reported also in the CNR *NEWS* on July 31, 2012) about the results obtained by the joint Italian-Japanese collaboration on "Highly Sensitive Detection of a High-molecular-weight Ion Using Nano-structured Superconductors that overcomes the limitations of existing mass spectrometers [15].

Non conventional superconductors

The research activities and projects concern the study and development of devices and sensors based on HTS superconductors and Josephson junctions. These represent very important physical systems for analyzing basic mechanisms in non-conventional materials. Moreover, their unusual properties are of interest for the fabrication of specific devices that cannot be obtained with conventional superconductors (i.e. π-junctions). To this aim, both micrometric and nanometric Josephson junctions and SQUIDs are fabricated and characterized. On this base, we may contribute to strategic fields, as for instance quantum electronics. Moreover, the development of sensors and devices allows also contributions in applicative sectors like aeronautics, cultural heritage, geophysics.

The first Italian junctions and SQUIDs of YBCO with very low-noise have been fabricated and characterized by us [16]. Since then, several national and European projects have been activated on YBCO devices, regarding either basic physics studies or applications. Important advances in the comprehension of the physics mechanisms of the electrical transport in YBCO Josephson-like junctions [17-24] and SQUIDs [25] has been done. Anisotropy properties of coherence length and noise figure in YBCO films have been investigated [26,27] and specific experimental studies related to the phase and the amplitude of the order parameter in both [100] and [001] oriented YBCO bicrystal grain boundary junctions have been done in the last years [28-31], using two different technological approaches for fabricating high-quality submicron YBCO junctions. In order to account for experiments, dedicated theoretical models, based on the description of Josephson junctions through Andreev bound states, have been developed [32].

Moreover, development of special prototypes using HTS devices have also been done during these years. Indeed, at the present, a scanning SQUID microscope for room-temperature samples and a multi-SQUID portable system for archaeometry have been developed. Nondestructive analysis of materials for aeronautics have been carried out [19, 33-36].

Recently, the research has been addressed to iron pnictides and iron calcogenides superconductors. In this context, the research has been concentrated to the development of an appropriate photolithographic process for the fabrication of Josephson devices [37-38]. The aim is to study the symmetry of the order parameter in such superconductors using Josephson-like junctions with appropriate geometrical configurations. A strong effort has been done on microscopic theories of tunneling in heterogeneous, nanoscopic structures with non-conventional order parameter symmetries (*d*-wave and iron-pnictited junctions). A specific theory based on Andreev bound states and double gap superconductors with different signs has been developed [39].

Superconducting devices for Terahertz radiation

The research activity in the field of Terahertz radiation is aimed to investigate the potential use of technologies and knowledge of superconductivity and Josephson effect for the development of devices operating in the frequency range of THz. The development of THz technology is today considered a demanding task for its potential application in many fields, like medical and biological imaging, molecular spectroscopy and security control, since THz radiation can deeply penetrate into many materials. Moreover the unique properties of pulsed terahertz radiation to follow the time evolution of ultra fast processes have demonstrated for protein–water dynamics upon folding [Kim S J, Born B, Havenith M, Gruebele M, *Angew. Chem. Int.* **Ed. 47** (2008) 6486]. In this field, the Josephson effect provides a promising way for designing ultra-fast detectors due to its intrinsic short response time. Moreover, the high non-linearity of the Josephson junction current-phase relation has relevant implications on the high-frequency electrodynamics behaviour of high-T_c superconductors with unique and appealing perspectives in the design and development of innovative devices at THz frequencies, including lenses and amplifiers.

In the last 4 years we have tried to exploit our competencies in superconductivity to intervening in this field. A researcher exchange project with Japan was active in the years 2008-09 on “Terahertz radiation emitter based on HTCS materials”. The great potentiality of a fast response detector for THz pulsed radiation based on Josephson effect has been pointed out, with appealing implications for the design of advanced devices in the field of ultra-fast electronics [40]. At present one of us (C.C.) is participating to the 2012 PRIN project proposal on “THz imaging using compressive sensing ”.

micro-Raman spectroscopy

Over the past decade we have employed micro-Raman Spectroscopy (m-RS) to characterize materials, superconductor thin films and to assist the device fabrication processes. [41,42]. The experience gained in the analysis of weak Raman signals, such as those typically produced by thin films, allowed us to implement specific measurement methods and data treatments. These methodologies have found applications in fields other than the original one, [43,44] as in the case of a numerical method for de-noising and removal of signal background based on wavelets algorithm [45] widely applied to characterize carbon nanotubes, organic and biomedical samples. Furthermore, the method for estimate the thickness of ultra-thin metal films by m-RS that was recently proposed and applied to characterize superconductor nanometre thick NbN films [46], resulted appealing for the characterization of the hydrophobins protein layers used in nano-biotechnology for enabling biocompatible surface functionalization.

FUTURE TRENDS AND PERSPECTIVES

A possible future development of the activities lies in the general framework of quantum science and technology. The distinctive peculiarity of quantum mechanics with respect to classical physics can be found in the quantum correlations, coherence phenomena and entanglement. Quantum technologies exploit the enormous potential of this properties to realize devices with superior performances. Moreover, quantum technologies have the possibility to generate and manipulate in an extremely controlled way quantum states which are the basis of various information, quantum communication and metrology protocols.

Finally, we could also contribute to the fabrication and characterization of hybrid devices, that may be useful in realizing electronic interfaces to organic devices for biological applications.

In perspective, in the future, we would like to explore the possibility that our background and expertise could evolve toward new frontiers like the emerging field of *Quantum Biology*. [Ball P, *Nature* 474, (2011) 272] There, quantum effects are the key ingredient, although non-ubiquitous, that nature may use. As examples one can find biological systems that exploit quantum effects like coherence or entanglement for some practical purpose (for instance energy harvesting), or one can imagine hybrid electronic/biological systems that mimic the behaviour of complex biological systems for achieving functionalities. The testing techniques of this hypothesis seem very similar to those we currently use and the involved physics is close to our background.

Superconducting Quantum Detectors

Superconducting optics is an emerging new area that highlights the growing role of superconducting materials, devices and circuits in quantum optics, quantum information and quantum computing. It focuses on the exploration of the wide ranging applications of superconducting detectors and devices in quantum optics and quantum information, highlighting high performance superconducting technologies for infrared single photon detection, and implementations in applications such as quantum key distribution, quantum metrology and quantum information processing, realization of qu-bits.

In this context we intend to continue the investigation and development of superconducting quantum detectors and devices which, thanks to the progress in the nanotechnologies, can represent a cornerstone in this field.

Non-conventional superconductors

The research on Josephson junctions made by Fe-based superconductors will be carried out in the next future in the framework of the IronSea project, through three different cooperations: SPIN Genova, Iida (IFW Dresden) and Seidel (FSU-Jena), for high critical current density devices, and Naito (Tokyo University) for development of ramp-edge Josephson junctions.

Another field of interest is the investigation of noise mechanisms and fluctuations phenomena in Fe-based junctions and SQUID and YBCO nanostructured devices. To this aim we will set up a high-sensitivity low-temperature facility based on LTS SQUID. This technique can be also of interest for the investigation of fluctuations phenomena in physical systems like nanowires and nanotubes composed by other materials.

Moreover, our expertise on Andreev mechanisms could be relevant for the development of Andreev interferometers, regarded as the most direct competitors to SQUIDs because of the possibility to reach higher sensitivity and speed readout.

Amongst future developments and methodological upgrades, we necessarily include also the use of modern computer simulations (DFT, first principles) to fully integrate advanced device design with material science.

Superconducting devices for THz radiation

In our opinion, beyond most popular applications, pulsed THz probe method could play an important role in the experiments and comprehension of some basic mechanisms underlying biomaterial functionality. The importance of physical mechanisms, beside chemical ones, on the protein and enzyme functionality is today widely recognized.[Lambert L et al, *Nature Phys.* **9** (2013) 10] In this case superconductor devices could play an essential role. In this aim we should intend to continue efforts to develop fast, high-sensitive and reliable methods of detection for THz (*and optical single photon*) radiation.

micro-Raman spectroscopy

In order to improve characterization potentiality of the m-RS system, we are planning to set up a cryo-cooled stage for collect Raman signal on sample at low temperatures, in the range of 20-300 K. The low temperatures should allow to study Raman scattering from electron excitations, with interesting insights in the characterization of system with nontrivial electron dynamics.

REMARK

All the abovementioned activities can positively benefit and contribute to the current activities in SPIN carried out by the groups presently participating to the Tafuri's Commessa as well as to all activities in SPIN related to thin film fabrication of innovative materials.

REFERENCES (Authors involved in the passage from ICIB to SPIN are in bold. To remark the links with SPIN, authors with SPIN affiliation are in green).

[1] **Ejrnaes M, Cristiano R**, Quaranta O, Pagano S, Gaggero A, Mattioli F, Leoni R, Voronov B, Gol'tsman G, APPL PHYS LETTS 91, (2007) 262509

[2] **Ejrnaes M, Casaburi A**, Quaranta O, Marchetti S, Gaggero A, Mattioli F, Leoni R, Pagano S, **Cristiano R**, SUPERCOND SCI & TECHNOL, 22 (2009) 055006

[3] **Ejrnaes M, Casaburi A, Cristiano R**, Quaranta O, Marchetti S, Martucciello N, Pagano S, Gaggero A, Mattioli F, Leoni R, Cavalier P, Villégier JC, APPL PHYS LETTS 95 (2009) 132503

[4] Annunziata AJ, Quaranta O, Santavicca DF, **Casaburi A**, Frunzio L, **Ejrnaes M**, Rooks MJ, **Cristiano R**, Pagano S, Frydman A, Prober DE, J APPL PHYS 108, (2010) 084507-1/7

[5] **Ejrnaes M, Casaburi A**, Mattioli F, Leoni R, Pagano S, **Cristiano R**, PHYS REV B 81 (2010) 132503-1-4

[6] Marrocco N, Pepe GP, Capretti A, Parlato L, Pagliarulo V, Peluso G, Barone A, **Cristiano R, Ejrnaes M, Casaburi A,** Kashiwazaki N, Taino T, Myoren H, Sobolewski R, APPL PHYS LETTS 97, (2010) 092504

[7] **Casaburi A, Ejrnaes M,** Mattioli F, Gaggero A, Leoni R, Martucciello N, Pagano S, Ohkubo M and **Cristiano R,** J NANOPARTICLE RESEARCH 13 (2011) 6121

[8] **Ejrnaes M, Casaburi A, Cristiano R**, Martucciello N, Mattioli F, Gaggero A, Leoni R, Villègier JC, Pagano S, SUPERCOND SCI & TECHNOL, 24 (2011) 035018

[9] Grimaldi G, Leo A, Nigro A, Silhanek AV,Verellen N, Moshchalkov VV, Milosˇevic´ MV, **Casaburi A, Cristiano R**, Pace S, APPL PHYS LETT 100 (2012) 202601

[10] Mattioli F, **Ejrnaes M**, Gaggero A, **Casaburi A**, **Cristiano R**, Pagano S, Leoni R, J VAC SCI TECHNOL B 30 (2012) 031204-1

[11] **Casaburi A**, Zen N, Suzuki K, **Ejrnaes M**, Pagano S, **Cristiano R**, Ohkubo M, APPL PHYS LETTS 94 (2009) 212502

[12] Zen N, **Casaburi A**, Shiki S, Suzuki K, **Ejrnaes M**, **Cristiano R**, Ohkubo M, APPL PHYS LETTS 95, (2009) 172508

[13] **Casaburi A, Ejrnaes M,** Zen N, Ohkubo M, Pagano S, **Cristiano R**, APPL PHYS LETTS 98 (2011) 023702

[14] **Casaburi A** Esposito E, **Ejrnaes M**, Suzuki K, Ohkubo M, Pagano S, **R Cristiano R**, SUPERCOND SCI & TECHNOL 25 (2012) 115004

[15] See http://www.aist.go.jp/aist_e/latest_research/2012/20120731/20120731.html

[16] **Sarnelli E**, Testa G, **Camerlingo C**, Ruggiero B, Russo M, J. SUPERCOND. 9, 513 (1996)

[17] **De Nicola S**, **Adamo M, Sarnelli E, and Nappi C,** PHYS LETTS A 375 (2011) 1598

[18] Del Rio L Altshuler E, Niratisaraik S, Haugen O, Johansen TH, Davidson BA, Testa G, and **Sarnelli E**, SUPERCOND SCI & TECHNOL 23 (2010) 085005

[19] **Adamo M**, Calvano F, **Nappi C**, **Sarnelli E**, J APPL PHYS 106 (2009) 123913

[20] Navacerrada MA, Lucia, ML, Sanchez-Quesada F, **Sarnelli E,** J APPL PHYS 104 (2008) 113915

[21] Polak T and **Sarnelli E**, PHYS REV B 76 (2007) 014531

[22] Navacerrada MA, Lucia ML, Sanchez-Soto LL, Sanchez-Quesada F, **Sarnelli E**, **Nappi C,** PHYS REV B 74 (2006) 024507

[23] Nappi C, **Sarnelli E**, **Adamo M**, Navacerrada MA, PHYS REV B 74 (2006) 144504-10

[24] **Nappi C**, Goldobin E, **Adamo M,** and **Sarnelli E**, LOW TEMP PHYS 36, (2010) 920

[25] Prigiobbo A and **Sarnelli E**, J APPL PHYS 103 (2008) 043906-1

[26] **Camerlingo C** and Jung G, SUPERCOND SCI & TECHNOL 18 (2005) 1106

[27] Jung G, **Camerlingo C**, Zilber E, ACTA PHYS POLONICA A 115 (2009) 69

[28] Lombardi F, Tafuri F, Ricci F, Granozio FM, Barone A, Testa G, **Sarnelli E**, Kirtley JR, Tsuei CC, PHYS REV LETTS 89, (2002) 207001

[29] Testa G, Monaco A, Esposito E, **Sarnelli E**, Kang DJ, Mennema SH, Tarte EJ, Blamire MG, APPL PHYS LETTS 85, (2004) 1202

[30] Testa G, **Sarnelli E**, Monaco A, Esposito E, **Ejrnaes M**, Kang DJ, Mennema SH, Tarte EJ, Blamire MG, PHYS REV B 71, (2005) 134520

[31] **Sarnelli E**, **Adamo M**, **De Nicola S**, Cibella S, Leoni R, **Nappi C**, SUPERCOND SCI & TECHNOL 2013 (submitted)

[32] **Nappi C**, **De Nicola S**, **Adamo M**, **Sarnelli E**, PHYS REV B 86, 024517 (2012)

[33] **Adamo M**, Bonavolontà C, Valentino M, **Sarnelli E**, SENSOR LETTS 7, (2009) 397

[34] **Adamo M, Nappi C, and Sarnelli E**, SUPERCOND SCI & TECHNOL 23, (2010) 095010

[35] **Adamo M**, **Nappi C**, **Sarnelli E**, MEAS SCI TECHNOL 19 (2008) 015508

[36] Bonavolontà C, Valentino M, **Adamo M** and **Sarnelli E**, MEAS SCI TECHNOL 18 (2007) 2116

[37] Bellingeri E, Kawale S, Pallecchi I, Gerbi A, Buzio, Braccini V, Palenzona A, Putti M, **Adamo M, Sarnelli E**, Ferdeghini C, APPL PHYS LETTS 100, (2012) 082601

[38] Barone C, Bellingeri E, **Adamo M, Sarnelli E**, Ferdeghini C, Pagano S, SUPERCOND. SCI. AND TECHNOL. 2013 (in press)

[39] **Nappi C**, **De Nicola S**, **Adamo M**, **Sarnelli S**, EUROPEN PHYS LETTS 2013 (submitted) arXiv: 1212.4039v2

[40] **Camerlingo C**, PHYSICA C 471 (2011) 493

[41] Barboy I, **Camerlingo C**, Bar I, Bareli G, Jung G, J APPL PHYS 110 (2011) 033912

[42] Carotenuto G, **De Nicola S**, **Camerlingo C**, Peluso A, Nicolais L, ADV IN POLYMER TECHNOL 31 (2012) 246

[43] Delfino I, **Camerlingo C**, Portaccio M, Della Ventura B, Mita L, Mita DG, Lepore M, FOOD CHEMISTRY 127 (2011) 735.

[44] **Camerlingo C**, Delfino I, Perna G , Capozzi V, Lepore M, SENSORS 11 (2011) 8309.

[45] **Camerlingo C**, Zenone F, Gaeta GM, Riccio R, Lepore M, MEAS SCI TECHNOL 17 (2006) 298.

[46] **Camerlingo C,** Lisitskiy M, De Stefano L, Rea I, Delfino I, Lepore M, THIN SOLID FILMS (2013) in press.