A Special Section

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A Special Section on Thermoelectrics

The thermoelectric (TE) direct conversion between thermal and electrical energy has drawn vast interest of the international scientific community in the recent years aiming, in particular, to the recycling of waste heat for power generation. The conversion of heat into electricity using TE materials is primarily based on the Seebeck effect and the material conversion efficiency is scaled by the dimensionless figure of merit, defined as $ZT = (\alpha^2/\rho\lambda)T$, where α, ρ, λ, and T are the Seebeck coefficient, electrical resistivity, thermal conductivity and temperature, respectively. As well known, achievable ZT values were limited below one for more than half a century, relegating thermoelectricity to a niche. While photovoltaics took the floor as the key actor for renewable energies, thermoelectricity was considered of relevance only for deep–space probes, where sunlight is too weak to power instruments and electronics. On planet earth, instead, the Seebeck effect seemed to be important only in metrology, to make accurate temperature measurements.

Things have abruptly changed around year 2000, when nanotechnology hit thermoelectrics. Since then, ZT has escalated values that nowadays exceed 2.5, and a number of companies and start-ups have begun proposing thermoelectric generators as a viable alternative or complement to other renewable energy technologies. At the same time, we have witnessed an impressive surge of interest all over the world by scientists and technologists, both from academia and industries. Scientific societies have been founded, both nationally and internationally.

The Italian community of thermoelectricians began meeting in 2013, in a two-day workshop series named "Giornate sulla Termoelettricità" (Thermoelectricity Days–GiTe), collecting a widely interdisciplinary scientific community. Every year GiTe embraced scientists with widely diverse expertise, ranging from chemistry to materials science, physics and engineering–and coming from academy and private companies. GiTe made up a very informal, friendly and lively opportunity for the rather large Italian community working on thermoelectrics to share presentations spanning from fundamental aspects and material innovation to device and module prototyping. Since 2015 the GiTe workshop is organized under the auspices of the *Italian Thermoelectric Society*, a non-profit scientific organization founded in 2014 and affiliated to the *European Thermoelectric Society*, which aims at stimulating and supporting Italian scientific and technological research on thermoelectrics.

In view of the quality of presentations hosted by GiTe, some of which found room in top–tier scholar journals, we considered as a due service to the Italian community (and to the International thermoelectric community as well) to collect the best papers from GiTe and to publish them. This special section of the *Journal of Nanoscience and Nanotechnology* collects the most qualified papers that were presented at GiTe 2016 in Pisa along with contributions of internationally renowned European scientists, setting the state of art of this field in Italy through the research work of the Italian laboratories and of the European research centers more closely collaborating with the Italian scientific community.

Among the many papers of this special section, a large number focuses on the study of the properties of nanostructured materials and nano-systems and on the way they may be improved, both from the experimental and the theoretical point of view. Nonetheless, ample room is also taken from technology and applications, which remain the driving force of this field.

We are therefore indebted to all authors who contributed with their valuable work to this special section, and to all the referees who contributed to keep high the scientific level of these publications. Special thanks go to the journal staff, the Editor-in-Chief Dr. Hari Singh Nalwa, and the European Editor Dr. Davide Barreca for their precious and patient support.

Guest Editors

Simone Battiston, Stefano Boldrini, Monica Fabrizio
CNR-ICMATE

Dario Narducci
University of Milano Bicocca

Giovanni Pennelli
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ABOUT THE GUEST EDITORS

Simone Battiston was born in Dolo (Venice, Italy) in 1980. He graduated in Materials Science at Padua University in 2005. Since 2006, he worked at Institute for Energetics and Interphases (IENI) of National Research Council of Italy (CNR) with several fellowships and as associate member. Meanwhile, he obtained the Italian Second Level University Master degree on Superficial treatments for Industry in 2007, and the Ph.D. in Molecular Science (Chemical Sciences) in 2010, with a thesis entitled: "Preparation and characterization of C/TiO_2 composites for the development of nanostructured photoactive material." Few months later, he became researcher at IENI (now renamed Institute of Condensed Matter Chemistry and Technologies for Energy, ICMATE) of CNR. His research activity has been addressed to the synthesis and characterization of ceramic and alloy bulk materials and thin films for applications on energetics. In particular, it has been focused on the synthesis and morphological, structural, compositional characterizations of photocatalytic hybrid nanocomposites, bulk magnesium silicide and tetrahedrite based thermoelectric materials for intermediate temperatures, and their protection against oxidation by means of protective coatings. Most of the work carried out on the thermoelectric material field has been performed in close collaboration with the Royal Institute of Technology (Sweden), Stockholm University (Sweden), and Tokyo University of Science (Japan). He is a member ofthe Italian Thermoelectric Society (Associazione Italiana di Termoelettricità, AIT) board and of the organizing and scientific committee of the two-day workshop series named "Giornate sulla Termoelettrictà" (Thermoelectricity Days-GiTe), which are held in Italy every year since 2013. Up to date, he authored and co-authored about 30 papers published on ISI journals on the fields of materials science and energy.

Stefano Boldrini obtained his degree in Physics in March 2004 at the University of Padua. Since 2007 (since February 2010 as a permanent researcher), he has being working in ICMATE institute (former IENI) of the National Research Council of Italy (CNR). He has been involved in several research projects concerning the development of materials and components for the new generation fuel cells for co-generative applications and the development of thermoelectric materials and devices for energy systems. In particular, he has been working on electrochemical characterizations of electrodes and ionic or protonic electrolytes for SOFCs and hydrogen separation membranes, both as bulk and thin films, on SOFC testing, and he developed experimental setup for the functional characterization of high temperature thermoelectric materials (conductivity and Seebeck coefficient measurements). Recently, he has been developing thermoelectric modules for medium-high temperatures and devices for their characterization. He is a member of the Italian Thermoelectric Society (Associazione Italiana di Termoelettricità, AIT) board and of the organizing and scientific committee of the workshop series named "Giornate sulla Termoelettrictà" (Thermoelectricity Days-GiTe), since 2013. He authored and co-authored about 30 papers published on ISI journals in the fields of materials science and energy.

Monica Fabrizio is senior researcher at the Institute for Energetics and Interphases of CNR. She is coordinator of the Project "Materials and enabling technologies for the electric system" in the framework program of the CNR-Italian Ministry of Economic Development Agreement for the National Electric System Research. She has been member of the Scientific Board of the CNR Department "Energy and Transport." She is Secretary of the Italian Thermoelectric Society and member of the Organizing Committee of the Italian Conference on Thermoelectrics. Her technical skills have been acquired during the working experience at the CNR formerly as researcher and then as project manager. Her competences are in the following fields: —Materials for electricity conduction (ionic conductors) and conversion (thermoelectric silicides and oxides) in the medium-high temperature range, —Nanofluids for thermal exchange and lubrication, —Water hydrolysis and hydrogen storage properties of PGM and alloys. She has over 150 articles in international journals and international conferences.

Dario Narducci was born in Milan (Italy) in 1960. Graduated in Chemistry at the University of Milan in 1984, from 1985 to 1988 he was a Ph.D. student in Chemistry at the University of Milan, where he worked in the area of solid state physical chemistry, also visiting the Physics Laboratory of the University of Amsterdam where he worked in the field of electron spin resonance of defects and impurities in silicon. From 1988 to 1990 he was Post-Doctoral Fellow at IBM Thomas J. Watson Research Center in Yorktown Heights, NY, studying the electrical properties of semiconducting diamond. In 1990 he re-joined the University of Milan, Department of Physical Chemistry and Electrochemistry, as an Assistant Professor, moving in 1997 to the Department of Materials Science, University of Milano Bicocca, where he became Associate Professor of Physical Chemistry in 2000. Dario Narducci has an extensive record of projects he led or participated in, both at the National and at the European level. He was also the project leader of three privately-funded projects on gas detection systems and of several SME-funded research contracts. Research interests of Dario Narducci have focused on the physical chemistry of solids and materials with a special emphasis on silicon. His activity has actually centred on transport properties of disordered materials that have been studied also in view of applications to energetics; and on surface science, where he has been active both on fundamental issues (physical chemistry of oxides and their surfaces, chemical reconstruction of single-crystal silicon surfaces, self-assembling of organic molecules onto silicon, and gas-surface supramolecular interactions) and on more applicative and technological issues (oxide and silicon-based chemical sensors and biosensors). Dario Narducci was a founding member of the Scientific Board of the Nanotechnology Interuniversity Centre of Como (L-NESS) and of the Babbage Project (SISSA, Trieste). He is also a member of the National Inter-University Consortium for Material Science (CNISM), of the Materials Research Society, of the American Chemical Society, and of the Italian Chemical Society, where he served for two terms in the Regional Board. Since 2008 Narducci has developed an intense research activity on thermoelectricity and on its applications to energy harvesting, mostly focused ontop-down (nanowires and nanolayers) and bottom-up nanostructured silicon. In 2010 he was appointed Chief Technical Officer (CTO) and Board Member of a start-upco-financed by ERG SpA and LFoundry aimed at the development of silicon-based thermoelectric generators. As the start-up CTO he has promoted collaborations between industrial partners and research centres throughout Europe, encompassing institutions in Italy, Greece, Austria, and the UK. Narducci is also currently under contract with the EC (FP7) within the SiNERGY consortium, working at the development of all-silicon harvesters, wherein he leads the thermoelectric work package. Recently, his interests have further extended to the thermoelectric properties of multiphase systems and nanocomposites, leading to explorative research endeavours jointly carried out with Stanford University and with the CNRS–Aix-Marseille University. Narducci also co-promoted the foundation of the Italian Thermoelectric Society, which was established in 2014. He is currently serving as its President while serving as treasurer of the European Thermoelectric Society. Author of more than one hundred scientific publications, Narducci is also the author of a book on Nanotechnology and of fifteen patents as well.

Giovanni Pennelli, Ph.D. in Electronics Engineering in 1997, is associated professor at the University of Pisa (IT), Department of Information Engineering, where he is teaching Electron Device Physics. Research activities have been mostly devoted to the development and organization of the nanofabrication facilities of the Department, with the main target of nanodevice fabrication and electrical transport characterization. Giovanni Pennelli designed and developed the hardware and software of a Pattern Generator, to be applied to a Scanning Electron Microscope (SEM). He improved innovative solutions for positioning, with high precision, the electron beam, so that *e*-beam lithography can be performed with higher resolution with respect to commercially available *e*-beam systems. Giovanni Pennelli investigated and developed innovative technical solutions for the fabrication of nanostructures and nanodevices, principally in silicon. He developed and improved top down processes, based on Silicon-On-Insulator (SOI) substrates, for the reliable fabrication of devices based on silicon nanowires (SiNWs). These top-down techniques allow the reliable fabrication of silicon nanowires as narrow as 15 nm, and with a length of several micrometers, positioned between contacts and pads for the electrical characterization. The particular properties of Field-Effect-Transistors based on these narrow silicon nanowires, with all-around gate, have been demonstrated. Recently, he focused his activity on the design and development of nanostructured materials for energy harvesting purposes, and in particular for the direct conversion of heat into electrical power by thermoelectric generation. The strong reduction of phonon thermal conductivity in nanostructures opens interesting possibilities because it allows the use for thermoelectric purposes of materials that are cheap and technologically affordable, such as silicon, but that have a high bulk thermal conductivity. As silicon nanowires showed a thermal conductivity reduction

of two order of magnitude with respect to that of bulk silicon, Giovanni Pennelli concentrated his activity on the development of processes for thermoelectric devices based on networks made of a large number of nanowires. These networks can handle high currents, thus they can deliver high powers, and furthermore they are very reliable for their high level of interconnections. Giovanni Pennelli developed experimental techniques for the measurement of the Seebeck coefficient and of the thermal conductivity of silicon nanodevices. He developed also theoretical models for the optimization of silicon nanowires for thermoelectric applications. Giovanni Pennelli is author, or coauthor, of more than 60 publications on international, high impact factor, scientific reviews.