Nanoengineered Materials for Solid Oxide Cells

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This book is dedicated to my teachers, advisers, colleagues, and collaborators,
who have been instrumental in my pursuit of knowledge and stimulated my curiosity
for the unknown; and to my family—Baggy and Aya, my sisters—Karen and Karla,
and my parents—Jun and Genny, who had passionately taught me the value of
perseverance and education.

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Preface

Solid oxide cells (SOCs) are one of the key technologies receiving global scientific and technological interest due to their enormous potential to alleviate the environmental problems associated with the widespread use of fossil fuels. SOCs can provide highly efficient, low-carbon power generation and constitute the core technology used to produce hydrogen, syngas, and synthetic fuels in combination with renewable electricity.

In recent years, the nanoengineering of materials used for SOCs has emerged as a versatile tool for the production of high-performance components such as electrodes, interlayers, and electrolytes with far superior properties than those of conventional materials. Over the years, several methods have been explored to tune various material structures at the nanoscale via 1D, 2D, and 3D nanostructures fabricated using advanced thin-film technology and other related nanoprocessing techniques. These developments are further complemented by significant advancements in nanocharacterization tools that can be used to elucidate the complex mechanisms governing the behavior of nanostructured materials. This strategic approach has enabled the discovery of novel structures and provided an understanding of fundamental mechanisms at the nanoscale, which are crucial in the development of next-generation devices. The use of thin-film technology and related nanotechnology techniques in the materials development of energy conversion devices such as SOCs has significantly proliferated over the last decade, but until now, no book published on this topic has consolidated the advances achieved to date into one volume. While there is a consensus among research communities that the nanoengineering of materials could enable far superior properties than those of conventional materials, there is also a general lack of awareness regarding current research activities that specifically address the issues of integrating such nanomaterials into practical devices. This book aims to bridge this gap and contribute to a better understanding of the breakthroughs achieved in this area.

With this goal in mind, I have invited active researchers and experts in the field of SOC materials development to contribute chapters covering specific topics related to the development and application of nanomaterials. Ten chapters have been selected for this volume; each chapter provides a comprehensive survey of the state-of-the-art experimental approaches and offers perspectives on the current progress achieved as well as future directions in the area. This volume covers the following topics in great detail: an overview of the various approaches used to fabricate nanostructured air electrodes and their implementation in full cells (chapter 1); the influence of surface chemistry and microstructure on the stability and performance of air electrodes (chapter 2); multilayering strategies and characterization tools used to tune the heterointerfaces of air electrodes (chapter 3); interface engineering to improve the activity and stability of SOC air and fuel electrodes (chapter 4); recent progress on atomic layer deposition, which is used to modify various cell components (chapter 5); the development of novel electrode materials and nano-oxide composite electrolytes which are different from conventional materials (chapter 6); a redox exsolution approach for tailoring nanostructured fuel electrodes (chapter 7); an infiltration technique for engineering nanostructured fuel electrodes (chapter 8); microstructural modifications of the electrolyte/electrode interfaces via numerical and experimental approaches (chapter 9); and last but not least, an overview of synchrotron x-ray radiation techniques as advanced characterization tools for probing nanoscale structures (chapter 10).

I hope that this book will be of great interest to groups working on the development of next-generation energy conversion devices, especially those working on the materials development of solid oxide cells but also those developing oxygen separation membranes and memristive devices. Furthermore, I hope that it will be a useful reference not only for academics and researchers actively working in the field, but also for people in the industry who are currently developing systems and devices for commercial applications.

On a final note, I would like to acknowledge the valuable support and hard work of all the contributors to this volume, without which this project would have been impossible. My sincere thanks go to the Institute of Physics Publishing (specifically Caroline Mitchell and Robert Trevelyan) for providing this wonderful opportunity to work on this project.

Katherine Develos-Bagarinao
Tsukuba, Japan
October 2022

Acknowledgements

I would like to thank my colleagues at the National Institute of Advanced Industrial Science and Technology (AIST) for initiating me in this exciting field and providing the opportunity for me to explore new ideas and approaches. I am also grateful to Professor Harumi Yokokawa (The University of Tokyo) for our insightful discussions and encouraging me to pursue this book project. Lastly, I would like to acknowledge the enthusiastic collaboration of all contributors, without whom this book would not have been possible.

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Editor biography

Katherine Develos-Bagarinao

Katherine Develos-Bagarinao is a Senior Researcher in the Global Zero Emission Research Center at the National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan. Her current research focuses on the development of nanostructured and thin-film materials for SOC applications, as well as advanced characterization techniques used to understand the degradation mechanisms governing the behaviors of surfaces and heterointerfaces. She obtained her PhD from Yamagata University (1999), and an MS and a BS in Physics from the University of the Philippines (1996 and 1994, respectively). Between 2008 and 2009 she was a visiting scientist in the Department of Materials Science and Metallurgy of the University of Cambridge. She currently serves as an editorial board member for the journal *Scientific Reports*, which is published by Nature Portfolio.

Author biographies

Federico Baiutti

Federico Baiutti holds a MSc in Materials Engineering from the University of Trieste and a PhD in Chemistry from the University of Stuttgart. He has carried out PhD (2011–15) and postdoctoral (2015–16) research at the Max-Planck Institute for Solid State Research (Stuttgart, Germany) in oxide thin films, high-temperature superconductivity, and interface effects. He was a visiting researcher at Cambridge University, UK (2018) and Brookhaven National Labs, USA (2011). His current affiliations are as a research scientist at the Catalonia Institute for Energy Research (IREC), Barcelona, Spain (since 2019) and an associate researcher at the National Institute of Chemistry, Ljubljana, Slovenia (since 2020). His main research interests are related to the fabrication of thin films by physical methods and to fundamental studies of ceramic chemistry and related functionalities for low- and high-temperature energy applications. Federico's current activities are focused on the development of novel electrode materials based on nanostructuring and nanoengineering for high-temperature fuel cells, electrolyzers, electrocatalysis, and microdevices for energy storage.

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Mónica Burriel is a CNRS Research Scientist and leads the Oxides for Nanoionic Devices group at the Materials and Physical Engineering Laboratory (LMGP, CNRS, Grenoble-INP) in Grenoble, France. After completing her PhD at the ICMAB Institute, Barcelona, Spain, she worked in the Karlsruhe Institute of Technology, Germany, Imperial College London, UK and IREC, Barcelona, Spain. She recently obtained her Habilitation degree from the Grenoble Alpes University (2021). She has an extensive expertise in the effects of structure, microstructure, and composition on the functional properties of oxide thin films. Her current research into thin films for electrochemical and memristive microdevices focuses on the deposition (by atomic layer deposition and metal–organic chemical vapour deposition), structural/microstructural control, and optimization of the electronic and ionic transport of functional oxides.

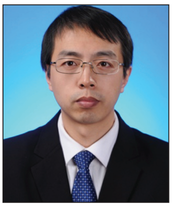
Fjorelo Buzi

Fjorelo Buzi holds a MSc degree in Chemical Sciences with a focus on physical and inorganic chemistry for materials and energy from the University of Genova, Italy. He is a predoctoral researcher at IREC, Spain. His research focuses on the development of nanostructured thin films for solid oxide fuel cells for long-term electrical energy storage. In particular, his work includes the fabrication and study of novel nanocomposite layers as air electrodes.

Ozden Celikbilek

Ozden Celikbilek obtained her PhD from the Grenoble Alpes University in 2016 on the development of air electrodes for solid oxide fuel cells. She subsequently held a postdoctoral research fellow position at Imperial College London from 2018 to 2021. She investigated metal/metal-oxide heterointerfaces for high-performance solid-state energy devices using *in situ* and *ex situ* surface analysis tools. She is currently working as a CNRS postdoctoral researcher at the Materials and Physical Engineering Laboratory (LMGP, CNRS, Grenoble-INP) focusing on the development of thin films for reversible micro-SOC applications.*

Gang Chen



Gang Chen is an Associate Professor in the School of Metallurgy at Northeastern University, Shenyang, China. His current research focuses on the development of new lithium compound electrode ceramic fuel cells that can operate at low temperatures as well as high-performance oxide anode materials for solid oxide cell applications. He obtained his PhD from Hirosaki University (2011), his MS from Dalian University of Technology (2008), and his BS from Chang'an University (2004). Between November 2011 and December 2013, he worked as a research fellow in the Fuel Cell Materials Group of the National Institute of Advanced Industrial Science and Technology. He currently serves as an editorial board member for the journal *Carbon Resources Conversion* of KeAi.

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Ming Chen holds a full professor position at the Department of Energy Conversion and Storage, Technical University of Denmark, Denmark. He completed his PhD at the Swiss Federal Institute of Technology (ETH Zurich) on the topic of solid oxide fuel cells. His research interests lie in the characterization and modelling of solid oxide cells, high-temperature corrosion, thermodynamics, diffusion, and phase field modelling.

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Yan Chen is a professor at the School of Environment and Energy at the South China University of Technology. She received her BS and ME degrees from Peking University and her PhD from the Massachusetts Institute of Technology. Prior to her current position, she worked as a postdoctoral fellow at MIT. Her research focuses on the rational design of new materials to enable high-performance, economical energy and environmental devices based on understanding and controlling surface and interface properties under extreme conditions (electric polarization,

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reactive environments, radiation, etc). She is also working on the application of ion-beam implantation in low-dimensional materials for energy and electronics.

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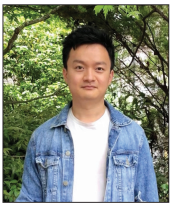
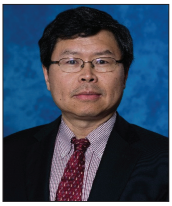
Shuai He



Shuai He graduated as a Bachelor in 2014 from the School of Materials Science and Engineering, South China University of Technology. In 2015, he studied as a PhD candidate under the supervision of Professor San Ping Jiang from the Department of Chemical Engineering of Curtin University, Australia and then engaged in postdoctoral research in the research group of Dr Xiangling Yue in the University of St Andrews, UK. He has been devoted to the research and development of functional energy materials and solid oxide fuel cells/electrolyzers as well as the interface characterization of solid materials using electron microscopy. He has published more than 30 research papers as the first or co-author in academic journals such as *Appl. Catal. B*, *ACS Appl. Mater. Interfaces*, *J. Mater. Chem. A*, *Adv. Sci.*, *ACS Catal.*, *J. Power Sources*, which have been cited more than 1000 times, and his H-factor is 19.

Kevin Huang



Kevin Huang currently holds a SmartState-endowed chair and is a director of the Solid Oxide Fuel Cell center at the University of South Carolina. His research interests include reversible fuel cells, rechargeable batteries, gas separation membranes, and multiscale computational modeling. He has been published in 220+ peer-reviewed journal papers, two books, and three book chapters and has been granted 14 US patents. He is a recipient of the 2018 Breakthrough Leadership in Research Award; the 2017 Educational Foundation Award for Research in Science, Mathematics, and Engineering; the 2015 College of Engineering and Computing Research Achievement Award; and the 2014 University of South Carolina Breakthrough Stars Award.

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Maxime Hubert is a scientist at the French Alternative Energies and Atomic Energy Commission (CEA). He graduated from the Grenoble Institute of Technology (INPG) in Materials Science and obtained his PhD at the Grenoble Alpes University (France) in 2017 for his work on the degradation of SOCs. He has since conducted postdoctoral research using x-ray micro- and nanotomography at the European Synchrotron Radiation Facility. His research interests are currently focused on the improvement of SOC performance and durability using advanced characterization techniques and multiscale modelling.

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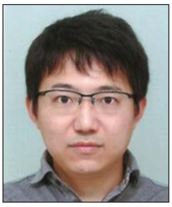

Tomohiro Ishiyama is a senior researcher in the Research Institute for Energy Conservation at the National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan. His current research focuses on the elucidation of the degradation mechanism of solid oxide fuel cell materials. He is also working on the development of a new type of fuel cell using phosphate glass proton conductors. He obtained his PhD from Osaka University (2014) by writing a thesis on a new fabrication technique for proton-conducting phosphate glasses.

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Federico Monaco is a postdoctoral researcher at the European Synchrotron Radiation Facility working on phase contrast and chemical nanotomography.* He studied energy and nuclear engineering at the Polytechnic School of Turin, where he also worked as a research assistant on the production of synthetic fuels. He obtained his PhD in electrochemistry on the degradation of SOCs at the French Alternative and Atomic Energies Commission. His research interests are currently focused on the physicochemical characterization of energy materials, in particular, SOCs and Li-ion batteries.

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Albert Tarancón holds an MSc and a PhD in Physics from the University of Barcelona (2001, 2007) and MEng in Materials Science from the Polytechnic University of Catalonia (2007). He worked as research associate at the IMB-CSIC (ES) and as a visiting researcher at the University of Oslo (Norway), Imperial College, London (UK), and Caltech (USA). In 2010, Albert gained a Ramon y Cajal Fellowship and joined the Catalonia Institute for Energy Research (IREC) as the Head of the Nanoionics and Fuel Cells Group. He is currently the ICREA Professor at IREC and leads a group of 20 + people devoted to nanomaterials for alternative energy technologies and their applicability to powering portable devices and hydrogen/synthetic fuel production. He has been the principal investigator of ten EU projects, including one ERC-CoG and two coordinated H2020 projects, attracting a total of 20+ M€. He is currently an editor of *J. Phys. Energy* (IOP) and *J. Eur. Ceram. Soc.* (Elsevier).

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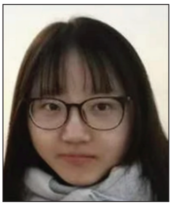

Miao Yu is a PhD student at the Department of Energy Conversion and Storage, Technical University of Denmark, under the supervision of Professor Ming Chen. She holds an MSc in Energy Conversion and Storage from the Technical University of Denmark and a BSc in Building Environment and Energy Application Engineering from Chang'an University, Xi'an, China. Her PhD project focuses on improving the performance and durability of SOCs and interconnects at intermediate temperatures.

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Xiangling Yue is a Rutherford Fellow at the School of Chemistry, University of St Andrews. She was awarded a master's degree in chemical engineering by the Dalian Institute of Chemical Physics, Chinese Academy of Sciences in 2009 and in 2014, she obtained a PhD in Chemistry at the University of St Andrews. Her PhD thesis focused on development of alternative materials for high-temperature electrolysis. After her PhD, she continued to work with professor John Irvine as a postdoctoral researcher for a few years before being awarded the EPSRC UKRI Innovation Fellowship to start her independent research in 2018. She has developed expertise in SOC manufacture, ceramic processing, electrochemical characterisations, and the microstructural engineering of the solid-state materials used in fuel cells and electrolysers for low-carbon energy storage and conversion, in particular for applications involving CO_2 utilisation. She is also working on biomass combustion and understanding the biomass ash deposition process in order to alleviate ash accumulation in biomass boilers and plants, which is a project undertaken in close collaboration with industry.

Mengzhen Zhou

Mengzhen Zhou is currently pursuing her PhD degree at the School of Environment and Energy at the South China University of Technology. Her research focuses on the cathodes of solid oxide fuel/electrolysis cells.

Glossary

p_{O_2}	Oxygen partial pressure
$V_O^{\bullet\bullet}$	Oxygen vacancies
3D	Three-dimensional
ALD	Atomic layer deposition
A-PBC	A-site deficient $PrBa_{0.94}Co_2O_{5+\delta}$
APHAXPES	Ambient-pressure hard x-ray photoelectron spectroscopy
APT	Atom probe tomography
APUs	Auxiliary power units
AP-XPS	Ambient-pressure x-ray photoelectron spectroscopy
ASR	Area-specific resistance (Ω cm^2)
BCO	$BaCoO_{3-x}$
BL	Barrier Layer
BMCNO	$PrBaMn_{1.7}Co_{0.1}Ni_{0.2}O_{5+\delta}$
BSCF	$Ba_{1-x}Sr_xCo_{1-y}Fe_yO_{3-\delta}$
BSCFZY	$Ba_{0.5}Sr_{0.5}Co_{0.6}Fe_{0.2}Zr_{0.1}Y_{0.1}O_{3-\delta}$
BSFM	$Ba_{0.3}Sr_{0.7}Fe_{0.9}Mn_{0.1}O_{3-\delta}$
CB	Conduction band
CHP	Combined heat and power
COBRA	Coherent Bragg rod analysis
CR	Crystal reconstruction
CTE	Coefficient of thermal expansion
CVD	Chemical vapor deposition
c_ν	Oxygen vacancy concentration
D	Oxygen diffusivity
D^*	Oxygen self-diffusion coefficient (cm^2 s^{-1})
DCMS	Direct current magnetron sputtering
DFT	Density functional theory
DOS	Electron density of states
DPB	Double phase boundary
DRM	Dry reforming of methane
DRT	Distribution of relaxation times
D_ν	Oxygen vacancy diffusivity
EELS	Electron energy loss spectroscopy
EIS	Electrochemical impedance spectroscopy
E_k	Apparent activation energy k
ESM	Electrochemical strain microscopy
$E_{\mathrm{Sr,vac}}$	Vacancy formation energy of Sr
EXAFS	Extended x-ray absorption fine structure
FE	Fuel electrodes
FEM	Finite element method
FIB-SEM	Focused ion beam-scanning electron microscopy
FSM	$SrFe_{0.75}Mo0.25O_{3-\delta}$
FT-IR	Fourier transform infrared spectroscopy
GDC	Gadolinia-doped ceria (alternatively, CGO), $Gd_xCe_{1-x}O_{2-\delta}$
GLAD	Glancing angle deposition
GSTF	Gradient structured thin films
HAADF STEM	High-angle annular dark field scanning transmission electron microscopy

HOR	Hydrogen oxidation reaction
HRXRD	High-resolution x-ray diffraction
IE	Isotope exchange
IE-APT	Isotope exchange atomic probe tomography
IEDP	Isotope exchange depth profiling
IT-SOC	Intermediate temperature solid oxide cell
IV-IP	Current/voltage-current/power
k^*	Oxygen surface exchange coefficient (cm s^{-1})
k_{chem}	Chemical oxygen surface exchange coefficient (cm s^{-1})
KFM	Kelvin force microscopy
k^{q}	Electrical oxygen surface exchange coefficient (cm s^{-1})
L2NO4	$La_2NiO_{4\pm\delta}$
LAO	$LaAlO_3$
LC95	$La_{0.95}CoO_{3-\delta}$
LCCFC	Lithium compounds ceramic fuel cell
LCeNT	$La_{0.8}Ce_{0.1}Ni_{0.4}Ti_{0.6}O_3$
LCNT	$La_{0.43}Ca_{0.37}Ni_{0.06}Ti_{0.94}O_{3-\gamma}$
LCO	$LiCoO_2$
LCTCF	$La_{0.43}Ca_{0.37}Ti_{0.8}Co_{0.1}Fe_{0.1}O_{3-\delta}$
LEIS	Low energy ion scattering spectroscopy
LMO	$LiMnO_2$
LNCM-523	$LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$
LNCM-622	$LiNi_{0.6}Co_{0.2}Mn_{0.2}O_2$
LNCM-811	$LiNi_{0.83}Co_{0.11}Mn_{0.06}O_2$
LNF	$LaNi_{0.6}Fe_{0.4}O_{3-\delta}$
LNO	$La_2NiO_{4+\delta}$
LNZ	Lithium nickel zinc oxide
LPNO	$La_{2-x}Pr_xNiO_{4+\delta}$
LSC	$La_{1-x}Sr_xCoO_3$
LSC_{113}	$La_{1-x}Sr_xCoO_3$
LSC_{214}	$LaSrCoO_{4-\delta}$
LSC_{214}	$La_{2-x}Sr_xCoO_4$
LSC64, LSC_{113}	$La_{0.6}Sr_{0.4}CoO_{3-\delta}$
LSC82	$La_{0.8}Sr_{0.2}CoO_{3-\delta}$
LSCF	$La_{1-x}Sr_xCo_{1-y}Fe_yO_3$
LSCM	$(La_{0.75}Sr_{0.25})Cr_{0.5}Mn_{0.5}O_3$
LSCNi	$(La_{0.7}Sr_{0.3})(Cr_{0.85}Ni_{0.15})O_{3-x}$
LSCNi-Fe	$(La_{0.7}Sr_{0.3})(Cr_{0.85}Ni_{0.15-x}Fe_x)O_{3-\delta}$
LSCoT	$La_{0.3}Sr_{0.7}Co_{0.07}Ti_{0.93}O_{3-\delta}$
LSCr	$La_{1-x}Sr_xCrO_3$
LSCrFeCo	$La_{0.3}Sr_{0.7}Cr_{0.3}Fe_{0.6}Co_{0.1}O_{3-\delta}$
LSCrT	$(La_{0.75}Sr_{0.25})Cr_{0.5}Ti_{0.5}O_3$
LSCuT	$La_{0.43}Sr_{0.37}Cu_{0.12}Ti_{0.88}O_{3-\delta}$
LSF	$La_{1-x}Sr_xFeO_3$
LSF_{113}	$La_{0.8}Sr_{0.2}FeO_{3-\delta}$
LSF_{214}	$(La,Sr)_2FeO_{4-\delta}$
LSFCNb	$La_{0.5}Sr_{0.5}Fe_{0.8}Cu_{0.15}Nb_{0.05}O_{3-\delta}$
LSFN	$La_{0.6}Sr_{0.4}Fe_{0.8}Ni_{0.2}O_{3-\delta}$
LSM	$La_{1-x}Sr_xMnO_3$
LSMF	$La_{1.2}Sr_{0.8}Mn_{0.4}Fe_{0.6}O_{4-\delta}$

LSNT	$La_{0.4}Sr_{0.4}Ni_{0.06}Ti_{0.94}O_{3-\delta}$, $La_{0.52}Sr_{0.28}Ni_{0.06}Ti_{0.94}O_3$
LST	$La_{0.4}Sr_{0.4}TiO_{3-\delta}$
LSTN	$La_{0.4}Sr_{0.4}Ti_{0.94}Ni_{0.06}O_{3-\delta}$
MDC	$Mo_{0.1}Ce_{0.9}O_{2+\delta}$
MIEC	Mixed ionic electronic conductor
MLLS	Multiple linear least squares
MPD	Maximum power density
NAP-XPS	Near-ambient-pressure x-ray photoelectron spectroscopy
NBMO	$NdBaMn_2O_{5+\delta}$
NCAL	$Ni_{0.8}Co_{0.15}Al_{0.05}LiO_{2-\delta}$
NEXAFS	Near-edge x-ray absorption fine structure
Ni/GDC	Nickel/gadolinia-doped ceria
Ni/SDC	Nickel/samaria-doped ceria
Ni/YSZ	Nickel/yttria-stabilized zirconia
NLM	$La_{0.9}Mn_{0.8}Ni_{0.2}O_3$
NPs	Nanoparticles
NSC_{113}	$Nd_{0.5}Sr_{0.5}CoO_{3-\delta}$
NSC_{214}	$Nd_{0.8}Sr_{1.2}CoO_{4\pm\delta}$
$NSC_{214/113}$	$Nd_{0.8}Sr_{1.2}CoO_{4\pm\delta}/Nd_{0.5}Sr_{0.5}CoO_{3-\delta}$
ECR	Electrochemical conductivity relaxation
OCV	Open circuit voltage
OE	Oxygen electrodes
OER	Oxygen evolution reactions
ORR	Oxygen reduction reactions
O-SOCs	Oxygen ion-conducting solid oxide cells
OTR	Optical transmission relaxation
PBCC	$PrBa_{0.8}Ca_{0.2}Co_2O_{5+\delta}$
PBCFN	$PrBaCo_{1.6}Fe_{0.2}Nb_{0.2}O_{5+\delta}$
PBCM	$Pb_{0.5}Ba_{0.5}Co_{0.1}Mn_{0.9}O_x$
PBMCo	$PrBaMn_{1.7}Co_{0.3}O_{5+\delta}$
PBMF	$PrBaMn_{1.7}Fe_{0.3}O_{5+\delta}$
PBMO	$PrBaMn_2O_{5+\delta}$
PEMS	Plasma-enhanced magnetron sputtering
pFIB	Plasma focused ion beam
PLD	Pulsed laser deposition
PNM	$PrNi_{0.5}Mn_{0.5}O_3$
PSCFN	$Pr_{0.4}Sr_{0.6}Co_{0.2}Fe_{0.7}Nb_{0.1}O_{3-\delta}$
PSFM	$(Pr_{0.4}Sr_{0.6})_3(Fe_{0.85}Mo_{0.15})_2O_7$
P-SOCs	Proton-conducting solid oxide cells
PVD	Physical vapor deposition
QCM	Quartz crystal microbalance
RFMS	Radio frequency magnetron sputtering
R_p	Polarization resistance (Ω cm^2)
RP	Ruddlesden–Popper
R-PCECs	Reversible protonic ceramic electrochemical cells
R_s	Surface polarization resistance (Ω cm^2)
RVE	representative volume element
R_Ω	Ohmic resistance (Ω cm^2)
SAED	Selected area electron diffraction
SCF	$Sr_{0.8}Ce_{0.2}FeO_3$

SCN10	$SrCo_{0.9}Nb_{0.1}O_{3-\delta}$
ScSZ	Scandia-stabilized zirconia
SDC	Samaria-doped ceria, $Sm_xCe_{1-x}O_{3-\delta}$
SEM	Scanning electron microscopy
SEM-WDS	Scanning electron microscopy-wavelength dispersive x-ray spectroscopy
SERS	Surface enhanced Raman spectroscopy
SIMS	Secondary ion mass spectrometry
SMT	Semiconductor-to-metal transition
SOCs	Solid oxide cells
SOECs	Solid oxide electrolysis cells
SOFCs	Solid oxide fuel cells
SPM	Scanning probe microscopy
SSC	$Sm_{0.5}Sr_{0.5}CoO_{3-\delta}$
SSOFC	Symmetrical solid oxide fuel cell
SSPM	Scanning surface potential microscopy
STEM	Scanning transmission electron microscopy
STEM-EDS or EDX	Scanning transmission electron microscopy-energy dispersive x-ray spectroscopy
STF	$SrTi_{1-x}Fe_xO_3$
STFN	$Sr_{0.95}(Ti_{0.3}Fe_{0.7-x}Ni_x)O_{3-\delta}$
STM/STS	Scanning tunneling microscopy and spectroscopy
STO	$SrTiO_3$
SYTN	$Sr_{0.92}Y_{0.08}Ti_{1-x}Ni_xO_{3-\delta}$
SZ	$SrZrO_3$
SZY	Yttrium-doped $SrZrO_3$
t	Tolerance factor
TEM	Transmission electron microscopy
TGA-DSC	Thermogravimetric analyzer-differential scanning calorimetry
ToF-SIMS	Time-of-flight secondary ion mass spectrometry
TPB	Triple-phase boundary
TPD	Temperature programmed oxidation
TPR	Temperature programmed reduction
TRF-XAS	Total-reflection fluorescence x-ray absorption spectroscopy
TXM	Transmission x-ray microscopy
UV-Vis	Ultraviolet–Visible absorption spectra
VAN	Vertically aligned nanocomposite
VB	Valence band
XANES	X-ray absorption near-edge structure
XAS	X-ray absorption spectroscopy
XCT	X-ray computed tomography
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction
XRF	X-ray fluorescence
XRR	X-ray reflectivity
YSZ	Yttria-stabilized zirconia, $(YO_{1.5})_{0.16}(ZrO_2)_{0.84}$
ZDC	$Zr_{0.35}Ce_{0.65}O_{2-\delta}$