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Ceramic membranes that transport ions play an essential role in numerous energy conversion systems, including solid-state Li-ion batteries, proton and oxygen separation membranes, intermediate-temperature solid oxide fuel cells and solid oxide electrolysis cells,<sup>1</sup> and partial oxidation of methane for natural gas processing.<sup>2</sup> The operation of membranes in realistic operating scenarios may lead to changes in the phase formation, interfacial characteristics, and microstructure of material systems, thus affecting performance. With decreasing thickness of membranes aimed at enhanced transport, surface and interfacial effects become more important and can dramatically impact membrane performance.

The purpose of this themed collection is to provide a snapshot of current research in the field and highlight challenges and opportunities. The use of ceramic-based ion conducting membranes for a wide range of applications in energy conversion and storage is a challenging task; however, the research outlined in this collection contributes to an improved understanding of the fundamentals and new materials opportunities and approaches, while providing

## Introduction to 'Conducting ceramic membranes for energy conversion and storage'

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concurrent opportunities for early-career researchers to publish alongside established leaders in the field. This themed collection consists of 12 papers addressing the following primary topics:

- Li-based solid state batteries.
- Beyond Li conductors (Na, K).

• Protonic ceramic reversible fuel cells: electrolyte and anode/cathode electrode and catalyst design, cell components, cell design, reversible and dynamic operation, and testing.

• Oxygen-ion fuel cells and electrolysis cells, cell components, cell design,



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*Department of Energy's Savannah River National Laboratory. He has published ~120 journal articles, holds five patents and has authored and coauthored ~150 presentations at national and international venues. He is a Fellow of the American Ceramic Society (FACERs), a Fellow of the Royal Society of Chemistry in the UK (FRSC), an Academician of the World Academy of Ceramics and a NETL ORISE Faculty Fellow, received the Brimacombe Medalist Award and the Young Leader International Scholar Award from The Minerals, Metals & Materials Society, the Navrotsky Award for Experimental Thermodynamics and the Karl Schwartzwalder-Professional Achievement in Ceramic Engineering (PACE) Award from the American Ceramic Society (Awarded to top Ceramic Engineer in Country, 40 or under). Professor Brinkman currently serves as the Editor of Journal of Materials Science and the co-director of Clemson's Center for Nuclear Environmental Engineering Sciences and Radioactive Waste Management (NEESRWM).*

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reversible and dynamic operation, and testing.

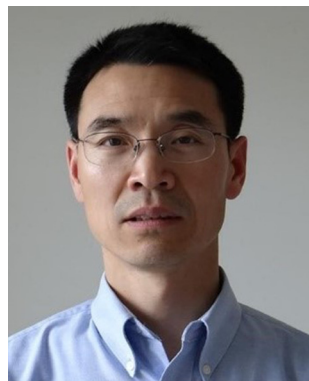
- Ceramic-based oxygen and hydrogen separation membranes and membrane systems for natural gas processing and upgrading.
- Computational materials science of ceramic ionic conductors.

Highlights include work by Sun *et al.* (<https://doi.org/10.1039/d2ma01003h>), who present a review linking structure with ionic conduction mechanisms for solid-state proton and hydride anion materials.

Zheng *et al.* (<https://doi.org/10.1039/d3ma01167d>) examine a triple oxygen,

proton and electron conducting candidate material,  $\text{PrNi}_{0.7}\text{Co}_{0.3}\text{O}_3$ , under dynamic operating conditions to investigate the degradation behaviors *via* novel accelerated stress testing.

Sozal *et al.* (<https://doi.org/10.1039/d3ma00793f>) fabricated patterned Ag electrodes on BZCYb4411 proton-conducting



**Fanglin (Frank) Chen**

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*Georgia Institute of Technology (USA). He spent six years as a Senior/Staff Engineer and Task Leader working in the Solid Oxide Fuel Cells Program at the United Technologies Research Center (currently the RTX Technology Research Center) prior to his faculty appointment at the University of South Carolina in Fall 2007. Dr Chen was a Summer Faculty Fellow at the Air Force Research Laboratory (2009 and 2010) and at the NASA Glenn Research Center (2022). Dr Chen is a core faculty member of the South Carolina SmartState Solid Oxide Fuel Cell Center, leading materials development and electrochemical performance evaluation activities. Dr Chen's primary teaching responsibilities at the University of South Carolina are in the areas of engineering materials and fuel cell technologies. His research interests are in the area of materials design for solid oxide fuel cells, solid oxide electrolysis cells, and gas separation membranes. Dr Chen has authored/co-authored more than 250 peer-reviewed journal articles and holds 12 US patents in his research areas. Dr Chen has received several awards and recognitions, including the Great Job Award (2002 and 2007) and Outstanding Achievement Award (2005) from the United Technologies Research Center, the Rising Star Faculty Award (2010), the Young Investigator Award (2010), the Research Progress Award (2012), the Research Achievement Award (2016), and the Breakthrough Leadership in Research Awards (2019) from the University of South Carolina, and the South Carolina Governor's Young Scientist Award (2013). Dr Chen serves as the Chief Specialty Editor for *Frontiers in Energy Research – Fuel Cells, Electrolyzers and Membrane Reactors*, and Associate Editor for *International Journal of Hydrogen Energy*. Dr Chen also serves on the editorial board of *Clean Energy and Ceramics*.*



**Dong Ding**

*Dr Dong Ding is a distinguished staff engineer/scientist in the directorate of Energy and Environmental Science & Technology at Idaho National Laboratory, leading the electrochemical processing and electrocatalysis (EPEC) team consisting of >20 researchers. Dr Ding is a technical lead and steering committee member for two hydrogen related consortia: HydroGEN of the Energy Materials Network (EMN) and*

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electrolyte by photolithography and E-beam evaporation to characterize interfacial properties, leading to improved intermediate-temperature proton ceramic fuel cells (IT-PCFC).

Ishii *et al.* (<https://doi.org/10.1039/d3ma00901g>) present an alternative use of the popular solid-state ceramic-based Li-ion conductor LLZO as a potential proton-conducting solid-state electrolyte for fuel cells and electrolyzers.

Rowberg *et al.* (<https://doi.org/10.1039/d3ma00308f>) use computational methods to demonstrate that high ionic conductivity can be achieved through optimizing synthesis conditions to maximize the concentrations of interstitial protons in conventional BaZrO<sub>3</sub> and BaCeO<sub>3</sub> proton-conducting materials systems.

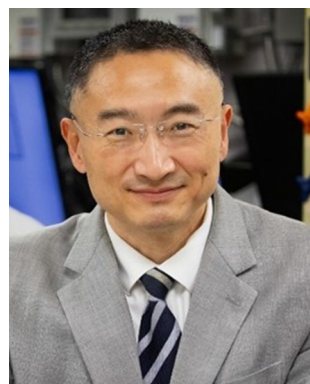
Fischer *et al.* (<https://doi.org/10.1039/d3ma01095c>) discuss work on a dual-phase composite 60 wt% Ce<sub>0.8</sub>Gd<sub>0.2</sub>O<sub>2-d</sub>-40 wt% FeCo<sub>2</sub>O<sub>4</sub> (60CGO20-FCO) oxygen transport membrane (OTM) with demonstrated high levels of oxygen permeability. They discuss the stability and oxygen permeance related to mechanically and chemically stable compositions and an optimized microstructure.

We appreciate all authors for their submissions and interest in the themed collection and the reviewers for their comments and suggestions. We would like to thank the editorial staff of the Royal Society of Chemistry (RSC) for assistance putting together this themed collection and hope that the reader will enjoy this collection of articles highlighting current trends in the

field of conducting ceramic membranes for energy conversion and storage.

## References

- 1 P. S. Gaikwad, K. Mondal, Y. K. Shin, A. C. T. van Duin and G. Pawar, *npj Comput. Mater.*, 2023, **9**, 149.
- 2 G. Chen, A. Feldhoff, A. Weidenkaff, C. Li, S. Liu, X. Zhu, J. Sunarso, K. Huang, X.-Y. Wu, A. F. Ghoniem, W. Yang, J. Xue, H. Wang, Z. Shao, J. H. Duffy, K. S. Brinkman, X. Tan, Y. Zhang, H. Jiang, R. Costa, K. A. Friedrich and R. Kriegel, *Adv. Funct. Mater.*, 2022, **32**, 2105702.



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