Functionalized Metal-Supported Reversible Protonic Ceramic Cells with Exceptional Performance and Durability

Yuhao Wang, Yufei Song, Jiapeng Liu, Kaichuang Yang, Xidong Lin, Zhibin Yang, and Francesco Ciucci*

Reversible protonic ceramic cells (RePCCs) are limited by several factors, including high cost, poor stability, and insufficient fuel electrode activity toward fuel oxidation/generation reactions. Herein, a novel Ni–Fe metal-supported RePCC (MS-RePCC) to address these issues simultaneously is proposed. Specifically, the Ni–Fe support possesses good mechanical strength and thermal compatibility with cermet-based electrodes/electrolytes, ensuring a facile cell fabrication and robust durability. Density functional theory calculations suggest that Fe in the Ni–Fe support enhances the fuel electrode functional layer by providing additional and more active sites for the electrocatalytic reactions. The as-fabricated MS-RePCC at 700 °C achieves an excellent peak power density (PPD) of 586 mW cm$^{-2}$ and an electrolysis current of $428$ mA cm$^{-2}$ (at 1.3 V). Furthermore, the cell is exceptionally stable, as evidenced by 930 h of fuel cell operation with ultralow degradation ($\approx 0.78\%$ kh$^{-1}$), and much better than an analogous anode-supported cell ($\approx 17.78\%$ kh$^{-1}$). In addition, the cell is stable for 50 h of reversible fuel cell/electrolyzer cycling, further demonstrating the potential of this MS-RePCC. This article proposes a simple and new approach to enhance the electrochemical activity and durability of RePCC, thereby accelerating the commercialization of this technology.

1. Introduction

The development of efficient energy storage/conversion technologies is crucial to support the rapid growth of power generation from renewable resources, including solar and wind.[11] Reversible solid oxide cells (ReSOCS) are excellent candidates for that because they can provide highly efficient, scalable, and fuel-flexible energy generation and storage at the grid level. ReSOCS can either function as fuel cells to generate power or as electrolyzers to produce hydrogen.[2] Conventional oxygen-conducting ReSOCS usually operate at high temperatures (700–900 °C) to activate oxygen conduction.[3] Working at these high-temperature triggers several issues, including poor durability and high cost of components, including interconnects and sealings. Compared to ReSOCS, reversible protonic ceramic cells (RePCCs) can operate at lower temperatures (500–700 °C) due to the lower activation energy of proton conduction in oxides compared to oxygen conduction.[4]

Despite the widespread interest in this technology, RePCCs have drawbacks, such as long-term operational degradation,[4a] which limit their large-scale diffusion and application. The literature[4b] suggests that a major issue with commonly used Ni/electrolyte cermet supports is poor durability during cycling.[4c] Metal-supported ReSOCS (MS-ReSOCS)[5] are promising alternatives to conventional Ni-based anode-supported SOCs.[6] By replacing expensive ceramic materials with inexpensive metals as the support (Table S1, Supporting Information), MS-ReSOCS are characterized by lower cost, higher mechanical strength, better redox tolerance, and more effective thermal cycling ability.[7] Common MS-ReSOC support materials are Ni-based or Fe-based alloys.[8a] Ni-based materials have shown excellent catalytic activity.[10] However, high thermal expansion coefficient (TEC, $\approx 16–18 \times 10^{-6} \text{K}^{-1}$[11]) and poor redox tolerance[12] limit the long-term operational stability of Ni-based cells. In comparison to Ni, Fe-based alloys (e.g., SUS430,[13] ZMG232,[14] and Crofer22 APU[15]) are cheaper (Table S1, Supporting Information) and have a lower TEC value ($10–12 \times 10^{-6} \text{K}^{-1}$[16][17]) but are characterized by lower catalytic activity, compromising cell performance.[18]

To overcome the challenges outlined earlier, Ni–Fe alloy was used as a support to fabricate a metal-supported RePCC...
(MS-RePCC). This is in contrast with conventional RePCCs, which are cermet supported (Figure 1a). Specifically, the fabricated full cell consisted of 1) an alloy of Ni and Fe as the support; 2) Ni–BaZr0.5Ce0.5Y0.1Yb0.1O1.9 (BZYb) as the fuel electrode; and 3) BZCYyb as the electrolyte and Sr0.9Ce0.1Fe0.8Ni0.2O3 (SCF) as the air electrode (Figure 1b). The alloy showed excellent compatibility and synergy with the Ni/electrolyte functional cermet.[21] Further, the alloy was thermally compatible with the fuel electrode,[8] ensuring robust operational durability and easy cosintering during cell fabrication.[22] Fe was also found to diffuse from Ni–Fe to the fuel electrode during cell preparation (Figure 2e), providing additional active sites for hydrogen oxidation reaction (HOR)/hydrogen evolution reaction (HER),[23] while simultaneously overcoming the complexity and high cost of metal impregnation.[24] In turn, the addition of Fe to the electroactive layer enhanced the HER kinetics as suggested by DFT calculations, which show that H° adsorbs more weakly on Ni–Fe than on Ni. The developed MS-RePCC exhibited a high PPD of 586 mW cm−2 in fuel cell mode and a current density of −428 mA cm−2 at 1.3 V in electrolysis mode at 700 °C. Remarkably, in fuel cell mode, the developed MS-RePCC had an ultralow degradation rate of 0.78 % kh−1 during 930 h of operation. As a comparison, the degradation rate of an analogous anode-supported cell (Ni–BZYb/BZYb|SCF) prepared by one of the coauthors was measured to be ≈17.78% kh−1.[25] Furthermore, the fabricated MS-RePCC could be operated reversibly for 50 h (25 cycles) at 600 °C without noticeable degradation.

![Figure 1. Schematic depiction of a) a conventional anode-supported RePCC and b) a Ni–Fe metal-supported RePCC.](image1)

![Figure 2. a) XRD patterns of NFO-1400 °C and Ni–Fe–H2 samples. XPS spectra of the b) Ni 2p and c) Fe 2p of the sintered and reduced samples. d) SEM cross-sectional image of the Ni–Fe[Ni–BZYb|BZYb|SCF cell. e) Cross-sectional EDS map of the Ni–Fe[Ni–BZYb|BZYb|SCF cell.](image2)
2. Results and Discussion

2.1. Physicochemical Properties

The Ni–Fe precursors (NiO–Fe₂O₃) were prepared by ball milling NiO and Fe₂O₃ in a molar ratio of 1:1 (Figure S1, Supporting Information). X-ray diffraction (XRD) (Figure 1a) analysis showed that the Ni–Fe precursor powders, calcined at 1400 °C, formed single-phase NiFe₂O₄ (NFO, JCPDS 54-0964, Figure 1a). NFO was then reduced in H₂ at 700 °C for 10 h to form the Ni–Fe alloy (Ni–Fe–H₂, JCPDS 47-1405, Figure 1a). To identify Ni and Fe oxidation states before and after reduction in H₂, X-ray photoelectron spectroscopy (XPS) was performed (Figure 1b,c). Ni and Fe in NFO-1400 °C were found as Fe²⁺/Fe³⁺ and Ni²⁺/Ni³⁺, while the Ni–Fe-containing and H₂-reduced samples (Ni–Fe–H₂) also had noticeable metallic Fe⁰ and Ni⁰ peaks.[26] XRD analysis of the synthesized SCFN powder (Figure S2, Supporting Information) suggests that, in agreement with previous studies, SCFN consisted of two major perovskite phases (T-SCFN and RP-SCFN) and two minor oxide phases (NiO and CeO₂).[22,25]

The cross section of the reduced MS-RePCC was imaged by scanning electron microscopy (SEM), as shown in Figure 2d. The porous Ni–Fe alloy support layer (Figure S3, Supporting Information) was 650 μm thick and made tight contact with the 90 μm-thick Ni–BZCYYb layer. The thicknesses of the dense BZCYYb electrolyte and porous SCFN cathode layers were 30 and 35 μm, respectively. Energy-dispersive X-ray spectroscopy (EDS) indicates that the cell had a multilayer structure (Figure 2e). It is particularly important to note that Fe diffused into the fuel electrode from the support after cosintering, as highlighted by the yellow dotted line in Figure 2e and the cross-sectional EDS line scans shown in Figure S9, Supporting Information.

2.2. Sintering Behavior

To allow the diffusion of reactants and products and achieve high performance, the MS-RePCCs’ electrodes and supports need to be porous. Furthermore, all of its components need to be thermally compatible.[3] Figure 3a compares the diameter of NFO, NiO–BZCYYb, and BZCYYb pellets after 1 h of sintering in the 1200–1500 °C range. As the temperature increased, all three samples shrunk with similar compactification rates, implying that NFO, BZCYYb, and NiO–BZCYYb are likely to experience negligible stresses during cosintering. It is worth noting that even after high-temperature sintering, NFO maintained a porosity in the 62–48% range (Figure S4, Supporting Information). The TEC is another important parameter used to evaluate the thermal compatibility among MS-RePCC components.[27] The TEC of NFO estimated from high-temperature XRD (Figure S5, Supporting Information) is 11.97 × 10⁻⁶ K⁻¹ in the 100–800 °C range (Figure 3b). This value is close to those of NiO–BZCYYb (10.42 × 10⁻⁶ K⁻¹, close to reported literature[28]) and BZCYYb (9.82 × 10⁻⁶ K⁻¹, close to reported literature[29]), demonstrating that the support has excellent compatibility with other components. It is worth noting that the TEC value of NFO is also similar to that of other proton ceramic conductors and other reported Ni–Fe alloys (i.e., 10.2 × 10⁻⁶ K⁻¹ of BaZr₀.₇₅Y₀.₂₅O₃–δ[30] 11.2 × 10⁻⁶ K⁻¹ of BaCeO₃–δ[31] 11.6 × 10⁻⁶ K⁻¹ of BaCr₀.₈Y₀.₂O₃–δ[32] and Table S6, Supporting Information).

To characterize the Fe diffusion, two pressed NiO–BZCYYb pellets were prepared, one of the pellets was used as control and the other was placed above powders of NFO (Figure S10, Supporting Information). After sintering (at 1400 °C for 10 h) and polishing, the two pellets were analyzed using EDS, XRD, and XPS. Fe was detected only in the NFO–BZCYYb sample, as evidenced by EDS (Figure S11, Supporting Information), XPS (Figure S12, Supporting Information), and XRD (Figure S13, Supporting Information).

2.3. Electrochemical Performance

A cell with a Ni–Fe[Ni–BZCYYb]BZCYYb|SCFN configuration was prepared (Figure 2c). Before testing, H₂ was fed into the fuel electrode of the cell for 10 h at 700 °C so that NFO could be reduced to Ni–Fe alloy and NiO–BZCYYb to Ni–BZCYYb. During fuel cell testing, the anode was fed H₂, while the cathode was exposed to ambient air. As shown in Figure 4a, the

![Figure 3](https://www.advancedsciencenews.com)

**Figure 3.** a) Shrinkage of BZCYYb, NiO–BZCYYb, and NFO pellets sintered from 1200 to 1500 °C. b) TECs of BZCYYb, NiO–BZCYYb, and NFO with the temperature range of 100–800 °C.
MS-RePCC had PPDs of 586, 435, 320, 222, and 139 mW cm⁻² at 700, 650, 600, 550, and 500 °C, respectively. The performance exceeds that of many previously reported anode-supported PCFCs, as shown in Table S2, Supporting Information. In addition, the low impedance measured by electrochemical impedance spectroscopy (EIS) at the open-circuit voltage (OCV) confirms low cell polarization (Figure S6, Supporting Information). It is worth noting that the MS-RePCC was exceptionally stable for about 930 h under H₂/ambient air operation at 600 °C. The calculated degradation rate of the fuel cell is only 0.078% kh⁻¹, a value significantly lower than those reported in the literature (Table S3, Supporting Information) and within the range of commercial SOFC (0.2–1.6% kh⁻¹).[33] We must stress again that an analogous anode-supported cell (Ni–BZCYYb BZCYYb|SCFN) previously prepared by one of the coauthors of this article could only be operated for 300 h and had a far higher degradation rate of 0.78% kh⁻¹. Such a significant difference highlights the excellent stability of the MS-RePCC developed here.

Figure 4. a) I–V and I–P curves of the MS-RePCC in H₂ fuel at 500–700 °C. b) Operational stability of the MS-RePCC in H₂ fuel at 600 °C. c) I–V curves of the MS-RePCC measured in a reversible mode in H₂ fuel at 600–700 °C. d) Continuous cyclic operation between electrolysis and fuel cell mode at 600 °C.

The fabricated MS-RePCC was also tested for reversible performance. The I–V curves were measured in the temperature range of 600–700 °C by feeding pure H₂ and air with 3 vol% H₂O to the fuel and air electrodes, respectively (Figure 4c). It can be observed that the current densities at 1.3 V were −428, −331, and −124 mA cm⁻² at 700, 650, and 600 °C, respectively. Electrolysis performance exceeded that of many previously reported anode-supported cells (Table S4, Supporting Information). Cell reversibility was evaluated by cycling between 1.3 V (electrolysis mode) and 0.9 V (fuel cell mode) at 600 °C. The cell operated stably for 50 h (25 cycles) at 600 °C (Figure 4d). The MS-RePCC’s performance also demonstrates the potential of Ni–Fe support in water splitting in RePCCs.

2.4. DFT Calculations

We carried out DFT calculations to elucidate the contribution of the Ni–Fe support to HER (Figure 5). In particular, we computed the H⁻ adsorption energy on the Ni(111) surface. As shown in the literature, H⁻ adsorption on Ni(111) can occur at four different sites (i.e., face-centered cubic (FCC), hexagonal close packed (HCP), bridge, and top) with the fcc being the most favorable.[35] (Figure S7, Supporting Information). For Ni–Fe, the (001) termination is the most stable.[36] In that termination, H⁻ adsorption can occur at three different sites (i.e., Fe top, Ni top, and bridge) (Figure S8, Supporting Information). H⁻ adsorption on Ni–Fe (001) is favored at the bridge site with a free energy (ΔGₜₚᵣₑₒ₅) of −0.11 eV. In contrast, the ΔGₜₚₑₒ₅ on the Ni (111) is more negative (−0.28 eV), implying a stronger interaction between Ni and H⁻.[37] To unveil the mechanisms leading to the different adsorption energies of H⁻ between the substrates, we further calculated the Bader charge, listing the resulting values in Table S5, Supporting Information. The weaker interaction between Ni–Fe (001) and H⁻ can be attributed to the charge transfer from surface Fe to surface Ni in Ni–Fe (001), where a negatively charged Ni enhances the repulsion between the slab and the adsorbed H⁻. The weakened adsorption of H⁻ decreases the energy required for desorption on Ni–Fe (001), as shown in Figure 5c. Therefore, HER on the Ni–Fe surface is expected to be more favorable than on pure Ni, in agreement with the excellent electrochemical performances of the metal-supported cell shown in Figure 4c.
3. Conclusion

This work develops a novel Ni–Fe support for high-performance and exceptionally durable MS-RePCC in the Ni–Fe|Ni–BZCY Yb|BZCY Yb|SCFN configuration. This Ni–Fe alloy support exhibited similar sintering shrinkage characteristics and TECs to BZCY Yb and NiO–BZCY Yb, implying facile cell fabrication and long-term stability. The fabricated MS-RePCC achieved a high PPD of 586 mW cm\(^{-2}\) at 700 °C in fuel cell mode, while exhibiting exceptional operational stability of about 930 h with an ultralow degradation rate of \(0.78\%\ h^{-1}\). In reversible tests, the fabricated MS-RePCC has the current densities of \(-428\) mA cm\(^{-2}\) at 1.3 V at 700 °C, while retaining robust reversible cycling of 50 h in 25 fuel cell/electrolysis cycles at 600 °C. Furthermore, DFT calculations showed that Fe self-diffusion from the support to the fuel electrode facilitates HER. This study provides a promising direction for the development of future commercial RePCCs with exceptional performance and durability.

4. Experimental Section

Materials Synthesis and Cell Fabrication: NiO and Fe\(_2\)O\(_3\) (molar ratio of 1:1) with 20 wt% extra corn starch (AR, Sinopharm Chemical Reagent Co., Ltd) were first mixed and ball milled (QM-3SP04) for 24 h and then dried overnight. The BZCY Yb electrolyte material was synthesized using a conventional solid-state reaction method.[21] NiO–BZCY Yb was prepared by ball milling 45 wt% of NiO and 55 wt% of BZCY Yb. An extra 10 wt% of corn starch was added. SCFN was synthesized by a combined EDTA–CA complexing method described in the study by Wang et al.[22] Metal-supported half cells in the NiO–Fe\(_2\)O\(_3\)|NiO–BZCY Yb|BZCY Yb configuration were prepared by copressing and cosintering and then sintered at 1400 °C for 10 h in air to densify the electrolyte. The SCFN slurries were finally sprayed onto the surface of the BZCY Yb electrolyte with an active area of 0.4 cm\(^2\) and then sintered in air at 900 °C for 5 h. More details are given in the Supporting Information.

Electrochemical Measurements: I–V data were obtained using a Keysight B2901A source meter. Before the test, H\(_2\) was fed into the support side for 10 h of in situ reduction at 700 °C. The MS-RePCC cells were tested between 500 and 700 °C (for fuel cell testing) and 600 and 700 °C (for reversible cell testing). Potentiostatic EIS was carried out at the OCV using a VSP Biologic workstation. More details are given in the Supporting Information.

Characterizations: The crystal structures were analyzed by XRD (Philips X’Pert) with Cu K\(_\alpha\) radiation (\(\lambda = 1.5406\) Å, 40 kV, 40 mA). The scanning angle 2\(\theta\) ranged from 20° to 80° with steps of 0.02°. TEC was calculated from high-temperature XRD carried out in the 100–800 °C range. XPS (PHI 5000 VersaProbe) was performed on an Axis Ultra DLD instrument with an achromatic Mg K\(_\alpha\) X-ray source. TEM characterization was performed on a JEOL-6390 instrument, and EDS was conducted on a Bruker QUANTAX 70 instrument.

DFT Calculations: All spin-polarized DFT calculations were performed using the Vienna ab initio simulation package[18] (VASP) with the projector-augmented wave (PAW) method.[19,20] The Perdew–Burke–Ernzerhof (PBE) functional under the generalized gradient approximation (GGA) scheme was used to handle electron-exchange correlations.[21] The energy cutoff for the plane-wave basis set was 450 eV. A vacuum layer along the out-plane direction of 15 Å was constructed to limit the interactions between adjacent slabs. The Brillouin zone for Ni(111) and Ni–Fe(001) was sampled by a \(\Gamma\) point mesh. The Broyden method was employed for the structural relaxation until the atomic force maximum was calculated from high-temperature XRD carried out in the 100–800 °C range. The catalytic activity for HER was correlated to the hydrogen adsorption Gibbs free energy, \(\Delta G_{\text{H}}\), as proposed by Noskov et al.[22] \(\Delta G_{\text{H}}\) can be defined as

\[
\Delta G_{\text{H}} = \Delta E_{\text{H}} + \Delta E_{\text{ZPE}} - T \Delta S_{\text{H}}
\]

where the hydrogen adsorption energy, \(\Delta E_{\text{H}}\), is given by

\[
\Delta E_{\text{H}} = E_{\text{H}} - E_{\text{AB}} - \frac{1}{2} E_{\text{H}}^0
\]

and \(E_{\text{H}}\) and \(E_{\text{AB}}\) are the total energies of the catalyst with and without a hydrogen atom, respectively. In this study, \(\Delta E_{\text{ZPE}} - T \Delta S_{\text{H}}\) (zero-point energy \(\Delta E_{\text{ZPE}}\), temperature \(T\), and entropy \(\Delta S_{\text{H}}\)) was selected as 0.24 eV according to the literature.[22]

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.
Acknowledgements

Y.W., Y.S., and J.L. contributed equally to this work. Y. W., Y. S., J. L., X. L., and F. C. thank the Research Grant Council of Hong Kong for support through the projects 16201820 and 16206019. K. Y. and Z. Y. acknowledge the National Natural Science Foundation of China (52072405). The authors also thank the Advanced Engineering Materials Facilities (AEMF) and the Materials Characterization and Preparation Facilities (MCPF) of HKUST for their kind technical assistance.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

metal-supported electrolyzers, metal-supported fuel cells, Ni–Fe alloys, reversible protonic ceramic cells, ultralow degradation

Received: October 18, 2021
Revised: November 7, 2021
Published online: December 2, 2021

[1] a) M. B. Mogensen, Curr. Opin. Electrochem. 2020, 21, 265; b) D. Huan, N. Shi, L. Zhang, W. Tan, Y. Xie, W. Wang, C. Xia, R. Peng, Y. Lu, ACS Appl. Mater. Interfaces 2018, 10, 1761.
[2] M. S. Khan, X. Xu, R. Knibbe, Z. Zhu, Renewable Sustainable Energy Rev. 2021, 143, 110918.
[3] Z. Han, Y. Wang, Z. Yang, M. Han, J. Mater. Sci. Technol. 2016, 32, 681.
[4] a) C. Duan, R. Kee, H. Zhu, N. Sullivan, L. Zhu, L. Bian, D. Jennings, R. O’Hayre, Nat. Energy 2019, 4, 230; b) S. Choi, T. C. Davenport, S. M. Haile, Energy Environ. Sci. 2019, 12, 206; c) Y. Song, Y. Chen, W. Wang, C. Zhou, Y. Zhong, G. Yang, W. Zhou, M. Liu, Z. Shao, Joule 2019, 3, 2842; d) C. Duan, J. Huang, N. Sullivan, R. O’Hayre, Appl. Phys. Rev. 2020, 7, 011314.
[5] P. Tanasini, M. Cannarozzo, P. Costamagna, A. Faes, J. Van Herle, A. Hessler-Wyser, C. Comninellis, Fuel Cells 2009, 9, 740.
[6] W. Zhang, Y. H. Hu, Energy Sci. Eng. 2021, 9, 984.
[7] V. V. Krishnan, WIREs Energy Environ. 2017, 6, e246.
[8] N. Xu, M. Chen, M. Han, J. Alloys Compd. 2018, 765, 757.
[9] a) M. C. Tucker, J. Power Sources 2010, 195, 4570; b) Z. Han, Z. Yang, M. Han, Int. J. Hydrogen Energy 2016, 41, 10935.
[10] Q.-A. Huang, J. Oberste-Berghaus, D. Yang, S. Yick, Z. Wang, B. Wang, R. Hui, J. Power Sources 2008, 177, 339.
[11] F. C. Nix, D. MacNair, Phys. Rev. 1940, 60, 597.
[12] H. Ding, Z. Tao, S. Liu, J. Zhang, Sci. Rep. 2015, 5, 18129.
[13] J.-T. Gao, J.-H. Li, Y.-P. Wang, C.-J. Li, C.-X. Li, J. Therm. Spray Technol. 2020, 29, 2001.
[14] X. Montero, F. Tietz, D. Stöver, M. Cassir, I. Villarreal, Corros. Sci. 2009, 51, 110.
[15] K. Lee, J. Kang, J. Lee, S. Lee, J. Bae, Int. J. Hydrogen Energy 2018, 43, 3786.
[16] C. Jia, Y. Wang, S. Molin, Y. Zhang, M. Chen, M. Han, J. Alloys Compd. 2019, 787, 1327.
[17] E. Dogdibegovic, R. Wang, G. Y. Lau, M. C. Tucker, J. Power Sources 2019, 410–411, 91.
[18] Y. Larrinog, M.-L. Fontaine, Solid Oxide Fuels Cells: Facts and Figures: Past Present And Future Perspectives For SOFC Technologies (Eds: J. T. S. Irvine, P. Connor), Springer London, London 2013, p. 71, https://doi.org/10.1007/978-1-4471-4456-4_4.
[19] L. Yang, S. Wang, K. Blinn, M. Liu, Z. Liu, Z. Cheng, M. Liu, Science 2009, 326, 126.
[20] Y. Song, Y. Chen, M. Xu, W. Wang, Y. Zhang, C. Yang, R. Ran, W. Zhou, Z. Shao, Adv. Mater. 2020, 32, 1906979.
[21] A. Faes, A. Hessler-Wyser, D. Presvytes, C. G. Vayenas, J. Van Herle, Fuel Cells 2009, 9, 841.
[22] X. Wang, K. Li, L. jia, Q. Zhang, S. P. Jiang, B. Chi, J. Pu, L. Jian, D. Yan, J. Power Sources 2015, 277, 474.
[23] H. A. Shahri, M. H. D. Othman, M. A. Mohamed, T. A. Kurniawan, S. M. Jamil, Fuel Process. Technol. 2021, 212, 106626.
[24] Z. Han, Z. Yang, M. Han, J. Alloys Compd. 2018, 750, 130.
[25] Y. Song, J. Liu, Y. Wang, D. Guan, A. Seong, M. Liang, M. J. Robson, X. Xiong, Z. Zhang, G. Kim, Z. Shao, F. Ciucci, Adv. Mater. 2021, 11, 2101899.
[26] U. Y. Qazi, C.-Z. Yuan, N. Ullah, Y.-F. Jiang, M. Imran, A. Zeb, S.-J. Zhao, R. Jia, A.-W. Xu, ACS Appl. Interfaces 2017, 9, 28627.
[27] Y. Zhang, B. Chen, D. Guan, M. Xu, R. Ran, M. Ni, W. Zhou, R. O’Hayre, Z. Shao, Nature 2021, 591, 246.
[28] A. Loken, S. Ricote, S. Wachowski, Crystals 2018, 8, 365.
[29] D. Xie, K. Li, Y. Zhang, D. Yan, L. Jia, B. Chi, J. Pu, J. Li, Int. J. Hydrogen Energy 2021, 46, 10007.
[30] D. Han, N. Hatada, T. Uda, J. Am. Ceram. Soc. 2016, 99, 3745.
[31] S. Yamanaka, M. Fujikane, T. Hamaguchi, H. Muta, T. Oyama, T. Matsuda, S.-I. Kobayashi, K. Kurosaki, J. Alloys Compd. 2003, 359, 109.
[32] L. Malavasi, C. Ritter, G. Chiodelli, Chem. Mater. 2008, 20, 2343.
[33] a) Q. Fang, U. de Haart, D. Schäfer, F. Thaler, V. Rangel-Hernandez, R. Peters, L. Blum, J. Electrochem. Soc. 2020, 167, 144508; b) D. Yan, L. Liang, J. Yang, T. Zhang, J. Pu, B. Chi, J. Li, Energy 2017, 125, 663; c) U. S. O. Energy, Report on the Status of the Solid Oxide Fuel Cell Program; https://www.energy.gov/fe/report-congress-status-solid-oxide-fuel-cell-program (accessed: May 2021).
[34] C. Duan, R. J. Kee, H. Zhu, C. Karakaya, Y. Chen, S. Ricote, A. Jarry, E. J. Crumlin, D. Hook, R. Braun, N. P. Sullivan, R. O’Hayre, Nature 2018, 557, 217.
[35] J. Greeley, M. Mavrikakis, Surf. Sci. 2003, 540, 215.
[36] A. A. Mubarak, J. Magn. Magn. Mater. 2016, 401, 816.
[37] P. Wang, X. Zhang, J. Zhang, S. Wan, S. Guo, G. Lu, J. Yao, X. Huang, Nat. Commun. 2017, 8, 14580.
[38] G. Kresse, J. Hafner, Phys. Rev. B 1993, 47, 558.
[39] a) G. Kresse, J. Furthmüller, Comput. Mater. Sci. 1996, 6, 15; b) P. E. Blöchl, Physical Review B 1994, 50, 17953.
[40] J. P. Perdew, K. Burke, M. Ernzerhof, Phys. Rev. Lett. 1996, 77, 3865.
[41] J. K. Nørskov, T. Bligaard, A. Logadottir, J. R. Kitchin, J. G. Chen, S. Pandelov, U. Stimming, J. Electrochem. Soc. 2005, 152, J23.
[42] S. H. Noh, M. H. Seo, J. Kang, T. Okajima, B. Han, T. Ohsaka, NPG Asia Mater. 2016, 8, e312.