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Thermo-mechanical stability of multi-scale-architectured thin-film-based solid oxide fuel cells assessed by thermal cycling tests

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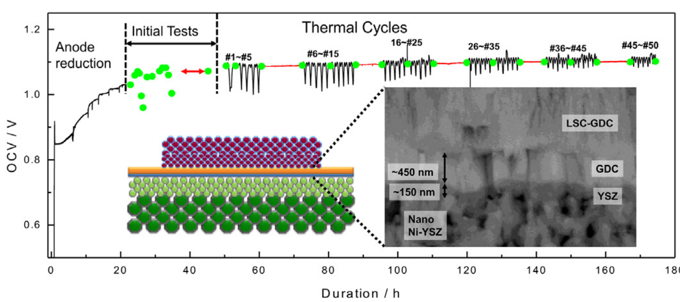
HIGHLIGHTS

- Improved thermo-mechanical stability of thin film-SOFCs (TF-SOFCs) is reported.
- The TF-SOFC is composed of a 600-nm-thick electrolyte and nano-structured electrodes.
- Multi-scale-architecture enables the TF-SOFC to survive 50 thermal cycles (TCs).
- The TF-SOFC sustains a peak power density over 1 W cm^{-2} at 600 °C after 50 TCs.
- The whole cell comes out intact after over 150 h of operation and 50 TCs.

GRAPHICAL ABSTRACT



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ABSTRACT

The thermo-mechanical stability of a thin-film and nanostructure-based SOFC (TF-SOFC) is assessed by thermal cycling tests. An ultrathin bi-layer electrolyte composed of 150-nm-thick yttria-stabilized zirconia (YSZ) and 450-nm-thick gadolinia-doped ceria (GDC) is successfully built on a NiO-YSZ anode support the microstructure scale of which changes from μm to nm (multi-scale architecture). The concept of multi-scale architecture in the TF-SOFC not only enables the reliable implementation of thin-film electrolytes and nanostructured electrodes to improve the critical low-temperature performance of the SOFC but also secures the thermo-mechanical stability of TF-SOFC. Competent cell performance is obtained, including a peak power density about 1.4 W cm^{-2} at 600 °C. The TF-SOFC survives 50 thermal cycle tests between 600 and 400 °C over 124 h without suffering a drastic failure. Although some cell output degradation is observed after the thermal cycling tests, the cell sustains a peak power density over 1 W cm^{-2} at 600 °C, which indicates the superior thermo-mechanical stability of the multi-scale-architectured TF-SOFC.

1. Introduction

In the field of solid oxide fuel cell (SOFC) research, thin-film and nanostructured components are being implemented at an ever-increasing rate. In conventional, powder-processed SOFCs, thin-film components are often employed to avoid high processing temperatures that would cause chemical reactions between the cell components, *e.g.*, a ceria-base barrier layer [1–3]. More serious applications of thin-film components, however, have been attempts to develop micro-SOFCs based on micro electro-mechanical system (MEMS) techniques [4–11] and to improve the performance

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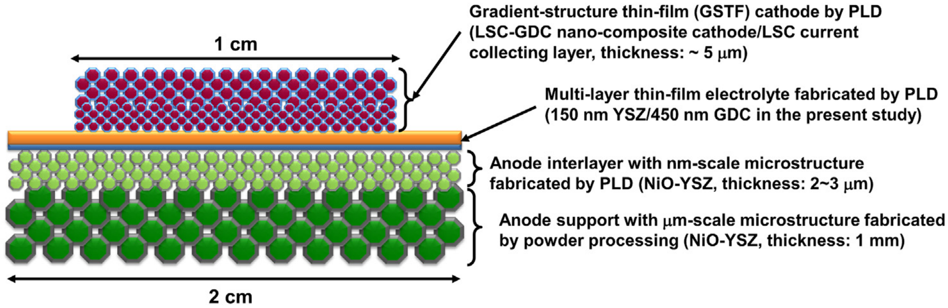

Fig. 1. A schematic showing the concept of the multi-scale-architectured TF-SOFC. The dimensions of the TF-SOFC in the present report are listed.

of low-temperature-operation SOFCs (LT-SOFCs) [12–18]. In particular, MEMS-based micro-SOFCs have attracted attention due to their remarkably high performance at low temperatures including peak power densities over 1 W cm^{-2} at 500 °C [4,8].

Nevertheless, the extremely poor thermo-mechanical stability of the free-standing MEMS platform and the unbearably short lifetime caused by the instability of the nano-porous noble metal electrodes have made this technology unrealistic so far. Very few results have been reported regarding the lifetime or degradation of cells based on this technology [7], and the level of degradation (more than 50% in 12 h at 400 °C [8]) of micro-SOFCs in those reports is far from that needed for practical application. In a previous study by the authors [10], it was shown that a supporting porous structure made out of anodized aluminum oxide (AAO) could improve the degradation level to less than 10% after 17 h (1000 min). Although this was quite a substantial improvement, the degradation is still quite serious.

To alleviate the thermo-mechanical frailty while at the same time obtaining the significantly enhanced low-temperature performance of thin-film and nanostructure-based SOFCs (denoted as TF-SOFCs), the authors investigated the TF-SOFCs built on conventional anode supports in previous reports [12–14]. Through optimization and improvements, peak power densities exceeding 500 mW cm^{-2} at 500 °C in an active area of 1 cm by 1 cm can now routinely be obtained [19]. These achievements were possible by realizing the cell platform based on 'multi-scale architecture'.

In Fig. 1, a schematic shows the concept of multi-scale architecture. The main structural support is fabricated using conventional powder processing and consists of micrometer-scale grains. The anode interlayer, which consists of nanometer-scale grains, is fabricated using thin-film processing (pulsed laser deposition, PLD, in this case) over the anode support to complete the combination of micro to nano-scale (multi-scale) microstructures at the anode. A bi-layer thin-film electrolyte having a thickness less than 1 μm is formed over the nanostructure interlayer. The cathode is composed of a multi-layer structure as well. Nano-composite layers composed of the mixture of electrolyte and electrode materials are deposited using PLD. By controlling the ambient pressure during deposition, a porosity-gradient structure can be realized in the nano-composite cathode [20]. The top layer is a single electrode material layer that functions as a current collecting layer. The lateral dimensions of the cell are at the cm level, so the whole cell contains multiple scales of physical dimensions (cm–mm–μm–nm). This concept is denoted as multi-scale architecture.

There are several critical features that are expected to remarkably improve the thermo-mechanical stability of TF-SOFCs based on multi-scale architecture. First, the ultrathin electrolyte exhibits greatly improved stability in comparison with the free-standing membrane because it is supported by the nano-porous structure. Second, the porosity-gradient structure at both the anode and cathode will sandwich the ultrathin electrolyte; as a result, stronger electrolyte/electrode interfaces can be produced. In addition, the anode and cathode are composed of nano-composites of the electrode and electrolyte materials. Because this composite material is not simply a single material or a nano-porous noble metal, the degradation of the cell is expected to be suppressed to quite an extent.

Even in light of all of these facts, an investigation regarding the durability of a multi-scale-architectured TF-SOFC has never before been quantitatively performed. Therefore, in the present article, the thermo-mechanical stability of the cells on this platform is reported. To assess the thermo-mechanical stability of the multi-

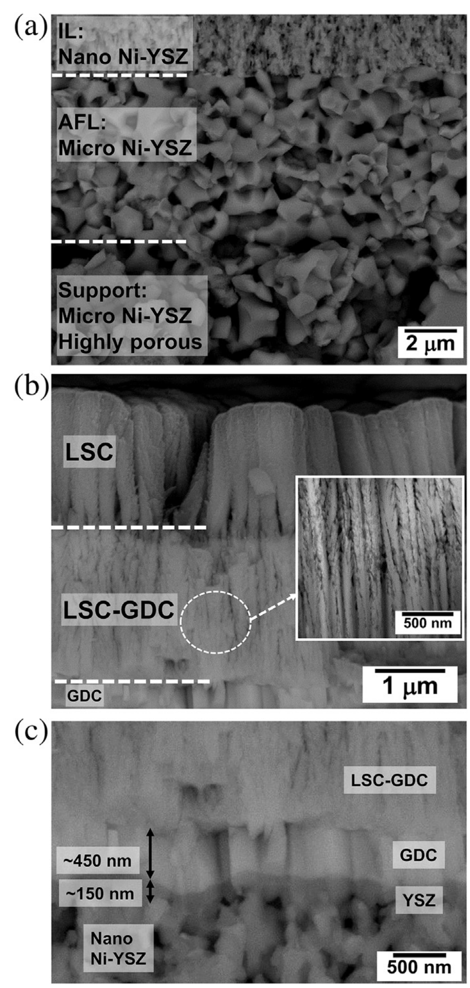

Fig. 2. Cross-sectional SEM micrographs showing (a) the anode structure; (b) the cathode structure (inset shows the porosity-gradient structure at the junction of LSC-GDC layers); and (c) the bi-layer electrolyte structure of the multi-scale-architectured TF-SOFC presented in this study (taken after the cell test).