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Performance enhancement in bendable fuel cell using highly conductive Ag nanowires

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ABSTRACT

Flexible polymer electrolyte fuel cells are made of novel current collectors including highly conductive metal nanowires with extremely high stretchability. Endplates with flexible current collectors maximize clamping forces under bent conditions, which is beneficial in reducing ohmic resistances. These cells show an increased power density as the radius of curvature of the cell decreases. Cells in an asymmetric configuration, where the thicknesses of plates at the anode and cathode sides are different, shows higher power density than symmetric cells because of enhanced normal pressure, and thus, decreased ohmic loss under a given cell curvature. The peak power density of a highly bent stack with a bending radius of 15.6 cm is measured to be actually larger than a flat stack by 95%.

Introduction

Flexible electronics are considered as a major future technology due to their wide applicability in products such as light-emitting diodes (LEDs), displays, and circuits [1–3]. With the development of these technologies, flexible energy sources have also been actively studied in order to fabricate "fully flexible" electronics [4–9]. However, research on flexible fuel cells is at its fledging stage. Recently, Tominaka et al. fabricated a membraneless-type microscale bendable fuel cell on a polymer substrate, resulting in a power density of 83 $\mu W\ cm^{-1}$ [7]. Wheldon et al. reported scalable fuel cells using polymer

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electrolytes with reactive areas of 10–100 mm^2 and a peak power density of 57 mW cm^{-1} [2,8]. In order to fabricate reliable bendable fuel cells, flexible and highly conductive current collectors are required. We recently fabricated a flexible fuel cell using soft lithography and thin film current collectors as well as plastic separators [10–13]. In order to realize flexible current collectors, we employed highly conductive and reliable Ag nanowire (Ag NW) with percolation networks deposited on polydimethylsiloxane (PDMS) [14]. In this report, we calculated the clamping forces (i.e., forces perpendicular to the cell surface) between two PDMS endplates using a numerical approach, and ohmic losses were observed under different bent conditions (15.6 cm $\leq R \leq \infty$) [14]. As a mean to maximize the normal force in the cell, we proposed so-called an asymmetric stack assembly, in which the thicknesses of plates at the anode and cathode sides are different in Fig. 1. Compared with the symmetric assembly (Fig. 1(A)) of flexible fuel cells under bent conditions, asymmetric assembly (Fig. 1(B)) can maximize the clamping force which reduces the ohmic loss as well as the activation loss [14].

Experimental

Ag NWs were fabricated via the conventional polyol synthesis as shown in Fig. 2(A). A successive multi-step growth (SMG) method was also introduced to enhance the length of the Ag NWs For the successive multistep growth of long Ag NWs, capping agent and additional Ag ions are continually added and Cu additive solution is added to 5 ml of heated ethylene glycol at 151.5 °C. 1.5 ml of 94 mM $AgNO_3$ solution and 1.5 ml of 147 mM Polyvinylpyrrolidone (PVP) solution are added continually. After the first synthesis, the obtained Ag NW plays a role of seed for further increase and repeated growth step; PVP an $AgNO_3$ injection. After SMG steps, synthesized Ag NWs were cleaned by ethanol and acetone Cleaned Ag NWs were dispersed in isopropyl alcohol (IPA) with 0.006 mg m^{-1} concentration. Fig. 2(B) shows a novel current collector of Ag NWs percolation networks on the featured PDMS endplate.

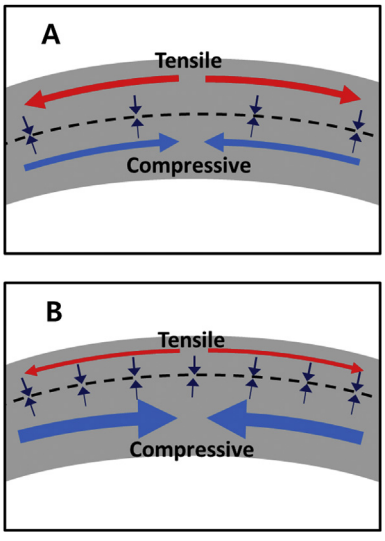

Fig. 1 – Internal stress schematics of bendable fuel cells; (A) Symmetric and (B) Asymmetric stack assemblies.

We reported that the percolation networks in bendable fuel cells are very important due to the reliable electrical conductivity under bent conditions [3]. As the bending radius of fuel cell stack decreases, the electrical conductance of the current collector with short Ag NWs (<15 μm) are poor and thus, the fuel cell performance decreases significantly [3,13]. However, long Ag NWs (≒50 μm) could improve the electrical conductance and mechanical stability under various bent conditions [3,14]. Also, compared to the low density Ag NWs (Fig. 2(C)), the electrical conductance of high density Ag NWs (Fig. 2(E)) in bendable fuel cells is increased under mechanical stress and bent conditions due to the reliable Ag NWs percolation networks which can show high mechanical stretchability. The reliable electrical conductance under bent conditions can be acquired by using very long Ag NWs. This is attributed to a higher chance of maintaining the electrical connection through interweaved networks of longer Ag NWs even under large stress conditions than the shorter Ag NWs.

As shown in Fig. 3, the PDMS layer was first mixed with a curing agent in a stainless steel mold where anode and cathode flow channels were reversely machined to realize the channels on the PDMS endplates. The weight ratio of the PDMS and the curing agent was 10:1. Then, the mold was treated at 70 °C for four hours to solidify the PDMS. The dimensions of a cross-sectional area of the flow channels in the anode and cathode PDMS endplates were 1 × 1 mm^2 and 2 × 1 mm^2 respectively. Inset image of Fig. 4(A) shows the Ag NWs (red square) on the stack assembly. As stated in the introduction, the thicknesses of symmetric and asymmetric PDMS pads are 5 mm (anode), 5 mm (cathode), and 4 mm (anode), 6 mm (cathode), respectively. An MEA (0.45 mg cm^{-2} Pt/C loading, Fuel Cell Power Inc., Korea) with an active area of 3 × 3 cm^2 was attached to the center of the anode PDMS endplate using polyprophylene tape (3M, USA). The thicknesses of Nafion 212 membrane and carbon paper electrodes were 50 μm and 350 μm, respectively. This assembled anode PDMS endplate was then attached to that of the cathode using a silicon sealant (SS900, Okong, Korea). Finally, the two PDMS pads in contact with the MEA were clamped altogether using two steel clips. In order to supply fuel gases, flexible polyurethane tubes were inserted into each inlet of the endplates. Humidified hydrogen and air were provided to the anode and cathode at volumetric flow rates of 0.5 and 1 L min^{-1}, respectively, at room temperature and pressure. The current–voltage (*I*–*V*) curves and electrochemical impedance spectra (EIS) were obtained using Solartron 1260/1287. The *I*–*V* curves were measured using the galvanodynamic mode at a scanning rate of 0.1 mA s^{-1}. To identify the area specific resistance (ASR), the EIS were measured with the perturbation amplitude of 30 mV and a dc bias of 0.5 V with respect to the open circuit voltage (OCV). The frequency range was 10^5–1 Hz. The Ag NW-coated PDMS pads were characterized by a field emission secondary electron microscope (SEM; SUPRA 55VP, Germany).

Results & discussion

Since it is believed that the normal force at the interface of the MEA is a key factor in reducing ohmic loss and thus increasing