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Laminar flow-based micro fuel cell utilizing grooved electrode surface

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HIGHLIGHTS

- Electrode patterned with grooves is proposed for passive control of depletion zone.
- The depleted layer is recharged by a chaotic flow generated by the electrode pattern.
- Groove height and gap between the electrodes are optimized.
- The efficacy of the grooved pattern is increased when the electrode is long.
- Power density of grooved electrode is improved compared to that of a flat electrode.

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ABSTRACT

Microfluidic fuel cells have low power density and poor fuel utilization due to the generation of a reaction depletion zone. In this study, cell electrodes patterned with grooves are proposed for passive control of the depletion zone, where a secondary transport flow over the grooved electrode replenishes the depleted layers. The proposed membrane-less fuel cell is composed of a polydimethylsiloxane layer over a photoresist microchannel wall and a glass substrate that contains platinum electrodes. The optimum gap between the electrodes and the height of grooves are designed based on a computational fluid dynamics simulation. Hydrogen peroxide is used both as a fuel (when it is mixed with sodium hydroxide) and as an oxidant (when it is mixed with sulfuric acid). During the experiments, electrodes of various lengths are integrated on the bottom of the Y-channel. Experimental results show that the effect of grooves on cell performance is independent of fuel rate and fuel concentration, but the effect is remarkable when the length of the electrode is large. The peak power density with grooved electrodes improves by a maximum of 13.93% compared to that of planar electrodes. This grooved electrode-based fuel cell is expected to be a useful microdevice for power generation.

1. Introduction

Fuel and oxidant streams flow without turbulence when they are injected into the microchannel of a microfluidic fuel cell, and a liquid–liquid interface forms between the fuel and oxidant. As a result, a microfluidic fuel cell can easily solve problems inherent to the proton exchange membrane fuel cell (PEMEC). Also, since an expensive membrane is not necessary, the fabrication process becomes simple, and the production cost can be reduced [1]. Various types of fuels and oxidants and several materials for the electrode, catalyst, and electrolytes have been investigated to improve the power density of the microfluidic fuel cell [2–6]. It is difficult, however, to commercialize microfluidic fuel cells because their power density is still insufficient. During the operation of a microfluidic fuel cell, a reaction depletion zone and inter-diffusion zone appear in the microchannel flow. The reaction depletion zone occurs on the surface of the electrode, where by-products undergo an oxidation–reduction reaction with the fuel and oxidant, preventing continuous oxidation–reduction reactions at each of the electrodes [7].

The depletion boundary layer deteriorates the performance of the microfluidic fuel cell, and methods to control this phenomenon have been reported. Yoon et al. [8] arranged multiple inlets along the channel in the form of electrodes installed in the channel wall, and they refreshed the depletion zone by supplying fresh fuel and oxidants. In another setup, they placed many outlets along the channel wall and discharged the depleted fuel and oxidants many times to prevent accumulation over the electrodes. These sorts of active control methods increase power requirements because additional injection or emission and control of many fluids can be complicated. These disadvantages can be remediated through passive control methods. For example, they equipped a passive

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micromixer with herringbone ridge patterns at the base of the channel and made an exchange at the depletion zone with new fuel and oxidants through advection. The inter-diffusion zone in the center of the microchannel can be amplified by the mixer inside the channel; however, this can cause undesirable fuel crossover [9]. Another passive control method for suppression of the depletion zone expansion was proposed by Lim et al. [10]. They made a number of separate electrodes in the same direction as the flow of the fuel and oxidant in order to recharge the fuel and oxidant to their original concentrations in the gap between electrodes. Power density was somewhat reduced as a result of the non-electrode parts that exist in the channel, though [9]. Further, a flow-through porous anode electrode has been used as a smooth way to replenish the fuel depletion zone. This method provided good results when the flow rates of the fuel and electrolyte were medium to low [11,12]. On the other hand, an adjunctive mixing channel structure is needed to effectively pump fuel through the porous electrode. Flow resistance through the electrode brings a higher pressure drop, so a higher fuel injection power may be required.

Two or more fluids injected into a microchannel do not mix well due to the characteristics of laminar flow. In biochips, which use a microchannel, the process of mixing and reacting a variety of fluids is frequently essential. A micromixer, which blends the fluids within the microchannel, has been an important area of research in the microfluidics field. Stroock [13] et al. made herringbone ridges on the bottom of the microchannel and published information on a passive micromixer, which needs no additional apparatus to operate the mixer for the first time. Afterwards, many researchers have reported on micromixers utilizing diverse slant grooved structures [14–17]. This is because external equipment, such as a pump, valve, or pneumatic actuator is not necessary in these types of passive micromixers. Further, fabrication is comparatively easy among the micromixers that have been proposed up to now, but mixing efficiency is high and applications are varied.

To prevent stagnation of products created by the oxidation–reduction reaction of the fuel and oxidant on the electrode surfaces, i.e., to reduce the thickness of depletion boundary layer, flows on the electrode surface toward the fuel layer above the depletion zone must be produced. A passive micromixer is the simplest method to achieve this. On the contrary, other methods employing external equipment or additives, such as microbeads, are not suitable for inducing the mixed flow over the electrode surface within the microchannel, considering the operating principle of the device and the efficiency of the energy generated using the microfluidic fuel cell [18–21].

This study presents a microfluidic fuel cell that has grooved electrodes as a passive control method for the reaction depletion zone. A flow field is developed over the electrode surface using a grooved pattern to improve the power density and electrode surface area. Using software for computational fluid dynamics, the microfluidic fuel cell was designed to have an optimum height in the groove of the electrodes. By using an optimum design, liquid flow occurs in order to effectively lessen the thickness of the depletion layer on the electrode surfaces without affecting the inter-diffusion zone. The fuel cell that was designed is composed of a glass substrate on which a metallic thin film of grooved electrodes is deposited. Furthermore, a microchannel layer made of photoresist and a polydimethylsiloxane (PDMS) layer for the inlet and outlet are formed. Microfluidic fuel cells were fabricated with grooved electrodes and with general planar electrodes for a comparative experiment. The effects of the fuel concentration, flow rate, and length of the electrodes on the cell performance were investigated. The efficiency of the grooved electrode with respect to the improvement in the power density was analyzed.

2. Materials and methods

2.1. Design of the microfluidic fuel cell

A membrane-less fuel cell was designed to have a Y-shaped microchannel with electrodes on the base plane of the microchannel. The microchannel has an outlet and two inlets, and the width and height of the microchannel were set to 1.0 mm and 50 μm, respectively, using the previously reported characteristics of microfluidic fuel cells as a reference [9]. The length of the electrodes was then set to three different possible lengths of 20, 30, and 40 mm, and the microchannel was 2.2 mm longer than the electrode in all cases. In addition, the dimensional design of the fuel cell progressed in the order of the width of the electrode, the gap between the electrodes, and the height of the groove on the electrode surface. The mixing inside the microchannel was analyzed using the commercial fluid dynamics program CFD-ACE$^+$ (ESI Group, France) for the design, and the analysis was based on the simple concentration transport equation and the Navier-Stokes equation of fluid dynamics. The zone to be analyzed was modeled with a 3-dimensional structured grid, and the number of total volumes and total nodes were 4 and 19,950, respectively. The flow module and user scalar module were used. A numerical analysis technique was used for the velocity field, and the upwind scheme was used with respect to the space difference in the enthalpy analysis. Squared conjugate gradient and preconditioning (CGS + Pre) were used in the calculation method. This method was also used for the calculation of the pressure field. The two injected fluids were assumed to be of deionized water for the computer aided analysis, and the assumed density and viscosity were 997 kg m^{-3} and 0.000855 kg m^{-1} s^{-1}, respectively. In this simulation, pressure at the two inlets was set at 10,000 N m^{-1}, so the fuel and oxidant were injected into the two inlets of the Y-shaped microchannel, each at a flow rate of about 0.1 m s^{-1}.

2.2. Microdevice fabrication

The microfluidic fuel cell was fabricated as shown in Fig. 1. It consisted of grooved electrodes, a microchannel, inlets for fuel and oxidant, and outlets. The fuel cell is made up of three primary layers: a lower glass substrate, a middle photoresist thick film, and an upper PDMS sheet. The anode and cathode electrodes are made

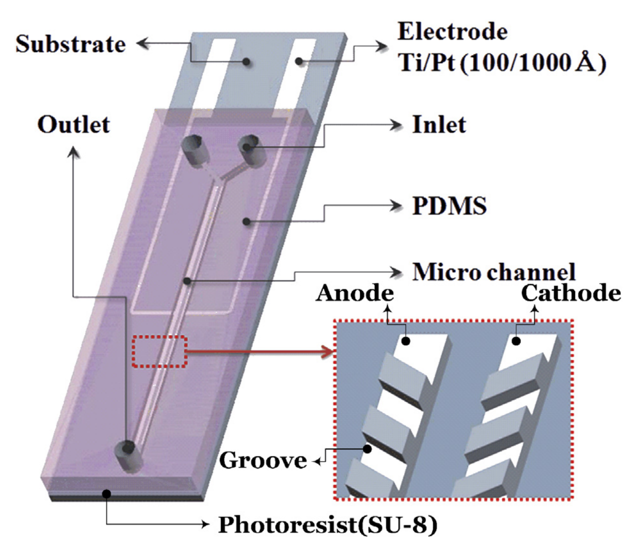

Fig. 1. Schematic diagram of proposed microfluidic fuel cell.