



Short communication

In situ monitoring of high-temperature proton exchange membrane fuel cell stack using flexible micro temperature and voltage sensors

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ABSTRACT

Internal local temperature and voltage not only affect reactions that occur in a membrane electrode assembly (MEA); they can also cause dehydration of the MEA in the electrochemical process that occurs in a proton exchange membrane fuel cell (PEMFC) stack, affecting its performance. In this work, micro-electro-mechanical systems (MEMS) are utilized to develop novel integrated micro sensors for use in high-temperature proton exchange membrane fuel cell stack, and integrated micro temperature and voltage sensors on stainless steel foil as a flexible substrate. These micro sensors can measure temperature and voltage data simultaneously and have the following advantages over other sensors: (1) they are small, (2) they are highly sensitive, (3) they can be batch-produced, (4) they can be placed anywhere to make measurements *in situ*.

In this work, six micro sensors are embedded in the flow field of a high-temperature fuel cell stack and used to monitor local temperature and voltage *in situ* given various operating parameters. The results demonstrate that embedding micro sensors do not affect on cell performance and that the temperature and voltage distribution are non-uniform in a high-temperature fuel cell stack.

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1. Introduction

The high-temperature proton exchange membrane fuel cell (HT-PEMFC) has been attracting increasing attention over recent years because it poses less of a water management problem than the low-temperature PEMFC, and the HT-PEMFC stack has greater potential to be used in large power supply systems and transportation. However, some problems, such as membrane degradation, catalytic corrosion, and interior monitoring, must still be solved.

The interior temperature and voltage are crucial to the high performance of the HT-PEMFC stack, because temperature very strongly affects the activity of the catalyst, membrane dehydration, mass transfer, and heat management [1], and voltage also importantly influences the performance of the HT-PEMFC stack. Hence, monitoring and understanding local temperature and voltage in such cells are very important.

Ali [2] fabricated thin-film thermocouples (TFTCs) on a polyimide (Kapton) substrate to measure the internal temperature of a polybenzimidazole (PBI)-based high-temperature PEMFC. Gagliardo [3] fabricated 10×10 array sensors on a

polytetrafluoroethylene (PTFE) substrate to measure *in situ* the temperature distribution using a signal data-acquisition system, and they analyzed the voltage distribution of a fuel cell by capturing a neutron image. Inman [4] embedded optical temperature sensors in a PEMFC to measure temperature *in situ* using phosphor thermometry. Chang [5] connected conducting wires to the anode and cathode of bipolar plates to measure the local voltage distribution in a fuel cell under various conditions. Büchi [6,7] interlaid thin gold wires as potential probes to decide the resistance distribution across the thickness of membranes. Lebak [8] inserted T-type thermocouples into the anode and cathode plates of an HT-PEMFC to measure internal temperature distributions with different operating gas stoichiometries. Andreasen [9] utilized thermocouples and simulation to compare the temperature distributions in two bipolar plates and to determine the output power of a fuel cell stack.

The authors' research team already has experience of developing film-shaped flexible micro temperature and voltage sensors to monitor local physical parameters in a low-temperature proton exchange membrane fuel cell [10]. However, this work develops an innovative approach for fabricating integrated flexible micro sensors (temperature and voltage) on a flexible stainless steel foil substrate using micro-electro-mechanical systems (MEMS). Stainless steel foil has many favorable properties, including corrosion resistance, compression resistance, high temperature resistance, and flexibility. The home-made micro sensors were embedded into a high-temperature proton exchange membrane fuel cell (HT-PEMFC) stack. The experimental results of fuel cell stack tests were

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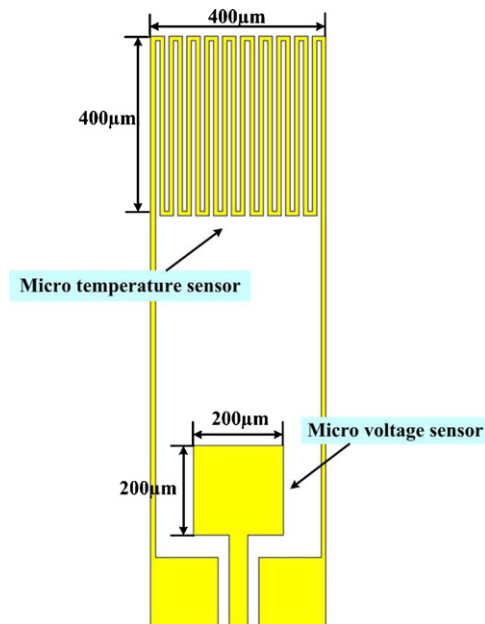


Fig. 1. Schematic drawing of micro temperature and voltage sensors.

used not only to compare the performance curves obtained with-out and with micro sensors, but also to determine variations of local temperature and voltage under various operating conditions.

2. Design and sensing principle

Flexible micro temperature and voltage sensors that were integrated on a flexible substrate were developed. Fig. 1 schematically depicts a strip-shaped micro sensor.

The micro temperature sensor is a resistance temperature detector (RTD). The electrodes of the micro temperature sensor are serpentine structures, with a sensing area of $400\ \mu\text{m} \times 400\ \mu\text{m}$. Sensing is based on the principle that as the environmental temperature increases, the resistance of the micro temperature sensor also increases, because the RTD has a positive temperature coefficient (PTC). When the temperature of the RTD is in the linear region, the

relationship between the measured resistance and the change in environmental temperature can be expressed as:

$$R_t = R_r(1 + \alpha_T \Delta T) \quad (1)$$

where R_t is the resistance at $t^\circ\text{C}$; R_r is the resistance at $r^\circ\text{C}$, and α_T is the sensitivity of the micro temperature sensor ($^\circ\text{C}^{-1}$).

The miniaturized voltage probe is utilized as the micro voltage sensor herein. The sensing area of the micro voltage sensor, which is in contact with the membrane electrode assembly (MEA), is $200\ \mu\text{m} \times 200\ \mu\text{m}$. The rest of the conducting wire is insulated to enable measurements to be made at particular locations inside a fuel cell.

3. Fabrication

Flexible micro temperature and voltage sensors were fabricated and integrated on a stainless steel foil (SS-304, $40\ \mu\text{m}$ thick) as a flexible substrate using micro-electro-mechanical systems (MEMS). Stainless steel foil has several favorable characteristics advantages, including high corrosion resistance, high compression resistance, and high temperature resistance. The fabrication proceeds by the following steps (Fig. 2): (a) sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) in a ratio of 3:1 are used to remove the passivation layer at 80°C ; (b) aluminum nitride (AlN) is sputtered to form a button insulating layer, with several favorable properties, including good electrical insulation, high thermal conductivity and high compression resistance; (c) an E-beam evaporator is used to deposit a chromium (Cr) adhesive layer and a gold (Au) sensing layer; (d and e) lithography and wet etching are carried out to define the sensing patterns of micro temperature and voltage sensors; (f and g) lithography and phosphoric acid are used to etch away unnecessary AlN; (h and i) double-side lithography is performed to form a protective layer before the stainless steel foil is etched using aqua regia; (j) a photoresist (PR) film is coated as an insulating layer and to protect the micro sensors during fuel cell testing, and lithography is then used to define the sensing voltage area and the pads of micro sensors.

Fig. 3 presents an optical microscopic photograph of flexible micro temperature and voltage sensors. The home-made flexible micro temperature and voltage sensors have numerous favorable characteristics, including smallness, high sensitivity, precision of

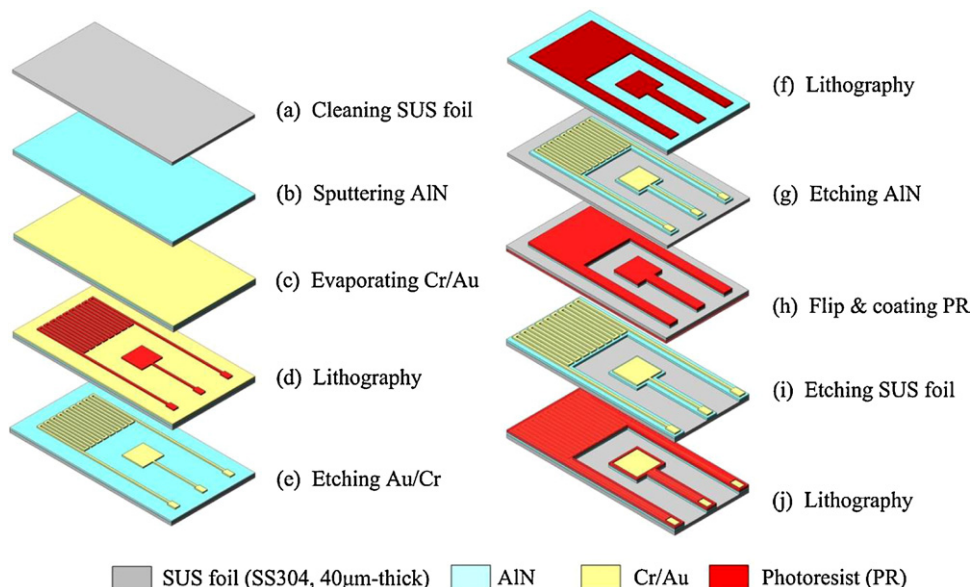


Fig. 2. Fabrication flowchart of flexible micro temperature and voltage sensors.

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