EVTeC 2023
6th International Electric Vehicle Technology Conference 2023
20231101

Developing Next Generation High Performance Polymer Electrolyte Membrane Fuel Cells Using Metal Foam as Gas Diffusion Layer

Improved Mass Transport in Gas Diffusion Layer with Embedded Gas Flow Channels

Gaohua Zhu[1)], Liang Wang[1)], Yuqing Zhou[2)], Ercan M. Dede[2)], Hongfei Jia[1)], and Debasish Banerjee[1)]

1) Materials Research Department, Toyota Research Institute of North America, Ann Arbor, MI, USA 48105

2) Electronics Research Department, Toyota Research Institute of North America, Ann Arbor, MI, USA 48105

E-mail: gaohua.zhu@toyota.com

ABSTRACT: In recent years, low-temperature polymer electrolyte membrane fuel cells (PEMFCs) have played an increasingly important role in zero emission strategy to halt climate change. The performance improvement is a particular focus of fuel cell research and development, with water management being one of the major areas of interest. Here we report the development of a novel Titanium (Ti) foam gas diffusion layer (GDL) material with embedded gas flow channels. Owing to the porous nature of the gas channel walls, the membrane electrode assembly (MEA) performance is significantly improved because of enhanced mass transport. When Ti GDL is characterized using 2nd Gen catalyst and membrane materials, high power density of 2.09 W/cm^2 was observed at 90% relative humidity (RH), which are respectively 12% improvement over state-of-the-art 2nd Gen Mirai performance. Furthermore, we demonstrated that with our metal foam GDLs can be used with flat bipolar plates, which may lead to potential manufacturing cost reduction of the fuel cell components. The work provides new pathway to achieve both high performance and low cost for fuel cells, water electrolyzers and other related technologies.

KEY WORDS: fuel cell, gas diffusion layer, mass transport

1. INTRODUCTION

Over the last few decades, the increasing environmental concerns such as climate change, air pollution, and greenhouse gas emissions are limiting further usage of fossil fuels and emphasizing the importance of developing clean energy technologies. Fuel cells are electrochemical energy conversion devices that offers a reliable low-carbon alternative for electrical power output. Among several types of fuel cells, the polymer electrolyte membrane fuel cell (PEMFC) is one of the most promising, due to its relatively low operating temperature and ease of fabrication.

PEMFCs typically employ a per-fluorinated sulfonic acid (Nafion) membrane which is sandwiched by anode and cathode catalyst layers (CLs). Carbon-based gas diffusion layers (GDLs) and microporous layers (MPLs) are used as the intermediate layers between CLs and flow fields, which are patterned on the surface of bipolar plates. Flow fields acts as both current collectors, as well as providing a pathway to deliver reactant gases to the CLs and remove water generated from fuel cell (oxygen reduction) reaction.

While membrane and catalyst are the key materials that affect output performance and fuel efficiency of H_2, GDLs and flow fields also play a critical role that determines the fuel cell performance, especially at high operation current conditions. Flow fields and GDLs can be considered as the “lungs” of the fuel cell, which determine the mass transport within fuel cell. They not only dominate the delivery of the reactant gases and removal of the water, but also affect the uniformity of reactant distribution over the entire CL. Various designs of flow fields, which are preprocessed on bipolar plates, and different types of GDLs have been explored in the past.[(1), (2)] However, due to the “land-channel” structure, conventional flow fields inevitably form inert areas where flow field ribs and GDLs are in contact: First of all, saturated water vapor generated from CLs tends to transport through GDLs and condense underneath the ribs. Secondly, as a result of greater compression of the pores in GDLs under the ribs, those areas have poor water evacuation, causing higher water accumulation and flooding, and consequently a loss of reactivity and efficiency of the fuel cell.[(3), (4)]

To resolve such issues in conventional fuel cells, we explore the feasibility to apply a flat metal plate as the bipolar plate to get rid of conventional bipolar plate’s land-channel structure and resulting inert areas. Moreover, we replace carbon-based GDLs by

titanium (Ti) foams, which presents much large pore size and permeability especially along the in-plane direction. The overall porosity of Ti GDL can be further tuned by fabricating flow fields onto its surface to balance between the cross-plane direction reactant gas diffusion and in-plane direction convective gas flow for water removal. In this work, using a cell with flat-metal plate and Ti GDL embedded flow fields, we demonstrate that mass transport can be significantly enhanced, leading to high power density of 2.09 W/cm^2 at 90% relative humidity conditions.

2. METHOD AND EXPERIMENT

Fig.1(a) shows the conceptual schematics of our cell configuration in comparison with a conventional cell. The bipolar plate of the testing cell is fabricated using oxygen-free copper (C1020) and pre-coated with chromium and gold. Ti foams made by slurry foaming method are used for all experiments. Carbon slurry for MPL is prepared by mixing carbon, Teflon PTFE dispersion, Triton, DI water, and IPA. MPL is coated onto one side of Ti foam without any hydrophobic treatment of the Ti foam, followed by sintering at 350 ºC. The thickness of MPL is around 20 µm.

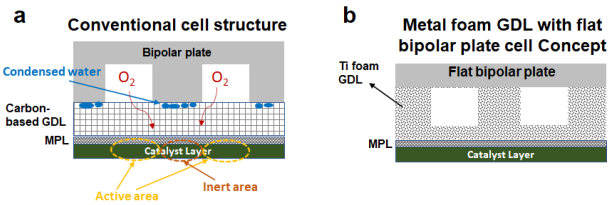

Fig.1 Schematics of (a) conventional single-cell structure; (b) our concept cell structure which utilizes metallic (Ti) foam with flat-metal bipolar plate.

Different flow field channel designs with various channel depths are fabricated onto Ti foam surface to modify the effective permeability of the Ti foam to achieve both efficient delivery of reactants by cross-plane direction diffusion and water removal by in-plane direction convective flow. The flow field channels are fabricated using a pulsed laser system.

Two flow field designs are reported in this paper: (1) straight flow field channels; (2) discrete channels. The discrete channel flow field is designed using topology synthesis algorithm to further optimize the gas transport in Ti GDL. A general sketch of the design method is presented in Fig. 2, which comprises the following three steps: To find the homogenized porous medium permeability, a 3D microstructure unit cell fluid flow model is first constructed with variable cell dimensions. For the 2D porous media optimization step, a gradient-based method is used to find the optimal permeability distribution inside the GDL flow field domain. Once the optimized functionally-graded porous media design is obtained, the explicit microstructure pattern is obtained through a dehomogenization process based on a bio-inspired reaction-diffusion system. More detailed is reported in our previous publication.[5]

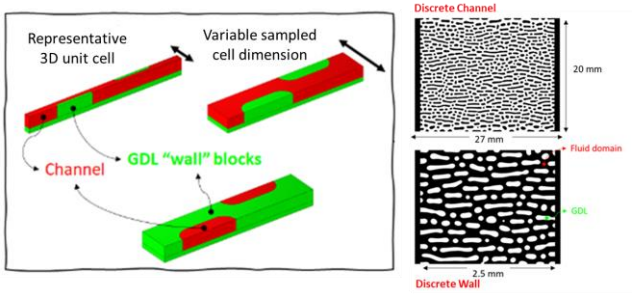

Fig. 2 Sketch of the discrete flow field channels designed using topology synthesis.

The Ti GDL is evaluated in a testing cell and a catalyst layer with active area of 2 x 2 cm^2 is applied. Since water is generated from the oxygen reduction reaction on the cathode side, we adopt Ti foam GDL and flat metal bipolar plate only on the cathode side. The anode side uses conventional bipolar plate with straight gas flow channels and carbon paper GDL (Sigracet, SGL, 29 BC). 2nd Gen Mirai catalyst and membranes are used in our single-cell performance evaluation. The single-cell is assembled with twelves screws using a torque wrench at 30 in-lb. Fully humidified H_2 and air are supplied to the anode and cathode during the performance evaluation. The single-cell test is carried out at 80 ºC and relative humidity (RH) of 90%. The flow rate of H_2 and air are 1.5 and 2.0 L/min respectively. The total pressures of both anode and cathode are maintained at 200 kPa.

Oxygen gas transport resistance (GTR) is obtained from limiting current measurement using diluted O2 (1% O_2 in balance N_2) at 60 °C and RH 80% with 150 kPa total pressure.

3. RESULTS AND DISCUSSION

3.1 Material Microstructure Analysis.

Fig. 3(a)(b) shows pictures of the Ti GDLs with straight channels and discrete channels fabricated on the surface by pulsed laser milling. Surfaces of the laser-processed areas show black color due to oxidation of Ti. Since these oxidized areas are located at the side wall and bottom of the gas flow channels, which do not have direct contact with the bipolar and thus the contact resistance is not affected. As shown in the SEM image in Fig 3(a), after removal of low porosity surface, surfaces of the channels exhibit much higher porosity, which is desired for good mass transport.

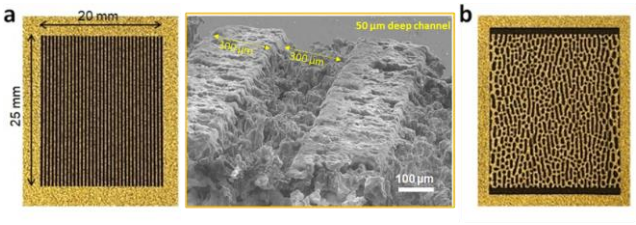

Fig. 3 (a) Picture and SEM image of Ti GDL with straight flow field channels. (b) Picture of Ti GDL with discrete channels. The dimension of the flow field area is 25 mm x 20 mm.

3.2 Single-cell Performance of Ti GDLs

Fig. 4 displays the single-cell performance of the MEAs with flat-metal bipolar plate and Ti foam as the cathode GDL, in comparison with that of the MEA with conventional carbon paper GDL (SGL 29 BC). Commercial SGL 29 BC GDL consists of PTFE-treated carbon fibers with surface contact angle > 130°, whereas all Ti GDLs evaluated using 2nd Gen materials are without any hydrophobic treatment. The contact angle of Au-coated Ti GDL surface as measured by goniometer (Rame-Hart, Model 200), is 87°. In Fig. 4(a), the MEA with flat Ti GDL, which is the original Ti foam without flow fields, shows the worst I-V performance and highest high-frequency resistance (HFR) in RH 90%. Since air is directly forced through the pores, the gas transport within flat Ti GDL is dominated by convective flow, instead of concentration-driven diffusion, resulting in membrane dry-out and high HFR.

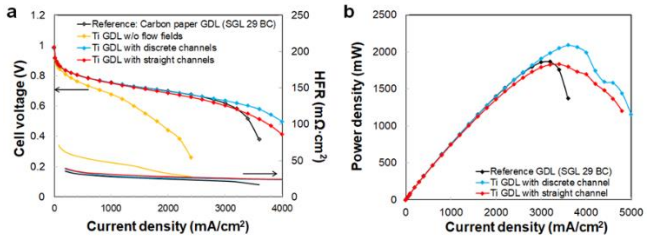

Fig. 4 Single-cell performance of 2nd Gen MEAs employing various type of Ti GDLs plotted in comparison with conventional GDL(SGL 29 BC) at RH 90% and comparison of the power densities.

With the presence of flow field channels, Ti GDL with embedded straight channels shows more balanced performance in gas diffusion and water removal, leading to improved I-V performance, especially at high current densities. At 3.2 A/cm^2, the measured voltage are 0.58 V for RH 90%. Its performance is slightly lower than that of the reference cell with carbon paper GDL in low current densities. The lower cell voltage mainly results from its higher HFR, suggesting that the cell with straight channel Ti GDL might still have dry-out issue in dry conditions.

The I-V performance of the discrete channel Ti GDL is significantly improved over the reference sample under all current densities (Fig. 4(a)). Enhanced power density of 2.09 W/cm^2 was observed at RH 90% as shown in Fig. 4(b), which is respectively 12% higher than 2nd Gen Mirai performance.

To further understand Ti GDL's impact on I-V performance, we characterized the oxygen gas transport resistance (GTR) to determine gas transport resistance which includes molecular and Knudsen diffusion, and permeation through the ionomer film. While molecular diffusion resistance is associated with GDL and flow fields, Knudsen diffusion resistance and permeation resistance are associated with gas diffusion in nano-scaled pores and through ionomers.[6] Fig. 5 shows the oxygen transport resistance of Ti GDL with straight channels, plotted in comparison with that of carbon paper GDL in a conventional cell. The molecular diffusion resistance of conventional carbon-based GDL is 43 s/m as compared to only 22 s/m for Ti GDL. The significantly lower transport resistance is consistent with I-V performance enhancement in the high current density regions. We also noticed that Ti GDLs show high Knudsen and ionomer permeation resistances. The reason could be related to the relatively viscous carbon ink used for casting MPL on Ti GDL. Since Ti foam's surface wettability is different from carbon paper, MPL recipe requires further optimization.

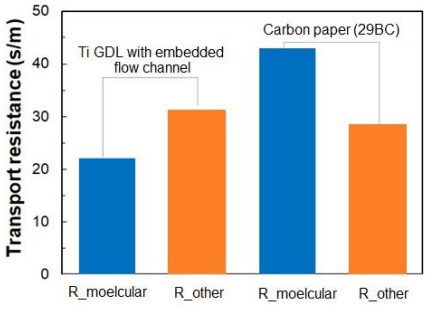

Fig. 5 Transport resistance measured, respectively, with Ti GDL and conventional carbon paper GDL at 60 °C and RH 80% with 150 kPa total pressure. Molecular diffusion resistance is associated with transport in GDL and flow fields. Other resistance includes Knudsen and ionomer permeation resistances.

It is worth noting that all Ti GDLs reported in this work are without any hydrophobic treatment with surface contact angle < 90°. We call these Ti GDLs as "hydrophilic" Ti GDLs, as to differentiate from PTFE-treated "hydrophobic" Ti GDLs, which have contact angle various from 112° – 130°. As shown here, the hydrophilic Ti GDLs works very well in even wet condition (RH 149%). Although we did not present the hydrophobic Ti GDL data in this work, we, surprisingly found in our studies that the

hydrophilic Ti GDLs consistently performs better than the hydrophobic Ti GDLs, which is counter intuitive.

Finally, we compare the similarity and difference between our Ti GDL and 3D fine mesh. 3D fine mesh was previous adopted in Toyota Mirai fuel cell vehicle, and it is also employed with a flat bipolar plate cell design. However, 3D fine mesh is basically a flow field structure, and thus carbon paper GDLs are still required. In contrast, our Ti GDL reported has both GDL and flow field functions. Thus, it allows us to get rid of conventional carbon paper GDLs. Moreover, it does not require PTFE-treatment. Therefore, we believe the Ti GDLs could be potentially a cost-effective alternative to 3D fine mesh with even better performance.

4. CONCLUSION

We have demonstrated that Ti foam with embedded flow field structure can be a promising candidate for highly efficient GDL electrodes in MEAs of PEMFC. When combined with flat-metal bipolar plate, Ti GDL exhibits outstanding single-cell performance, which results from enhanced mass transport. The significantly improved transport could come from the high permeation of the Ti foam and embedded flow fields with porous walls. Further modeling and experiments are still ongoing to help understand the complex two-phase (water-gas) transport phenomena inside the pores of Ti GDLs. This work provides insights on designing a metallic foam structure with dual function of both GDLs and flow fields. It provides a new pathway to achieve high performance and low cost for fuel cells, water electrolyzers, and other related technologies.

REFERENCES

(1) Li, X. & Sabir, I. Int. J. Hydrog. Energy 30, 359 – 371 (2005).
(2) Watanabe, M., Yanai, H., and Nasu, M. J. Electrochem. Soc. 166(7) F3210 – F3215 (2019).
(3) Xu, H., et al. J. Electrochem. Soc.168 074505 (2021).
(4) Ziesche, R. F., et al. Nat. Commun. 13, 1616 (2022).
(5) Zhou, Y., et al. Chem. Eng. J. 435(2), 134587 (2022).
(6) Nonyama, N., Okazaki, S., Weber, A. Z., Ikogi, Y., and Yoshida, T. J. Electrochem. Soc.158(4) B416 – B423 (2011).