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Wafer-Scale Development of 0.36 mm^2 228mV Open-Circuit-Voltage Solid-State CMOS-Compatible Glucose Fuel Cell for Healthcare IoT Application

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Abstract

The world's smallest (0.36 mm^2) solid-state CMOS-compatible glucose fuel cell, which delivers the world's highest open circuit voltage (OCV) of 228 mV, has been demonstrated here. By employing dry etching (reactive ion etching) to the patterning procedure, the damage to the anode and cathode can be reduced when compared with conventional wet etching, resulting in smaller size and higher OCV. The measurement results show 228-mV OCV and 1.32 μW/cm^2 power generation with a 30 mM glucose solution.

1. Introduction

Power generation is one of the most critical issues in IoT development today. Biofuel cells have attracted attention as a stable energy source in healthcare IoT because they are stable thanks to human's homeostasis and these cells can be used as both an energy source and a target sensing system [1,2]. Solid-state complementary metal-oxide semiconductor (CMOS)-compatible glucose fuel cells have been proposed and developed for enabling the integration of small-sized systems (small system size allows low invasiveness) with energy-efficient CMOS circuitries [3]. However, the size used in the literature is 1 mm^2, which is insufficient for low invasiveness. Moreover, the open circuit voltage (OCV) of the conventional prototype is 192 mV [3], which is also insufficient for driving typical CMOS circuitries fabricated by the cost-competitive legacy CMOS technology, which is commonly used in volume-limited healthcare applications.

For addressing this issue, this work presents a 0.36 mm^2 (0.6 mm × 0.6 mm) solid-stage glucose fuel cell that generates 228 mV OCV. Because the conventional wet etched patterning is one of the bottlenecks in fine patterning and OCV improvement, we have newly introduced dry etching (reactive ion etching; RIE) for this purpose and verified its effectiveness for the first time.

2. Wafer-scale development of glucose fuel cells

The structure of the developed fuel cell is illustrated in Fig. 1. The process for fabrication of wafer-scale glucose fuel cells is based on previous research [3]. Fig. 2 shows the conceptual image of the development procedure of the fuel cell. The summary of the development process is as follows:

1) Prepare 6-inch silicon wafer with 1 μm of thermal oxide. Ti/Pt deposition is used for electrode formation. The porous-Pt anode is formed by Al etching. Patterned by metal masking.
2) A Nafion membrane is formed to act as a separation between anode and cathode. Patterned by RIE.
3) The carbon nanotube (CNT)-based cathode is developed by coating CNT/Nafion solution and patterned by RIE.

The difference in above process from [1] is the introduction of RIE instead of wet etching in steps 2) and 3). The damage to the Nafion membrane and cathode is comparatively lesser here than in [1] because the Nafion membrane and CNT-based cathode have low robustness against the wet etching process.

3. Prototype and measurement setup

Fig. 3 depicts the developed prototype and its measurement setup. Stealth dicing was introduced to minimize the damage in the die cut process, and the wafer was diced to 0.36-mm^2 chips. Wafer-level measurements were performed with a manual prober and DC multi-contact probe.

The fuel cell was soaked in the phosphate buffered saline (PBS)-based glucose solution, which simulates the body fluid. The dropping of glucose solution using a micropipette was performed carefully for avoiding an undesired electrical shortage. D(+)-Glucose (Wako) and PBS 10X (Irvine Scientific) were used in the measurements. A tester (Kaise, KT-2010) was utilized for measuring the electrical performance. The dependence of performance on load resistance was measured by using discrete resistors.

4. Measurement results

The dependence of the measured output voltage and power on the output current is shown in Fig. 4. The measurement was performed with 30 mM glucose concentration, which simulates the blood glucose level of diabetic patients. Each point on the graph is obtained from various load resistances. The OCV of 228 mV was successfully verified. The peak power was 0.53 nW with a load resistance of 2MΩ, which corresponds to 1.32 μW/cm^2 considering the anode area of 0.04 mm^2. The power density is less than that in the previous study due to insufficient dispersion of the CNT in the cathode. The peak power was 5.2 nW considering the internal resistance of the tester (10MΩ).

Fig. 5 shows the output voltage as a function of the glucose concentration. A linear characteristic was verified. The PBS in the glucose samples results in an offset voltage with 0 mM glucose concentration. The measurement was performed with samples different from that used in Fig. 3.

Fig. 6 shows the performance variation of the developed fuel cell. We measured 132 samples for evaluating the performance variation. Six samples achieved over 100 mV OCV. The performance variation was considerable due to insufficient distribution of the CNT in the cathode.

5. Discussion

The developed fuel cell outperformed the previously developed cell in terms of OCV; however, it underper-

formed in terms of power density. High OCV is much preferable from the viewpoint of total system development. The reason is that high OCV enables the introduction of today's state-of-the-art leakage reduction techniques using the switching transistor. Therefore, this high-OCV fuel cell will contribute to size-limited healthcare IoTs.

6. Conclusions

This work demonstrated a 0.36-mm^2-sized CMOS compatible solid-state glucose fuel cell fabricated using the RIE patterning process. The measurement results show that this fuel cell has the world's highest OCV of 228 mV, which will be beneficial for healthcare IoT development.

Acknowledgement

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References

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[2] A. Kobayashi, et al., Proc. IEEE BioCAS (2016) 148.
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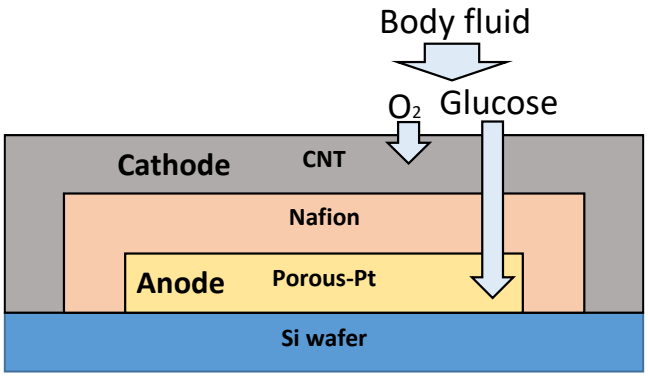

Fig. 1. Conceptual image of the developed fuel cell.

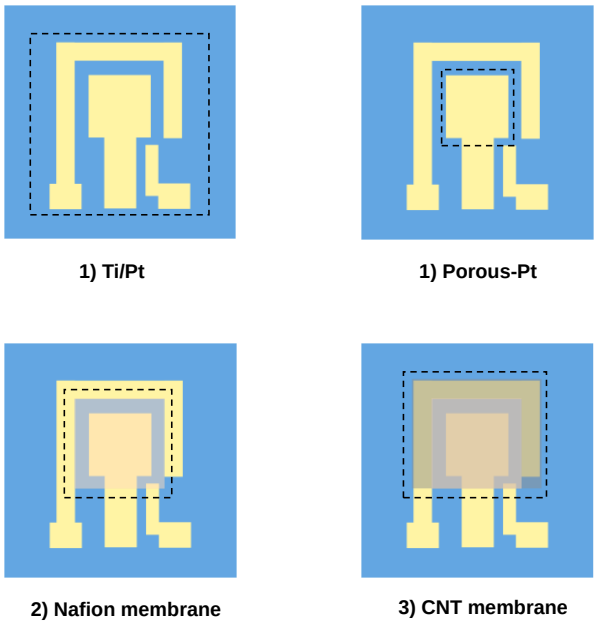

Fig. 2. Conceptual image of the development procedure.

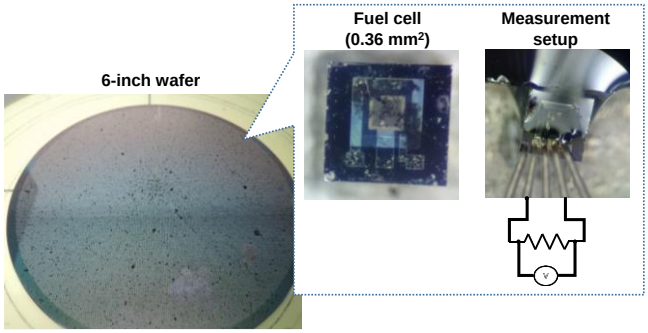

Fig. 3. Photograph of the developed prototype and measurement setup.

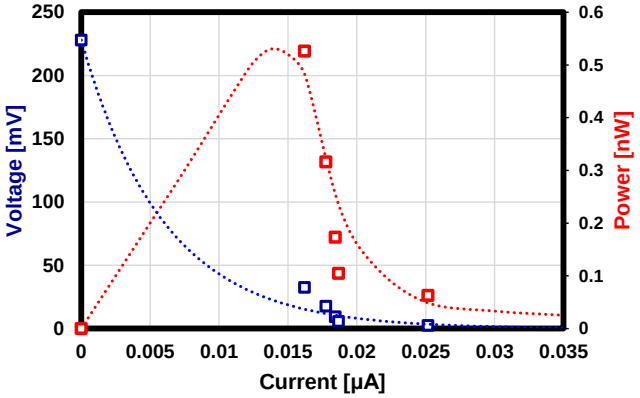

Fig. 4. Output voltage and power dependence on output current.

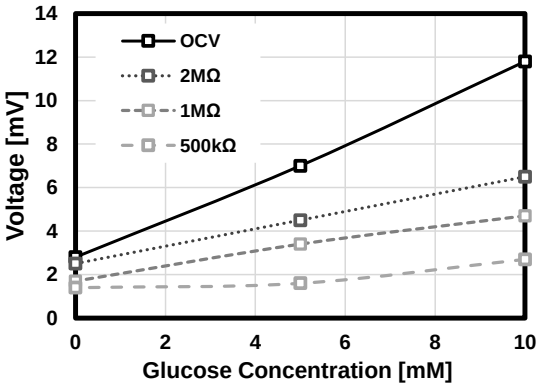

Fig. 5. Output voltage as a function of glucose concentrations.

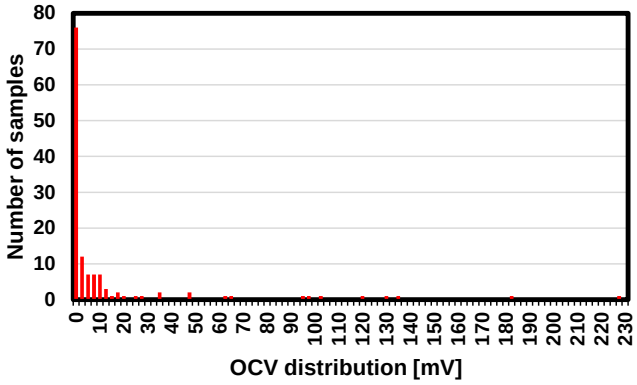

Fig. 6. Performance variations in 132 samples.