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All-Solid-State Glucose Fuel Cell for Energy Harvesting in the Human Body

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Abstract

Efficiently powering sensors, pacemakers and bioelectronic devices for the human body defines the new era of medicine to track, support and operate body functions. Here, glucose fuel cells have seen a renaissance in recent years as an implantable power source harvesting energy from readily available fuels in the human blood stream. Compared to existing implantable batteries, glucose fuel cells do not require frequent replacement surgery. However, state-of-the-art glucose fuel cells are primarily based on polymer electrolytes being relatively bulky, suffer from long-term stability issues and exhibit low power densities. Here, we innovate a miniaturized glucose fuel cell, which is fully composed of solid state materials based on thin film processing. This all-solid-state glucose fuel cell can be scaled down to the sub-micrometer range for unprecedented miniaturization and is built on a Si-chip using standard semiconductor fabrication methods suitable for integrated and direct powering of bioelectronic devices and implants. Through the use of abiotic catalysts instead of conventional biological catalysts such as enzymes and microbes, long term stability and increased power density are in perspective.

1. Introduction

Today's challenge in implantable medicine is that the miniaturization of biomedical devices and implants such as sensors, pacemakers, bioelectronic devices and electroceuticals requires small, powerful and long-lasting power sources. Traditionally, batteries are used to power implants such as pacemakers, however, those are based on rather "bulky" set ups and require replacement by surgery on the patient due to their limited life time every 7-10 years.[1] In contrast, glucose fuel cells, harvesting energy readily available in the bloodstream, are perpetual power sources which would not need frequent replacement. This makes them candidates for small scale, long term implantable power sources, and explains the increased research efforts in recent years.[2]

Importantly, all glucose fuel cell systems described in literature so far are based on either liquid electrolytes or polymer electrolyte membranes such as Nafion, which makes them comparably bulky and challenging to integrate on Silicon technologies (CMOS). Moreover, most glucose-powered fuel cells to date utilize biocatalysts such as enzymes or microbes to catalyze the electrode reactions of glucose oxidation and oxygen reduction. These enzyme/microbe glucose fuel cells have been reported to reach areal power densities of up to 1.1 mW cm^{-2}.[3] Despite their promise these systems show high stability issues as extracellular enzymes and microbes at the electrodes have only a limited lifetime.[4]

To overcome these biotechnological challenges, we – for the first time – designed and fabricated a glucose micro fuel cell which is fully composed of *i)* all solid state materials, *ii)* operates on abiotic catalysis, and aims for *iii)* high power density above the 1 mW cm^{-2} range.[5] By utilizing solid state materials and abiotic catalysts, we created a smaller fuel cell with the potential for higher long term stability than what is currently available in polymer-based glucose fuel cells. This can be achieved by the use of free standing membranes[6] of a solid state proton conductor, which are fabricated down to a thickness of 250 nm, compared to 20 µm for Nafion HP, the thinnest Nafion type available from DuPont. While the conductivity of the solid ceramic electrolyte is typically lower compared to the polymer electrolyte, this can be overcompensated by the reduced conduction path length employed, resulting in a potentially lower ohmic resistance of the solid electrolyte. *I.e.* comparable or better areal power densities as for Nafion-based systems can be achieved, while simultaneously reducing the volumetric footprint of the fuel cell by 2 orders of magnitude.

2. Design and results

Fuel cell membranes based on a proton conducting oxide on Si-chips were assembled using a microfabrication route with standard semiconductor processing techniques. Oxide

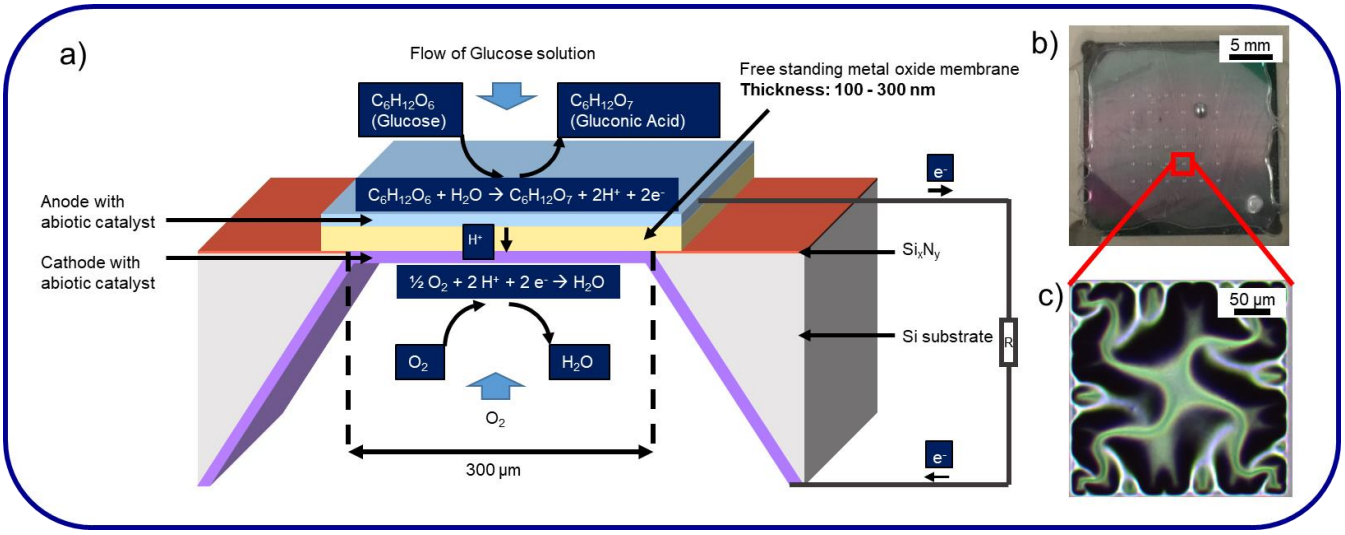

Fig. 1: a) Schematic of the free-standing glucose solid state fuel cell implemented on a Si-chip. At the anode, glucose is oxidized to gluconic acid. The released protons travel through the solid electrolyte to the cathode, where they react with oxygen and electrons to form water. The electrons, going through an external circuit, can power a load. b) Close-up of the fuel cell chip with 36 fuel conversion membranes integrated on a silicon chip. c) Optical micrograph of an individual glucose fuel conversion membrane.

thin films were prepared via pulsed laser deposition. Fig. *1* a) schematically depicts the cross section of the free-standing glucose fuel cell design for the newly developed solid state energy devices, as well as the involved materials and chemical reactions. At the anode, glucose is oxidized and thereby releases 2 protons and 2 electrons. The protons then travel through the electrolyte to the cathode, where they react with oxygen and electrons to form water. The electrons travel through an external circuit to power a load. Fig. *1* b) and c) show the fuel cell chip as a whole as well as an individual free standing solid state glucose fuel cell membrane, respectively. Nano-porous Pt fabricated via a reactive sputtering route was deposited on both sides of the membranes to serve both as catalyst and as current collector. [7] The anode is in contact with glucose in phosphate buffered saline solution to mimic blood, whereas the cathode is in contact with oxygen. Fig. *2* shows a successful test of a solid state glucose fuel cell chip: The plot displays the open circuit voltage (OCV) of the glucose fuel cell over time when droplets of glucose solution are dripped onto the surface of the fuel cell. Each of the sharp peaks of the potential occur at the instances when drops of glucose solution are added to the surface of the electrode of the fuel cell chip. A maximum OCV of 140 mV is detected. This demonstrates that the proposed cell is electrochemically active and shows promise in functioning as a first solid state glucose fuel cell with a roughly 100-fold lowered thickness of the device (only 250 nm) compared to polymer-based glucose fuel cells.

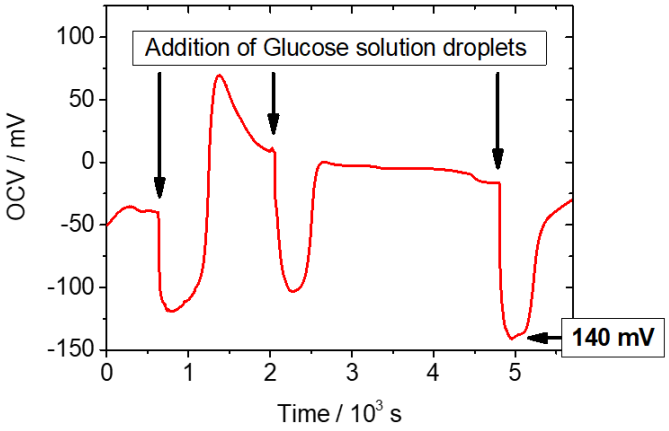

Fig. 2: Open circuit potential (OCV) as a function of time. Experiment was conducted by dropping glucose solution on the chip, and a peak OCV of 140 mV indicates the functionality of the fuel cell.

3. Conclusions

A novel glucose fuel cell with an unprecedented level of miniaturization has been invented, with the goal of powering the next generation of miniaturized implants beyond state-of-the-art batteries requiring replacement surgeries. Free standing fuel cell membranes have been fabricated, and it has been demonstrated that the fuel cell system is indeed electrochemically active showing Open Circuit Voltage upon glucose injection mimicking blood stream concentrations.

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