TOWARDS IMPLANTABLE AUTONOMOUS SYSTEMS: A LOW-POWER TRANSDUCER PLATFORM POWERED BY A GLUCOSE FUEL CELL

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Abstract: The autonomy of a low-power transducer platform powered by an implantable glucose fuel cell (IGFC) is demonstrated. The integration combines the efficient IGFC technology from IMTEK with the power management (PM) and the low-power wireless technology available at imec/Holst Centre. The IGFC is based on platinum catalysts and has an electrode area of 18 cm^2, which equates to the surface of a cube with only 1.7 cm edge length. The combined system is operated over a period of 21 days with a start-up power output of about 40 µW at a battery voltage of 3 V.

Keywords: implantable, autonomous, energy harvesting, glucose fuel cell, DC-DC-converter, low-power transducer, porous platinum

INTRODUCTION

At present battery-independent, implantable autonomous systems (IAS) are of great interest in the field of next generation medical implants. They can be used to monitor *e.g.* body temperature or blood pressure. Compared to present medical implants, in which spent batteries regularly need to be surgically replaced, the great advantage of IAS is their theoretically unlimited time of operation. For these IAS energy harvesters are needed to generate electricity from energy resources available in the body. Possible body-integrated harvesters are *e.g.* thermoelectric generators, or motion-driven energy harvesters, which generate electrical power from temperature gradients or body movement, respectively [1].

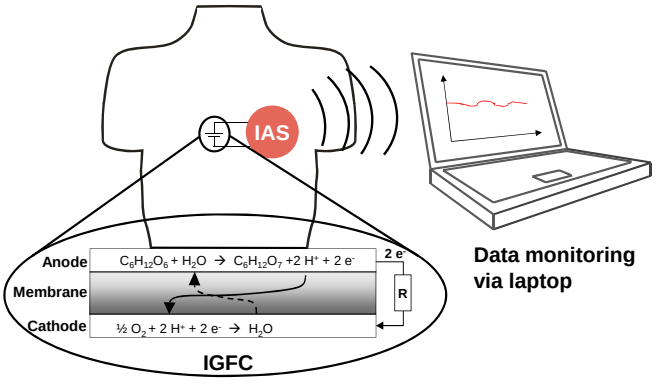

Fig. 1: Concept of an implantable autonomous system (IAS) powered by an IGFC used for e.g. temperature or blood pressure monitoring.

In the present work we use the implantable glucose fuel cell (IGFC) to achieve energy autonomy for an IAS, as is schematically depicted in *Fig. 1*. The advantage of the IGFC is its continuous energy generation independent of body movements or temperature gradients. IGFCs generate electrical energy by the electrochemical conversion of glucose and oxygen available from tissue fluid. Their key components – the electrode catalysts – are based on noble metals, such as platinum. Several studies in the last four decades have shown the feasibility of operating an IGFC *in vivo* [2;3] and their advantages regarding biocompatibility and long-term stability [4]. Previously mainly considered as power supply for pacemakers [4;5], we now demonstrate that the IGFC also is suitable for a broader range of applications, such as (wireless) sensor systems or other electrical stimulating electrodes [6]. To adapt the IGFC voltage, *i.e.* 0.5 V, to the voltage needed by typical medical implants a power management system (PMS) is used. This PMS exists of a DC-to-DC-converter that charges a lithium-ion battery as a buffer to cover peak load demands. The output power of our complete system is up to 40 µW, which is in the power demand range of typical low-power medical implants, *e.g.* pacemaker (less than 15 µW) [5] or a wireless temperature sensor (about 10 µW) [7].

EXPERIMENTAL

The porous platinum electrodes of the IGFC were fabricated by performing cyclic voltammetry in an acidic solution of platinum and copper (H_2PtCl_6, 0.02 mol l^{-1}, Chempur, Germany; $CuSO_4 \cdot 5\,H_2O$, 0.02 mol l^{-1}, Merck, Germany; H_2SO_4, 0.05 mol l^{-1}, Merck, Germany). This process consists of two steps: (1) the co-deposition of a platinum-copper alloy and (2) the dissolution of the copper. This way a tunable specific surface area of our electrodes can be achieved by choosing an appropriative number of process cycles. The cathode, which was fabricated on a slotted silicon substrate, had a RF (roughness factor = ratio between active and geometric area) of 150 ± 13, and the anode, fabricated on a ceramic substrate had a RF of 3050 ± 250 [8]. Both the slotted silicon substrate and the ceramic substrate were covered with an evaporated platinum layer before electrodeposition was performed.

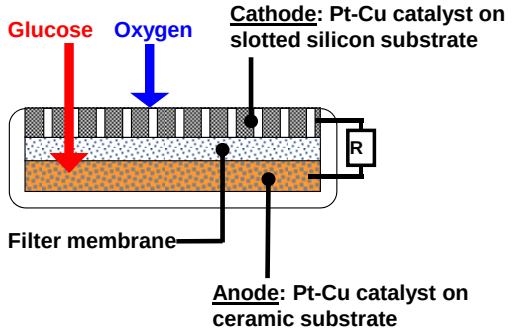

Fig. 2: Assembly of the fuel cell module. The cathode fabricated on a permeable silicon substrate is placed in front of the anode, which is fabricated on a ceramic substrate.

In the fuel cell assembly the permeable cathode was placed in front of the anode, as is depicted in *Fig. 2*. By this an optimal utilization of the available space and the lowest possible fuel cell size (geometrical footprint) was realized. The electrodes were electrical insulated by a filter membrane (Supor-450, Pall, USA), which is also placed in front of the cell to simulate encapsulation in tissue. The IGFC consists of 8 single modules in parallel with a total geometric electrode footprint of 18 cm^2. The fuel cell was operated in a phosphate buffered saline solution containing physiological amounts of glucose (3 mmol l^{-1}) and oxygen (7 % saturation) at 37 °C. The IGFC voltage was converted to 3 V using a DC-to-DC-converter operating in discontinuous operating mode. This voltage was used to charge a 3 V Li/V_2O_5 VL2020 button cell battery. The complete assembly is depicted in *Fig. 3*.

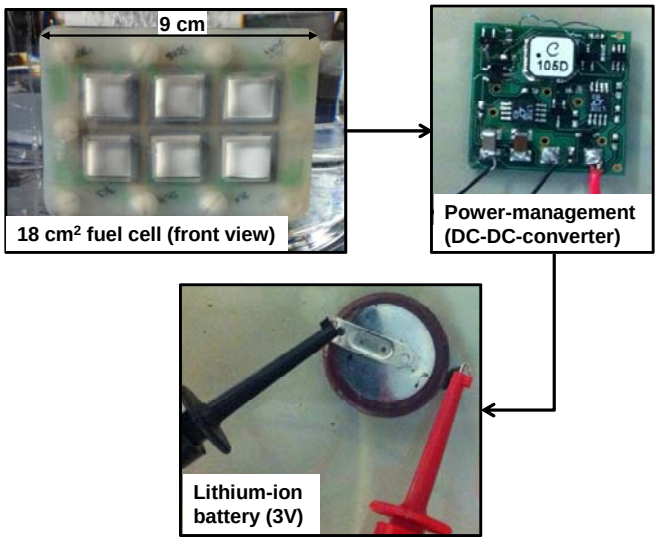

Fig. 3: Schematic layout of the complete IGFC-PM-battery-system.

RESULTS

Based on previous work the typical power density of our platinum-based IGFC is in the range of 5 µW cm^{-2} at a cell voltage of about 450 mV and a current density of about 12 µA cm^{-2} [8]. The current output and hence the power output is adjustable simply by matching the geometric area of the fuel cell to the power demand of the energy consuming device.

For the present work we chose an IGFC module with a geometric electrode area of 18 cm^2. The resulting total power output was maximally 101 µW at a cell voltage of 455 mV. *Fig. 4* shows the load curve of the complete fuel cell. From this, the operation range of the fuel cell can be identified with a maximum voltage of about 600 mV at open circuit.

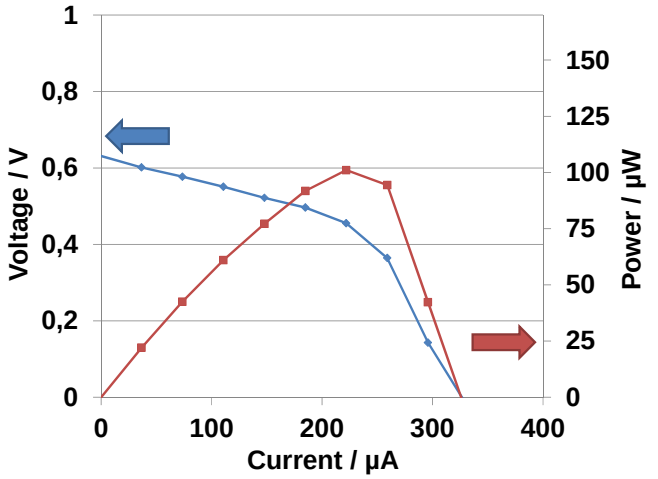

Fig. 4: Cell voltage and power output of the IGFC module consisting of 8 single fuel cells (connected in parallel) with an overall area of 18 cm^2.

IGFCs cannot be connected in series in a body environment since otherwise an electrochemical short circuit between the individual fuel cells in the common electrolyte would occur. The fuel cell voltage is therefore limited to values in the range between 600 and 450 mV. To increase these low cell voltages

to the typical voltages of low-power devices (about 3 V) a PMS including a DC-to-DC-converter is used. It was designed for the operating range of our IGFC, and characterized by applying different voltages and recording the corresponding current input, power output and hence efficiency of the conversion system (see *Table 5*). The critical value from this measurement is the lower limit of the input voltage of the PMS. Below 400 mV the efficiency of the system decreases significantly. This means that at fuel cell voltages significantly below 400 mV the complete system would not work.

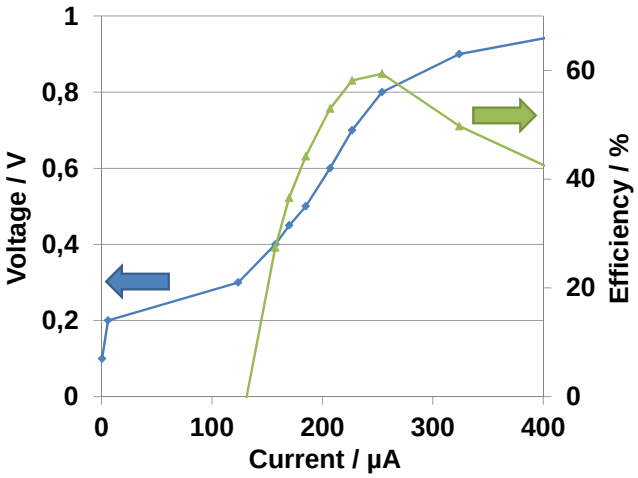

Fig. 5: Input voltage and calculated resulting efficiency of the PMS.

Corresponding to these results, the operation point of the complete IGFC-PMS can be calculated. The IGFC will deliver an output voltage of about 450 mV when operated at its maximum power point. With this input voltage the PMS needs a current input of about 170 µA. This corresponds to a fuel cell current density of about 9.4 µA cm^{-2} which is slightly lower than the current density of the maximum power point (12 µA cm^{-2}).

After connecting the IGFC to the PMS-battery unit the fuel cell voltage and current as well the resulting battery charging current was monitored (*Fig. 6*). As calculated before the IGFC delivers an output voltage of about 450 mV. The corresponding current (about 200 µA) is the value expected from the fuel cell performance, but is higher than the expected consumption of the PMS. This difference may be caused by small leakage currents due to the measuring instruments in the circuit.

The system was operated over a period of 21 days. During this period the voltage of the fuel cell decreased from 450 to 380 mV. This decrease of the fuel cell voltage showed the typical poisoning behavior of platinum catalysts caused by poisoning substances such as chloride or gluconic acid [9].

Consequently, the charging current at the battery showed a decrease from 13.6 µA to 5.5 µA. In the first seven days the fuel cell delivered about 93 µW and calculated from the charging current and the battery voltage the output power of the PMS was about 40 µW. This means a conversion efficiency of 43.5 %. After that time the output power decreased because of the lower cell voltage of the fuel cell and hence the lower efficiency of the PMS. At the end of 21 day period the power output of the PMS was 17 µW and the system was operated with a conversion efficiency of 25 %.

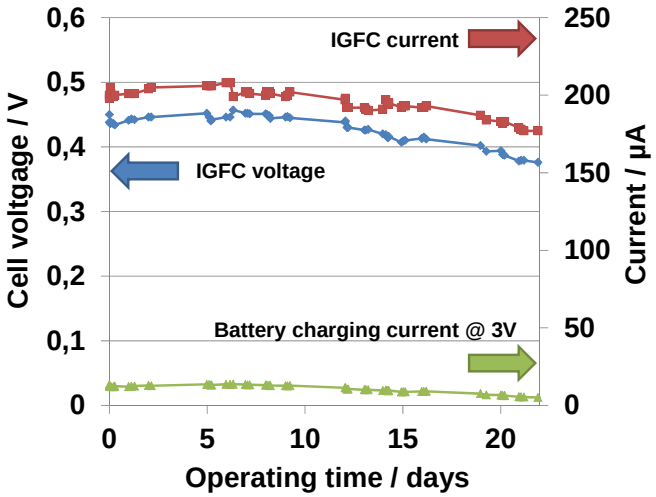

Fig. 6: Operating data of the IGFC-PMS-battery-unit. IGFC voltage, IGFC output current and battery charging current over a period of 21 days.

CONCLUSION

We successfully demonstrated the first steps towards battery-independent implantable autonomous systems (IAS) by charging a 3 V lithium-ion battery with about 40 µW by means of a glucose fuel cell for a period of 1 week. After 21 days of continuous operation the power output of the system decreased to 17 µW, because of catalyst poisoning at the platinum anode. This power output may be used for example to enable autonomous temperature monitoring and wireless transmission over a range of about 10 meters. The DC-DC-converter shows a conversion-efficiency of about 40 %, and consequently a fuel cell area of 18 cm^2 is required. This equates to the surface of a cube with only 1.7 cm edge length, which is comparable to the size of a typical medical implant.

OUTLOOK

Future research will focus on a further decrease of fuel cell size and reduction of catalyst poisoning. The main strategy here is to increase the specific surface area of the catalyst. Furthermore, operation of the fuel cell in artificial tissue fluid as well as biocompatibility investigations is envisaged. Another point for optimization is the matching of the operation point of the PMS to the maximum power point of the fuel cell. Besides these investigations the combination of our IGFC-PMS-battery-unit with an energy consuming device like *e.g.* a wireless temperature sensor is the next step in the development of IAS.

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