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Performance evaluation of aluminum/phosphate cell for powering small electronic devices

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ABSTRACT

We report on an innovative membrane-free aluminum/phosphate cell based on the activation of aluminum (Al) as anodic material using ZnO nanocrystal in phosphate rich electrolyte that is capable of generating sufficient power to power a light-emitting diode (LED), selected as a model of a small electronic device. The energy from the cell is periodically supplied in high power bursts due to the charge and discharge cycle of the capacitor. The entire process is controlled by a switched capacitor regulator. The Al/phosphate cell was studied in neutral 100 mM phosphate buffer solution (7.4) at a temperature of 25 °C. We demonstrate that two Al/phosphate cells connected in series can generate an open circuit voltage (Voc) up to 1.66 V to continuously power a LED via a switched capacitor regulator circuit. The switched capacitor regulator circuit enabled the 1 μF capacitor to store the incoming power from the cell and discharge it in a large power burst to supply the necessary drive strength required by the LED. This new Al/phosphate cell configuration is a 'green' alternative to the use of glucose abiotic and biofuel cells for powering ultra-low power implantable electronic devices.

1. Introduction

Abiotic fuel cells represent a promising technology for the conversion of organic fuel, such as glucose into electricity for powering bio-implantable devices that require ultra-low power sources [1–3]. Abiotically catalyzed glucose fuel cells employ abiotic catalysts such as noble metals, activated carbon, and zinc oxide to electrochemically catalyze the oxidation of glucose fuel and reduction of oxygen, thereby converting the chemical energy stored in the glucose fuel into electricity [3–9]. Although abiotic fuel cells use catalysts that do not denature and/or desorb from the electrode surface as observed with enzymes used in enzymatic based glucose biofuel cells, they usually operate at extremely low power (μW) compared to enzymatic based fuel cells. This key disadvantage has resulted in the development of an alternative energy generator for powering bio-implantable devices.

Al/phosphate hybrid cell systems have been proven as an attractive strategy to generate energy from the activation of Al via ZnO nanocrystal in neutral phosphate buffer solution and physiological saline buffer [10]. However, the generated power from a single Al/phosphate cell is not sufficient for operating any device. Several research groups have used power management systems to enhance the voltages produce in electrochemical power cells through the use of capacitors to store the energy from fuel cells and then deliver it in large power burst [11–13]. While an enhanced performance of the fuel cells have been demonstrated in terms of increased voltages, this typically involves a series of manually charging and discharging a capacitor using different capacitor values and charging and discharging potentials by connecting/disconnecting it to the fuel cell. However, this approach alone is not practical when considering fuel cells or Al/phosphate cell application in bio-implantable devices. Here, we present the construction of capacitor circuit via a switched capacitor regulator to automatically charge and discharge the capacitor and provide sufficient power to drive a light-emitting diode (LED).

2. Experimental section

2.1. Materials for abiotic fuel cell construction

Zinc chloride (99.99%), triethenamine (TEA, 99.99%), and all chemical reagents were purchased from Sigma-Aldrich and all supplementary chemicals were of analytical grades and used without further purification. The fabrication of the Al/Au/ZnO anodic substrate was previously reported [10]. Briefly, rectangular (6 mm × 5 mm) strips of pure Aluminum foils (Alfa Aesar, 99.9999%, 250 μm thick) were used as support substrates for the deposition of a thin film of gold and the subsequent hydrothermal growth of ZnO seed layers. The ZnO precursors were prepared using zinc chloride and propanol. Equimolar of triethenamine was added dropwise to stabilized the precursor solution to produce a final 100 mM homogeneous ZnO nanosol, which was then aged. The ZnO seed layers were established on the Al/Au support substrate via multiple dip-coating and annealing methods to form a thick layer

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of seeds. The resulting Al/Au/ZnO electrode was rinsed and dried overnight, in a desiccator. The cathode was achieved by utilizing platinum rod ($\phi = 500\ \mu m$).

2.2. Al/phosphate cell characterization

The Al/phosphate cell characterizations were carried out in air-saturated phosphate buffer solution (100 mM, pH 7.4). The configuration of the experiment setup consisted of an Al/Au/ZnO anode and the platinum rod cathode positioned 20 mm apart in the single compartment cell. The voltages of the cell were measured under varying loads in the range from 1 MΩ to 1 kΩ. The power density was obtained for the cell and all current densities were calculated using geometrical area of electrode. Fig. 1 provides the schematic representation of the experimental set-up for the Al/phosphate cell, which serves as the power supply to power the low voltage switched capacitor regulator (S-882Z18-M5T1G, Seiko Instruments) combined with the capacitor circuit. In addition, the Al/phosphate cell was characterized in the presence of various concentration of phosphate buffer solution. The charge/discharge cycles were monitored at 25 °C and pH 7.4.

3. Results and discussion

The representative configuration of the Al/phosphate cell constructed in Fig. 1 was based on the electrochemical property of the ZnO modifier on Al/Au electrode to activate Al/Al^{3+} oxidation via pitting mechanism originating from the defect site to overcome the thin oxide film on the Al substrate to generate $Al(OH)_3$ and hydrogen [14]. Briefly, during the electrochemical reaction, the generated hydrogen diffuses to the top of the $Al(OH)_3$ film and facilitate the reduction of $H_2PO_4^-$ to HPO_3^{2-} ions that in turn react with the solid phase surfaces of ZnO nanocrystals by adsorption and precipitation to form $ZnHPO_3$ [10]. This configuration resulted in the generation of electrons and the generated electrons from the anode flow to the cathode through the external load circuit. Fig. 2 shows the representative current voltage behavior and the power curve of the Al/phosphate cell at different external loads (1 kΩ to 1 MΩ) in 100 mM phosphate buffer solution (pH 7.4) saturated with air. An open circuit voltage of 820 mV, a maximum power density of 56.7 μW cm^{-2} at 15 kΩ and a current density of 147.3 μA cm^{-2} was observed. As the separation distance between the anode and cathode varied from 1 mm to 50 mm, an insignificant impact was observed on the power density. In addition, the stability of the Al/phosphate cell was evaluated under constant load (15 kΩ) discharge for 1 h each day in small cell with a capacity of 3 mL. Fig. 3 shows the successive 1 h constant load discharge curve acquired during the 34 days. The results show good stability of the power density, near 48.8 μW cm^{-2} on average with approximately 16.5% drop in power density after 14 days of operation in 100 mM phosphate buffer solution (pH 7.4) under air-saturated environment at 25 °C. Therefore, the Al/phosphate cell retains 76.4% of its performance in phosphate buffer solution over the course of 31 days.

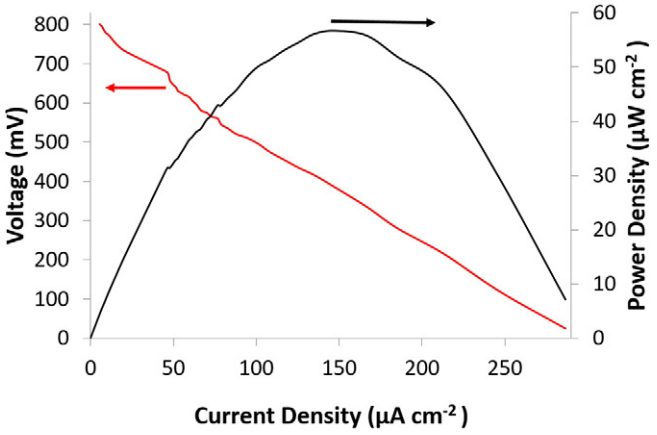

Fig. 2. Polarization and power density curves of the Al/phosphate cell at different external loads in 100 mM phosphate buffer (pH 7.4 and 25 °C) saturated with air.

We investigated the effect the number fuel cells had on the charge/discharge frequency of the 1 μF capacitor circuit. Fig. 4A shows the charging/discharging frequencies of various capacitances and the optimal charge/discharge frequencies were achieved with 1 μF. The charge/discharge cycle of 1 μF capacitor using a single cell (Fig. 4B) and 2-cell (Fig. 4C) connected in series resulted in the charging potentials of approximately 0.86 mV and 1.7 V, respectively, and the discharging potential of approximately −0.037 V. The average capacitor charging time observed for the 1 μF capacitor using a single cell and the 2-cell configuration were 1.18 ± 0.09 s and 0.52 ± 0.01 s, corresponding to a charge/discharge frequencies of 0.85 Hz and 1.92 Hz, respectively. The circuit with the 2-cell configuration charged the capacitor faster because the total surface area for energy generation was larger than that of the single Al/phosphate cell operating under the same conditions. Therefore, the charge/discharge frequency increases with the number of fuel cells connected to the capacitor circuit and is dependent on the electric power generated by the cell.

The constructed Al/phosphate cell was then connected to a 1 μF capacitor via a switched capacitor regulator circuit in order to amplify the voltage generated by the Al/phosphate cell. The electric power generated from the Al/phosphate cell was charged into the 1 μF capacitor via the switched capacitor regulator in order to obtained sufficient power to operate a LED. The ultra-low power switched capacitor regulator depicted in Fig. 1 requires a minimal input voltage of 250 mV in order to drive its oscillation circuit to automatically charge/discharge the capacitor. The 820 mV generated by the Al/phosphate cell is sufficient to serve as the input voltage source to the charge pump IC. The power supplied to the switched capacitor regulator via

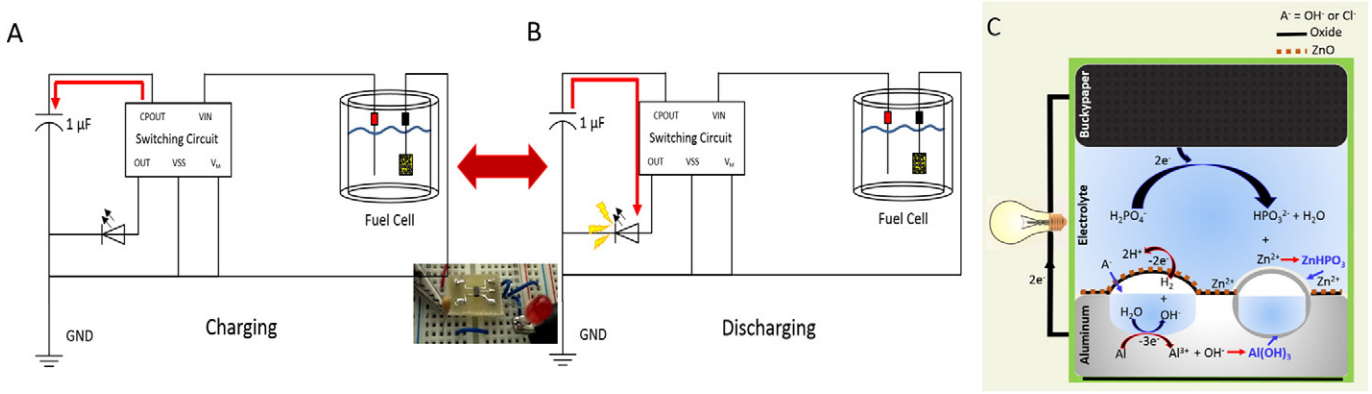

Fig. 1. Switched capacitor regulator based circuit (A) charging capacitor in parallel (B) discharging capacitor and (C) schematic illustrating the reaction mechanism.