A Micro-Watt Electrolytic Power Scavenger driven by Eye-Blinking Motion

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***Abstract*—We have fabricated and tested an electrolytic energy harvester to supply power to smart contact lenses using natural eye blinking motion. The energy harvester consists of two polarizable electrodes of two different metals in contact with an eye tear. The periodic flow of the tear over the electrodes during blinking modulates the electrode polarization resulting in an observable pulsed unipolar voltage output. We have measured energy outputs of 0.264 and 4.865 µJ per blinking cycle, respectively. The maximum observed voltage and current outputs were 700 mV and 48.8 µA, respectively. This device, which is based on the aluminum anode, can fully charge up a 4.7 µF capacitor in 0.75s, corresponding to the power output of 1.53 µW.**

Keywords—Smart Contact Lenses, Energy Harvesting, Power Supply, Electrolytic Rectification

I. Introduction

The use of the internet of thing (IoT) devices in wearable and implantable biomedical applications are significantly rising [1]–[3]. One of the most applicable IoTs is smart contact lenses which are highly beneficial to disease diagnosis and treatments [4], [5]. Smart contact lenses are not only useful for vision correction [6], but also for health monitoring [7] and drug delivery [8], [9]. However, one of the major obstacles toward its commercialization is the power source for these devices. In the present study, we demonstrate a novel energy generation mechanism based on natural eye-blinking to supply power to smart contact lenses.

Batteries [10], photovoltaics [11], [12], and wireless power transfer via radio scavenging [13], [14] are the common techniques to supply power to smart contact lenses. However, all these methods suffer from serious challenges. Batteries that require periodic charging necessitates the removal of smart contact lens which is not a user-friendly practice. Solar cells require the presence of light and stop working in dark or low-intensity light conditions. Although batteries and solar cells are useful, mechanical to electrical energy conversion is independent of the environmental condition, and natural muscle motion, particularly eye blinking, can be utilized to supply power to smart contact lenses. There are several physical mechanisms, including triboelectricity [15], piezoelectricity [16], reverse electrowetting [17], and electrostatic energy conversion [18], which have been applying to convert the mechanical motion to electricity.

Low density and poor stability of surface charges make triboelectric energy harvesters unreliable sources of energy. Electrostatic power generation is another option that works based on the capacitance gradient (ΔC). Since ΔC rules the performance of this harvester, the embedded surface charges and the area of the device matter. The charge injection can be done either externally or internally. External charge injection using a battery is not an option due to the limited lifetime of a battery and the low available surface area on a smart contact lens [19]–[21]. Electret-based electrostatic harvester is another choice, but non-uniform and unstable electret-charging processes (corona-discharge and ion injection) bring about a short lifetime harvester with random electrical outputs [22], [23].

Very recently, we observed an additional power scavenging mechanism that produces a much higher energy output than the previous two. This mechanism does not require charge injection to the surface. The new mechanism is based an electrolytic cell that is formed by the contact of a sliding tear with two different metal electrodes which produces a potential difference and polarization-induced rectification [24], [25]. Fig. 1 schematically illustrates the innovative electrolytic rectification energy harvester driven by eye blinking. The placement of the electrolytic rectifier on the surface of a smart contact lens results in voltage and current outputs only in one direction after every single natural eye blinking.

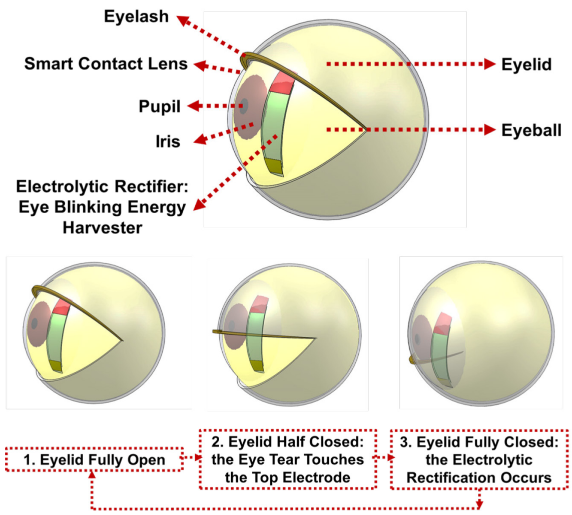

Fig 1. A schematic illustration of the electrolytic rectification energy harvester mounted on a smart contact lens, showing three modes of the harvester during eye blinking.

II. Working Principle

We believe the observed scavenged power is the result of three phenomena. First is the polarization of the electrodes when in contact with the tear, second the periodic modulation of the electrode polarization due to the tear

The project sponsored under the National Science Foundation grant 10053422.

sliding motion and third the formation of an electrolytic rectifier that converts the periodic changes on the electrode polarization charge into pulsed unipolar voltages.

An electrolytic rectifier is composed of a combination of an anode, a cathode, and an electrolyte solution. Guthe first introduced this phenomenon and named it the oxide-gas film theory [26]. The surface interaction of the electrolyte solution with the anode metal results in the formation of a thin oxide or hydroxide layer. Subsequently, a thin gas film forms on the oxide layer due to the electrochemical reactions. A metal anode that goes through the oxidizing electrochemical reactions loses electrons, and the generated mobile carriers flow into the liquid electrolyte. The frequent sliding motion of the electrolyte and its connection to the cathode results in the current flow. Thus, the generated charges transport from the anode to the cathode via the electrolytic solution.

The formation of the thin oxide and gas film on the anode's surface prevents the passage of ions to the anode and the current flow in the reverse direction. Therefore, resulting in a rectifying behavior. Having a rectifier as a power supply is significantly important, mainly because it eliminates the need for using a full-bridge rectifier in a power management circuit. The turn-on voltage of a full-bridge rectifier adversely increases the dissipated power. Fig. 2 shows the formation of the electrolytic rectifier energy harvester employing a frequent sliding motion.

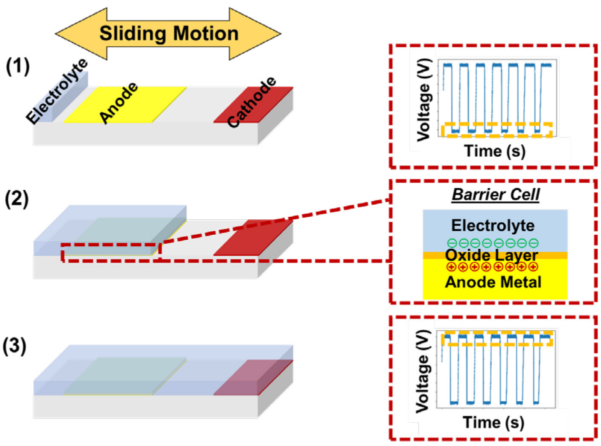

Fig 2. Three modes of the energy harvester while the back and forth sliding motion occurs, resulting in the formation of a barrier cell and, therefore, an electrolytic rectifier.

Accordingly, in the first step of the power generation, when the eyelid is open, the eye tear does not touch the anode, and the harvester is in the off mode. Next, while the eyelid is closing, it goes into contact with the anode surface, and the oxidation reaction occurs, resulting in the formation of the oxide and gas layers. Finally, when the eyelid is fully closed, the eye tear touches the cathode metal and the anode simultaneously.

The electrochemical potential difference of the two metals determines the voltage output of the device. Therefore, an electric current flow from the anode to the cathode, and its magnitude depends on the voltage and the liquid's resistance. It should be noted that the oxide-gas layer is basically a semi-permeable membrane that permits the passage of some ions depending on their ionic radius and the membrane's structural features. Hence, a proper selection of the anode is vitally important to reduce the leakage current. It is noteworthy that the temperature's uprise due to the dissipated power (RI^2) can break down the oxide film and deteriorates the rectifier energy harvester. Thanks to the relatively low body temperature and low frequency of eye blinking, temperature deterioration is not a severe concern in the case of power generation to smart contact lenses.

III. Experimental

The electrolytic rectifier energy harvester was made by growing 300 nm thermal SiO_2 and spin coating of 1 µm thick Cytop (CTL-800M) as a hydrophobic layer on a silicon chip. A part of the SiO_2/Cytop stack was dry etched with CF_4/O_2 gases under the plasma power of 500 W. A 100 nm thick gold (Au) was deposited at one side of the silicon chip utilizing the Denton SJ20C at the base pressure of 1 µTorr and the deposition rate of 3 $Å.s^{-1}$. Different metals, including aluminum (Al), copper (Cu), nickel (Ni), and chromium (Cr), were used at the other side of the silicon chip as the anode.

As it is schematically shown in Fig. 3, a Firgelli programmable linear actuator was used to provide the frequent back and forth motion (at the speed of 20 mm s^{-1} to replicate the average eye blinking speed [27]) of the device mentioned above on a commercialized moisturizing eye drop to replicate the eye tear conditions.

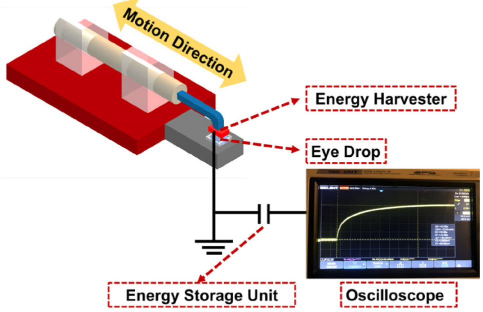

Figure 3. The testing setup to detect the electrical performance of the energy harvester.

A digital oscilloscope (Siglent SDS1202X-E) was used to detect the electrical output of the harvester. The SR570 low noise current preamplifier from the Stanford research system was used to measure the current output of the device.

IV. Results and Discussion

As it was mentioned in the experimental section, we have used Cu, Ni, Cr, and Al as the anodes for the eye blinking energy harvester. Fig. 4 demonstrates the voltage, current, and charging curve of the harvester while using Cu anode and a 4.7 µF capacitor as an energy storage unit.

As it is shown in Fig. 4, the maximum voltage and instantaneous current output of the energy harvester while using Cu as the anode are 240 mV and 20 µA, respectively. The integration of the current-time curve shows the charge generation of 2.2 µC, corresponding to the energy output of 0.264 µJ. On average, an adult blinks twelve times per minute, resulting in the cumulative energy generation of 3.17 µJ when using Cu as the anode of the electrolytic rectification harvester. In addition, we added a 4.7 µF capacitor to evaluate the charging ability of the energy harvester. The device with a sliding speed of 20 mm s^{-1} can fully charge up the capacitor in 0.53 s, resulting in an effective power output of 0.26 μW.

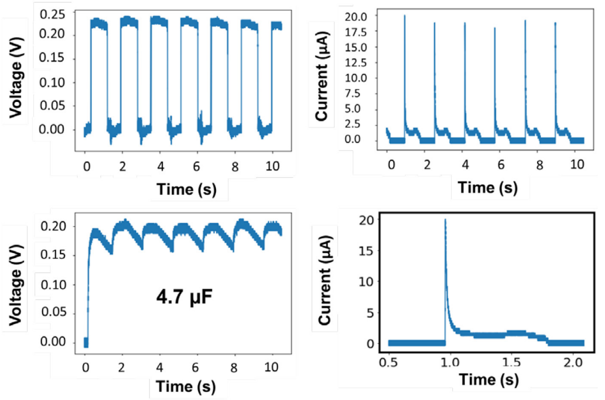

Fig 4. Voltage, current, and the charging curve of the energy harvester while using Cu as the anode.

These results prompted us to use other types of metals as the anode and practically measure the electrical performances. Fig. 5 shows the electrical outputs of the harvester while using Al as the anode.

As it is shown in Fig. 5, the maximum voltage and instantaneous current output of the energy harvester while using Al as the anode are 700 mV and 48.8 μA, respectively. The integration of the current-time curve shows the charge generation of 13.9 μC, corresponding to the energy output of 4.865 μJ. The device with the same motion condition and based on the Al anode can fully charge up a 4.7 μF capacitor in 0.75 s, corresponding to the power output of 1.53 μW.

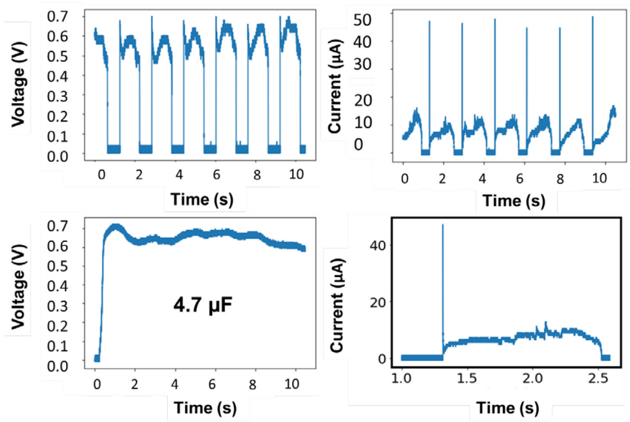

Fig 5. Voltage, current, and the charging curve of the energy harvester while using Al as the anode.

We have also tested Ni and Cr as the anode, but very weak or no electrical output could be detected. The maximum voltage and current output for the Cr anode are 2 mV and 14 μA, respectively. As it is discussed in the working principle, the formation of the oxide and gas films is the ruling mechanism of energy generation. Thus, we expect that no oxide film was formed on the nickel and chromium anodes, and the barrier cell is not created.

Greater results for the case of Al anode comparing to the Cu is mainly due to the electrochemical potential difference of these metals. Furthermore, some irregularity of the voltage output while using Al anode is due to the structural properties of the aluminum oxide film.

V. Conclusion

For the first time, we could be able to make and test an energy harvester device to supply power to the smart contact lenses by means of natural eye blinking. An electrolytic rectifier was made using a specific combination of an anode, a cathode, and a moisturizing eye drop as an electrolyte to replicate the eye tear. Results show the energy output of 0.264 and 4.865 μJ while using Cu and Al as the anode of the energy harvester device.

Acknowledgment

All the fabrication was performed at the state-of-art Utah Nano Fabrication Facility, Salt Lake City, Utah, USA sponsored under NSF CPS grant 10053422.

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