Sustainable Printed Electrodes for Energy Harvesting from Urine to Power IoT Sensor Nodes in Smart Diapers

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Abstract: The expansion of Internet of Things (IoT) devices is rapidly increasing across various aspects of life, notably in wearable healthcare. With billions of already deployed IoT sensor nodes, this figure is anticipated to escalate into the hundreds of billions in coming years. One of the most significant challenges is how to economically power these devices by adopting sustainable and environment-friendly solutions as the conventional power sources are inadequate to meet the demands of this vast IoT ecosystem. In recent years, innovative approaches have emerged to design energy-optimized electronic systems, opening a pathway for applications based on energy harvesting. In this study, a novel energy harvesting solution is proposed by developing sustainable and disposable harvesting electrodes, leveraging the capabilities of printed electronics technology. These electrodes are engineered to harvest energy from human urine, a readily available resource, to power the energy-efficient wearable IoT sensor nodes of smart diapers. A comprehensive characterization of these harvesting electrodes is conducted using pseudo-urine as an electrolyte within a controlled laboratory environment. The results demonstrate great promise for the development of self-powered IoT sensor nodes of smart diapers, with the capacity for overnight operations lasting up to 12 hours.

1 INTRODUCTION

Energy harvesting from saltwater, for example, salt concentration gradient in seawater, has been a topic of interest since the 1970s. Despite its potential, it has historically received limited attention due to its comparative limitations against more promising energy sources (Muhthassim et al., 2018). However, with advancements in integrated circuit technology, the development of power-efficient circuits and systems that operate at micro- and nano-watt scales has emerged. This technological progress has paved the way for energy harvesting from ambient surroundings on a microscale, enabling the powering of IoT devices.

Zinc-carbon-based dry batteries with manganese dioxide and ammonium chloride electrolytes have been available commercially for more than 150 years (Kordesch and Taucher-Mautner, 2009; Linden and Reddy, 2001). A market growth trend is expected for zinc-carbon batteries because of their sustainable and environment-friendly nature as compared to other competitors (Reports, 2022). However, the wide use of ammonium chloride as an electrolyte in dry batteries still poses challenges of being hazardous for humans (NJ-Gov, 2016; Pelner, 1956) and harmful to aquatic life (Rani et al., 1998).

Typical human urine contains sodium, chloride, and potassium electrolytes along with more than 150 different constituents as studied by investigators at National Aeronautics and Space Administration (NASA) (Putnam et al., 1971). The specific conductivity of sodium chloride solution (1.3 $k\mho cm^2/mol$) is close to the specific conductivity of ammonium chloride solution (1.5 $k\mho cm^2/mol$) of the same concentration at room temperature (Murtomäki et al., 2018). The presence of these electrolytes in urine makes it suitable to be used as an electrolyte for harvesting electrodes printed with materials like zinc-carbon to harness chemical energy from urine. In this study, a novel energy-harvesting approach is proposed involving the design and development of zinc-carbon-based flexible electrodes using printed electronics technology to harvest chemical energy

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from urine in diapers. The electrodes are printed directly onto the diaper back-sheets, aiming to offer a sustainable, environmentally friendly, and cost-effective disposable solution. This innovation intends to eliminate the need for batteries, which are not only hazardous but also challenging to recycle. The primary objective is to harvest the chemical energy to supply power to the energy-optimized circuits of IoT sensor nodes and integrate the printed harvesting electrode seamlessly into smart diapers.

The materials used to develop the printed harvesting electrodes, the preparation of pseudo urine, the experimental setup, and the various measurement scenarios are discussed in section 2 of this article. Section 3 includes a discussion of the obtained measurement results with the help of plots. Finally, section 4 concludes the work by discussing the findings and limitations along with the potential prospects of the research.

2 MATERIALS AND METHODS

The rolled sheets and printable inks of zinc and carbon materials are used to develop the electrodes to harvest chemical energy from indigenously developed pseudo-urine. The design and development of electrodes, formulation of pseudo-urine, and the details of measurement setup for various measurements are discussed in the following subsections.

2.1 Energy Harvesting Mechanism

Off-the-shelf flexible rolled sheets of carbon material and zinc metal are used initially to develop the harvesting electrodes for the preliminary measurements to establish the proof-of-concept. A sheet of pure conductive carbon holding a thickness of 0.1 mm (Fly Fiber, 2022) is used to develop the cathode having a size of 7 cm x 7 cm. The anode of the same size is developed with an off-the-shelf flexible rolled sheet of 99.99% pure zinc metal (Tools Store, 2022) with a thickness of 0.2 mm. Both electrodes have a surface area of 98 cm^2 each with 49 cm^2 on either side of the electrode. The electrical connections for the carbon cathode are implemented using a small patch of copper tape with conductive adhesive (3M, StPaul, Minnesota, USA) and for the zinc anode by directly soldering the copper wire to the sheet surface.

The printed harvesting electrodes of 7 cm x 7 cm size are developed using zinc and carbon inks on the inner side of the diaper back sheet. The Figure. 1(a) depicts the cross-section of the cathode electrode with printed carbon ink on the single side of the diaper back sheet and 1(b) shows the cross-section of the anode with printed zinc ink on top of the carbon-based current collector layer.

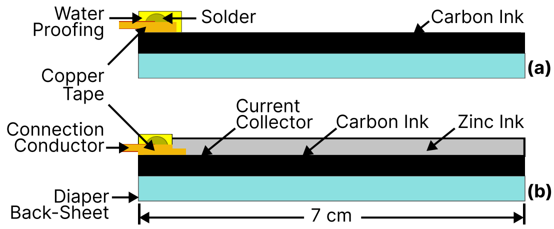

Figure 1: Printed electrode design for energy harvesting; (a) carbon ink cathode, (b) zinc ink anode over the current collector layer of carbon ink.

2.1.1 Fabrication of Printed Electrodes

The cathode (reducing electrode) with the same geometry as described in Figure 1 is fabricated by deposition and curing of electrically conductive carbon ink (Saral Carbon 700A, by Saralon GmbH). Consecutive two layers of carbon ink with a sheet resistance of 30 $\Omega/\square/25\ \mu m$ are deposited sequentially and each layer is thermally dried in a 95 °C preheated oven (ProtoFlow E, by LPKF Laser & Electronics) at 100 °C for 10 minutes. The electrical connections are implemented using a small patch of copper tape with conductive adhesive (3M, StPaul, Minnesota, USA) on the dried carbon ink layer. The water-resistant tape is employed to make the connections waterproof, preventing short circuits.

The anode (oxidizing electrode) is fabricated by depositing and curing the electrically resistive zinc ink (Saral Zinc 700, by Saralon GmbH). Consecutive two layers of Zinc ink with a thickness of 100 microns are deposited sequentially and each layer is thermally dried in a 95 °C preheated oven (ProtoFlow E, by LPKF Laser & Electronics) at 100 °C for 10 minutes. Two consecutive layers of carbon ink are printed as a current collector under the zinc layer as

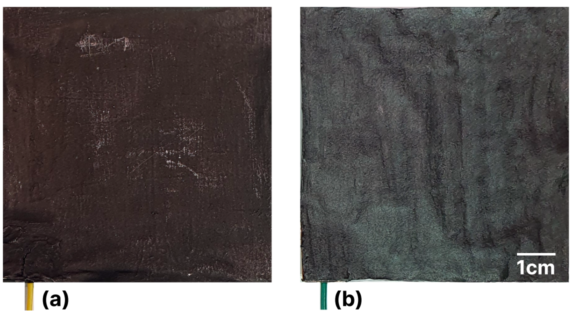

Figure 2: Fabricated flexible harvesting electrodes on diaper back sheets; (a) carbon ink cathode, (b) zinc ink anode.

shown in Figure 1(b) because of the low conductive properties of zinc ink. The finished version of the printed cathode and anode are shown in Figure 2.

2.1.2 Pseudo-Urine as Electrolyte

The pseudo-urine is used as an electrolyte to replace the hazardous electrolyte ammonium chloride (NH_4Cl) which is used in commercial zinc-carbon dry batteries. The reference concentration of sodium electrolytes in human urine exhibits a range of 80 to 240 mmol/l and the concentration of chloride electrolytes has a range of 85 to 260 mmol/l for adults, as reported by the Laboratory of Helsinki University Hospital and FimLabs of Finland (HUS, 2023; FimLab, 2023). In this study, the chemical composition of pseudo-urine is formulated at Aalto University labs using sodium chloride (NaCl) at an electrolyte concentration of 220 mmol/l. The designed concentration falls within the referenced concentrations for sodium and chloride electrolytes in the human urine. It is noteworthy that a one-mole solution of NaCl consists of a molar mass of 23 g/mol for sodium and 35.5 g/mol for chloride, as outlined in a reference source (Lide, 2009).

2.2 Measurement Setup

A galvanic cell is established as a vertical container, holding the pseudo-urine of one liter as electrolyte. The harvesting electrodes are deployed on the inner side of the container in a parallel orientation. The salt bridge of pseudo-urine connects the oxidation and reduction reactions of these half cells. Figure 3 depicts the established measurement setup to evaluate the harvested energy. Various measurement scenarios are employed to analyze the harvested voltage level and amount of energy from pseudo-urine. The multimeter (73 III, Fluke) is used to measure the open circuit voltages (OCV) of the developed galvanic cell. A direct current (DC) energy analyzer and power profiler instrument Otii Arc Pro (Qoitech AB, Sweden) is employed with Otii Battery Toolbox (Qoitech AB, Sweden) to characterize the zinc-carbon flexible electrodes for energy harvesting from pseudo-urine as an electrolyte.

In the first measurement scenario, the rolled sheet-based zinc-carbon harvesting electrodes with a surface area of 98 cm^2 are deployed in the galvanic cell with an inter-electrode distance of 7 cm. The pseudo-urine-based electrolyte is poured inside the cell and the immersed depth of electrodes is increased by 1 cm in each measurement hence increasing the immersed electrode area by 14 cm^2 for each measurement to analyze the effect of the

Figure 3: Measurement setup to harvest energy from pseudo-urine.

variations in the partially immersed electrode area on harvested energy. The voltage level and the amount of harvested energy are analyzed to emulate the frequent urination events when the electrodes are partially immersed in small urine quantities inside diapers. The second measurement scenario uses fully immersed zinc-carbon electrodes in a one-liter pseudo-urine electrolyte of the galvanic cell and the inter-electrode distance is varied from 5 mm to 30 mm with an increment of 5 mm for each measurement.

In the third measurement scenario, the printed zinc-carbon flexible electrodes are fully immersed in one liter of pseudo-urine electrolyte of the galvanic cell in parallel orientation at a distance of 7 cm to evaluate the change in voltages and current flow when a constant power of 800 uW is continuously withdrawn. The fourth measurement scenario evaluates the intermittent energy harvesting sessions every 30 minutes where the same printed zinc-carbon electrodes are fully immersed in the pseudo-urine electrolyte of a galvanic cell for 11 hours to understand the possibility of powering the IoT sensor node overnight to perform measurements for multiple urination events inside the same diaper.

3 RESULTS AND DISCUSSION

In the evaluation measurements, the OCV level of 1032 mV is measured for the developed single galvanic cell and 2060 mV when the two galvanic cells are connected in series. The harvested voltage level of the single galvanic cell, with fully immersed electrodes, drops to 875 mV when connected to a constant power load of 100 uW and further drops to 831 mV when the load is increased to 800 uW. The effect of variation in the immersed electrode area out of the total area on the amount of harvested energy from the first measurement scenario is depicted in Figure 4. It is observed that the amount of harvested energy is linearly proportional to the immersed surface area of the harvesting electrode with a variation of 1.9 uWh/cm^2 to 4.3 uWh/cm^2 when the percentage of the immersed surface area of the single electrode increases from 14% to 100%.

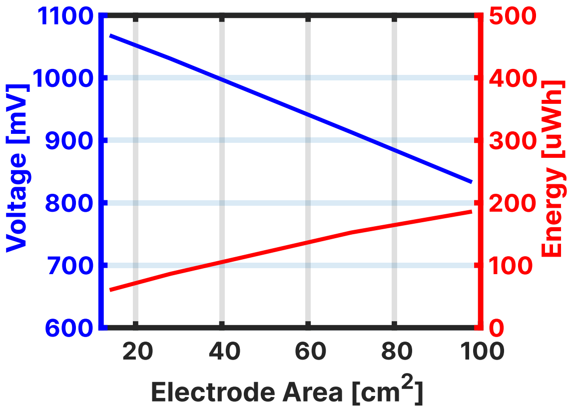

Figure 4: The effect of surface area on the harvested energy and voltages.

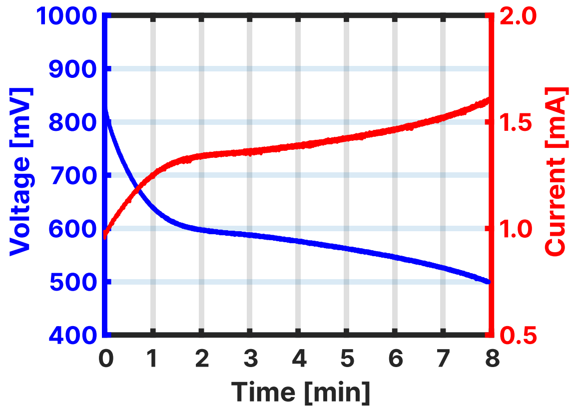

Figure 6: The output voltage and output current response of printed harvesting electrodes.

Another interesting observation is that the voltage level gets as high as 1068 mV when the percentage of the submerged surface area is reduced to 14% and the galvanic cell is connected to a constant power load of 100 uW.

The effect of variations in the inter-electrode distance on the amount of harvested energy is analyzed in the second measurement scenario. The galvanic cell with fully immersed zinc-carbon electrodes in the pseudo-urine electrolyte is loaded with 100 uW for the initial 10 seconds. The load is increased to 500 uW power afterward and the harvested energy is recorded until the voltage level drops to 500 mV, the lower threshold of Otii Battery Toolbox (Qoitech AB, Sweden). The measurement is repeated by increasing the inter-electrode distance by 5 mm for each measurement using the same electrodes and electrolyte. The results of harvested energy and starting voltage levels with inter-electrode distance variations are presented in Figure 5. It is observed that the amount of harvested energy reduces linearly with an increase in the inter-electrode distance and drops 25% when the distance is doubled. The non-linearity at the inter-electrode distance of 15 mm is observed due to measurement errors because each measurement was taken only once. The starting voltage level of the galvanic cell has also seen a drop of 130 mV because the redox process deteriorates the surface of the harvesting electrodes over the harvesting time period (Singh et al., 2021).

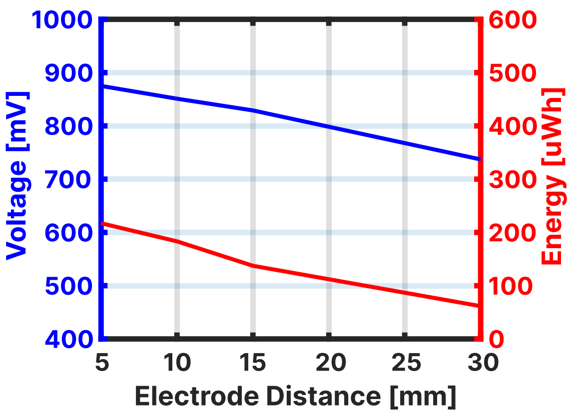

Figure 5: The effect of inter-electrode distance on the harvested energy and voltages.

The third measurement scenario involves the utilization of printed zinc-carbon electrodes on the inner side of the diaper back sheet having 50% surface area (49 cm^2) compared to sheet-based electrodes. The printed electrodes are fully immersed in the one-liter pseudo-urine electrolyte and connected to the constant power load of 800 uW. The trend of voltage level and current flow is observed over time until the voltage level drops to 500 mV. The voltage and current response of the printed zinc-carbon electrodes is depicted in Figure 6. It is observed that the single cell of single-side printed zinc-carbon electrodes is capable of supporting output current flow up to 1.6 mA.

The same setup of printed zinc-carbon electrodes from the previous measurement scenario is further used in the fourth measurement scenario to evaluate the performance of harvesting electrodes when fully immersed in the same electrolyte for a longer period. A fixed power amount of 800 uW is withdrawn in each harvest session until the voltage level reduces to 500mV and the session is repeated every 30 minutes for up to 11 hours. The results of the harvested energy and the starting voltage level of the single galvanic cell are shown in Figure 7. It is observed that the starting voltage level and the amount of the harvested energy from the same electrodes in the same electrolyte drop linearly for each subsequent harvesting session. It is evident that even after 11 hours the printed zinc-carbon electrodes are still

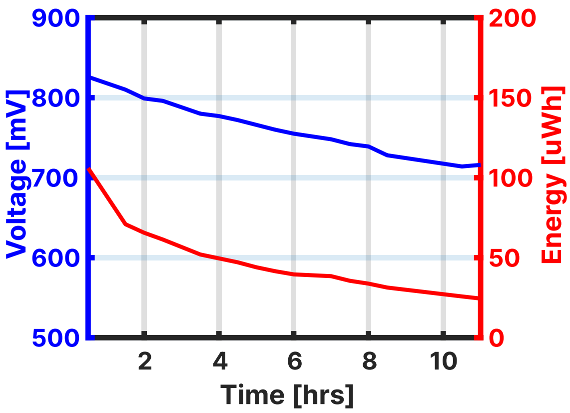

Figure 7: The harvested energy and voltages of the printed electrode over a longer time in the electrolyte.

capable of providing 25% of the energy amount from the first harvesting session. The total drop in single cell starting voltage level is measured as low as 110 mV after 22 harvesting sessions.

The proposed novel chemical energy harvesting solution using printed zinc-carbon electrodes in a pseudo-urine electrolyte has yielded promising results. These electrodes may be adopted with a power-optimized on-chip system for smart diapers as developed by (Tanweer et al., 2023b) interfaced with printed coplanar capacitive sensors developed by (Tanweer et al., 2023c) to detect wet diapers and quantify voided volumes in diapers.

The harvested energy from the proposed printed harvesting electrodes is sufficient to power on-chip circuits fundamental for most of the front-end sensor interface electronics such as 0.39–3.56 μW wide dynamic range universal multi-sensor interface circuit by (Moayer et al., 2020) and 462 nW 2-axis gesture sensor interface based on capacitively controlled ring oscillators (Pulkkinen et al., 2017). It can also power energy-optimized wireless communication blocks of the IoT sensor nodes such as a low-power wireless transceiver with a 67 nW differential pulse-position modulation (DPPM) transmitter (Pulkkinen et al., 2020). The on-chip sensor-end electronics can also be combined with the low-power DPPM transmitter to develop a self-powered IoT sensor node for smart diapers running on harvested energy from urine with sustainable and economical printed harvesting electrodes.

4 CONCLUSIONS

This research introduces an innovative approach to creating printed electrodes that can harvest energy from pseudo-urine, offering a sustainable solution for powering IoT sensors in smart diapers. The study explores the potential of using urine as a renewable energy source to operate these sensors and interfaces, emphasizing the importance of eco-friendly practices in the development of wearable technology. By utilizing zinc and carbon materials, these electrodes are printed directly onto the back sheets of diapers, a process that aligns well with current diaper manufacturing techniques. The primary focus of the research is to test the effectiveness of these disposable zinc-carbon electrodes in generating power from urine. This breakthrough presents for the first time a significant step towards developing smart diaper sensors that operate overnight without the need for traditional batteries, promoting sustainability and energy efficiency.

In the future, an on-chip power management unit might be incorporated with the single cell of proposed flexible printed harvesting electrodes to harness energy from urine and to ensure the continuous supply of regulated voltage to the on-chip front-end sensor interface circuits, control systems, and communication interfaces of an IoT sensor node developed for smart diapers. The changes in the level of generated voltages from printed harvesting electrodes might also be further studied to provide an additional parameter together with measurement data from the printed coplanar capacitive sensors for reliable and precise quantification of the voided volume inside the diaper which is otherwise affected by body weight on the wet diaper as discussed by (Tanweer et al., 2023a).

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