

# Implementation of a Microfluidic Conductivity Sensor — a Potential Sweat Electrolyte Sensing System for Dehydration Detection

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**Abstract**— as dehydration continues to plague performance athletes and soldiers, the need for improved dehydration detection is clear. We propose the use of a conductometric sensor as the foundation of a sweat-sensing patch to address this need. The conductometric sensor evaluates the conductivity of solutions with varying sodium concentrations. A lithographic process was used to fabricate a Polydimethylsiloxane (PDMS) microfluidic channel through which solution was flowed. The ionization of the solution that occurs when a voltage is applied results in an effective resistance across the channel. The measured resistance therefore, reflects the ionization of the solution and the corresponding sodium concentration.

The potential application of the conductometric sensor in a sweat-sensing patch requires compatibility with a microcontroller and Bluetooth module. Thus, a circuit interface was created. A voltage divider was utilized to convert the output resistance of the sensor to a voltage that could be input into a microcontroller. An AC voltage signal with a frequency of 10 kHz was used as the source voltage of the voltage divider to minimize the faradaic impedance and the double layer effect of the ionized solution. Tests have revealed that the conductometric is capable of precisely measuring the conductivity of a sodium solution. The conductometric sensor will be applied to a sweat sensing patch through future work involving studying the link between sodium concentration in sweat and an individual's dehydration level, developing a sweat-collection method, and developing a method of consideration for the other ions contained in sweat.

**Index Terms**— Conductometric Sensor, Conductivity, Wireless Data Transmission, Sodium Concentration Measurement.

## I. INTRODUCTION

Often difficult to detect, dehydration continues to hamper athletes and soldiers in high-pressure environments. Current methods of dehydration include blood tests and urinalysis, both of which are inconvenient and fail to provide real-time dehydration feedback [1]. Thus, there is a strong need for real-time detection of hydration levels, which we propose can be addressed by the development of a sweat-sensing patch. This paper will introduce a conductivity sensor that has been developed as the foundation of the hydration technology

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utilized by the sweat-sensing patch. The application of the conductivity sensor to hydration detection relies upon the relationship between the electrolyte concentration of an individual's sweat and his or her hydration. In general, there are four major constituents of sweat; sodium, potassium, lactate, and urea [2, 3]. Compared with other constituents, sodium is the most concentrated electrolyte, ranging from 20 mM to 100 mM. This concentration increases significantly as the dehydration increases [4]. Although potassium ions are also present in the sweat, their concentrations are 1 to 2 orders of magnitude less than sodium ions [4, 5]. Therefore, sodium monitoring provides an efficient way for dehydration detection.

As the rate and duration of perspiration increases, the loss of water and the loss of electrolytes (particularly sodium) occur at differing rates. Therefore, the concentration of sodium in an individual's sweat reveals information regarding his or her hydration. Dehydration occurs when an individual's body does not have the appropriate fluids to carry out its normal functions [6]. This dearth of fluid is reflected in an individual's sweat concentration, as the concentration of sodium in the sweat will be greater than it would be if the individual was properly hydrated [6, 7]. Given the correlation between dehydration and the concentration of sodium in sweat, early detection of dehydration can be achieved through monitoring of the sodium concentration of sweat.

When compared with other categories of biosensors, conductometric sensors have several advantages. First, the measurement of conductance can be fast and sensitive [8-10]. Unlike Ion Selective Electrodes (ISE), conductometric sensors are also suitable for miniaturization since they do not require a reference electrode in the system [11, 12].

With the potential sweat-sensing application of the conductometric sensor in mind, a circuit interface is proposed to interpret the conductometric sensor measurements. The focus of the paper is the development of a conductometric sensor to determine the sodium concentration of a given solution, but the development of a circuit interface will allow for future exploration of the applications of this sodium detection technology. Using the conductometric sensor output to provide insight into sodium concentrations and eventually dehydration levels requires amplification, data conversion, and wireless transmission. Thus, the proposed circuit interface is comprised of an operational amplifier, microcontroller, and a Bluetooth module. The ultimate goal of our project is to achieve multiple dehydration wireless monitoring as it shown in Fig. 1. The first step, however, was the development and fabrication of the conductometric sensor.

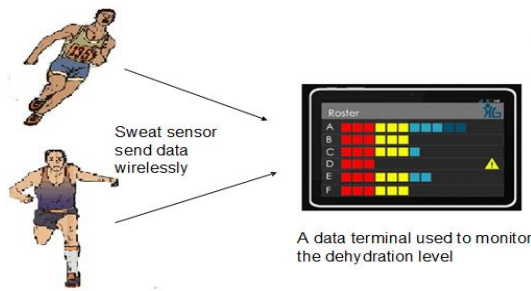


Figure 1: Illustration of the dehydration detection application of the conductometric sensor.

## II. CONDUCTIVITY SENSOR

### A. Sensor Design

We propose using Polydimethylsiloxane (PDMS) to fabricate a microfluidic channel through which a solution is flowed using a simple bar-shaped microfluidic device. Wires connected to the inlet and outlet of the channel is utilized to evaluate the resistance of the device. The resistance will be a reflection of the ionic conductivity of the solution. Fig. 2 shows a schematic layout of the conductometric sensor. The prototype of the device was fabricated.

The conductometric microfluidic device was fabricated at the Material Testing Lab of Central Michigan University by using conventional soft lithography techniques. A channel mold was created using SU-8 on a 2 inch wafer resulting a 4mm wide and 24 mm long. The distance between the two electrode wires was 20 mm. The SU-8 negative photoresist was spun onto a silicon wafer substrate at 500rpm for 5 seconds and then 3000rpm for 30 seconds. The wafer was then pre-baked for 5 minutes at 65°C, then was allowed to cool to room temperature, and was baked again for 20 minutes at 95°C. The substrate was exposed using a mask aligner under UV for 10 seconds, and the pre-bake step was repeated. The wafer was immersed into the SU-8 developer and agitated until extraneous photoresist was gone, leaving only the desired shape for the mold. The mold was rinsed with DI water and allowed to dry. PDMS was prepared with 1:10 curing agent: PDMS base and poured onto the mold and baked at 65 °C for 2 hours. A rectangular shape including the pattern was cut and the PDMS was removed from the mold. Holes were punched on the PDMS and the PDMS piece was attached onto the glass substrate.

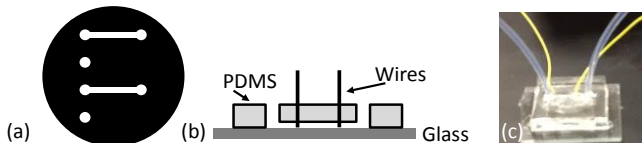


Figure 2: The schematic layout of the conductivity microfluidic sensor; (a) the mask for lithography, (b) a cut-way view of the conductivity microfluidic device, (c) the fabricated device.

Given that the application of the conductivity sensor as a dehydration device requires the use of a microcontroller, the resistance of the conductivity sensor needs to be converted to a voltage for compatibility with the analog to digital conversion (ADC) function of the PIC16F1823 microcontroller. To convert the resistance of the conductivity sensor to a voltage, a simple voltage divider was implemented.

### B. Solution Polarization and Double Layer Effect

The magnitude and nature of the voltage source for the voltage divider was complicated by the polarization characteristics of sodium solutions. Fundamentally, the conductivity of solutions results from the dissolution of a substance into ions and the subsequent electrically induced migration of these ions [6]. As a result of the ion migration, a current passes through the solution.

When an electrical field is applied to the solution, the anions will move to the anode and the cations will move to the cathode, resulting in an internal electrical potential. The internal electric potential has an opposing polarity to the external electric field. The internal electric potential prevents the directed movement of ions, resulting in the solution having a larger resistance. An equivalent circuit for the electrolytic conductance cell is shown in Fig. 3 [13], where  $Z_f$  represents the equivalent impedance (capacitive) caused by the polarization effect,  $C_{dl}$  is the double-layer capacitance resulting from the interface of the wires and the electrolyte, and  $R_b$  represents the resistance of the electrolyte. The existence of  $C_{dl}$  and  $Z_f$  introduced non-ideal characteristics to the conductance cell. In order for the measured resistance to be a true reflection of the conductivity of the solution, the effect of  $C_{dl}$  and  $Z_f$  must be minimized. A DC voltage would cause polarization of the solution that would make the capacitive impedance component too large causing instability in the resistance measurements. The instability will be more severe for solutions with larger sodium concentrations as the polarization of the solution, and the resulting faradaic impedance, will become more significant. Therefore, an AC voltage was applied as the input voltage for the voltage divider. The fluctuation between positive and negative voltages does not allow the solution to polarize, significantly reducing the impact of the polarity impedance. While using an AC voltage source reduces the impact of the polarity impact, the frequency needs to be chosen properly.

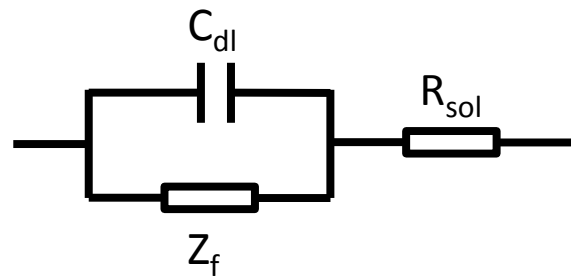


Figure 3: The schematic representation of half of the conductance cell.

It should be noted that a relatively small AC voltage swings peak value should be used for the AC source voltage signal [14, 15]. When the amplitude of the AC voltage signal is less than 10mV, the effects of noise are significantly increased. While the input AC signal's amplitude is greater than 10mV, the effect of polarization would increase. The polarization increases the faradaic impedance,  $Z_f$ , causing error in the resistance measurement. Different values of AC amplitude were tested and plotted in Fig. 4 by normalizing each output to its initial value. The result shows that as the amplitude increases, the output voltage of the sensor increases, introducing error to the measurement. Based on these results, 10mV peak value was selected as the optimal amplitude. The frequency was chosen to be 10 kHz to ensure that the Faradaic processes of electro-active species in the test solution can be considered negligible [14, 15].

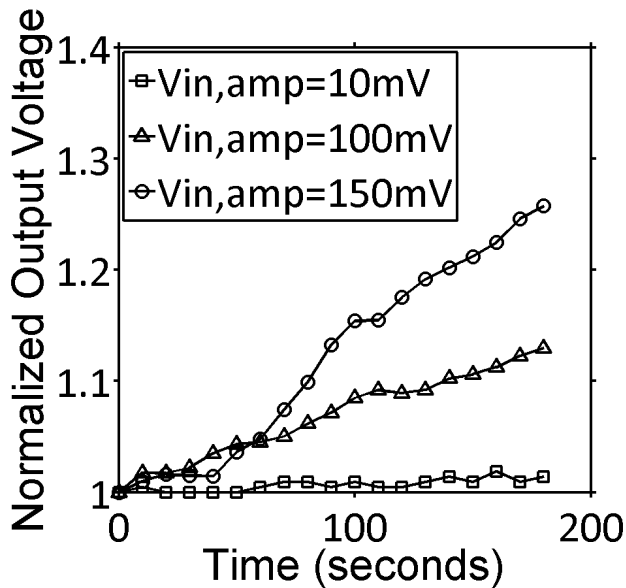


Figure 4: The sensor's output voltage with different amplitudes of input signal. A solution with 990 ppm sodium concentration was used to perform this test.

### III. TESTING AND CHARACTERIZATION

The conductometric sensor was tested using sodium chloride solutions with various concentrations from 300ppm to 4300ppm. The AC signals are presented in rms (root mean square) values. As the resistance of the solution is directly correlated to the salt concentration of the solution, the voltage of the voltage divider is the measure of the salt concentration. As it can be seen in Fig. 5, the relationship is not linear. A nonlinear fit (with an  $R^2$  value of 0.975) was applied to the data that resulted the following equation:

$$R_{sol} = 2219 * C^{-0.648} \quad (1)$$

Where  $C$  represents the concentration of the sodium in the solution in ppm and  $R_{sol}$  is the resistance value of the solution in kilohms. It should be noticed that even in the most extreme dehydration cases, the concentration of sodium ions in human sweat will not exceed 150 mM. Therefore, the performance of the sodium sensor within this range is considered satisfactory.

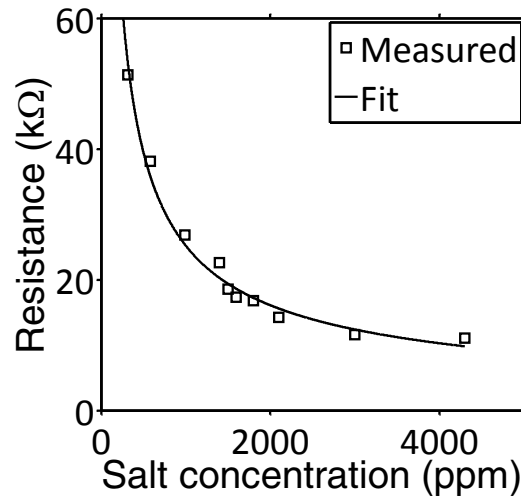


Figure 5: The testing results and characterization curve of the conductometric sensor.

### IV. CIRCUIT INTERFACE

Given that the application of the conductivity sensor as the foundation of a dehydration monitor requires compatibility with the PIC16F1823 microcontroller, a circuit interface was utilized. While the 10mV peak value was optimal for the resistance measurement, the implementation of the ADC function is limited by the 10mV magnitude. With a DC source voltage of 3.7V, the 10-bit ADC (analog to Digital Converter) function of the microcontroller allows for a distinction to be made between inputs differing by 3.617mV. Thus, the measurements from the voltage divider must be amplified such that significant changes in the sodium concentration will yield a voltage difference in excess of 3.617mV. In order to achieve this desired amplification, a non-inverting operational amplifier was employed as shown in Fig. 6. The optimal amplification was found to be 10. Thus,  $R_3$  was chosen to be nine times larger than  $R_2$ .

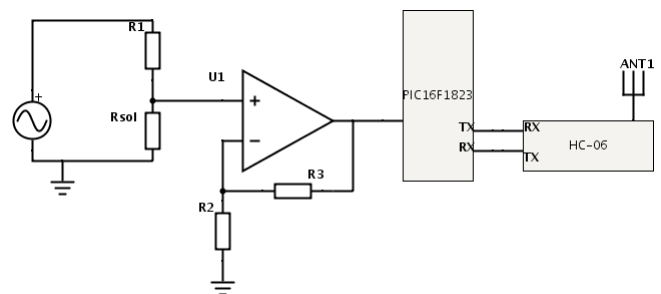


Figure 6: The schematic representation of the whole system.

Once amplified, the voltage can be input into the microcontroller for conversion and manipulation. It should be noted that the ADC of PIC microcontroller is unipolar, rendering it incapable of accepting a negative input voltage. To accommodate this feature of the ADC function, a special sampling method was used to receive the input voltage.

In a given sampling period, the microcontroller converts and compares the input voltage, quickly erasing the smaller value to accommodate incoming data. The sampling period is 0.15 ms, which is larger than the period of the 10 kHz input voltage signal. The PIC microcontroller provides a very fast



sampling rate, with potential to achieve a rate of one sample every 10  $\mu$ s. After one period of sampling, we can find the positive maximum voltage of the input signal, which is the amplitude of the input signal. This maximum voltage will be stored in the microcontroller until the maximum voltage of next sampling period come to replace it. Considering that the input signal is sinusoidal, the rms value of the signal can easily be calculated (0.707 of the peak input voltage).

In order to send the data to a monitoring platform, an HC-06 Bluetooth module was used to transmit the sodium concentration data. A UART interface was established between the PIC16F1823 microcontroller and the HC-06 Bluetooth module as sketched in Fig. 6. The Bluetooth module was set to standby mode as a server, periodically sending communication request. As soon as a client response is requested, the Bluetooth module begins contentiously transmit data to that Client.

As a proof of concept, the Bluetooth module was paired with a Windows Smart phone to show the operation. The overall circuit with the conductivity sensor is shown in Fig. 8.



Figure 8: Overall conductivity sensing platform.

## V. CONCLUSION AND FUTURE WORK

At this point, we have fabricated and tested our proposed conductometric microfluidic sensor. Using a voltage divider, the sensor outputs an AC voltage signal, which is related to its conductance. A special sampling method was used to input the AC signal to the PIC microcontroller. Based on the characterization curve, the PIC microcontroller can calculate the sodium concentration of the tested solution. Then, the PIC microcontroller transmits the concentration data to the Bluetooth module HC-06 via a UART interface. An Android application was created to receive and display the data. Once the communication between HC-06 and Android application was established, the Bluetooth module was capable of continuously sending the data to the Android phone and the application can display those data on the screen.

Our future work will focus on three parts. First, the clear relationship between dehydration level and sodium concentration in sweat will be studied. We will try to find an algorithm which illustrates the relationship of dehydration level, sodium concentration, temperature, and humidity. Second, we need to find an efficient method of collecting the

sweat from human body. While we have already tested a sweat-collection patch, we still need to do further research to improve the efficiency of the sweat collection. We also need to add micro valves and pumps, which can be controlled by the microcontroller to automatically input the sweat to the sensor's channel. Third, we need to find a way to take into consideration the various kinds of ions inside sweat, which can all affect the conductivity. Although sodium is the most concentrated ion in sweat, it is imperative that we study and analyze the content of sweat in order to reduce the error in our results. Also, we will try different kinds of electrodes like silver or platinum electrodes to figure out the influences of the electrode material on the sensor.

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