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KAUSTat: A Wireless, Wearable, Open-Source Potentiostat for Electrochemical Measurements

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Abstract— **Advanced technology is needed every day for wireless, wearable sensors/potentiostats to record real-time measurements and monitor the chemical processes and physiological signals of the human body. Most of the potentiostats present on the market work as "black boxes" without access to their internal structure and their limited information of circuitry makes it challenging to develop new measurement methods and further integration with other instruments. Despite high resolution (e.g., measure low currents with high precision and low noise) of commercial potentiostats, the potentiostats used in laboratories are heavy, non-portable, and expensive. To fill this void, we introduce KAUSTat, a wireless, wearable, open-source potentiostat. The KAUSTat device interfaces with a smartphone to generate cyclic voltammetry curves using a Bluetooth Low Energy (BLE) protocol. Experiments with buffer and hexacyanoferrate solutions were conducted to assess the efficiency of the device. The results generated by KAUSTat are in agreement with those of the commercial potentiostat "Emstat." Considering wireless and wearable features of KAUSTat, it represents a convenient portable device for on-site sensing with low-power requirements.**

Keywords— Biosensors, Electrochemical sensing, wearable, cyclic voltammetry

I. Introduction

A potentiostat is an indispensable instrument in electrochemical research due to its potential application in numerous fields (e.g., analytical chemistry, biology, energy storage, material science, environmental sensing, and medicine) [1-8]. The potentiostat instrument is virtually always required when controlling and measuring current and voltage during the electrochemical detection of target analytes, such as certain biomarkers and biomolecules [9, 10]. Commercially available potentiostats offer high resolution (e.g., measure low currents with high precision and low noise), but are not wearable and costly [11-15]. Another challenge with such commercial potentiostats is that they prevent the user from gaining a better understanding of the collected data, since they function only as a "black box." Thus, additional steps are required to reach the desired result.

Advances in electronics have provided portable and low-cost potentiostats via "do-it-yourself" manufacturing. With their open-source features, such devices possess valuable advantages over the standard commercial ones [16-21]. For example, Lopin and Lopin developed an open-source potentiostat based on the Programmable System on a Chip (PSoC®) "PSoC-Stat" with an operating voltage and current ranges of ± 2 V and 100 μA, respectively [16]. Dryden and Wheeler introduced DStat with an operating voltage and current ranges of ± 1.5 V and 10,000 μA, respectively [17]; Rowe et al. developed Cheapstat with an operating voltage and current ranges of ± 0.99 V and 50 μA, respectively [18]; Dobbelaere et al. designed a low-cost USB-controlled potentiostat/galvanostat with a potential range as wide as ±8 V [7]; and Nemiroski et al. introduced a universal mobile electrochemical detector (uMED) with an operating voltage and current range of ± 2 V and 156 μA, respectively [19]. Among these devices, Dstat offers the most advanced features in terms of precision, current resolution, and friendly interface [17]. However, most of the devices were designed to work in conjunction with computers/mobile devices using a wired USB connection port.

In this work, we introduce a wireless, wearable, open-source, and low-power potentiostat named "KAUSTat." To demonstrate the practical applicability of the designed KAUSTat potentiostat, the electrical characteristics were tested in the various buffer solutions using different electrodes (bare and nanomaterial modified). The experimental results show that KAUSTat is a viable potentiostat that can measure electrical signals by using a smartphone and has the potential to be customized as a wearable device for real-time measurements.

II. Materials and Methods

A custom-developed application, KAUSTat allows the user to choose the necessary parameters to perform the cyclic voltammetry measurement. These parameters are the start voltage, the final voltage, the scan rate, the step voltage, and the number of cycles. Once these parameters are defined, calculations are executed to calculate the DAC values.

To demonstrate the efficiency of the KAUSTat, experiments were conducted in buffer solutions. Three solutions—(i) phosphate buffer saline (PBS) containing 137 mM sodium chloride (NaCl), (ii) sodium hydroxide (NaOH), and (iii) hexacyanoferrate probe (5 mM $[Fe(CN)_6]^{3-/4-}$ and 0.1 M KCl) solution—were commonly used to assess the performance of a potentiostat. All the CV measurements were conducted using platinum (Pt) as the counter, Ag/AgCl as reference, and glassy carbon electrode (GCE) working electrodes, as used in our previous work [18]. During CV measurements, RTIA value of 300 kΩ was selected for optimum result. The results were then compared to the CV responses obtained from the commercial portable potentiostat "EmStat Blue." The working electrode was modified with nanomaterial to observe the effect of modifications on the functionality of the potentiostat. We used Mathematica software to smooth the CV curves as they are noisy in shape due to the very low current.

III. DESIGN OF THE KAUSTAT

Figure 1 depicts the block diagram of the KAUSTat system, which is based on the open-source design of DStat.17 The KAUSTat instrument consists of a printed circuit board (PCB), containing the analog circuit for the potentiostat and a Bluetooth Low Energy (BLE) chipset. In addition, this features a three-terminal potentiostat capable of basic electrochemical measurements, such as cyclic voltammetry (CV) and chronoamperometry. The user interfaces with the board using a custom-made smartphone application that enables the user to set measurement parameters and save obtained data, which may later be forwarded to the user's e-mail address. This current version of KAUSTat's board and mobile application enables a cyclic voltammetry mode. As compared to DStat, the KAUSTat is suitable for use in wearable applications due to reduced size and wireless capability.

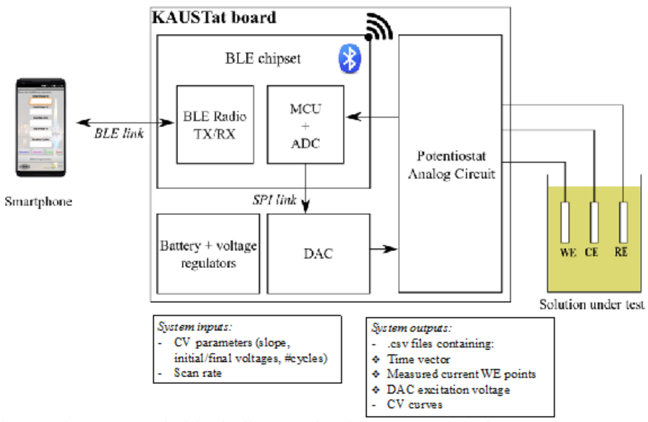

Fig. 1. The systematic block diagram for the proposed design

The voltage after the TIA is read by a 12-bit analog-to-digital converter, which is also part of the BLE chipset's MCU. The board is powered by a 3 V battery and has two voltage regulators: a 1.2-V low-dropout regulator (LDO) to set the common mode voltage of the op-amps (Vcm) and a 2.5-V LDO to provide the reference voltage for the DAC (VDAC ref). The size of the KAUSTat board is 3.0-cm x 5.4-cm, with its main components highlighted above.

Figure 2b shows the KAUSTat's circuit board at the elbow and its potential application and utilization as wearable device. The board houses three terminals to be connected to an electrochemical solution: a working electrode (WE), a reference electrode (RE), and a counter electrode (CE). The board is interfaced with the smartphone application through the BLE chipset's internal transceiver, which is connected to an onboard chip antenna. The main operation of the board is controlled by a microcontroller unit (MCU) internal to the BLE chipset. A conventional three op-amp topology is used as the potentiostat's circuit. The combination of the control amplifier and the electrometer sets a constant voltage between WE and RE, while a transimpedance amplifier (TIA) converts the current at WE to a voltage with the aid of a bank of resistors, which provides a variable RTIA. The potential between WE and RE is set by an onboard 16-bit digital-to-analog converter (DAC), whose code is sent from the MCU through a serial peripheral (SPI) link. The operation commands to the device are through the KAUSTat mobile application as shown in figure 2c.

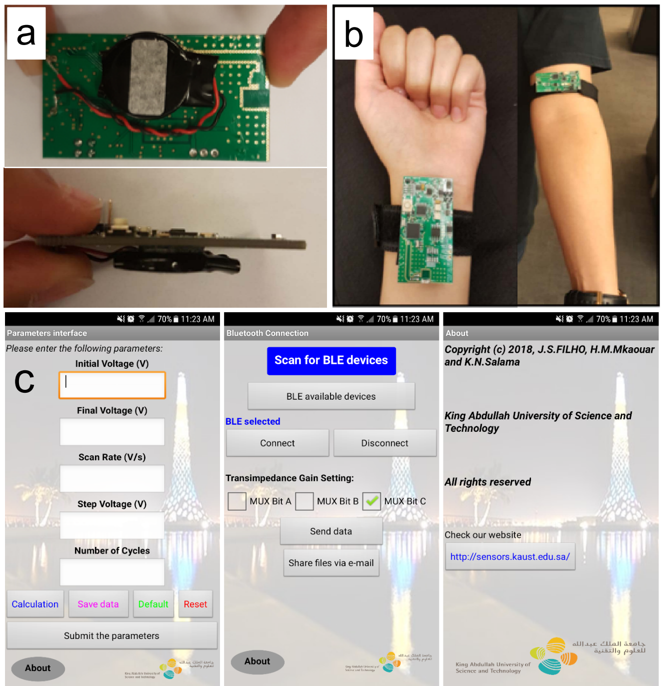

Fig. 2. (a) KAUSTat potentiostat powered by 3V lithium battery, (b) possible usages of KAUSTat as a wearable potentiostat, and (c) the three main screens of the custom KAUSTat application.

IV. ELECTROCHEMICAL TESTING USING KAUSTAT

In this paper, to evaluate the utility of our potentiostat, experiments with a hexacyanoferrate probe solution were carried out (Figure 3). The electrochemical cell was filled with a 10 mL hexacyanoferrate probe (5 mM $[Fe(CN)_6]^{3-/4-}$ and 0.1 M KCl) solution, electrodes were dipped into cell, and connected with KAUSTat (see inset of Figure 3a). As shown in Figure 3, the classic double-peak shaped CV was observed for the KAUSTat. The CV response in hexacyanoferrate probe solution presents no noise due to the high current level reaching almost 40 µA at the peak; thus, no smoothing of the curve was done. Additionally, to further check the workability of KAUSTat with surface modified GCE, NiO nanoparticles were added to the GCE working electrode's surface and CV response was measured (Figure 3b). As shown in Figure, CV curve obtained using KAUSTat is smooth and oxidation and reduction peaks reached 30 µA and -50 µA, respectively.

Considering KAUSTat for bio-analyte detection, the electrochemical test of the KAUSTat is conducted in a 0.1 M PBS solution. Initially, the potentiostat produced low current (maximum peak current is only 1µA), which is noisy. A curve smoothing method was proceeded to eliminate the noisy points. The PBS buffer solution is generally characterized by very low current, especially when the solution is free of any analytes. Furthermore, to increase the current level, we added nanoparticles on the GCE working electrode surface and CV responses were measured in PBS. Finally, we observed KAUSTat's CV response was increased and presented less noise. Thus, with the current findings, we find that the platform is suitable for our other wearable application using Mxenes [19, 20]. Regarding the current intensity of ferricyanide oxidation, it has witnessed a decrease of 25 %. This current change could be due a different surface area provided by the nickel oxide and as well as their electrocatalytic effect.

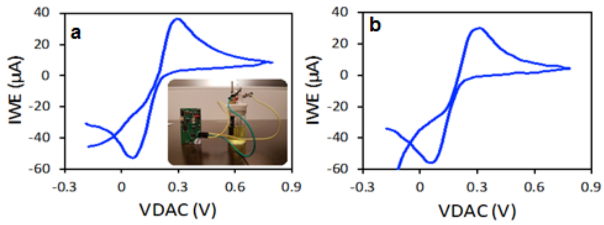

Fig. 3. CV response of (a) bare GCE in hexacyanoferrate probe (5 mM $[Fe(CN)_6]^{3-/4-}$ and 0.1 M KCl) solution at a scan rate of 50 mV/s in the potential range of -200-800 mV (b) NiO nanoparticle modified GCE in hexacyanoferrate probe (5 mM $[Fe(CN)_6]^{3-/4-}$ and 0.1 M KCl) solution at a scan rate of 50 mV/s

TABLE I. COMPARISON OF WEARABLE DEVICES

Device	Size (cm*cm)	Max current	wearable	wireless
Creditcard device [21]	8.5*5	200 µA	no	RFID
Smart band [22]	8.5*5	~ 5 µA	yes	NFC
wearable FISA [4]	~6*2.5	~ 1 µA	yes	Bluetooth
KAUSTat	5*3.5	500 µA	yes	Bluetooth

Additionally, to compare the current response of our KAUSTat with commercial Emstat, we conducted CV measurements in PBS and electrochemical probe solution of $Fe(CN)_6]^{3-/4-}$ and KCl (Figure 4). In the PBS buffer, both the CV curves of KAUSTat and Emstat were comparable (Figure 4a). A slight difference in peak heights could be caused by the difference in the clock timing (the ADC reading is performed at 80% of the chosen measurement period) set by our application. As Emstat is working as a black box, the exact measurement timing could not be known. This difference would cause a difference in the peak's heights. Similarly, the CV curves of both potentiostats in electrochemical probe solution were smooth and comparable. However, the maximum current point of the KAUSTat was a little bit lower than that of the EmStat and the redox area of the CV curve for the KAUSTat was smaller than that of the Emstat. We further intend to replace GCEs with flexible substrates [23, 24] in combination with KAUSTat, which will potentially yield a low-cost wearable device with less complexity and more flexibility.

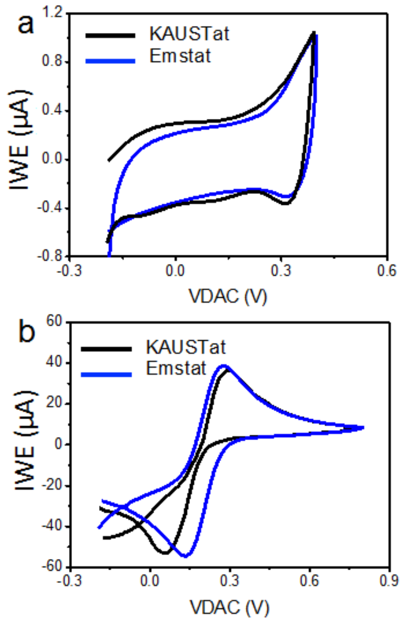

Fig. 4. Comparative study of KAUSTat with commercial Emstat. CV measurements of KAUSTat (black line) and Emstat (blue line) in PBS (a) and in hexacyanoferrate probe (5 mM $[Fe(CN)_6]^{3-/4-}$ and 0.1 M KCl) solution (b).

V. CONCLUSION

A wireless, wearable, open-source potentiostat (KAUSTat) is presented. It allows cyclic voltammetry to be performed as demonstrated here for various kinds of solutions. The application was designed using the MIT App Inventor interface. The user friendly interface allows for an easy definition of parameters. The BLE offers wireless communication and a testing distance of up to 16-20 m. The BLE exhibits lower power consumption compared to that of a standard Bluetooth system. This facilitates access to the user's database and the point-to-point investigation with minimal errors. The results were comparable to the ones generated by the "Emstat" for most of the measurements. The device has been shown to function more efficiently with a high level of current (≥ 10 µA). However, experimental results show that the KAUSTat could work up to 500 µA and can be a good commercial potentiostat used in laboratories.

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