Development of signal conditioning system for biosensor applications

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ABSTRACT

This signal conditioning circuit design is a micro-power, three terminal electrochemical cell amplifier that uses less than 1-μA total supply current for battery-powered or energy-harvested sensor applications. Electrochemical cells necessitate constant bias, which requires the amplifier circuit to be powered continuously to eliminate sensor start-up and settling times. The design is assembled on a dotted board compatible with the development Kit platform to allow testing with an MSP430 ultra-low-power processor to utilize the launch-pad processor analog to digital converters (ADCs) and liquid crystal display (LCD) for stand-alone operation. The whole design consideration is done after taking into consideration of three-terminal screen printed electrode that can have several applications as verified by experimentations and results. The design can be used for agricultural applications as a wide range of sensor current has been taken into design consideration. This needs simple modification based on sensitivity and response time of sensor.

KEYWORDS

MSP430,
Op-Amp,
Screen Printed Electrode,
Trans-Impedance Amplifier,
Potentiostat,
Current Source.

1. Introduction

Modern biosensors play a critical role in healthcare and have a rapidly developing commercial market. The electrochemical biosensors are attractive due to superior performance in response time, cost, complexity and potential for miniaturization.

This paper is limited to signal conditioning part which is capable to acquire 10uA to 200uA current generated by an electrode when it is subjected to a sample. As current produced from the electrode and number of antigens present in the sample have a proportional relationship, our signal conditioning circuit will display the number of antigens on the LCD screen as per the suitable relationship between output current of sensor and number of antigens present in the sample. Instead of an electrochemical sensor, a current source has been used taking into the consideration that the output of the sensor will be current. A wide range of sensor current is taken into consideration so that the design can meet the requirements of large number of electrochemical sensors.

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Into the context of electrochemical sensors, ampere-metric biosensors are the most promising ones, in terms of sensibility. They monitor the faradaic currents resulted of electronic interchanges between the biological system and the electrode. The measuring of the quantity of analyte present in the sample is made from the current generated in the induced electrochemical reaction, keeping a constant potential between the electrodes in the ampere-metric biosensors. The value of this voltage depends on the substance to determine.

In all kind of electrochemical experiment it is always necessary to have at least two electrodes: the working electrode (WE) which works as the cathode, and the reference electrode (RE) which is the anode. Thus, electrons go out from the cathode into the solution, being attracted by the anode. To make the result obtained repeatable, it is essential for the difference of potential between both electrodes to remain constant. However, as soon as current passes through the reference electrode (usually a silver wire) it gets polarised, which means that it's potential will vary with this current. Hence, to maintain a stable potential no current is allowed to pass by the RE electrode.

To avoid this drop of voltage a third electrode is added to the electrochemical cell: the counter

electrode (CE). A current is forced between WE and CE, high enough and in appropriate polarity to keep the working electrode potential at a constant value with respect to the RE electrode.

Using the proposed system our objectives are: (a) to measure the potential difference between WE and RE without polarising the reference electrode, and (b) to compare this potential difference to the preset voltage and force a current though the CE towards WE in order to counteract the difference between them.

2. Experimental

2.1 Current source

In our case, current source is the replica of electrochemical sensor which is basically a voltage to current converter. It is a voltage dependent current source. When voltage is varied from 0V to 0.5V voltage, current varies linearly from 10uA to 200uA which is our desired range. The simulation of the same is done in TINA software and later hardware design is done on dotted board.

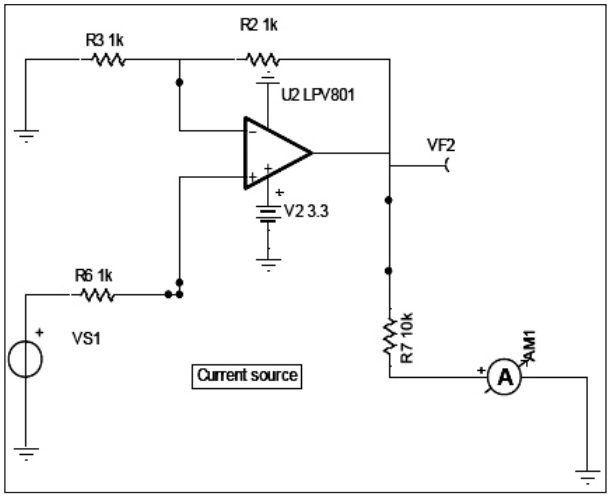

Fig. 1. Current source circuit diagram.

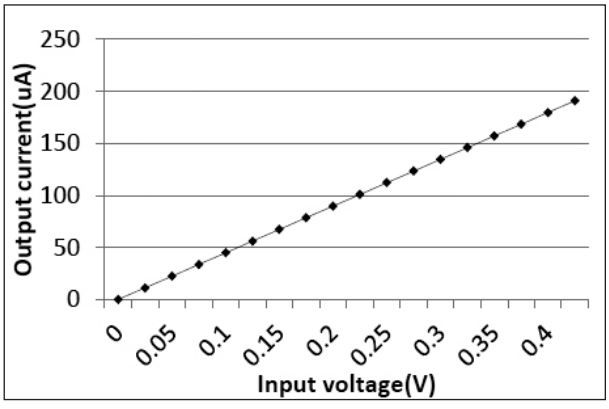

Fig. 2. Current source output.

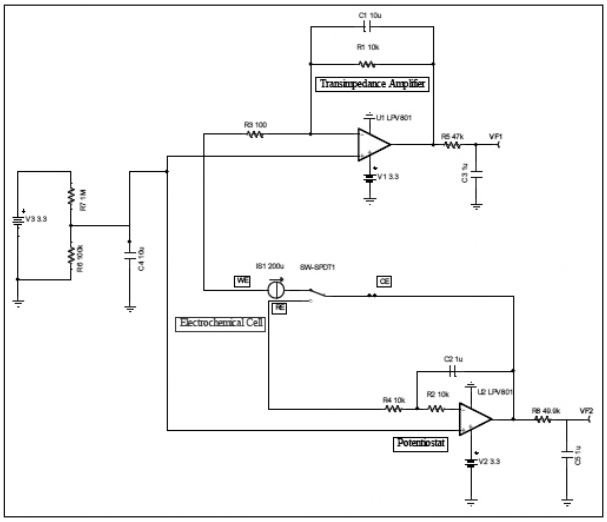

Fig. 3. Transimpedance amplifier and potentiostat.

2.2 Transimpedance amplifier & potentiostat

The system functions by maintaining the potential of the working electrode at a constant level with respect to the reference electrode by adjusting the current at a counter electrode. It consists of an electric circuit which is usually described in terms of simple op amps.

Transimpedance amplifier is a current to voltage converter, almost exclusively implemented with one or more operational amplifiers. The TIA can be used to amplify [1] the current output of Geiger-Muller tubes, photo multiplier tubes, accelerometers, photo detectors and other types of sensors to a usable voltage. Current to voltage converters are used with sensors that have a current response that is more linear than the voltage response.

An operational amplifier (LPV802) with a very low offset current, low noise and great input impedance is used to measure these low levels of current. A small capacitor for the phase compensation and eliminating highfrequency noises is used with the feedback loop. The LPV802 dual, micropower amplifier has been selected for its ultra-low power (typically 320 nA per channel) so that the entire potentiostat circuit uses less than 1 µA of supply current, which allows the circuit to stay continuously powered in battery-powered applications.

2.2.1 Calculations

The output current of the WE is converted to a voltage by TIA, which is represented as VF1.

$V_{F1} = V_{WE} + I_{WE}^{*} R_F$

Where, V_{WE} is working electrode voltage , I_{WE} is current through working electrode and R_F is feedback resistance of TIA.

R_L is the load resistor whose value is given by manufacturer of sensor and it is usually in the 5- to 100-Ω range.

2.2.2 Defining component values

The first condition is to establish the system reference voltage level. Assuming, a zero-bias sensor, V_{WE} and VRE are at the same potential and may be knotted together. The difference in potential between the WE and RE changes as the concentration increases. Unfortunately, most sensor data sheets do not specify this voltage change, so this change may require experimentation to discover or may be obtained from the manufacturer. Taking into consideration of a standard sensor, we took 300 mV as reference voltage (V_{RE}). There is an adjustment between the permissible CE swing headroom and available output signal range because the TIA output signal holds the sum of the TIA output signal plus the reference voltage. Therefore 300 mV is to be used as the minimum voltage (V_{ZERO}) corresponding to zero concentration of antigens to add some headroom.

The maximum TIA output is 2.5 V to drive the ADC of microcontroller. The specification is to measure up to 300 ppm. The sensor used in the test has a specified current output of 633.3 nA per ppm.

Sensor sensitivity = 633.3 nA/ppm
Maximum Concentration = 300 ppm

The maximum sensor current at the highest expected concentration is calculated as below

$I_{MAXIMUM}$, Sensor = 190 uA

The available output swing range above the reference voltage available for the measurement is calculated as

$V_{SWING} = V_{TIA} – V_{REFERENCE} = 2.5\ V – 0.3\ V = 2.2\ V$

The trans-impedance resistor (RF) value can be calculated by using the maximum swing and the maximum sensor current as below:

$R_F = V_{SWING} / I_{MAXIMUM}$, Sensor
$= 2.2/20.7u = 11.57\ k\Omega$

Use 10 kΩ as the next convenient common value and to also allow for some headroom. The sensitivity in mV per ppm is calculated as below:

$V_{SENSE} = R_F$ * Sensor sensitivity
$= 10\ k\Omega$ * 633.3 nA/ppm
$= 6.33$ mV/ppm

The resulting output of the TIA is 300 mV at a 0-ppm concentration and increases at a rate of 6.33 mV per ppm. The readings below $V_{WORKING}$ are invalid and may indicate sensor damage, contamination, or that an overload recovery time is required. The actual concentration measurement is the difference between $V_{WORKING}$ and V_{OUT}, thus a difference measurement must be made. Two channels of the ADC are used to measure both V_{OUT} and $V_{WORKING}$ and obtain the difference of the reading.

To reduce noise, a 1-µF capacitor CF has been added across RF. Because the sensors have a long response time (< 20 s), and the nano-power amplifiers have higher noise than standard power amplifiers, it is beneficial to reduce as much of the broadband noise as possible by limiting the bandwidth of the measurement circuit. The upper limit of the capacitor value would be dominated by leakage issues (do not use aluminium electrolytic) The system functions by maintaining the potential of the working electrode at a constant level with respect to the reference electrode by adjusting the current at a counter electrode. It consists of an electric circuit which is usually described in terms of simple op amps.

2.3 Microcontroller

The design consists of a three-terminal electrochemical sensor amplifier circuit providing the sensor bias and current to voltage conversion, a selectable shunt reference or resistive divider bias voltage circuit, an MSP430 Launchpad providing the analog-to-digital conversion, processing functions, and display functions. The design has been realized on a PC board compatible with the TI MSP430 LaunchPad BoosterPack specification. This configuration allows us to control the MSP430 LaunchPad platform to acquire, calculate, log, and display the measurement results. The MPS430FR6989

LaunchPad board has been carefully chosen because of the multiple ADC input pins, ultra-low-power mode capability, USB connectivity, and on-board LCD.

3. Results & Discussion

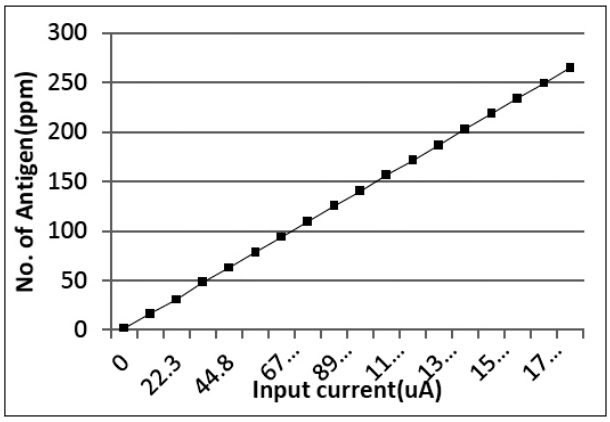

Fig. 4. No. of antigens in sample versus input current to TIA.

Table 1
No. of antigens (ppm) as per the change in current.

Vin (V) to current source	Output Current (uA) from current source (uA)	No. of antigens (ppm)
0		1.8
0.025	11.13	16.7
0.05	22.3	30.7
0.075	33.59	48.1
0.1	44.8	63
0.125	56.09	78.5
0.15	67.29	93.7
0.175	78.54	109.5
0.2	89.75	125
0.225	100.9	140
0.25	112.4	156.5
0.275	123.4	171
0.3	134.7	186.6
0.325	145.9	203
0.35	157.18	218.4
0.375	168.44	234
0.4	179.65	249
0.425	190.9	264.7

4. Conclusion

The measurement results are very suitable. There is a linear variation in the number of antigens with respect to the input current to the TIA. The supply standby current was below the requested 1 μA for the amplifier circuit.

5. Reference

1. Gray, P.E. (1969). *Electronic Principles.* Campbell Searle. 641.

Prabhat Ranjan is working currently as Project Fellow in Centre for Sensor Vision Technology & Control at Central Manufacturing Technology Institute, Bangalore, India. He graduated in 2015 in Instrumentations & control Engineering and obtained his post-graduation in 2018 in Instrumentation Engineering. He has 9 months of working experience in the field signal conditioning and interfacing module for various sensors. His areas of interest are Senor Design & Development, readout and interfacing electronics.

Harsha S. is currently working as a Scientist in Sensors and Vision Technology at Central Manufacturing Technology Institute, Bangalore. He is a post graduate in VLSI design and embedded systems, and is a bachelor of engineering in Electronics and Communications. He is mainly involved in micro systems packaging processes viz., wafer dicing, wire bonding, bond testing, flip chip bonding and thin film deposition.

Megha Agrawal is presently holding the position of Scientist in Central Manufacturing Technology Institute, Bangalore since 2012. Eariler she had worked as a project engineer in Thapar University, Patiala under SMDP. She has done B.Sc from Jiwaji University, Gwalior in 2006, M.Sc. from Banasthali University, Jaipur in 2008 and M.Tech from Thapar University, Patiala in 2010. Her research interests are MEMS fabrication, Wafer bonding for advanced micro-system packaging and sensor integration for machine health management and ROIC design for Micro-sensors. She has published/ presented 12 papers in journals and international/national conferences.