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BIOSENSOR SYSTEM DESIGN FOR DISSOLVED OXYGEN MEASUREMENT USING CURRENT MIRROR CIRCUIT

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ABSTRACT

A biosensor system using a current mirror circuit has been designed and characterized. Biosensor system usually implements an amperometric circuit such as a trans-impedance topology to measure current flowing in the solution due to the contained dissolved oxygen. The trans-impedance circuit implemented for the biosensor has some drawbacks and disadvantages. The implementation of this circuit exhibits rather high noise, besides the impracticality of the power supply used due to bipolar voltage need to allow negative voltage output. In this paper, a classical current mirror circuit is used to convert the flowing current in the solution. The use of the classical current mirror circuit is aimed to obtain lower noise level, besides the easiness in providing the power supply for the system, since the circuit consists only of small number of active components and does not need a bipolar power supply. The measurement is performed utilizing an algae species as a bio-receptor for the measured dissolved oxygen. By utilizing this circuit, the biosensor measurement system can be optimized with better precision and noise performance. Consequently, the dissolved oxygen measurements can be improved and achieve good results. Besides, the system can detect the changes in dissolved oxygen due to the photosynthetic process of the algae.

Keywords: biosensor, dissolved oxygen, current mirror, amperometric, electrochemical

INTRODUCTION

The measurement of dissolved oxygen is very important in determining water quality on environment. Dissolved oxygen level is one indicator that describes environmental quality other than color and pollutant materials. Oxygen levels in water are affected by pollutants that cause oxygen levels to decrease. The amount of oxygen dissolved in water can also be affected by the photosynthetic activity of living organisms in water such as algae. Thus, these living organisms can be used as a source of oxygen for determining water quality.

During this time, the electrochemical method is often used to process biological systems into electronic information [1-2]. The trans-impedance electronics circuit is mostly used to measure oxygen levels in solution amperometrically. This circuit has many disadvantages, including low stability due to the presence of virtual ground points so that it is susceptible to outside noise such as electromagnetic interference (EMI), this circuit also requires bipolar power supply and requires quite a number of active components such as op-amps. In this study, a change is applied to signal processing circuits in order to reduce the deficiencies encountered when using trans-impedance circuits. The circuit applied to overcome these deficiencies are a current mirror circuit. The variations of the current mirror circuit have been described in [3], but the performance of the circuits are not analyzed. A more advance current mirror-based circuit was analyzed by [4], where they investigated the noise characteristics of the circuit. However, the circuit is very complex and possible to produce noisier signal than the classical circuit. In addition, power consumption can be higher than the classical one. The other method is using fully differential difference amplifier (FDDA) as described in [6], which achieves high linearity and low power consumption, but on the other hand has low sensitivity and higher noise.

The current-mirror-based circuit offers a solution to the problems encountered when using a trans-impedance circuit or other complex current mirror circuits such as higher noise or higher power need. By using this circuit, the better results are obtained compared to the trans-impedance circuit.

METHOD

Biosensor Measuring Principle

Biosensor is a Clark type oxygen sensor which consists of three electrodes namely AE, RE, and WE. The AE electrode is the current source electrode, the RE electrode is the sensor reference voltage electrode, and the WE electrode is the output current electrode. The biosensor symbol is shown in FIGURE 1.

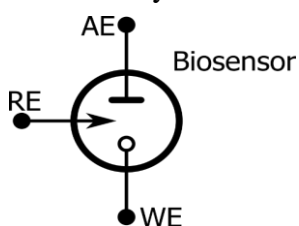
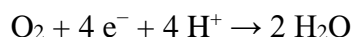


FIGURE 1. Biosensor symbol

The electrodes are made of inert metal materials such as a Pt or Au so that they do not participate in the reaction. The oxygen reaction that occurs at the electrode is as follows:



The more oxygen is dissolved, the more electrons are involved so that the current flowing gets bigger. So there is a linear correlation between the amount of dissolved oxygen and the large flowing current. The amount of current flowing due to dissolved oxygen in the solution ranges from 1 nA to 1 μ A [3]. It appears that the amount of dissolved oxygen can be reduced due to the reaction that occurs. This is an unavoidable thing in measuring oxygen using the amperometric method.

During the operation, the potential of the RE electrode should be at 0.7 V above the WE electrode. This is the requirement needed for the oxygen-based reaction to occur. The potential of RE is controlled by an op-amp utilizes a current through the AE electrode. This current will be adjusted depending on the resistance of measured solution. On the other hand, the resistance depends on the amount of dissolved oxygen in the solution. Therefore, this current represents the impedance and the amount of dissolved oxygen in the solution. The voltage of RE electrode is controlled by an op-amp. The controlling system is in negative feedback, so that high stability could be achieved to obtain low noise signal. A low bias current op-amp is used as the op-amp for the controlling system, which is aimed to obtain high resolution of measured current in the biosensor.

Current Mirror Circuit

The current mirror circuit consists of two loops, namely the main current and reflection. Biosensor is located in the main current loop, while in the flow of reflection current there is a resistor that will change the current that flowing in it to voltage [6]. The change of the current in the reflection current does not interfere with the current on the sensor. This is the advantage of using current mirror circuit. In addition, the voltage representing the current at the output is in a configuration relative to ground, so it is easy to process further. This is different if the resistor is in a floating (high) side configuration that requires the conversion of differential voltage to single ended which is relative to ground.

In order for the circuit to work properly, the characteristics of the components that build the loops should be the same. Like both transistors used should be the same in the geometrical size such as the length and width of the channel area. Otherwise, the mirroring process could not meet the same current reflection from the main current loop to the reflection current loop. In the calculation, the gate current of the transistor assumes zero, so that there is no current flowing to the gate terminal from the main current loop. The current mirror circuit used can be seen in FIGURE 2.

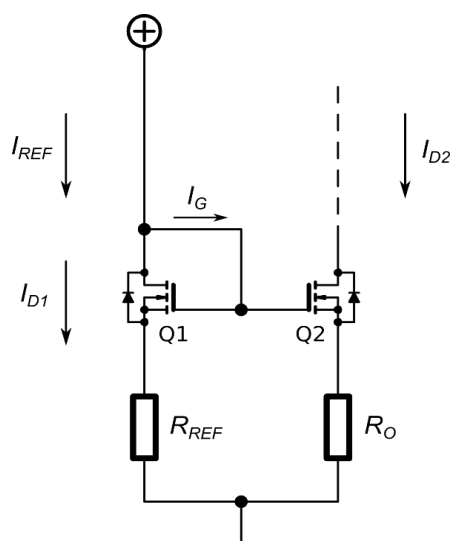


FIGURE 2. Current mirror circuit

From FIGURE 2, the current in the left loop ($I_{REF} = I_{D1}$) is determined by R_{REF} , which will be replaced by the biosensor. This current is reflected in the right loop (I_{D2}) with the same magnitude and then converted into voltage by the R_o shunt resistor. This voltage represents the I_{D1} current which is affected by the dissolved oxygen content in the solution.

Testing the output voltage response to the input current will provide an overview of the sensitivity and output errors. The output sensitivity is determined by the value of R_o , where the output voltage is proportional to the value of the resistance and the current through it according to the equation:

$$V_o = I_{D2}R_o \quad (1)$$

The conductivity of the oxygen solution is very small; the current produced can reach the order of nano ampere. Therefore, the value of R_o must be made very large. However, on the other hand, the R_o value is limited by the offset current on the transistor.

Algae *Chlorella Kessleri*

An algae *Chlorella Kessleri* is utilized as the bio-receptor of the dissolved oxygen. The algae is obtained from *Sammlung von Algenkulturen der Universität Göttingen* (SAG), Germany. The algae from this source is preferred because the strain is pure, so that the characteristics of the algae species are similar. This algae is optimizngly growing in good environment such as in laboratory scale culture with the 20-hours interval. The growth of algae is taking place through a cultivation process fed with an algae culture broth (ACB) as a nutrient for algae seedlings, which is obtained from Sigma Aldrich SKU-17124. The cultivation is started by mixing a 1.86 gr of ACB powder in a litre of distilled water before it is autoclaved to sterilize the alga medium. The desired final pH of the ACB is 7. The algae is then treated in phototrophically under continuously white lighting of T521 W fluorescent lamp ($72.63 \mu\text{mol photons m}^{-2}\text{s}^{-1}$) and bubbling air. The cultivation process of the algae is performed for 15 days.

MEASUREMENTS

Testing the output voltage response to the current flowing in the current mirror is done by giving a dummy current generated from a resistor fed with a reference voltage. The voltage applied varies from 0 to a maximum of 1 V with an increase of 1 mV. This voltage is derived from a 12-bit DAC with a range of 0 - 4,096 V, which is controlled by a microcontroller type ATmega8A from Atmel. Thus, one bit of DAC data is represented by 1 mV output. The output voltage acquisition is read by a 12-bit ADC also in the range of 0 - 4,096 V, where 1 bit also represents 1 mV. From the DAC and ADC specifications above, the voltage resolution used can reach 1 mV. So that for the entire range of measurements, it is needed as many as 1000 data. The data acquisition interval is set to 1 second.

There are two output resistors values R_o which is used as a comparison of system sensitivity. The first resistor is 1 M Ω and the second one is 10 M Ω . If the output voltage range is kept constant, the current range that can be measured is different, according to the Ohm's law equation the current is

$$I = \frac{V_o}{R_o} \quad (2)$$

Where V_o is the output voltage, and R_o is the resistance of the output of the current mirror. So if the resistor used is 1 M Ω , the current range that could be measured is 0 - 1 μ A with a resolution of 1 nA. If the resistor used is 10 M Ω , the measurable current range is 0 - 100 nA with a resolution of 0.1 nA. To produce these two current ranges, two dummy current resistors are needed. The voltage range-fed to the resistor is the same, i.e. maximum 1 V. By applying the Ohm's law equation once again, the corresponding resistor value is also set to 1 M and 10 M Ω .

The block diagram of the biosensor measurement system can be seen in FIGURE 3.

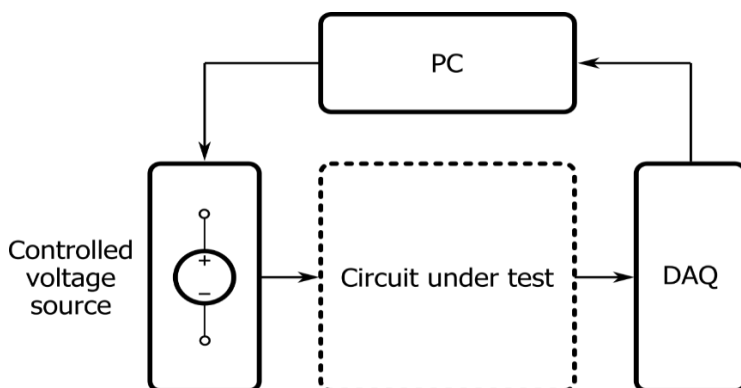


FIGURE 3. Block diagram of the measurement of dummy current on the current mirror.

From FIGURE 3, the electronic biosensor measurement system is quite simple. This measurement system is connected to a PC that functions as the main controller of the working system. The programs run on PCs are made with Visual Studio software with a Graphical User Interface (GUI), so that it is easily operated by users. This measurement system is connected to a PC with RS-232 serial communication via COM port. This program for communication is already available in Visual Studio software so that it can be used immediately.

Dissolved oxygen measurements are carried out by using algae living cells as oxygen producers. Dissolved oxygen around the algae can be affected by photosynthetic activity. So to see the effect of oxygen, photosynthetic stimulation is needed for these algae. The stimulation of photosynthesis can be done by giving light to the algae as artificial sunlight. This light must have a certain wavelength to match the sensitivity of the algae. In this study, the light with a wavelength of 450 to 750 nm was used [7]. To determine the difference in the amount of dissolved oxygen, the light is given and removed. The period of giving and removing light lasts for 1000 seconds or about 16.67 minutes. At the same time, the output voltage response of the measurement system is recorded and analyzed.

RESULTS AND DISCUSSIONS

The curves of output voltage measurement for the current mirror circuit with input currents of 0 - 1 μA and 0-100 nA are shown in FIGURE 4. This measurement uses a different R_o value. The first measurement uses the value $R_o = 1 \text{ M}\Omega$, while the second measurement uses the value of $R_o = 10 \text{ M}\Omega$. So that the maximum value of these two measurements are equal to 1 V. Because the resolution of the voltage used can reach 1 mV, then the current resolution for the first measurement is 1 nA, and for the second measurement is 0.1 nA. From the measurement chart, it appears that the measurement results have a tiny error. This is indicated by the value of R_2 , which is very close to 1, which is 0.999908 for 1 $\text{M}\Omega$ and 0.999918 for 10 $\text{M}\Omega$. The sensitivity of each curve is 106 V/A and 107 V/A, respectively, for $R_o = 1 \text{ M}\Omega$ and 10 $\text{M}\Omega$.

The results obtained above are far better than the results of current measurements using the trans-impedance circuit shown in FIGURE 5 [6]. Although the curves are very linear and have the same sensitivity, these curves have a relatively larger error than the current mirror. This is indicated by smaller R^2 values, where the values are 0.999314 for 1 $\text{M}\Omega$ and 0.994516 for 10 $\text{M}\Omega$.

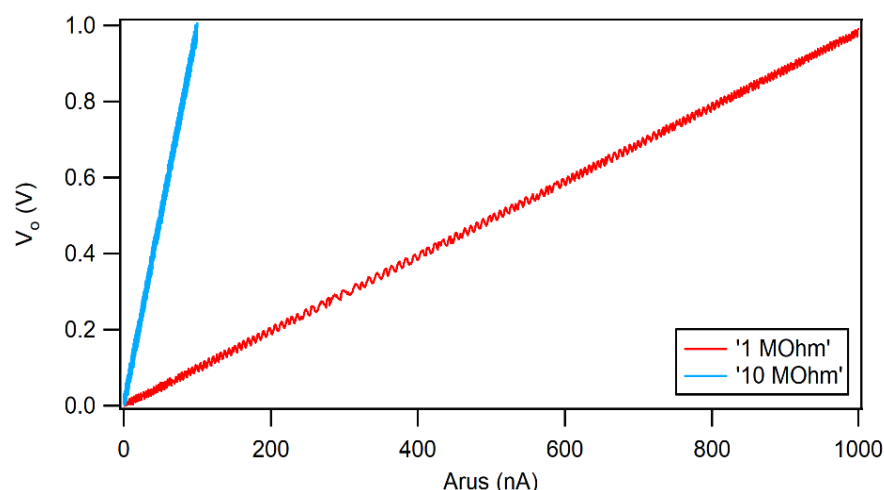


FIGURE 4. Measurement results of current mirror circuit implementation.

Visually, it appears that the measurement curves of the trans-impedance circuit are thicker because there is a considerable deviation compared to the current mirror. This indicates that

the results of the trans-impedance circuit are more fluctuating than the current mirror circuit. It is clear that the current mirror circuit is more stable and has a smaller error than the previous circuit that uses a trans-impedance circuit.

Dissolved oxygen measurements are carried out when algae are stimulated with varied light. The results of observations of photosynthesis are shown in FIGURE 6. From the curve in the figure, it can be seen that the system output voltage changes when the biosensor is illuminated and not illuminated by the light.

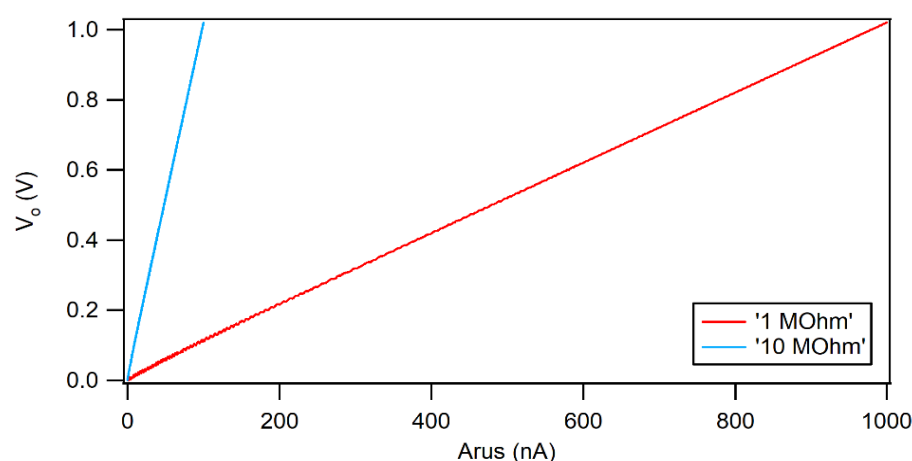


FIGURE 5. Measurement results of trans-impedance circuit implementation [6].

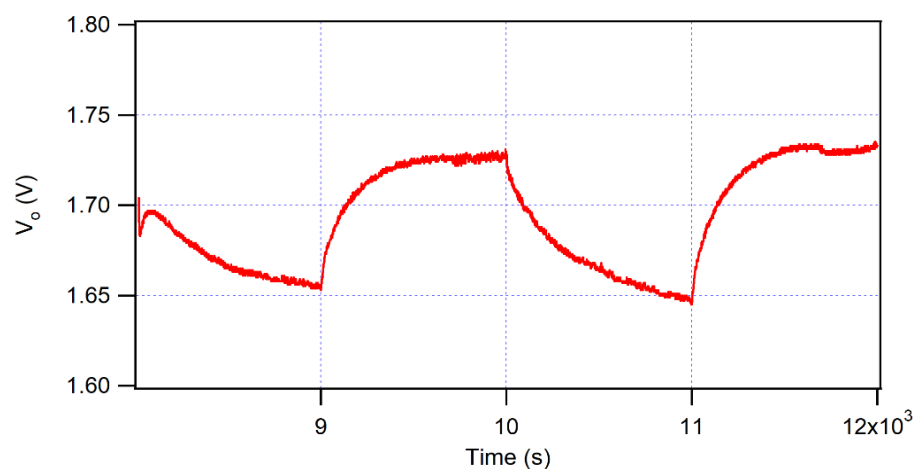


FIGURE 6. The dissolved measurement result of photosynthetic experiment.

When starting to be illuminated by the light in the seconds of 9000, the output voltage appears to rise sharply and then the increase decreases to a stationary condition. This indicates that at the moment when the lights are turned on, photosynthetic activity jumps so that the increase is very sharp. Then, in the next few moments, the change is not so large because the increase of oxygen decreases and then stops. At that time it was the maximum condition of oxygen that was able to be produced from the photosynthetic process of algae. This maximum condition is influenced by the number of algae used. When the light beam is removed, there is a decrease in voltage due to a decrease in the amount of oxygen produced by algae; this decrease is a

result of photosynthetic activity which is reduced to a stationary state as well. This condition is a basic condition where the amount of oxygen cannot change again.

CONCLUSIONS

The design of the biosensor system for measuring dissolved oxygen has shown good results. This can be seen from the results of the measurement system testing for the dummy current given in the current mirror circuit. The resulting curves are very linear and have a smaller variance compared to the trans-impedance circuit. So this current mirror circuit has a smaller error which will make it more precise in measuring dissolved oxygen.

The measurement of dissolved oxygen that has been carried out shows a change in the measurement system output voltage in response to changes in dissolved oxygen in the algae solution. The increase in voltage which indicates an increase in dissolved oxygen occurs when the light beam is given to the algae. Vice versa, there is a decrease in voltage as a sign that the amount of dissolved oxygen is reduced. With these results, it means that this system has been able to measure the amount of dissolved oxygen using algae living cells.

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