A Potentiometric Sensor System with Integrated Circuitry for in situ Environmental Monitoring

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Abstract—The need to monitor the conditions prevailing in the external environment in order to control environmental pollution is one of the prime necessities of the modern age. This paper introduces a robust, self-contained, inexpensive integrated potentiometric sensor that can be used for in situ environmental monitoring. The primary focus is to design, implement and integrate a potentiometric CMOS circuit with the sensor device to measure the potential developed across a working probe (microelectrode sensor) and the reference probe. The magnitude of the output voltage signal is dependent on the characteristics (pH) of the solution being evaluated by the system. A Printed Circuit Board has been built to integrate the microelectrode sensor device and the sensor chip with the aim of producing a fully integrated system. The microelectrode sensor device may be replaced by a NEMS based sensor device in areas that require further miniaturization like biomedical applications.

Keywords – potentiometric, sensor, integrated, noise

I. INTRODUCTION

There are various kinds of environmental applications like bioremediation process of hazardous waste sites, water distribution systems, waste water treatment reactors and stream or lake sediments that require substantial and uninterrupted monitoring. This kind of constant monitoring of the environment necessitates a robust, portable and integrated sensor capable of producing a fast response and having a high sensitivity. The microelectrode sensors devised till now for these kind of applications are fragile, difficult to manufacture and operate; and susceptible to electrical interference. This limits their usage to closed laboratories under highly controlled conditions. Thus, there is a requirement for a robust, yet fast and sensitive integrated microelectrode sensor that has inbuilt signal processing circuitry, to render it capable to be used in situ for environmental monitoring. In situ monitoring also finds its applications in bio-films where the microelectrode sensing device may be replaced by a still smaller but precise NEMS device. To fulfill this requirement, a field-deployable environmental microelectrode sensor had been designed and implemented [1]. This paper introduces a sensor chip that is integrated with the microelectrode in order to accurately sense the signal reproduced by the microelectrodes and provide convenient means of measuring the sensed signal. A CMOS ASIC sensor circuitry is developed to perform the potentiometric analysis of the solutions under test. Potentiometric testing is conducted to measure the voltage developed across a working probe (microelectrode) and a reference probe under varying environmental conditions. It is shown that the voltage measured by the sensor system varies with the change in the external conditions in which the probes are placed. The chip is embedded in a Printed Circuit Board to produce a fully integrated system along with the microelectrode probes.

The system level block diagram representation of the integrated sensor system is shown in Fig. 1. It broadly consists of two components. The first one is the microelectrode sensor device that monitors the external environmental conditions. These electrodes produce a voltage signal and pass it on to the second component, the sensor chip embedded on the Printed Circuit Board. The chip contains the required circuitry to amplify and process the signal. The output signal from the chip is measured with suitable measuring instruments.

The rest of the paper is arranged into the following sections. Section II introduces the design of the potentiometric circuitry for sensing the voltage signal. Section III discusses the PCB that is designed and fabricated to contain the chip along with the microelectrode probes. Section IV details the potentiometric testing procedure adopted and Section V reports the results. Finally the paper is concluded in Section VI.

![Figure 1. System level block diagram of the integrated sensor](image-url)
II. POTENTIOMETRIC CIRCUIT DESIGN

The sensor chip contains the required circuitry for potentiometric measurement with the microelectrode probes. It is a 40 pin DIP chip laid out using the Tanner Tools L-Edit layout editor in the 1.5um process and fabricated through the MOSIS foundry [4]. Fig. 2 shows the potentiometric circuit in the chip. It essentially consists of the following two stages connected in succession.

A. Voltage Follower Circuit

The first part of the potentiometric circuit is a set of two separate voltage follower circuits. The input impedance of the operational amplifier used in the circuit is designed to be very high. This provides an effective isolation of the output from the input signal source. Loading effects are avoided and very little power is drawn from the signal source. The working probe is connected to Pin_4, input of one voltage follower circuit, and the reference probe to Pin_3, input of the other voltage follower circuit.

B. Differential Instrumentation Amplifier

The second stage of the circuit consists of a buffered differential amplifier with three resistors linking the two buffer circuits together. It establishes a voltage drop across the resistor $R_{GAIN}$ equal to the voltage difference between $V_1$ and $V_2$. The resistor $R_{GAIN}$ is connected externally to the sensor chip between Pin_6 and Pin_11 by connecting Pin_6 to the fixed end of a 100k-Ohm potentiometer and Pin_11 to the variable end. The regular differential amplifier in the next part of this sub-circuit takes the voltage drop $V_{2-4}$ and amplifies it further. However, since all resistors used are of value 1 k-Ω, this gain is equal to unity. The advantage of the differential amplifier lies in the fact that the overall gain can be varied by varying only a single resistor $R_{GAIN}$. The other advantages are related to its high input impedance, high common mode rejection ratio (CMRR) and noise elimination capability. The output differential voltage is obtained at Pin_31.

III. PRINTED CIRCUIT BOARD

Initial testing of the chip using a bread-board shows that the chip measures voltage in the range of millivolts. Noise, being an external disturbance, poses serious problems in the measurement of signals of such a low range. In addition, board testing necessitates the use of various active elements like voltage supply for the chip as well as passive elements like resistors to be connected externally. In order to have all types of components needed for testing the chip on a common platform, a Printed Circuit Board (PCB) has been designed and laid out. The PCB is designed using the Express PCB software [5] and fabricated through the foundry service of Express PCB. It has two copper layers, one on the top to accommodate all the components and the other at the bottom required for soldering work. The main components of the PCB are as follows:

- Power Supply for the chip: This is provided by a 9V battery and a necessary voltage regulatory circuit.
- Voltage Regulator Circuit: The required voltage regulation for providing a 5V DC supply to the chip from the 9V battery supply is achieved through an adjustable Low Dropout voltage regulator (National Semiconductor LM1086 3-lead TO-220 package).
- Two ribbon cable connectors (10 pin and 14 pin) acting as the Input/Output interface for the PCB.
- 40 Pin DIP socket for holding the chip.
- Appropriate sockets with proper connectivity for holding the working and reference electrodes.
- A 20 pin and an 18 pin DIP socket for providing necessary wire connectivity.

IV. TEST PROCEDURE

A. Potentiometric Testing

The purpose of potentiometric measurement with the chip is to measure the Oxidation Reduction Potential (ORP) of the solution in which the two electrodes are immersed [3]. This potential generated across the electrodes is directly related to metal used for the working electrode and the chemical nature of the solution. The working and reference electrode probes, placed in the solution, are connected to the two input pins, pin_4 and pin_3, of the potentiometric circuit. The output voltage is obtained at Pin_31. The test setup is shown in Fig. 3. Two types of solutions are used for the test – 225 mV standard solution and pH7 solution. In order to replicate the known value of the potentials that are expected with the given solution, the variable resistor $R_{GAIN}$ is kept open (pins 6 and 1 disconnected), i.e. overall gain of the circuit equal to unity. The output voltage readings are taken with a precise digital multimeter and monitored using the National Instruments LABVIEW automated software program designed for the measurement purpose.
B. Noise Measurement

One of the primary purposes of the chip along with the PCB is the elimination of external noise effect as far as possible. So to have an idea about the effects of noise and thereby to ensure its proper elimination, two kinds of testing procedures are adopted. They are:

- All of the testing equipments and the probes are placed outside the Faraday’s cage.
- All of the testing equipments and the probes are placed inside the Faraday’s cage.

Again, to verify the appropriateness of the PCB in eliminating noise in addition to that already eliminated by the chip, both of the above testing procedures are adopted for two different kinds of situations. They are:

- Noise measurements taken with the chip placed on a conventional breadboard.
- Noise measurements taken with the chip placed on the PCB.

The root-mean-square (rms) value of the noise signal obtained is measured continuously over the time range (0-300s) and then an average of the rms values obtained is noted. The measurements are obtained with a high precision digital multimeter and monitored using an automated LABVIEW measurement software program.

V. RESULTS AND DISCUSSIONS

A. Potentiometric Measurement

The voltage values obtained in the potentiometric testing are given in Table I. It is seen that the potentiometric circuit in the sensor chip is capable of reproducing the voltage developed across the two probes in an efficient way eliminating the effects of extraneous noise to a great extent. These voltage measurements are in unison with the nominal (theoretical) voltage values that are specified for the provided solutions (of definite pH) within an accuracy of more than 90%. The temperature of the surroundings during the testing was 22 degrees Celsius. An LED display may be attached to the output of the chip to read the voltage signal produced. Comparable results are obtained inside and outside the Faraday’s cage that justifies the usefulness of the microelectrode sensor system in eliminating the necessity of any kind of external shielding mechanism. In other words, the system is immune to the effects of external noise.

B. Transient Response

To note the change in behavior of the probes over time, the measurements are taken for a time interval ranging from 0-300 seconds. The transient behavior of the probes for the two solutions is shown in Fig. 4. It is seen that the measured potential attains a high value as soon as the probes are placed in the solution under test. But soon, after a transient drop, it settles down to a steady state value. This owes to the finite initial response time of the microelectrode probes. The response times for the probe, i.e. the time required to attain the final steady state value for the two solutions are approximately:

- 37 seconds for 225mV standard solution
- 32 seconds for pH7 solution

![Figure 3. Schematic layout of potentiometric test setup](image)

![Figure 4. Transient response of the potentiometric sensor system in the (a) 225 mV standard solution (b) pH7 solution; T=300s](image)
The response times of commercial electrodes under the same conditions are in the range of several minutes for the solutions used. The results undoubtedly prove the fact that the microelectrode sensor system demonstrates much faster response time than the commercial electrodes available.

C. Noise Measurement Results

Extensive measurements are done to estimate noise throughout the whole test procedure. The average external noise distribution is shown in Fig. 5(a). The mean of the rms values obtained is 28.40 mV with randomly distributed intermittent spikes as shown. Figs. 5(b)-5(c) gives the noise distributions and the mean of the rms values obtained for the different test conditions over the specified time range. It can be observed that the chip helps in eliminating external noise by virtue of the differential amplifier circuitry contained inside it. In addition to that, the printed circuit board helps in eliminating noise further by removing the need of external cabling and external power supply, both of which acts as potential sources of noise injection. It is to be noted though that the potentiometric results given in Table I are those obtained using the chip placed on the PCB. Also, in Figs. 5(b) – 5(e), an inset plot is provided showing the distribution of noise for that particular configuration, but on the same scale as that used for Fig. 5(a), i.e. the total external noise. Using the same scale gives the reader a ground for comparison of the noise signals in different configurations and thus helps to gauge the elimination of noise in the process. Thus the chip together with the PCB is capable of producing a robust system that eliminates noise to a great extent and preserves the integrity of the signal.

VI. CONCLUSION

The paper introduced a portable, mobile microelectrode based integrated potentiometric sensor system used for in situ environmental monitoring. The potentiometric circuit in the sensor chip measures the voltage signal developed across the probes eliminating the effects of external noise. The PCB helps in the further elimination of noise. The sensor helps in evaluating the environmental conditions around the probes from a knowledge of the voltage signal measured. The application of this sensor system can be extended to the biomedical field where the test solution may be a biofilm and the sensor device may be a NEMS-based device.

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