Ultra Low-Input Impedance CMOS Potentiostat for Environmental Sensing Applications

Sungkil Hwang and Sameer Sonkusale
Department of Electrical and Computer Engineering, Tufts University
Medford, USA
Sungkil.hwang@tufts.edu

Abstract—This paper reports an integrated CMOS potentiostat for detection of heavy metal ions in water and other solvents based on electrochemical sensing. The proposed potentiostat features a low input impedance, high sensitivity, high gain and low power trans-impedance amplifier front end, with programmable control of electrode potential, thus facilitating continuous bi-directional measurement of reduction-oxidation (redox) current in a potentiostat for cyclic voltammetry (CV) experiment. For proof of concept, we use the proposed integrated potentiostat to perform CV on a reference ferricyanide (K₃Fe(CN)₆) using external microelectrodes. Results compared with standard benchtop potentiostat confirm microelectrode behavior with accurate estimate of redox potential with varying redox currents proportional to the ferricyanide concentration.

I. INTRODUCTION
Measurement of trace heavy metal ions like mercury and lead is critical for public safety. With the advancement of micro- and nanotechnology, electrochemical sensing using microelectrodes offers a smaller, cheaper and more sensitive approach compared to the conventional optical sensing systems for chemical sensing and bio sensing[1][2][3]. An electrochemical measurement topology utilizes a three electrodes system (a working electrode, a counter electrode, and a reference electrode) and a potentiostat to apply and sense signals as shown in fig. 1(a). The potentiostat makes potential changes between the working electrode (WE) and reference electrode (RE). It allows analyte species to be measured, to get reduced or oxidized (redox reaction) on the surface of the WE and to generate current flowing between the WE and CE. Then, the potentiostat detects and amplifies the faradaic current. Typically, sensing of trace metal ions in micro-analysis environment produces weak current signals at the surface of electrode due to the small size of electrodes and reduced analyte concentration. The reason is that the current achieved by redox reaction is linearly dependent on the size of the electrode as well as the number of electrons involved in the redox reaction of species and the bulk concentration of species [4]. This puts an additional burden on the sensing electronics requiring high gain and high dynamic range with very low input referred noise. Also, the environments used for sensing could be highly resistive (organic solvents) or very conductive (inorganic salts), requiring very low input impedance from the potentiostat. Additionally, continuous bi-directional measurement of redox current is an essential function in potentiostat for CV experiment which is popular electrochemical analysis technique, as shown in fig. 1(b).

To overcome these limitations of the sensing electrodicenics, we present a new front-end topology for the potentiostat employing a resistive T- network to increase gain and a novel input stage to guarantee ultra low input impedance over high dynamic gain while maintaining high level of required gain and dynamic range.

II. PROPOSED POTENTIOSTAT TOPOLOGY
The most critical element in the potentiostat is the transimpedance amplifier (TIA) used to read currents generated at the working electrode (WE). In fig. 1(c), the gain
and the input impedance of the conventional TIA are given by \( R \) and \( R/(1+A) \), respectively, where \( R \) is resistance and \( A \) is a gain of the OTA. The larger feedback resistance of the TIA increases the gain at the expense of higher input impedance and smaller bandwidth. Also, for CV measurement, it is typically required to control the DC bias at the WE and consequently the potential applied between WE-RE signals. This will affect the input common mode and the output common mode of the TIA. Such a change will affect the gain and signal swing of the circuit. This degrades dynamic range of the potentiostat.

A. Operation

Fig. 2 shows a schematic of the proposed front end for the potentiostat which is composed of input stage and gain stage. The proposed input stage consisting of a Wilson current mirror structure (M1–M4) serving as a current buffer with an additional operational amplifier (OTA) in feedback around M1. The Wilson current mirror feedback loop guarantees that all input current goes into drain of M2, allowing for a bidirectional measurement over input currents, which are generated by redox reaction on WE. By using OTA in negative feedback around M1, it will force the inputs of the OTA to track each others; we can therefore apply and control voltages at WE node. It allows us to sweep the potential between WE and RE (typically a triangular waveform as seen in fig. 1(b) for CV measurement without scarifying dynamic range.

B. Input impedance and dynamic gain

For achieving high current sensitivity, low input impedance in the TIA is required to avoid current loss. The input impedance \( Z_{in} \) of the input stages is given by

\[
Z_{in} = \frac{1}{g_{m1}(1+A)} \left[ \frac{1}{1+A_{\text{Wilson}}/A_1} \right] \approx \frac{1}{1+A_{\text{Wilson}}/A_1}
\]

(1)

where \( A_{\text{Wilson}} \) is the feedback loop gain of the Wilson current mirror and \( A_1 \) is the gain of the OTA around M1. As seen in (1), the input stage can be independently set for low input impedance by controlling \( A_1 \). Also, the TIA gain can now be increased (higher effective trans-resistance) without affecting the input impedance. For the gain stage, we propose

Fig. 2. Schematic view of the proposed potentiostat showing low input impedance front end stage.

Fig. 3. Telescopic OTA used in the potentiostat: (a) operational transconductance amplifier and (b) replica bias circuit.

Fig. 4. Die micrograph of proposed potentiostat.
the TIA with resistive T network as seen in Fig. 2. The gain is given by,

\[
\text{Gain} = - \left[ R_1 + \left( 1 + \frac{R_1}{R_2} \right) R_3 \right]
\]

(2)

According to (2), when R1 and R3 are much greater than R2, the TIA can achieve high gain using only small resistors while maintaining the bandwidth of the TIA. The telescopic OTA used in this design is shown in Fig. 3. Replica bias circuit on chip generates bias voltages of the OTA.

**C. Noise performances**

The noise contribution consists of thermal noise and flicker noise. As the OTA is dominant on noise contribution in the TIA, sizing of transistor is important to achieve low noise for sensing low-level redox current. Noise analysis of this OTA shows input-referred thermal noise power of the OTA as

\[
\frac{\nu_{\text{in,thermal}}^2}{\Delta f} = \frac{16kT}{3g_m} \left( 1 + \frac{g_{m3}}{g_{ml}} + \frac{g_{m5}}{g_{ml}} + \frac{g_{m7}}{g_{ml}} \right) \Delta f
\]

(3)

where \(g_m\) is the transconductance of the MOSFET, \(k\) is Boltzmann’s constant and \(T\) is the absolute temperature. Based on equation (3), we make \((W/L)_1 \gg (W/L)_3 , (W/L)_5, (W/L)_7\) to decrease the thermal noise of the TIA. Noise induced by input stage directly affects input-referred noise of the potentiostat. Thus, the size of the transistors used in the input stage must be small.

Flicker noise is another source of noise in the output spectrum, and it becomes major noise contribution for low frequency applications such as in electrochemical analysis. To reduce flicker noise effects, all transistor size (channel width and length of MOSFET) in the OTA is set as large as possible without affecting the stability of the amplifier due to increased parasitic capacitance.

**III. MEASUREMENT RESULTS**

Fig. 4 shows the chip micrograph of the proposed potentiostat. To verify performances of input stage and gain stage, we measure input stage followed to conventional TIA (T1) and TIA with resistive T network (T2), respectively. The gain of the proposed TIA with resistive T network and the conventional TIA with input stage is measured to be 4.58M\(\Omega\) and 330k\(\Omega\), respectively. Fig. 5 shows the comparison of the input referred current noise. The all electrical performances of the prototype chip are summarized in Table I. The CV experiments were performed to verify electrochemical sensing operation of this chip by comparing results with a commercial
potentiostat. Commercial 10μm diameter platinum microelectrode was used as working electrode with platinum counter electrode and Ag/AgCl reference electrode. Fig. 6 shows comparisons between commercial potentiostat and implemented potentiostats. Fig. 7 shows the plot of the measured CV curve in 10mM, 25mM, and 50mM ferricyanide solution. We can see that the magnitude of output current varies accurately with the change in the concentration with the redox potential of 0.3V indicative of the ferricyanide solution with the S-shaped curve indicative of microelectrode array behavior. The results have been compared to commercial potentiostat with only 7% offset error and negligible gain error.

IV. CONCLUSION

A CMOS potentiostat with novel low power, low input impedance front end has been proposed and characterized experimentally using a standard ferricyanide solution. The chip is ideally suited for detection of trace metal ions in drinking water for commercial deployment. Further improvement in detection limits towards nanomolar range is expected using an array of microelectrodes and using averaging over multiple scan cycles because the array of microelectrodes can be integrated with the proposed potentiostat on silicon substrate for a higher SNR detection.

ACKNOWLEDGMENT

The authors would like to thank Dr. C. LaFratta from Dr. D. Walt group at Tufts University for his help on chemistry experiments.

REFERENCES


TABLE I

| Performances | T1 | T2 |
|--------------|------------------|
| Process      | Standard 0.5 μm CMOS |
| Core area    | 670x130 μm²          | 340x150 μm²          |
| Core Power(A) | 3.8μA @ 5V             | 2.2μA @ 5V             |
| Gain(Ω)      | 330K                | 4.58M                |
| Zin(Ω)       | 2(±10%)             | 500K(±10%)            |
| Dynamic range| 120dB               | 120dB                |
| Input referred current noise density@ 1kHz | 15.8 pA/√Hz | 1 pA/√Hz |
| Measurement  | Continuous and bidirectional |

T1: input stage + gain stage (resistive feedback TIA)  
T2: gain stage (resistive T network TIA)