A Compact Low-Power Current-to-Digital Readout Circuit for Amperometric Electrochemical Sensors
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Abstract—This paper introduces a novel compact low-power amperometric instrumentation design with current-to-digital output for electrochemical sensors. By incorporating the double layer capacitance of an electrochemical sensor’s impedance model, our new design can maintain performance while dramatically reducing circuit complexity and size. Electrochemical experiments with potassium ferricyanide, show that the circuit output is in good agreement with results obtained using commercial amperometric instrumentation. A high level of linearity ($R^2 = 0.991$) between the circuit output and the concentration of potassium ferricyanide was also demonstrated. Furthermore, we show that a CMOS implementation of the presented architecture could save 25.3% of area, and 47.6% of power compared to a traditional amperometric instrumentation structure. Thus, this new circuit structure is ideally suited for portable/wireless electrochemical sensing applications.

Keywords – amperometric instrumentation, electrochemical sensor, low power, compact, current-to-digital readout.

I. INTRODUCTION

Electrochemical sensors are widely used for environmental monitoring such as gaseous pollutants [1], and medical/healthcare diagnosis such as detection of antigen-antibody binding events, hybridized DNA, neuronal tissue, bacteria, glucose and enzymes reaction [2]. The most prevalent electrochemical sensor mode is the amperometric mode, in which the sensor reaction current is proportional to the analyte concentration. Recently, there is a trend in developing sensor microsystem for wireless, portable and implantable monitoring applications. These applications bring extreme requirements for instrumentation circuits in terms of power, area and cost, especially in applications that demand a large number of sensors [3].

Amperometric instrumentation consists of two parts: a potentiostat and a current readout circuit. The potentiostat provides current required for the reaction while maintaining the electrode/electrolyte interface at the correct potential. The current readout circuit conditions the electrochemical measurement and digitizes the reaction current. It is common to use bulky instrumentation to collect the amperometric readout. Many of the electrochemical instruments reported utilize commercial instrumentation and do not focus on the challenges of miniaturization for portable applications [4], [5]. However, the bulky instrumentation is expensive and not good for system miniaturization. Existing research has focused on optimizing individual parts (either potentiostat or readout circuit) for given power/size/resolution requirements [6]–[12], which help to push forward the circuit design for portable/wireless electrochemical sensing applications. However, no research has considered topology optimization from the perspective of the complete sensor-circuit system level. A great deal of recent research has focused on CMOS amperometric circuit designs for specific applications [13]–[21]. However, for many low volume and research applications, the economics of CMOS are not beneficial, and a simple amperometric circuit that is easy to build and can perform well without CMOS fabrication would be of great value.

This paper introduces a novel compact and low power amperometric instrumentation circuit topology that utilizes the inherent nature of electrochemical sensor interfaces to enable system-level optimization. The new amperometric circuit provides complete current-to-digital readout with reduced component count compared to traditional amperometric instrumentation. Specifically, our new topology saves two operational amplifiers (opamp) and one integrator capacitor, thus significantly lowering circuit power and area compared to a traditional design. Therefore, the new electrochemical instrumentation circuit is well suited for portable, wireless, and implantable sensory microsystem applications. This paper makes major reuse of the content published in Xiaoyi’s thesis [22] with permission.

Section II introduces the electrochemical sensor model and the traditional amperometric instrumentation circuit. Section III details the new compact amperometric instrumentation design concept. Section IV presents performance comparisons to traditional instrumentation circuits and evaluates the errors caused by model simplification. Circuit implementation and test results are shown in Section IV, and a conclusion is presented in Section V.

II. ELECTROCHEMICAL SENSOR MODEL AND TRADITIONAL AMPEROMETRIC INSTRUMENTATION CIRCUITS

A. Electrochemical sensor and its equivalent circuit model
Electrochemical sensors in amperometric mode work under the following sensing principle: the reaction current is proportional to the analyte concentration when reacted electrode/electrolyte interface is biased at a constant voltage. To accurately control the reaction taking place at the interface, three-electrode cell configuration has been applied to amperometric electrochemical sensors. In such three-electrode cell, the reaction takes place at the interface between the working electrodes (WE) and electrolyte. A constant potential is maintained between the reference electrode (RE) and the WE. The third electrode, counter electrode (CE), provides a current path to the WE.

To analyze the electrochemical sensor’s electrical response, equivalent circuit models have been proposed in electrochemical impedance spectroscopy (EIS) theory. Randles circuit model [23], as shown in Fig. 1 (a), is a classic equivalent circuit model widely used to describe a three-electrode sensor. The impedance between the RE and the WE consists of an uncompensated solution resistor \( R_s \) (relatively small), in series with the parallel combination of the double layer capacitor \( C_{dl} \) at the WE interface (charging current \( i_C \) follows through this path), and an impedance of a faradaic reaction caused by AC stimulus (AC faradaic current \( i_f \) follows through this path). The faradaic reaction consists of a charge transfer resistor \( R_{ct} \) and Warburg element \( Z_w \) which can be calculated as:

\[
Z_w = \frac{A_w}{\sqrt{j\omega}}
\]

where \( A_w \) is the Warburg coefficient and \( \omega \) is the angular frequency. Since our only interest is in the WE interface, the impedance between the CE and the RE is denominated as simple impedance \( Z \). Notice that this model only represents sensor’s response to small AC stimulus. To represent both AC and DC response, a complete equivalent circuit model is shown in Fig. 1(b) [23], [24]. A current source is added to represent DC faradaic current \( I_f \). Here, \( I_f \) is the constant reaction current proportional to the analyte concentration in amperometric electrochemical sensors, which is the main interest in sensor current measurements. In general, \( i_f \ll i_C \) and \( R_s \) is relative small. They can be considered as second-order effects in sensors response. For analysis simplicity, \( R_s \) and \( i_{i,ac} \) are omitted during following instrumentations derivation and will be re-discussed in Section III. The simplified model is shown in Fig. 1(c).

B. Traditional amperometric instrumentation

As introduced in Section I, the amperometric instrumentation circuit consists of two parts: a potentiostat and a current readout circuit. The potentiostat provides current from the CE to the WE while maintaining the voltage between the RE and the WE. A typical potentiostat can be implemented by a single opamp with appropriate connections [9], [25], [26]: the positive input node is connected with bias for the RE (\( V_{RE} \)), the negative input node is connected to the RE, and the output is connected with the CE to provide the current path. The current readout circuit collects \( I_f \) either at the WE or the CE, then conditions and digitizes it. Two topologies have been used to implement the current readout circuit: a current-to-voltage converter followed by a voltage-mode analog-to-digital convertor (ADC) [27] and a single current-mode ADC [11], [28]. Given the requirement of sensor applications for low power and low complexity, a model amperometric instrumentation circuit, as shown in Fig. 2, utilizes the single opamp for potentiostat design and the current-mode ADC for current readout design. In the current-mode ADC, two reference current sources \( I_{ref} \) of opposite direction are alternately connected with the integrator through switches, which are controlled by the digital output of the hysteresis comparator \( D_n \). Thus, the input current of the integrator \( I_{int} \) is given by

\[
I_{int} = I_f - (-1)^{D_n} \cdot I_{ref}
\]

As the waveforms in Fig. 3 illustrate, the integrator capacitor is charged/discharged according to the direction of \( I_{int} \).
Consequently, the output of the integrator $V_{\text{int}}$ rises/falls corresponding to $I_{\text{int}}$ direction. While $V_{\text{int}}$ reaches the hysteresis comparator upper/lower bound $(V_{\text{ref}} +\Delta V/2)$ (where $\Delta V$ is the hysteresis window width and $V_{\text{ref}}$ is the reference voltage), $D_n$ flips, changing $I_{\text{int}}$ according to (2). The square waveform at the output of the hysteresis comparator is then digitized by a counter with the reference clock at a much higher frequency. The time interval $T_1$ of the digital “high” for $D_n$ is given by

$$T_1 = \frac{C_{\text{int}} \Delta V}{I_{\text{ref}} + I_f}$$  \hfill (3)$$

and the time interval $T_0$ of the digital “low” for $D_n$ is

$$T_0 = \frac{C_{\text{int}} \Delta V}{I_{\text{ref}} - I_f}$$  \hfill (4)$$

From (3) and (4), $I_f$ can be expressed as a function of $I_{\text{ref}}$, $T_1$, and $T_0$ by

$$I_f = \frac{T_0 - T_1}{T_0 + T_1} I_{\text{ref}}$$  \hfill (5)$$

If the duty cycle $\alpha$ of $D_n$ is defined as

$$\alpha = \frac{T_1}{T_1 + T_0}$$  \hfill (6)$$

then by combining (5) and (6), $I_f$ can be expressed as a function of $\alpha$ and $I_{\text{ref}}$ given by

$$I_f = (1 - 2\alpha) \cdot I_{\text{ref}}$$  \hfill (7)$$

Therefore, given a known $I_{\text{ref}}$, $I_f$ is obtained by measuring duty cycle of $D_n$. Notice that $I_f$ is independent of both the integrator capacitor $C_{\text{int}}$ and the hysteresis comparator parameters ($\Delta V$ and $V_{\text{ref}}$).

III. COMPACT AMPEROMETRIC INSTRUMENTATION DESIGN

In the model amperometric instrumentation circuit in Fig. 2, replacing the sensor symbol with the simplified electrochemical sensor equivalent circuit model of Fig. 1(c) produces the fully electrical schematic of an electrochemical sensor system represented in Fig. 4. Notice that the sensor operates at the steady state when no current flows through $C_{\text{dl}}$ and only $I_f$ is collected in the readout circuit. From a system point of view, the sensor system contains two capacitors: $C_{\text{dl}}$ and $C_{\text{int}}$. $C_{\text{int}}$ is part of the readout circuit and used for charging/discharging; $C_{\text{dl}}$ is the inherent interface capacitor. Since capacitors occupy large area in integrated circuits, if $C_{\text{dl}}$ could be utilized to play the role of $C_{\text{int}}$, then $C_{\text{int}}$ could be eliminated from the circuit to save area. Modifying the traditional structure to incorporate $C_{\text{dl}}$ into the circuit and eliminate $C_{\text{int}}$, we develop a compact amperometric instrumentation topology.

As shown in Fig. 5, a current source $I_f$ can be used to represent the electrochemical sensor equivalent model. Given that node $B$ is a low-impedance node, folding the current source to the output of the integrator is equivalent to the typical topology of the current readout circuit. Notice that the parallel connection of $I_f$ and $C_{\text{int}}$ is the same as the equivalent circuit between $RE$ and $WE$ in Fig. 1(c). Because the value $C_{\text{int}}$ is arbitrary, $I_f$ still can be calculated from (7) when $C_{\text{int}}$ is replaced with $C_{\text{dl}}$.

To satisfy sensor’s bias condition, a potentiostat function is incorporated into the current-mode ADC by the following modification steps. First, by flipping the direction of $I_f$ and substituting $V_{\text{ref}}$ and $V_{\text{WE}}$ with $V_{\text{WE}}$ and $V_{\text{RE}}$, the voltage between the $RE$ and $WE$ can be held by feedback loops of the integrator (loop1) and of the ADC (loop2). Although $WE$ potential is not strictly held constant due to a nonzero value of $\Delta V$ in the loop2, the perturbation on $WE$ does not affect the sensor’s steady state as long as $\Delta V$ is set small enough (less than 10 mV) [29]. In addition, because current can only flow from the CE to the WE, node $A$ should be connected to CE rather than $RE$.

Following the modification described above, a modified amperometric instrumentation circuit with the sensor model can be illustrated as Fig. 6. Because the direction of the current source $I_f$ is opposite from the direction of $I_f$ in Fig. 5, $I_f$ in Fig. 6 should be written as

$$I_f = (1 - 2\alpha) \cdot I_{\text{ref}}$$

Fig. 3. Waveforms of the current on the integrator input $I_{\text{int}}$, the voltage on the integrator output $V_{\text{int}}$, and the digital output of the comparator $D_n$.

Fig. 4. Schematic of the electrochemical sensor system consisting of a model amperometric instrumentation circuit and the simplified electrochemical sensor equivalent circuit model.
This topology successfully realizes the functions of both current-mode ADC and potentiostat. Compared to a traditional topology in Fig. 2, it utilizes $C_{dl}$ for integrator, and eliminates one opamp required by the potentiostat and $C_{int}$ required by the integrator. Notice that voltages at RE and WE in Fig. 6 are both held by the feedback loops and no constrains are required for $V_{RE}$ and $V_{WE}$ from circuit perspective. Therefore, nodes RE and WE are interchangeable. By swapping WE with RE, the simplified structure shown in Fig. 7 can be achieved. Notice that the WE is connected to a unit-gain buffer, and this buffer can be discarded for further simplification. By connecting the WE to ground and replacing $V_{RE}$ with $V_{RE-WE}$, the resulting schematic in Fig. 8 defines a new compact current-to-digital amperometric instrumentation (CCDAI) topology. Here, it has been assumed that the sensor bias requires $V_{RE}>V_{WE}$ and thus $V_{RE-WE}>0$. If the sensor bias requires $V_{RE}<V_{WE}$, the WE could alternatively be connected to the power supply.

Following the derivation from the schematic in Fig. 4 to the one in Fig. 8, the CCDAI topology was designed functionally equivalent to the traditional amperometric instrumentation, when the parameters of the hysteresis comparator in the CCDAI meet the following constraints: $V_{ref}$ is set to $V_{RE-WE}$, and $\Delta V$ is set to 10mV.

**IV. PERFORMANCE ANALYSIS**

Although the function of the CCDAI is equivalent to the traditional amperometric instrumentation, structure differences and additional constrains will cause performance differences. In addition, as mentioned in Section I, the equivalent circuit used to derive the circuit topology was the simplified model in Fig. 1 (c). The sensors’ second-order effects should be fully considered in terms of performance. This section evaluates the performance of the CCDAI in two aspects: performance difference from the traditional amperometric instrumentation and performance affected by second-order elements in equivalent circuit model.

A. **Performance relative to traditional amperometric instrumentation**

Compared to the traditional potentiostat that drives the electrochemical cell from an opamp output, the CCDAI drives the electrochemical cell by a constant current source with much a lower current value. Therefore, it would take longer time to stabilize the electrochemical cell potential. Nevertheless, differences in the potential stabilization time would not affect steady state operation of the electrochemical cell.

Compared to a traditional current mode ADC, the main differences of the CCDAI include: 1) the integrator capacitor $C_{int}$ is replaced by sensor’s double layer capacitor $C_{dl}$; 2) the hysteresis comparator voltage window is limited to 10mV. These two differences could affect the resolution of the calculated $I_f$. From (7), $I_f$ is obtained by calculating measured $\alpha$ with a known $I_{ref}$ value. From (6), the resolution of $\alpha$ is determined by how short $T_0$ and $T_1$ are given a fixed counter reference clock frequency. From (3) and (4), $T_0$ and $T_1$ are proportional to $C_{dl}$ and $\Delta V$. Therefore, $C_{dl}$ and $\Delta V$ do affect the resolution of $I_f$. Assuming $|l_f|<I_{max}$, the given max time interval width is expressed by:

\[
I_f = (2\alpha - 1) \cdot I_{ref}
\]
\[ T_{\text{max}} = \frac{C_{\text{dl}} \cdot \Delta V}{I_{\text{ref}} - I_{\text{max}}} \]  

For a fixed counter reference clock frequency \( f_0 \), the maximum relative quantization error \([28]\) is given by

\[ |\delta|_{\text{max}} = \frac{1}{f_0 \cdot T_{\text{max}}} = \frac{I_{\text{ref}} - I_{\text{max}}}{f_0 \cdot C_{\text{dl}} \cdot \Delta V} \]  

The ADC’s effective resolution (in bits) \( N \) is determined by

\[ N = -\log_2 |\delta|_{\text{max}} = \log_2(f_0 \cdot C_{\text{dl}} \cdot \Delta V) - \log_2(I_{\text{ref}} - I_{\text{max}}) \]  

Therefore, larger \( \Delta V \) and \( C_{\text{dl}} \) would improve the effective resolution \( N \). In the traditional current-mode ADC, \( \Delta V \) can be up to the power supply voltage, \( V_{\text{dd}} \), which can be 5V in a portable device. In the CCDAI, \( \Delta V \) is restricted to maximum 10 mV. \( \Delta V \) in the CCDAI is 500 times smaller than in the traditional current-mode ADC, resulting in 9 bits of effective resolution loss for the CCDAI. However, in the meantime, electrochemical double layer capacitor \( C_{\text{dl}} \) has much larger capacitance density than a capacitor that can be fabricated by CMOS process in a single IC chip. For instance, double layer formed on 1 mm\(^2\) electrode can generate \( \mu \)F level capacitance; while a capacitor in a single IC chip is up to tens of pF. The 10000 times larger capacitance in the CCDAI would result in 13 bits of effective resolution improvement for the CCDAI. Therefore, the total effect of \( C_{\text{dl}} \) and \( \Delta V \) provides an improvement of around 4 bits of the effective resolution. As a tradeoff, the sampling rate drops as the effective resolution increases. Fortunately, electrochemical systems typically have a slow response and do not need a fast sampling rate.

**B. Second-order effects of the sensor equivalent circuit model**

The derivation in Section III was based on a simplified model in Fig. 1(c). Given a complete model in Fig. 1(b), an evaluation is needed to determine whether the solution resistor \( R_s \) and AC Faradaic components in the complete equivalent circuit model would introduce significant errors.

If we first consider adding \( R_s \) to the circuit, the corresponding waveform of \( V_{\text{int}} \) is illustrated in Fig. 9.

![Fig. 9. \( V_{\text{int}} \) waveform illustration when considering \( R_s \) in the equivalent circuit model.](image)

Although the abrupt jump in \( V_{\text{int}} \) caused by \( R_s \) can be observed, this does not change \( T_1 \) and \( T_0 \). Thus (8) is still valid. However, the abrupt jump decreases the effective charging/discharging window from \( \Delta V \) to \( \Delta V - I_{\text{ref}} R_s \). In a standard electrochemical cell configuration, the RE is placed close to the WE and a typical experimental value of \( R_s \) is on the order of \( 10 - 10^2 \Omega \). With \( \mu \)A level of \( I_{\text{ref}} \), this only gives 10 ~ 100\( \mu \)V error, which is less than 1% of 10 mV. Therefore, \( R_s \) has negligible impact on the resolution.

Next, AC Faradaic components were evaluated. The AC Faradaic components are in parallel with the double layer capacitor \( C_{\text{dl}} \) and the DC Faradaic current source \( I_f \). Because both the Warburg element and \( C_{\text{dl}} \) block DC current, only AC current \( i_t \) can pass through those AC Faradaic components. The sensor current \( I_{\text{sens}} \) is the sum of the DC current \( I_f \) and the AC current \( i_{t} + i_f \). Observe that the sensor current \( I_{\text{sens}} \) should be equal to the current provided by the current source at any time,

\[ I_{\text{sens}}(t) = I_c + I_{f,\text{ac}} + I_{f,\text{dc}} = \begin{cases} I_{\text{ref}} & \text{during } T_1 \\ -I_{\text{ref}} & \text{during } T_0 \end{cases} \]  

where \( T_1 \) is the time interval when \( D_n = 1 \) in the CCDAI, \( T_0 \) is the time interval when \( D_n = 0 \) in the CCDAI. Here \( T_1 \) and \( T_0 \) do not follow (3) and (4). The waveform of \( I_{\text{sens}} \) is illustrated in Fig. 10. Given the waveform in the time domain, \( I_{\text{sens}} \) can also be expressed by Fourier series as

\[ I_{\text{sens}} = \left[ (2\alpha - 1) + 4 \sum_{k=1}^{\infty} \frac{\sin(k\alpha \pi)}{k\pi} \cos(k \cdot 2\pi f_c \cdot t) \right] I_{\text{ref}} \]  

where \( f_c = 1/(T_1+T_0) \). The first term in (13) represents the DC part of \( I_{\text{sens}} \), and the second term represents the AC part. Because the AC components \( (C_{\text{dl}} \text{ and Warburg elements}) \) block DC currents, and DC current source blocks AC currents, \( I_f \) is equal to the DC part of \( I_{\text{sens}} \). Thus \( I_f \) is

\[ I_{f,\text{dc}} = (2\alpha - 1) \cdot I_{\text{ref}} \]  

Because (14) is identical to (7), one can conclude that the readout value of the CCDAI is the same as the result obtained in Section III, even when considering the complete electrochemical sensor equivalent circuit model.

**V. RESULTS**

**A. CCDAI implementation**

To verify the functionality and performance of the CCDAI, the test setup shown in Fig. 11 was built. The CCDAI was implemented on a printed circuit board with the following commercial IC chips: high precision current source (LM334SM (TI)), high speed switches (DG4157 (Vishay), turn on/off time ~ 228 ns), push-pull output comparator (MCP6542), and the buffer gate (SN74LV). The circuit power supply was set to 5 V and current bias \( I_{\text{ref}} \) was set to 1 \( \mu \)A, which are suitable values for a portable sensor.
application. To implement a hysteresis comparator with upper and lower bounds that can be adjusted independently during testing, the circuit shown in Fig. 12 was implemented using two comparators, an AND gate and an OR gate. A USB-6259 data acquisition card (National Instruments Inc.) was used to set the voltage on the reference electrode, $V_{\text{RE,WE}}$, and the comparator’s upper/lower bound voltages, $V_u$ and $V_l$. It was also used to measure the time intervals $T_1$ and $T_0$ of comparator output $D_n$ using an internal 10MHz clock. A Labview user interface was built for communication between a PC and the data acquisition card. The current $I_t$ was calculated using (8) with the measured $T_1$ and $T_0$ values.

B. Experimental Results

To evaluate the ADC performance of the CCDAI, an electrical test model was connected with the CCDAI board. To implement the simplified model in Fig. 1(c), the electrical test model consisted of a 1 μF capacitor and a Keithley 6430 Source Meter connected in parallel. CE and RE were shorted in the test. The current readout accuracy of the CCDAI was tested by sweeping $I_t$ from -800 nA to 800 nA with 2 nA step. Differential non-linearity (DNL) and integral non-linearity (INL) of the readout current are plotted in Fig. 13. The worst DNL equals to -56dB and the worst INL equals to -49dB, meaning that CCDAI achieves a resolution of better than 6nA, equivalent to 8 bits over the tested range. To increase the resolution of the CCDAI, tradeoffs with other performance metrics could be considered. For example, as shown in Eq. (11) the main factors to determine resolution are $\Delta V$, $C_{\text{wl}}$, and $f_0$. In theory, resolution will be enhanced by increasing $\Delta V$. However, as described in section III, $\Delta V$ has to be set to less than 10 mV to avoid inaccuracy in RE-WE voltage and degradation of the electrochemical result. $C_{\text{wl}}$ is an inherent parameter of the electrochemical cell and is already much higher than the capacitors implemented on chip in conventional CMOS designs. The resolution could be enhanced by increasing $f_0$ at the expense of higher power consumption. Considering this tradeoff, in our design, we set the $f_0$ as 100 kHz. It is a remarkable fact that, increasing $f_0$ for better resolution, not only increase the power consumption of the counter, but also increase the size of the counter to support greater number of bits. Therefore, by considering a fixed counter clock frequency of $f_0=100$ kHz, 8 bit resolution has been implemented which enables us to reach 6 nA resolution. This resolution meets the requirements for many electrochemical sensor applications [30].

To verify the electrochemical functionality of the CCDAI board, an electrochemical test was performed using an electrochemical cell with potassium ferricyanide as the analyte. The electrolyte consists of 0.1M potassium chloride as buffer solution and potassium ferricyanide with varied concentrations (from 0 to 6 mM). Ag/AgCl (CH Instruments Inc.) was used as standard RE. Pt wire (CH Instruments Inc.) was used as the CE. Au plate with 1 mm² area (CH Instruments Inc.) was used as the WE. $V_{\text{WE-RE}}$ was set to 190 mV.

The faradaic current generated by potassium ferricyanide redox reaction was recorded by the CCDAI as a function of time. The commercial electrochemical instrumentation CHI760C was used as a reference to record current data at the same condition setup. As an example, data for a 6mM concentration is plotted in Fig. 14 and shows that both the currents recorded by CCDAI and CHI760C converged to the same level with negligible differences after the chemical system reached the steady state. The transit pattern

![Fig. 11. Test setup for electrical and chemical experiment.](image1)

![Fig. 12. A hysteresis comparator realization with adjustable upper/lower bound.](image2)

![Fig. 13.DNL and INL of the CCDAI. Both DNL and INL in the current range are better than -49dB, implying an 8 bit of effective resolution.](image3)
differences are caused by the different stimulus provided by the two instrumentations. CHI760C applies large current to set the initial $V_{\text{WE,RE}}$ to the desired voltage in the very short time; while CCDAl applies a constant current to raise $V_{\text{WE,RE}}$ to the desired voltage in a gentle way. In addition, initial current recorded by CHI760C includes charging current caused by step stimulus, while current recorded by the CCDAl does not contain the charging current. Due to unavoidable convection in the solution [31], the currents at the steady state fluctuate slightly in amplitude. This phenomenon was observed from the data recorded by both instrumentations. Results obtained from the CCDAl at different potassium ferricyanide concentrations are plotted in Fig. 15. The data obtained from CHI760C are plotted as dot/dash curves as references. Steady state current values recorded by the CCDAl and by CHI760C have good agreements with negligible differences in all tested concentration cases. The average current values from 200 s to 300 s, which were recorded by CCDAl and CHI760C, were taken to plot the calibration curve as shown in Fig. 16. The least-squares correlation coefficients ($R^2$) of the fitting curve are 0.991 and 0.996 for the data acquired by CCDAl and CHI760C respectively. The electrochemical experiment results demonstrate the functionality and the accuracy of the CCDAl.

C. Analysis of area and power savings

The CCDAl realizes a compact topology while maintaining the functionality of a traditional amperometric instrumentation circuit. Compared to the model instrumentation circuit presented in Fig. 2, the CCDAl (Fig. 8) eliminates two opamps and one integrator capacitor. In microelectronic circuits, both of these components usually occupy larger area than comparators and current sources. In addition, opamps are a major source of power consumption in ICs. To provide a qualitative comparison, Table I and Table II lists the area and power consumption, respectively, of each component based on results from circuit blocks within a 0.5μm CMOS analog chip [32]. The total estimated area and power of the potential CCDAl chip and the model electrochemical circuit are shown in the last row of the tables. The CCDAl can be seen to reduce area by 25.3% and power consumption by 47.6% compared to the model amperometric instrumentation circuit. Area savings can be further improved using an advanced process node; the large area digital counter would be much smaller and the area savings due to CCDAl’s eliminating the integration capacitor would be amplified because capacitors do not scale with feature size. For further comparison, Table III shows performance characteristics of several amperometric instrumentation circuits that also target low power applications. In comparison, our CCDAl design demonstrates good resolution and power performance while potentially utilizing very low area.

VI. Conclusion

A novel compact amperometric instrumentation design with current-to-digital readout for electrochemical sensor was presented. Compared to a model amperometric instrumentation structure, the new design dramatically saves area, cost and power by utilizing the sensor’s double layer capacitor as a circuit element and adopting EIS mode, without sacrificing its resolution and detection of limitation performance. A board-level CCDAl was implemented and tested, demonstrating an 8-bit effective resolution in the range of -800 nA to 800 nA. Functionality of the instrumentation was verified by an electrochemical experiment in potassium ferricyanide. High linearity of current-to-concentration

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**Fig. 14.** The faradaic current generated by 6 mM of potassium ferricyanide as function of time when $V_{\text{WE,RE}}$=190mV. Red line represents data recorded by CHI760C and blue line represents data recorded by CCDAl.

**Fig. 15.** The faradaic current recorded by the CCDAl at $V_{\text{WE,RE}}$=190mV as function of time for 0-6 mM of potassium ferricyanide. The dot and dash curves present the data recorded by CHI760C for reference.

**Fig. 16.** Calibration curve of faradaic current vs potassium ferricyanide concentration. The current values were the average values from 200s to 300s. Fitting curve was presented as a straight line. $R^2$ values of the fitting line are 0.991 and 0.996 for the data acquired by CCDAl and CHI760C, respectively.
transfer was acquired with an $R^2$ of 0.991. A CMOS implementation of the CCDAI is estimated to save 25.3% of area and 47.6% of power compared to the model amperometric instrumentation structure. Thus this new compact circuit topology is well suited for portable/wireless electrochemical sensor applications.

**REFERENCES**


