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A dual-channel wide input range interface circuit for electrochemical amperometric sensors

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Abstract: A wide input range, compliant with electrochemical amperometric sensors interface circuit is proposed in this paper. The interface circuit consists of a potentiostat which is fabricated on PCB board and an interface ASIC which is realized in a single chip. The ASIC employs current integrator (CI) and transimpedance amplifier (TIA) to deal with the input current in the order of nA and µA separately, achieving the advantage of wide input range and high resolution. An incremental sigma-delta ADC is employed to digitize the transferring signal to achieve the feature of one-to-one mapping between input and output. The ASIC is fabricated in 0.18 µm 1P5M mixed-signal CMOS process, has a dynamic range of 120 dB, and consumes 4.2 mA.

Keywords: wide range, electrochemical sensor, interface circuit, TIA

Classification: Integrated circuits

References

[1] L. Li, X. Liu, W. A. Qureshi and A. J. Mason: IEEE Trans. Biomedical Circ. Systems **5** (2011) 439. DOI:10.1109/TBCAS.2011.2171339

[2] M. M. Ahmadi and G. A. Jullien: IEEE Trans. Circuits Syst. I, Reg. Papers **56** (2009) 1339. DOI:10.1109/TCSI.2008.2005927

[3] M. M. Ahmadi and G. A. Jullien: IEEE Trans. Biomedical Circ. Systems **3** (2009) 169. DOI:10.1109/TBCAS.2009.2016844

[4] S. M. Martin, F. H. Gebara and T. D. Strong: IEEE Sensors J. **9** (2009) 135. DOI:10.1109/JSEN.2008.2011085

[5] W. Wang, W. Kuo, H. Huang and C. Luo: Sensors **10** (2010) 1782. DOI:10.3390/s100301782

[6] C. H. Chen, J. Crop, J. Chae and P. Chiang: IEEE ISCAS (2012) 2969. DOI:10.1109/ISCAS.2012.6271940

[7] K. L. Kraver and M. R. Guthaus: Sens. Actuators A **91** (2001) 266. DOI:10.1016/S0924-4247(01)00596-9

[8] S. M. Martin, F. H. Gebara, B. J. Larivee and R. B. Brown: IEEE J. Solid-State Circuits **40** (2005) 2777. DOI:10.1109/JSSC.2005.858478

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[9] K. Hyuntae and K. Bharatan: Analog Integr. Circ. Signal Process. **70** (2012) 15. DOI:10.1007/s10470-011-9638-1

1 Introduction

Electrochemical sensors have been widely used to measure the analyte concentrations both in research and commercial applications, including water environment monitoring, biological systems, quality control, disease diagnosis and biological threat detection [1]. Electrochemical sensors typically utilize three-electrode electrochemical measurement techniques and interface with electronics through a potentiostat, which can be configured for potentiometric or amperometric operation [2]. In order to detect the very weak output signals of electrochemical sensors, high sensitivity interface readout circuits are essential for the sensors. Several integrated-circuit (IC) amperometric readout circuits have been previously reported, including wireless implanted potentiostat using current-to-frequency conversion of sensing current [3], a fully differential potentiostat that enables detection of a wide range of analytes [4], a wide dynamic range CMOS potentiostat for amperometric chemical sensor [5], and so on. To support diverse classes of electrochemical sensors, the circuits must accommodate a wide range of signal, 120 dB based on reported electrochemical sensors. However, all the reported works cannot meet this demand. In this paper, a dual-channel interface circuit which employs current integrator (CI) and transimpedance amplifier (TIA) to deal with the sensors' current in the order of nA and μA separately, achieving the advantage of wide input range and high resolution.

2 Implementation of the interface circuit

In electrochemical amperometric method, a current corresponding to the concentration of a solution is generated as a result of a voltage applied to the chemical solution. Typically, a transimpedance amplifier (TIA) is the most popular approach to convert the redox current to a voltage. But there are three drawbacks of this architecture: firstly, to deal with a very small current, a very large transistor which is difficult to realize in integrated circuit is inevitable, and a large transistor will introduce large noise. Secondly, in this architecture an amplifier forces a virtual ground at the working electrode of the three-electrode sensor, if its connection to the potentiostat is not carefully shielded, it can pick up environmental noise. Thirdly, it is difficult to achieve high dynamic range.

In this work, dual-channel is employed to extent the input range. Depending on the output current range of sensors, current integrator (CI) and TIA can be chosen. When the current is in the range of 1 nA–1 μA, the CI is selected to complete current-to-voltage conversion, at the same time, TIA is shut down so as to avoid the detection of very weak current requiring large resistance to achieve high gain. When the current is in the range of 1 μA–1 mA, TIA achieves the current-to-voltage conversion, and the CI is shut down to avoid detection of lager current demanding a large integration capacitor or high integral frequency. The architecture of the interface circuit is shown in Fig. 1. The interface circuit is composed of two main

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parts: potentiostat which controls the voltage difference between two electrodes of the sensor, making the redox current flow from the third electrode, and the interface ASIC which is used to measure the redox current and converter it to digital signal. Three-electrode electrochemical sensor consists of a working electrode (WE), on which an electrochemical reaction takes place; a reference electrode (RE), which is used to measure the solution potential; and a counter electrode (CE), which is an inert conductor supplying the current required for electrochemical reaction at WE [2]. For a special application, potentiostat can be realized with other circuits in a same chip, but in this work, the potentiostat is fabricated on PCB board, this is because we hope the interface ASIC can support diverse classes of sensors. The interface ASIC is composed of CI with sample/hold (S/H), TIA, a digital programmable gain amplifier (PGA), CDS with S/H, and a 16 bit incremental sigma-delta (IΣΔ) ADC. In addition, the ASIC includes a 10 bit resistor string digital-to-analog convert (DAC) to generate a slope signal as sensors' stimuli, a band-gap, a low dropout voltage regulator, voltage buffers and digital blocks.

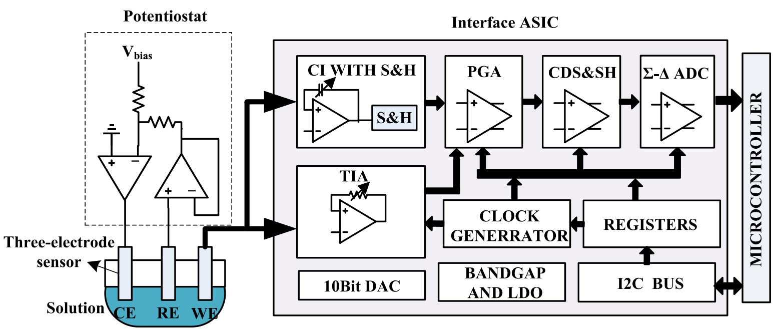

Fig. 1. Architecture of the interface circuit

When the sensors' output current is very small, integrating the current on a capacitor is the best method to achieve C-V conversion. The circuit of the CI with S/H is shown in Fig. 2(a). *Clk1* and c*lk2* are two-phase non-overlapping clocks. In *clk1* phase, the current from sensor's work electrode flows to one plate of the integration capacitor C_{int} and causes voltage at the other plate increasing accordingly. At the same time, the output voltage will be sampled by the sampling capacitor C_S. At the end of integration period, *clk1* turns to low, and *clk2* turns to high, the charge sampled by C_S is transferred to C_H, leading to the output of S/H. In this design, there is a switch controlled by *clk2* between I_{IN} and positive port of amplifier, making the sensing node WE fixed to be VCM both at *clk1* and *clk2* phase. TIA is used to convert large current ranging from 1 µA–1 mA to voltage. TIA provides low input impedance while offering high gain, which is in particular very appealing in electrochemical sensors. The circuit diagram of TIA is shown in Fig. 2(b). R_1 is a current limiting resistor, whose value is selected to be 1 Kohm, R_2 is the trans-impedance used for C-V conversion. Like CI system, the voltage at the sensing node is fixed to be VCM in TIA, which means that the characteristic of the sensor is kept unchanging during the sensing. In order to maximize the input and output swing, a rail-to-rail class AB opamp is designed in this TIA and the value of R_2 is controlled by a 3-bit register, according to the range of input current.

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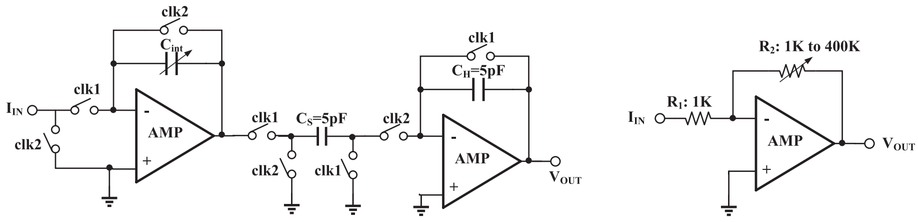

(a) (b)

Fig. 2. (a) Current integrator with S/H (b) TIA

Several improvements have been implemented in this interface ASIC to increase measurement sensitivity and range. Firstly, as CI and TIA deal with small (in the range of 1 n–1 μA) and large current (in the range of 1 μ–1 mA) separately, the integration capacitor and trans-impedance do not need large value, so they can be integrated in the chip. Secondly, the PGA is designed with single-end (SE) input and full-differential (FD) output. As the output signal of CI or TIA is single-end, however, to increase dynamic range, both common-mode and power supply rejection, the best design choice for ADC is to use FD architecture. So in addition to amplification, the PGA design in this work also converts SE input to FD output. Thirdly, correlated double sampling (CDS) technique is introduced in this work. The CI and PGA operate at the frequency of 30 KHz, with this operating frequency the circuit noise will be dominated by $1/f$ noise rather than thermal noise. And since the response current of the sensor could be very small, the $1/f$ noise and DC offset of operational amplifier would significantly affect measurement sensitivity. CDS technique is employed to sample and subtract a portion of the noise and DC offset, thereby suppressing noise at the output. Fourthly, an incremental ΣΔ ADC is designed in this work rather than conventional ΣΔ ADC. IΣΔ ADCs, which reset their memory elements before each conversion, can offer sample-by-sample conversion as Nyquist-rate ADCs. The feature of one-to-one mapping between input and output, providing precise high-resolution conversion with low offset and gain errors makes them suitable for the requirement of instrument and measurement (I&M) applications [6]. So a 16 bit third-order cascaded-integrator feed-forward (CIFF) IΣΔ ADC is designed to digitized analog signal in this paper.

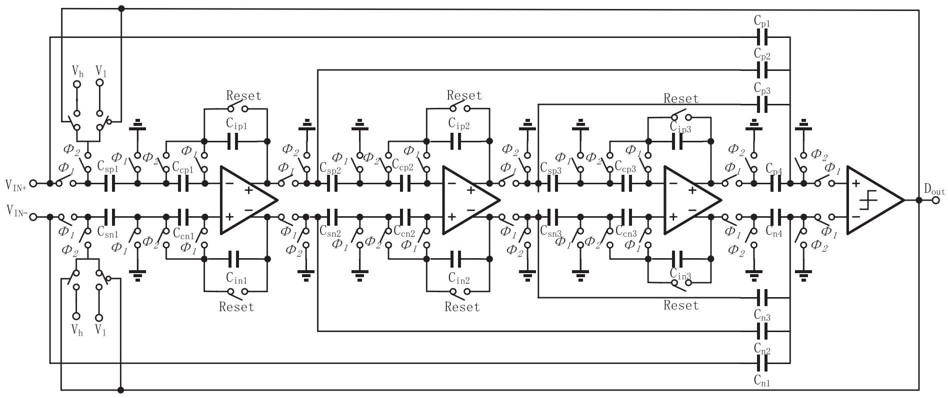

Fig. 3. Fully differential third-order incremental ΣΔ modulator

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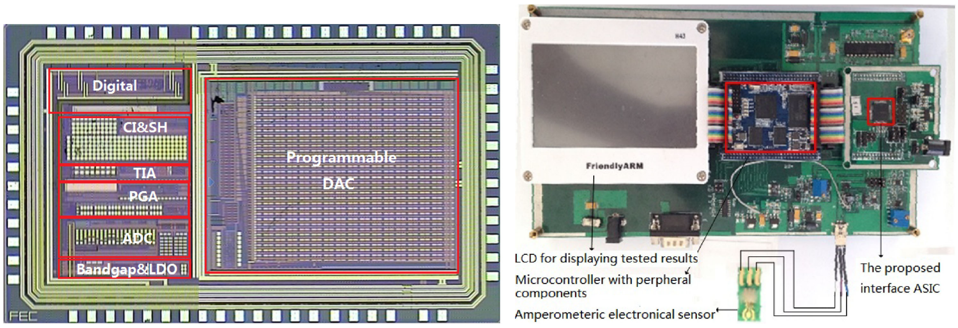
The third-order IΣΔ modulator is shown in Fig. 3. A third-order cascaded integrator filter composed of a ripple counter for the first integrator and two accumulators for the second and third one separately is used as the digital filter, which saves a great deal of areas and power dissipation.

3 Results and discussion

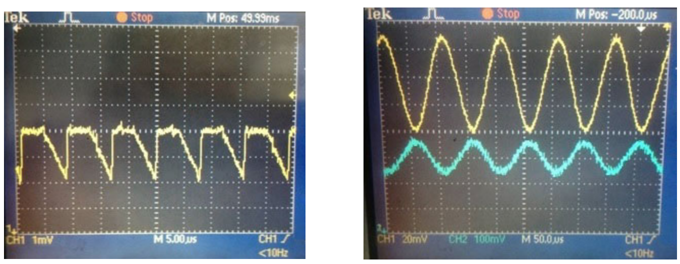
The interface ASIC is fabricated using 0.18 µm 1P5M CMOS process. Occupying an area of 3.2 mm × 2 mm, as shown in the chip microphotograph in Fig. 4(a). The tested system is shown in Fig. 4(b), which consists of tested chip, three-electrode sensor, potentiostat fabricated on PCB board, microcontroller and LCD for displaying tested results. The interface ASIC's 16 bit digital output is sampled by microcontroller and displays on the LCD. In this chip, the IΣΔ ADC and other switch capacitor (SC) circuits operate at different frequency, the clock frequency for IΣΔ ADC is 5 MHz, the others operate at the frequency of 30 KHz, every conversion cycle includes 150 cycles of A/D conversion, one reset pulse and one data readout pulse.



(a) (b)

Fig. 4. (a) Chip microphotograph. (b) Tested system

Fig. 5(a) shows the CI tested result, the input is 6 nA DC current generated by constant current source fabricated on PCB board, in this test, the clock whose frequency is 133.3 KHz is supplied by ARM directly. Fig. 5(b) is the TIA tested result, the input is a sine AC current with 5 µA peak-peak value. The results indicate the CI and TIA designed in this paper can work well.



(a) (b)

Fig. 5. (a) Current integrator tested result. (b) TIA tested result

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To measure the electrical characterization of the interface circuits, a resistor is inserted between any two electrodes, forming a triangular resistor network to generate known current. The value of the generated current is adjusted by changing the value of resistors. Fig. 6(a) is the current in the order of nA tested result, CI is chose as the measured channel and TIA is shut down. The tested result indicates that the minimum current could be detected is 1 nA, the output has a good linearity and the interface ASIC proposed in this paper could detect and digitize the very weak current from sensors well. Fig. 6(b) is the current in the order of μA detected result via TIA channel, which also has a good performance.

To measure the input-referred noise, the interface is configured as TIA detection mode, the current input port is connected to VCM, the trans-impedance is selected to be 12.5 Kohm, the gain of PGA is set to 1, and the noise waveforms at the output of CDS&SH are recorded with dynamic signal analyzer HP35670. Fig. 7 is the spectrum of the output tested result, which indicates that the output noise is $-99.75\,dBV/Hz^{1/2}$, equal to $10\,\mu V/Hz^{1/2}$. The calculated input-referred noise current is $0.8\,nA/Hz^{1/2}$. The results indicated that the ASIC has a high dynamic range of 120 dB.

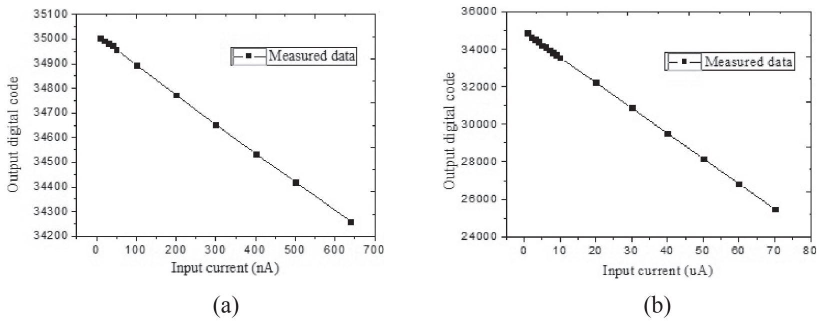

Fig. 6. (a) Current in the order of nA detected result via CI channel. (b) Current in the order of μA detected result via TIA channel

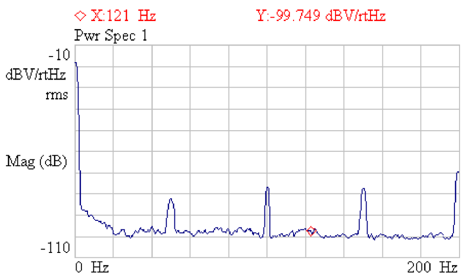

Fig. 7. Spectrum of the output noise

After measuring electrical characterization of the interface circuit with known current, the interface is used to detect unknown output of electrochemical sensor. An electrochemical total phosphorus sensor is connected to the three electrodes of potentiostat, the 10 bit DAC integrated in this chip generates a slope voltage as scanning signal, a current representing concentration of solution is generated at electrode WE which is connected to the current input of chip. Fig. 8 shows the total phosphorus tested result, which indicated that the output digital code is linear to

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concentration of solution, and the resolution is about 800LSB/0.1 mg/L. The performance comparison with previous works is shown in Table I.

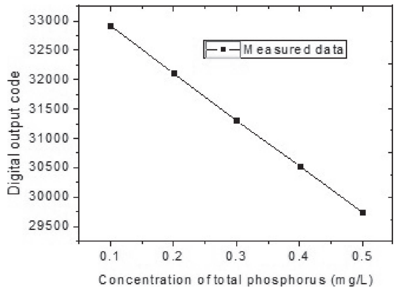

Fig. 8. Total phosphorus measured result using the interface circuit

Table I. Performance comparison with previous works

	[7]	[8]	[5]	[9]	This work
Technology	0.35 µm	0.5 µm	0.18 µm	0.18 µm	0.18 µm
Range	—	36.6 pA–4 µA	0.5 nA–10 µA	10 nA–100 µA	1 nA–1 mA
Dynamic range	—	100 dB	86 dB	80 dB	120 dB
Output type	12 bit digital	16 bit digital	Analog	16 bit digital	16 bit digital
Supply voltage	3 V	5 V	1.8 V	1.8 V	3.3 V
Current	16 mA	3.2 mA	0.7 mA	13 mA	4.2 mA

4 Conclusions

A wide input range, compliant with electrochemical amperometric sensors interface circuit has been proposed. This circuit employs CI and TIA to deal with the input current in the order of nA and µA separately, achieving the advantage of wide range and high resolution.

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