

Low Power Noise Immune Circuit for Implantable CMOS Neurochemical Sensor Applied in Neural Prosthetics

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Abstract- In this manuscript, we present the features and describe the operation of a low power, noise immune circuit for a CMOS based neurochemical sensor for implantable neural prosthetics. This microsystem consists of a single ended low noise low power amplifier and an integrator, in addition to a 10-bit first order sigma delta Analog to Digital Converter (ADC). Using electrochemical techniques, it senses picoscale to microscale current which corresponds to micro molar neurotransmitter concentration and converts the measurement to a 10-bit digital code. Combining amperometry and fast-scan cyclic voltammetry electrochemical technique results in a sensor with a high selectivity while having elevated temporal resolution. The microsystem consumes 120.85 μW which is the lowest reported brain implant and biosensor power consumption [1-5]. This circuit is designed in CMOS 0.18 μm technology. Integration is an averaging operation and provides significant noise immunity. The low noise characteristics of our design make this device suitable for the noisy environment often encountered in-vivo.

I. INTRODUCTION

Brain Machine interfaces promise to improve the lives of many patients. Action Potential and Local Field Potential have been shown to contain viable information for controlling prosthetic devices [6-10]. However, the brain is an electrochemical system and contains additional signals that may improve BMI performance. Action potentials are initiated by the release of neurotransmitters from presynaptic neurons. Many psychiatric and neurological disorders such as Parkinson's disease, depression, dystonia, or obsessive compulsive disorder are related to neurotransmitters deficiency or imbalance [11-13]. Detection of these chemicals may carry additional information that can be used to enhance BMI performance.

In order to detect and measure neurotransmitters, a highly sensitive device such as potentiostat is needed. Potentiostats generate an electrochemical current that is proportional to the chemical concentration around the electrodes (Fig. 1).

Traditional bench-top potentiostats are not suitable for in-vivo neurotransmitter recording applications. Because these

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have low sensibility (designed for large chemical concentrations that result in current in microamps to milliamps), large size (tens of kilograms) and cost (tens of thousands of dollars per channel).

Our goal in this paper is to minimize power consumption and the microsystem's noise [16-17]. We present a circuit for an implantable low power low noise CMOS Neurochemical sensor which is able to sense micro molar concentration of different neurotransmitters such as dopamine and serotonin. Obstacles to prolonged electrode life after implantation [14-15] are not addressed here. The sensing component of the device consists of a reference, counter and working electrode connected to low noise low power integrator amplifier and a current mode 10-bit first order sigma delta Analog to Digital Converter (ADC). It converts the measured red-ox current (pico-scale to microscale) to digital codes for further processing. Its power consumption is 120.85 μW . To the best of our knowledge, this is the lowest reported power consumption [1-5]. The design also introduces minimum input referred noise (transistor noise) which will be discussed in more detail in the design section.

II. ELECTROCHEMICAL SENSING

A. Sensing Methods: Every neurochemical is associated with certain voltage [18]. To sense the chemical, this voltage is applied between the working and reference electrode. The potential difference generates a reduction-oxidation (red-ox) current which is proportional to the neurotransmitter concentration (Fig. 1) [3].

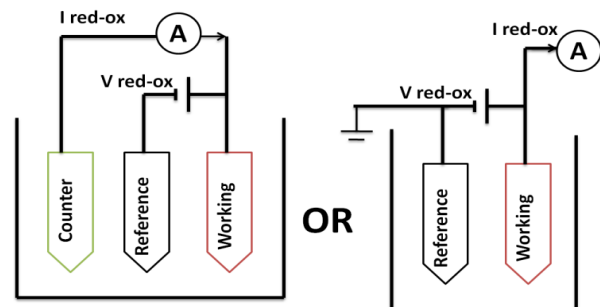


Fig. 1. Schematic of the electro analysis setup, specific red-ox voltage is applied between Working and Reference electrode and red-ox current is measured.

There are several neurochemical methods to measure extracellular neurotransmitters such as microdialysis, constant-potential amperometry, fast-scan cyclic voltammetry, high speed chronoamperometry and differential normal-pulse voltammetry [18]. Our design goals are to have a device possess high sensitivity, high chemical selectivity, and fast temporal resolution.

Although a high degree of chemical selectivity and sensitivity is achieved with microdialysis, this method has very low temporal resolution. In addition, due to its large size, it is not suitable for implantable sensors. In contrast, amperometry has very low selectivity but a very high temporal resolution. Selectivity can be improved by using biological filters and coating the electrodes with Nafion [19]. However, this process significantly decreases the life time of the electrode [20]. Fast-scan cyclic voltammetry possesses good chemical selectivity while maintaining subsecond temporal resolution [18]. Fast-scan cyclic voltammograms are repeated every 100 ms, thus changes in chemical concentration can be monitored on a sub-second time scale [18]. These characteristics make fast-scan cyclic voltammetry suitable for detecting phasic neurotransmitter changes in behaving animals. We combined amperometry and fast-scan cyclic voltammetry to create a new neurochemical sensor that takes advantage of both methods. Using both techniques at the same time results in a sensor with a high chemical selectivity while having high temporal resolution.

B) CMOS potentiostats: Many attempts have been made to fabricate CMOS potentiostats [2-4]. Methods employed to develop a VLSI DNA sensor will not be considered here as the device is optimized for its different function [2]. However, another similar device for chemical sensing has been developed [4]. This device contains a different circuit topology than [2] and an on-chip electrode array but the design did not improve on power consumption or decrease the noise level. Although mentioned potentiostats are suitable for in-vitro applications; due to their high power consumption they cannot be used for brain implants.

Another integrated potentiostat has been reported by Murari and colleagues [3]. The novelty of this design is using delta sigma ADC in each channel instead of using off-chip ADC or single ADC for several channels. Although this design reduced power consumption and noise, components in the design still required high power. For brain implant circuits, Low power dissipation is vital. An implantable microsystem with less power consumption generates less heat and more importantly can function longer with smaller source of energy. Here, we further reduce the power consumption on every circuit components, develop a novel electrochemical technique to simultaneously obtain high selectivity, sensitivity and temporal resolution. Noise Immunity is another feature of our circuit which will be discussed in more detail.

III. CIRCUIT ARCHITECTURE

To record and digitize the picoscale red-ox current (we designed a current conveyor and a current to digital converter circuit in CMOS 0.18 μ technology. Fig. 2 depicts the fully integrated system. It consists of a current conveyor which converts the red-ox current to voltage followed by a sigma-delta Analog to Digital Converter (ADC). Total microsystem power consumption is 120.85 μ W. The bandwidth of the system is 1.5 KHz with 10-bit digital resolution.

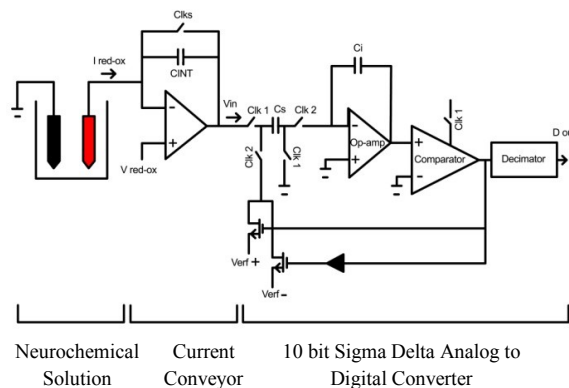


Fig. 2. System-Level Chip Overview

A. Low Power Low Noise Current Conveyor

To measure the electrochemical current, the red-ox potential is applied between working and reference electrode. Current conveyer converts pico to nano-amp red-ox current to voltage. The core of the current conveyor is the operational amplifier. Instead of using power hungry front end amplifiers; a wide swing folded cascade amplifier (Fig. 3) is used for its high gain and stability [21]. Power dissipation is minimized since the Op-Amp is designed to operate in the subthreshold region. We chose a folded cascade due to its high gain and low bandwidth. The measured current is then integrated onto the op amp feedback capacitor C_{INT} .

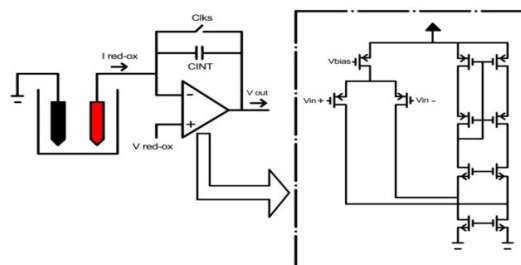


Fig. 3. Folded Cascade Circuit

V_{red-ox} is applied over R_{Sensor} . I_{red-ox} which is proportional to neurochemical concentration, accumulates charge on C_{INT} over integration period T_{INT} . Output voltage is calculated by Equation (1).

$$V_{out} = \frac{1}{C_{INT} \times R_{Sensor}} \int_0^{T_{INT}} V_{red-ox} dt \quad (1)$$

The designed Op-Amp consumes $0.55 \mu W$. To the best of our knowledge, this power dissipation is the lowest reported [21-22]. Table I summarizes the amplifier's specifications in addition to comparing our work to other similar designs.

TABLE I
Amplifier Specifications and Comparison.

Specifications	[21]	[22]	This Work
Architecture	Class AB	Telescopic	FoldedCascode
Technology (μm)	0.09	0.18	0.18
DC Gain (dB)	50	79	74.3
Unity Gain	57	8.5	19.81
Bandwidth (MHz)			
Phase Margin (deg)	57	78	65
Supply Voltage (V)	1	0.925	1
Output Swing (V)	[-0.2,+0.2]	[-0.2,+0.2]	[-0.45,+0.43]
Power (μW)	80	4.6	0.55

B. 10 bit, First Order, Sigma Delta ADC

A 10 bit first order sigma delta Analog to Digital Converter (ADC) is designed to convert the current conveyor's output voltage into a digital code. Delta Sigma ADC was chosen for their high resolution, low power and small area. Chemical reactions are slow (mille second to second) therefore high speed ADCs are not required for our application. Delta Sigma ADC owes its performance to oversampling and noise shaping. Quantization noise is pushed out of the band of interest. It consists of an integrator followed by a quantizer in forward path and a Digital to Analog Converter (DAC) in feedback path followed by a decimator, Fig. 4.

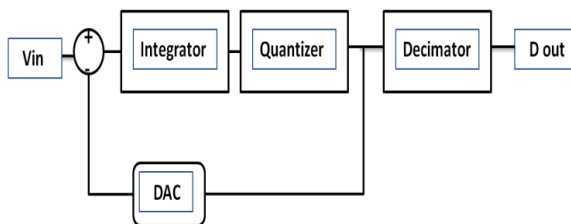


Fig. 4. 1st Order Sigma Delta ADC, System Level

The integrator is implemented using a two stage op-amp and switch-capacitor circuit. Clk1 and Clk2 are

non overlapping clocks (Fig. 5). A comparator acts as the quantizer block. In order to minimize the kick-back noise a pre-amp followed by a D-Latch was used as a comparator (Fig. 5). In order to minimize the Integrated Circuit (IC) area which is essential for implantable circuits a simple two switch Digital to Analog Converter (DAC) is placed in a feedback path which is fed by the comparator's output. The main ADC design goal was to minimize the power consumption while meeting required specifications. In order to do so, a lower sampling frequency was selected in addition to low power biasing.

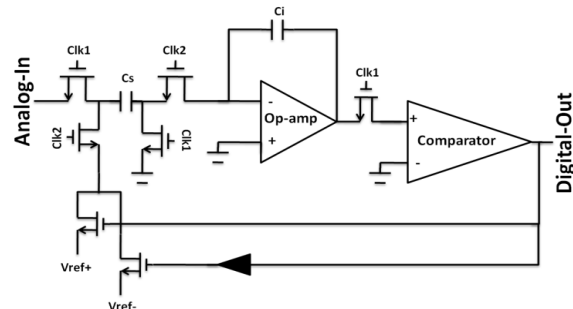


Fig. 5. 1st Order Sigma Delta ADC, Circuit Level

Total ADC power dissipation is $120.3 \mu W$ which is lower than similar designs [23 – 25]. ADC bandwidth is 1.5 KHz while sampling at 384 KHz with 66.1 dB Signal-to-Noise (SNR) ratio which is equivalent to 10 bit resolution Equation (2). The Oversampling Ratio (OSR) is 128. Equation (3) Demonstrate the relationship between bandwidth, sampling frequency and oversampling ratio.

$$Bit Resolution = \frac{SNR(dB) - 1.76}{6.02} \quad (2)$$

$$Bandwidth = \frac{F_{sampling}}{2 \times OSR} \quad (3)$$

Table II summarizes the designed 10-bit, 1st Order Sigma Delta Analog to Digital Converter's specifications and compares our work to former Sigma Delta modulators.

TABLE II
Sigma Delta ADC Specifications and Comparison

Specifications	[23]	[24]	[25]	This Work
Technology (μm)	0.18	0.18	0.18	0.18
SNR (dB)/ #-Bit	85.76/ 13	60/ 9	67.8/ 10	66.1/ 10
Bandwidth (KHz)	50	5	4	1.5
Supply Voltage (V)	1.8	0.8	1.8	1
Power (μW)	38000	180	400	120.3

IV. NOISE AND POWER ANALYSIS

Both major components of the microsystem, the current conveyor and Analog to Digital Converter are designed to have minimum power dissipation. Total current pulled out from power supply by the designed microsystem is $67.13\mu\text{A}$. Thus, the total power consumption is $120.83\mu\text{W}$ calculated from

$$\text{Power} = V \times I_{\text{total}} = 1.8 \times 67.13 \mu = 120.83 \mu\text{W} \quad (4)$$

Fig. 6 shows a simplified circuit for the microsystem's front end in addition to the electrode model and noise sources. There are two possible noise sources; V_{n1} and V_{n2} .

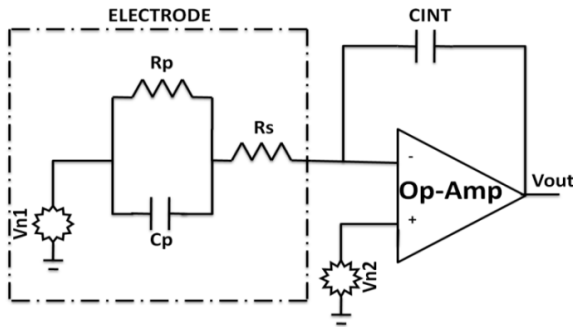


Fig. 6. Microsystem's Front End with Electrode Model and Noise Sources

V_{n1} stands for the noise of the electrode and V_{n2} represents input referred noise of the amplifier. Since this circuit operates in low frequency, the series resistance of the electrode is negligible. The input referred current noise is formulated in (5).

$$I_n^2 = \left| j\omega C_p + \frac{1}{R_p} \right|^2 \times (V_{n1}^2 + V_{n2}^2) \quad (5)$$

In order to minimize the input referred current noise and improve sensors selectivity, V_{n1} and V_{n2} should be minimized. Differential pair and bias transistors in the folded cascade transistor have maximum contribution to input referred noise of the amplifier. To minimize their effect they were designed to operate in strong inversion. Total current input referred noise of this microsystem over the bandwidth of interest is 0.6 femto Amperes (fA) which is thousand times less than device selectivity which is Pico-Amperes.

In addition, Integration in Equation (1) is an averaging operation and provides significant noise immunity. The

larger the time-constant, the higher the noise rejection capability of the circuit.

V. SIMULATION RESULTS

We tested the 10 bit first order sigma delta ADC by computing the Fast Fourier Transform (FFT) of the output to calculate the power and Signal-to-Noise-Ratio (SNR). The Power Spectral Density (PSD) was computed by $\text{PSD} = 10\log(\text{power})$ and the SNR is defined as:

$$\text{SNR} = \frac{\text{Power}_{\text{out-signal bin}}}{\sum_j^N \text{Power}_{\text{out-j th bin}}} \quad (6)$$

Where j is the first bin outside of the bandwidth and N is total number of samples. Fig. 7 shows the power spectral density of the 10 bit first order sigma delta ADC. The total number of samples is 1024 and Over Sampling Ratio (OSR) is 128. The input signal frequency is 1.125 KHz with 0.15 amplitude peak to peak. The calculated SNR is 66.1 dB which is equivalent to 10 bit.

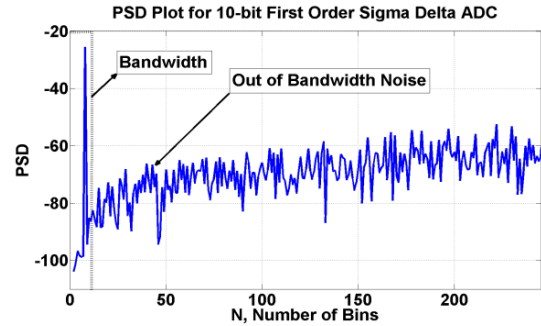


Fig. 7. PSD Plot for 10-bit First order Sigma Delta ADC

Fig. 8 is obtained from measurements using VersaSTAT 4 potentiostat. It shows the measured red-ox current in response to addition of five μM Dopamine. From Fig. 8 it is clear that by changing Dopamine concentration in Micro scale the red-ox current varies in order of 100 Pico Amperes.

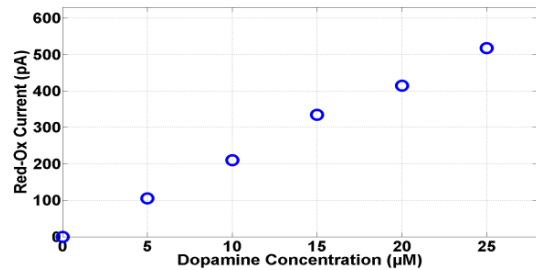


Fig. 8. The Static red-ox Current in Response to Addition of 5 μM Dopamine

In order to test the neurochemical micro sensor, the input current was swept from 100 to 100000 Pico Amperes to resemble change in Dopamine concentration. Fig. 9 shows that how current is converted to 10 bit digital code.

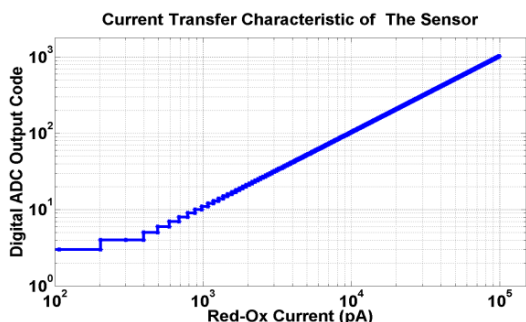


Fig. 9. Current Transfer Characteristic of the Micro Sensor

VI. CONCLUSION

A Low Power Low noise CMOS circuit for Implantable Neurochemical Sensor is presented. This circuit is able to convert Pico to Micro scale current to 10 bit digital code. Measured and quantized current is proportional to neurotransmitter concentration. This microsystem may be used in new generation of neural prosthetics and provides a better solution to neurological disorders. The total power consumption is 120.85 μW and its current input referred noise in femto level. The power dissipation is lower than similar designs.

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