A Bidirectional Current-Mirror Based Potentiostat Using a Slice-Based Class-AB Amplifier

Markus Haberler, Student Member, IEEE, Inge Siegl, Christoph Steffan, and Mario Auer, Member, IEEE

Abstract—A pico-ampere sensitive electrochemical sensor signal acquisition chain consisting of a multi-channel bidirectional current-mirror based potentiostat and a multiplexed current-input delta-sigma (ΔΣ) ADC is presented. Slice-based class-AB amplifiers with output stage current replication using reconfigurable current-mirrors enable bidirectional current sensing over a range of five decades. The replicated current is digitized by the ADC. The proposed circuit achieves a minimum detectable current of 91.7 pA, resulting in a dynamic range of 147 dB for sensor currents up to ±1 mA. The potentiostat is operated at a 3 V supply, the ADC at 1.5 V. The static power consumption of a single interface channel depends on the number of active amplifier slices and is between 14.1 µW and 39.3 µW. The highest power efficiency among similar systems and the low voltage headroom consumption of less than 500 mV enables a versatile use of the interface for multiple sensing applications.

Index Terms—bidirectional, biosensor, class-AB, current-mirror, delta-sigma ADC, frequency compensation, potentiostat, sensor array, wireless operation

I. INTRODUCTION

In order to improve the medical situation in rural areas, fast and inexpensive diagnostics are of great importance. Point-of-care (PoC) diagnostics promise to replace the need for specialized equipment by offering rapid and accurate test results while keeping the medical costs at a minimum [1]. The integration of biochemical functionalities with a performance comparable to laboratory-based equipment, combined with wireless operation, are key aspects to enable widespread adoption of PoC devices.

To analyze various biochemical parameters, different electrochemical sensing methods including constant potential amperometry (CA), cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS) have to be provided. These analyses require a controlled-potential sensor interface that is able to process bidirectional (reduction and oxidation) sensor currents. The limited available power in wireless operation requires a low power and low voltage headroom consuming implementation of the corresponding circuits.

A PoC diagnostic platform that uses a two-chip solution for this purpose was recently presented [2]. One chip is used to perform the desired electrochemical measurements, the other is used for data acquisition and data transfer. Additionally, an external energy storage device is used to power the diagnostic platform. A battery-less single-chip solution was presented in [3]. The platform uses the electromagnetic field for power supply and data transfer. A low voltage topology of the sensor front-end is used; however, the front-end is only capable of processing unidirectional sensor currents. This limits the usability of the system to analyses that obtain the information from either reduction or oxidation currents. To address this problem, an adaption of the interface circuit was performed in [4]. Bidirectional currents are possible, provided by a manual selection of the expected current direction. However, this has only limited suitability for accurate dynamic measurements as required in CV. Several other works also addressed the problem of bidirectional current sensing using various techniques. The solution presented in [5] requires manual adaption. In [6] offset currents are added, which influence the accuracy and the power consumption. A topology that consumes considerable voltage headroom is proposed in [7].

In this letter, we present a sensor interface circuity which is able to process bidirectional sensor currents without additional measures, while keeping the voltage headroom consumption at a minimum. This is achieved by a signal chain consisting of a class-AB amplifier based sensor front-end followed by a delta-sigma (ΔΣ) ADC. The low power and area consumption allows the circuit to be integrated into a single-chip PoC diagnostic platform that uses the electromagnetic field for power supply and data transfer.

II. CONTROLLED-POTENTIAL SENSOR INTERFACE

Electrochemical analyses like CA, CV or EIS are usually carried out by a controlled-potential sensor interface. A block diagram of the interface used in this work is shown in Fig. 1. The controlled-potential interface is based on a three-electrode potentiostat that sets the voltage across the
bidirectional current-mirror based potentiostats that avoid a operation of the ADC allows multiplexing between the multi-

accuracy. The current-input AΔΣ ADC is multiplexed between the WE channels and processes the scaled sensor current.

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potentiostat. As will be discussed in Section IV, incremental potentiostat is given in Section III. A current-input AΔΣ ADC

desired electrochemical analysis, the potentiostat maintains a potential difference between the working electrode (WE) and

The implemented multi-WE sensor front-end consists of 6 independent WE channels

control differently composed electrodes. To induce the redox reaction for the target biomolecules, potential differences of up
to 2.5 V are necessary at the sensor electrodes. Together with the wireless operation of the platform, stringent requirements
on the individual circuit blocks of the sensor interface result.

The implemented multi-WE sensor front-end consists of bidirectional current-mirror based potentiostats that avoid a
electrochemical sensor by two operational amplifiers that are operated in a feedback-configuration. Depending on the
desired electrochemical analysis, the potentiostat maintains a potential difference between the working electrode (WE) and
the reference electrode (RE) by adjusting the potential of the counter electrode (CE). The current that arises due to the

electrochemical reaction is measured [8].

To simultaneously determine several biochemical key figures, multiple sensor interface channels are required that
control differently composed electrodes. To induce the redox reaction for the target biomolecules, potential differences of up
to 2.5 V are necessary at the sensor electrodes. Together with the wireless operation of the platform, stringent requirements
on the individual circuit blocks of the sensor interface result.

The implemented multi-WE sensor front-end consists of bidirectional current-mirror based potentiostats that avoid a
voltage headroom consuming current-to-voltage transformation, thus allowing proper operation with a supply voltage as
does not exceed 3 V. Reconfigurable current-mirrors combined with the application of matching improvement techniques provide
a wide dynamic range in the potentiostats. Sensor current and sensor properties dependent frequency compensation techniques enable a versatile use of the interface for multiple sensing applications. A detailed description of the implemented

potentiostat is given in Section III. A current-input AΔΣ ADC is used to process the sensor current replica provided by the
potentiostat. As will be discussed in Section IV, incremental operation of the ADC allows multiplexing between the multi-

III. BIDIRECTIONAL CURRENT-MIRROR BASED

The proposed circuit draws on the well-known topology of current-mirror based potentiostats [3], extended for bidirec-
tional sensor currents. This is achieved by using a class-AB output stage in the WE controlling amplifier that replicates the
currents through both output stage transistors. These transistors are driven by a folded-cascode amplifier that uses floating class-AB control transistors [9]. Since the bidirectional current-mirror relies on the subtraction of two currents, a low quiescent current in the output stage is required to achieve the

desired current accuracy [10]. This is achieved by suitable design of the floating class-AB control transistors and the
output stage transistors.

The use of programmable current-mirrors that enable a ratio dependent optimization based on current scaling ensure the
desired accuracy over the wide dynamic range with minimum area and voltage headroom consumption [11]. The potentiostat
is able to process bidirectional currents in a range of 10 nA to 1 mA. The 2-bit programmable current-mirrors with scaling
factors of 1, 10, 100, and 1 000, allow a downscaling of the sensor current to a range of ± µA to 1 µA.

Regulated-cascodes in the current-mirrors are used to minimize errors related to the finite output impedance of the
transistors. Proper operation of both regulated-cascodes is ensured by adding transistors with a constant bias voltage in the class-AB output stage. Depending on the applied WE
potential, these transistors operate either in saturation or triode region, thereby generating the required voltage shifts for the
regulated-cascodes. These voltage shifts additionally allow the use of low-voltage, thin gate oxide transistors in the current-mirrors, which further improve the current processing accuracy due to better matching properties. The utilization of dynamic element matching (DEM) techniques results in an additional accuracy improvement in the current-mirrors. Depending on the sensing application, either manual switching
or chopping at a frequency of 300 kHz can be performed for the mirror side transistors. The wide dynamic range of sensor currents and the thereby associated strong varying load conditions require an adaptive approach for the frequency compensation to ensure stability in the feedback system. A dynamically scalable folded-cascode amplifier enables a sensor current dependent shifting of the first stage pole without changing the gain of the stage. This is achieved by a slice-based implementation of the first stage of the amplifier which is controlled by 3 bits. Together with an adjustable Miller compensation, stability for sensors with an ohmic and ohmic-capacitive behavior is achieved.

IV. DELTA-SIGMA ADC BASED CURRENT READOUT

The potentiostat provides a downscaled version of the sensor current in the range of 1–1 µA to 1 µA. For an accurate biochemical analysis, this current needs to be digitized with a resolution of 500 pA. Hence, the required resolution of the ADC is roughly 12 bits. Furthermore, a signal bandwidth of up to 10 kHz is necessary to perform EIS analyses. A current-to-frequency (I-to-F) converter was used in [3], whereas a dual-slope topology was used in [4]. Without manual adaption, both of these ADC types are again just able to process unidirectional sensor currents.

In this work a current-input ∆Σ modulator is used. A second-order continuous-time loop filter in a feedforward topology is implemented, as shown in Fig. 2. An oversampling ratio of 120 is used to achieve the desired resolution, resulting in a sampling frequency of 2.4 MHz. A current-steering feedback DAC is used to apply the feedback signal. Due to the closed loop operation of ∆Σ modulators, direct processing of bidirectional sensor currents is possible.

A selection of the input full-scale range can be performed using a 4-bit adjustable current DAC and feedback capacitor in the first integrator. This allows to increase the current resolution for applications with low sensor currents.

Since the expected biochemical sensor signals are in the low frequency range, flicker noise is the main limiting factor in the design. As a countermeasure, source degeneration in the current-steering feedback DAC is applied, which reduces the flicker noise of the implementation by more than 6 dB.

Due to the limited available power in wireless operation, the ADC is designed to operate down to 1.5 V. This is achieved by independently selectable input and output common-mode voltage levels of the input integrator. Feedforward-compensated amplifiers are used in the loop filter due to their high power efficiency [12]. Furthermore, only one multiplexed ADC is used for the multiple sensor interface channels. This is realized by operating the ∆Σ ADC in incremental mode in case a multi-WE analysis is performed.

The digitized sensor current is stored in the on-chip RAM and prepared for wireless data transmission. Additionally, the information of the sensor current is used to reconfigure the potentiostat to achieve optimum performance.

V. MEASUREMENT RESULTS AND EVALUATION

The transfer characteristic of the bidirectional potentiostat and the error of the current processing are shown in Fig. 3. In these plots, the solid traces show the current processing performance for currents that flow from WE to CE (reduction currents), whereas the dashed traces show the performance for currents that flow from CE to WE (oxidation currents). Similar performance in both directions is achieved with a maximum error of less than 2%, verified for a set of 10 randomly chosen dies. The circuit exhibits high linearity with an $R^2$ value of 0.999997. The voltage headroom consumption of the potentiostat is less than 500 mV over the complete dynamic range. The current consumption of a single channel of the potentiostat depends on the number of active slices of the folded-cascode amplifier. Each slice consumes 1.2 µA, which leads to a maximum static power consumption of less than 29 µW at a nominal supply of 3 V. The area consumption of a single channel of potentiostat is approximately 0.11 mm².

The power spectral density (PSD) of the ∆Σ modulator for a sinusoidal input current with an amplitude of 500 nA is shown in Fig. 4. The achieved SNDR in a signal band of 10 kHz is higher than 73.3 dB, which results in an ENOB of almost 12 bits. Hence, with nominal settings the scaled sensor current can be digitized with a resolution of 530 pA. By adjusting the full-scale range of the ADC, the minimum detectable current can be reduced to 91.7 pA. The circuit consumes 30 µA from a 3 V supply. Reducing the supply voltage to 1.5 V results in a reduction of the power consumption by a factor of 2, without affecting the performance of the modulator. This results in a Schreier FOM of 156.8 dB. The area consumption of the modulator is only 0.05 mm².

The circuit was realized in a 130 nm standard CMOS process as a main building block of a wirelessly-operated electrochemical measurement platform IC. Fig. 5 shows a micrograph of the presented circuits. The IC contains the multi-WE potentiostat consisting of six equal implementations of the presented bidirectional current-mirror based topology.

![Image]
VI. CONCLUSION

A power-efficient bidirectional sensor signal acquisition chain was presented. The proposed circuit, which consists of a potentiostat with output stage current replication and ΔΣ ADC based current processing, enables wide dynamic range current sensing with minimal voltage headroom consumption. The class-AB topology of the front-end amplifier keeps the current consumption at a minimum, which results in the highest power efficiency of the implementation when compared to state-of-the-art solutions. These properties make the biochemical measurement platform broadly applicable as a low-cost solution for wirelessly-powered PoC diagnostics.

TABLE I

|                  | This work | [2] | [3] | [4] | [5] |
|------------------|-----------|-----|-----|-----|-----|
| Technology (µm)  | 0.13      | 0.18| 0.18| 0.35| 0.18|
| Sensor Current Range (A) | ±10 nA to ±1 m| ±200 µ| +1 nA to +1 µ| ±p to ±µ| ±18 µ|
| Dynamic Range (dB) | 91.7 pA @ ±100 nA| 94 pA @ ±2 µA| <1 nA| -| -|
| Supply Voltage (V) | 3 / 1.5 | 2.5 | 1.8 | 1.2 | 1.5 |
| Voltage Headroom Consumption (V) | <0.5 | <1.5 | - | - | - |
| Static Power Consumption / Ch. (µW) | 14.1-39.3 | 3250 | 50.4 | 12.1 | 2.9 |
| Power Efficiency<sup>b</sup> | 0.66 | 0.12 | 0.02 | 0.59 | 0.59 |
| Bidirectional Currents | yes | yes | no | yes<sup>d</sup> | yes<sup>d</sup> |
| Sensing Methods (CA/CV/EIS) | yes/yes/yes | yes/yes/- | yes/-/- | yes/yes/- | yes/yes/- |
| ADC type | delta-sigma | - | 1-to-F | dual-slope | I-to-F |
| Resolution | - | - | - | - | - |
| Full-scale range: | ±100 nA | - | - | - | - |

<sup>a</sup>Based on simulation  
<sup>b</sup>Sensor current excluded  
<sup>c</sup>Power Eff. = max. current range / dyn. power consumption  
<sup>d</sup>Based on manual adaption

The ADC is multiplexed between the individual channels. The average static power consumption per interface channel is between 14.1 µW and 39.3 µW. Due to the class-AB amplifier based front-end topology, the power consumption during current sensing is mainly determined by the sensor current itself. This leads to a maximum power consumption of only 3 mW while sensing a current of 1 mA, resulting in a power efficiency [5] of 0.66. The active area consumption of the interface is approximately 0.7 mm<sup>2</sup>.

A comparison of the presented design to a selection of existing biochemical signal acquisition chains is provided in Table I. The proposed solution achieves the highest power efficiency and a wide dynamic range. The low voltage headroom consumption together with the ability to process bidirectional sensor currents enables the circuit to induce the redox reaction for multiple sensing applications.

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