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Design and Reliability Analysis of Differential Resistance to Current Conversion Circuit for Biomedical Application of Gas Sensing

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Abstract: Gas sensing in biomedical applications shows a conversion of the concentration of the exhaled gas to a variation in resistance, so an electronic integrated interface circuit is required to analyse the exhaled gases, which are indications for many diseases. In this paper, a resistance to current conversion circuit based on differential biasing for Electronic nose (E-nose) breath analyser is presented. Over more than 5-decades (500Ω to 100MΩ) input resistance range, a precision, less than 1%, required by novel gas sensing system in portable applications, is preserved. Therefore, the proposed circuit obtains high accuracy under simulation. The outputs of the proposed Resistance to Current (R-to-I) conversion circuit achieve a percentage error below 0.25% under environment corners. The reliability of the proposed circuit is also investigated under the effect of process variations. In order to assess the correctness of the proposed architecture, the circuit was compared to similar solutions presented in literature where the proposed architecture attains a worst-case percentage error of 0.05%.

Keywords: resistive gas sensors; E-nose; portable applications; R-to-I conversion; process variation; environmental corners;

1. INTRODUCTION

Nowadays, breath analysis has become a patient friendly technique that allows rapid disease diagnosis and permits the early detection of impairment organs and/or other illness. Indeed, human breath contains thousands of volatile organic compounds (VOCs) that may be used as predictive biomarkers of various diseases [1]. Currently, exhaled breath analysis is proposed as a novel effective and alternative technique to blood or urine tests. This technique, which is applicable on all patients, allows early, real time status monitoring and diagnoses plenty of diseases without the need for any medical screening and with no limitations in supply [2]. Portable machines for continuous monitoring, and personal health care is a need. The electronic nose (E-nose) used as portable breath analyzer was developed to copy the human olfactory system. The latter is one of the human five senses. Inspired from biology, E-nose has the ability to differentiate and classify various chemical odours and mainly use gas sensors to generate chemical changes on odour molecules, and conduct further analysis on the gases. Fig. 1 shows the E-nose system versus the human smelling system.

In [3], an electronic nose based on conductive polymer sensors was designed and fabricated. The electronic interface circuit was able detect three hazardous gases that lead to liver damage. However, the resistance of the sensor ranged between 1kΩ and 1.5MΩ. In [4] a breath analyser prototype for detecting ammonia gas in exhaled human breath is described. Such prototype was specialized for ammonia gas detection where the sensor resistance ranges from 15MΩ to 65MΩ. In [5]

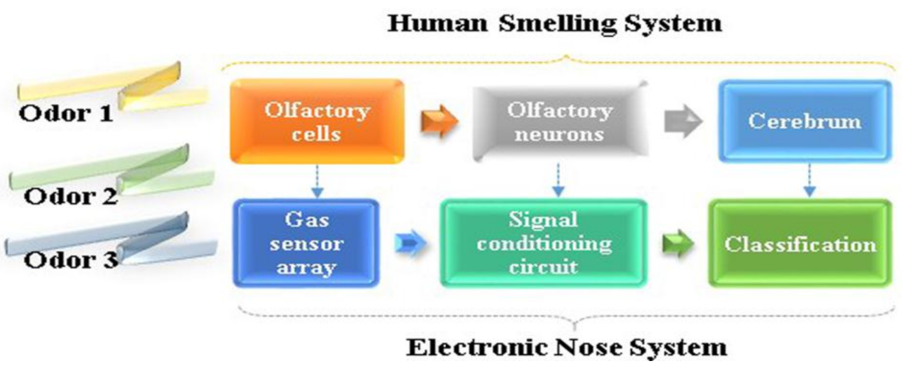

Fig. 1. E-nose system verses human smelling system

ethanol-sensing properties for alcohol breath analysis using metal oxide (MOX) resistive gas sensors was presented. This study verified that increasing the sensors resistance range allows to measure low gas concentrations. This concludes that wider resistance range allows identifying gases with lower concentration.

This work aims to design of a wide range reliable electronic solution providing high accuracy in measuring the resistance value for exhaled breath proper identification. The wide range readout circuit targets to condition wide resistance range resulting in detecting low gas concentrations. The objective of this paper is to realize the R-to-I conversion circuit for a wide resistance range extending from 500Ω to 100MΩ while preserving a precision better than 1% to satisfy the requirements of novel portable gas sensing monitoring [6]. Wider resistance range results in detecting more VOCs, thus, identifying more diseases [5]. The proposed interface takes advantage from the enhanced oscillator approach resistance to time conversion architecture used for environmental monitoring proposed in [7] and [8]. In order to ensure the correctness of the proposed architecture, the R-to-I conversion circuits in [7], [8] and [9] for gas sensing in environmental monitoring, were designed. The proposed R-to-I conversion circuit achieved a maximum percentage error of 0.05%.

2. READOUT ELECTRONIC INTERFACE

MOX gas sensors are characterized by their small sizes, economical cost, high sensitivities in detecting trace concentrations of chemical compounds, possibility of on-line operation and possible bench production. However, MOX gas sensors respond in a similar way to different types of oxidizing or reducing species, hence, these sensors are not selective. Integration of heterogeneous nano-structured microarray gas sensors having different sensing materials was proposed in [10] to overcome this limitation.

MOX gas sensors operate on the principle of chemo resistive sensing. Alteration of the nano-structured oxide thin films occurs in the presence of targeted analyte. Therefore, the transducer of the sensor converts the chemical information about the concentration of the gas in the atmosphere into an electrical signal, which is a variation of resistance. Such sensors show a wide range performance since the baseline resistance depends on several chemical and physical parameters, fabrication process, technology, and the sensor operating conditions [11].

Several possible readout circuits for wide range resistive gas sensors are proposed in literature. Expensive Pico ammeters or high-resolution analog-to-digital converters (ADCs) with a programmable gain amplifier (PGA) or a scaling factor system can be used [12]. On the other side, logarithmic sub-range detector based resistance to digital conversion architecture presents another solution. In this method, the resistance range is first converted to a voltage and then measured by an ADC. In order to accommodate the wide range resistance, such architecture divides the input resistance into sub ranges and uses logarithmic sub range detection to detect the correct sub range [13]. Quasi-digital electronic interface circuits based on enhanced oscillator approach in which the information about the sensor is converted into duty cycle, frequency, or period represent an effective solution since it is possible to merge the ingrained simplicity to analog devices with the accuracy and noise immunity typical of digital sensors [14]. Therefore, our proposed approach takes advantage of the resistance-to-time conversion technique, which is advisable when wide-range resistances are to be considered [7], [11], and [14]. This paper focuses on the implementation of the resistance to current conversion circuit, which is an essential part to achieve the overall readout conversion accuracy.

3. PROPOSED METHOD

a. Resistance to Time Conversion

Due to their wide input resistance range, designing an electronic interface circuit for resistive sensors is considered as a challenging task [7], [11], and [13]. Over the years, various techniques were proposed to measure electrically a gas change. These studies were either based on the conventional method of adding an analog to digital converter or based on the resistance to frequency or resistance to time period conversion. The latter conversion techniques are advantageous since it is possible to translate the sensed signal into a frequency value, which is subsequently digitized and acquired via a counter. Another advantage of this approach is the robustness of the sensor output signal with respect to noise and disturbances. In addition, the hardware costs in the resistance to frequency based interface circuits are lower than that in conventional ADC methods.

As a result, it is more convenient to transform the resistive information to period of a square wave and perform a time measurement. In resistance to digital conversion, the resistance of the sensor (Rsens) is first converted to a current through a

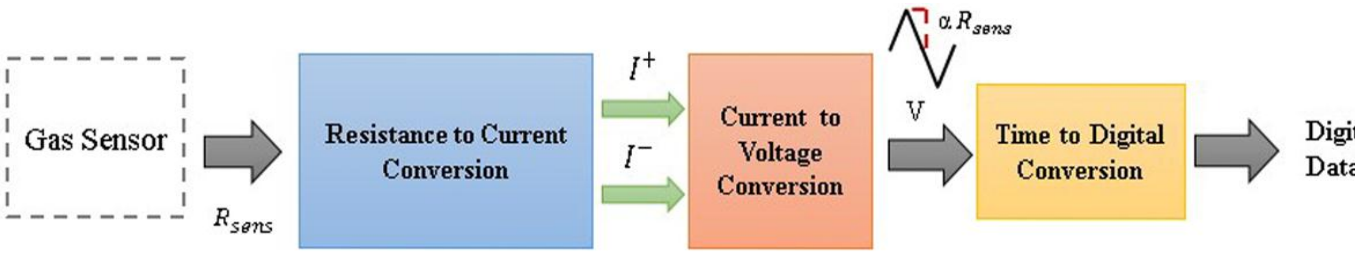

Fig.2. Block diagram of the resistance to digital conversion.

voltage buffer, which fixes the voltage across Rsens resulting in a current variation. An accurate current mirror preserves the accuracy while delivering alternate current to an integrator to be converted into a voltage signal is needed. The latter is then converted into period using window comparators and a flip-flop. Finally, the sensor signal will be converted into a digital code through period to code conversion, so to be directly delivered to the digital processing stage of recognition system without requiring an ADC. Such architecture is considered as area efficient [15]. Fig.2 describes the conversions required by the electronic interface for achieving the resistance to digital conversion signal.

b. R-to-I Conversion Circuit

A novel circuit architecture able to cover a resistance range from 500Ω to 100MΩ (more than 5-decades) into current with high accuracy is proposed. Fig. 3 represents the architecture proposed to obtain such goal. In this architecture, the voltage across the sensors resistance is bounded between two Operational Transconductance Amplifiers OTA1 and OTA2, such that:

$$V_{sens} = V_{ref1} - V_{ref2} \tag{1}$$

In this configuration, the variation of Rsens is converted into a current signal variation (Isens), such that:

$$I_{sens} = \frac{V_{ref1} - V_{ref2}}{R_{sens}} \tag{2}$$

Where, Vref1= 0.5V, Vref2=-0.5V, this results in 1V fixed across the sensor's resistance Rsens. Therefore, for Rsens varying between 500Ω and 100MΩ, Isens will ideally vary between 2mA to 10nA.

A new differential R-to-I conversion circuit with push-pull current mirror architecture required to feed the following integrator with alternate accurate current is proposed. The generated sensed current (Isens) is sourced through transistors Mp1-Mp2 being in parallel with Mp1'-Mp2' and sinked through transistors Mn1-Mn2 being in parallel with Mn1'-Mn2'. The sensed current is then replicated through transistors Mp3-Mp4 with a scaling ratio K: 1 being K= (800µm+800µm) to 800µm i.e. K=2/1 for the PMOS current mirror side. Whereas for the NMOS current mirror, the sensed current is replicated through transistor Mn3-Mn4 with a similar scaling ratio K=2/1, but of different geometric size where, K= (300µm+300µm) to 300µm. The output current of the current mirror (Iout) is equal to Isens divided by the scaling factor K (Isens/K). To improve the accuracy of the current mirror a cascode branch, formed by transistors Mp2, Mp4 from the PMOS side and Mn2, Mn4 from the NMOS side, are added. Scaling the input branch of the current mirror using parallel-connected transistors for both push and pull current mirrors in the proposed architecture allows increasing the transistor's width, thus, improving the accuracy while supporting more current especially when Rsens is low.

4. SIMULATUIN RESULTS

The proposed R-to-I conversion circuit was designed in 3.3V- 0.35µm, N-WELL, four metal AMS CMOS technology. The functionality of this circuit is simulated in PSPICE OrCAD CAD tool.

The OTAs used in the architecture are two stage Capacitor Multiplier Miller Compensated whose topology is shown in Fig.3. TABLE I presents the specifications of both OTAs used in the proposed architecture where the OTA1 is biased by Vref1=0.5V and OTA2 is biased by Vref2=-0.5V. The compensation capacitor used is only 0.7pF while the compensation resistor is equal to 60 kΩ.

To measure the accuracy of the converted current, the relative absolute percentage error (% Error) of both mirrored output currents through the PMOS and NMOS current mirrors (IoutPMOS) and (IoutNMOS), taking the input current across the sensor's resistance (Isens) as a reference, is computed according to (3).

$$\%Error = \frac{|I_{sens} - I_{out}|}{I_{sens}} \times 100 \tag{3}$$

The designed architecture was simulated under environmental corners that are Best, Typical, and Worst cases, to test the reliability of the designed architecture. Where, Best corresponds to high voltage supply i.e. ±1.8V and low temperature -40^{0}C, on the contrary, Worst corresponds to low voltage i.e. ±1.5V and high temperature 80^{0}C, and Typical corresponds to ±1.65V at 27^{0}C. Fig. 5 shows the absolute percentage error of output currents of the circuit i.e. the output

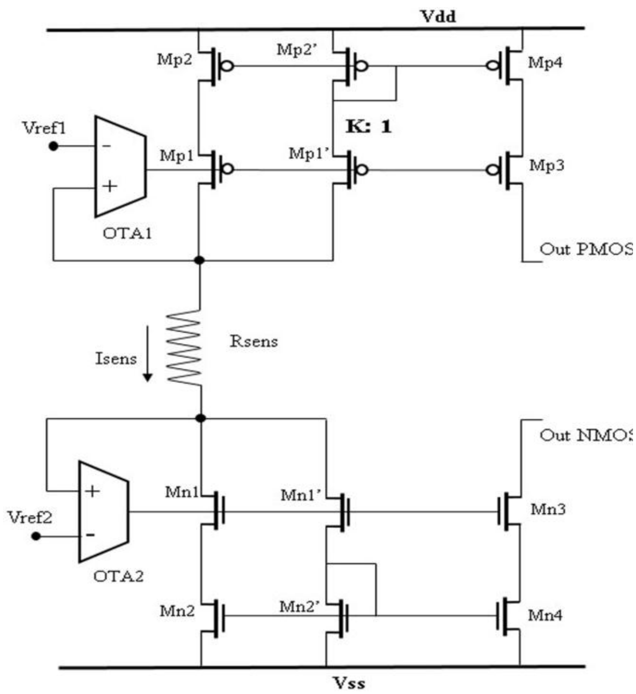

Fig. 3. Proposed resistance to current conversion circuit for resistive gas sensor

TABLE I. SPECIFICATIONS OF THE OTAS USED IN THE PROPOSED R-TO-I CONVERSION ARCHITECTURE

	OTA1	OTA2
DC Gain	58dB	90.5dB
BW	4.2kHz	103.6Hz
PM	112^0	104^0

through the PMOS current mirror (out PMOS), where, the output through the NMOS current mirror (out NMOS) is grounded, Fig.5.a and vice versa Fig.5.b.

The maximum percentage error obtained along the full studied resistance range was calculated, while simulating the circuit under different process variations with typical environmental corners. Fig.6 and Fig.7 illustrate the obtained results along a resistance range from 500Ω to 100MΩ considering both outputs of the circuit (Out PMOS) and (Out NMOS) each at once. As shown in Fig.6 and Fig.7, the resulted accuracy verifies the proper performance of the proposed architecture, and the corner analysis assures the reliability of the implemented circuit. The low values of the achieved % Error validates the requirements of new portable gas sensing systems preserving a precision ≤ 1%.

To ensure the correctness of the proposed architecture the R-to-I conversion circuit presented in [7], [8] were designed. Such architectures are used for gas sensing systems in environmental monitoring where the minimum input resistance value was 1kΩ. Considering the input resistance range proposed for portable breath analysis applications from 500Ω to 100MΩ, the proposed architecture has extended the minimum range to 500 Ω where it achieves an accuracy of 0.05%. Over the remained range, Table II shows the comparison between the proposed architecture and the other architectures over the range 1kΩ to 100 MΩ. The proposed architecture achieved a maximum percentage error better than 0.044% over the compared resistance range, which assure the capability of the proposed architecture to be used for E-nose (breath analyzer) systems.

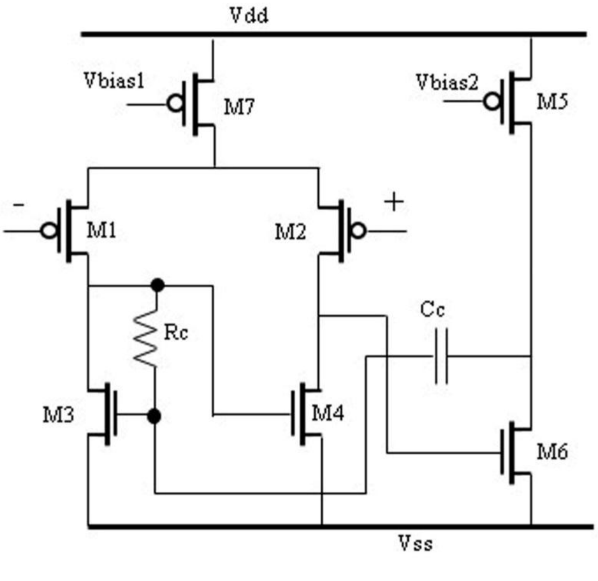

Fig.4. Capacitor Multiplier OTA architecture

To test the non-ideal effects caused by the current mirrors for the sensor current signal transfer in the current mode conversion, the sensitivity of the output current with respect to the input sensor's current is studied. For both outputs i.e. Out PMOS and Out NMOS, the circuit achieves a sensitivity of 0.5003 and 0.499 respectively knowing that the ideal computed sensitivity is 0.5. The sensitivity is defined as:

$$S = \frac{dI_{out}}{dI_{sens}} \quad (4)$$

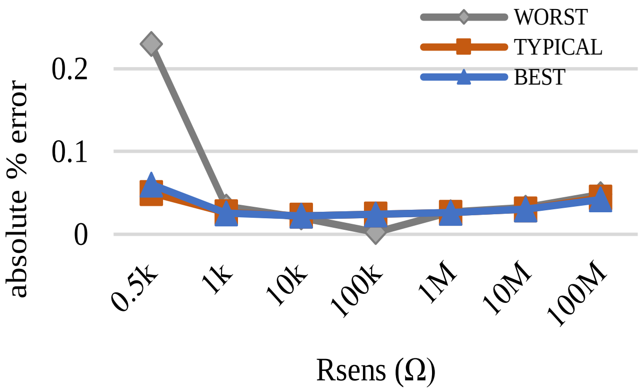

Fig.5.a. Absolute percentage error on the output of the PMOS current mirror for the designed architecture under environmental corners.

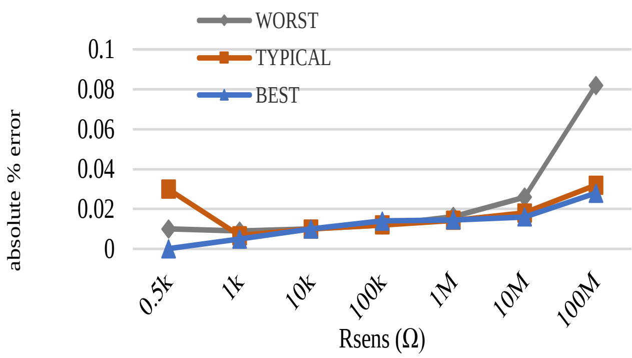

Fig.5.b. Absolute percentage error on the output of the NMOS current mirror for the designed architecture under environmental corners.

FIG. 6. PROCESS CORNER CHECK CONSIDERING THE OUTPUT THROUGH PMOS CURRENT MIRROR

FIG7. PROCESS CORNER CHECK CONSIDERING THE OUTPUT THROUGH THE NMOS CURRENT MIRROR

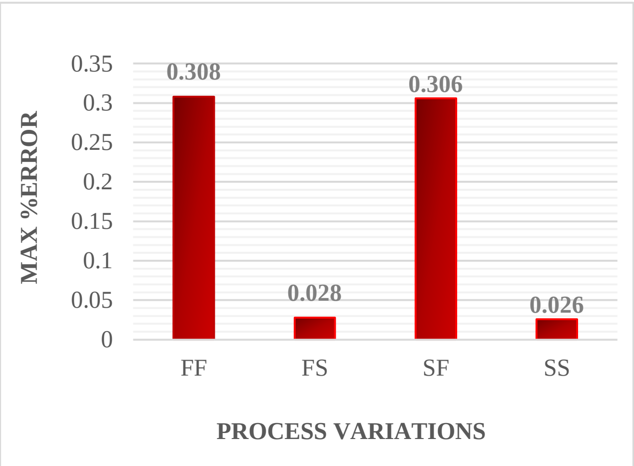

TABLE .II. COMPARISON BETWEEN MAX PERCENTAGE ERROR OBTAINED FROM THREE DIFFERENT R-TO-I ARCHITECTURES

	[7]	[8]	[9]	Proposed
Max.% Error under Typical Case	0.29%	0.24%	0.25%	0.044%

5. CONCLUSIONS AND FUTURE WORK

This paper presented the design of R-to-I conversion circuit for gas sensing in biomedical applications. The proposed resistance to current conversion circuit architecture achieved high accuracy and preserved a precision less than 1% required by novel gas sensing system in portable applications over a wider resistance range (500Ω to 100MΩ) compared to the solutions presented in literature. The percentage error of both considered outputs of the circuit Out PMOS and Out NMOS was always below 0.25% and 0.1% respectively under environment corners. The reliability of the proposed circuit was also investigated under the effect of process parameters. The sensitivity of the PMOS and NMOS current mirrors was 0.5003 and 0.499 respectively. Compared to other R-to-I architectures proposed in literature, the proposed architecture achieved a max % Error of 0.05% over the proposed resistance range. The presented work is a step towards the implementation of an electronic readout circuit for resistive gas sensors based on the design and architecture provided herein.

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