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Flexible and low-cost interface circuit for electrochemical and resistive gas sensors

A. Depari*, A. Flammini

Dept. of Information Engineering, University of Brescia, Via Branze 38, 25123 Brescia, Italy

Abstract

This work presents a low-cost interface circuit for both electrochemical and semiconductor sensors for gas detection. The proposed circuit offers a high sampling rate, on the order of 25 ms, allowing the monitoring of the sensor behaviour even in presence of fast transients. The front-end has a single-voltage 3.3 V power supply and a time-coded digital signal output, thus it is suitable to be directly interfaced to a microcontroller for the management of the measurement process. Possible integration in a single-chip solution, together with the digital electronics is furthermore facilitated. Experimental results, conducted on a discrete component prototype and with sample resistors to emulate the sensor, have shown a maximum linearity error in the estimation of the sensor current or resistance of about 5% over a measurement range of seven decades, demonstrating the validity of the proposed solution. The power dissipation of the front-end is less than 30 mW (at 3.3 V) and the front-end cost less than 10 EUR, making it suitable for the employment in low-cost and low-power gas detection systems.

Keywords: Resistive gas sensors; electrochemical sensors; wide range measurement.

1. Introduction

Chemical sensors for gas detection are nowadays used in several applications. When the detection of low concentrations of gases is required, usually electrochemical sensors are employed. Conversely, when the low-cost is the key point, semiconductor sensors, such as metal oxide (MOX) devices, are generally used. From the electronic interface point of view, in the former case, the quantity to be monitored is the current I_s flowing from the working electrode (*WE*) of the sensor; in the latter situation, the sensor is

* Corresponding author. Tel.: +39-030-371-5899; fax: +39-030-380014.
E-mail address: alessandro.depari@ing.unibs.it.

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modelled with a gas-dependent electrical resistance R_s, which needs to be estimated. Due to the vast variability of available sensors, each of them dedicated to the detection of particular target substances and/or tuned to specific analyte concentrations (e.g., by setting the operating temperature of MOX sensors), the range of current I_s or resistance R_s to estimate is quite wide (usually 1 nA ÷ 1 mA for I_s and 10 kΩ ÷ 10 GΩ for R_s). If the aim is the realization of flexible and low-cost systems for gas detection, the electronic interface should be identical for each sensor. In fact, developing and/or tuning an electronic interface just for a specific sensor would require significant resources both economically and in terms of time; in addition, the resulting system is bound to the chosen sensors, thus limiting the flexibility.

Low-cost interfaces for wide output range sensors are usually based on multiple-range [1], [2] or current/resistance-to-time conversion architectures [3], [4]. In the former, the main issue is the calibration procedure; in the latter, the main drawback is the long measuring time which can occur, making such circuits not suitable when semiconductor sensors are operated with a thermal pulse strategy [5], [6].

The aim of this work is to design a low-cost and flexible interface for both electrochemical and resistive sensors, offering both wide operative range and fast readout characteristics.

2. The proposed solution

The proposed system, shown in Fig. 1(a), is based on previous works, published in [7] and [8]. The circuit is oriented to the input current measurement and therefore it can be easily interfaced to an electrochemical sensor, for the sensor current I_s estimation as well as to a resistive sensor, for the sensor resistance R_s evaluation, as shown in Fig. 2(a) and (b). In the former case, only the connection between the working electrode (*WE*) and the proposed circuit is shown, whereas the connections between the counter electrode (*CE*) and the reference electrode (*RE*) (e.g. by means of a traditional potentiostat circuit, [7]) are not reported; in the latter case, the management of a possible sensor heater is not considered.

The *PulseGen* block of Fig. 1(a) is a monostable circuit and it is devoted to the creation of the reset/output signal V_o, as will be detailed in the following. A simple implementation of *PulseGen* is shown in Fig. 2(c).

The integration of the current I_s coming from the sensor produces a ramp V_s, the slope α_s of which depends on the I_s magnitude. A ramp V_t, with a constant slope α_t, opposite to α_s, is used to intercept the ramp V_s and to generate the output signal V_o, which is furthermore utilised to reset the integrators Int_s and Int_t and iterate the measurement, as shown in Fig. 1(b).

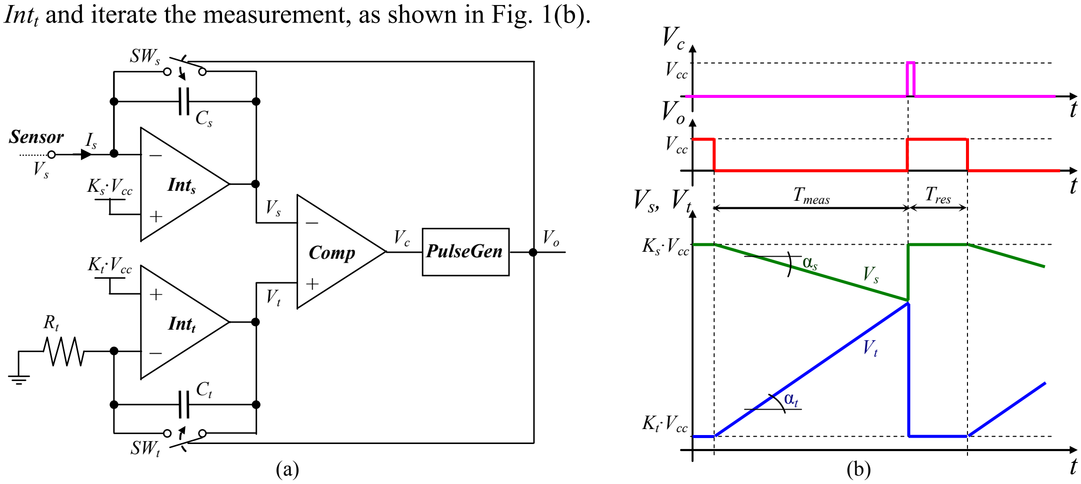

Fig. 1. (a) Scheme of the proposed interface circuit. Sensor connection and the *PusleGen* block are detailed in Fig. 2. (b) Time diagram of the circuit signals; for the sake of simplicity, the comparator and the *PulseGen* block delays have not been considered.

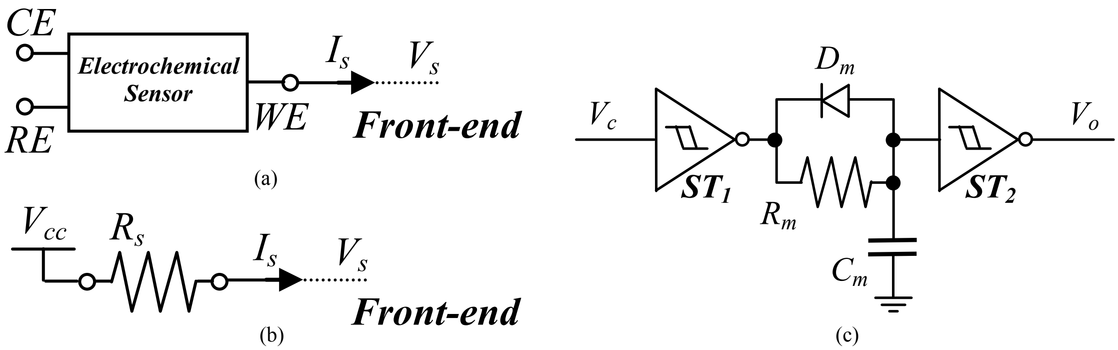

Fig. 2. The connection of the sensor to the front-end in Fig. 1(a) in case of: (a) electrochemical sensor; (b) resistive sensor. (c) The *PulseGen* block of Fig. 1(a) for the creation of the reset/output signal V_o.

The rising edge of V_o is caused by the comparator output V_c low-to-high commutation; the delay between the commutation of V_c and V_o is on the order of hundreds of nanoseconds, being mainly due to the propagation delay of the Schmidt Trigger NOT gates and the fast discharge of the capacitor C_m through the diode D_m. Conversely, whereas the duration of the V_c pulse is also on the order of hundreds of nanoseconds (due to the switch *SW* and comparator *Comp* delays), the duration T_{res} of the V_o pulse, which depends on the time constant $R_m \cdot C_m$, must be suitably designed to guarantee a complete reset of the integrators Int_s and Int_t, being V_o the signal driving the reset switches SW_s and SW_t.

The time T_{meas} is related to the unknown quantities I_s or R_s by means of the Eq. (1).

$$T_{meas} = V_{cc} \frac{K_s - K_t}{\dfrac{I_s}{C_s} + V_{cc}\dfrac{K_t}{R_t \cdot C_t}} = \frac{K_s - K_t}{\dfrac{(1-K_s)}{R_s \cdot C_s} + \dfrac{K_t}{R_t \cdot C_t}} \quad \text{with} \quad K_t < K_s < 1 \tag{1}$$

The use of a moving threshold V_t, instead of a fixed value, allows the measurement time T_{meas} to be limited, particularly when small I_s current or large resistance R_s values (almost flat V_s ramp) are under examination [9]. The maximum value $T_{meas,MAX}$ for the measurement time is given by Eq. (2).

$$T_{meas,MAX} = R_t \cdot C_t \left(\frac{K_s}{K_t} - 1 \right) \quad \text{with} \quad K_t < K_s < 1 \tag{2}$$

A discrete component prototype has been realized to test the proposed architecture. The sensor configuration in Fig. 2(b) has been used, adopting sample resistors to emulate the sensor. The sensor current I_s is calculated considering a voltage across the resistor R_s of 1 V ($V_{cc} = 3.3$ V and $V_s = K_s \cdot V_{cc} = 2.3$ V). Components have been chosen to minimize the nonidealities error, particularly significant when small current values are under examination. Thus, low input bias current operational amplifiers and high off-state resistance switches have been employed. Power dissipation related to the front-end is about 30 mW, whereas the front-end cost, including the component and production expenses, can be considered less than 10 EUR. The relative linearity error ε_{Lin} of R_s and I_s has been computed by considering the weighted least mean square linearization and referring the absolute linearity error to the value of R_s and I_s respectively. Table 1 shows the results obtained with the experimental setup. The measuring time T_{meas} spans across five decades (from hundreds of nanoseconds to about 25 ms), whereas the linearity error is below 5% in the whole considered range (seven decades) for both the I_s and R_s estimations, demonstrating the validity of the proposed approach.

Table 1. Experimental results obtained with the discrete component prototype and sample resistors emulating the sensor.

R_s [MΩ]	I_s [μA]	T_{meas} [μs]	ε_{Lin} (R_s) %	ε_{Lin} (I_s) %
1.00E-03	1.00E+03	3.40E-01	-0.12%	0.12%
1.00E-02	1.00E+02	2.48E+00	1.13%	-1.11%
1.00E-01	1.00E+01	2.37E+01	0.35%	-0.35%
1.00E+00	1.00E+00	2.34E+02	0.38%	-0.38%
1.00E+01	1.00E-01	2.11E+03	-1.75%	1.78%
1.00E+02	1.00E-02	1.20E+04	-2.66%	2.73%
1.00E+03	1.00E-03	2.27E+04	-2.40%	2.46%
1.00E+04	1.00E-04	2.50E+04	4.68%	-4.47%

3. Conclusions

Electrochemical and MOX sensors are nowadays used for gas detection in several applications. The current trend is toward the realization of compact, portable and inexpensive systems for analyte detection. In this paper, an electronic circuit for the interface of both those kinds of gas sensors is proposed, offering low-cost, low-power and fast sampling rate characteristics. Thanks to the capability of acquiring a wide range of sensor output values, without recalibration and tuning procedures, the presented front-end is particularly flexible and advantageous for the realization of a broad variety of gas detection systems. Furthermore, the single-supply and single-digital-output features simplify the connection of the front-end with the data processing digital stage and allows a single-chip solution to be easily implemented.

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