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Design and simulation of a smart ratiometric ASIC chip for VOC monitoring

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Abstract

This paper reports on the design and simulation of a novel ratiometric application specific integrated circuit (ASIC) chip for the monitoring of volatile organic compounds (VOCs) or gases. The design integrates two polymeric chemoresistors in a ratiometric configuration, together with smart circuitry, into a single chip fabricated through a standard silicon CMOS process. The circuit provides automatic compensation of signal from variations in both supply voltage and ambient temperature. On-chip control of the operating temperature of the sensors is also an option. The response of the ratiometric set of polymeric chemoresistors to different concentrations of gases at different temperatures and humidities was simulated with the aid of a novel parametric Cadence model. Simulations confirm that the ratiometric configuration is less sensitive to temperature variations and that it also has a better performance in terms of humidity dependence when compared to an individual chemoresistor. These features, together with its ability to compensate for a large range in values of polymer resistance, make us believe that the circuit offers relevant smart capabilities at a very low-cost and so it can be used as the main component for the mass production of a self-calibrating, programmable, palm-top instrument.

Keywords: Smart sensor; ASIC; Resistive gas sensor; Ratiometric sensor array; Behavioural models

1. Introduction

Further advances, in the field of polymer resistors for the sensing of vapours, require the development of low-cost smart devices capable of addressing the problems of both process variation and changes in environmental conditions. The use of integrated circuits capable of self-calibration and compensation within a single chip unit can provide a good solution. The adoption of a standard fabrication process allows the integration of smart interface circuitry and arrays of polymer-based sensors, leading to the development of novel intelligent sensor systems for gas or vapour monitoring.

Some of the problems associated with conducting polymers, such as temperature dependence, have already been addressed through the design of four- and five-element microbridge devices [1–3] and a significant reduction in the values of temperature and humidity coefficients was achieved.

In this paper we describe an application specific integrated circuit (ASIC) chip for gas monitoring that provides several smart features and incorporates a pair of polymer resistors in a ratiometric configuration [4]. In order to perform detailed analyses of the behaviour of this ratiometric chip, a parametric model was developed to simulate the polymer resistance on exposure to a given gas at different temperatures and humidities [5]. This model is particularly useful because it permits the response of polymeric chemoresistors to be predicted before CMOS processing. Cadence software was used for the design and simulation of the ASIC chip as well as for the implementation of the model. An Alcatel 0.7 μm CMOS process was chosen for the design and fabrication of the chip through the low-cost Europractice scheme.

2. Description of the design

Fig. 1 shows the overall structure of the new smart gas sensor system. The main component is the ASIC chip, which performs two basic functions: (a) sensing the gas presence and concentration and (b) controlling the operating temperature of the gas sensor. Within the ASIC chip, the top section corresponds to the gas sensor circuit, whereas the bottom sections correspond to temperature control and monitoring. A microcontroller unit is used for processing the inputs and

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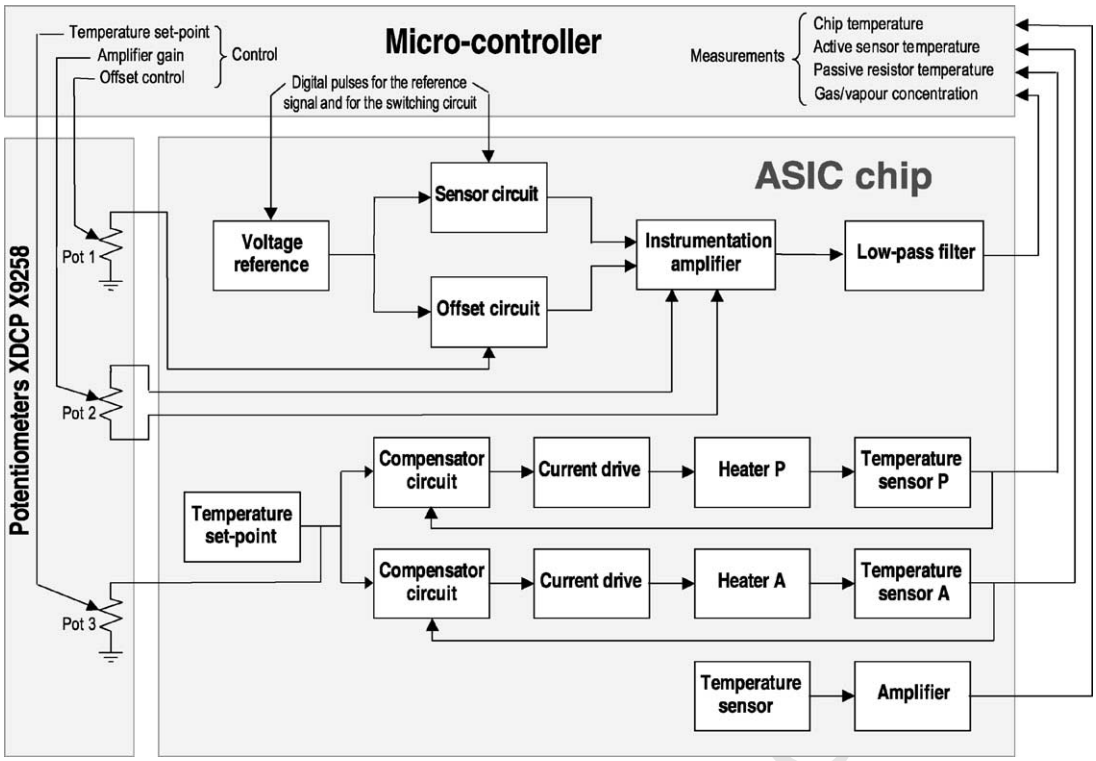

Fig. 1. Top representation of the ratiometric sensor system.

outputs of the ASIC chip. Additionally, three digitally controlled potentiometers (available in the Xicor's X9258 integrated circuit) are used in order to accomplish some specific trimming functions.

2.1. Gas sensor section

The first section of the ASIC chip is the circuit that includes two polymeric sensing resistors in a ratiometric con-

Table 1
Model parameters used in the simulations

Parameter used in the Cadence model	Value(s)[a]	Symbols used for Cadence parameters in the Eq. (1)	Description
C_{gas}	1*k*	C_G	Gas concentration (ppm)
Humid	0–30*k*	C_H	Humidity concentration (ppm)
Temper	40–100	T	Sensor temperature (°C)
K_{sH}	31.32	K_{sH}	Temperature coefficient for the humidity (°C)
k_H	−94*n*	k_H	Sensitivity coefficient for the humidity (1/ppm)
gamma$_H$	1	γ_H	Power low exponent for the humidity
Slope	1	–	Slope of the flicker noise ($1/f^{slope}$)
Vol	30×10^{-15}	–	Polymer volume (m^3)
X	300×10^{-27}	–	Polymer coefficient to evaluate flicker noise
SDS_Ct	−1	–	SDS control (positive → active, negative → inactive)
w1SDS_off	–	–	Pole for off-dynamics SDS
w1SDS_on	–	–	Pole for on-dynamics SDS
w2_on	10*k*	–	Second pole on-dynamics chemical transient
w2_off	4*k*	–	Second pole off-dynamics chemical transient
w1_on	10*m*	–	First pole on-dynamics chemical transient
w1_off	4*m*	–	First pole off-dynamics chemical transient
R_0	9512	R_{SC_0}	Sensor baseline resistance (Ω)
B	2	B	Temperature coefficient for sensor baseline resistance (°C)
K_s	88.42	K_{sG}	Temperature coefficient for the gas (°C)
k_1	3.2μ	k_G	Sensitivity coefficient for the gas (1/ppm)
gamma	1.07	γ_G	Power low exponent for the gas

[a] The values of the parameters used for simulations are obtained from measurements on carbon-black polymer film performed at the Sensors Research Laboratory of the University of Warwick with exception of the noise measurements which were performed by University of Torvegata (Rome).

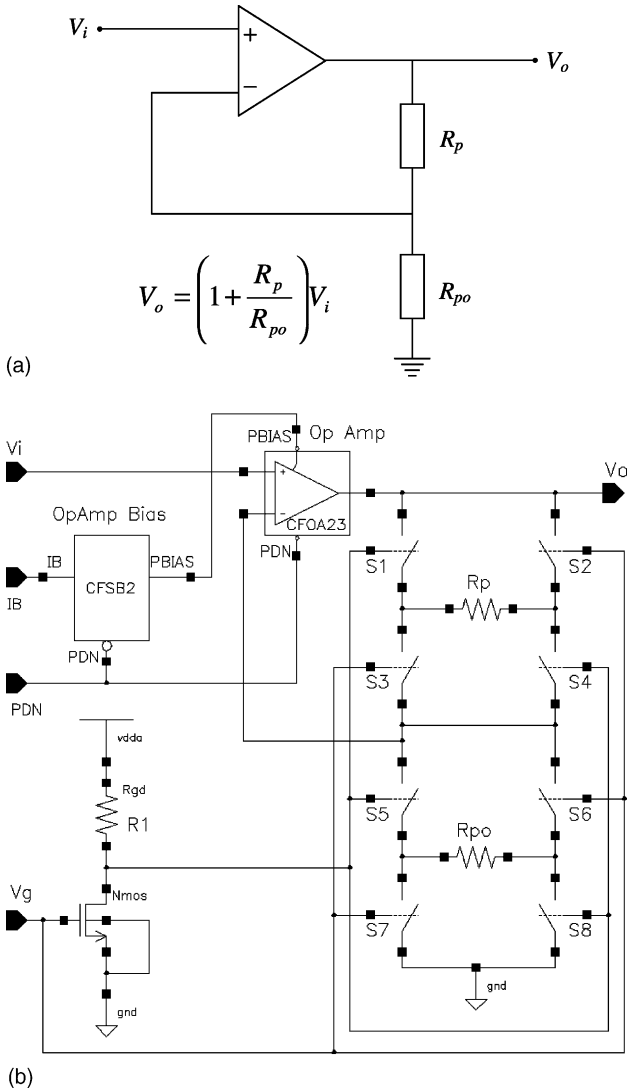

Fig. 2. Ratiometric sensor circuit: (a) basic principle; (b) Cadence implementation including analogue switching.

figuration for the monitoring of gases. The basic operating principle of ratiometric configuration is shown in Fig. 2(a). In this, two sensors are connected in a non-inverting operational amplifier configuration. One of the sensors R_p, is exposed to gas whilst the second one R_{po}, is passivated with an inert material, such as Nafion, which also offers common mode rejection of humidity signals, reduces the temperature sensitivity of the responses and produces an increase in response with an increase in temperature. When exposed to the presence of gases, the electrical resistance of the active polymer element changes, giving an indication of the concentration of the gas, whilst any common mode effects, such as aging, temperature dependence and humidity dependence, will cancel each other through the simple ratio R_p/R_{po}.

The gas microsensors are constructed by spray-coating a polymer across the aluminium electrodes. The electrodes are fabricated in a CMOS process, with the subsequent steps of polymer deposition and passive coating completing the fabrication of the active and passive chemoresistors. The actual behaviour of these resistors cannot be precisely predicted. It is known from previous research [1–3,6,7] that the polymer resistance will vary in the presence of gases, but there are several factors which affect these variations, e.g. temperature, humidity, ageing, and applied voltage. Even the actual resistance value of the devices is not easily controllable during the deposition process and significant differences appear between resistors fabricated through apparently identical batches.

Consequently, the structure of the gas sensor circuit was designed to overcome these problems. Firstly, a ratiometric pair of polymer resistors is used in order to provide at least partial cancellation of the above-mentioned variations. Secondly, the polymeric sensors are excited through the use of circuitry that also reduces these effects. Finally, smart circuitry is added for the self-cancellation of offset errors for the calibration of the device. As a result, the gas sensor circuit produces an amplified and filtered voltage signal proportional to the change in resistance experienced by one of the polymer resistors on gas exposure while the other resistor is used as a passive reference.

The blocks in the top section of the ASIC chip diagram in Fig. 1 perform this sensing function. A reference pulsed voltage signal is sent to a pair of ratiometric circuits. The first of these is the sensor circuit, whose schematic view is shown in Fig. 2(b). The polymer resistors R_p and R_{po} are connected, as described before, to an operational amplifier in a non-inverting configuration, following basically the same ratiometric principle reported previously [4]. In this, R_p is the active sensor exposed to the gas, while R_{po} remains passive. Apart from the elimination of temperature, humidity, and aging effects on the baseline resistance, the sensor circuit also incorporates polarity pulse switching in order to cancel long-term drift problems caused by the polarisation effect. The FET-based switches S1 to S8, controlled through pulses applied to the input V_g, invert alternately the voltage at the terminals of R_p and R_{po}, providing compensation against any polarisation effect or drifting associated

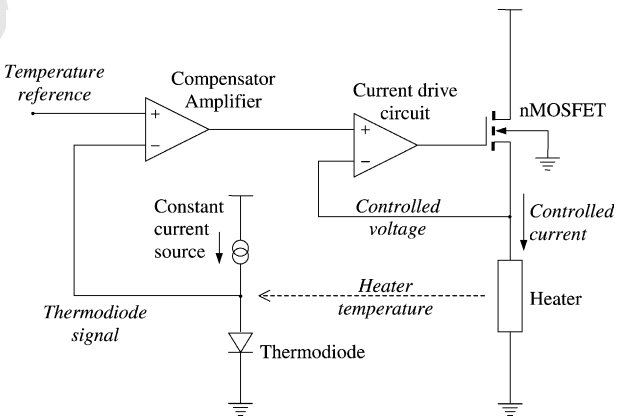

Fig. 3. Simplified schematic diagram of the temperature control circuit.

with a constant dc voltage. The benefits obtained with the ratiometric configuration of the sensors were confirmed via simulations as described below.

The second ratiometric circuit is used to offset the output signal of the sensor ratiometric circuit under non-exposure circumstances, thus removing any variation in the polymer resistance ratio from unity. This offset signal is digitally adjusted through the external potentiometer *Pot 1* (Fig. 1). The outputs of both ratiometric circuits are fed into an instrumentation amplifier in which any difference between the input signals will cause an output approximately proportional to the concentration of the monitored gas. The signal is then adjusted with the aid of the potentiometer *Pot 2*, which sets the gain of the amplifier. Finally, a Bessel low-pass filter was found to be the most suitable to remove high frequency switching errors from the amplified signal (Table 1).

2.2. Temperature control section

The second major task to be performed by the ASIC chip is the control of temperature, which is known to seriously affect the response of polymer sensors [1–3,6,7]. The bot-

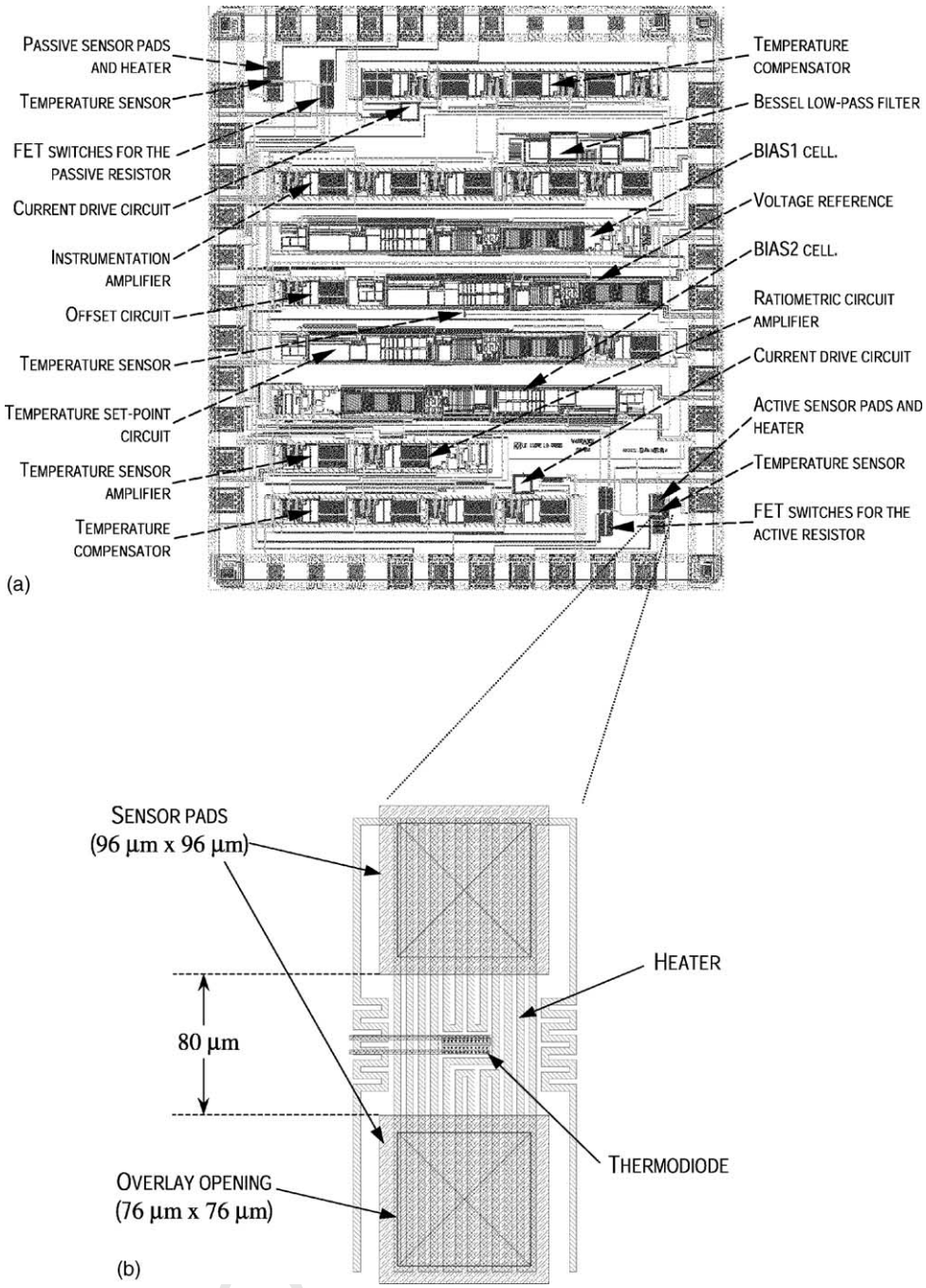

Fig. 4. Layout view of (a) the complete smart ratiometric ASIC chip and (b) the sensor area including heater and thermodiode.

tom sections on the ASIC chip diagram in Fig. 1 correspond to this control and monitoring function. In order to maintain the proper operating conditions and to minimise variations, a controlled heater is placed underneath the electrodes of each polymer resistor. A temperature sensor closes the control loop by feeding back a signal to the compensator circuit, where it is compared with a reference point that is set with the aid of a third external potentiometer. Here, a differential amplifier produces a compensating signal proportional to the difference of temperatures between the heater and the set point. This compensating signal controls the current through the heaters thus in turn controlling the temperature of the polymer resistors. A simplified schematic diagram of the temperature control section is shown in Fig. 3. An additional temperature sensor, whose output is amplified, is used to monitor the ambient temperature of the chip. The outputs of the temperature sensors are made available to the microcontroller unit.

2.3. Layout view

The layout view for the chip, shown complete in Fig. 4(a), was drawn with the *Virtuoso* layout editor according to the specifications and layout rules of the Alcatel Microelectronics 0.7 μm CMOS technology. The dimensions of the ASIC chip are 3300 μm × 3750 μm and it contains all the components that are represented in the block diagram of Fig. 1. The cells are placed along several rows in the layout, thus obtaining a symmetrical distribution with the two gas sensors located at opposite corners of the chip, to aid post-CMOS polymer deposition.

The sensor area of the layout is shown in Fig. 4(b). The electrodes, in metal 2 layer, are 96 μm × 96 μm in size, with 80 μm interelectrode gap, in order to achieve approximately 10 kΩ resistance when using carbon-black polymer composite films [8]. The heaters are constructed underneath the electrodes in the metal 1 layer, which has a nominal sheet resistance of 50 mΩ/sq. Each heater has a nominal design resistance of 50 Ω. The thermodiodes are placed in the centre of the heater regions, just between the electrodes.

The cells *Bias1* and *Bias2* provide the bias current for the operational amplifiers according to the bias strategy required by the Alcatel analogue cells and they also supply the current for the driving of the temperature sensors. Several test points are available at the bonding pads for testing purposes, allowing the realisation of measurements at different sections of the circuit.

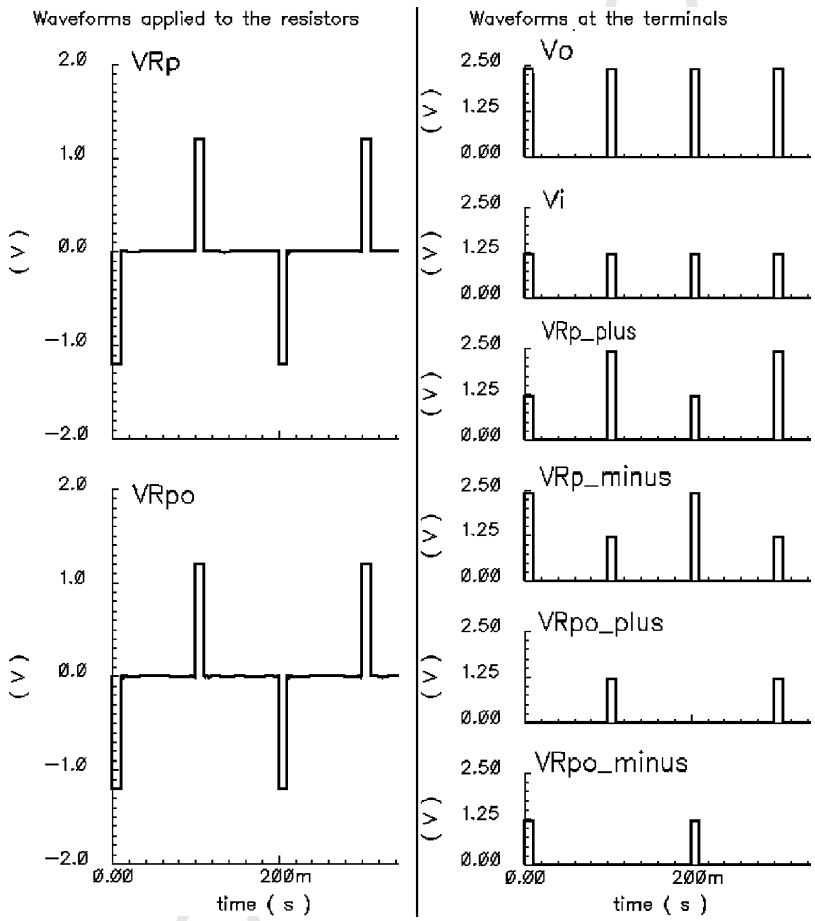

Fig. 5. Simulation of sensor voltages in the circuit.

A number of tests where performed with the *Diva* and *Dracula* software packages in order to check the consistence of the design with the layout rules, with the electrical rules and with the substrate requirements under the particular CMOS process selected for the fabrication of the ASIC chip. In order to obtain the openings down to metal 2 layer for the deposition of the polymers onto the sensor electrodes, it was necessary to include some special modifications while still following the standard CMOS process.

3. Simulations

The *Spectre* simulator was used to test each part of the design. Fig. 5 shows the voltages obtained at the ratiometric sensor circuit when assuming initially equal resistances for R_p and R_{po} and hence disregarding any variations due to exposure to reactive gases. The left plots correspond to the actual voltage waveforms at the terminals of the resistors, i.e. the differences in the corresponding positive voltages, plotted on the right, appearing at the *plus* and *minus* terminals of each resistor. The simulation results confirm the advantage of using the switching circuitry in order to invert the sign of the voltages at the chemoresistors terminals and thus providing compensation against polarisation effects.

Fig. 6 shows the voltage waveforms appearing at every stage of the gas sensor section. The reference signal V_{ref} (Fig. 6(a)) produced by feeding pulses to a standard bandgap cell consists of pulses that are 10 ms in width and have an amplitude of 1.2 V. This signal produces the response that is registered at the output of the offset circuit (Fig. 6(c)), which is calibrated to the baseline signal, i.e. the sensors unexposed to gases. After calibration, exposure to gases is simulated via the change in resistance δ applied to the active sensor. The sensor output V_{sensor} (Fig. 6(b)) differs from the offset signal V_{offset} and the difference in voltage is applied to the input of the instrumentation amplifier. This differential voltage V_{diff} (Fig. 6(d)) was only 60.37 mV in the simulation when the change in resistance δ was set to 0.05, i.e. 5% of R_{po}. When the gain of the amplifier set to 50, the amplitude of the signal is raised to approximately 3 V in amplitude (V_{amp}, Fig. 6(e)). Finally, V_{out} represents the filtered signal at the output of the circuit (Fig. 6(f)).

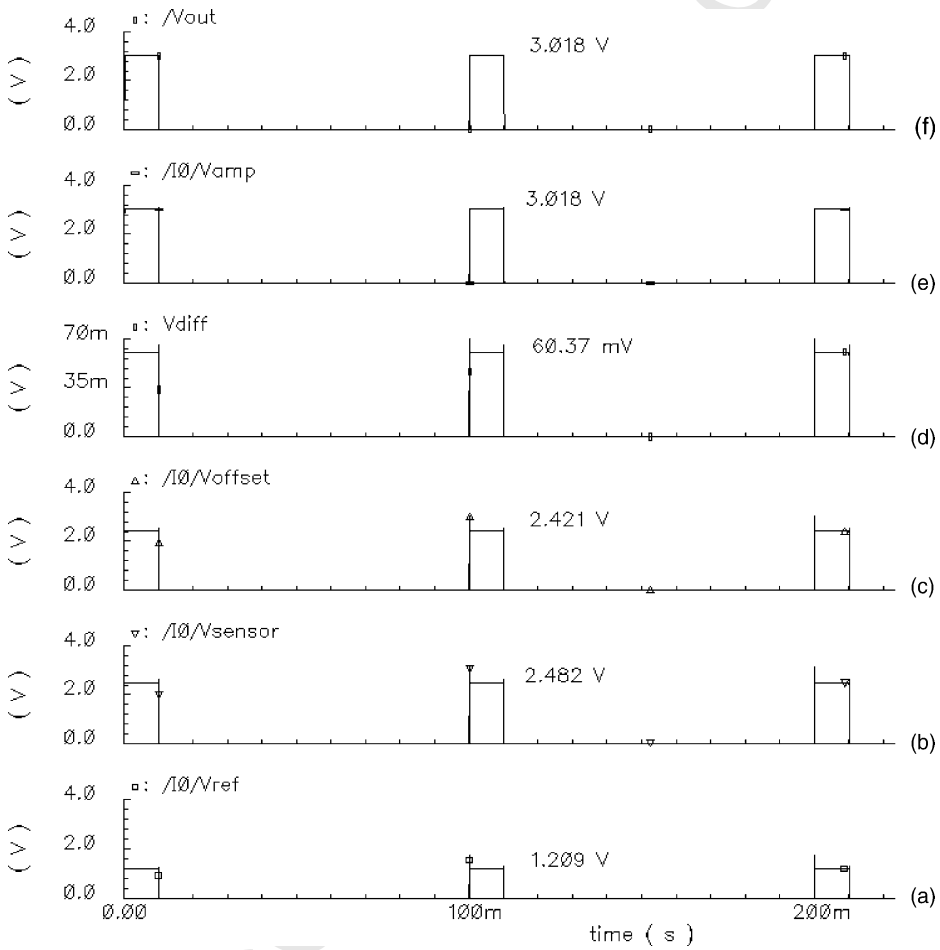

Fig. 6. Voltage simulation with a change in resistance equal to 5% of R_{po}: (a) reference voltage, (b) voltage at the output of the sensor circuit, (c) offset voltage, (d) differential input at the instrumentation amplifier, (e) amplified voltage, and (f) output of the low-pass filter.

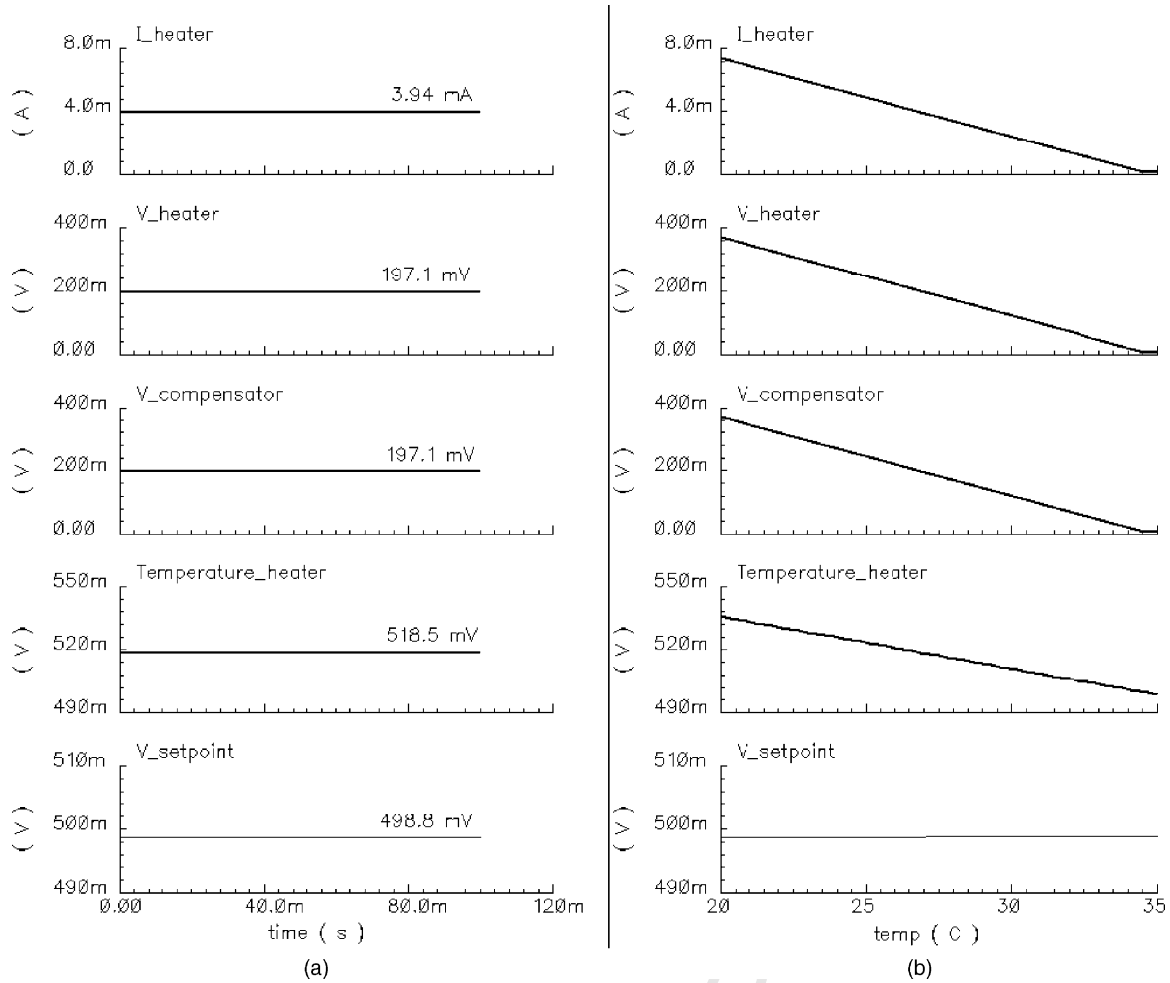

Fig. 7. Waveforms for the temperature control system: (a) results at 27 °C, (b) response between 20 and 35 °C.

The performance of the temperature control section was also simulated. Fig. 7(a) shows the voltages obtained at 27 °C, whereas Fig. 7(b) shows the voltage waveforms resulting when temperature varies between 20 °C and a nominal setpoint at 35 °C.

Further simulations also showed that the circuit is capable of dealing with the wide range in the actual resistance obtained for the different types of polymer sensors (e.g. three orders of magnitude).

3.1. Application of the polymeric chemoresistor model

In order to compare performances of ratiometric configuration to discrete chemoresistors, the polymeric chemoresistor model was used. This model, implemented in Cadence and described thoroughly elsewhere [5], is able to simulate accurately the polymeric chemoresistor response to gas and humidity under different operating conditions. The model simulates the static and dynamic sensor response to gas or gas mixture exposure, and includes flicker and Johnson noise. It also takes account of the sensor sample delivery system. Fig. 8(a) shows the conceptual structure of the proposed model having three inputs (C_G, C_H, T) for gas and humidity concentration and sensor temperature, and two pins (R_+, R_-) for sensor connection with the rest of the circuitry. The inputs are connected to voltage sources whose voltage level emulates both the gas and humidity concentrations (1 V ↔ 1 ppm) and the sensor temperature (1 V ↔ 1 °C). The model has been implemented as a standard cell (SC) in Cadence software (Fig. 8(b)). The polymeric sensor is represented as a complex impedance Z_{SC}, with two noise sources in series (thermal and flicker noise [8]). Z_{SC} is the impedance resulting from the parallel combination of the sensor capacitance C_{SC} and the sensor resistance R_{SC}. Parasitic resistances and capacitances are neglected because they are insignificant when compared with R_{SC} and C_{SC} [5].

The sensor static response is a function of the gas concentration C_G, the sensor temperature T and the water vapour concentration C_H, while the dynamic response depends both on the gas transfer method and/or on the gas reaction kinetics. The static resistance of the SC, R_{SC}, is evaluated in the block 'Sensor Static Response' (see Fig. 8(a)) which implements the developed model, assuming that carbon-black composite polymer films are used as gas sensitive materials.

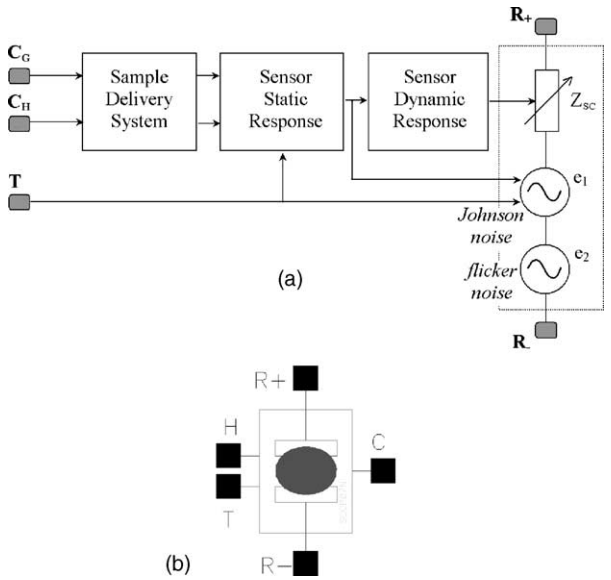

Fig. 8. (a) Model framework of the SC for a polymeric gas sensor. (b) symbol for the cell.

The model developed for these materials in Ref. [5] has been expanded in order to include the temperature variations of the baseline resistance and the static resistance is given by

$$R_{SC} = R_{SC_0} \exp\left(\frac{B}{T}\right) \times \left[1 + k_G C_G^{\gamma_G} \exp\left(\frac{K_{sG}}{T}\right) + k_H C_H^{\gamma_H} \exp\left(\frac{K_{sH}}{T}\right)\right] \quad (1)$$

where R_{SC_0} is the baseline sensor resistance (measured in presence of a reference gas, generally synthetic air or nitrogen), k_G and k_H are sensitivity coefficients, C_G and C_H are the gas/vapour concentrations expressed in ppm, γ_G and γ_H are the power law exponents, B, K_{sG} and K_{sH} are the temperature coefficients, and T the temperature in Kelvin. The subscripts G and H refer to the gas and the water vapour, respectively. The sensitivity coefficients can be positive or negative depending on the nature of the gas and the polymer, producing an increase or decrease of the sensor resistance after the gas injection. The transient behaviour of the polymeric gas sensor is simulated by a second-order multi-exponential model implemented through a second-order low-pass filter ('Sensor Dynamic Response' in Fig. 8(a)). Since the on-dynamics are generally faster than the off-dynamics, two filters with different poles have been used. The sample delivery system is also modelled ('Sample Delivery System' in Fig. 8(a)) in order to include the real gas transfer [5].

The general parametric model described above was used to simulate the response of the polymeric chemoresistors in the ratiometric configuration. Fig. 9 shows how the cells SC_a and SC_p were used to represent the active and passive sensors.

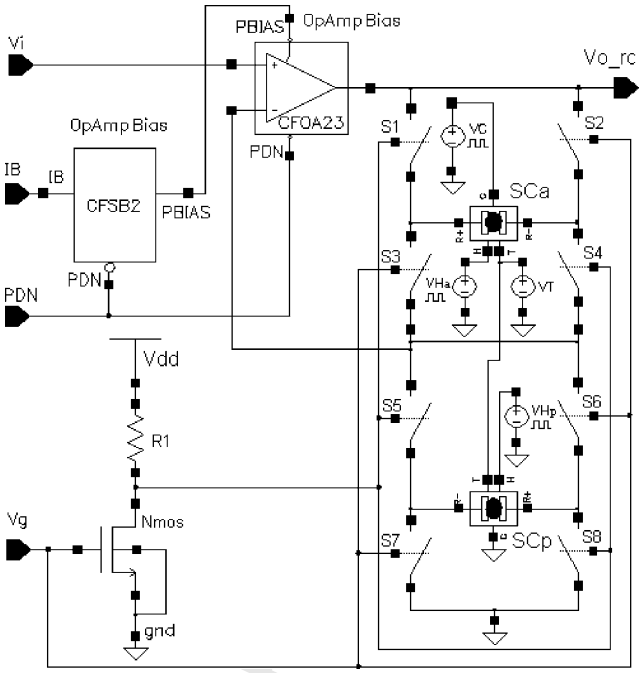

Fig. 9. Ratiometric sensor circuit. The sensor cell SC_a emulates the behaviour of the active polymeric sensor, while the cell SC_p mimics the passive sensor.

Two passivation methods were tested in the simulations. In the first case, represented in Fig. 10(a), one of the polymeric sensors is coated with an inert material to avoid the gas effect. In this way, the passive sensor is sensitive to temperature variation but it does not respond to the gas or ambient humidity. The water vapour concentration is fixed to the concentration present at the moment of the coat deposition (e.g. RH = 40% at 20 °C corresponding to 9214 ppm). The gas flow is split in two paths to expose both sensors. The passivation was simulated by connecting the input 'C' of the SC_p cell to gnd (gas concentration = 0 ppm) and the input

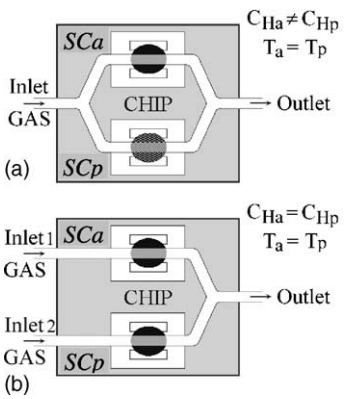

Fig. 10. The use of the reference sensor SC_p in the ASIC chip: (a) the polymer sensor SC_p is coated with an inert material to avoid the reaction with a gas which flow over sensors SC_a and SC_p; (b) two separate flow paths are used to expose the two sensors to different gases but to the same water vapour concentration; this enables for humidity rejection.

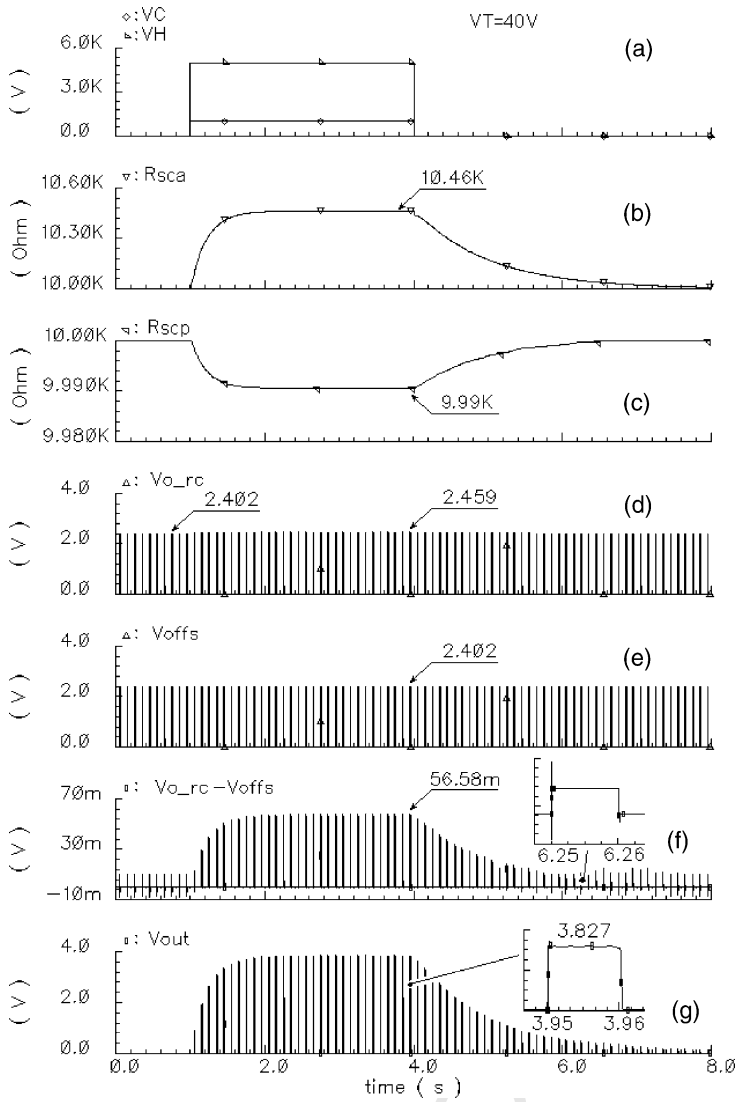

Fig. 11. Transient analysis of the ratiometric circuit for active and passive baseline resistances of 10 kΩ at 40 °C, gas concentration = 1000 ppm, water vapour mixed to the gas = 5000 ppm: (a) voltage pulses applied to the sensor cell SC_a simulating the humidity and gas concentration (1 V ↔ 1 ppm); (b) resistance of the active sensor; (c) resistance of the passive sensor; (d) output voltage of the ratiometric circuit; (e) output voltage of the offset circuit; (f) differential input of the instrumentation amplifier; (g) output of the gas sensor section.

'H' to a voltage source (e.g. $VH_p = 9214\,V \rightarrow 9214$ ppm).

The second method requires two separate inlets to carry the gas under test and a reference gas to the sensors SC_a and SC_p (Fig. 10(b)). In this case the sensor SC_p is not coated but it acts as a reference device because the reference gas is injected in the second inlet ('Inlet 2 GAS'). This solution allows cancelling the humidity effect, when the reference gas has the same water vapour concentration as the gas under test injected in the 'Inlet 1 GAS'.

Fig. 11 shows the results of simulations performed using polymer resistors of 10 kΩ at 40 °C under the second passivation method. Gas and humidity concentrations of 1000 and 5000 ppm, respectively were applied to the sensors terminals. The changes in resistances of active and passive sensors are shown in Fig. 11(b) and (c). The output signals from ratiometric and offset sections are also shown. The differential input to the amplifier is depicted in Fig. 11(f) and the output signal of the gas sensor section is shown in Fig. 11(g).

The benefits of the ratiometric circuit structure are compared to the potential divider configuration (Fig. 12) already discussed elsewhere [5]. In particular, the temperature and humidity dependencies of the circuits are explored.

Figs. 13 and 14 show the percentage variation of the circuit output voltage with varying sensor temperature and humidity. The two setups depicted in Fig. 10 are taken into account. The ratiometric configuration shows less sensitivity to temperature variation compared to the discrete circuit. In particular, the baseline output value is not sensitive to the temperature variation when the configuration with reference gas shown in Fig. 10(b) is adopted. These results can be observed in the curves for the ratiometric circuit with

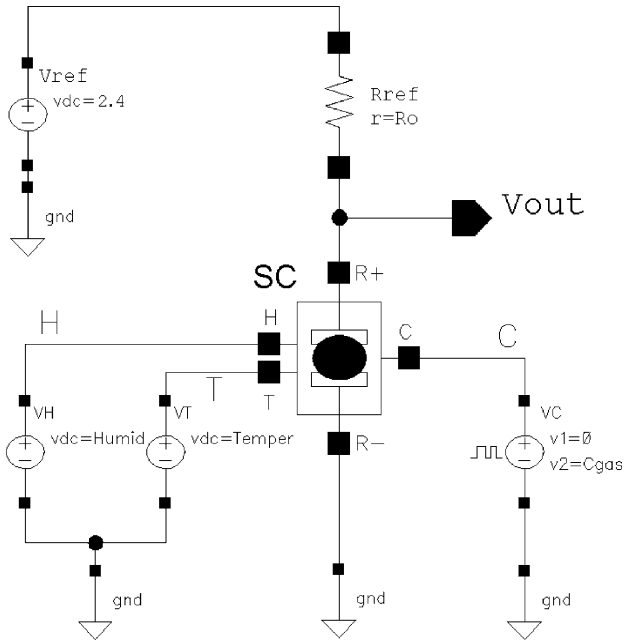

Fig. 12. Schematic view of the single chemosensor circuit.

$C_{Ha} = C_{Hp}$, depicted in Fig. 13(a) and (b). This is expected, since the sensors are fabricated under the same conditions and they should respond to temperature changes with the same exponential law. The plots in Fig. 13(c) and (d) show that the ratiometric circuit has superior performance when compared to a single chemosensor circuit exposed to gas at varying temperature.

The ratiometric circuit shows better performance also in terms of linear humidity dependence (Fig. 14). The water vapour effect is cancelled by the reference sensor SC_p when this one is not coated and the configuration depicted in Fig. 10(b) is adopted ($C_{Ha} = C_{Hp}$). If the reference sensor SC_p is coated with an inert material, as in Fig. 10(a), the humidity effect cannot be annulled (ratiometric curves for $C_{Ha} \neq C_{Hp}$ in Fig. 14) but the ratiometric circuit is still less sensitive with respect to the potential divider configuration.

Noise simulation was also performed based on the model developed in Ref. [5]. Fig. 15 shows the simulated noise analysis of the ratiometric circuit. The operational amplifier CFOA23 (Fig. 9) gives the main contribution to the total output noise. The polymeric sensor noise is also shown and it is assumed to be dominated by flicker noise measured for polymer carbon films [8]. The RMS value of the noise volt-

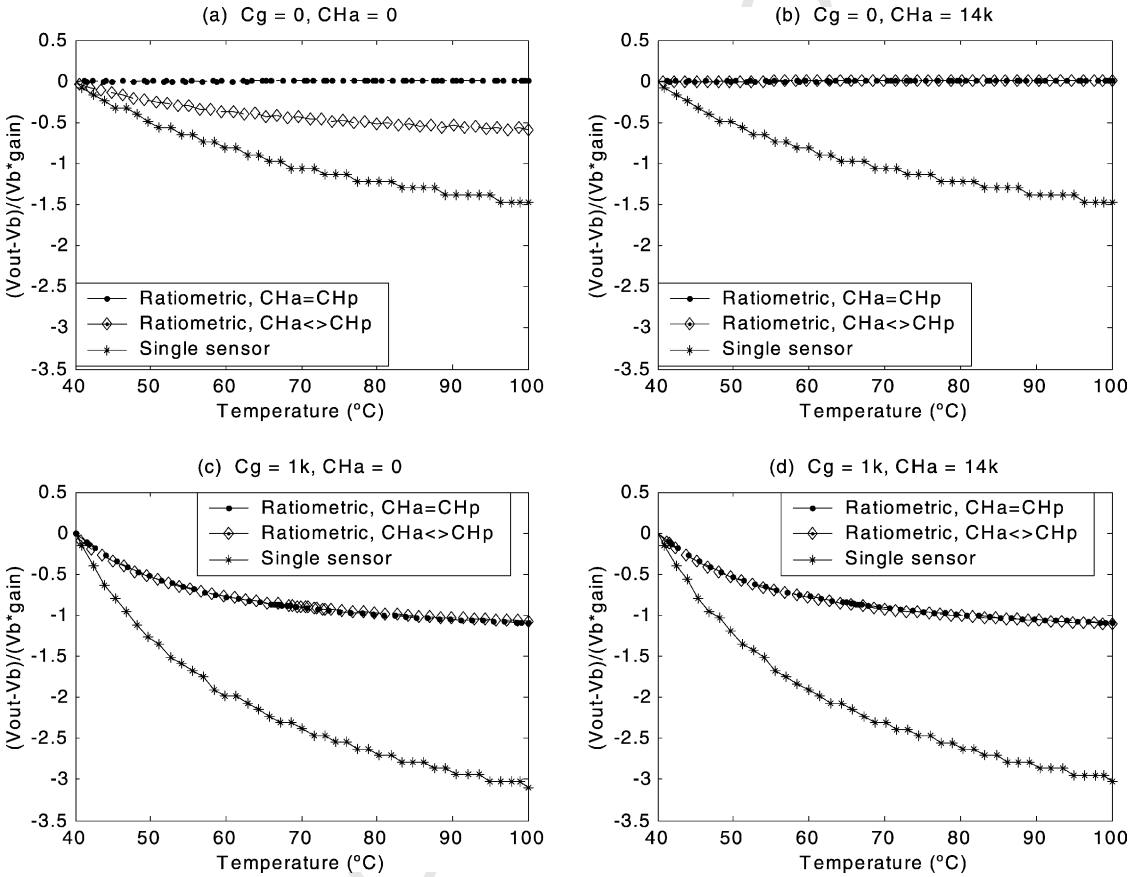

Fig. 13. Percentage variation of the output voltage for the ratiometric and potential divider circuits when the temperature of the sensors spans from 40 to 100 °C: (a) response to gas and water vapour concentrations equal to zero; (b) response with wet air and without gas exposure; (c) response to gas exposure with dry air; (d) response with gas exposure and wet air.

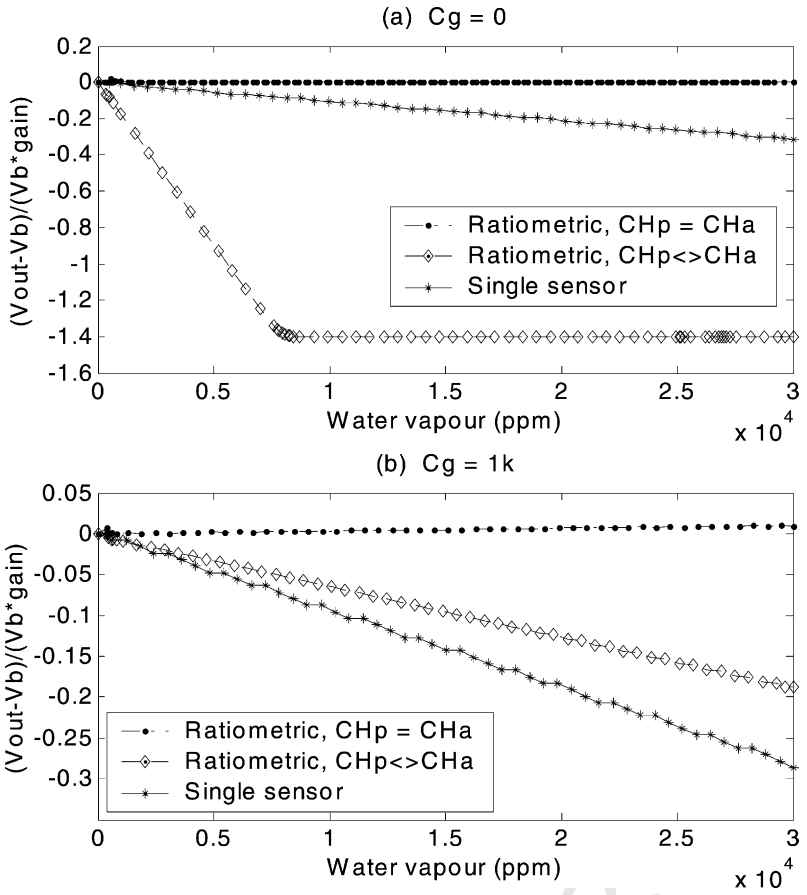

Fig. 14. Percentage variation of the output voltage for the ratiometric and potential divider circuits when the water vapour concentration spans from 0 to 30 ppt: (a) response without gas exposure; (b) response to gas exposure.

age at the ASIC chip output is evaluated from the simulation results to be $v_n = 33\,\mu V$. Considering a RMS signal output of 3.3 V the signal-to-noise ratio is

$$\mathrm{SNR} = 20\log\left(\frac{3.3}{33\mu}\right) = 100\,\mathrm{dB}$$

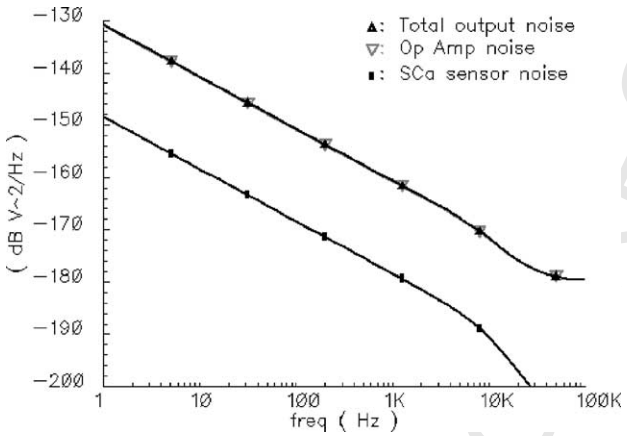

Fig. 15. Noise power spectral density at the ratiometric circuit output and noise contributions of the active sensor and the operational amplifier CFOA23.

4. Conclusions

A novel smart ratiometric ASIC chip has been designed for gas sensing applications and fabricated using a standard CMOS process. Simulations have shown that the ratiometric configuration shows superior performance when compared to conventional resistive polymer devices. Its characteristics of pulsed-mode operation to prevent polarisation effects/voltage induced drifting, and on-chip compensation of temperature and humidity variations, are considered to be crucial features for the development of an accurate low-cost, palm-top gas monitor.

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References

[1] M. Cole, J.W. Gardner, J.A. Covington, D. Fife, C.Y. Kwok, J.E. Brignell, P.N. Bartlett, Active bridge polymeric resistive device for vapour sensing, Eurosensors XIV, W2P41, (Bio)chem. Sens. III (2000) 895–898.

[2] J.W. Gardner, M. Vidic, P. Ingleby, A.C. Pike, J.E. Brignell, P. Scivier, P.N. Bartlett, A.J. Duke, J.M. Elliot, Response of a poly(pyrrole) resistive micro-bridge to ethanol vapour, Sens. Actuators B 48 (1998) 289–295.

[3] M. Cole, J.W. Gardner, A.W.Y. Lim, P.K. Scivier, J.E. Brignell, Polymeric resistive bridge gas sensor array driven by a standard cell CMOS current drive chip, Sens. Actuators B 58 (1999) 518–525.

[4] M. Cole, J.W. Gardner, P.N. Bartlett, Low-drift odour and vapour ratiometric resistive elements for analogue CMOS smart sensors, in: J.R. Stetter, W.R. Penrose (Eds.), Proceedings of the Artificial Chemical Sensing: Olfaction and the Electronic Nose (ISOEN 2001), vol. 15, The Electrochemical Society Inc., USA, 2001, pp. 117–120.

[5] M. Cole, N. Ulivieri, J. García-Guzmán, J.W. Gardner, Parametric model of a polymeric chemoresistor for use in smart sensor design and simulation, submitted for publication. http://www.eng.warwick.ac.uk/srl.

[6] P. Bruschi, A. Nannini, B. Neri, Vapour and gas sensing by noise measurements on polymeric balanced bridge microstructures, Sens. Actuators B 24–25 (1995) 429–432.

[7] J.V. Hattfield, P. Neaves, P.J. Hicks, K. Persaud, P. Travers, Towards an integrated electronic nose using conducting polymer sensors, Sens. Actuators B 18–19 (1994) 221–228.

[8] S.M. Briglin, M.S. Freund, P. Tokumaru, N.S. Lewis, Exploitation of spatiotemporal information and geometric optimisation of signal/noise performance using arrays of carbon black-polymer composite vapor detectors, Sens. Actuators B 82 (2002) 54–74.

Biographies

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Nicola Ulivieri received his Laurea degree in Telecommunication Engineering at the University of Siena in 1999. He is currently a PhD student in Information Engineering (Electronics) at the University of Siena. In 2002 he spent a 6 months period at the School of Engineering of the University of Warwick to develop a Cadence model for chemoresistors gas sensors and to collaborate to an ASIC chip layout design. His main research activity is related to the development of laboratory electronic noses based on metal oxide sensors and QCM sensors. Recently, his interests were also devoted to integrated analogue and mixed signal electronics design and smart sensors development.

Marina Cole (BSc, PhD, MIEEE), received his BSc degree from the University of Montenegro (Yugoslavia) and the PhD from Coventry University (UK). She joined the School of Engineering at Warwick University in 1996 as a postdoctoral research assistant and in 1998 she was appointed to a lectureship in electronic engineering. Her main research interests are integrated silicon-based sensors, SAW-based sensors, analogue and mixed signal ASICs, smart sensors, actuators and microsystems.

Julian W. Gardner (BSc, PhD, DSc, CEng, FIEE, SMIEEE), joined the School of Engineering at Warwick in 1987. His research interests are microsensors, microsystems technology, electronic noses, intelligent sensors and multivariate data processing methods. He has previously spent 5 years in industry working first at AEA Technology Ltd. and later at Molins Advanced Technology Unit on Instrumentation. At Molins he developed a novel opto-electronic sensor that has been packaged in the UK and US for implementation on high speed packaging machinery. In 1989 he received his Esso Centenary Education Award sponsored by the Royal Society and Fellowship of Engineering to pursue his research interests. He has published over 300 technical papers and is an author of six books in Nanotechnology (1991), Electronic Noses (1992), Microsensors (1994), Electronic Noses (1999), and MEMS (2001). He was an Alexander von Humboldt Fellowship in Germany in 1994. He currently heads the Sensors Research Laboratory in the Centre for Nanotechnology and Microengineering at Warwick University, where he is Professor of Electronic Engineering.