CMOS Interfacing for Integrated Gas Sensors: A Review

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***Abstract*—Modern gas sensor technology is becoming an important part of our lives. It has been applied within the home (monitoring CO levels from boilers), the workplace (e.g., checking levels of toxic gases) to healthcare (monitoring gases in hospitals). However, historically the high price of gas sensors has limited market penetration to niche applications, such as safety in mines or petrochemical plants. The high price may be attributed to several different components: 1) cost of a predominantly manual manufacturing process; 2) need for interface circuitry in the form of discrete components on a PCB; and 3) fireproof packaging, making the cost of gas detection instruments typically many hundreds of dollars. Consequently, there has been a considerable effort over the past 20 years, towards the goal of low-cost ($1–$5) gas sensors, employing modern microelectronics technology to manufacture both the sensing element and the signal conditioning circuitry on a single silicon chip. In this paper, we review the emerging field of CMOS gas sensors and focus upon the integration of two main gas-sensing principles, namely, resistive and electrochemical and associated circuitry by CMOS technology. We believe that the combination of CMOS technology with more recent MEMS processing is now mature enough to deliver the exacting demands required to make low-power, low-cost smart gas sensors in high volume and this should result in a new generation of CMOS gas sensors. These new integrated, mass-produced gas sensors could open up mass markets and affect our everyday lives through application in cars, cell phones, watches, etc.**

***Index Terms*—CMOS sensors, gas sensors, interfacing, microsensors, smart sensors.**

I. Introduction

SINCE THE industrial revolution took place in the 1900s, there has been a need to detect toxic gases (e.g., carbon monoxide) and explosive gases (e.g., hydrogen) within coal mines. More recently, this need has expanded into the monitoring of green house gases that are believed to cause global warming (e.g., methane and carbon dioxide). These demands have led to the development of a number of different discrete and distinct sensor technologies. Almost exclusively, these sensors combine a discrete gas sensing element—fabricated through a specialized process—and are combined with a separate drive and signal conditioning circuit. It has been the aspiration of researchers for more than 20 years to combine the different parts of a gas sensor with microelectronics in order to create an integrated or smart gas sensor [1]–[8]. However, the single most significant impediment to having the widespread application of gas sensors is their price. Most of the gas sensors marketed today cost well in excess of $10 and are embedded in instruments that then brings the price up to and excess of $500. This limits their application to areas of high capital risk such as commercial processing plants, laboratories, power stations, etc. The current market has been estimated to be worth some $500 M and growing at a rate of 10% per annum [9]. However, the growth in the market in recent years has been achieved by a lowering of the unit cost through the development of miniature solid-state gas sensors (e.g., the tin oxide resistive gas sensor). There are several mass markets that could open when the gas sensor (including read-out interface) falls below $10 and many more when it falls below $1. Once the unit cost falls below $1, then the gas sensor could be embedded into laptop computers, personal digital assistants (PDAs), cell phones, and even wrist watches. Therefore, the only way in which the potential mass market can be penetrated is to employ low-cost manufacturing technologies (i.e., CMOS technology) and integrate the drive and interface circuitry into a single smart chip. A related success story is that of a low-cost IC humidity sensor, which incorporates the sensing element with integrated electronics, and sells for around $10 [10].

Of course, price is not the only barrier to making a commercially successful gas sensor. The sensor must not only be sensitive and selective (nontrivial demands) to the target gas but also have a low enough power consumption to be driven off a battery for a significant period of time. The latter requirement is particularly challenging when you consider that many solid-state gas sensing materials operate at temperatures from 300 °C to 550 °C and that users often want to detect many different gases at the same time, e.g., carbon monoxide, nitrogen dioxide, and hydrogen.

We believe that the intelligent design and integration of the electronic circuitry (for drive, signal conditioning/compensation, and read-out) with the gas sensing element can mitigate some of the significant issues inherent in solid-state gas sensors, such as strong temperature and humidity dependence, signal drift, aging, poisoning, and weak selectivity. As the effort towards commercially implementing, fully integrated gas sensors in CMOS technology, has not yet been realized for the detection of almost all gases we have decided to review the field of gas sensors with integrated electronics (i.e., CMOS silicon technology).

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In the past, there have been other reviews of this field, particularly papers published by Joo *et al.* [11] and earlier by Hierlemann *et al.* [13]; however, these reviews focus mainly on microfabrication techniques and the challenges for the integration of different chemical- and biosensors with CMOS platform. The purpose of this review is to highlight the technological issues of incorporating gas sensors into a CMOS process (and the postprocessing MEMS step required) and on the challenges of designing interface electronics required for integrated CMOS resistive and electrochemical gas sensors.

In this review, we first examine some of the technological issues faced when seeking to integrate gas sensing elements into a silicon-based, full commercial CMOS fabrication process. Next, we explore different types of gas sensors and different designs that can offer benefits in terms of performance; some of which may be regarded as smart or intelligent sensors. Finally, we look forward into the future and discuss some of the emerging technologies (e.g., nanotechnology) and tools (thermally modulated time series algorithms) that could improve existing performance and stimulate further mass market penetration.

II. Integration of the Gas Sensing Element

In order to understand why full CMOS integration has not been widely adopted, we must consider the operating conditions and structure of existing gas sensors. Clearly, there are differences in the skills of the people who develop gas sensitive materials (normally chemists and material scientists) from those who design integrated electronics (electronic engineers). We will not discuss here the issues associated with projects demanding teams with disparate multidisciplinary skills, but will concentrate instead on technological issues. If we consider common solid-state gas sensors, such as the metal oxide semiconductor (MOS) chemoresistor, they typically comprise of a heater to elevate the sensing material temperature to hundreds of degrees Celsius above ambient and a transducer to monitor a property of the gas-sensitive material. Thus, both the gas sensing material and the heating element must be CMOS compatible. This raises a number of important challenges.

- Chemical sensors often have operating temperatures that are well above those at which standard bulk or epitaxial CMOS circuits can work (typically a maximum of 125 °C).
- The use of non-standard CMOS materials for the heater (platinum is commonly used) and the gas sensing layer (ceramics) as well as nonstandard post-CMOS process steps (e.g., high annealing temperature).
- Heaters are normally formed on membranes to reduce power consumption. They can be formed through either back-etch or front-etch using dry or wet etching. Both these processes are non-CMOS and are referred to as MEMS or micromachining processes.
- IC fabrication laboratories offer only specific materials with fixed properties and geometric constraints (e.g., single crystal silicon, polysilicon, silicon dioxide, silicon nitride, and aluminium).
- Heater materials formed from doped polysilicon and aluminium can have poor long term stability at higher temperatures causing heater resistances to increase significantly during use, thus affecting calibration.
- The physical design and characteristics of the CMOS layers including the inter dielectric and passivation layers are totally dependent upon the IC fabrication process.
- Electrode materials formed from aluminium do not make good electrical contact with gas sensing layers, due to native oxide formation.
- Many pre- and post-treatments for sensing material deposition contain highly reactive chemicals that can attack either the CMOS metal, silicon or even passivation layers.
- Post-deposition anneals are often close to or above the melting point of aluminium (660 °C).

Despite the fact that all these challenges have to be overcome, it is still highly desirable to integrate interface CMOS electronics with microsensors to produce low-cost, reliable, reproducible, and smart gas sensors. Thus, there are two possible ways of implementing smart gas sensors: i) a hybrid approach and ii) a monolithic approach, as described below.

i) In the case of a hybrid system, as the name suggests, there are separate chips containing the gas sensor and the interface circuitry. Here, the two chips can be fabricated by different foundries and so suffer from fewer thermal and material design constraints. Also, in this case, the electronic circuit dies can be reused even if there is a problem with the sensing chip. However, the parasitic capacitance/resistance, due to having to interconnect between the chips, is clearly larger, and less predictable and repeatable than with the monolithic approach. Furthermore, there is the additional cost of fabricating, interconnecting and mounting two chips (with a larger area) onto a single package.

ii) In the monolithic case, both the sensors and interface electronics are on the same silicon chip and benefit from a well established microelectronics process that leads to a reliable reproducible performance with less parasitic effect. However, the gas sensing component can only be made with foundry provided materials and a defect in the sensing element will result in the failure of the whole integrated chip even if the circuitry is working properly – so the cost of device failure is significantly higher.

Several efforts have been made to accommodate sensor requirements into the basic CMOS process flow and thus take advantage of well established fabrication technologies; however, there are some limitations when employing standard CMOS processes. First of all, standard CMOS constrains the fabrication process owing to the limited number of pre- and post-CMOS options. In the case of a pre-CMOS process, the wafers have to meet stringent criteria, in particular avoiding contaminations from the material used, in order to be able to enter a microelectronics foundry. Post-CMOS offers more options to the designer. Back-etches can be performed post-CMOS at the wafer level and in the last few years, have become an established so-called MEMS process (e.g., anisotropic wet KOH etching or isotropic deep reactive ion etching). Nevertheless, care must be taken not to etch the CMOS layers away in the process! Furthermore, aluminium electrodes can be plated (e.g., bump bonded) with nickel and gold to allow connection to the

sensing material or an additional sensing electrode layer of gold or platinum can be deposited onto the wafer and patterned after CMOS fabrication. Heaters can now be made from tungsten [14] (some foundries have included tungsten for a high-temperature CMOS process) or doped single crystal silicon [15]. Both of which can operate at much higher temperatures than doped polysilicon or aluminium with less thermal drift and especially tungsten with negligible electromigration.

III. Interface Electronics for Chemical Sensors

Once the gas sensing material(s) and heater structure have been integrated onto the CMOS chip, the use of device miniaturization of the CMOS electronics integration brings along a fresh set of issues. Generally, a gas sensor generates an electrical signal in the form of a change in electrical resistance, voltage, frequency, capacitance, etc. However, a common problem of microsensors is the small electrical signal generated at the output of the sensing element. This is often due to the scaling down of the sensing layer, thus a smaller sensing area, leads to a smaller sensor response relative to noise.

In essence, the function of the front-end interface circuit is to extract the critical feature from the signal, amplify it and often convert it into the digital domain [16]. However, there are a number of design parameters that require careful consideration. For example, see the following.

- The differential transistor pair of any designed operational amplifier at the front end must be of *p*-type to take advantage of lower $1/\mathrm{f}$ noise. Again, to remove the effect of any dc offset or drift dynamic technique (e.g., chopper or autozero) can be used – this will also reduce the influence of high $1/\mathrm{f}$ noise [17]. The signal level should not reach a value close to the power rail at any part of the circuit blocks (due to signal amplification and conditioning), because it can generate distortion or can give rise to harmonics in the signal.
- Current submicron CMOS technology can often run off very low supply voltages (0 to 1.8 V or even 0 to 1.1 V) to reduce power consumption and to keep electric field consistent in the MOSFET channel region, but this makes the design of the front-end analogue interface electronics much harder, as sensor drift (due to aging and incomplete release of analyte at the end of a measurement etc.) shifts both the baseline (baseline resistance refers to the initial resistance of the sensing material when there is no chemical analyte present) and the magnitude of any response.
- The baseline resistance varies enormously depending on the sensing material used, e.g., sensing materials like metal oxides can have sheet resistances R_{sheet} from 1 $\mathrm{k}\Omega$ per square up to even 10 $\mathrm{G}\Omega$ $\mathrm{per\ square}$. Hence, even with different electrode aspect ratios, interface circuits can still need to cover a very wide resistance range of, say, 100 Ω/10 $\mathrm{M}\Omega$ (~ 100 dB), which is equivalent to the resolution of a 16 bit A/D converter.

Clearly, the limited operating range of standard CMOS electronics reduces the practical operating resistances of most layers. Traditionally, the very large resistance of sensing films (for example metal oxides) can be reduced by using interdigitated electrodes with high aspect ratios (thousands). The higher the aspect ratio (r) of the electrodes the more they can reduce the resistance (R) of the sensing material, thus

$$R = \frac{R_{\mathrm{sheet}}}{r} \text{ and } r = \frac{nL}{d} \tag{1}$$

where n is the number of fingers of the interdigitated electrode, L is the length of the fingers, and d is the distance between adjacent fingers.

The fabrication of these interdigitated electrodes within a CMOS process can be achieved by exposing the top metal layer during the same process step used for bond pad opening. It is difficult to have high numbers of fingers (narrow pad opening on electrodes or closely spaced pad openings) on a specified area and maintain the design rules provided by the foundry (bond pads are much larger in size compared to pad openings required for interdigitated electrodes). Thus, if the design rules are ignored there is always the possibility of either under-etching (hence poor contact with sensing material) or over-etching (which might cause shorting between different fingers or metal layers) of the passivation layer. It is possible to have higher aspect ratios by omitting the top passivation layer over the electrodes (or removing the passivation over the whole of the sensing area), which will dramatically increase the aspect ratio, but these both break the normal CMOS process flow rules. Interdigitated electrodes of higher aspect ratio can also be fabricated post-CMOS, but will incur additional cost and still require interfacing to the circuitry below. Again, it might be necessary to have electrodes of different aspect ratios to accommodate higher and lower sensing material sheet resistances. This may not be significant in large volumes (as with IC humidity sensors), but in present batch sizes it is still significant. Nevertheless, the interface electronics needs to cover wide dynamic ranges of the sensing material. This makes the design very difficult to ensure that the circuitry keeps the operating voltages within the working range (and it also adds cost). Furthermore, many traditional drive circuits, employing external components, are configured with a trimmed Wheatstone bridge or constant resistance circuit, but in CMOS high value resistors (and capacitors for filters/oscillators) take up large areas on the chip and thus increase the cost greatly. This makes the direct replication of normal "off-chip" circuitry undesirable.

If we consider a generic or universal interface electronic and measurement system, with integrated sensors, as shown in Fig. 1, we can see a series of common blocks.

The number of on-chip electronic blocks and their accuracy depends on the specific requirements and on the gas sensing material. To simplify the discussion we have subdivided the integrated circuits into the two different sensing techniques, which dominate the gas sensor market, namely *resistive* and *electrochemical*.[1] In addition to these gas sensor types, we will consider a number of different heater drive circuits (not required for electrochemical).

[1]We are focussing here on hazardous gases and so have ignored capacitive sensors as often used for humidity.

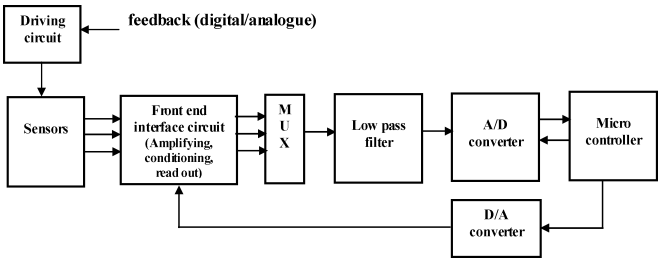

Fig. 1. Sensor array with interface electronics blocks.

IV. Interface Circuits for Resistive Gas Sensors

Chemoresistive gas sensors are based on the change in the electrical conductivity of a gas sensitive layer. This can either be an electronically semiconducting metal oxide (e.g., SnO_2, ZnO, TiO_2) operating at an elevated temperature (typically 200 °C–500 °C) or an electronically conducting polymer (generally operating close to ambient where temperature control is critical to stabilize sensitivity) in the presence of a gas.[2] In the former case, one of the earliest and commercially successful sensors of this type is the Taguchi Gas Sensor (TGS), patented in the early 1970s, and produced by the Japanese company Figaro, Inc. [18]. The high operating and control of temperature for metal oxide sensors allow reasonable specificity to target gases, reaction kinetics are fast ($\sim$ seconds) and the effect of ambient humidity is reduced [19]. In the case of chemoresistive conducting polymers, sensing usually takes place just above ambient (25 °C to 40 °C), so it is well within the operating range of normal integrated electronics. The main components of a chemoresistive gas sensor are typically a heater, temperature sensor and the sensing material. Thus, electronic blocks are required to drive the heater, temperature sensor and sensing material, and also circuits to measure/control the temperature in the sensing area and measure the change in resistance of the sensing material in the presence of a gas or gases.

A. Heater Driving Circuit

Heaters can be driven either by a voltage or current source. Circuits can be designed to provide a source at either a static level (e.g., a dc voltage) or modulated level (e.g., ac or pulsed). In terms of an integrated solution, circuits can operate at a dc level or low hertz because the thermal response of the heater is, at best, some milliseconds; these circuits can be classified as quasi-static. The following conditions need to be met to integrate the driver.

a) *Voltage drive* usually requires a constant voltage supply reference circuit (e.g., bandgap voltage reference). An additional current limiting resistor may be required in series with the microheater to avoid any damage due to spurious high currents [20].
b) *Current drive* usually employs a current mirror circuit; a *cascode* current mirror (which has a larger output resistance compared to an ordinary current mirror) can be used when there is sufficient voltage head room.

In either case, it is desirable to measure the power through the heater (for current drive by measuring the voltage and vice versa for voltage drive) to give an indication of temperature and general operating status.

An *accurate* measurement of the heater resistance requires a four wire measurement, i.e., two leads for current and two to measure the voltage dropped across the heater. This removes any lead resistance from the measurement, giving a more informed indication of the heater functionality. However, a two wire interface offers lower cost, lower heat loss and simplicity and is most commonly reported in the literature and employed in the gas sensor industry today.

B. Temperature Sensors and Interface Circuitry

As discussed earlier, the temperature of the sensing material plays a vital role in improving the selectivity of almost all sensing materials. Thus, to control accurately this temperature, a temperature sensor could be deployed but will add both complexity and costs. Notwithstanding, such sensors, if they themselves are stable over long periods, can make up for poor stability in a heater material, by providing feedback control to a heater drive circuit. In most commercial gas sensors, the change in heater resistance with temperature is used to determine the temperature of the heater itself. However, it can be difficult to measure accurately small changes in resistance when applying high currents to the heater – particularly when it is being driven in a pulse mode. When a pulse mode operating regime is applied, a small constant current source can be used between large voltage pulses (to heat up the sensing material) to measure the temperature of the sensing area. Often designers prefer to use a separate temperature sensor rather than relying on the heater itself, as it allows for an optimized sensor design and gives flexibility in designing interface circuitry without disturbing the heater drive. Usually, either a silicon resistor or a silicon diode is embedded in the heater area and used to measure the temperature of the sensing element. Work carried out at Delft University has shown that a temperature sensitive sensor bipolar transistor (diode-connected bipolar transistor) is possible up to 125 °C. Later work by Santra *et al.* has shown that a silicon diode temperature sensor can be used reliably up to very high temperatures of 550 °C, by employing SOI rather than standard bulk or epi CMOS technology, together with high temperature metalization [21], [22]. Usually temperature sensors need calibration to obtain good accuracy, which will also incur additional costs. The group from Delft reported the improved uncalibrated sensor accuracy by using on-chip circuits. In general, the diode temperature sensor driving circuit is a constant current source. A small current is used ($\sim \mu$A) in order to avoid any self-heating effects. A temperature sensor can also be made from a metal but they require higher currents, due to their low resistivities (which can cause long-term stability issues because of electromigration).

The signal from a temperature sensor is often amplified using an instrumentation amplifier (IA). A popular principle [23], [24] is to have one temperature sensor on a thin membrane (where the heater is embedded) and an identical sensor off the membrane (to offset changes in room temperature and any nonidealities of the temperature sensor). The instrumentation amplifier will therefore amplify the difference of signals coming from these two temperature sensors. Also, the IA can have gain control and offset adjustment from outside the chip.

[2]Ionically conducting zirconia oxygen (Lambda) sensors operate at even higher temperatures and are not considered here.

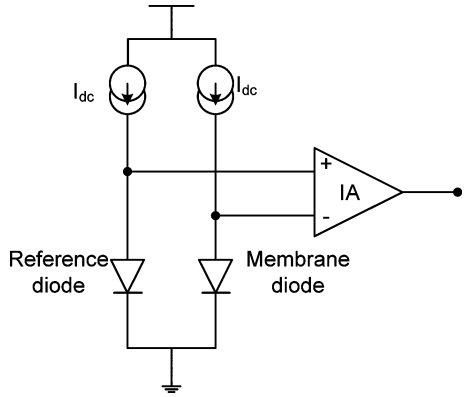

Fig. 2. Schematic circuit for on-chip temperature sensing with silicon diode and IA.

C. Temperature Control of Microheaters

With the incorporation of a heater and temperature sensor, the next obvious question is how to monitor and control the temperature. The amount of power required to maintain a set temperature depends upon ambient conditions, but more importantly, it depends on the nature and thickness of the sensing material. As mentioned above, heaters are driven either with a dc or an ac signal. The latter (e.g., pulse mode heating) has some advantages, e.g., when ultra low power consumption is required, because it allows a reduction in the average power consumption by turning the heater on for short periods of time then off for a considerable amount of time in a periodic cycle, for example taking one measurement every 10 s. Pulse mode heating is usually achieved with a pulse width modulator (PWM). In this configuration a switch is used in series with the microheater. The heating can be controlled in on-off mode (sometimes called a "bang-bang" controller), proportional mode, or Proportional Integral Derivative (PID) mode. In all these cases, a temperature sensor is used to stabilize/control the heater temperature. The on–off controller is the simplest form, where if the microhotplate is cooler than a set-point temperature, the heater is turned on at maximum power, and once it is hotter than the set-point temperature the heater is switched off completely. Cardinali *et al.* [25] designed a simple scheme employing this concept, where Rm is compared with the reference resistor and the power is switched on (off) if Rm is smaller (higher) than $Rref$. The temperature cycle was selected by switching between two reference resistors (specific to two temperatures 150 °C and 400 °C, as shown in Fig. 3), according to the control logic signal.

Malfatti *et al.* [26] proposed a Wheatstone bridge circuit configuration for controlling heater temperature with an on–off technique (as shown in Fig. 4). Here, the temperature sensor was used as one of the branches of the Wheatstone bridge. The circuit is based on a relaxation oscillator implemented by an off chip amplifier and a window comparator. On–off control is very simple and easy to design, but persistent oscillation (jittering) of the process variable can occur and there is a continuous cycling of the controlled variable that can give rise to instability and might, unless controlled carefully, damage the heater due to very rapid changes in voltage (hence temperature). This jitter can be reduced by including hysteresis (deadband) in the design, i.e., a region around the set-point value in which no control action is needed. Barrettino *et al.* [27], [28] proposed a simple proportional temperature controller circuit as shown in Fig. 5. They managed to control the temperature of the membrane from room temperature to 350 °C with a sensitivity of 0.63 °C/mV. The operational amplifier (which contains an integral stabilization capacitor of 8 pF) drives a power transistor that provides current to the polysilicon heater. The inputs of the operation amplifier consist of the control voltage (Vcontrol) and the voltage drop across the temperature sensor. The same group also designed an on chip digital PID controller using an 0.8 μm commercial CMOS process [29]. They digitized

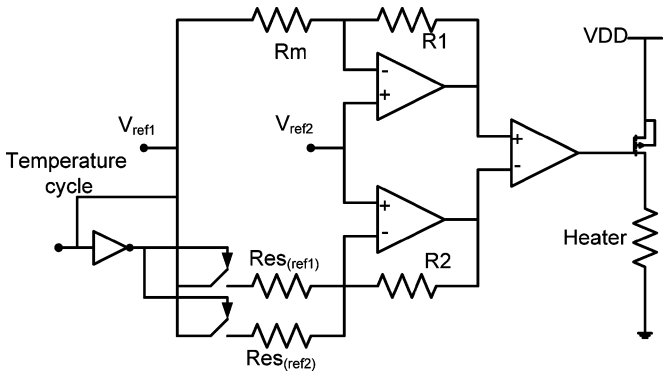

Fig. 3. Schematic of the on–off temperature control loop (adapted from [25]).

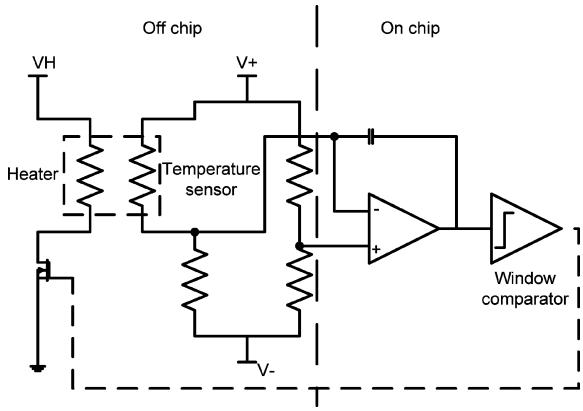

Fig. 4. Wheatstone bridge temperature control schematic (adapted from [26]).

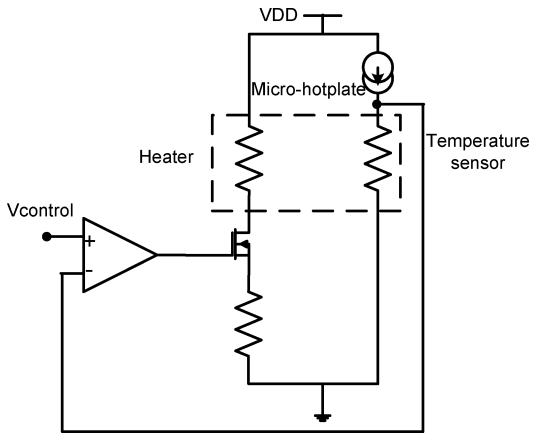

Fig. 5. Schematic of proportional temperature controller circuit (adapted from [27]).

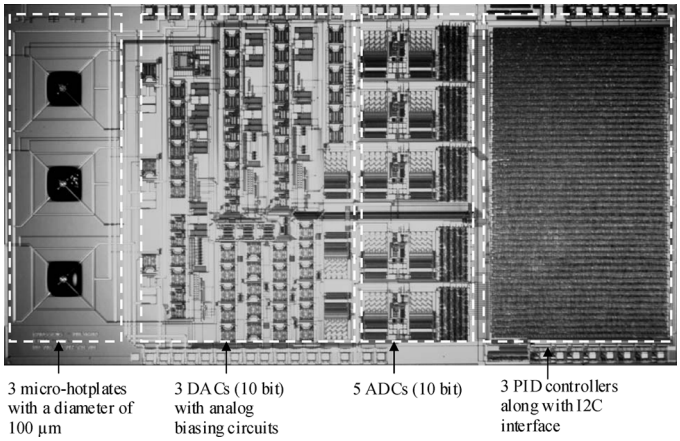

Fig. 6. Micrograph of the integrated sensor chip with microhotplate and CMOS circuitry for signal processing. Reprinted with permission from [29].

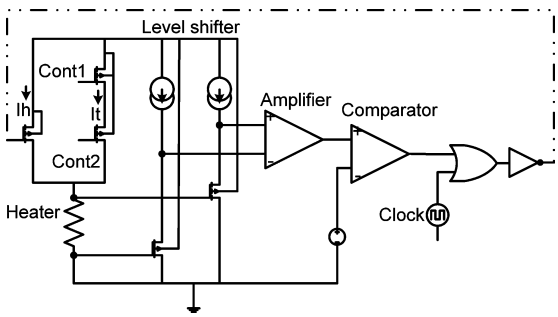

Fig. 7. Bang-bang temperature controller circuit (adapted from [30]).

the temperature sensor reading and compared it with a preset digital temperature value through a PID controller to maintain the heater temperature. Hence, very accurate and stable temperature control of the heater is possible. However, it is rather complicated and not easy in practice to implement. The chip contains an array of three sensors (each sensor contains a polysilicon heater of 100 μm diameter, a polysilicon temperature sensor and aluminium electrodes coated with platinum; the microhotplate was covered with a gas sensing layer of tin dioxide doped with platinum 0.2% by weight with three ADCs and three PID controllers, hence occupying a large area (chip size 4.5 mm $\times$ 5.5 mm). Fig. 6 shows the micrograph of the integrated sensor chip.

A slightly different approach was adopted by Bota *et al.* [30]. They use the same resistor element as the heater and temperature sensor (as shown in Fig. 7). They used a PWM technique, where during the off mode of the heater a small current (It) was driven through the heater to measure its temperature. The main purpose of this circuit is to measure the voltage across the heater, shift it through the level shifter, amplify it through a differential amplifier, and compare it with an external reference that sets the temperature of the heater (via heater resistance). This method minimizes the required voltage headroom and provides a high heating rate (the current ranges from 46 to 100 mA through the heater), though successful, the scheme was power hungry (400 °C required a power consumption of 250 mW) and requires external components to operate.

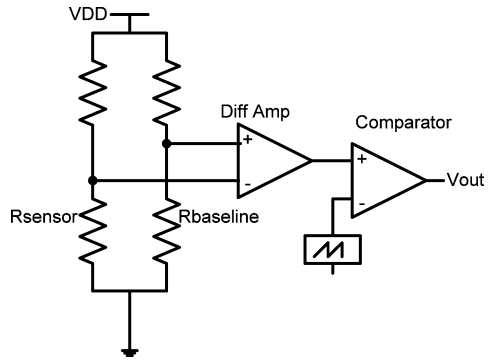

Fig. 8. Chemiresistance to digital conversion circuit scheme (adapted from [35]).

D. Sensing Material Resistance Measurement

The next question is how to interface/drive and measure the resistance changes of the sensing material. The interface electronic circuit must handle the precision and dynamic range that is demanded by the gas sensing element. Once again, the literature reports differing solutions to this problem. The modulation of the sensing materials resistance through the exposure to a gas can be detected accurately by resistance-to-voltage conversion techniques (e.g., a voltage divider or a Wheatstone bridge) if the resistance variations are relatively small. Early work by Shurmer and Gardner *et al.* [31] on odor discrimination with an electronic nose (but not using a CMOS process), made use of the potential divider methodology for the interfacing of chemoresistors. Although potential dividers are a simple circuit to implement, they are not very sensitive to small changes in sensor resistance and require the integration of very large resistors, on the chip, to accommodate the significant variations of resistance of the sensing material. In addition, the circuit output signal is nonlinear (for large variations of resistance cf. reference resistor) when driven by constant voltage. They have also showed a possible linearizing technique to remove the nonlinear output of potential divider. The Wheatstone bridge technique has been employed in the past by Cole *et al.* [32] and Gardner *et al.* [33] as a front end interfacing circuit for conducting polymer chemoresistors. Once more the output is nonlinear with a large resistance swing [34]. Leung *et al.* [35] also designed a Wheatstone bridge configuration for polymer chemoresistive sensors, where they used an active and another identical less-sensitive polymer layer as two arms of a Wheatstone bridge. The result is a differential signal between the baseline and sensing films. This signal is first amplified, through a differential amplifier, and then compared with a saw tooth signal to perform a resistance-to-digital conversion (as shown in Fig. 8). In [36] and [37], Guo *et al.* designed and fabricated (with an in-house 5 μm CMOS process) a simple differential read out circuit (DRC) followed by a voltage shifter and an amplifier to characterize a 4×4 tin oxide-based gas sensor array. The DRC was made of a current source (M3–M6), current sink (M7–M10) and a ratioed inverter (M1–M2) with M1 being the load. This scheme has the potential to make the voltage across the sensor independent of the transistor process parameters and supply voltage variations (as shown in Fig. 9), but required a supply voltage of 10 V to

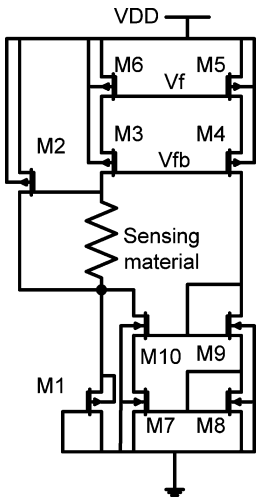

Fig. 9. Differential readout circuit for sensing material interface (adapted from [36]).

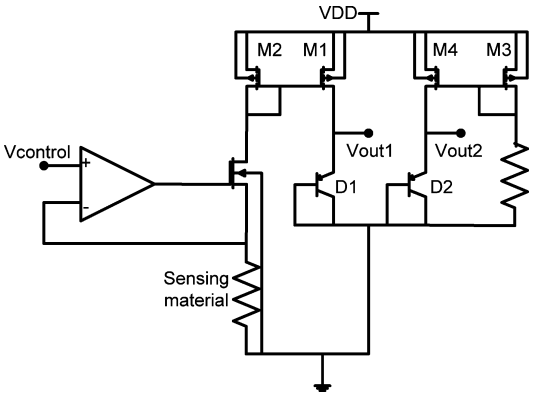

Fig. 10. Logarithmic compression circuit for sensing material interface (adapted from [27]).

cover the wide dynamic range (0 to 20 $\mathrm{M}\Omega$). A logarithmic converter (as shown in Fig. 10) forms the interface circuitry in [27]. The circuit was implemented with a voltage to current converter and a pair of diodes (D1 and D2) connected vertical *pnp* transistors. Although this supports the wide dynamic range due to compression (log scale in diode equation), it loses out on precision (~ 8 bit resolution). Also, the differential voltage across the two diodes is nonlinear because it is a logarithmic function.

In [38], a trans-resistance amplifier followed by an ADC and DSP block were used as an interface circuit (as shown in Fig. 11). In this scheme, the sensor resistance is connected between a dc reference voltage and the op-amp virtual ground – the output voltage (Vo) inaccuracy (which can occur due to baseline drift and offset of amplifier) was removed by a programmable subtracting current generated by a series of resistors. This gives better accuracy than logarithmic conversion, reaching an effective relative resolution over 12 bits. In an alternative approach, the sensor can be placed in an oscillator circuit [30], [39] where the main time constant depends directly upon the sensor resistance. This technique (as shown in Fig. 12) used a 4×1 multiplexer to select one sensor out of an array of four and deployed an external capacitor to cover the wide dynamic range and save space. Thus, this scheme can cover a wide resistance range with regular ADCs because it is not

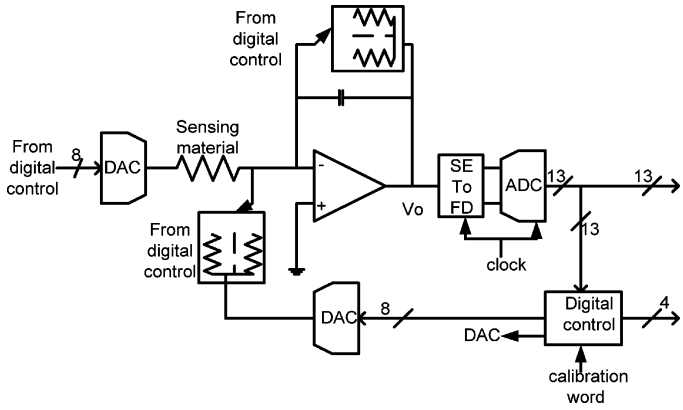

Fig. 11. Reconfigurable circuit for sensor interface (adapted from [38]).

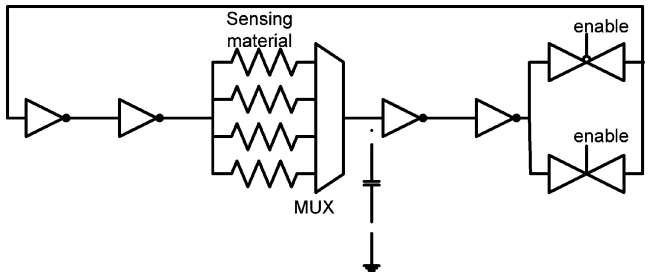

Fig. 12. RC oscillator circuit for sensor interface (adapted from [39]).

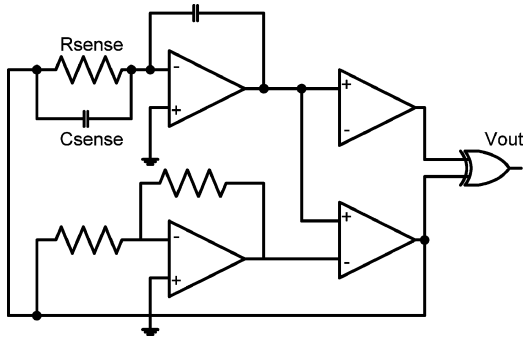

Fig. 13. Sensing material interface circuit in RC oscillator configuration (with provision for parasitic capacitance measurement) (adapted from [40]).

limited by the voltage dynamic range of the analogue circuits, though oscillator accuracy can be affected by the parasitic capacitance of the sensor layer.

In [40] and [41], a resistance-to-frequency converter is used that covers a very high dynamic range, and also gives information on the parasitic capacitance of the sensing material. The basic circuit contains two comparators, an inverting integrator and an EX-OR digital logic block (as shown in Fig. 13). The parasitic capacitor role can be avoided by isolating the sensor resistor from the oscillator portion of the circuit (as shown in Figs. 14 and 15). The circuit structure [35], [42]–[44] for this can be achieved by using the sensing material resistor as a voltage-to-current converter or at the reference arm of a current mirror, and then using that current (as a current mirror) to charge and discharge a capacitor. The capacitor voltage is fed to a Schmitt trigger, which controls the charging (M6)/discharging (M7) switches (as shown in Fig. 15). The resultant square wave output of the Schmitt trigger has its time period proportional to

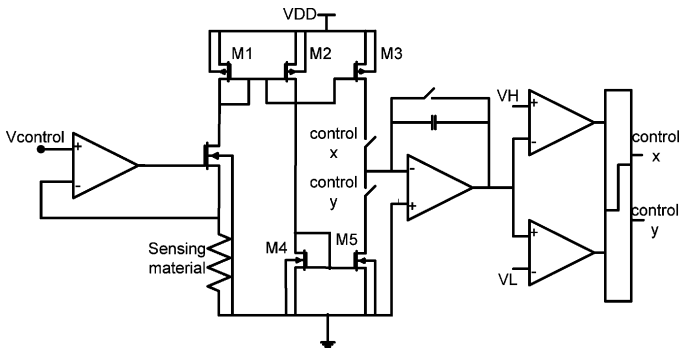

Fig. 14. Resistance controlled oscillator circuit for sensing material interface (adapted from [42]).

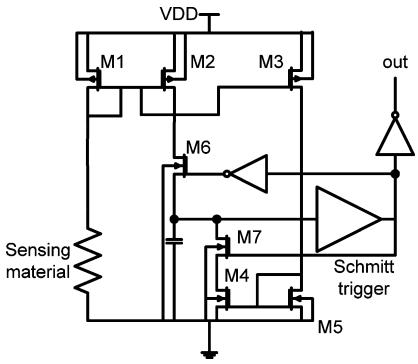

Fig. 15. Resistance to frequency conversion scheme (adapted from [35]).

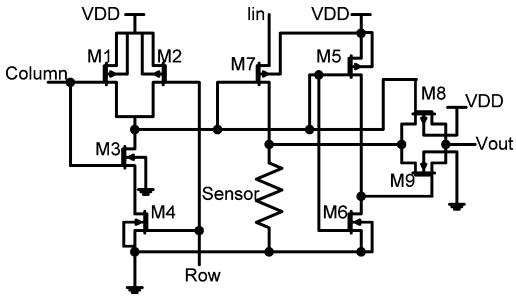

Fig. 16. Schematic for sensor selection (adapted from [45]).

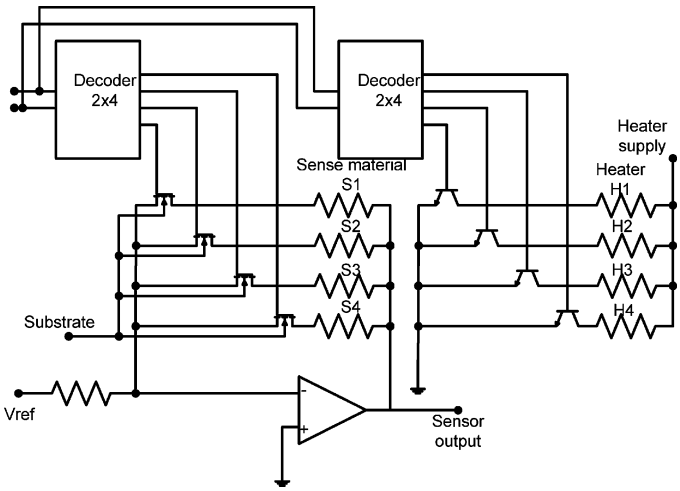

Fig. 17. Scheme of sensor selection through decoder circuit (adapted from [46]).

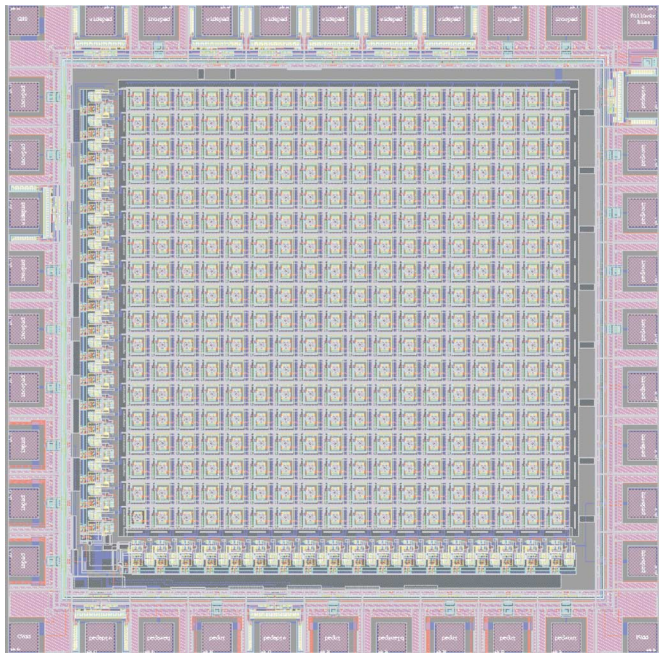

Fig. 18. Photograph of sensor chip with 324 sensor sites (18 × 18 array) after post fabrication electroless gold plating and polymer deposition. Reprinted with permission from [45].

the sensor material resistance. Here, as the sensing resistor is not directly involved in the oscillation path of the circuit and also the voltage across it is dc, the parasitic capacitance can be ignored.

Researchers have also been designing arrays of chemical sensors to improve the overall selectivity of sensors for single and multicomponent gases, e.g., Dickson *et al.* [45] designed a chemical sensor array ($18 \times 18 = 324$ sensor nodes) by combining polymer-based chemoresistors (which does not contain any microheater) with a standard integrated circuit technology to classify different odors. To improve electrical contact (electrodes made of aluminium gets oxidized easily), post CMOS electroless plating was carried out using nickel and gold at die level – this process is sometimes referred to as bump bonding. Fig. 16 shows the scheme of the unit sensor cell, which consists of ROW and COL selection signals (M1 to M4 transistor switches) to select the sensor and read-out circuit in the form of a transmission gate (M5 to M9 transistor switch) – which passes the sensor voltage to a column output bus for amplification and off-chip processing. Similarly, Afridi *et al.* [46] also designed an on-chip array of four sensors with interface electronics. The sensors are in a suspended microhotplate structure (with a 1 ms time constant and $10\,^{\circ}\mathrm{C}/\mathrm{mW}$ thermal efficiency) formed by a bulk micromachining technique. Different sensing films (based on tin oxide and titanium oxide) were grown on post patterned gold electrodes at different temperatures using LPCVD technique. The circuit scheme is shown in Fig. 17. They used a decoder to select one of the microheaters, with a bipolar transistor switch and to select corresponding sensing resistor used a MOSFET switch. The chip layout of Dickson and Afridi is shown in Figs. 18 and 19. A more compact and

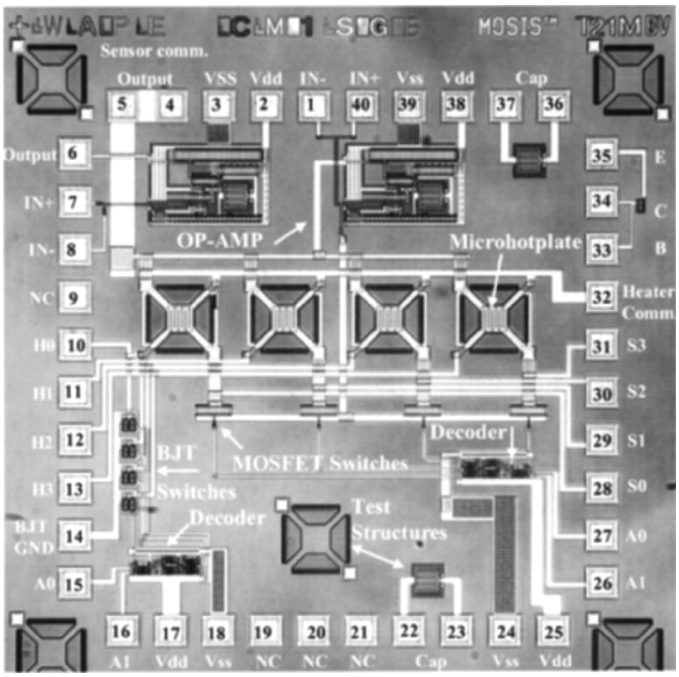

Fig. 19. Micrograph of the integrated gas sensor system. Reprinted with permission from [46].

highly integrated CMOS gas sensor chip was reported by Frey *et al.* The chip ($5.5\,\mathrm{mm} \times 4.5\,\mathrm{mm}$) comprises an array of three metal oxide coated microhotplates with integrated MOS transistor heaters and needed driving and signal conditioning circuitry. They used three PID controllers to enable individual temperature regulation for each hotplate [47].

An additional technique to aid sensitivity is to remove the baseline resistance of the sensing material. This makes the sensor reading more accurate (as you can maximize dynamic range) and reduces the possibility of output saturation in the subsequent signal conditioning amplifier stages. Importantly, it removes baseline drift—a major issue in the field of gas sensors. The rate of baseline drift (through poisoning, aging or a change in morphology) of the sensing layer is generally much slower (days or months) than its reaction to the presence of a gas, hence a baseline compensator needs only to compensate the drift periodically to maintain a near constant baseline value [48]. Researchers provide a number of different techniques to achieve this. The schematic of the sensor interface electronics for cancelling the baseline (dc) signals designed by Koickal *et al.* [49], [50] is shown in Fig. 20 (deployed on an array of 80 sensing elements, employing conducting polymers, using a cell-based design). During the setup phase, each sensor is driven by a small value current source and the voltage across the sensor is digitally stored using a simple counting A/D converter. This stored value is converted back to an analogue signal (using a D/A) and then subtracted from the sensor signal, thus removing the baseline. A more simplified scheme was proposed by Rairigh *et al.* [51] (as shown in Fig. 21). They used an analogue memory to store the baseline voltage and then the baseline cancellation stage was used to remove the baseline value. The change in resistance in the presence of gas was amplified with a gain control differential amplifier. The authors

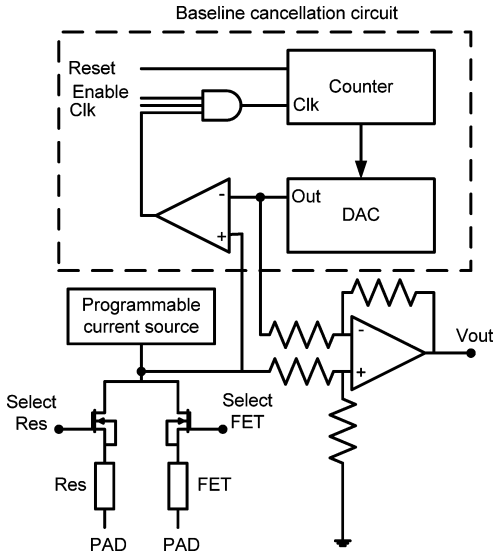

Fig. 20. Schematic for base line removal circuit (adapted from [50]).

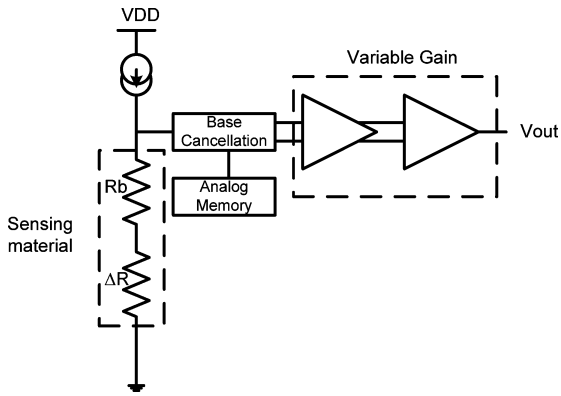

Fig. 21. Baseline cancellation circuit with analogue memory (adapted from [51]).

reported that the conventional approach of using DAC-based analogue memory was not accurate, because it is limited by the resolution of the D to A converter.

The characteristics of various sensors with interface electronics are summarized in Table I.

V. Electrochemical Gas Sensor

One of the most popular and widely available [54], [55] type of gas sensor is the electrochemical gas sensor. Electrochemical sensors can be operated in different modes, namely, *Voltammetric* and *Potentiometric*. In the first case, sensors are based on the measurement of the current-voltage relationship. A potential is applied to the sensor, and a current proportional to the concentration of the electroactive species of interest is measured (*amperometry* is a special case of voltammetry, where the potential is kept constant and current measured). In case of *Potentiometric*, the sensors measure an equilibrium potential difference between a sensing electrode and a reference electrode. Ideally, there is no current flow through the electrodes at equilibrium. The measured potential is proportional to the logarithm of the concentration of the electroactive species (Nernst equation). Liquid electrolytes are commonly used, but solid electrolytes

TABLE I
CHEMORESISTIVE GAS SENSOR WITH INTERFACE ELECTRONICS

Authors	Integrated circuits			Sensing material & target gas	Process	Chip Area No of sensors	Power and temperature rise/mw
	Temperature Control	Sensing material interface	Additional circuits				
Guo *et al.* [36, 37]	-	Differential readout circuit (0-20 MΩ)	Decoder, voltage shifter, subtractor	SnO_2 CH_4, H_2, ethanol, CO	In house 5μm,10V	4x4 sensor array	15.5 mW for heater (300 ºC)
Marcellis *et al.*[41,42]	-	R to T converter (100 kΩ- 100 GΩ)	-	-	3.3V	-	-
Cardinal *et al.*[25]	On-off(at 150 & 400 ºC)	ASIC	Bandgap reference, ΣΔ modulator, control logic etc.	SnO_2 (Pt & Au doped) CO, ethanol	1.2 μm	3 sensors	100 mW for heater (at 450ºC)
Grassi *et al.*[52]	-	Transresistance continuous amplifier (100Ω -20 MΩ) resolution 0.1%	Bias circuit, ADC, DAC, calibration	-	0.35 μm 3.3 V	-	6 mW (max channel power consumed),total 4 channels
Grassi *et al.*[42]	-	Resistance controlled oscillator (1 kΩ-1GΩ)	Schmitt trigger, control logic	SnO_2 (undoped) CO, NO_2,CH_4,ethanol	0.35 μm 3.3 V	-	15 mW (circuit)
Dieguez *et al.*[35]	On-off(ripple <4ºC)	Oscillator circuit (10 kΩ-200MΩ)	Low gain amplifier, comparator, level shifter	-	2.5 μm 5V	-	250 mW (400 ºC)
Barrettino *et al.* [27]	Proportional (27 – 350 ºC) resolution 0.5 ºC	Logarithmic converter	-	SnO_2 CO, CH_4	0.8 μm 5V	1 sensor	4.8ºC/mW
Barrettino *et al.* [29]	(Three) Digital PID resolution 2ºC	Logarithmic converter (1kΩ - 10MΩ)	3 DAC, 5ADC,	SnO_2 (Pd doped)	0.8 μm	3 sensors	10ºC/mW
Frey *et al.* [47]	(Three) Digital PID control	Programmable current source (up to 12 MΩ)	SAR ADC, ΣΔ, DAC,	SnO_2 (Pd doped) CO, CH_4	0.6 μm 5V	3 sensors 4.5x 5.5mm^2	190mW (all three heaters simultaneously to 350ºC)

are also possible in electrochemical gas sensors [56]. The latter usually operate at elevated temperatures as ionic conductors – most solid electrolytes have low ionic conductivity at room temperature but, at a high temperature, electrode reactions proceed at a useful rate. For example, zirconia-based oxygen lambda sensors operate at over 800 °C.

The basic structure consists of two electrodes, but three electrodes [working electrode (WE), reference electrode (RE), and counter electrode (CE)] are better because the addition of a reference electrode removes any wire resistance. The WE is usually made of gold or platinum and consists of a catalytic material, oxide or a porous, hydrophobic polymer. The WE contacts both the electrolyte and the ambient air to be monitored usually via a porous membrane. The gas diffuses into the sensor, through the back of the porous membrane to the working electrode where it is oxidized or reduced. This electrochemical reaction results in an electrical current that passes through the external circuit. In addition to measuring, amplifying and performing other signal processing functions, the external circuit maintains the voltage across the sensor between the working and counter electrodes for a two electrode sensor or between the working and reference electrodes for a three electrode cell. The magnitude of the current is controlled by how much of the target gas is oxidized at the working electrode. Sensors are usually designed so that the gas supply is limited by diffusion and thus the output from the sensor is linearly proportional to the gas concentration. This linear output is one of the advantages of electrochemical sensors over other sensor technologies, (e.g., metal oxide), whose output is approximately a square root power law (Freundlich isotherm) of the concentration. A linear output allows for more precise measurement at low concentrations and much simpler calibration (only the baseline and one point are needed).

Although liquid (and solid) electrochemical gas sensors are a real success story in the chemical sensor market, CMOS integrated versions are still confined to the research level. The heart of the interface circuit required for this is a circuit that holds the potential constant at the working electrode (relative to reference electrode in 3-cell configuration) by varying the current flowing, i.e., a potentiostat. One of the earliest efforts to integrate a potentiostat was carried out by Atkinson *et al.* [57], where the electrode assembly is interfaced via a thick-film hybrid circuit potentiostat. The potentiostat is controlled by a thick-film hybrid circuit voltage ramp generator, also fabricated as a 28-pin DIP [57]. More recently, Strong *et al.* [59] (as shown in Figs. 22 and 23) and Zhang *et al.* [58] (Figs. 24 and 25) showed an integrated electrochemical cell array with on chip interface electronics for biomedical applications. Huang *et al.* [60] proposed an on-chip potentiostat that had the ability to process the long-term electrochemical signals in both the amperometric and potentiometric modes at a remote site. Their architecture is shown in Fig. 26. For wireless transmission they have incorporated the widely used GPRS (General Packet Radio Service) communication system.

A further popular potentiometric technique can be found in gas sensors – these are based on a chemically sensitive *Field Effect Transistor or ChemFET.*

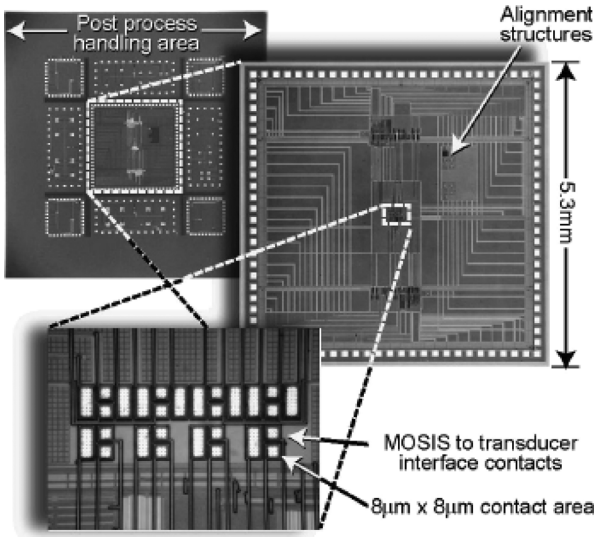

Fig. 22. Photograph of the active neural test die. Reprinted with permission from [59].

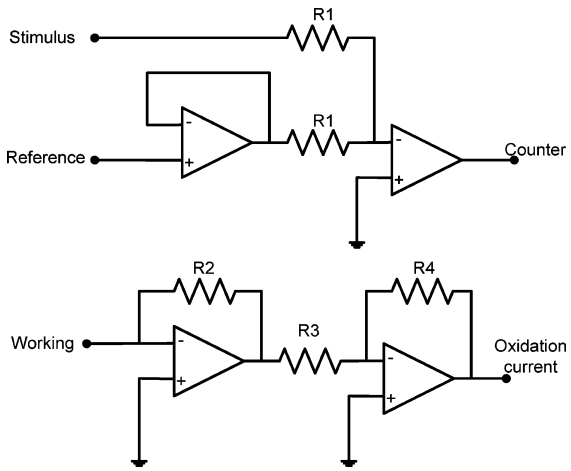

Fig. 23. Simplified schematic for on-chip potentiostat. Reprinted with permission from [59].

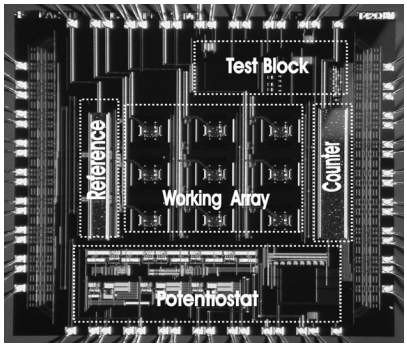

Fig. 24. Die photo of 3 mm × 3 mm electrochemical array chip. Reprinted with permission from [58].

ChemFET sensors are formed by replacing the traditional Al or polysilicon gate of the transistor with a catalytic gate (Pd, Pt, Ir) or a polymer gate [61], which can be solid, suspended or porous. The most studied case for gases is an FET with a Pd gate that is used for H_2 detection. Lundstrom (who was the

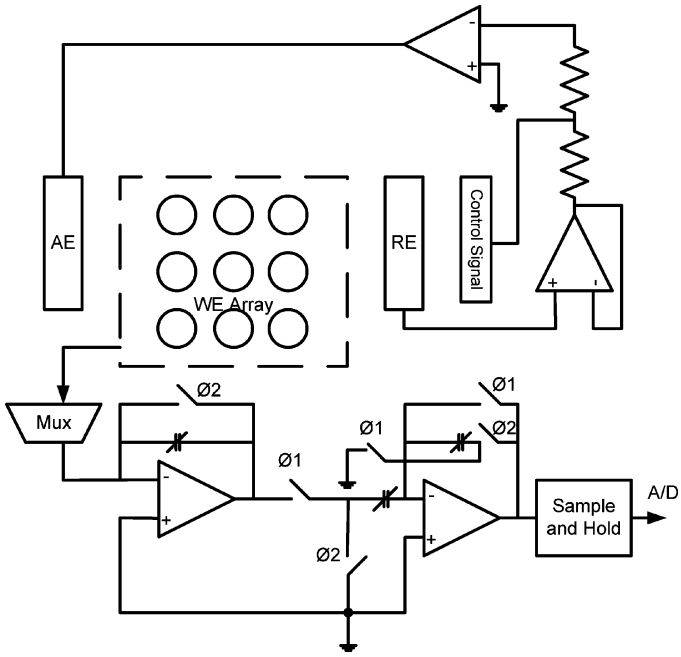

Fig. 25. Configuration of the CMOS potentiostat and on-chip electrochemical array (adapted from [58]).

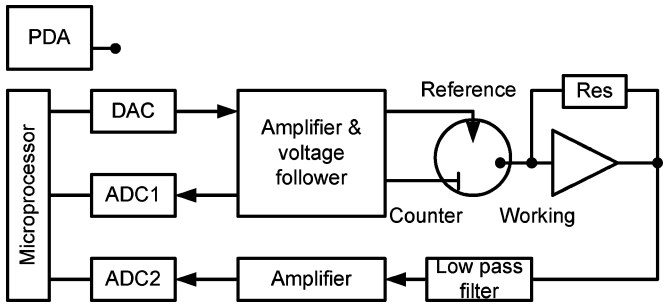

Fig. 26. Circuit diagram of a portable potentiostat (adapted from [60]).

first person to study this kind of gas sensor) and his co-workers discovered that hydrogen dissolved into the Pd gate (at approximately 150°C) and moves to the Pd/SiO_2 interface, forming a dipole layer [62]. The dipole changes the gate potential and hence shifts the I-V characteristics of a MOSFET device. This process is reversible, since the dipole molecule disappears in the absence of the gas and the threshold voltage of the sensor returns to its initial level. ChemFETs are popular because the MOSFET is available within the CMOS process, hence, one can integrate the circuits required for signal conditioning along with sensors, although a post-CMOS step is necessary to expose the gate area. Thus, there have been a number of such devices reported in the literature, including [63], [64]. Furthermore companies, (e.g., Applied Sensor [65] and SenSiC AB [66]), have commercialized ChemFET technique for gas detection.

In case of an ion-selective FET,[3] the gate oxide of the MOSFET is exposed to electrolyte solution with a reference electrode also immersed in the solution. The integration of ISFET with standard CMOS process is not a straightforward task, because the gate insulating region must be in contact with

[3]ISFETs (ion selective FETs) are an important class of chemical sensors in the liquid phase but because this review relates to gas and not ion sensing we only mention them briefly for the sake of completeness.

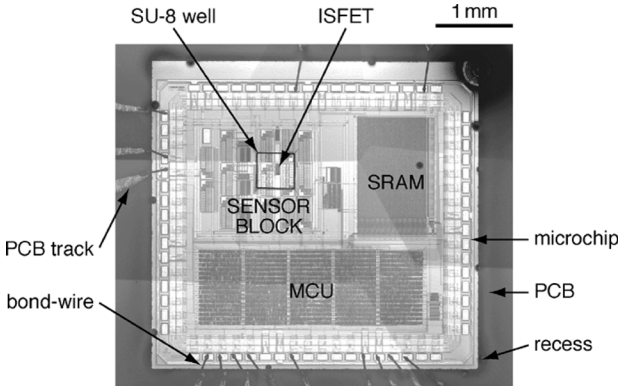

Fig. 27. Micrograph of pH sensor chip layout. Reprinted with permission from [69].

the liquid solution - which is not CMOS compatible because the polysilicon electrode in the gate region is required to define the self-aligned source/drain region of the MOS transistor. However, Bausells *et al.* reported the integration of ISFET with an unmodified standard CMOS process using the silicon oxynitride CMOS passivation layer as a pH sensitive material of the ISFETs [67]. ISFETs are thermally unstable, to reduce this temperature effect Chen *et al.* reported a summation circuit where they combined the −ve slope of p-n diode temperature sensor and +ve slope of ISFET [68]. A more compact and highly integrated ISFET pH sensor was reported from Cummings' group [69], [70]. They developed a system-on-a-chip pH sensor using 3 V standard CMOS process. The ISFET is based on floating gate with analogue interface circuits (with differential sensing facility), programmable voltage reference, ADC, microcontroller unit, and on-chip memory with wireless functionality which can be used as diagnostic capsule. The chip layout is shown in Fig. 27.

VI. Some Comments on Nanomaterials

Gas sensing materials are usually deposited or grown as a post-CMOS process. The main two types of sensing materials are polymers and metal oxides. Polymers and polymer composites are generally deposited onto a substrate using an electrochemical technique or by chemical polymerization. Gardner *et al.* have discussed five probable causes which might contribute to the overall change in conductance of the polymer in presence of gas [71]. Polymers usually react with the gas (or vapor) near room temperature; however some polymers are sensitive towards humidity and also the sensor response can drift with time. Sensing materials in the form of metal oxides (e.g., tin oxide, zinc oxide) have been more extensively studied and exploited because of their superior sensitivity with respect to a variety of gases [72]. Unlike polymers, they need much higher temperature (200 °C–500 °C) for effective reaction with chemical analytes, hence metal oxides consume more power. Also conventional metal oxides in the form of bulk material structures are not effective on gas sensors fabricated on CMOS substrates because of the miniaturized dimensions of the sensors.

In recent years, many researchers have been reporting upon the incorporation of new types of materials called "nanomaterials" (e.g., nanostructured metal oxides [73], carbon nanotubes [74]) onto the CMOS sensing structure in order to increase the gas sensitivity (since nanomaterials have a higher surface to volume ratio) in a miniaturized area. However, it is extremely challenging to grow/deposit material on a CMOS substrate because of the constraint introduced by the latter (e.g., high-temperature annealing $> 400\,^{\circ}\mathrm{C}$ is not suitable due to electromigration and any harsh environment, like using a plasma (if not use gently), can destroy the MEMS structures).

The conventional methods of growing nanomaterials are different forms of chemical vapor deposition (CVD) and hydrothermal deposition. Thermal CVD growth requires the substrates to be heated to a very high temperature (generally more than 500 °C depending on the specific recipe), which may be too high for the on-chip circuitry and internal metal layers to remain intact. Hydrothermal methods usually require a lower temperature (compared to CVD) but care needs to be taken to ensure that the chemicals used do not affect the passivation layers. There is a recent report (published by Santra *et al.*) of using this method for growing zinc oxide nanowires on a fully processed CMOS substrate for ethanol detection [75]. Apart from the above two methods, researchers have also been using commercially available nanomaterials to deposit onto CMOS gas sensor devices by different techniques, such as drop coating, dip coating, inkjet printing, spray coating, spin coating, etc., so that they can avoid the potential harsh environments necessary for nanomaterial growth. Even though these methods are CMOS friendly, often getting the material to adhere to the substrate surface can be difficult and special cleaning/roughening of the substrate is required [76]. Also, deposition using above methods often caused agglomerated bunches of nanostructures and this leads to the poor sensitivity and slow response. Also, these methods have their own problems, e.g., in inkjet printing one needs to use a very dilute solution in order to avoid any nozzle clogging or in case of dip coating one needs to cover bond pads to avoid any chemical contaminations. It is also necessary to mention that some of the above methods (except inkjet printing and drop coating) require conventional lithography approach (i.e., steps like deposition of photoresist, exposure of ultra violet light, liftoff, etc.) or use of some masking process (e.g., shadow mask) to grow/deposit nanomaterials on predefined areas of the chip. Furthermore, the use of these techniques is strictly speaking restricted to low volumes and hence negates the use of CMOS technology. A different approach of depositing nanomaterial using Flame Spray Pyrolysis (FSP) technique has also been reported. This process is quite attractive because it can employ a wide array of precursors compared to conventional vapor-fed flame reactors. Each droplet contains the precursor in the same stoichiometry as desired in the product so a broad spectrum of functional metal and mixed metal oxide nanoparticles can be synthesized applying, e.g., for catalysis, sensors and electroceramics [77]. Recent report of CMOS-compatible wafer-level fabrication process for monolithic CMOS/MEMS sensor systems coated with sensitive layers (SnO_2/Pt layer) using FSP shows very encouraging prospects for batch fabrication of nanomaterials [78].

Apart from nanostructured metal oxides, single walled carbon nanotubes (CNTs) are also gaining popularity as sensing layers,

because they can sense gases at a relatively lower temperature ($< 200\,^{\circ}\mathrm{C}$). However, the gas sensitivity can be much lower compared with metal oxides and it is nonspecific unless functionalized with metal coating (e.g., Pt sputtering) or used in the form of nanocomposites (e.g., with polymer). Some research groups are trying to use a single CNT in an FET configuration (measuring the change in threshold voltage in presence of gas) rather than using CNTs in resistive mode to improve the performance [79], [80]. Other researchers have also been trying to develop mixed metal oxides in the form of nanomaterial to increase sensitivity and selectivity [81], [82].

Thus, although CNTs, metal oxide nanorods, and other nanomaterials can be deposited onto a CMOS gas sensor chip, it still remains to be seen whether they will become commercial successes.

VII. Conclusion and Future Prospects

In this review, we have looked at some common types of solid-state gas sensors and the recent efforts to make integrated versions of them by combining the sensing element and interface circuitry. It is evident that there are numerous issues and constraints that limit our ability to integrate gas sensors with a standard CMOS process and the development of such integrated products requires expertise in many different fields, such as VLSI circuit design, semiconductor chip fabrication, sensor device design and proper packaging, development of highly selective materials, modeling and simulation. However, the integration of sensors and electronics on the same silicon substrate is highly desirable for batch manufacturing (i.e., it leads to a much cheaper unit cost) and it results in a more reliable performance through superior heater control. In addition, multiple and complex analysis can be performed very precisely with on-chip analogue/digital circuits and processors.

We believe that ongoing research (in both industry and academia) will bring significant improvements in sensing and enable the production of these smart devices for mass markets, e.g., automotive. For example, the selectivity of semiconductor gas sensors can be obtained through various methods, such as: the use of filters or chromatographic columns to discriminate between gases on the basis of molecular size or other properties, the use of catalysts and the analysis of transient sensor responses to changes in analyte concentration or sensor temperature. In the last couple of years, the last method has been extensively investigated [83]–[86], which involves controlling the temperature of the semiconductor surface, whether by selecting a fixed temperature to maximize sensitivity to a particular analyte gas or by programming or modulating the temperature – through these a single sensor device can provide the type of selectivity that would otherwise require arrays of various doped fixed temperature sensors. Recently, Iwaki (2007) *et al.* reported a temperature modulation technique to measure the concentration of different vapors in air using a single carbon black/polymer composite resistive sensor [87]. They reported a *fractional transient response*, which was produced from analyzing the temperature transients measured with and without vapors. They found not only that the shape of the fractional difference transient conductance curve depends only on vapor type and so can be used for vapor identification; but also that the amplitude of the fractional difference transient conductance curves is proportional to the concentration of the vapor and so can be used to predict vapor concentration. Moreover, researchers have also been using gas sensor arrays to determine different gas concentrations from multicomponent gases using pattern recognition techniques, based on feature extraction, fuzzy logic, or artificial neural network (ANN) approaches [88]–[91]. Though this kind of analysis requires signal processing algorithms, some emerging intelligent sensors could be integrated with an on-chip Application Specific Integrated Circuit (ASIC) embedded with specific algorithms and thus have the potential to detect more than one gas with a single sensor device.

Recently, there has been increased demand for multigas sensing units and so the realization of hybrid multisensor systems on a single chip (i.e., with different sensors for gas, humidity, and pressure) with the necessary interface electronics is highly desirable and will also be possible in the near future through CMOS technology.

This integration of sensors and circuits also has the major advantage that it reduces the power consumption and hence gives rise to the possibility of their use within handheld, battery-operated devices such as PDAs, mobile phones, and even wrist watches. These markets each offer hundreds of millions of units per year with potential annual sales of billions of dollars!

In conclusion, we believe that the ubiquitous CMOS gas sensor will become a reality in the next decade and we may also see the introduction of new sensing materials from the field of nanotechnology, such as gas sensitive nanotubes, nanorods, or nanofibers.

References

[1] K. D. Wise, "Integrated sensors – interfacing electronics to a non-electronic world," *Sens. Actuators*, vol. 2, no. 3, pp. 229–237, 1982.

[2] H. Baltes and O. Brand, "Progress in CMOS integrated measurement systems," in *Proc. 16th IEEE Instrum. Meas. Technol. Conf.*, Venice, Italy, 1999, pp. 54–59.

[3] J. García-Guzmán, N. Ulivieri, M. Cole, and J. W. Gardner, "Design and simulation of a smart ratiometric ASIC chip for VOC monitoring," *Sens. Actuators B: Chem.*, vol. 95, no. 1–3, pp. 232–243, 2003.

[4] K. D. Wise and K. Najafi, "Microfabrication techniques for integrated sensors and microsystems," *Science*, vol. 254, no. 5036, pp. 1335–1342, Nov. 1991.

[5] C. Hagleitner, A. Hierlemann, D. Lange, A. Kummer, N. Kerness, O. Brand, and H. Baltes, "Smart single-chip gas sensor microsystem," *Nature*, vol. 414, no. 6861, pp. 293–296, Nov. 2001.

[6] A. Hierlemann, D. Lange, C. Hagleitner, N. Kerness, A. Koll, O. Brand, and H. Baltes, "Application-specific sensor systems based on CMOS chemical microsensors," *Sens. Actuators B: Chem.*, vol. 70, no. 1–3, pp. 2–11, Nov. 2000.

[7] M. Graf, D. Barrettino, M. Zimmermann, A. Hierlemann, H. Baltes, S. Hahn, N. Barsan, and U. Weimar, "CMOS monolithic metal-oxide sensor system comprising a microhotplate and associated circuitry," *IEEE Sensors J.*, vol. 4, no. 1, pp. 9–16, Feb. 2004.

[8] J. W. Gardner, M. Cole, and F. Udrea, "CMOS gas sensors and smart devices," in *Proc. IEEE Sensors*, Orlando, FL, 2002, pp. 721–726.

[9] [Online]. Available: http://mnt.globalwatchonline.com/epicentric_portal/site/MNT/

[10] [Online]. Available: http://www.sensirion.com/en/00_home/00_home.htm

[11] S. Joo and R. B. Brown, "Chemical sensors with integrated electronics," *Chem. Rev.*, vol. 108, no. 2, pp. 638–651, Feb. 2008.

[12] A. Hierlemann and H. Baltes, "CMOS-based chemical microsensors," *Analyst*, vol. 128, no. 1, pp. 15–28, 2003.

[13] A. Hierlemann, O. Brand, C. Hagleitner, and H. Baltes, "Microfabrication techniques for chemical/biosensors," *Proc. IEEE*, vol. 91, pp. 839–863, Jun. 2003.

[14] S. Z. Ali, F. Udrea, W. I. Milne, and J. W. Gardner, "Tungsten-based SOI microhotplates for smart gas sensors," *J. Microelectromech. Syst.*, vol. 17, pp. 1408–1417, Dec. 2008.

[15] T. Iwaki, J. A. Covington, J. W. Gardner, F. Udrea, C. S. Blackman, and I. P. Parkin, "SOI-CMOS based single crystal silicon micro-heaters for gas sensors," in *Proc. IEEE Sensors Conf.*, Daegu, South Korea, 2007, pp. 460–463.

[16] F. Maloberti and P. Malcovati, "Microsystems and smart sensor interfaces: A review," *Analog Integr. Circuits Signal Process.*, vol. 15, no. 1, pp. 9–26, 1998.

[17] C. C. Enz and G. C. Temes, "Circuit techniques for reducing the effects of op-amp imperfections: Autozeroing, correlated double sampling, and chopper stabilization," *Proc. IEEE*, vol. 84, pp. 1584–1614, 1996.

[18] [Online]. Available: http://www.figarosensor.com/

[19] J. W. Gardner, V. K. Varadan, and O. O. Awadelkarim, *Microsensors MEMS and Smart Devices*. Chichester, U.K.: Wiley, 2001, pp. 282–297.

[20] M. Graf, D. Barrettino, H. Baltes, and A. Hierlemann, *CMOS Hotplate Chemical Microsensors*. New York: Springer-Verlag, 2007, pp. 87–89.

[21] G. C. M. Meijer, "Thermal sensors based on transistors," *Sens. Actuators*, vol. 10, no. 1–2, pp. 103–125, Sep.-Oct. 1986.

[22] S. Santra, P. K. Guha, S. Z. Ali, I. Haneef, F. Udrea, and J. W. Gardner, "SOI diode temperature sensor operated at ultra high temperatures – A critical analysis," in *Proc. IEEE Sensors Conf.*, Lecce, Italy, 2008, pp. 78–81.

[23] F. Udrea, J. W. Gardner, D. Setiadi, J. A. Covington, T. Dogaru, C. C. Lu, and W. I. Milne, "Design and simulations of SOI CMOS microhotplate gas sensors," *Sens. Actuators B: Chem.*, vol. 78, no. 1–3, pp. 180–190, 2001.

[24] P. K. Guha, S. Z. Ali, C. C. C. Lee, F. Udrea, W. I. Milne, T. Iwaki, J. A. Covington, and J. W. Gardner, "Novel design and characterisation of SOI CMOS micro-hotplates for high temperature gas sensors," *Sens. Actuators B: Chem.*, vol. 127, no. 1, pp. 260–266, 2007.

[25] G. C. Cardinali, L. Dori, M. Fiorini, I. Sayago, G. Faglia, C. Perego, G. Sberveglieri, V. Liberali, F. Maloberti, and D. Tonietto, "A smart sensor system for carbon monoxide detection," *Analog Integr. Circuits Signal Process.*, vol. 14, no. 3, pp. 275–296, Nov. 1997.

[26] M. Malfatti, D. Stoppa, A. Simoni, L. Lorenzelli, A. Adami, and A. Baschirotto, "A CMOS interface for a gas-sensor array with a 0.5%-linearity over 500 k Ω -to-1 G Ω range and $+/-2.5$ °C temperature control accuracy," in *Proc. IEEE Int. Solid-State Circuits Conf.*, San Francisco, CA, 2006, p. 10.

[27] D. Barrettino, M. Graf, M. Zimmermann, A. Hierlemann, H. Baltes, S. Hahn, N. Barsan, and U. Weimar, "A smart single-chip micro-hotplate-based chemical sensor system in CMOS-technology," in *Proc. Int. Symp. Circuits and Systems*, 2002, pp. 157–160.

[28] D. Barrettino, P. Malcovati, M. Graf, S. Hafizovic, and A. Hierlemann, "CMOS-based monolithic controllers for smart sensors comprising micromembranes and microcantilevers," *IEEE Trans. Circuits Syst. I*, vol. 54, no. 1, pp. 141–152, 2007.

[29] D. Barrettino, M. Graf, S. Hafizovic, S. Taschini, C. Hagleitner, A. Hierlemann, and H. Baltes, "A single-chip CMOS micro-hotplate array for hazardous-gas detection and material characterization," in *Proc. Int. Solid-State Circuit Conf.*, San Francisco, CA, 2004, pp. 312–313.

[30] S. A. Bota, A. Dieguez, J. L. Merino, R. Casanova, J. Samitier, and C. Cane, "A monolithic interface circuit for gas sensor arrays: Control and measurement," *Analog Integr. Circuits Signal Process.*, vol. 40, pp. 175–184, 2004.

[31] H. V. Shurmer and J. W. Gardner, "Odor discrimination with an electronic nose," *Sens. Actuators B: Chem.*, vol. 8, no. 1, pp. 1–11, Apr. 1992.

[32] M. Cole, J. W. Gardner, A. W. Y. Lim, P. K. Scivier, and J. E. Brignell, "Polymeric resistive bridge gas sensor array driven by a standard cell CMOS current drive chip," *Sens. Actuators B: Chem.*, vol. 58, no. 1–3, pp. 518–525, 1999.

[33] J. W. Gardner, M. Vidic, P. Ingleby, A. C. Pike, J. E. Brignell, P. Scivier, P. N. Bartlett, A. J. Duke, and J. M. Elliott, "Response of a poly(pyrrole) resistive micro-bridge to ethanol vapor," *Sens. Actuators B: Chem.*, vol. 48, no. 1–3, pp. 289–295, 1998.

[34] K. Arshak, G. Lyons, L. Cavanagh, and S. Clifford, "Front-end signal conditioning used for resistance-based sensors in electronic nose systems: A review," *Sensor Rev.*, vol. 23, no. 3, pp. 230–241, 2003.

[35] C. K. Leung and D. M. Wilson, "Integrated interface circuits for chemiresistor arrays," in *Proc. IEEE Int. Symp. Circuits and Systems*, Kobe, Japan, 2005, pp. 5914–5917.

[36] B. Guo and A. Bermak, "A differential readout circuit for tin oxide gas sensor array," in *Proc. 2005 IEEE Conf. Electron Devices and Solid-State Circuits,* , Kowloon, Hong Kong, 2005, pp. 635–638.

[37] B. Guo, A. Bermak, P. C. H. Chan, and G.-Z. Yan, "A monolithic integrated 4×4 tin oxide gas sensor array with on-chip multiplexing and differential readout circuits," *Solid-State Electron.*, vol. 51, no. 1, pp. 69–76, 2007.

[38] M. Grassi, P. Malcovati, and A. Baschirotto, "A high-precision wide-range front-end for resistive gas sensors arrays," *Sens. Actuators B*, vol. 111–112, pp. 281–285, 2005.

[39] J. L. Merino, S. A. Bota, R. Casanova, A. Dieguez, C. Cane, and J. Samitier, "A reusable smart interface for gas sensor resistance measurement," *IEEE Trans. Instrum. Meas.*, vol. 53, pp. 1173–1178, 2004.

[40] A. De Marcellis, A. Depari, G. Ferri, A. Flammini, D. Marioli, V. Stornelli, and A. Taroni, "Uncalibrated integrable wide-range single-supply portable interface for resistance and parasitic capacitance determination," *Sens. Actuators B: Chem.*, vol. 132, no. 2, pp. 477–484, 2008.

[41] A. De Marcellis, A. Depari, G. Ferri, A. Flammini, D. Marioli, V. Stornelli, and A. Taroni, "A CMOS integrable oscillator-based front end for high-dynamic-range resistive sensors," *IEEE Trans. Instrum. Meas.*, vol. 57, no. 8, pp. 1596–1604, Aug. 2008.

[42] M. Grassi, P. Malcovati, and A. Baschirotto, "A 141-dB dynamic range CMOS gas-sensor interface circuit without calibration with 16-bit digital output word," *IEEE J. Solid-State Circuits,* , vol. 42, no. 7, pp. 1543–1554, 2007.

[43] M. Grassi, P. Malcovati, and A. Baschirotto, "Wide-range integrated gas sensor interface based on a resistance-to-number converter technique with the oscillator decoupled from the input device," in *Proc. IEEE Int. Symp. Circuits and Systems*, Kos Isl, Greece, 2006, pp. 4395–4398.

[44] B. Jayaraman and N. Bhat, "High precision 16-bit readout gas sensor interface in 0.13 μm CMOS," in *Proc. Int. Symp. Circuits and Systems*, New Orleans, LA, 2007, pp. 3071–3074.

[45] J. A. Dickson and R. M. Goodman, "Integrated chemical sensors based on carbon black and polymer films using a standard CMOS process and post-processing," in *Proc. Int. Symp. Circuits and Systems*, Geneva, Switzerland, 2000, pp. 341–344.

[46] M. Y. Afridi, J. S. Suehle, M. E. Zaghloul, D. W. Berning, A. R. Hefner, R. E. Cavicchi, S. Semancik, C. B. Montgomery, and C. J. Taylor, "A monolithic CMOS microhotplate-based gas sensor system," *IEEE Sensors J.*, vol. 2, pp. 644–655, Dec. 2002.

[47] U. Frey, M. Graf, S. Taschini, K. U. Kirstein, and A. Hierlemann, "A digital CMOS architecture for a micro-hotplate array," *IEEE J. Solid-State Circuits*, vol. 42, pp. 441–450, Feb. 2007.

[48] S. McKennoch and D. M. Wilson, "Electronic interface modules for solid-state chemical sensors," in *Proc. IEEE Sensors 2002*, Orlando, FL, 2002, pp. 344–349.

[49] T. J. Koickal, A. Hamilton, S. L. Tan, J. Covington, J. W. Gardner, and T. Pearce, "Smart interface circuit to ameliorate loss of measurement range in chemical microsensor arrays," in *Proc. IEEE Instrum. Meas. Technol. Conf.*, Ottawa, ON, Canada, 2005, pp. 548–550.

[50] T. J. Koickal, A. Hamilton, S. L. Tan, J. A. Covington, J. W. Gardner, and T. C. Pearce, "Analog VLSI circuit implementation of an adaptive neuromorphic olfaction chip," *IEEE Trans. Circuits Syst. I*, vol. 54, no. 1, pp. 60–73, 2007.

[51] D. Rairigh, A. Mason, M. P. Rowe, and E. T. Zellers, "Baseline resistance cancellation circuit for high resolution thiolate-monolayer-protected gold nanoparticle vapor sensor arrays," in *Proc. Int. Symp. Circuits and Systems*, Seattle, WA, 2008, pp. 2002–2005.

[52] M. Grassi, P. Malcovati, and A. Baschirotto, "A 0.1% accuracy 100 Ω-20 M Ω dynamic range integrated gas sensor interface circuit with 13+4 bit digital output," in *Proc. 31st Eur. Solid-State Circuits Conf.*, Grenoble, France, 2005, pp. 351–354.

[53] A. Dieguez, J. L. Merino, R. Casanova, S. A. Bota, J. Samitier, M. J. Lopez, J. A. Plaza, I. Gracia, and C. Cane, "A CMOS monolithically integrated gas sensor array with electronics for temperature control and signal interfacing," in *Proc. Annu. Conf. IEEE Ind. Electron. Soc.*, Seville, Spain, 2002, pp. 2727–2732.

[54] [Online]. Available: http://www.customsensorsolutions.com

[55] [Online]. Available: http://www.detcon.com/electrochemical01.htm

[56] P. Jasinski, "Solid-state electrochemical gas sensors," *Mater. Sci. Poland*, vol. 24, no. 1, pp. 269–278, 2006.

[57] J. K. Atkinson, S. S. Shahi, M. Varney, and N. Hill, "A thick-film electrochemical instrument," *Sens. Actuators B: Chem.*, vol. 4, no. 1–2, pp. 175–181, May 1991.

[58] J. Zhang, Y. Huang, N. Trombly, C. Yang, and A. Mason, "Electrochemical array microsystem with integrated potentiostat," *IEEE Sensors*, vol. 1 and 2, no. 1–2, pp. 381–385, 2005.

[59] T. D. Strong, S. M. Martin, R. F. Franklin, and R. B. Brown, "Integrated electrochemical neurosensors," in *Proc. IEEE Int. Symp. Circuits and Systems*, Kos Isl, Greece, 2006, pp. 4110–4113.
[60] C. Y. Huang, Y. C. Wang, H. C. Chen, and K. C. Ho, "Design of a portable potentiostat for electrochemical sensors," in *Proc. Intelligent Sensors, Sensor Networks and Information Processing Conf.*, Melbourne, Australia, 2004, pp. 331–336.
[61] J. A. Covington, J. W. Gardner, D. Briand, and N. F. de Rooij, "A polymer gate FET sensor array for detecting organic vapors," *Sens. Actuators B*, vol. 77, no. 1–2, pp. 155–162, 2000.
[62] I. Lundstroem, S. Shivaraman, C. Svensson, and L. Lundkvist, "Hydrogen-sensitive MOS field effect transistor," *Appl. Phys. Lett.*, vol. 26, no. 2, pp. 55–57, 1975.
[63] J. L. Rodriguez, R. C. Hughes, W. T. Corbett, and P. J. McWhorter, "Robust, wide range hydrogen sensor," in *Proc. IEEE Int. Electron Devices Meeting*, San Francisco, CA, 1992, pp. 521–524.
[64] R. C. Hughes, D. J. Moreno, M. W. Jenkins, and J. L. Rodriguez, "The response of the Sandia robust wide range hydrogen sensor to H /sub 2/-O/sub 2/ mixtures," in *Tech. Dig. Solid-State Sensor and Actuator Workshop*, Hilton Head Island, SC, 1994, pp. 57–60.
[65] [Online]. Available: http://www.appliedsensor.com/
[66] [Online]. Available: http://www.sensic.se/
[67] J. Bausells, J. Carrabina, A. Errachid, and A. Merlos, "Ion-sensitive field-effect transistors fabricated in a commercial CMOS technology," *Sens. Actuators B*, pp. 56–62, 1998.
[68] Y. L. Chin, J. C. Chou, T. P. Sun, W. Y. Chung, and S. K. Hsiung, "A novel pH sensitive ISFET with on chip temperature sensing using CMOS standard process," *Sens. Actuators B*, vol. 76, pp. 582–593, 2000.
[69] P. A. Hammond, D. Ali, and D. R. S. Cumming, "Design of a single-chip pH sensor using a conventional 0.6-μm CMOS process," *IEEE Sensors J.*, vol. 4, pp. 706–712, Dec. 2004.
[70] P. A. Hammond, D. Ali, and D. R. S. Cumming, "A system-on-chip digital pH meter for use in a wireless diagnostic capsule," *IEEE Trans. Biomed. Eng.*, vol. 52, pp. 687–694, 2005.
[71] J. W. Gardner, P. N. Bartlett, and K. F. E. Pratt, "Modeling of gas-sensitive conducting polymer devices," *Proc. IEEE Circuits Devices and Systems*, vol. 142, no. 5, pp. 321–333, Oct. 1995.
[72] I. Simon, N. Barsan, M. Bauer, and U. Weimar, "Micromachined metal oxide gas sensors: Opportunities to improve sensor performance," *Sens. Actuators B: Chem.*, vol. B73, no. 1, pp. 1–26, Feb. 2001.
[73] S. Santra, S. Z. Ali, P. K. Guha, P. Hiralal, H. E. Unalan, S. H. Dalal, J. A. Covington, W. I. Milne, J. W. Gardner, and F. Udrea, "CMOS alcohol sensor employing ZnO nanowire sensing films," in *Proc. 13th Int. Symp. Olfaction and Electronic Nose*, Brescia, Italy, 2009, pp. 119–122.
[74] F. Udrea, S. Maeng, J. W. Gardner, J. Park, M. S. Haque, S. Z. Ali, Y. Choi, P. K. Guha, S. M. C. Vieira, H. Y. Kim, S. H. Kim, K. C. Kim, S. E. Moon, K. H. Park, W. I. Milne, and S. Y. Oh, "Three technologies for a smart miniaturized gas-sensor: SOICMOS, micromachining, CNTs challenges and performance," in *Proc. IEEE Int. Electron Devices Meeting*, Washington, DC, 2007, pp. 831–834.
[75] S. Santra, S. Z. Ali, P. K. Guha, P. Hiralal, H. E. Unalan, S. H. Dalal, J. A. Covington, W. I. Milne, J. W. Gardner, and F. Udrea, "CMOS alcohol sensor employing ZnO nanowire sensing films," in *Proc. 13th Int. Symp. Olfaction and the Electronic NoseOlfaction and Electronic Nose*, Brescia, Italy, 2009, pp. 119–122.
[76] F. Udrea, S. Santra, P. K. Guha, S. Z. Ali, J. A. Covington, W. I. Milne, J. W. Gardner, and S. Maeng, "Nanotubes and nanorods on CMOS substrates for gas sensing," in *Proc. 13th Int. Symp. Olfaction and Electronic Nose*, Brescia, Italy, 2009, pp. 19–26.
[77] H. K. Kammler, L. Madler, and S. E. Pratsinis, "Flame synthesis of nanoparticles," *Chem. Eng. Technol.*, vol. 24, no. 6, pp. 583–596, Jun. 2001.
[78] S. Kuhhe, M. Graf, A. Tricoli, F. Mayer, S. E. Pratsinis, and A. Hierlemann, "Wafer-level flame-spray-pyrolysis deposition of gas-sensitive layers on microsensors," *J. Micromech. Microeng.*, vol. 18, no. 3, p. 10, Mar. 2008.
[79] J. Kong, N. R. Franklin, C. W. Zhou, M. G. Chapline, S. Peng, K. J. Cho, and H. J. Dai, "Nanotube molecular wires as chemical sensors," *Science*, vol. 287, no. 5453, pp. 622–625, Jan. 2000.
[80] T. Helbling, R. Pohle, L. Durrer, C. Stampfer, C. Roman, A. Jungen, M. Fleischer, and C. Hierold, "Sensing NO_2 with individual suspended single-walled carbon nanotubes," *Sens. Actuators B: Chem.*, vol. 132, no. 2, pp. 491–497, 2008.
[81] M. Ferroni, D. Boscarino, E. Comini, D. Gnani, V. Guidi, G. Martinelli, P. Nelli, V. Rigato, and G. Sberveglieri, "Nanosized thin films of tungsten-titanium mixed oxides as gas sensors," *Sens. Actuators B: Chem.*, vol. 58, no. 1–3, pp. 289–294, 1999.
[82] T. Anukunprasert, C. Saiwan, E. Di Bartolomeo, and E. Traversa, "Nanostructured TiO2-based mixed metal oxides prepared using microemulsions for carbon monoxide detection," *J. Electroceramics*, vol. 18, no. 3–4, pp. 295–303, Aug. 2007.
[83] A. Heilig, N. Barsan, U. Weimar, M. Schweizer-Berberich, J. W. Gardner, and W. Gopel, "Gas identification by modulating temperatures of SnO2-based thick film sensors," *Sens. Actuators B*, vol. 43, pp. 45–51, 1997.
[84] T. A. Kunt, T. J. McAvoy, R. E. Cavicchi, and S. Semancik, "Optimization of temperature programmed sensing for gas identification using micro-hotplate sensors," *Sens. Actuators B: Chem.*, vol. 53, no. 1–2, pp. 24–43, 1998.
[85] D. C. Meier, J. K. Evju, Z. Boger, B. Raman, K. D. Benkstein, C. J. Martinez, C. B. Montgomery, and S. Semancik, "The potential for and challenges of detecting chemical hazards with temperature-programmed microsensors," *Sens. Actuators B: Chem.*, vol. 121, no. 1, pp. 282–294, 2007.
[86] A. P. Lee and B. J. Reedy, "Temperature modulation in semiconductor gas sensing," *Sens. Actuators B: Chem.*, vol. 60, no. 1, pp. 35–42, 1999.
[87] T. Iwaki, J. A. Covington, and J. W. Gardner, "Identification of different vapors using a single temperature modulated polymer sensor with a novel signal processing technique," *IEEE Sensors J.*, vol. 9, pp. 314–328, 2007.
[88] S. Xiajing, S. Lu, W. Lingyan, and Z. C. Jian, "Responses of nanostructured sensing array to mixed VOCs: Feature extraction and pattern recognition analysis," in *Proc. 7th IEEE Int. Conf. Nanotechnology*, Hong Kong, 2008, pp. 1058–1061.
[89] K. A. Ngo, P. Lauque, and K. Aguir, "High performance of a gas identification system using sensor array and temperature modulation," *Sens. Actuators B: Chem.*, vol. 124, no. 1, pp. 209–216, Jun. 2007.
[90] L. Meegahapola, J. P. Karunadasa, K. Sandasiri, D. Tharanga, and D. Jayasekara, "Fuzzy logic and artificial neural network approaches in odor detection," in *Proc. 2nd Int. Conf. Information and Automation*, Colombo, Srilanka, 2006, pp. 92–97.
[91] X. J. Shi, L. Y. Wang, N. Kariuki, J. Luo, C. J. Zhong, and S. Lu, "A multi-module artificial neural network approach to pattern recognition with optimized nanostructured sensor array," *Sens. Actuators B: Chem.*, vol. 117, no. 1, pp. 65–73, Sep. 2006.

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