CMOS SINGLE-CHIP MULTISENSOR GAS DETECTION SYSTEM

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ABSTRACT

We present a novel single-chip smart chemical microsensor system fabricated using industrial CMOS technology and post-CMOS micro machining. It combines three different micromachined transducers (mass-sensitive, capacitive, and calorimetric) all of which rely on polymeric coatings as sensitive layers to detect airborne volatile organic compounds (VOC). A temperature sensor is included to account for the strong temperature dependence of volatile absorption in polymers. Integration of microelectronics and micromechanical components on the same chip allows for controlling of the sensor functions, and enables on-chip signal conditioning that drastically improves the sensor performance. The circuitry includes biasing, amplification, and a serial interface to transmit data to off-chip recording units. The chip forms an integral part of a handheld chemical sensor unit to discriminate and quantify VOC's.

INTRODUCTION

Two major trends govern current chemical gas sensor research: (a) the search for highly selective (bio)chemical layer materials, and (b) the use of arrays of different partially selective sensors with subsequent pattern recognition and multi-component analysis [1]. The chip developed in this work comprises three transducers that respond to fundamentally different analyte properties. The first transducer responds to the mass of the absorbed analyte, the second to the heat of absorption and the third responds to a combination of the dielectric properties of the analyte and the swelling of the polymer. Arrays of identical chips coated with different partially selective polymer layers enable the quantitative and qualitative analysis of gas mixtures in real-time. The cointegration of signal-conditioning circuitry together with the sensors in CMOS-MEMS technology is ideally suited to realize such multisensor systems due to features such as a minimum number of connections, arrays of sensors on a single three wire bus, direct read-out by any micro-controller via this serial bus-interface, self-test functions, and power-management capabilities. The miniaturization of the system reduces the volume of the measurement chamber and therefore decreases the response time of the system.

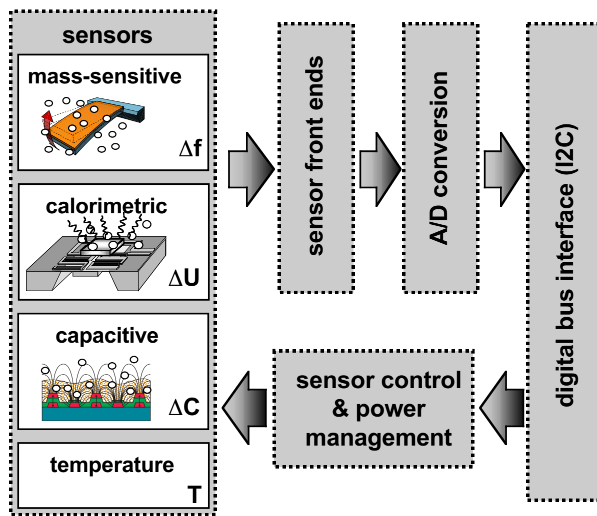

Figure 1: Schematic of the overall microsystem architecture comprising sensors, biasing and signal conditioning circuitry, analog/digital converters, sensor control and power management unit, and a digital interface.

MULTISENSOR SYSTEM

Fig. 1 shows a block diagram of the chip. The mass-change is recorded as a resonance frequency change of a polymer-coated silicon cantilever made from the n-well of the CMOS process [2]. Polysilicon resistors are used to thermally excite the cantilever making use of the bimorph effect due to the layer-

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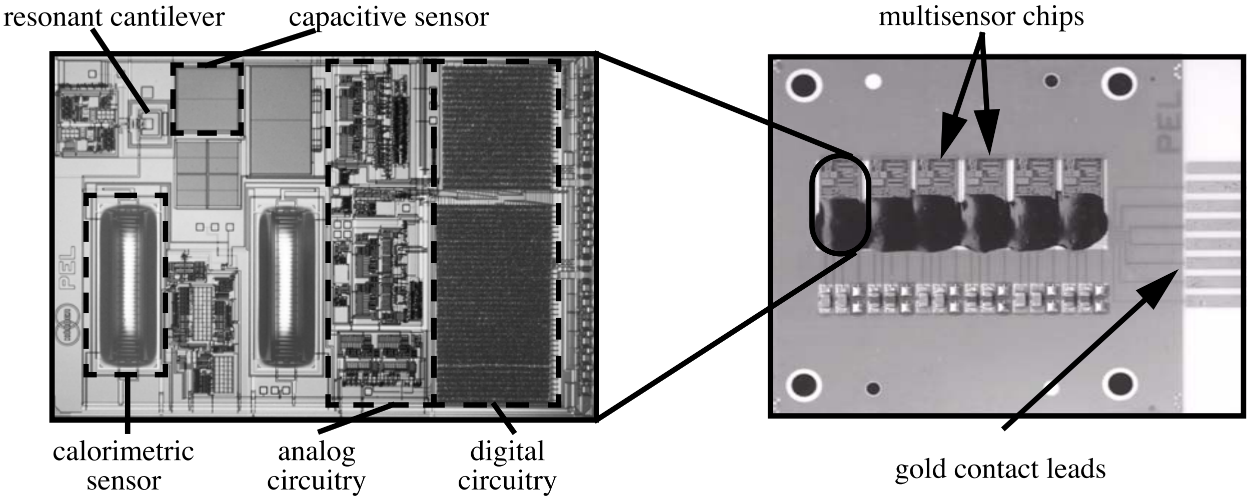


Figure 2: Ceramic substrate with six multisensor chips and close-up view of a single chip.

sandwich of silicon and the dielectric layers. A piezoresistive Wheatstone-bridge made from diffused resistors detects the vibrations. This way, the cantilever can be used as the frequency determining element of an oscillation circuit. The change in resonance frequency is then assessed using an on-chip counter.

The dielectric properties are measured by monitoring the capacitance change of a polymer-coated interdigitated capacitor upon volatile absorption in the polymer. The capacitance change can be positive or negative according to the difference between the dielectric constants of analyte and polymer. A second-order switched capacitor ΣΔ-modulator is used to convert the difference between the sensing capacitor and an insensitive reference into a digital bitstream by incorporating them both into the input stage of a second-order switched capacitor ΣΔ-modulator. This bitstream is then decimated by a counter.

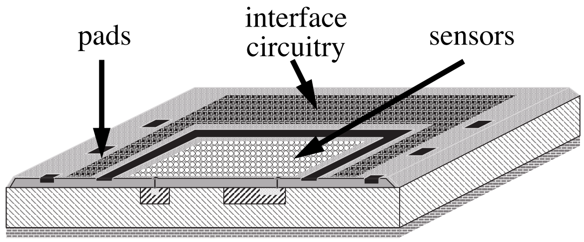
The calorimetric sensor detects enthalpy changes upon absorption (heat of condensation) or desorption (heat of vaporization) of analyte molecules in the polymer. The enthalpy changes result in temperature changes on a thermally insulated n-well island. An array of 256 polysilicon/aluminum thermocouples is used to measure the resulting temperature difference between the suspended membrane and the bulk silicon chip. The difference between the signals of a polymer-coated membrane and an uncoated reference membrane is first amplified by a low-noise chopper amplifier with a programmable gain of up to 8000. An overall resolution of 13 bits is obtained after A/D-conversion and decimation filter.

The temperature sensor is based on the fact that the difference between the base-emitter voltage of two bipolar transistors is proportional to absolute temperature (PTAT). In a standard CMOS process, two bipolar transistors are available: A vertical pnp-transistor with the collector tied to ground and a lateral pnp-transistor using a polysilicon gate to create two p-diffusions with a small separation inside an n-well. The vertical transistor was chosen in this design because it has less parasitic effects and better reproducibility. The temperature of the chip does not need to be recorded at a high rate. Therefore, the A/D-converter and decimation filter is shared with the calorimetric sensor in order to save area.

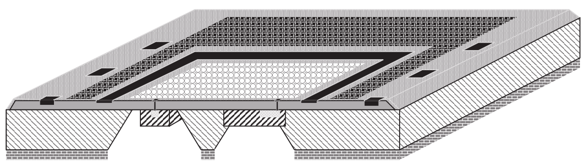
The on-chip circuitry includes a serial interface (I^2C, [3]) to transmit the digital values to an off-chip data port. Up to sixteen chips can be simultaneously connected to the I^2C-bus. Furthermore a digital controller for power management, timing of the data transmission, and setting of the calibration parameters was included on the chip.

FABRICATION AND PACKAGING

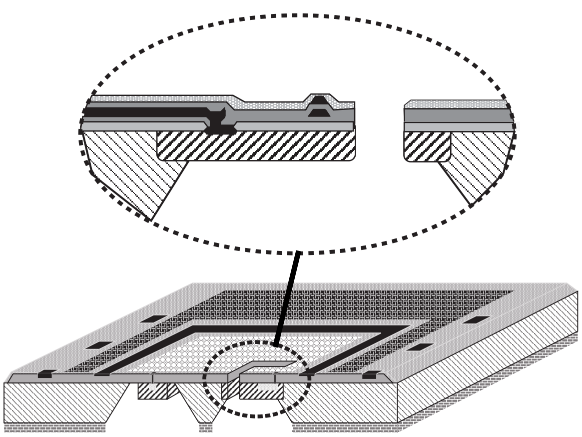
The circuitry and the basic sensor elements (thermocouples, heating resistors, piezoresistive Wheatstone-bridge, etc.) are fabricated in an industrial 0.8 μm CMOS-technology provided by austriamicrosystems, Austria. The pad-etch of the CMOS process can be used to remove the passivation on top of the capacitive sensor. Finally the wafers are thinned to a thickness of 380 μm and a silicon-nitride layer that serves as a mask for the subsequent etching is deposited on the backside. After comple-



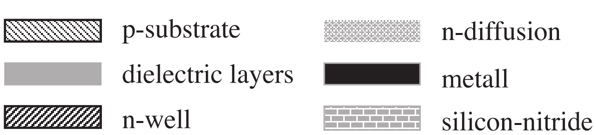
a) CMOS wafer thinned to 380 µm with silicon-nitride layer on the backside



b) KOH etching from the backside with electro-chemical etchstop at the n-well of the CMOS process



c) Two RIE steps are necessary to release the cantilever: One to remove the remaining dielectric layers and a second to etch through the n-well



d) legend

Figure 3: Post-CMOS processing sequence for the multisensor system.

tion of the industrial CMOS process sequence, the n-well-membrane for the mass-sensitive device and the thermally insulated island structure for the calorimetric sensor are released simultaneously (see Fig. 3c). This is done by anisotropic silicon etching with KOH from the back of the wafer with an electrochemical etch stop technique that stops at the n-well of the CMOS process. Next, the silicon cantilever is released by two subsequent Reactive Ion Etching (RIE) steps as shown in Fig. 3c. The wafers are then diced using a protective foil on the front-side to protect the microstructures. After exposure with UV-light, the foil has no adhesion to the silicon microstructures and can be removed without damage. Three masks are needed for the silicon-micromachining, one for the KOH-etching and two for the release of the cantilevers.

Two different packaging methods for the gas sensor system were developed. The first method is a chip-on-board solution where six identical chips (5 x 7 mm) are die-attached on a common ceramic substrate (see Fig. 2). Electrical interconnects are made by wire bonding. The wire bonds and the circuitry are protected with a glob top. Finally, the sensing structures of each chip are spray-coated with a different polymer using a shadow mask.

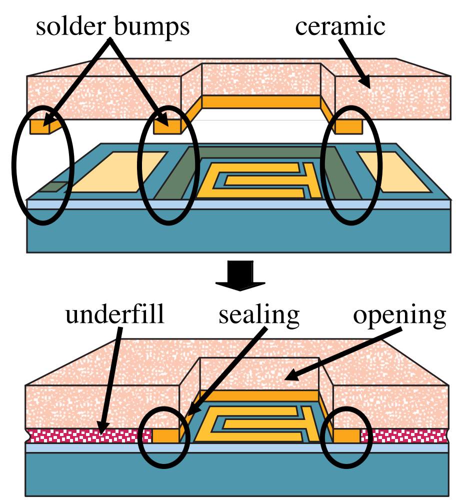


Figure 4: Schematic of flip-chip packaging.

Alternatively, a flip-chip packaging scheme for the chemical sensors on the ceramic substrate has been developed (see Fig. 4). Laser cutting is used to open a window for the sensors in the ceramic substrate. Then, the electric connections are screen-printed on the ceramic. A soft solder paste is applied to the ceramic using stencil printing. Before dicing the wafers, the metallic frame surrounding the sensors and the pads are covered with nickel/gold bumps. Then a glass wafer is bonded to the backside of the wafer to prevent gas-flow through the opening of the cantilever. After dicing, six chips are flip-chip mounted on the ceramic substrate and a reflow at

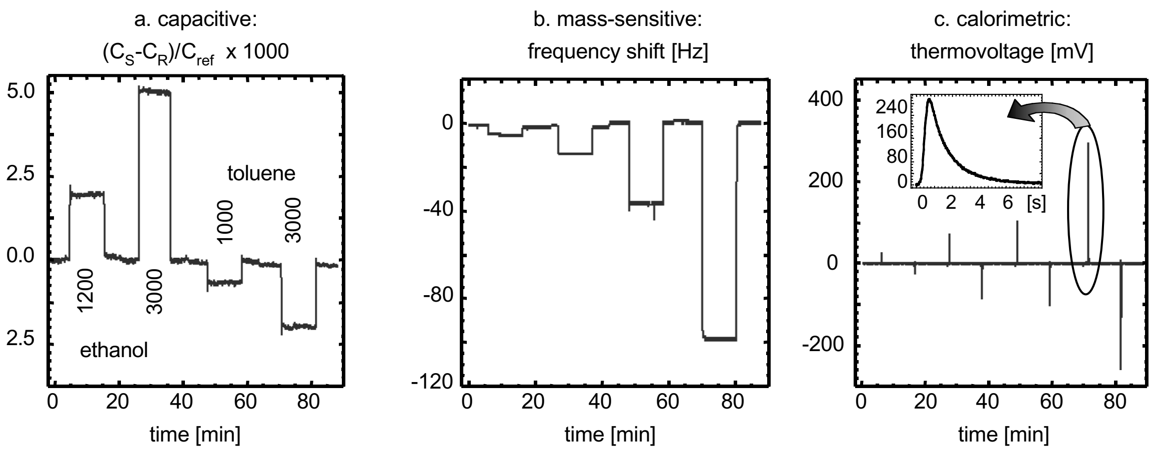


Figure 5: Sensor signals simultaneously recorded from all three polymer-coated transducers upon exposure to 1200 and 3000 ppm of ethanol and 1000 and 3000 ppm of toluene at 301 K: (a) frequency shifts (Sigma-Delta converter output) of the capacitor, (b) frequency shifts of the resonating cantilever, and (c) thermovoltage transients of the calorimetric sensor. The close-up shows the development of the calorimetric transient within 6s.

230°C is performed. Finally, an epoxy-based underfill is applied and cured at 160°C. The sensors are then coated with different polymers using a drop-coating method developed at the University of Tübingen.

The advantage of the packaging with glob top protection is its simplicity. The flip-chip packaging reduces the volume of the gas flow system, isolates the circuitry from the gas-flow, and provide a better reliability.

MEASUREMENTS

The system has been characterized in a computer-controlled flow-setup by periodically switching between analyte-loaded and pure air. The data were recorded and analyzed using a microcontroller board. Fig. 5 shows measurement results of a chip coated with Polyetherurethane (PEUT) upon exposure to 1200 and 3000 ppm of ethanol and 1000 and 3000 ppm of toluene. The sensor responses provided by the different transducers are sufficiently diverse to allow for reliable analyte identification or quantification. Together with a miniaturized flow unit the system has been assembled into a handheld chemical sensor unit. Using the hand-held unit, we have successfully performed recognition of various solvents as it is required for workplace-safety applications.

ACKNOWLEDGEMENTS

The authors are greatly indebted to former staff of the Physical Electronics Laboratory at ETH Zurich involved in the chemical microsensor development. The services of the prototype manufacturer austriamicrosystem, Austria are gratefully acknowledged. This work forms part of a cooperation project involving the University of Tübingen (Dr. U. Weimar), the University of Bologna (Prof. M. Rudan), and ETH Zürich, which is financially supported by the Körber Foundation, Hamburg, Germany.

REFERENCES

[1] A. Hierlemann, A. Koll, D. Lange, C. Hagleitner, N. Kerness, O. Brand, and H. Baltes, "Application-Specific Sensor Systems Based on CMOS Chemical Microsensors", Sensors & Actuators B, vol. 70, pp. 2 - 11, 2000.

[2] T. Müller, T. Feichtinger, G. Breitenbach, M. Brandl, O. Brand, and H.Baltes, "Industrial Fabrication Method for Arbitrarily Shaped Silicon N-well Micromechanical Structures", Proc. 11th IEEE Workshop on Micro Electro Mechanical Systems, pp. 240 - 245, 1998.

[3] Philips Semiconductors, "http://www.semiconductors.philips.com/buses/i2c/facts".