16.1 A CMOS Multi-Parameter Biochemical Microsensor with Temperature Control and Signal Interfacing

Erik Y. Lauwers, Jan Suls, Geert Van der Plas, Erik Peeters, Walter Gumbrecht¹, David Maes², Filip Van Steenkiste², Georges G. Gielen, Willy M. Sansen

Katholieke Universiteit Leuven, Leuven, Belgium

¹Siemens AG, Erlangen, Germany

²Imec, Heverlee, Belgium

A fully-integrated multi-parameter microsensor chip is for use in continuous monitoring of concentrations of blood gases (pH, pO₂, pCO₂), ions, biomolecules and for conductometric measurements. The chip monitors up to 7 different chemical substances depending on the membranes deposited on the sensor units (on-chip ISFETs, amperometric and conductometric cell). The sensors, positioned in a flow channel, are surrounded by on-chip interfacing and processing electronics so that external readout is via a simple data-acquisition card. In addition, temperature control of the measured fluids and a one-time-use security check are provided for proper operation. Fabrication is in a standard 1.2µm CMOS process to which extra post-processing steps are added for the chemical sensors and membranes. The 25.7mm² chip operates at 5V. Full integration is obtained including the ISFETs and ISFET buffers, as well as a reference electrode structure, all integrated on one chip in the same technology.

The integrated microsensor system is divided in three parts (Figure 16.1.1). One part contains the sensors and their interfacing electronics. A second part contains the temperature control function and an EPROM. The third part contains all the control electronics for the chip, external communication, and the biasing. The EPROM is imperative in medical applications to indicate that the device has not been used. Temperature control is important for reproducibility and stability. The number of external connections is limited to 7. The chip has eight integrated sensors indicated by letters on the die photograph: six ion sensitive field effect transistors or ISFETs (b, c, d, e, f and g), one oxygen sensor (h) and one conductometric sensor (a). The conductometric sensor is built with two parallel sensors sharing one (middle) electrode. The ISFETs can be used to measure the voltages between the conductometric electrodes allowing a four-point conductometric measurement. More information on the backend processing for the sensors is given in Reference 1. Selective-membrane dispensing techniques to give each sensor a specific functionality are explained in Reference 2. No external reference electrodes are used based on a design described in Reference 3. A bypass structure traps some calibration fluid on top of the reference ISFET during the calibration cycle. During measurement this calibration solution remains in place while all other ISFETs see the fluid being measured.

The gate voltage of the ISFET is buffered and sent to the monitor for analysis. For stable operation, the drain to source voltage of the ISFET must be constant. Both operations are combined in an ISFET buffer with low offset, which is a modified symmetrical OTA with pMOS source follower (Figure 16.1.2). The ISFET and its buffer are integrated in one process and on the same device, for more stable operation. By introducing the bootstrap transistors T2a,b using the same technology as T1a,b, i.e. with an oxide-nitride gate dielectric and a Pt-gate, the drain-source voltages over transistors T1a,b are kept constant. The pMOS source follower T5 is added to match the input and output voltage swing and to lower the output impedance.

In Figure 16.1.3, a schematic of the potentiostatic setup is given for an amperometric measurement. The voltage at the counter

electrode is regulated so the reference electrode is kept in the same operating point V_{set} as for the ISFETs. By changing the input voltage V_{IN}, the potential at the working electrode is set to induce an electrochemical, Faradaic current. This current is then converted and amplified to a voltage through a feedback resistor R_f. A value of 10MΩ is used to convert a 100nA input current into a 1V output signal. The complete set-up of Figure 16.1.3 is integrated on chip.

To keep the on-chip temperature constant, a heat-regulating loop including temperature-sensing and heating devices are integrated. The temperature-sensing device is a parasitic vertical pnp bipolar transistor connected as a diode, through which the current is kept constant to make V_{EB} linearly dependent on the temperature. The thermal pole (on the order of seconds) is the dominant pole of the feedback control system. The heating device is integrated as well and generates up to 0.25W.

To bring the analog signals off chip, a rail-to-rail line driver (Figure 16.1.4) is also integrated. The current of the two complementary input differential pairs is summed and amplified. The output stage is a modified Miller opamp stage [4]. The dynamic linearity error depends on the operating range of the individual sensors, and for the temperature measurement signal V_{BE}, for example, it is below 1mV.

Figure 16.1.5 shows results of an amperometric oxygen measurement, performed on two different packaged sensors. Through the V_{set} and V_{IN} inputs, the working electrode is set at a voltage of -0.6V versus the reference electrode. When the oxygen concentration in the fluid is varied, a linear relation of about 25mV/10%[O₂] full scale can be observed at the output voltage of the IV-Ota. The difference in slope between measurements is explained by membranes that are deposited manually on these prototype devices (clark-type O₂-sensor).

Next, a measurement of the potassium concentration using an ISFET with a K⁺-selective membrane is given. In Figure 16.1.6, the output of the ISFET buffer connected directly to a plotter (bypassing the multiplexer) is shown. Hence the absence of an absolute voltage level in the figure. It can clearly be seen that the output voltage follows the potassium concentration according to:

$$E = Cte + 53.10^{-3} \log[K^{+}] \quad (1)$$

This is close to the theoretical slope of 59mV/log[K⁺]. The response time is typically within one minute.

Strong points of the system chip include low pin count, on-chip integrated ISFETs and ISFET buffers, temperature control and built-in security EPROM. In addition, the same system allows up to 7 different measurements. Measurements prove functionality of the system and the feasibility of the integration of multiple chemical sensors on one chip, including the interfacing electronics.

References:

- [1] F. Van Steenkiste et al., "A biochemical CMOS integrated multi-parameter microsensor", Proc. of Transducers, p.1188, 1999
- [2] C. Jorgensen et al., "Fully automated membrane dispensing in nl. scale and its application in sensor manufacturing", Proc. of SPIE, vol.3857, p.207, 1999
- [3] W. Gumbrecht et al., "Integrated pO₂, pCO₂, pH sensor system for online blood monitoring", Sensors and Actuators B, 8-19, 1994, p.704
- [4] M. Steyaert et al., "A High-Dynamic-Range CMOS opamp with low-distortion output structure", IEEE Journal of Solid-State Circuits, vol.22, Dec.1987, p1204

Figure 16.1.1: Sensor chip block diagram.

Figure 16.1.2: ISFET buffer schematic.

Figure 16.1.3: Schematic view of the potentiostatic setup.

Figure 16.1.4: Rail-to-rail line driver (biasing circuit not drawn).

Figure 16.1.5: Amperometric measurement of O_2 on a fully-packaged device.

Figure 16.1.6: Measured plotter output voltage of a fully-packaged K⁺-sensor.

Figure 16.1.7: Sensor chip die micrograph.