Modeling and Simulation of Silicon Microsystem of Chemical Signals

Marcin Daniel, Michal Szermer, Krzysztof Slusarczyk, Andrzej Napieralski

Department of Microelectronics & Computer Science, Technical University of Lodz
Al. Politechniki 11, 93-590 Lodz, POLAND, daniel@dmcs.p.lodz.pl

ABSTRACT

The purpose of this paper is to introduce the new approach to the integrated microsystem oriented for water monitoring. Nowadays it becomes extremely important to analyze and estimate the chemical composition of water. Presented microsystem is an important part of the complex monitoring system that in future is going to be set up in Europe. It bases on the two major parts. First one is the microsensor part which the sensor of chemical signal is included in. Second part of the microsystem is responsible for acquiring and processing of the signal from the sensor. It consists of the preprocessing part and analogue/digital conversion part, which bases mainly on the analogue/digital sigma – delta converter. The whole design of microsystem was simulated in ELDO (Mentor Graphics) environment in which the behavioral model of ISFET as well as model of processing part was implemented. Afterwards verification of this part was performed in ELDO simulator.

Keywords: CHEMFET, VHDL–AMS, MEMS, MICROSYSTEM, CADENCE

1 INTRODUCTION

During last years an increase of interest of silicon microsystems has been denoted. They can be often found in many different industrial realizations. The development was possible due to new micromachine technologies. In this article, the idea of the new microsystem of chemical signals is presented. Mentioned microsystem can be divided into two major parts. The first one is the sensor part in which various ion-sensitive sensors (ISFET/CHEMFET) can be included. The second part consists of the processing units. It consists of analogue to digital converter as well as additional electronics circuits for example operational amplifiers, memories, buffers etc.

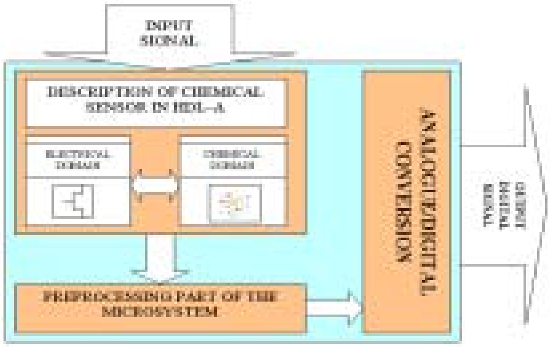

Figure 1: Block scheme of the microsystem

To obtain the results of the measurement the external noise should be minimized. This can be achieved by using the module that converts analogue signals into digital, which is much more resistant to external interference and can be easily used in further computer calculations. For proper design of silicon microsystem, specialized CAD software is required i.e. CADENCE, which allows to design the scheme and layout of the microsystem and simulation of A/D converters. It is also necessary to use ELDO simulator for appropriate modeling the whole microsystem.

The proper modeling of the microsystem requires the multidomain simulator in which all parts of the microsystem can be modeled and simulated together. For that reason the ELDO simulator was used. The CHEMFET sensor is modeled with HDL-A – built in the ELDO environment. Besides the results of modeling of CHEMFET in the new standard VHDL–AMS are presented and further compared with HDL–A model. The data processing circuits are simulated as it was mentioned above in ELDO simulator. Moreover this part of microsystem was simulated also in SPICE and SPECTRES. Both simulators are available in CADENCE environment. Simulation results are presented in this paper.

2 MODEL OF THE SENSOR

The CHEMFET **CHE**mically **M**odified **F**ield **E**ffect **T**ransistor has been described in the literature [1,2,3]. The aim of work of such sensor is to transform the chemical signal carried by the concentration of particular chemical compounds in the tested solution into electrical domain. CHEMFET consists of two main parts. First one – the semiconductor part bases on standard MOS transistor while the second one is the ion–selective membrane responsible for chemical signal detection.

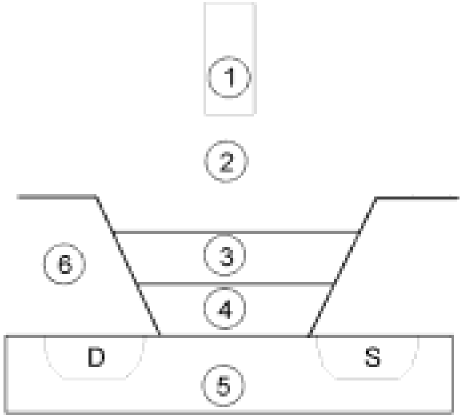

Figure 2: Cross–section of CHEMFET sensor

where:
1 – reference electrode
2 – tested solution
3 – ion–selective membrane
4 – reference solution (polyHEMA)
5 – MOS structure
6 – pasivation

As it can be seen (fig. 1) the structure of CHEMFET remains simple MOS transistor with modified gate circuit where metallic gate contact is replaced by the reference electrode, measured electrolyte and ion–selective membrane [1]. Let us now consider the MOS equation:
For linear and saturation region respectively:

$$I_D = \mu_n \cdot \frac{W}{L} \cdot C_{ins} \cdot (V_{GS} - V_T - 0.5 \cdot V_{DS}) \cdot V_{DS} \tag{2.1}$$

$$I_D = 0.5 \cdot \mu_n \cdot \frac{W}{L} \cdot C_{ins} \cdot (V_{GS} - V_T) \tag{2.2}$$

Changes in the structure of MOS presented above effects the threshold voltage of MOS transistor. The factor connected with the metal gate is replaced by factors connected with the reference electrode, electrolyte and ion–selective layer.

Original MOS threshold equation:

$$V_T = \Phi_{ms} - \frac{Q_{ins}}{C_{ins}} - \frac{Q_{inv}}{C_{ins}} + 2\Phi_F \tag{2.3}$$

Modified CHEMFET threshold voltage equation:

$$V_T = E_{ref} - E_M - \Phi_s - \frac{Q_{ins}}{C_{ins}} - \frac{Q_{inv}}{C_{inv}} + 2\Phi_F \tag{2.4}$$

Where:
E_{ref} – reference electrode potential
E_M – membrane potential
_$_F$ – Fermi potential
_$_S$ – silicon work function
_$_M$ – metal work function
C_{ins} – insulator capacitance per unit area
Q_{ins} – charge per unit area in the insulator
Q_{inv} – charge per unit area in the inversion layer

_$_{ms}$ = _$_M$ − _$_S$ (2.5)

Now consider the factors that modified the equation (2.3). E_{ref} remains independent on the concentration of ions in the tested solution and from the CHEMFET's point of view the most important factor is membrane potential (fig. 3) E_M [2].

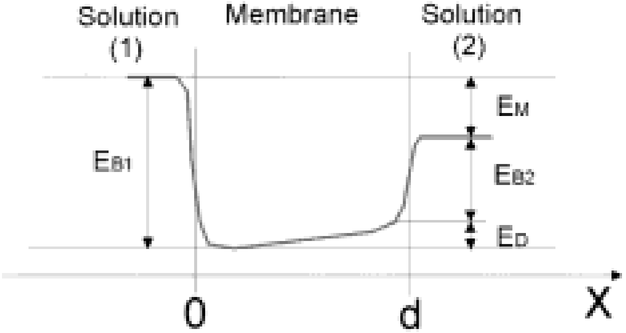

Figure 3: Schematic representation of potential distributions of a solution – membrane – solution system

Membrane potential can be expressed as:

$$E_M = E_{B1} - E_{B2} + E_D \tag{2.5}$$

Where:
E_{B1} – boundary potential solution(1)–membrane
E_{B2} – boundary potential membrane–solution(2)
E_D – diffusion potential
E_M – membrane potential

E_D can be expressed by well–known Henderson equation if linear concentration profile is assumed [1,2].

$$E_D = \frac{\sum z_k \mu_k c_k(0) - \sum z_k \mu_k c_k(d)}{\sum z_k^2 \mu_k c_k(0) - \sum z_k^2 \mu_k c_k(d)} \cdot 2.303 \frac{RT}{F} \log \frac{\sum z_k^2 \mu_k c_k(0)}{\sum z_k^2 \mu_k c_k(d)} \tag{2.6}$$

Where:
z_k, _$_k$, c_k – charge, mobility and concentration of the ion k respectively
R, F – chemical constants
T – absolute temperature

Boundary potentials can be derived from the condition of thermodynamic equilibrium between the different phases.

$$E_{B1} = 2.303 \frac{RT}{z_k F} \log \frac{K_k(1) c_k(1)}{c_k(0)} \tag{2.7}$$

$$E_{B2} = 2.303 \frac{RT}{z_k F} \log \frac{K_k(2) c_k(2)}{c_k(d)} \tag{2.8}$$

Where:
$K_K(i)$ – partition parameter of ion k in the absence of electrical field between the solution (i) and the membrane phase.

Neglecting the diffusion in the membrane (diffusion potential is in fact much less than boundary potential) concentration $c_k(0) = c_k(d)$ [1,2,4]:

$$E_M = 2.303\frac{RT}{z_k F}\log\frac{K_k(1)c_k(1)}{K_k(2)c_k(2)} \tag{2.9}$$

Under the condition $K_k(1) = K_k(2)$ membrane potential resembles ideal Nerstian behavior. By introducing the factors responsible for interfering ions it is possible to obtain semi–empirical Nikolsky equation [1,2,5]:

$$E_M = 2.303\frac{RT}{z_k F}\log[c_i(1) + \sum k_{ij}c_j(1)] \tag{2.10}$$

Where:

$c_i(i)$ – concentration of the detected ion in solution i
$c_j(i)$ – concentration of disturbing ion
k_{ij} – selectivity of the ion–selective layer

3 MODELING OF THE PROCESSING PART OF THE MICROSYSTEM

As it was mentioned in the previous part of this paper the second crucial part of presented microsystem is data processing unit. It consists of two major parts: sigma–delta modulators and decimation filter (fig.4).

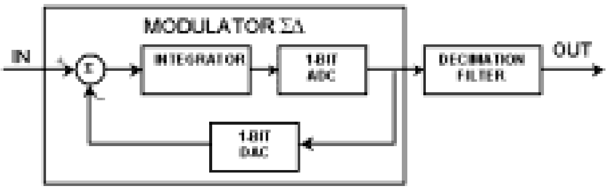

Figure 4: Block diagram of the data processing unit

All parts were designed in CADENCE environment. The simulations of sigma–delta modulator were performed in SPICE and tested in multidomain ELDO simulation environment. The modulator realized in SC techniques was tested. It was a first order modulator. The electrical scheme of simulated modulator was presented on fig.4.

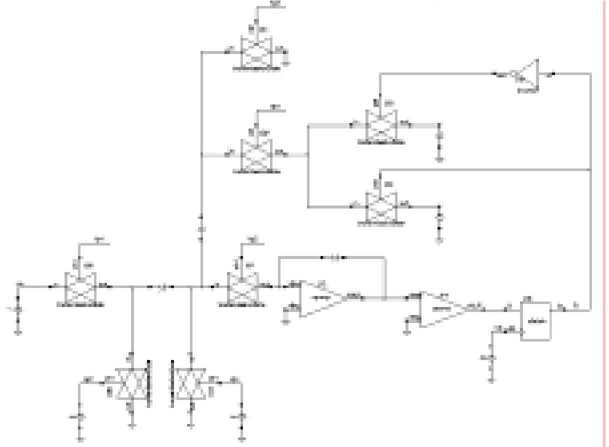

Figure 5: Electrical scheme of the SC modulator

The second part of data processing unit is decimation filter. This circuit is necessary to create digital output word. The filter was described in VHDL language, which is dedicated to design digital circuits. Next step was design verification in SYNOPSYS software. Last step was layout generation by using CADENCE environment. The full design flow was presented on fig.6.

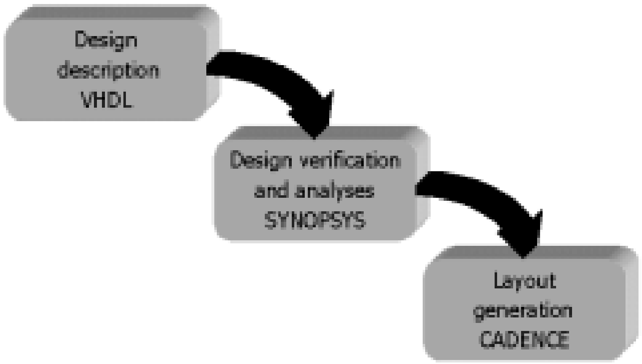

Figure 6: Design path of decimation filter

To obtain the whole data processing unit it was necessary to connect modulator and decimation filter using CADENCE schematic editor. In this way the data processing unit was designed.

4 SIMULATION AND FINAL RESULTS

In this chapter the simulation results are presented according to the two presented previously parts of the microsystem.

a) electrical (Ids, Vds signals of the transistor)
b) chemical (concentration of the ion in the solution)

First the influence of the concentration of the certain ion on the membrane potential and output curves of CHEMFET will be considered.

Figure 7: $E_M(actK_i)$ for SOVAMS environment

The influence of concentration of the main ion is presented below.

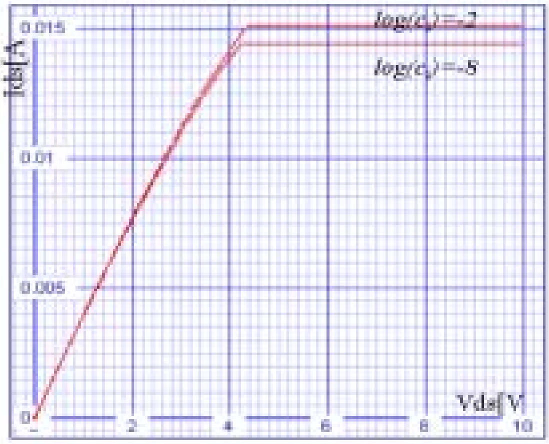

Figure 8: The influence of concentration of ion in the tested solution on the output characteristics of CHEMFET

Secondly the thermal influences on the output characteristics of CHEMFET are shown.

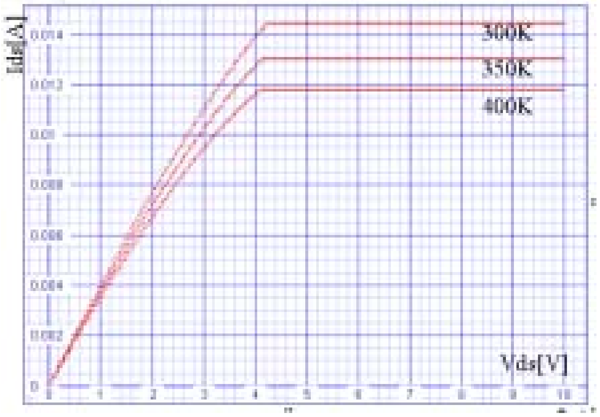

Fig. 9: The temperature influence on the CHEMFET system

In the next figure the simulation of data processing circuit is presented.

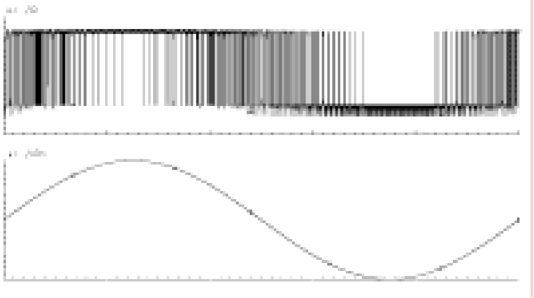

Fig. 10: Input and output signals of sigma–delta modulator

The simulation results of first order sigma–delta modulator was presented in fig. 10. Using modulators the analogue signal is changed in frequency modulated signal. It causes the minimization of the external interference on analogue signal.

5 CONCLUSIONS

The silicon microsystem presented in this paper had been fully designed in CADENCE environment. The behavior of the microsystem was simulated using ELDO–ANACAD environment. Chemical sensors were simulated in ELDO and SOAVMS simulators (the first one uses Hdl–A description language standard and the second one uses VHDL–AMS standard). The obtained results both from SOVAMS and ELDO–ANACAD environments are comparable. Moreover the data processing unit was simulated in SPECTRES and SPICE simulator. Results of the simulations were presented in this paper. There are also library files that include basic electronic cells as symbol schematics, layouts and models were created. The main aim of this work was to simplify design process of the integrated circuits applied to the water monitoring.

6 ACKNOWLEDGEMENTS

The authors would like to thank all SEWING partners. Especially prof. A. Filipkowski from Warsaw University of Technology, Institute of Electronics Systems, and prof. Z. Brzozka, dr A. Dybko and dr W. Wroblewski form Warsaw University of Technology, Institute of Chemistry for helpful discussions.

REFERENCES

[1] H. H. van der Vlekkert „*Some fundamental and practical aspects of CHEMFETs*" Ph.D thesis Universite de Neuchatel, 1998
[2] A. van der Berg „*Ion sensor based on ISFET's with synthetic ionophores*", 1998
[3] P. Bergveld, *IEEE Trans Biomed ENg.*, BME-17 (1970), 70
[4] S.D. Moss, J. Janata, C.C. Johnson Anal. Chem., 47, 2238, (1975)
[5] W. Torbicz, „*Teoria i wlasno_ci tranzystorów polowych jako czujników biochemicznych*" (in Polish), Wroc_aw, Ossolineum, 1988
[6] Raports for SEWING program www.sewing.mixdes.org
[7] K. de Langen, J. H. Huijsing "Compact Low–Voltage Power–Efficient Operational Amplifiers Cells for VLSI" *IEEE Journal of Solid-State Circuits, vol. 33, no. 10 October 1998, pp. 1482-1496*
[8] Y. Dong, A. Opal "Time–Domain Thermal Noise Simulation of Switched Capacitor Circuits and Delta–Sigma Modulators" *IEEE Transactions on Computer–Aided Design of Integrated Circuits and Systems, vol. 19, no. 4 April 2000, pp. 473-481*
[9] R. Baraniecki "Makromodele VHDL dla uk_adów analogowo-cyfrowych" *Ph.D. thesis* (in Polish), *Instytut Technologii Elektronowej Warszawa 1998*
[10] M. Grad "Analiza i synteza modulacji sigma–delta" *M.Sc. thesis* (in Polish), *Politechnika Lodzka, Lodz 1999*

Department of Microelectronics & Computer Science
Technical University of Lodz
Support from SEWING program IST–2000–28084 – **S**ystem for **E**uropean **W**ater monitor**ING**