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ABSTRACT: This paper reports on the techniques to integrate the chemically sensitive field effect transistors (CHEMFET) to the interface electronics. The electrical properties of the CHEMFETs are studied and the primary requirements for the CHEMFET interface electronics are outlined. The interface electronics topologies are discussed and finally the results from the Sewing CHEMFET sensor simulations are presented.

INTRODUCTION

Chemical sensors include a chemical recognition element, which is in close contact with the transducer. The aim of the transducer is usually to provide an analog or a digital signal. There are many types of chemical sensors and commonly they operate in liquid or gaseous environments. Generally transduction is performed electrochemically.

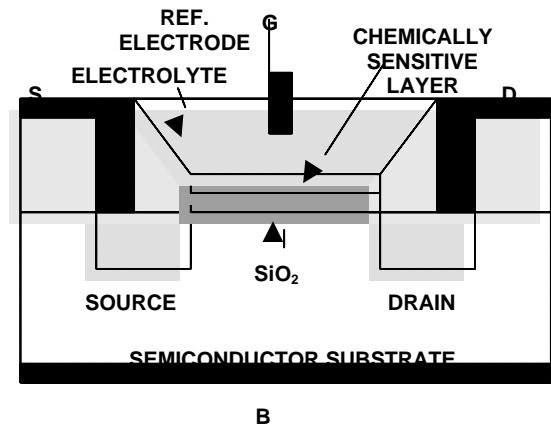
Inherently solid-state chemical sensors open up a solution to a wide variety of portable chemical sensing system applications where small size and low power consumption are required. Silicon technology enables the integration of the chemical recognition element to the supporting electronics. Although the dimensions of the chemical recognition element have remain the same in the past decade, the feature size shrinkage in the silicon technology helps to minimise the overall system size.

SILICON CHEMFET TECHNOLOGY

The chemical sensors based on silicon technology are MOSFET devices (CHEMFET) where the gate metal is replaced by an electrolytic solution in which a reference electrode is immersed. CHEMFETs or potentiometric sensors obtain their analytical information from an explicit relationship between the potential of the reference electrode and the concentration in the electrolytic solution. The structure of the typical CHEMFET is shown in the Fig. 1. Most CHEMFETs are fabricated on the top of a semiconductor substrate, where drain, source, and conductive channel are resided. The material of the insulator layer deposited on the substrate is typically silicon dioxide SiO_2 . On the top of insulating layer is a chemically sensitive membrane layer [1].

The vital part of the CHEMFET sensor is the ion-selective membrane. When the membrane responds only to one particular type of ion or chemical compound it is called selective. A widely utilised selective sensor is the ion sensitive field effect transistor (ISFET), which is sensitive for the hydrogen ion and almost non-sensitive for the other types of the chemical compounds. Commonly the ion selective membranes react to the various types of the chemical compounds. The membranes are

generally most sensitive for one particular ion (main ion) and the responses for the disturbing ions are defined by the respective selectivity coefficients. The output of the sensor is the sum of the responses for the main and the disturbing ions.



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Fig.1. CHEMFET structure.

CHEMFET ELECTRICAL PROPERTIES

The CHEMFET operation is similar to that of a conventional MOSFET, except that a electrolyte gate is used instead of a metal gate. The threshold voltage of the MOSFET can be written as [2]:

$$V_T(MOS) = j_{ms} + 2j_F - \frac{Q_{ss} + Q_{sc}}{C_{ox}} \quad (1)$$

where j_{ms} is the work function difference between the metal and semiconductor, j_F is the Fermi potential of the semiconductor, Q_{ss} is the fixed surface-state charge density per unit area at the insulator-semiconductor interface, Q_{sc} is the semiconductor surface depletion region charge per unit area and C_{ox} is the gate insulator capacitance per unit area.

Replacing the metal gate by reference electrode, electrolytic solution and chemically sensitive membrane modifies the MOSFET threshold voltage. In the case of the ISFET the potential drop on the interface of the ion selective membrane and the measured solution can be approximated by the Nerstian equation. When the mem-

brane responds to more than one ion the modified threshold voltage can be defined by using the Nikolski – Eisenman equation [3]:

$$V_T(\text{CHEM}) = E - j_{eo} + 2j_F - \frac{Q_{ss} - Q_{sc}}{C_{ox}} \quad (2)$$

where j_{eo} is the potential of the electrolyte-insulator interface and

$$E = E0 + \frac{RT}{z_i F} \ln \left(a_i + \sum_j K_{ij} a_j^{\frac{z_i}{z_j}} \right) \quad (3)$$

where $E0$ is a constant depending on the reference electrode and the diffusion in the membrane, R is the gas constant, T is the temperature, F is the Faraday's constant, a_i and a_j are the activities of the main ion I and disturbing ion J in the solution and z_i and z_j are the valences of the main ion I and the disturbing ion J in the solution, respectively. K_{ij} is the selectivity coefficient. The value of the selectivity coefficient depends on the main and the disturbing ions and it is usually extracted from the measurements.

The CHEMFET devices are commonly biased in the linear region ($V_{DS} \ll V_{GS} - V_T$) where the drain current I_{DS} can be expressed as

$$I_{DS} = b \left[(V_{GS} - V_T) - \frac{V_{DS}}{2} \right] V_{DS} \quad (4)$$

$$\approx b(V_{GS} - V_T)V_{DS}$$

and hence

$$V_{GS} \approx \frac{I_{DS}}{bV_{DS}} + V_T \quad (5)$$

where $b = \frac{mC_{ox}W}{L}$ and μ is the mobility of the elec-

trons or holes in the channel, C_{ox} the capacitance per unit area of the gate insulator, W the channel width and L the channel length.

If the drain current and the drain-source voltage are kept constant, any change in the CHEMFET threshold voltage V_T will reflect to the gate-source voltage V_{GS} .

INTERFACE ELECTRONICS

The response of a CHEMFET can be measured in two ways. The gate (reference electrode) -source voltage is kept constant and the change in the drain current is measured as a function of the ion activity. Alternatively, the ion activity is utilised to modulate the gate voltage and the drain current is kept unchanged. In both cases the drain-source voltage is fixed.

The ion activity measurement is essentially DC level measurement due to relatively slow response times of the CHEMFETs. The measurement accuracy is limited by the CHEMFET sensor itself as well as by the interface electronics' offset voltage, the long-time and the temperature stability and the low frequency noise sources of the interface electronics.

INTEGRATED SENSORS

When CHEMFETs and the interface electronics are integrated on the same chip, the CHEMFET can be integrated into the differential input stage of a CMOS operational amplifier, Fig. 2 [4]. When CHEMFET operational amplifier is configured as a voltage follower, the output voltage is equal to the reference electrode voltage. Any difference in the threshold voltages or the bias currents between the two input transistors at the differential input stage will also appear at the output of the amplifier. The output voltage includes also the offset voltage, which arises from the mismatch of the input transistors. The mismatch between CHEMFET and MOSFET is caused by the mismatch of the total gate capacitances, semiconductor bulk charges, insulator interface charges and gain. The offset voltage is temperature and light sensitive but chemically insensitive.

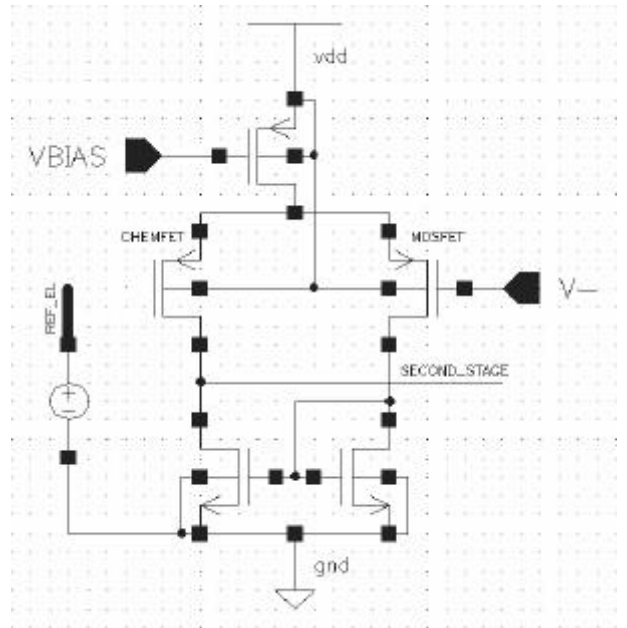


Fig. 2. CHEMFET amplifier.

DISCRETE SENSORS

The discrete CHEMFET interface electronics provides the correct bias for the CHEMFET and allows an analogue low-impedance output voltage to be achieved. To guarantee good system accuracy, the circuit has to keep the drain-source voltage and the drain current of the CHEMFET as constant as possible over the whole range of variability of its threshold voltage [5].

Two interface electronics topologies have been presented in Fig. 3a and Fig. 3b. In the first topology the reference electrode voltage is kept constant and the CHEMFET source voltage is changed when the ion activity varies. The constant current sink I_D sources bias current for the CHEMFET. The resistor and the current source I_{BIAS} set the drain-source voltage of the CHEMFET [6].

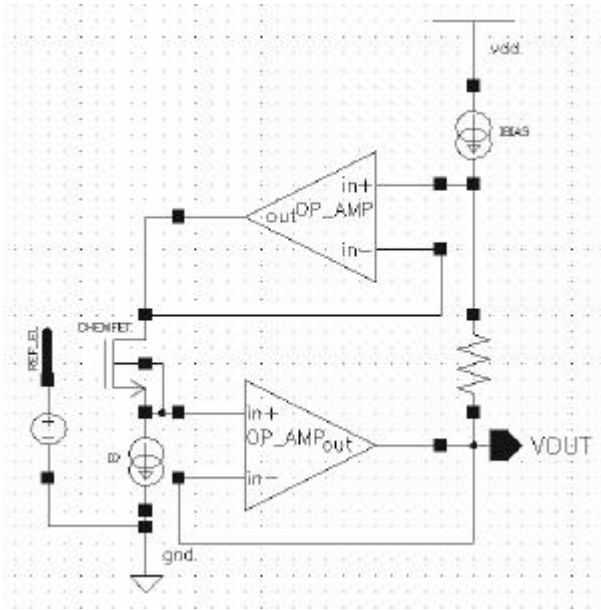


Fig. 3a. Constant V_G and I_D interface.

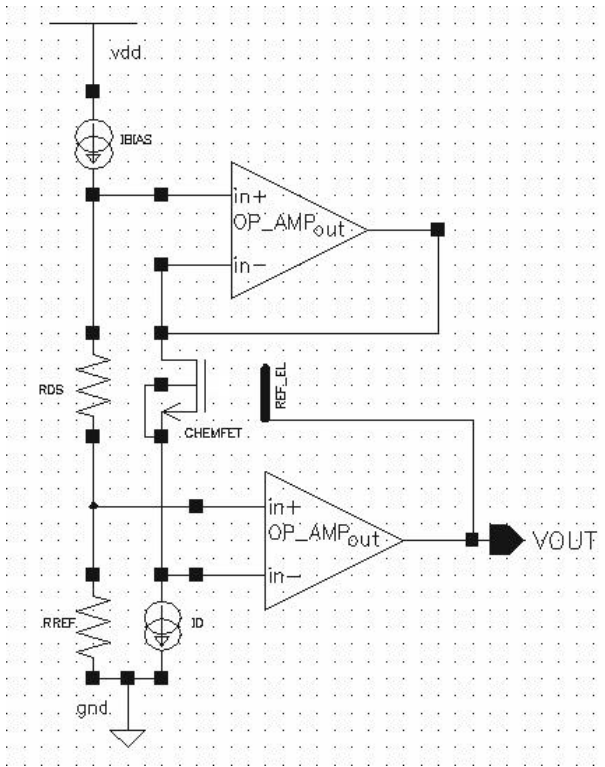


Fig. 3b. Constant V_S and I_D interface.

In the Fig. 3b the drain current is again defined by the current sink I_D . The drain-source voltage and the source voltage of the CHEMFET are set by the current source I_{BIAS} and the resistors R_{DS} and R_{REF} . The output of the lower amplifier drives the reference electrode. In drain current is kept constant by varying the reference electrode voltage if the ion activity changes.

The measurement accuracy is limited by the amplifier offset and noise voltages. Also the current source should keep the drain current as constant as possible over the whole range of the CHEMFET threshold voltages. Typically ISFET sensor sensitivity is 50-60 mV/pH . To

obtain a 0.1 pH resolution the worst case maximum error voltage is thus 5 mV . The opamp offset voltage can be compensated by the external trimming.

SIMULATIONS

The Institute of Electron Technology (ITE) from Warsaw, Poland develops CHEMFET sensors and one of their sensors was used in the simulations. The ITE CHEMFET is based on a depletion N-MOSFET ($W=638\mu m$, $L=14\mu m$) technology. The gate insulator oxide (SiO_2) is coated with chemically active Polysiloxan or Silopren membrane depending on which ion is measured. The HSPICE model of the sensor was based on simplified and linear Nikolski – Eisenman equation where sensor response is calculated for main ion and one disturbing ion. The value of the selectivity coefficient in the model was given for the K^+ ion with presence of the Na^+ ion.

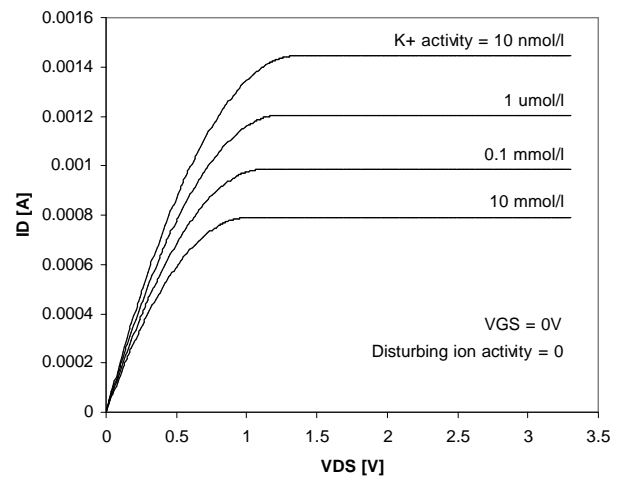


Fig. 4. CHEMFET I_D vs. V_{DS} .

The characteristic curves of the ITE CHEMFET are shown in the Fig. 4. The gate source voltage has kept constant ($V_{GS} = 0V$). The main ion activity has been varied from $1e-8$ mol/l to $1e-2$ mol/l and the activity of the disturbing ion was zero. It's clearly seen that the CHEMFET behaves like a MOSFET and the ion activity modulates the CHEMFET threshold voltage.

The output characteristic of the CHEMFET transducer electronics is shown in the Fig. 5. The CHEMFET was connected to the constant V_G - I_D interface (Fig. 3a). The operational amplifiers implemented in the system were single supply (3.3V) CMOS low-voltage class AB type [7].

The CHEMFET drain current was biased to $100\mu A$ and drain to source voltage was 0.1V. The change of the CHEMFET source voltage (V_{OUT}) as a function of the ion activity was simulated. The simulated ion activity response of the ITE CHEMFET was 59 $mV/decade$.

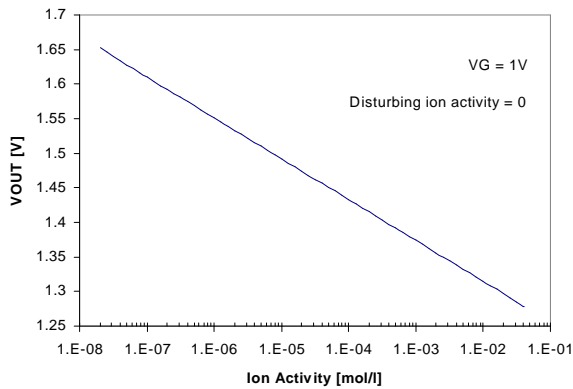


Fig. 5. Output characteristics.

In the high ion activity levels the simulation accuracy is limited by the linear Nikolski – Eisenman model. Improved accuracy in the high concentration levels is achieved by employing the Van der Bergh's physical based model.

CONCLUSIONS

The chemical and electrical properties of the chemical field effect transistors (CHEMFET) have been studied. Several CHEMFET interface electronics topologies were presented. Simulations showed linear operation in wide range of the ion activities.

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