DEVELOPMENT OF A MEASUREMENT INTERFACE FOR CHEMFETS MICROSENSORS

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Abstract: The paper presents a measurement interface for ChemFETs sensors, also called ChemFET-meter. This simple electronic circuit based on the indirect measurement of the threshold voltage, has a voltage output signal and has been standardized in term of connexions and optimised in term of power consumption. It can be used with both normally-off and normally-on ChemFETs sensors, and is compatible with standard reference electrode as well as metallic wire used as pseudo-reference electrode. Finally, it enables the simultaneous bias and measurement of two sensors (eventually in two different solutions), operating in common mode or in differential mode according to the application. The ChemFET-meter performances are demonstrated by studying the influence of temperature, illumination and temporal drift on pH-ISFET microsensors.

INTRODUCTION

Chemical field effect transistors ChemFETs are being developed for many applications in the field of water or blood analysis [1]. As a solid-state sensor derived from microelectronics, they are compatible with silicon technologies and provide many advantages like mass fabrication, low cost and low power. In return, they are sensitive to temperature and illumination and their detection principle is responsible for measurement drift.
In order to tackle off these drawbacks, measurement interfaces have been developed, introducing features such as temperature compensation, reference chemical field effect transistor (ReFET) operation, sensitivity control. Monolithic implementation of ChemFET-based microsystems has therefore been fabricated using conventional integrated circuits [2, 3]. Nevertheless, the CMOS technology is not always compatible with the ChemFET sensors market. Indeed, if it has been successfully developed for the pH measurement, its cost and its lack of flexibility is often a handicap for the development in small series of low-cost, disposable ChemFETs microsensors required by various applications. Therefore, discrete readout and data treatment interfaces have still to be developed.
This paper deals with the conception and the study of a measurement interface, also called ChemFET-meter, adapted to the characterization of normally-off and normally-on ChemFETs sensors, either in common or differential mode.

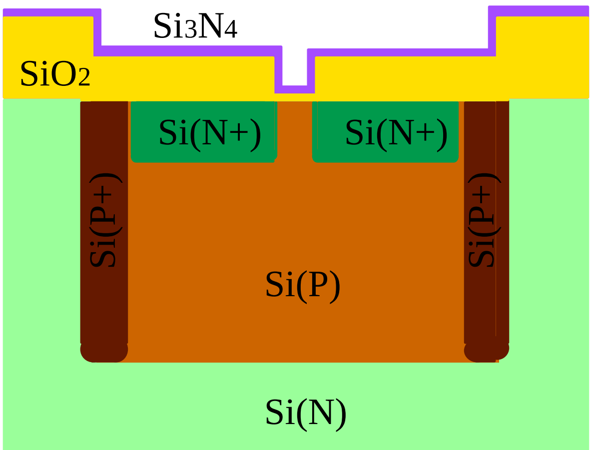

Fig. 1. *Cross section of the P-well, N channel, normally-off pH-ISFET microsensor*

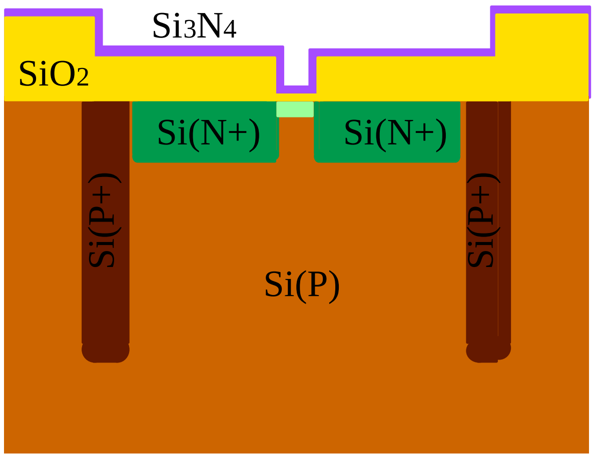

Fig. 2. *Cross section of the N channel, normally-on pH-ISFET microsensor*

CHEMFETS SENSORS

Ion sensitive field effect transistors (ISFETs) were fabricated using standard silicon technology. N-channel, normally-off and normally-on ISFETs were realised on <100>-oriented, N-type (500 Ω.cm) and P-type (10 Ω.cm) silicon substrates respectively (figures 1 and 2).

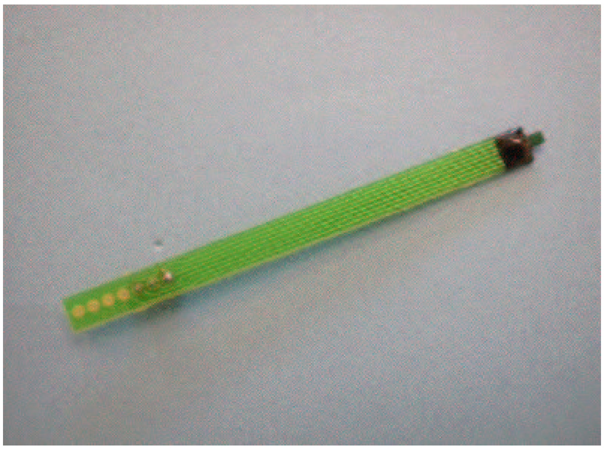

Fig. 3. *Photograph of the pH-ISFET microsensor*

A 30nm thermally grown SiO_2 layer and an 80nm Si_3N_4 layer deposited on the top of a formed pH-sensitive gate structure. Taking into account the whole technological processes and characteristics, the normally-off and normally-on pH-ISFET microsensors were optimised in order to have a threshold voltage V_t lower than 1 volt in absolute value. Thus, optimal conditions for both normally-off and normally-on pH-ISFETs characterization were defined for a drain-source current I_{DS} and a drain-source voltage V_{DS} lower than 0.1 mA and 2 V respectively [4].
The pH-ISFET silicon chips were reported on a specific printed circuit board. After wire bonding, encapsulation was finally performed using epoxy resin and leaving the pH-sensitive parts uncovered (figure 3).

MEASUREMENT INTERFACE DESIGN

The general circuit of the ChemFET measurement interface is given in figure 4. Two identical read-out circuits are used for each ChemFET sensor. The drain-source current I_{DS} of both ChemFETs are fixed to an identical value using a current mirror M1. Similarly, the drain-source voltage V_{DS} of both ChemFETs is fixed to an identical value using the bandgap reference voltage D1 and the voltage inverter A1. Finally, the gate electrodes of the two ChemFETs are connected together and grounded.
Taking into account the read-out circuit (see subcircuit in a dashed line), a change in chemical activity will be responsible for the variation of the ChemFET threshold voltage V_{T1}. Since its drain-source current I_{DS1} and its drain-source voltage V_{DS1} are fixed and since the gate is grounded, the source voltage V_{S1} shifts accordingly. Nevertheless, thanks to the voltage differential amplifier A2 and to the voltage follower A4, the drain-source voltage remains constant V_{DS1} and the output voltage V_{OUT1} gives a continuous monitoring of the source voltage V_{S1}, i.e. of the threshold voltage V_{T1}.
Thus, the indirect measurement of both threshold voltages V_{T1} and V_{T2} is performed by the ChemFET-meter and differential measurement between the two ChemFETs is possible using an adequate voltage amplifier (not shown in figure 4).

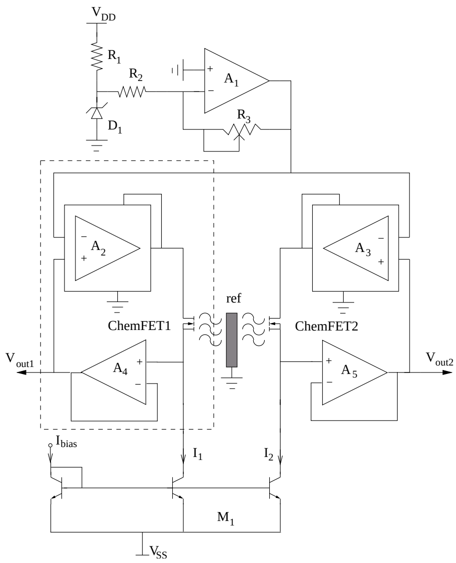

Fig. 4. *Schematic of the ChemFET measurement interface*

Fig. 5. *Photograph of the whole ChemFET-meter*

The whole ChemFET-meter (figure 5) is simple, autonomous (using 9 V power supply batterie) and allows setting and/or measuring the different corresponding data with a 1% accuracy in the following ranges:

- drain-source voltage: $0 \leq V_{DS} \leq 2$ V
- drain-source current: $0.05 \leq I_{DS} \leq 0.5$ mA
- source voltage (output): $-2 \leq V_S \leq 2$ V

Finally, the ChemFET-meter has been standardized in term of connexion using BNC connectors for reference electrodes and RJ45 connectors for ChemFET or metallic pseudo-electrodes. Thus, it is able to characterize simultaneously two ChemFETs microsensors in two different solutions if necessary (test and reference for example), using either a gate reference electrode or a metallic wire used as gate pseudo-electrode.

RESULTS AND DISCUSSION

A specific characterization stand has also been developed in order to prepare and supply continuously liquid samples. It regroups different fluidic equipments (liquid distribution system, cooling/heating stirrer, peristaltic pump, liquid flow controller, pneumatic valves and measurement chamber) and is monitored by a personal computer to do data acquisition and control. Thanks to this characterization stand, the ChemFET-meter has been tested using pH-ISFETs microsensors (see below) and standard buffer solutions (pH = 4; 5; 7; 8; 10) purchased from Merck.

The first test has been performed using two different pH-ISFETs microsensors: a normally-off and a normally-on (figure 6). Since the ChemFET-meter is measuring the source voltage while the gate electrode is grounded, the normally-off and normally-on ISFETs are characterized by a negative and a positive output voltage respectively. Nevertheless, both of them are characterized by a typical quasi-nernstian response to pH (sensitivity around 50 mV/pH). Such results validate the technological process of both ISFET microsensors (normally-off and normally-on) and demonstrate the good functioning of the measurement interface.

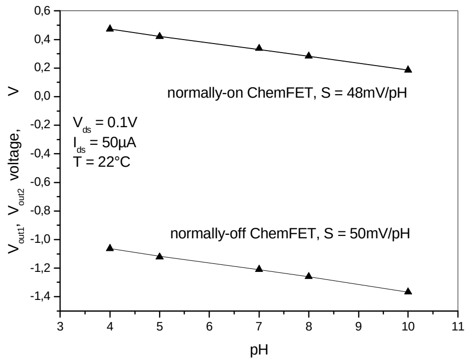

Fig. 6. *Simultaneous characterization of two pH-ISFETs microsensors (normally-off and normally-on)*

Thus, the ChemFET-meter has been used to study the main drawbacks of the ChemFET sensor: temporal drift, sensitivity to temperature, sensitivity to illumination. Two similar pH-ISFETs microsensors (normally-off) have therefore been tested simultaneously in a buffered (pH = 10) solution for a 4-hour duration (figure 7).

Firstly, the pH-ISFETs responses are characterized by a strong decrease which should be related to their adaptation to the watery medium. After this 20-minutes initial period, the two sensors give different results, evidencing a 35 mV discrepancy. This phenomenon should be related to the threshold voltage shift (for technological reasons) from one pH-ISFET to another.

Nevertheless, both sensors follow similar variations whatever the different interferences, noises and/or disturbances. This demonstrates the measurement reproducibility of the ChemFET-meter.

The temperature effect has been studied by introducing a heating/cooling cycle during the measurement period (figure 7). Thus, the increase of temperature from 22°C to 40°C is responsible for an increase of the output voltage V_S around 25 mV. This phenomenon is related to the decrease of the ISFET threshold voltage V_T [5]. The temperature sensitivity of the pH-ISFETs has been estimated to 2 mV/°C, i.e. 0.04 pH/°C.

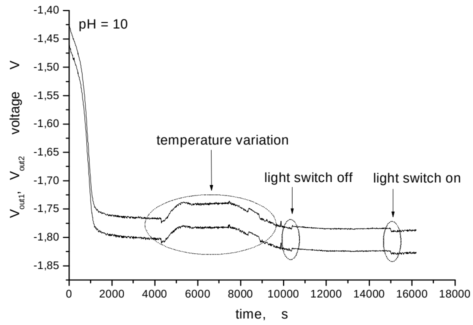

Fig. 7. *Influence of temporal drift, temperature and illumination on the pH-ISFETs response*

During the heating/cooling cycle, the use of the ChemFET-meter has evidenced variations of the output voltage due to the light switch-off and switch-on in the experiment room. Therefore a specific study of the illumination influence has been performed (figure 7).

By switching on the light, the room illumination has been found to increase from 70 to 1500 Lux. This illumination increase is responsible for a decrease of the output voltage V_S around 5 mV. This phenomenon is related to the increase of the current under threshold I_{off}, and more precisely to the photo-generation of electron-hole pairs into the channel [6, 7]. All in all, the illumination sensitivity of the pH-ISFETs can be estimated to 3.5 µV/Lux, i.e. the shift from darkness to standard illumination is responsible for a 0.1 pH measurement error.

The initial period being apart, the complete experiment has also allowed estimating the temporal drift of the pH-ISFETs around 7.5 mV/hour, i.e. 0.15 pH/hour. This result is in contradiction with the previous one [4]. However, such high temporal drift should be related to the lasting influence of the initial regime. This should be investigated through further experiments.

Finally, the ChemFET-meter has been used to perform the differential measurement between the two pH-ISFET sensors (figure 8). Thus, the initial regime as well as the illumination influence is no longer. The temperature sensitivity and the temporal drift are still evidenced but are strongly reduced. They can be estimated to 0.25 mV/°C and 1 mV/hour, i.e. 0.005 pH/°C and 0.02 pH/hour, respectively.

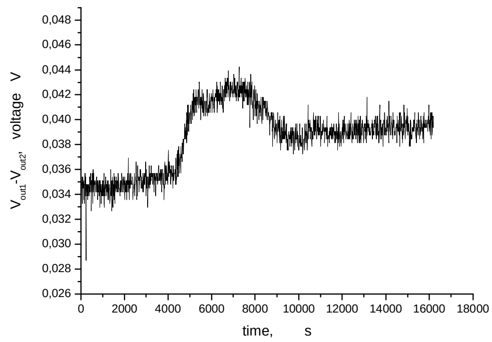

Fig. 8. *Influence of temporal drift, temperature and illumination on the differential measurement response*

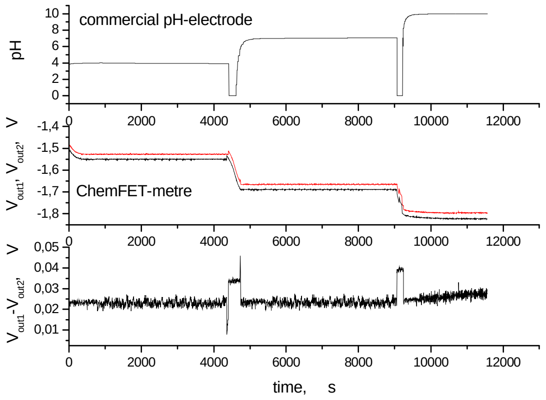

Fig. 9. *Characterisation of the pH: sensitivity of the ISFETs response and immunity of the differential measurement*

It is here necessary to remind that the differential measurement between to pH-ISFETs is obviously no longer sensitive to pH (figure 9). However, the use of a reference metal oxide silicon field effect transistor (ReMOS) and finally the use of the ChemFET-meter for the characterization of ISFET/ReMOS structures will allow to retain pH quasi-nernstian response (according to the pH-ISFET chemical properties…) while elimination and/or reducing the influences of temperature, illumination and temporal drift. Such result can of course be extended to the development of ChemFET/ReFET structures.

CONCLUSION

A measurement interface for ChemFETs microsensors, also called ChemFET-meter, has been developed, standardized and optimised for industrial applications. Its performances have been demonstrated through the characterization of normally-off and normally-on SiO_2/Si_3N_4 pH-ISFETs. Thanks to an adapted characterization stand, the ChemFET-meter has been used to study and analyse the influence of temperature, illumination and temporal drift on the behaviour of these microsensors. Thus, the main advantages of the differential measurement technique have been evidenced, requiring the development of reference devices, either reference metal oxide silicon field effect transistor (ReMOS), either reference chemical field effect transistor (ReFET).
Such reference operations will have to be undertaken for many different industrial applications. However, the ChemFET-meter has still to be further improved. Special attentions must therefore be brought to be compatible with standard personal computer and to be finally thoroughly adapted to data acquisition and treatment.

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