ISFET pH Sensor characterization: towards Biosensor Microchip Application

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ABSTRACT

The ion-sensitive field effect transistor (ISFET) based pH sensor has the advantages of smaller size, fast response time and fabrication compatible with standard MOS technology. Beside that, the functionality of pH ISFETs is various especially in biomedical areas. In the design and characterization of an ISFET pH sensor, the ISFET model was characterized and a final design has been evolved with the assistance of the Tanner tools software. To provide a better understanding of pH ISFET as a biosensor, the C-V characteristics, temperature dependence of the ISFET and pH sensitivity of Electrolyte-Insulator-Semiconductor in response to different pH are examined. The insulator, Aluminium oxide (Al_2O_3*) has been applied as a pH sensitive layer. The ISFET is matched with a metal oxide field effect transistor (MOSFET) at the differential input stage of a CMOS operational amplifier and realized in a 0.8 um CMOS technology. From the output of ISFET operational amplifier, the pH sensitivity is approximately 54.8 mV per pH.*

1. INTRODUCTION

For the most recent of 30 years, the developments of ISFET are very furious and create pride [1]. ISFET have a very fast response time, high sensitivity, micro size, robustness and the potential for on-chip circuit integration. Because of the advantages, the ISFET can be widely used in many areas especially in biomedical areas such as medical diagnostics, monitoring clinical or environmental samples, fermentation and bioprocess control and testing pharmaceutical or food products [2]. An ISFET-based Penicillin sensor [3], ISFET-based zeta potential analyzer (protein detection) [4], urea detection [5] and ISFET glucose sensor [6] are the several examples of ISFET application in medical area. As a milestone, the ISFET pH sensor has been designed and simulated using Tanner Tools (L-Edit, S-Edit and Tspice), in order to develop the biosensor microchip. The key building blocks of an ISFET pH sensor system are shown in Fig. 1. The system consists of three major modules, including ISFET sensor, analog signal readout module and A/D converter module.

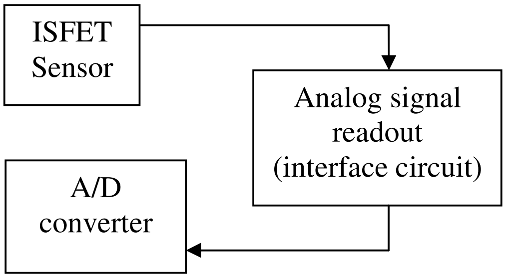

Fig.1 Block diagram of a ISFET pH sensor system

2. DESIGN CONSIDERATION

2.1. ISFET sensors

ISFETs use an MOS (metal oxide semiconductor) transistor arrangement where the metallic gate is not a control electrode. The physical difference in the ISFET structure is the replacement of the metal gate of the MOSFET by the series combination of the reference electrode, electrolyte and chemically sensitive insulator or membrane [7]. Instead, the medium in the ISFET is in direct contact with the gate insulator layer. An ISFET was introduced by P.Bergveld in 1970 and the first reported ISFET device was using a SiO_2 as a gate insulator layer [8]. Some other ion-sensitive materials (Al_2O_3, Si_3N_4, Ta_2O_5, SnO_2) was used as an alternative for the SiO_2 because they are more stable and have some important properties [8],[9]. These properties are sensitivity, selectivity, long-term drift, temperature dependency and responses time.

The gate insulator of the ISFET senses the specific ion concentration (i.e. ISFET pH sensor senses H^+ ions) generating an interface potential on the gate; the corresponding drain-source current change in the semiconductor channel is observed. The potential developed across the Al_2O_3 insulator layer directly depends on the number of H^+ ions in

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contact with it. Thus, the ISFET channel would be affected by the potential at the gate, which would modulate the current flow across the source and drain when the device is turned on. The concentration of the H^+ ions could be thus measured by calibrating the amount of current flow. In other words, the relationship between the current and H^+ ion concentration will allow that the pH value is depends to the measured current value.

For the project modeling, the ISFET used was an n-channel device with a gate insulator consisting of 40nm SiO_2 that is covered by an Al_2O_3 layer (80nm). The dimensions of the sensor gate are 400/20 µm. The W/L must be in suitable size to ensure a good contact with the liquid at the gate. Besides that, the W and L size affects the current flow across the drain and source. As reported in Swaminathan et al. [7], the higher drain-source current, Ids can be obtained by increasing W and/or decreasing L. Fig. 2 shows the cross section of ISFET gate.

2.2. Interface circuit

The interface circuit used for reading out the pH response of ISFET is shown in Fig. 3. Based on approach by Chan and White [10], the interface circuit for the ISFET is a differential pair with MOSFET and ISFET in a feedback configuration. Any change in the solution pH affects the solution gate interface potential of an ISFET, which is detected by the ISFET gate as a proportional threshold voltage change. When the ISFET operational amplifier is configured as a voltage follower, the output voltage is equal to the input voltage; any difference in threshold voltage and bias currents between the two input transistors at the differential input stage will also appear at the output.

For this project, the ISFET integrated circuit schematic and layout was designed using S-Edit and L-Edit, and then simulated by T-Spice. A physical layout of an ISFET interface integrated circuit is shown in Fig. 4. For the schematic design, the ISFET macromodel as in [11] has been used as an ISFET device.

3. RESULTS AND DISCUSSIONS

3.1. I-V characteristics of an ISFET

Based on the simulation result, the Id-Vds (drain current versus drain to source voltage) characteristics of the ISFET in a concentration range between pH 2 and pH 12 presented Fig. 5. It showed that the discrete structure has a linear pH response in the saturation region under the different pH values.

3.2. pH sensitivity of the Al_2O_3/SiO_2 gate ISFET

The transfer characteristics of an integrated pH ISFET at various reference voltages (Vref) and pH values are shown in Fig. 6. The pH sensitivity of the Al_2O_3/SiO_2 gate ISFET can be obtained through a shift in the threshold voltage of an ISFET sensor. The results are as shown in Fig. 7, in which the total voltage output response of the differential ISFET interface, has linear pH sensitivity in a concentration range between pH 1 and pH 12. The pH sensitivity for acid region and basic region is approximately 54.8 mV per pH and 48.5 mV per pH unit, respectively.

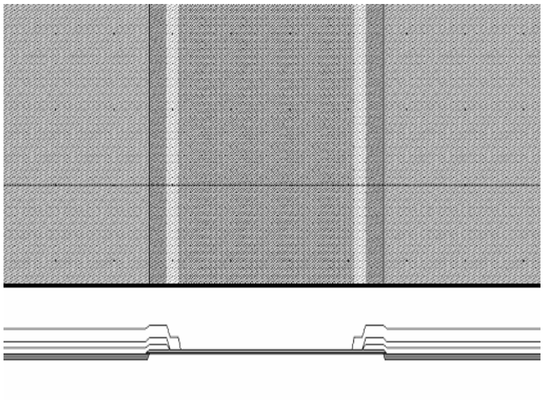
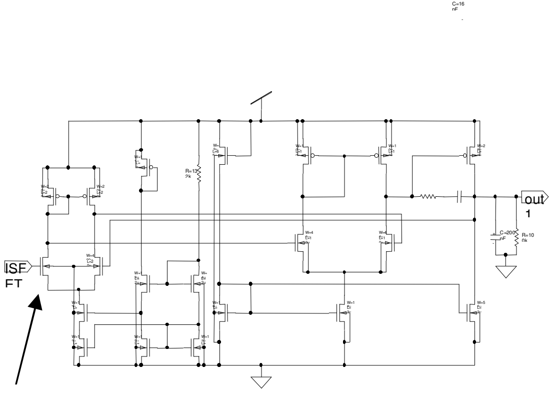


Fig.2. ISFET gate layout cross section



ISFET device

Fig.3. Representation of the ISFET operational amplifier as an interface circuit.

3.3. Temperature analysis

For the temperature analysis, simulation results have been also carried out over a temperature range, each at T=15ºC, T=27ºC, T=37ºC and T=50ºC for pH=7. Based on MOSFET theory, the temperature affects the Vth value [9]. From the Fig. 8, it showed that the model predicts behaviour for the temperature variation, where the Vth values decreases when the temperature rises.

In addition, the isothermal point, where $\delta I_{ds}/\delta T$ is a minimum, i.e. where the drain current is not significantly thermally dependent, of an Al_2O_3 type ISFET has been determined. The optimum drain-source current, Ids value of 90.57 μA, where the temperature effect on Ids is zero, has been chosen for the isothermal point. As reported by Martinoia et al. [12], it is useful to know this point in order to design integrated circuits that contain ISFET whose operating point is near the isothermal point to have minimum temperature effects on pH measurement.

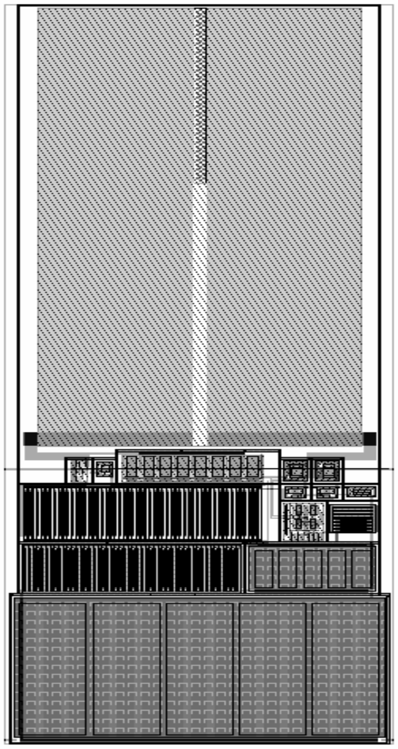


Fig.4. Physical layout of ISFET interface integrated circuit.

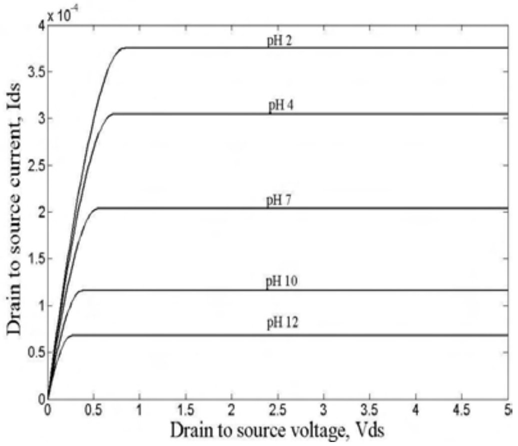


Fig.5. pH sweep: Ids Vs. Vds

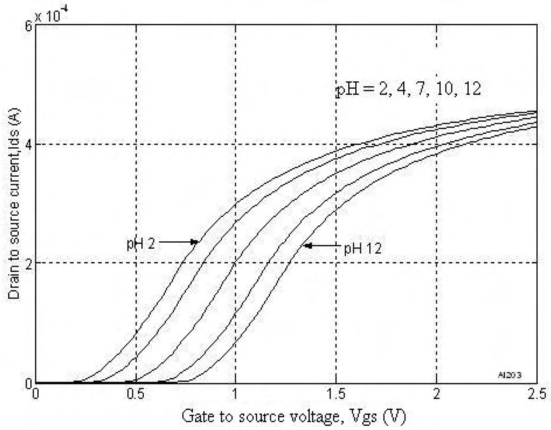


Fig.6. Curves of the drain to source current versus reference voltage under the different pH.

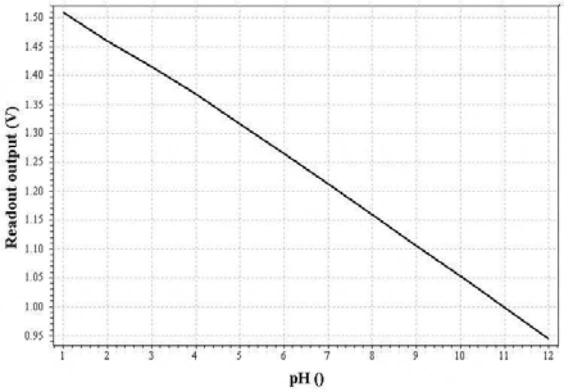


Fig.7. Total simulation plot of the ISFET sensor interface at T=27°C and Vgs=1.0V, pH sweep.

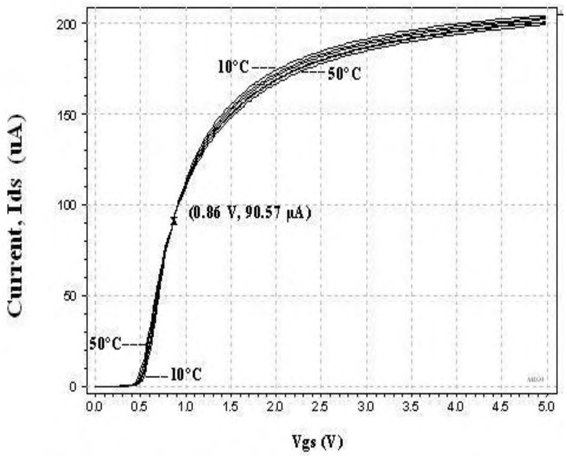


Fig.8. Simulated of Ids variation at six different temperatures for pH=7.

4. CONCLUSION

The objective of designing and characterizing an ISFET pH sensor for biosensor microchip application has been achieved. The simulation data showed that the Al_2O_3/SiO_2 gate ISFET sensor has linear pH sensitivity of approximately 54.8 mV per pH to 48.5mV per pH in a concentration range between pH 1 and pH 12. It means the ISFET with Al_2O_3 insulator gate has a good performance in terms of sensitivity and Ids current performance.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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