Abstract

In analytical chemistry, the measurement of the hydrogen ion activity (pH) in aqueous solutions by means of the glass membrane electrode had been an established technique for many decades. In parallel with the developments in ion-selective electrodes (ISE) techniques, there was a growing awareness in the semiconductor industry in the field of sensor development. Ion Sensitive Field Effect Transistor (ISFET) a chemical sensitive semiconductor device, the importance of which has increased manifold as it is used in several fields such as medicine, food safety, military, biotechnology areas etc. ISFETs are similar to metal oxide semiconductor field effect transistors (MOSFET) wherein the former is devoid of gate material and the electrolyte is in direct contact of the insulator. The threshold voltage of an ISFET is affected by the surface charges adsorbed from the solution or electrolyte at the gate oxide interface.

Threshold voltage is an important electrical parameter for any field effect transistor (FET) devices since it indicates the onset of significant flow of the drain current. MOS structure resembles a capacitor. In contrary to an ideal capacitor in a MOS structure the voltage is not only a function of charges stored but also depends on surface potential. Therefore for precise modeling of the threshold voltage, capacitance voltage (CV) characteristics are to be considered.

In ISFET devices the active sites of the insulator react with the hydrogen ions present in the electrolyte to bring about a change in the charges resulting in the modification of the threshold voltage of the device. Long term exposure of the device to an electrolyte may lead to diffusion of hydrogen ion into the sensing layer. The presence of these additional charges affects the capacitance of the insulating layer, which changes the threshold voltage of the device. This slow, temporal change in the threshold voltage is termed as drift and must be considered for precise modeling.

The scope of the ISFET device in its original form is limited to hydrogen ion detection. Integration of biologically active material and ISFET results into different types of biosensors. Enzyme Field Effect Transistor (ENFET) is a device where enzymes are used as bio-receptors. For ease of fabrication, faster production rate and reduction in the cost of production a different method has been adopted in this work. Schottky rectifying contacts can act as source and drain requiring less number of fabrication steps unlike the source and drain region doping in the conventional method. This proposition can be used in the fabrication of an ISFET. This ISFET if further used in conjunction with an enzyme can be easily transformed into an ENFET.

Cytochrome P450 monooxygenase is an enzyme which is extracted from the bacteria present in oilfields. Cytochrome P450 is a heme-containing superfamily, which catalyzes the oxidative biotransformation of lipophilic substrates to hydrophilic metabolites. This property can therefore be utilized for the development of a biosensor for detection of hydrocarbon.

ISFET and its related bio-sensors require reference electrode for completion of the gate to source circuit. The insulator oxide interfacial potential is not only dependent on pH of the electrolyte but also on the distance of the reference electrode from the sensing layer. A rule for placement of reference electrode was proposed in 2009 which required experimental validation for designing pH measuring system to bring down the device dimension.

Objectives: The threshold voltage of conventional MOS device under the ideal condition is the summation of bulk potential and surface potential. Therefore, the equivalent MOS capacitance cannot be considered by the ratio of charge and voltage. This can be tackled by modeling the threshold voltage considering the MOS capacitance as a variable capacitor that overcomes the drawbacks associated with conventional threshold voltage extraction method. The need for a model explaining the occurrence of drift in threshold voltage caused by hydrogen ion diffusion into the oxide layer has to be addressed. Existing bio-monitoring techniques are expensive as well as complex, so a cheaper alternative device for hydrocarbon detection can be developed which will be effective, convenient and can be easily fabricated. To minimize the overall device dimension, the optimal position of the reference electrode for a Si_3N_4 gate pH ISFET has to be modeled and validated experimentally. In view of the need to address these issues, the objectives have been formulated as

1. Modeling of the threshold voltage of MOSFET using Capacitance Voltage characteristics and its extension for ISFET
2. Modeling of long term drift in SiO_2 gate pH ISFET's
3. a. Design, fabrication, and characterization of Schottky based ISFET
   b. Immobilization of the bare ISFET with Cytochrome P450 enzyme and characterization of the ENFET device
4. Modeling for the detection of optimal positioning of the reference electrode for Si_3N_4 gate pH ISFET and validation of this rule using a hardware setup developed for this purpose.

The Methodologies adopted to achieve the objectives in brief are

Objective 1:

A physics-based model has been proposed for the threshold voltage determination of MOSFET based on Capacitance-Voltage (CV) characteristics. It is further extended to ISFET, as the ISFET structure is basically that of a MOSFET, the only difference being the absence of the gate over layer.

Objective 2:

Long term drift of SiO_2 gate pH ISFET has been modeled considering the hydrogen ion diffusion which penetrates into the sensing layer after reacting with the compatible sites. The electric field which results due to the diffusion of hydrogen ions has also been considered. Hence a mathematical expression dealing with long term drift has been formulated with the consideration of diffusion of the hydrogen ions.

Objective 3:

Schottky based ISFET has been designed and fabricated. Thermally deposited silicon dioxide is utilized as the sensing layer. Silver is directly deposited on the silicon substrate to form the Schottky contact eliminating the need for doping for source and drain region. The enzyme Cytochrome P450 is extracted from bacterial strain *Bacillus stratosphericus sp*. which is obtained from oil contaminated soil. Partial purified enzyme has been then immobilized on the sensing layer. The characterization of this fabricated device has been carried out as Hg-MOSFET and CYP450-ENFET.

Objective 4:

The rule for optimal positioning of the reference electrode indicated that unambiguous measurement can be obtained if the reference electrode is positioned at three times of Debye length from the sensing layer for each pH values of the electrolyte. Based on this rule, modeling of the effective insulator electrolyte potential with respect to the position of the sensing layer has been done initially for a Si_3N_4 gate pH ISFET. Finally, an experimental hardware setup with the required precision for the movement of the reference electrode with the necessary data acquisition system has been developed for the validation of the theoretical model.

Organization of the thesis

Chapter 1: Introduction

In this chapter, the motivation, the objectives and the organization of the thesis in details have been presented.

Chapter 2: Overview on Ion Sensitive Field Effect Transistor and Enzyme FET

In this chapter, a detailed review on the fundamentals of ISFET, oxide/electrolyte interface of site binding model, physico-chemical modeling and formation of ENFET when it is used in conjunction with biological material such as enzyme has been presented from a historical and chronological perspective.

Chapter 3: Threshold voltage modeling using capacitance voltage characteristics

In this chapter, a new threshold voltage model of a MOSFET based on equivalent MOS capacitance has been proposed. The model has been compared with existing Shockley's model and the results obtained were in good agreement with each other. This technique has been extended to ISFET as ISFET can be considered as a MOSFET devoid of the gate over layer.

Chapter 4: Long term drift in ISFET due to Hydrogen ion diffusion

In this chapter physics-based model for long term drift in SiO_2 surface under the effect of diffusion of hydrogen ions after the protonation and deprotonation of the sensing surface have been formulated. Further, due to the diffusion of the hydrogen ions into the oxide, an electric field is created which leads to a drift in the threshold voltage. Hence, a final mathematical expression has been formulated for long term drift in ISFET's with SiO_2 as gate material considering the effect of diffusion of hydrogen ions.

Chapter 5: Fabrication of a Schottky based ISFET immobilized with enzyme CYP450

In this chapter, Schottky ISFET immobilized by using Cytochrome P450 (CYP 450) monooxygenase for detection of hydrocarbon has been presented. The sensitivity of the ISFET sensor has been found to be about 50.65 millivolt/pH and that of the Cytochrome based ENFET is about 54.34 millivolt/molar. In addition, the output and transfer characteristics, stability, hysteresis, detection limit and change in pH after the reaction, reproducibility of the sensor system are other factors which have also been analyzed here.

Chapter 6: Modeling and experimental validation of the optimal positioning of reference electrode for a Silicon Nitride gate pH ISFET

In this chapter modeling for the optimal positioning of the reference electrode for a silicon nitride gate pH ISFET has been done. Further, an experimental hardware set up has been developed to validate the model. The data obtained from the experimental setup is in reasonable agreement with theoretically calculated values.

Chapter 7: Conclusion

The summary of the work, results, and contribution of the thesis have been presented in this chapter.