ISFET Characterization using Constant Voltage Constant Current Readout Circuit

R. Jarmin, Khuan Y. Lee, S. F. Mohammed Esa, H. Hashim, A. Z. Mohd Sih , and M. H. Abd Ghani

Abstract: - This paper presents a constant voltage constant current readout circuit for ion-sensitive field-effect transistor (ISFET). The study and investigation of ISFET performance using Linear Technology Simulation Program with Integrated Circuit Emphasis (LTspice) in order to identify the characteristics relationship of an ISFET variable is included. A macromodel of an ISFET had been created and tested using simulation program, in order to make sure the performance results of ISFET as the ion concentration (pH) changes, the current of the transistor will change accordingly. The graphs showing relationship between Id with Vd, Vref and VpH were produced, in order to make sure the macromodel function as stated characteristic. This paper also consists of analysis results before and after combining an ISFET voltage constant current (CVCC) readout circuit. The results of the simulation are taken in order to monitor the behavior of ISFET variable by changing in the pH of the electrolyte which affects the voltage output at CVCC circuit

Key-Words: - ISFET, CVCC, LTspice, macromodel, readout circuit

I. Introduction

Chemical sensing environment is one of the basic functions of a micro system which can be used in many applications such as pharmaceuticals, food processing and healthcare to validate process industry [1-2].

ISFET, an ion sensitive sensor, emerges recently as a popular sensing device for environment monitoring for sensing formaldehyde and methylamine [3], analytical chemistry such as glucose [4] and penicillin [5] detection, pharmaceutical for bacterial activity monitoring [6] and biomedical applications for the detection of myocardial ischemia during cardiac surgery [7] and urea for haemodialysis applications [8-9]. ISFET is derived from the idea of an ion sensitive solid state device based on field effect transistor, proposed by Bergveld in 1970, initially intended for physiologic measurement [10].

Structure-wise, ISFET adopts a MOS (Metal Oxide Semiconductor) transistor arrangement. The physical variance between ISFET and MOSFET are the substitution of the metal gate of the latter by a combination of reference electrode, electrolyte and chemically sensitive insulator or membrane [11]. It is by eliminating the metal gate electrode from a MOSFET so as to expose oxide to the electrolyte that empowers ISFET to detect pH of electrolyte, which varies with the concentration of H+ ions.

The oxide layer, which is pH sensitive, is deposited on the ISFET sensor.

When the oxide layer comes into contact with the electrolyte, biased with a reference potential from the reference electrode, a change in pH of the electrolyte will be detected. The H+ ions react with the negatively charged active sites at the dielectric surface. This influences the transistor channel current through the variation of the threshold voltage[12]. The pH of electrolyte can be gauged by measuring the drain current (Id) as the gate voltage is swept. The value of Vds were decided based on the isothermal point behavior of the ISFET that shows less current/voltage variation to temperature [13]. However, this method is not practical as the measurement has to be done graphically.

Readout circuit is used to produce for in-situ applications, for direct output voltages to indicate different ion concentrations. Values of Id and Vds is biased at 100μA and 0.5V from isothermal stability as at these values the ISFET is said to be the least temperature dependent from the circuit [13].

Here, a conventional floating-source constant-voltage and constant-current circuit (CVCC), introduced by Caras, Janata etc [14] in 1980, is integrated with an ISFET macromodel. Objective of the readout circuit is to produce a continuous time series of the output voltage in response to pH concentration of the electrolyte. The CVCC circuit is chosen because circuit is capable to withstand the drift effect at high temperature as compared to single-stage amplifier. In our implementation, the CVCC circuit applies a constant Id to the ISFET which monitors changes in pH of electrolyte and reads the output voltage which comes from the source (Vs) as well as the drain voltage (Vd), in response to changes in Vref at the electrode. This is the first attempt that an ISFET macromodel is integrated with a CVCC circuit for circuit analysis and simulation on LTspice IV platform.

The paper presents the analysis behavior and graphs of Id, Vd and Vs after merging an ISFET with the CVCC circuit. A macromodel of an ISFET and CCVV circuit is created for analysis and simulation using LTspice IV software.

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II. ISFET THEORY

The structure of an ISFET is illustrated in Figure 1. As observed, the construction of ISFET is the same as MOSFET, if the metal part of electrode is replaced with the metal gate of MOSFET.

For ISFET, the reason for removing the metal-polysilicon-dielectric gate from MOSFET is so that the electrolyte solution can come into contact with the gate. The insulator or surface of gate oxide that is exposed directly to the aqueous electrolyte solution commonly uses silicon. This is because silicon contains OH-functionalities, meaning that silicon has inherently electrochemical equilibrium with H+ and OH ions in the sample solution. As the metal gate oxide comes into contact with the electrolyte, the silicon surface potential changes [15-16]. Hence, the gate potential is influenced by the ion concentration in the electrolyte solution, which causes changes to the threshold voltage (Vth). In other words, the change in pH concentration of the electrolyte produces change in the threshold voltage, due to ionic activity at the electrolyte-insulator interface.

The following explains how the concentration of H+ ion produces an electrostatic control on the drain-source current. The pH of solution is derived from the concentration of H^+ ions. High concentration of H^+ gives low value of pH while low concentration of H^+ gives high value of pH. These ions will become positively charge, thus produce electrostatic potential (electrical potential) by way of diffuse through the membrane at the silicon insulator layer and the oxide layer tend to except proton of H^+ ions. An additional gate voltage is needed to overcome the threshold voltage and create the channel for drain to source current to flow because of the electrical potential is too small. As a result, the variation of drain current (Id) due to the variation of the ion concentration in the electrolyte solution is compensated by the alteration of the reference electrode potential (Vref).

ISFET usually operates at constant drain current mode. With reference to Figure 1, the drain current flows from the source to the drain via the channel, dependent on the potential difference at the gate oxide. The selectivity and sensitivity of an ISFET depends on the selection of the gate dielectric material. Materials such as aluminum oxide and silicon nitride will have better properties than silicon, in terms of pH response, hysteresis and drift. Hence, silicon nitride is chosen for our work here.

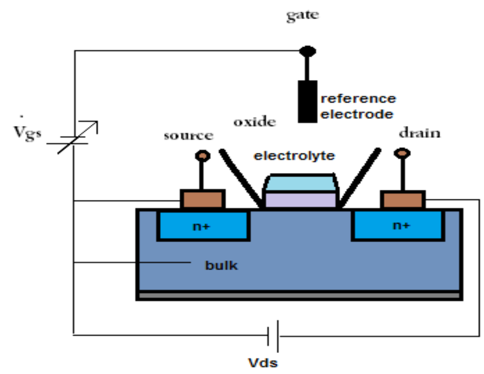

Figure 1: Structure of an ISFET

III. ISFET MACROMODEL

The macromodel specification for the ISFET to be used in combination with LTspice for simulation and analysis is based on previous work. LTspice is chosen because of its capabilities, facilities and easy to create new library for new component. This paper only covers on LTspice macromodel specification.The description of ISFET macromodel subcircuit is based upon MOSFET parameter model [17-20].

The ISFET macromodel is designed to emulate the electrochemical behavior of a real ISFET through equivalent circuit as in Figure 2. A CVCC circuit is included in the design so that output voltage from the source as well as the drain voltage, in response to changes in reference voltage at the electrode, can be read for simulation and analysis. The pH-independent source, demonstrated by an independent voltage source connected to a dummy resistor, mimics as input from the chemFET. This input voltage represents an equivalent value in pH as detected by the ISFET. The macromodel is built with the specification that n-type semiconductor as the bulk and silicon nitride as the insulator. Silicon nitride is the medium to receive the aqueous electrolyte solution from our previous works [21-22].

The pH-independent source is a chemical input signal demonstrated by an independent voltage source connected to a dummy resistor. This voltage is used to indicate as pH value. These macromodel was made based on n-type semiconductor and silicon nitride as the insulator [17]. The silicon nitride was placed linearly in an aqueous electrolyte solution.

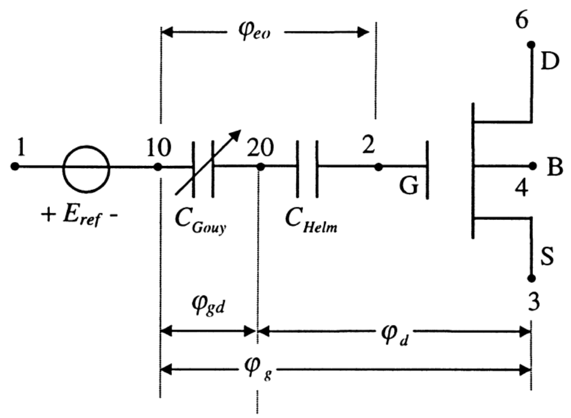

Figure 2: Equivalent circuit of an ISFET

This macromodel was created for monitoring ISFET variable simulation in order to combine ISFET with readout circuit. The results of the ISFET macromodel is to identify the characteristics of an ISFET. Graphs of Id versus Vd, Vref and Vph were produced in order to make sure the macromodel function as stated characteristic.

IV. CVCC Readout Circuit

The CVCC readout circuit in Figure 3 is used to obtain the change in voltage output in variation of the pH of the electrolyte as detected by the ISFET.

This readout circuit features of constant drain-source voltage (Vds) and constant draincurrent (Id) operation. The changes of pH can be obtained by the measurement of Vref at constant Id.

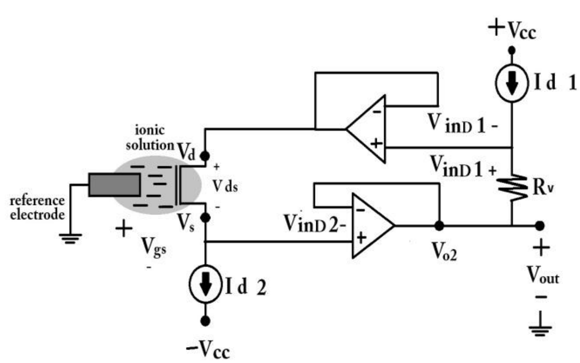

Figure 3: The CVCC readout circuit

The circuit in Figure 3 uses a current source and voltage follower to provide constant-voltage constant-current (CVCC) biasing. The two operational amplifiers are used to keep the voltage biasing constant. It functions like a voltage follower with unity gain. Current source (Id1) together with resistor (Rv), keeps the drain-source voltage (Vds) constant. It is because the non-inverting input of op-amp draws negligible current. So, Rv keeps Vds constant together with Id1. As the gate potential change in variation to pH electrolyte solution, Vgs changes[13]. Since the gate voltage (Vg) is grounded, the source voltage (Vs) becomes the final output by default. This is because any modulation of Vgs, changes Vs, and in turn Vout.

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V. Result and Discussion

The main objective of simulation of ISFET macromodel and readout circuit is to determine on the relationship between pH electrolyte of an ISFET and output voltage from readout circuit. The simulation focused on the ISFET macro model in order to analyse the relationship of ISFET variable and to make sure ISFET macro model function as stated characteristics. The values of pH4, pH7 and pH10 is based on the acidity, neutrality and alkaline of the electrolyte solution.

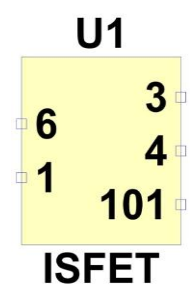

Figure 4: The ISFET capture symbol in LTspice

Figure 4 illustrates an ISFET capture symbol in LTspice schematics. The connection points of the symbol, 6 = Drain; 1 = Reference Electrode; 3 = Source; 4 = Bulk; 101 = pH input. This is then connected to the circuit in Figure 3 on LTSpice platform, to produce the circuit in Figure 5, for simulation.

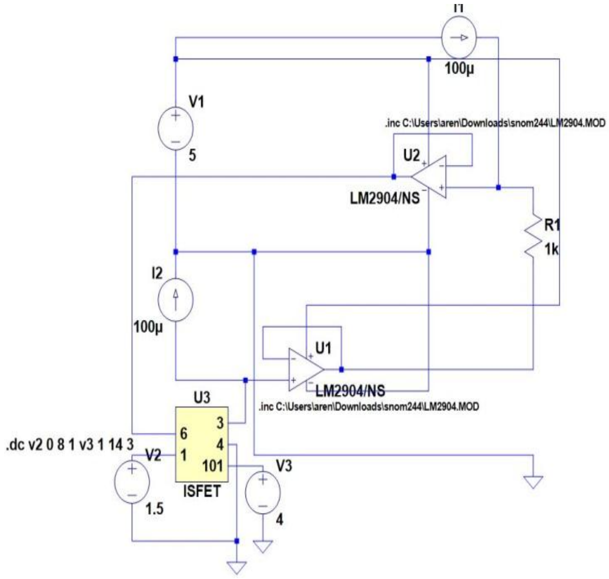

Figure 5: Schematic Diagram of ISFET Macromodel Readout Circuit

Figure 5 illustrates the schematic for integrated circuit of ISFET macromodel and CVCC readout circuit captured from LTSpice. The output from ISFET macromodel (connection point 3) becomes input to the CVCC circuit. This integrated circuit is then enabled to read the output voltage from CVCC circuit, Vs at connection point 3, in response to changes in pH input from the sensor. This is an enhancement from our previous work [21-22]. Changes in pH of the electrolyte is determined through measurement of Vref (connection point 1) with Id constant. For isothermal stability, an appropriate value for Id is 100µA.

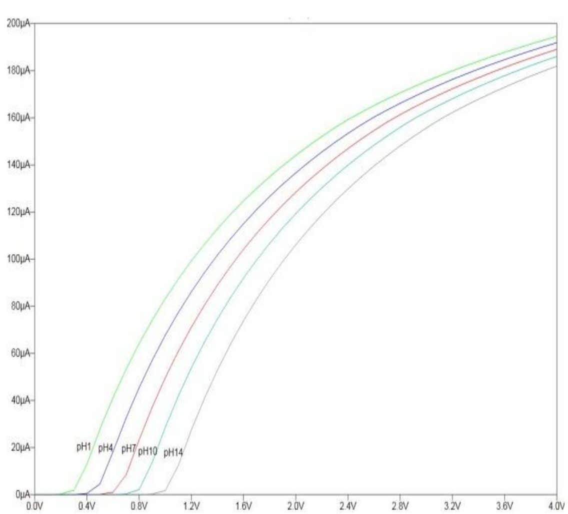

Figure 6: Variation in drain current (Id) with reference voltage (Vref) with drain voltage (Vd) constant at 0.1V

Figure 6 displays the variation in drain current with reference voltage, at constant Vd of 0.1V, for pH1, pH4, pH7, pH10 and pH14. At Vd of 0.1volt, the sensitivity is highest, which explains it being selected as the optimal parameter for H+ ISFET.

It can be observed that current Id is controlled by voltage Vref. The cut-off voltage for different values of pH is different, with 0.3V, 0.5V, 0.6V, 0.8V and 1.0V for pH1, pH4, pH7, pH10 and pH14 respectively. For low values of pH, H^+ ion present is high, hence the cut-off voltage is low. As the value of pH increases, since H^+ ions present is lower, the cut-off voltage increases. The 'Turn On'value for all the pH values equals and less than Vref of 1.0V. It can also observed that Vref are inversely proportional to the sensitivity (I/V). Results here concur with our previous work on PSpice platform [21-22].

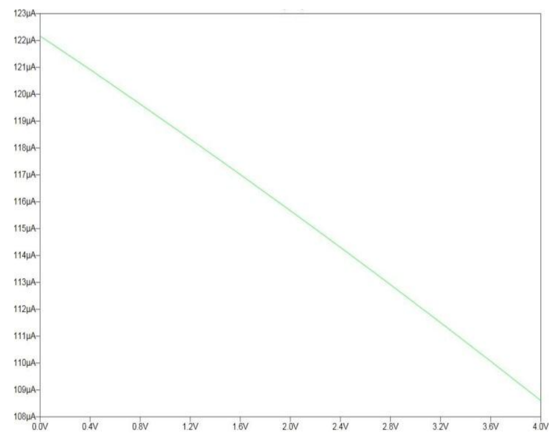

Figure 7: Variation in drain current (Id) with equivalent voltage of pH (VpH) at a constant Vref of 1.5V

Figure 7 shows the relationship between Id and VpH, with Vref constant at 1.5V, determined from Figure 6. It displays a linear relationship, yielding a sensitivity of 3.39µA/V. Linearity and sensitivity are important aspects to consider in the operation of ISFET. Results here concur with our previous work on PSpice platform [21-22].

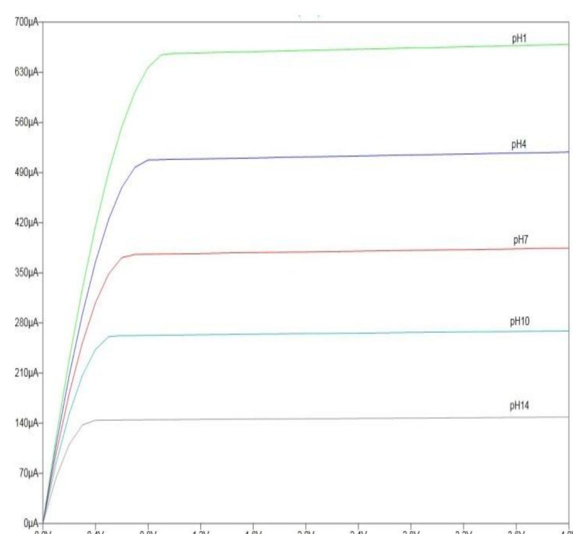

Figure 8: Variation of drain current (Id) with drain voltage (Vd) at reference voltage (Vref) constant at 1.5V

With Vref fixed at 1.5V, for linear and sensitive measurement of VpH against Id, the behaviour of Id towards Vd is examined in Figure 8. Id is observed to increase proportionally to Vd and then settles, to give the constant value for Id, which is dependent on the value of pH. Different value of pH yields different values of constant Id. The lower the value of pH, the higher the value of constant Id. For constant Id, Vd needs to be equal or more than 1.0V. It is also observed that the chosen ISFET parameters gives equal distribution of constant Id for different pH values, reflecting the linear characteristics between Id and VpH as shown in Figure 7. Results here concur with our previous work on PSpice platform [21-22].

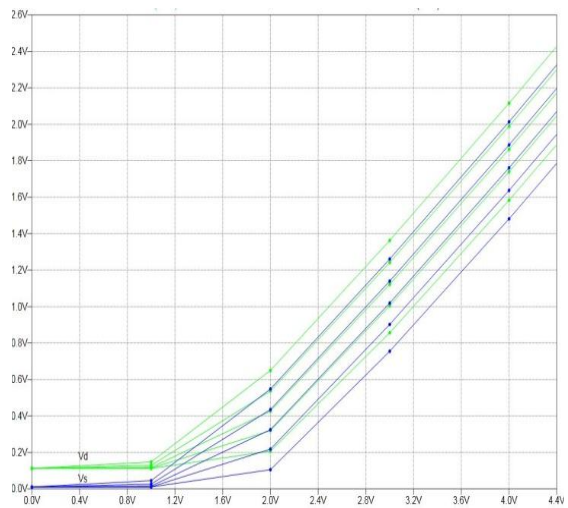

Figure 9: Variation in drain voltage (Vd) and source voltage (Vs) with reference voltage (Vref)

Figures 9 and 10 illustrate the variation in Vd and Vs with Vref. From Figure 5, it can be seen that the output voltage (Vs) is a direct feedback to the changes in Vref. Variation in Vd and Vs to Vref shows similiarity, except they differ in value by 0.1V. The output voltage (Vs) is found 0.1V higher than Vd, for all values of pH. Based on the result, we can conclude that Vds is constant at 0.1V

Figure 11: Variation in drain current (Id) with reference voltage (Vref)

Figure 11 show the variation of Id with Vref. The current Id is forced to be constant at 100µA even though Id supposedly to react at different pH. It also shows that at 1V (Vref) is the turning point which all different pH will become constant current. This is to make sure that the measurement due to pH changes only is taken.

Table 1 shows data collection of output CVCC circuit after changing Vref with six different set values. It also shows the proportional change of Vd and Vs towards Vref. Furthermore, although Vd and Vs change accordingly to Vref, CVCC readout circuit will make sure that Vds is constant at 0.1V.

TABLE 1: SIMULATION DATA FROM ISFET MACROMODEL READOUT CIRCUIT

Vref(V)	Vph(V)	Vd(mV)	Vs=Vout(mV)	Vds(mV)
0.4	1	112.509	10.738	101.771
	4	112.300	10.167	102.133
	7	112.267	10.134	102.133
	10	112.260	10.116	102.144
	14	112.368	10.107	102.261
0.8	1	125.673	23.581	102.092
	4	116.119	14.013	102.106
	7	112.883	10.755	102.128
	10	112.388	10.206	102.182
	14	112.271	10.138	102.133
1.2	1	179.659	77.701	101.958
	4	151.705	49.720	101.985
	7	132.012	29.981	102.031
	10	119.261	17.173	102.088
	14	113.150	11.240	101.910
1.6	1	381.154	279.201	101.953
	4	275.083	173.134	101.949
	7	197.447	95.495	101.952
	10	162.155	60.184	101.971
	14	135.000	32.977	102.022
2	1	649.909	547.943	101.966
	4	537.157	435.196	101.961
	7	427.000	324.583	101.955
	10	319.672	217.722	101.950
	14	206.876	104.925	101.951
2.4	1	929.211	827.131	102.080
	4	812.349	710.376	101.973
	7	697.300	595.332	101.968
	10	585.295	483.332	101.963
	14	445.388	343.432	101.956

VI. CONCLUSION

This paper has presented a novel CVCC readout circuit integrated with an ISFET macromodel on LTSpice platform, for characterizing the behavior of ISFET. The output voltage (Vs) from the ISFET macromodel integrated with CVCC readout circuit changes as pH of the electrolyte solution changes. From our simulation, it can be observed that current Id is controlled by voltage Vref. The cut-off voltage for different values of pH is different. The cut-off voltage and the "Turn ON" value for all pH equals and less than Vref of 1.0V. With respect to linearity and sensitivity for operation of the ISFET, Vref of 1.5V is deduced to be an appropriate value, which gives a sensitivity of 3.39µA/V. Vref is found inversely proportional to the sensitivity (I/V). Also, at this value of Vref, the Id is found constant for Vd equal or more than 1.0V, leaving Vd and Vs only to react towards Vref. In other words, Vd and Vs change in accordance to changes in the electrolyte concentration. Variation in Vd and Vs to Vref shows similiarity, except they differ in value by 0.1V. Based on this, Vds is selected constant at 0.1V. All the results here are found concur with our previous work on PSpice platform.

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