MODELING AND SIMULATION OF ISFET MICROSENSOR FOR DIFFERENT SENSING FILMS

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Abstract: Electronic circuit simulation programs like SPICE have built-in models for semiconductor devices like MOSFET and BJT. However, they do not provide models for electrochemical sensors like ISFETs (Ion-Sensitive Field-Effect Transistors). This paper presents a behavioral macromodel for ISFET-based pH-sensors implemented using PSPICE\textsuperscript{TM}. The macromodel is then utilized to present a comparative analysis of four different insulators, viz.: SiO\textsubscript{2}, Si\textsubscript{3}N\textsubscript{4}, Al\textsubscript{2}O\textsubscript{3} and Ta\textsubscript{2}O\textsubscript{5} used as sensing films for the ISFET. Simulations of ISFET devices with Al\textsubscript{2}O\textsubscript{3} and Ta\textsubscript{2}O\textsubscript{5} sensing films showed better performance with sensitivities of 58.8 mV/pH and 59.15 mV/pH, respectively. This complements the previously reported experimental and theoretical behaviour of ISFETs. Performance of corresponding MOSFET test structure using SILVACO\textsuperscript{®} simulations with the same insulators in the gate region is also presented.

Keywords: ISFET, SPICE, SILVACO, pH sensor

1. INTRODUCTION

Silicon-based microsensors are one of the most widely used sensors due to their advantages of on-chip integration with signal conditioning and processing circuitry and well established technology. Also, advancement in IC fabrication technology has reduced their cost of production. Recently, the demand for chemical/biochemical sensors has seen tremendous growth in the market which can have various applications such as blood monitoring, environment monitoring, biological analysis, chemical analysis and clinical detection [1-2]. They can be used for in-vivo monitoring of different parameters such as pH, glucose level, alkali metallic ions etc. The detection of pH is a powerful tool to monitor chemical changes in an analyte. A common method of measuring pH is to use glass membrane electrode [3]. However, it has inherent short comings such as durability, inability to operate at high temperatures, handling issues etc [2-3]. Its bulky size does not allow it to be used for in-vivo monitoring. Chemical microsensors like ISFETs have the ability to overcome the drawbacks of conventional glass membrane electrode due to its solid state nature [3]. It was invented by P. Bergeveld in 1970 primarily for neurophysiological measurements [4]. However, ISFETs can be used for chemical as well as biochemical sensing. According to the requirement, the ion sensing film of ISFET can be coated with different materials [5].

ISFET is a field-effect transistor, similar to a MOSFET, with the metal gate replaced by a reference electrode inserted in an electrolyte [6]. The gate connection is separated from the chip and the electrolyte solution is in contact with the gate oxide. The exposed gate region contains an insulator, acting as the sensing film. The sensing layer is an area of active research where different types of insulators like SiO\textsubscript{2}, Si\textsubscript{3}N\textsubscript{4}, Ta\textsubscript{2}O\textsubscript{5}, Al\textsubscript{2}O\textsubscript{3} etc have been investigated by researchers [7]. As shown in Fig. 1(b), the ISFET source and drain leads along with the chip edges need to be encapsulated fully, with the exception of gate area which is left open for contact with the electrolyte. However, MOSFET needs to be completely encapsulated.

This differentiates the techniques used to package these devices.

![Schematic diagram of (a) MOSFET, (b) ISFET.](image)

Figure 1: Schematic diagram of (a) MOSFET, (b) ISFET.

Availability of computer aided design (CAD) tools has made it possible to simulate semiconductor based devices even before going through the complete fabrication process, reducing the cost and design cycle. SPICE is one of the most
powerful electronic circuit simulation programs, which has built-in models for active devices like MOSFETs and BJTs [8]. However, they do not provide models for silicon based sensors. To address this problem, Martinioa et al. modified the original SPICE-2G and created BIOSPICE which contains built-physico-chemical models to deal with the electrochemical devices such as ISFET-based sensors [9]. In order to use the program, one needs to have deep knowledge of code subroutines and they are strictly version dependent. Therefore, they further created a new macromodel for ISFET which could be used in conjunction with HSPICETM [10]. This allowed adaptation of the algorithm into other commercial SPICE simulators like PSPICETM [11]. In this paper, PSPICE has been chosen to simulate the behaviour of a pH-sensitive FET. Firstly, a macromodel for ISFET is developed by modifying the built-in n-channel MOSFET model in PSPICETM. Then, the performance of different sensing films has been compared and their behaviour is summarized. Finally, simulated results MOSFETs with stacked insulators in SILVACO® Atlas™ has been presented.

2. ISFET MODEL FORMULATION

For both ISFET and MOSFET, the general expression for drain current in the non-saturated region is [3]

\[ I_D = \frac{\mu_C W}{L} \left( V_{GS} - V_T \right) \left( V_{DS} - \frac{1}{2} V_{DS}^2 \right) \]  \hspace{1cm} (1)

where \( \mu_C \) is the mobility of electrons in the inversion layer (assuming n-channel transistor), \( C_{ox} \) is the gate insulator capacitance per unit area, \( W \) and \( L \) are width and length of the channel, respectively. The expression of threshold voltage in ISFET is different from MOSFET owing to the fact that the inversion layer is obtained using reference electrode and gate oxide-electrolyte interface. The flatband voltage expression includes effect of reference electrode, interfaces between the liquid and the gate oxide on one side and the liquid and the reference electrode at the other side. The threshold voltage expression for an ISFET is:

\[ V_T = E_{ref} - \psi_o + \chi^{\text{tot}} - \frac{\phi_{Si} + Q_{ss} + Q_{ox} + Q_{g}}{C_{ox}} + 2\phi_F. \]  \hspace{1cm} (2)

Here, \( E_{ref} \) is the reference electrode potential relative to vacuum. \( \chi^{\text{tot}} \) represents the surface dipole potential of the solution, which is a constant. \( \psi_o \) represents the surface potential, which results from a chemical reaction, governed by the dissociation of oxide surface groups. The mechanism of oxide surface charge creation can be described by the site-binding model [12]. It describes the equilibrium between the amphoteric MOH solution sites and the H^+ ions in the solution.

\[ \text{MOH} \leftrightarrow n^+ \text{MOH} + n^+ \text{H}^+. \]  \hspace{1cm} (a)

\[ \text{MOH}^+ \leftrightarrow n^+ \text{MOH} + n^+ \text{H}^+. \]  \hspace{1cm} (b)

where, \( n^+ \text{H}^+ \) represents proton in the bulk of the solution. Each reaction has an associated dissociation constant (\( K_a \) and \( K_b \), respectively) and the concentration of \( n^+ \text{H}^+ \) is stated in terms of activity. We had earlier introduced \( \psi_o \) as the difference between the potential of the oxide surface \( \psi_S \) and the bulk of the solution \( \psi_B \):

\[ \psi_o = \psi_S - \psi_B. \]  \hspace{1cm} (3)

The activity of protons in the vicinity of insulator surface differs from bulk protons and their relationship is derived using Poisson-Boltzmann equation:

\[ a_{H_\text{ox}^+} = a_{H_\text{ox}^+} \exp \left( -q\psi_o / kT \right). \]  \hspace{1cm} (4)

The surface charge density \( \sigma_o \) is given by

\[ \sigma_o = qN_s \left( \frac{a_{H_\text{ox}^+}^2 - K_a K_b}{K_c K_b a_{H_\text{ox}^+} + a_{H_\text{ox}^+}^2} + qN_s \left( \frac{a_{H_\text{ox}^+}}{a_{H_\text{ox}^+} + K_n} \right) \right), \]  \hspace{1cm} (5)

where \( N_s \) and \( N_c \) represent the surface densities of silanol sites and primary amine sites and \( K_n \) represents the dissociation constant of primary amine sites [13].

The electrical double-layer theory derived from Gouy-Chapman-Stern model can be used to describe the charges and capacitances in the electrolyte [5]. The surface charge is balanced by an equal and opposite charge in the electrolyte. The resultant charge \( \sigma_o \) defines the so-called double layer and the integral double layer capacitance \( C_{DL} \) is the resultant of two capacitances in series, i.e., the Stern capacitance (Helmholtz layer) and the diffuse charge layer (Gouy-Chapman layer). The Stern layer can be divided into two sections, as shown in Fig. 2, for SiO\textsubscript{2} as the sensing layer.

![Figure 2: Helmholtz double layer at electrolyte-insulator interface.](image-url)

The locus of centers of the adsorbed ions on the insulator surface, which form pairs with the charged surface sites is known as Inner Helmholtz plane (IHP). The locus of centers of hydrated ions which is the next plane after IHP is known as Outer Helmholtz plane (OHP).

To develop a pH-sensitive FET model, the electrochemical stage in the electrolyte has to be considered to calculate the current flowing through the channel. An n-channel ISFET built using p-type silicon substrate has been considered with wafer resistivity of 10–20 \( \Omega \)-cm. To use the built-in MOSFET model, the electronic stage, i.e., the MOSFET has to be decoupled from the electrochemical stage which consists of the...
electrolyte-insulator interface. This is not possible if the following charge neutrality of the structure is considered

$$\sigma_0 + \sigma_{dl} + \sigma_s = 0,$$

(6)

where $\sigma_s$ is charge in the semiconductor. However, considering $\sigma_s$ to be constant with pH and much smaller than $\sigma_0$ and $\sigma_{dl}$ [14], the equation reduces to

$$\sigma_0 + \sigma_{dl} = 0.$$  

(7)

This allows us to decouple the electronic and electrochemical stages. The change in diffuse layer is given by the following expression using Gouy-Chapman-Stern model:

$$\sigma_{dl} = -\sqrt{8kT \varepsilon_o \varepsilon_r n_o} \sinh \left( \frac{zq \psi_2}{2kT} \right).$$

(8)

Here, $\psi_2$ is the potential at the $x_o$, i.e., the starting plane of diffuse layer with reference to bulk, $n_o$ is the concentration of each ion in the bulk solution in number/litre and $z$ is the valence of ion. It can also be written in the form

$$\sigma_{dl} = -\sigma_0 = -C_{df} \psi_o$$

(9)

The potential difference across Stern capacitance is $\psi_2 - \psi_0$. Also, the Stern capacitance has the value $C_{stern} = \varepsilon_r \varepsilon_o / x_H$.

Therefore, the potential $\psi_2$ can be found as shown in Fig. 3.

$$\psi_2 = \psi_o - \frac{\sigma_0}{C_{stern}} = \psi_o - \frac{\sigma_0 x_H}{\varepsilon_r \varepsilon_o}$$

(10)

![Figure 3: Potential variation in n-channel ISFET.](image)

Differential double layer capacitance $C_{df}$ expresses the ability of the double layer to store charge in response to a small change in potential and is given by

$$C_{df} = \frac{\partial \sigma_o}{\partial \psi_o} = -\frac{\partial \sigma_{dl}}{\partial \psi_o}.$$  

(11)

For the sake of simplicity, the inverse of $C_{df}$ is expressed [3]. It consists of the two components. Using Eq. 10 and 11,

$$\frac{1}{C_{df}} = \frac{\partial \psi_o}{\partial \sigma_o} = \frac{1}{C_{Helm}} + \frac{1}{\sqrt{2 \varepsilon_r \varepsilon_o z^2 q^2 n_o}} \cosh \left( \frac{zq \psi_2}{2kT} \right).$$  

(12)

Let, $C_{Gouy} = \sqrt{\frac{2 \varepsilon_r \varepsilon_o z^2 q^2 n_o}{kT}} \cosh \left( \frac{zq \psi_2}{2kT} \right)$.

As thermal voltage $V_T = kT/q$, for $\psi_2 << 2V_T$ and $z = 1$, we obtain

$$C_{Gouy} = \frac{\sqrt{8 \varepsilon_r \varepsilon_o kT n_o}}{V_T},$$

(13)

and,

$$C_{Helm} = \frac{\varepsilon_{HiP} \varepsilon_{OHP}}{\varepsilon_{HiP} d_{HiP} + \varepsilon_{OHP} d_{OHP}}.$$  

(14)

where $\varepsilon_{HiP}$ and $\varepsilon_{OHP}$ are the relative permittivities of IHP and OHP respectively while $d_{HiP}$ and $d_{OHP}$ are the locus of centers of adsorbed ions and hydrated ions respectively.

Hence, the expression for equivalent capacitance is

$$C_{df} = \frac{C_{Helm} C_{Gouy}}{C_{Helm} + C_{Gouy}}.$$  

(15)

From Eq. 5,

$$\sigma_o = qN_a f_a (\psi_o, pH) + qN_n f_b (\psi_o, pH).$$  

(16)

Combining Eq. 13 and Eq. 14 and introducing them into Eq. 9, the potential of electrolyte-insulator interface is obtained as

$$\psi_o = \frac{q}{C_{df}} \left[ N_a f_a (\psi_o, pH) + qN_n f_b (\psi_o, pH) \right]$$

(17)

This potential can be modeled as a non-linear voltage controlled voltage source depending on potential of $\psi_o$ itself along with the pH of electrolyte.

The general expression for the pH sensitivity of an ISFET is

$$\frac{\partial \psi_o}{\partial pH} = -2.3 \frac{kT}{\alpha q},$$

(18)

where, $\alpha = \frac{1}{2.3kT C_{df} \beta_{int}}.$

Here, $\beta_{int}$, the intrinsic buffer capacity is the effect of a small change in proton activity on the surface charge density due to
change in pH, i.e., $\frac{\partial \sigma}{\partial \text{pH}}$. The parameter $\alpha$ is a dimensionless sensitivity parameter whose value varies from 0 to 1 depending on the value of $\beta_{\text{act}}$ and $C_{\text{diff}}$. The surface buffer capacity and the double layer capacitance together determine the final value of the potential $\psi_o$. If $\alpha = 1$, the ISFET will have its maximum sensitivity of 59.2 mV/pH known as the Nernstian sensitivity. The electrical schematic of the model is shown in Fig. 4.

3. PSPICE MACROMODEL OF ISFET

The electrochemical stage derived in the previous section is coupled to an n-channel MOSFET, the electronic stage, leading to a behavioral ISFET macromodel. To create the macromodel, a new sub-circuit block is defined in PSPICE™. It consists of a conventional n-channel MOSFET, differential double layer capacitance and a pH input modeled as an independent voltage source equivalent to electrochemical input from the analyte. It is connected to a dummy resistor. Fig. 5 shows the terminal connections for the ISFET. Connections are as follows: D: Drain, S: Source, R: Reference electrode, B: Bulk, pH: solution pH value.

4. ISFET SIMULATION USING PSPICE

The ISFET macromodel developed in the previous section is used to analyse the behaviour of devices with different sensing layers. A comparison of four different sensing films is presented, viz., SiO$_2$, Si$_3$N$_4$, Al$_2$O$_3$ and Ta$_2$O$_5$. Simulations using different films require the dissociation constants and the number of surface sites to be changed. These parameters have been used from the available literature [11, 16] and listed in Table 1.

These films are used in conjunction with MOSFET previously fabricated in the institute laboratory [15]. MOSFET test structures were fabricated in order to extract various parameters and it also acts as a reference to see the behaviour of ISFETs with different sensing films and their response to different pH values of analyte. The MOSFET parameters as listed in Table 2. They are fed into the in-built MOSFET model, altering the parameters as and when required. Fig. 6 shows the simulated transfer characteristics of the MOSFET model used for ISFET macromodel. Output characteristics at different gate voltages are shown in Fig 7.

Table 1: Electrochemical parameters for different sensing films [11,16]

<table>
<thead>
<tr>
<th>Insulator</th>
<th>$K_a$(mol/l)</th>
<th>$K_b$(mol/l)</th>
<th>$N_m$(m$^{-2}$)</th>
<th>$K_n$(mol/l)</th>
<th>$N_n$(m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>15.8</td>
<td>63.1E-9</td>
<td>5.0E18</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Si$_3$N$_4$</td>
<td>15.8</td>
<td>63.1E-9</td>
<td>4.5E18</td>
<td>1.0E-10</td>
<td>0.5E18</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>12.6E-9</td>
<td>79.9E-10</td>
<td>8.0E18</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ta$_2$O$_5$</td>
<td>1.0E-4</td>
<td>1.0E-2</td>
<td>10.0E18</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2: PSPICE parameter values for ISFET simulation

<table>
<thead>
<tr>
<th>ISFET Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width (W)</td>
<td>500 µm</td>
</tr>
<tr>
<td>Length (L)</td>
<td>20 µm</td>
</tr>
<tr>
<td>Threshold voltage ($V_{th}$)</td>
<td>0.36 V</td>
</tr>
<tr>
<td>Silicon dioxide thickness ($T_{ox}$)</td>
<td>0.05 µm</td>
</tr>
<tr>
<td>Silicon nitride thickness ($T_{nit}$)</td>
<td>0.08 µm</td>
</tr>
<tr>
<td>Aluminium oxide thickness ($T_{AlOx}$)</td>
<td>0.027 µm</td>
</tr>
<tr>
<td>Sheet resistance ($R_{sh}$)</td>
<td>1.64 Ω/square</td>
</tr>
<tr>
<td>Substrate doping ($N_{sub}$) p-type</td>
<td>1.3E+15 cm$^{-3}$</td>
</tr>
<tr>
<td>Junction depth ($X_J$)</td>
<td>1.2 µm</td>
</tr>
<tr>
<td>GAMMA</td>
<td>0.3</td>
</tr>
<tr>
<td>Gate oxide capacitance ($C_{ox}$)</td>
<td>6.9E-04 F/m$^2$</td>
</tr>
<tr>
<td>Lateral Diffusion ($LD$)</td>
<td>0.96 µm</td>
</tr>
<tr>
<td>Fermi Potential ($PHI$)</td>
<td>0.59 V</td>
</tr>
</tbody>
</table>

Figure 4: Electrical schematic of ISFET.

Figure 5: Terminal connections for ISFET sub-circuit.

Figure 6: Transfer characteristics of MOSFET.
Fig. 8 shows the simulated transfer characteristics with SiO$_2$ as the sensing film at $V_{ds}=0.5$ V and bulk electrolyte concentration of 0.1M. It can be observed that the threshold voltage of ISFET varies according to different pH values (pH=4, 7 and 10). This variation in threshold voltage is non-linear, which is an indication of varying sensitivity of the device according to pH input. This is not desirable and it has been shown previously that stacking another layer of insulator like Si$_3$N$_4$, Al$_2$O$_3$, Ta$_2$O$_5$, SnO$_2$ etc can reduce this non-linearity [6].

The average simulated sensitivity is 36.95 mV/pH. Using the sensing layers mentioned above also improves the sensitivity. Fig. 9 shows the simulated transfer characteristics of Si$_3$N$_4$ as the sensing layer. To simulate different sensing films, the electrochemical parameters namely surface site density and dissociation constants have to be changed. The average simulated sensitivity is 52.93 mV/pH for Si$_3$N$_4$-gate ISFET, higher than that of SiO$_2$-gate ISFET.

Fig. 10 and 11 show the transfer characteristics obtained using Al$_2$O$_3$ and Ta$_2$O$_5$ as the sensing films, respectively. The average simulated sensitivities of ISFETs with Al$_2$O$_3$ and Ta$_2$O$_5$ as sensing films are 58.8 mV/pH and 59.15 mV/pH, respectively, higher than Si$_3$N$_4$. It can be seen that the sensitivity is quite linear in contrast to the behaviour of SiO$_2$.

Fig. 12 shows the transfer characteristics of ISFETs at pH=7 for different sensing films at $V_{ds}=0.5$V.
It is observed that the transconductance, which is the slope of the curve, remains constant for all curves. However, the threshold voltages are different for different sensing films. This can be explained by the fact that flat-band voltage for ISFET changes as the number of surface sites and dissociation constant changes. The transconductance of the channel remains same because the gate capacitance remains same in the MOSFET model used. Fig. 13 shows the corresponding output characteristics of ISFETs at pH=7 for different sensing films at $V_{ref}=1.5V$.

Fig. 14 shows the output characteristics of Al$_2$O$_3$-gate ISFET at different pH values keeping $V_{ref}=1.5V$. It can be observed that lower pH leads to higher saturation current because the threshold voltage is lesser for lower pH values.

The substrate bias effect is shown for ISFET with Al$_2$O$_3$ as the sensing layer in Fig. 15. The characteristic is similar to MOSFET where threshold voltage increases as $V_{ds}$ increases.

Fig. 16 shows a comparison of sensitivity obtained using different sensing films as a function of pH value. The sensitivities of SiO$_2$ and Si$_3$N$_4$ vary with pH while sensitivities of Al$_2$O$_3$ and Ta$_2$O$_5$ remain constant at 58.8 and 59.15 respectively. This is because the value of intrinsic buffer capacity and surface site density are very high for both of them in comparison to SiO$_2$ [16]. The value of double layer capacitance has almost no variation for all the films. Thus, the value of alpha in Eq. 18 is close to 1 in both the cases. Ta$_2$O$_5$ has higher value of intrinsic buffer capacity and surface site density in comparison to Al$_2$O$_3$. Fig. 17 shows the variation in drain current as the pH value of the analyte is varied keeping $V_{gs}=1.5V$ and $V_{ds}=0.5V$. It can be seen that initially, the change in drain current for SiO$_2$ is quite less. At higher pH values, it shows greater sensitivity to pH change.

5. **Sensitivity Analysis**
Another way to observe the sensitivity of an ISFET is to see the constant-current constant-drain voltage characteristics as $V_{\text{ref}}$ is varied.

The sensitivity can be obtained by calculating change in reference voltage required to obtain the same drain current ($I_{d} = 500\mu\text{A}$) per unit change in pH. Fig. 18 shows the variation in $V_{\text{ref}}$ with pH to obtain constant current. The slope of each curve gives the sensitivity of each ISFET with particular sensing film. The sensitivity of SiO$_2$-gate ISFET is initially very low but increases at higher pH values.

The role of surface site density is further elucidated by changing the parameters for Si$_3$N$_4$ sensing film. It has been shown previously that SiO$_2$ is the limiting case of Si$_3$N$_4$ \cite{10}. Fig. 19 shows the variation in applied $V_{\text{ref}}$ with pH input to obtain constant drain current ($I_{d} = 500\mu\text{A}$) at $V_{ds} = 0.5\text{V}$ as the ratio of silanol sites ($N_{s}$) to amine sites ($N_{n}$) is varied. The limiting case appears when there are no more amine sites, the behaviour corresponds to SiO$_2$-gate ISFET.

The MOSFET was also simulated in SILVACO™. The MOSFET was built using Athena process simulator. It allows us to stack different insulators in the gate region. The device simulations were carried out in Atlas. The effect of stacking various dielectric layers can be seen in the transfer characteristics as shown in Fig. 20.

Due to change in effective gate capacitance, the transconductance of transistors change. It also affects the threshold voltage of the MOSFET. It can be observed that $V_{gs}$ in the MOSFET has a significant effect on $V_{\text{ref}}$. The threshold voltage of the MOSFET is varied with $V_{gs}$.
stacking $\text{Si}_3\text{N}_4$ reduces transconductance more in comparison to $\text{Al}_2\text{O}_3$. $\text{Ta}_2\text{O}_5$ could not be simulated due to non-availability of the material in Atlas®. Output characteristics have been shown in Fig. 21. The simulations have been carried out in 2-D environment.

![Simulated output characteristics for different sensing films using SILVACO™ at $V_{gs}=1.5V$](image)

Figure 21: Simulated output characteristics for different sensing films using SILVACO™ at $V_{gs}=1.5V$

### 7. CONCLUSIONS

In this paper, we have presented a comparative analysis of ISFET-based pH sensors implemented with the help of PSPICE™. The behavioral macromodel uses two stages, i.e., an electrochemical stage which contains parameters for the electrolyte-insulator interface and electronic stage which consists of a MOSFET. The parameters for MOSFETs are taken from previously fabricated test structure at the institute laboratory. The electrochemical parameters have been taken from previously reported work. The simulated sensitivity for $\text{Ta}_2\text{O}_5$-gate ISFET is found to be 59.15 mV/pH close to Nernstian limit. $\text{Al}_2\text{O}_3$-gate ISFET also shows high sensitivity of 58.8 mV/pH. $\text{SiO}_2$-gate ISFET shows very low sensitivity at lower pH values and it has been shown that it is the limiting case of $\text{Si}_3\text{N}_4$-gate ISFET. The change in threshold voltage is clearly shown for different sensing films due to variation in electrochemical parameters namely surface site density and dissociation constants. Based on pH input, the output characteristics are shown to be varying because of change in threshold voltage of ISFET.

The behavior of MOSFETs with stacked dielectric layers is also shown using SILVACO®. A variation in transconductance was observed with stacked $\text{Si}_3\text{N}_4$-gate MOSFET having the lowest value. This also affects the output characteristics. Process simulation was carried out in Athena™ and device simulation was done in Atlas™.

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