Chapter 3

Novel Device Geometry – The Cylindrical ISFET
3.1 Introduction
In the last few years, surrounding gate cylindrical MOSFET has attracted an increased research interest because it possesses better electrostatic gate control [1]. The cylindrical structure MOSFET can be scaled down to sub few nm, indicating its suitability for use in bioelectronic devices oriented for biomedical and bioanalytical practices in vivo. Cylindrical MOSFET can be rendered H⁺ sensitive by eliminating its surrounding gate electrode by a series combination of a surrounding reference electrode and an electrolyte solution. In this chapter we propose a physico chemical model of threshold voltage, electrolyte potential profile model and drain current of the Cylindrical ISFET based on the solution of Poisons equation and Poisson Boltzmann equation in cylindrical coordinate. As far as semiconductor side is concerned, it is validated by comparing it with the model given in reference [2], while the electrolyte modeling is validated by comparing the result given in reference [3]. Good agreement is found with the models already available. The surface phenomenon of the device is based on the site binding theory [4] and the implementation of the corresponding model is done in cylindrical coordinate using basic formulae viz. the diffuse layer capacitance and normalized potential are developed for cylindrical geometry.

3.2 Threshold Voltage model of the Cylindrical ISFET
Structurally, cylindrical ISFET is obtained by replacing the surrounding metal gate of cylindrical MOSFET by the series combination of a surrounding reference electrode, electrolyte solution and a chemically sensitive insulator. Cylindrical MOSFET is basically a Gate All Around MOSFET with a cylindrical geometry. The schematic description of cylindrical ISFET structure is shown in fig 3.1
Fig. 3.1 Structure of the Cylindrical ISFET
The one dimensional Poisson’s equation for a MOS structure in cylindrical coordinate is given by

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \phi(r)}{\partial r} \right) = - \frac{\rho}{\varepsilon_{\text{Si}}} \tag{3.1}
\]

Where

\[
\rho = q \left( N_a^+ - N_a^- + p - n \right) \tag{3.2}
\]

\(\phi(r)\) potential distribution in the cylindrical silicon pillar,

\(N_a\) Acceptor doping concentration (per metre\(^3\))

\(N_d\) Donor doping concentration (per metre\(^3\))

\(q\) Charge of an electron (1.6x10\(^{-19}\) coulomb)

\(r\) radial direction of the cylindrical coordinate (metre)

\(\varepsilon_{\text{Si}}\) is the dielectric permittivity of silicon.

\((\varepsilon_{\text{Si}} = \varepsilon_0 \varepsilon_r = 103.59 \times 10^{-12} \text{ F/m})\)

For a p-type semiconductor \(N_a = 0\) and equation 3.2 becomes

\[
\rho = q \left( -N_a^- + p - n \right) \tag{3.3}
\]

For a moderately doped semiconductor \(p \gg n\), and therefore the equation 3.3 reduces to

\[
\rho = q \left( -N_a^- + p \right)
\]
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\[ \rho = q \left\{ -N_a^- + p_a \exp \left( -\frac{q\phi}{KT} \right) \right\} \]

\[ \rho = q \left\{ -N_a^- + N_a^- \exp \left( -\frac{q\phi}{KT} \right) \right\} \]

\[ \rho = qN_a^- \left\{ \exp \left( -\frac{q\phi}{KT} \right) - 1 \right\} \]

Putting this expression of charge density into the equation 3.1 we get

\[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial}{\partial r} \phi(r) \right) = -\frac{qN_a^- \left\{ \exp \left( -\frac{q\phi}{KT} \right) - 1 \right\}}{\varepsilon_{Si}} \]

Expanding the exponential term and neglecting the higher order terms we get

\[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial}{\partial r} \phi \right) = \left( \frac{q^2N_a^-}{\varepsilon_{Si}KT} \right) \phi \]

The equation 3.6 can finally be reduced to

\[ r^2 \frac{d^2\phi}{dr^2} + r \frac{d\phi}{dr} - \left( \frac{q^2N_a^-}{\varepsilon_{Si}KT} \right) r^2 \phi = 0 \]

\[ \Rightarrow r^2 \frac{d^2\phi}{dr^2} + r \frac{d\phi}{dr} - A.r^2 \phi = 0 \]
Where \( A = \left( \frac{q^2 N_a}{\varepsilon_s KT} \right) = L_D^{-2} \).

\( L_D \) is the extrinsic Debye length of the bulk semiconductor.

The equation 3.7 is Hyperbolic Bessel’s Differential Equation and the solution of this equation is given as [5]

\[
\phi(r) = B I_0(\sqrt{A} r)
\]

\[ \text{-------3.8} \]

Where \( I_0(\sqrt{A} r) \) is the Bessel’s function of first kind of order zero which is given as follows [6]

\[
I_0(\sqrt{A} r) = \sum_{k=0}^\infty \left( \frac{1}{4} (\sqrt{A} r)^k \right) \frac{1}{(k!)^2}.
\]

\[ \text{-------3.9} \]

‘B’ is a constant. Its value can be found by using the boundary condition.

\[
\phi_{r \to a_1/2} = \phi_s
\]

\[ \text{-------3.10} \]

And at threshold condition

\[
\phi_s = 2|\phi_f| = 2 \left| \frac{KT}{q} \ln \left( \frac{N_a}{n_i} \right) \right|
\]

\[ \text{-------3.11} \]
Therefore at the onset of inversion the equation 3.8 becomes

\[ 2|\phi_f| = B \sum_{k=0}^{\infty} \frac{\left\{ \frac{1}{4} \left( \sqrt{A_r} \right)^2 \right\}^k}{(k!)^2} \]  
\[ \cdots \cdots \cdots \text{3.12} \]

\[ \Rightarrow B = \frac{2|\phi_f|}{\sum_{k=0}^{\infty} \frac{\left\{ \frac{1}{4} \left( \sqrt{A_r} \right)^2 \right\}^k}{(k!)^2}} \]

\[ \Rightarrow B = \frac{\frac{KT}{q} \ln \left( \frac{N_a}{n_i} \right)}{\sum_{k=0}^{\infty} \frac{\left\{ \frac{1}{4} \left( \sqrt{A_r} \right)^2 \right\}^k}{(k!)^2}} \]  
\[ \cdots \cdots \cdots \text{3.13} \]

Now the bulk charge or depletion charge term for a cylindrical ISFET can be expressed as \( Q_{\text{depl_cyl}} \) at threshold condition is given by

\[ Q_{\text{depl_cyl}} = -\varepsilon_{SO_2} E_S \]  
\[ \cdots \cdots \cdots \text{3.14} \]

Where \( E_S \) is the electric field at the semiconductor surface at threshold condition.
The threshold voltage of a planar MOSFET is given as [7]

\[ V_{th\text{(mosfet)}} = V_{fb\text{(mosfet)}} + 2|\phi_f| + \frac{|Q_{\text{depletion}}|}{C_{ox}} \]  

\[ \text{-----3.17} \]

And consequently, the same for a cylindrical device can be written as

\[ V_{th\_cyl\text{(mosfet)}} = V_{fb\text{(mos)}} + 2|\phi_f| + \frac{|Q_{\text{depletion\_cyl}}|}{C_{ox\_cyl}} \]  

\[ \text{-----3.18} \]

\[ \phi_f \]: Fermi potential of the doped silicon pillar (in volts)

\[ V_{fb\text{(mos)}} \]: Flat band voltage (in volts) of the MOS structure and is given by equation 2.2

\[ C_{ox\_cyl} \]: Oxide capacitance per unit area for the cylindrical device (F/m²)

\[ Q_{\text{depletion\_cyl}} \]: Depletion charge per unit area for a cylindrical ISFET (F/m²)
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\[ C_{ox, \text{cyl}} = \frac{2 \varepsilon_{st}}{t_{st} \left( \ln \left( 1 + \frac{2 t_{ox}}{t_{st}} \right) \right)} \] \hspace{2cm} \text{-------3.19}

\( \varepsilon_{st} \): Dielectric constant of the oxide

\( t_{st} \): Diameter of the silicon pillar

Now using the reference [9], [10] and combining it with equation 3.18 the threshold voltage for the cylindrical ISFET can be written as

\[ V_{th, \text{cyl(ISFET)}} = V_{fb(\text{max})} + 2|\phi_j| + \frac{|Q_{\text{depletion, cyl}}|}{C_{ox}} + E_{\text{ref}} + \phi_j + \chi_e - \phi_{eo} - \phi_m \] \hspace{2cm} \text{-------3.20}

\[ V_{th, \text{cyl(ISFET)}} = V_{fb(\text{isfet})} + 2|\phi_j| + \frac{|Q_{\text{depletion, cyl}}|}{C_{ox}} \] \hspace{2cm} \text{-------3.21}

Where

\[ V_{fb(\text{isfet})} = V_{fb(\text{max})} + E_{\text{ref}} + \phi_j + \chi_e - \phi_{eo} - \phi_m \] \hspace{2cm} \text{------- 3.22}

\( E_{\text{ref}} \): Reference electrode potential (in volts)

\( \phi_j \): Liquid junction potential (in volts)

\( \chi_e \): Liquid dipole potential (in volts)

\( \phi_{eo} \): Electrolyte oxide interface potential (in volts)
The electrolyte oxide potential $\phi_{eo}$ is given by [11], [12]

$$\phi_{eo} = 2.303 \frac{KT}{q} (pH_{pzc} - pH) \left( \frac{\beta}{1 + \beta} \right)$$  \hspace{1cm} \text{(---3.23)}

Where

$pH_{pzc}$: The value $pH$ of the electrolyte at which the surface becomes neutral

$\beta$: Dimensionless sensitivity factor [13] given by

$$\beta = \frac{2 q^2 N_s (k_a k_b)^{1/2}}{kTC_d}$$  \hspace{1cm} \text{(---3.24)}

The two equilibrium constants are given by

$$k_a = \frac{[Si-O^-][H^+]_s}{[Si-OH]}$$  \hspace{1cm} \text{(---3.25)}$$

$$k_b = \frac{[Si-OH_2^+][H^+]_s}{[Si-OH][H^+]_s}$$  \hspace{1cm} \text{(---3.26)}$$

$N_s = \text{Number of binding sites per unit area}$
The equivalent double layer capacitance per unit area $C_d$ is given by [14]

$$\frac{1}{C_d} = \frac{1}{C_D} + \frac{1}{C_H} \quad \text{(3.27)}$$

Where, $C_H$ is the Helmholz capacitance per unit area. The Helmholz capacitance is the series combination of two capacitances – Inner Helmholz Plane (IHP) capacitance per unit area and Outer Helmholz Plane (OHP) capacitance per unit area [14].

$$C_H = \frac{1}{\frac{1}{C_{\text{IHP}}} + \frac{1}{C_{\text{OHP}}}} \quad \text{(3.28)}$$

For planer device $C_{\text{IHP}}$ and $C_{\text{OHP}}$ are given as

$$C_{\text{IHP}} = \frac{\varepsilon_{\text{IHP}}}{t_{\text{IHP}}} \quad \text{(3.29)}$$

$$C_{\text{OHP}} = \frac{\varepsilon_{\text{OHP}}}{t_{\text{OHP}}} \quad \text{(3.30)}$$

For a cylindrical device, it may be shown that IHP capacitance per unit area and OHP capacitance per unit area are given as (Appendix-2)
The general expression for diffuse layer capacitance per unit area $C_D$ is

$$C_D = \frac{d \sigma_{dl}}{d \phi_{eo}}$$  \hspace{1cm} \text{(3.33)}$$

$\sigma_{dl}$ is the charge in the diffuse layer \cite{15}

$$\sigma_{dl} = -\left(\sqrt{8e_{eo}f_{eo}}kTn_0\right)\sinh\left(\frac{ze_{eo}}{2kT}\right)$$  \hspace{1cm} \text{(3.34)}$$

Where $n_0 = c_0 \times 1000 \times N_{AV}$  \hspace{1cm} \text{(3.35)}$$

$N_{AV}$: Avogadro's number ($6.023 \times 10^{23}$ per mol)

$c_0$: molar concentration (mol/L)
Fig. 3.2: Cross sectional view of a cylindrical ISFET surrounded by electrolyte.
3.3 Drain Current Model of the ISFET

In a planer MOSFET the drain current is given by [16]

\[ I_{DN} = \mu C_{ox} \frac{W}{L} \left( (V_{GS} - V_{TH}) W_{DS} - \frac{V_{DS}^2}{2} \right) \]

\[ V_{GS} - V_{TH} > V_{DS} \]  
Active region------ 3.36

\[ I_{DN} = \mu C_{ox} \frac{W}{L} \frac{(V_{GS} - V_{TH})^2}{2} \]

\[ V_{GS} - V_{TH} < V_{DS} \]  
Saturation region------3.37

Where ‘W’ is the channel width for a planer device. In case of a cylindrical MOSFET ‘W’ is the effective width of the current path given by the following equation (Appendix-3)

\[ W = \pi \left[ \frac{r_0^2 - (t_{in} - t_{inv})^2}{4t_{inv}} \right] \]  
-------3.38

Where \( t_{inv} \) = thickness of the inversion layer. So the equation 3.36 and 3.37 the drain current equations for a cylindrical ISFET can be expressed as

\[ I_{DN} = \mu C_{ox_{-cyl}} \frac{\pi r_0^2}{4L_{inv}} \left( V_{GS} - V_{th_{-cyl(iffer)}} \right) W_{DS} - \frac{V_{DS}^2}{2} \]

\[ V_{GS} - V_{th_{-cyl(iffer)}} > V_{DS} \]  
Active region  ------3.39
Potential profile modeling of ISFET includes potential profile of the electrolyte and that of the semiconductor side.

3.4.1 Electrolyte Potential Profile

i) Stern Layer potential profile
In the stern layer there exist two charge layers viz. IHP and OHP. In between these charge layers there exist no charges and hence the Gauss law reduces to Laplace equation and consequently its solution yields a linear potential variation from the insulator surface to IHP and from IHP to OHP as given below.

\[
\phi_{\text{insulator}} - \phi_{\text{IHP}} = -\frac{\sigma_0 + Q_{\text{inversion}} + Q_{\text{depletion}}}{C_{\text{IHP}}} \quad \text{-------- 3.41}
\]

\[
\phi_{\text{IHP}} - \phi_{\text{OHP}} = -\frac{\sigma_{\text{diffuse}}}{C_{\text{OHP}}} \quad \text{--------3.42}
\]

From the condition of charge neutrality we get
\[ \sigma_{\text{diffuse}} + \sigma_{\text{IHP}} + \sigma_{\text{insulator}} + Q_{\text{inversion}} + Q_{\text{depletion}} = 0 \]  

\[ 3.43 \]

Again the potential at any point in between insulator surface and IHP the potential is given as

\[ \phi_{\text{IHP - region}}(r) = \phi_0 + \left( \frac{\phi_{\text{IHP}} - \phi_{\text{insulator}}}{t_{\text{IHP}}} \right) \left( r - \left( \frac{t_{\text{II}}}{2} + t_{\text{ox}} \right) \right) \]  

\[ 3.44 \]

For \( \left( \frac{t_{\text{II}}}{2} + t_{\text{ox}} \right) \leq r \leq \left( \frac{t_{\text{II}}}{2} + t_{\text{ox}} \right) + t_{\text{IHP}} \)

\[ \phi_{\text{OHP - region}}(r) = \phi_{\text{IHP}} + \left( \frac{\phi_{\text{OHP}} - \phi_{\text{IHP}}}{t_{\text{OHP}} - t_{\text{IHP}}} \right) \left( r - \left( \frac{t_{\text{II}}}{2} + t_{\text{ox}} + t_{\text{IHP}} \right) \right) \]  

\[ 3.45 \]

For \( \left( \frac{t_{\text{II}}}{2} + t_{\text{ox}} + t_{\text{IHP}} \right) \leq r \leq \left( \frac{t_{\text{II}}}{2} + t_{\text{ox}} \right) + t_{\text{OHP}} \)

ii) Diffuse layer potential profile

Since the device is of cylindrical shape, the surrounding electrolyte also takes the same form. The diffuse layer potential decays in the radial direction of the cylinder. This can be derived using the Poisson Boltzmann equation in cylindrical coordinate as [17]
\[ \frac{1}{r} \frac{d}{dr} \left( r \frac{d\phi}{dr} \right) = 2qn_0 \frac{zq\phi}{\varepsilon k_BT} \]

Where, \( z \) is the valence of the electrolyte ions.

For small value of \( \phi < 0.025V \) the term \( \left( \frac{zq\phi}{k_BT} \right) \) is smaller than unity and therefore the above equation can be approximated as

\[ \frac{1}{r} \frac{d}{dr} \left( r \frac{d\phi}{dr} \right) = \frac{2q^2z^2n_0}{\varepsilon k_BT} \frac{\phi}{k_BT} \]

or

\[ \frac{1}{r} \frac{d}{dr} \left( r \frac{d\phi}{dr} \right) = k^2 \phi \]

Where,

\[ k^2 = \frac{2q^2z^2n_0}{\varepsilon k_BT} \]

and

\[ k^{-1} = L_D \]

\( L_D \) is known as Debye length of the electrolyte solution. It is a measure of double layer thickness comprising of Helmholtz and Diffuse layer. At this length
the potential falls to around 33% that of the insulator surface if the surface is planar. For a curved surface this percentage is even smaller.

Now using the boundary conditions

\[ \phi(0) = \phi_0 \quad \text{and} \quad \frac{d\phi}{dr}\bigg|_{r=\sigma} = 0 \]  

\[ \tag{3.51} \]

The solution of the above equation is given below [17]. This gives the potential profile in the Diffused layer

\[ \phi(r) = \phi_0 \frac{K_0(kr)}{K_0(k(r_s + 2t_{ox}))} \]  

\[ \tag{3.52} \]

Where, \( K_0 \) is the modified Bessel function of zeroth order [18][19]

\[ \phi(r) = \frac{K_0(kr)}{\phi_0 K_0(k(r_s + 2t_{ox}))} \]  

\[ \tag{3.53} \]

The equation 3.53 gives the normalized potential profile in the diffused layer.

The diffuse layer charge density can be found as

\[ \sigma_{dl} = \varepsilon \frac{d\phi}{dr}\bigg|_{r=t_s+2t_{ox}/2} \]  

\[ \tag{3.54} \]
Fig 3.3: Charge distribution and potential profiles of an EIS system based on the Site Binding Model explains the reaction at the surface of insulator. This kind of charge distribution occurs for pH $>$ $p\text{H}_{\text{pzc}}$. 

*Tezpur University*
3.4.2 Semiconductor Potential Profile

For this part of modeling, two assumptions

i) Inversion layer is situated exactly at the semiconductor insulator interface. The inversion charge density for a cylindrical MOSFET is given by

\[
Q_{\text{inv}} = -C_{ax\_cyl} \left( V_{\text{ref}} - V_{m\_CYL(MOSFET)} \right) \quad --- 3.55
\]

\[
Q_{\text{inv}} = -C_{ax\_cyl} \left( V_{\text{ref}} - V_{m\_CYL(ISFET)} \right) \quad --- 3.56
\]

ii) Under depletion approximation the maximum thickness of the depletion layer is \( W_{depletion\_max} \) i.e. the depletion layer starts at the semiconductor–insulator interface and extends towards the far side of the interface up to \( W_{depletion\_max} \). The depletion charge density is given by equation 3.14 as follows.

\[
Q_{\text{depletion}} = -\varepsilon_{SiO_2} E_S \quad ----- 3.57
\]

Using the above, the potential drop across the inversion layer can be expressed as follows

\[
\phi_{\text{insulator}} - \phi_{\text{inversion}} = -\frac{Q_{\text{inv}} + Q_{\text{depletion}}}{C_{ax}} \quad ----- 3.58
\]
And similarly the potential variation across the depletion can be found by the following expression

\[ \phi_{\text{inversion}} - \phi_{\text{depletion}} = -\frac{Q_{\text{depletion}}}{C_{\text{depletion}}} \]  ----3.59

3.5 Amperometric Sensitivity

As defined in chapter 2, amperometric sensitivity is expressed as follows

\[ \frac{dl_{DS}}{dpH} = \mu C_{ox} V_{DS} \frac{W}{L} \frac{d}{dpH} (\phi_{eo}) \]  -------3.60

For a cylindrical device, the effective channel width of the cylindrical device is considered here. The effective width of a cylindrical device is as given in equation 3.38 is

\[ W_{ofi} = \frac{\pi \left[t_{H}^{2} - (t_{H} - t_{inv})^{2}\right]}{4t_{inv}} \]  -------3.61

Therefore the amperometric sensitivity of a cylindrical device is

\[ \frac{dl_{DS}}{dpH} = \mu C_{ox} V_{DS} \frac{W_{\text{cyl}}}{L} \frac{d}{dpH} (\phi_{eo}) \]  -------3.62
3.6 Simulation results and conclusions

The main goal of this work is to evaluate the behaviors of a cylindrical ISFET from its simulation results and compare the same with a planar ISFET. For this purpose a cylindrical ISFET has been modeled considering a long channel.

The simulation result in Fig. 3.4 shows variation of threshold voltage with change in acceptor doping concentration. Here a comparison is shown between the threshold voltage model developed in present work for a cylindrical MOSFET and model available in [2] equation no.(29). From low to moderately high doping concentration, good consistency of the simulation result of the present model is seen with results obtained from available literature, but at higher doping concentration the present model shows considerable deviation. This happens due to the fact that, during development of the model the assumptions were made for low to moderate doping concentration and not for high doping concentration.

Fig 3.5 shows drain current vs. gate to source voltage of the cylindrical MOSFET and same is compared model available in [2] equation no.(29).

Fig. 3.6 shows variation of electrolyte oxide interface potential vs. pH. This relation is almost linear throughout the range except at very low value of pH. This happens because at low value of pH, the value of $\beta$ is small. As the value of pH increases, $\beta$ also increases and consequently $\frac{\beta}{\beta + 1} = 1$ and hence the $\phi_{en}$ becomes linear. This variation of $\beta$ is shown in the fig. 6.

The fig. 3.7 shows variation of drain current of cylindrical ISFET vs. pH. As the pH value increase, electrolyte oxide interface potential decreases and this result in increase in threshold voltage of the ISFET. Consequently, an increase in
pH causes decrease in drain current. The figure shows a linear variation of the drain current for varying pH.

Fig. 3.8: shows relationship between pH and the dimensionless sensitivity factor β of the electrolyte oxide interface. This factor remains almost constant from pH=5 to 14. This range may be different for different material. For pH below 5, the value of this factor decreases and becomes stable around pH≤2.5. This transition is linear and sharp around the value of pH_{PZC} which is 4.2.

In the Fig.3.9:, the variation of diffuse layer capacitance is shown as a function of pH. For high value of pH i.e. at lower ionic concentration this capacitance is low. But as the pH decreases and falls below pH_{PZC}, this capacitance sharply increases. This happens because of high ionic concentration at low value of pH.

The variation of double layer capacitance with pH is shown in Fig.3.10: This also shows similar variation of capacitance as in the case of diffuse layer capacitance around pH_{PZC}.

Fig. 3.11 shows variation of Debye length as pH varies. For low value of pH the Debye length is few nanometers only, but as the pH increases the Debye length increases considerably.

The normalized potential profile vs. distance from the OHP is shown in Fig. 3.12. The normalized potential decays fast for low value of pH, whereas there is very slow variation of this at high value of pH. This is the main reason behind the sharp increase in the diffused layer capacitance at low pH.

Fig.3.13: shows the comparison of the normalized potential profile of a cylindrical and a planar ISFET at pH= 4. From this figure it can be observed that
the normalized potential decays faster in case of a cylindrical device as compared to that of a planar device.

Fig.3.14 and Fig.3.15: shows the comparison of the normalized potential profile of a cylindrical and a planar ISFET at pH= 7 and pH=10 respectively. From these three figures it can be observed that as the value of pH increases, the normalized potential decay for a cylindrical device becomes faster as compared to that for a planar device, but in absolute terms both becomes slow at high value of pH (fig.11).

Fig.3.16 shows the device Drain current variation with variation of Drain to source voltage at various pH. From this figure we can get indication of threshold voltage shift with pH by linear extrapolation.

Fig.3.17: shows drain current of the cylindrical ISFET vs. V_{ref} at different pH indicating pH response of the Cylindrical Device. When this figure is compared with the figure 2.7 of chapter 2, the increase in amperometric sensitivity for the cylindrical ISFET is observed which is presented in figure 3.19.

Fig.3.18 (a) shows variation of inversion charge density with pH. A decrease in inversion charge density is observed with increase in pH. Fig. 3.18 (b) shows variation of depletion charge density with pH. For this analysis the reference electrode voltage is kept at V_{ref} = 6.5 volts, so that inversion does not occur at any value of pH. A decrease in inversion charge density is observed with increase in pH.
Fig. 3.4: Threshold voltage vs. Doping concentration for a cylindrical MOSFET
**Fig. 3.5**: Drain current vs. Gate to source voltage

- $N_{d,poly} = 10^{25}$
- $N_p = 10^{23}$
- $t_o = 200 \text{nm}$
- $t_{ox} = 20 \text{nm}$
Fig. 3.6: Electrolyte oxide interface potential vs. pH
Fig. 3.7: Drain current vs. pH

- Cylindrical ISFET
- Planar ISFET

Parameters:
- $N_e = 10^{22}$
- $t_{ox} = 200 \text{nm}$
- $W = 200 \text{nm}$
- $V_{DS} = 2 \text{ V}$
- $pH_{ref} = 4.2$
- $t_{ox} = 20 \text{nm}$
- $L = 400 \text{nm}$
- $V_{ref} = 10 \text{V}$
Fig. 3.8: Surface buffer capacity vs. pH
Fig. 3.9: Diffuse layer capacitance vs. pH
Fig. 3.10: Double layer capacitance vs. pH
Fig. 3.11: Debye length vs. pH
Fig. 3.12: Normalized potential vs. distance from the OHP

- $t_d = 200 \text{ nm}$
- $t_{ox} = 20 \text{ nm}$

Normalized potential vs. distance from the OHP (nm)
Fig. 3.13: Comparison of Normalized potential vs. distance from the OHP at pH=4
Fig. 3.14: Comparison of Normalized potential vs. distance from the OHP at pH=7
Fig. 3.15: Comparison of Normalized potential vs. distance from the OHP at pH=10
Fig: 3.16: Drain current vs. Drain to source voltage at different value of pH
Fig: 3.17: Drain current vs. the voltage applied to the reference electrode at different value of pH.
Fig. 3.18: (a) Inversion layer charge density vs. pH ($V_{ref}=10V$).

(b) Depletion charge density vs. pH ($V_{ref}=6.5\, \text{V}$)
Fig. 3.19: Amperometric sensitivity of planar and cylindrical ISFET

- Planar ISFET
- Cylindrical ISFET

- Planar ISFET
  - $N_e = 10^{22}$
  - $W = 200\text{nm}$
  - $L = 400\text{nm}$
  - $V_{DS} = 2\text{V}$

- Cylindrical ISFET
  - $t_{ox} = 200\text{nm}$
  - $t_{ox} = 20\text{nm}$
  - $pH_{HCl} = 4.2$
  - $V_{ref} = 10\text{V}$

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3.7 References


