Prospects of Hysteresis-Free Abrupt Switching (0mV/dec) in Landau Switches

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Abstract—Sub-threshold swing (S) defines the sharpness of ON-OFF switching of a Field Effect Transistor (FET) with S = 0 corresponding to abrupt switching characteristics. While thermodynamics dictates S ≥ 60 mV/dec for classical FETs, “Landau switches” use inherently unstable gate insulators to achieve abrupt switching. Unfortunately, S = 0 switching is always achieved at the expense of an intrinsic hysteresis, making these switches unsuitable for low-power applications. The fundamental question therefore remains: Under what condition, hysteresis-free abrupt switching can be achieved in a Landau switch? In this paper, we first provide an intuitive classification of all charge based switches in terms of their energy landscapes and identify two well energy landscape as the characteristic feature of Landau switches. We then use nanoelectromechanical field effect transistor (NEMFET) as an illustrative example of a Landau switch and conclude that a flat energy landscape is essential for hysteresis-free abrupt switching. In contrast, a hysteresis-free smooth switching (S ≤ 60 mV/dec) is obtained by stabilizing the unstable gate insulator in its unstable regime, so as to provide internal voltage amplification necessary to achieve S ≤ 60 mV/dec. Our conclusions have broad implications and may considerably simplify the design of next charge based logic switch.

Keywords: Phase Transition, Ferroelectric, Two-well energy landscape, Nonlinearity, Bi-stable systems, Instability

I. INTRODUCTION

Scaling of field effect transistors (FETs) may eventually come to an end due to the non-scalability of sub-threshold swing (S); whose minimum value is thermodynamically limited to 60 mV/dec at room temperature. There is a worldwide search for the next logic switch [1] that can overcome the “Boltzmann tyranny” [2] of classical FETs and reduce S below the Boltzmann limit. Sub-threshold swing (S) of any FET is defined as the change in gate voltage (V_G) required for one order change in the drain current (I_DS), i.e.

\[ S \equiv \frac{dV_G}{d \log_{10}(I_{DS})} = \left( \frac{dV_G}{d \psi_s} \right) \left( \frac{d \psi_s}{d \log_{10}(I_{DS})} \right) = m \times n \]  

where transport factor \( n \equiv \frac{d \psi_s}{d \log_{10}(I_{DS})} \) is dictated by the current transport in the channel and body factor \( m \equiv \frac{dV_G}{d \psi_s} \) governs the coupling between the gate voltage (V_G) and channel potential (\( \psi_s \)). The value of \( m \) can be obtained by the schematic and equivalent capacitor divider model shown in Figs. 1A-B, and is given by:

\[ m \equiv \frac{dV_G}{d \psi_s} = 1 + \frac{C_s}{C}, \]  

where \( C_s \) is the depletion capacitance, \( C \equiv C_{ax} C_{ins}/(C_{ax} + C_{ins}) \) is the series capacitance of gate insulator (\( C_{ins} = \epsilon/\gamma \)) and thin SiO_2 layer (\( C_{ax} \)). Here, \( \epsilon \) and \( \gamma \) are respectively the permittivity and thickness of the gate insulator.

In classical Boltzmann switch, top of the barrier transport in the channel dictates \( n = 60 \text{ mV/dec} \) [3] at room temperature and traditional gate insulator with \( C_{ins} > 0 \) dictates \( m > 1 \) (Eq. 2). These two facts combined limit \( S \geq 60 \text{ mV/dec} \) for classical FETs (Eq. 1). In literature, there have been two major approaches to reduce S below 60 mV/dec (Fig. 1C). The first scheme involves reducing \( n < 60 \text{ mV/dec} \) (while keeping \( m \) fixed) by modifying the transport within the channel (e.g. source to channel tunneling in tunnel-FETs [4], impact ionization in I-MOS [5], etc.). In the second approach, \( m \) is reduced below one by changing the gate-insulator. In this scheme, the classical gate insulator (\( C_{ins} \)) characterized by a single well energy landscape as shown in Fig. 1D is replaced by an inherently unstable gate insulator which exhibits a two-well energy landscape, Fig. 1E. We call these new class of switches Landau switches, because of the similar two well energy landscape associated with phase transition [6]. Known examples of Landau switches include Ferroelectric-FET (FE-FET) [7], and nanoelectromechanical field effect transistor (NEMFET) [8].

Gate insulator is a ferroelectric material in FE-FET whereas NEMFET has an air-gap as the gate insulator is (Fig. 2). In FE-FET, instability in \( C_{ins} = \epsilon/\gamma \) arises due to instability in \( \epsilon \), whereas in NEMFET due to instability in \( \gamma \), i.e. pull-in instability [9]. The two wells (\( W_1 \) & \( W_2 \)) refer to two polarization states (\( P \)) in the ferroelectric, whereas they refer to gate up (\( y = y_0 \)) and down (\( y = 0 \)) positions in NEMFET. The abrupt switching from one well (e.g. \( W_1 \)) to another (e.g. \( W_2 \)) causes \( m = 0 \) (the role of inherent instability) and thus gives rise to abrupt switching characteristics equivalent to 0mV/dec as shown in Fig. 1F.

In principle, abrupt switching of Landau switches could potentially reduce the energy dissipation to the absolute minimum (if operated between points \( O_1 \) and \( O_2 \) in Fig. 1F). But, abrupt switching always comes at the cost of an intrinsic hysteresis, because once switched from \( W_1 \) to \( W_2 \) (or vice versa), switching back from \( W_2 \) to \( W_1 \) does not occur at the same applied voltage. Therefore, hysteresis in Landau switches (Fig. 1F) dictates the minimum energy dissipation \( \Delta E_d = Q_H H_d \) with \( Q_H \) being the difference in charge between two states and \( H_d \) being the width of the hysteresis), because
the switch must operate between points $O_3$ and $O_2$ (Fig. 1F). The fundamental question therefore remains under what condition hysteresis-free abrupt switching ($H_y = 0, S = 0$) can be realized in a Landau switch leading to minimum energy dissipation (when operated between points $O_3$ and $O_2$ in Fig. 1G)?

We consider this question in a general context, because the energy landscape of all Landau switches is characterized by two isolated energy wells separated by an energy barrier (Fig. 1E) and therefore the conclusions reached by analyzing one switch (e.g., NEMFET) should apply broadly to all other switches of this class. We emphasize that abrupt switching in Landau switches occur irrespective of the transport mechanism within the channel. In this article, therefore, we restrict ourselves to $n = 60 \text{mV/dec}$ of a typical Boltzmann switch to focus exclusively on strategies that make $m < 1$.

The paper is organized as follows. In section II, we discuss the physics of hysteresis in NEMFET. The question of hysteresis-free $0 \text{mV/dec}$ switching is addressed in section III. Section IV shows a unique material independent way of achieving hysteresis-free sub $60 \text{mV/dec}$ switching in NEMFET. In section V, we explore the prospects of hysteresis-free abrupt switching in FE-FET to verify whether the conclusions based on NEMFET are general enough to be applicable to another example of a Landau switch. Our conclusions are summarized in section VI.

II. THEORY OF HYSTERESIS IN NEMFET

Figure 2A shows the schematic of NEMFET in which gate is a fixed-fixed beam and air-gap creates the gate insulator; the structure is similar to a suspended-gate FET [10] and resonant gate transistor [9]. The essential operation of NEMFET can be understood in terms of a spring-mass system [9] in which the movable gate is suspended from a spring as shown in Fig. 2B. When a dc bias $V_g$ is applied, the position of the gate can be obtained by minimizing the total system energy ($U = U_s + U_e$). Mechanical spring energy ($U_s$) and the electrostatic energy ($U_e$) are given by:

$$U_s = \frac{1}{2} k (y_0 - y)^2,$$

$$U_e = -\frac{1}{2} \frac{\varepsilon_0 A}{y + y_{eff}^e} y_G^2,$$

where $k = \alpha E L H^3 / W^3$ is stiffness of the gate, $\alpha$ is a geometrical constant, $E$ is the Young’s modulus of gate material, $L$ is the channel length (also equal to the gate width), $W$ is the channel width (also equal to gate length), $H$ is the thickness of the gate, $y_0$ is the initial air-gap, $y$ is the gap between the gate and $\text{SiO}_2$, $\varepsilon_0$ is the permittivity of free space, $A = WL$ is area of the gate, and $y_{eff}^e = \varepsilon_0 / C_s$ is the effective depletion width (normalized to air) of semiconductor channel.

To understand the operation of NEMFET, let us consider the evolution of $U - y$ landscape as a function of $V_g$. For a given $V_g$, the system is stabilized at the minimum of $U$, shown by open circles in Fig. 3A. With increasing $V_g$, gate is stabilized at smaller gap and $y$ decreases (Figs. 3 A & C). When $V_g$ exceeds the pull-in voltage ($V_{pl}$), $U - y$ landscape does not exhibit any local minima making NEMFET inherently unstable. Therefore, gate can no longer be stabilized in air. The gate is now pulled-in to stabilize at $y =$
0, corresponding to the global minima of $U$ (Figs. 3A & C). This well-known pull-in instability [9], [11] of NEMFET occurs at a critical air-gap $y_c$ given by (see section A1 of Appendix for derivation)-

$$y_c = \frac{2}{3}y_0 - \frac{1}{3}y_{d}^{eff}.$$  \hspace{1cm} (5)

Note that, for $y_{d}^{eff} \ll 2y_0$, $y_c$ reduces to $\frac{2}{3}y_0$. In other words, gate can only be stabilized in the region $\frac{2}{3}y_0 < y < y_0$, with rest of the gap positions inaccessible due to stability considerations. This well-known result is shown schematically in Fig. 3D. The position of the gate remains clamped at $y = 0$ with further increase in $V_G$ (Fig. 3C). We stress that this discontinuous jump in $y - V_G$ characteristic (i.e., $y_c \neq 0$) makes $C_{air} = C_{ais} = \varepsilon_0/y$ discontinuous, with a corresponding discontinuous jump in the $I_{DS} - V_G$ characteristic corresponding to $S = 0 mV/dec$ switching characteristics.

When $V_G$ is reduced, gate does not immediately spring back in air at $V_G = V_{pf}$. This is because of the presence of an energy barrier (Fig. 3B, green curve). Therefore, gate remains at $y = 0$ (shown by open triangles in Figs. 3B-C) until $V_G$ is reduced such that energy barrier vanishes (Fig. 3B, magenta curve). This occurs at pull-out voltage ($V_{po}$) and any reduction in $V_G < V_{po}$, releases the gate (Figs. 3B-C). This asymmetry between pull-in and pull-out due to the presence of an energy barrier at pull-in, results in hysteretic $y - V_G$ characteristic i.e., $H_V = V_{pf} - V_{po} \neq 0$ (Fig. 3B) and also hysteretic $I_{DS} - V_G$ characteristic as shown in Fig. 1E. Despite the $S = 0 mV/dec$ transition, this $H_V \neq 0$ makes Landau switches unsuitable for ultra-low voltage applications. Given this background, we now explore the prospects of hysteresis-free ($H_V = 0$) abrupt switching $S = 0$ in Landau switches.

III. HYSTERESIS-FREE ABRUPT SWITCHING

Hysteresis-free abrupt switching ($H_V = 0 \& S = 0 mV/dec$, see Fig. 1E) in NEMFET must display a $y - V_G$ characteristic similar to that of Fig. 4A, i.e., $H_V = 0$ and $y_c \neq 0$. Such a $y - V_G$ characteristic can be obtained only if the total energy of the system ($U_T$) is flat at the pull-in point, as shown in Fig. 4A, i.e., $H_V = 0$. Indeed, an equivalent of such $U_T$ is $y_c = y_0$.

4B. A flat energy landscape allows switching of the gate between $y = y_c$ and $y = 0$ with infinitesimally small change in $V_G$. Figure 4C shows (based on Eqs. 3-4) that energy landscape of a NEMFET at pull-in exhibiting energy barrier. Therefore, the requisite for flat energy landscape in Fig. 4B can only be achieved by incorporating an external energy component ($U_{ext}$) to compensate the energy barrier at the pull-in point. This additional energy can be given by-

$$U_{ext} = \frac{0}{U_1}; \quad y_c < y < y_0 \hspace{1cm} (6a)$$

$$U_1 = \frac{1}{2}\varepsilon_0 A V_0^2 \left(1 + \frac{1}{y_{d}^{eff}} + \frac{1}{y_c} + \frac{1}{2}k(y_0 - y_c)^2 - (y_0 - y)^2 \right), \hspace{1cm} (6b)$$

and is plotted in Fig. 4D. Note that, $U_{ext}$ does not depend on $V_G$. In principle, $U_{ext}$ could be provided by a nonlinear spring [12] i.e., $U_{ext}^{NC} = U_s + U_{ext}$. Indeed, an equivalent of such “nonlinear spring” to flatten the energy landscape is the prerequisite for all Landau switches to achieve hysteresis-free abrupt switching. In NEMFET, however, it is well-known that a realistic spring (made up of linear elastic material) can only provide nonlinearity of up to third order i.e., $U_{s}^{real} = \frac{1}{2}k(y_0 - y)^2 + \frac{1}{4}k'(y_0 - y)^4$, where $k'$ is a geometrical constant associated with spring of cubic nonlinearity [13], [14], and therefore cannot adequately compensate the energy barrier of a typical spring-mass system (Eqs. 3-4 & 6). Lack of such highly nonlinear spring makes us to conclude that hysteresis-free abrupt switching is practically impossible in present state-of-the-art NEMFET. It should however inspire new material or spring designs that can compensate highly
nonlinear energy landscape of NEMFET to achieve hysteresis-free abrupt switching.

IV. HYSTERESIS-FREE SMOOTH SWITCHING

In contrast to Hysteresis-free abrupt switching ($H_V = 0$ & $S = 0$), hysteresis-free smooth switching ($H_V = 0$ & $S > 0$) requires a benign $y-V$ characteristic which displays no hysteresis, but then have no pull-in instability either, i.e., $H_V = 0$ & $y_c = 0$, as shown in Fig. 5A. Since $H_V \ll y_c^2$ (see section A1 of Appendix for derivation) and $y_c$ given by Eq. 5, $y_d^{eff} = 2y_0$ makes both $H_V$ and $y_c$ zero. It means that a series capacitor $C_s = \epsilon_0/2y_0^{eff}$ (semiconductor depletion capacitance) with half the value of the initial air-gap capacitance ($\epsilon_0/2y_0$) in Fig. 1B, enables hysteresis-free smooth switching. Note that, this switching behavior has fundamentally been made possible by stabilizing the gate in its inherently unstable regime, as shown in Fig. 3D. This stabilization comes from an inherent negative feedback provided by the series capacitor ($C_s$), so that the voltage-drop across air-gap capacitor ($V_{air}$) decreases when the gate enters in the unstable regime (Fig. 5B). This decrease in $V_{air}$ amplifies the voltage-drop across $C_s$ (channel potential ($\psi_s$)) (Fig. 5B). This amplification in $\psi_s$ is directly reflected in the body factor $m < 1$, symbols in Fig. 5C. If one accounts for the charge build up inside the semiconductor (i.e., voltage dependence of $y_d^{eff}$), it can be shown that (see section A3 of Appendix for derivation)-

$$m \equiv \frac{dV_s}{d\psi_s} = 1 + \frac{C_s}{C_{air}^{eff}}, \quad 7(a)$$

$$C_s = \frac{q\epsilon_0\epsilon_s N_A}{2\psi_s}, \quad C_{air}^{eff} \approx \frac{\epsilon_0}{3\left(\frac{2}{3}\gamma_0\right)}, \quad 7(b)$$

where $q$ is the charge on an electron, $\epsilon_s$ is dielectric constant of channel material, and $N_A$ is the channel doping. $C_{air}^{eff}$ is the effective air-gap capacitor that determines the coupling between $V_s$ and $\psi_s$. Interestingly, air-gap capacitor acts effectively like a negative capacitor when gate enters in the unstable regime (i.e., $C_{air}^{eff} < 0$ when $y < \frac{2}{3}\gamma_0$, Eq. 7(b)) and therefore, provides necessary voltage amplification to reduce $m$ below one. Equation 7 correctly reproduces the numerical simulations results (see for SI-II for numerical simulations framework and Ref. [15]) in Fig. 5C.

It is important to note that the value of $N_A$ must be carefully optimized so that it provides the necessary series capacitance to stabilize the gate throughout the air-gap. The corresponding $I_{DS} - V_s$ for the same NEMFET obtained from the self-consistent numerical simulations (see section A2 of Appendix for numerical simulations framework) is shown in Fig. 5D which indeed confirms the hysteresis-free smooth switching of NEMFET. In sub-threshold regime, $I_{DS} - V_s$ characteristic is highly nonlinear and does not exhibit a constant sub-threshold swing. Therefore, we define an effective sub-threshold swing ($S_{eff}$) for $I_{DS}$ ($y = \frac{2}{3}\gamma_0$) < $I_{DS}$ ($y = 0$) when NEMFET is biased in negative capacitance regime. Considering this, $S_{eff}$ is given by $\Delta V/\log\left(\frac{I_{DS}(y=0)}{I_{DS}(y=\frac{2}{3}\gamma_0)}\right)$, where $\Delta V$ is defined in Fig. 5D. The value of $S_{eff}$ for the chosen parameters is capacitance regime.
Note that, the idea of using a series capacitor to achieve $\gamma_e = 0$ is long known in MEMS literature [17], [18], however, its implications as a negative capacitor for voltage amplification in a FET has not been appreciated. Finally, the hysteresis-free sub—60mV/dec switching in NEMFET is obtained by utilizing the nonlinear electromechanical coupling between electrostatic and mechanical energy/forces of NEMFET. As opposed to other sub—60mV/dec switching schemes, such as Ferroelectric-FET with negative capacitance [16], Tunnel-FETs [4], and Impact Ionization FETs [5], NEMFET is unique as it only utilizes the electromechanical coupling, rather than any specific material property, to achieve hysteresis-free sub—60mV/dec switching.

V. DISCUSSIONS ON FE-FET

Based on the analysis of NEMFET, let us summarize the general conclusions regarding Landau switches-

- Hysteresis-free abrupt switching ($S = 0$) in Landau switches require an extra energy component to go from an intrinsic two well energy landscape to a flat energy landscape.
- Hysteresis-free sub—60mV/dec switching is obtained by stabilizing the unstable gate insulator in its unstable regime.

We now validate the generality of these conclusions using FE-FET—another example of a Landau switch. We again follow the same procedure and look at the evolution of energy landscapes of FE-FET. Total energy ($U$) of a ferroelectric dielectric system in terms of its polarization ($P$) is given by:

$$U = \alpha P^2 + \beta P^4 + \gamma P^6 - PE,$$

where $\alpha, \beta$ and $\gamma$ are material dependent constants and $E = V_G/y$ is the applied electric field. Figure 6(A) shows energy landscapes when $V_G$ is increasing assuming that dielectric is negatively polarized to begin with ($P < 0$ at $V_G = 0$). Open circles denote the position of stable equilibrium. As $V_G$ increases, energy landscape changes such that value of $P$ at equilibrium increases (though keeping the same negative sign, see Fig. 6C). Beyond a certain $V_G > V_{sp}$, however, the left minima of energy landscape (occurring at $P < 0$, Fig. 6A) is flat and $P$ has to abruptly switch from a negative value to a positive value (Fig. 6A, energy landscape corresponding to $V_G = V_{sp}$). Like a NEMFET, if $V_G$ is reduced below $V_{sp}$, $P$ can not switch back from a positive value to a negative value, because of the presence of an energy barrier (Figs. 6A-B). $V_G$ has to be reduced below $V_{sn}$ for switching the polarization back to a positive value (see Figs. 6B-C) and that causes the hysteretic $P - V_G$ characteristic as shown in Fig. 6C.

For hysteresis-free abrupt switching in FE-FET, a $P - V_G$ characteristic as shown in Fig. 6D is required (similar to the $-V_e$ characteristic of NEMFET in Fig. 4A). Similar to a NEMFET, such $P - V_G$ characteristic can only be achieved if energy barrier at $V_G = V_{sp}$ can be compensated by an extra energy component ($U_{ext}$) as shown in Fig. 6E to give rise to a flat energy landscape in Fig. 6F. Therefore, the requirement of an extra energy component to make energy landscape flat is the requirement of all Landau switches.

Regarding hysteresis-free smooth switching in FE-FET, it has previously been shown that stabilizing the ferroelectric in its unstable regime using a series capacitor (like NEMFET in Fig. 5) puts it into negative capacitance regime and exhibits sub—60mV/dec switching [16], [19], [20]. Although the detailed physics of NEMFET and FE-FET is completely different, the general conclusions regarding hysteresis-free abrupt and smooth switching are essentially the same.

VI. CONCLUSIONS

We have shown that FE-FET and NEMFET belong to a general class of switches called Landau switches characterized by a two-well energy landscape similar to that of a phase transition. We determined that an extra energy component is needed to make the energy landscape of Landau switches flat to achieve hysteresis free abrupt switching. In contrast, stabilization of the unstable gate insulator in its unstable
regime provides necessary internal voltage amplification to achieve hysteresis-free sub-60mV/dec switching. NEMFET provides a unique material independent way to achieve hysteresis-free sub-60mV/dec only by utilizing nonlinear electromechanical coupling unlike any other proposal of sub-60mV/dec switch e.g., Tunnel FETs. Impact Ionization FETs, Ferroelectric negative capacitance FETs. Although, the results are discussed for top of the barrier transport, the general conclusions are valid for other transport mechanisms also.

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**APPENDIX**

**A1-Pull-in instability and hysteresis**

The static behavior of NEMFET is governed by the minimization of total system energy \( U = U_s + U_e \) (Eqs. 3-4 in main text). Minimization of \( U \) with respect to the gap \( y \) i.e. \( \frac{dU}{dy} = 0 \), yields the following force balance equation-

\[
k(y_0 - y) = \frac{1}{2} \left( \frac{\epsilon_0 A}{\epsilon_a^e f f + y} \right) V_G^2, \tag{A1}
\]

where left hand side of Eq. A1 is the spring force and right hand side is the electrostatic force. Pull-in instability occurs when \( U - y \) profile exhibits an inflection point i.e. \( \frac{d^2U}{dy^2} = 0 \), that yields-

\[
k = \frac{\epsilon_0 A}{\epsilon_a^e f f + y} V_G^2. \tag{A2}
\]

Solution of Eqs. A1-A2 gives the critical gap \( y_c \) at which pull-in instability occurs-

\[
y_c = \frac{2}{3} y_0 - \frac{1}{3} \epsilon_a^e f f y_0, \tag{A3}
\]

which is same as Eq. 3 in the main text. Using Eq. A1 & A3 value of pull-in voltage \( (V_{pi}) \) is given by-

\[
V_{pi} = \frac{\sqrt{8k (y_0 + \epsilon_a^e f f y_0)^3}}{3 \epsilon_0 A}. \tag{A4}
\]

Once the gate is pulled-in, it does not spring back at the same voltage as discussed in the main text, rather voltage has to be reduced below pull-out voltage \( (V_{po}) \). Expression of \( V_{po} \) can simply be obtained by putting \( y = 0 \) in Eq. A1 and is given by-

\[
V_{po} = \sqrt{2k y_0 (\epsilon_a^e f f y_0)^2}. \tag{A5}
\]

Now using the analytical formula of \( V_{pi} \) and \( V_{po} \), expression for hysteresis \( H_Y = V_{pi} - V_{po} \) is given by-

\[
H_Y = \frac{8k (4y_a^e f f + y_0)}{3 V_{pi} + V_{po}} V_G^2, \tag{A6}
\]

which suggests that \( y_c = 0 \) implies \( H_Y = 0 \).

**A2-Simulation framework for NEMFET**

In a practical NEMFET the buildup of charge inside the channel should be taken into account. Considering that, the static behavior of NEMFET is dictated by the balance of spring and electrostatic forces, i.e.

\[
k(y_0 - y) = \frac{1}{2} \epsilon_0 E_{air}^2 A, \tag{A7}
\]

where \( E_{air} \) is the electric field in the air and is equal to \( \epsilon_0 E_s (\psi_s) \), where, \( \epsilon_0 \) is the dielectric constant of the substrate, and

\[
E_s (\psi_s) = \frac{2qN_i}{\epsilon_0 \epsilon_s} \left[ \psi_s + \left( e^{\frac{q \psi_s}{k_B T}} - 1 \right) \frac{k_B T}{q} \right]^{\frac{1}{2}}, \tag{A8}
\]

where, \( E_s (\psi_s) \) is the electric field at the substrate-dielectric interface, \( \psi_s \) is the surface potential, \( q \) is the charge on an electron, \( N_i \) is the substrate doping, \( k_B \) is the Boltzmann constant, \( T \) is the absolute temperature, and \( n_i \) is the intrinsic carrier concentration in the substrate. Voltage drop in air \( (ye_0 E_s (\psi_s)) \), dielectric \( \left( e^{-\frac{q \psi_s}{\epsilon_0 k_B T}} - 1 \right) \frac{k_B T}{q} \), and substrate \( (\psi_s) \) can be related to the applied gate bias \( V_G \) as follows-

\[
V_G = V_{FB} + \left( y + \frac{y_a}{\epsilon_0} \right) \epsilon_0 E_s (\psi_s) + \psi_s, \tag{A9}
\]

where, \( y_a \) is the dielectric thickness and \( V_{FB} \) is the flat band voltage. Equations A7-A9 are solved self-consistently for \( y \) and \( \psi_s \) at each \( V_G \). The corresponding inversion charge density \( (Q_i) \) in the channel and drain current \( (I_{DS}) \) are given by,

\[
Q_i = \frac{q n_i^2}{N_A} \int_0^{\psi_s} \frac{q \psi_s}{E_s (\psi)} d\psi, \tag{A10}
\]

\[
I_{DS} = \mu_n L Q_i \frac{V_{DS}}{W}, \tag{A11}
\]

where, \( \mu_n \) is the channel mobility for electrons, \( V_{DS} \) is the applied drain to source voltage.

**A3- Derivation of body factor \( (m) \) for NEMFET**
In order to derive body factor $m = \frac{dV_G}{d\psi_s}$, we consider the sub-threshold regime in which electrostatic force is given by $q\varepsilon_N A \psi_s$ (using Eqs. A7-A8). Therefore, equation A7 reduces to:

$$k(y_0 - y) = q\varepsilon_N A \psi_s. \quad (A12)$$

Similarly, Eq. A9 reduces to:

$$V_G = V_{FB} + \psi_s + \left(y + \frac{y_d}{\varepsilon_d}\right)\sqrt{\frac{q}{\varepsilon_d}}. \quad (A13)$$

where $\beta = \sqrt{\frac{2q\varepsilon_N A}{\varepsilon_0}}$. Now using $y = y_0 - \left(\frac{q\varepsilon_N A}{k}\right) \psi_s$ (from Eq. A12), Eq. A13 reduces to:

$$V_G = V_{FB} + \psi_s + \left(y_0 - \frac{q\varepsilon_N A}{k}\right) \psi_s + \frac{y_d}{\varepsilon_d} \sqrt{\frac{q}{\varepsilon_d}}. \quad (A14)$$

Now taking derivative of Eq. A14 with respect to $\psi_s$, we get:

$$\frac{dV_G}{d\psi_s} = 1 + \left(y_0 + \frac{y_d}{\varepsilon_d}\right) \frac{\beta}{2\sqrt{\psi_s}} - \frac{3}{2} \frac{q\varepsilon_N A}{k} \sqrt{\psi_s}. \quad (A15)$$

Simplifying this we get:

$$m \equiv \frac{dV_G}{d\psi_s} = 1 + \frac{C_s}{C_{air}^{eff}}, \quad (A16)$$

$$C_{air}^{eff} = \frac{\varepsilon_0}{3 \left(y - \frac{2}{3}y_0 + \frac{2y_d}{3\varepsilon_d}\right)} \approx \frac{\varepsilon_0}{3 \left(y - \frac{2}{3}y_0\right)}. \quad (A17)$$

where $C_s$ is the depletion capacitance and $C_{air}^{eff}$ is the effective air-gap capacitance. Equations A16-A17 predicts that air-gap capacitor acts as a negative capacitor if gate is stabilized in its unstable regime i.e. $y < \frac{2}{3}y_0$ and thus making $m < 1$.

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