Simulating Ideal and Non-ideal Behavior of N-Channel MOSFET using Python Programming

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Abstract - *Metal Oxide Semiconductor Field Effect Transistor (MOSFET) is used in various analog and digital electronic devices. MOSFET devices can have ideal as well as non-ideal characteristics. Understanding these characteristics is essential to utilize the full potential of MOSFET devices. Open-source Python libraries like Tkinter, Matplotlib, and math are used. N-channel MOSFET is considered for these simulations. Different parameters like channel length modulation, body effect, and subthreshold conduction are considered for the non-ideal behavior of the NMOS device.*

Key Words: Python, N-channel MOSFET, Body effect, Subthreshold conduction, Channel Modulation effect, ideal and non-ideal NMOS behavior

1. INTRODUCTION

N-channel MOSFET (NMOS) is formed by n-type doping in the drain and the source terminal of the MOSFET. The body or substrate of this NMOS has a doping of p-type. When enough voltage is applied at the gate terminal, the inversion layer is formed between the source and the drain allowing current to flow.
The behavior of this MOSFET can be understood by the relationship between the drain current and voltage sources at the gate and drain terminal. Transconductance (gm) is the ratio of change in drain current with respect to change in gate voltage when the drain voltage is constant can also be used to visualize the behavior of the MOSFET.

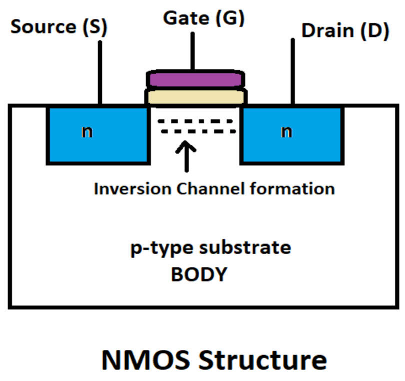


Figure 1: NMOS Structure

2. PROPOSED METHODOLOGY

First, we will start with simulating the ideal behavior of the NMOS. NMOS ideally has three regions of operation- cut-off, linear, and saturation. Mathematical modeling for these three regions of operation of NMOS can be utilized to simulate the drain current and voltage characteristics of the NMOS using python.

Table -1: Units and their symbol used for the design

Symbol	Meaning	Units
I_D	Drain Current	A
μ_n	Mobility	$cm^2/V.s$
V_{GS}	Gate voltage	V
V_{TH}	Threshold Voltage	V
V_{DS}	Drain Voltage	V
$V_{DS,sat}$	Drain Saturation Voltage	V
W/L	Width to Channel Length Ration	Unit less
R_{on}	On Resistance	Ohm
gm	Transconductance	S
C_{OX}	Oxide capacitance	F

2.1 To simulate ideal Behavior of N Channel Metal Oxide Semiconductor Field Effect Transistor (Ideal NMOS)-

Mathematical equations of I_D and gm are incorporated in the programming of the simulation.

First Region- Cut off region ($V_{GS}<V_{TH}$)
The MOSFET in this region acts as an open switch. SO ideally, there will not be any current flow. $I_D=0$. So, there will not be any conduction in this region. And, the MOSFET will be OFF.

Second Region- Linear or triode region ($V_{GS}>V_{TH}$, $V_{DS}<V_{DS,sat}$)-
MOSFET acts as a resistor in a linear region.
$I_D = \mu_n C_{OX} (W/L) [(V_{GS} - V_{TH}) V_{DS} - (1/2) V^2_{DS}]$

If $V_{DS} << 2(V_{GS} - V_{TH})$,
$I_D = \mu_n C_{OX} (W/L) (V_{GS} - V_{TH}) V_{DS}$
In linear region, $gm = \mu_n C_{ox} (W/L) V_{DS}$
$R_{on} = 1/ (\mu_n C_{ox} (W/L) (V_{GS} - V_{TH}))$

Third Region- Saturation Region
($V_{GS} > V_{TH}$, $V_{DS} >= V_{DS,\,sat}$)
The drain current formula can be given as-

$I_D = (1/2)\ \mu_n C_{OX} (W/L_{eff}) (V_{GS} - V_{TH})^2$

I_D is relatively independent of V_{DS} as long as L_{eff} is nearly equal to L.
The transconductance equation can be given as-

$gm = \mu_n C_{OX} (W/L) (V_{GS}-V_{TH})$

2.2 To simulate non-ideal Behavior of N Channel Metal Oxide Semiconductor Field Effect Transistor (non-ideal NMOS)-

Channel Length Modulation-

By increasing the value of drain voltage, the depletion region around the drain widens. It results in moving the pinch-off point away from the drain. And, channel length shortens.

The effective channel length gradually decreases as the potential difference between the gate and the drain decreases. We can say, L' (Effective channel length) is a function of V_{DS}.

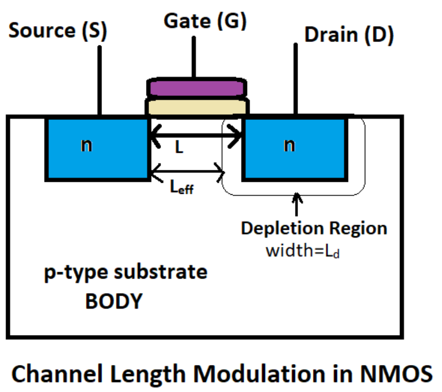


Figure 2: Channel length modulation NMOS structure

$\triangle L/L = \lambda V_{DS}$... ($\triangle L$ is the depletion width)
Lambda is inversely proportional to channel length.
($\lambda \propto 1/L$)

$I_{D,\,tri} = \mu_n C_{OX} (W/L) [(V_{GS} - V_{TH}) V_{DS} - (1/2) V^2_{DS}]$

$I_{D,\,sat} = (1/2)\ \mu_n C_{OX} (W/L) [(V_{GS} - V_{TH})^2 (1 + \lambda V_{DS})]$

$gm = \mu_n C_{OX} (W/L) (V_{GS}-V_{TH}) (1 + \lambda V_{DS})$

$gm = [\,2\ \mu_n C_{OX} (W/L) I_D (1 + \lambda V_{DS})]^{0.5}$

The Body Effect-

Ideally, we assume threshold voltage remains constant throughout the operation. But its value can be dynamic dependent on few parameters. One of them is the body effect. The threshold voltage is related to the total charge in the depletion region, so the gate charge can mirror Qd before forming an inversion layer.

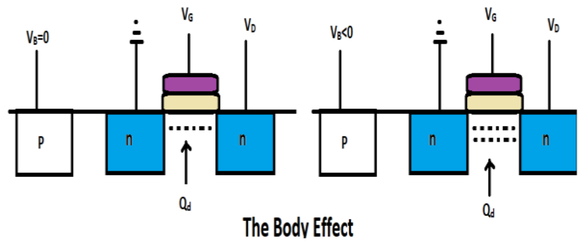


Figure 3: Body Effect NMOS structure

When the V_B (Bulk voltage) value decreases, the value of Q_d increases. And, V_{TH} also increases. This phenomenon can also be referred to as the back-gate effect.

$V_{TH} = V_{TH0} + \gamma\ [(2\phi_F + V_{SB})^{0.5} - (|2\ \phi_F\,|)^{0.5}]$

$\gamma = (2q\ \varepsilon_{si} N_{sub})^{0.5} / C_{ox}$

γ denotes the body-effect coefficient, and VSB is the source-bulk potential difference.

$\phi_F = (kT / q) \ln (N_{sub} / n_i)$

k is Boltzmann's constant, q is the electron charge, N_{sub} is the doping density of the substrate, and n_i is the density of electrons in intrinsic silicon semiconductor.

The Subthreshold Conduction-

In ideal behavior of the MOSFET, we have assumed that the device turns off abruptly as V_{GS} drops below V_{TH}. In a non-ideal scenario, for $V_{GS} \approx V_{TH}$, a weak inversion layer still exists and some current flows from Drain to Source. When $V_{GS} < V_{TH}$, we can observe that I_D is finite, but it is exponentially dependent on V_{GS}.
This phenomenon can be observed for V_{DS} nearly greater than 100 mV as follow,

$I_D = I_0 \exp (V_{GS} / \varepsilon V_T)$

3. RESULT

All the mathematical equations are incorporated in the python program with the Tkinter library to generate the graphical user interface of the simulator.

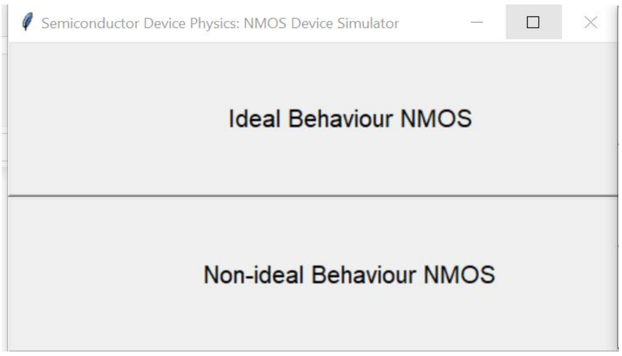


Figure 3: Graphical user interface (First screen) of the program

The primary window of the simulator shows two options- Ideal behavior of NMOS and Non-ideal behavior of NMOS. Clicking on the first option, the user will have to provide some inputs, and then the user will be able to observe various plots to understand the behavior of the NMOS for those inputs.

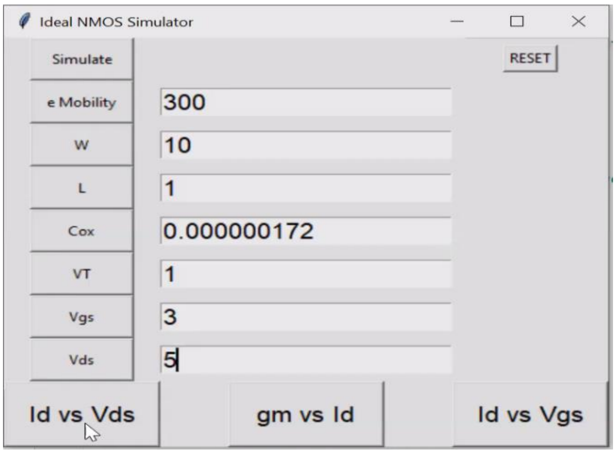
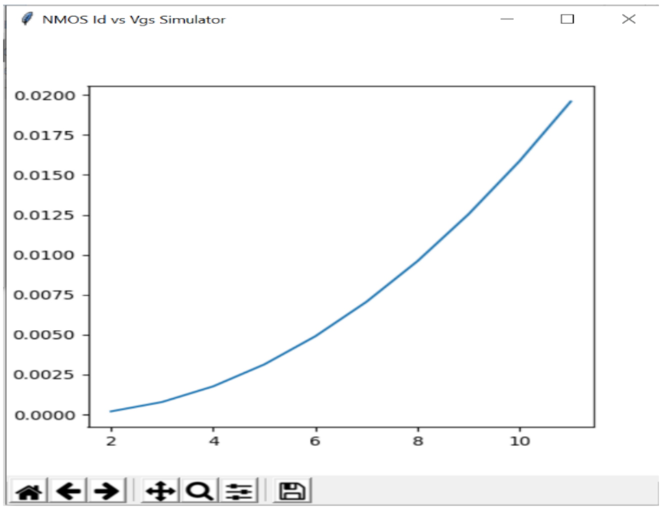


Figure 3: Simulator input screen for ideal behavior

A similar procedure will follow after clicking the second option on the primary window. But before that user can select the non-ideal effect to observe.



Graph 1: Id vs Vgs graph plotted after simulating the ideal behavior input screen

4. CONCLUSION

The behavior of the NMOS transistor can be simulated using open-source python libraries in the form of current vs voltage graphs. It is also possible to observe the difference in behaviors when the input parameters are changed. As the world is not ideal, such simulations help understand the working of these devices more accurately. Understanding of parameters such as body effect, channel length modulation, and subthreshold conduction can provide the more practical values of Id and V_{TH} for the operations to avoid any undesired effect.

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