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A physical and Compact Model of extremely Scaled MOSFET Devices for Circuit Simulation.

Mustafa EL MURADI *, Abdulhakim TREKI * and Omar JUBRAN *

*Electronic and Electric Engineering Department University of Al Fatah, Tripoli-Libya

elmradi2005@yahoo.com

hakim@libohosting.net

ojubran@ymail.com

Abstract: A new physical, compact and continuous Model for extremely Scaled MOSFET Device is formulated, based on the Maxwellian approximation where the electron temperature is controlled by acoustic phonon scattering which simultaneously includes the hot electrons and the thermoelectric effects. The demonstration involving predicted current voltage characteristics and ring oscillator propagation delays reveals a significant benefit of velocity overshoot is also presented for circuit simulation. The extracted model describes current characteristics from linear to saturation operating regions with a single I-V expression, and guarantees the continuities of I_{ds}, conductance and their derivative throughout all V_{gs}, V_{bs} and V_{ds} bias conditions. The model has been implemented in the circuit simulation such as HSPICE, Smart Spice and BSIM4v6. The new model has extensive built-in dependencies of important dimensional and processing parameters. Furthermore, the model accounts for all the major physical effects of the MOSFET characteristics.

Keywords: Compact of extremely scaled MOSFET Model, thermoelectric effect, electron temperature, velocity overshoot, circuit simulation.

INTRODUCTION

As the size of silicon devices shrinks towards nano dimension scale, electron velocity overshoot, and transport theory starts to play a significant role in determining current voltage characteristics. This phenomena in a semiconductor is because the energy relaxation time is greater than the momentum relaxation time. While the momentum relaxation time is determined by the carrier temperature, that temperature itself may be lower than the steady state value corresponding to the local field in the channel [XZ 04] , [XZ 01]. This means that the electrons do not have time to heat up as a result higher mobility will be reached. Due to spatially varying electric field on the carrier along the channel it is difficult to analytically model MOSFET with velocity overshoot. For this reason there is disagreement in the literature over electron energy relaxation parameters [JBR 97]. As the development of extremely scaled MOSFET technology progresses the circuit designers need VLSI models for use in circuit simulations the continuity, accuracy, scalability, and simulation performance are basic requirements for a an extremely scaled MOSFET device model to meet the optimal needs of both analog and digital circuit designs. The models performed using several versions of BSIM that have been developed and implemented in HSPICE for using Analog/Digital circuit simulations for different device regimes from linear, sub threshold to strong inversion. The expression can accurately describe device behavior within their own respective region of operation. Several continuous expressions from linear to saturation region have been reported as a trade off between accuracy and complexity is considered in most models, Problems can occur in transition region between linear weak inversion and strong inversion regions [XZ 04] – [JBR 97]. That is why accurate modeling of device parameters are essential in circuit simulators of state of the art MOSFET's. The current-voltage of MOSFET is one of the most important device parameters for advanced analogue and digital circuits as it determines the delay of logic gates and the conductance gds as well as trans-conductance gm. In this paper a new model has been presented with a simpler forms of electron transport in extremely scaled MOSFET device with high field mobility. By simplifying the moments of the Boltzmann transport equation and implementing it to derive the device characteristics for circuit simulation including the thermal effect and show the behavior due to velocity overshoot as the model shows the physical insight of the device and if the ballistic limits is reached in scaled MOSFET technology. Following this introduction the theoretical model is introduced in section II, the results and discussion is present in section III, circuit simulation is demonstrated and discussed in section IV and ended this paper by a conclusion.

1. Model Derivation

In extremely scaled devices, carrier transport affected by the presence of high electric fields and field gradients; as a result the electron temperature, lags the local field due to finite energy relaxation time, or relaxation length. Assume a quasi-steady state model of the energy balance:

$$qEvdN = \frac{-dE}{dt}$$

where N is the total number of electrons per unit volume and $\frac{dE}{dt}$ is the net rate of loss to acoustic phonon. The average gain or loss of energy in a single collision is given by

$$\overline{\Delta\varepsilon} = 4mu^2(1 - \frac{mv^2}{4kt}) \quad (1)$$

Where u is the velocity of sound for longitudinal acoustic wave, v is the electron random velocity before collision. However, if the kinetic energy before collision is $2kT$, $\overline{\Delta\varepsilon} = 0$. The electron will lose energy or gain energy if the initial energy is greater than or less than $2kT$. If ($1/\tau$) is the rate of collision for electrons of velocity v and n (v) is the number of electrons whose velocities lie in a range dv and v, then we have

$$\frac{\partial\varepsilon}{\partial t} = \int_0^{\infty} \frac{\overline{\Delta\varepsilon}}{\tau} n(v)dv \quad (2)$$

As we assume the mean free path $\lambda = \tau v$ is independent of velocity and the electrons have a Maxwellian velocity distribution, at an electron temperature Te that is

$$n(v) = 4\pi N(\frac{m}{2\pi kT})^{3/2} V^2 Exp(\frac{-mV^2}{2kT_e}) \quad (3)$$

Combining equation (1), (2) and (3) yields

$$\frac{\partial\varepsilon}{\partial t} = \frac{16mu^2 N}{\lambda\sqrt{\pi}}(\frac{m}{2kT_e})^{3/2}\int_0^{\infty} V^3(1 - \frac{mV^2}{4kT_e})Exp(\frac{-mV^2}{2kT_e})dV \quad (4)$$

The average drift velocity is:

$$V_d = \mu E \quad (5)$$

where μ is the electron mobility

$$\mu_o = \frac{q(\overline{V^2\tau})}{m\overline{V^2}} \quad (6)$$

Carrying out the above integration one can get together with equations (5) and (6) the mobility is:

$$\mu_o = \frac{4q\lambda_o}{3(2\pi mkT_e)^{1/2}} \quad (7)$$

Where λ_o is the low field mean free path, $\lambda_o = \frac{A}{T_e}$, A is a constant and $A = \frac{d}{2kT_l\mu_o}$ From equation (4) and (7)

$$\frac{-\partial\varepsilon}{\partial t} = \frac{32qNu^2}{3\pi\mu}\left[\frac{T_e}{T_l} - 1\right]$$

where T_l is the lattice temperature and with $\frac{\partial T_e}{\partial y}$ can be modeled

$$E_y\frac{\partial E}{\partial y} = \frac{A}{q}k\frac{\partial T_e}{\partial y} \quad (8)$$

$$\frac{T_e}{T_l} = 1 + (\frac{q\mu_o}{d})E_y^2$$

$$(\mu E)^2 = \frac{32u^2}{3\pi}\left[\frac{T_e}{T_l} - 1\right] \quad (9)$$

Equations (8) and (9) show that at zero electric field $T_e = T_l$ and hence the net rate of change of energy due to collision is zero. Similar the mobility of low field is obtained [IRM 85].

$$\mu = \frac{\mu_o\sqrt{2}}{\left\{1 + \left[1 + 4(\frac{E}{E_o})^2\right]^{1/2}\right\}^{1/2}} \quad (10)$$

Simplifying this equation gives

$$\mu = \frac{\mu_o}{\{1 + 2(\frac{E}{E_o})^{\alpha}\}^{1/\alpha}} \quad (11)$$

Where $\alpha = 2$ for electrons and $\alpha = 1$ for holes. The velocity is limited by optical phonon scattering. For simplicity and as it leads to an analytical solvable equation for drain current α is to be 1 [MME 02].

A numerical problem occurring for other values of α, if the electron current density J becomes:

$$J = -qnv = qn\mu E + \mu kT_e \nabla n + \mu kn \nabla T_e \quad (12)$$

Where y is along the channel, the first and second term are the conventional particles drift and diffusion currents, respectively while the third term is the thermal diffusion current due to the electron temperature gradient. The motion of electrons from low field to high field (from source to drain) the mobility of electrons be reduced upon the equation (10) and travel at a higher velocity than that implied by local velocity field model. This phenomena is the physical origin of velocity overshoot which is explained by the above energy balance presented. The hot electron effect can be modeled at the drain as the difference $\Delta T_e(drain) = T_e(drain) - T_l(drain)$.

The hot electron can be interpreted as translating group velocity moves faster as it moves in the y direction and the thermal electric effect is reduced due to electron temperature gradient

$$\frac{[T_e(drain) - T_e(source)]}{L_{eff}}$$

The electron temperature gradient causes a thermal diffusion current, which is in the opposite direction of the drift current across the channel must be accounted for a position independent the velocity overshoot which is present in scaled MOSFET devices. This velocity overshoot effect contributes to an increased $I_{ds} - V_{ds}$ current voltage characteristics, using the Einstein relation:

$$T_e = \frac{qD_n(T_e)}{K_B \mu_n(T_e)} \quad (13)$$

With this assumption of constant effective mass

$$T_e = (\frac{\mu_o}{\mu_n})^k T_l \quad (14)$$

Where k is a new parameter $1 \leq k \leq 2$, it depends on the carrier and the temperature value. The electron velocity at high electric field assumed to be:

$$v = v_{sat}\left[1 + \frac{2v_{sat}}{3E_y}.\tau \frac{dE_y}{d_y}\right] \quad (15)$$

Where $\lambda = \tau v$, τ is the electron transit time. As a result the electron velocity can be obtained:

$$v = v_{sat}\left[1 + \frac{kT_e \mu_o}{qE_y v_{sat}} \frac{dEy}{dy}\right] \quad (16)$$

By using BSIM for an absolute value of saturation voltage and including the smoothing function [YC 97]

$$v_{dss} = v_{dsat} - \frac{1}{2} \times \left[v_{dsat} - v_{dso} - \delta_s + \sqrt{(v_{dsat} - v_{dso} - \delta_s)^2 + 4\delta_s v_{dsat}}\right] \quad (17)$$

This smoothing function can provide smooth transition between device regions of operation for all voltages and parameters δ_s can be modeled to give the right value [YC 97] as the voltage of the gate and drain-source voltage introduce the lateral electric field Ey .

$$E_y = E_{sat} \cosh(\frac{y'}{l}) \quad (18)$$

$l^2 = (\varepsilon_s X_{dep} / \eta.C_{ox}).(1 + DVT_2 V_{bs})$, where l is the characteristic length, η is a fitting parameter and X_j is the drain junction depth, DVT_2 is the effect of substrate bias on SCE,(X_{dep} / η) represents the average depletion width along the channel and $X_{dep} = \sqrt{\frac{2\varepsilon_{si}(\Phi_s - V_{bs})}{qN_{DEP}}}$.

The current equation including the thermal effect can be derived. The saturation voltage V_{dss} is related to the gate voltage and the substrate voltage

$$V_{dss} = V_{gss} / [1 + \delta_1 \frac{\delta_2}{2\sqrt{\Phi_s - V_{bs}}}] + \delta_3 V_{gss} / \sqrt{\Phi_s - V_{bs}} \quad (19)$$

Where $\delta_1, \delta_2, \delta_3$ fitting parameters are numerically calculated to fit the curves during transitions [YC 97]

$$\delta_2 = \sqrt{\frac{2q\varepsilon_s N_{bs}}{\varepsilon_{ox}}}$$

$$I_{ds} = -qnvw = qn\mu E_y + \mu k_n \frac{\partial T_e}{\partial y} \quad (20)$$

By adding the second term and substract it one can get

$$I_{ds}(tot) = qn\mu_n E_y w.\left[(1 + \frac{2k}{qE_y}\frac{dT_e}{dy}) - \eta \frac{\delta E}{L_{eff}}\right] \quad (21)$$

With $\delta E = E_{drain} - E_{source}$ at maximum values of both sides of the electric field. From (11), (15) and (18) one can get the velocity overshoot equation at extremely scaled MOS device [DS 97] .

2. RESULTS AND DISCUSSIONS

A unified results of this approach is presented with different channel length in the range of extremely scaled measurements. The results are obtained with different Vds, Vgs and Vbs bias voltages, Figure 1. shows Ids - Vds at different gate voltages. Figure 2. presents the thermoelectric effects and the hot-electron effects, the reduction in the drain current is due to the electron temperature gradient increasing from source to drain, which results in electrons from drain to source in other words thermal-diffusion current in the opposite direction to the drift current.

This temperature gradient is proportional to field gradient. Figure 1. schematically shows that the hot electron effect is evaluated at the drain by fitting parameter while the thermoelectric effect is approximated by the average slope. The approximated position dependent field gradient between source and drain by $\Delta E / L_{eff}$ which is equivalent to modeling $[T_e(drain) - T_e(source)] / L_{eff}$ based on the

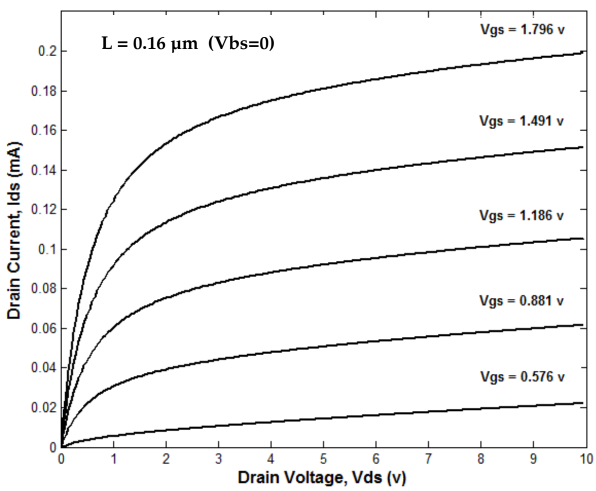

Figure 1. *Ids – Vds Curves for 0.16 µm device.*

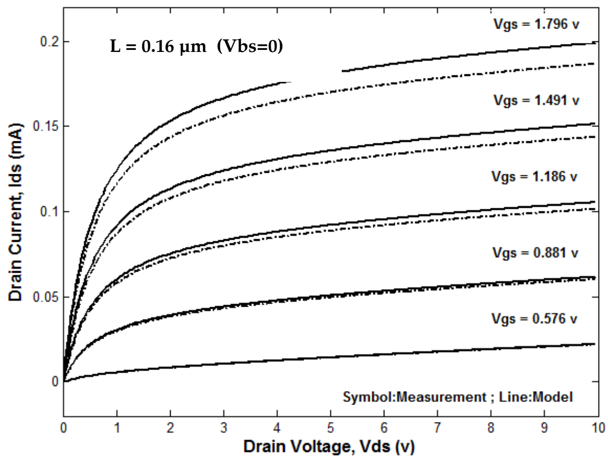

Figure 2. *Ids-Vds with thermoelectric effect.*

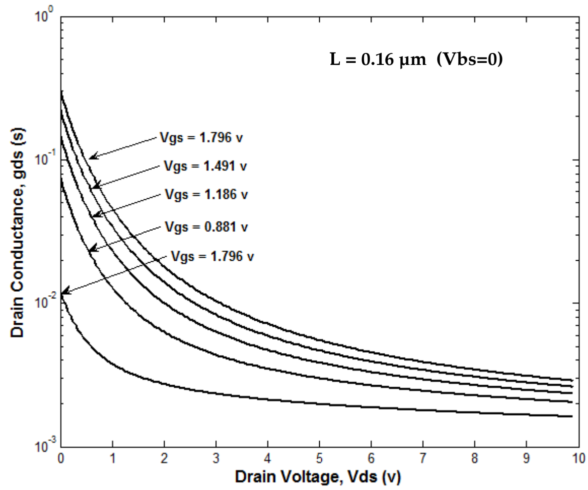

Figure 3. *$g_{ds} - V_{ds}$ Curves for 0.16 µm device.*

interpretation of the current equations. The effective fitting parameters are extracted numerically with a default value of 1 used to adjust the electron temperature gradient from source to drain. Figure 3. is the models gds - Vds curves directly obtained from numerical differentiation of the current model Ids - Vds curves. The bias and length – dependent effective Early voltage, together with Esat and Eav affecting the carries velocity in the device model.

This approach of modeling the effective field is somewhat equivalent to velocity overshoot [XZ 04] where here in this model velocity saturation has been applied with high value of vsat.

Since $v_{sat} = \mu_{eff} . E_{sat} / 2$ Figure 4. shows the transconductance behavior at different values of Vds. As seen gm-Vgs decreases as the gate voltage increases which is confirmed in other published reports [MME 06] . MOSFET transconductance gm is known to be the most important figure of merit in dealing with the large signal switching performance of logic devices, as the time constant for a small MOSFET to charge a load is proportional to C/gm, where C is the node capacitance

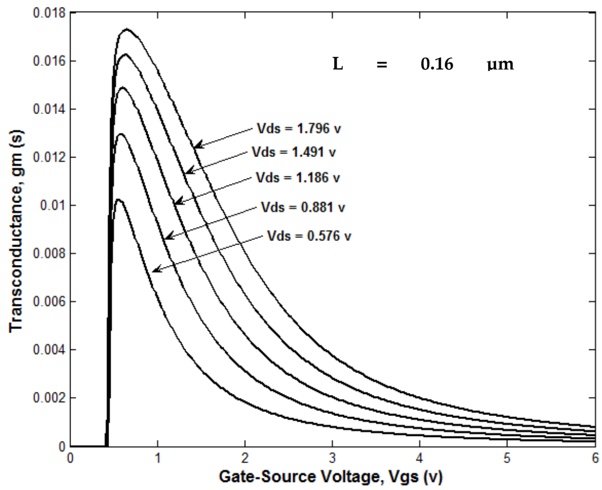

Figure 4. *g_m-V_{gs} Curves.*

3. Circuit Simulation Results

The new MOSFET model has been implemented in HSPICE for circuit simulation on to simulate a number of CMOS circuits for a ring oscillator Figure 5-a. The circuit with n-channel and p-channel CMOS inverter shown in Figure 5-b. together with simulation output to verify both the accuracy and the robustness of the modified model and its general capability in the simulation and basic design of different circuits results of the inverter output circuit is shown in Figure 6. as predicted for the rise and the full times. However the ring oscillator is in Figure 7. for channel length output extremely small [OAA 06]. Delay model in the previous work is used to see the performance of the new device model [MME 06].

The accuracy, simplicity, continuity and the small number of model parameters that extracted with a simple and accurate method are key features of the proposed model. Applying the excellent continuous behavior at the transition regions makes the proposed model very suitable for this applications including analog / digital low voltage applications [XZ 01] – [XYL 02] .

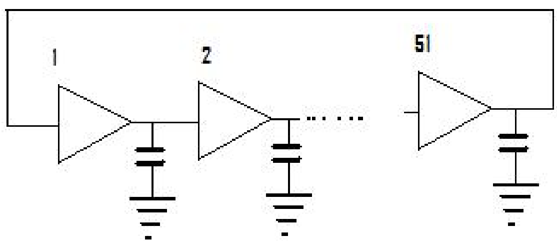

Figure 5-a. *Schematic Diagram of 51 Stages. Ring Oscillator.*

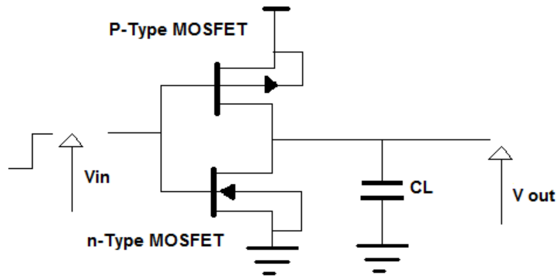

Figure 5-b. *CMOS inverter cell*

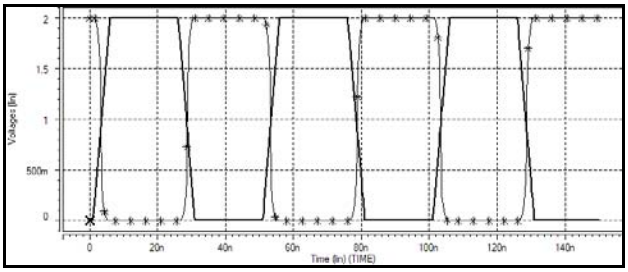

Figure 6. *CMOS inverter behavior for 160 nm channel length (bold curve represent the input pulse signal and the curve with stars represent the output behavior).*

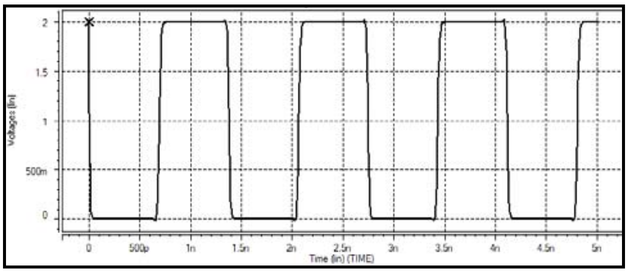

Figure 7. *Output response of 51 stage ring oscillator for 160nm channel length CMOS inverter.*

4. Conclusion

In conclusions, the finite and unified compact Ids-Vds model including the effect of electron-temperature gradient formulated from momentum/ energy balance equations as well as the field solution in the velocity saturation region. The model based on numerical simulation of two opposite effects the hot electron and thermoelectric diffusion current are simultaneously modeled in a single expression. This proposed model of Ids-Vds is applied in obtaining accurate gds and gm which has significant application in deep submicron MOSFET device and circuit modeling. Results of CMOS inverters applied for ring oscillators are demonstrated showing the performance of the model on the delay time. The effect of the channel length on the current value is also predicted the velocity overshoot which illustrate the physics that has built in to the model.

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