A Unified MOSFET Channel Charge Model for Device Modeling in Circuit Simulation

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***Abstract*— In this paper, we present a simple and accurate MOSFET channel charge model for device modeling in circuit simulation. The model can guarantee good continuities and smooth transitions of charge, capacitance, current, and transconductance from subthreshold to strong inversion with a unified analytical expression, and agrees with the experimental data well at various process and bias conditions from subthreshold and strong inversion, including the moderate inversion region of growing importance for low-voltage/power circuits.**

***Index Terms*— Circuit simulation, device modeling, MOSFET model.**

I. Introduction

THE design of VLSI has recently trended toward mixed analog–digital circuits for low-power operation, which requires accurate and continuous MOSFET models in different operation regimes, i.e., strong, moderate, and weak inversion regions. But most reported models are derived based on piecewise channel charge density models, and use different *I–V* and *C–V* equations in different regions [1], [2]. These models can work well in some specific operation regime, but generally cannot ensure good accuracy, continuity, and smooth transition of the charge, *I–V*, or *C–V* models in the transition region. It has been known that a continuous and accurate channel charge model is a bias to develop a robust and accurate *I–V* and *C–V* model. A physical and continuous channel charge sheet model has been reported [3]. However, this charge sheet model does not have a fully closed analytical form. A numerical iteration process is needed to compute the charge density or surface potential at each bias condition [4]. This is a disadvantage, and is not suitable for use in circuit simulation. Also, some new physical effects such as velocity saturation/overshoot, inversion-layer quantization, and other short channel phenomena may be difficult to incorporate into such a charge sheet model.

As a solution to the above issue, in this paper, we present a unified channel charge model that is continuous and accurate from subthreshold to strong inversion regions. The model has a full-closed analytical expression so that it is suitable for use in device modeling, and can be the basis for the *I–V* and *C–V* models for circuit simulation.

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II. Model

The expression for channel charge density in strong inversion region is well known [1], [2]

$$Q_{chs0} = C_{\rm ox}(V_{gs} - V_{\rm th}), \qquad V_{gs} > V_{\rm th} \tag{1}$$

where $C_{\rm ox}$ is the gate oxide capacitance in unit area, V_{gs} is the gate bias, and $V_{\rm th}$ is the threshold voltage.

With the considerations of short channel and narrow width effects in modern MOSFET's in the derivation of the threshold voltage model, $V_{\rm th}$ can be given as follows [5], [6]:

$$\begin{aligned} V_{\rm th} = {} & V_{\rm tho} + K_1(\sqrt{\phi_{so} - V_{bs}} - \sqrt{\phi_{so}}) - K_2 V_{bs} \\ & + K_1\left(\sqrt{1 + \frac{N_{LX}}{L_{\rm eff}}} - 1\right)\sqrt{\phi_{so}} + (K_3 + K_{3b}V_{bs}) \\ & \times \frac{T_{\rm ox}}{W_{\rm eff} + W_0}\phi_{so} - D_{VT0}\left(\exp\left(-D_{VT1}\frac{L_{\rm eff}}{2l_t}\right)\right. \\ & \left. + 2\exp\left(-D_{VT1}\frac{L_{\rm eff}}{l_t}\right)\right)(V_{bi} - \phi_{so}) \\ & - \left(\exp\left(-D_{\rm sub}\frac{L_{\rm eff}}{2l_{to}}\right) + 2\exp\left(-D_{\rm sub}\frac{L_{\rm eff}}{l_{to}}\right)\right) \\ & \times (E_{ta0} + E_{tab}V_{bs})V_{ds} \\ & - D_{VT0w}\left(\exp\left(-D_{VT1w}\frac{L_{\rm eff}}{2l_{tw}}\right)\right. \\ & \left. + 2\exp\left(-D_{VT1w}\frac{L_{\rm eff}}{l_{tw}}\right)\right)(V_{bi} - \phi_{so}) \end{aligned} \tag{2}$$

where $V_{\rm tho}$ is the threshold voltage for a long channel device at $V_{bs} = 0$, $T_{\rm ox}$ is the thickness of the gate oxide, ϕ_{s0} is termed as $2\phi_b$ and is given by $2v_t \ln((N_{\rm ch}/n_i))$, $N_{\rm ch}$ is the doping concentration in the channel, n_i is the intrinsic carrier density, V_{bi} is the built-in potential of drain/source–body junction, and l_t and l_{tw} are functions of $T_{\rm ox}$, channel doping concentration, and body bias. $K_1, K_2, D_{VT0}, D_{VT1}, D_{VT0w}, D_{VT1w}, D_{\rm sub}$, E_{ta0}, E_{tab}, W_0, K_3, K_{3b}, and N_{lx} are parameters to be extracted from the measured data.

In (2), the second and third terms describe the vertical nonuniform doping effect, the fourth term models the lateral nonuniform doping effect, the fifth term is for the narrow channel width effect, the sixth and seven terms consider the short channel (including DIBL) effects, and the last term accounts for the small size effect in a short and narrow device.

The channel charge density in weak inversion (subthreshold) region can be given approximately as follows [7]:

$$Q_{chs0} \approx \sqrt{\frac{\varepsilon_0 \varepsilon_{si} q N_{\rm ch}}{2\phi_{so}}} v_t \exp\left(\frac{\phi_s - \phi_{so}}{v_t}\right) \tag{3}$$

where ϕ_s is the surface potential in the subthreshold regime.

In the weak inversion region, the relationship between the surface potential and the applied gate bias V_{gs} can be written approximately

$$\phi s \approx \phi_{so} + \frac{V_{gs} - V_{\rm th,sub}}{n} \tag{4}$$

where n is the subthreshold swing parameter, which is a function of body bias, channel length, and the interface state density [6]. $V_{\rm th,sub}$ is the theoretical threshold voltage determined according to the definition, that is, the gate bias V_{gs} when $\phi_s = \phi_{so}$ [7].

It has been found that the theoretical threshold voltages $V_{\rm th,sub}$ is different from the characterized $V_{\rm th}$, with measured data, and the surface potential corresponding to the $V_{\rm th}$ is actually higher than ϕ_{so}. The difference between the threshold voltages discussed above is several v_t [8]. To account for this fact, a parameter called $V_{\rm off}$ is introduced

$$V_{\rm off} = V_{\rm th,sub} - V_{\rm th}. \tag{5}$$

Combining (3)–(5), the channel charge density in subthreshold region can be written as

$$Q_{\rm chs0} = H \exp\left(\frac{V_{gs} - V_{\rm th}}{n v_t}\right), \qquad V_{gs} < V_{\rm th} \tag{6a}$$

$$H = \sqrt{\frac{q \varepsilon_{si} N_{\rm ch}}{2\phi_{so}}} v_t \exp\left(-\frac{V_{\rm off}}{n v_t}\right). \tag{6b}$$

To improve the accuracy, $V_{\rm off}$ is treated as a model parameter to be determined experimentally from measured *I–V* characteristics in the subthreshold region, and ranges from -0.06 to -0.12 (in unit of volts) depending on the technologies of the devices used in this paper.

Based on the charge expressions in the strong inversion and subthreshold regimes given in (1) and (6), a unified channel charge density model has been obtained, which can describe the charge characteristics in both the strong inversion and subthreshold regimes including the important moderate weak inversion region:

$$Q_{\rm chs0} = C_{\rm ox} V_{gs{\rm teff}}, \qquad \text{for all } V_{gs} \tag{7a}$$

$$V_{gs{\rm teff}} = \frac{2 n v_t \ln\left[1 + \exp\left(\frac{V_{gs} - V_{\rm th}}{2 n v_t}\right)\right]}{1 + \frac{2 n v_t C_{\rm ox}}{H} \exp\left(-\frac{V_{gs} - V_{\rm th}}{2 n v_t}\right)}. \tag{7b}$$

It is easy to understand the unification of (7). It can become (1) in the strong inversion region and follow (6) in the subthreshold region. However, the analytical unified equation ensures a continuous and smooth transition of the channel charge from subthreshold to strong inversion.

III. Comparison and Discussion

To verify the model, a comparison between the present model and the measured data from the devices at different bias and design conditions ($T_{\rm ox} = 4$ nm–6.9 nm and $N_{\rm ch} = 9 \times 10^{16}$ cm^{-3}–2×10^{18} cm^{-3}) has been made. We measure the gate–channel capacitance versus V_{gs}, and numerically integrate them to get the channel charge densities for comparison with the model.

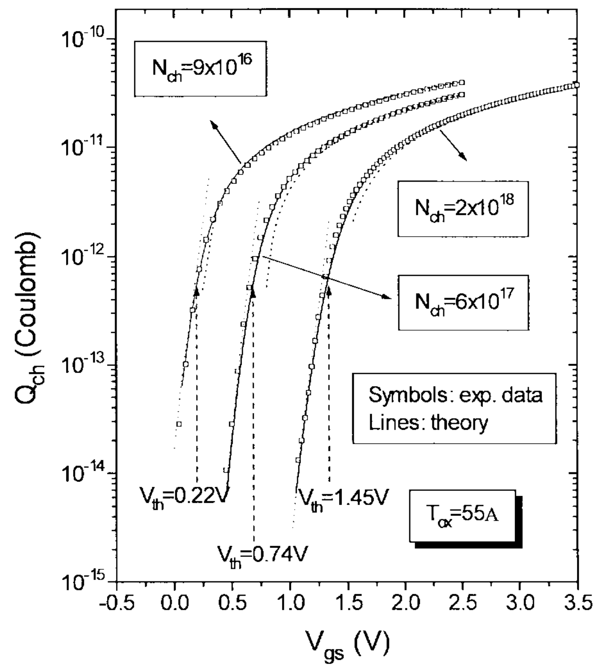

Fig. 1. Channel charge model fits the measurement data taken from devices with different $N_{\rm ch}$ well, and also can match the simulation results (dashed lines) from the model equations (1) and (6) in strong inversion and subthreshold regions respectively. The model covers weak, moderate, and strong inversion regions of NMOSFET's.

Fig. 1 shows the comparison between the unified charge expression (7) and experimental data as well as the charge expressions of (1) and (6) in the strong inversion and subthreshold regions, respectively. It can be found that the unified expression can fit the data and match (1) and (6) well in the strong inversion and subthreshold regions, respectively. Furthermore, the model not only shows a smooth transition at the boundary of the two regions, but accurately predicts the charge in the transition (moderate inversion) region without any additional fitting parameters. The advanced feature of the model makes it very attractive and promising in circuit simulation since the moderate inversion region is becoming more important for low-voltage/power circuit application.

The comparisons between the model and measured data are given further in Figs. 2 and 3 under different process and body bias conditions, respectively. The model parameter $V_{\rm off}$ in H is determined for each process technology, and is independent of body bias. To show the model accuracy in the strong inversion region, Fig. 4 shows the curves of channel charge versus V_{gs} in linear scale. It can be seen that the model can fit the measured data well for the devices with different channel doping concentration.

An *I–V* equation has been derived from the present unified channel charge model, including the most important physical effects such as velocity saturation, channel length modulation, polysilicon gate depletion, etc. [9], [10]. As a simple example

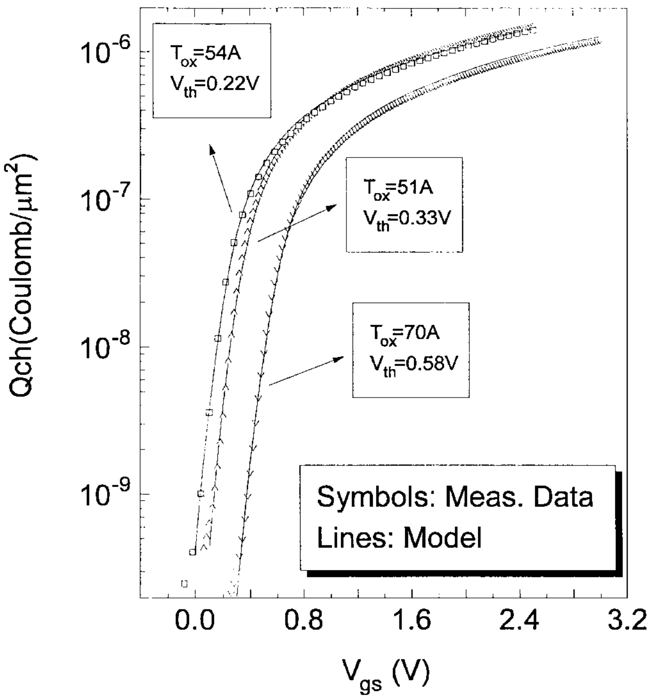

Fig. 2. Channel charge model fits the measurement data taken from devices with different gate oxide thickness of NMOSFET's.

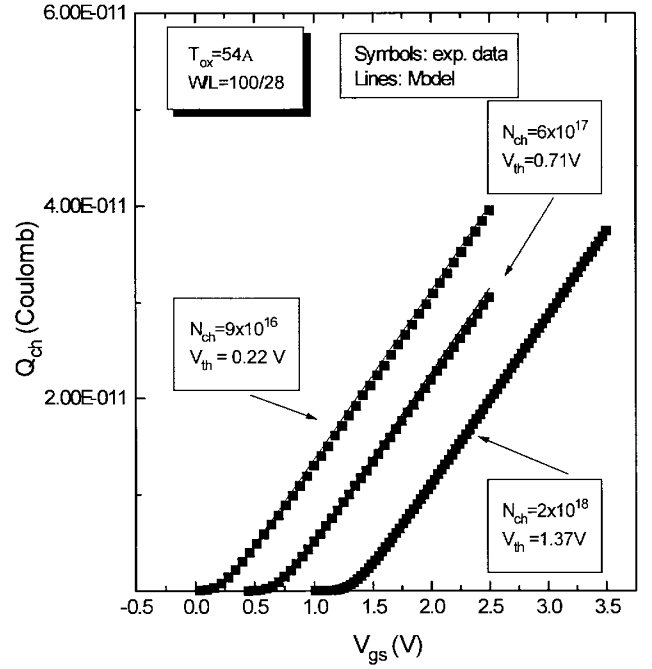

Fig. 4. Same data used in Fig. 1 is plotted in linear scale to show the model accuracy in strong inversion for different devices with different oxide thickness.

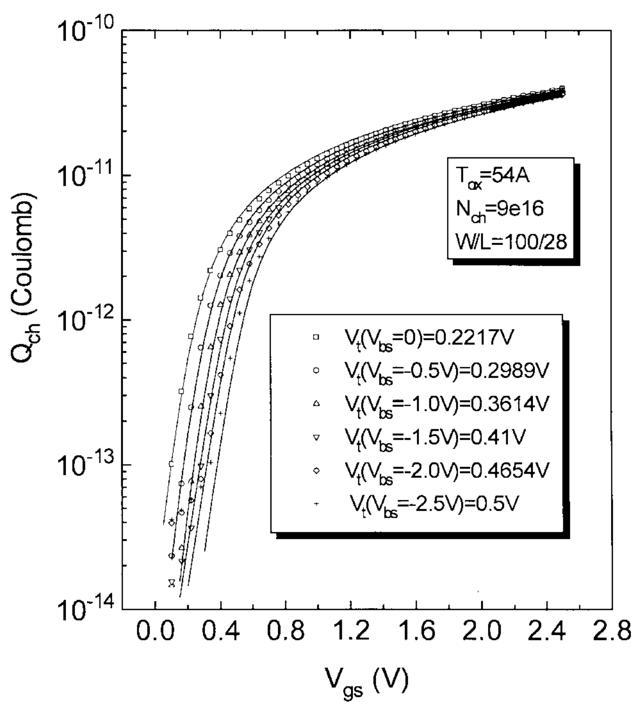

Fig. 3. Channel charge model fits the measurement data well for different substrate body biases of NMOSFET.

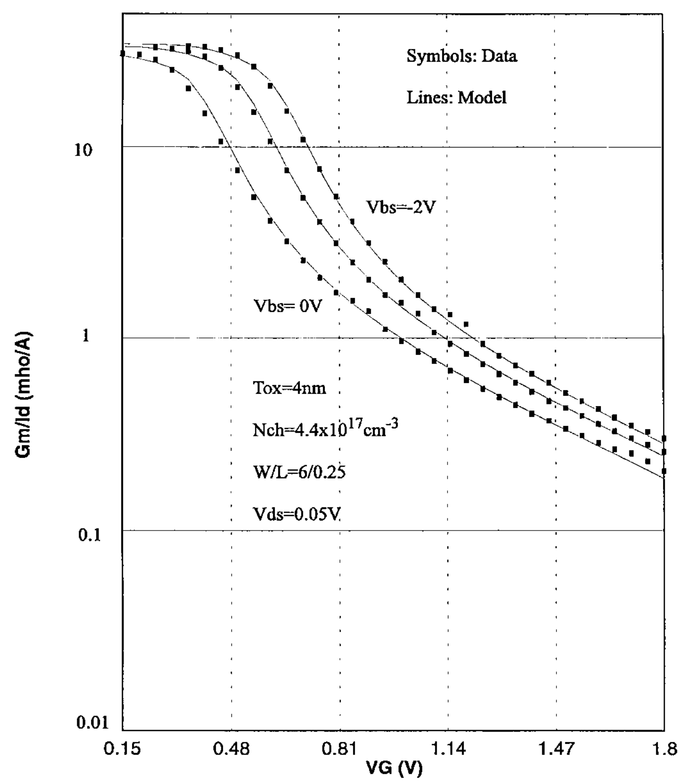

Fig. 5. *I–V* model that implements the presented channel charge model shows excellent continuity characteristics as well as fits the measurement data of g_m/I_d well. g_m/I_d is an important parameter for model continuity and analog design merit test.

here, in the case of the linear region

$$I_d = \frac{W_{\rm eff}}{L_{\rm eff}} \mu_{\rm eff} Q_{\rm chs0} V_{ds}. \tag{8}$$

In Fig. 5, we show the comparison results of the g_m/I_d of a device with $W/L = 6$ μm/0.25 μm, which is a sensitive test for the accuracy of a charge model. It emphasizes the model accuracy and continuity in the moderate and weak inversion regions in both $Q_{\rm chs0}$ (and I_d) and its derivative (g_m). Fig. 5 shows that the *I–V* model with the unified channel charge equation can accurately describe the characteristics of

MOSFET's in the whole region from subthreshold and strong inversion, especially the moderate inversion region

IV. Summary

A unified channel charge density model has been presented. It can model the channel charge accurately and smoothly from subthreshold to strong inversion. The comparisons between the model and measured data in n-channel MOSFET's show that the charge model can describe the charge characteristics of devices with various process and bias conditions well. This empirical charge model can be the basis for a new class of MOSFET *I–V* and *C–V* models for the important moderate inversion region.

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