A Charge Based Non-Quasi-Static Transient Model for SOI MOSFETs

Jian Zhang[1, 2], Jin He[1, 2], Yun Ye[1] , Yu Cao[1] , Hongyu He[1], and Mansun Chan[3]

[1] Peking University Shenzhen SOC Key Lab., PKU-HKUST Shenzhen-Hongkong Institution, Shenzhen 518057, China
[2] TSRC, School of Electronic Engineering and Computer Science, Peking University, Beijing 100871, China
[3] Department of ECE, Hong Kong University of Science and Technology, Hong Kong, Clear Water Bay, China

ABSTRACT

A non-quasi-static (NQS) transient model for SOI MOSFETs is presented based on charge based dc model which is extensively verified with various structure parameters. From the inversion charge and current-continuity equation, the partial differential equation on inversion charge is derived and solved using spline collection method. With the non-quasi-static inversion charge distribution, the terminal currents in rapid transient analysis are obtained and have good agreements with two-dimension numerical simulation. The variation of NQS effect coming from the unique silicon-on-insulator structure is also analyzed.

Keywords: SOI-MOSFET, non-quasi-static effect, high frequency, transient effect, compact model, circuit simulation.

I. Introduction

In the high speed and RF circuit design, the non-quasi-static (NQS) effect needs consideration as the quasi-static approximation is failed for rapid transient or high frequency small signal analysis [1]. Despite many NQS models for bulk MOSFET, few aim at SOI MOSFET which has become a mainstream technology for high-performance and low-power application nowadays [2-4].

Among various approaches to model NQS effect [5-17], the spline collection method [14, 15] is flexible for accuracy and efficiency requirements compared with the relaxation time model [9] and channel segmentation method counterparts [10]. Also, the spline collection method needs no additional parameters for NQS simulation. Thus, this method is suitable in prediction for the structure variation.

In this paper, starting from Poisson-Boltzmann's equation, a charge-based dc model for SOI MOSFETs is derived as well as the relationship between the inversion charge and the bias. Substituting this relationship into current-continuity equation, the partial differential equation on inversion charge is obtained and solved with spline collection method. With the non-quasi-static inversion charge distribution, the terminal currents in rapid transient analysis are obtained. Both the dc model and the transient current are verified with TCAD. The proposed NQS model is also used to predict the NQS effect for different thickness of silicon film and buried oxide.

II. Charge-Based DC Model

The analyzed four-terminal n-channel SOI MOSFET with the corresponding coordinates is illustrated in Fig.1. The doping concentration of the substrate is assumed high enough and the voltage drop on the substrate is neglected.

Under the gradual channel approximation, one-dimension Poisson-Boltzmann's equation is written as

$$\frac{d^2\phi}{dx^2}=\frac{qN_A}{\varepsilon_{si}}\left[1+\exp\left(\frac{\phi-2\phi_F-V_{ch}}{V_t}\right)\right] \tag{1}$$

Where Vch is the quasi-Fermi potential and the other symbols have their usual meanings.

Integral the Poisson-Boltzmann's equation, thus [18]

$$\varepsilon_{si}{}^2\left(E_s{}^2-E_0{}^2\right)=2qN_A\varepsilon_{si}\begin{bmatrix}\left(\phi_s-\phi_0\right)\\ +V_t\exp\left(\frac{\phi_s-2\phi_F-V_{ch}}{V_t}\right)\left(1-\exp\left(\frac{\phi_0-\phi_s}{V_t}\right)\right)\end{bmatrix} \tag{2}$$

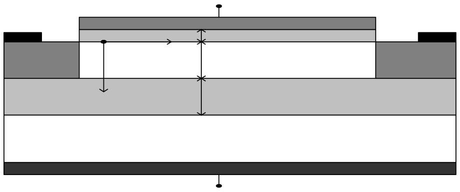

Fig.1. Schematic diagram of SOI MOSFET with the corresponding coordinates.

To obtain the relationship between the potentials at the interfaces between silicon and oxides, i.e. front surface and back surface pontentials, depletion approximation is used [18-20] to result in

$$\phi_s-\phi_0=\frac{qN_At_{si}{}^2}{2\varepsilon_{si}}+E_st_{si} \tag{3a}$$

On the other hand, the charge equilibrium condition between the silicon film and substrate layer leads to the following expression

$$\frac{qN_A t_{si}{}^2}{2\varepsilon_{si}} + E_s t_{si} = V_B + E_0 t_{si} \qquad (3b)$$

Substituting (3) into (2), and combining it with Gauss's law,

$$\varepsilon_{si}\left(E_s - E_0\right) = Q_{dep} + Q_{inv} \qquad (4)$$

yields the logarithm of the normalized expression,

$$q_{inv} + \ln q_{inv} + \ln\left(1 + Hq_{inv}\right) = v_1 - q_{dep} - 2\varphi_f - v_{ch} + \ln\left[\frac{C_{si}q_{dep}}{\left(C_{ox} + C_1\right)q_1}\right] \qquad (5)$$

The charge and voltage terms in (5) are normalized by $q_0 = \left(C_{ox} + C_1\right)V_t$ and V_t, respectively. The lowercase letters represent the corresponding normalized terms.

In Eq.(5),

$$C_1 = \frac{C_{oxb}C_{si}}{C_{oxb} + C_{si}}, \quad q_1 = \frac{1}{q_0}\frac{C_{ox}}{C_{ox} + C_1}\left[\frac{Q_{dep}}{\beta} + C_1\left(V_{GF} - V_B - V_{GB}\right)\right],$$

$$H = \frac{C_{ox} - C_1}{C_{ox} + C_1}\frac{1}{2q_1}, \text{ and } v_1 = \frac{1}{V_t}\frac{C_{ox}V_{GF} + C_1\left(V_B + V_{GB}\right)}{C_{ox} + C_1}$$

with $\beta = 1 - \exp\left(-2v_b\right)$ for the accurate modeling from intrinsic to heavy channel doping concentration [21-24].

The normalized drain current is derived as [25]

$$i_{ds} = \int_0^{V_{ds}} q_{inv}\,dv_{ch} = -\left[\frac{q_{inv}{}^2}{2} + 2q_{inv} - \frac{1}{H}\ln\left(1 + Hq_{inv}\right)\right]\Bigg|_{q_s}^{q_d}$$

(6)

where qd, qs are the normalized inversion charge density at the source (Vch=Vs) and drain (Vch=Vd) ends, respectively, which is calculated from the inversion charge density equation (5).

III.Non-Quasi-Static Transient Model

In the derivation of inversion charge density equation (5), the quasi-static approximation is not used. Thus, (5) becomes the base of the proposed NQS transient model. Combining it with the current-continuity equation and the current transport equation, yields partial differential equation

$$\frac{\partial q_i(y,t)}{\partial t} = \mu V_t \frac{\partial}{\partial y}\left[\left(q_i(y,t) + 2 - \frac{1}{1 + Hq_i(y,t)}\right)\frac{\partial q_i(y,t)}{\partial y}\right] \qquad (7)$$

Equation (7) is solved using the spline collection method in Wang's work [14-15]. The initial condition and boundary condition are decided from quasi-static results. In the following calculation with spline collection method, N=2 are used considering both the accuracy and efficiency requirements [14-15].

With the inversion charge depending on time and position, the non-quasi-static terminal currents are obtained as

$$I_S(t) = I_0(t) - K_n\left(\frac{11}{90}\frac{dq_S}{dt} + \frac{4}{15}\frac{dq_{1/3}}{dt} + \frac{1}{10}\frac{dq_{2/3}}{dt} + \frac{1}{90}\frac{dq_D}{dt}\right) \qquad (8a)$$

$$I_D(t) = I_0(t) + K_n\left(\frac{1}{90}\frac{dq_S}{dt} + \frac{1}{10}\frac{dq_{1/3}}{dt} + \frac{4}{15}\frac{dq_{2/3}}{dt} + \frac{11}{90}\frac{dq_D}{dt}\right) \qquad (8b)$$

Where $I_0(t)$ is the dc drain current reflecting only the time dependence of the boundary condition, and $K_n = WL\frac{C_{ox}C_1}{C_{ox} + C_1}V_t$.

In the transient analysis, the gate and substrate currents are no longer zero. The solution of them starts from the gate and substrate charges

$$Q_{GF} = W\int_0^L C_{ox}\left(V_{GF} - \phi_s\right)dy \qquad (9a)$$

$$Q_{GB} = W\int_0^L C_{oxb}\left(V_{GB} - \phi_0\right)dy \qquad (9b)$$

According to Poisson-Boltzmann's equation (1) and Gauss's law (4), yields

$$Q_{GF} = \frac{WC_{ox}}{C_{ox} + C_1}\int_0^L\left(C_1\left(V_{GF} - V_B - V_{GB}\right) + Q_{dep} + Q_{inv}\right)dy \qquad (10a)$$

$$Q_{GB} = -\frac{WC_1}{C_{ox} + C_1}\int_0^L\left(C_{ox}\left(V_{GF} - V_B - V_{GB}\right) - Q_{dep} - Q_{inv}\right)dy \qquad (10b)$$

Thus, the gate and substrate currents are obtained using the non-quasi-static inversion charge distribution as

$$I_{GF} = -K_n\left[\frac{dv_{GF}}{dt} + \frac{C_{ox}}{C_{ox} + C_1}\left(\frac{2}{15}\frac{dq_S}{dt} + \frac{11}{30}\frac{dq_{1/3}}{dt} + \frac{11}{30}\frac{dq_{2/3}}{dt} + \frac{2}{15}\frac{dq_D}{dt}\right)\right] \qquad (11a)$$

IV. Results and Discussion

To verify the proposed analytical model, a long-channel SOI MOSFET with constant mobility is designed for the two-dimension numerical simulation [26]. The doping concentration of the substrate silicon film is 1e18cm^{-3}, metal gate with mid-gap work-function are used, and the width of the channel is $1\mu m$.

Fig.2 shows the drain current calculated from the charge-based dc model compared with the numerical results for different channel doping levels from intrinsic to heavily doped condition. Figs.3-4 illustrate the drain currents for different structure parameters such as the thickness of silicon film and buried oxide. The impact of different silicon thickness on the drain current is shown in Fig.3 for both intrinsic and heavily doped channels. As the subthreshold leakage is linearly proportional to t$_{si}$, the volume inversion is observed for lightly doped device [27, 28]. Fig.4 also shows accurate modeling of the devices with different oxide thickness.

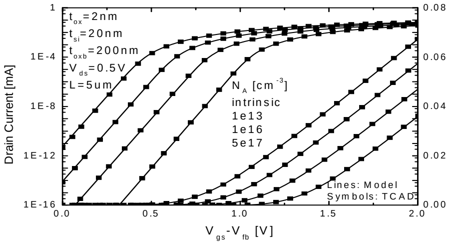

Fig.2. Transfer characteristics of devices with different doping levels from intrinsic to heavily doped condition.

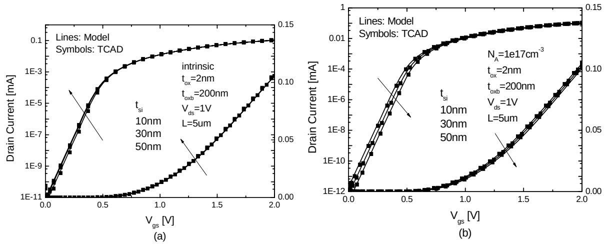

Fig.3. Transfer characteristics of devices with different thickness of silicon film obtained from dc current model (lines) and numerical simulation (symbols). (a) Devices with intrinsic channel, (b) devices with heavily doped channel.

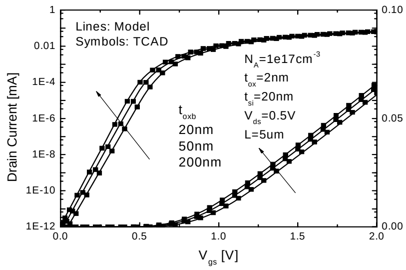

Fig.4 Transfer characteristics of devices with different thickness of buried oxide obtained from dc model and numerical simulation.

The currents flowing through all the four terminals in the signal-gate SOI MOSFET i.e. drain, source, gate and substrate, are verified with numerical simulation for rapid transient analysis. Good agreements between proposed non-quasi-static model prediction and numerical results are observed in Fig.5. The quasi-static results are also plotted proving the advantage of non-quasi-static analysis in rapid transient analysis [29, 30]. Compared to that in Fig.5(a), the input signal with shorter rise time and fall time enhances the NQS effect, thus, the quasi-static results produce more evident error in Fig. 5(b).

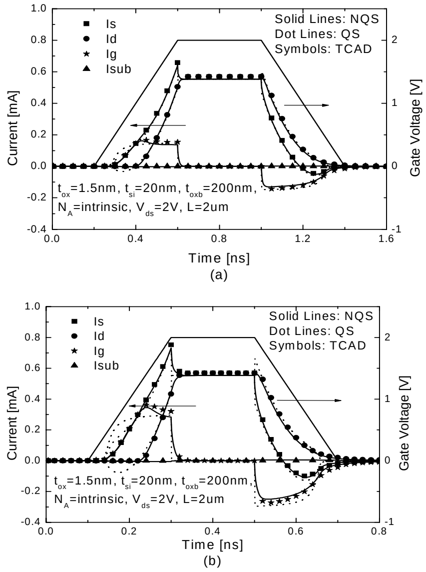

Fig.5. Transient terminal currents calculated from the non-quasi-static model (solid lines) compared with numerical results (symbols) and quasi-static results (dot lines). (a) V_{gs} changes at a ramp rate of 5e9V/s, (b) V_{gs} changes at a ramp rate of 1e10V/s.

In contrast with bulk MOSFETs, the SOI MOSFETs own the unique silicon-on-insulator structure. Figs.3-4 show the accuracy of the dc model accounting for the SOI structure. Further more, Fig. 6 plots $\left|I_{d,nqs}-I_{d,qs}\right|_{\max}$ (the maximum difference between NQS and QS drain currents in a period of input signal as that in Fig.5(b)) for different thickness of silicon film and buried oxide, presenting the variation of NQS effect coming from the variation of SOI structure. It is observed that the variation of SOI structure affect the NQS effect little although the thinner silicon film and buried oxide enhance it a little.

V. Conclusion

In this paper, a non-quasi-static transient model is presented based on a charge-based dc model for SOI MOSFETs. The partial differential equation on inversion charge density obtained from the inversion charge relationship and current-continuity equation is solved with spline collection method. With the non-quasi-static inversion charge distribution, the transient currents in rapid transient analysis are obtained. Both the dc model and the transient currents are verified with the two-dimension numerical simulation. The variation of NQS effect coming from the unique silicon-on-insulator structure is also analyzed.

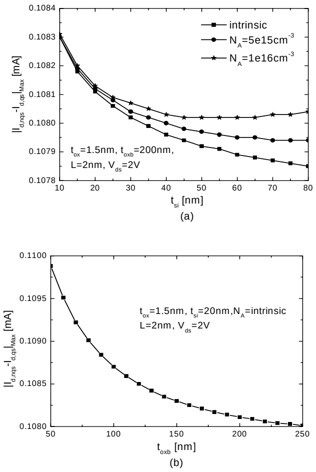

Fig.6. The maximum difference between NQS and QS drain currents in a period of input signal as that in Fig.5(b) with (a) different thickness of silicon film for different channel doping concentration, (b) different thickness of buried oxide.

Acknowledgements

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References

[1] Y. P. Tsividis and K. Suyama, “MOSFET modeling for analog circuit CAD: Problems and prospects,” *IEEE J. Solid-State Circuits*, vol. 29, no. 3, pp. 210–216, Mar. 1994.

[2] R.-H. Yang, A. Ourmazd, and K. F. Lee, “Scaling the Si MOSFET: From bulk to SOI to bulk,” *IEEE Trans. Electron Devices*, vol. 39, no. 7, pp. 1704–1710, Jul. 1992.

[3] D. J. Frank, R. H. Dennard, E. Nowak, P. M. Solomon, Y. Taur, and H.-S. P. Wong, “Device scaling limits of Si MOSFETs and their application dependencies,” in *Proc. IEEE*, vol.89, no.3, pp. 259–288, Mar. 2001.

[4] J.-P. Colinge, “Novel gate concepts for MOS devices,” in *Proc .ESSDERC 2004*, pp. 45–49. Sep. 2004.

[5] C. Turchetti, P. Mancini, and G. Masetti, “A CAD-oriented non-quasistatic approach for the transient analysis of MOS ICs,” *IEEE J. Solid-State Circuits*, vol. 21, pp. 827–836, Oct. 1986.

[6] P. Mancini, C. Turchetti, and G. Masetti, “A non-quasi-static analysis of the transient behavior of the long-channel MOST valid in all regions of operation,” *IEEE Trans. Electron Devices*, vol. 34, pp. 325–334, Feb. 1987.

[7] H. J. Park, P. K. Ko, and C. Hu, “A non-quasi-static MOSFET Model for SPICE – Transient Analysis,” *IEEE Trans. Electron Devices*, vol. 36, no. 3, pp. 561-576, Mar. 1989.

[8] W. Liu, C. Bowen, and M. Chang, “A CAD-compatible non-quasi-static MOSFET model,” in *IEDM Tech. Dig.*, 1996, pp. 151–154.

[9] M. Chan, K. Y. Hui, C. Hu, and P. K. Ko, “A robust and physical BSIM3 non-quasi-static transient and AC small-signal model for circuit simulation,” *IEEE Trans. Electron Devices*, vol. 45, no. 4, pp. 834–841, Apr. 1998.

[10] A. J. Scholten, L. F. Tiemeijer, P. W. H. de Vreede, and D. B. M. Klaassen, “A large signal non-quasi-static MOS model for RF circuit simulation,” in *IEDM Tech. Dig.*, 1999, pp. 163–166.

[11] A. S. Roy, J. M. Vasi, and M. B. Patil, “A new approach to model nonquasi-static (NQS) effects for MOSFETs – part I: large-signal analysis,” *IEEE Trans. Electron Devices*, vol. 50, no. 12, pp. 2393-2400, Dec. 2003.

[12] T. Pesic, and N. Jankovic, “A Compact Non-Quasi-Static MOSFET Model based on the Equivalent Non-Linear Transmission Line,” *IEEE Trans. CAD*, vol. 24, no. 10, pp. 1550-1561, Oct. 2005.

[13] N. Jankovic, and T. Pesic, “Non-quasi-static physics-based circuit model of fully-depleted double-gate SOI MOSFET,” Solid-State Electronics, vol. 49, pp. 1086-1089, 2005.

[14] H. Wang, T.-L. Chen, and G. Gildenblat, “Quasi-static and Nonquasi-static Compact MOSFET Models Based on Symmetric Linearization of the Bulk and Inversion Charges,” *IEEE Trans. Electron Devices,* vol. 50, no. 11, pp. 2262-2272, Nov. 2003.

[15] H. Wang, X. Li, W. Wu, G. Gildenblat, R. Langevelde, Geert D. J. Smit, A. J. Scholten, and Dirk B.M. Klaassen, “A Unified Nonquasi-Static MOSFET Model for Large-Signal and Small-Signal Simulations,” *IEEE Trans. Electron Devices,* vol. 53, no. 9, pp. 2035-2043, Sep. 2006.

[16] T. Ezaki, D. Navarro, Y. Takeda, N. Sadachika, G. Suzuki, M. Miura-Mattausch, H.J. Mattausch, T. Ohguro, T. Iizuka, M. Taguchi, S. Kumashiro, S. Miyamoto, “Non-quasi-static approach with surface-potential-based MOSFET model HiSIM for RF circuit simulations,” *Mathematics and Computers in Simulation*, vol. 79, pp. 1096-1106, 2008.

[17] Matthias Bucher, Antonios Bazigos, “An efficient channel segmentation approach for a large-signal NQS MOSFET model,” *Solid-State Electronics*, vol. 52, pp. 275-281, 2008.

[18] J. W. Sleight, and Rafael Rios, “A Continuous Compact MOSFET Model for Fully- and Partially-Depleted SOI Devices,” *IEEE Trans. Electron Devices,* vol. 45, no. 4, pp. 821-825, 1998.

[19] E. R. Worley, “Theory of the fully depleted SOS/MOS transistor,” *Solid-state Electron,* vol. 23. pp. 1107-1111, November 1980.

[20] H. Lim and J. G. Fossum, “Threshold voltage of thin-film Silicon-on-insulator (SOI) MOSFET’s,” *IEEE Trans. Electron Devices,* Vol. 30, pp. 1244 - 1251, October 1983.