A Comparative Study of Double-Gate and Surrounding-Gate MOSFETs in Strong Inversion and Accumulation Using An Analytical Model

Yijian Chen* and Jianfeng Luo**

* EECS Department, University of California, Berkeley, CA94720, USA
Tel: 510-642-9210, Fax: 510-642-2739, Email:chenyj@eecs.berkeley.edu
** Department of Mechanical Engineering, University of California, CA94720, USA

ABSTRACT

An analytical model for the electric characteristics of ultrathin double-gate and surrounding-gate MOSFETs in strong inversion and accumulation is presented. The analytical solutions to the 1-D simplified Poisson's equation in both Cartesian and cylindrical coordinates with symmetric boundary conditions are examined. The concentration of the induced inversion charge by the same surface potential is found significantly higher in the surrounding-gate MOSFET, which indicates its better gate control and achievable higher current. Finally, the full 1-D Poisson's equation is numerically solved and compared with the analytical solution of the simplified equation, and an excellent agreement between them is found.

Keywords: Double-gate and surrounding-gate MOSFET, ultrathin body, strong inversion, volume inversion.

1 INTRODUCTION

As MOSFETs are scaled down to sub-50 nm, two promising structures such as the symmetric double-gate and surrounding-gate MOSFETs have attracted an increased research interest. It has been demonstrated that with the symmetric-gate design, the channel area is raised to increase the saturation current and the Si body control is enhanced to reduce the short-channel effects [1-6]. Recently, the development of ultrathin double-gate MOSFET introduces the concept of volume inversion: the inversion charge spreads throughout the whole ultrathin Si body, which improves the device characteristics (e.g., higher current due to the substrate mobility) [7-8]. Strong inversion plays an important role in MOSFET device physics as it provides the information of the swept charge as well as the saturation current. The work of Hauser et al. [9] and Taur [10] has led to an analytical solution to the simplified 1-D Poisson's equation in the Cartesian coordinate for a double-gate MOSFET. However, interpretation of a surrounding-gate MOSFET should be performed using the Poisson's equation in the cylindrical coordinate (with a more complex form which brings more mathematical difficulties). The simple integration technique [9-10] to analyze a double-gate MOSFET in the Cartesian coordinate fails to give an analytical solution to a surrounding-gate MOSFET.

In this paper, we shall apply a variable transformation technique, which has been used in the theory of combustion explosion and astrophysics [11], to solve the simplified 1-D Poisson's equation in the cylindrical coordinate for a surrounding-gate MOSFET in strong inversion and accumulation. Based on the analytical solutions obtained, we compare the inversion charge concentration of a double-gate MOSFET with that of a surrounding-gate MOSFET. It is found that significantly higher charge concentration is induced in the surrounding-gate structure than in the double-gate structure (when the same surface potential is applied), which indicates a better gate control and potentially higher current in the surrounding-gate MOSFET. Finally, we perform numerical simulation using the full 1-D Poisson's equation and results are found in excellent agreement with above analysis.

2 MODEL AND ANALYSIS

A general model to describe NMOSFET is known as the Poisson's equation [12]:

$$\nabla^2 j = -\frac{q}{e_s}\left(-N_a + N_a e^{-qj/kT} - \frac{n_i^2}{N_a} e^{qj/kT}\right) \quad (1)$$

In 1-D situation, equation (1) becomes:

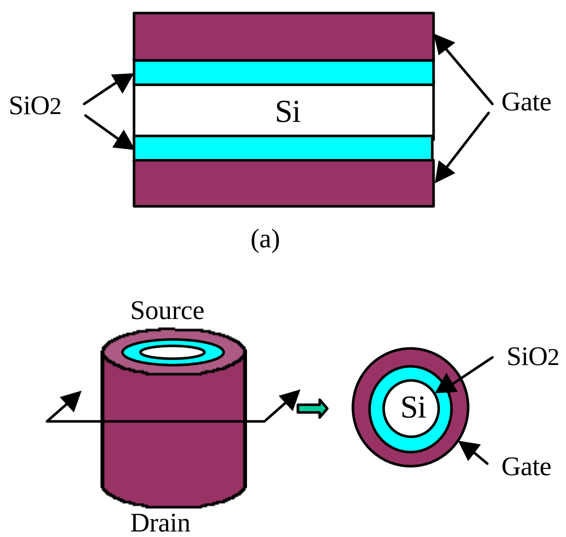
$$\frac{d^2 j}{dr^2} + \frac{m}{r}\frac{dj}{dr} = -\frac{q}{e_s}\left(-N_a + N_a e^{-qj/kT} - \frac{n_i^2}{N_a} e^{qj/kT}\right) \quad (2)$$

For the double-gate structure in the Cartesian coordinate: *m*=0, for the surrounding-gate structure in the cylindrical coordinate: *m*=1. The schematic description of the device structure is shown in Fig. 1. N_a is the doping concentration of the Si body and other symbols are following those widely used in the literature. The symmetric boundary conditions for both structures are as following:

$$\tfrac{dj}{dr}(r=0)=0 \tag{3a}$$

$$j\,(r=r_0)=j_s \tag{3b}$$

Here $r=0$ is at the center of the Si body and $r=r_0$ is on the surface, j_s is the surface potential.



(a)

(b)

Fig. 1. The structure of a double-gate MOSFET (a), and a surrounding-gate MOSFET (b).

When NMOSFET is in strong inversion, the holes and depletion-charge terms in equation (2) are neglected and equation (2) is simplified to:

$$\frac{d^2j}{dr^2}+\frac{m}{r}\frac{dj}{dr}=\frac{q}{e_s}\frac{n_i^2}{N_a}e^{qj/kT} \tag{4}$$

When NMOSFET is in strong accumulation, the electrons and depletion-charge terms in equation (2) will be neglected. The resultant Poisson's equation can be transformed to a form close to (4) by defining $-j=j'$. Thus similar analysis can be extended from strong-inversion to strong-accumulation regime and we shall only focus on strong inversion in this paper.

Since the analytical solution to equation (4) with m = 0 subject to boundary conditions (3a,b) has been given by Taur [10], we shall quickly go through the mathematical procedure (in a different way) for a background knowledge. A new variable z is defined: $z=qj/kT$ with which equation (4) is rewritten as:

$$\frac{d^2z}{dr^2}+\frac{m}{r}\frac{dz}{dr}=d\,e^z,\left(d=\frac{q^2n_i^2}{e_skT\,N_a}\right) \tag{5}$$

Equation (5) with m = 0 is equivalent to:

$$\frac{d}{dz}\left[\frac{1}{2}\left(\frac{dz}{dr}\right)^2\right]=d\,e^z \tag{6}$$

Integration of (6) yields:

$$\frac{dz}{dr}=\pm\sqrt{2d\,(e^z+a)} \tag{7}$$

The constant a in (7) will be determined from the boundary conditions. Set $u=e^z$, then we have the relation: $dz=du/u$ which can be substituted into (7) to get the following equation:

$$\pm\frac{du}{u\sqrt{2d\,(u+a)}}=dr \tag{8}$$

It will be shown later that in the real domain, a can only be negative. Thus for a<0, equation (8) is integrated to get the following form:

$$u=e^z=|a|\cos^{-2}\left(r\sqrt{\frac{|a|d}{2}}+b\right) \tag{9}$$

Boundary condition (3a) along with equations (7) and (9) leads to: $|a|[1-\cos^{-2}(b)]=0$. Since $a\neq 0$, thus $b=0$ is the simplest value to satisfy above equation. a is obtained from the boundary condition (3b) as below:

$$\exp\left(\frac{qj_s}{kT}\right)=|a|\cos^{-2}\left(r_0\sqrt{\frac{|a|d}{2}}\right) \tag{10}$$

From equation (9), we have the potential j:

$$j=\frac{kT}{q}\ln\left[|a|\cos^{-2}\left(r\sqrt{\frac{|a|d}{2}}\right)\right] \tag{11}$$

The surface charge density is:

$$|Q_s|=\left|\frac{dj}{dr}(r=r_0)\right|\cdot e_s=\frac{kT}{q}e_s\sqrt{2d\,[a+\exp(qj_s/kT)]}$$

When a>0, we find: $z=\ln[-a\,ch^{-2}(r\sqrt{ad/2}+b)]$ which, however, is not a real function.

To study a surrounding-gate MOSFET in strong inversion, equation (4) with $m=1$ should be considered. The integration technique we just demonstrate is not useful. Two transformation variables are introduced as:

$$h=r^2e^z,\ b=r\frac{dz}{dr} \tag{12}$$

Thus we have:

$$\begin{aligned}\frac{d^2z}{dr^2}&=\frac{d}{dr}\left(\frac{b}{r}\right)=\frac{db}{dr}\frac{1}{r}-\frac{b}{r^2}=\frac{db}{dh}\frac{dh}{dr}\frac{1}{r}-\frac{b}{r^2}\\&=\frac{db}{dh}\frac{d}{dr}(r^2e^z)\frac{1}{r}-\frac{b}{r^2}=\frac{db}{dh}\left(\frac{hb}{r}+\frac{2h}{r}\right)\frac{1}{r}-\frac{b}{r^2}\end{aligned} \tag{13}$$

Substituting (12) and (13) into the Poisson's equation (5) yields:

$$\frac{db}{dh}=\frac{d}{b+2} \tag{14}$$

Integration of above equation gives:

$$b^2+4b+h=2d\,h \tag{15}$$

The constant h=0 is required by $h(r=0)=0$, $b(r=0)=0$, and (15). Substituting (12) into equation (15) with h=0 results in a new differential equation:

$$\frac{1}{2}\left(\frac{dz}{dr}\right)^2+\frac{2}{r}\frac{dz}{dr}=d\,e^z \qquad (16)$$

(16) is used to remove the common term in the original equation (5) with m=1 :

$$\frac{d^2z}{dr^2}-\frac{1}{r}\frac{dz}{dr}-\frac{1}{2}\left(\frac{dz}{dr}\right)^2=0 \qquad (17)$$

Equation (17) has a well-known solution:

$$z=A-2\ln(Br^2+1) \qquad (18)$$

The boundary condition (3a) is automatically satisfied by (18). A relationship between A and B is found by substitution of (18) into (5):

$$A=\ln(-8B/d) \qquad (19)$$

The boundary condition (3b) yields a formula for B:

$$\exp\left(\frac{qj_s}{kT}\right)=-\frac{8B}{d\,(Br_0^2+1)^2} \qquad (20)$$

The surface charge density is:

$$|Q_s|=\left|\frac{dj}{dr}(r=r_0)\right|\cdot e_s=\frac{kT}{q}e_s\sqrt{-2Bd\,r_0^2\exp\left(\frac{qe_s}{kT}\right)}$$

3 RESULTS AND DISCUSSIONS

The potential and inversion charge concentration, both as a function of the distance r from the silicon substrate center, are calculated and shown in Fig. 2. Fig. 2(a) and Fig. 2(b) are for the ultrathin double-gate MOSFET with a 30-nm-thick body, e.g., $r_0=15nm$, $N_a=10^{17}cm^{-3}$, $j_s=1.0V>2j_B=\frac{2kT}{q}\ln\left(\frac{N_a}{n_i}\right)$. And Fig. 2(c) and Fig. 2(d) are for the surrounding-gate structure with the same parameters. A significant difference in the inversion charge concentration of these two structures is evident in Fig. 2(e). It is expected that the saturation current of a surrounding-gate MOSFET will be larger than that of a double-gate structure. Usually, the gate voltage rather than the surface potential is given. However, the surface potential can be solved in the iteration method if the voltage drop in the gate oxide is considered [10]. It should be kept in mind that there is only one physically correct value in the double roots of the equations (10) and (20) which are used to determine the constants of integration. Numerical simulation using the full Poisson's equation (2) for both structures has also been carried out and the results are shown in Fig. 3. An excellent agreement between the analytical solution of the simplified Poisson's equation and the simulation of the full Poisson's equation is observed.

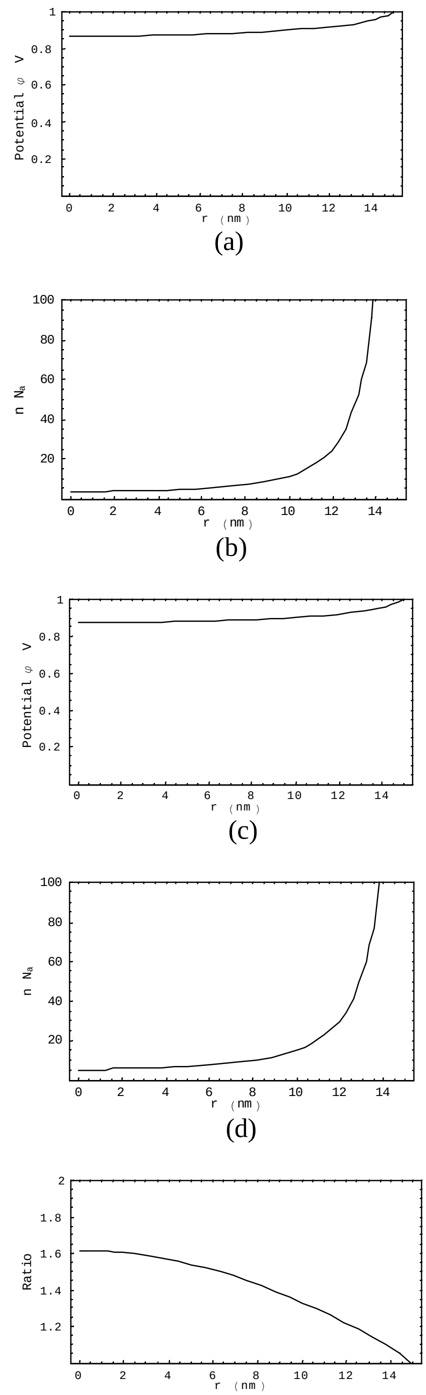
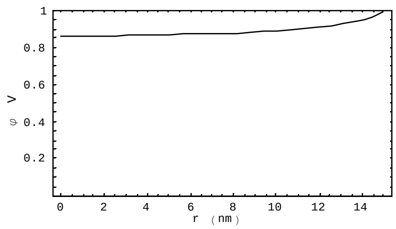
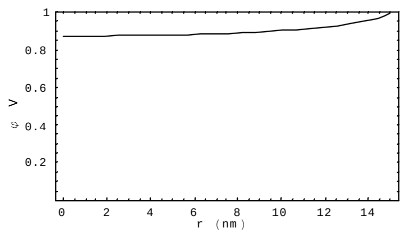


Fig. 2. MOSFET electric characteristics according to the analytical solution to the simplified Poisson's equation. (a) The potential of a double-gate MOSFET as a function of r. (b) The inversion charge concentration as a function of r. (c) The same as (a) except for a surrounding-gate MOSFET. (d) The same as (b) except for a surrounding-gate MOSFET. (e) Ratio of the inversion charge concentration of a surrounding-gate MOSFET to that of a double-gate MOSFET.



(a)



(b)

Fig. 3. MOSFET potential according to numerical simulation of the full 1-D Poisson's equation, $r_0 = 15\,nm$, $N_a = 10^{17}\,cm^{-3}$ and $j_s = 1.0V$. (a) The potential of a double-gate MOSFET as a function of the r. (b) The potential of a surrounding-gate MOSFET as a function of r.

4 CONCLUSIONS

In this paper, we have extended the analytical model of Taur to study the surrounding-gate MOSFET in strong inversion and accumulation. A variable transformation technique is applied to analytically solve the simplified Poisson's equation in the cylindrical coordinate. A comparison between the inversion charge concentration of a double-gate MOSFET and a surrounding-gate MOSFET has been made and we found that the surrounding-gate structure is more attractive in the sense of more inversion charge induced. Numerical simulation is finally performed to confirm the validity of our simplification and the analytical solution.

REFERENCES

[1] F. Balestra, J. Brini and P. Gentil, "Deep depleted SOI MOSFETs with back potential control: a numerical simulation," *Solid-State Electronics*, Vol. 28, No. 10, pp.1031-1037, 1985.

[2] J. P. Colinge et al., "Silicon-on-insulator gate-all-around device," *IEDM Technical Digest*, pp.595-596, 1990.

[3] H. Takato et al., "Impact of surrounding gate transistor (SGT) for ultra-high-density LSI's," *IEEE Trans Elec. Devices*, pp.573-578, March 1991.

[4] C. Wann et al., " A comparative study of advanced MOSFET concepts," *IEEE Trans Elec. Devices*, Vol. 43, No. 10, pp.1742-1753, October 1996.

[5] X. Huang et al., "Sub 50-nm FinFET: PMOS," *IEDM Technical Digest*, pp.67-70, 1999.

[6] S.-H. Oh et al., "Analytic description of short-channel effects in fully-depleted double-gate and cylindrical, surrounding-gate MOSFETs," *IEEE Electron Device Lett.*, vol. 21, No. 9, pp.397-399, September 2000.

[7] F. Balestra et al., "Double-gate silicon-on-insulator transistor with volume inversion: a new device with greatly enhanced performance," *IEEE Electron Device Lett.*, vol. EDL-8, No. 9, pp.410-412, September 1987.

[8] P. Francis et al., "Modeling of ultrathin double-gate nMOS/SOI transistors," *IEEE Trans Elec. Devices*, Vol. 41, No. 5, pp.715-719, May 1994.

[9] J. R. Hauser and M. A. Littlejohn, "Approximation for accumulation and inversion space-charge layers in semiconductors," *Solid-State Electronics*, Vol. 11, pp.667-674, 1968.

[10] Yuan Taur, "An analytical solution to a double-gate MOSFET with undoped body," *IEEE Electron Device Lett.*, vol. 21, No. 5, pp.245-247, May, 2000.

[11] P. L. Chambre, "On the solution of the Poisson-Boltzmann equation with application to the theory of thermal explosions," *J. Chem. Phys.*, Vol. 20, No. 11, pp.1795-1797, Nov. 1952.

[12] S. Wolf, *Silicon Processing*, vol. 3-The submicron MOSFET, Sunset Beach: Lattice Press, pp.106-112.