Structure-Dependent Subthreshold Swings for Double-gate MOSFETs

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***Abstract*— In this paper, subthreshold swing characteristics have been presented for double-gate MOSFETs, using the analytical model based on series form of potential distribution. Subthreshold swing is very important factor for digital devices because of determination of ON and OFF. In general, subthreshold swings have to be under 100mV/dec. The channel length L_g is varied from 30nm to 100nm, and channel thickness t_{si} from 15 to 20nm according to channel length, and oxide thickness 5nm to investigate subthreshold swing. The doping of channel is fixed with $10^{16}cm^{-3}$ p-type. The results show good agreement with numerical simulations, confirming this model.**

***Index Terms*— DGMOSFET, gate oxide thickness, subthreshold swing , digital devices, transport model.**

I. INTRODUCTION

IN accordance with Hwang's low, the packing density of transistors per unit chip area is ever increasing in the VLSI microelectronic industries. This has been possible due to comprehensive scaling of MOSFET. The inherent benefits of MOSFET scaling are the speed improvements, increased packing density and energy reduction associated with binary logic transition. However the aggressive reduction in channel length leads to short-channel effects (SCEs)[1]. The main SCEs are the threshold voltage roll-off, the degradation of the subthreshold swing, and the drain induced barrier lowering(DIBL) effect. As a result, the off-stage current increases, and the ON-OFF current ratio is degraded, and therefore, device performance is worsened. The double-gate(DG) MOSFET technology has emerged as one of the most promising candidates to extend the CMOS beyond the scaling limit of conventional technology due to excellent control of SCEs[2]. The subthreshold swing is important parameter associated with DG MOSFETs, which is usually used to describe the turn-on characteristic of the device[3]. This is defined as the needed variation in gate voltage that results in ten times magnitude change in the subthreshold drain current. The subthreshold swing and threshold voltage play a important role with low-power consumption and high speed in device operation. The advantages of DG MOSFETs include their better control to SCEs, excellent subthreshold swing and their ability to get scaled down to very short scale length[4]. The miniaturization of the feature size of the DG MOSFET in the nanometer regime arises due to its reinforced electrostatic gate control of the channel region[5]. In the sub-100nm structure, since the channel doping is difficult due to very thin silicon body, the subthreshold swing influenced on doping concentration of channel is not determined precisely[6].

This paper is organized in four major sections. A 2D analytical model with Poisson's equation is explained in Sec. II. In Sec. III, we discuss subthreshold swings of this model and validates with results of 2D simulator. The conclusion has been drawn in Sec. IV.

II. POTENTIAL AND SUBTHRESHOLD SWING MODEL

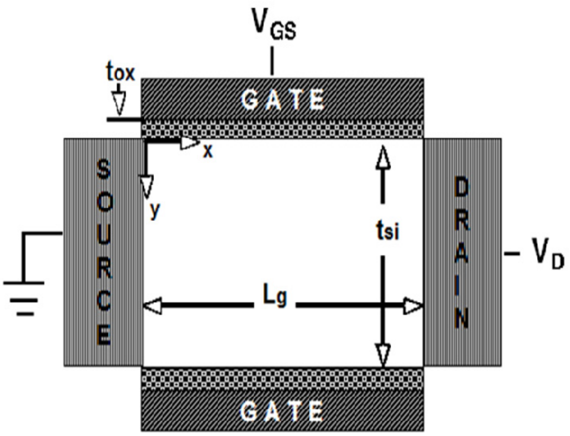

Fig. 1. Schematic structure of symmetric DGMOSFET

The schematic structure of a DGMOSFET used for our analysis and simulation is shown in Fig. 1, where L, t_{si}, and t_{ox} are the gate length, channel thickness and gate-oxide thickness of the device respectively. The x-and y- axes of the 2D structure are considered to be along the channel-upper oxide interface and source-channel interface as shown in the Fig. 1.

The Poisson equation in the silicon body is [7]

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$$\frac{\partial^2\psi(x,y)}{\partial x^2}+\frac{\partial^2\psi(x,y)}{\partial y^2}=\frac{qN_A}{\varepsilon_{si}} \tag{1}$$

where q is the electron charge, N_A doping density, ε_{si} the permittivity of silicon, and $\psi(x,y)$ the electric potential in the channel. To solve equation (1), the boundary conditions are the followings;

$$\begin{aligned}
&\psi(0,y)=V_{bi}\\
&\psi(L,y)=V_{bi}+V_{DS}\\
&\psi(x,0)=V_{GF}+\frac{\varepsilon_{si}}{C_{ox}}\frac{\partial\psi}{\partial y}\Big|_{y=0}\\
&\psi(x,t_{si})=V_{GF}-\frac{\varepsilon_{si}}{C_{ox}}\frac{\partial\psi}{\partial y}\Big|_{y=t_{si}}
\end{aligned} \tag{2}$$

where V_{bi} is the built-in voltage of the source and drain junctions and V_{DS} is applied drain-source voltage. $C_{ox}=\varepsilon_{ox}/t_{ox}$, being ε_{ox} the permittivity of the gate oxide. $V_{GF}=V_{GS}-V_{FB}$, being V_{GS} the voltage applied to the front and back gates, V_{FB} the flat-band voltage.

Using the method proposed by Ding et al [7], the modified 2D Poisson's equation described by Eq.(1) can be solved to express the 2D channel potential function $\psi(x,y)$ as

$$\psi(x,y)=V_{bi}+\frac{V_{DS}}{L}x\sum_{n=1}^{\infty}A(n)(y)\sin\frac{n\pi x}{L} \tag{3}$$

The subthreshold swing is an important key design parameter pertaining to DGMOSFETs, which is commonly used to describe the turn on characteristics of the device. The subthreshold slope can be calculated using the expression[8].

$$S=\ln 10\frac{kT}{q}\times\left(\frac{\partial\psi_{\min}}{\partial V_{GS}}\right)^{-1} \tag{4}$$

where k is Boltzman's constant , T is temperature, respectively. $\psi_{\min}$ is the minimum value of the surface potential function. Using Eq.(4), subthreshold swing in the followings;

$$S(x,y)=\ln 10\frac{kT}{q}\left\{\sum_{n=1}^{100}\sin\left(\frac{n\pi x}{L}\right)\frac{2}{n\pi}\times\frac{P}{H}\right\}^{-1} \tag{5}$$

$$P=\left(e^{(n\pi/L)d_{eff}}+e^{-(n\pi/L)d_{eff}}e^{(n\pi/L)t_{si}}\right)C_{ox}\left[1-(-1)^n\right]$$

$$H=\left[e^{(n\pi/L)t_{si}}\left(C_{ox}+(\varepsilon_{si}n\pi/L)\right)+\left(C_{ox}-(\varepsilon_{si}n\pi/L)\right)\right]$$

where d_{eff} is the charge centroid, which in our model is obtained from

$$d_{eff}=\int_0^{tsi/2}ye^{\psi\min/V_t}dy\Big/\int_0^{tsi/2}e^{\psi\min/V_t}dy$$

Now, with Eq.(3), one obtains the electric potential in the channel. An important point to note here is that, although the number of summation terms in Eq.(3) is infinite, $A(n)(y)$ converges very fast with respect to argument n, and n=100 is large enough for a very good approximation.

III. RESULTS OF SUBTHRESHOLD SWING

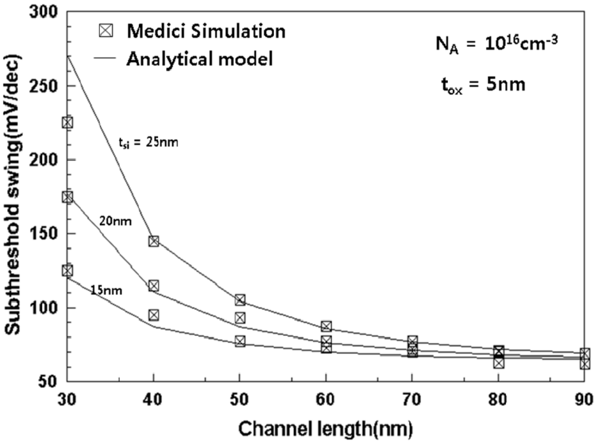

Fig. 2. Subthreshold swing with channel length for different values of channel thickness

Figure 2 shows the substhreshold swing obtained from our model Medici simulations[9]. Good agreement is obseved. Figure 2 depicts the variation of subthreshold swing with channel length for three different channel thicknesses. As shown in Fig. 2, the subthreshold swing increases with decreasing channel length due to SCEs and the curve shifts downward for lower values of t_{si}. When the channel length is small, the subthreshold swing will be large due to short channel effects. The subthreshold swing, and gets improved with the increase of the channel length to the ideal value(60mV/dec).

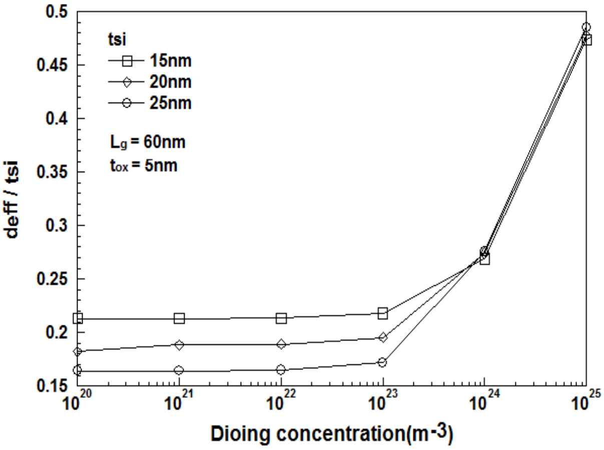

Fig. 3. Change of conduction center for doping Concentraion

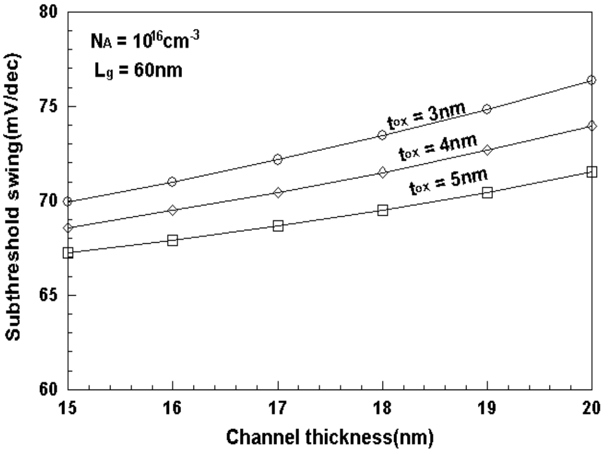

Fig. 4. Subthreshold swings with channel thickness for different values of gate oxide thickness

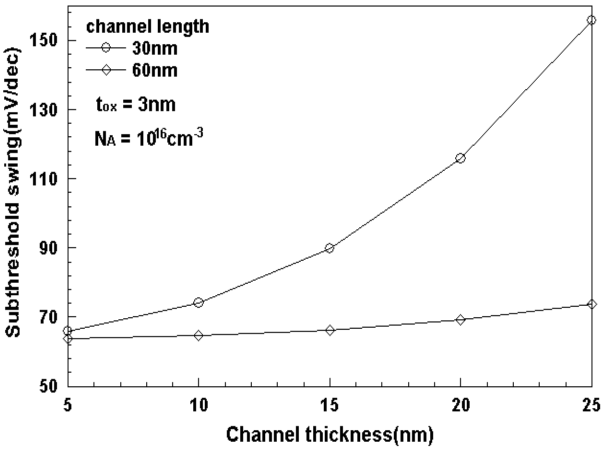

Fig. 5. Subthreshold swings with channel thickness for different values of channel length

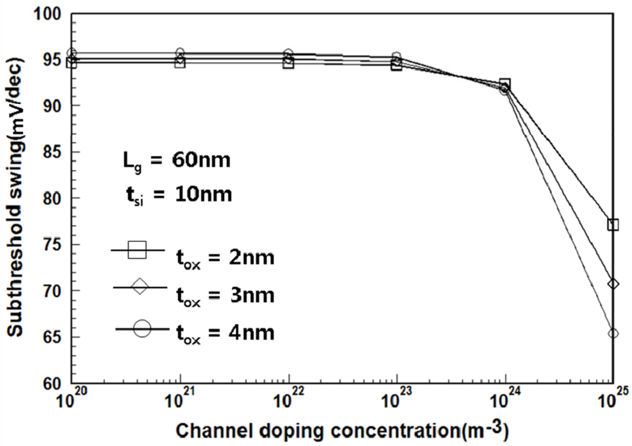

Fig. 6. Subthreshold swings with channel doping concentrarion for different values of oxide thickness

Given increasing of channel thickness, the conduction of free electron is not confined to the channel center and the effective conduction path must be between surfaces and channel center since the controllability of gate voltage for spreading of carrier is weak increasing of channel thickness.

The dependence of the effective conduction path parameter(d_{eff}) on the peak concentration N_a has been shown in Fig.3 according to different channel thickness. Figure 3 shows a good matching is found below the doping value of $10^{23}m^{-3}$. In case of ligher doping of $N_a(10^{23}m^{-3})$ the centre potential is higher than the surface potential. And the charge carrier responsibe for subthreshold conduction mainly flows through the centre of the device. On the other hand, as N_a increases further, the surface potential becomes much larger near the surface than that of other positions along the transverse direction of the channel. Hence the overall conduction becomes highly confined to gate contact.

Figure 4 displays the variation of subthreshold swing with channel thickenss for three different oxide thickness. Subthreshold swing increases with increasing oxide thickness and the curve shifts downward for a low channel thickness. As shown in Fig. 4, the variations of subthreshold swing is larger due to SCE in thick channel thickness when channel thickness increases, and the variation of subthreshold swing according to oxide thickness is trivial at small channel thickness. Note the relation of subthreshold swing and channel thickness is nearly linear. Also the variation of subthreshold swing is large at lower gate oxide thickness. So we know small channel thickness has to be used to design of DGMOSFET for small and consistent subthreshold swing.

Figure 5 shows the variation of subthreshold swing with channel thickenss for two fixed channel length. From the graph we observe that subthreshold swing decreases with decreasing channel thickness and the curve shifts upward as the channel length is reduced. When channel length is 60nm, subthreshold swing is near 60mv/sec regardless of channel thickness. It is known that the subthreshold swing is improved to smaller ratios of channel thickness vs channel length.

Figure 6 shows the subthreshold swing for the variation of channel doping concentration of DGMOSFET . From the Fig. 6 we may observe that subthreshold swing decreases with increasing values of channel doping concentration. When channel doping concentraion is less than 10^{24}m^{-3}, subthreshold swing increases with increasing values of oxide thickness whereas for channel doping concentration exceeding 10^{24}m^{-3}, subthreshold swing increases with a lower value of oxide thickness. Subthreshold swing is improved when doping concentration is increasing since conduction path is near gate contact, and the optimum threshold voltage can be obtained by adjusting the doping concentration in channel. However, increasing doping concentration to improve subthreshold swings causes degradation of carrier transport due to impurity scattering and does not result in fully depletion in channel.

IV. CONCLUSIONS

This study has presented subthreshold swing for DGMOSFET using analytical potential model. Based on the model, the analytical expression of subthreshold swing is obtained. Model predictions are compared with Medici simulations and results show good agreement. The subthreshold swing has been defined as the derivative of gate voltage to drain current and is theoretically minimum of 60mS/dec, and very important factor in digital application. When the channel length is small, the subthreshold swing will be large. The subthreshold swing gets improved with the increase of the channel length. The subthreshold swing will be improved with the decrease of the silicon body thickness, owing to the channel being controlled by the gates more easily. We note that the subthreshold swing is decreasing with increasing of doping concentration. We may use our results in design of DGMOSFET.

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