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Analysis of Subthreshold Characteristics for Device Parameter of DGMOSFET Using Gaussian Function

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***Abstract*— This paper has studied subthreshold characteristics for double gate(DG) MOSFET using Gaussian function in solving Poisson's equation. Typical two dimensional analytical transport models have been presented for symmetrical Double Gate MOSFETs (DGMOSFETs). Subthreshold swing and threshold voltage are very important factors for digital devices because of determination of ON and OFF. In general, subthreshold swings have to be under 100mV/dec, and threshold voltage roll-off small in short channel devices. These models are used to obtain the change of subthreshold swings and threshold voltage for DGMOSFET according to channel doping profiles. Also subthreshold swings and threshold voltages have been analyzed for device parameters such as channel length, channel thickness and channel doping profiles.**

***Index Terms*— DGMOSFET, subthreshold swing, threshold voltage, Gaussian function, digital devices, transport model, Poisson's equation.**

I. INTRODUCTION

THE scaled down CMOS into sub-20nm channel length is very important for future electronic engineering to integrate various fields. The International Technology Roadmap for Semiconductors(ITRS) suggests that CMOS technology is approaching the fundamental physical limits in the near future[1]. The conventional MOSFET has limits to decrease into sub-20nm because of the short channel effects(SCEs) such as threshold voltage roll-off, drain induced barrier lowering(DIBL), subthreshold swing and so forth. To solve these problems, multiple gate transistors have been studied and investigated to improve gate controllability. The symmetric double-gate(DG) MOSFET has been intensive subjects of research to reduce or remove SCEs. Since DGMOSFETs have two gates, top and bottom gate, they may drive nearly twice current, and offer effectively electrostatic coupling between the conduction path in channel and the gate electrodes. Since the DGMOSFETs also can have lower doping channel or intrinsic, they have advantages to reduce impurity scattering, enhance mobility and transport carriers ballistically[2,3]. Subthreshold swing is defined as the needed variation in gate voltage that results in ten times magnitude change in the subthreshold drain current. The light doping of the channel derives ideal subthreshold swing due to reduced influence of drain voltage on the channel charge. DGMOSFET could control threshold voltage by two gates, and reduce SCEs like threshold voltage roll-off and subthreshold swing. The important parameters for digital applications that indicates the problems of SCEs in MOSFET are subthreshold swing and threshold voltage roll-off. Also subthreshold swing and threshold voltage play a important role with low-power consumption and high speed in device operation. Zhang et al.[4] has reported a 2D model for potential distribution and threshold voltage of fully depleted SOI MOSFETs with a vertical Gaussian profile in the channel. Tiwari et al[5] has presented valid potential model for the nonuniform channel doping. However, they donot discuss subthreshold characteristics in details according to device parameters. This paper presents a their 2D model for potential distribution, and subthreshold swing and threshold voltage model with Gaussian doping in channel of DGMOSFETs, and explains the dependence of subthreshold swing and threshold voltage on the channel thickness, channel length and channel doping profiles using this model.

This paper is organized in four major sections. A 2D analytical potential and subthreshold swing, and threshold voltage models are presented in Sec. II. In Sec. III, we discuss subthreshold swings and threshold voltages based on this models and validate with results of 2D simulator. The conclusion has been drawn in Sec. IV

II. POTENTIAL AND SUBTHRESHOLD MODELS

Ion implantation has been generally used for impurity doping in semiconductor. The total distance that an ion travels to rest is called its range R, and the projection of this distance along the axis of incidence is called the projected range R_p. The statistical fluctuations in the projected range are called the standard projected deviation σ_p. Along the axis of incidence implanted impurity profile can be approximated by Gaussian distribution function:

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$$n(x) = \frac{S}{\sqrt{2\pi}\sigma_p}\exp\left[-\frac{(x-R_p)^2}{2\sigma_p{}^2}\right] = N_p\exp\left[-\frac{(x-R_p)^2}{2\sigma_p{}^2}\right] \quad (1)$$

where S is the ion dose per unit area and $S/\sqrt{2\pi}\sigma_p$ is constant N_p.

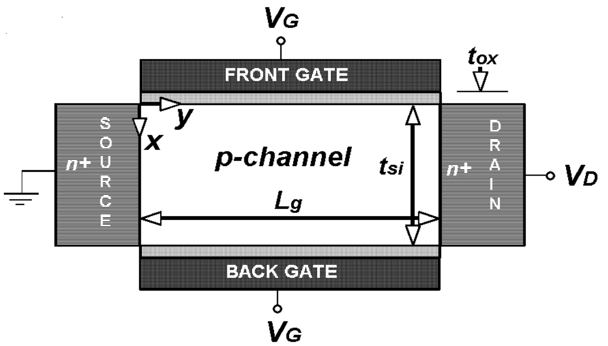

Fig. 1. The schematic diagram of a symmetric DGMOSFET.

Figure 1 is the schematic diagram of a symmetric DGMOSFET, where L_g, t_{si}, t_{ox} are channel length, channel thickness and gate oxide thickness, respectively.

As shown in Fig. 1, $x-$ and $y-$ directions are considered to be along channel thickness and channel length. The 2D Poisson's equation to solve potential $\varphi(x,y)$ is

$$\frac{\partial^2\varphi(x,y)}{\partial x^2} + \frac{\partial^2\varphi(x,y)}{\partial y^2} = \frac{qn(x)}{\varepsilon_{si}} \quad (2)$$

where ε_{si} is permittivity of silicon. To solve equation (2), the boundary conditions are the followings ;

$$\begin{aligned}
&\varphi(x,y)|_{x=0} = \varphi_s(y) \\
&\frac{\varepsilon_{ox}}{t_{ox}}\left[V_G - V_{fb} - \varphi(0,y)\right] = -\varepsilon_{si}\frac{\partial\varphi}{\partial x}|_{x=0} \\
&\varphi(0,0) = V_{bi} \\
&\varphi(0,L_g) = V_{bi} + V_D
\end{aligned} \quad (3)$$

where φ_s is surface potential, ε_{ox} is the permittivity of silicon dioxide, V_{bi} is the built-in potential of source and channel, V_{fb} is flat-band voltage, and V_G and V_D are gate and drain biased voltage, respectively. Using the methods proposed by Zhang et al[4] and Tiwari et al[5] and previous paper[6], the subthreshold swing SS is derived from definition such as the needed variation in gate voltage that results in ten times magnitude change in the subthreshold drain current. Assuming that the drain current(I_D) is proportional to the total amount of free electrons at the virtual cathode and their density follows Boltzmann distribution as

$$n_m(x) = (n_i^2/N_p)\exp(q\varphi(\varsigma, y_{\min})/kT)$$

where n_i is the intrinsic electron density, k is Boltzmann constant, T is absolute temperature, and $\varphi(\zeta, y_{\min})$ is minimum potential, the subthreshold swing is derived from

$$\begin{aligned}
SS &= \frac{\partial V_G}{\partial \log I_D} = \frac{kT}{q}\ln 10\left[\frac{\partial\varphi(\varsigma, y_{\min})}{\partial V_G}\right]^{-1} \\
&= \frac{kT}{q}\ln 10\left[1 + \Gamma\left(\frac{d\varphi_{s\min}}{dV_G} - 1\right)\right]^{-1} \\
&= \frac{kT}{q}\ln 10\left[1 + \Gamma\left\{\frac{2HKV_G - (HP+KN)}{\sqrt{FG}}\right\}\right]^{-1}
\end{aligned} \quad (4)$$

$$\Gamma = \frac{E - D\varsigma + \varsigma erf(\varsigma) + \exp(-\varsigma^2)/\sqrt{\pi}}{E - D\varsigma + Berf(B) + \exp(-B^2)/\sqrt{\pi}}$$

The q is electronic charge and refer previous paper[6] for $\varphi(\zeta, y_{\min})$, $\varphi_{s\min}$, D, E, H, K, N, P, ζ.

The threshold voltage V_{th} is derived from definition such that surface potential is twice of Fermi potential when gate voltage is threshold voltage. By definition, $\varphi_s = 2\varphi_f$ at $V_G = V_{th}$. The V_{th} can be obtained using quadratic formula as following by method proposed by Tiwari et al[5]

$$V_{th} = \frac{R - \left\{R^2 - 4(4HK-1)\times(4NP - S^2)\right\}^{1/2}}{8HK - 2} \quad (5)$$

$$\begin{aligned}
&S = V_{fb} + 2\phi_f + \lambda^2 qN_p\exp(-B^2)/\varepsilon_{si} \\
&R = 2S - 4(HP+KN)
\end{aligned}$$

Refer previous paper[6] for B, H, K, N, P, R, S, λ.

III. RESULTS OF POTENTIAL AND SUBTHRESHOLD CHARACTERISTICS

Figure 2 shows the variation of the surface potential φ_s along the channel length with $L_g = 65nm$, $t_{si} = 20nm$, $t_{ox} = 1.5nm$, $V_{bi} = 0.868V$, $V_{fb} = -0.26V$. The parameters of the Gaussian function are $R_p = 10nm$, $\sigma_p = 5nm$, and $N_p = 10^{15}/cm^3$. Using various gate voltages and drain voltages, these results have been compared with those of 2D simulator indicated with stars. We know these results are good agreements with those of 2D simulators.

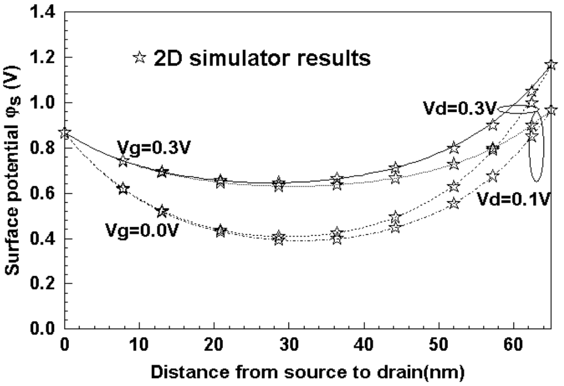

Fig. 2. Surface potential from source to drain with Gaussian doping profile having $R_p = 10nm$, $\sigma_p = 5nm$, and $N_p = 10^{15}/cm^3$.

We used, therefore, this potential model to calculate the subthreshold swing and threshold voltage for various doping profile and structure parameters. Note as V_D and V_G increases the minimum of surface potential is increasing, causing the significant reduction of channel barrier height.

Figure 3 shows the subthreshold swings with the variation of the doping concentration N_p derived from Eq. (4). As shown in Fig. 3, the projected range R_p and the standard projected deviation σ_p have influenced on the subthreshold swings. With decreasing of doping concentration, subthreshold swing rapidly degraded. 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. Our subthreshold swings have been compared with those of analytical model of Chen et al[7]. We know our subthreshold swings agree with Chen's results in low doping region to be generally used in DGMOSGET.

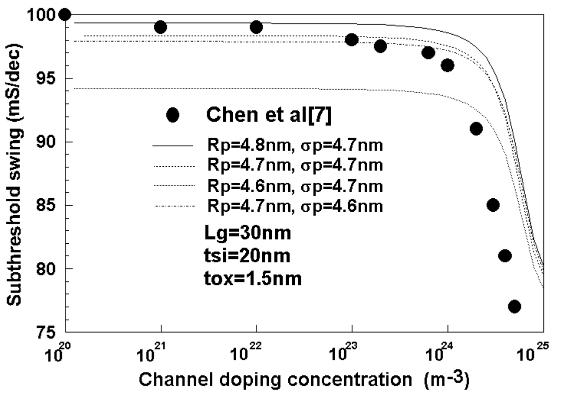

Fig. 3. Subthreshold swings derived from Eq. (4) with the variation of the doping concentration N_p, compared with results of Chen et al[7].

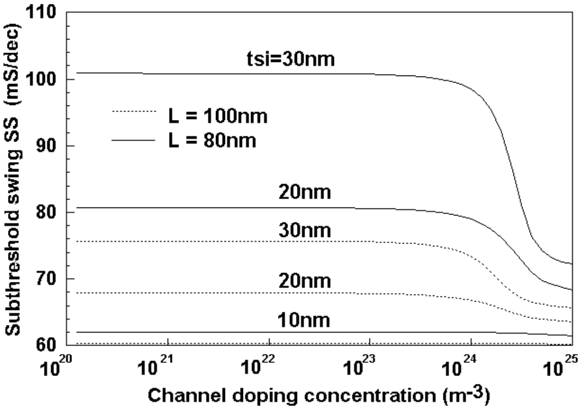

Fig. 4. Subthreshold swings according to structure parameter and doping concentration.

To investigate subthreshold swings according to structure parameter and doping concentration in details, we calculated subthreshold swings with variation of channel thickness and channel length as shown in Fig. 4. We have to use thin channel thickness for digital application since subthreshold swing increases and degraded with increase of channel thickness. Also the variation rate of subthreshold swing is increasing with decreasing of channel length due to SCEs. When channel thickness is thin under 10nm, subthreshold swings is near 60mS/dec regardless of channel length. We know DGMOSFETs for digital application must have thin channel thickness for fully depletion of channel. If thin channel thickness has been used in fabricating DGMOSFET, subthreshold swings are nearly constant regardless of doping concentration.

Figure 5 shows subthreshold swings according to channel thickness, channel length and constant N_p related with doping concentration.

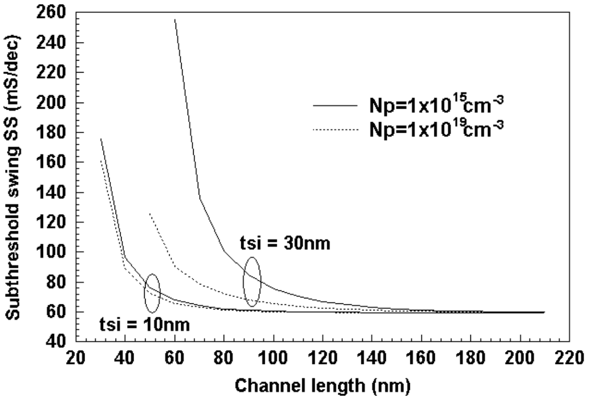

Fig. 5. Subthreshold swings according to channel length and constant N_p.

We know subthreshold swing is decreasing with increase of doping concentration as shown in Fig. 3 and Fig. 5. In the region of sub-100nm channel length, subthreshold swings is critically reduced with thin channel thickness, and doping concentration in channel is trivial in thin channel thickness of sub-10nm and long channel length. If channel length is reduced, channel thickness has to be ultra-thin around sub-10nm to use DGMOSFET in digital application.

In case of using ultra-thin channel thickness, note DGMOSFETs have advantage of low channel doping, which impurity scattering is rapidly reduced and ballistic transport is possible.

Figure 6 shows threshold voltages for DGMOSFET based on Equation (5) according to channel length, channel thickness and maximum doping concentration. Threshold voltage is increasing with increase of maximum doping concentration and decreasing with decrease of channel length due to SCEs. Also we have compared with variation of channel thickness. The SCEs is strong with increase of channel thickness. Therefore we have to use ultra-thin channel thickness for fabrication of DGMOSFET if possible. In the case of the long channel, threshold voltage is nearly constant regardless of channel thickness. Such effect happened for all of the doping concentrations.

In the region of sub-50nm, SCEs is very strong, especially in the lower doping concentration as shown in Fig. 6. To weeken the SCEs such as threshold voltage roll-off, we don't have to use very low channel doping for DGMOSFET. However since the light doping of the channel derives ideal subthreshold swing, another SCEs, due to reduced influence of drain voltage on the channel charge, threshold voltage and subthreshold swing have the relation of trade-off.

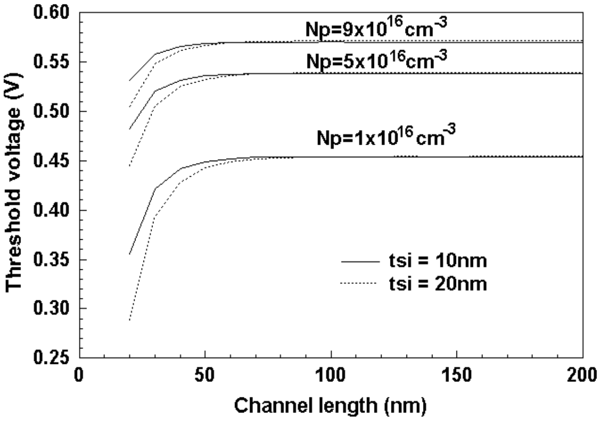

Fig. 6. Threshold voltages for DGMOSFET based on Equation (10) according to channel length, channel thickness and maximum doping concentration

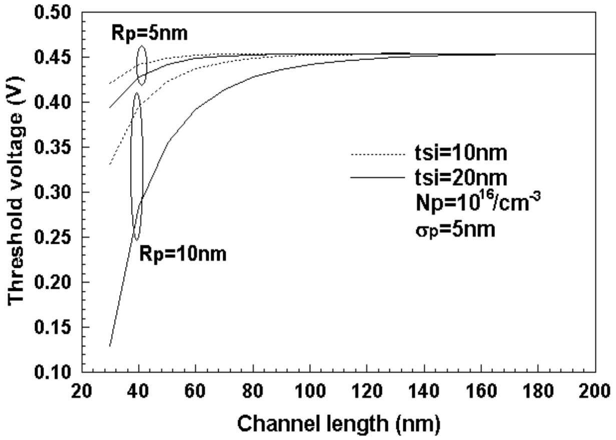

Fig. 7. Threshold voltage according to variations of projected range R_p with $\sigma_p = 5nm$ and $N_p = 10^{16}/cm^3$.

Figure 7 shows threshold voltage according to the variations of projected range and channel thickness. As shown in Fig. 6 and Fig. 7, SCEs have occurred in the range of sub-100nm and is strong with increase of channel thickness. The influence on increase of channel thickness increases with the increase of projected range. We know if projected range increases in the condition of same channel thickness, threshold voltage roll-off occurred strongly. Therefore during ion implantation projected range has to be small to reduce SCEs. As known in Fig. 7, nonuniform doping profiles have influenced on threshold voltage roll-off.

IV. CONCLUSIONS

This study has presented subthreshold swing and threshold voltage roll-off for DGMOSFET in case of using Gaussian function to solve Possion's equation. Two dimensional analytical potential model and subthreshold swing model, and threshold voltage model have been presented for symmetrical Double Gate MOSFETs (DGMOSFETs), based on Tiwari's model. This potential model has good agreement with results of 2D simulator. This potential model is used to obtain the analytical model of subthreshold swings and threshold voltage for DGMOSFET according to device parameters. We know 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. Also note the variation rate of subthreshold swing is increasing with decreasing of channel length due to SCEs. Note threshold voltages derived from this model are increasing with increase of maximum doping concentration to be in proportion to ion doses and decreasing with decrease of channel length due to SCEs. Since the lightly doped channel results in ideal subthreshold swing due to reduced influence of drain voltage on the channel charge, note threshold voltage and subthreshold swing have the relation of trade-off. Since threshold voltage roll-off occurred strongly if projected range increases in the condition of same channel thickness, projected range has to be small during ion implantation. With reducing of channel length, channel thickness has to be ultra-thin around sub-10nm to use DGMOSFET in digital application. We may use our results in design of DGMOSFET.

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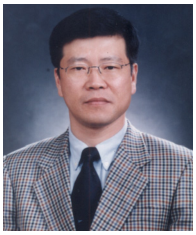

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