Analysis of Doping Profile Dependent Threshold Voltage for DGMOSFET Using Gaussian Function

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Abstract— **This paper has presented doping profile dependent threshold voltage for DGMOSFET using analytical transport model based on Gaussian function. Two dimensional analytical transport model has been derived from Poisson's equation for symmetrical Double Gate MOSFETs(DGMOSFETs). Threshold voltage roll-off is very important short channel effects(SCEs) for nano structures since it determines turn on/off of MOSFETs. Threshold voltage has to be constant with decrease of channel length, but it shows roll-off due to SCEs. This analytical transport model is used to obtain the dependence of threshold voltage on channel doping profile for DGMOSFET profiles. Also we have analyzed threshold voltage for structure of channel such as channel length and gate oxide thickness.**

Index Terms— **DGMOSFETs, threshold voltage roll-off, digital devices, transport model, channel doping profile.**

I. INTRODUCTION

THE major memory company has plan to product memory chips based on 20nm MOSFET in this year. Now single gate conventional CMOS in planar technology is dominant in the semiconductor market and industry. The vast development has been achieved to scale down the CMOS transistor to obtain faster and low-power transistor. The smaller dimension could obtain lower costs per transistor in terms of transistor per chip area. However, with scaling down device dimension, short channel effects(SCEs) greatly increase, and cause degradation of device operation. With critical device size down beyond sub-30nm, the conventional MOSFET faces difficulties and challenges due to SCEs and excessive threshold voltage roll-off[1]. The multiple gate transistors have been studied as the candidate to solve these problems and investigated to improve gate controllability. The multiple gate transistor could overcome SCEs and improve effectively controllability of gate on drain currents. The double gate(DG) MOSFET is the most simple multiple gate transistor and candidate to be able to reduce SCEs. The static power consumption is a limiting factor in scaled down MOSFET, and down-scaling causes SCEs such as threshold voltage roll-off, drain induced barrier lowering (DIBL), and subthreshold swing degradation and so forth. In the International Technology Roadmap for Semiconductors (ITRS) 2007 for the DGMOSFET[2], the physical channel length is 4.5nm for the year 2022. The DGMOSFET could obtain low leakage and low threshold voltage, and control currents nearly twice. Since DGMOSFETs have two gates, top and bottom gate, they may drives not only nearly twice current, and offer but also effectively electrostatic coupling between the conduction path in channel and the gate electrodes.

Since scaled down may lead to such obstacles as nonuniform carrier distribution and serious theoretical modeling, subthreshold characteristics have to be analyzed in the condition of nonuniform channel doping profile[3]. Tiwari et al[4] have investigated potential and threshold voltage using Gaussian distribution. They donot, however, analyze for projected range and standard projected range based on Gaussian function. We have investigated threshold voltage according to shapes of Gaussian function when channel doping profile is Gaussian distribution. Since the Gaussian distribution is general doping profile, we use this distribution to solve Poisson's equation, and explain Tiwari's analytical threshold voltage model. Using this model, this study has explained the dependence of threshold voltage according to gate oxide thickness and channel length for various channel doping profiles.

This paper is organized in four major sections. A 2D analytical potential and threshold voltage models of Tiwari et al. with Poisson's equation are presented in Sec. II. In Sec. III, Gaussian function shape dependent threshold voltages derived from this model are discussed and validated with results of 2D simulator. The conclusion has been drawn in Sec. IV.

II. POTENTIAL AND THRESHOLD VOLTAGE MODEL

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

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projected range are called the standard projected deviation σ_p. Along the axis of incidence implanted impurity

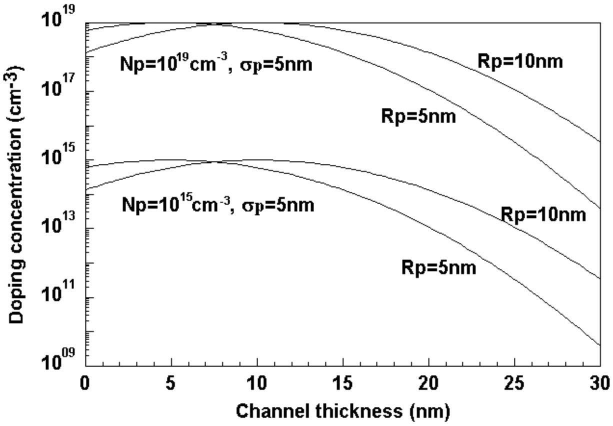

Fig. 1. Doping profile in channel according to N_p, σ_p and R_p when channel thickness is 30nm.

profile can be approximated by Gaussian distribution function:

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

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

Figure 1 is the doping profiles calculated by Eq. (1) according to N_p, σ_p and R_p for channel thickness of 30nm. Note doping profile is changed by parameters. We know the projected range is distance from gate to channel of maximum doping profile, and N_p is maximum doping profile. We have used this doping profiles to obtain threshold voltage model for DGMOSFET.

Figure 2 is 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. 2, $x-$ 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 Eq. (2), the boundary conditions are the followings ;

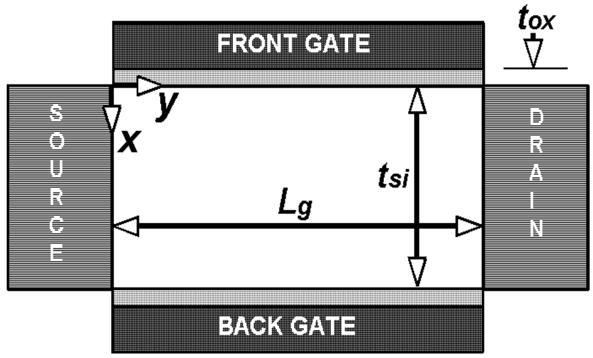

Fig. 2. The schematic diagram of a symmetric DGMOSFET.

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

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[3] and Tiwari et. al[4], the surface potential can be derived as the following;

$$\begin{aligned}
\varphi_s &= F\exp(y/\lambda) + G\exp(-y/\lambda) + V_G - V_{fb} \\
&\quad - \lambda^2 q N_p \exp(-B^2)/\varepsilon_{si}
\end{aligned} \quad (4)$$

where λ is the following as the characteristic length related with surface potential

$$\lambda^2 = \sqrt{\pi}\sigma^2 \left\{ \frac{DB - E - Berf(B) - \exp(-B^2)/\sqrt{\pi}}{\exp(-B^2)} \right\}$$

$$A = (t_{si} - R_p)/\sqrt{2}\sigma_p$$

$$B = -R_p/\sqrt{2}\sigma_p$$

$$C = \frac{t_{ox}\varepsilon_{si}}{\sqrt{2}\varepsilon_{ox}\sigma_p}$$

$$\begin{aligned}
D = \{&Cerf(B) - Berf(B) - \exp(-B^2)/\sqrt{\pi} + Aerf(A) + \\
&\exp(-A^2)/\sqrt{\pi} + Cerf(A)\}/\{2C - B + A\}
\end{aligned}$$

$$E = D(A+C) - Aerf(A) - \exp(-A^2)/\sqrt{\pi} - Cerf(A)$$

$$H = \frac{\exp(-L/\lambda) - 1}{\exp(-L/\lambda) - \exp(L/\lambda)}$$
$$K = \frac{\exp(L/\lambda) - 1}{\exp(L/\lambda) - \exp(-L/\lambda)}$$
$$M = V_{bi} + V_{fb} + \lambda^2 q N_p \exp(-B^2)/\varepsilon_{si}$$
$$N = H(M - V_D/(\exp(-L/\lambda) - 1))$$
$$P = K(M - V_D/(\exp(L/\lambda) - 1))$$
$$F = N - HV_G$$
$$G = P - KV_G$$

The erf is error-function. Note that $\varphi_{s\min} = \varphi_s(y_{\min})$ represents the minimum of $\varphi_s(y)$. Using the $y_{\min}$ derived from $d\varphi_s(y)/dy\big|_{y=y_{\min}} = 0$, the minimum surface potential can be obtained as

$$\varphi_{s\min} = 2\sqrt{FG} + V_G - V_{fb} - \lambda^2 q N_p \exp(-B^2)/\varepsilon_{si} \quad (5)$$

The threshold voltage V_{th} is derived from definition such that minimum surface potential is twice of Fermi potential when gate voltage is threshold voltage. By definition, since Eq. (5) is $2\phi_f$ at $V_G = V_{th}$, V_{th} can be obtained using formula as following ;

$$V_{th} = \frac{R - \{R^2 - 4(4HK - 1)\times(4NP - S^2)\}^{1/2}}{8HK - 2} \quad (6)$$
$$S = V_{fb} + 2\phi_f + \lambda^2 q N_p \exp(-B^2)/\varepsilon_{si}$$
$$R = 2S - 4(HP + KN)$$

III. POTENTIAL AND THRESHOLD VOLTAGE BASED ON OUR MODEL

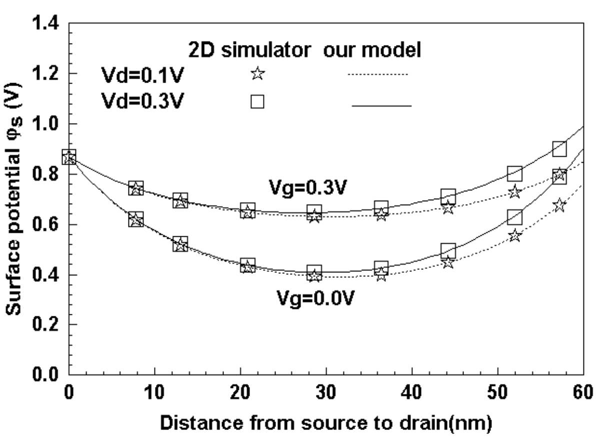

Fig. 3. Surface potential from source to drain with Gaussian doping profile having $R_p = 10nm$, $\sigma_p = 5nm$, and $N_p = 10^{15}/cm^3$.

Figure 3 shows the variation of the surface potential φ_s along the channel length with $L_g = 60nm$, $t_{si} = 20nm$,

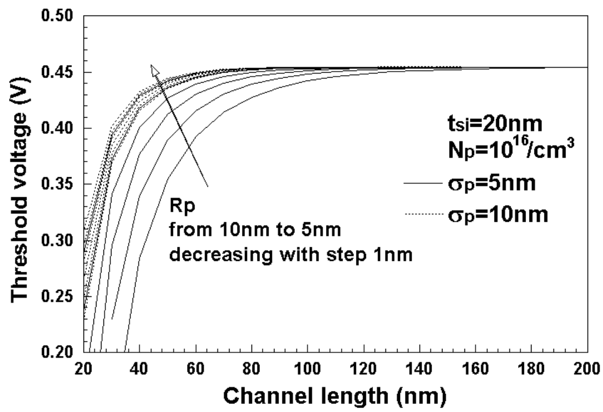

Fig. 4. Threshold voltages for channel length according to standard projected deviation of 5nm and 10nm when projected range is changed from 5nm to 10nm.

$t_{ox} = 1.5nm$, $V_{bi} = 0.868V$, $V_{fb} = -0.26V$. 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, our results have been compared with those of 2D simulator, indicated with stars and squares. We know our results are good agreements with those of 2D simulators. We used, therefore, this potential model to calculate the threshold voltage for Gaussian doping profile and structure parameters.

Figure 4 shows threshold voltages for channel length according to standard projected deviation of 5nm and 10nm when projected range is changed from 5nm to 10nm. Regardless of projected range and standard projected deviation, the SCEs have been occurred at short channel. The large projected range and small standard projected deviation show severe threshold voltage roll-off as shown in Fig. 4. In the large standard projected deviation, the change of projected range has not influenced on the threshold voltage roll-off, but the deviation of threshold voltage roll-off for projected range is great in the region of small standard projected deviation..

Figure 5 shows threshold voltages for channel length according to projected range of 5nm and 10nm when standard projected deviation is changed from 5nm to 10nm. Compared with Fig. 4 and Fig. 5, note the SCEs have always been occurred at short channel regardless of the value of projected range and standard projected deviation. In small projected range, constant threshold voltage roll-off has been occurred irrelevantly to the standard projected deviation, whereas difference of threshold voltage roll-off is distinct in large projected range.

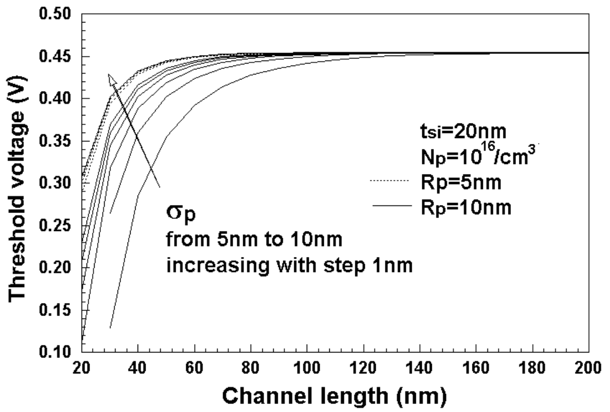

Fig. 5. Threshold voltages for channel length according to projected range of 5nm and 10nm when standard projected deviation is changed from 5nm to 10nm.

To investigate the change of threshold voltage in details for projected range and standard projected deviation in Gaussian function, the contours of equal threshold voltages for maximum doping concentration have been shown in Fig. 6. Two plots shows very differences. In low doping concentration, equal threshold voltage line shows nearly linear change for projected range and standard projected deviation, while standard projected deviation has greatly influenced on equal threshold voltage line than projected range in large doping concentration.

Figure 7 shows threshold voltages for standard projected deviation according to channel length and doping concentration. In low doping concentration, threshold voltage roll-off has been shown, but SCEs such as threshold voltage roll-off could not be found out nearly in high doping concentration regardless of standard projected deviation. Note threshold voltage roll-off could shrink in high doping concentration but higher doping in channel may cause the other problem such as a band-to-band tunneling[5].

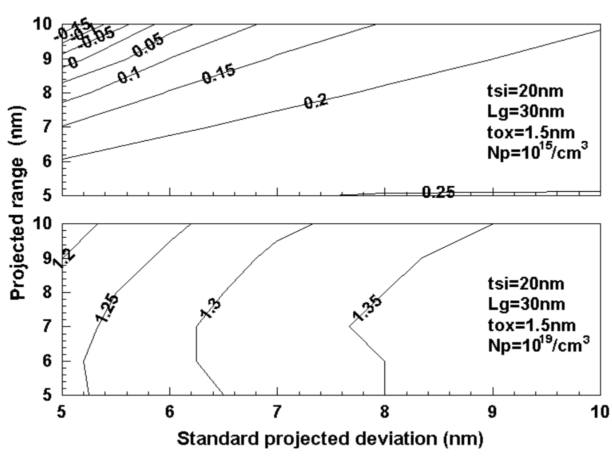

Fig. 6. The contours of equal threshold voltages for projected range and standard projected deviation.

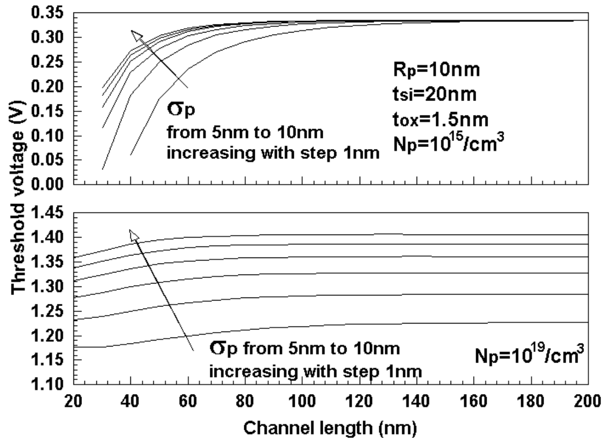

Fig. 7. The threshold voltages according to standard projected deviation for channel length and doping concentration.

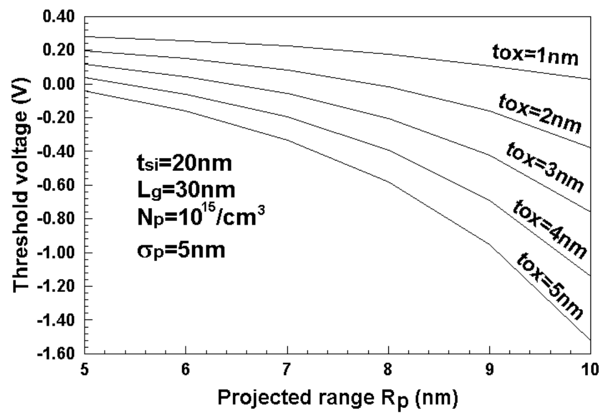

Fig. 8. Threshold voltages for projected range according to gate oxide thickness.

Figure 8 shows threshold voltages for projected range with a parameter of gate oxide thickness. Basically the large projected range may cause lowing of threshold as shown in previous figures, and thicker gate oxide also derived lower threshold voltage. Threshold voltage roll-off is greatly occurred in thicker gate oxide, and gate oxide thickness has greatly influenced on threshold voltage in large projected range as shown in Fig. 8.

IV. CONCLUSIONS

This paper has presented threshold voltage for DGMOSFET, based on analytical transport model derived from Gaussian doping profile when Poisson's equation is solved. Since threshold voltage determines the On/Off switching, it has to be constant with decrease of channel length, but it shows roll-off due to SCEs. This model is used to obtain the change of threshold voltage for DGMOSFET according to channel doping profiles. We know DGMOSFET with the large projected range and small standard projected deviation shows great threshold voltage roll-off. In the point of doping concentration, note that standard projected deviation has greatly influenced on equal threshold voltage line than projected range in large doping concentration, and threshold voltage roll-off could shrink in high doping concentration but higher doping in channel may cause a band-to-band tunneling. Also we know threshold voltage roll-off is greatly occurred in thicker gate oxide. Our threshold model will be used to design DGMOSFET to operate ideally in subthreshold region.

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