Analysis of Subthreshold Swing of Symmetric Junctionless Double Gate MOSFET Using Gaussian Doping Profile

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Abstract—The variation of subthreshold swing(SS) according to the projected range (R_p) and standard projected deviation (σ_p) was analyzed when the symmetrical junctionless double gate (JLDG) MOSFET was doped with Gaussian doping profile. For this purpose, the analytical SS model was presented. We compared with the TCAD results to turn out the validity of this model, and the SSs of this model agreed with those of TCAD. The effective conduction path and mean doping concentration affecting the SS were analyzed according to the R_p and σ_p . As a result, the SS increased as the R_p and σ_p increased simultaneously. The smaller the R_p and the larger the σ_p , the lower the SS. When $R_p = 1.5$ nm, it showed the SS below 100mV/dec without being affected by the change of σ_p or silicon thickness. When $\sigma_p = 3$ nm, it was also 100mV/dec or less regardless of the change of R_p and silicon thickness.

Keywords— Double gate, Junctionless, Subthreshold swing, Gaussian, Projected range, Standard projected deviation

I. INTRODUCTION

The junctionless MOSFETs are the most advanced transistors that can be used in digital circuits and systems as well as analog devices [1-3]. Unlike the junction-based double gates operating in inversion-mode, the junctionless MOSFETs operate in accumulation-mode. That is, by using the work-function difference between the gate metal and the silicon being used as the channel, in the off state, the channel is maintained in a fully-depleted state, and the gate voltage is gradually increased to apply a voltage above the threshold voltage in a partially-depleted state. Then it is turned on while changing to the accumulation state [4-6]. Since it is known to have the subthreshold behavior superior to that of a junction-based double gate MOSFET, many studies have been conducted as transistors capable of reducing the short-channel effect inevitably occurring in scale down [7-9]. In particular, the junctionless double-gate (JLDG) MOSFET has the advantage of operating in bulk conduction mode, unlike the junction-based double gates MOSFET where interface roughness scattering occurs by operating in surface conduction mode [10-11].

The junction-based double gate MOSFET mainly uses an undoped or low doping channel. However, the number of carriers in the channel results in a strange number of carriers of approximately $10^{15}/\text{cm}^3 \times 10^{-6} \text{ cm} \times 10^{-6} \text{ cm} \times 10^{-6} \text{ cm} = 10^{-3}$ if the volume of the channel decreases to $10 \text{ nm} \times 10 \text{ nm} \times 10 \text{ nm}$ at a constant doping concentration of about $10^{15}/\text{cm}^3$. In particular, it is difficult to form a pn junction between a source/drain doped at a high concentration and a channel doped at a low concentration as the channel length is shortened [12-13]. In the case of a JLDG MOSFET, the doping concentration in the channel is increased almost the same as the doping concentration of the source/drain, thereby minimizing the problem of the doping process occurring in the junction-based double gate as well as solving the irrationality of the number of impurities in the channel by doping the channel at a high concentration [14-15].

Many researchers have used a constant channel doping distribution to analyze the JLDG MOSFET [16-20]. However, it is impossible to maintain a constant doping distribution in the channel in the ion-implantation or diffusion process used for doping impurities in the actual MOSFET manufacturing [21]. In this study, we propose and analyze a subthreshold swing model of a JLDG MOSFET when the doping distribution in the channel is a Gaussian distribution function. Singh et al. used a Gaussian-like doping profile to avoid the difficulties of Gaussian function integration in order to analyze the threshold voltage of a JLDG FET [22]. In addition, Kumari et al. analyzed the subthreshold characteristics using the Gaussian doping profile, but only for transistors with a channel length greater than 30 nm [23]. Tiwari et al. analyzed the threshold voltage by applying a Gaussian doping profile to the channel of a junction-based double gate MOSFET [24]. The Tiwari's model for potential distribution in channel is modified in this study so that it can be applied to a JLDG MOSFET, and a reasonable subthreshold swing model, which can be used even when the channel length is more than 20 nm, is presented using Gaussian doping profile.

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The Gaussian doping profile determines the form of the distribution function according to the projected range and standard projected deviation. Therefore, the potential distribution function in the channel will change depending on the two variables, which will directly affect the subthreshold swing. Consequently, in this paper, we will consider the effect of the two variables on the subthreshold swing.

II. SUBTHRESHOLD SWING MODEL FOR JLDG MOSFET USING GAUSSIAN DOPING PROFILE

Figure 1. Schematic cross-sectional diagram of the junctionless double gate (JLDG) MOSFET with Gaussian doping profile in channel for $R_p=1.7$ nm and $\sigma_p=1.5$ nm, $N_p=10^{19}/\text{cm}^3$

Figure 1(a) shows a schematic diagram of a JLDG MOSFET used in this paper. The source and drain were doped with a highly doped n-type, and the channel was highly doped with n-type for no junction between the source/drain and the channel with a Gaussian doping profile having a peak doping concentration $N_p=10^{19}/\text{cm}^3$. The channel length is L_g , the silicon thickness is t_{si} , and the t_{ox} indicates the gate oxide film thickness. Figure 1 shows the doping distribution in the channel of a JLDG MOSFET with a channel length of 20 nm and a silicon thickness of 10 nm when the peak doping concentration is $10^{19}/\text{cm}^3$. The projected range is 1.7 nm and the standard projected deviation is 1.5 nm in the doping distribution of Fig. 1. It can be found that the doping concentration decreases rapidly as it reaches the bottom gate while showing the maximum doping concentration near the top gate.

Since this doping distribution will affect the potential distribution and electron transmission characteristics in the channel, we will analyze the subthreshold swing for the changes of the two variables of the Gaussian doping profile, i.e. the projected range R_p and the standard projected deviation σ_p .

First, the following Poisson equation and boundary conditions were used to obtain the potential distribution in the channel.

$$\frac{\partial^2 \phi(x, y)}{\partial x^2} + \frac{\partial^2 \phi(x, y)}{\partial y^2} = -\frac{qN(x)}{\epsilon_{si}} \quad (1)$$

$$\phi(x, y)|_{x=0} = \phi_s(y)$$

$$\frac{\epsilon_{ox}}{t_{ox}} (V_{gs} - V_{fb} - \phi(0, y)) = -\epsilon_{si} \frac{\partial \phi}{\partial x} \Big|_{x=0}$$

$$\frac{\epsilon_{ox}}{t_{ox}} (V_{gs} - V_{fb} - \phi(t_{si}, y)) = \epsilon_{si} \frac{\partial \phi}{\partial x} \Big|_{x=t_{si}}$$

$$\phi(0, 0) = V_{bi}$$

$$\phi(0, L_g) = V_{bi} + V_{ds}$$

Here, ϵ_{si} are the dielectric constants of silicon and ϵ_{ox} gate oxide, respectively, and SiO_2 is used as the gate oxide. The V_{gs} is a gate voltage, V_{fb} is a flat voltage, V_{ds} is a drain voltage, V_{bi} is a built-in potential, and $N(x)$ is a Gaussian doping profile that can be expressed as follows.

$$N(x) = N_p \exp(-\tau^2) \quad (2)$$

$$\tau = \frac{x - R_p}{\sqrt{2}\sigma_p}$$

The potential distribution function in the channel obtained by using Tiwari's method is as follows.

$$\phi(\tau, y) = V_{gs} - V_{fb} + G(\phi_s - V_{gs} + V_{fb}) \quad (3)$$

$$G = \frac{K - P\tau + \tau \text{erf}(\tau) + \exp(-\tau^2)/\sqrt{\pi}}{K - PB + \text{Berf}(B) + \exp(-B^2)/\sqrt{\pi}}$$

Where the constants K , P , and B denotes in Tiwari's paper.

The subthreshold swing is a measure of the change in the gate voltage when the drain current changes by one order in the subthreshold region and can be expressed as follows.

$$SS = \frac{\partial V_{gs}}{\partial (\log I_{ds})} = 2.3V_t \left[\frac{\partial \phi_{min}}{\partial V_{gs}} \right]^{-1} \quad (4)$$

Using Eq. (3) to find $\partial \phi_{min} / \partial V_{gs}$ in Eq. (4),

$$\frac{\partial \phi_{min}}{\partial V_{gs}} = 1 - D_1 G \exp\left(\frac{y_{min}}{\lambda}\right) - E_1 G \exp\left(-\frac{y_{min}}{\lambda}\right) \quad (5)$$

$$D_1 = \frac{\exp\left(-\frac{L_g}{\lambda}\right) - 1}{\exp\left(-\frac{L_g}{\lambda}\right) - \exp\left(\frac{L_g}{\lambda}\right)}, \quad E_1 = \frac{\exp\left(\frac{L_g}{\lambda}\right) - 1}{\exp\left(\frac{L_g}{\lambda}\right) - \exp\left(-\frac{L_g}{\lambda}\right)}$$

$$\lambda^2 = \sqrt{\pi} \sigma_p^2 \left(\frac{PB - K - \text{Berf}(B) - \exp(-B^2) / \sqrt{\pi}}{\exp(-B^2)} \right)$$

Here, the value of $\partial \phi_{min} / \partial V_{gs}$ can be obtained if $y = y_{min}$ value satisfying $\partial \phi(x_{eff}, y) / \partial y = 0$ is obtained and substituted into Eq. (5). The x_{eff} represents the effective conduction path. If the channel has a constant doping concentration, most electrons move through the central path of the channel in the case of a symmetrical junctionless accumulation MOSFET; however, in the case of a Gaussian doping profile, the conduction path x_{eff} will change according to the projected range and standard projected deviation. In this paper, assuming that the drain current is in proportion to the electron concentration, $n_{min} = N_p \exp(\phi_{min} / V_t)$, of the effective conduction path, and assuming the Boltzmann distribution, the effective conduction path x_{eff} was derived using the following equation [25].

$$x_{eff} = \int_0^{t_{si}} x n(x, y_{min}) dx / \int_0^{t_{si}} n(x, y_{min}) dx \quad (6)$$

The potential distribution obtained using Eq. (3) is indicated in Fig. 2. Even in the case of a double gate MOSFET having a symmetrical structure as shown in Fig. 2, it can be seen that the potential distribution is changed according to R_p and σ_p of the Gaussian doping profile. This change in potential distribution will cause a change in conduction path. The effective conduction path is defined as the position when the value of ϕ_{min} is the maximum [26]. The point indicated by the horizontal line in Fig. 2 is the effective conduction path by definition. As expected, it can be seen that the effective conduction path changes according to changes in the projected range and the standard projected deviation. The ratio of y_{min} to the

channel length and x_{eff} to silicon thickness are shown in Table 1.

The position of y_{min} does not show a large change according to the changes of the projected range and the standard projected deviation, but it can be observed that the value of the effective conduction path x_{eff} shows a large change as can be seen from Table 1.

Figure 2. Contours of potential distributions for channel length and silicon thickness of the symmetric JLDG MOSFET. The horizontal lines indicate the conduction paths having maximum potential at y_{min} .

TABLE I.
THE y_{min}/L_g AND x_{eff}/t_{si} FOR THE PROJECTED RANGE AND STANDARD PROJECTED DEVIATION

R_p (nm)	σ_p (nm)	y_{min}/L_g	x_{eff}/t_{si}
1.5	1.5	0.496	0.245
1.5	3	0.496	0.348
3	1.5	0.490	0.358
3	3	0.494	0.416

As such, the effective conduction path changes with changes in the projected range and standard projected deviation, so the subthreshold swing will be affected by these two parameters.

The effective conduction path obtained using Eq. (6) is shown in Fig. 3 as a contour graph for changes in the projected range and standard projected deviation. The internal numbers in Fig. 3 show the ratio of the channel thickness and distance of the effective conduction path from the top interface. That is, x_{eff}/t_{si} . As shown in Fig. 3,

the conduction path also increases as the projected range and the standard projected deviation increase.

This indicates that the conduction path faces inside. As the conduction center moves away from the top interface, the control ability for electrons in the channel due to the gate voltage decreases. Thus, the subthreshold swing will increase [27].

Due to the characteristics of the Gaussian doping profile, the average doping amount will be more affected by the standard projected deviation than the projected range if the peak doping concentration is the same. This relationship is shown in Fig. 4 when the peak doping concentration is $N_p=10^{19}/\text{cm}^3$.

Figure 3. Contours of effective conduction path x_{eff}/t_{si} for the projected range and standard projected deviation in the case of $L_g=20$ nm, $t_{si}=10$ nm, and $t_{ox}=2$ nm.

As shown by the blue line in Fig. 4(a), the average doping amount is almost constant when the $\sigma_p=1.5$ nm and the projected range changes; however, the average doping amount increases significantly when the standard projected deviation changes. As shown by the red line in Fig. 4(a), when the standard projected deviation is increased to $\sigma_p=3$ nm, it can be seen that the average doping amount is significantly increased. It was also observed that the average doping amount was significantly increased in the case of $R_p=3$ nm as shown in Fig. 4(b). Comparing Figs. 4(a) and 4(b), the average doping amount is more sensitive to changes in the standard projected deviation than changes in the projected range. In the double-gate MOSFET, as the doping amount increases, the subthreshold swing decreases.

Therefore, the change in the subthreshold swing due to the change in the doping amount as well as the change of the conduction path due to the change of the standard projected deviation should be considered. In other words, as shown in Fig. 3, an increase in the standard projected deviation causes an increase in x_{eff} , which decreases the control ability of the conduction electrons by the gate voltage.

Figure 4. Mean doping concentration for the change of (a) projected range and (b) standard projected deviation in the case of $L_g=20$ nm, $t_{si}=10$ nm, $t_{ox}=2$ nm, and $N_p=10^{19} \text{ cm}^{-3}$

The subthreshold swing, thus, will eventually increase, but the average doping amount increases to decrease the subthreshold swing. As a result, the effect of changing of the standard projected deviation on the subthreshold swing will be very complicated.

In summary, the projected range and standard projected deviation, which are the parameters of the Gaussian doping profile, will have a great effect on the conduction path and mean doping concentration, and eventually become variables in the subthreshold swing. Among the two variables, the change of conduction path and mean doping concentration by standard projected deviation is more severe, so it can be predicted that the subthreshold swing will also change more severely by standard projected deviation.

III. ANALYSIS OF SUBTHRESHOLD SWING FOR JLDG MOSFET WITH GAUSSIAN DOPING PROFILE

Figure 5. Comparison of subthreshold swings of this model with the results of TCAD

First, in order to verify the validity of Eq. (4) presented in this paper, the TCAD results of other paper [28] were compared with those of this model in Fig. 5. A channel length of 20 nm or more was used, silicon thickness was 10 nm, gate oxide thickness was 2 nm, and peak doping concentration was $10^{19}/\text{cm}^3$. It can be seen that the specific values of the projected range and the standard projected deviation considered in this paper can be matched with the case of using a constant doping concentration. Therefore, it is considered that the model of Eq. (4) presented in this paper is valid. Looking at the results in Fig. 5, the value of the subthreshold swing induced almost the same result even if the values of the projected range and the standard projected deviation increased simultaneously.

Figure 6. Contours of subthreshold swing for the projected range and standard projected deviation in the case of $L_g=20$ nm, $t_{si}=10$ nm, and $t_{ox}=2$ nm

When the values of the projected range and the standard projected deviation increase at the same time, the effective conduction path moves inside, and the subthreshold swing can increase. The effect of decreasing the subthreshold swing occurs as the doping amount increases due to the increase of the standard projected deviation, and thus the nearly same subthreshold swing value is shown.

As described, the projected range and standard projected deviation have a great influence on the subthreshold swing. Figure 6 shows the contour graph of the subthreshold swing for changes in projected range and standard projected deviation. As shown in Fig. 6, it can be observed that the standard projected deviation of 1.5 nm above has excellent subthreshold swing value of less than 100 mV/dec when the projected range is less than 2 nm. In addition, it can be found that the subthreshold swing value increases significantly as the projected range increases. It can be seen that the subthreshold swing significantly changes with the change of the projected range when the standard projected deviation is relatively small with 1.5 nm; it has almost constant value regardless of the change in the projected range when the standard projected deviation increases to 3 nm. The large standard projected deviation in the Gaussian doping profile is similar to the uniform doping profile in the end. A large standard projected deviation, thus, should be used even if the effective conduction path is directed inward. That is, the doping profile shows a wide spreading if the standard projected deviation is large and the subthreshold swing value can be kept low if the projected range value is kept small so that the peak doping concentration value is formed near the top gate. Since the Gaussian doping profile represents the doping distribution in the vertical direction, the doping profile will be greatly affected by the vertical thickness of silicon.

Figure 7. Contours of subthreshold swing for the projected range and standard projected deviation in the case of $L_g=20$ nm, $t_{ox}=2$ nm, (a) $t_{si}=7$ nm and (b) $t_{si}=5$ nm

Figure 7 shows the contour graph of the subthreshold swing for the changes in the projected range and the standard projected deviation when the silicon thickness is 5 nm and 7 nm. As shown in Fig. 7, the subthreshold swing decreased as the silicon thickness decreased. As the thickness of silicon decreases, the area where the subthreshold swing is smaller than 100 mV/dec increases. It can be seen that the subthreshold swing is 100 mV/dec or less at the most region calculated when silicon thickness decreases to 5 nm, in the region of $1.5 \text{ nm} \leq R_p \leq 3 \text{ nm}$ and $1.5 \text{ nm} \leq \sigma_p \leq 3 \text{ nm}$.

Figure 8 shows the change in the subthreshold swing for the projected range with silicon thickness as a parameter when the channel length is 20 nm, the gate oxide thickness 2 nm, the peak doping concentration $10^{19} / \text{cm}^3$, and $\sigma_p=1.5$ nm and $\sigma_p=3$ nm in order to examine the change of the subthreshold swing in more detail with respect to changes in the projected range and the standard projected deviation. As shown in Fig. 8(b), there was little change in subthreshold swing due to changes in silicon thickness and projected range, and the subthreshold swing was maintained below 100 mV/dec when $\sigma_p=3$ nm. The reason for this is that the average doping amount increases as described above and it approximates the uniform doping profile when the standard projected deviation is large. Particularly, it can be observed that the subthreshold swing is not affected by the projected range due to its more uniform doping profile at $\sigma_p=3$ nm when the silicon thickness is reduced to about 6 nm.

However, it can be observed from Fig. 8(a) that the variation of the subthreshold swing according to the projected range and silicon thickness is very large when $\sigma_p=1.5$ nm.

Figure 8. Subthreshold swing for the projected range with silicon thickness as a parameter in the case of $L_g=20$ nm and $t_{ox}=2$ nm

When the standard projected deviation is small, the doping profile is very narrow; not only does the average doping amount decrease, but also the doping distribution will change greatly depending on the projected range. Thus, the subthreshold swing also changes significantly and it also changes significantly depending on the silicon thickness.

The change in the subthreshold swing according to the silicon thickness was hardly observed in the region where the projected range was small at $\sigma_p=1.5$ nm. The reason for this is that the effective conduction path is located close to the top gate in the region where the projected range and standard projected deviation are small regardless of the thickness of silicon as shown in Fig. 3. Thus, the gate voltage has a large control ability for channel electrons. The effective conduction path, however, is directed into the channel when the projected range is increased at $\sigma_p=1.5$ nm. Thus, the electron control ability of the gate voltage decreases and eventually the subthreshold swing increases significantly. It can be observed from Fig. 8(a) that this effect is larger as the silicon thickness increases.

Figure 9 shows the change in the subthreshold swing for the standard projected deviation with the silicon thickness as a parameter when the channel length is 20 nm, the gate oxide thickness is 2 nm, the peak doping concentration is $10^{19} / \text{cm}^3$ in the case of $R_p=1.5$ nm and $R_p=3$ nm.

When the projected range is small, such as $R_p=1.5$ nm, the effective conduction path increases as shown in Fig. 3 in proportional to the standard projected deviation; however, it can be seen that the subthreshold swing does not increase greatly because it is relatively close to the top gate. As shown in Fig. 4, the effect of decreasing the subthreshold swing due to the increased doping amount coexists.

Figure 9. Subthreshold swing for the standard projected range with silicon thickness as a parameter in the case of $L_g=20$ nm, $t_{ox}=2$ nm

As a result, as shown in Fig. 9(a), the subthreshold swing caused by the change of the standard projected deviation was kept low, and the change was almost negligible. It can be seen that this shows the same effect even when the silicon thickness is changed. The effective conduction path increases and the subthreshold swing will increase significantly when the projected range is large, such as in the case of $R_p=3$ nm. The reason for this is that the effective conduction path is relatively far away from the top gate. However, it can be seen that the subthreshold swing tends to decrease as the doping amount increases significantly as shown in Fig. 4 and Fig. 9, inversely proportional to the standard projected deviation. That is, in this case, it can be seen that the effect of increasing the doping amount is greater than the effect of the effective conduction path moving inside.

In summary, since the Gaussian doping distribution varies vertically from the top gate to the bottom gate, it changes with the silicon thickness as well as the projected range and standard projected deviation.

However, when the standard projected deviation is increased, the vertical doping distribution is almost constant regardless of the projected range, so the change in the subthreshold swing according to the silicon thickness hardly occurs. Also, when the projected range is small, the controllability of the gate voltage to the channel electrons increases, so the change in the subthreshold swing was hardly observed regardless of the standard projected deviation and the silicon thickness.

IV. CONCLUSIONS

In this paper, the change of the subthreshold swing was investigated according to the changes in the projected range and the standard projected deviation when the Gaussian doping profile is applied to the channel of a JLDG MOSFET. To this end, an analytical subthreshold swing model was proposed using a potential distribution model derived from the Poisson's equation. This model agrees well with the two-dimensional simulation values. When the projected range and the standard projected deviation are small, the effective conduction path is close to the top gate. Thus, the subthreshold swing is reduced. In addition, the subthreshold swing remained low and was hardly affected by the change in silicon thickness when the projected range was small and the standard projected deviation was large. In particular, the subthreshold swing was maintained at a constant low value regardless of the change in the standard projected deviation when the projected range was small. In the case where the standard projected deviation was large, the subthreshold swing was maintained at a constant low value regardless of the change in the projected range. As a result, in the JLDG MOSFET with Gaussian doping profile, it was found that the subthreshold swing changes with the effective conduction path and the average doping amount according to the change of the projected range and the standard projected deviation.

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