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Investigation of Random Dopant Fluctuation for Multi-Gate MOSFETs Using Analytical Solution of 3-D Poisson's Equation

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Introduction

Due to its better gate control, multi-gate structure is an important candidate for CMOS scaling. Dependent on the aspect ratio (AR), FinFET (AR>1), Tri-gate (AR=1) and quasi-planar (AR<1) devices are typical options in the multi-gate design. Whether there is an optimum choice among the three options merits investigation. With the scaling of device geometry, the impact of random dopant fluctuation becomes crucial to the threshold voltage (V_{th}) dispersion. Although A. Thean et al. [1] has examined the V_{th} variation of FinFET devices with various fin width experimentally, a detailed analysis of the random dopant fluctuation in multi-gate MOSFETs has rarely been seen. In this work, we investigate the V_{th} dispersion caused by the random dopant fluctuation among FinFET, Tri-gate and quasi-planar devices using analytical solutions of 3-D Poisson's equation [2]. Through our theoretical model, the impact of device aspect ratio on the random dopant fluctuation in multi-gate MOSFETs is examined.

Methodologies

Fig. 1 shows the schematic sketch of a multi-gate SOI structure. Based on the procedure shown in Fig. 2(a), the V_{th} of FinFET, Tri-gate and quasi-planar devices can be derived. Using the principle of superposition, the channel potential distribution ϕ, which satisfies the 3-D Poisson's equation, can be obtained by the solutions of 1-D, 2-D and 3-D sub-problems (Fig. 2(b)). Subthreshold current can be calculated from the potential solution, and the V_{th} can be derived using the calculated subthreshold current.

We assume that the dopant number in the channel follows the Poisson distribution [3] and the standard deviation (σ) of dopant number is $n_a^{1/2}$, where n_a is the average dopant number in the channel. We define the ΔV_{th} by the difference between V_{th} of devices with the dopant numbers $\pm 3\sigma$. For a given total width ($=2H_{fin}+W_{fin}$), multi-gate devices with three different aspect ratio are examined (Fig. 3). Besides, gate oxide (t_{ox}=1nm) is used for heavily doped devices (6×10^{18} cm^{-3}), while high k dielectric (t_{HfO2}=2nm) is used for lightly doped cases (1×10^{17} cm^{-3}) to sustain the device electrostatics [4].

Results and Discussion

Fig. 4 shows the AR dependence of ΔV_{th} caused by random dopant fluctuation for the heavily doped channel, and the results are verified with device simulation [5]. For heavily doped channel, the ΔV_{th} increases with the device AR, and the minimum ΔV_{th} occurs at AR=0.5, i.e. quasi-planar device. This is because for a given total width, devices with AR=0.5 possesses the largest channel volume (Fig. 5). Besides the volume, the V_{th} sensitivity to the channel doping also influences the ΔV_{th}. Fig. 6 shows the channel doping dependence of V_{th} for devices with heavily doped channel. FinFET, Tri-gate and quasi-planar devices show similar V_{th} sensitivity. Therefore, for heavily doped channel, quasi-planar device shows the best immunity to random dopant fluctuation than FinFET and Tri-gate because of its larger channel volume.

Fig. 7 shows that for lightly doped channel, the ΔV_{th} increases with decreasing AR. This is because for lightly doped channel, devices with different AR show different V_{th} sensitivities to channel doping (Fig. 8). For lightly doped channel, FinFET shows the smallest sensitivity to the channel doping because of its narrower W_{fin} for a given total width. In other words, W_{fin} scaling enhances the gate control and reduces the V_{th} dependence on the channel doping. Therefore, FinFET shows the best immunity to the random dopant fluctuation for lightly doped channel.

In Fig. 9, we calculate the proportion of ΔV_{th} caused by the random dopant fluctuation to the total V_{th} dispersion including L_{eff} variation, W_{fin} variation, doping level variation and random dopant fluctuation [6]. For heavily doped channel (Fig. 9(a)), random dopant fluctuation dominates the overall V_{th} dispersion, and the quasi-planar device shows better immunity than other structures to random dopant fluctuation. Lightly doped channel has been suggested [7] to suppress the V_{th} variation caused by random dopant fluctuation. However, Fig. 9(b) shows that the V_{th} variation caused by random dopant fluctuation is still significant for lightly-doped Tri-gate and quasi-planar devices.

Conclusions

We have investigated the V_{th} dispersion caused by random dopant fluctuation of multi-gate MOSFETs using analytical solutions of 3-D Poisson's equation verified with device simulation. Especially, we analyze the impact of aspect ratio on the random dopant fluctuation in multi-gate devices. With a given total width, lightly doped FinFET shows the smallest V_{th} dispersion because of its smaller V_{th} sensitivity to the channel doping. For heavily doped devices, quasi-planar device shows smaller V_{th} dispersion because of its larger channel volume. The V_{th} dispersions caused by random dopant fluctuation may still be significant in the lightly doped channel, especially for Tri-gate and quasi-planar devices.

Acknowledgement

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References

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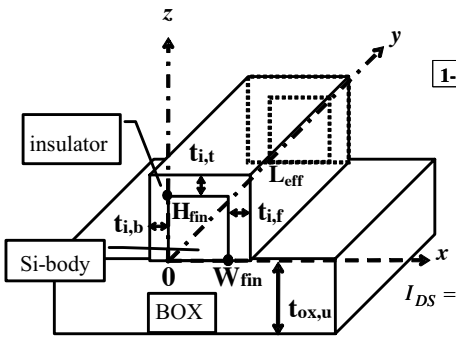
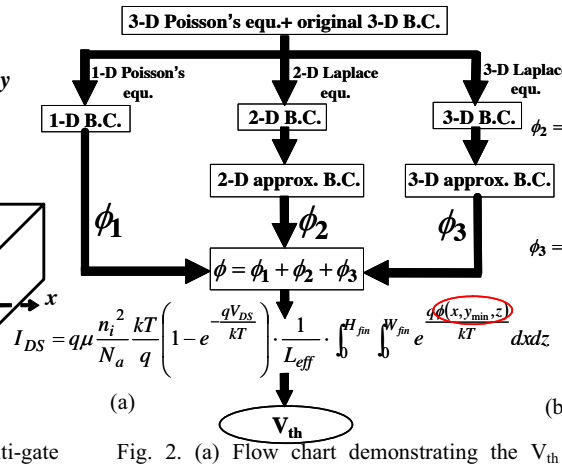


Fig. 1. The schematic sketch of a multi-gate device structure.



$$\phi = \phi_1 + \phi_2 + \phi_3$$

$$\phi_1 = -\frac{qN_d}{2\varepsilon_{si}}x^2 + ax + b$$

$$\phi_2 = \sum_{i=1}^{\infty}\left\{\left[c\sinh\left(\frac{i\pi}{W_{eff}}z\right) + c'\sinh\left(\frac{i\pi}{W_{eff}}(W_{eff}-z)\right)\right]\cdot\sin\left(\frac{i\pi}{W_{eff}}x\right)\right\}$$

$$\phi_3 = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\left\{\left[e\sinh(k_y y) + e'\sinh(k_y(L-y))\right]\cdot\sin\left(\frac{m\pi}{W_{eff}}x\right)\sin\left(\frac{n\pi}{H_{eff}}z\right)\right\}$$

$$W_{eff} = W_{fin} + \frac{\varepsilon_{si}}{\varepsilon_i}(t_{i,f} + t_{i,b})$$

$$H_{eff} = H_{fin} + \frac{\varepsilon_{si}}{\varepsilon_i}t_{i,t} + t_{ox,u}$$

(b)

Fig. 2. (a) Flow chart demonstrating the V_{th} calculation of multi-gate devices. Approximation was made to simplify the 2-D and 3-D boundary conditions (B.C.) to obtain a simplified potential solution form. (b) The solution form for the channel potential distribution.

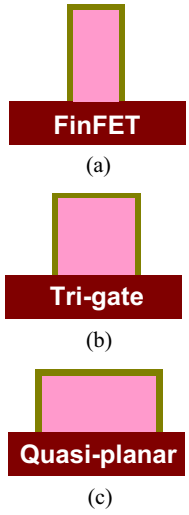


Fig. 3. Illustration of three different AR devices for a given total width: (a) FinFET (AR=2), (b) Tri-gate (AR=1), and (c) quasi-planar device (AR=0.5).

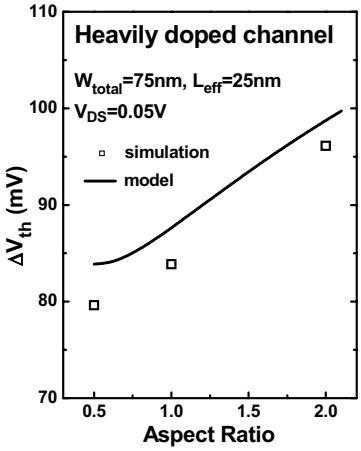


Fig. 4. The AR dependence of ΔV_{th} caused by random dopant fluctuation in the heavily doped channel.

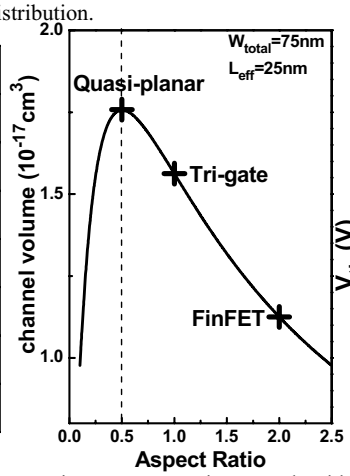


Fig. 5. For a given total width, devices with AR=0.5 possess the largest channel volume. Devices with larger channel volume will show less doping variation caused by the random dopant fluctuation.

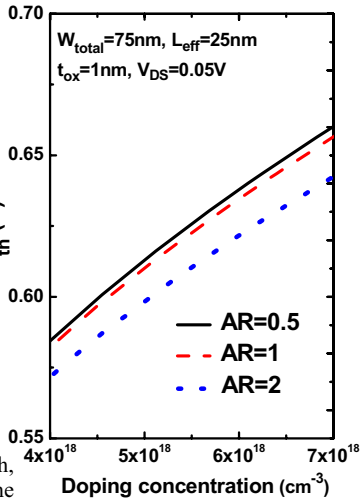


Fig. 6. Model prediction of the doping dependence of V_{th} for heavily doped channel with the same total width.

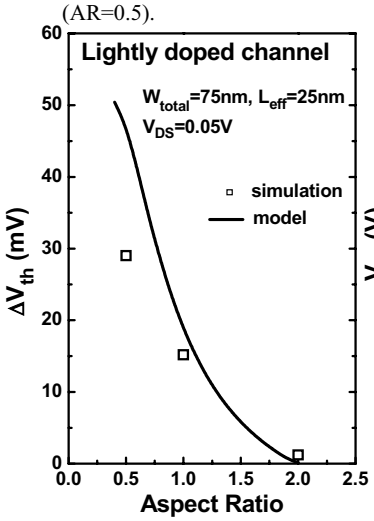


Fig. 7. The AR dependence of ΔV_{th} caused by random dopant fluctuation in the lightly doped channel.

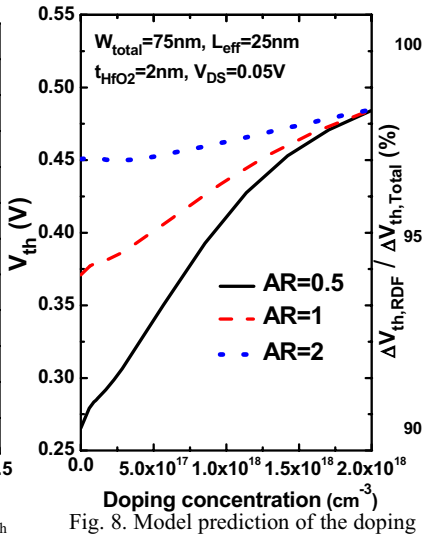


Fig. 8. Model prediction of the doping dependence of V_{th} for lightly doped channel with the same total width.

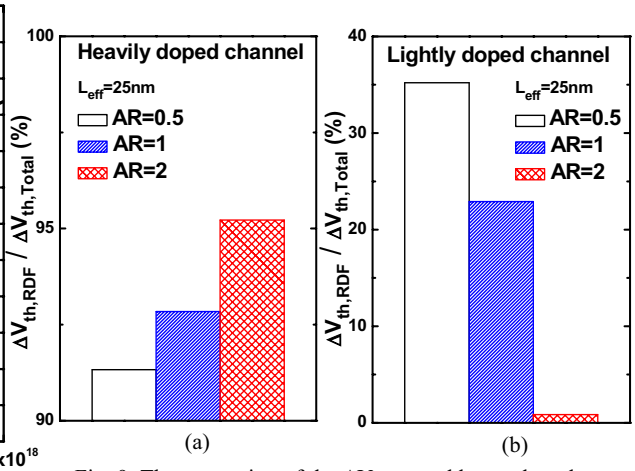


Fig. 9. The proportion of the ΔV_{th} caused by random dopant fluctuation to the overall ΔV_{th} for (a) Heavily doped channel and (b) Lightly doped channel. The overall ΔV_{th} includes L_{eff} variation, W_{fin} variation, doping level variation and random dopant fluctuation.