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Suppressed short-channel effect of DG-MOSFET and its modeling

Hideki Oka[1], Ryo Tanabe[1], Norio Sadachika[2], Akihiro Yumisaki[2] and Mitiko Miura-Mattausch[2]

[1]Fujitsu Laboratories Ltd.
50 Fuchigami, Akiruno, Tokyo 197-0833, Japan
Phone: +81-42-532-1439 E-mail: oka.hideki@jp.fujitsu.com
[2]Graduate School of Advanced Sciences of Matter, Hiroshima University
1-3-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8530, Japan

1. Introduction

Double gate (DG) MOSFET is considered to be a promising candidate for next 32nm technology node [1] due to its enhanced suppression of the short-channel effect. Here a development of the compact model for circuit simulation is a key for investigating advantages of the new device.

Developing three essential effects is prerequisite in the DG-MOSFET model; the quantum mechanical effect, the volume-inversion effect and the short-channel effect. We concentrate here on modeling of the short-channel effect, where the influence of the quantum mechanical effect is found to be not obvious in comparison to the volume inversion effect. The reason is that the quantum mechanical effect is not a function of the channel length directly. Whereas the volume-inversion effect is caused by the vertical field distribution, which modifies the lateral electric field, the cause of the short-channel effect. It is proved that the developed model reproduces the suppressed short-channel effect of the DG-MOSFET as a function of the silicon layer thickness Tsi of down to 10nm.

2. Device structure and Its Feature

We studied a DG-MOSFET structure shown in Fig. 1 with a symmetrical N+ double gate and p-type substrate. Tox is fixed to 1.5nm and impurity concentration of 5e18/cm$^{3.}$

The volume inversion occurs, when carrier distributions from both gates start to overlap. Fig. 2 shows carrier and potential distributions to the vertical to the surface for Tsi of 50nm, 20nm and 10nm, and the gate voltage Vgs is fixed to 1V. Schred2.0[2] is applied. Fig. 2a is without the quantum mechanical effect and Fig. 2b is with the effect. A clear feature of the DG-MOSFET is the carrier existence in the channel middle with reduced Tsi. This is the volume inversion causing the potential reduction in the channel middle. This feature is not changed either with or without the quantum mechanical effect.

Fig. 3 shows the potential difference ΔEc at the surface and in the channel middle. For comparison the case with the substrate impurity concentration of 1e17/cm^3 is depicted together. With reduced concentration both depletion layers extend deeply into the channel resulting in stronger volume inversion with reduced potential difference.

3. Modeling of the Short-Channel Effect (SCE)

Fig. 4 shows simulation results of the threshold voltage as a function of the gate length Lg with a 2D-device simulator for various Tsi thicknesses with and without the quantum mechanical effect. SCE is determined by threshold voltage shift from a long Lg case: ΔVth =Vth(Lg)-Vth(Long). As shown in Fig. 5, the difference between the results with and without the quantum mechanical effect is nearly negligible.

For modeling the short-channel effect, the Gauss law is applied to a small square in the depletion region in a similar way as the conventional bulk-MOSFET [3]. Fig. 6 shows a schematic of the treatment. From the Gauss law, ΔVth is

$$.\ \Delta Vth = W_d \frac{\varepsilon_{Si}}{C_{ox}} \frac{dE_y}{dy} \tag{1}$$

where Wd is the depletion layer thickness and E_y is the electric field along the channel direction.

This derives that the lateral field gradient causes the threshold voltage reduction. Here the field gradient at the end of the depletion region (along B-C in Fig. 6) is fixed to zero. If Wd exceeds Tsi/2, Wd is replaced by Tsi/2. Wd of the studied case is about 16nm. Calculation results with the equation are compared with the 2D simulation results in Fig. 7 by solid lines. The calculated results overestimate SCE under the volume inversion condition (solid lines).

If the integration along B-C in Fig. 6 is not neglected, Eq. (1) is written

$$\Delta Vth = \frac{T_{Si}}{2} \frac{\varepsilon_{Si}}{C_{ox}} \frac{dE_y}{dy} - E_{x'} \frac{\varepsilon_{Si}}{C_{ox}} \tag{2}$$

where $\varepsilon_{Si} E_{x'}$ gives the charge in the channel middle giving the volume inversion condition. Eq. (2) is rewritten

$$\Delta Vth = \left(\frac{Tsi}{2} \frac{\varepsilon_{Si}}{C_{ox}} - E_{x'} \frac{\varepsilon_{Si}}{C_{ox}} \frac{dy}{dE_y} \right) \frac{dE_y}{dy} \tag{3}$$

The existing of the charge in the channel center prevents carriers from further extension deep into the channel center due to the conventional lateral electric field contribution. This results in suppression of SCE.

Modeling the charge density $\varepsilon_{Si}E_{x'}$ is done by approximating a quadratic potential distribution perpendicular to the surface. The charge density in the channel middle is expected to be Lg dependent and is approximated to be compensated by dy/dEy. Thus the final equation is written

$$\Delta Vth = \left(\frac{Tsi}{2} \frac{\varepsilon_{si}}{C_{ox}} - VOLINV * E_{x'} \frac{\varepsilon_{Si}}{C_{ox}} \right) \frac{dE_y}{dy} \tag{4}$$

where VOLINV is treated as a model parameter. Calculation results with the improved model is depicted in Fig. 7 together. For any Tsi and Lg the model can reproduce the ΔVth -Lg characteristics well.

4. Conclusion

We have developed a model for the short-channel effect of the symmetrical DG-MOSFET. The model is proved to be applicable for Tsi down to 10nm with Lg of 25nm.

References

[1] ITRS : http://public.itrs.net/

[2] *Schred2.0 Manual,* Arizona State University

[3] *HiSIM 1.1.0 User's Manual,* Hiroshima University and STARC, 2002

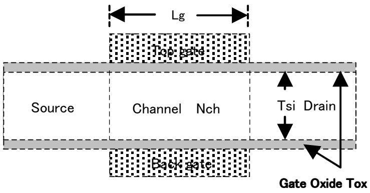

Fig. 1. Schematics of the studied double-gate MOSFET.

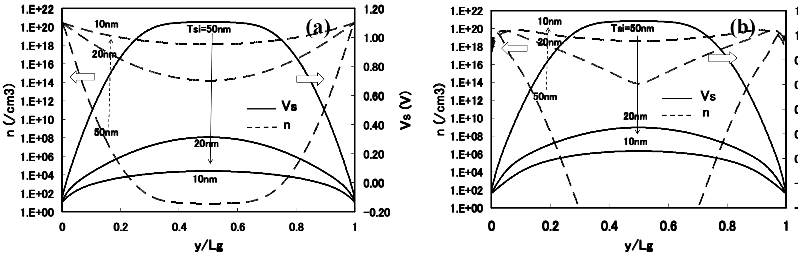

Fig. 2. Simulated carrier distributions (dashed lines) and potential distributions (solid lines) vertical to the channel surface with Schred2.0, solving the Schroedinger equation and the Poisson equation simultaneously [2]: (a) without the quantum mechanical effect, and (b) with the effect.

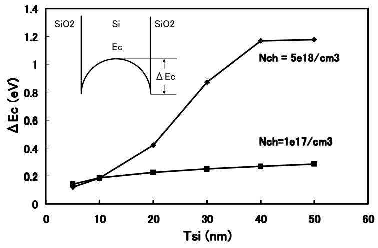

Fig. 3. Potential difference (ΔEc) between the surface and the channel middle of the vertical direction to the channel as a function of the silicon layer thickness Tsi. Two different impurity concentrations Nch, 5e18/cm^3 and 1e17/cm^3, are compared.

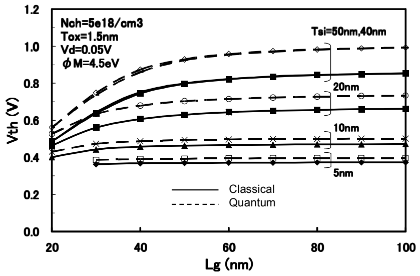

Fig. 4. Simulated threshold voltage Vth as a function of the gate length Lg for with the quantum mechanical effect (dashed lines) and without the effect (solid lines).

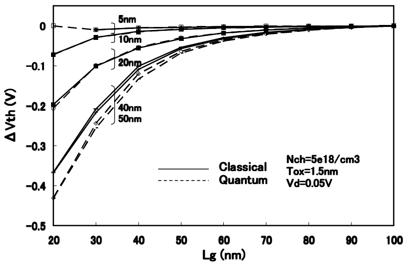

Fig. 5. Simulated threshold voltage shift Delta Vth from a long channel case (Lg=100nm). Dashed lines show results with the quantum mechanical effect and solid lines show results without the effect.

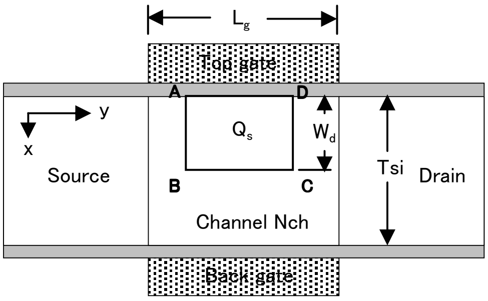

Fig. 6. Modeling approach of the short-channel effect. The Gauss law is applied in the square depicted by ABCD. The BC line is fixed to the channel middle.

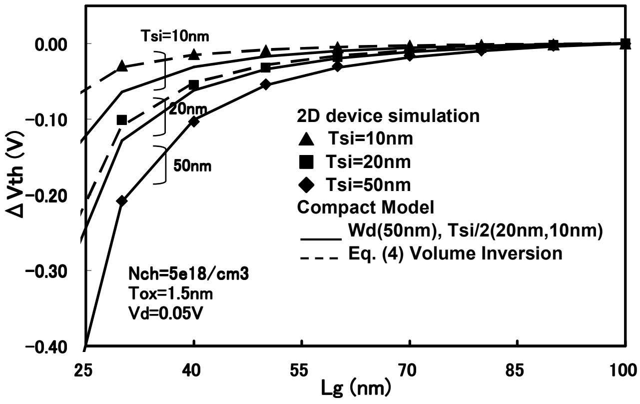

Fig. 7. Comparison of calculation results with the developed model to simulation results (symbols) Solid lines show the results without the volume-inversion contribution, and dashed lines show those with the contribution.