Extended Abstracts of the 2005 International Conference on Solid State Devices and Materials, Kobe, 2005, pp.594-595

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Comparison of Random Dopant-Induced Threshold Voltage Fluctuations in Nanoscale Single-, Double-, and Surrounding-Gate Field Effect Transistors

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1. Introduction

Nanoscale single-, double-, and surrounding-gate (SG, DG, and AG) metal-oxide-semiconductor field effect transistors (MOSFETs) have recently been of great interests from device structure point of view. Threshold voltage fluctuation of these devices is crucial for the integrated circuit design [1-6]. To explore the fluctuation-related issues, Monte Carlo simulation and small signal analysis of transport equations have been applied. Numerical solution of the Schrödinger-Poisson equations and Monte Carlo simulation are computationally expensive [2,3,6]. These approaches are physically accurate, but they are not convenient for TCAD application.

In this paper, we explore random dopant-induced threshold voltage fluctuations by solving quantum correction model. Fluctuation of threshold voltage of three nanoscale transistors, the SG, DG, and AG (MOSFETs) are computationally compared [7]. To calculate the variance of the threshold voltage of nanoscale MOSFETs, quantum correction model at equilibrium conditions is expanded and solved with perturbation technique. Fluctuations of threshold voltage resulting from the random dopant, variations of silicon film thickness, and the device gate length are obtained. It is found that the AG FET has smallest fluctuation of threshold voltage among three device structures. Compared with quantum Monte Carlo approach and small signal analysis of the Schrödinger-Poisson equations, this approach shows good accuracy and computational efficiency, and is ready for TCAD application.

2. Simulation Methodology

In this paper, we numerically calculate the threshold voltage fluctuation of nanodevices by solving the quantum correction model. Application of perturbation technique to quantum transport model at equilibrium conditions, we first approximate the model over a device structure, as shown in shown in Fig. 1. The approximated system of nonlinear algebraic equations is solved with the monotone iterative method. Thus, the variance of the threshold voltage of nanoscale FETs is calculated with respect to different physical quantities, such as the random dopant, variations of silicon film thickness, and the device gate length. Different quantum correction models, the Hänsch model and the model proposed in our recent work [4-5] are adopted to perform the quantum correction to classical electron density. We solve the explicit quantum correction models so that the fluctuation of threshold voltage can be immediately calculated through the perturbation of classical nonlinear Poisson equation. Thus, the variance of threshold voltage σ^2_{Vth}, i.e., the fluctuation of threshold voltage, is computed by assuming that the doping concentration are independent random variables at each mesh point (x_i,y_j) for all i and j [1]. We note that the Schrödinger-Poisson- and density-gradient-based quantum mechanical approaches require the numerical solution of nonlinear partial differential equations and the solution of eigenvalue problem. In contrast to these approaches, our approach of quantum correction models is of the first order accurate and is explicit so that the fluctuation of physical quantity can be immediately calculated through the perturbation and solution of classical nonlinear Poisson equation. Computation of this approach is cost-effective and has successfully been implemented into our nanodevice simulation prototype.

3. Results and Discussion

We first calculate the standard derivation versus the level of dopant for the SG, DG, and AG FETs. The standard deviation σ_{Vth} of threshold voltage versus the doping level is shown in Fig. 2. As shown in Fig. 2, both the classical (CL) and quantum (QM) corrected models predict that the standard derivation increases when the doping level increases. For the SG FET, there is about 20% difference between two CL and QM calculations under dopant level $1x10^{18}cm^{-3}$. It is a direct result from the quantum confinement effect in the nanoscale MOSFETs. The calculated σ_{Vth} with quantum correction is higher than that of classical result; it is because that the quantum confinement of electron enlarges the oxide thickness and shifts up the result of σ_{Vth}. The difference increases when the dopant level increases because the shift of peak electron density is significant and fluctuated. Among three device structures, the AG FET shows the most stable and smallest fluctuation of threshold voltage. One of the important reasons is that the AG FET has the best channel controllability among the SG, DG, and AG FETs [7].

To reduce the fluctuation of threshold voltage one should decrease the level of doping, which should compromise with the variation of the thickness of silicon film T_{si}, shown in Fig. 3. Fig. 3 suggests that the fluctuation of threshold voltage is proportional to the variation of the thickness of T_{si}. σ_{Vth} increases when T_{si} increases. The fluctuation of threshold voltage of SG FET is significant, compared with the DG and AG FETs. According to Figs. 2 and 3, there is a compromise between the doping level and the thickness of silicon film when reducing the σ_{Vth}. As shown in Fig. 4, we verify the σ_{Vth} with respect to the device length L. The σ_{Vth} decreases when the device length L increases for three device structures. Figure 5 shows the σ_{Vth} with respect to the oxide thickness T_{ox}. The AG FET shows smallest fluctuation among structures.

4. Conclusions

Random dopant-induced threshold voltage fluctuations are calculated by solving quantum correction model for nanoscale SG, DG, and AG FETs. Fluctuations of threshold voltage resulting from the random dopant, variations of silicon film thickness, and the device gate length are obtained. AG FET has shown good channel controllability and smallest threshold voltage fluctuation among device structures. Compared with quantum Monte Carlo approach and small signal analysis of the Schrödinger-Poisson equations, this approach shows good accuracy and

computational efficiency, and is ready for TCAD device simulation. This novel approach can apply to explore other physical quantities.

Acknowledgement

This work is supported in part by the National Science Council of Taiwan under Contract NSC-93-2215-E-429-008 and Contract NSC-94-2752-E-009-003-PAE, and by the Ministry of Economic Affairs, Taiwan under Contract 93-EC-17-A-07-S1-0011.

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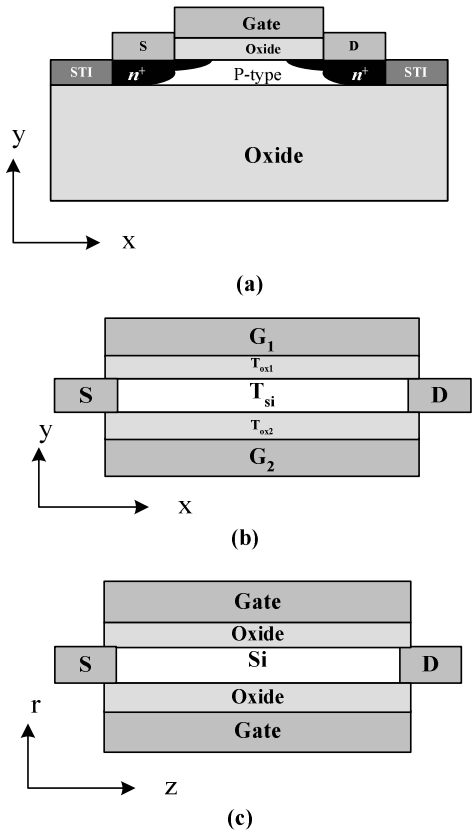

Figure 1. The three investigated nanoscale (a) SG, (b) DG, and (c) AG MOSFETs. The SG and DG MOSFETs are solved in the rectangular coordinates. The AG FET is solved in cylindrical coordinates.

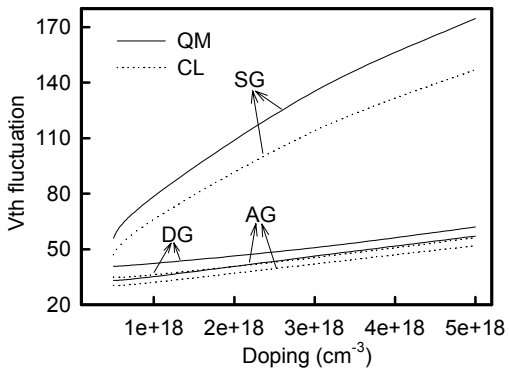

Figure 2. Plot of the standard deviation of the threshold voltage versus the doping level for the investigated SG, DG and AG MOSFETs, where T_{ox} = 1.5 nm, T_{si} = 30 nm and L = 30 nm.

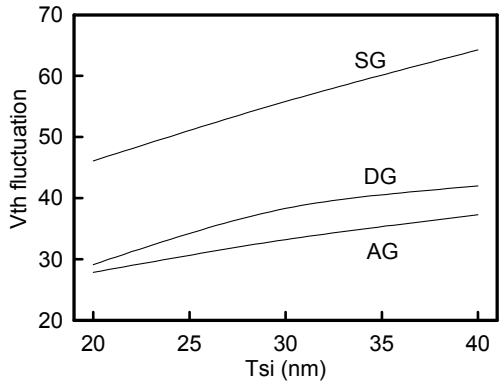

Figure 3. Standard deviation of the threshold voltage versus T_{si} where T_{ox} = 1.5 nm, N_A = 5e17 cm^{-3} and L = 30 nm. This calculation is with the quantum mechanical correction model for the SG, DG, and AG FETs.

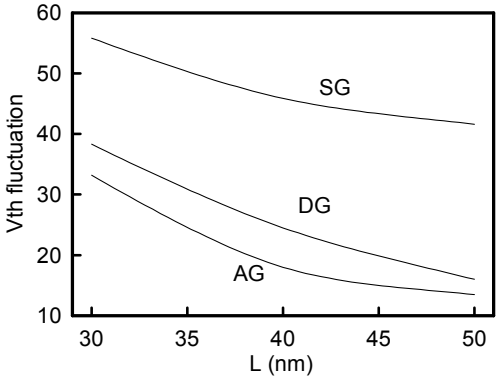

Figure 4. Standard deviation of the threshold voltage versus the device channel length L, where T_{ox} = 1.5 nm, N_A = 5e17 cm^{-3} and T_{si} = 30 nm. This calculation is with the quantum mechanical correction model for the SG, DG, and AG FETs.

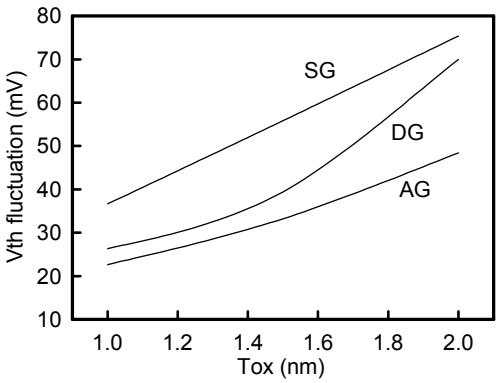

Figure 5. Standard deviation of the threshold voltage versus T_{ox} where L = 30 nm, N_A = 5e17 cm^{-3} and T_{si} = 30 nm. This calculation is with the quantum mechanical correction model for the SG, DG, and AG FETs.