2D Quantum Mechanical Device Modeling and Simulation: Single and Multi-fin FinFET

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ABSTRACT

A two-dimensional quantum mechanical modeling has been performed to simulate a nano-scale FinFET by obtaining the self-consistent solution of coupled Poisson and Schrödinger equations. Calculated current-voltage (I-V) curves are carefully compared with experimental data to verify the validity of our theoretical work. The transconductance (G_{mmax}=380) is optimized through varying the Si-fin thickness (T_{fin}) from 10nm to 75nm. In order to ascertain the current drivability of FinFET, we investigated the dependence on the number of fins. The electron distributions for single and multiple fins FinFETs are reported with several gate voltage V_g=1.5V, -0.3V, 1.5V. In addition, calculated I_d-V_g curve of single fin FinFET is also compared with three and five fins FinFET. From these simulation results, the mechanism of the formation of channel and high current drivability of multiple fins FinFET can be understood.

Keywords: FinFET, double gate MOSFET, quantum mechanical modeling and simulation, coupled Poisson and Schrödinger equations, high current drivability

1 INTRODUCTION

Recently, a double-gate (DG) structure has attracted a great deal of attention for the application of sub-40nm MOSFET. Among the proposed variations of DG MOSFETs, a self-aligned double-gate MOSFET structure including FinFET is one of the most attractive devices to implement a nano-scale planar MOSFET [1-4]. In order to optimize the structure of FinFET, it is necessary to undertake a two-dimensional (2-D) quantum mechanical (QM) simulation due to the inherent quantum effects on the electronic properties of nano-scale semiconductor devices. To fulfill the numerical simulation of nano-scale structures such as FinFET, we need to get a self-consistent solution of the coupled Poisson and Schrödinger equations.

In this paper, two-dimensional quantum-mechanical (QM) simulation of FinFET in a self-consistent manner is reported. We compare the current-voltage (I-V) characteristics with the experimental data. The simulation of multi-fin FinFETs has been performed to analyze the high current drivability of multi-fin FinFETs [1]. The electron densities of single fin and three-fin FinFETs are also demonstrated.

2 NUMERICAL MODEL FOR COMPUTER SIMULATION

For nano-scale device simulation, the nonlinear Poisson and Schrödinger equation should be solved in a simultaneous manner.

$$\nabla \varepsilon(r) \nabla \Phi(r) = -\rho(r) \tag{1}$$

$$-\frac{\hbar^2}{2} \nabla \frac{1}{m^*(r)} \nabla \psi(r) + V(r)\psi(r) = E\psi(r) \tag{2}$$

where, ε is the dielectric constant, Φ the electrostatic potential, ρ the total charge density, ψ the wave function, $\hbar$ the Planck's constant divided by 2π, m^* the effective mass, V the potential energy, and E the energy. Here, one of the most important parameter in these equations is the quantum electron density as follows:

$$n(r) = \frac{1}{\pi} \left(\frac{2m^*(r) k_B T}{\hbar^2} \right)^{\frac{1}{2}} \sum_n \psi_n^2(r) F_{-1/2} \left(\frac{E_F - E_n(r)}{k_B T} \right) \tag{3}$$

Here, k_B is the Boltzmann's constant, T the temperature, E_F the Fermi level, and the Fermi-Dirac integrals of order k. These integrals are defined as follows:

$$F_k(\eta) = \frac{1}{\Gamma(k+1)} \int_0^\infty \frac{\varepsilon^k d\varepsilon}{e^{\varepsilon - \eta} + 1}, \quad \mathrm{k} \geq -1 \tag{4}$$

and also have the following property

$$\frac{d}{dx} F_k(\eta) = F_{k-1}(\eta), \qquad \mathrm{k} \leq -1 \tag{5}$$

The continuity equation for current density is given by

$$divj(r) = 0 \tag{6}$$

To obtain quantum mechanical solutions, we have to employ an iterative procedure. The first step we have to undertake is to calculate an electric potential in Equation (1). With the potential value initiated, the program calculates a built-in potential from Equation (1) with the Newton's method. Thereafter, the program determines self-consistent solutions of Equations (1), (2) and (6). The Newton's method has been employed with a constraint that should satisfy a certain error criteria [3].

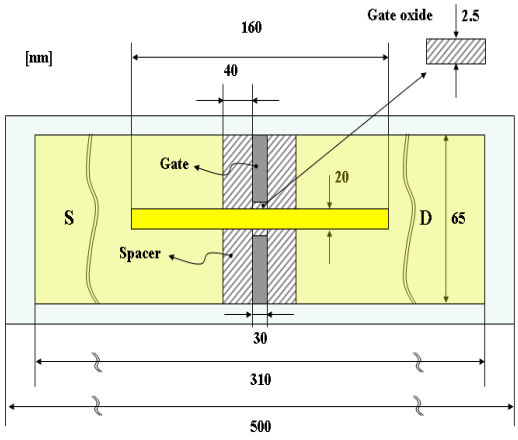


Figure 1: A schematic diagram illustrating the top view of the cross section of the single fin FinFET under this study.

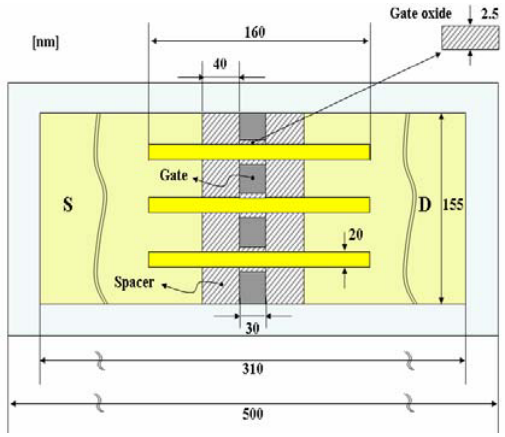


Figure 2: A schematic diagram illustrating the top view of the cross section of the three-fin FinFET under this study.

Figs. 1 and 2 show a top view of the cross section of the single and multiple fins FinFET used in this work. We employed a finite difference method (FDM) as a method of numerical analysis. As a test vehicle for verifying the validity of our numerical simulator, we chose an n-channel FinFET because the n-FinFET shows relatively good short-channel performance down to a gate-length of 17nm [4]. We investigated the short channel effect with a simple drift-diffusion model, which seems to be all right with the level of the driving current.

3 SIMULATION RESULTS

To verify the validity of our simulation, we compared our calculations with the experimental results of Digh Hisamoto et al [1] and Jakub Kedziersk et al [5]. Figs. 3 and 4 demonstrate the comparison of the typical current-voltage (I-V) characteristics for FinFET with L_{eff}=30nm and T_{si}=10nm, 20nm. The I_d-V_g curves of N-channel FinFETs are shown in Fig. 3 in a condition of V_d=0.1V and 1.5V, respectively. The calculated value of the subthreshold swing (S) is 74.58mV/dec at V_d=1.5V.

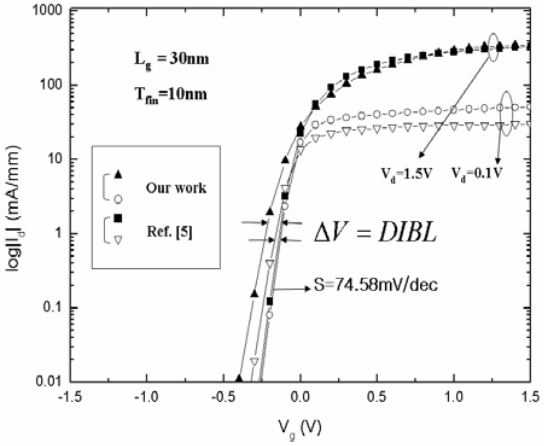


Figure 3: A plot showing the I_d-V_g curves for n-FinFET with L_g=30nm, T_{fin}=10nm which are compared with experimental data.

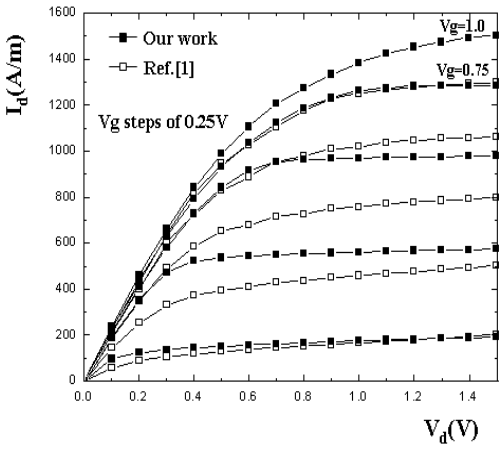


Figure 4: A plot showing the I_d-V_d curves for n-FinFET with L_g=30nm, T_{fin}=20nm which are compared with experimental data.

The I_d-V_d curves are also shown in Fig. 4. In spite of the low channel doping concentration, the subthreshold leakage current is well suppressed. Furthermore, there seems to be no kink effect, which comes from effect of floating body.

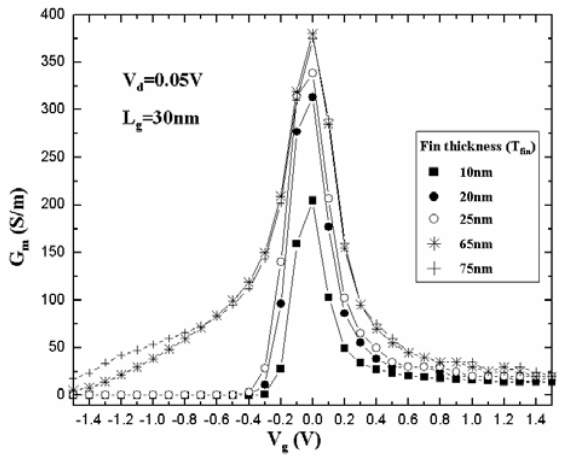
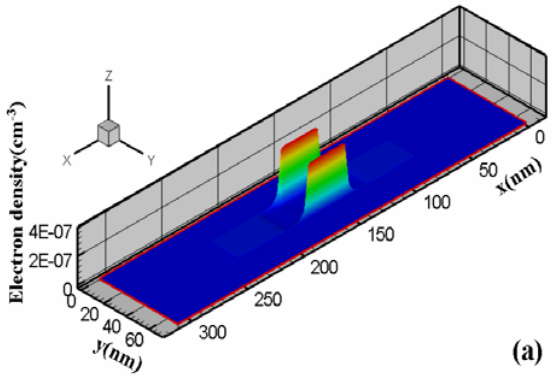


Figure 5: A plot showing the dependence of transconductance (G_m) on the Si-fin Thickness (T_{fin}). G_{mmax}=380 at T_{fin}=65nm, G_{mmax}=375 at T_{fin}=75nm.

Fig. 5 shows a functional dependence of transconductance (G_m) at V_d=0.05V on the thickness of Si-fin. The simulation reveals that G_m increases as the width of Si-fin increases. However, the value of G_m is found to be maximum at 65nm of Si-fin width. This is because as long as the Si-fin width increases the parasitic resistance, it also increases the carrier mobility. However, the charge centroid is reduced [1]. As a result of this reason, we can obtain the optimal Si-fin width.



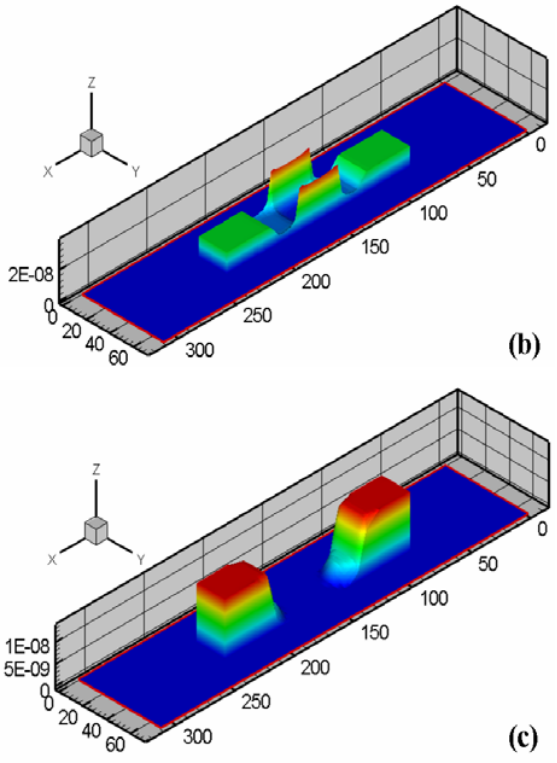
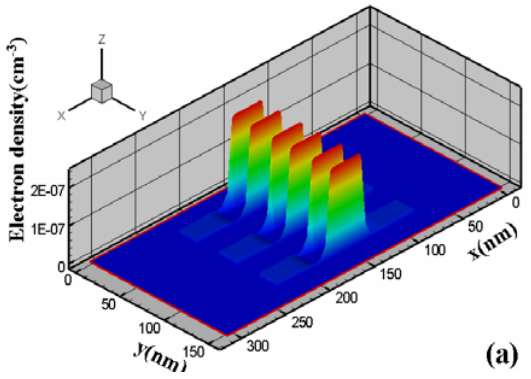


Figure 6: A plot showing the electron densities of single fin FinFET with L_g=30nm, T_{si}=20nm, V_d=0.1V. (a) V_g=1.5V, (b) V_g=0.3V, (c) V_g=-1.5V.

Figs. 6 and 7 demonstrate the distribution of electrons at several gate voltage (a) V_g=1.5V, (b) V_g=0.3V, (c) V_g=-1.5V. These figures exhibit how the channels of FinFET are formed, high current drivability of multi-fin FinFET is good because of the formation of multiple channels, and the electron density is high at S/D regions as the gate voltage decrease.



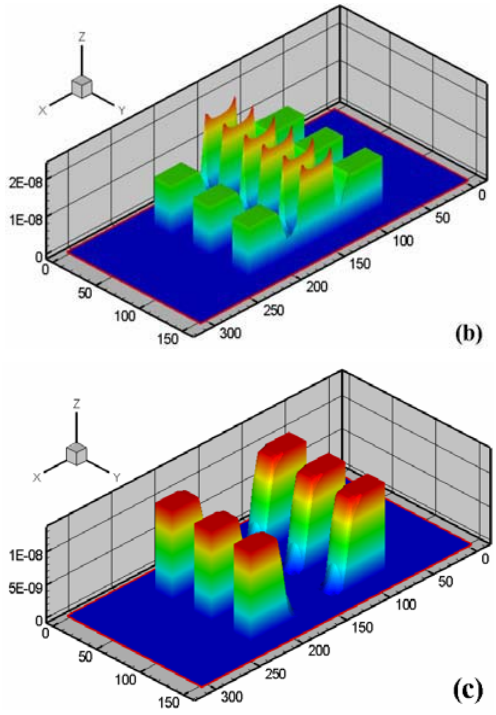


Figure 7: A plot showing the electron densities of three-fin FinFET with L_g=30nm, T_{si}=20nm, V_d=0.1V. (a) V_g=1.5V, (b) V_g=0.3V, (c) V_g=-1.5V.

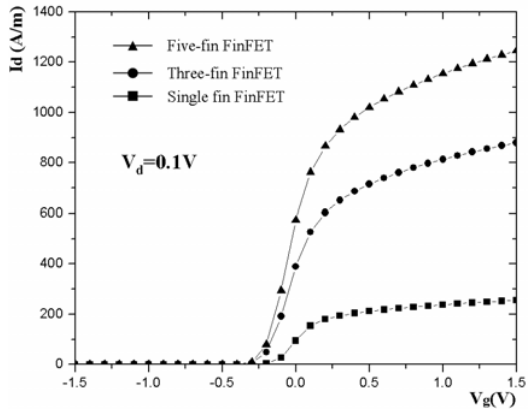


Figure 8: A plot showing the high current drivability of multi-fin FinFET which is proportional to the number of fins.

Finally, high current drivability of multi-fin FinFETs is shown in Fig. 8. The current of three-fin and five-fin FinFETs is about three and five times larger than single fin FinFET. This is because the multi-fin FinFET is designed to obtain larger channel width than single fin FinFET. These multi-fin devices are good structure for applying in self-aligned and quasi-planner structures like FinFET.

4 CONCLUSION

In this paper, 2D (two dimension) numerical modeling and simulations for N-channel FinFET were reported. The optimization of Si-fin width was also demonstrated through extracting the transconductance of different structures. We also demonstrated the high current drivability of multi-fin FinFETs with optimization. We note that the current drivability of multi-fin FinFET is proportional to the number of fins and multi-fin structure is suitable for self-aligned and quasi-planner devices.

5 ACKNOWLEDGEMENT

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