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Quantum hydrodynamic simulation of discrete-dopant fluctuated physical quantities in nanoscale FinFET

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ABSTRACT

Impact of the discrete dopants on device performance is crucial in determining the behavior of nanoscale semiconductor devices. Atomistic quantum mechanical device simulation for studying the effect of discrete dopants on device's physical quantities is urgent. This work explores the physics of discrete-dopant-induced characteristic fluctuations in 16-nm fin-typed field effect transistor (FinFET) devices. Discrete dopants are statistically positioned in the three-dimensional channel region to examine associated carrier's characteristic, concurrently capturing "dopant concentration variation" and "dopant position fluctuation". An experimentally validated quantum hydrodynamic device simulation was conducted to investigate the potential profile and threshold voltage fluctuations of the 16-nm FinFET. Results of this study provide further insight into the problem of fluctuation and the mechanism of immunity against fluctuation in 16-nm devices.

1. Introduction

Ion implantation, diffusion and thermal annealing induce significant random fluctuations in physical characteristics of nanometer scale field effect transistors (FETs) [1–3]. Fluctuations are caused not only by a variation in an average doping density, which is associated with the fluctuation in the number of impurities, but also with a particular random position of impurities in the channel region. Accordingly, devices with vertical channel structures, such as fin-typed FETs (FinFETs) are of great interest. Diverse approaches, such as small-signal analysis, drift-diffusion (DD) and Monte Carlo simulation have recently been reported to study fluctuation-related issues in semiconductor devices [4,5]. Unfortunately, the effect of the number and position of discrete dopants on the characteristics of nanoscale FinFET has not been clearly investigated.

In this study, we present a statistically sound "atomistic" approach to analyze effects of random on 16-nm FinFETs, concurrently capturing "dopant number variation" and "dopant position fluctuation". The statistically generated large-scale doping profiles mimic the physical process of ion implantation. Based on the doping profiles, each device simulation is performed by solving a set of three-dimensional (3D) quantum hydrodynamic (QHD) equations for proper quantum-mechanical corrections [6,7]. In the 3D numerical solution of QHD equations, we use the adaptive finite volume method [7]. Thus, intrinsic physical fluctuations could be examined properly.

2. Simulation technique

The devices in this study have nominal channel doping concentration of 1.48×10^{18} cm^{-3}, 16-nm gate length and width, 32-nm fin height and a gate oxide thickness of 1.2 nm. The source and drain doping concentrations are 3×10^{20} cm^{-3}. Dopants within the channel region are treated discretely. We first adjust the characteristics for the nominal case; the threshold voltage (V_{th}) is of 140 mV. To include randomness of the number and position of discrete dopants, we generate a large number of dopants in a large cuboid, where the equivalent concentration is 1.48×10^{18} cm^{-3}. Then the large cuboid is partitioned into small cuboids and each sub-cuboid is mapped into device channel, as shown in Fig. 1(a), for 3D device simulation. Characteristics of each discrete-dopant fluctuated device are estimated by solving a set of 3D QHD equations [6,7] for electrons, as listed below:

$$\Delta\phi = \frac{q}{\varepsilon}\left(n - \sum_{i=0}^{n} D\chi_{A_i}(x)\right), \tag{1}$$

$$\nabla \cdot \vec{J_n} = -qR, \tag{2}$$

$$\nabla \cdot \vec{S_n} = \vec{J_n} \cdot \nabla E_c + \left.\frac{dW_n}{dt}\right|_{coll}. \tag{3}$$

Eq. (1) is Poisson equation, Eq. (2) is the electron continuity equation and Eq. (3) is the energy balance equation. Eqs. (4) and (5) are the current density ($\vec{J_n}$) and energy flux ($\vec{S_n}$), respectively:

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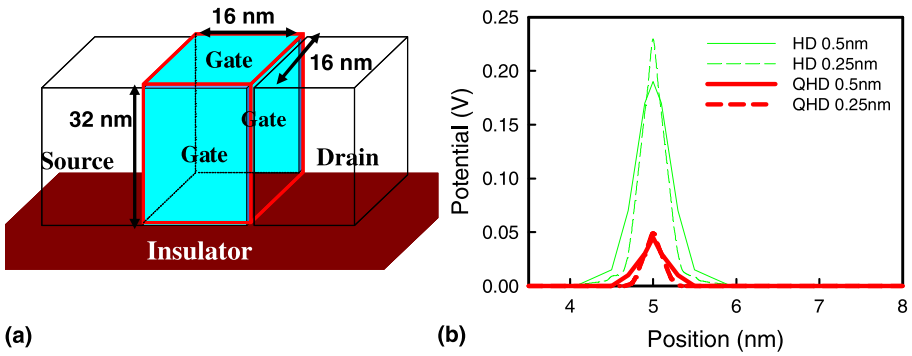

Fig. 1. (a) The FinFET structure, and (b) the potential profile of hydrodynamic (HD) and quantum hydrodynamic (QHD) with different mesh size.

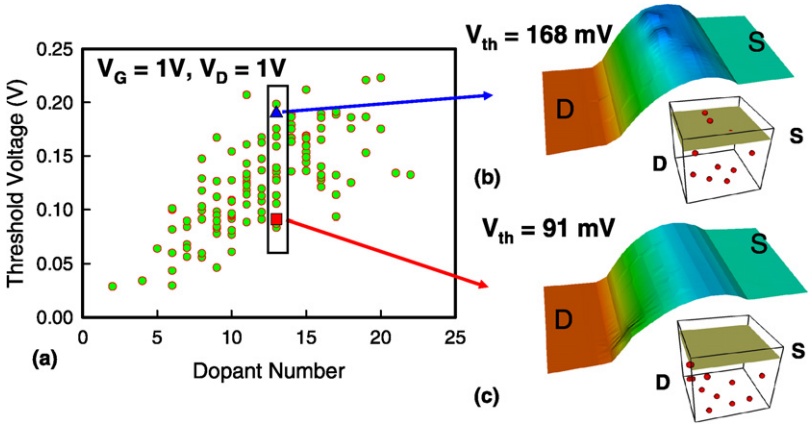

Fig. 2. (a) The threshold voltage distribution and the potentials of cases with the same dopant number but different dopant position ((b) and (c)).

$$\vec{J_n} = q\mu_n\left(n\nabla E_C + k_B T_n \nabla n + k_B n \nabla T_n - 1.5 n k_B T_n \nabla \ln m_e - n\nabla\frac{k_B T_n}{q}\log\left(\frac{n}{n_i}\right) + \gamma_n\right), \tag{4}$$

$$\vec{S_n} = -\frac{3\gamma_n k_B}{2q}(T_n\vec{J_n} + k_B n \mu_n T_n \nabla T_n), \tag{5}$$

where the ϕ is the electrostatic potential, n is the electron density, ε is the electric permittivity, q is the electronic charge, k_B is the Boltzmann's constant, E_C is the conduction band energy, T_n is the electrons temperature, D is the ionized purity density, n_i is the intrinsic density, R is the recombination term, μ_n is the mobility of electrons, m_e is the effective mass of electrons, $\frac{dW_n}{dt}|_{coll}$ is the electron collision term and $\gamma_n = 2b_n\frac{\Delta\sqrt{n}}{\sqrt{n}}$ is the quantum potential.

Note that for the best accuracy of simulation, the physical parameters were calibrated with experimentally measured current–voltage data [8,9]. We have fabricated a large number of devices and measured the V_{th} of each device and compared the experimental standard deviation of V_{th} to the calculated one [5].

3. Results and discussion

The resolution of individual impurities for the classical semiconductor device equations using a fine mesh will result in problems of singularities in the Coulomb potential. The sharp Coulomb potential wells un-physically trap majority carriers, reduce the mobile electron concentration and alter the threshold voltage. Therefore, the QHD simulation is used to handle discrete charges by properly introducing the related quantum effects, as shown in Fig. 1(b). The quantum mechanical potential shows less sensitivity to the mesh size and the potential barrier of the Coulomb well is about 45 mV, which roughly corresponds to the ground state of a hydrogen model of an impurity in silicon. Fig. 2(a) shows the threshold voltages with dopant concentration and position variations. Changing the number of discrete dopants in the channel indicates that the equivalent concentration of channel doping is altered; it will cause a significant potential variation and induce device's threshold voltage fluctuation. Moreover, the threshold voltage fluctuation is also happened even having the same equivalent channel doping concentration. Figs. 2(b) and 2(c) show the potential with the same dopant number but different dopant position; the potential spikes are associated with the corresponding dopants near the silicon surface. The channel dopant near the surface will introduce a relatively more negative surface potential inside the device channel. As electrons transport from the source to the drain, some of them encounter the negative potential and result in variations of threshold voltage. Fig. 3 shows the structural advantage of FinFET, the potential distribution of the spike B does not vary significantly like the spike A; because the lateral gate intrinsically enhances the controllability of fluctuation near the sidewall of the channel surface.

4. Conclusions

This work has elucidated the discrete dopants induced physical variation phenomenon in 16-nm FinFET using 3D atomistic quantum hydrodynamic device simulation. The distribution of potential and threshold voltage fluctuated by concentration and position of dopants were illustrated and discussed. The structural advantage of FinFET was also presented.

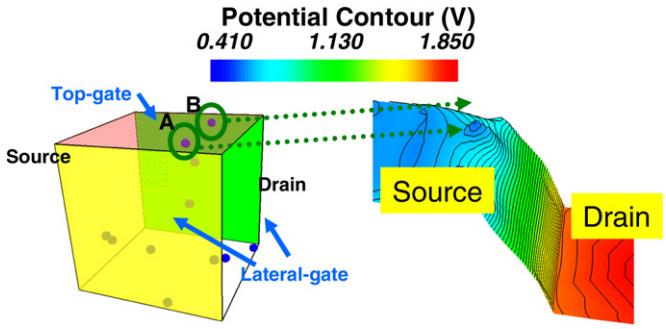

Fig. 3. Potential contours of the dopants locating at the middle of channel and near the lateral gate.

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References

[1] Y. Li, S.-M. Yu, Study of threshold voltage fluctuations of nanoscale double gate metal-oxide-semiconductor field effect transistors using quantum correction simulation, J. Comput. Electron. 5 (2006) 125–129.
[2] P. Andrei, I.D. Mayergoyz, Quantum mechanical effects on random oxide thickness and doping fluctuations in ultrasmall semiconductor devices, J. Appl. Phys. 94 (2003) 7163–7172.
[3] A. Asenov, Random dopant induced threshold voltage lowering and fluctuations in sub-0.1 gm MOSFET's: A 3-D atomistic simulation study, IEEE Trans. Electron Dev. 45 (1998) 2505–2513.
[4] C.J. Wordelman, U. Ravaioli, Integration of a particle-particle-particle-mesh algorithm with the ensemble Monte Carlo method for the simulation of ultra-small semiconductor devices, IEEE Trans. Electron Dev. 47 (2000) 410–416.
[5] Y. Li, S.-M. Yu, J.-R. Hwang, F.-L. Yang, Discrete dopant fluctuated 20 nm/15 nm-gate planar CMOS, IEEE Trans. Electron Dev. 55 (2008) 1449–1455.
[6] R. Stratton, Diffusion of hot and cold electrons in semiconductor barriers, Phys. Rev. 126 (1962) 2002–2014.
[7] Y. Li, S.-M. Yu, A parallel adaptive finite volume method for nanoscale double-gate MOSFETs simulation, J. Comput. Appl. Math. 175 (2005) 87–99.
[8] Y. Li, C.-H. Hwang, Effect of fin angle on electrical characteristics of nanoscale round-top-gate bulk FinFETs, IEEE Trans. Electron Dev. 54 (2007) 3426–3429.
[9] Y. Li, S.-M. Yu, A coupled-simulation-and-optimization approach to nanodevice fabrication with minimization of electrical characteristics fluctuation, IEEE Trans. Semicond. Manuf. 20 (2007) 432–438.