Three-dimensional quantum transport simulation of ultra-small FinFETs

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A variety of multiple-gate MOSFET structures have been proposed to further improve engineering of the channel electrostatics and to provide adequate control of short channel effects [1]. In a multiple-gate structure, carries are confined in a two-dimensional plane perpendicular to the current direction. A three-dimensional (3D) modeling is, therefore, required to simulate the carrier transport characteristics. Quantum-mechanical approach is also needed, because quantum-mechanical effects, such as quantum confinement and source-drain tunneling, are expected to significantly affect the transport characteristics in a nano-scale device. When the channel length becomes less than the mean free path, carrier transport becomes ballistic and carriers do not suffer scatterings in the channel region. Even in a ballistic regime, electron-phonon interaction may affect the transport characteristics, because it alters electronic states in the source/drain region through polaronic effects [2]. In the present study, we have performed 3D quantum transport simulation of ultra-small FinFETs based on a non-equilibrium Green's function (NEGF) method including the electron-phonon interaction.

We consider an n-channel FinFET structure whose geometry is given in Fig. 1. On a SiO_2 layer, there is a silicon Fin-structure with the length L, width W, and hight H. Channel region is under a midgap-metal gate with the length of $L_{\rm gate}$. n-type source/drain regions are connected to the both edges of the channel region. We define the x-direction as the source-drain direction and the y-direction as the channel width direction (see Fig. 1).

In our simulation, a coupled mode-space expansion method [3] is adopted for solving the NEGF transport equations. The device Hamiltonian is expanded in the coupled mode-space obtained with solving the y-z two-dimensional Schrödinger equations for real-space x-points. Quantum mechanical effects both along the transport direction (x-direction) and along the confinement direction (y- and z-directions) can be included in this procedure. The NEGF transport equations are then solved self-consistently with a 3D Poisson's equation based on the Hartree approximation. We assume that equilibrium reservoirs are connected to the edges of source/drain regions. The Fermi levels of the reservoirs are determined by the source/drain bias. Phonon scatterings with a constant matrix elements of $|M(q)|^2 = \hbar D^2/2\rho\omega_0$ are included in the simulation, where D is the deformation potential, ρ is the density of silicon, and ω_0 is the phonon frequency.

A typical simulation result for a FinFET with $L = 30\,\mathrm{nm}$, $W = 6\,\mathrm{nm}$, $H = 11\,\mathrm{nm}$ and $L_{\rm gate} = 10\,\mathrm{nm}$ is shown in Fig. 2, where we plot the energy resolved electron-density distribution of the lowest energy subband along the x-direction (a) and the electron density at the source edge, $x = 0\,\mathrm{nm}$ (b) for $V_{\rm G} = 1.0\,\mathrm{V}$, $V_{\rm SD} = 0.5\,\mathrm{V}$, and $T = 300\,\mathrm{K}$. We see that electrons exist in the energy region below the subband energy (shown by dotted line in Fig. 2(b)) due to the electron-phonon coupling.

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[2] N. Mori, H. Momose, and C. Hamaguchi, Physica Status Solidi (b) **204**, 268 (1997).
[3] R. Venugopal, S. Goasguen, S. Datta, and M.S. Lundstrom, J. Appl. Phys. **95**, 292 (2004).

A full journal publication of this work will be published in the Journal of Computational Electronics.

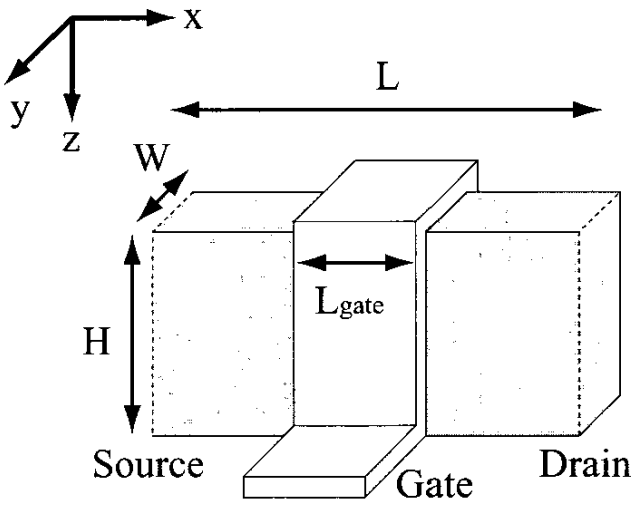

Figure 1: Schematic diagram of a FinFET structure together with the coordinate system.

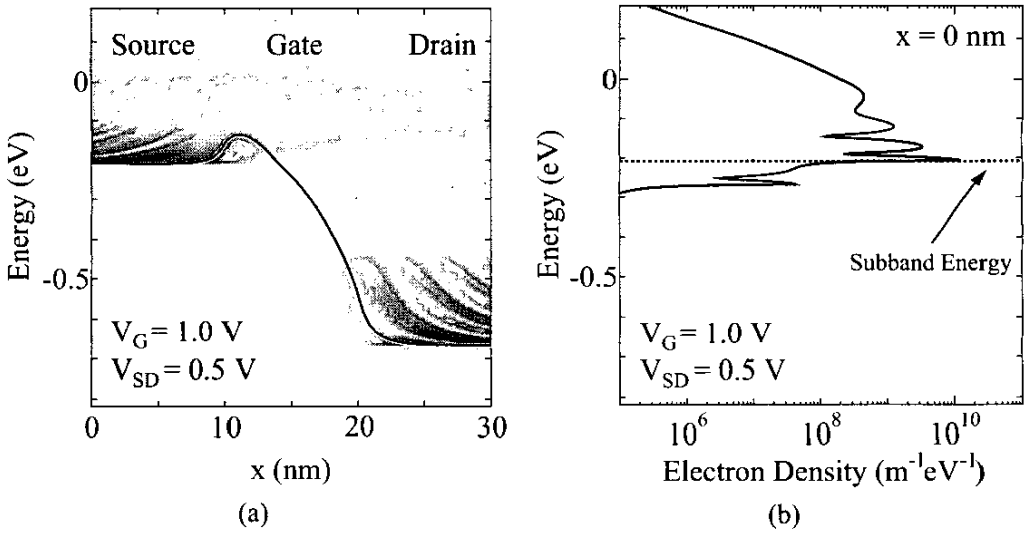

Figure 2: (a) Energy resolved electron-density distribution of the lowest energy subband along the x-direction. Solid line represents the subband energy. (b) Electron density distribution at the source edge, $x = 0\,\mathrm{nm}$. Dotted line indicates the subband energy.

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