Analysis of carrier transport in Si and Ge MOSFETs including quantum confinement and hot carrier effects

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INTRODUCTION

New channel materials such as Ge and Ⅲ-V semiconductors are needed to achieve high performance and low power in nanoscale CMOS devices[1]. A number of authors have presented numerical and theoretical studies of carrier transport in MOSFETs on high mobility substrates and Si [2], [3], [4].

In this paper, transport properties in Si and Ge n-MOSFETs are evaluated using a 4 moments quantum energy transport(QET) model[5]. The QET model allows analysis of carrier transport including quantum confinement and hot carrier effects.

4 MOMENTS QUANTUM ENERGY TRANSPORT MODEL

We develop a 4 moments QET model, assuming the classical form of the fourth moment tensor and neglecting quantum corrections in the diffusive contributions to the energy flux density[5]. For electrons, the carrier continuity and energy balance equations are derived as

$$\frac{1}{q} div J_n = 0, \tag{1}$$

$$\nabla \cdot S_n = -J_n \cdot \nabla\varphi - \frac{3}{2} kn \frac{T_n - T_L}{\tau_\epsilon}, \tag{2}$$

where φ, n and T_n are the electrostatic potential, electron density and electron temperature, respectively. q, k, τ_ϵ and T_L are the electronic charge, Boltzmann's constant, energy relaxation time, and lattice temperature. The quantum corrections of the current density J_n and energy flux density S_n are given by

$$J_n = q\mu_n(\nabla(n\frac{kT_n}{q}) - n\nabla(\varphi + \gamma_n)), \tag{3}$$

$$\begin{aligned} S_n = & -\frac{\mu_s}{\mu_n}(\frac{5}{2}\frac{kT_n}{q} - \frac{\hbar^2}{24mq}\Delta \log n - \gamma_n)J_n \\ & -\frac{\mu_s}{\mu_n}\frac{5}{2}(\frac{k}{q})^2 q\mu_n n T_n \nabla T_n, \end{aligned} \tag{4}$$

where μ_n and μ_s are the electron and energy flow mobilities, respectively. $\hbar$ and m are Plank's constant and effective mass. The quantum potential is written as

$$\gamma_n = \frac{\hbar^2}{6mq}\frac{\Delta\sqrt{n}}{\sqrt{n}}. \tag{5}$$

NUMERICAL RESULTS

Si and Ge n-MOSFETs with high-k/metal gate are examined. Selected material parameters are listed in Table I. Both devices have gate length L_g=35nm, EOT=0.7nm and the S/D dopings of $1.0 \times 10^{20} cm^{-3}$. The dielectric permittivity considered here is 22, and the value is known as ”HfO_2”. For metal gates, the work functions of 4.2 eV for Si devices, and 4.14 eV for Ge devices are adopted. Fig. 1 (a) and (b) shows comparisons of the classical and quantum mechanical average inversion layer depths versus effective normal field for Si and Ge n-MOSFETs. In both devices, the classical value is less than 1.0 nm, and the difference between two devices is small. The QM value of the Ge n-MOSFET is larger than that of the Si n-MOSFET by 0.8nm-1.2nm for a wide range of channel doping because of the low effective mass and high permittivity of Ge. This effectively reduces the charge control by the gate in Ge n-MOSFETs. The electron

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density distributions perpendicular to the interface are shown in Fig. 2 (a) and (b). The results clearly indicate that the quantum confinement effect at the drain end of the channel is further reduced by the enhanced diffusion towards the bulk due to the high electron temperature. Fig. 3 shows electron density distributions of a double gate Si n-MOSFET with high-k/metal gate. The silicon layer thickness is 6nm. It is seen that the device exhibits two channels at the source end of the channel and a single channel at the drain end of the channel due to high electron temperature near the drain.

CONCLUSION

A 4-moments QET model allows simulations of quantum confinement transport with hot-carrier effects in Si and Ge n-MOSFETs. The charge control by the gate is effectively reduced in the Ge n-MOSFET due to low effective mass and high permittivity. The quantum confinement effect is further reduced by high electron temperature near the drain.

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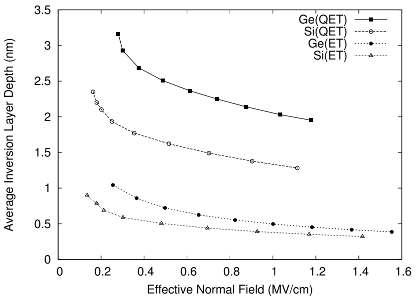
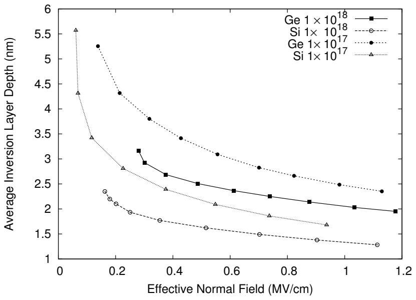
TABLE I

SELECTED SEMICONDUCTOR MATERIAL PARAMETERS

semiconductor	Si	Ge
$\mu_{eff}(cm^2/Vs)$ [4]	400	1040
$E_G(eV)$	1.12	0.66
$\epsilon_R(\epsilon_0)$	11.7	16.0
$m_{eff}(m_0)$	0.26	0.10
$n_i(cm^{-3})$	1.105×10^{10}	2.0×10^{13}

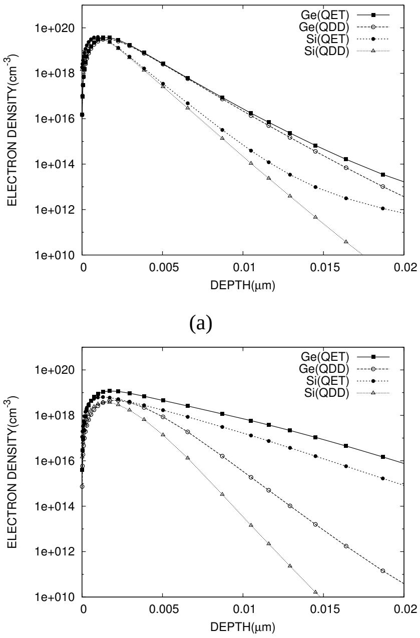


(a)



(b)

Fig. 1. Average inversion layer depth as a function of gate effective normal field for Si and Ge n-MOSFETs. (a) The results are calculated by the QET and ET models. The channel doping is $1.0 \times 10^{18} cm^{-3}$. (b) The uniform channel dopings are $1.0 \times 10^{18} cm^{-3}$ and $1.0 \times 10^{17} cm^{-3}$, respectively.



(a)

(b)

Fig. 2. Electron density distributions perpendicular to the interface for a 35nm MOSFET, (a) at the source end of the channel, (b) at the drain end of the channel. V_g=0.8V, V_d=0.8V.

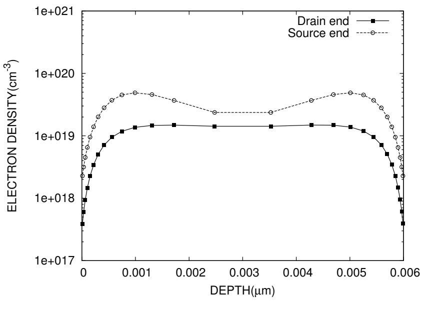


Fig. 3. Electron density distributions perpendicular to the interface at the source and drain end of the channel for a 35nm double gate Si n-MOSFET. V_g=0.8V, V_d=0.8V.