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Impact of Attractive Ion in Undoped Channel on the Characteristics of Nanoscale Multi-Gate FETs: A 3D NEGF Study

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1. Introduction

Random impurities are one of the major sources of variability of the transport characteristics in nano-scale MOSFETs, which have brought motivation for introducing multi-gate (MG) FETs with ultra-thin undoped channel [1]. However, even in the undoped channels, undesirable fixed point charges still may be present and their impact on the device performance is expected to be significant. So far, theoretical studies of both repulsive (acceptor) and attractive (donor) ions in the undoped channel of double-gate (DG) nFETs have been performed using the drift-diffusion simulator with quantum corrections [2, 3]. However, a special care should be paid particularly for the problem with attractive ion, because it confines the carrier in a very narrow and infinitely deep potential well, and hence the quantum mechanical treatment as accurate as possible is desirable [4, 5] (e.g., a purely classical treatment causes a collapse of electrons into the ion [6]). In this study, we perform quantum ballistic transport simulations of a single attractive ion in undoped MGFETs within non-equilibrium Green's function (NEGF) formalism.

2. Simulation Methodology

Fig.1 shows DG and gate-all-around (GAA) n-type MOSFETs used in the calculations. We have implemented a newly developed quantum simulator based on the local basis representation technique [7] for the electronic Green's function and self-consistent solution of the Poisson equation. Apart from its numerical efficiency, our method allows for accurate treatment of charged impurities since using local spherical coordinate around the ion effectively removes Coulomb singularity [4].

3. Results and Discussion

Donor Position Dependence: Fig. 2 presents the calculated $I_D - V_G$ characteristics of DG-MOSFET ($t_{\rm Si} = 4$ nm, $W = 10$ nm) for various locations of the donor ions in Si channel. As seen from this figure, the attractive ion changes the subthreshold behavior but does not affect much the on-current. The corresponding shift of the threshold voltage V_T is shown in Fig. 3. In the linear region, the strongest effect is observed for the donors in central area of the channel which agrees with earlier studies [3]. In the saturation region, however, the largest variation of the drain current is found for the donors located closer to the source. Fig. 4 shows the electrostatic potential profile in the DG-MOSFET. In the subthreshold region ($V_G = 0.2$ V), the effective potential barrier is lowered by the attractive donor ion which enhances the electron injection from the source and causes the V_T shift. Such an "ion-induced-barrier-lowering (IIBL)" is most pronounced for the donor at the barrier top, and increasing the gate voltage moves the "worst" donor position to the source side. On the other hand, the IIBL is weak in strong inversion region ($V_G = 0.5$ V) and the on-current is not sensitive to the presence of the donor ion. Fig. 5 presents the energy spectrum of the electron density in strong inversion. We observe a localized electronic state trapped by the ion with characteristic length comparable to the Bohr radius in bulk silicon, and it screens the ion's positive charge. Populating such a state is a resonant process which strongly depends on the resonant energy, i.e., on the gate voltage.

Device Structure Dependence: In Fig. 6 we show the $I_D - V_G$ characteristics of DG and GAA MOSFETs with various channel cross sections with and without a dopant ion at the center of the channel. For comparison, we have also calculated the electric current in the channel with uniformly distributed unit positive charge. In the latter case, an analytical expression for the threshold voltage shift ΔV_T can be obtained from a simple electrostatic consideration (see Fig. 7). This model indicates that ΔV_T inversely proportional to the total width of the gate wrapping the Si body $W_{G,\rm total}$, and hence the GAA structure is expected to be less sensitive to the body charging. For the homogeneous charge, our model agrees well with the simulation results (see Fig. 8), but the point charge ion causes much larger ΔV_T, indicating a significant effect of the localized current leakage path induced by the ion. However, in both cases the GAA shows less sensitivity to the presence of the ion ($\sim$x0.5) compared to DG structure in agreement with the analytical model.

4. Conclusions

We have reported on comprehensive numerical study of quantum transport through an attractive donor ion in the intrinsic channel of MGFETs. We have shown that the ion reduces the effective potential barrier in the channel and changes the threshold voltage. The effect depends strongly on the ion position and applied bias. The on-current is found to be less sensitive due to effective screening of the ion by the electrons in the strong inversion regime. We have also confirmed that the GAA MOSFETs have better robustness against the V_T variation compared to the DG structures.

Acknowlegement

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References

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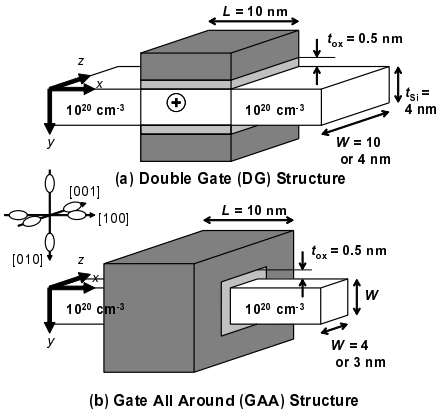

Fig. 1 MOSFET structures used in the simulation. Si conduction band is modeled by six ellipsoidal valleys in the effective mass approximation. The gate work function is set to 4.25 eV.

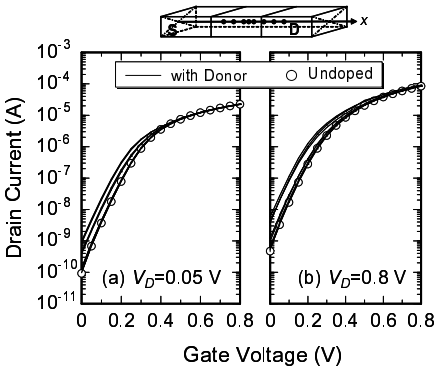

Fig. 2 Computed $I_D - V_G$ characteristics of DGMOSFETs ($t_{\rm Si} = 4$ nm and $W = 10$ nm) at (a) $V_D = 0.05$ and (b) 0.8 V. Solid lines represent the devices with a single donor at various positions along the x-direction in the center of the channel cross-section. Open dots correspond to the undoped channel.

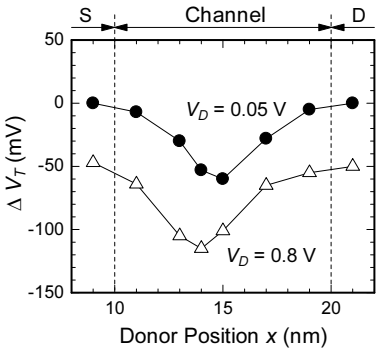

Fig. 3 Variation of the threshold voltage caused by a donor at various positions along the x-direction. The shifts of the threshold voltage (ΔV_T) from the undoped device biased at $V_D = 0.05$ V are evaluated from the data in Fig. 2.

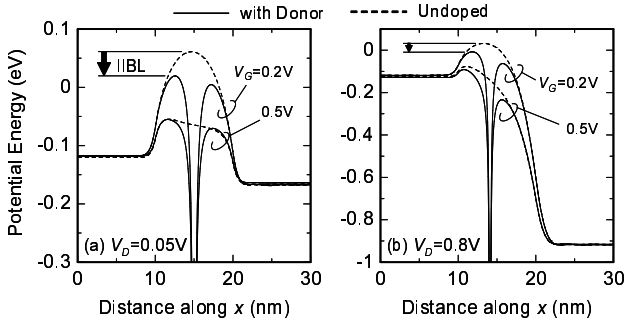

Fig. 4 Potential profiles in DG-MOSFETs biased at (a) $V_D = 0.05$ and (b) 0.8 V. The data for undoped channel device (dashed line), and the device with a single donor at (a) $x = 15$ and (b) 14 nm are compared. The potential profile along the line passing through the donor is plotted, and hence the Coulomb singularity is comfirmed.

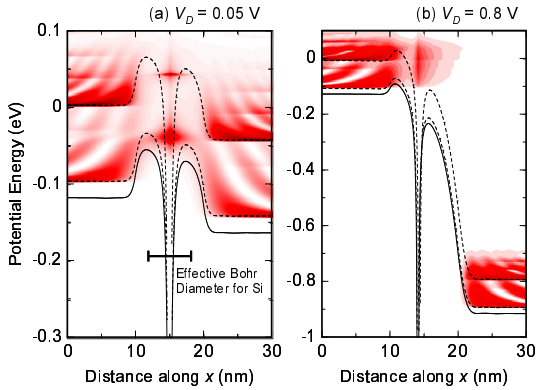

Fig. 5 Energy spectrum of the electronic density along the current direction at $V_G = 0.5$ V. The donor is located at the center of the channel. The bottoms of the conduction band and two lowest subbands are shown by solid and dashed lines, respectively. The source Fermi energy is fixed at 0 eV.

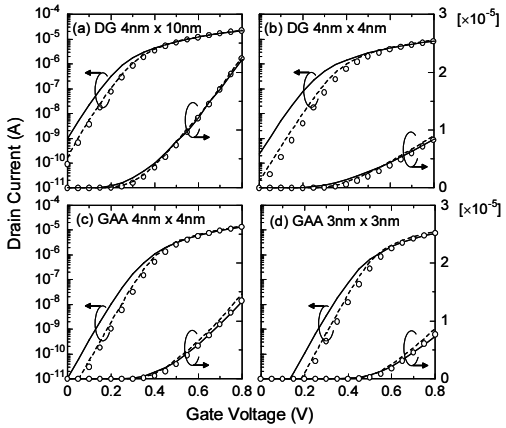

Fig. 6 Calculated $I_D - V_G$ characteristics of DG and GAA MOSFETs for various $t_{\rm Si} \times W$ at $V_D = 0.05$ V. Solid lines represent the devices with a single donor in the center of Si channel, open dots are for the undoped channel, and dashed lines correspond to the channel doped by homogeneous unit charge.

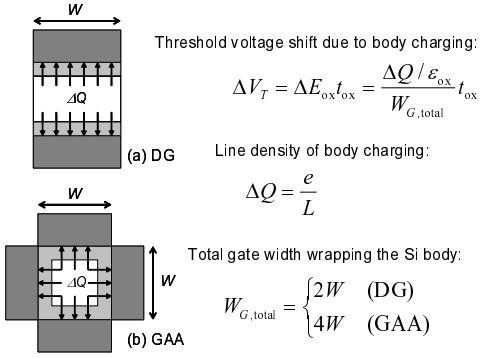

Fig. 7 An analytical model for evaluating the threshold voltage shift ΔV_T due to depletion charge ΔQ in the channel. The electric field lines from ΔQ are terminated at the gate, which modulates the electric field $E_{\rm ox}$ in the oxide and causes the threshold voltage shift.

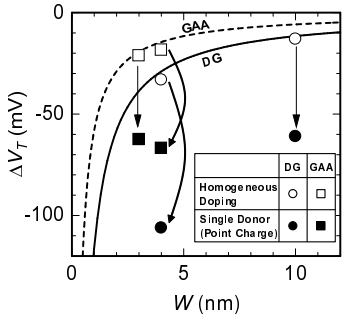

Fig. 8 The threshold voltage shifts obtained from the data in Fig. 6 (symbols). The results of analytical model in Fig. 7 are shown by solid (DG) and dashed (GAA) lines.