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Ballistic and Quasi-ballistic Hole Transport Properties in Germanium Nanowire pMOSFETs Based on an Extended "Top of the Barrier" Model

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Abstract

We calculated the ballistic hole transport properties in rectangular cross-sectional germanium nanowire transistors with various geometries, based on the "Top of the Barrier" model. Then, by extending this model, the quasi-ballistic hole transport properties were also computed taking into account phonon and surface roughness scattering in the channel and direct tunneling from source to drain. Among several nanowire geometries targeted in this work, the [110] nanowire with large height along $[1\bar{1}0]$ ($[110]/(1\bar{1}0)$ NW) exhibited the largest ballistic current, owing to its large density of states. Large density of states, however, increases back scattering. Thus when scattering is considered, the [110]/(001) NW with small density of states showed the largest drain current.

1. Introduction

Germanium (Ge) nanowire (NW) MOSFETs, which can utilize the high hole mobility of Ge and high short channel effect immunity of NW structure, are a potential candidate for pMOSFETs in future generation. To estimate the performance and to present a design guideline of Ge NW MOSFETs, understanding the carrier transport in Ge NWs is essential, and several studies have been devoted to this subject [1]. In particular, rectangular cross-sectional Ge NWs, which can be realized as scaled FinFETs, are expected to possess high hole mobility in proper geometry [2], owing to anisotropic quantum confinement effects on holes.

In this study, we calculated the ballistic and quasi-ballistic hole transport properties of rectangular cross-sectional Ge NWs. The dependence of hole transport properties on NW orientations and cross-sectional geometries is analyzed, and favorable geometries for Ge NW pMOSFETs are investigated.

2. Ballistic Transport by a Top of the Barrier Model

In this section, an analysis of ballistic hole transport properties based on a Top of the Barrier model [3] is presented. The assumed device structure is a gate-all-around Ge NW MOSFET with a gate oxide of 0.6-nm-thick SiO_2. The NW channel is undoped and its cross section is a rectangle with 2 nm width and 6 nm height. The considered orientations and sidewalls of Ge NWs are $[001]/(0\bar{1}0)/(\bar{1}00)$, $[110]/(1\bar{1}0)/(001)$, $[111]/(1\bar{1}0)/(\bar{1}\bar{1}2)$, and $[112]/(1\bar{1}0)/(\bar{1}\bar{1}1)$. Valence band structures were computed self-consistently, based on an $sp^3d^5s^*$ tight-binding method [4] with spin-orbit coupling. The drain voltage was fixed at −0.6 V, and the gate voltage was referenced from the voltage where ballistic drain current is 2.0×10^{-10} A.

Drain current characteristics

The calculated gate voltage dependencies of drain current, hole density and injection velocity of ballistic Ge NW p-FETs are depicted in Fig. 1. Fig. 1(a) indicates the high hole transport abilities of [110] and [111] NWs. The calculated hole density (Fig. 1(b)) and injection velocity (Fig. 1(c)) show that high current is caused by different mechanisms. The high current of the [110] NW with height along $[1\bar{1}0]$ ($[110]/(1\bar{1}0)$ NW) originates from the large hole density. On the other hand, [110]/(001) and [111] NWs are owing their high current to the high injection velocity.

Impacts of gate capacitance

To understand the geometry dependence of hole density in Fig. 1(b), the gate voltage V_G dependence of total capacitance and quantum capacitance C_Q was calculated (Fig. 2). When V_G has a small (< 0.3 V) absolute value, the gate capacitance is limited by small C_Q. Even when $|V_G|$ is larger, the total capacitance is still affected by C_Q. Thus, the [001] and [110]/(110) NWs, whose density of states (DOS) and C_Q are large, show larger total capacitance than other geometries, which leads to higher hole density.

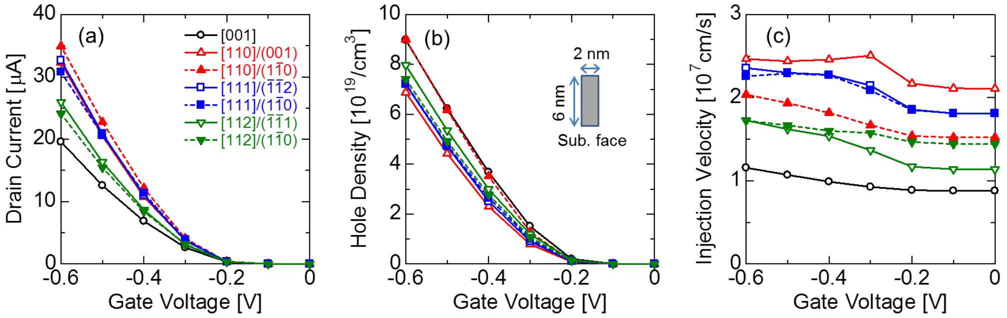

Fig. 1 Calculated gate voltage dependence of (a) drain current, (b) hole density, and (c) injection velocity in 2 nm × 6 nm rectangular cross-sectional ballistic Ge NW p-FETs with various orientations and substrate faces. The drain voltage is −0.6 V.

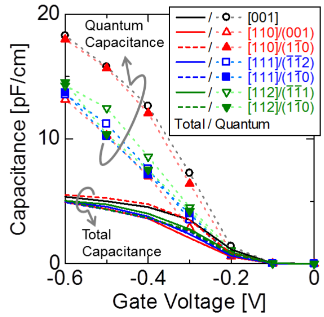

Fig. 2 Gate voltage dependence of total capacitance and quantum capacitance.

3. Modeling and Analysis of Quasi-Ballistic Transport

As discussed above, large DOS increases the hole density and ballistic current. However, large DOS enhances scattering, resulting in reduction of drain current. Light effective mass is beneficial to high injection velocity, but it degrades off-characteristics of FETs through tunneling. To analyze such competing effects, the impacts of backscattering and tunneling are investigated in this section.

Model of tunneling and backscattering

The model introduced in this work to treat tunneling and backscattering is described schematically in Fig. 3. In this model, the potential barrier in the channel is assumed to be flat, and thus the channel length L_{ch} should be interpreted as an effective length of the barrier under an operating condition. Tunneling probability is calculated from the effective mass near the valence band maximum considering the two subbands from the band edge. The effect of backscattering is taken into account by using the transmission coefficient for each state shown in Fig. 3. This expression is derived by applying a flux method [5] to each pair of hole states in the same subband (n) and with positive ($+k$) and negative ($-k$) wave vectors. Considered scattering mechanisms are phonon [6] and surface roughness [7] with RMS of 0.48 nm and correlation length of 1.3 nm. Backscattered holes increase the hole density at the top of the barrier compared to the ballistic case, and thus increase the barrier height. This effect is taken into account by adjusting the electrostatic potential using the capacitance of oxide and inversion layer calculated from the ballistic results, while keeping the E-k dispersion unchanged to reduce computational cost.

Channel length dependence of drain current

Using the model mentioned above, L_{ch} dependence of quasi-ballistic drain current was investigated. Fig. 4 depicts the off-state ($V_G = 0$ V) current considering tunneling but not scattering. When L_{ch} is below 6-10 nm (depending on geometries because NWs with a light effective mass have large tunneling current), the off-current is increased by tunneling. This means that miniaturizing the channel length of Ge NW p-FETs below 6-10 nm is unfavorable.

Then, L_{ch} dependencies of on-current ($V_G = -0.6$ V) are shown in Figs. 5(a) and (b) for the cases with phonon scattering only and with both phonon and roughness scattering,

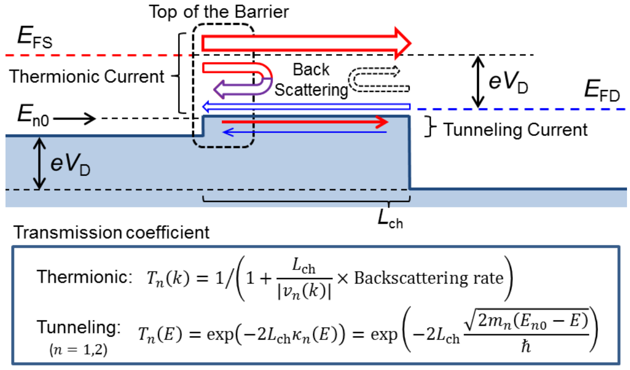

Fig. 3 Schematic image of the model of quasi-ballistic carrier transport. The band alignment in the source and drain is shifted so that the carrier density in them is 2.0×10^{20} cm^{-3}. The "backscattering rate" is the sum of transition rate to electronic states with group velocity with opposite sign.

respectively. Tunneling is also taken into account in both cases. The on-current degrades with L_{ch} by scattering, and the degradation in the [110]/(1$\bar{1}$0) NW with large DOS is more severe than in [110]/(001) or [111] NWs, as shown in Fig. 5. The small degradation by scattering in the [110]/(001) NW, which has small DOS and high mobility [2], leads to its largest on-current.

4. Conclusions

The hole transport properties of Ge NW pMOSFETs were analyzed. The [110]/(1$\bar{1}$0) NW, whose DOS of holes is large, showed the largest ballistic drain current owing to the large hole density. When the source-to-drain direct tunneling and the backscattering in the channel are taken into account, the [110]/(001) NW with less backscattering showed larger on-current than the [110]/(1$\bar{1}$0) NW where the on-current is greatly degraded by scattering. Thus, [110]/(001) NWs will be suitable for Ge NW pMOSFETs.

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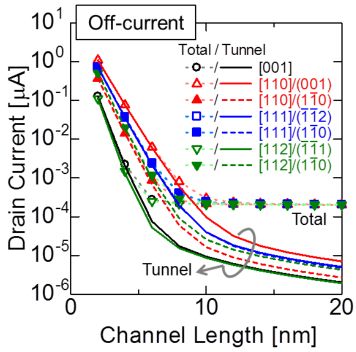

Fig. 4 Effective channel length dependence of off-state ($V_G = 0$ V) current considering tunneling and ignoring backscattering. "Tunnel" indicates tunneling current.

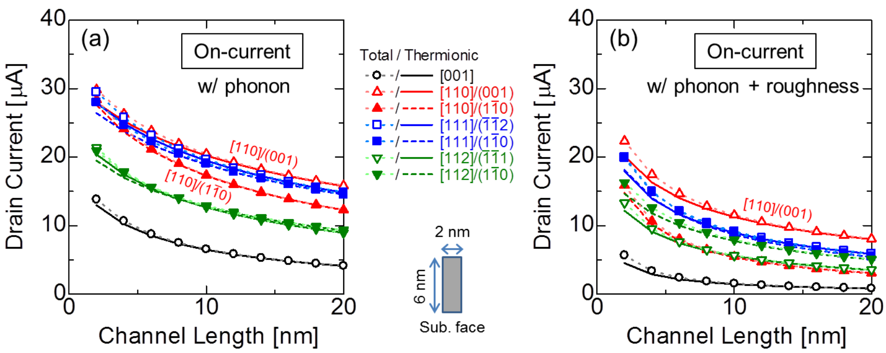

Fig. 5 Effective channel length dependence of on-current ($V_G = -0.6$ V) taking account of backscattering and tunneling. (a) Only phonon scattering is considered. (b) Phonon and roughness scattering are considered. "Thermionic" indicates non-tunneling current, and the difference between "Total" and "Thermionic" corresponds to tunneling current.