Physical Origin of Drive Current Enhancement in Ultra-thin Ge-On-Insulator (GOI) MOSFETs under Full Ballistic Transport

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1. Introduction

It is expected for MOSFETs with ultra-short \( L_g \) around or less than 10 nm that carriers are dominated by ballistic or quasi ballistic transport with few scattering events inside channels. Under full ballistic transport regime, the current drive of MOSFETs is determined by the product of injection carrier velocity at the source edge, \( v_{\text{inj}} \), and surface carrier concentration, \( N_s \), suggesting that the increase in \( v_{\text{inj}} \) is important for further improving the drive current of ballistic MOSFETs. Therefore, I have proposed a scenario of injection velocity engineering by the optimum choice and modulation of the subband structures in MOS inversion layers, where one of promising device structures is ultra-thin GOI (Ge-On-Insulator) MOSFETs [1].

However, physical mechanisms determining the drive current of GOI MOSFETs have not been clearly understood yet. Also, while it has recently been pointed out that the electrical properties of GOI MOSFETs with ultra-short \( L_g \) are strongly dependent on the surface orientations [2, 3], the surface orientation optimized in terms of device performance of ballistic GOI MOSFETs has not been fully identified yet. Thus, this paper examines the physical origin of the current drive enhancement of thin body ballistic GOI n-channel MOSFET, its GOI thickness (\( T_{\text{GOI}} \)) dependence and its surface orientation dependence, through theoretical calculations, by discriminating the effects of \( v_{\text{inj}} \) and \( N_s \) on the drive current.

2. Physical Parameters Related to Drive Current

A simple and analytical model of drain saturation current in n-MOSFET, \( I_{\text{sat}} \), under ballistic transport, formulated by Natori [4], is used in this study for qualitatively analyzing the drive current. As seen in Fig. 1, the calculated \( v_{\text{inj}} \) for 2-fold valleys of (100) Si suggests that lower effective mass (\( m^* \)) parallel to the channel direction and lower density-of-states (DOS) (lower \( m^* \) and lower valley degeneracy) are effective in increasing \( v_{\text{inj}} \) [1].

Table 1 shows the effective mass and the valley degeneracy of Si and Ge inversion-layer electrons on each surface orientation. According to the above guideline, Ge (111), particularly, the first subband ladder can be the optimum electronic system, in terms of obtaining high \( v_{\text{inj}} \). On the other hand, \( I_{\text{sat}} \) is also dependent on \( N_s \), which is affected by inversion-layer capacitance, \( C_{\text{inv}} \), as also shown in Table 1. Smaller \( C_{\text{inv}} \) leads to lower \( C_g \) and resulting lower \( N_s \) at a given \( V_g \) value, leading to lower \( I_{\text{sat}} \). Since, as shown later, the modulation of the subband structure due to changing surface orientations or thinning \( T_{\text{GOI}} \) [1] can provide the opposite influences on \( v_{\text{inj}} \) and \( C_{\text{inv}} \), the impact of the subband structures needs to be analyzed for \( v_{\text{inj}} \) and \( C_{\text{inv}} \) separately. Here, \( v_{\text{inj}} \), \( C_{\text{inv}} \) and \( I_{\text{sat}} \) are calculated from electron subband energies and occupancies of 7 and 5 subbands for the first and the second ladder, respectively, which are determined by Poisson-Schrodinger self-consistent calculations. The current flow direction is taken to be parallel to \( \langle 110 \rangle \), yielding the largest drive current on each surface orientation.

3. Results

Fig. 2 shows calculated \( v_{\text{inj}} \) of (111) GOI MOSFETs as a function of \( T_{\text{GOI}} \) at a fixed value of \( N_s \), confirming that \( v_{\text{inj}} \) increases with a decrease in \( T_{\text{GOI}} \). This enhancement is attributed to the preferential increase in the subband energy of the higher ladders, associated with thinning \( T_{\text{GOI}} \) and the resulting increase in the occupancy in the lower ladder on (111), having lower \( m^* \) and higher \( v_{\text{inj}} \). However, it is found in Fig. 3 that the increase in \( v_{\text{inj}} \) is not observed for (100), while (110) has a moderate \( T_{\text{GOI}} \) dependence. This dependence of \( v_{\text{inj}} \) on (100) is explained by the fact that the (100) has only one ladder and, thus, has no change in the occupancy with thinning \( T_{\text{GOI}} \). These interpretations are confirmed by comparing \( v_{\text{inj}} \) of each subband in higher and lower ladders on (100), (110) and (111) surfaces. It is also found that \( v_{\text{inj}} \) in thin \( T_{\text{GOI}} \) is largest for (111) and decreases, according to the order of (111), (110) and (100).

On the other hand, the amount and the \( T_{\text{GOI}} \) dependence of \( C_{\text{inv}} \) are opposite to those of \( v_{\text{inj}} \). Fig. 4 shows the calculated \( C_{\text{inv}} \) and inversion-layer thickness (\( T_{\text{inv}} = \varepsilon_{\text{GOI}}/Z_m \)) as a function of \( T_{\text{GOI}} \). \( C_{\text{inv}} \) on (100) significantly increases with decreasing \( T_{\text{GOI}} \), attributed to the decrease in \( T_{\text{inv}} \), caused by the decrease in the physical thickness of GOI films [5]. In contrast, it is found that \( C_{\text{inv}} \) on (111) gradually decreases with decreasing \( T_{\text{GOI}} \), attributed to the dominant contribution of lower DOS on \( C_{\text{inv}} \). It has been reported [6] that \( C_{\text{inv}} \) is composed of the component due to DOS and that due to a finite value of \( T_{\text{inv}} \). It is confirmed from the comparison of total \( C_{\text{inv}} \) with \( C_{\text{inv}} \) due to DOS in Fig. 5 that, in very thin \( T_{\text{GOI}} \), \( C_{\text{inv}} \) on (111) is perfectly dominated by DOS, because of much lower value of DOS on (111) than on (100). As a result, in \( T_{\text{GOI}} \) less than 10 nm, \( N_s \) on (111) at a given \( V_g \) value slightly decreases, as seen in Fig. 6, because the effect of lower DOS compensates or surpasses that of the decrease in \( T_{\text{inv}} \). On the other hand, \( N_s \) on (100) increases with a decrease in \( T_{\text{GOI}} \), simply attributed to the decrease in \( T_{\text{inv}} \). This \( N_s \) increase directly leads to the enhancement of \( I_{\text{sat}} \). \( C_{\text{inv}} \) and \( N_s \) on (110) have intermediate characteristics between (100) and (111).

To what degree the effect of \( C_{\text{inv}} \) contributes to \( I_{\text{sat}} \) is strongly dependent on equivalent gate insulator thickness, \( T_{\text{eq}} \). As a result, the optimum surface orientation also depends on \( T_{\text{eq}} \). In the limit of thin \( T_{\text{eq}} (= 0 \text{ ~nm}) \), as seen in Fig. 7, \( I_{\text{sat}} \) of ultrathin \( T_{\text{GOI}} \) at a given \( V_g \) is largest for (100).
and (110), while $I_{sat}$ is largest for (111) and (110) in $T_{eq}$ of 1 nm. Also, $I_{sat}$ of thick GOI or bulk Ge MOSFET is the largest for (111) and (110), irrespective of $T_{eq}$. These results suggest that (110) could be the optimum orientation. However, one drawback of (110) is the strong anisotropy in $I_{sat}$ (Fig. 8), attributed to the anisotropic effective mass, making the CMOS layout design quite complicated. Thus, an appropriate choice of (111) and (100) surfaces, depending on $T_{eq}$ and $T_{GOI}$, can be a reasonable solution for optimum device design of GOI MOSFET.

4. Conclusion

It was found that the physical origin of the drive current enhancement in GOI n-MOSFET with decreasing $T_{GOI}$ is different between (111) and (100), ascribed to the increase in $v_{inj}$ for (111) and the increase in $C_{inv}$ for (100).

References

Fig. 1 Calculated injection velocity of Si 2-fold valleys on (100) as a function of $N_s$

Fig. 2 Calculated $v_{inj}$ of (111) GOI n-MOSFET as a function of $T_{GOI}$ at a fixed $N_s$ value of $1 \times 10^{13}$ cm$^{-2}$

Fig. 3 Calculated $v_{inj}$ of (100), (110) and (111) GOI n-MOSFETs as a function of $T_{GOI}$ at $N_s$ of $1 \times 10^{13}$ cm$^{-2}$

Fig. 4 Calculated $C_{inv}$ and $T_m$ of (100) and (111) GOI as a function of $T_{GOI}$ at $N_s$ of $1 \times 10^{13}$ cm$^{-2}$

Fig. 5 Calculated total $C_{inv}$ and $C_{sub}$ due to DOS for (100) and (111) GOI with $T_{GOI}$ of 50 nm and 1 nm as a function of $N_s$

Fig. 6 Calculated $N_s$ on (100), (110) and (111) GOI at $V_g = V_{th}$ of 0.2 V as a function of $T_{GOI}$

Fig. 7 Calculated $I_{off}$ - $V_g$ characteristics of (100), (110) and (111) GOI ($T_{GOI}$ of 2 nm) and bulk Ge n-MOSFET with $T_{eq}$ of 0 nm and 1 nm at a fixed $I_{off}$ value of 0.3 $\mu$A/um

Fig. 8 Channel direction dependence of $I_{off}$ on (110) and (111) GOI with $T_{GOI}$ of 2 nm