Ballistic hole injection velocity analysis in Ge UTB pMOSFETs: Dependence on body thickness, orientation and strain

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Introduction: Ge exhibits a high bulk hole mobility making it an attractive channel material for pMOSFET devices [1,2]. For improving the device performance and suppressing short channel effects ultra-thin-body (UTB) Ge-on-insulator (GeOI) structures have been researched throughly [2]. Recently <110> oriented GeOI pMOSFETs grown on (110) surface were shown to exhibit enhanced hole mobility, which was 3 times compared to (100)/<100> Si and 2.3 times (100)/<100> Ge pMOSFETs [2]. Due to heavy warping within valence bands and finite atomic granularity in sub-10 nm thick devices, atomistic modelling becomes important. To analyse the recent experimental results a tight binding based 10 band sp3s*d5 (including SO coupling) bandstructure model for is used for UTB Ge [3]. It has been reported in literature that carrier mobility is closely correlated with carrier injection velocity near the top-of-the barrier or the virtual source region [4]. Hence in this paper ballistic injection velocity (v_inj) is used as the metric for analysing UTB Ge device performance.

Approach: Using the 2D E-k information density of states (eV.m^2) (DOS(E)) and density of modes (eV.m) (M(E)) values are extracted. Once the DOS(E) and M(E) information is obtained, v_inj can be defined in a non self consistent manner at a given inversion charge as,

\[ v_{\text{inj}} = \frac{I_{ds}}{N_{\text{inv}}} \text{ where } I_{ds} = \frac{q^{2}}{\hbar} \int_{E_{c}}^{E_{F}} M(E).f_{s} - f_{d}) dE \text{ and } N_{\text{inv}} = q \int_{E_{c}}^{E_{F}} D(E).f_{s} + f_{d}) dE. \]

In this study the analysis of v_inj in UTB Ge structures (Fig. 1) was carried out for different body thickness : 2 – 5 nm for three different type of orientations : (100)/<100> , (110)/<110> and (110)/<111> while applying a biaxial compressive strain \( \varepsilon_{xy/y} \) = 0-3.0%.

Results: As a first step experimental results from [2] were analyzed. Fig. 2 shows the comparison of experimentaly measured mobility in GeOI pMOSFETs and theoretically computed v_inj for Ge UTB at a constant N_{inv} = 1e13 /cm^2. A direct correlation is observed between the mobility and v_inj. This result provides a confidence in further exploring design options. Fig. 3 shows the 2D E-k contour for the three orientations at a body thickness of 4 nm for different strain values. Fig. 4 plots the improvement in v_inj for the same case against increasing compressive strain at N_{inv} = 1x10^{13}/cm^2. (100)/<100> orientation exhibits ~50% improvement in v_inj but (110)/<110> outperforms both of the other orientations. Fig. 5 shows the change in injection velocity with body thickness at a constant \( \varepsilon_{xy/y} \) = 3%. (110)/<110> orientation shows ~55% improvement in v_inj as opposed to degraded performance for other orientations. Fig. 6 shows a 2D contour plot of ballistic v_inj for (110)/<110> at N_{inv} = 1e13/cm^2 with dependence on body thickness and strain. Reducing body thickness enhances v_inj however the role of compressive strain diminishes at smaller thicknesses.

Conclusion: Demonstrated a direct correlation between experimentally observed mobility enhancement in (110)/<110> oriented Ge UTB pMOSFET and ballistic v_inj, (110)/<110> orientation outperforms (100)/<100> and (110)/<111> due to lighter transport mass. Reducing body thickness from 5nm to 2nm improves (110)/<110> ballistic v_inj by ~50%. Compressive strain can act as a performance booster when thickness>3nm.

This study explores improvement in ballistic $v_{inj}$ due to body thickness, strain and orientation.

Experimental values reported at $N_{inv}=1 \times 10^{13}/cm^2$. Theoretical $v_{inj}$ calculated for 5 nm unstrained Si and Ge structures at $N_{inv}=1 \times 10^{13}/cm^2$.

Effect of compressive strain on $v_{inj}$ calculated for 4 nm Ge UTB structures at $N_{inv}=1 \times 10^{13}/cm^2$. (100)/<100> shows ~50% enhancement as compared to only ~10% enhancement in (110)/<110>. However still (110)/<110> exhibits highest overall $v_{inj}$.

Dependence of $v_{inj}$ (at $N_{inv}=1 \times 10^{13}/cm^2$) with body thickness for 4 nm thick and $\epsilon_{xx/yy}=-3\%$ biaxial strained Ge UTB. (110)/<110> orientation shows ~55% improvement as body thickness is reduced from 5 nm to 2 nm. Other orientation show a degradation with reducing body thickness.

A 2D contour plot showing $v_{inj}$ (at $N_{inv}=1 \times 10^{13}/cm^2$) dependence on strain and body thickness. Reducing body thickness improves $v_{inj}$ however at the same time improvement due to strain diminishes. Best performance is still obtained at smaller body thickness.