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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 thoroughly [2]. Recently <110> oriented Ge-OI 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.m²) (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 high V_{ds} (=0.5V) & at a given inversion charge as, $v_{inj} = I_{ds} / N_{inv}$ where $I_{ds} = \frac{q^2}{h} \int_{E_c}^{\infty} M(E) \cdot (f_s - f_d) dE$ & $N_{inv} = q \int_{E_c}^{\infty} DOS(E) \cdot (f_s + f_d) dE$.

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 $\epsilon_{xx/yy}$ =0:-3.0%.

Results: As a first step experimental results from [2] were analyzed. Fig. 2 shows the comparison of experimentally measured mobility in GeOI pMOSFETs and theoretically computed v_{inj} for Ge UTB at a constant N_{inv} =1e13 /cm². A direct correlation is observed between the mobility and v_{inj} . 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} =1x10¹³/cm². (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 $\epsilon_{xx/yy}$ =-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/cm² 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 also act as a performance booster when thickness>3nm.

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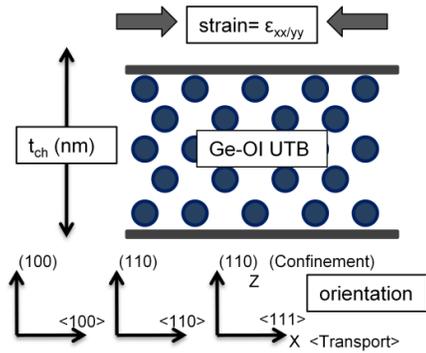


Fig. 1 Schematic of a Ge-OI ultra thin body pMOSFET. This study explores improvement in ballistic v_{inj} due to body thickness, strain and orientation.

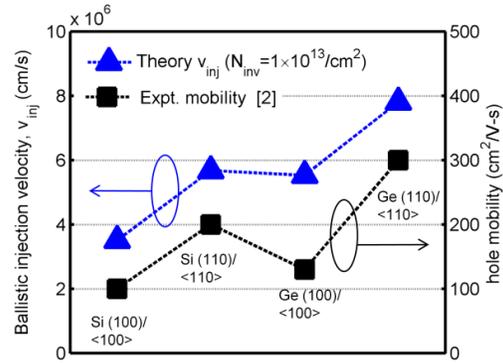


Fig. 2 Comparison of experimental mobility enhancement for (100) and (110) oriented Ge (12 nm thick) and Si UTB pMOSFETs with theoretical ballistic v_{inj} . Experimental values reported at $N_{inv}=1e13/cm^2$. Theoretical v_{inj} calculated for 5 nm unstrained Si and Ge structures at $N_{inv}=1e13/cm^2$.

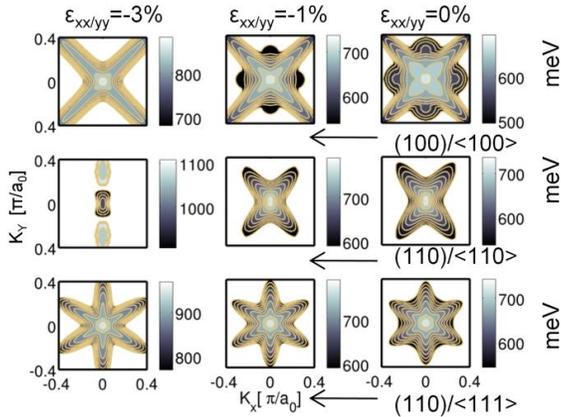


Fig. 3 In plane 2D E-k diagram for (100)/<100>, (110)/<110> and (110)/<111> oriented, 4 nm thick Ge UTB. Energies upto $8kT$ from valence band (VB) maxima are plotted. Effective mass for topmost (110)/<111> valence band = 0.33 as compared to 0.16 for (110)/<110> and 0.1 for (100)/<100>. Heavy warping in (100)/<100> leads to higher effective mass as fermi level is pushed inside the VB.

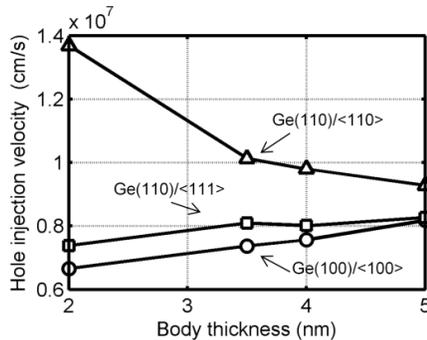


Fig. 5 Dependence of v_{inj} (at $N_{inv}=1e13/cm^2$) with body thickness for 4 nm thick and $\epsilon_{xx/yy} = -3\%$ biaxial strained Ge UTB. (110)/<110> orientation shows $\sim 55\%$ improvement as body thickness is reduced from 5 nm to 2nm. Other orientation show a degradation with reducing body thickness.

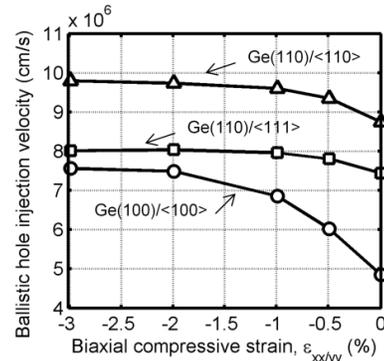


Fig. 4 Effect of compressive strain on v_{inj} calculated for 4 nm Ge UTB structures at $N_{inv}=1e13/cm^2$. (100)/<100> shows $\sim 50\%$ enhancement as compared to only $\sim 10\%$ enhancement in (110)/<110>. However still (110)/<110> exhibits highest overall v_{inj}

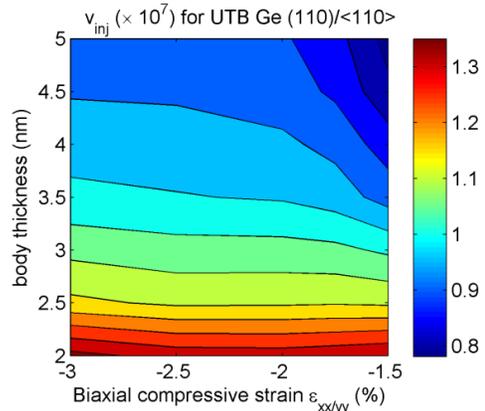


Fig. 6 A 2D contour plot showing v_{inj} (at $N_{inv}=1e13/cm^2$) dependence on strain and body thickness. Reducing body thickness improves v_{inj} , however at the same time improvement due to strain diminishes. Best performance is still obtained at smaller body thickness.