Student Paper

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 mobilty 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 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.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, $v_{inj} = {I_{ds}}/{N_{inv}}$ where $I_{ds} = \frac{q^2}{h}\int_{Ec}^{\infty} M(E).(f_s - f_d)dE$ and $N_{inv} = q\int_{Ec}^{\infty} DOS(E).(f_s + f_d)dE$. 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 $\varepsilon_{xx/yy}$=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 dirct 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 $N_{inv}=1\text{x}10^{13}/\text{cm}^2$.(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 thickess at a constant $\varepsilon_{xx/yy}$=-3% .(110)/<110> orientation shows ~55% improvement in v_{inj} as opposed to degraded performance for other orientatations. 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 also act as a performance booster when thickness>3nm.

References: [1] S. Takagi and M. Takenaka, “Prospective and Critical Issues of III-V/Ge CMOS on Si Platform”, ECS Trans. 35, 279 (2011) [2] S. Dissanayake, S. Sugahara, M. Takenaka, and S. Takagi, “High performance ultrathin (110)-oriented Ge-On-insulator pMOSFETs fabricated by Ge condensation technique,” Appl. Phys. Express, vol. 3, no. 4, p. 041 302, Apr. 2010.[3] T. B. Boykin, G. Klimeck and F. Oyafuso, “Valence Band Effective-Mass Expressions in the sp3d5s* Empirical Tight-Binding Model Applied to a Si and Ge Parametrization,” *Phys. Rev. B*, vol. 69, 115201/1-10, Mar. 2004.[4] A. Khakifirooz and D. A. Antoniadis, “Transistor performance scaling:The role of virtual source velocity and its mobility dependence,” in IEDM Tech. Dig., 2006, pp. 667–670.

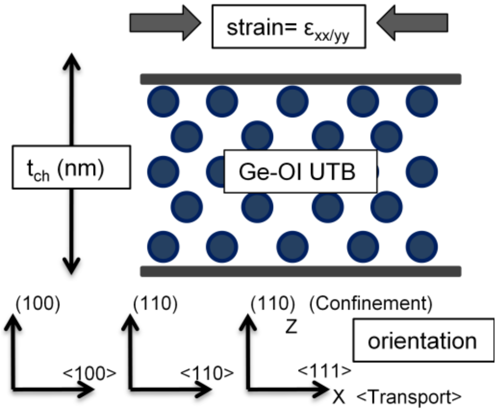

Fig. 1 Schematic of a Ge-OI ultra thin body pMOSFET. This study explores improvement in ballistic v_{inj} due to body thickness, strain and orientation.

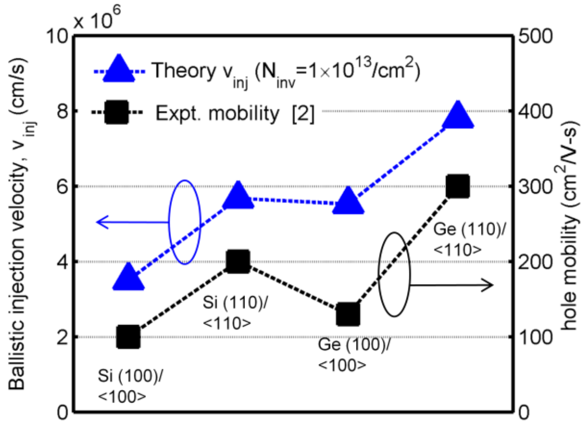

Fig. 2 Comparison of experimental mobility enhancement for (100) and (110) oriented Ge (12 nm thick) and Si UTB pMOSFETs with theoretical ballistic v_{inj} . Experimental values reported at N_{inv}=1e13/cm^2.Theoretical v_{inj} calculated for 5 nm unstrained Si and Ge structures at N_{inv}=1e13/cm^2.

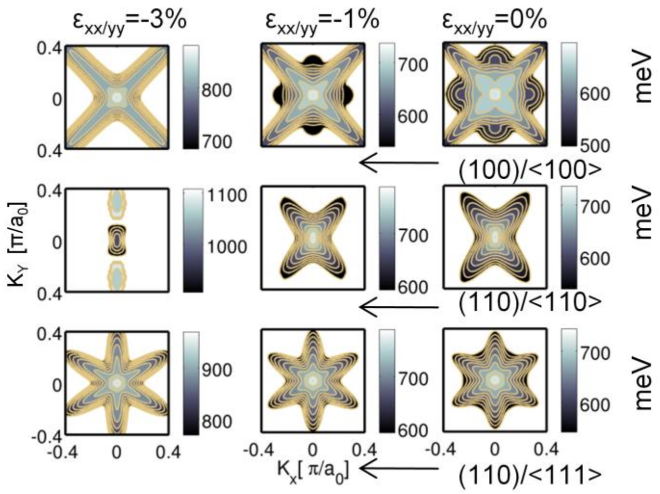

Fig. 3 In plane 2D E-k diagram for (100)/<100>, (110)/<110> and (110)/<111> oriented, 4 nm thick Ge UTB. Energies upto 8kT from valenve band (VB) maxima are plotted. Effective mass for topmost (110)/<111> valence band = 0.33 as compared to 0.16 for (110)/<110> and 0.1 for (100)/<100>. Heavy warping in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

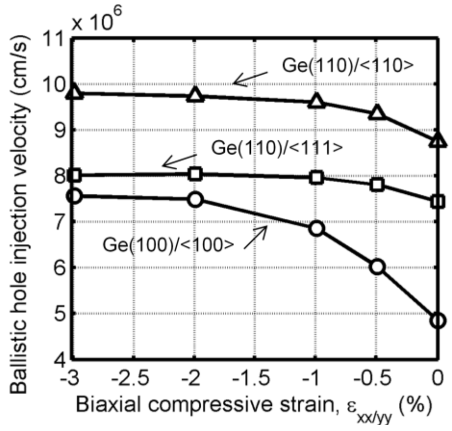

Fig. 4 Effect of compressive strain on v_{inj} calculated for 4 nm Ge UTB structures at N_{inv}=1e13/cm^2. (100)/<100> shows ~50% enhancement as compared to only ~10% enhancement in (110)/<110>. However still (110)/<110> exhibits highest overall v_{inj}

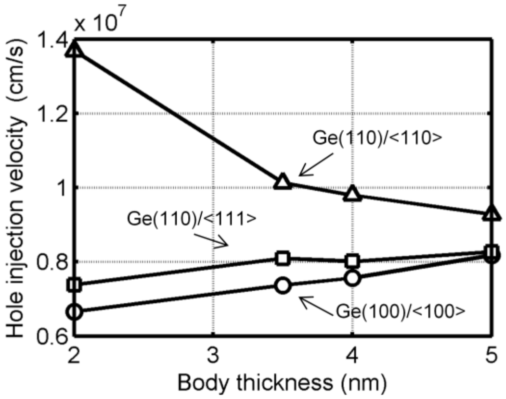

Fig. 5 Dependence of v_{inj} (at N_{inv}=1e13/cm^2) with body thickness for 4 nm thick and $\varepsilon_{xx/yy=}$ -3% biaxial strained Ge UTB. (110)/<110> orientation shows ~55% improvement as body thickness is reduced from 5 nm to 2nm. Other orientation show a degradation with reducing body thickness.

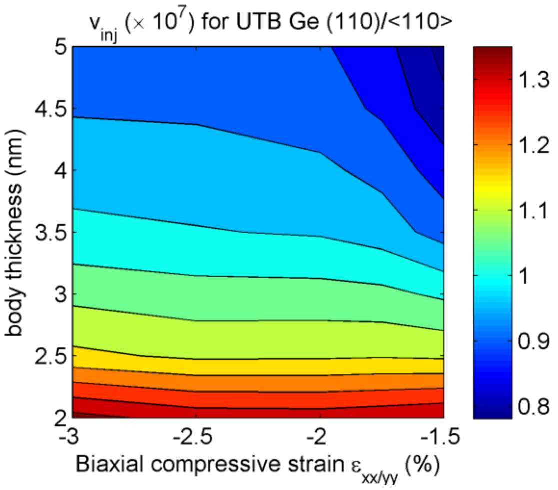

Fig. 6 A 2D contour plot showing v_{inj} (at N_{inv}=1e13/cm^2) dependence on strain and body thickness. Reducing body thickness improves v_{inj}, however at the same time improvement due to strain diminishes. Best performance is still obtained at smaller body thickness.