# Hole Mobility Enhancement in Uniaxially Strained SiGe FINFETs: Analysis and Prospects

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**Introduction:** Strain induced mobility enhancement in silicon (Si) FINFETs is attractive because of higher drive current and immunity to short channel effects. Uniaxial compressive strain combined with 110 channel orientation is found to give the best hole mobility enhancement in FINFETs [1]. However, further hole mobility enhancement in (110)/<110>Si pFINFETs is limited by strain relaxation issues and commonly observed limited impact of strain on (110) compared to (100) [2]. SiGe channel FINFET is an attractive replacement. Mobility enhancement with FINFET structure(SiGe channel with 25% Ge) that gives the best performance at low power has already been reported [3]. In this paper, we show for the first time that a 157% increase in hole mobility is possible in (110)/<110> SiGe FINFETs by increasing Ge content to 50% even in the presence of scattering due to enhanced interface charge density from increasing $D_{it}$, enhanced alloy scattering [4] and strain relaxation.

**Process Technology:** Biaxial compressively strained $Si_{0.75}Ge_{0.25}$ layer, 30nm thick, is epitaxially grown on 10nm thick (100) SOI wafers which, upon patterning, produced uniaxially strained 20nm wide, 40nm tall fins with {110}<110> channel orientation. Si fins were also fabricated for comparison. The FINFETs were formed by conventional process [3] and included a neutral/compressively strained contact etch stop layer (CESL) followed by interlayer dielectric (ILD) deposition, contact plug formation and copper metallization. Fig. 1 shows the TEM image of the fin cross section.

**Results and Discussions:** Finite element method (FEM) simulation in $SSGOI_{0.25}$ pFINFETs show an average sidewall stress of 1600 MPa (1% strain) which takes into account relaxation through amorphized S/D regions following the ion implantation. Higher performance of $SSGOI_{0.25}$ over (110)/<110>Si (SOI) pFINFETS is evident from Fig. 2. At 10n/um of Ioff, the $SSGOI_{0.25}$ pFINFETs with neutral and compressive CESL show 17% and 46% increase in Ion, respectively, over the silicon counterpart.. The subthreshold slope(SS) is slightly lower due to increased Dit in $SSGOI_{0.25}$ pFINFETs (Fig.3). A 57% net enhancement in hole mobility is seen at sheet carrier density (Ns) of $1x10^{13}cm^{-2}$ (Fig. 4) at 300K from long channel devices. However, the presence of alloy scattering in $SSGOI_{0.25}$ negates this enhancement at 77K (Fig 5). Hole mobility is extracted across temperatures and is then modeled by including the following scattering mechanisms: interface charge scattering ($\mu_{int}$), surface roughness scattering ($\mu_{SR}$), acoustic phonon($\mu_{ac}$) and optical phonon ($\mu_{opt}$). In $SSGOI_{0.25}$ pFINFETs additional mechanism of alloy scattering ($\mu_{alloy}$) is included the effect of which on $SSGOI_{0.25}$ mobility is seen clearly at T=77k (Fig. 5). Bulk coulomb scattering is ignored due to low doping levels in FINFET and remote high-k phonon scattering due to metal gate screening [4]. Excellent agreement between measured and modeled mobility values is seen (Fig 6). Mobility in $SSGOI_{0.25}$ and SOI pFINFETs at 300K and at $Ns=1x10^{13}cm^{-2}$ is dominated by phonon scattering whereas alloy scattering becomes important in $SSGOI_{0.25}$ at 77K. The different mobility components in $SSGOI_{0.25}$ are scaled appropriately (using linear extrapolation for the parameters listed in table1) to project the mobility for SiGe channel pFINFETs with higher Ge content(50%). A 157% enhancement is thus estimated at T=300K, $Ns=1x10^{13}cm^{-2}$ for $SSGOI_{0.50}$ over $SSGOI_{0.25}$ assuming 2x increase in the interface states(Fig. 7). At 300K hole mobility is still limited by phonon scattering but at 77K alloy scattering becomes the single dominant mechanism (Fig. 8). Decreasing fin length to 0.5um results in further strain relaxation (Fig. 9) and the net strain retained reduces to 1.5% which will degrade the mobility to 360 $cm^2V^{-1}s^{-1}$.

**Conclusions:** Experimental and theoretical hole mobility study in uniaxially strained (110)<110> $Si_{0.75}Ge_{0.25}$ pFINFETs shows that alloy scattering contributes only a small fraction of the overall mobility at 300K but plays a bigger role limiting 77K hole mobility. Increasing the Ge content to 50% increases the strain level. However, the extent of strain relaxation depends on the length of the fin. Fig. 10 shows the measured and projected hole mobility for SiGe FINFETs with 25% and 50% Ge mole fraction. Higher strain induced reduction of effective mass compensates for the increased interface charge density, Dit, in $SSGOI_{0.5}$ pFINFET and alloy disorder and results in 157% increase in the hole mobility observed at $Ns=1x10^{13}cm^{-2}$ and T=300K. Fig. 11 benchmarks the hole mobility in $SSGOI_{0.25}$ and $SSGOI_{0.5}$ pFINFETs as a function of electrical oxide thickness(TOXE) and shows its advantage over relaxed Ge channel MOSFETs. However strain relaxation for shorter length fins need to be addressed using careful layout techniques. High mobility combined with excellent short channel behavior make these devices a promising candidate for future technology node.

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[2] P.Packan et al., IEDM 2009
[3] I.Ok et al., IEDM 2010
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[5] R.Chau et al., IEEE EDL,vol.25, June (2004)
[6] Wei-Chin Wang et al., INEC, Jan(2010)

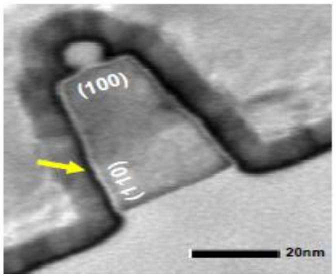


Fig 1. Cross section of SiGe/Si stack fin under gate with $Si_{0.75}Ge_{0.25}$(30nm)/Si(10nm)

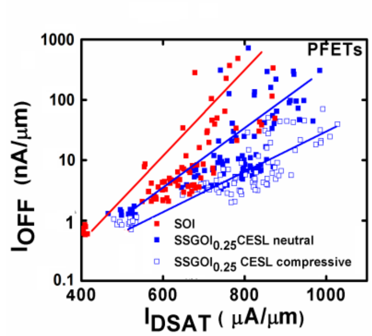


Fig 2. Ioff vs Idsat shows better performance of $SSGOI_{0.25}$ over SOI pFINFETs

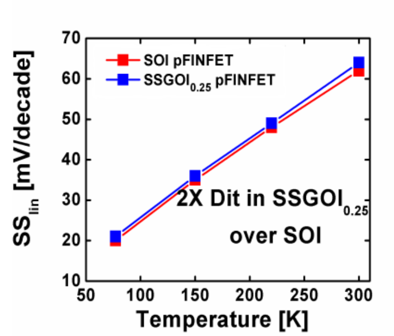


Fig 3. $SS_{lin}$ vs T for $SSGOI_{0.25}$ and SOI pFINFETs

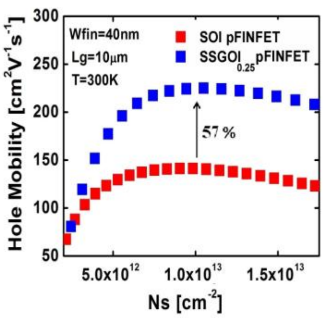


Fig 4. $SSGOI_{0.25}$ pFINFETs shows 57 % improvement in mobility over SOI pFINFETs

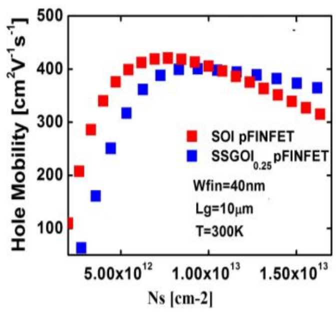


Fig 5. Hole mobility at T=77K in $SSGOI_{0.25}$ pFINFET flattening out at high Ns due to alloy scattering

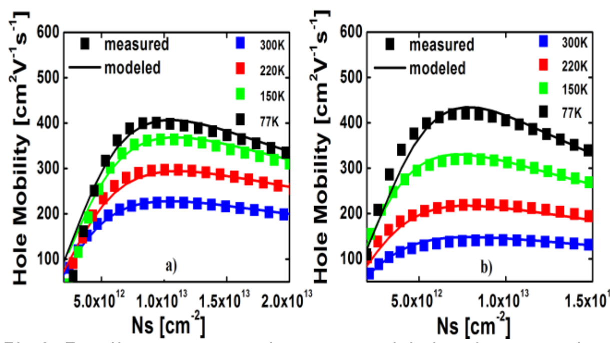


Fig 6. Excellent agreement between modeled and measured mobility values for a) SOI pFINFET b) $SSGOI_{0.25}$ pFINFET

| |
|---|
| $\mu_{int}$ $\alpha$ ($\varepsilon^{1.6}$ $m_c^{-1}$ $N_{it}^{-1}$) |
| $\mu_{SR}$ $\alpha$ ($\varepsilon^2$ $m_c^{-1}$ $m_{dos}^{-1}$) |
| $\mu_{ac}$ $\alpha$ ($\rho\varepsilon^{1/3}m_c^{-1}$ $m_{dos}^{-1}m_z^{-1/3}$) |
| $\mu_{opt}$ $\alpha$ ($\rho$ $m_c^{-1}$ $m_{dos}^{-1}$) |
| $\mu_{alloy}$ $\alpha$ ($x(1-x)\varepsilon^{1/3}m_c^{-2}$ $m_z^{1/3}$) |

Table 1. Scattering parameters that change upon increasing Ge content to 50%. **ε, $m_c$**, $m_{dos}$, $m_z$, **ρ** and x are dielectric constant, conductivity mass, DOS mass, quantization mass ,density and Ge mole fraction respectively.

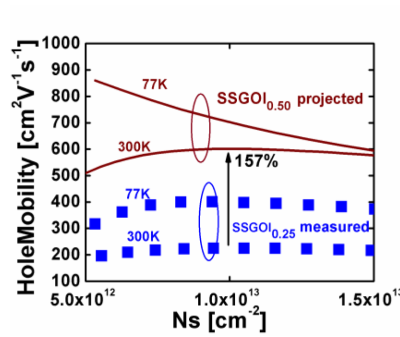


Fig 7. Measured and predicted hole mobilities in SiGe FINFETs

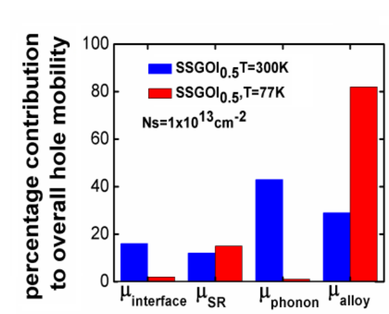


Fig 8. Alloy scattering is the single dominant mechanism at 77K in $SSGOI_{0.5}$ FINFET

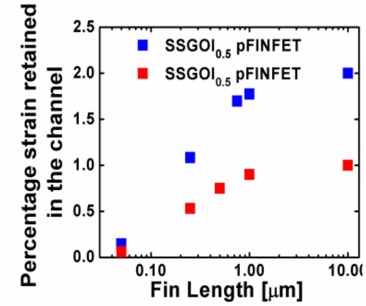


Fig 9. Strain relaxes at the fin edge due to the free surface after patterning

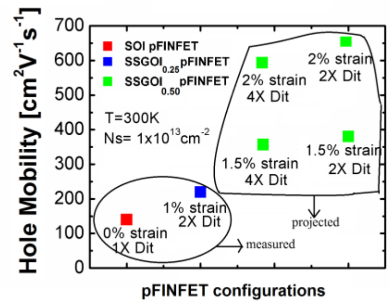


Fig 10. Measured and projected hole mobilities in SiGe FINFETs

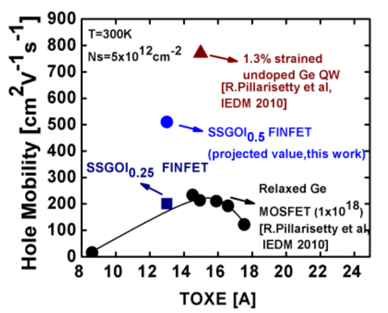


Fig 11. Hole mobility benchmarking as a function of TOXE