Quantum Well Model for

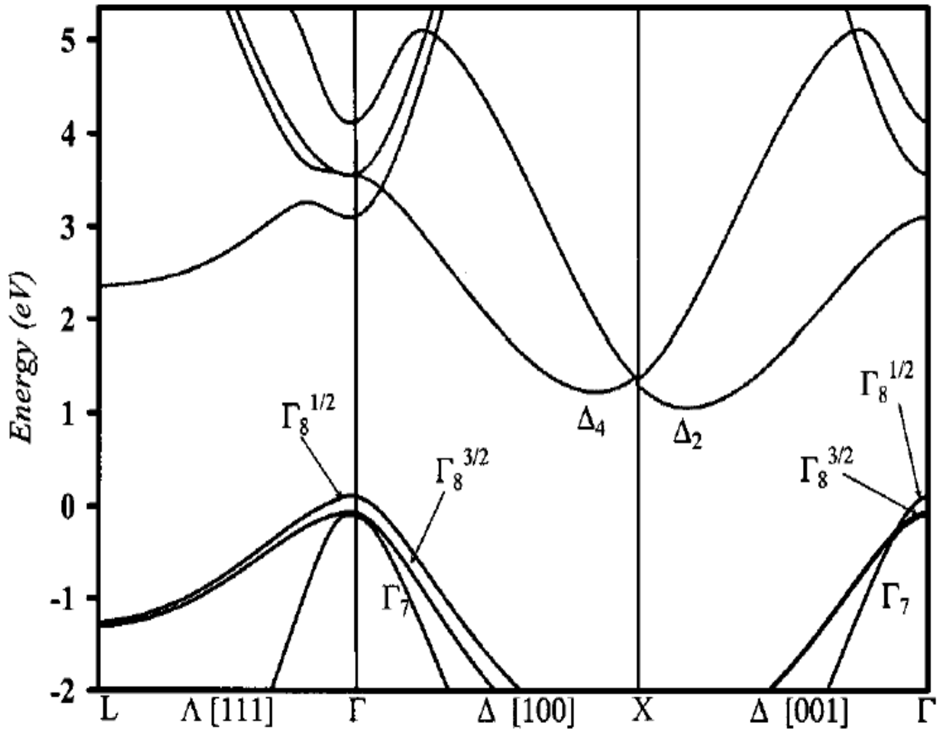
Strained MOSFET

CROSSLIGHT
Software Inc.

Contents

- **Strained silicon quantum well model**
- **Biaxial tensile strained Si/SiGe MOSFET (theory and experiment)**
- **Uniaxial strained MOSFET (simulation)**
- **Summary**

Strained Silicon



Strained Si on SiGe (Richard et. Al. J. Appl. Phys. Vol. 94,1795)

Complete first principle band Structure model too difficult To be included in 3D drift-Diffusion solver. Use Composition parameterization Instead.

Material macro needs for all composition range:

- **Strained bandgap for differen valleys.**
- **DOS masses for each valley, for both perpendicular and parallel directions.**
- **Bandgap discontinuities.**
- **Physical based anisotropic mobility.**

Crosslight's Strained Silicon Mobility Model

Crosslight's semi-classical valley-averaged mobility model.

1) **MOS mobility change= valley dependent bulk mobility averaged over valley subbands in quantized states in MOS conduction channel.**

2) **Valley dependent bulk mobility change= effective mass change (acoustic-phonon intravalley scattering part) + scattering suppression due to band valley splitting (optical phonon part).**

Bulk Silicon Mobility

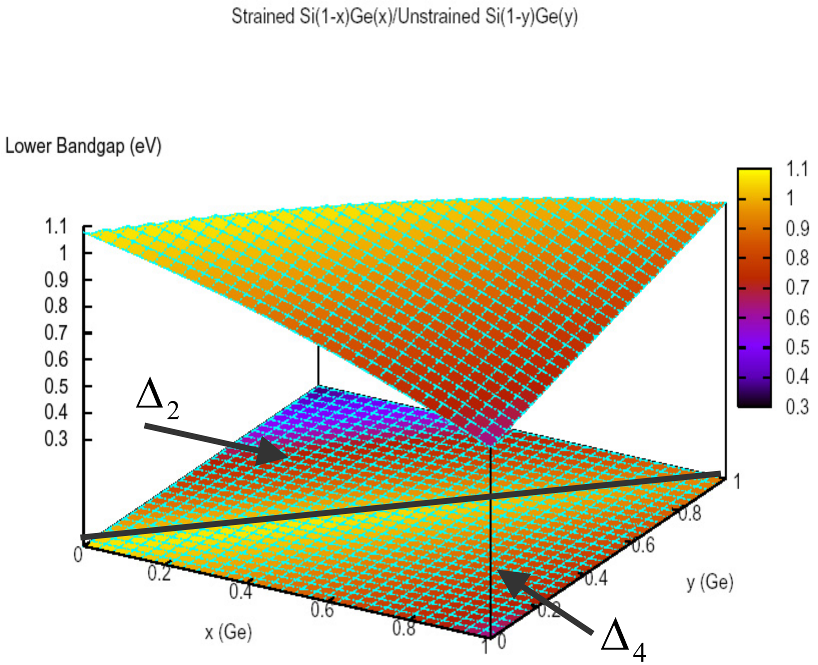
Intra-valley Acoustic Phonon Scattering part:

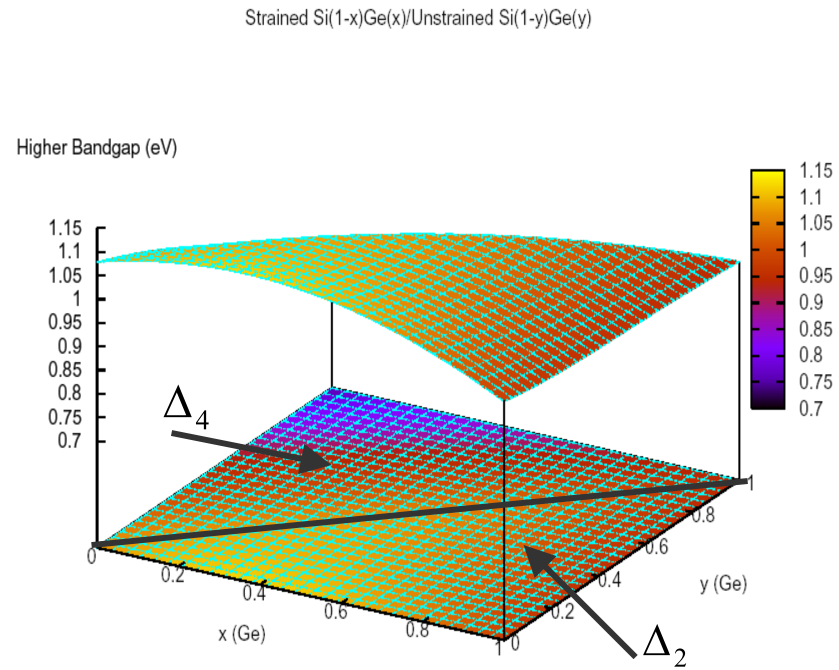
$$\mu_{ac} = \frac{2^{3/2}\sqrt{\pi}e\hbar^4\rho v_s^{\ 2}}{3m^{*5/2}D_{ac}^{\ 2}(k_B T)^{3/2}} \propto T^{-1.5}$$

Ref: K. Uchida and J. Koga, "Mobility in Si MOSFETs", short course at Symposium on Nano Devices Technology SNDT, (Hsinchu, Taiwan), May 2004.

Bulk valley mobility is calibrated against bulk silicon and biaxial strained Si/SiGe system.

Parameterization of Strained Silicon Band Structure

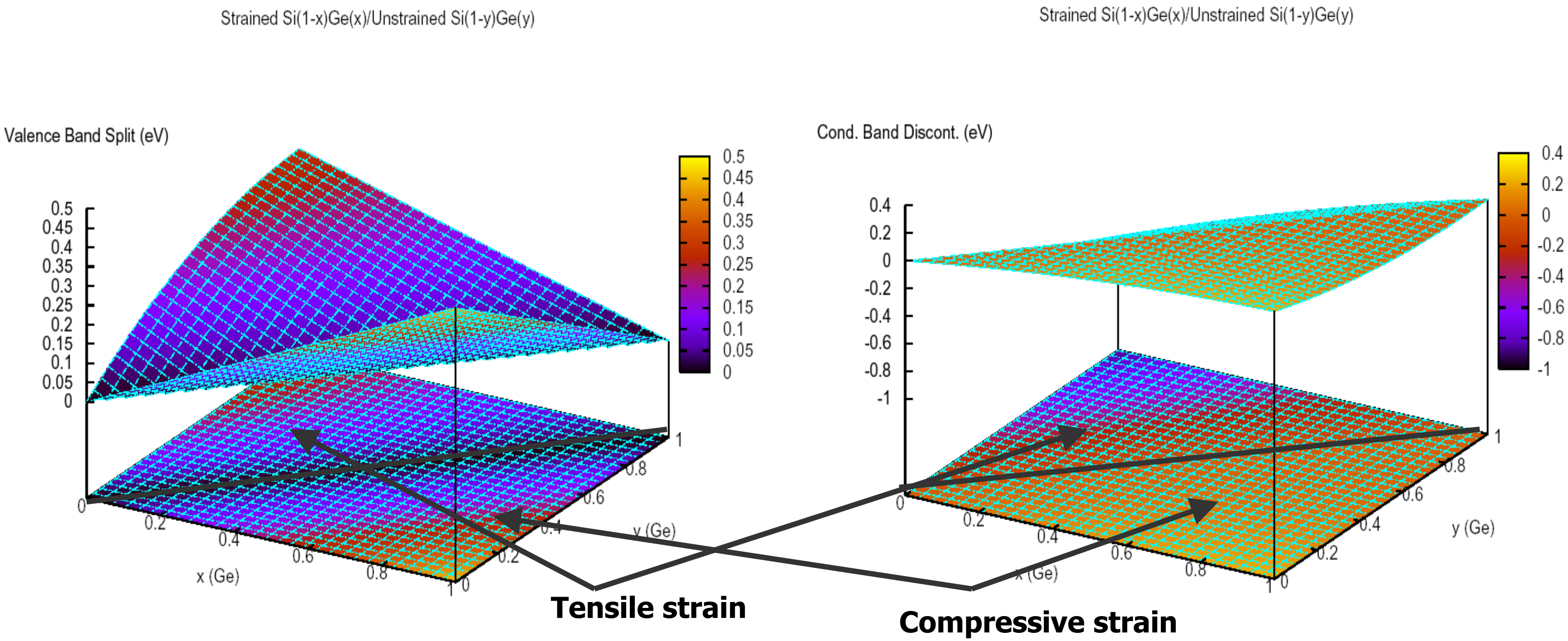




Implemented in Crosslight material macro library

Strained Si(1-x)Ge(x) on relaxed Si(1-y)Ge(y) (Rieger&Vogl, Phys. Rev B48, 14276)

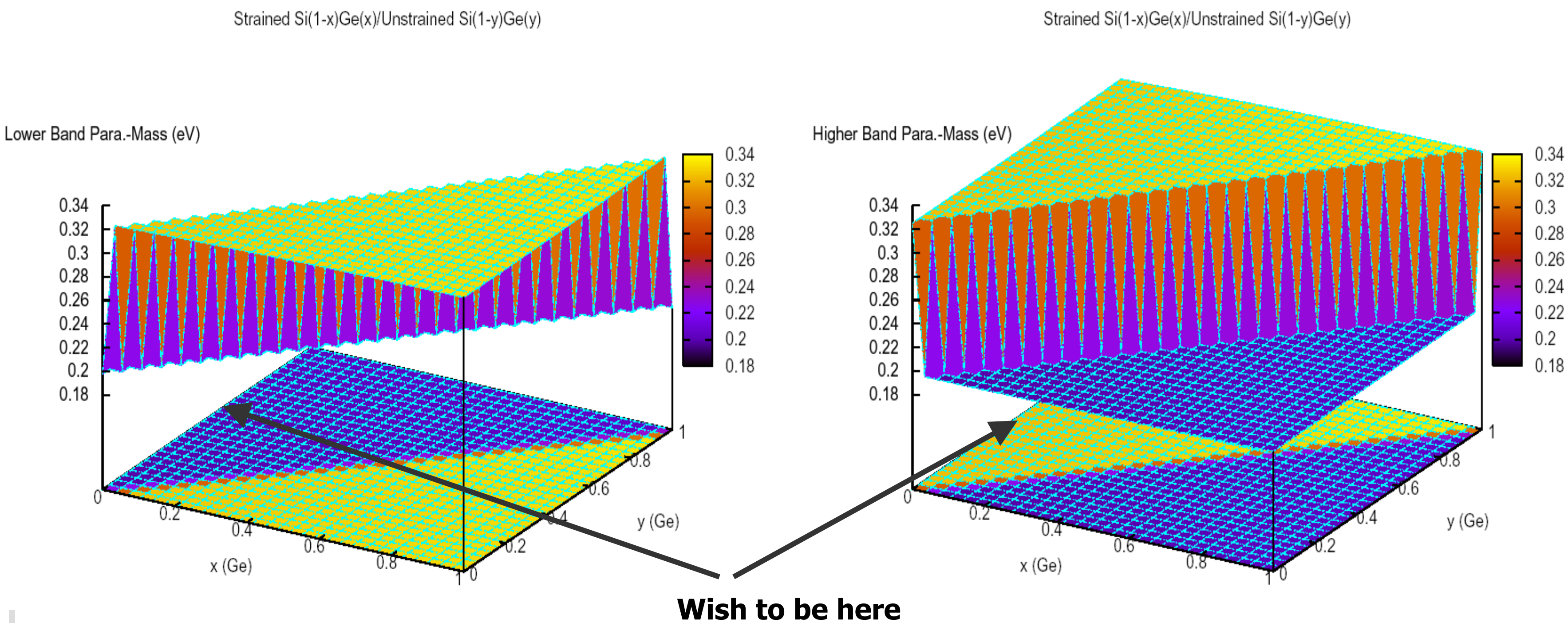
Parameterization of Valence Split & Band Discont.



Implemented in Crosslight material macro library

Strained Si(1-x)Ge(x) on relaxed Si(1-y)Ge(y) (Rieger&Vogl, Phys. Rev B48, 14276)

Parameterization of Effective Masses.



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Strained Si(1-x)Ge(x) on relaxed Si(1-y)Ge(y) (Rieger&Vogl, Phys. Rev B48, 14276)

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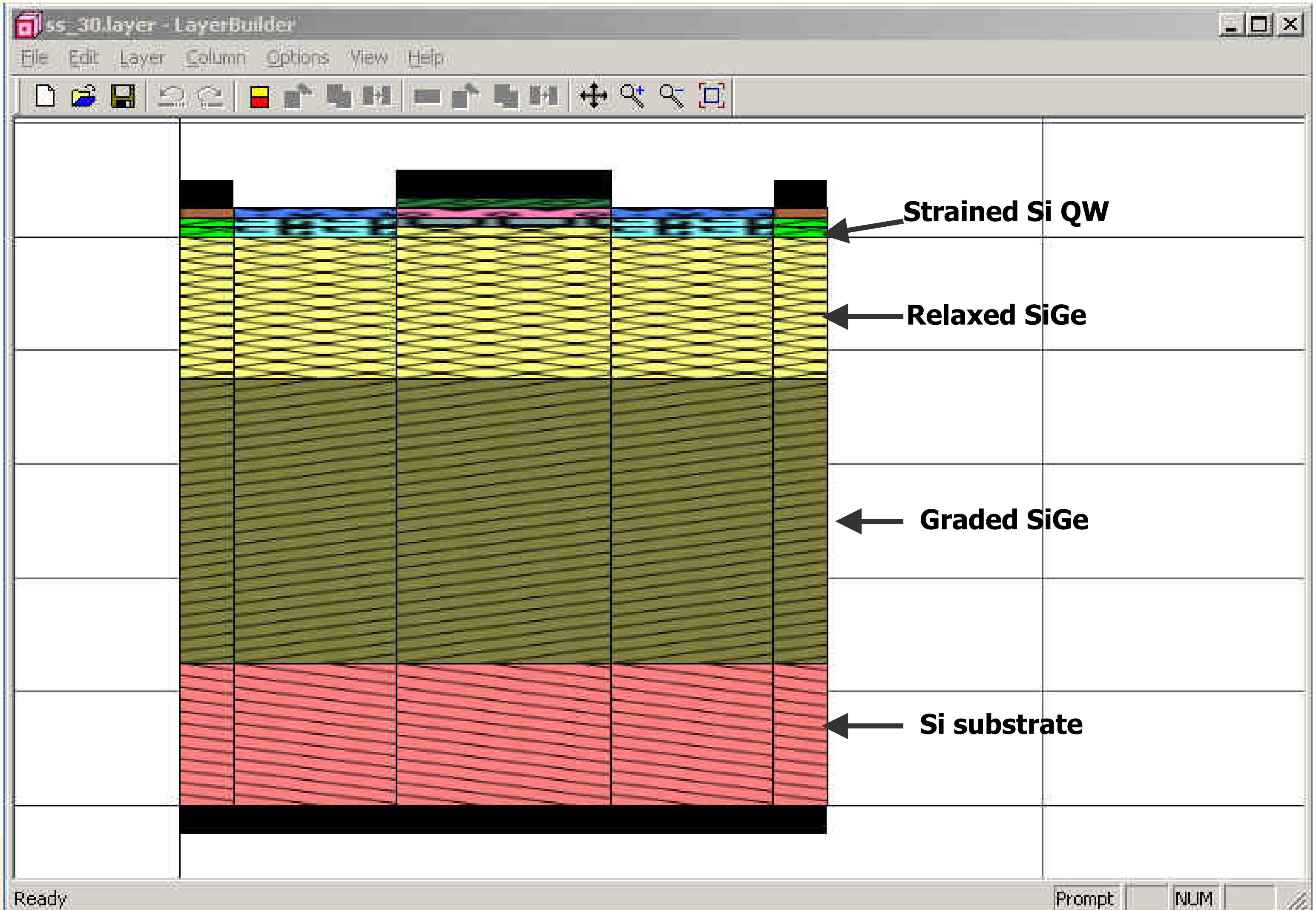
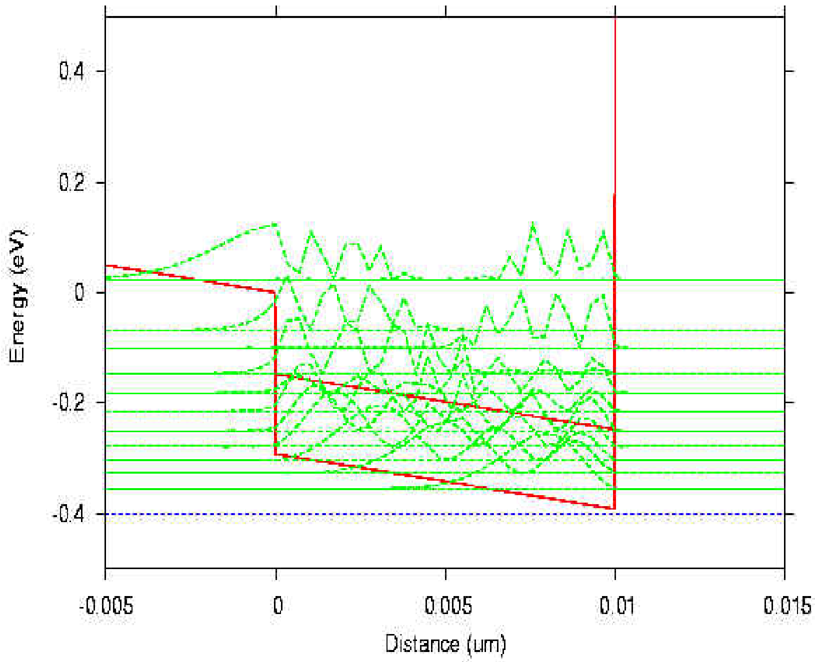
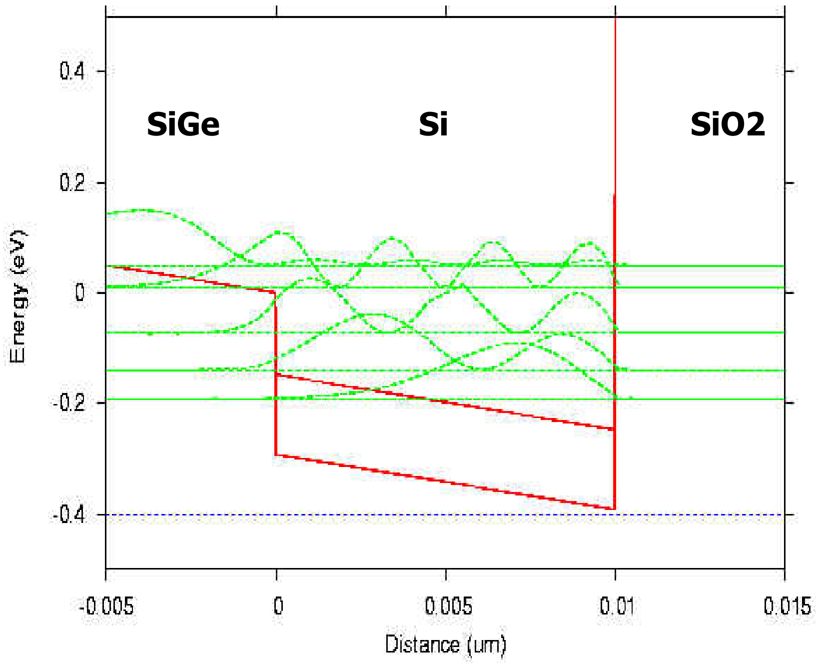
A simple 2D strained MOSFET structure



Quantized Electron States in Si/SiGe

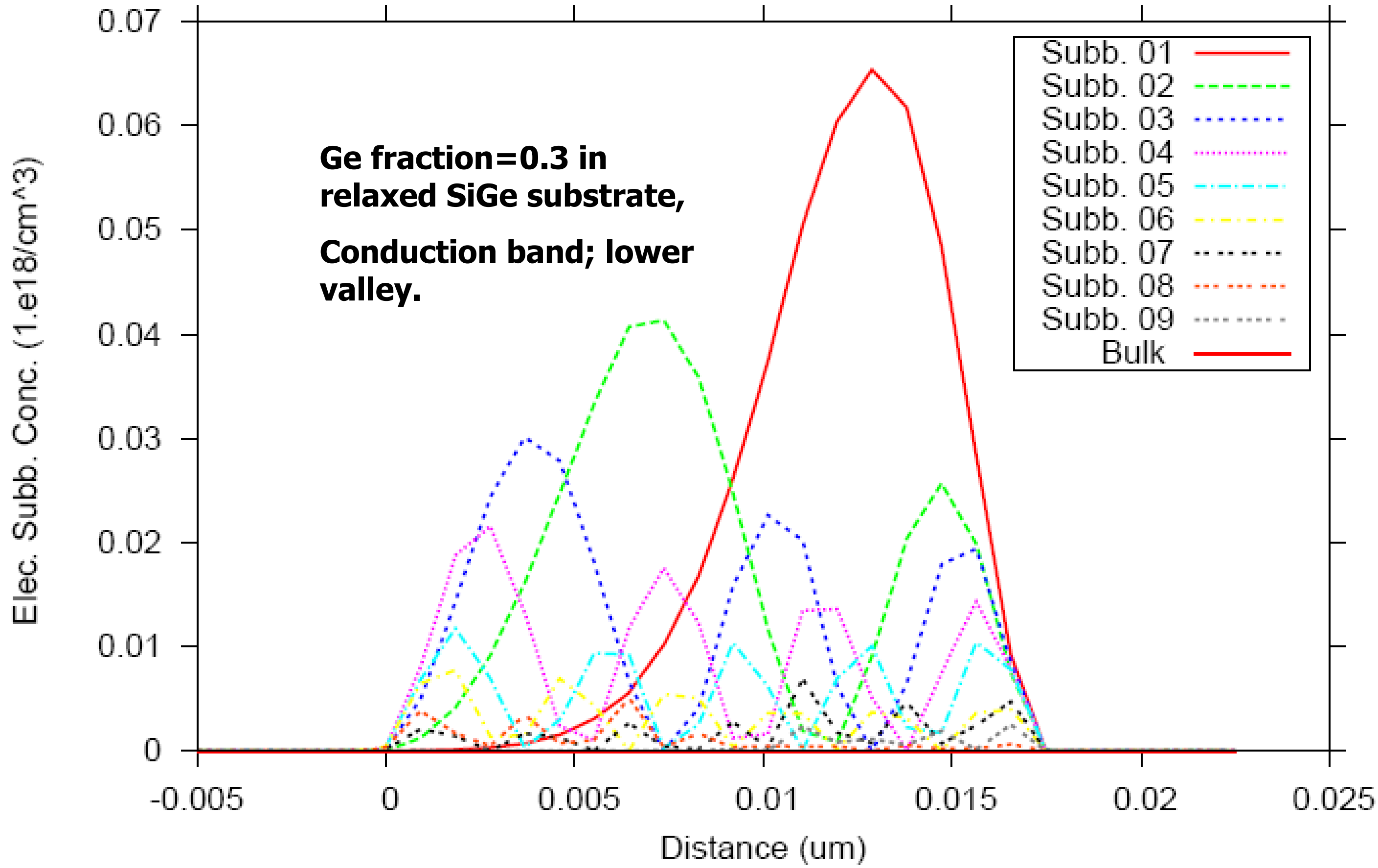




Lower valley: smaller parallel mass but larger perpendicular mass.

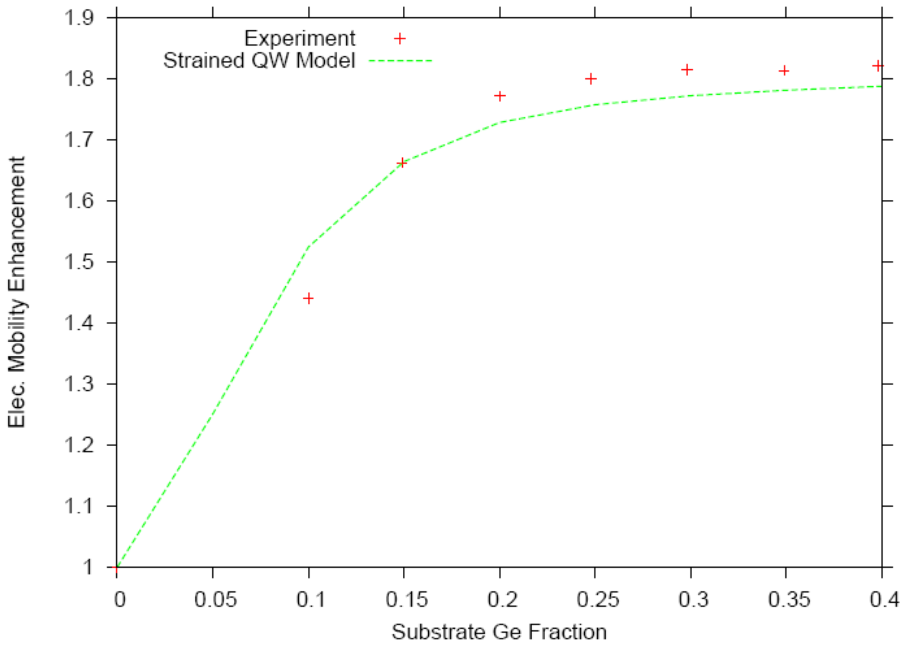
Higher valley: larger parallel mass but smaller perpendicular mass.

Carrier densities in Si/SiGe QW



Carrier density in each subband for different band valleys → weighted average of physical quantities such as mass dependent mobility

Simulated Mobility Enhancement for Si/SiGe MOS (biaxial tensile strain)



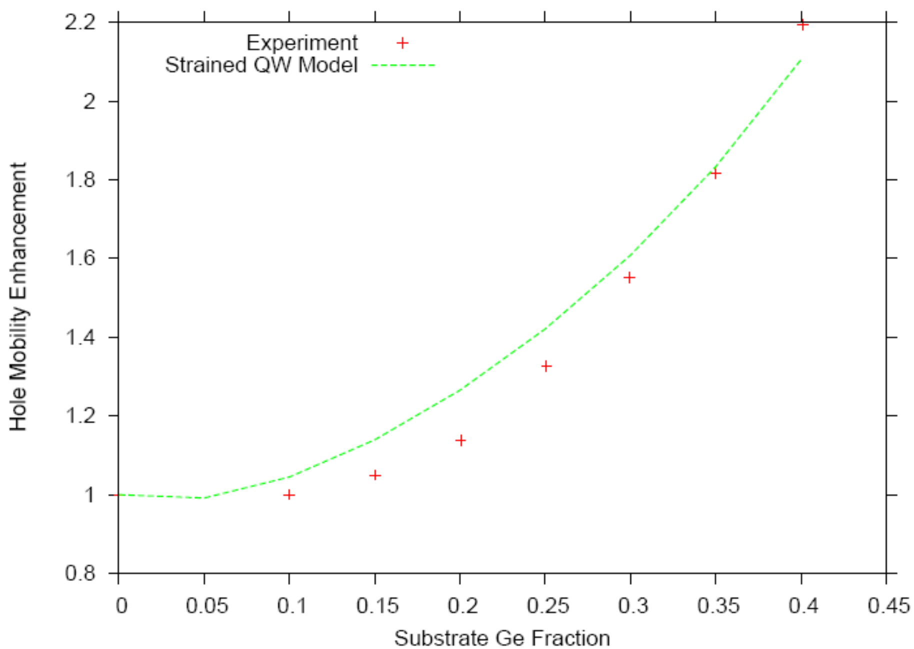
Effective mass change + valley splitting

➔ mobility in each confined quantum state.

Quantum subband population weighted average

➔Channel mobility enhancement

➔Id-Vd prediction

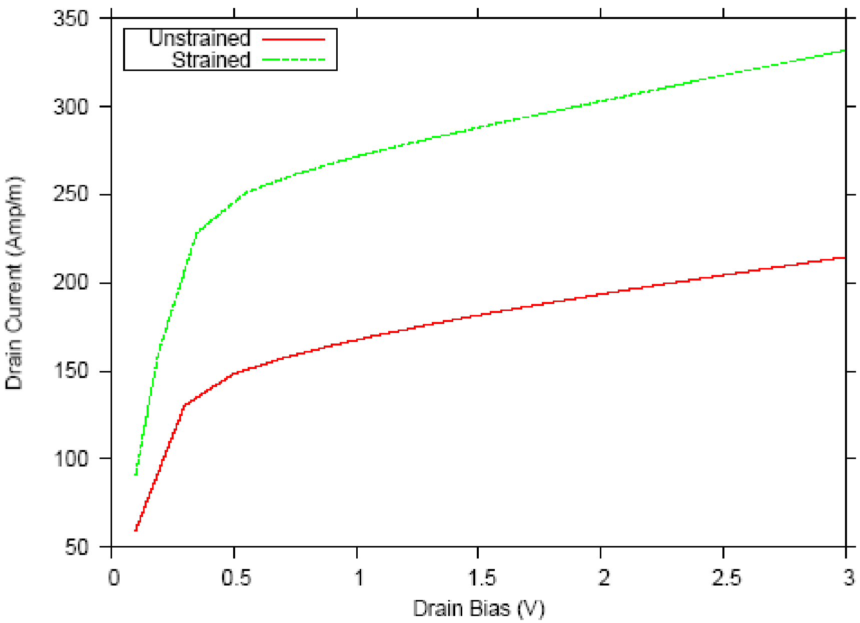


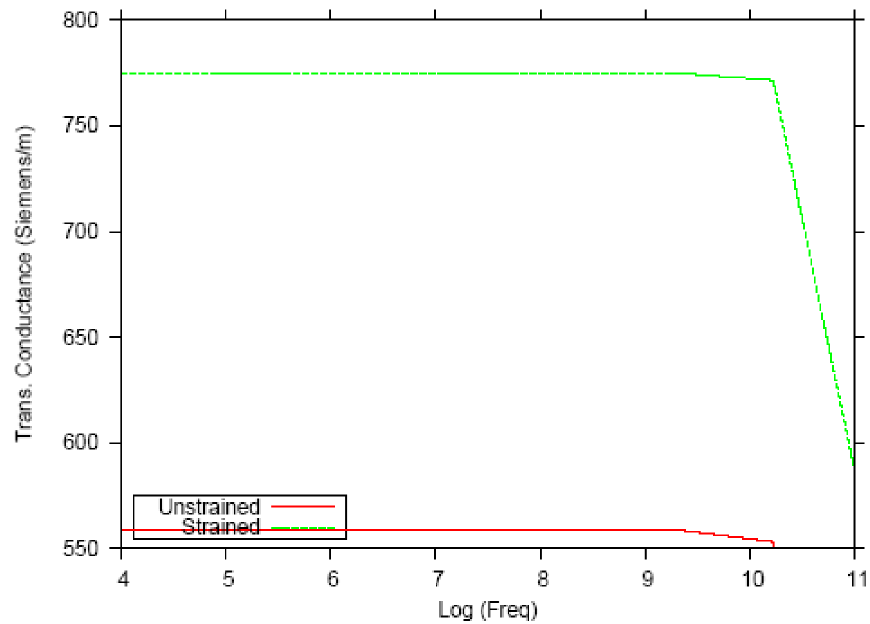
Experimental data taken from [1] and [2]:

[1] M. T. Currie, et.al, J. Vac. Sci. Technol. B 19(6),Nov/Dec. 2001, pp. 2268-2279

[2] M. Bulsara, Compound Semiconductor magazine, (September 2002)

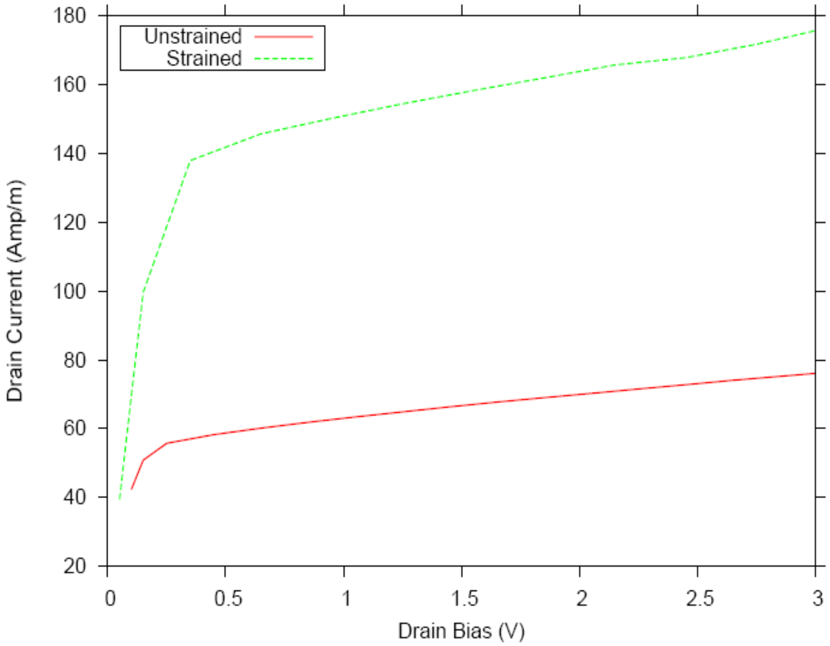
Simulated drive current for a Si/SiGe (biaxial tensile) n-MOSFET based on strained QW model

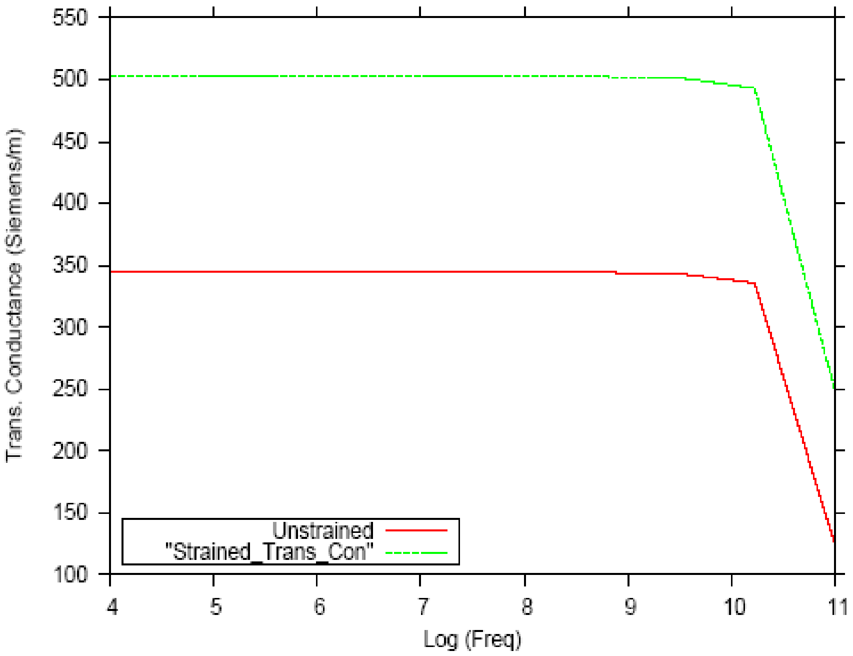




Ge fraction =0.3 biaxial tensile channel=17.5 nm

Benefits for a Si/SiGe p-MOSFET based on Crosslight's QW model





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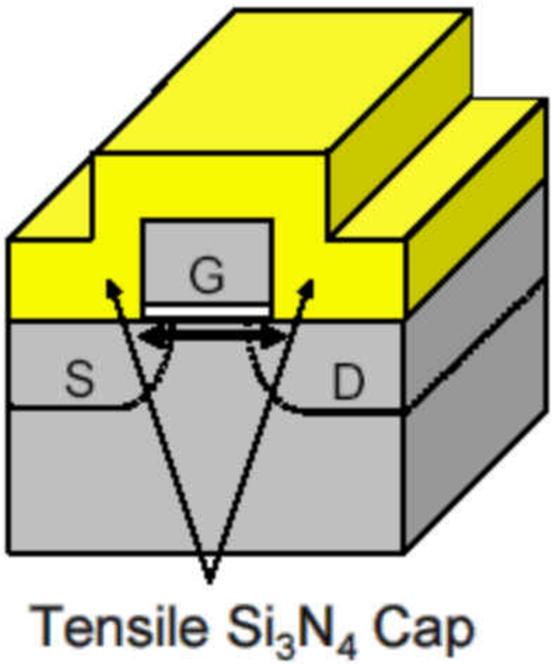
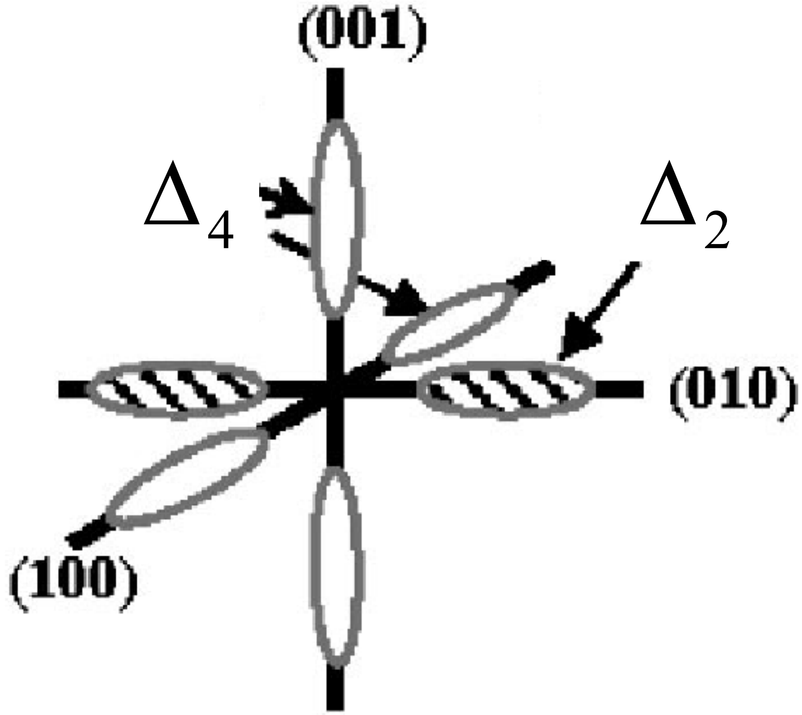
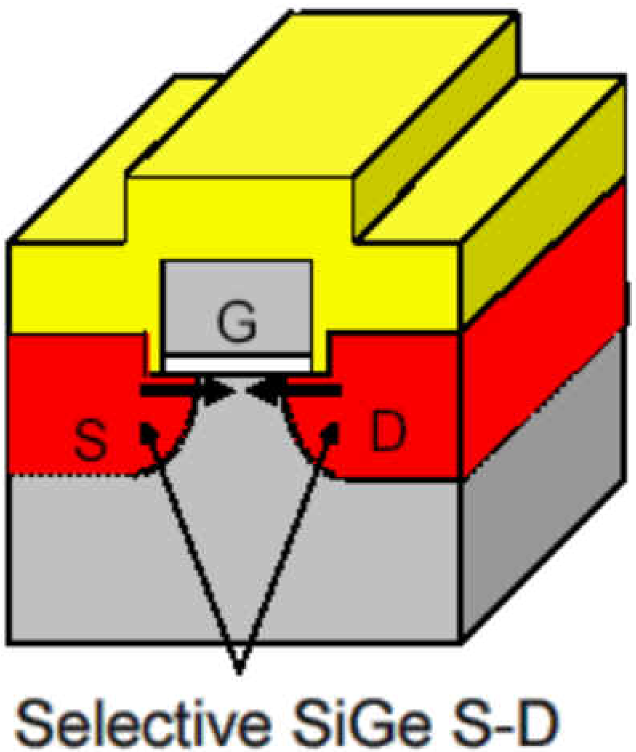
Uniaxial Tensile Strained-Silicon [100] direction

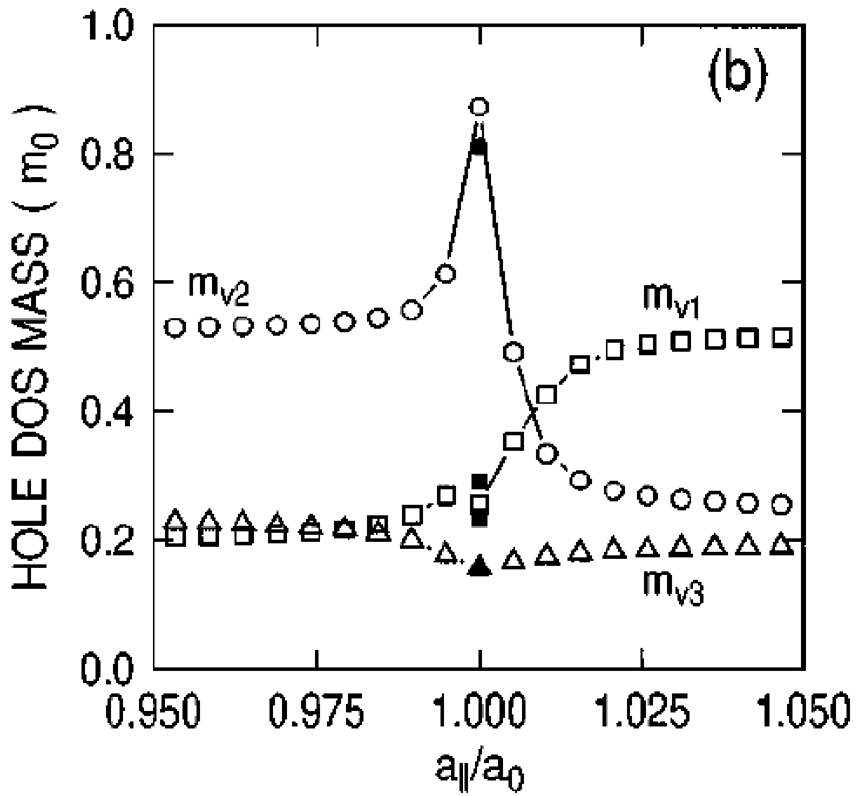




Delta4 has lower energy
➔transport/parallel mass=m_t
➔Good for mobility enhancement.

Uniaxial Compressive Strained-Silicon (PMOS)

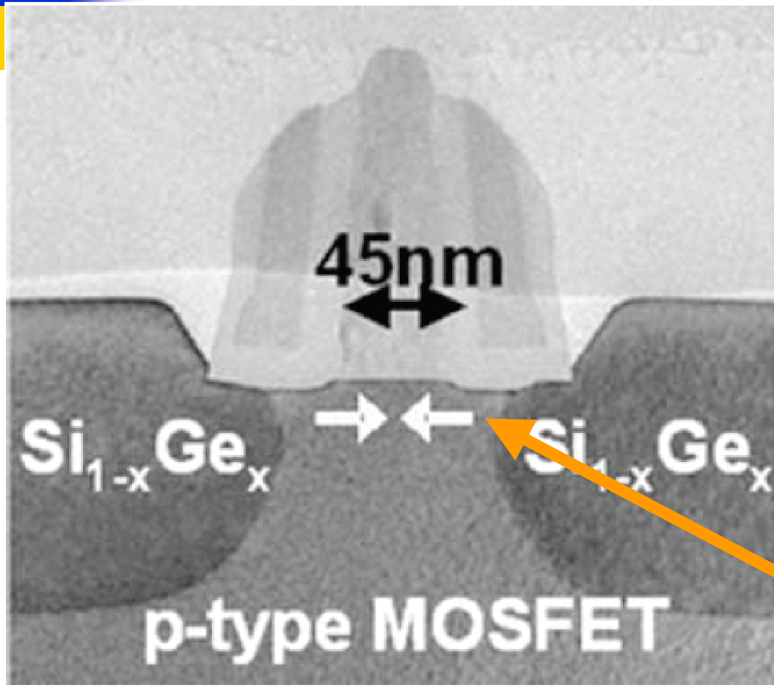




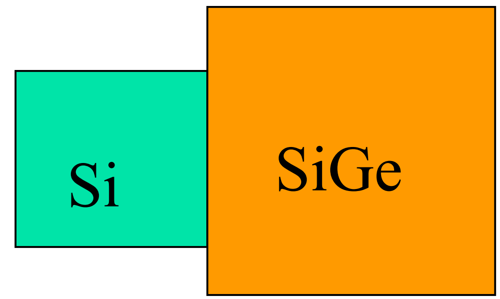
Ref: M.V. Fischetti and S.E. Laux, J. Appl. Phys., vol. 80, pp. 2234-2252, 1996.

Remark: Tensile biaxial strain splits HH/LH and quickly reduces the Heavy hole mass.

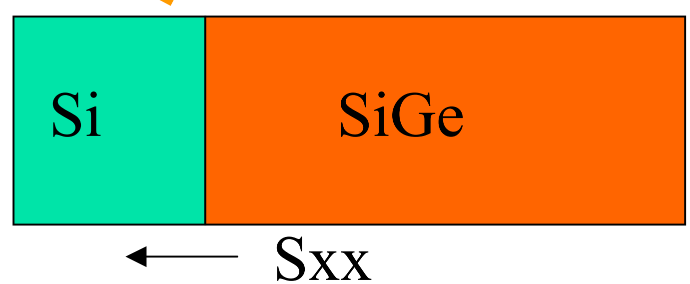
Conversion of parameters from biaxial to uniaxial



Lattice unit cell
before SiGe growth:



After SiGe growth:

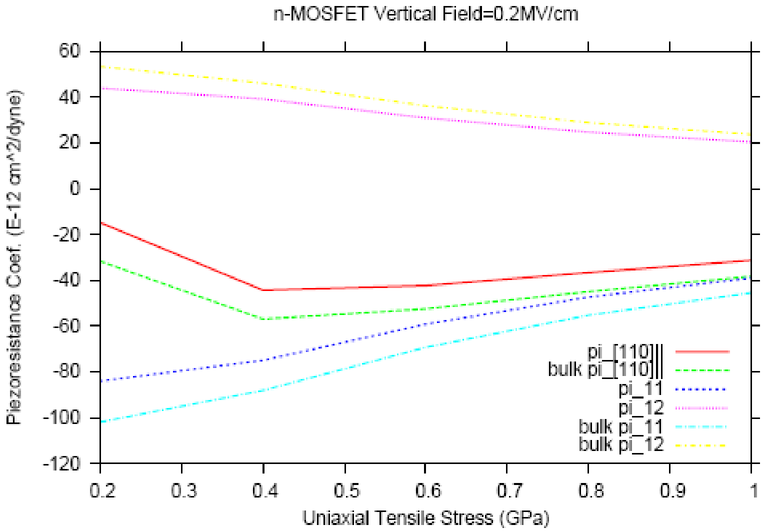


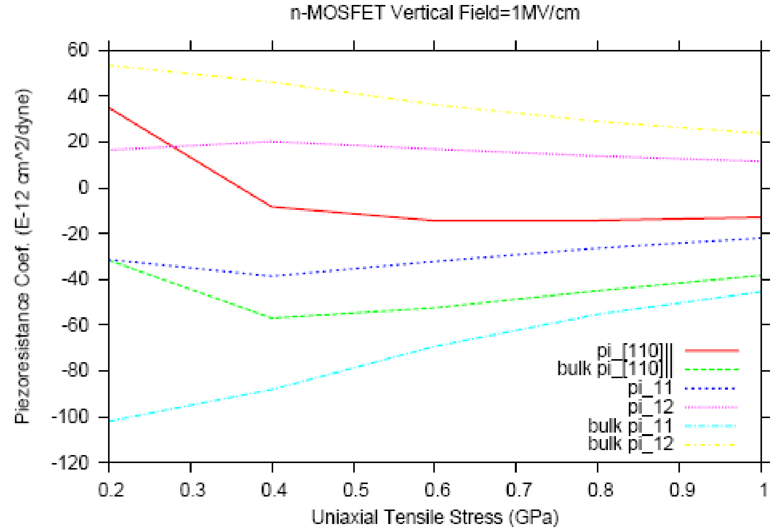
Direction of force

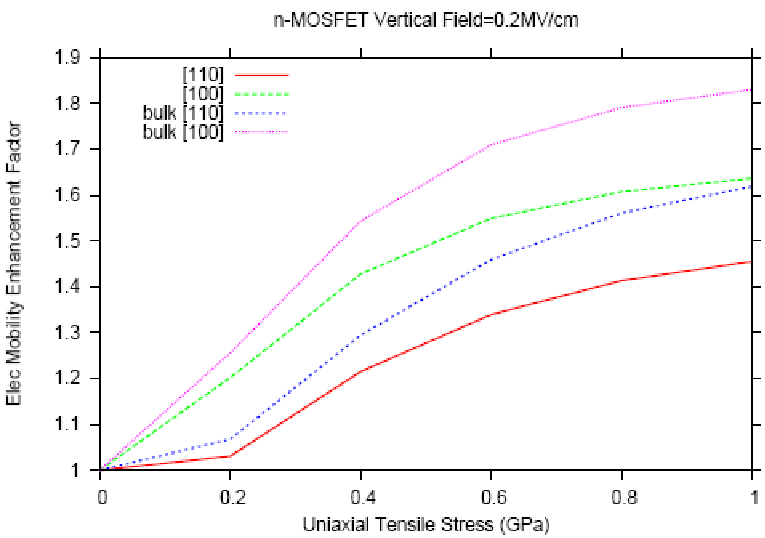
Assuming perfectly matched lattice constant in planes parallel to Si/SiGe interface + given thicknesses in xx direction

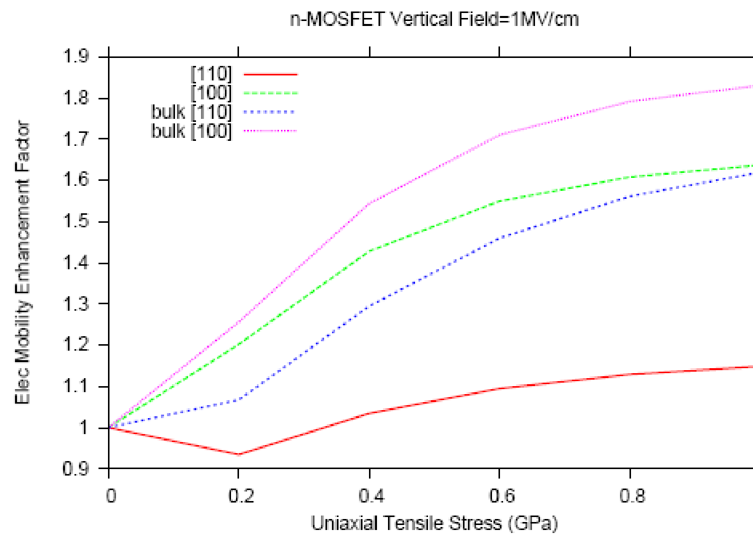
➔ Convert strain from biaxial to uniaxial so that all calibrated data from Si/SiGe data base can be used for uniaxial strained silicon

Simulated Electron Mobility Enhancement



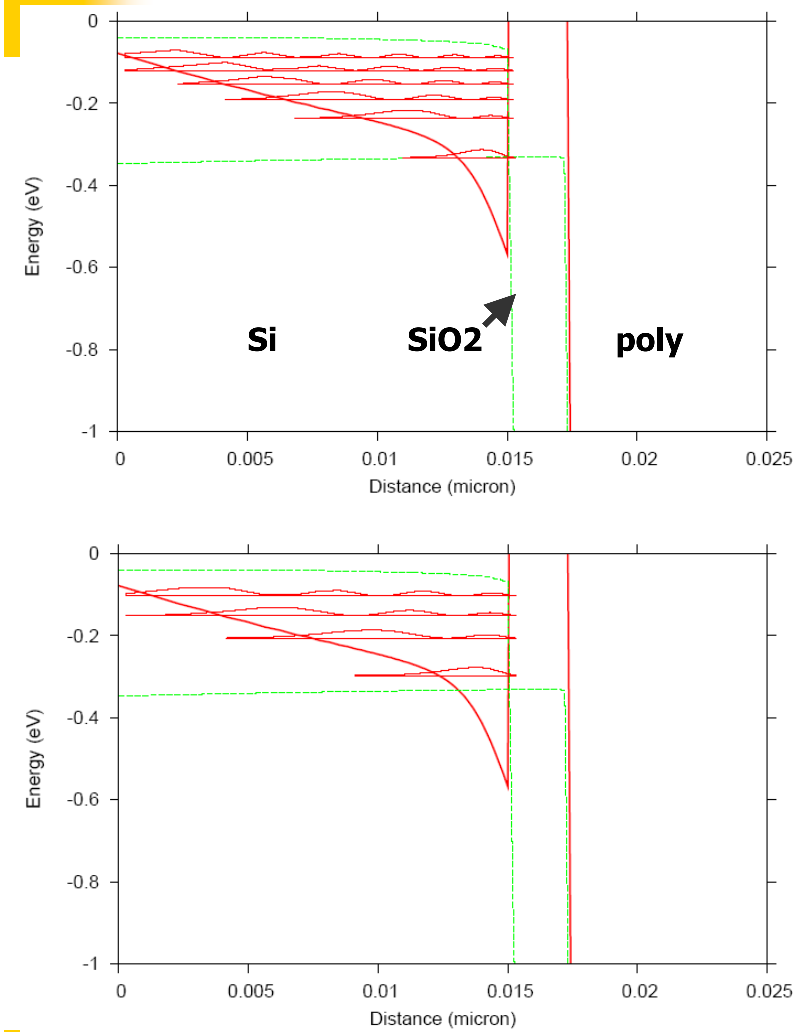




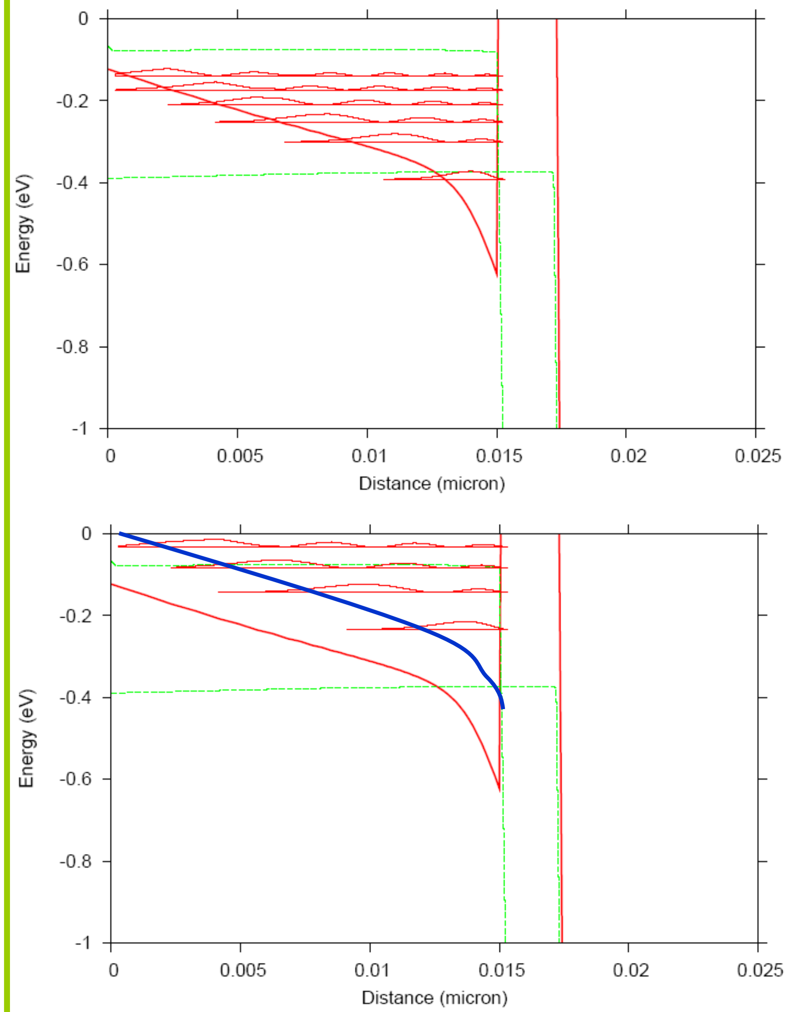


➔ **Effect of quantization is substantial due to large valley splitting**

Quantized states of conduction band valleys



Stress=0



Uniaxial tensile stress=1 GPa

N-MOSFET Gate length=80 nm, Vg=2 V, Vd=3 V

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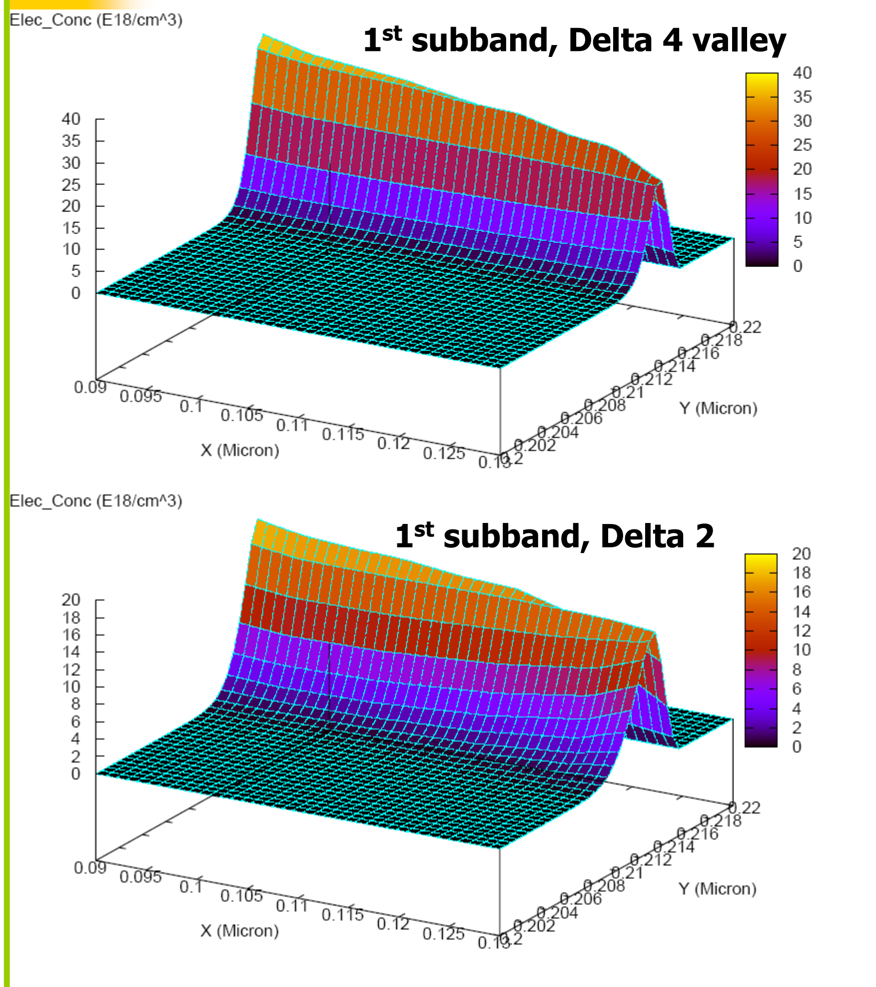
2D profile of quantized electron states under the gate



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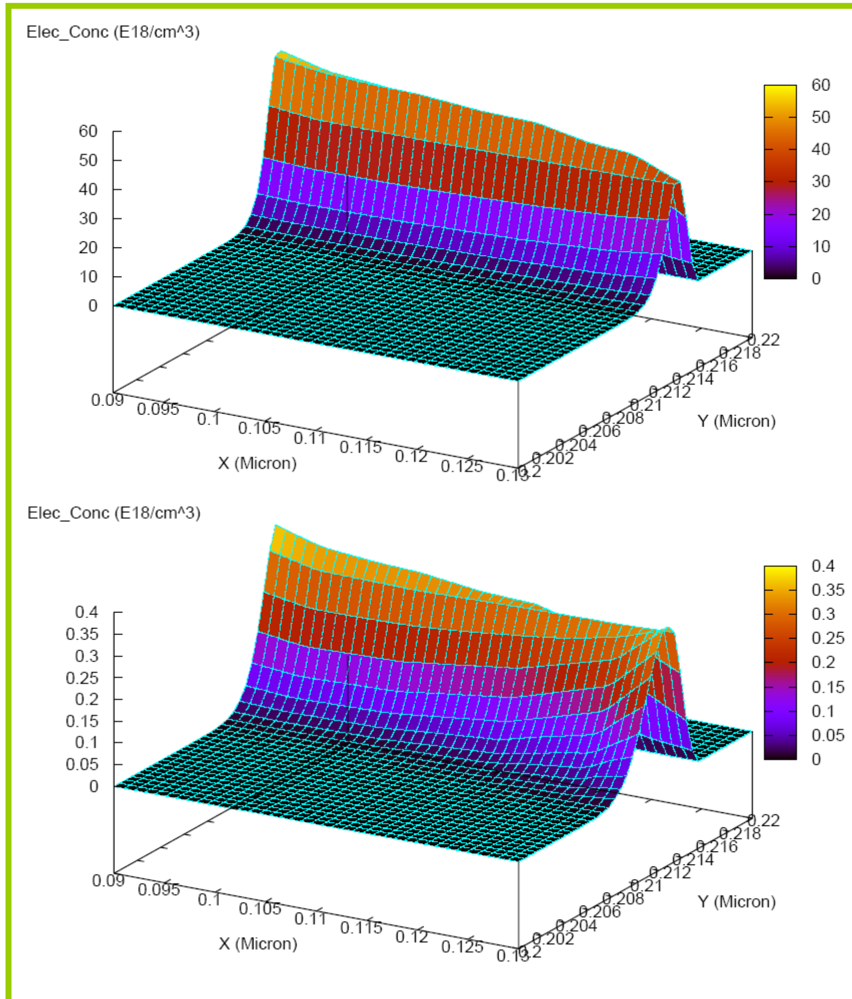

Uniaxial tensile stress=1 GPa

Gate length=80 nm, Vg=2 V, Vd=3 V

Remark: tensile stress strongly affects subband population

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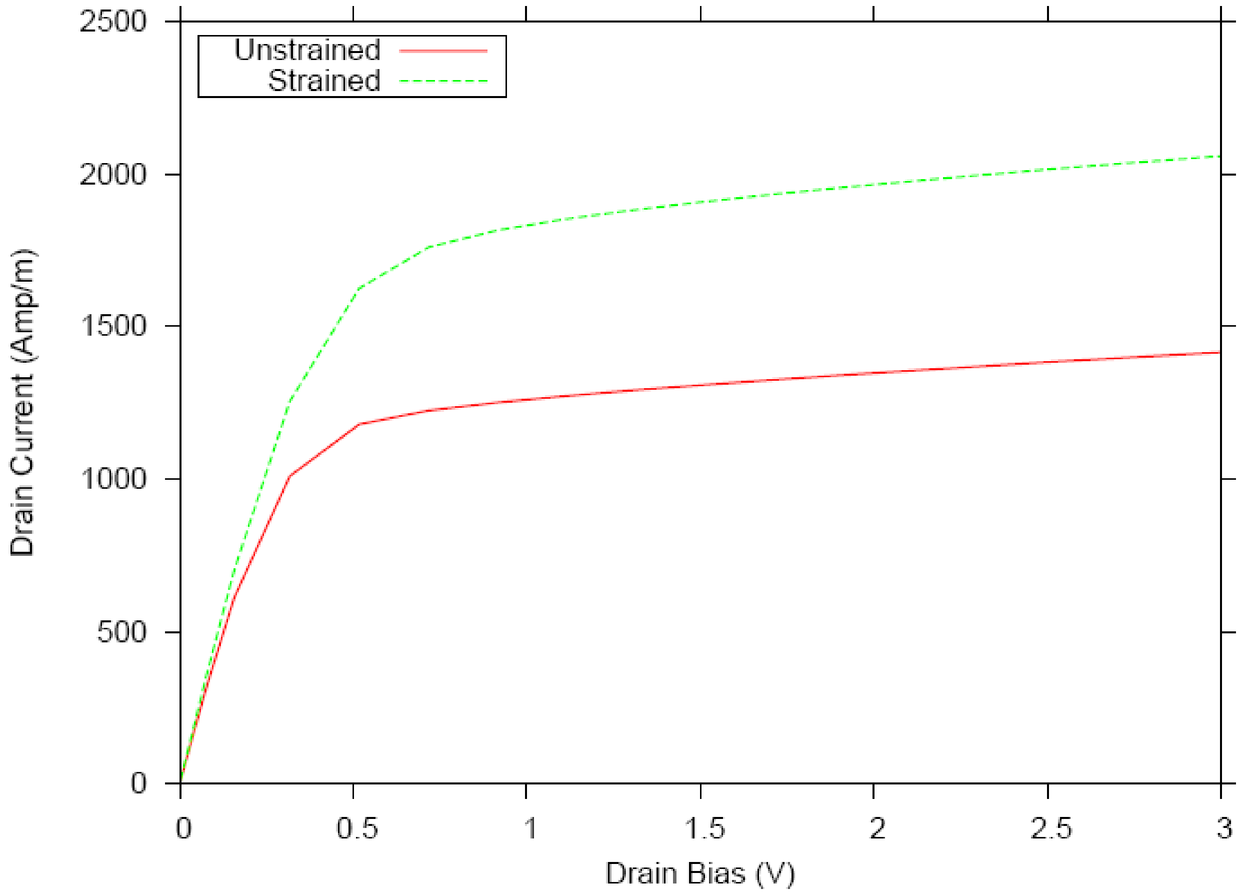
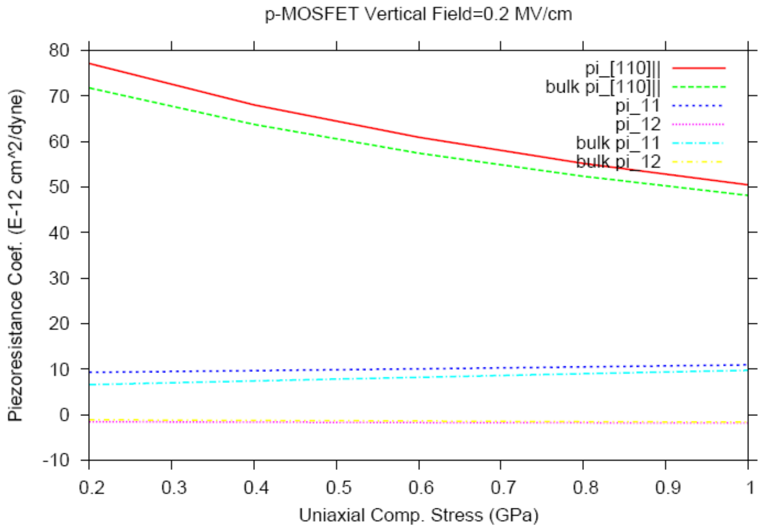
Benefits for typical Ux-S-Si n-MOSFET based on simulation

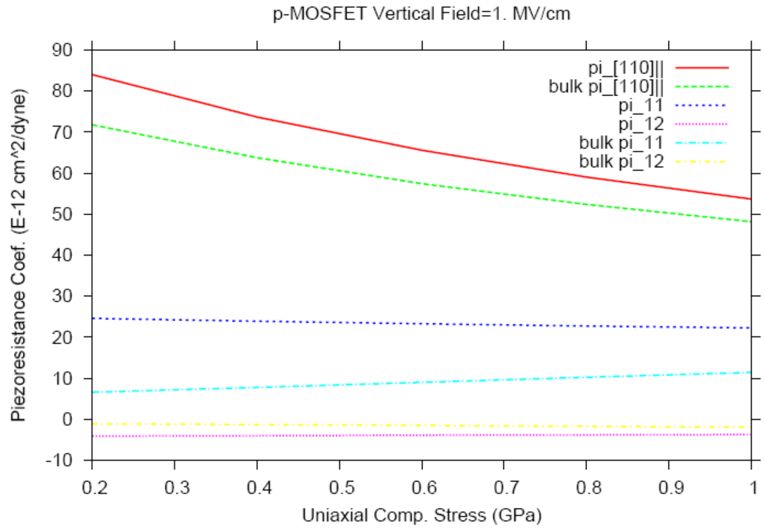


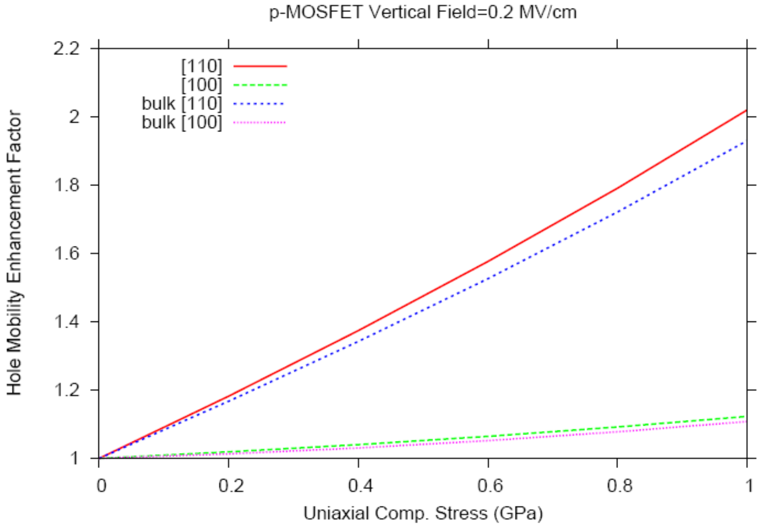
Gate length=80 nm, Uniaxial tensile stress=1GPa

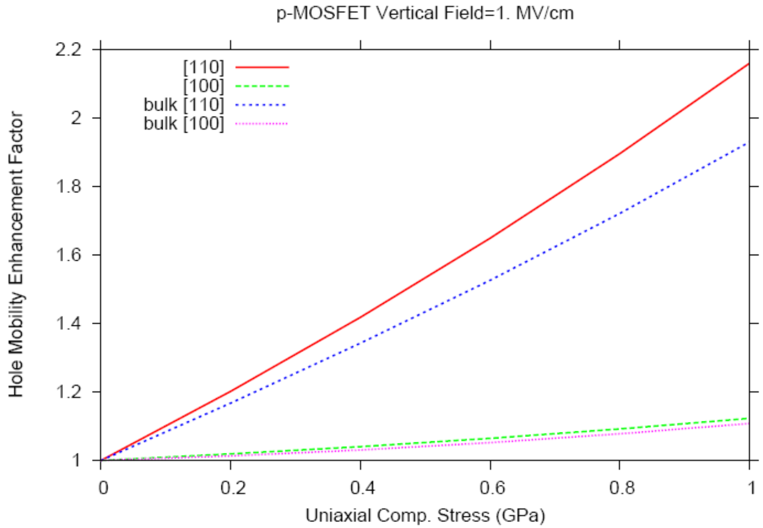
Saturation velocity enhancement=80 % of mobility enhancement

Simulated Hole Mobility Enhancement









➔ Effect of quantization is less pronounced due to heavier mass and smaller valley splitting as compared with its electron counterpart.

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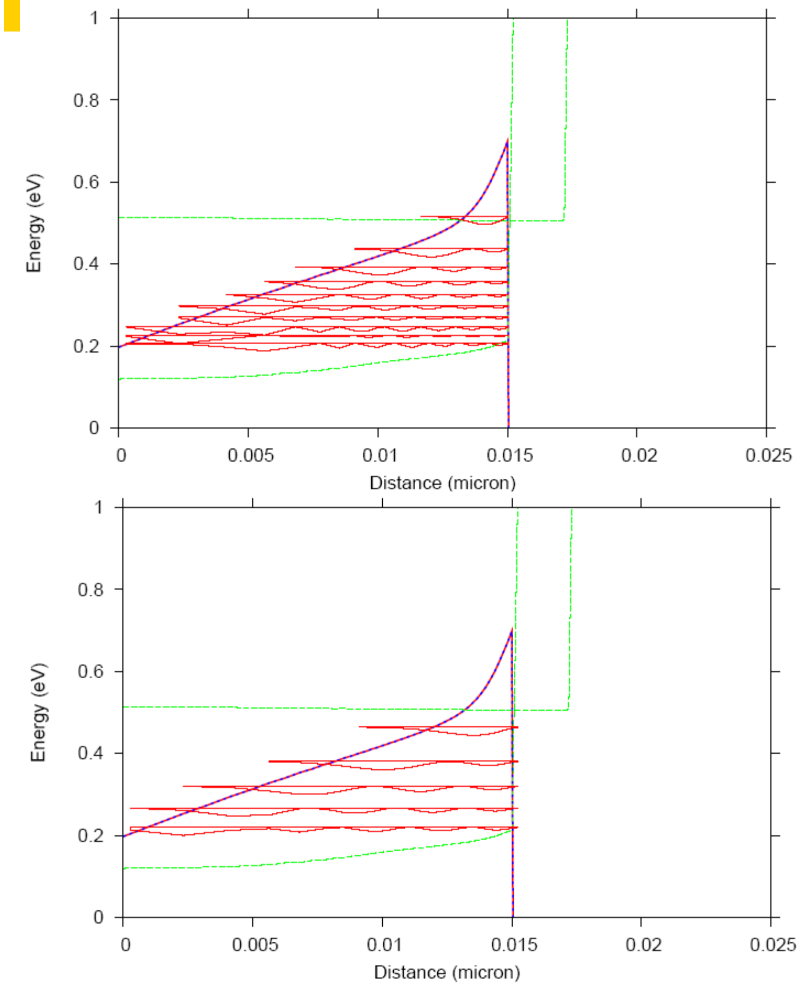
Quantized states of valence band valleys



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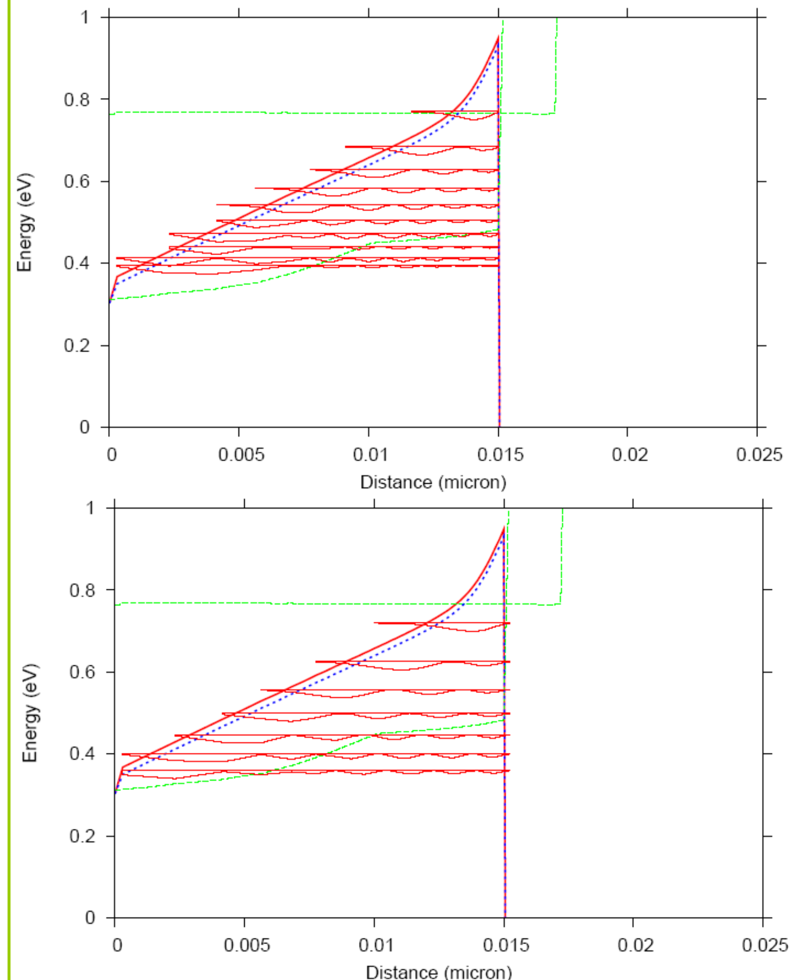

Uniaxial compressive stress=1 GPa

N-MOSFET Gate length=80 nm, Vg=-2 V, Vd=-3 V; Notice the shift in potential

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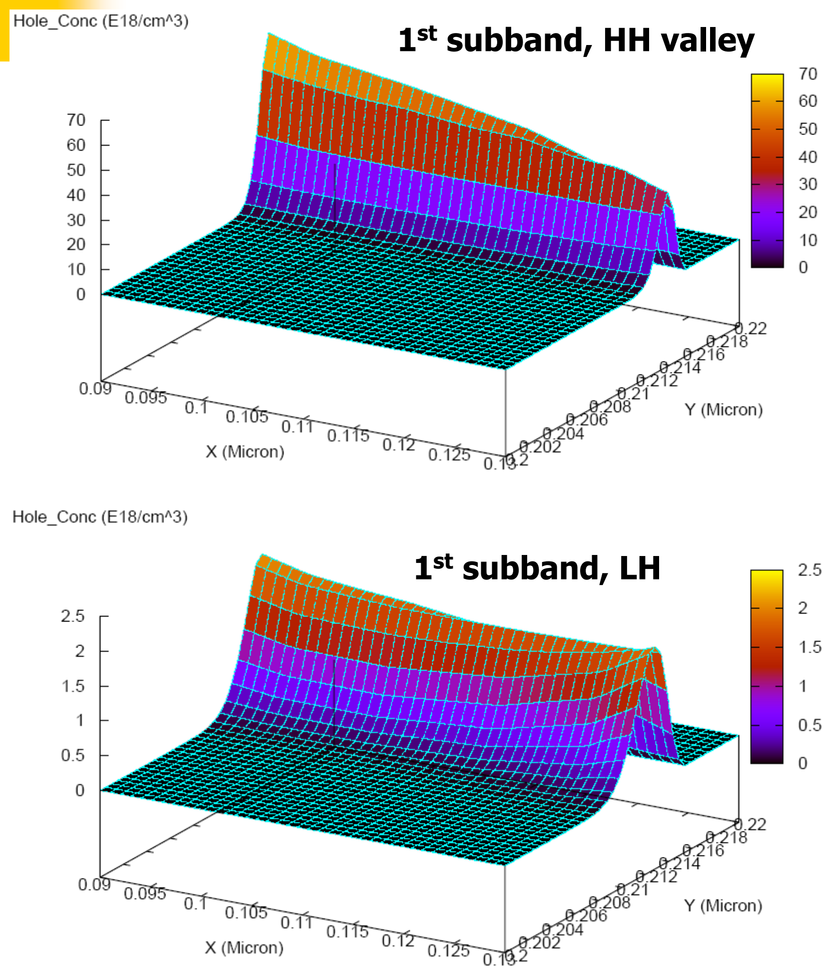
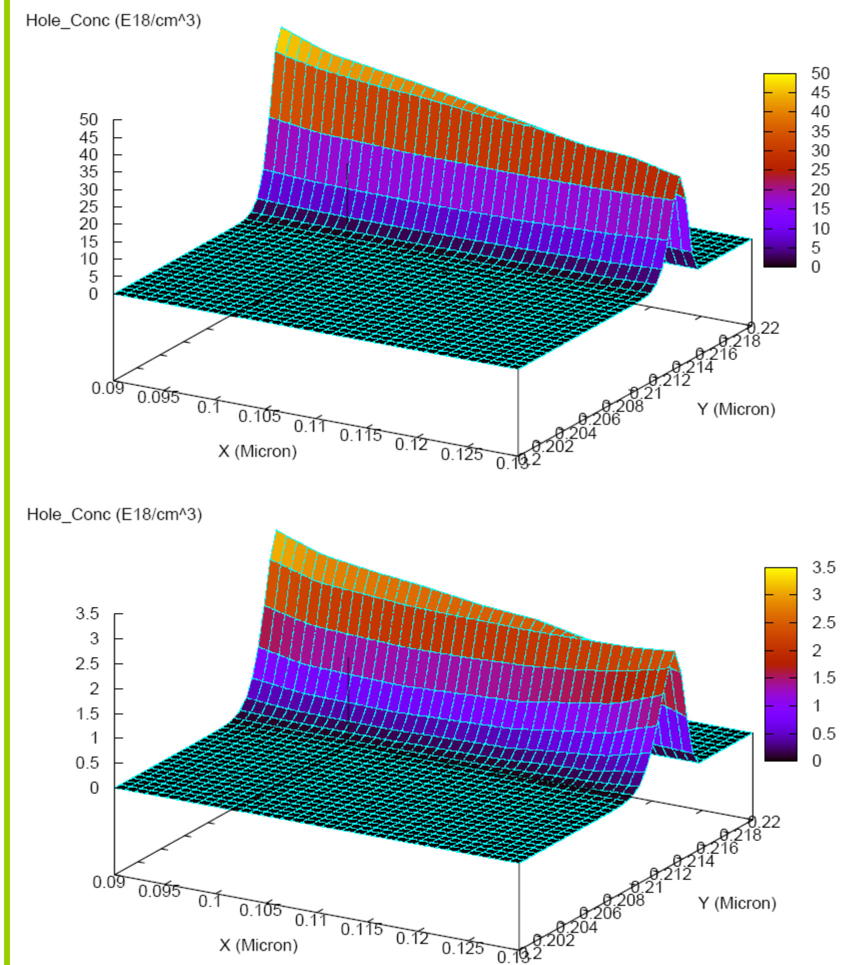
2D profile of quantized hole states under the gate



Stress=0



Uniaxial compressive stress [110]=1 GPa

Gate length=80 nm, Vg=-2 V, Vd=-3 V

Remark: stress affects subband population

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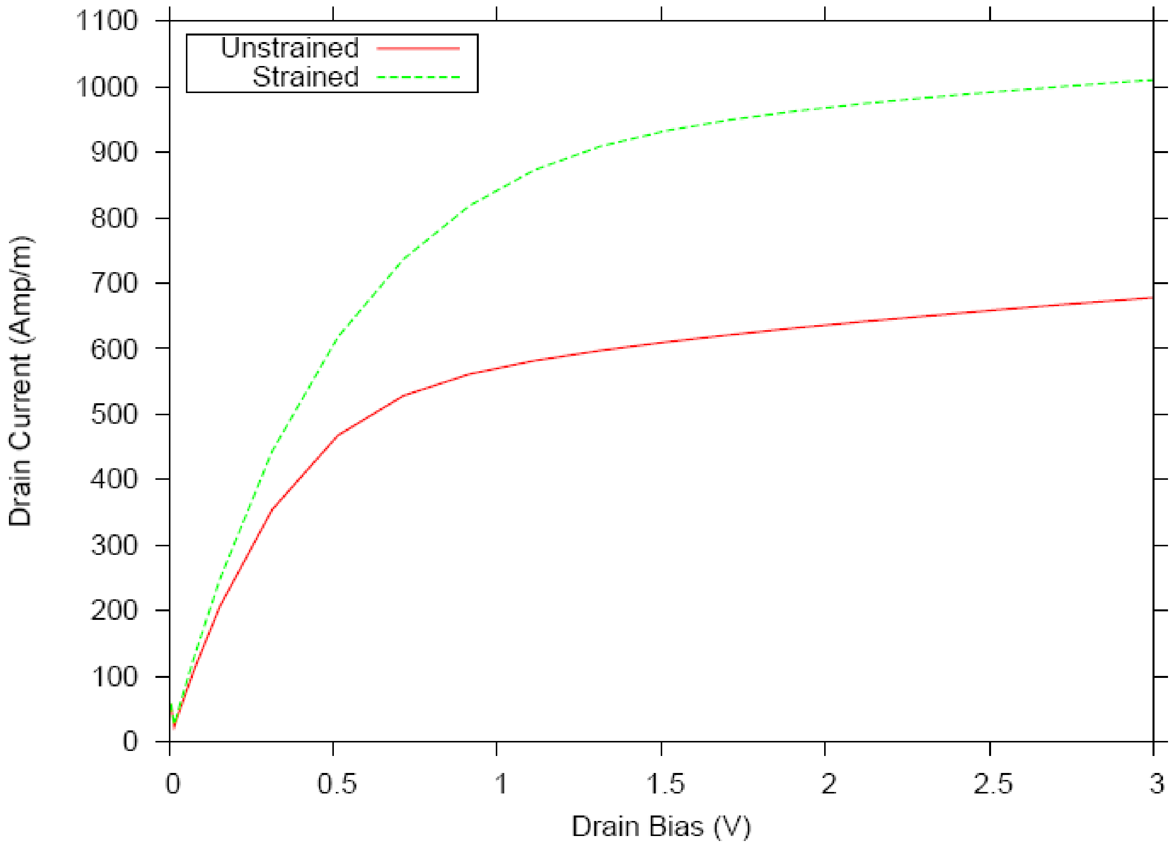
Benefits for typical Ux-S-Si p-MOSFET [110] based on simulation



Gate length=80nm, Uniaxial compressive stress=1 Gpa

Saturation velocity enhancement=50 % of mobility enhancement

Conclusions

- **Crosslight's semi-classical quantum subband valley-averaged mobility model takes into account mass dependence, valley splitting and anisotropy.**
- **Enables self-consistent solution of drift-diffusion equations with quantum corrections using subband averaged density of states and mobility.**
- **Maybe used as TCAD to predict and optimize strained silicon MOSFET in various stress and crystal orientation.**