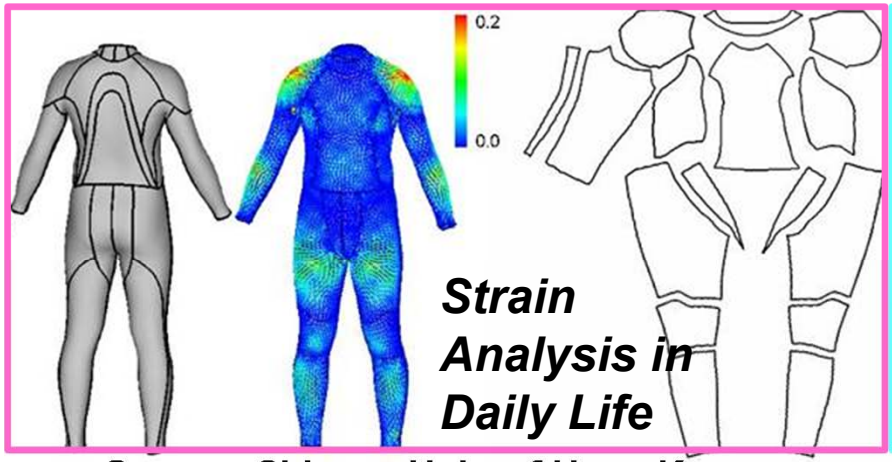
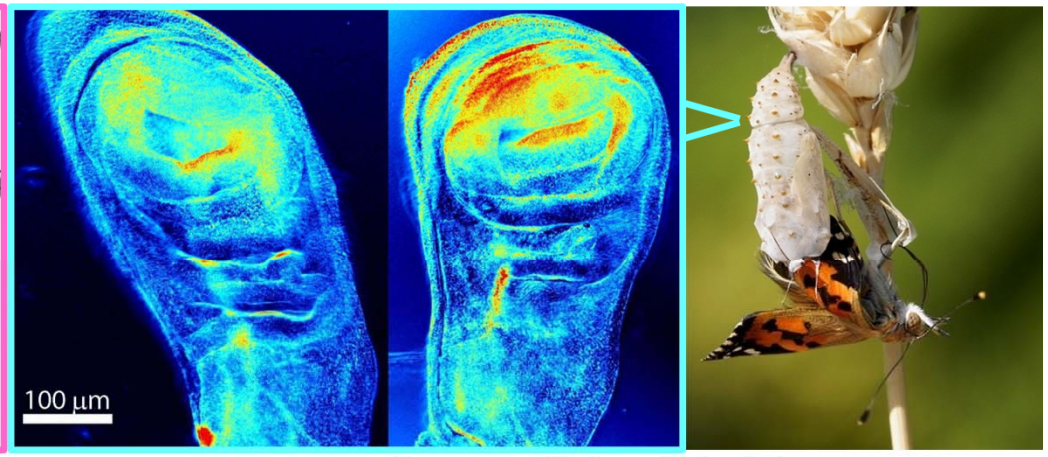


Source: Chinese Univ. of Hong Kong



Source: Univ. of Zurich

Lecture 9

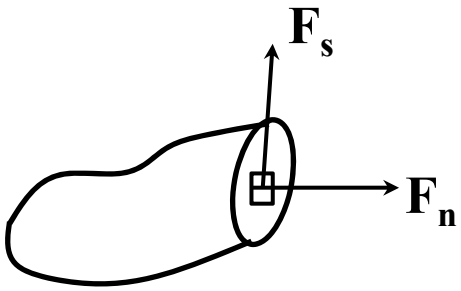
- **Strained-Si Technology I: Device Physics**
  - Background
  - Planar MOSFETs
  - FinFETs

Reading:

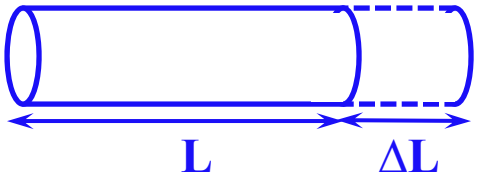
- Y. Sun, S. Thompson, T. Nishida, “Strain Effects in Semiconductors,” Springer, 2010.
- multiple research articles (reference list at the end of this lecture)

Mechanical Stress/Strain Analysis

Stress:
results from the repulsive electromagnetic force between ionic cores when the lattice atoms deviate from their equilibrium positions.

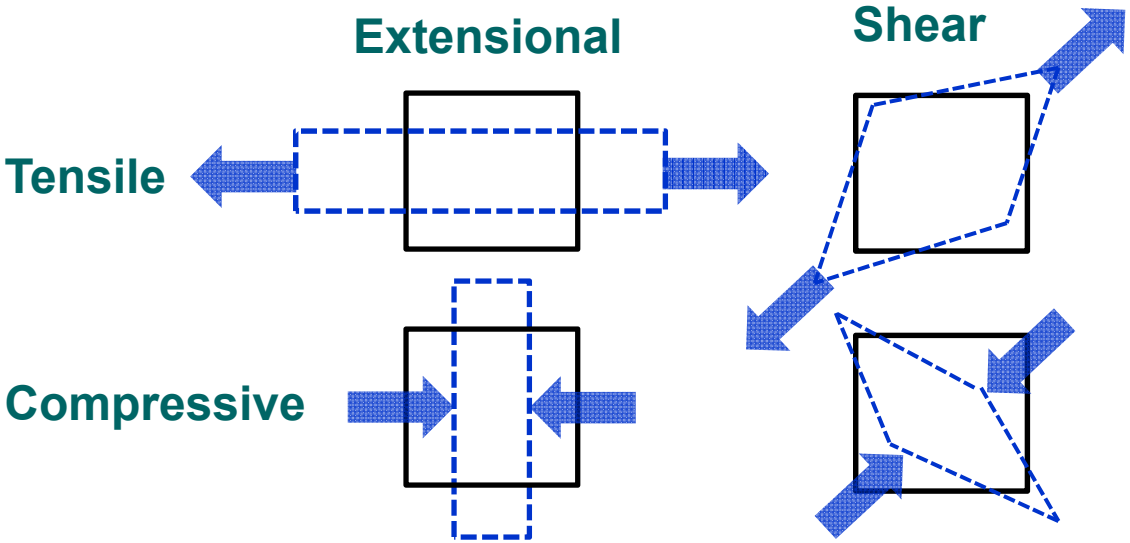


$$\text{Stress} = \lim_{\Delta A \to 0} \frac{\Delta F}{\Delta A}$$



$$\text{Strain} = \lim_{L \to 0} \frac{\Delta L}{L}$$

Stress Types



Stress Tensor

$$\hat{T} = \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix}$$

Strain-Stress Relationship

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{zx} \\ \gamma_{xy} \end{pmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{zx} \\ \tau_{xy} \end{pmatrix}$$

Elasticity Tensor:

- **assuming strain has linear response to stress (Hooke's Law)**
- **can be simplified into 3 independent variables, for cubic lattices (*e.g.* Si)**

If *x, y, z* along main crystal axis:

Extensional Strain/Stress

$$\varepsilon_x = C_{11}\sigma_x + C_{12}\sigma_y + C_{12}\sigma_z$$

Shear Strain/Stress

$$\gamma_{yz} = C_{44}\tau_{yz}$$

OR for a certain direction:

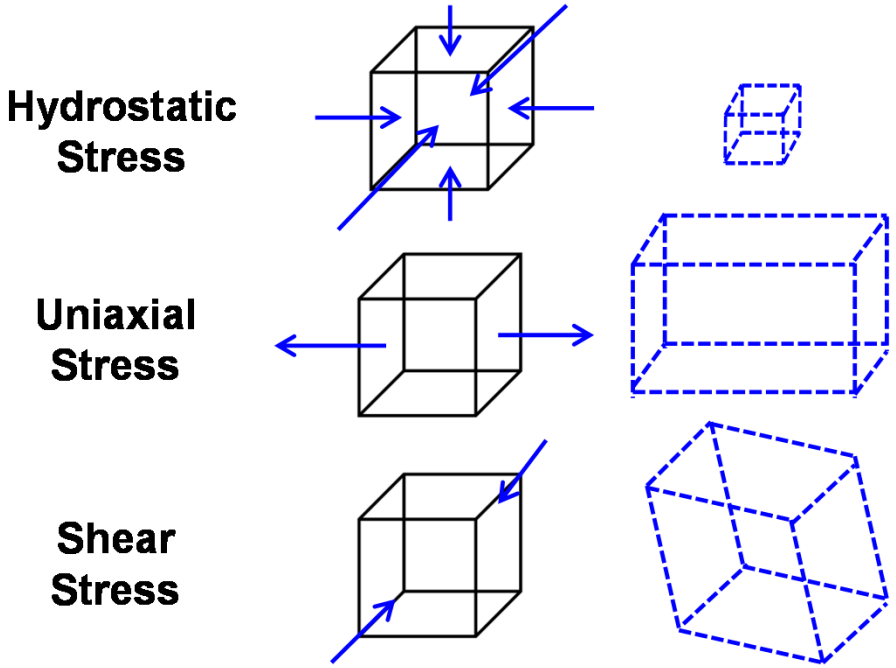
$$\varepsilon_x = \frac{1}{E}\sigma_x + \frac{\nu}{E}\sigma_y + \frac{\nu}{E}\sigma_z$$

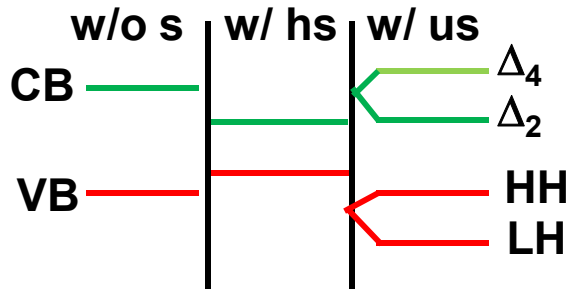
$$\gamma_{yz} = \frac{1}{G}\tau_{yz}$$

E: Young's Modulus
υ: Poisson's Ratio
G: Shear Modulus

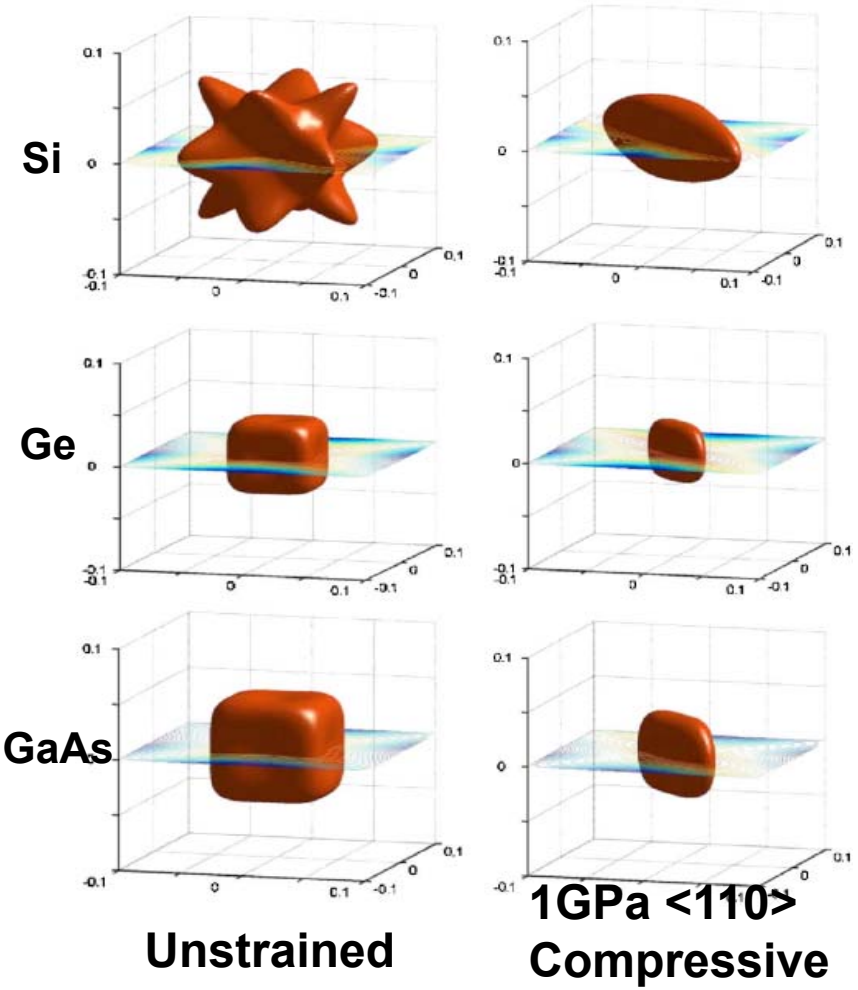
Impact of Strain on Semiconductors

- Energy Band Splitting



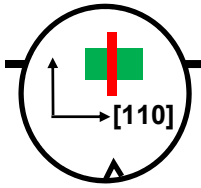


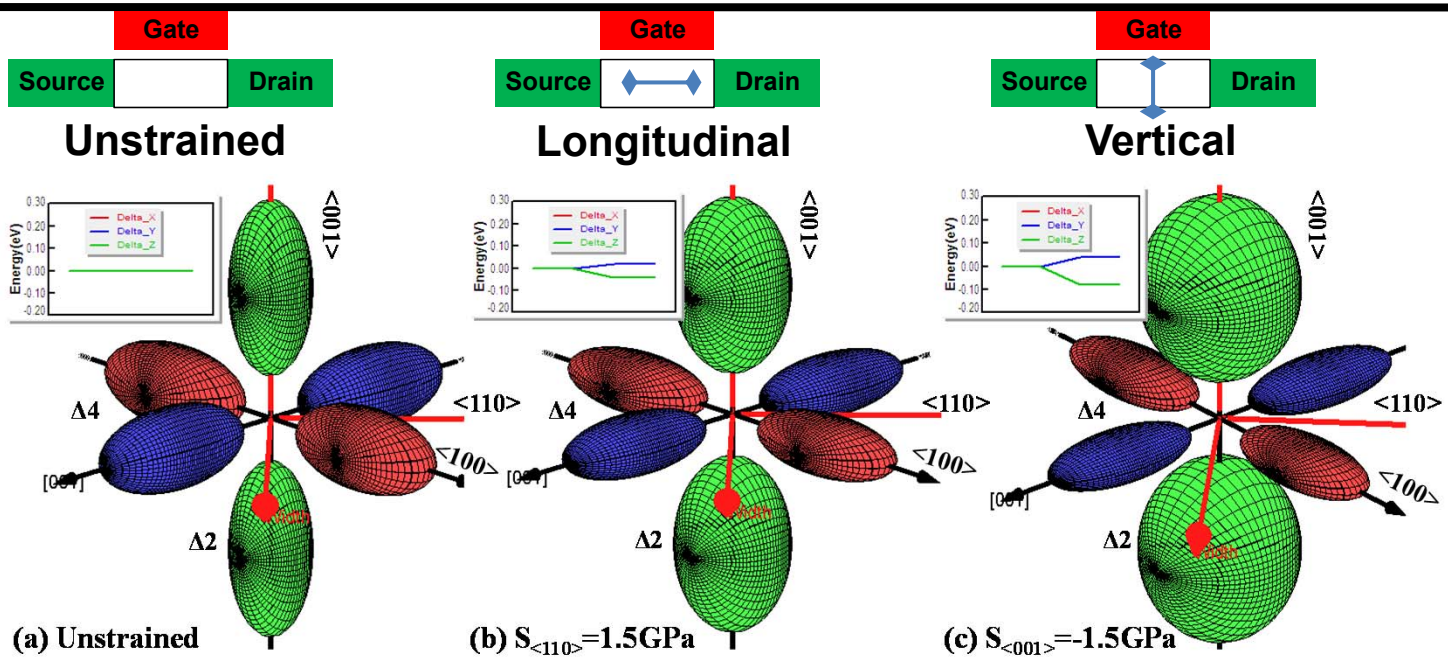
- *E vs. k* curvature change



Y. Sun, JAP (2007)

Strain Impact on Si Bandstructure: Planar N-MOSFET





applying strain

Energy Splitting

Lower DOS available for Scattering

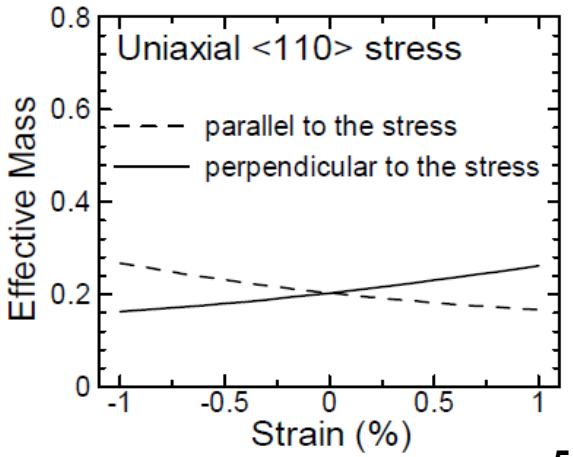
Reduced (Inter-valley) Scattering Rates

Sub-band reoccupation

Lowered average m*

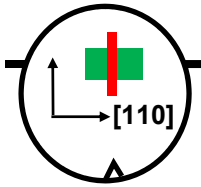
E-k Curvature Change

Transport *m** Reduction

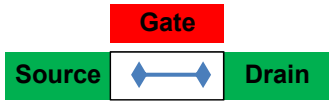


K. Uchida, IEDM (2008)

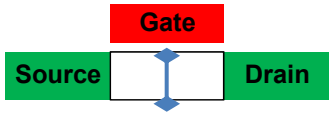
Strain Impact on Si Bandstructure: Planar P-MOSFET



Unstrained



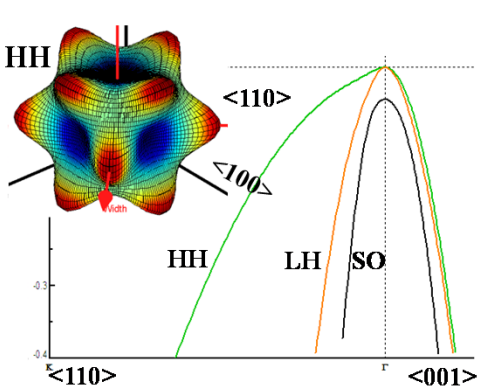
Longitudinal



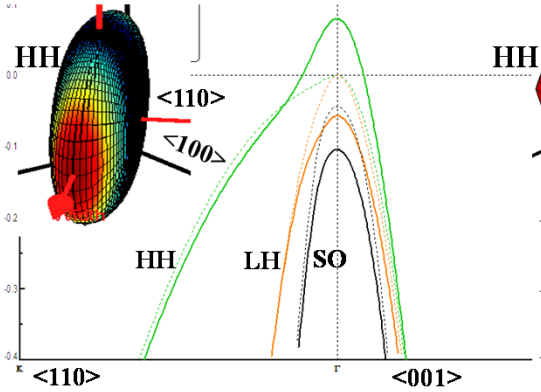
Vertical

Holes

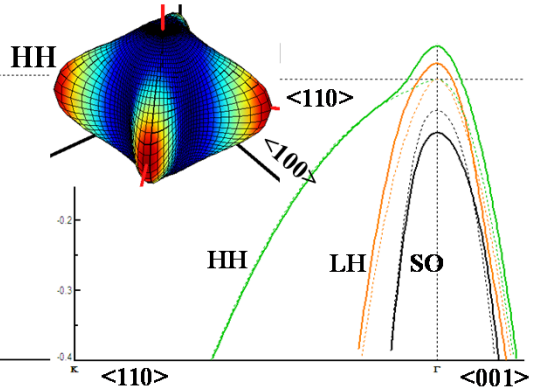
Heavy Hole
Light Hole
Split-off Hole



(d) Unstrained



(e) $S_{<110>}$=-1.5GPa

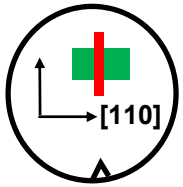


(f) $S_{<001>}$=1.5GPa

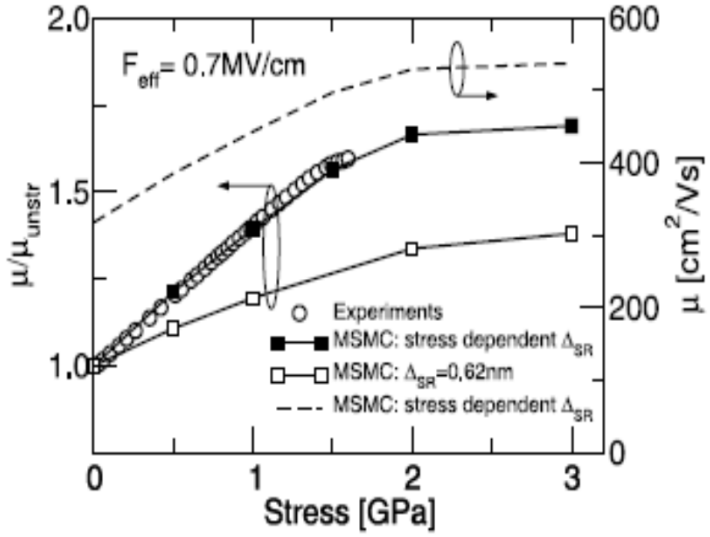
applying strain

- Energy Splitting
  - Lower DOS available for Scattering → Reduced (Inter-sub-band) Scattering Rates
  - Sub-band reoccupation → Lowered average m^*
- E-k Curvature Change → Transport m^* Reduction

Strain Enhancement on Si MOSFET Carrier Mobility

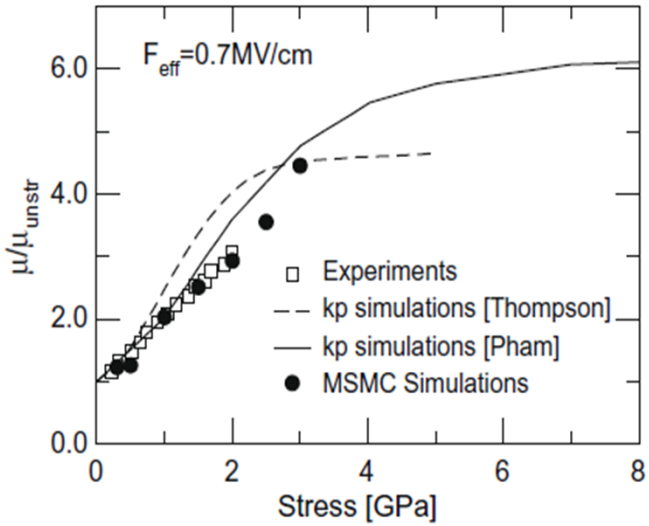


Electron



D. Esseni, JCE (2009)

Hole

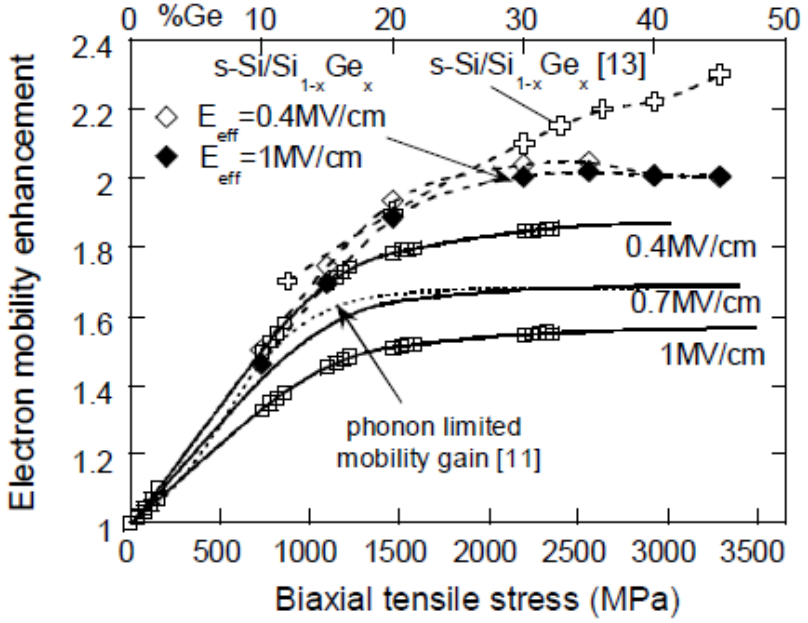


F. Conzati, SSE (2009)

- For N-MOSFET, electron mobility enhancement saturates at ~1.5 GPa <110>-uniaxial tensile stress .
- For P-MOSFET, hole mobility enhancement saturates at very high <110>-uniaxial compressive stress.

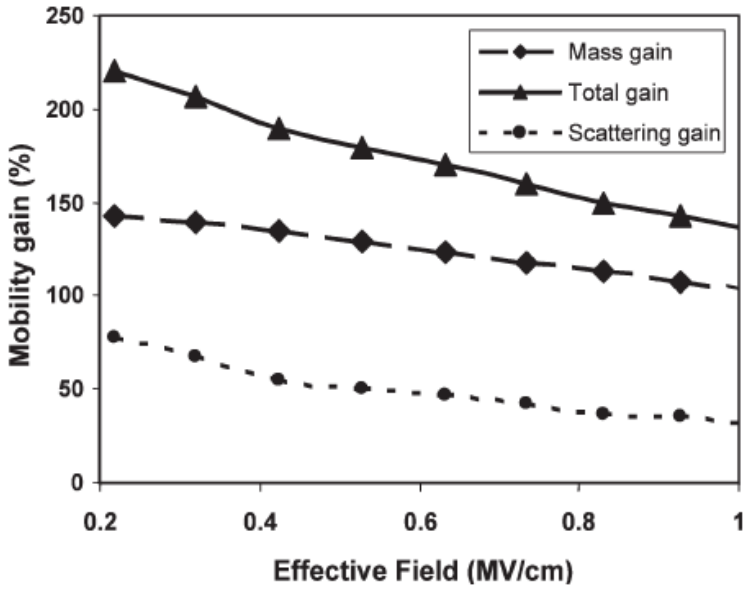
Impact of Quantum Confinement

Electrons under Biaxial Tensile Stress



O. Weber, IEDM (2007)

Holes under Uniaxial Comp. Stress



E. X. Wang, TED (2006)

- **N-MOSFET: μ_e% degrades at higher E_{eff}, due to the quantum confinement counters the strain-induced sub-band splitting.**
- **P-MOSFET: μ_h% maintains *vs.* E_{eff} due to the dominant m^* reduction.**

Analytical Modeling for Carrier Mobility Enhancement due to Strain

- **Piezoresistance (PR) Model**

$$\Delta\mu/\mu = -(\Pi_{xx}\sigma_x + \Pi_{yy}\sigma_y + \Pi_{zz}\sigma_z)$$

- **Too simple**
- **Limited predictive ability (by ignoring E_{eff}, Strain-dependence…)**

- **Sub-band Reoccupation Model**

$$\Delta E_V(\sigma) = \begin{cases} a(\varepsilon_1+\varepsilon_2+\varepsilon_3) \pm [b^2(\varepsilon_2-\varepsilon_3)^2 + (d^2/4)\varepsilon_6^2]^{1/2} \\ \text{for uniaxial [110] stress} \\ a(\varepsilon_1+\varepsilon_2+\varepsilon_3) + (1/2)(1\pm 3)(\varepsilon_3-\varepsilon_1) \\ \text{for biaxial stress} \end{cases} \quad (4)$$

$$H(\sigma) \equiv \exp\left[-\frac{|\Delta E_{lh}(\sigma)| + |\Delta E_{hh}(\sigma)|}{kT}\right]$$

$$m_p^*(\sigma) = \begin{cases} \left[m_{lh}^{3/2} * H(\sigma)^{3/2} + m_{hh}^{3/2}\right]^{2/3} \\ \text{for uniaxial [110] tensile stress} \\ \left[m_{lh}^{3/2} + m_{hh}^{3/2} * H(\sigma)^{3/2}\right]^{2/3} \\ \text{for biaxial in-plane tensile stress} \end{cases}$$

J.-S. Lim, EDL (2004)

- **Analytically models the energy-band top and m^* change *vs.* strain**
- **Trade-off between computing loads and accuracy**

Numerical Approach: Self-Consistent Poisson-Schrödinger Simulation

scPS Approach

Schrödinger equation

$$\left(-\frac{\hbar^2}{2m^*_z}\cdot\frac{d^2}{dz^2}-e\varphi(z)\right)\xi_n(z)=E_n\xi_n(z)$$

$$\downarrow$$

$$n_n(z)=\frac{g_n}{(2\pi)^2}\int_{\vec{k}} d\vec{k}\cdot f(E_{\vec{k}})\cdot\left|\xi_n(\vec{k},z)\right|^2$$

$$\downarrow$$

$$n(z)=\sum_n n_n(z)$$

$$\downarrow$$

$$\frac{d}{dz}\left(\varepsilon(z)\cdot\frac{d\phi(z)}{dz}\right)=-e\left(N_D-N_A+p(z)-n(z)\right)$$

Poisson equation

6x6 Luttinger-Kohn Hamiltonian for Holes

$$\begin{bmatrix} -P-Q & L & -M & 0 & \frac{L}{\sqrt{2}} & -\sqrt{2}M \\ -L^+ & -P+Q & 0 & -M & \sqrt{2}Q & -\sqrt{\frac{3}{2}}L \\ -M^+ & 0 & -P+Q & -L & -\sqrt{\frac{3}{2}}L^+ & -\sqrt{2}Q \\ 0 & -M^+ & -L^+ & -P-Q & \sqrt{2}M^+ & \frac{L^+}{\sqrt{2}} \\ \frac{L^+}{\sqrt{2}} & \sqrt{2}Q & -\sqrt{\frac{3}{2}}L & \sqrt{2}M & -P-\Delta & 0 \\ -\sqrt{2}M^+ & -\sqrt{\frac{3}{2}}L^+ & -\sqrt{2}Q & \frac{L}{\sqrt{2}} & 0 & -P-\Delta \end{bmatrix}$$

$$P=\frac{\hbar^2}{2m_0}\gamma_1(k_x^2+k_y^2+k_z^2)$$

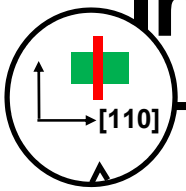
$$Q=\frac{\hbar^2}{2m_0}\gamma_2(k_x^2+k_y^2-2k_z^2)$$

$$L=\frac{\hbar^2}{m_0}\sqrt{3}\gamma_3(k_x-ik_y)k_z$$

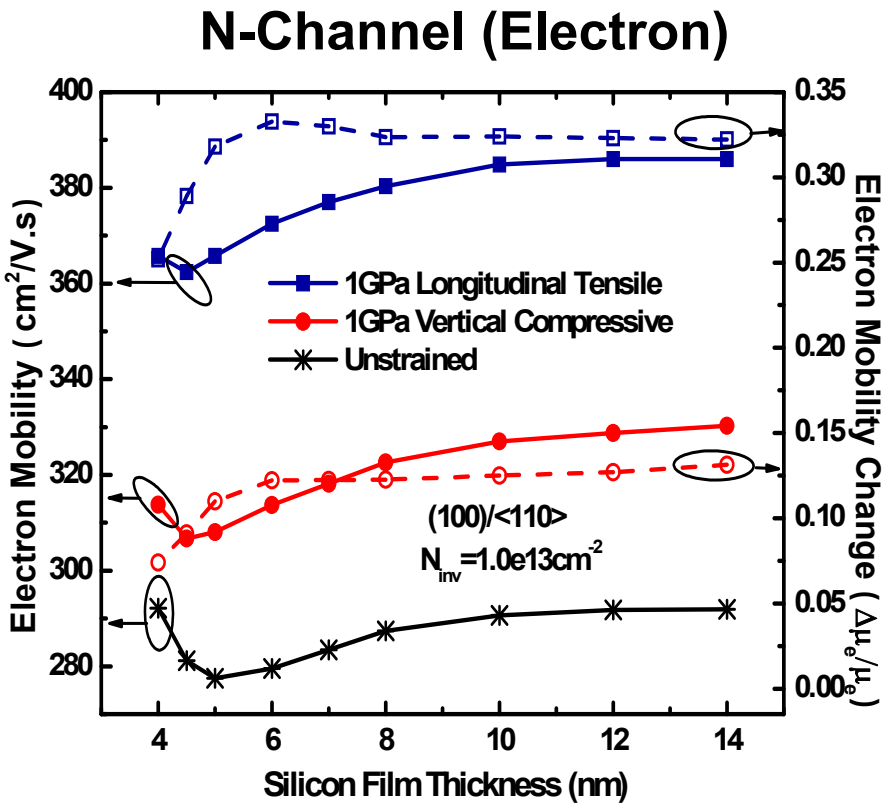
$$M=-\frac{\hbar^2}{2m_0}\sqrt{3}[\gamma_2(k_x^2-k_y^2)-i2\gamma_3k_xk_y)$$

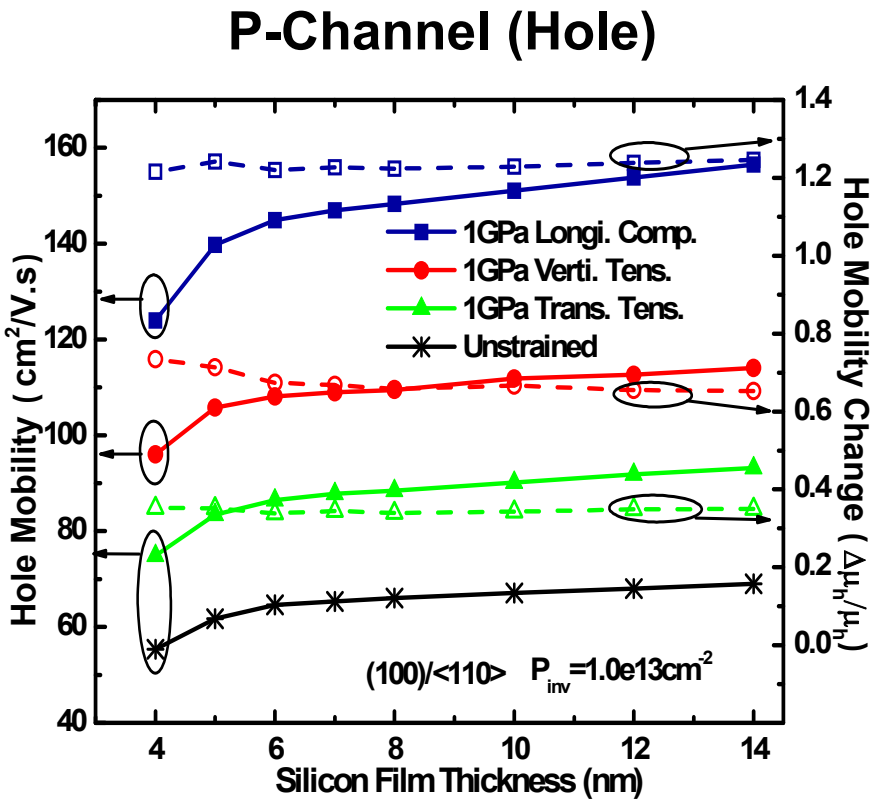
- **Impacts of strain on energy-band top as well as curvature change will be completely included into the Hamiltonian.**
- **Computationally intensive.**

Impact of Si Body Thickness Scaling



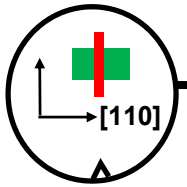
scPS simulations, N. Xu, VLSI-T (2011)





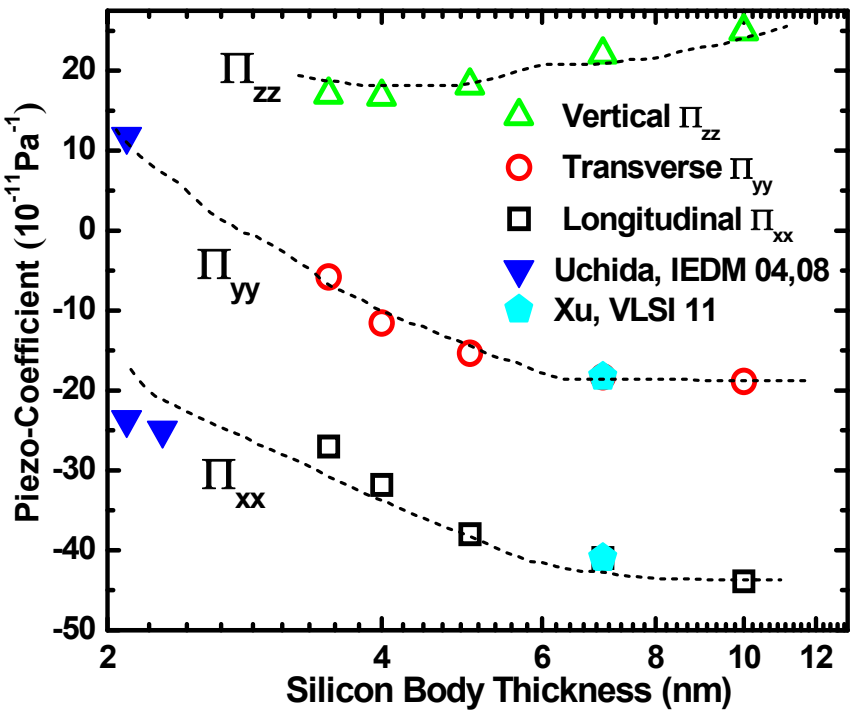
- **Stress enhancement diminishes for electrons as t_{SOI} scaled below 5nm, but not for holes.**

Impact of t_{Si} Scaling on Piezoresistive Coefficients

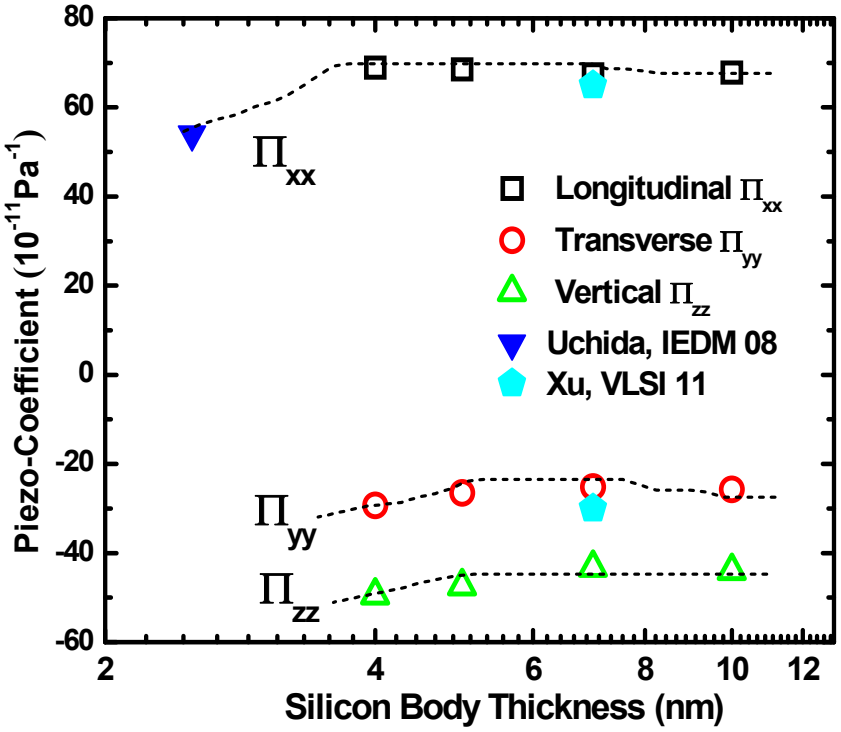


Open symbols → Simulated Closed Symbols → Measured

N-Channel (Electron)



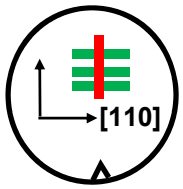
P-Channel (Hole)

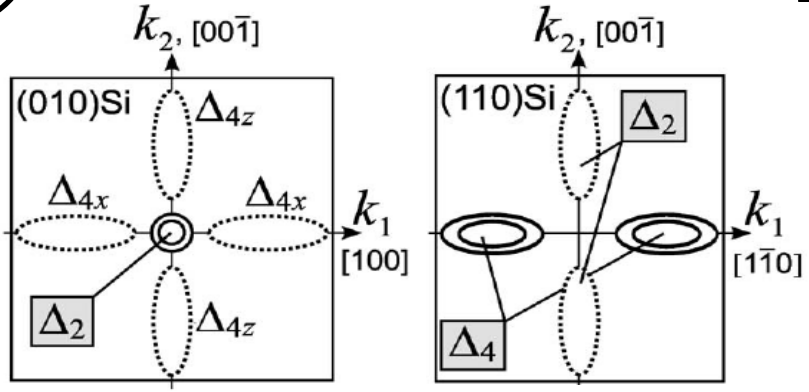


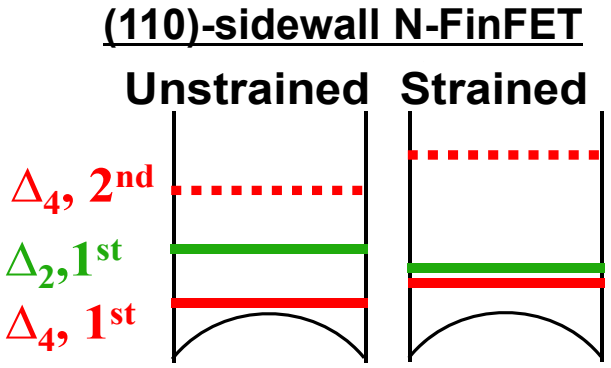
- As t_{Si} decreases, Π_{xx} decreases due to diminished sub-band reoccupation and inter-valley scattering reduction.

N. Xu, SOI Conf. (2012)

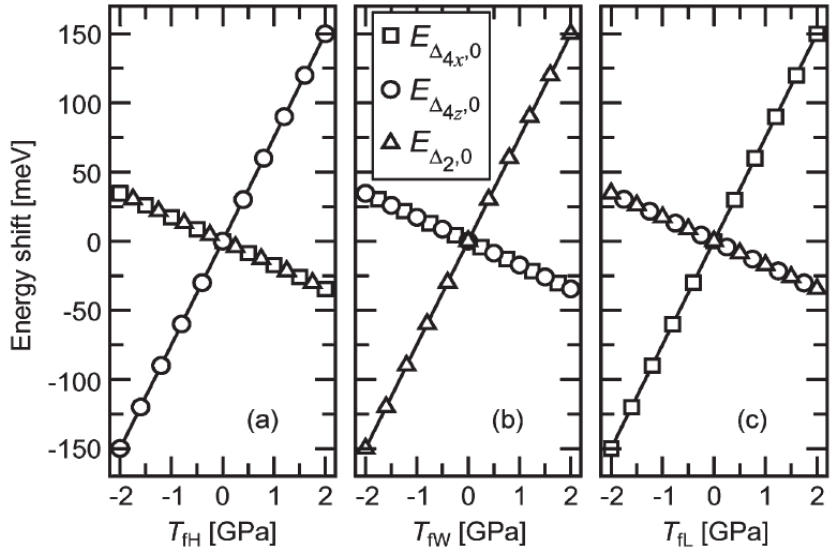
Strain Enhancement on FinFET Carrier Mobility: Electrons



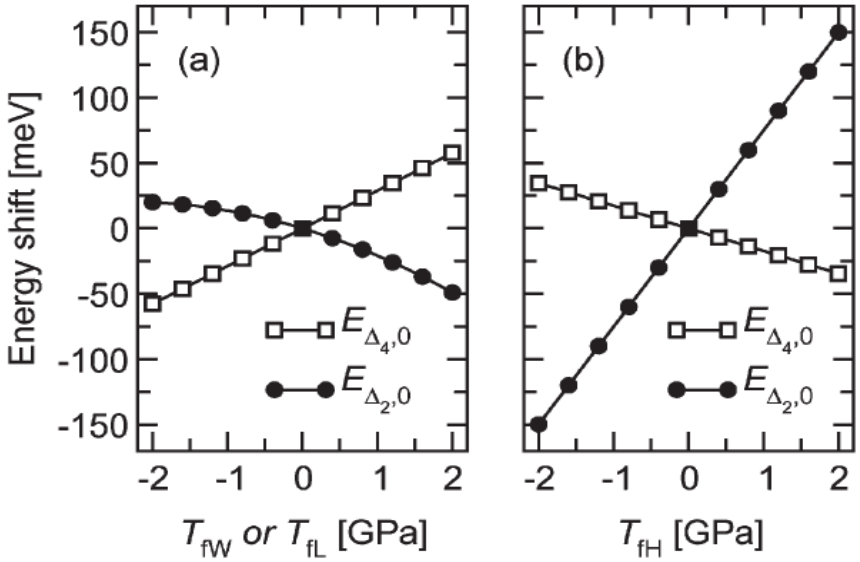




(100)-sidewall N-FinFET



(110)-sidewall N-FinFET

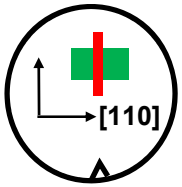


N. Serra, TED (2010)

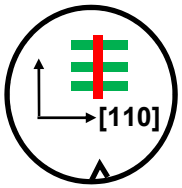
Strain Enhancement on FinFET Carrier Mobility: Holes

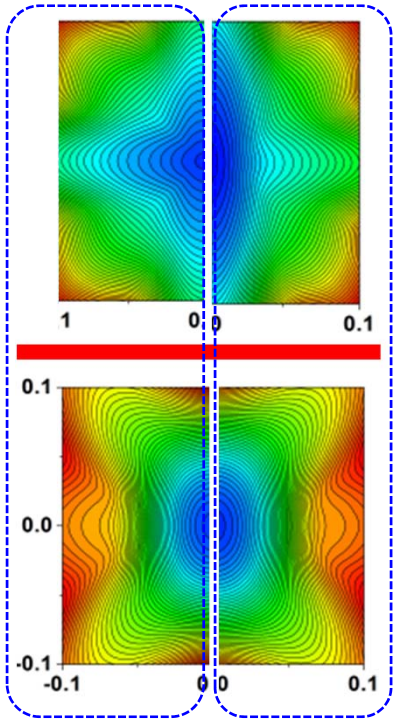
Equi-energy contours from the 1st HH

Planar MOSFET (100)/<110>

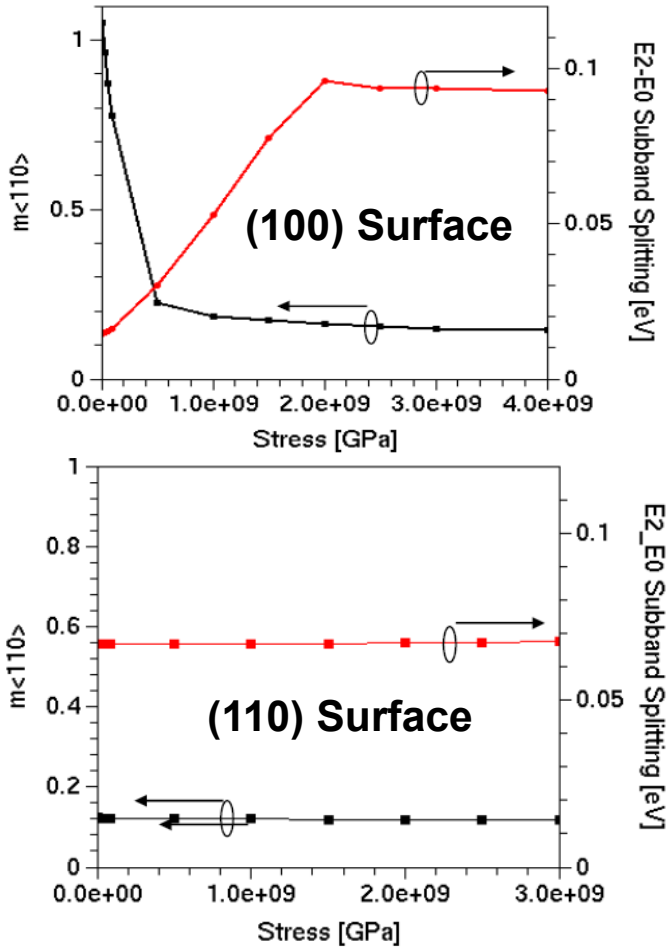


FinFET (110)/<110>



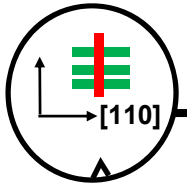


unstrained σ_x **= -1 GPa**

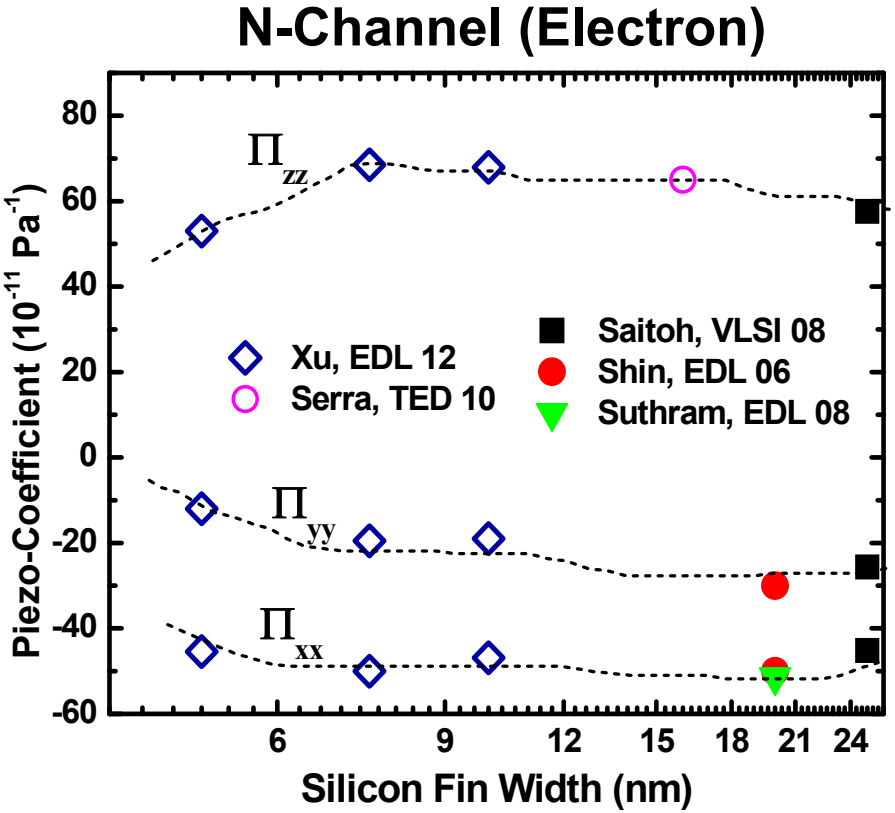


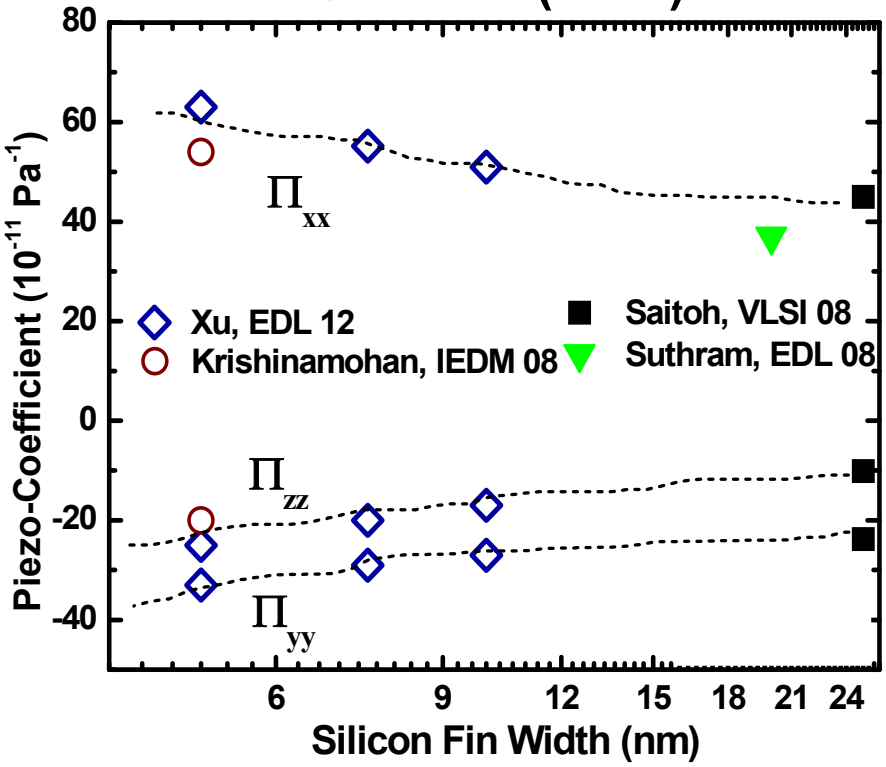
Courtesy of L. Smith (Synopsys)

Impact of Fin Width Scaling on Piezoresistive Coefficients



Open symbols → Simulated Closed Symbols → Measured

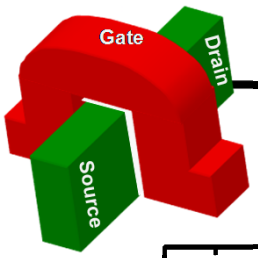


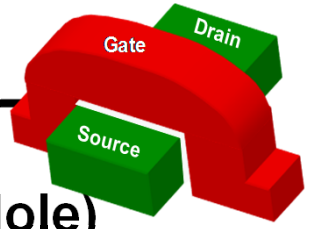


- **No substantial degradation in piezo-resistance is seen with decreasing fin width.**

N. Xu, SOI Conf. (2012)

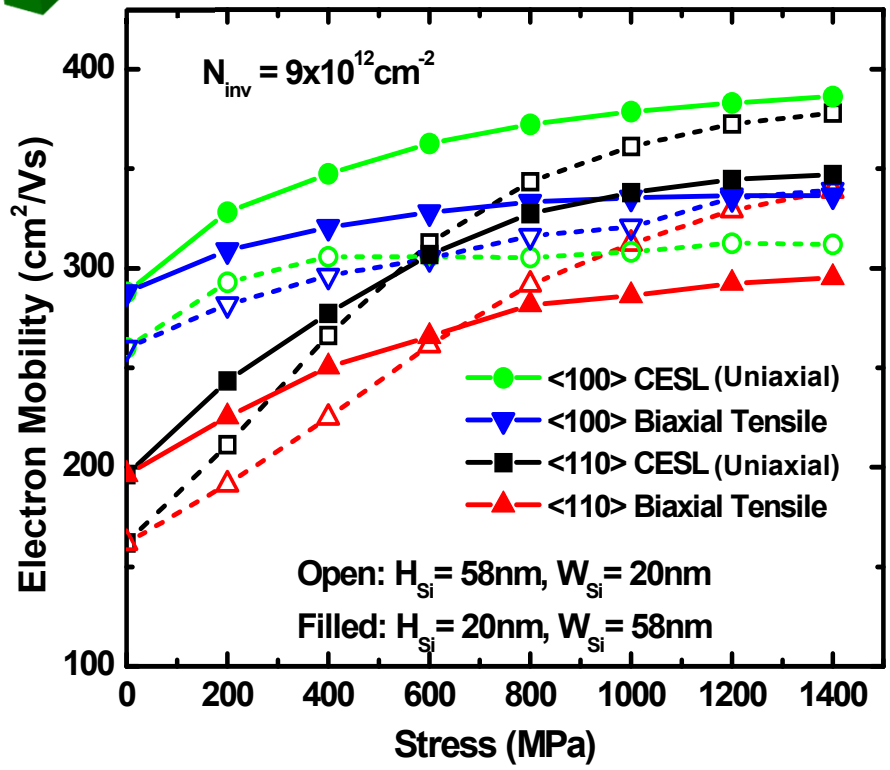
Impact of Fin Aspect-Ratio



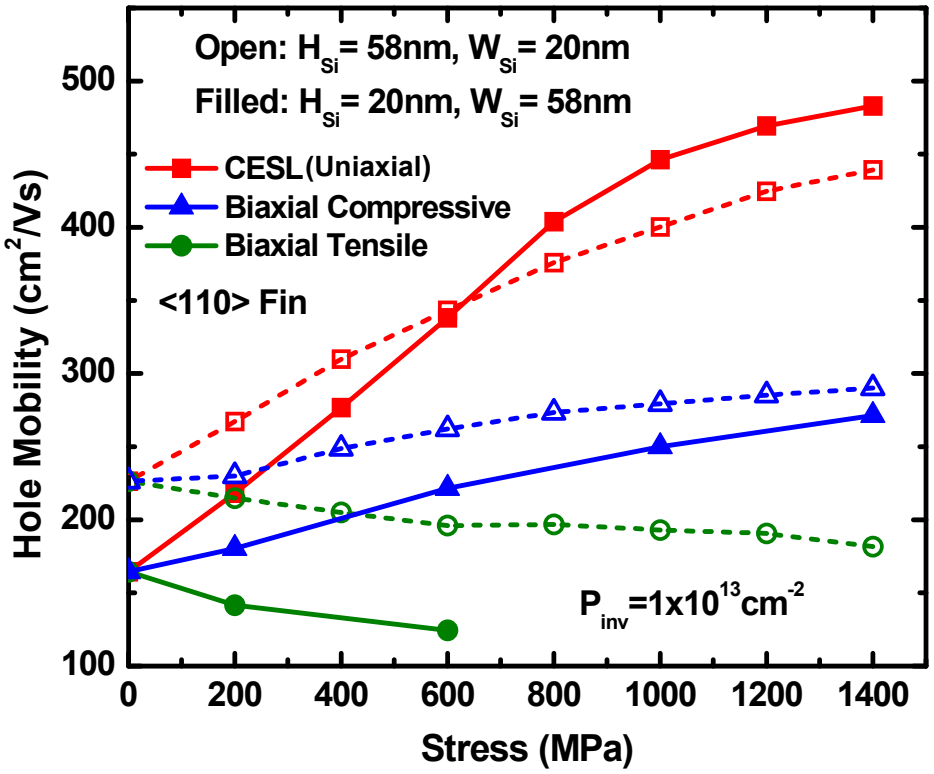


scPS simulations, N. Xu, IEDM (2010)

N-Channel (Electron)



P-Channel (Hole)

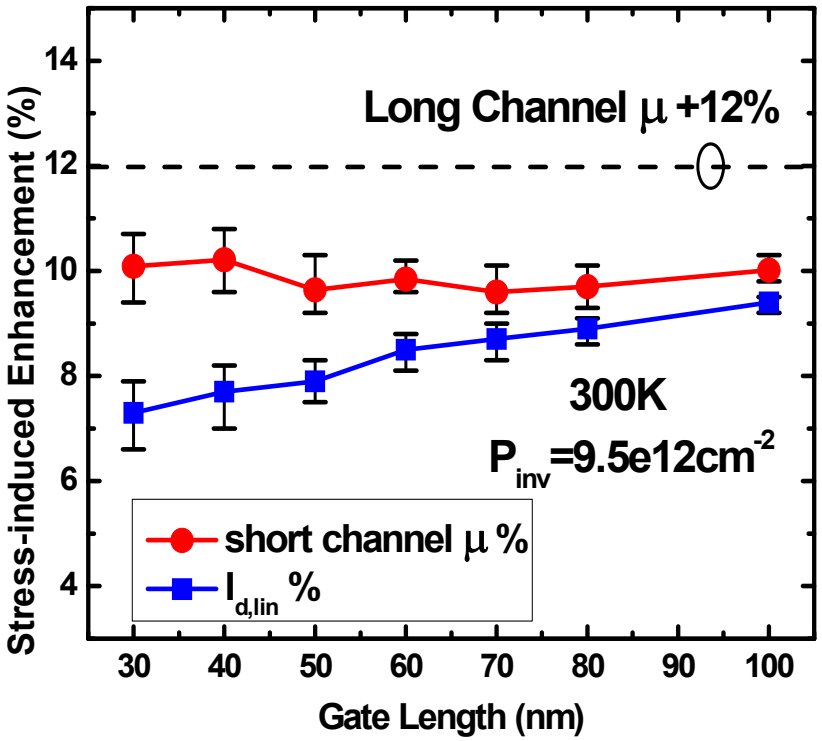


- μ_n is highest for <100> uniaxial-strained Tri-Gate, μ_p is highest for <110> uniaxial-strained Tri-Gate at high level stress.

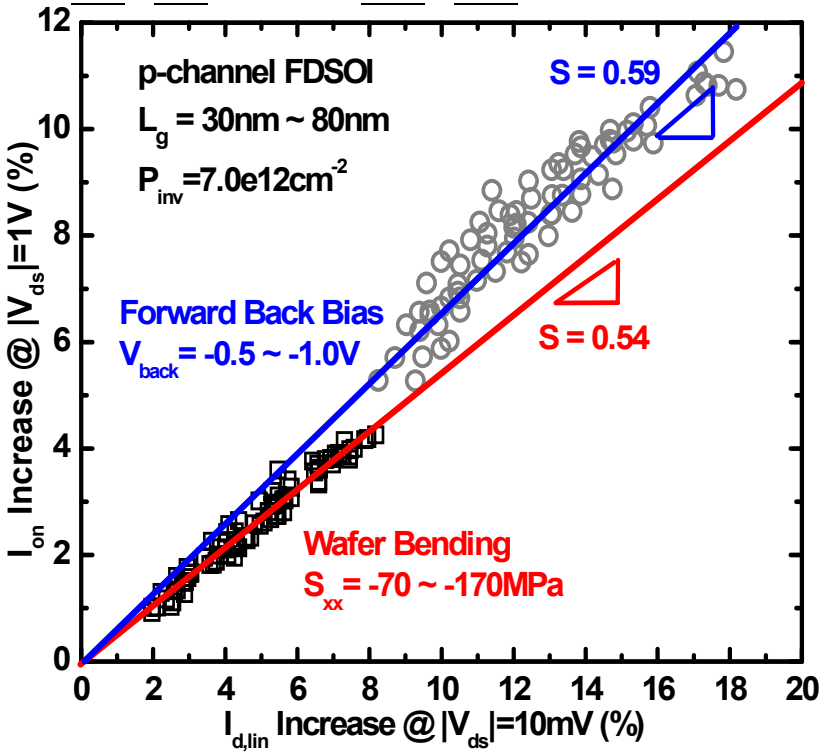
Strain Enhancement on Short-Channel MOSFET Performance

Expt. results, N. Xu, VLSI-T (2011,2012)

Mobility *vs.* Gate Length



$\Delta I_{ON}/I_{ON}$ *vs.* $\Delta i_{dlin}/I_{dlin}$ under strain



- Enhancement in apparent mobility is maintained *vs.* L_g scaling.
- ~50% of $\Delta\mu/\mu$ can be transferred to $\Delta I_{ON}/I_{ON}$.

References

1. Y. Sun *et al*., "Physics of Strain Effects in Semiconductors and metal-oxide-semiconductor field-effect transistors," *Journal of Applied Physics*, 101, 104503, 2007.
2. F. Conzati *et al*., "Drain Current Improvements in Uniaxially Strained P-MOSFETs: A Multi-Subband Monte Carlo Study," Solid-State Electronics, vol.53, pp.706-711, 2009.
3. D. Esseni *et al*.,"Semi-Classical Transport Modeling of CMOS Transistors with Arbitrary Crystal Orientations and Strain Engineering," *Journal of Computational Electronics*, vol.8, pp.209-224, 2009.
4. N. Xu *et al*., "Stress-induced Performance Enhancement in Ultra-Thin-Body Fully Depleted SOI MOSFETs: Impacts of Scaling," *Symposium on VLSI Technology Dig.*, p.162-163, 2011.
5. K. Uchida *et al.,* "Physical Mechanisms of Electron Mobility Enhancement in Uniaxial Stressed MOSFETs and Impacts of Uniaxial Stress Engineering in Ballistic Regime," *IEEE International Electron Device Meeting, Tech. Dig.,* p.229-232, 2004.
6. K. Uchida *et al.,* "Carrier Transport and Stress Engineering in Advanced Nanoscale Transistors From (100) and (110) Transistors To Carbon Nanotube FETs and Beyond," *IEEE International Electron Device Meeting, Tech. Dig.,* p.569-572, 2008.
7. N. Serra *et al.,* "Mobility Enhancement in Strained n-FinFETs: Basic Insight and Stress Engineering," *IEEE Transactions on Electron Devices*, vol.57, p.482-490, 2010.
8. T. Krishnamohan *et al.,* "Comparison of (001), (110) and (111) Uniaxial- and Biaxial- Strained-Ge and Strained-Si PMOS DGFETs for All Channel Orientations: Mobility Enhancement, Drive Current, Delay and Off-State Leakage," *IEEE International Electron Device Meeting, Tech. Dig.,* p.899-902, 2008.
9. M. Saitoh *et al.,* "Three-Dimensional Stress Engineering in FinFETs for Mobility/On-Current Enhancement and Gate Current Reduction," *Symposium on VLSI Technology Dig.*, p.18-19, 2008.
10. K. Shin *et al., "*Study of Bending-Induced Strain Effects on MuGFET Performance," *IEEE Electron Device Letters,* vol.27, p.671-673, 2006.

References

11. S. Suthram *et al.,* "Comparison of Uniaxial Wafer Bending and Contact-Etch-Stop-Liner Stress Induced Performance Enhancement on Double-Gate FinFETs," *IEEE Electron Device Letters,* vol.29, p.480-482, 2008.
12. J.-S. Lim *et al*., "Comparison of Threshold Voltage Shifts for Uniaxial and Biaxial Tensile-Stressed n-MOSFETs," IEEE Electron Device Letters, vol.25, no.11, pp.731-733, 2004.
13. E. X. Wang *et al*., "Physics of Hole Transport in Strained Si MOSFET Inversion Layers," *IEEE Transactions on Electron Devices*, vol.53, no.8, pp.1840-1851, 2006.
14. O. Weber *et al*., "Examination of Additive Mobility Enhancement for Uniaxial Stress Combined with Biaxially Strained Si, Biaxially Strained SiGe and Ge Channel MOSFETs," *IEEE International Electron Device Meeting, Tech. Dig.,* p.719-722, 2007.
15. N. Xu *et al*., "MuGFET Carrier Mobility and Velocity: Impacts of Fin Aspect Ratio, Orientation and Stress," *IEEE International Electron Device Meeting, Tech. Dig.,* p.194-197, 2010.
16. N. Xu *et al.,* "Impact of Back Biasing on Carrier Transport in Ultra-Thin Body and BOX (UTBB) Fully Depleted SOI MOSFETs," *Symposium on VLSI Technology Dig.*, p.113-114, 2012.