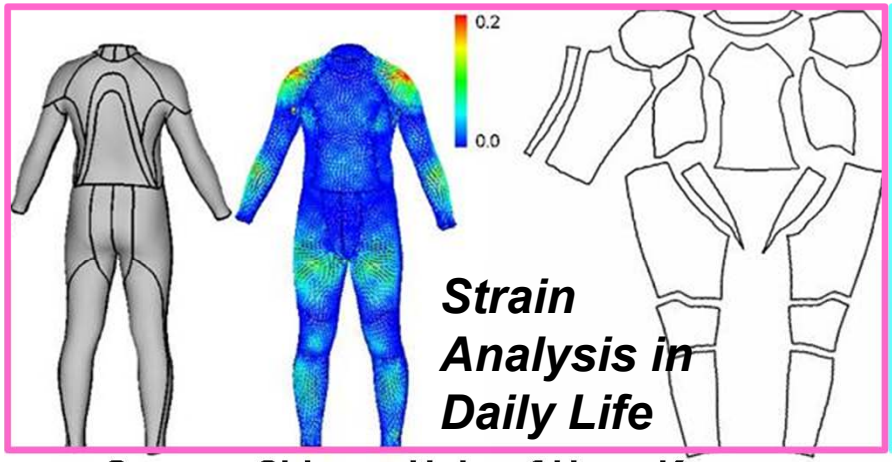
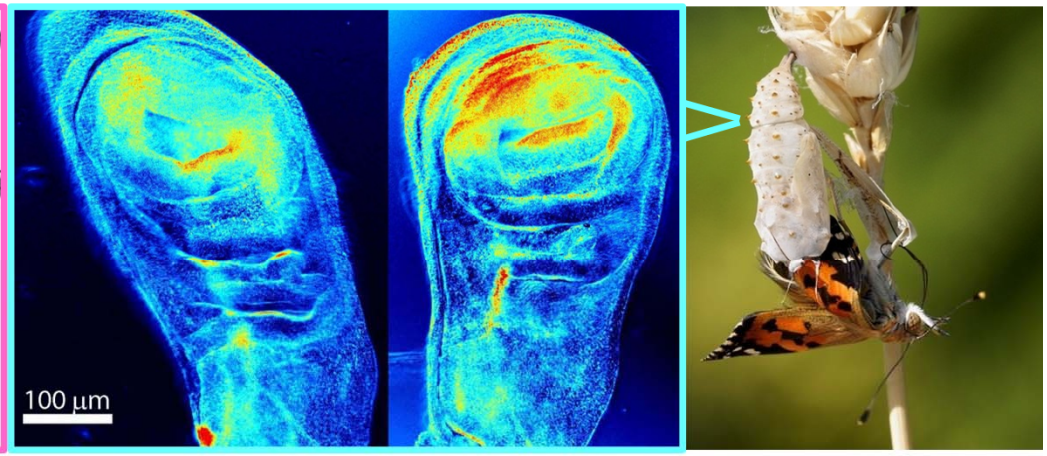


Source: Chinese Univ. of Hong Kong



Source: Univ. of Zurich

Lecture 9

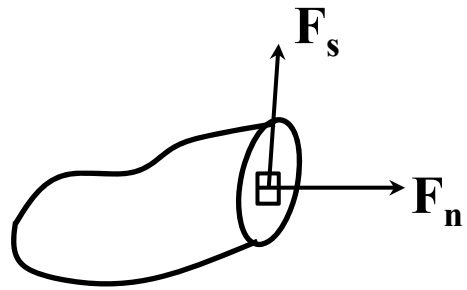
- **Strained-Si Technology I: Device Physics**
  - Background
  - Planar MOSFETs
  - FinFETs

<u>Reading</u>:

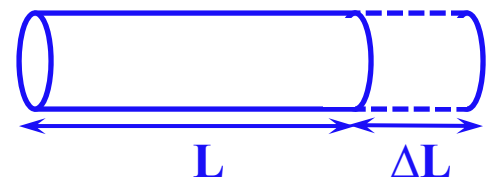
- Y. Sun, S. Thompson, T. Nishida, “Strain Effects in Semiconductors,” Springer, 2010.
- multiple research articles (reference list at the end of this lecture)

Mechanical Stress/Strain Analysis

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



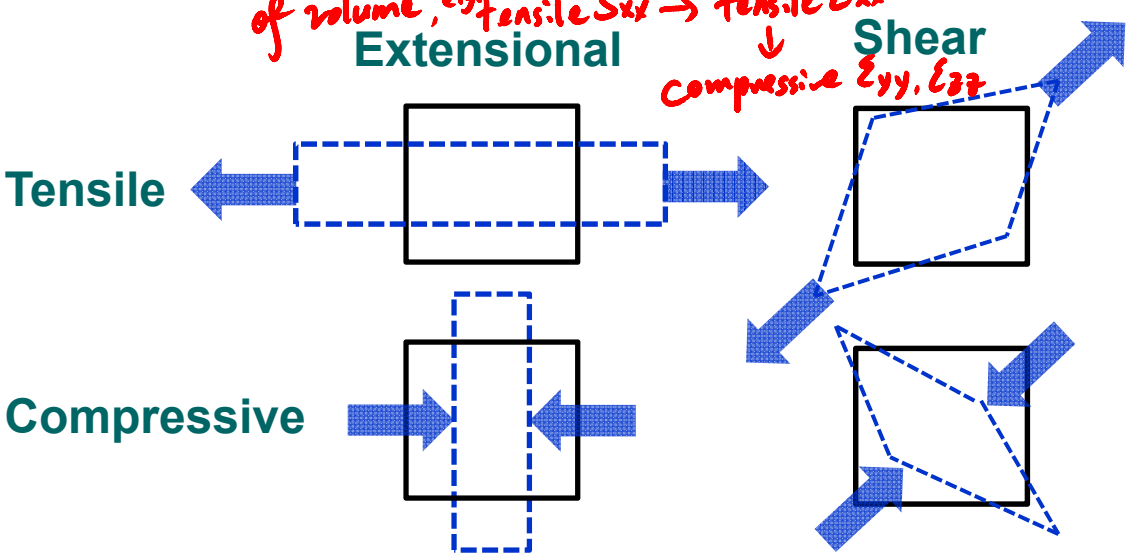
$$\text{Stress} = \lim_{\Delta A \to 0} \frac{\Delta F}{\Delta A}$$ σ_x or S_{xx}



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

Stress Types

Due to conservation of volume, e.g. tensile S_{xx} → tensile ε_{xx} ↓ compressive $\varepsilon_{yy}, \varepsilon_{zz}$



Stress Tensor

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

6 independent variables:

$\sigma_{x,y,z}$ & $\tau_{xy,yz,xz}$

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)**

represents the major crystal axis
i.e: <100> for 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:

when needs to evaluate along other directions, rotate the tensor

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

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

E, ν, G are directional

for <110> in Si:

$E = 1.6\ e10\ pa^{-1}$

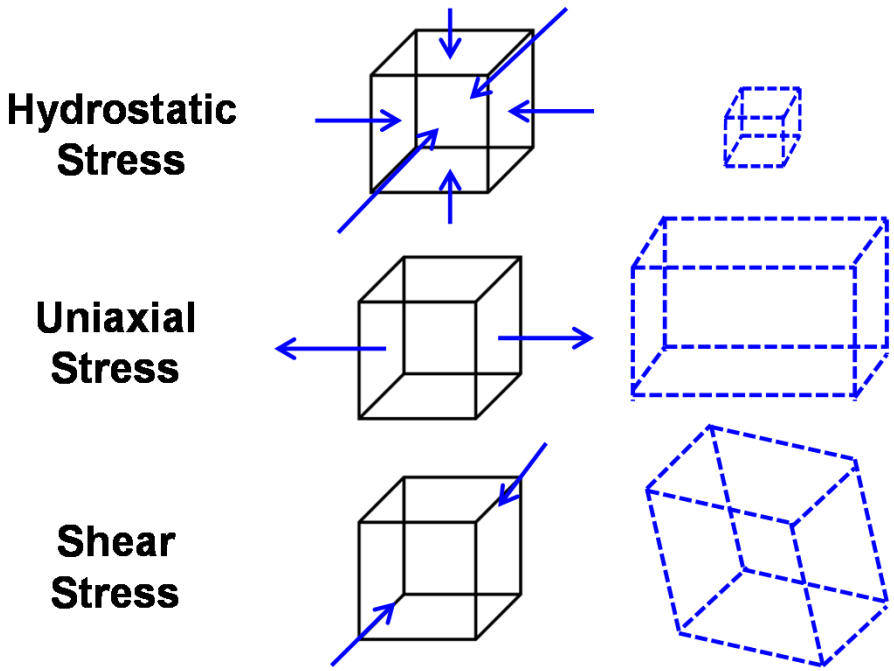
$\nu = -0.278$

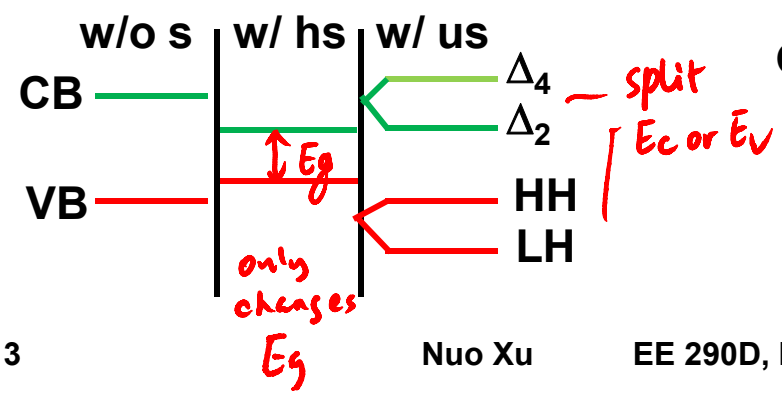
$G = 0.52\ e10\ pa^{-1}$

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

Impact of Strain on Semiconductors

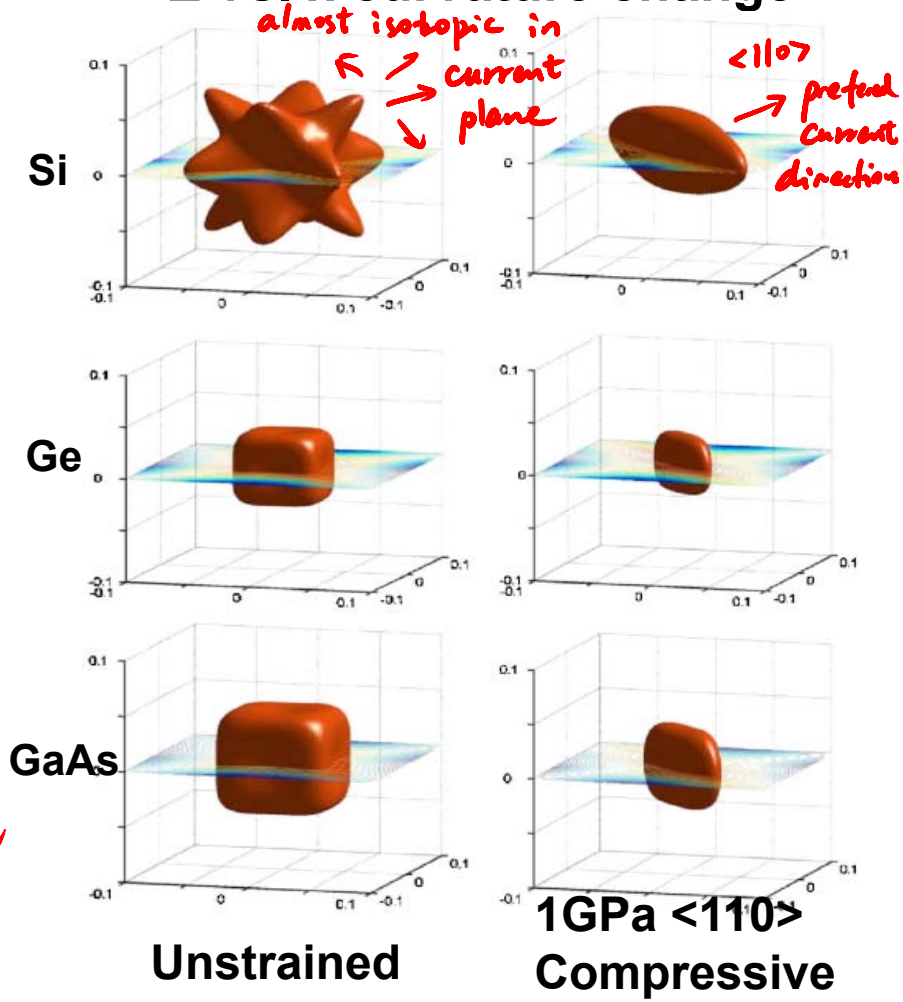
- **Energy Band Splitting**





- ***E* vs. *k* curvature change**

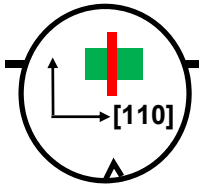
caused by shear stress

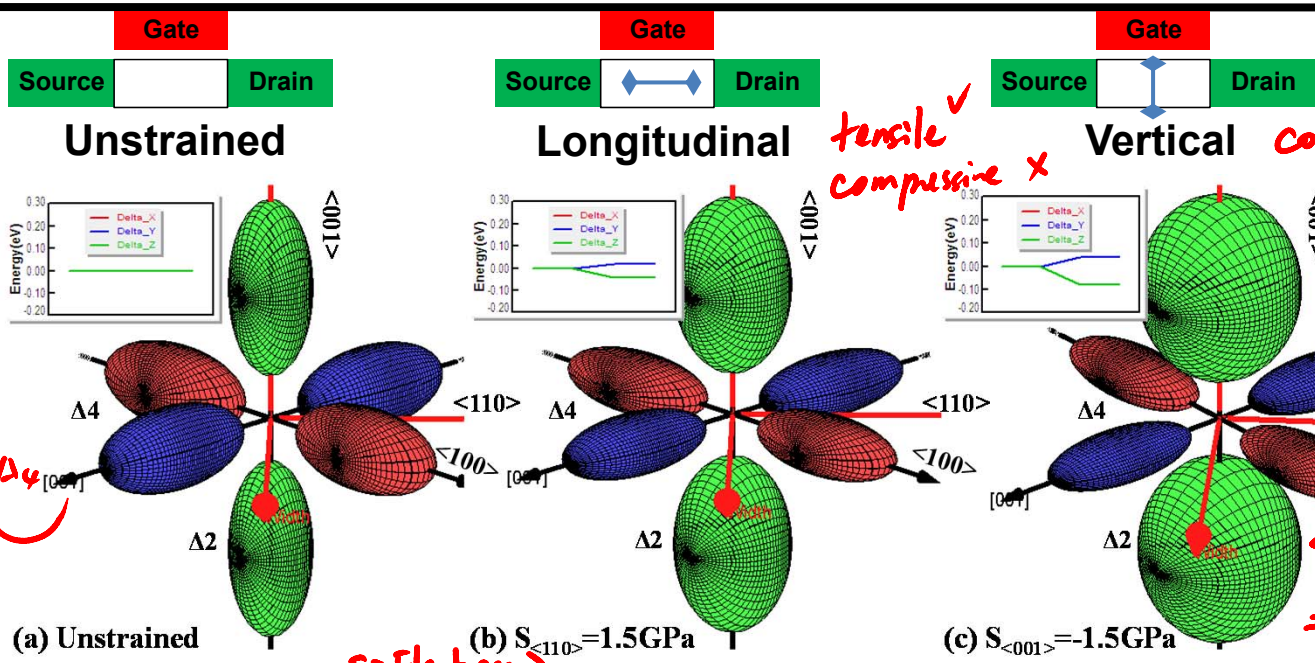


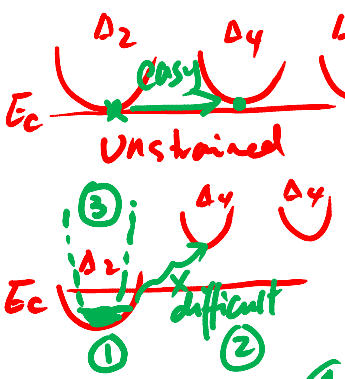
Y. Sun, JAP (2007)

Strain Impact on Si Bandstructure: Planar N-MOSFET

confinement (001)
current // <110>







applying strain

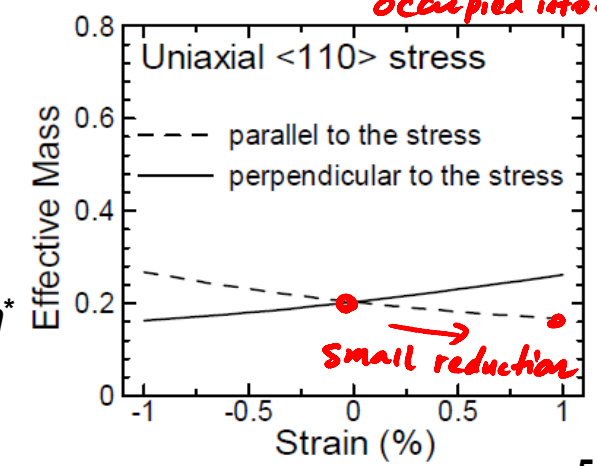
(Si Electrons) Dominant part for

Energy Splitting

1. Lower DOS available for Scattering → Reduced (Inter-valley) Scattering Rates

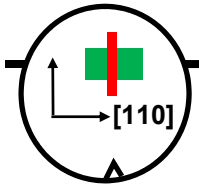
2. Sub-band reoccupation → Lowered average m^*

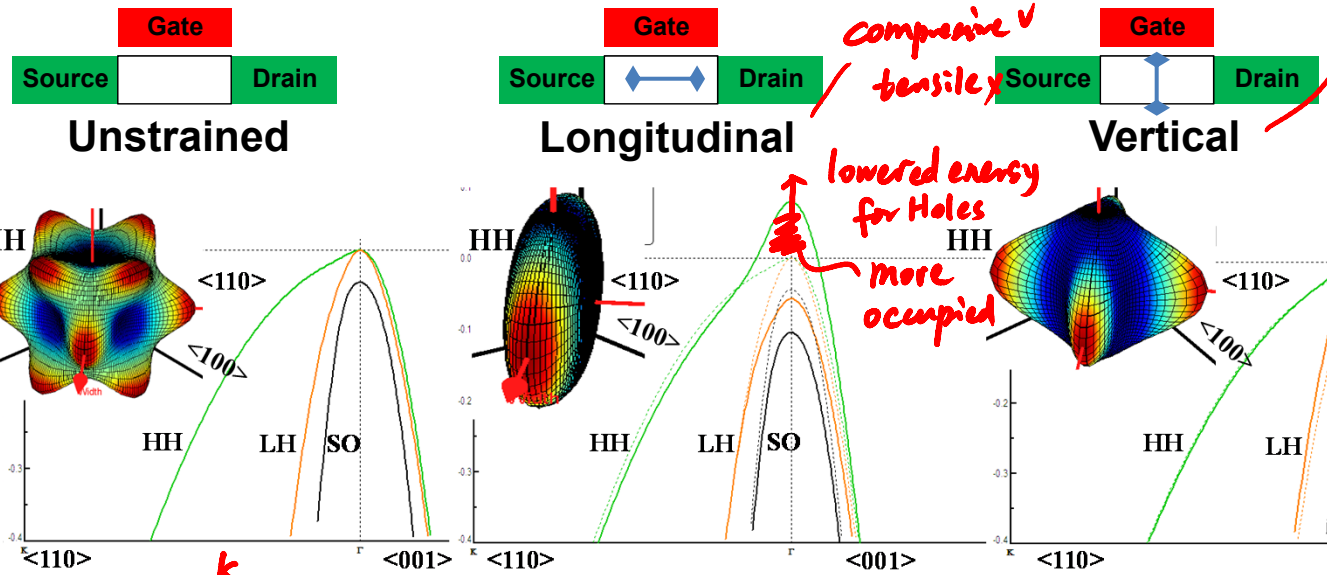
3. *E-k* Curvature Change → Transport m^* Reduction



K. Uchida, IEDM (2008)

Strain Impact on Si Bandstructure: Planar P-MOSFET





Holes

Heavy Hole
Light Hole
Split-off Hole

along <110>: k, E ⇒ $-S_{xx}$ // <110> ⇒ E

Huge curvature change ⇒ m^* ↓

applying strain

Energy Splitting

(Dominant for Si holes)

E-k Curvature Change

Lower DOS available for Scattering

↓

Reduced (Inter-sub-band) Scattering Rates

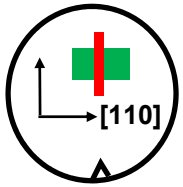
Sub-band reoccupation

↓

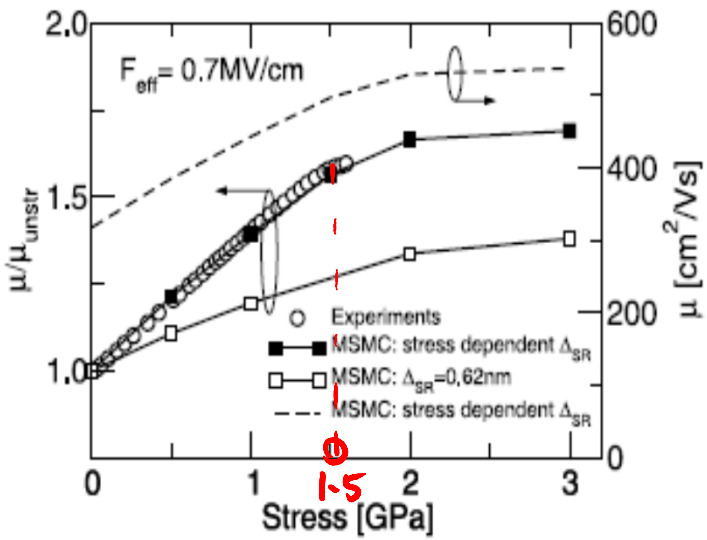
Lowered average m^*

Transport m^* Reduction

Strain Enhancement on Si MOSFET Carrier Mobility

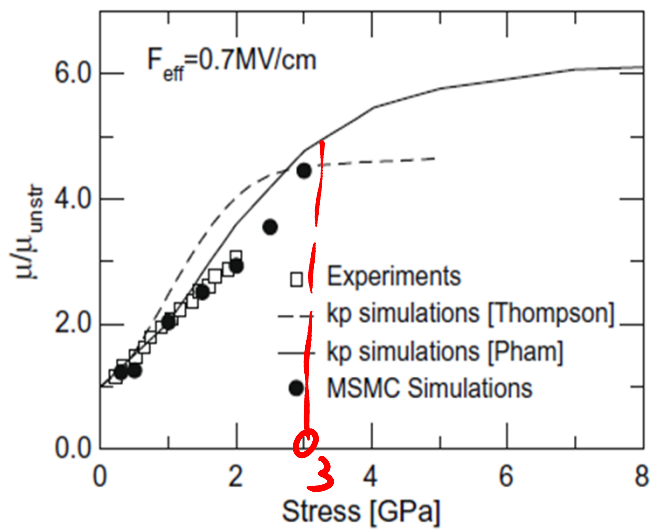


Electron



D. Esseni, JCE (2009)

Hole

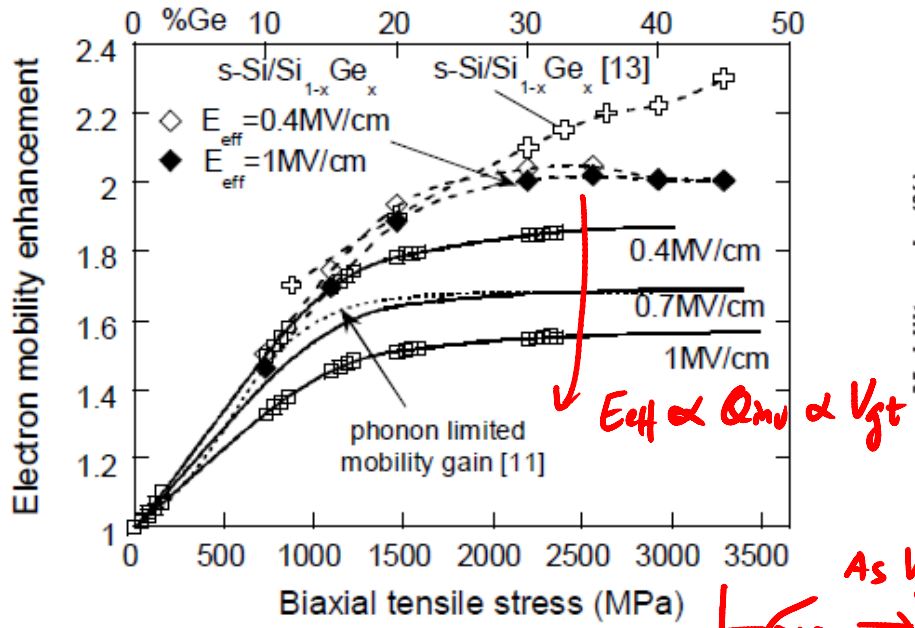


F. Conzati, SSE (2009)

- **For N-MOSFET, electron mobility enhancement saturates at ~1.5 GPa <110>-uniaxial tensile stress .** due to sub-band reoccupation-induced $\Delta\mu_e$ saturates
- **For P-MOSFET, hole mobility enhancement saturates at very high <110>-uniaxial compressive stress.** due to the maintained m^* reduction

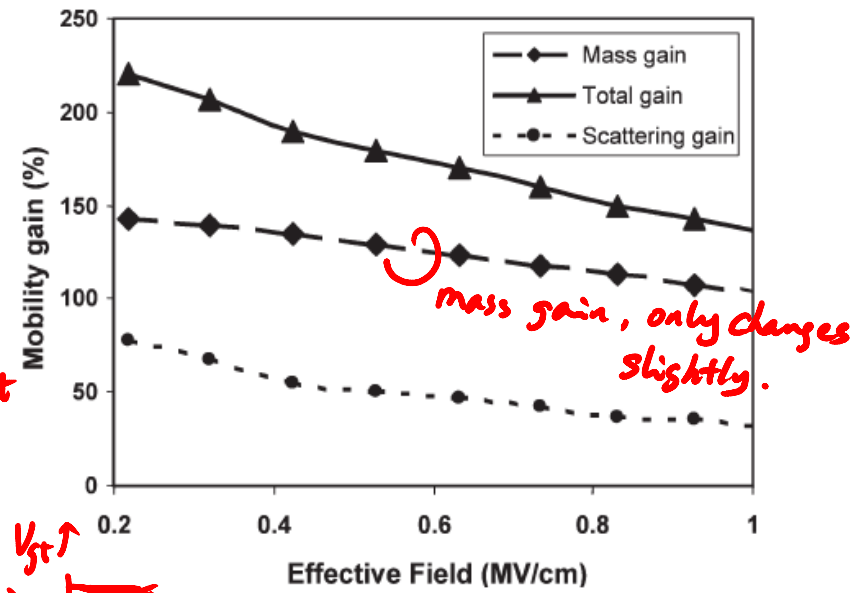
Impact of Quantum Confinement

Electrons under Biaxial Tensile Stress

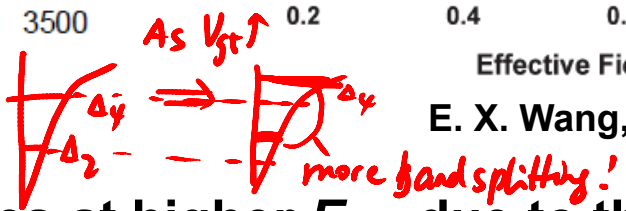


O. Weber, IEDM (2007)

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**

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

negative sign!

- **Sub-band Reoccupation Model**

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

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

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

J.-S. Lim, EDL (2004)

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

non-linear (saturation) dependence

- **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

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

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

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

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

Poisson equation

Hole's complicated E-K relationship

6x6 Luttinger-Kohn Hamiltonian for Holes

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

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

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

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

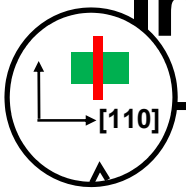
$$M=-\frac{\hbar^2}{2m_0}\sqrt{3}[\gamma_2(k_x^2-k_y^2)-i2\gamma_3k_xk_y)$$

$\rightarrow \mathcal{H}\cdot\xi(z)=E\cdot\xi(z)$

impacts of strain included in M, L, Q, P terms of $\mathcal{H}$

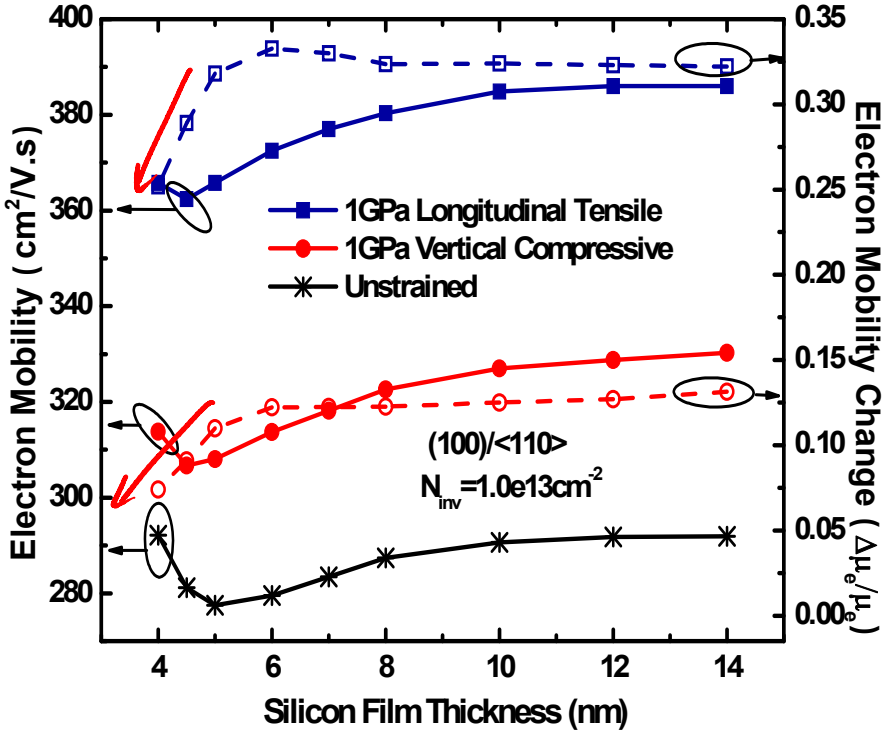
- Impacts of strain on energy-band top as well as curvature change will be completely included into the Hamiltonian.
- Computationally intensive.

Impact of Si Body Thickness Scaling

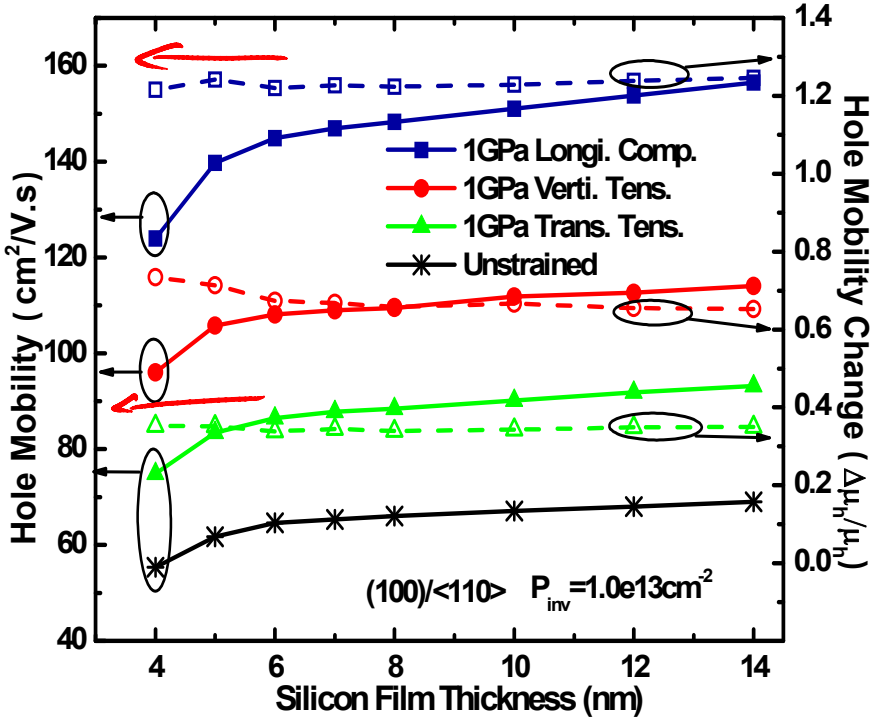


scPS simulations, N. Xu, VLSI-T (2011)

N-Channel (Electron)

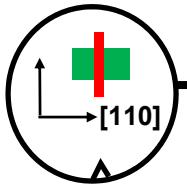


P-Channel (Hole)

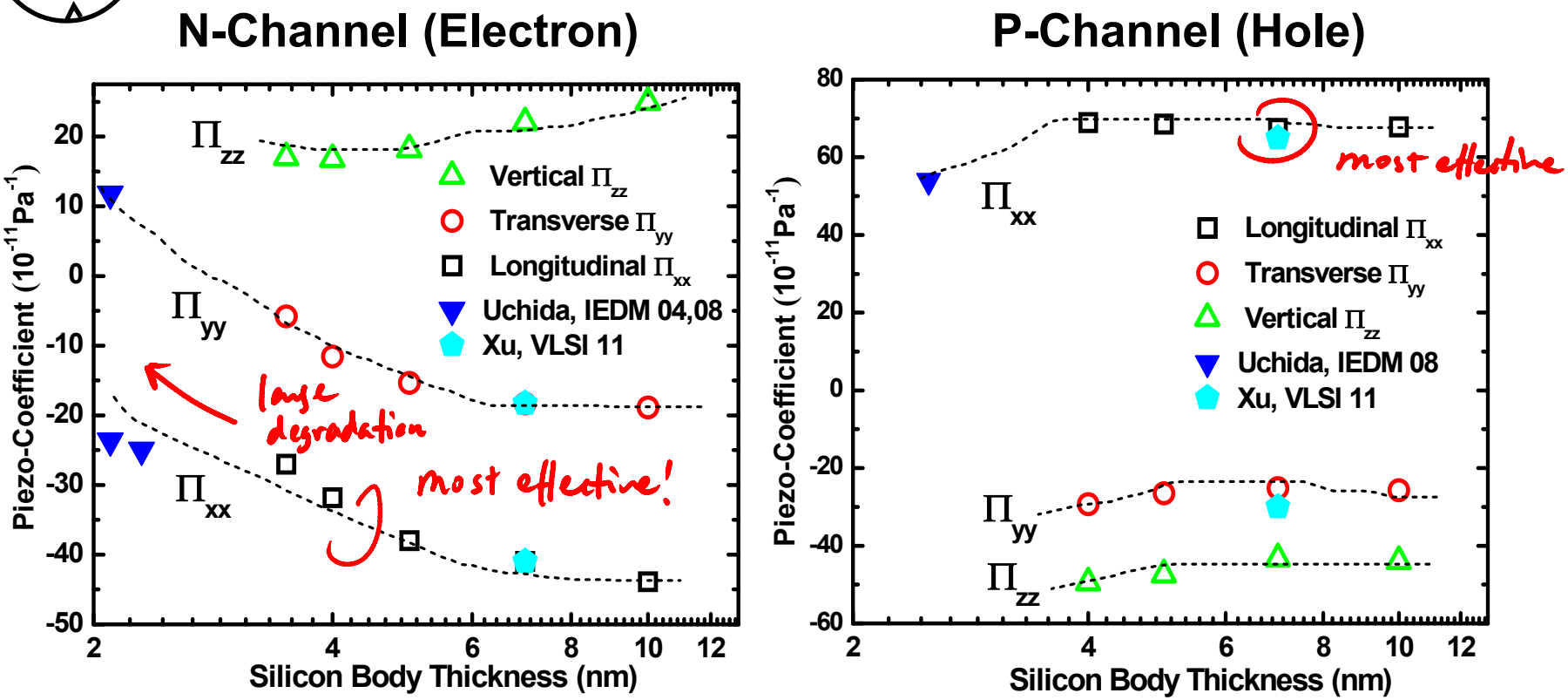


- **Stress enhancement diminishes for electrons as t_{SOI} scaled below 5nm, but not for holes.**

Impact of t_{Si} Scaling on Piezoresistive Coefficients



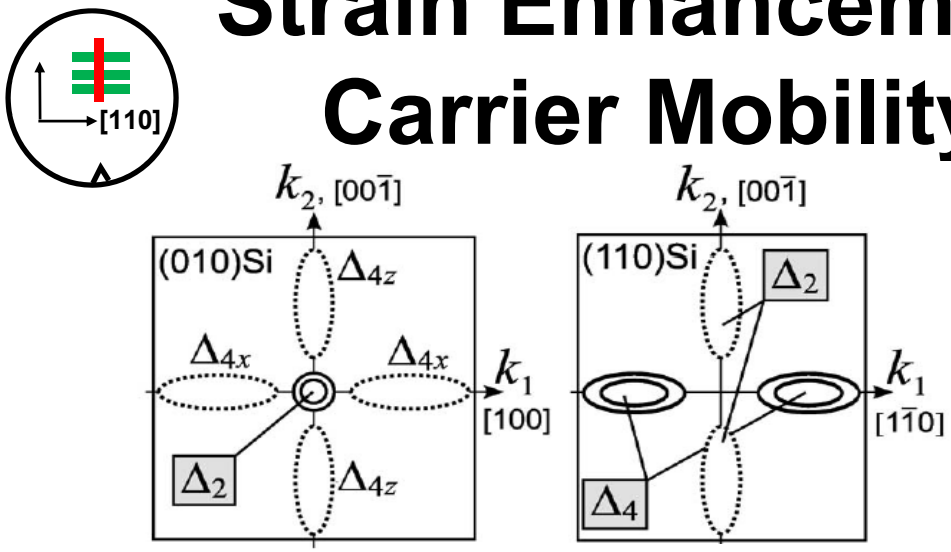
Open symbols → Simulated Closed Symbols → Measured



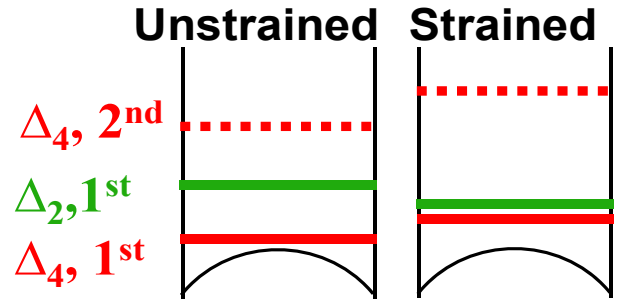
- As t_{Si} decreases, Π_{xx} decreases due to diminished sub-band reoccupation and inter-valley scattering reduction.

N. Xu, SOI Conf. (2012)

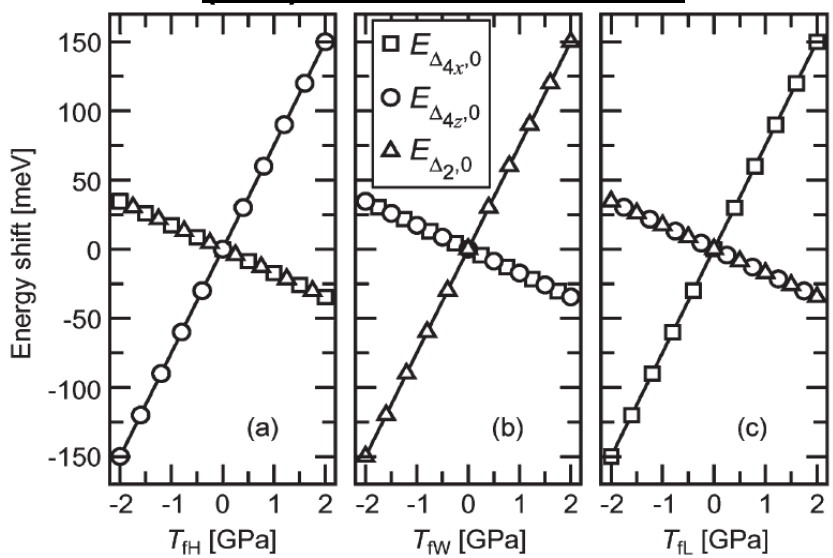
Strain Enhancement on FinFET Carrier Mobility: Electrons



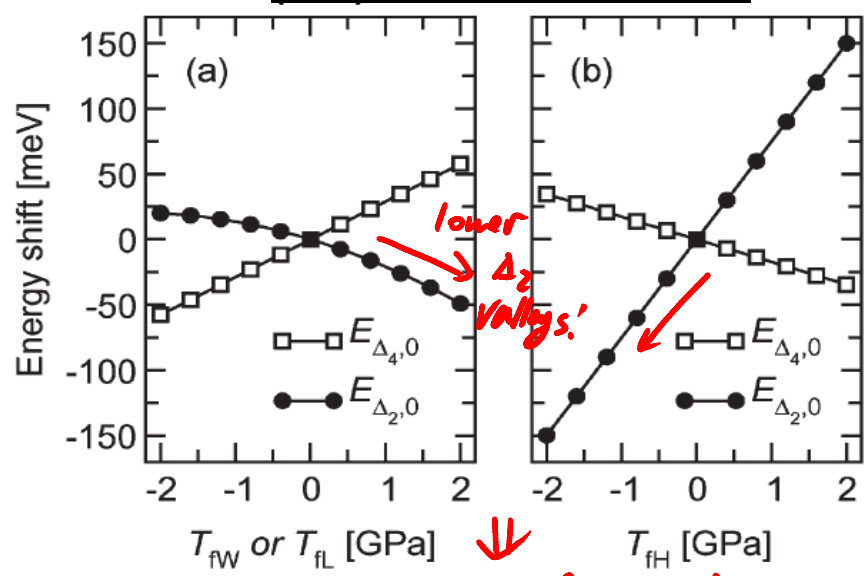
(110)-sidewall N-FinFET



(100)-sidewall N-FinFET



(110)-sidewall N-FinFET



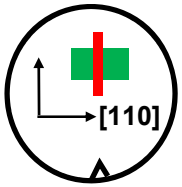
N. Serra, TED (2010)

Fin Height : Compressive
Fin length (Lg) : tensile

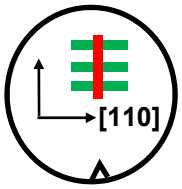
Strain Enhancement on FinFET Carrier Mobility: Holes

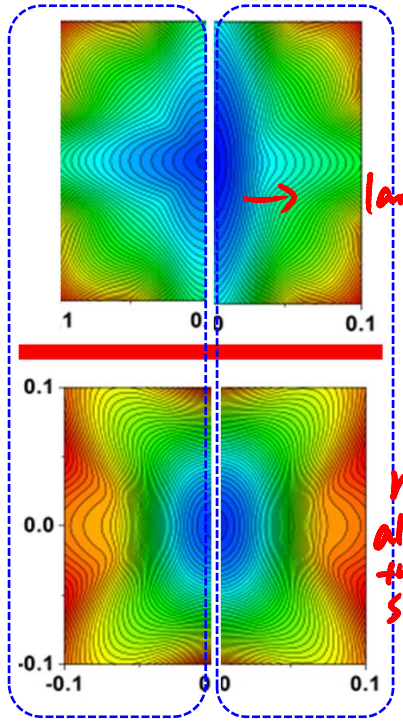
Equi-energy contours from the 1st HH

Planar MOSFET (100)/<110>



FinFET (110)/<110>

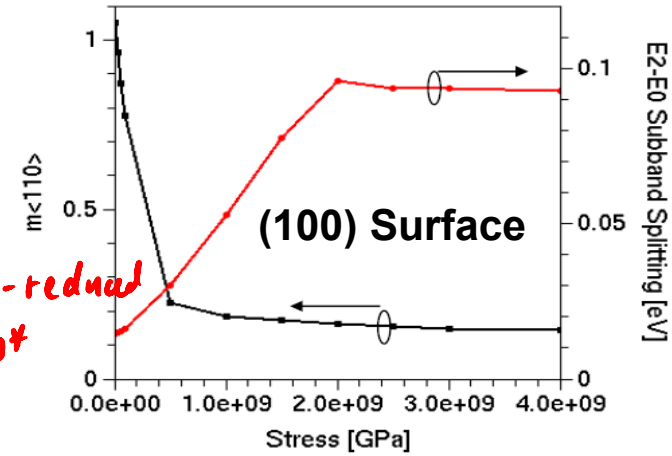


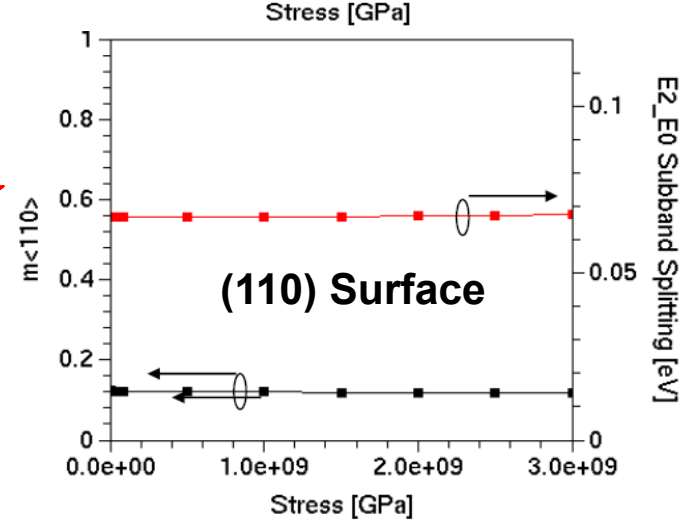


largely-reduced m*

m* almost the same

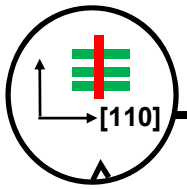
unstrained **σ_x = -1 GPa**



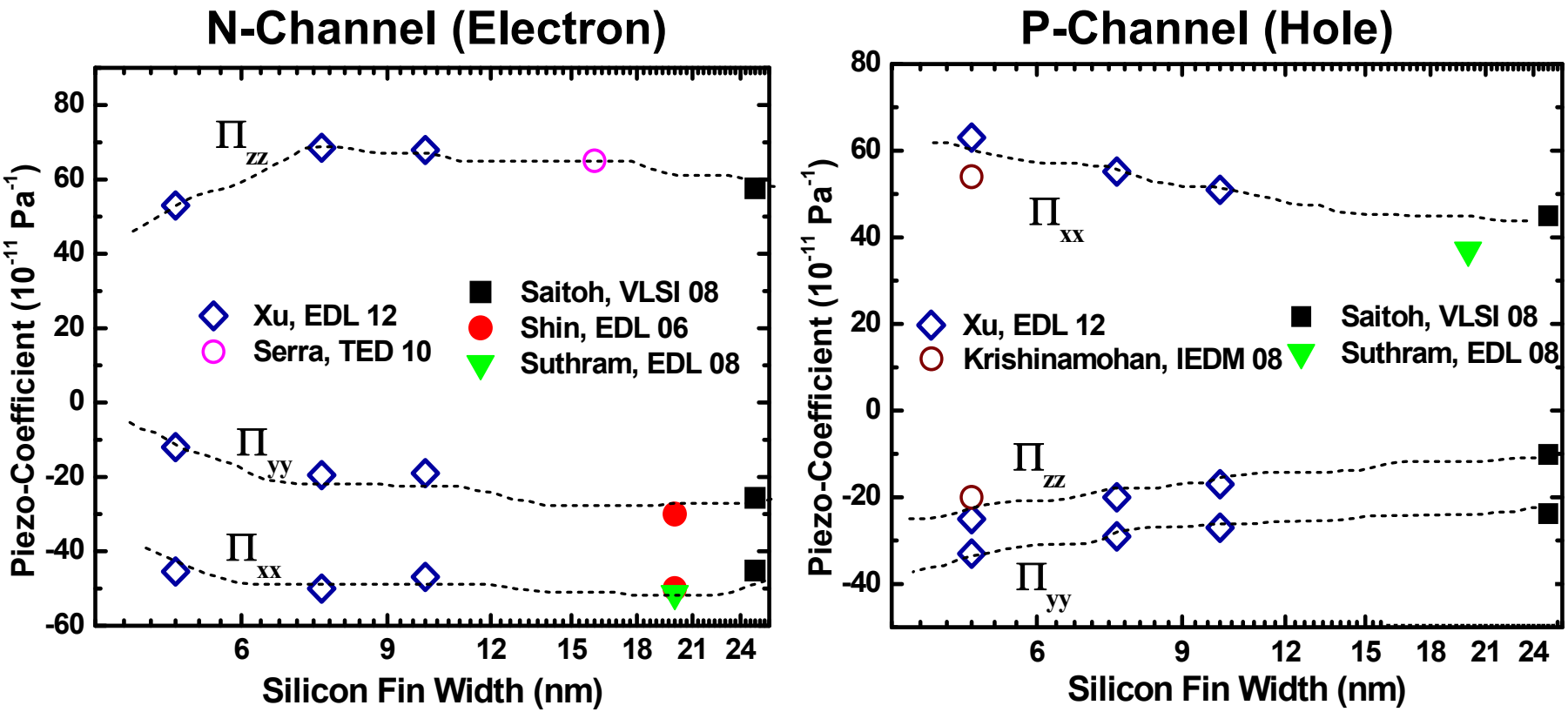


Courtesy of L. Smith (Synopsys)

Impact of Fin Width Scaling on Piezoresistive Coefficients



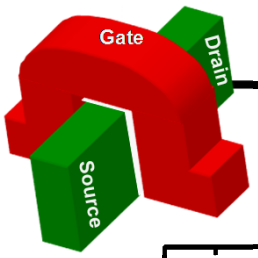
Open symbols → Simulated Closed Symbols → Measured



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

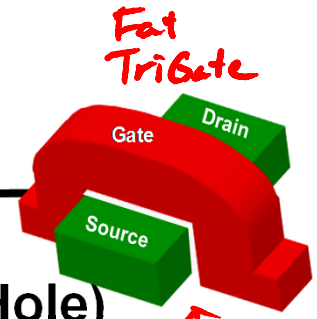
N. Xu, SOI Conf. (2012)

Impact of Fin Aspect-Ratio



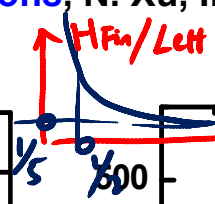
Thin FinFET

"Fossum's plot" in Lec. 3

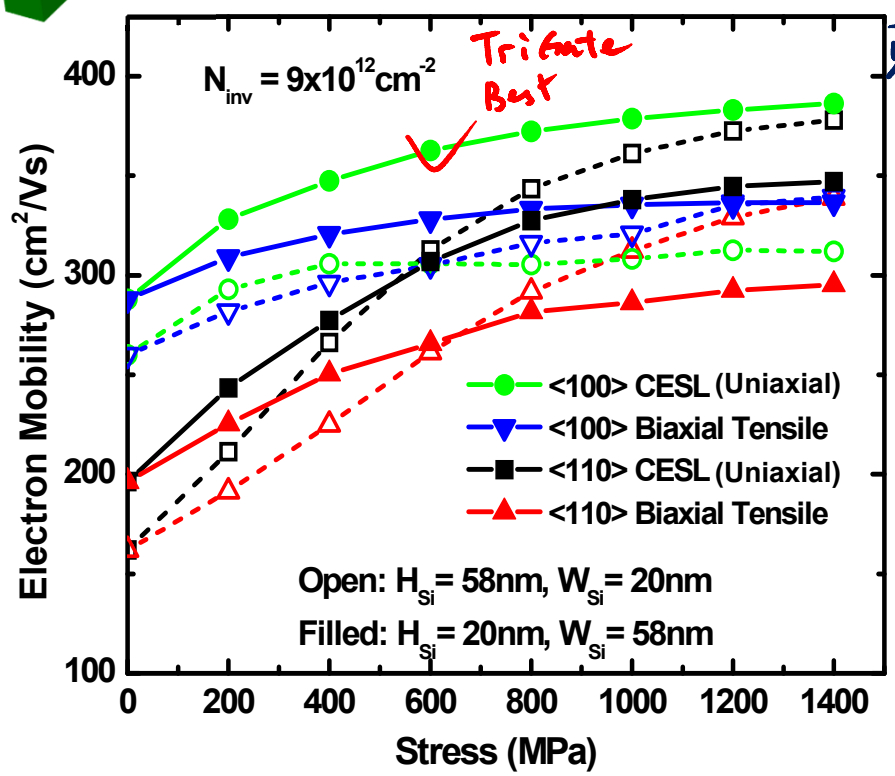


Fat TriGate

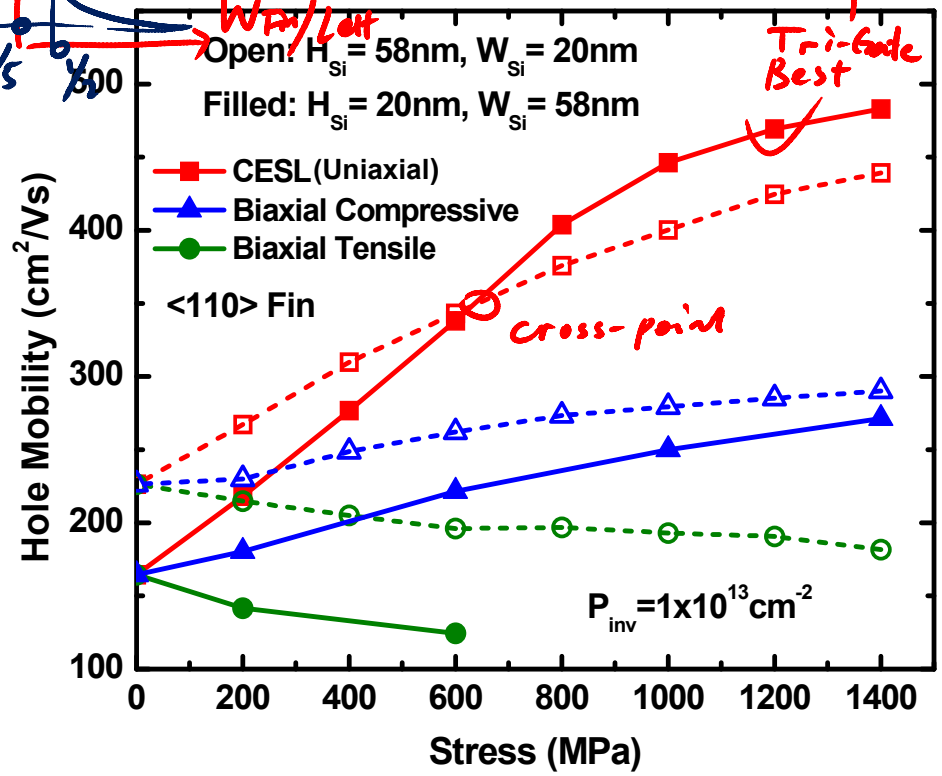
scPS simulations, N. Xu, IEDM (2010)



N-Channel (Electron)



P-Channel (Hole)

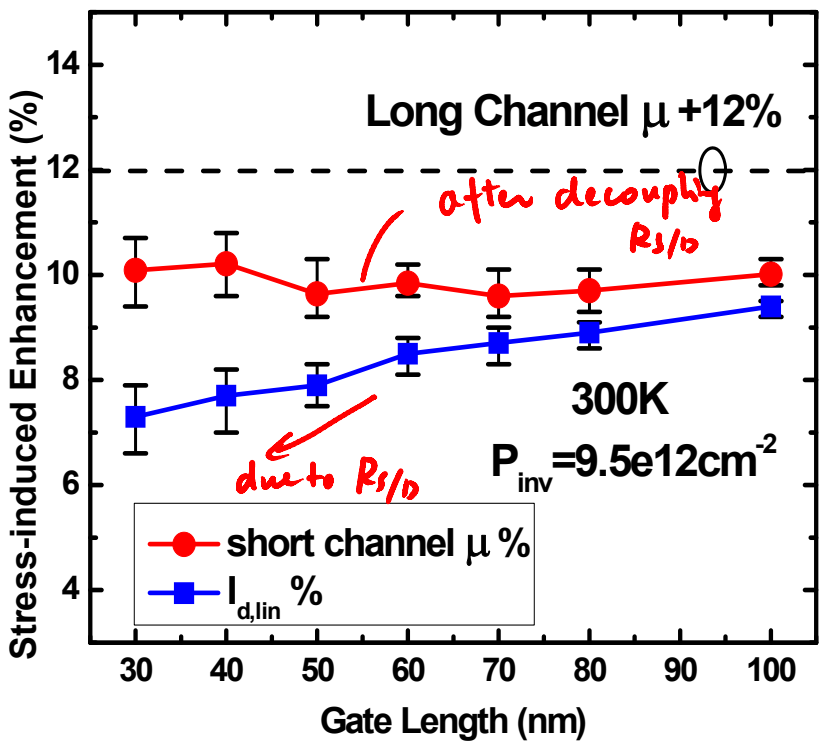


- μ_n is highest for <100> uniaxial-strained Tri-Gate, μ_p is highest for <110> uniaxial-strained Tri-Gate <u>at high level stress.</u>

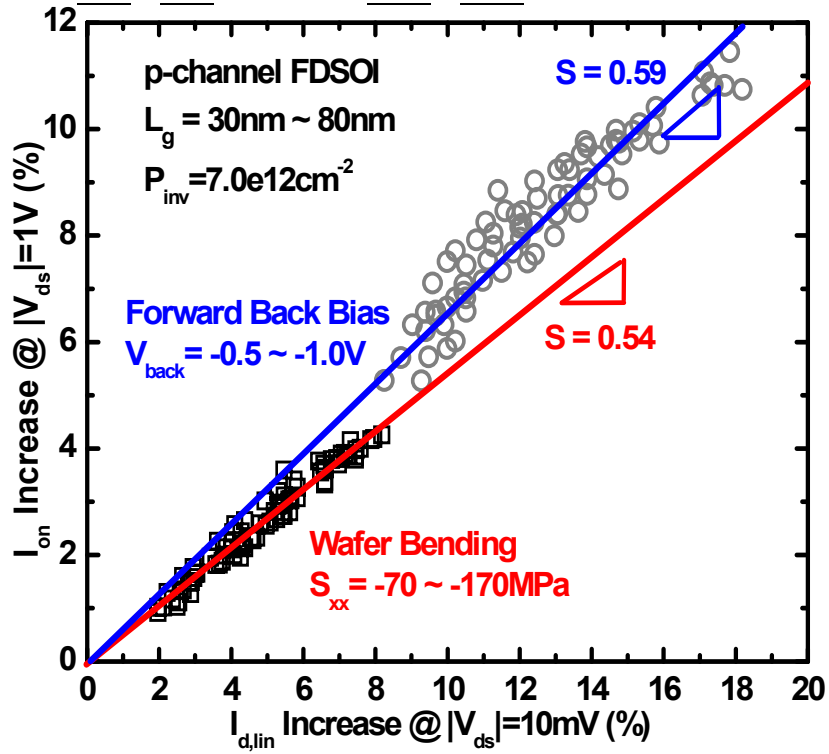
Strain Enhancement on Short-Channel MOSFET Performance

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 $\Delta I_{ON}/I_{ON}$.

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