Laser-Induced Current Transients in Strained-Si Diodes

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- Introduction
- Laser-induced current transients in diodes under mechanical stress

  - <110> uniaxial stress : Experiment and Simulation Results

  - <100> uniaxial and biaxial stress : Analytical Modeling

- Conclusion and future work

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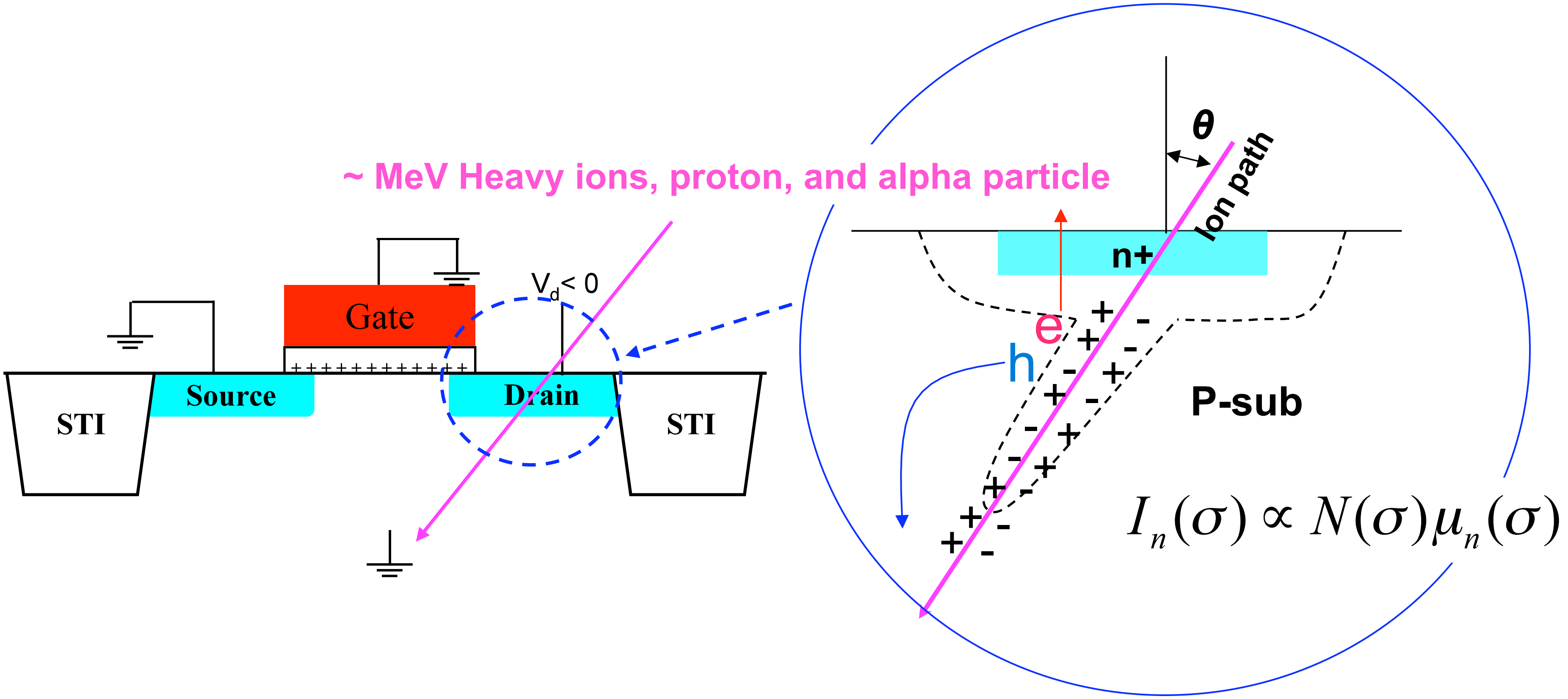
Single Event Effect in MOSFET

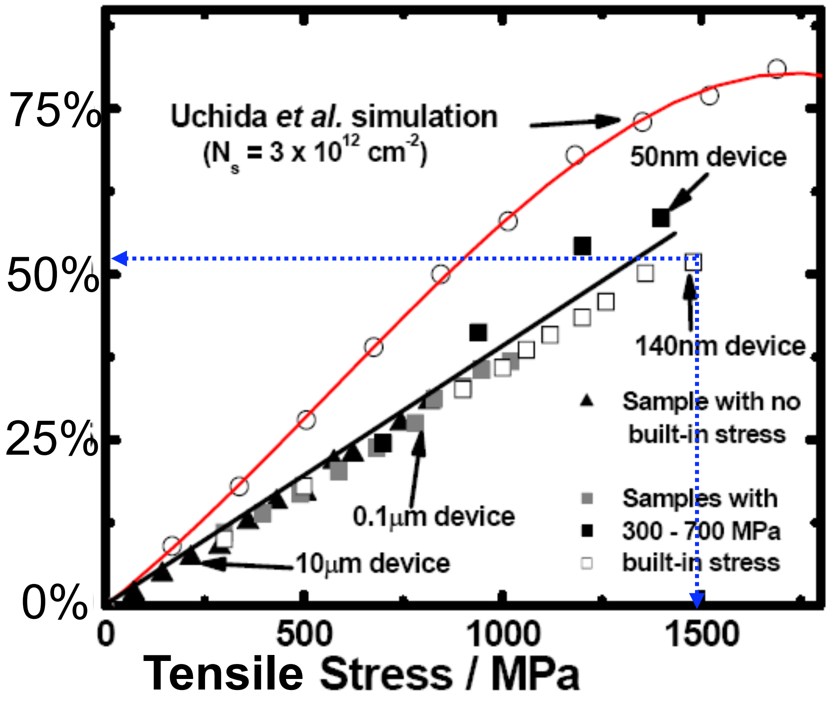


$$I_n(\sigma) \propto N(\sigma)\mu_n(\sigma)$$

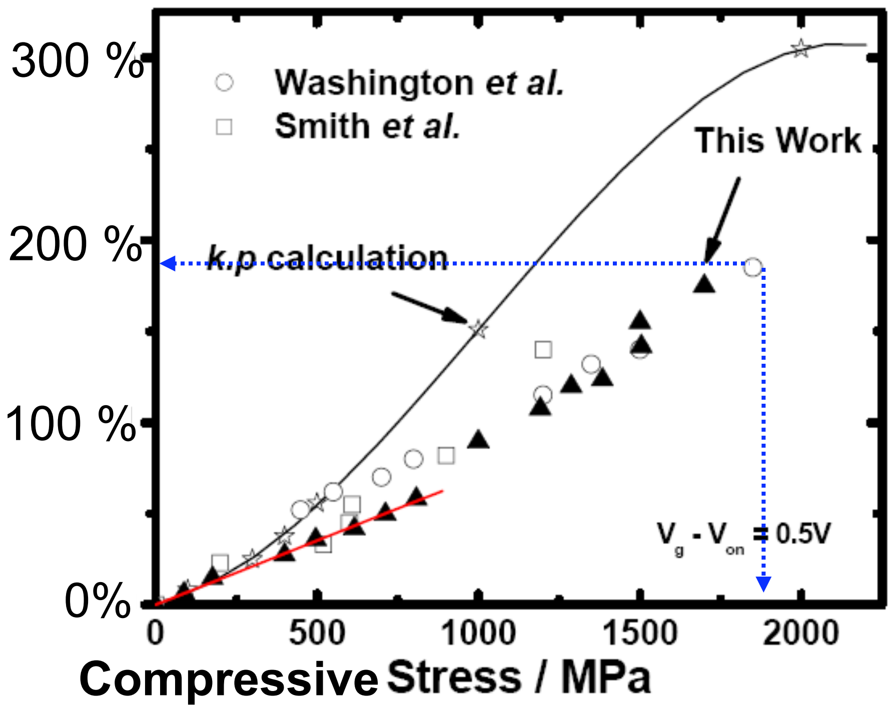
- Single Event Effect (transient pulse) occurs in MOSFET
  : Single Event Transient (SET) and Single Event Upset (SEU)
- Modern devices are sensitive to these effects.

Mechanical Stress Alters Mobility Significantly

Electron Mobility Enhancement



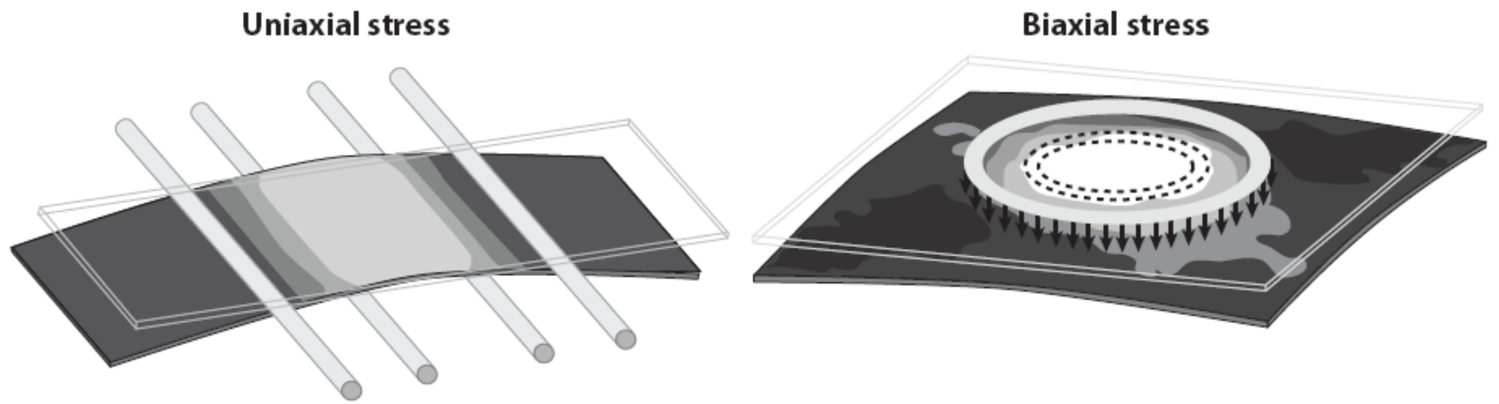
Hole Mobility Enhancement

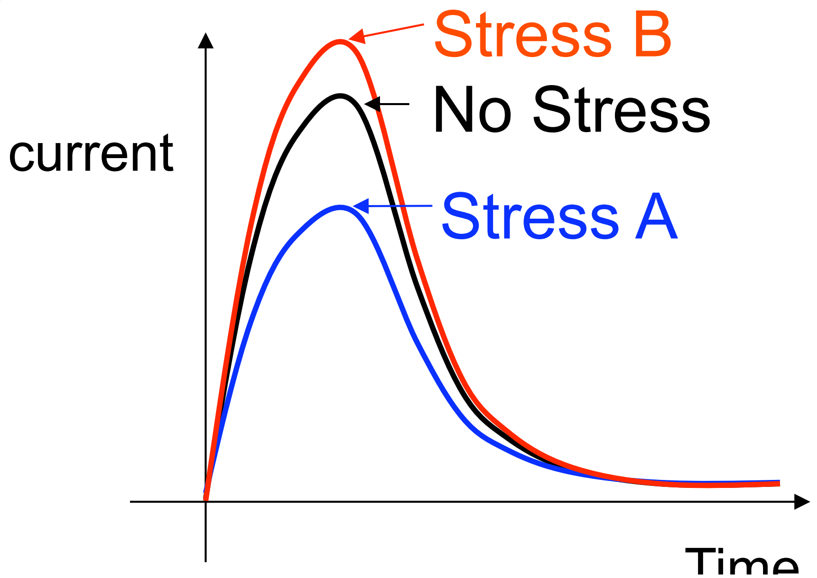


Suthram, 2008

- In modern devices, the strained-Si technology is implemented to boost transistor performance.
- Mechanical stress enhances electron and hole mobility significantly (Performance Booster).
- What if we put this technologies in radiation environment?

Current Transients under Different Type of Stress





- How does different type of stress change current transient in diodes?

(I_{max} : peak current, Q: charge collection)

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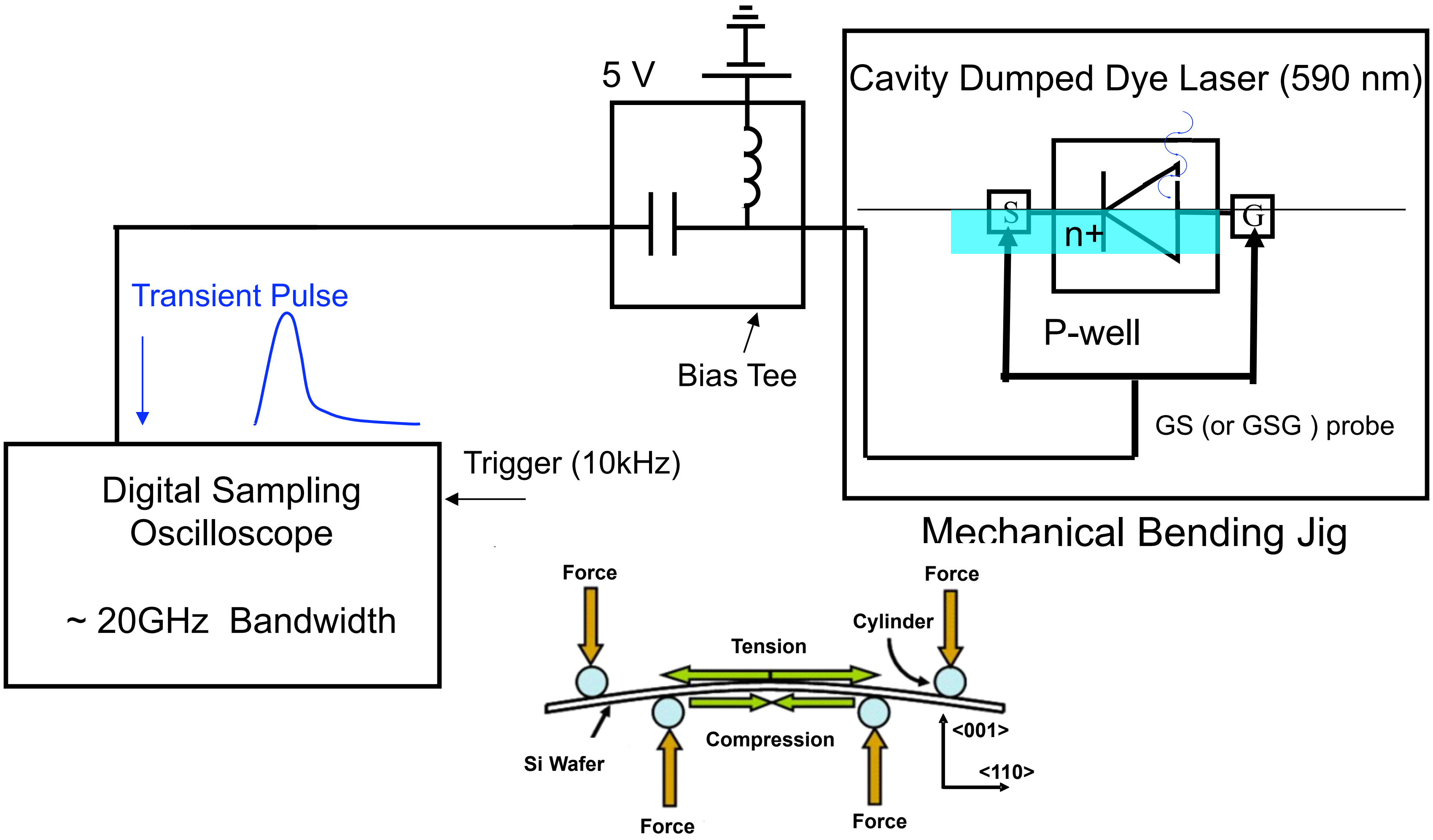
Laser-Induced Current Transient Measurement System



5 V

Cavity Dumped Dye Laser (590 nm)

Transient Pulse

Bias Tee

GS (or GSG) probe

Digital Sampling
Oscilloscope

~ 20GHz Bandwidth

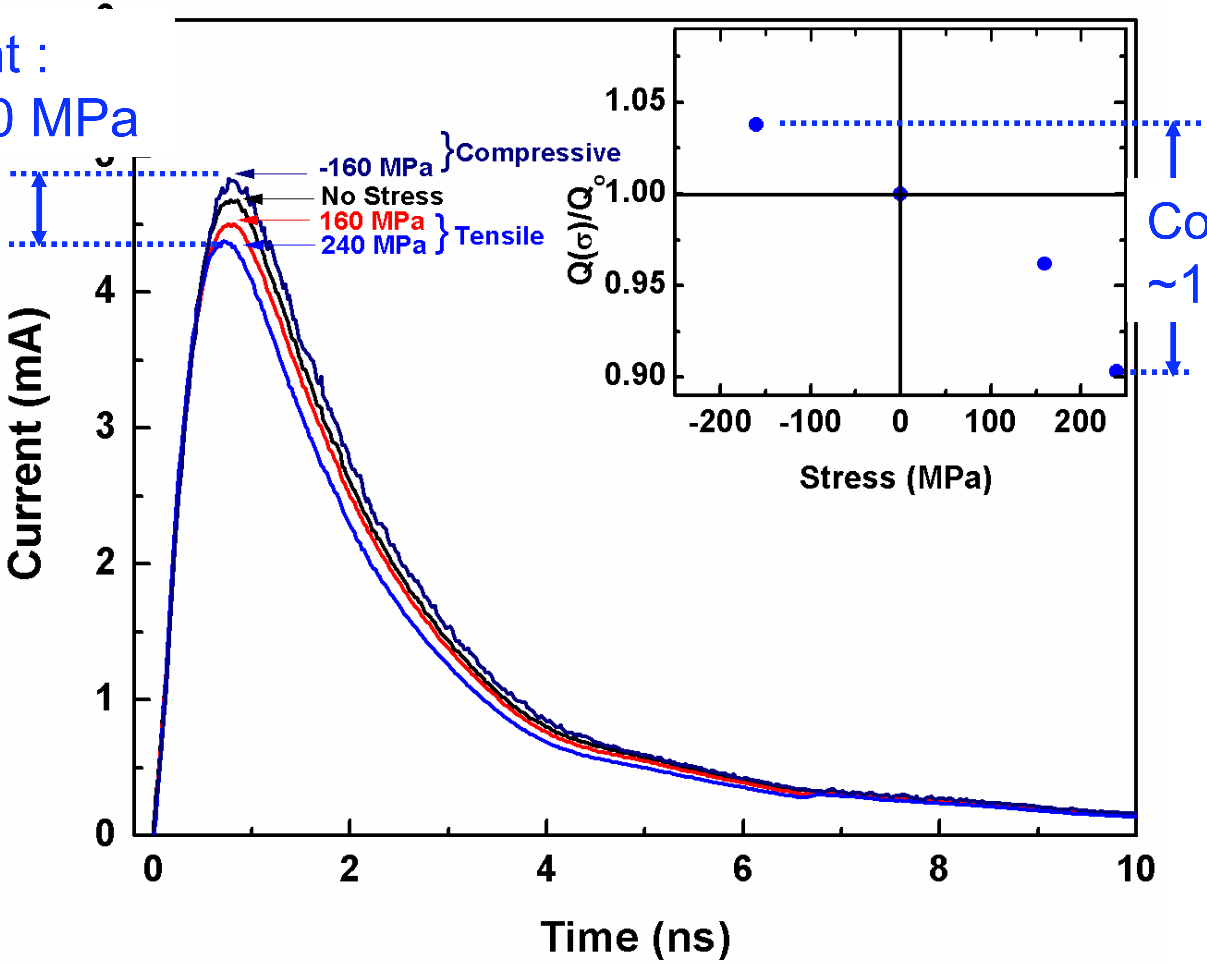
Trigger (10kHz)

Mechanical Bending Jig

- We can observe changes of current transient pulses under mechanical stresses
  It is possible to apply different tensile or compressive stress using mechanical bending jig

Laser-induced Current Transients (Experiment)

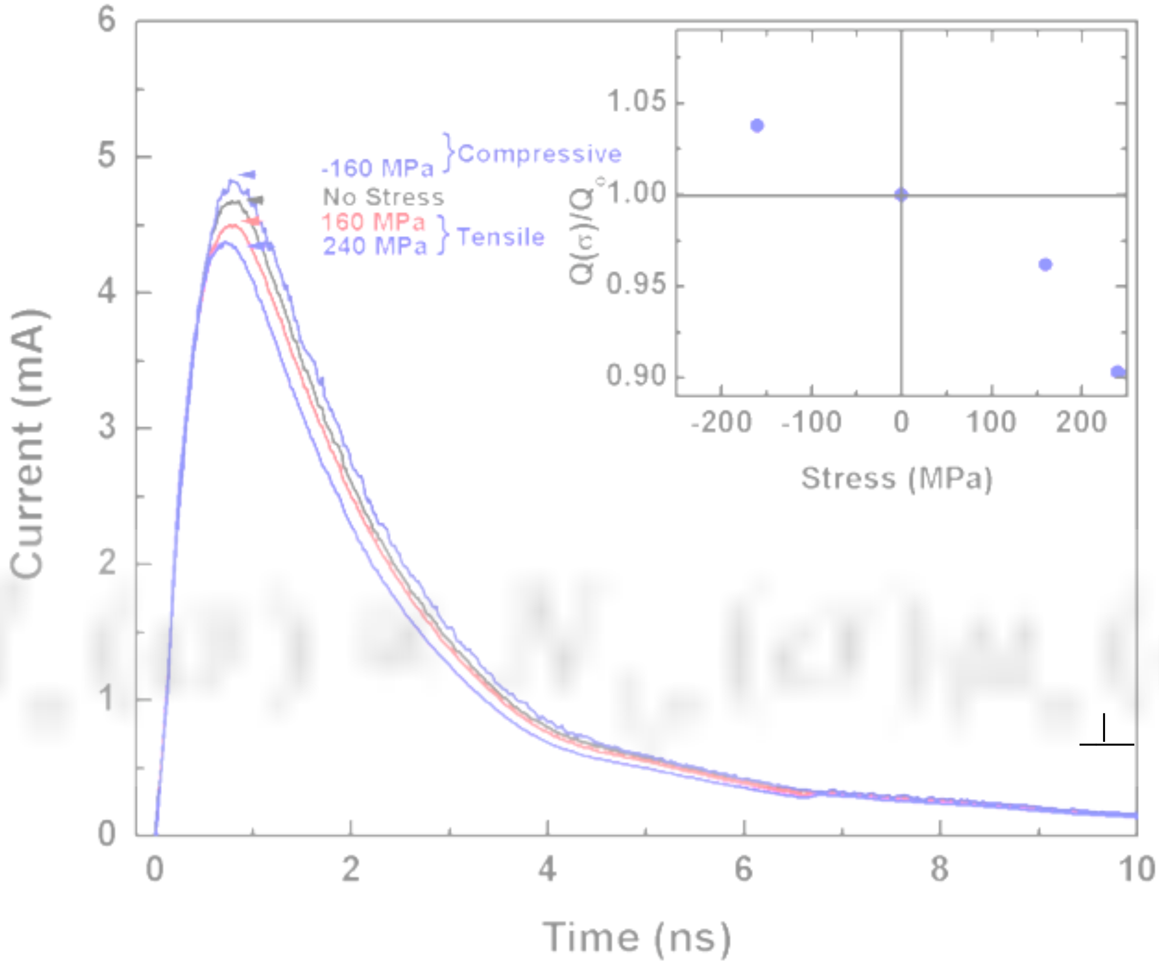
Peak current :
~11% at 400 MPa



Collected charges:
~14% at 400 MPa

- Tensile (Compressive) stress decrease (increase) peak current and collected charges.

Simplified Current



$$J_n(\sigma) \propto N_{1p}(\sigma)\mu_n(\sigma)$$

- $N_{1p}(\sigma)$ is related to bandgap narrowing under mechanical stress.
- Mechanical stress alters electron mobility along <001> direction.

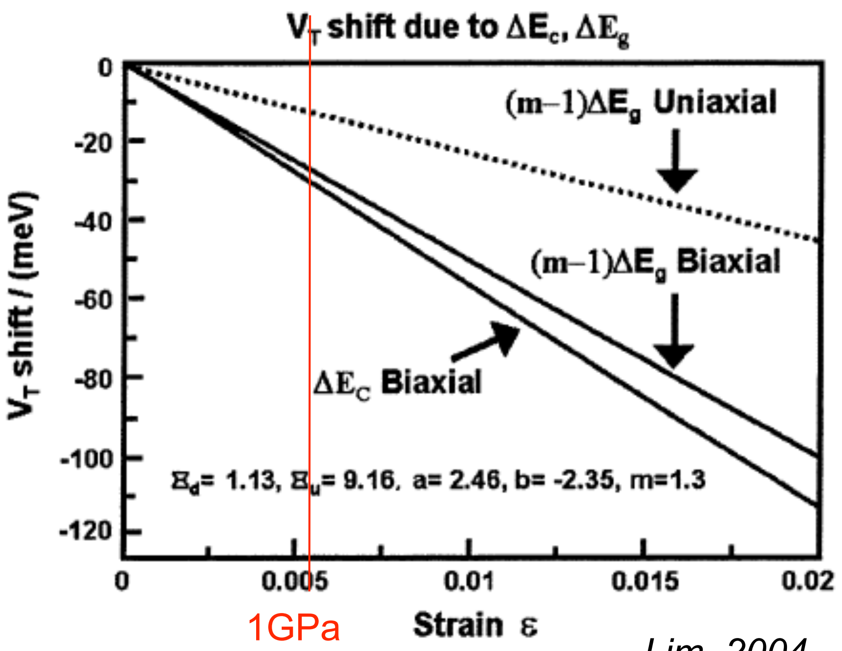
Strain Effect on Electron-hole Pair Generation (Bandgap Narrowing)

Absorption coefficient

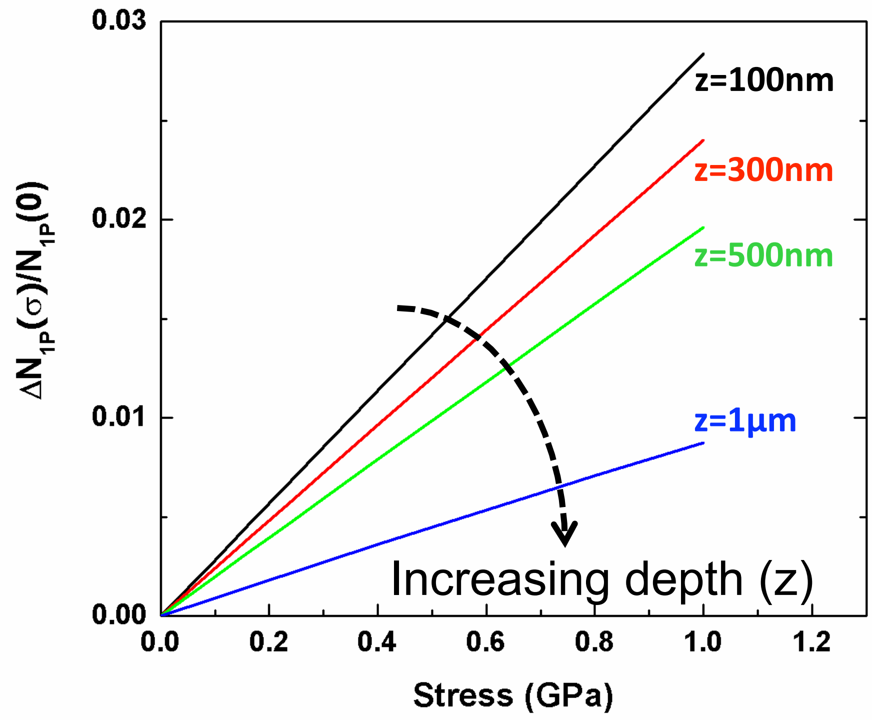
$$\frac{\Delta\alpha}{\alpha} = \frac{\Delta E_g(\sigma)}{h\nu - E_g} << 1, \quad h\nu > E_g$$

The number of generated e-h pairs

$$N_{1p}(z) = \frac{\alpha}{\hbar\omega}\exp(-\alpha z)\int_{-\infty}^{\infty} I_0(z,t)\,dt$$



Lim, 2004

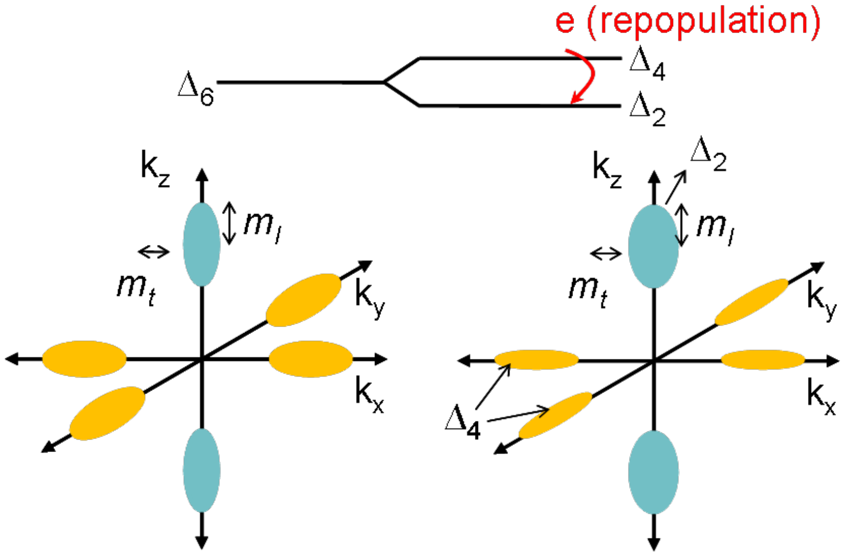


$\Delta E_g \cong 30\, meV$ at 1 GPa of uniaxial tensile stress

- Change in N_{1p} is less than 3% for 1 GPa of uniaxial tensile stress

Strain Effect on Electron Mobility

Under Tensile Stress :

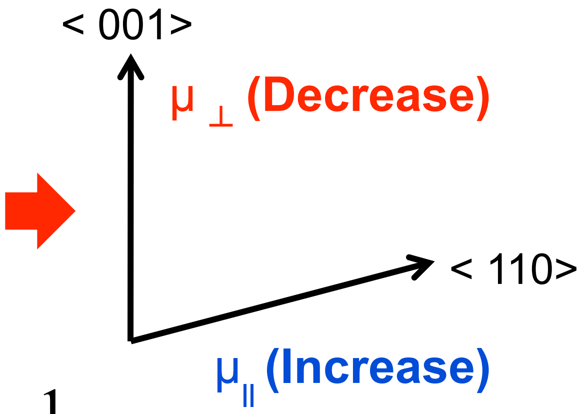


Unstrained Si

Strained Si

Mohta, 2005

$$I_n(\sigma) \propto N_{1p}(\sigma)\mu_{n\perp}(\sigma)$$



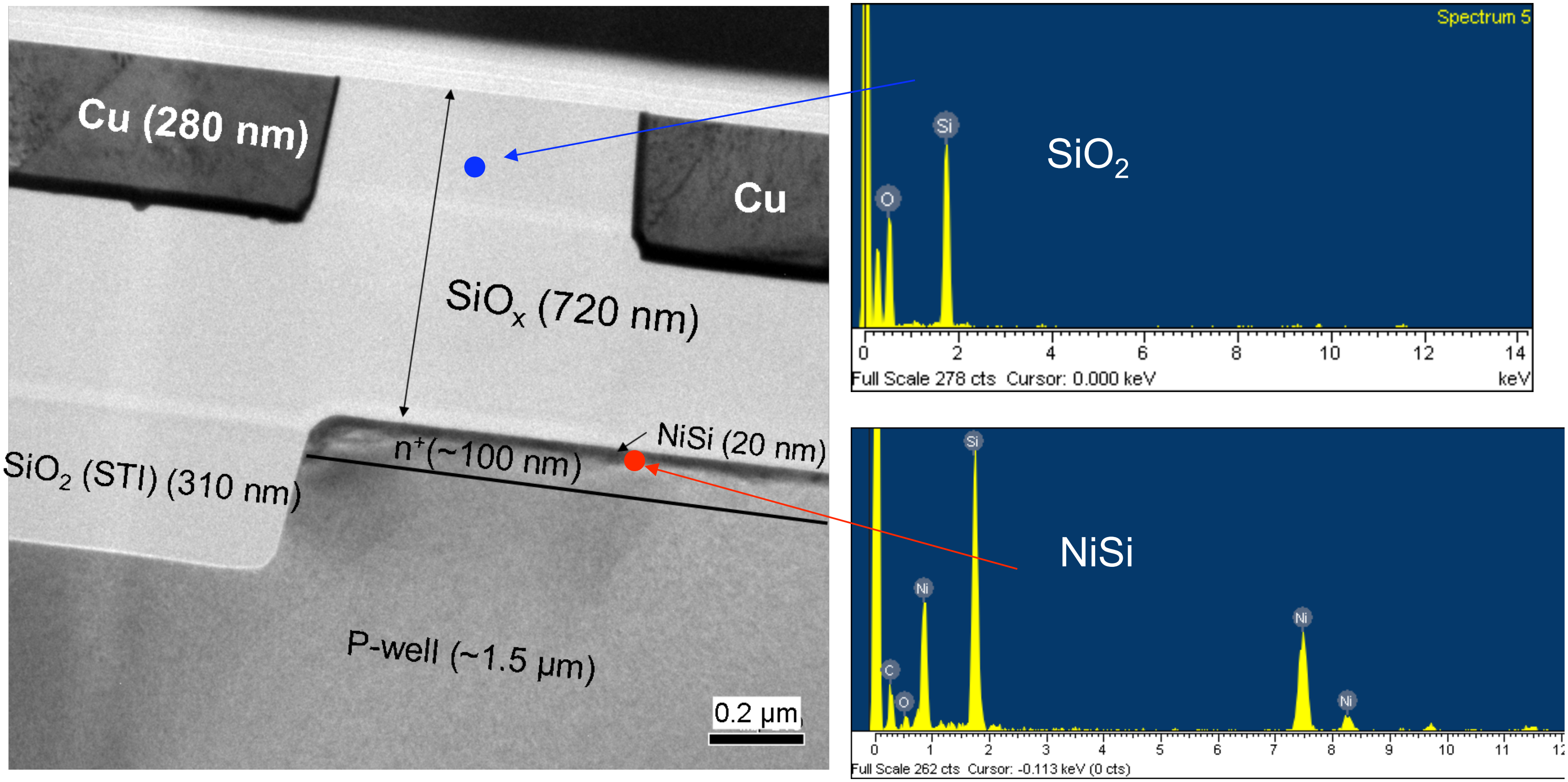
$$\mu \prec \frac{1}{m}$$

For 1 GPa of uniaxial tensile stress,

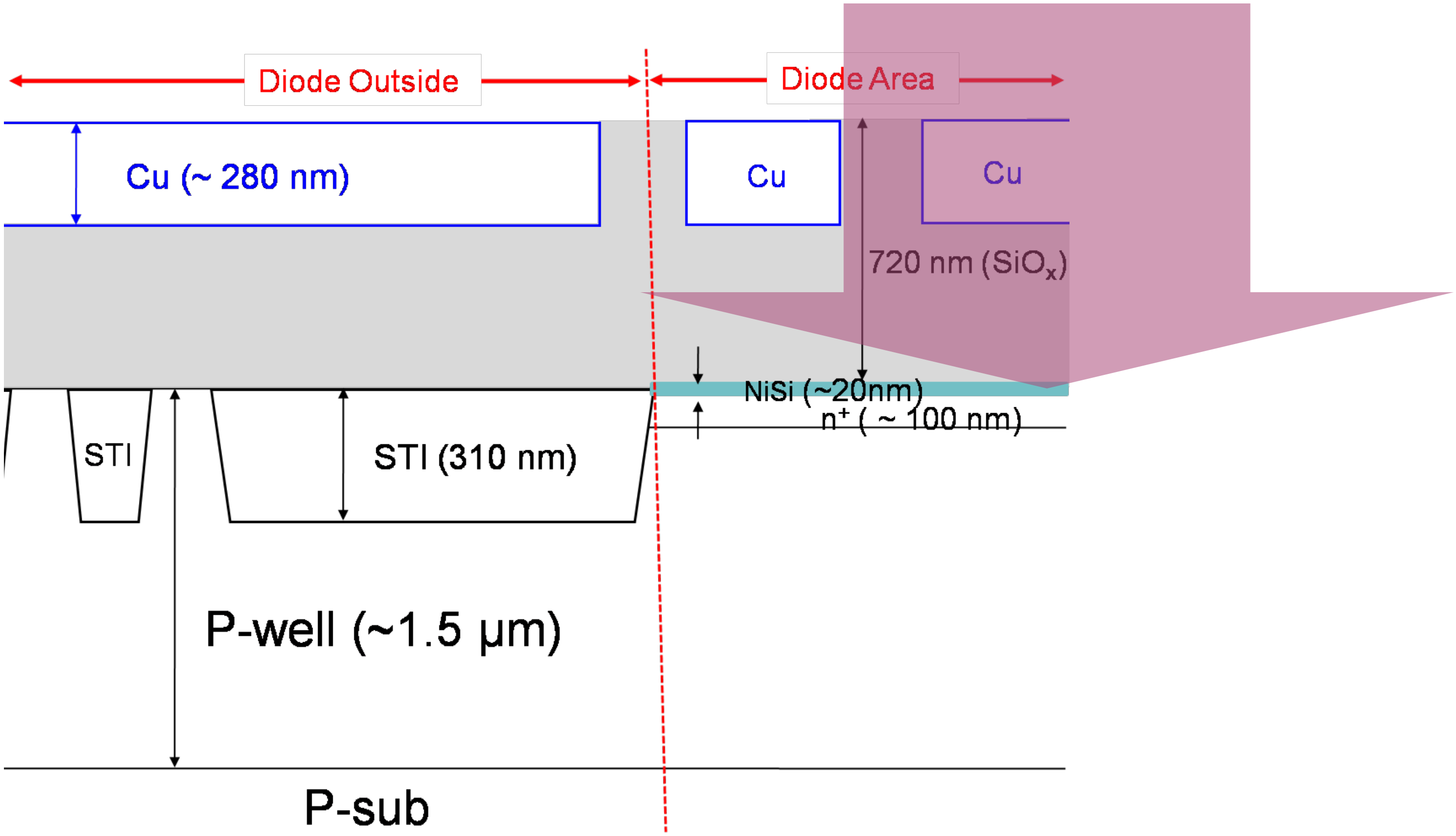
- electron mobility changes ~53% and Number of e-h pairs < 3%

→ Electron mobility change dominates current transient change under stress

Diode Structure through TEM and EDS

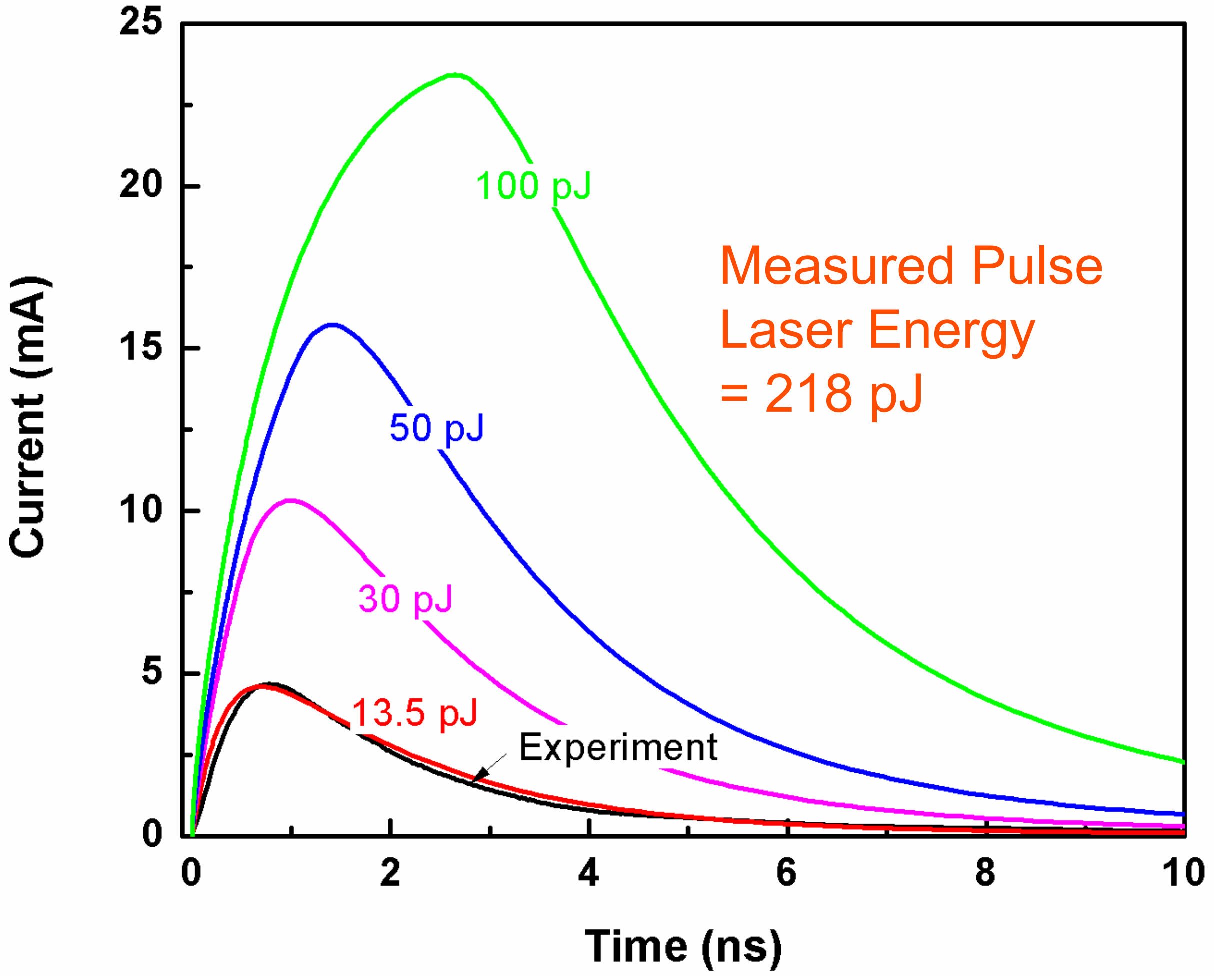


Deposition of Pulse Laser into n^+p diode



- Some of pulse laser energy are reflected and absorbed in layers on top of a diode.

Current Transients according to Pulse Laser Energy



- The discrepancy between simulated energy and measured energy is shown.

Laser Pulse Energy into Si

$$I_{Si} = I_{\text{intial}} \times (\text{transmission due to Cu/SiO}_2)$$
$$\times (\text{transmission in SiO}_2) \times (\text{transmission in NiSi})$$
$$= I_{\text{intial}} \times (0.57) \times (0.80) \times (0.51 \times 0.23)$$
$$= 0.056\, I_{\text{intial}}$$

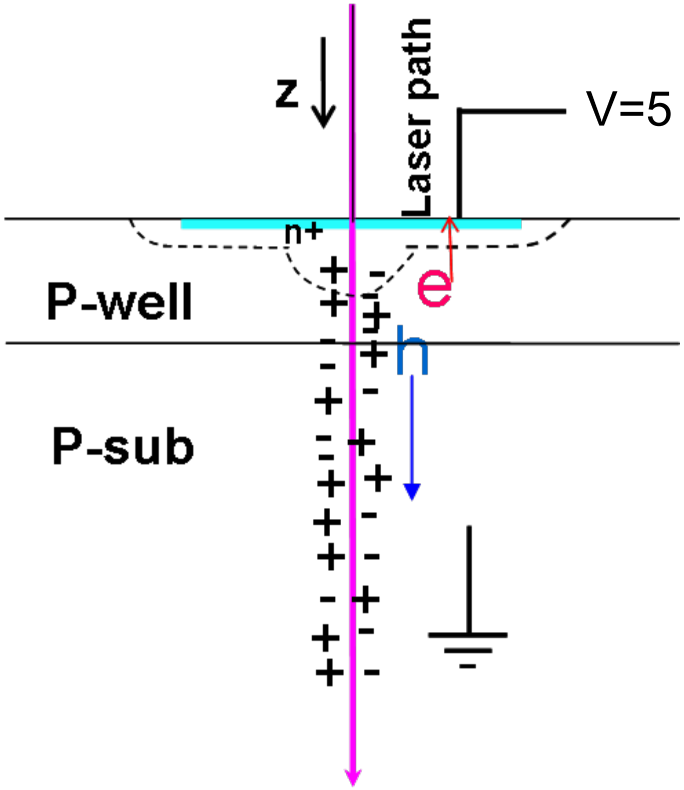
$$\text{Intensity}\,(I) \propto \text{Power}\,(P) \propto \text{Laser Pusle Energy}\,(E)$$
$$\text{Measured Laser Pulse Energy} = 216\ \text{pJ}$$
$$\text{Pulse Laser Energy deposited in Si} = (216\ \text{pJ}) \times (0.054)$$
$$\boxed{= 12\ \text{pJ}}$$

Melinger, 1994
Amiotti, 1990

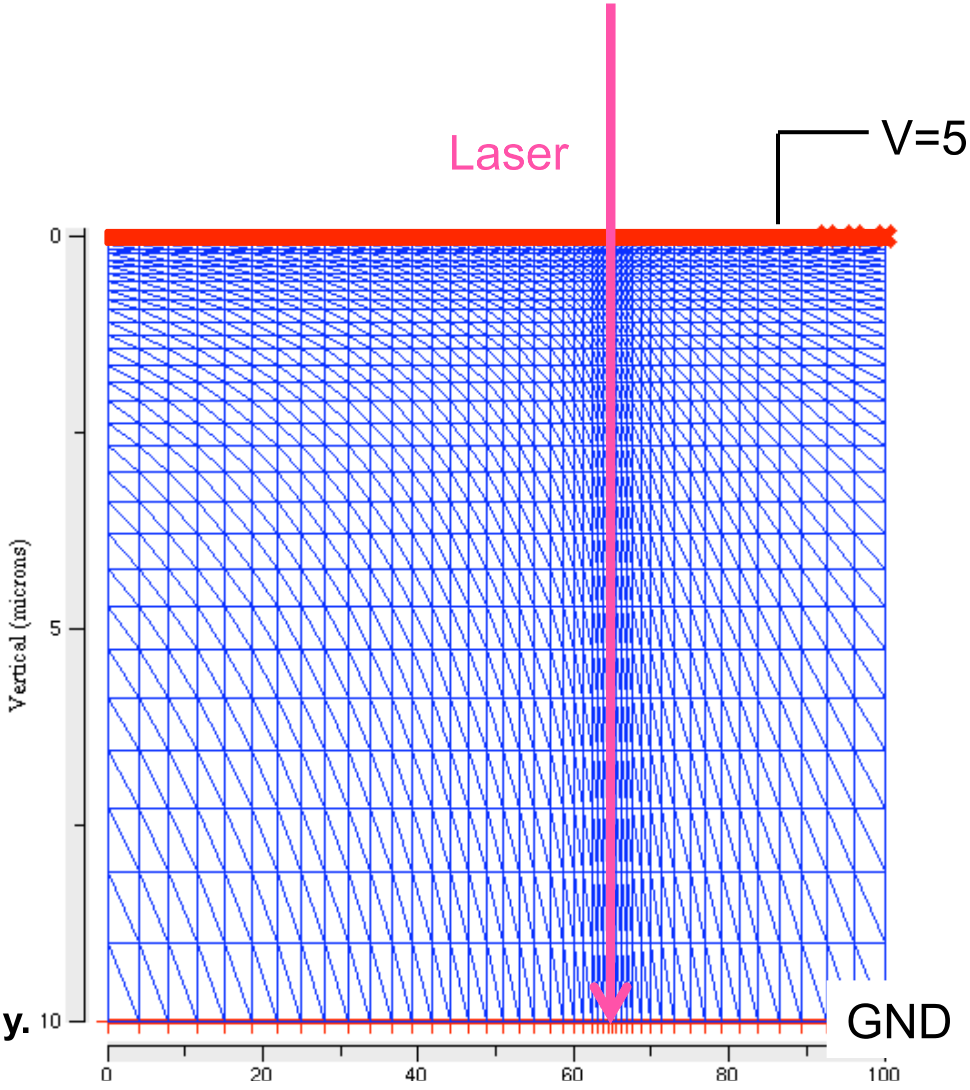
If we consider uncertainty of every layer characteristics, E = 10 ~ 25 pJ
Especially, consider the optical characteristics nickel silicide (NiSi,$NiSi_2$,Ni_2Si)

2D Simulation value => 13.5 pJ (It is very close to calculated values above)

2-D Simulation Structure of n$^+$p Diode



*Note : Carriers move along z-direction dominantly.**



- Using analysis from experimental results such as piezoresistance coefficient and bandgap narrowing effect, we did 2-D FLOOD current transient simulation under stress.

Strain Model (Piezoresistance Effect)

$$\begin{bmatrix} \pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \pi_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \pi_{44} \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{zx} \\ \sigma_{xy} \end{bmatrix} = \begin{bmatrix} \Delta\rho_{xx}/\rho_{xx} \\ \Delta\rho_{yy}/\rho_{yy} \\ \Delta\rho_{zz}/\rho_{zz} \\ \Delta\rho_{yz}/\rho_{yz} \\ \Delta\rho_{zx}/\rho_{zx} \\ \Delta\rho_{xy}/\rho_{xy} \end{bmatrix} = \begin{bmatrix} -\Delta\mu_{xx}/\mu_{xx} \\ -\Delta\mu_{yy}/\mu_{yy} \\ -\Delta\mu_{zz}/\mu_{zz} \\ -\Delta\mu_{yz}/\mu_{yz} \\ -\Delta\mu_{zx}/\mu_{zx} \\ -\Delta\mu_{xy}/\mu_{xy} \end{bmatrix}$$

$$\begin{bmatrix} \frac{\rho_{xx}+\Delta\rho_{xx}}{\rho_{xx}} & \frac{\Delta\rho_{xy}}{\rho_{xy}} & \frac{\Delta\rho_{xz}}{\rho_{xz}} \\ \frac{\Delta\rho_{xy}}{\rho_{xy}} & \frac{\rho_{yy}+\Delta\rho_{yy}}{\rho_{yy}} & \frac{\Delta\rho_{yz}}{\rho_{yz}} \\ \frac{\Delta\rho_{xz}}{\rho_{xz}} & \frac{\Delta\rho_{yz}}{\rho_{yz}} & \frac{\rho_{zz}+\Delta\rho_{zz}}{\rho_{zz}} \end{bmatrix} \begin{bmatrix} J_x(0) \\ J_y(0) \\ J_z(0) \end{bmatrix} = \begin{bmatrix} \frac{\mu_{xx}-\Delta\mu_{xx}}{\mu_{xx}} & \frac{-\Delta\mu_{xy}}{\mu_{xy}} & \frac{-\Delta\mu_{xz}}{\mu_{xz}} \\ \frac{-\Delta\mu_{xy}}{\mu_{xy}} & \frac{\mu_{yy}-\Delta\mu_{yy}}{\mu_{yy}} & \frac{-\Delta\mu_{yz}}{\mu_{yz}} \\ \frac{-\Delta\mu_{xz}}{\mu_{xz}} & \frac{-\Delta\mu_{yz}}{\mu_{yz}} & \frac{\mu_{zz}-\Delta\mu_{zz}}{\mu_{zz}} \end{bmatrix} \begin{bmatrix} J_x(0) \\ J_y(0) \\ J_z(0) \end{bmatrix} = \begin{bmatrix} J_x(\sigma) \\ J_y(\sigma) \\ J_z(\sigma) \end{bmatrix}$$

Mason, 1957
Smith, 1954

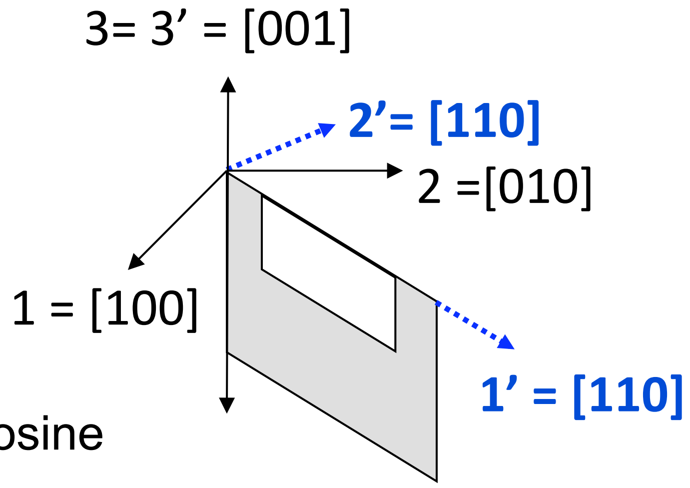
2-D Piezoresistance Coefficients

[100] Orientation "Smith" Coefficients:

Material	n-Si	p-Si
π_{11}	-102.2	6.6
π_{12}	53.4	-1.1
π_{44}	-13.6	138.1

10^{-5} MPa $^{-1}$

$$[\pi_{ij}] = \begin{bmatrix} \pi_{11} & \pi_{12} & 0 \\ \pi_{12} & \pi_{11} & 0 \\ 0 & 0 & \pi_{44} \end{bmatrix}$$



Using directional cosine transformation

[110] Orientation Coefficients:

Material	n-Si	p-Si
π'_{11}	-31.2	71.8
π'_{13}	53.4	-1.1
π'_{33}	-102.2	6.6
π'_{55}	-13.6	138.1

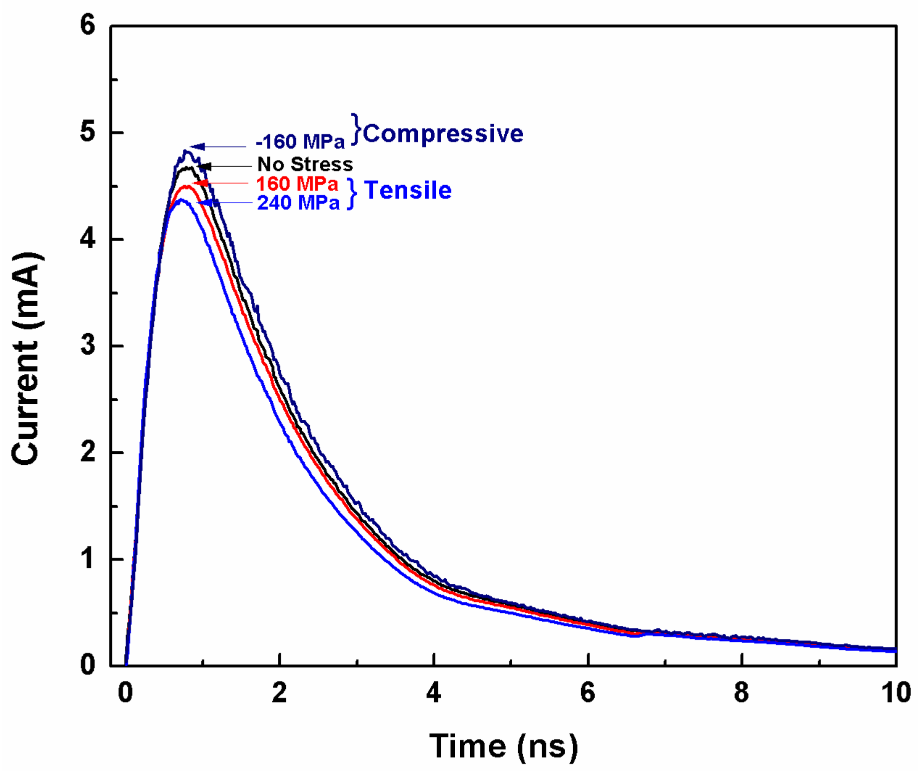
10^{-5} MPa $^{-1}$

$$[\pi'_{ij}] = \begin{bmatrix} \pi'_{11} & \pi'_{13} & 0 \\ \pi'_{13} & \pi'_{33} & 0 \\ 0 & 0 & \pi'_{55} \end{bmatrix}$$

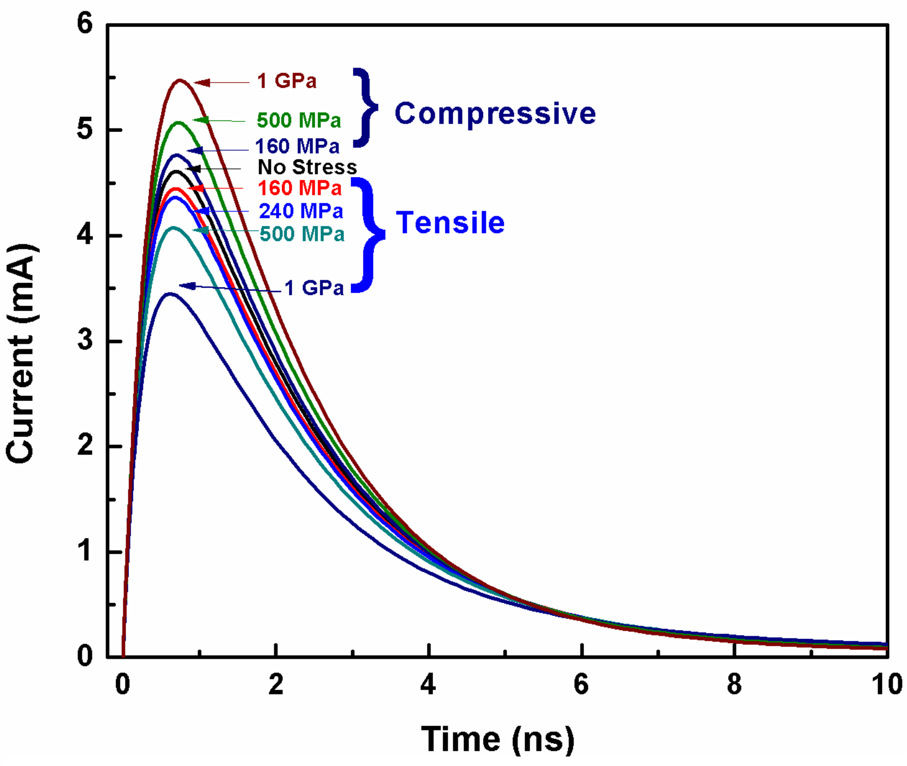
Smith, 1954
Kanda, 1982

Experiment vs. 2-D Simulation results

Experiment

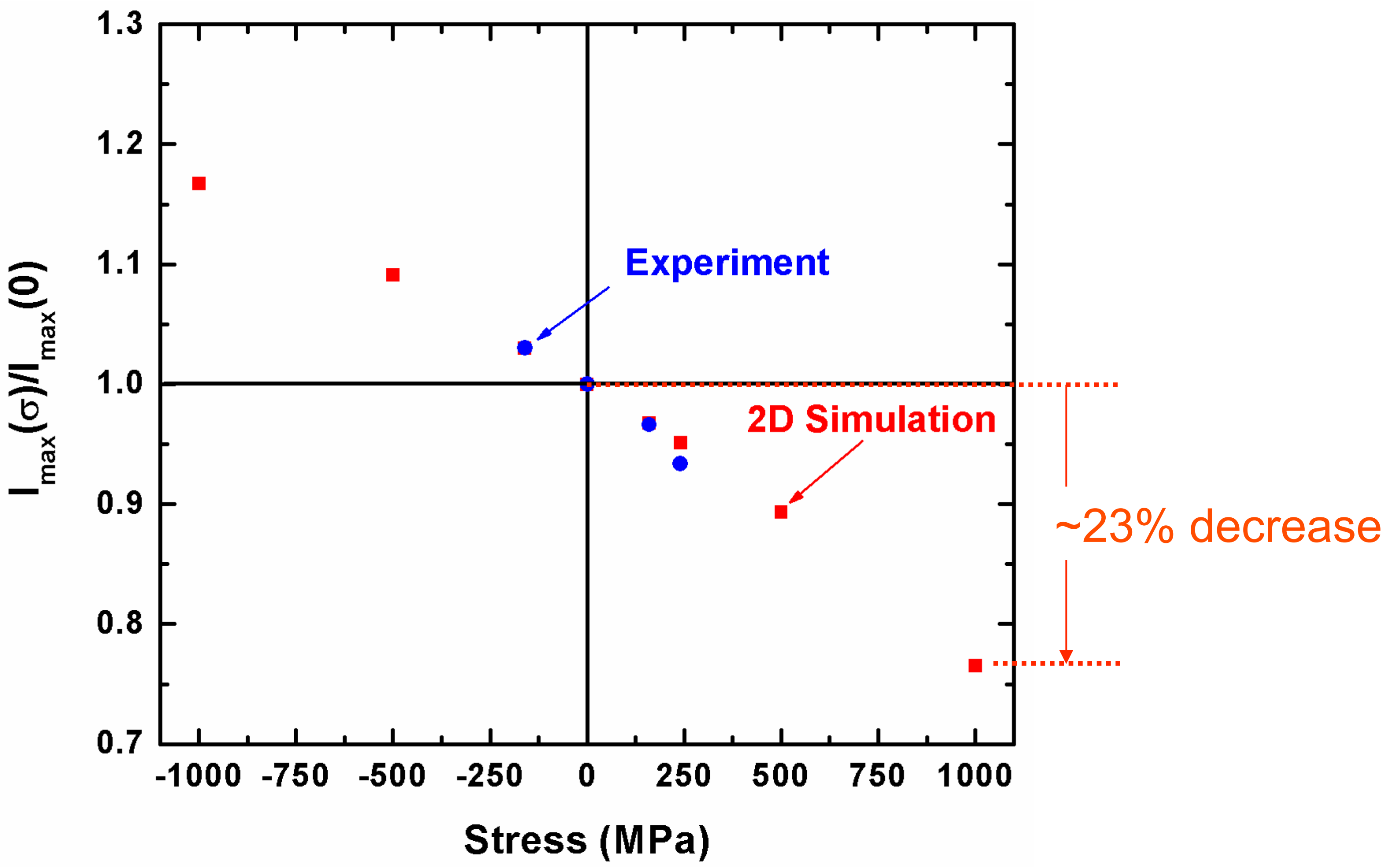


2-D Simulation



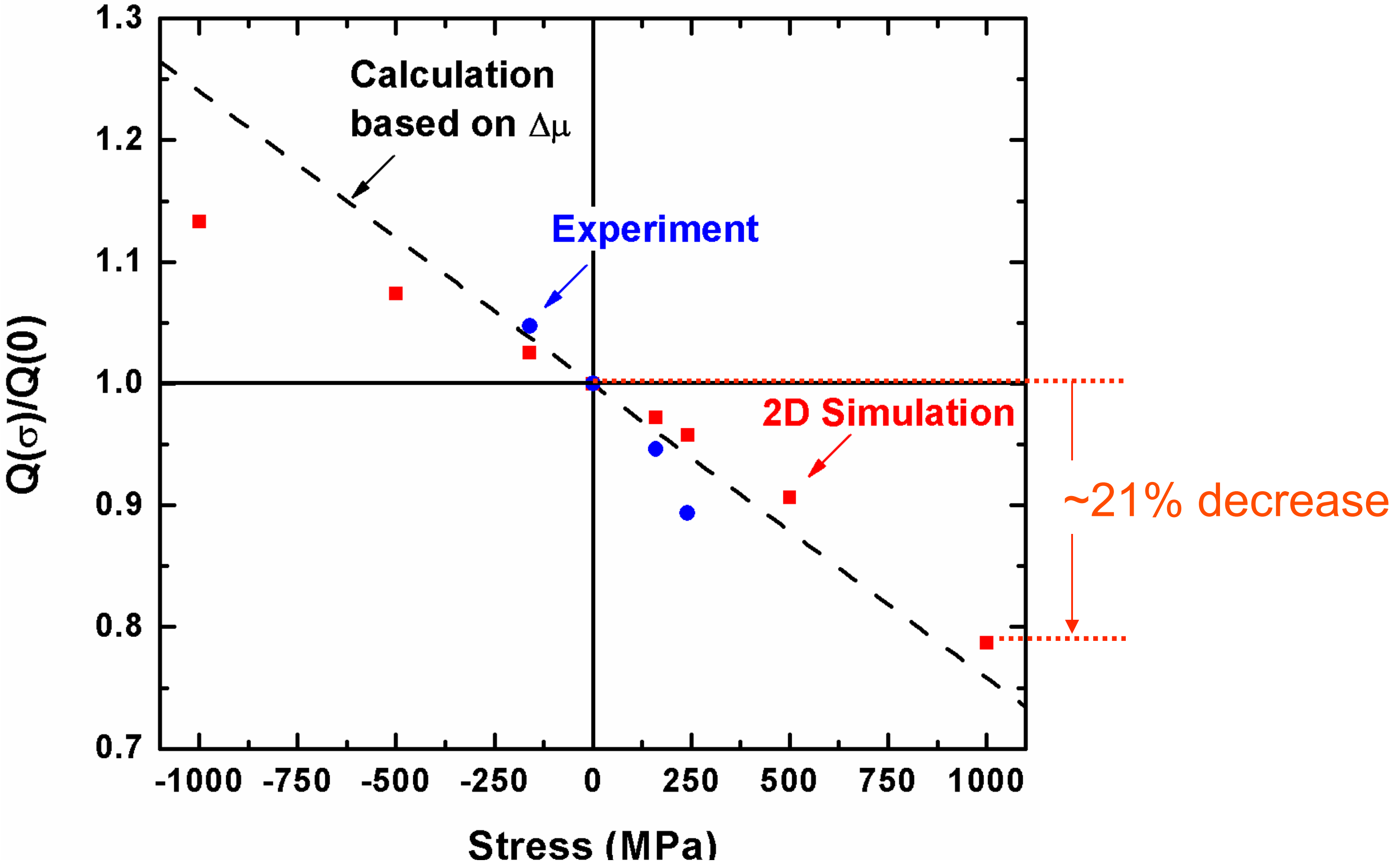
-2D simulation results have good agreement with experimental ones.

Imax under Uniaxial Mechanical Stress



- ~ 23% reduction of peak current under 1GPa of uniaxial tensile stress

Charge Collection until 10 ns



- ~ 22% reduction of collected charges under 1GPa of uniaxial tensile stress

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Strain Model (Piezoresistance Effect)

$$\Delta\rho_{zz} / \rho_{zz} = -\Delta\mu_{zz} / \mu_{zz} = \pi_{12}\sigma_{xx} + \pi_{12}\sigma_{yy} + \pi_{11}\sigma_{zz}$$

$\pi_{11} = -102.2\times10^{-5} / MPa$

$\pi_{12} = +53.4\times10^{-5} / MPa$

1) Uniaxial stress along the <110> direction

$$\Delta\rho_{zz} / \rho_{zz} = -\Delta\mu_{zz} / \mu_{zz} = \pi_{12}\sigma_{xx} / 2 + \pi_{12}\sigma_{yy} / 2 = \pi_{12}\sigma$$

2) Uniaxial stress along the <100> direction

$$\Delta\rho_{zz} / \rho_{zz} = -\Delta\mu_{zz} / \mu_{zz} = \pi_{12}\sigma_{xx} = \pi_{12}\sigma$$

3) Biaxial stress

$$\Delta\rho_{zz} / \rho_{zz} = -\Delta\mu_{zz} / \mu_{zz} = \pi_{12}\sigma_{xx} + \pi_{12}\sigma_{yy} = \pi_{12}(2\sigma)$$

- **Mobility along z <001>-direction change is dominant factor for current transients change.**
- **Biaxial tensile stress has the potential to decrease $\mu_{n\perp}$ more than uniaxial stresses do.**
- **It is expected that peak current under biaxial tensile stress is reduced more.**

Mobility Enhancement using π- coefficient

$$\frac{\Delta\rho_{zz}}{\rho_{zz}(0)} = \frac{\rho_{zz}(\sigma)-\rho_{zz}(0)}{\rho_{zz}(0)} = \frac{1/\mu_{zz}(\sigma)-1/\mu_{zz}(0)}{1/\mu_{zz}(0)}$$

$$= \frac{\mu_{zz}(0)-\mu_{zz}(\sigma)}{\mu_{zz}(\sigma)} = \pi\sigma$$

Using power series in $-1<\pi\sigma<1$,

$$\mu_{zz}(\sigma) = \frac{1}{1+\pi\sigma}\mu_{zz}(0)$$

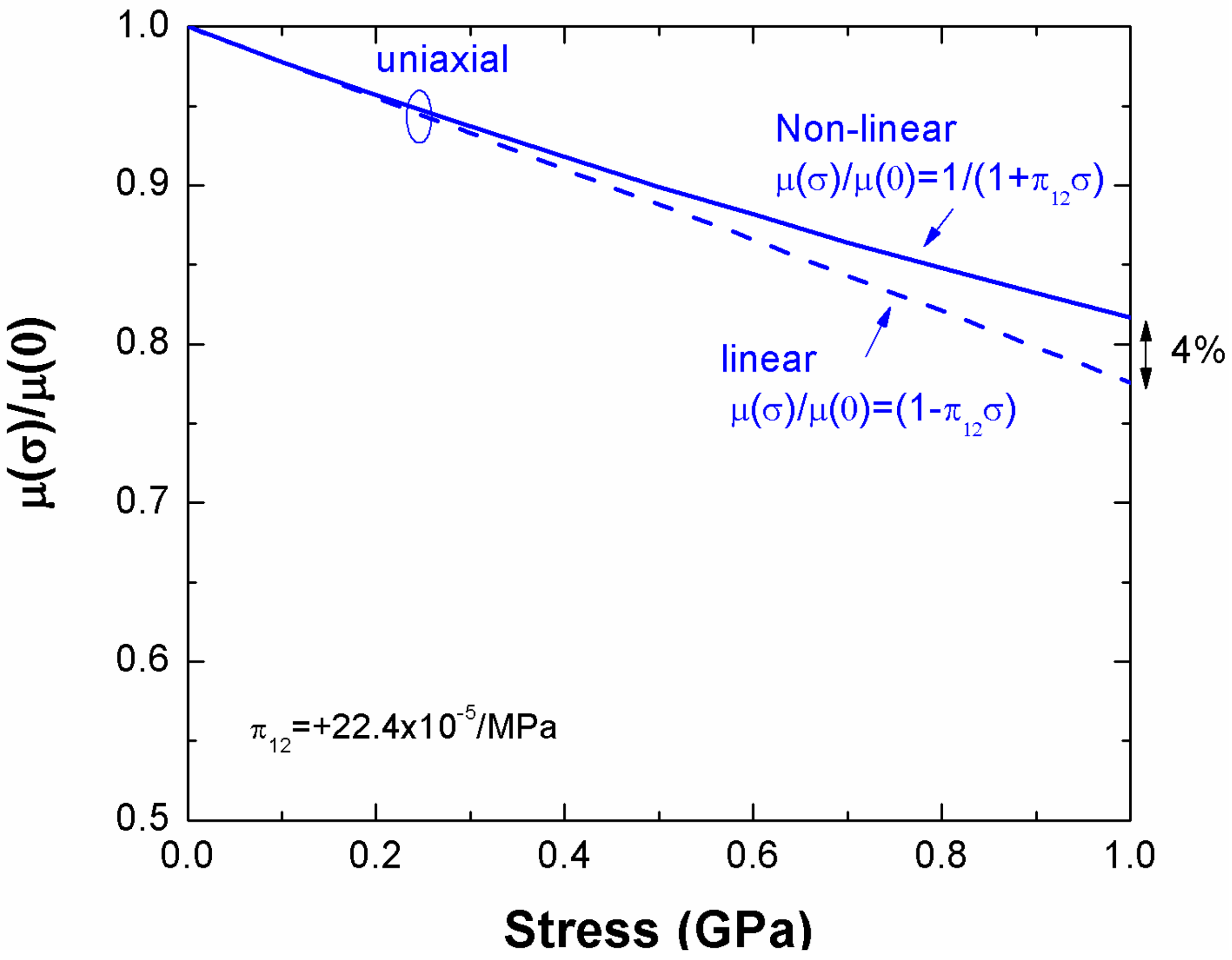
Non-Linear

$$\boxed{= [1-\pi\sigma+(\pi\sigma)^2-(\pi\sigma)^3+(\pi\sigma)^4-(\pi\sigma)^5+\cdots]\mu_{zz}(0)}$$

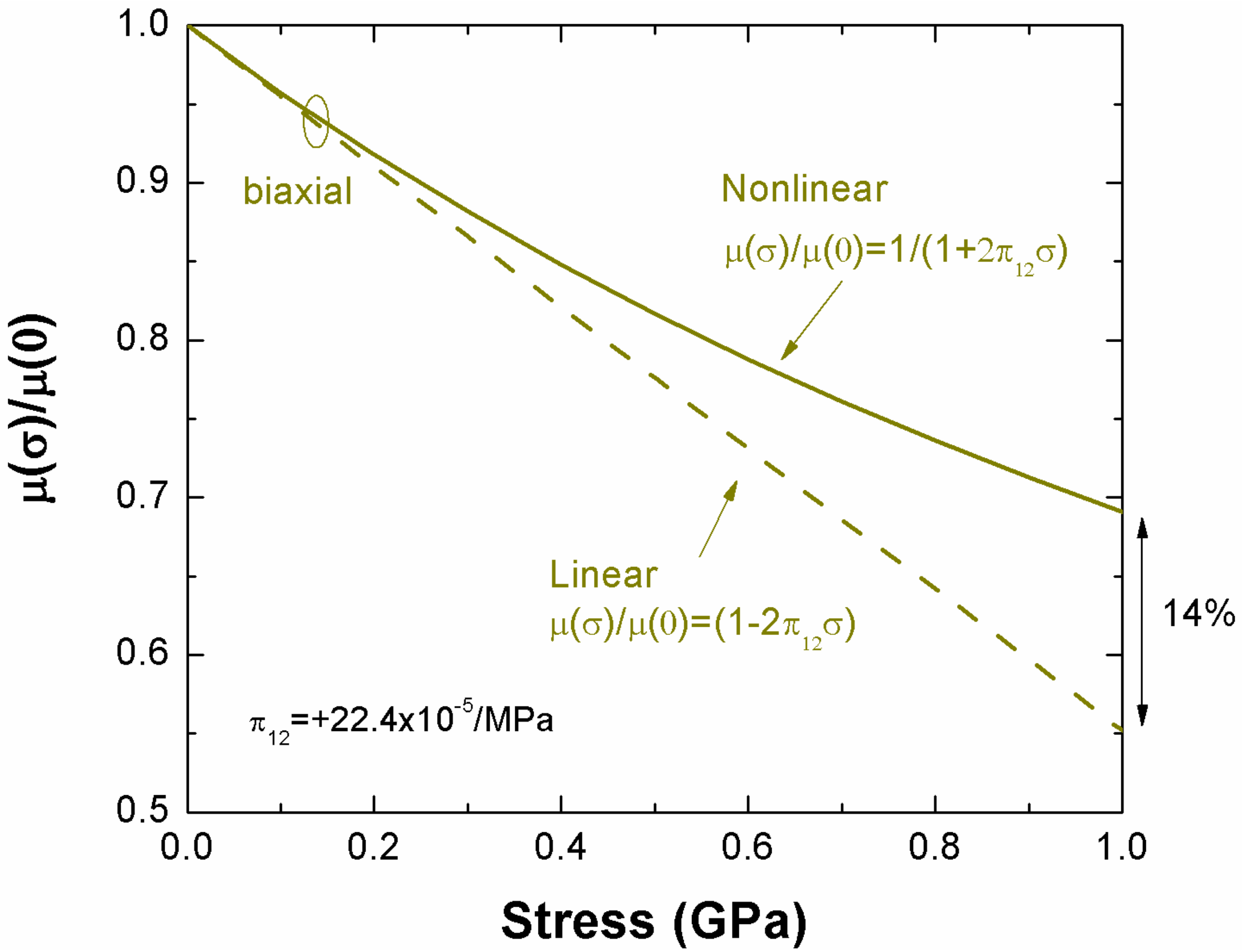
If $\pi\sigma$ is very small, $\mu_{zz}(\sigma) = \boxed{[1-\pi\sigma]\times\mu_{zz}(0)}$ **Linear**

- We need to consider nonlinear effect in high stress and large piezocoefficient.

Linear vs. Nonlinear in Uniaxial Stress

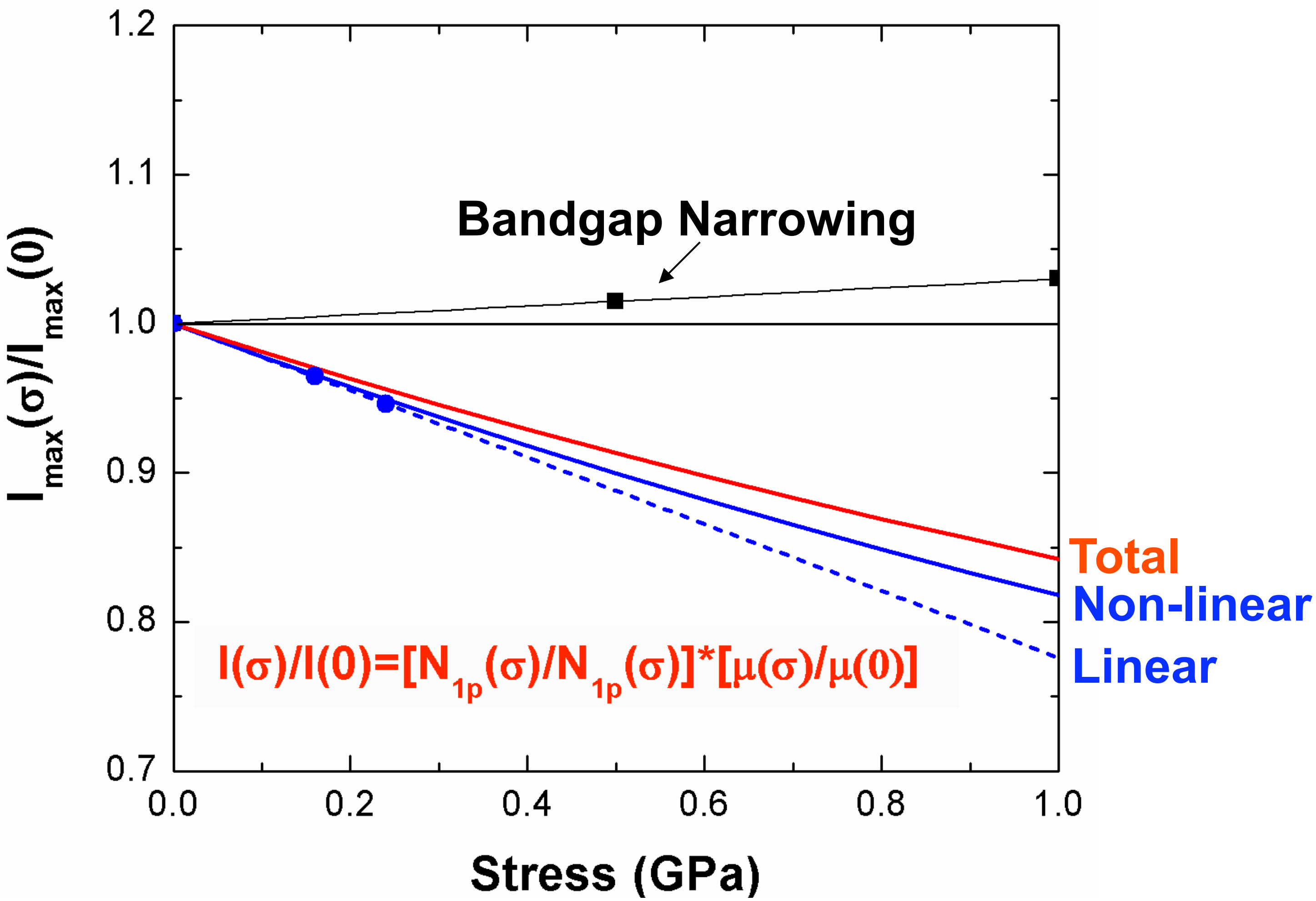


Linear vs. Nonlinear in Biaxial Stress

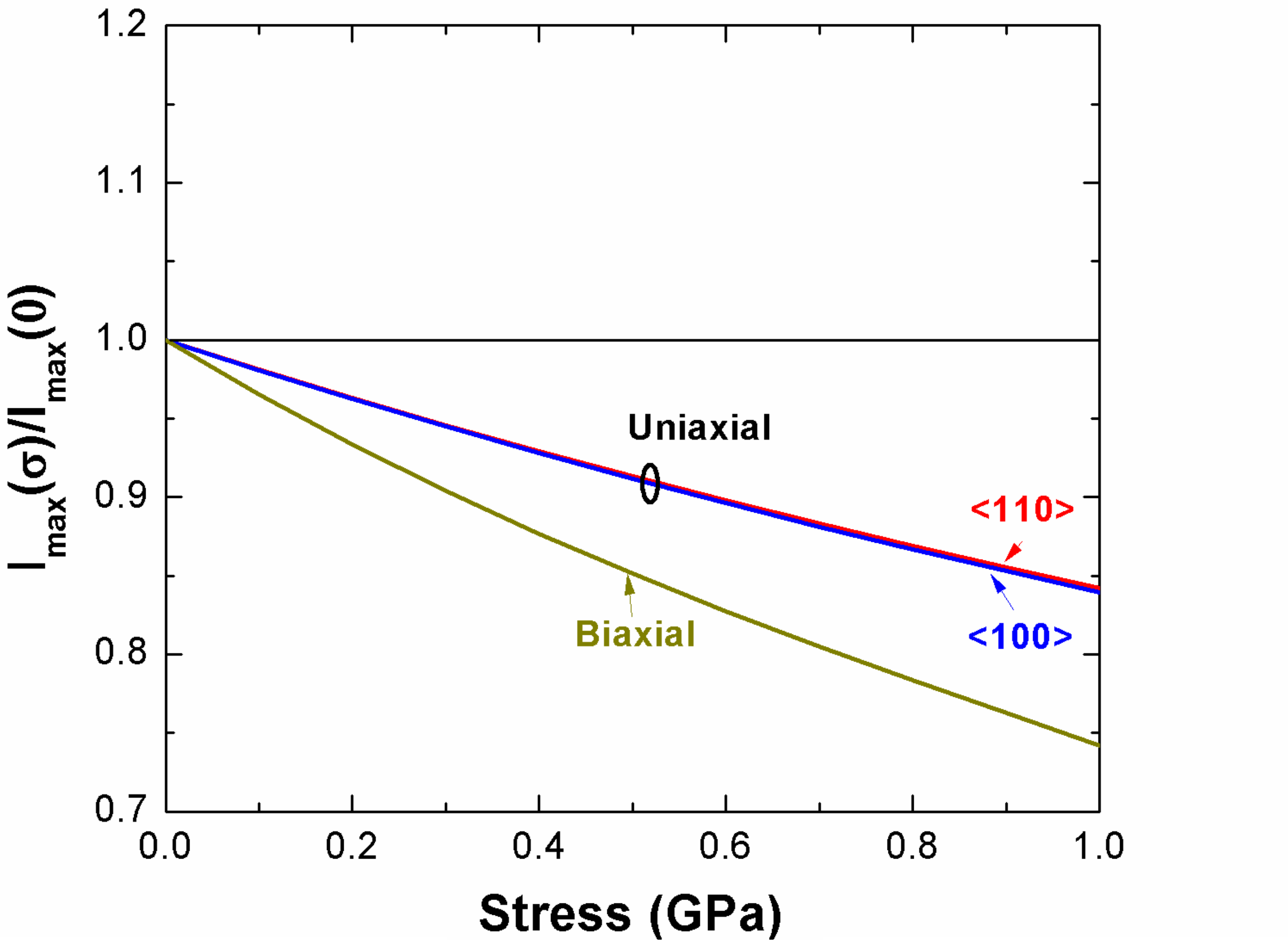


- Biaxial stress shows significant non-linear mobility effect more than uniaxial stress does.

I_{max} under <110> Uniaxial Stress



I_{max} under Uniaxial vs. Biaxial Stress



- Biaxial stress reduces peak current (Imax) more than uniaxial stress does.

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Conclusions/2009 Goals

- Conclusions

  - Experimental results show uniaxial mechanical stress alter current transients due to electron mobility change under stress.

  - 2D simulation results have a good agreement with experiment results in low stress region.

  - Less peak current (~23% decrease at 1 GPa) and charge collection (~21% decrease until 10 ns) in uniaxial tensile stressed diodes are observed.

  - Tensile biaxial stress decreases peak current more than uniaxial stress does.

- Future work

  - Biaxial stress modeling into TCAD simulation

  - Optimum stress type to minimize SET and SEE

  - Hole (P+/n-well) SET modeling

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Thank you!!

Q & A