Total Ionizing Dose and Single Event Effects in Strained Si Technologies

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Outline

- Introduction
- Project Focus

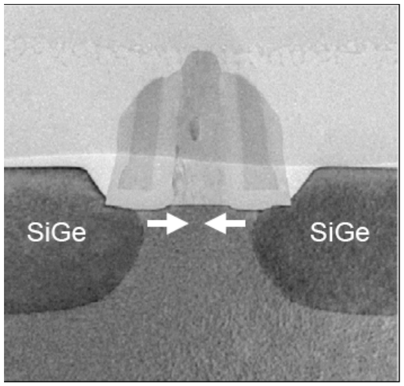
  1. Total Ionizing Dose (TID) Effects on Strained HfO_2-based nMOSFETs
  2. Laser-Induced Current Transients in Strained-Si Diodes
  3. Laser-Induced Current Transients in Strained-Si MOSFETs

- Summary
- Publication

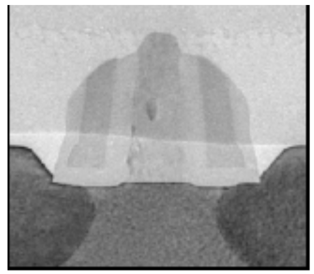
Uniaxial Stress in Si MOSFETs

PMOS

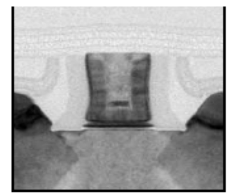
90 nm (2003)



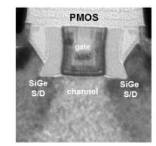
65 nm (2005)



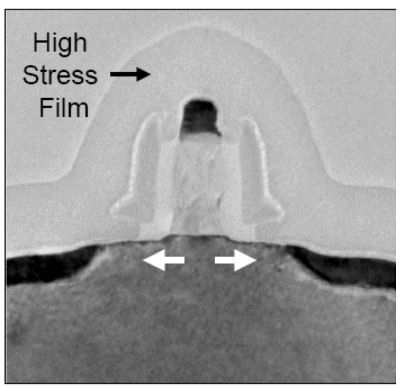
45 nm (2007)

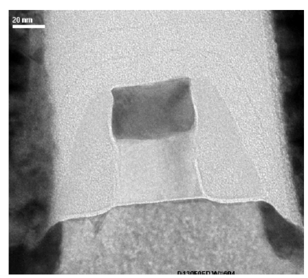


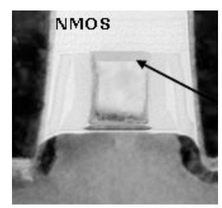
32 nm (2009)

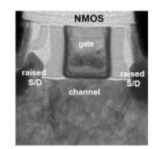


NMOS







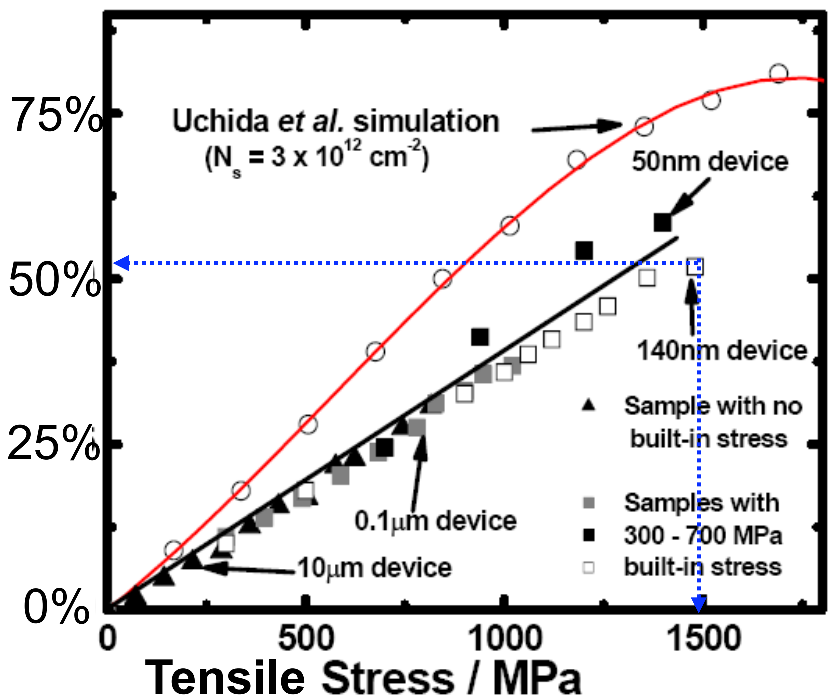


Source : Intel

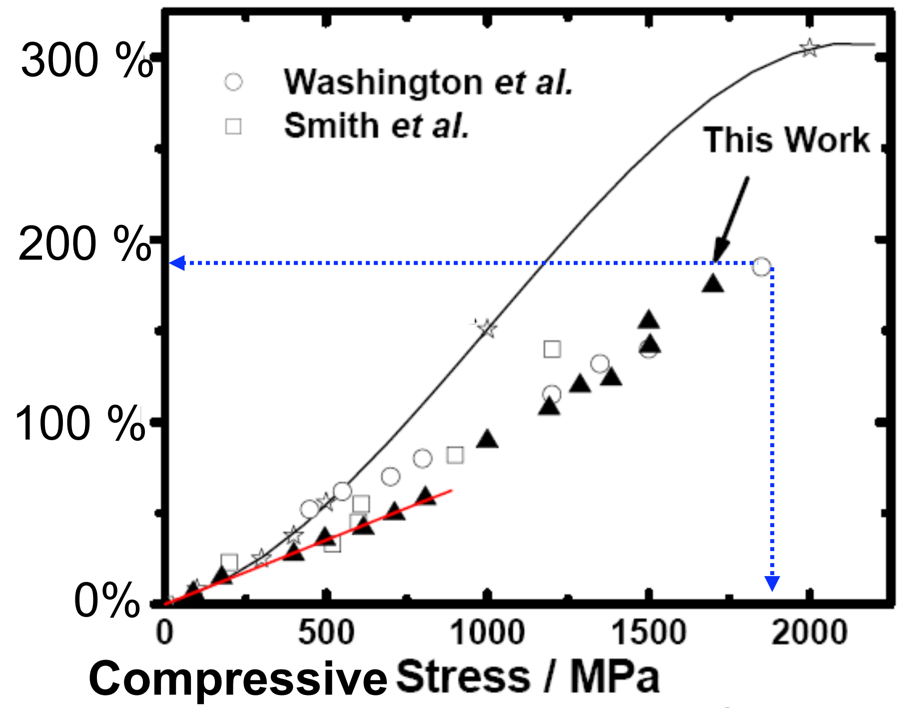
- Uniaxial strained Si technology is successfully implemented beyond 90 nm logic device.
- It is widely used in commercial electronics market.

Mechanical Stress Alters Mobility Significantly

Electron Mobility Enhancement



Hole Mobility Enhancement



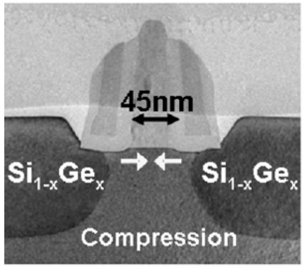
Suthram, 2008

- In modern devices, the strained-Si technology is implemented to boost transistor performance.
- Mechanical stress enhances electron and hole mobility significantly (Performance Booster).

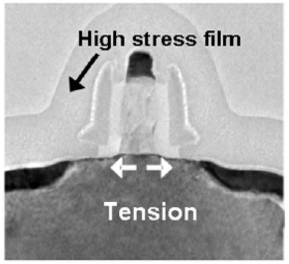
How about Radiation Environment?

David R. Myers, 2002

Reliability question for Strained Si



pMOSFET



nMOSFET

Thompson, 2004

- Researchers are interested in reducing the cost of chips using commercial technology.
- It is very important to understand reliability of strained Si under radiation.

Main Contributions

- The first systematic study about the effect of uniaxial-strained silicon technology under radiation.

1. Total Ionizing Dose (TID) Effects on Strained HfO_2-based nMOSFETs

   =>Uniaxial stress lower hole trap energy level in HfO_2 and SiOx

   =>Uniaxial stress decrease radiation-induced threshold voltage shift

   =>Mobility enhancement under uniaxial stress is not lost after irradiation

2. Laser-Induced Current Transients in Strained-Si Diodes

   => Uniaxial stress alters electron mobility along <001> direction

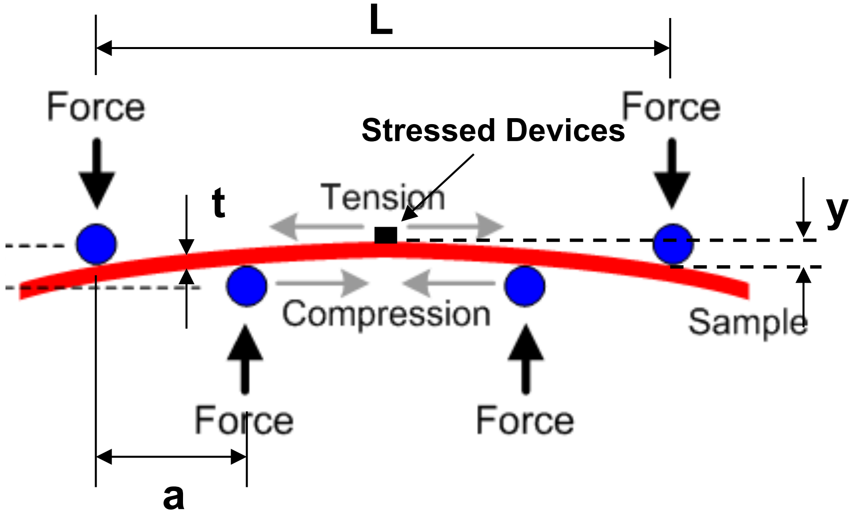
   => Uniaxial stress changes shape of single event transients in large N+/P diodes

3. Laser-Induced Current Transients in Strained-Si MOSFETs

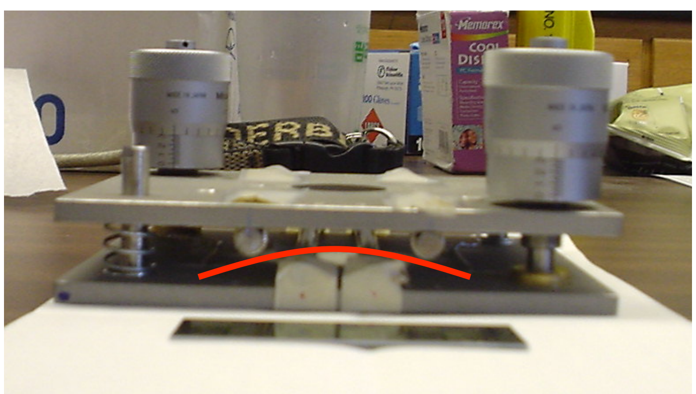
   => Impact of uniaxial stress on single event transients in submicron MOSFETs

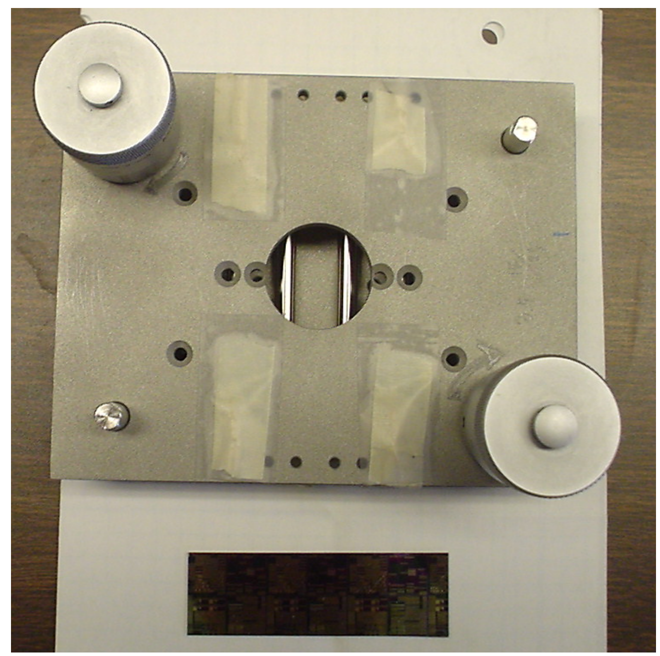
External Mechanical Stress

A four point bending jig is used to apply mechanical stress to devices.



$$\sigma = \frac{Eyt}{2a\left(\frac{L}{2} - \frac{2a}{3}\right)}$$





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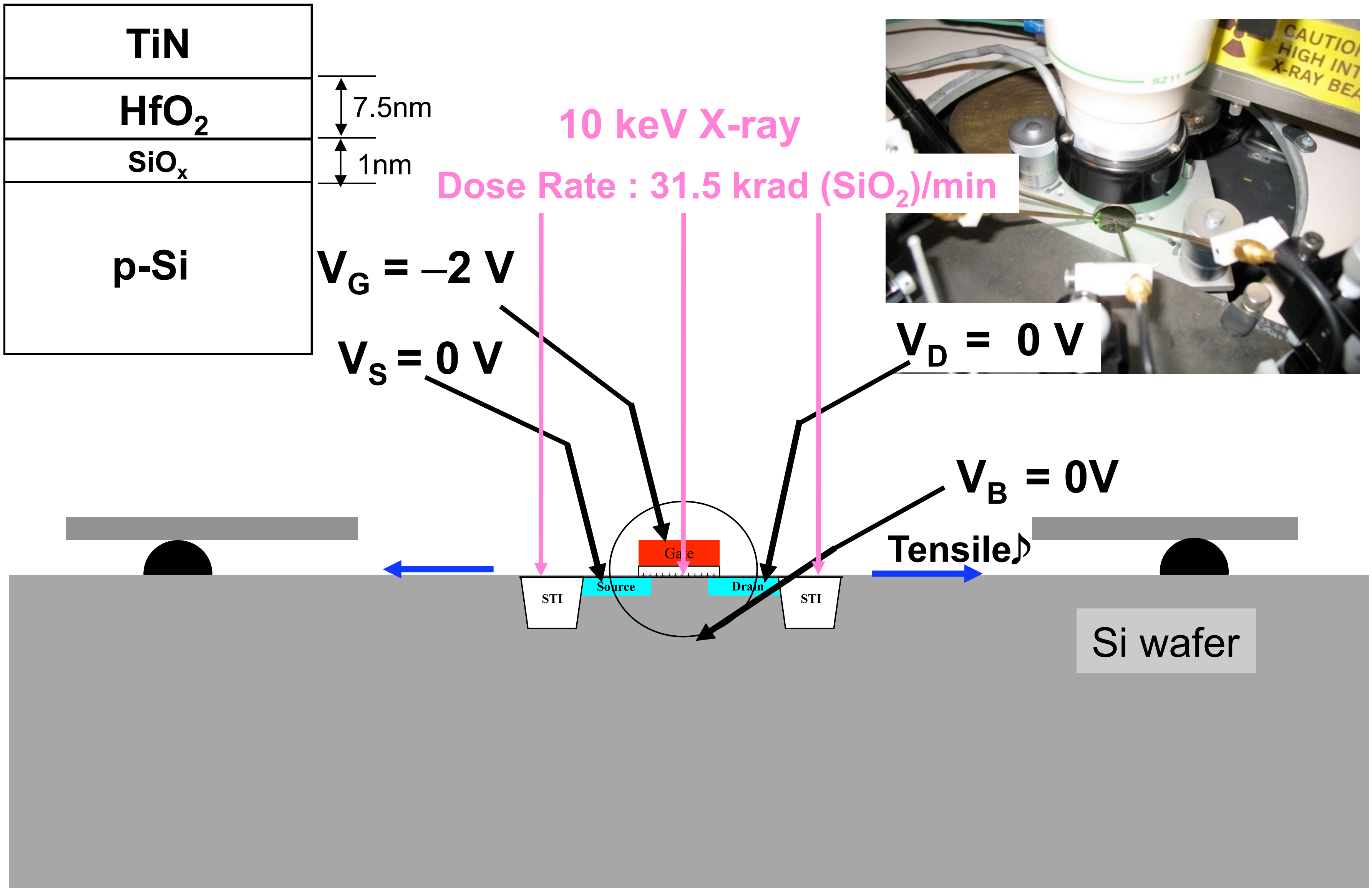
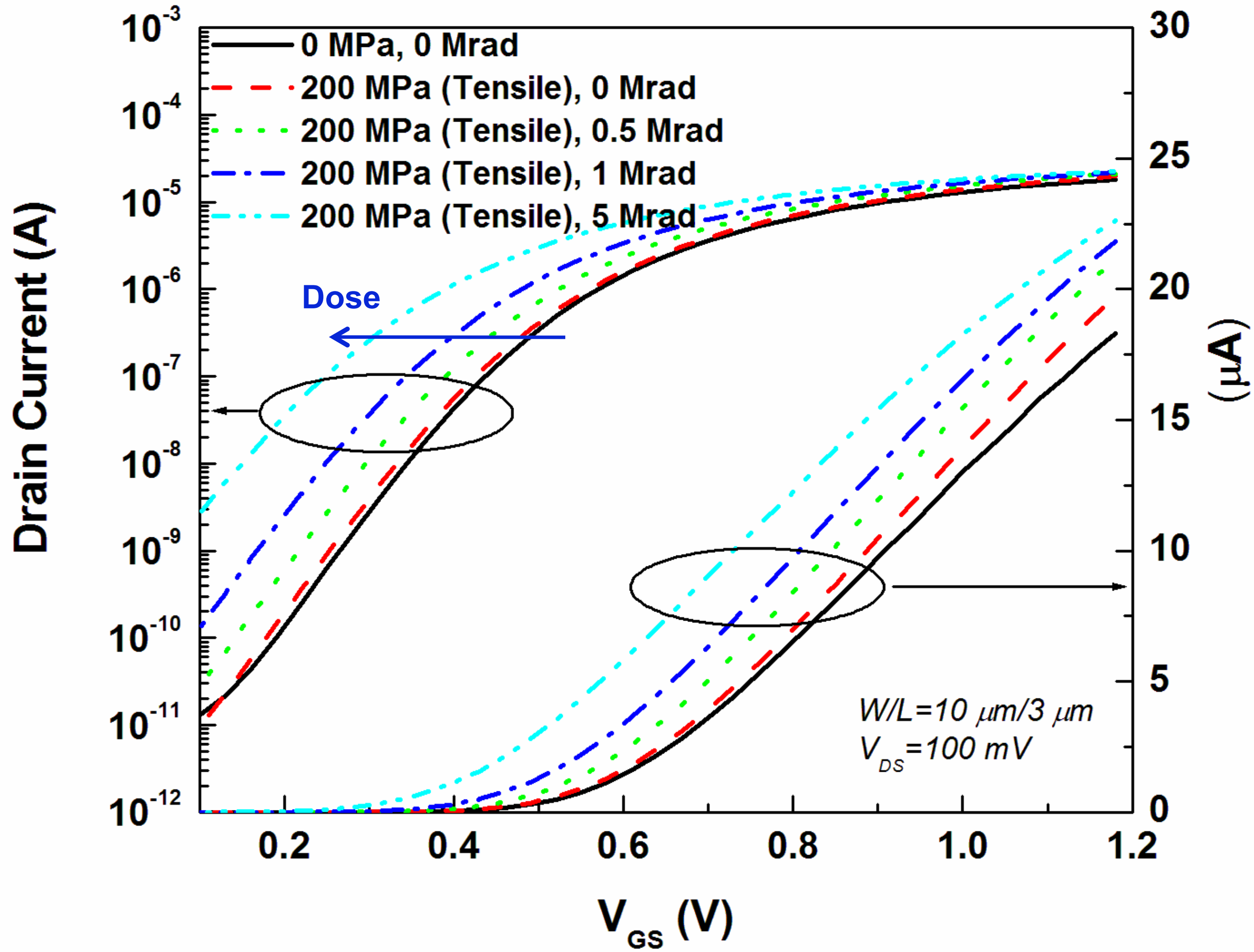
TID Experiment on Strained MOSFET



TID Experiment Matrix

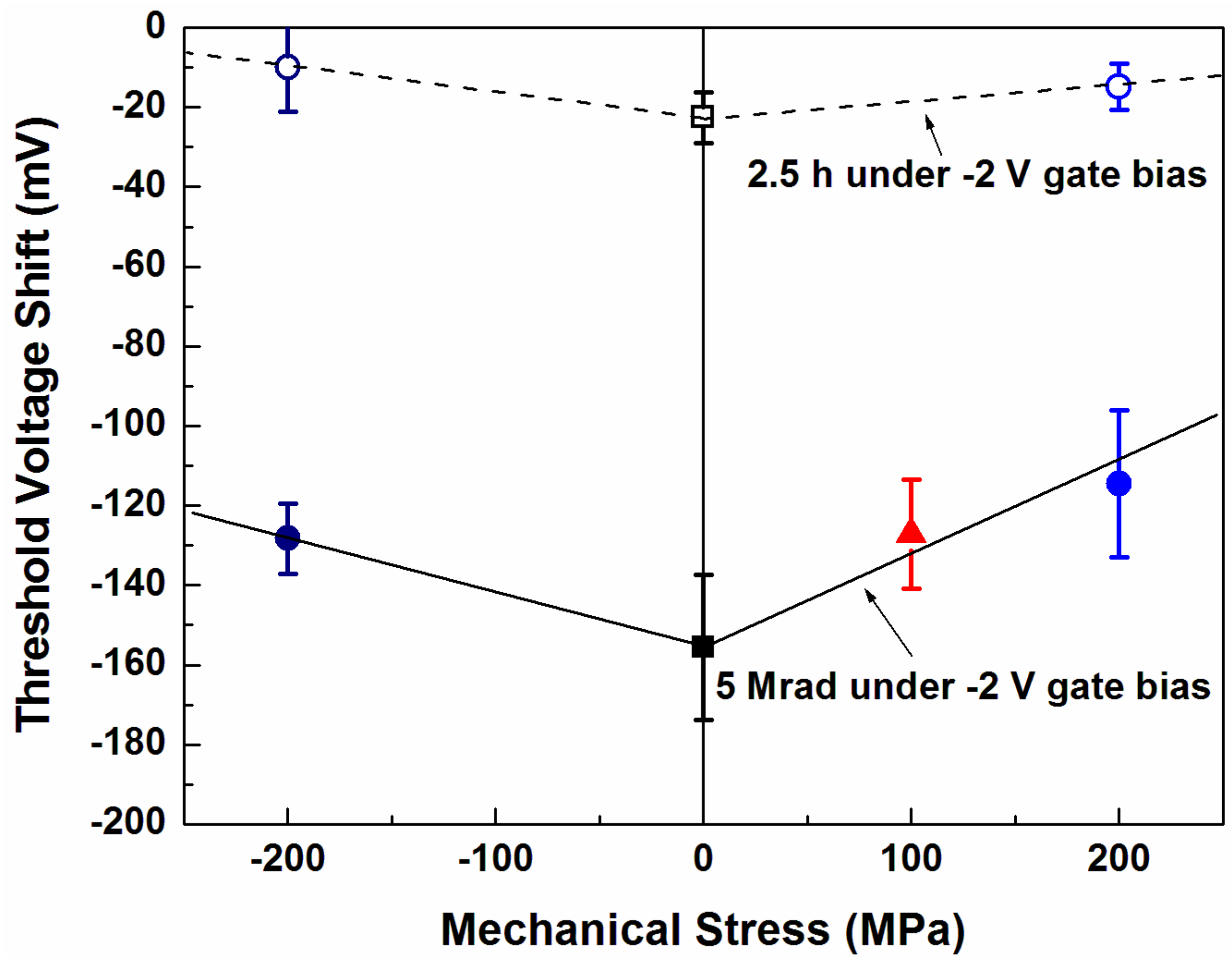
Mechanical Stress / Radiation Dose	Compressive 200MPa	0MPa	Tensile 100MPa	Tensile 200MPa
Pre-rad (0 Mrad)	✓	✓	✓	✓
0.5 Mrad	✓	✓	✓	✓
1 Mrad	✓	✓	✓	✓
5 Mrad	✓	✓	✓	✓

I_D-V_{GS} under Tensile (200 MPa)



- Positive charge trapping in HfO_2/SiO_x dielectrics is dominant.

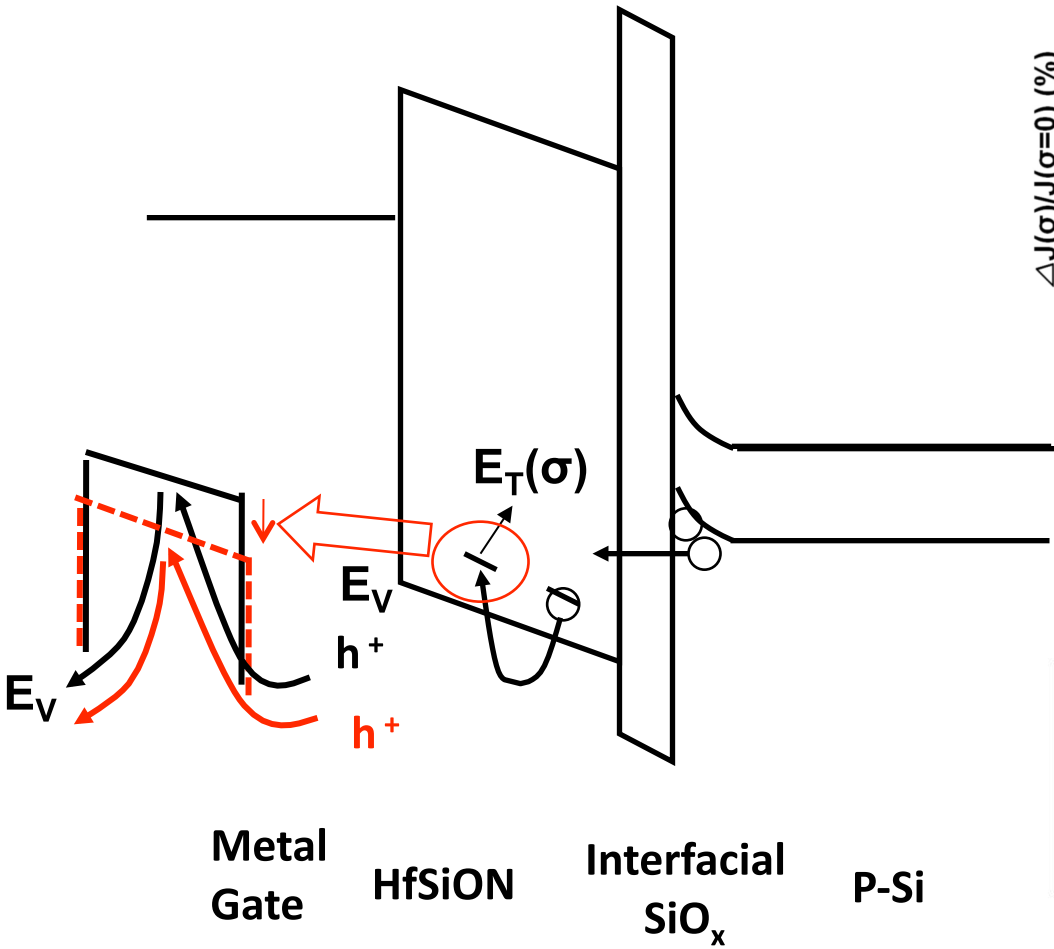
V_t Shift vs. Mechanical Stress



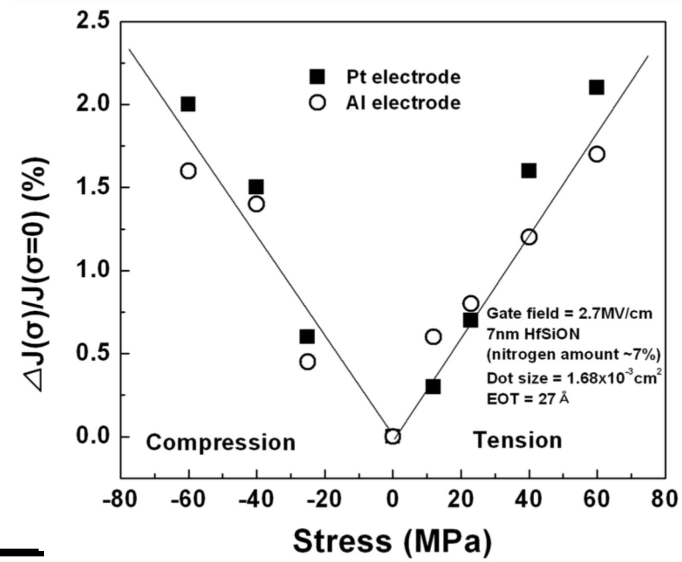
- Both stress reduce threshold voltage shifts.

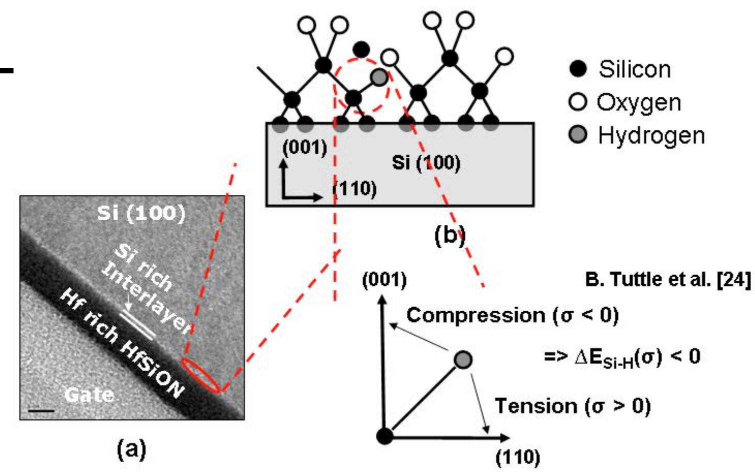
Uniaxial Stress on Hole Trap Energy Level

Hole Poole-Frenkel Emission Conduction



*Y.S. Choi and **H.Park** et al. APL 2008*

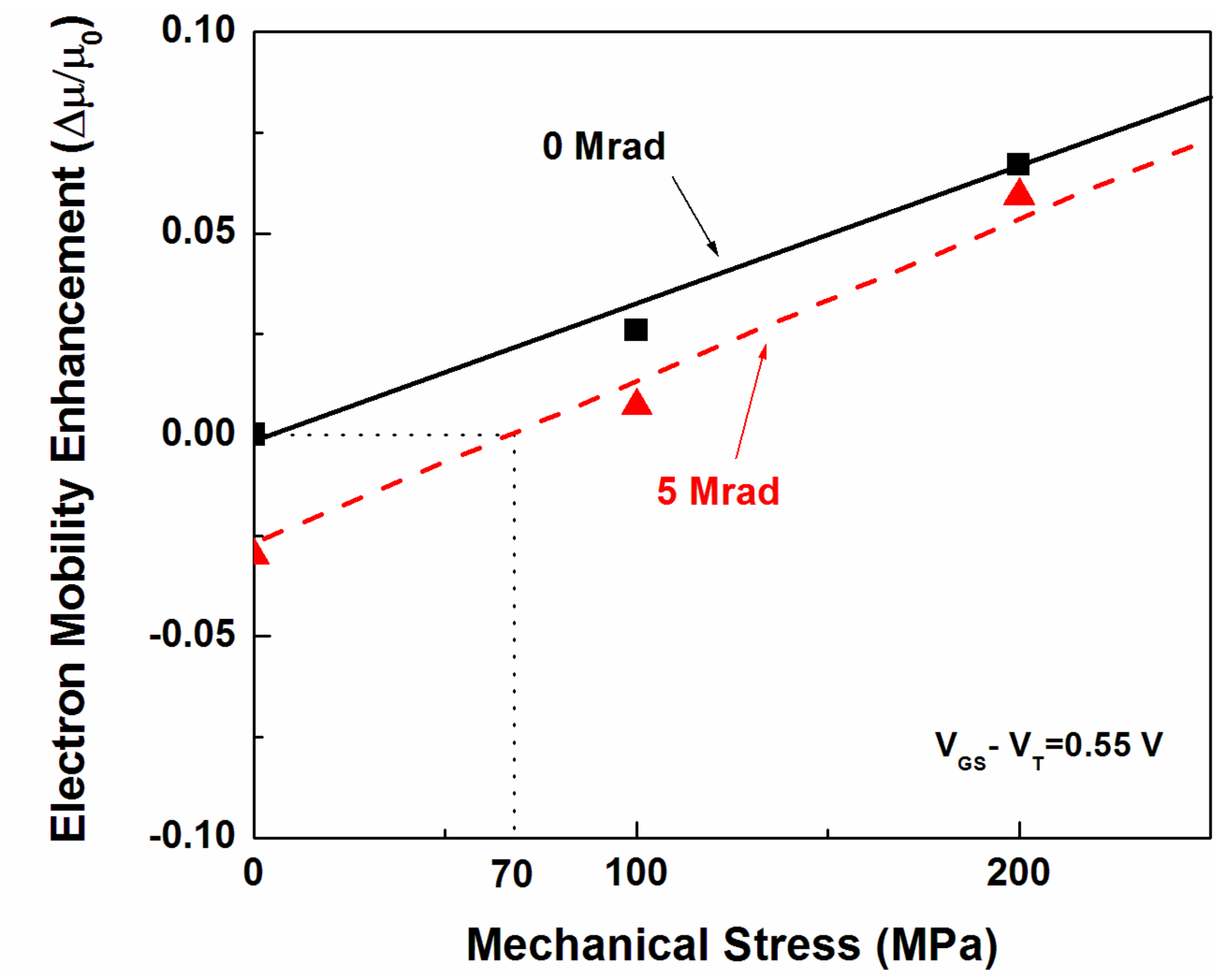




*Y.S. Choi and **H.Park** et al. JAP 2009*

- Both stresses lower hole trap activation level in dielectrics.

Stress and Radiation on Electron Mobility



- Benefit of Strained Si is not lost after a total dose of 5 Mrad (SiO_2)

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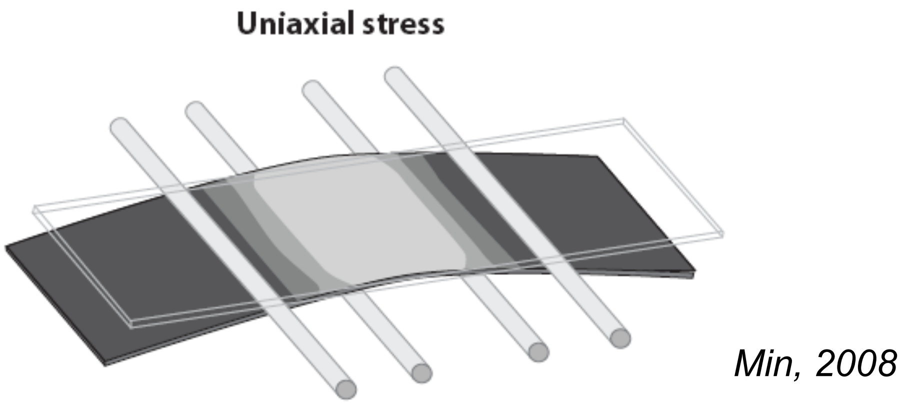
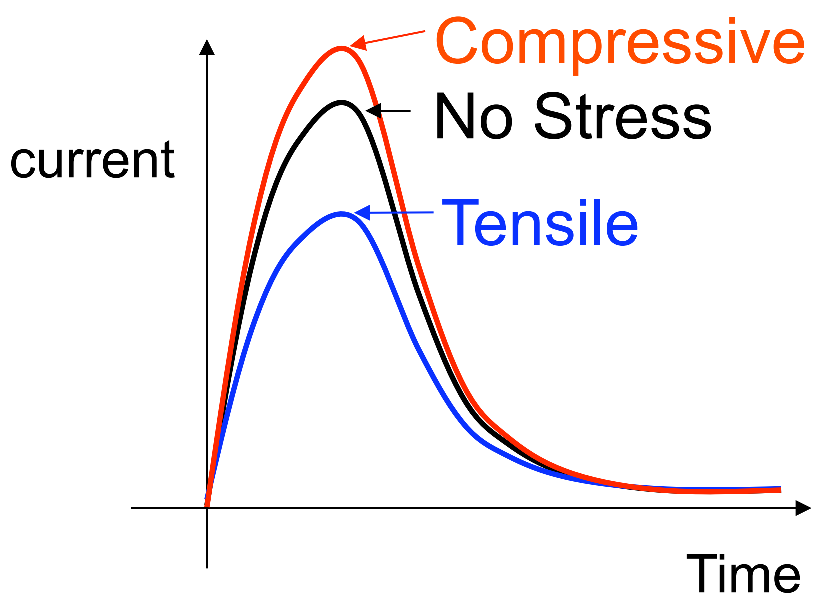
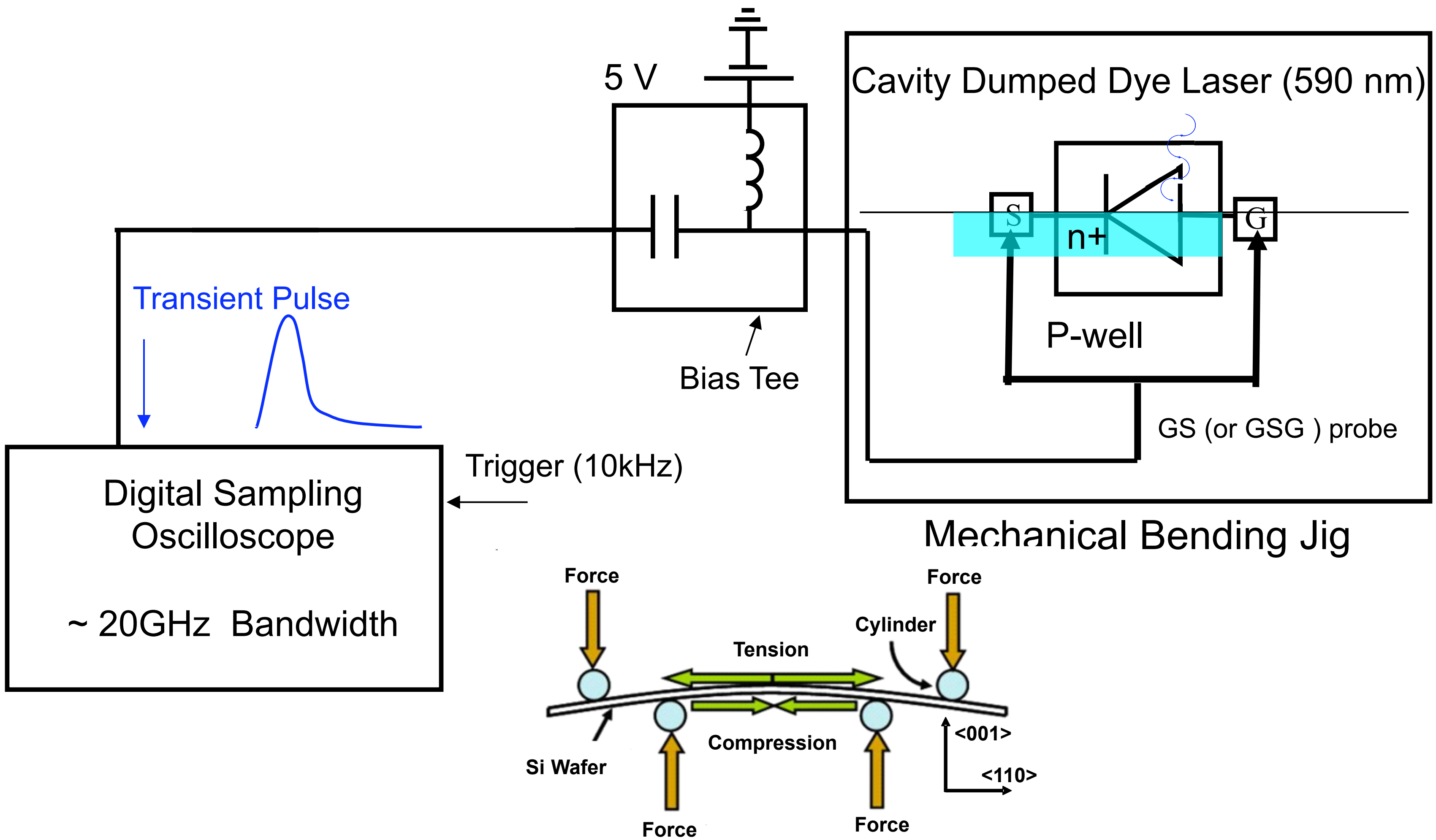
Current Transients under Uniaxial Stress





- How does uniaxial stress change current transients in diodes (source/drain) ?
(I_{max} : peak current, Q: charge collection)

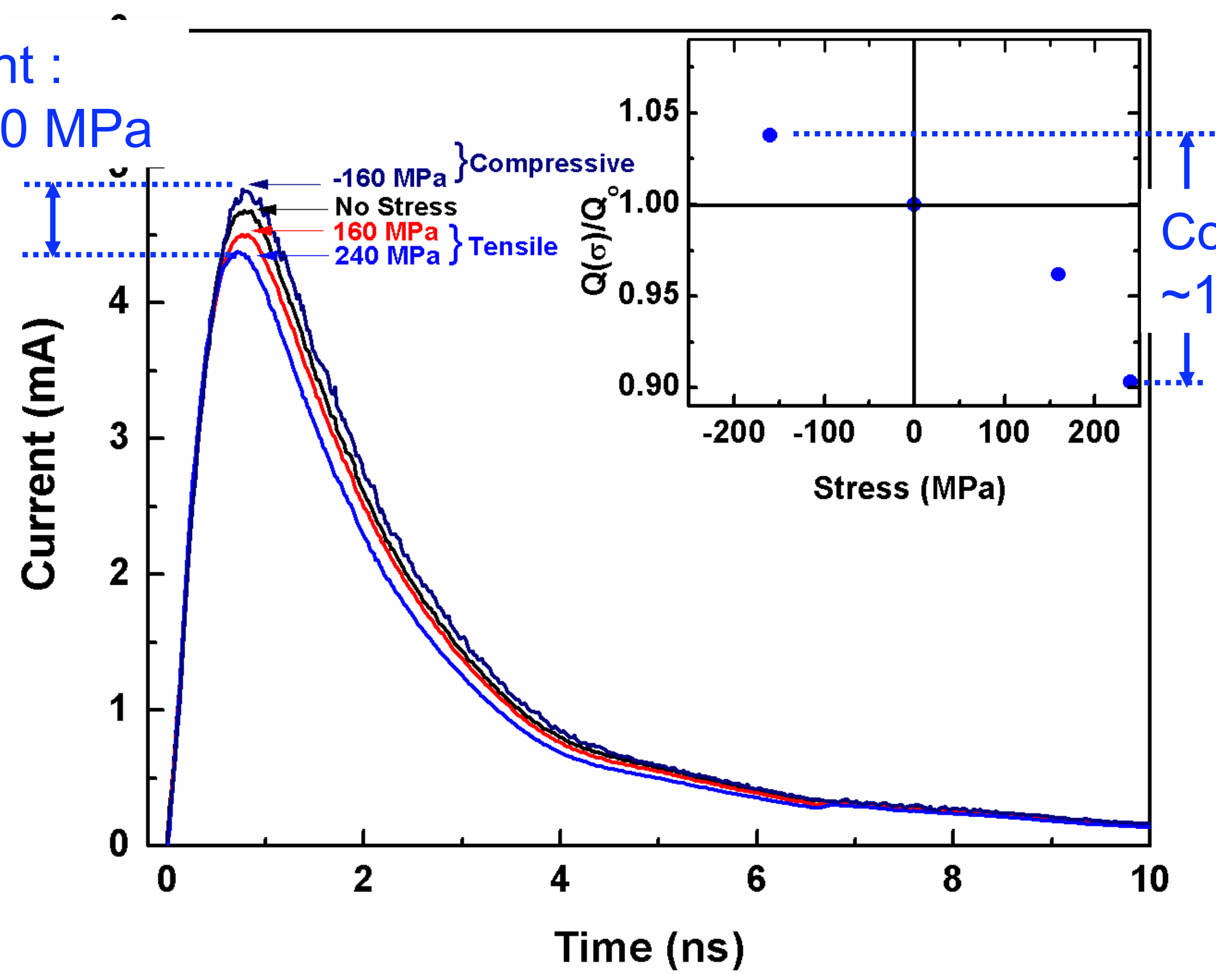
Laser-Induced Current Transients Measurement



-We can observe changes of current transient pulses under mechanical stresses

Laser-Induced Current Transients

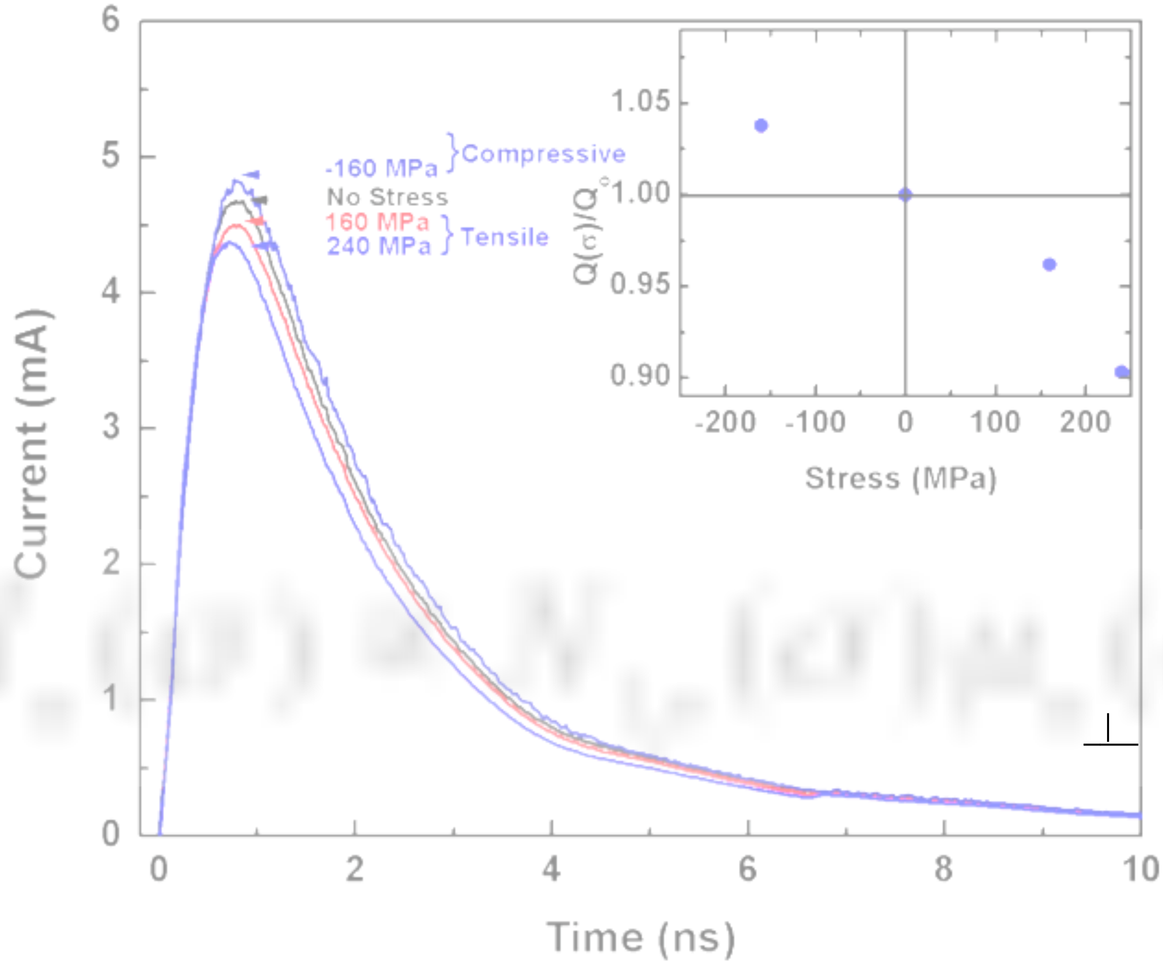
Peak current :
~11% at 400 MPa



Collected charges:
~14% at 400 MPa

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

Stress Dependence of Current



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

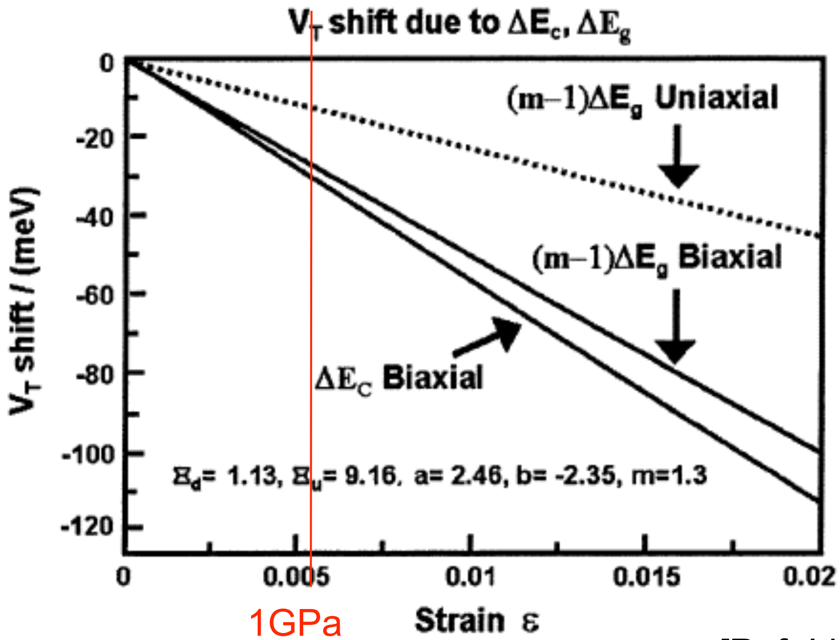
Strain Effect on E-H Pair Generation

Absorption coefficient

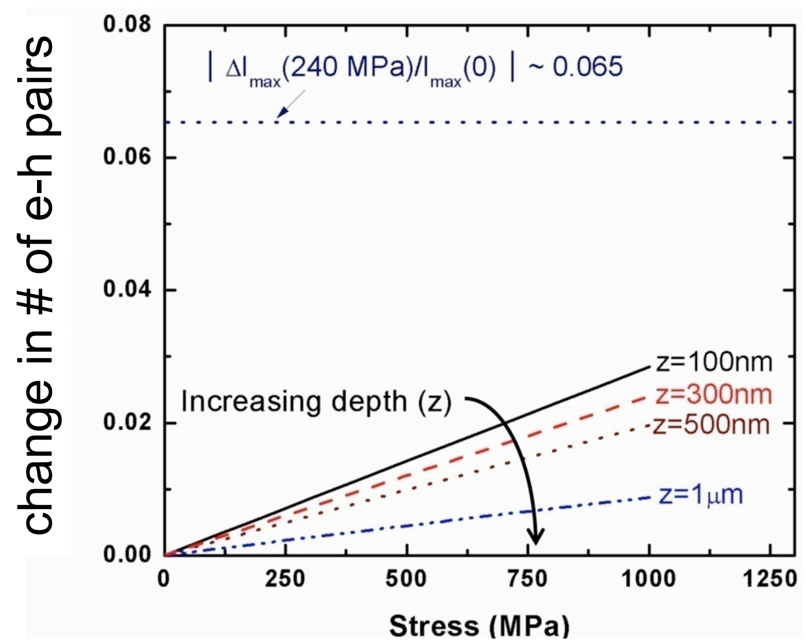
$$\frac{\Delta\alpha}{\alpha} = \frac{\Delta E_g(\sigma)}{h\nu - E_g} << 1, \quad h\nu > E_g$$

The number of generated e-h pairs

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



[Ref. Lim, 2004]

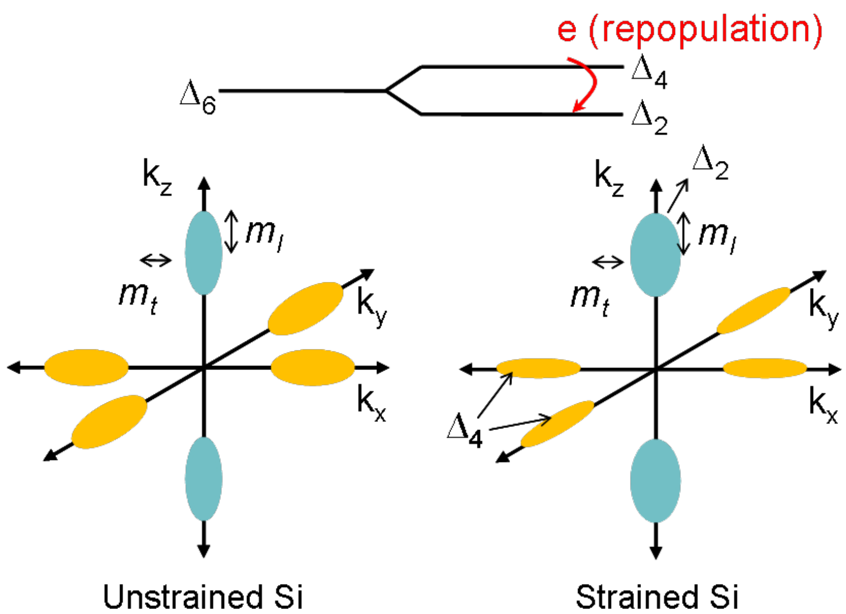


$$\Delta E_g \cong 30\, meV \text{ at 1 GPa of uniaxial tensile stress}$$

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

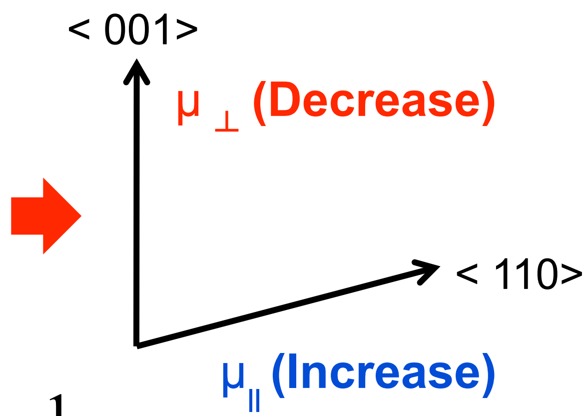
Strain Effect on Electron Mobility

Under Tensile Stress :



Mohta, 2005

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



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

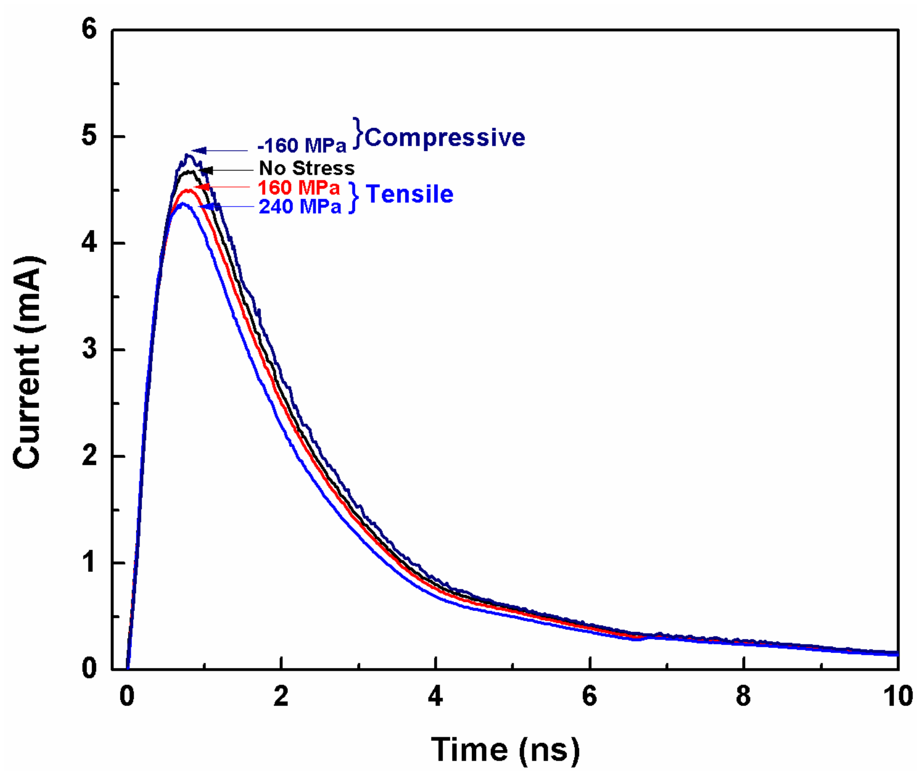
For 1 GPa of uniaxial tensile stress,

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

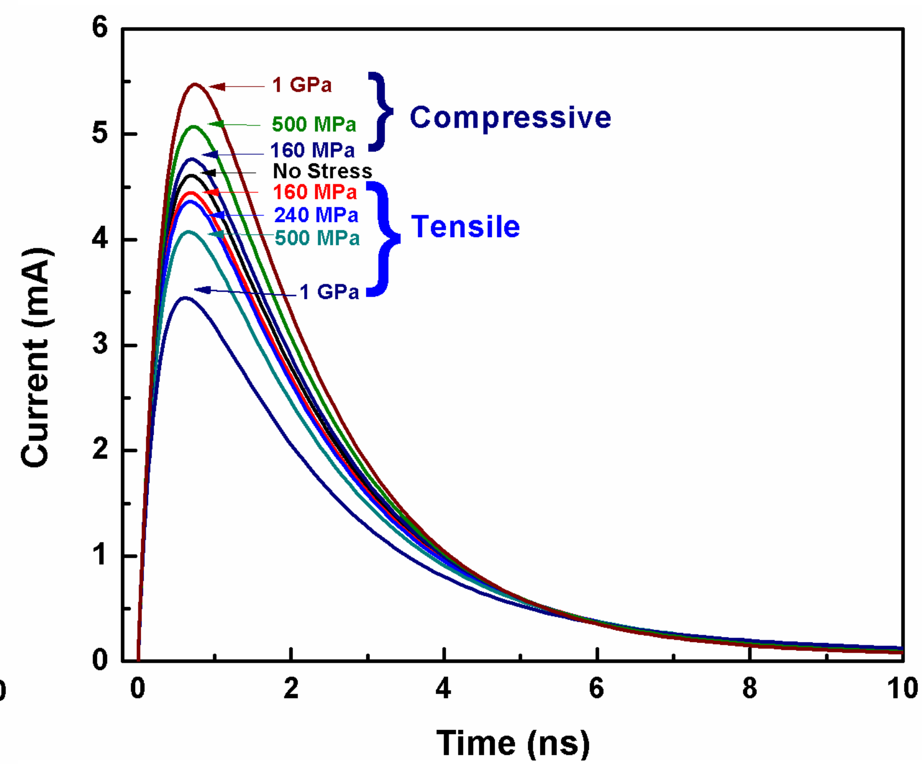
→ Electron mobility change dominates current transient change under stress

Experiment vs. 2-D Simulation results

Experiment



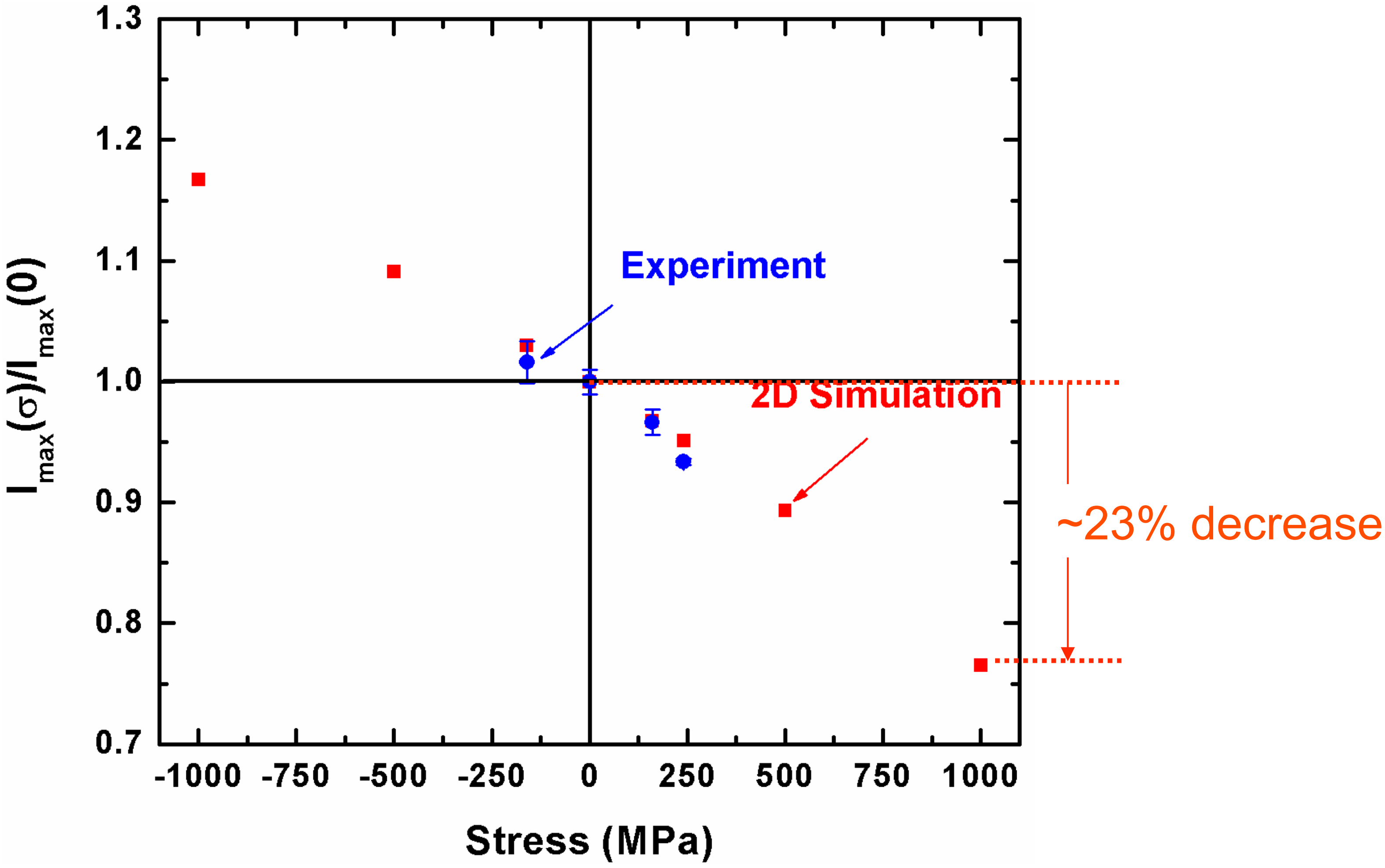
2-D FLOODS Simulation



** FLOODS : Florida Object Oriented Device Simulator*

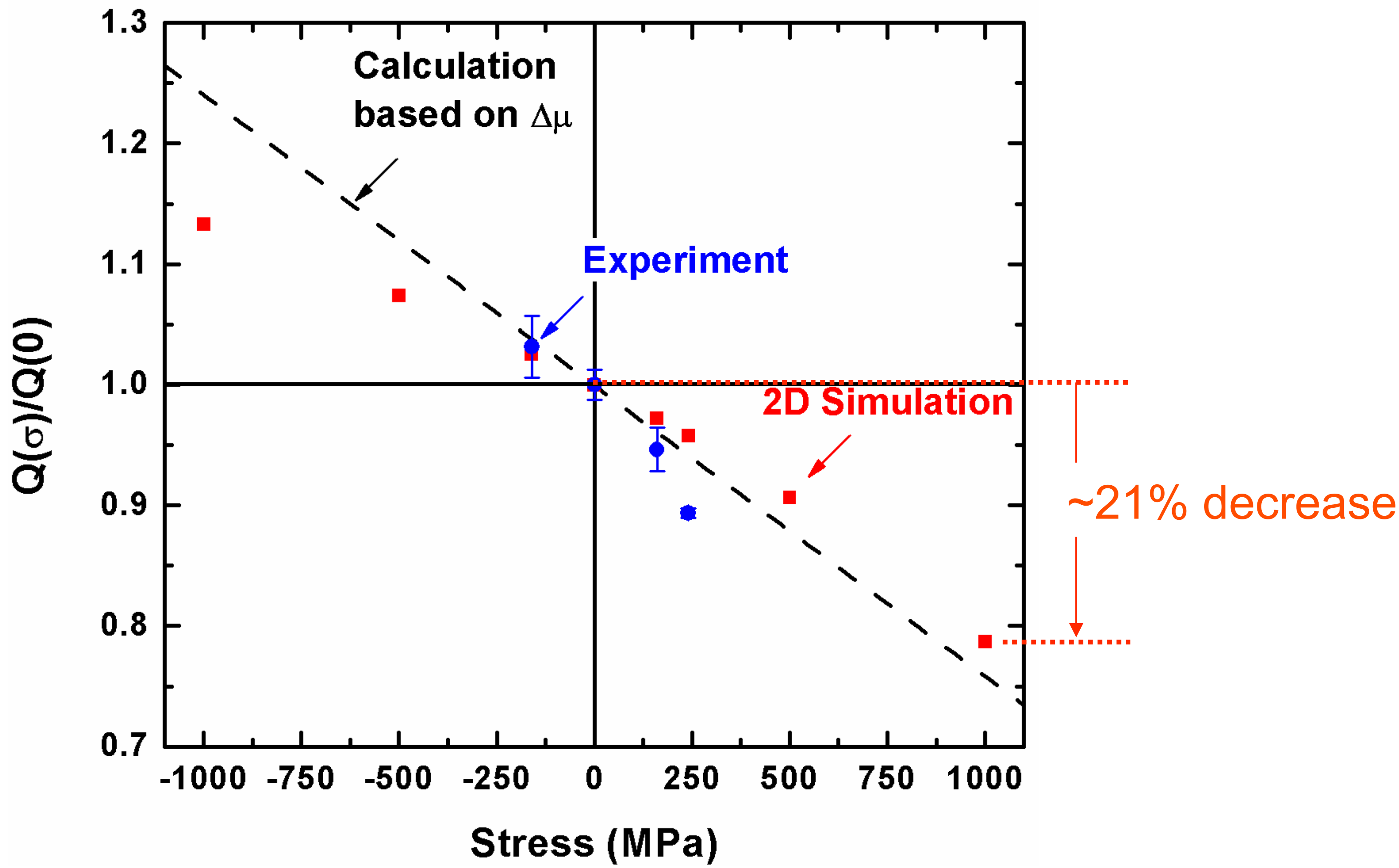
-2D simulation results have good agreement with experimental ones.

I_{max} under Uniaxial Stress



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

Charge Collection until 10 ns



- ~ 21% reduction of collected charges under 1GPa of uniaxial tensile stress

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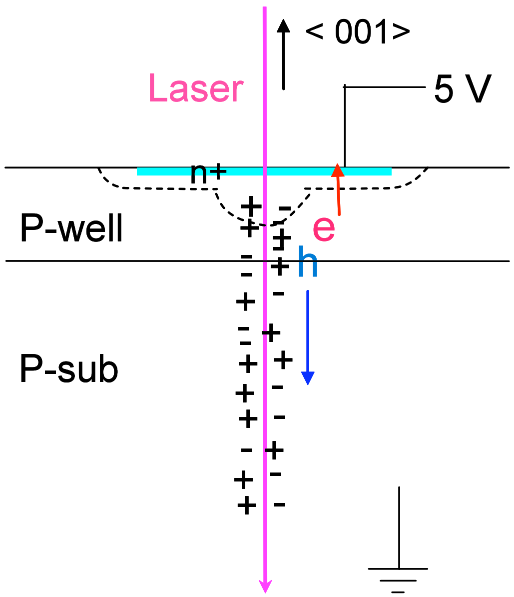
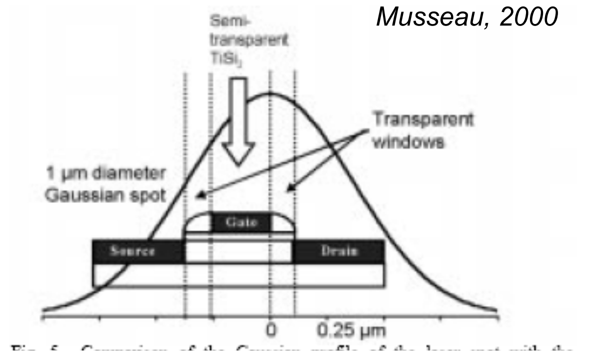
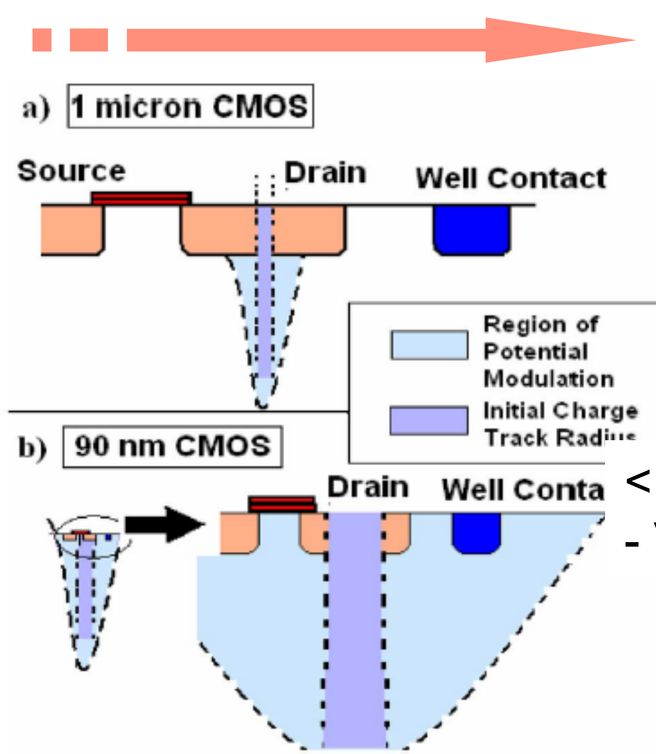
Motivation

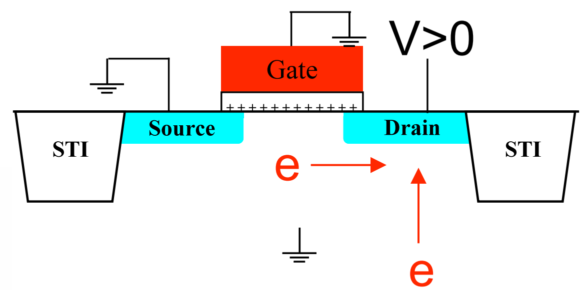


Musseau, 2000





DasGupta, 2007



< Large Diodes >

- Vertical transport

1D

< Deep Submicron Devices>

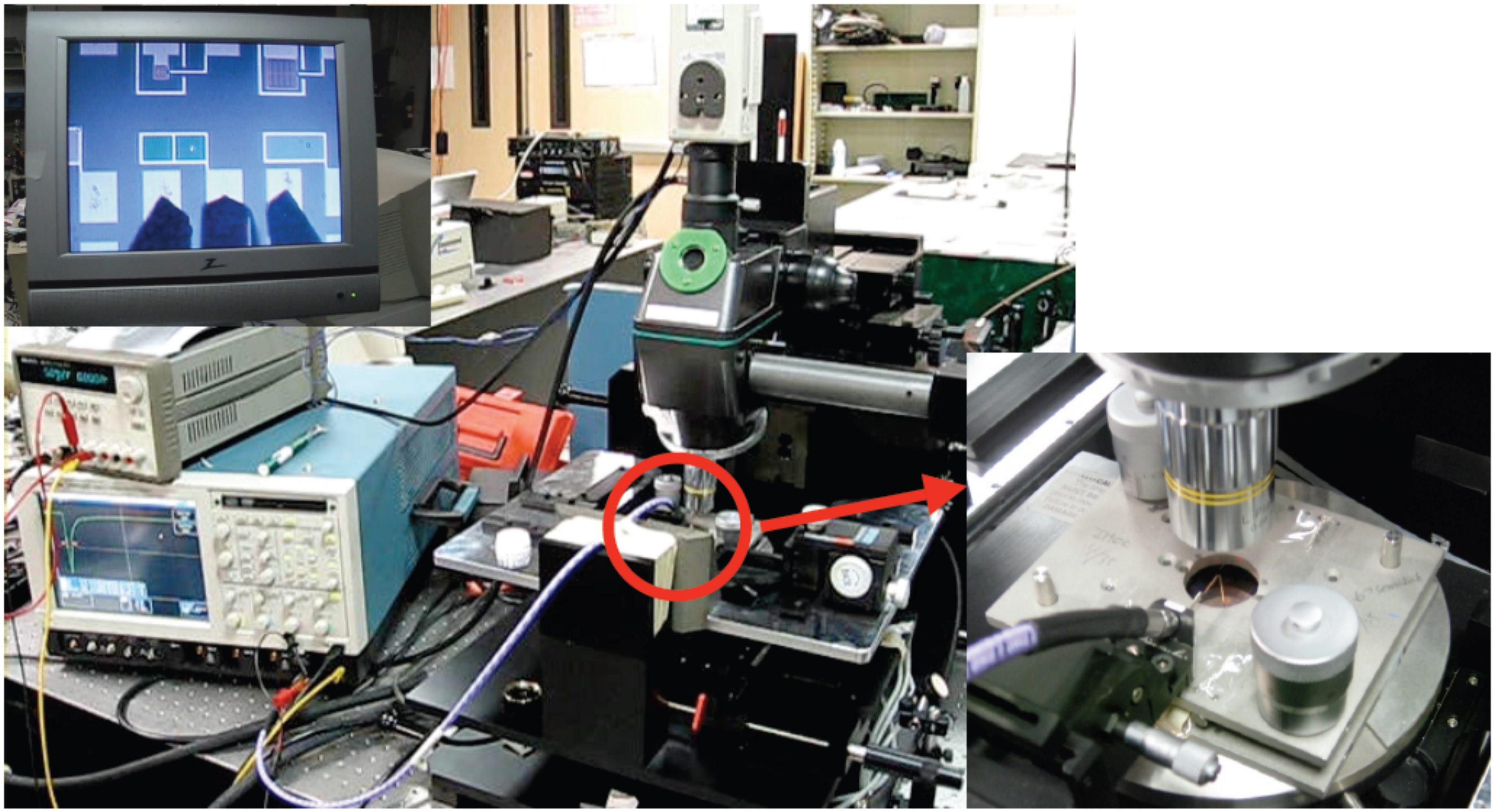
- Vertical/ Horizontal transport

2D or 3D

Goal :

- Investigate impact of uniaxial stress on laser-induced current transients in MOSFETs experimentally and theoretically.
- Suggest how to mitigate single event effects in highly-scaled MOSFETs using uniaxial stress.

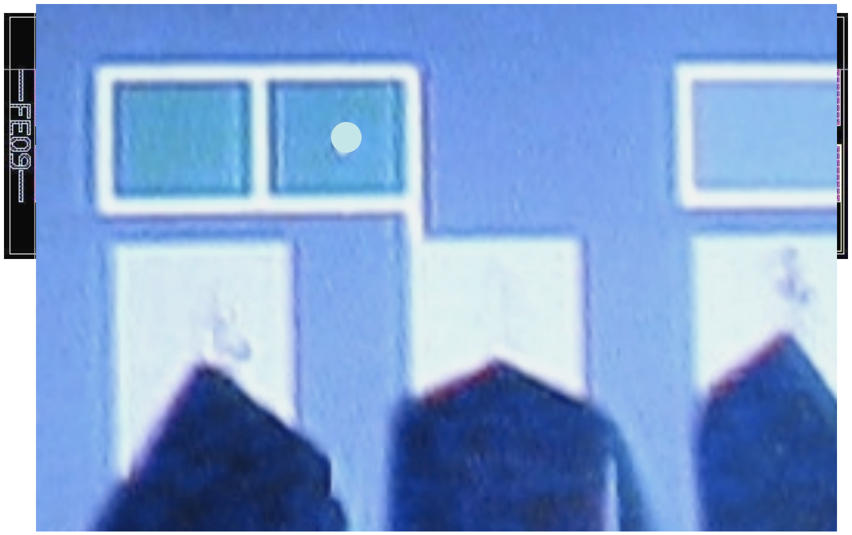
Laser-induced Current Transients Set up for "Large" diodes



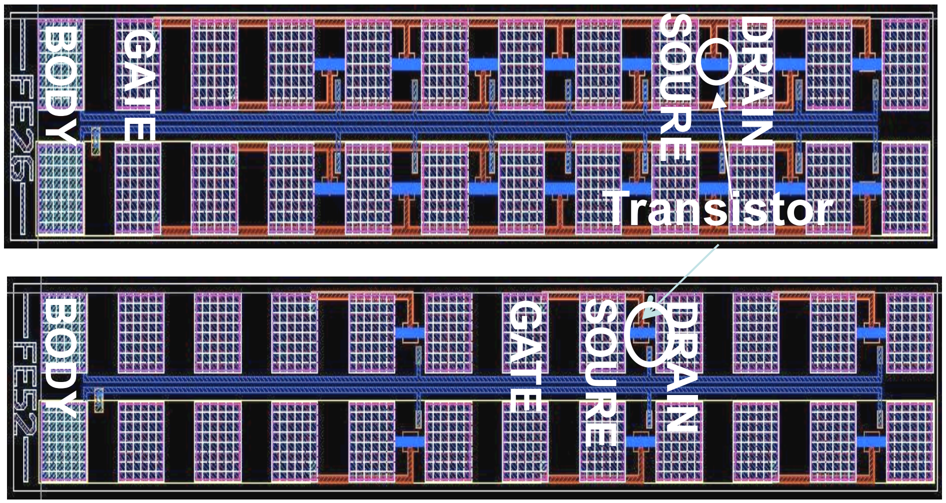
- Current transients in diodes are measured using high-speed probe station.
- A four point bending jig and high speed probes will be modified.

Diodes vs. Transistors

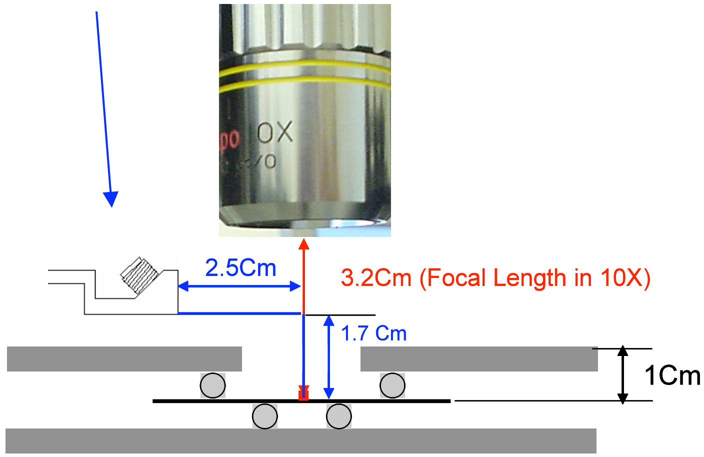
< Diodes >



< Transistors >

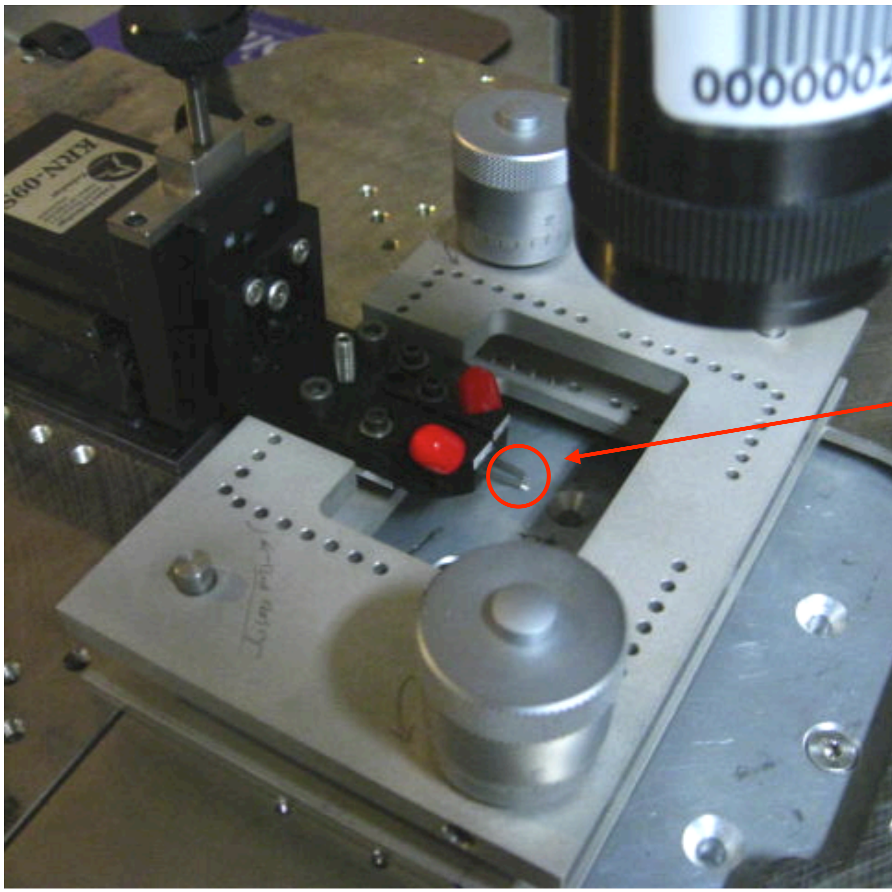


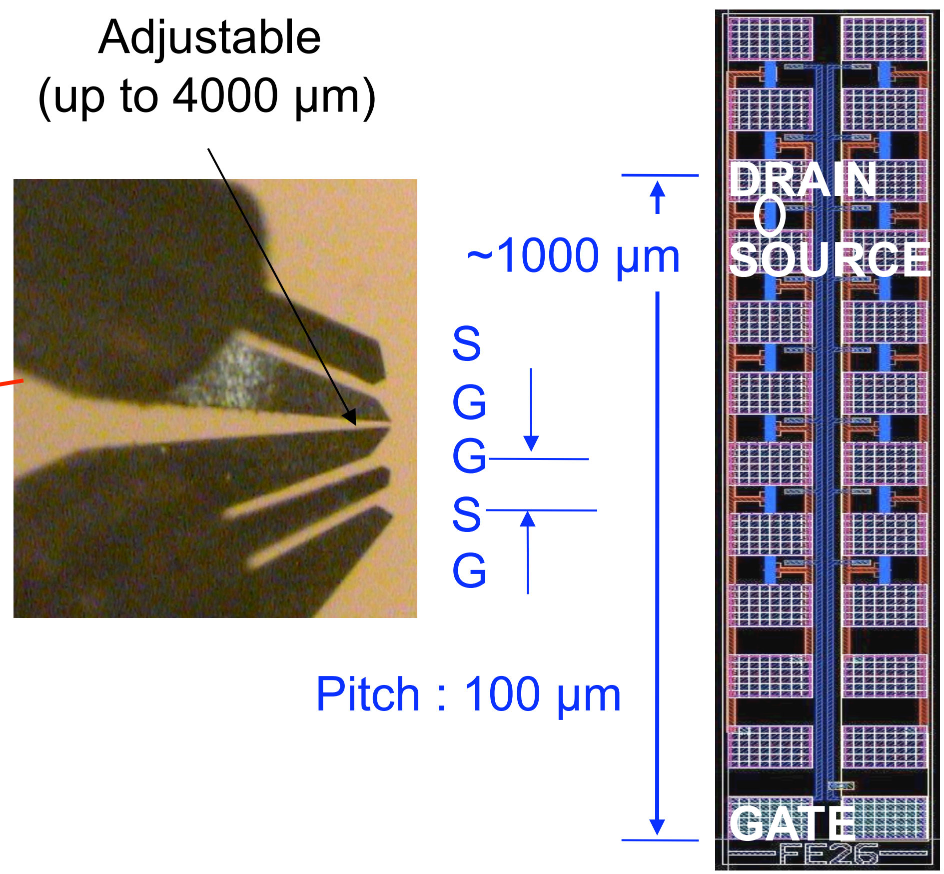
One RF(GSG) probe is used!



How can we solve this ?

New Mechanical Jig and Probes

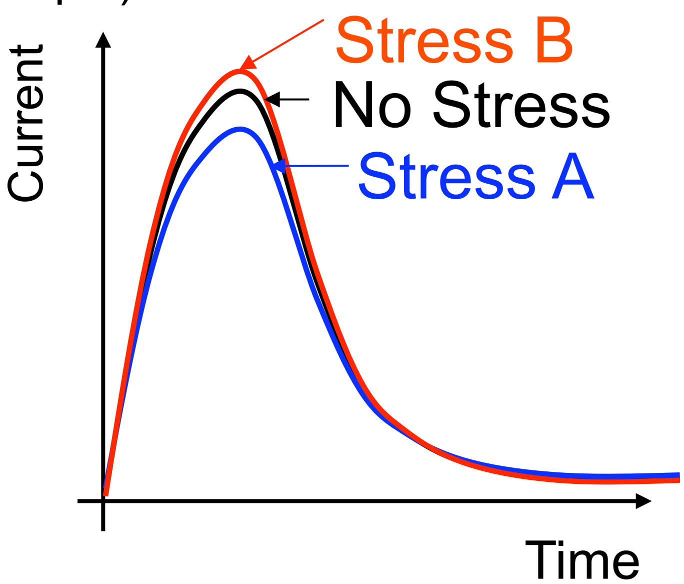


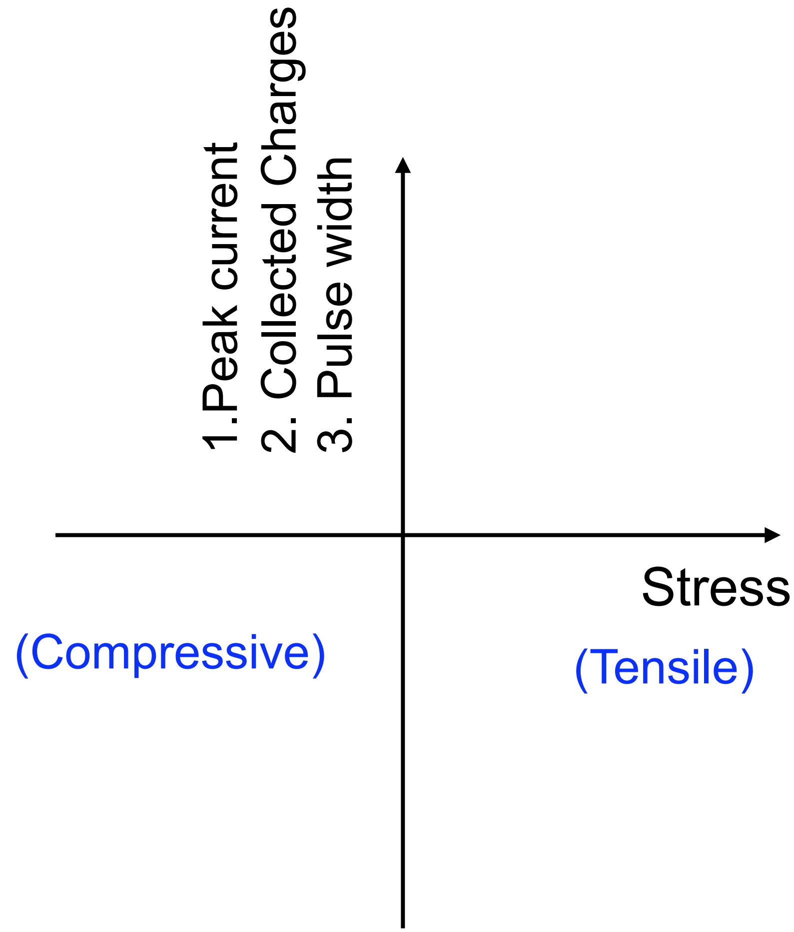


Data to be collected

Control parameter :
Stress, Width, Length,
Applied Voltage to Drain

(example)





-The trend of peak current and collected charge under MOSFET will be compared with that of diodes case (Fall 2010 and Spring 2011).
- It is also compared with FLOODS simulation .

Summary

- Uniaxial mechanical stresses reduces charge trapping in HfO_2-based nMOSFET due to lowering hole trap energy level in HfO_2/SiO_x dielectrics.
- Electron mobility enhancement remains under mechanical stress after irradiation.

- Uniaxial stress alter current transients due to vertical electron mobility change in large N+/P diodes.
- 2D simulation can predict current transient under high (~1GPa) uniaxial stress.

- The first experimental study of stress effects on current transients in MOSFETs is proposed.

Publication

1. **<u>H. Park</u>**, S. K. Dixit, C. Youn Sung, R. D. Schrimpf, D. M. Fleetwood, T. Nishida, and S. E. Thompson, "Total Ionizing Dose Effects on Strained HfO2-Based nMOSFETs,", ***IEEE Transactions on Nuclear Science****,* vol. 55, pp. 2981-2985, 2008.

2. Y. S. Choi, **<u>H. Park</u>**, T. Nishida, and S. E. Thompson, "Reliability of HfSiON gate dielectric silicon MOS devices under [110] mechanical stress: Time dependent dielectric breakdown," ***Journal of Applied Physics****,* vol. 105, p. 044503, Feb 15 2009.

3. S. Y. Son, Y. S. Choi, P. Kumar, **<u>H. Park</u>**, T. Nishida, R. K. Singh, and S. E. Thompson, "Strain induced changes in gate leakage current and dielectric constant of nitrided Hf-silicate metal oxide semiconductor capacitors," ***Applied Physics Letters****,* vol. 93, p. 153505, Oct 13 2008.

4. **<u>H. Park</u>**, D. J. Cummings, R. Arora, J. A. Pellish, R. A. Reed, R. D. Schrimpf, D. McMorrow, S. E. Armstrong, U. Roh, T. Nishida, M. E. Law, and S. E. Thompson, "Laser-Induced Current Transients in Strained-Si Diodes,", ***IEEE Transactions on Nuclear Science****,* vol. 56, pp. 3203-3209, 2009.

5. D. J. Cummings, **<u>H. Park</u>**, S. E. Thompson, and M.E. Law, “An Adaptive Grid Scheme for Single-Event Effects Simulations”, **accepted to *Nuclear and Space Radiation Effect conference***, July, 2010

6. D. J. Cummings, A. F. Witulski, **<u>H. Park</u>**, R. D. Schrimpf, and S. E. Thompson, "Mobility Modeling Considerations for Radiation Effects Simulations in Silicon," ***under review of IEEE Transaction on Nuclear Science.***