

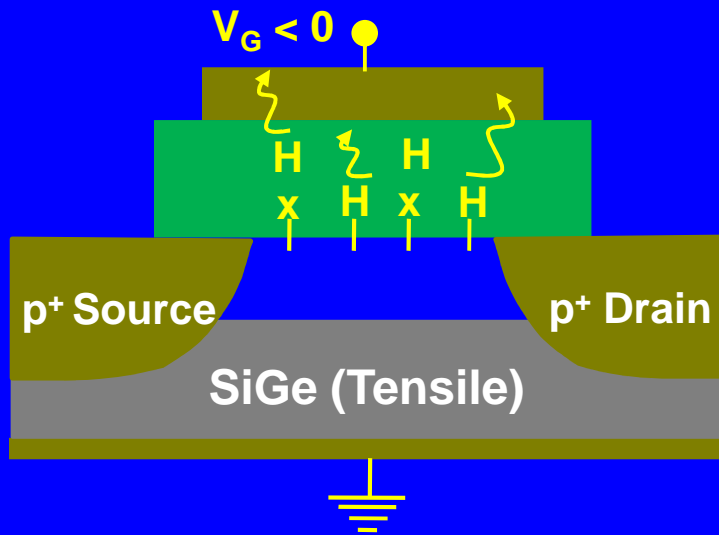
Universality of NBTI-Induced N_{IT} Generation and Its Impact on I_D Degradation in Strained/Unstrained PMOS Transistors

A. E. Islam, ¹J. H. Lee, ¹W. H. Wu, ¹A. Oates, M. A. Alam

Purdue University, West Lafayette, IN, USA

¹Taiwan Semiconductor Manufacturing Company

Introduction / Motivation



Source/Drain Material:
Compressive → SiGe
Tensile → Si

Strain on NBTI-induced N_{IT}

No variation in terms of ...

Defect type¹, activation energy^{2-4,7},
and field acceleration²

but ...

on magnitude : No consensus²⁻⁷

N_{IT} on $\Delta\mu_{eff}$, ΔI_D ⁸

μ_{eff} improves with N_{IT}

$\Delta I_D \sim 0$ in appropriate condition

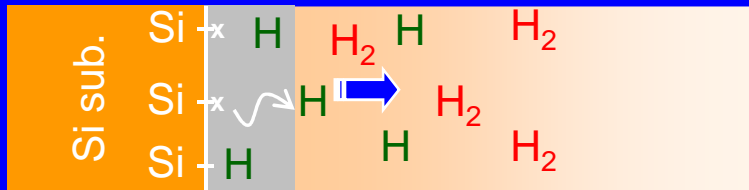
Degradation-free CMOS

¹Stesmans, APL '03 ²Irisawa, VLSI '07 ³Shih, IRPS '05 ⁴Rhee, IEDM '05 ⁵Lu, JJAP '06
⁶Liu, TED '07 ⁷Shickova, EDL '07 ⁸Islam, APL '08

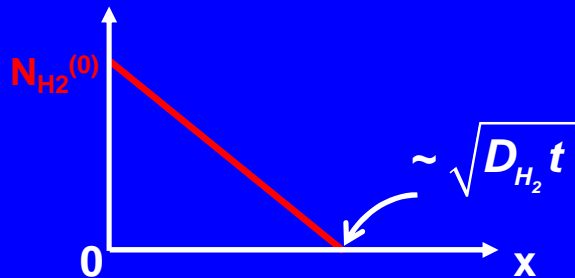
Outline

- Overview: Reaction-Diffusion Model
- Strain dependence of N_{IT}
- Effect of N_{IT} & strain on ΔI_D
- Conclusion

Overview: Reaction-Diffusion Model



*Alam, IRPS (T) 05; Krishnan, APL '06
Islam, TED '07*



a) Reaction $\frac{dN_{IT}}{dt} = k_F [N_0 - N_{IT}] - k_R N_{IT} N_H^{(0)} \sim 0$ Si-H \leftrightarrow Si⁺ + H

b) H-H₂ Conversion $N_{H_2}^{(0)} \sim [N_H^{(0)}]^2$ H \leftrightarrow H₂

c) Diffusion $N_{IT} \sim \frac{1}{2} N_{H_2}^{(0)} \times \sqrt{D_{H_2} t}$ H₂ Diffusion

$$N_{IT} \sim \left(\frac{k_{F0} N_0}{k_{R0}} \right)^{2/3} \exp \left(-\frac{E_A}{k_B T} \right) t^{1/6}$$

Outline

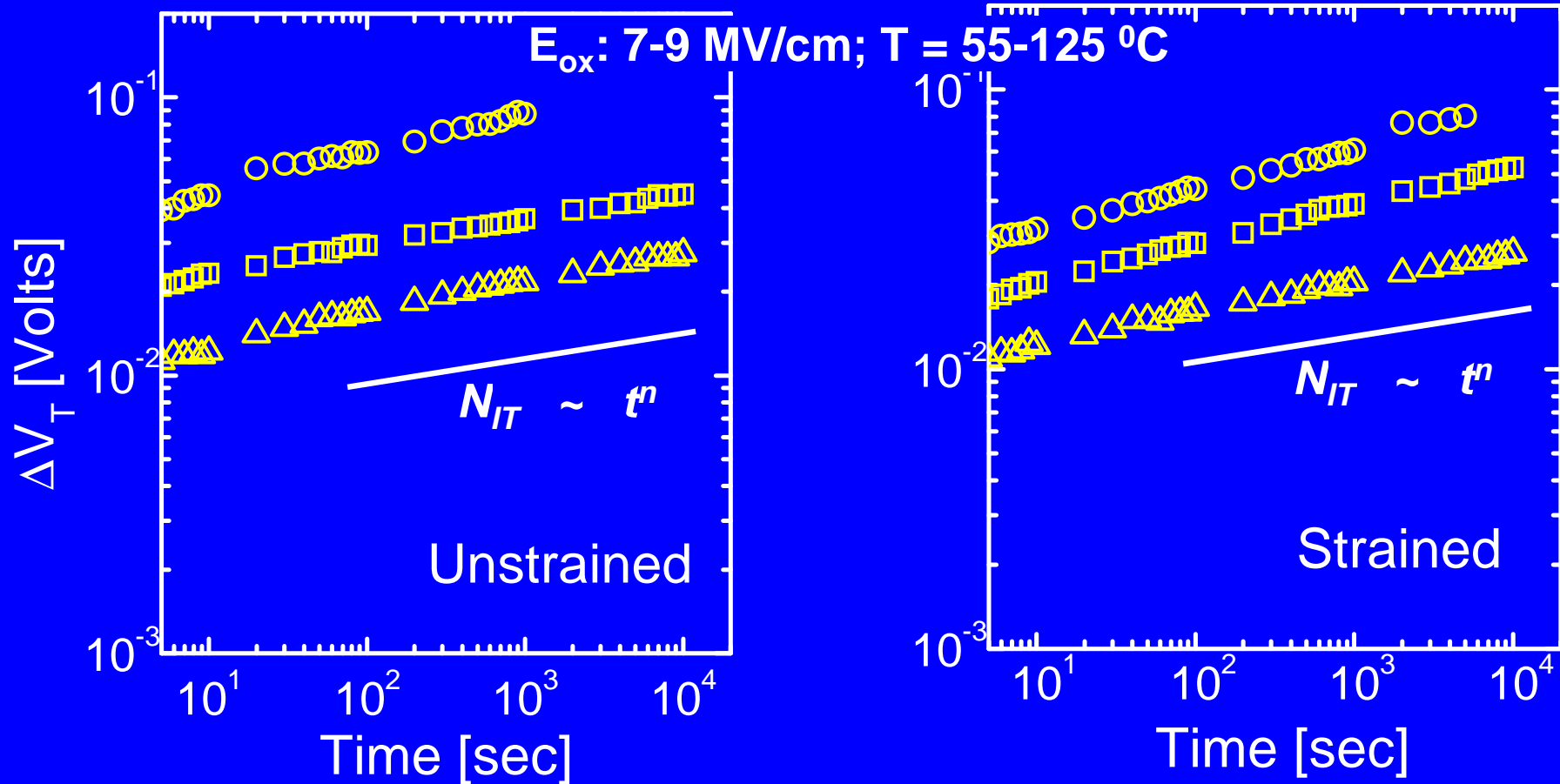
- Reaction-Diffusion Model

$$N_{IT} \sim [E_C N_0 P_T \exp(\gamma E_{ox})]^{2/3} \exp(-E_A/k_B T) t^n$$

- Strain dependence of N_{IT}
- Effect of N_{IT} & strain on I_D
- Conclusion

Time Exponent: Strain Dependence

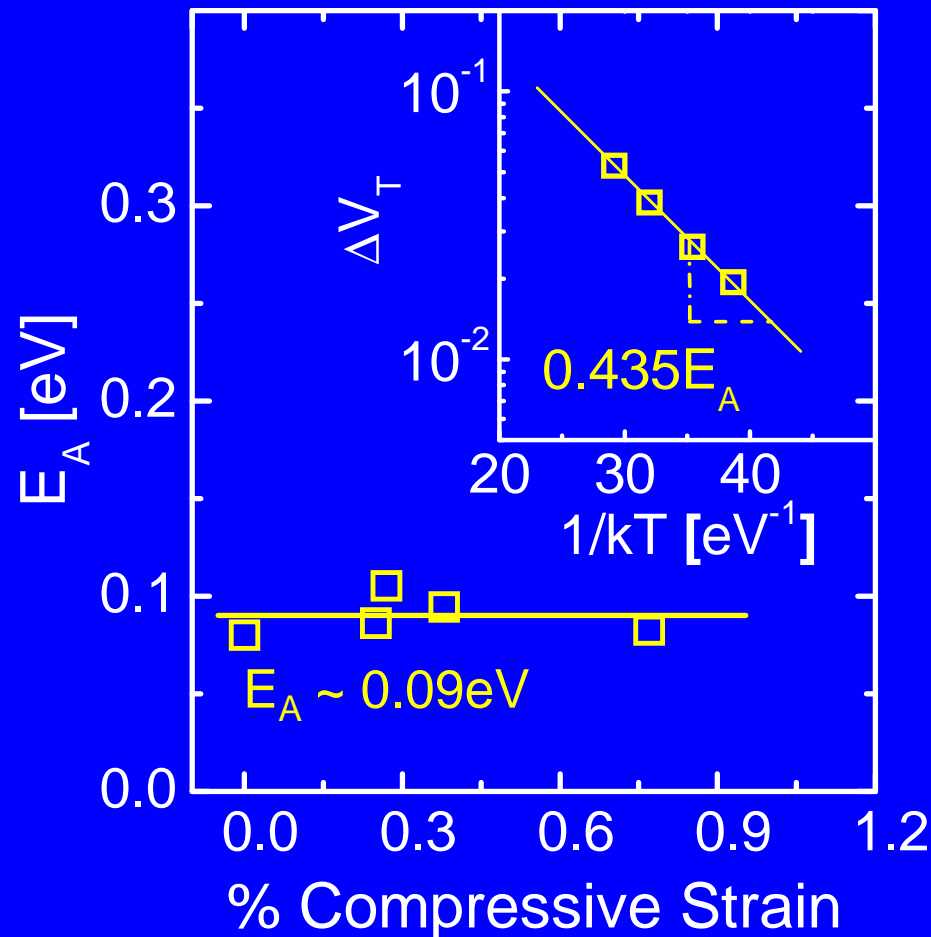
On-the-fly $I_{D,lin}$ Measurement



$$N_{IT} \sim [E_C N_0 P_T \exp(\gamma E_{ox})]^{2/3} \exp(-E_A/k_B T) t^n$$

Strain Invariant $n \sim 0.14$

Activation Energy: Strain Dependence

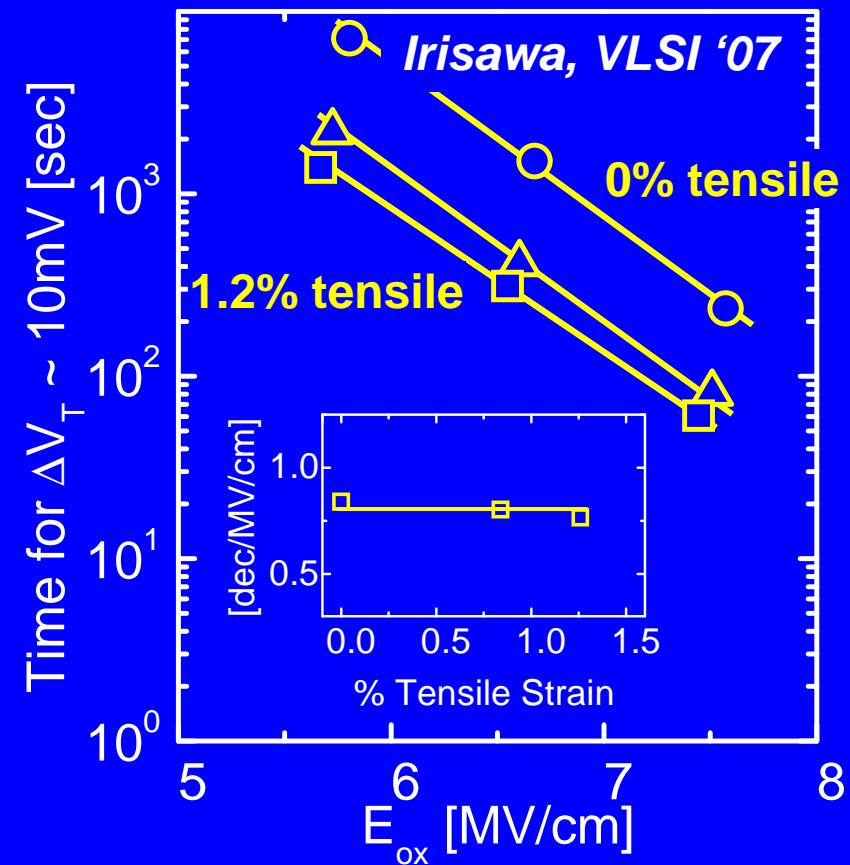
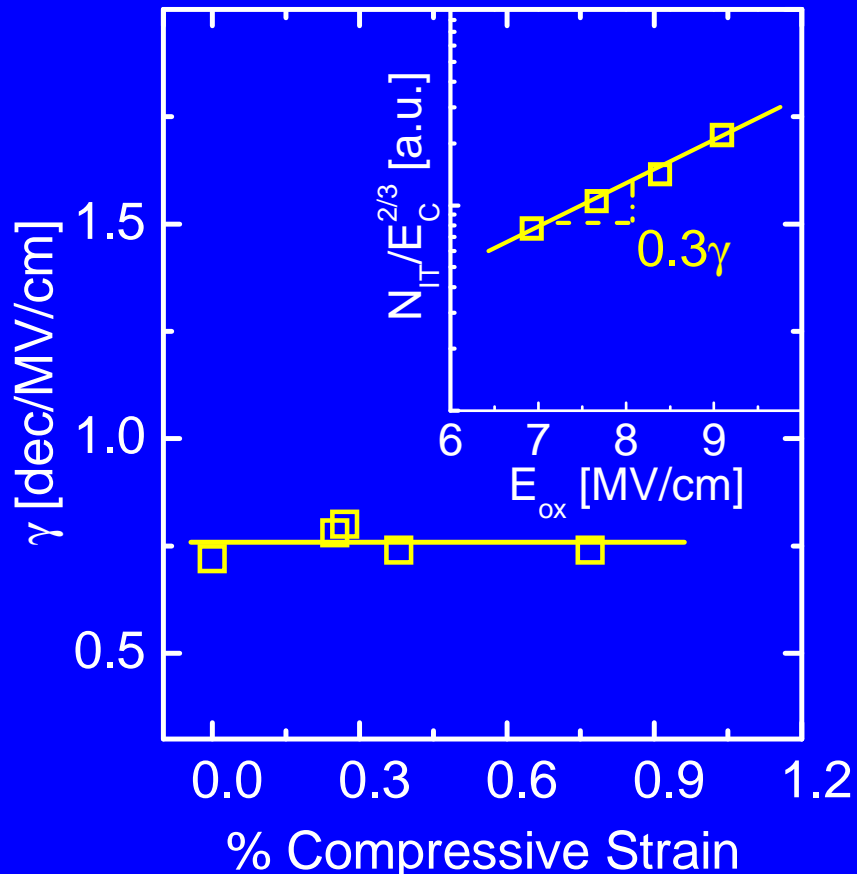


Similar observation for
TENSILE STRAIN in *Irisawa, VLSI '07*;
Shih, IRPS '05

$$N_{IT} \sim [E_C N_0 P_T \exp(\gamma E_{ox})]^{2/3} \exp(-E_A/k_B T) t^n$$

Strain Invariant E_A

Field Acceleration: Strain Dependence

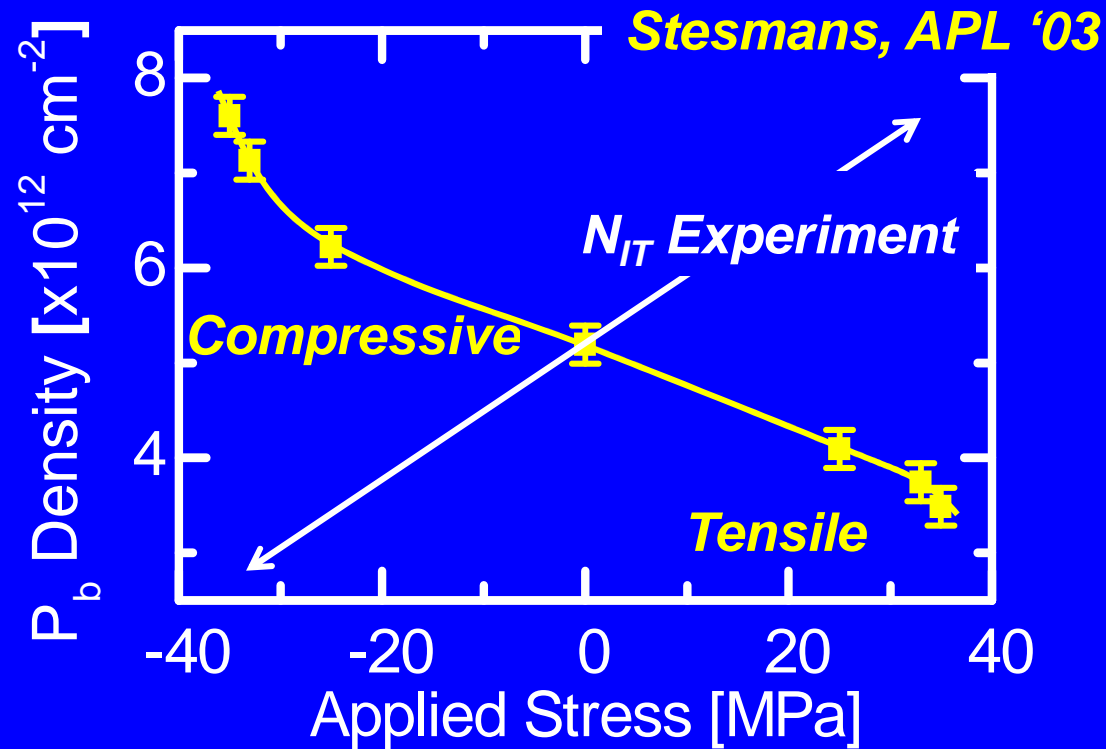


$$N_{IT} \sim [E_C N_0 P_T \exp(\gamma E_{ox})]^{2/3} \exp(-E_A/k_B T) t^n$$

γ is strain invariant

Strain Dependence of N_{IT}

$$N_{IT} \sim [E_C N_0 P_T \exp(\gamma E_{ox})]^{2/3} \exp(-E_A/k_B T) t^n$$



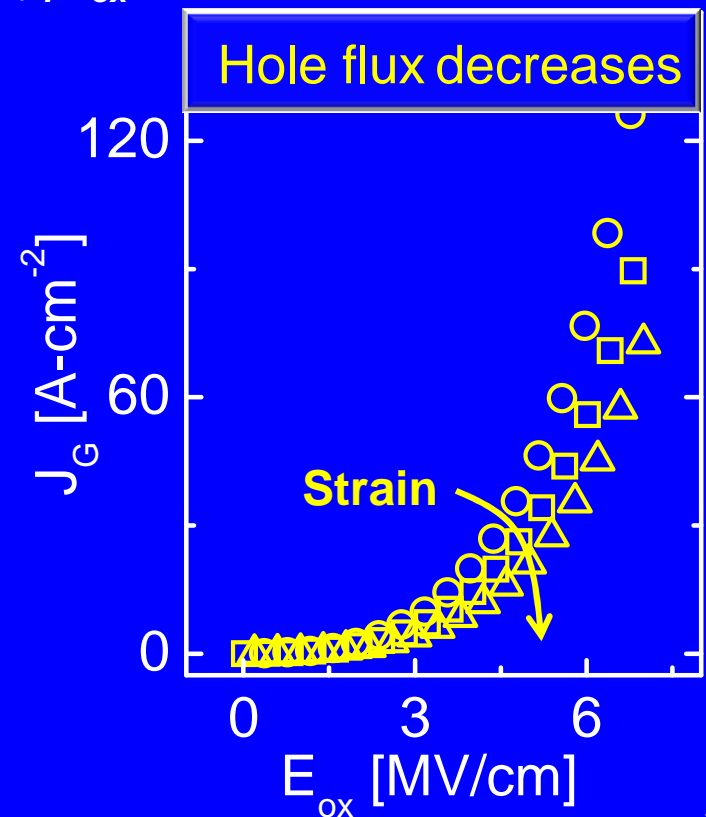
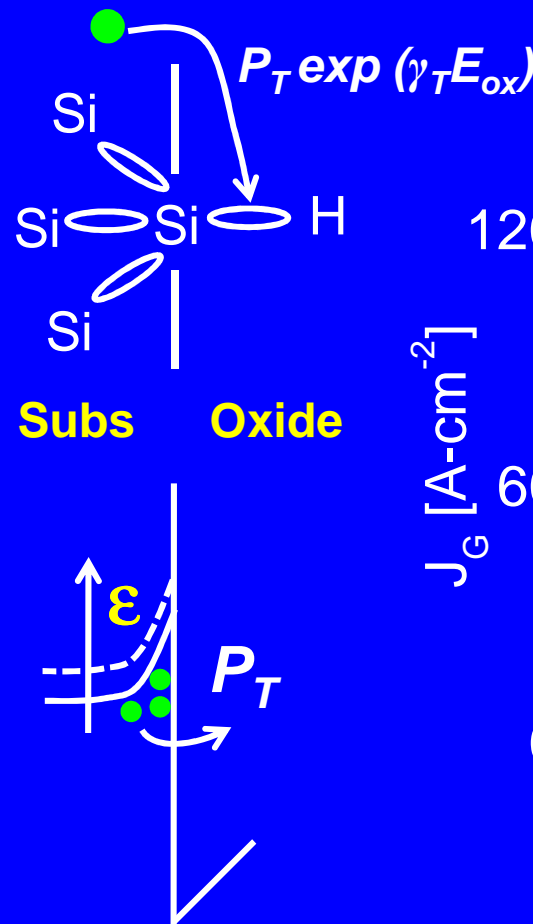
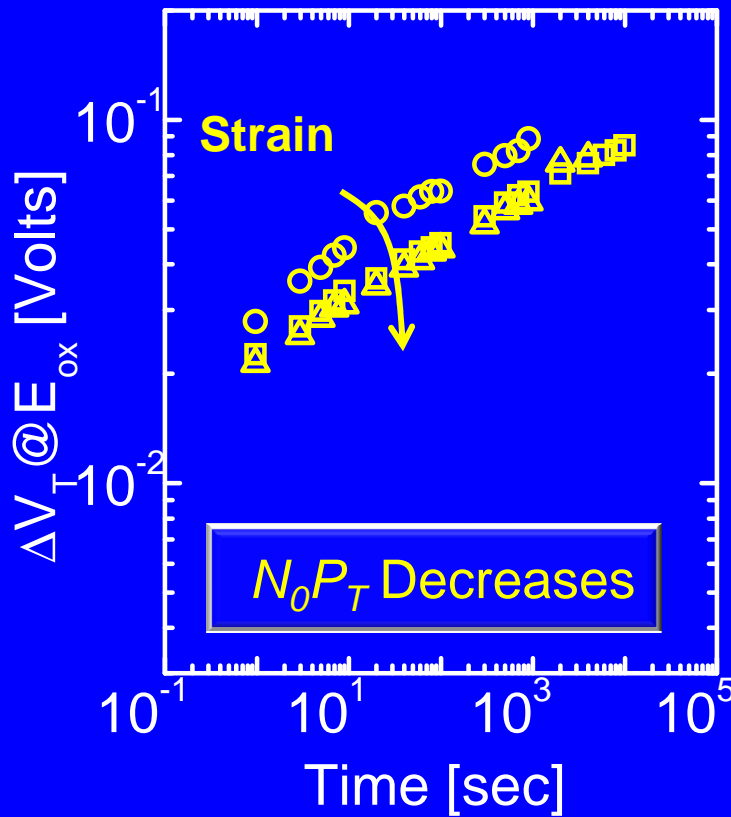
- Strain:
- ❑ Same type of dangling bond
 - ❑ SiH Precursor (N_0) can't explain N_{IT}

N_{IT} : Compressive Strain

$$N_{IT} \sim [E_C N_0 P_T \exp(\gamma E_{ox})]^{2/3} \exp(-E_A/k_B T) t^n$$

Compressive Strain:

- Same n, γ, E_A
- N_0 increases

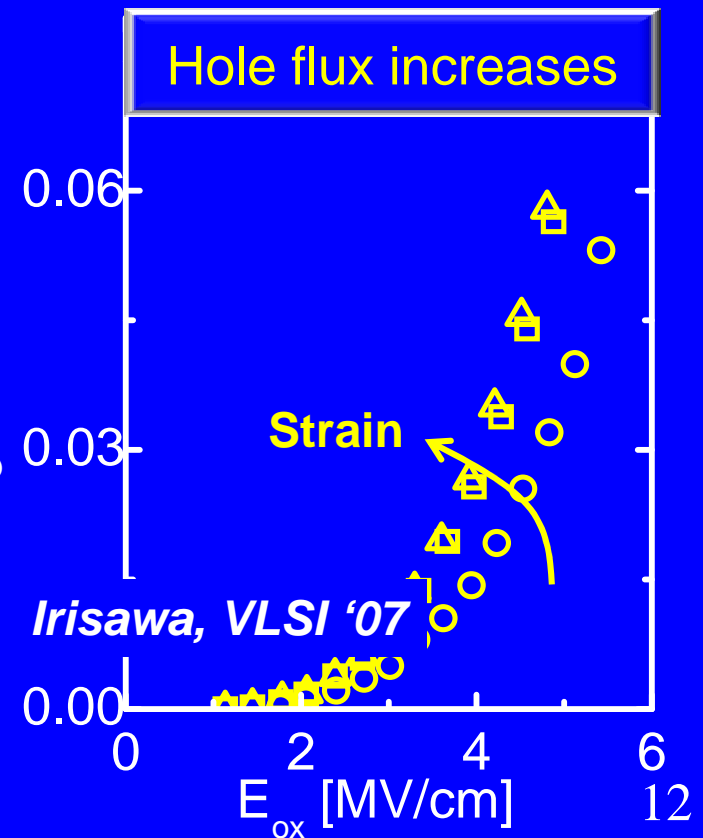
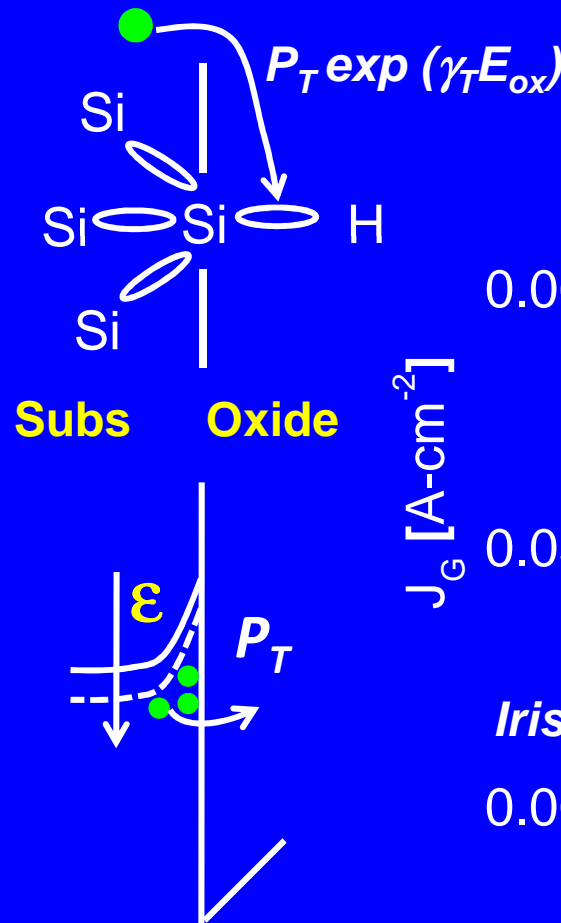
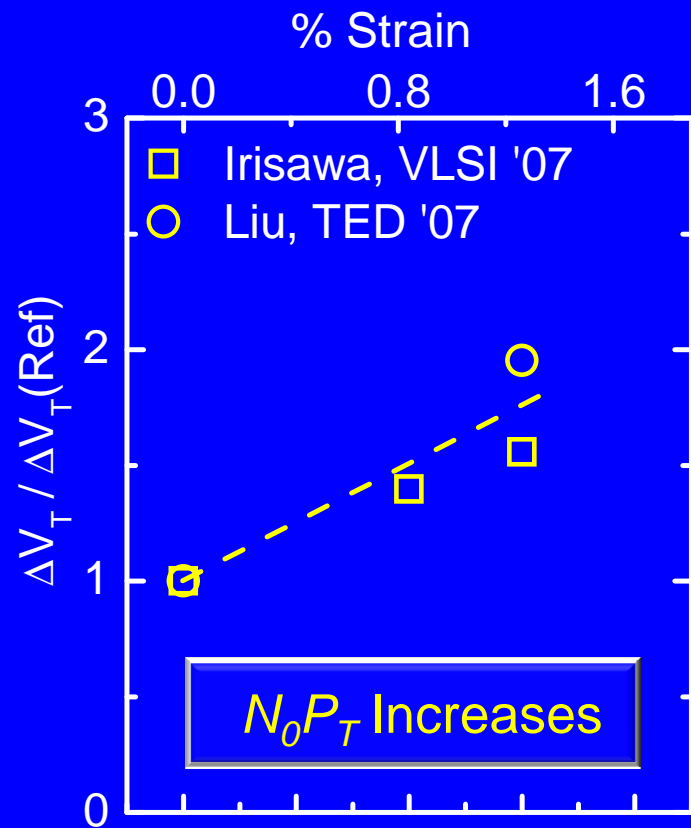


N_{IT} : Tensile Strain

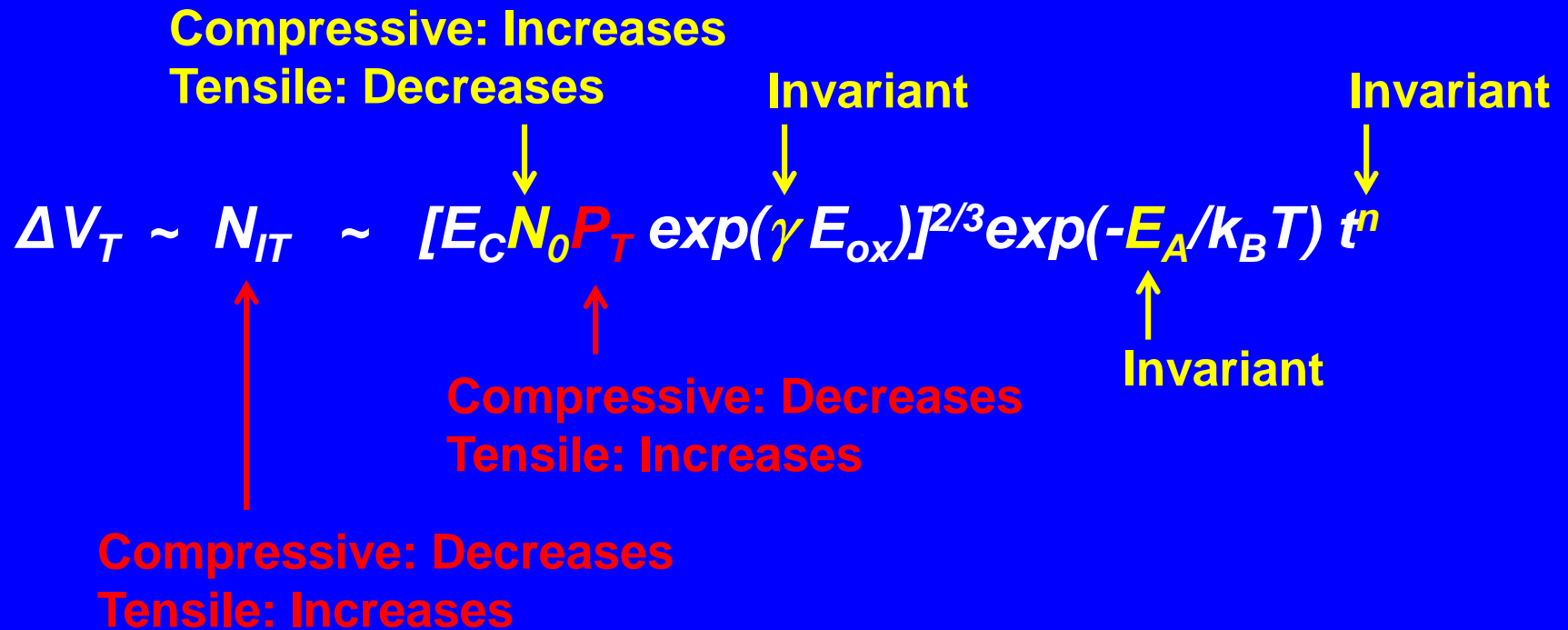
$$N_{IT} \sim [E_C N_0 P_T \exp(\gamma E_{ox})]^{2/3} \exp(-E_A/k_B T) t^n$$

Tensile Strain:

- Same n, γ, E_A
- N_0 decreases



Summary: Strain Dependence of N_{IT}

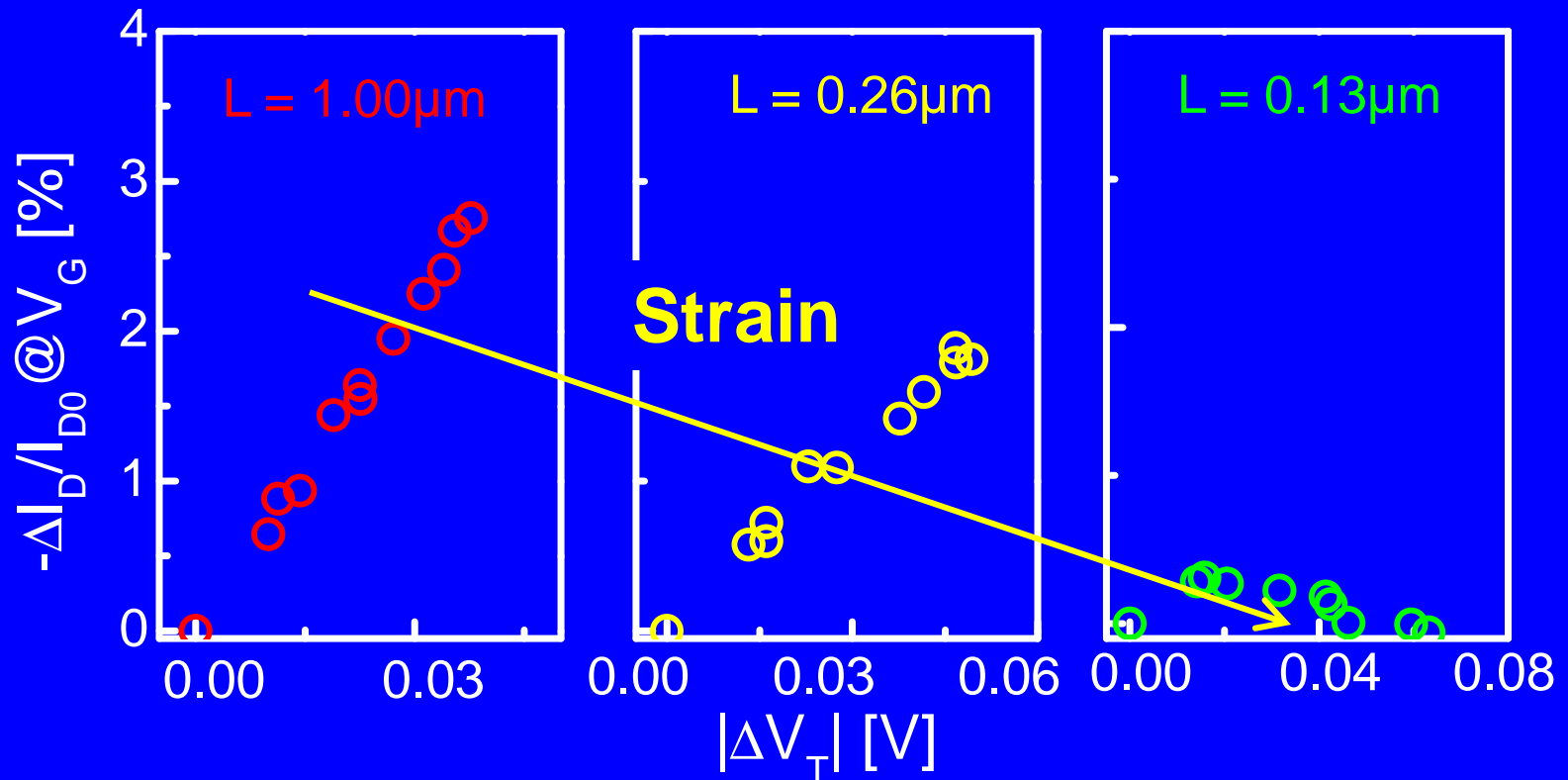
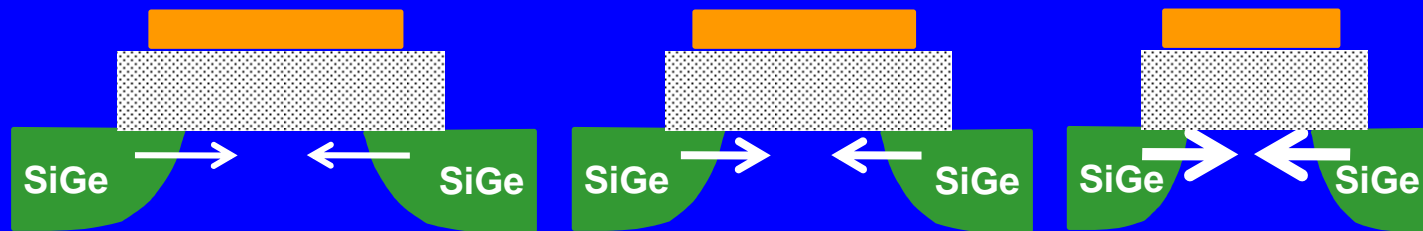


What is the impact on I_D Degradation?

$$I_D \sim \mu_{eff} (V_G - V_T)$$

I_D should decrease ($\Delta I_D < 0$) with N_{IT}

Strain Dependence of ΔI_D



$$I_D \sim \mu_{\text{eff}} (V_G - V_T)$$

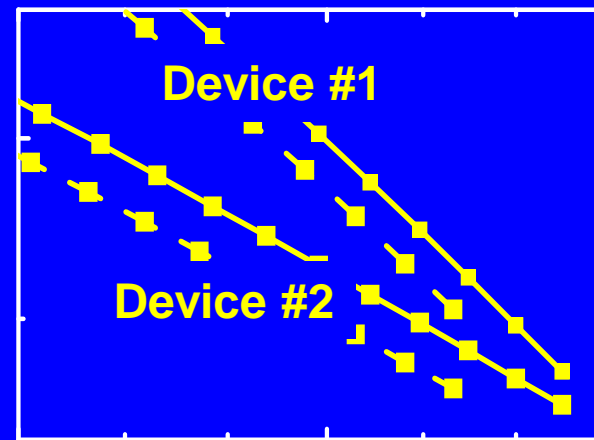
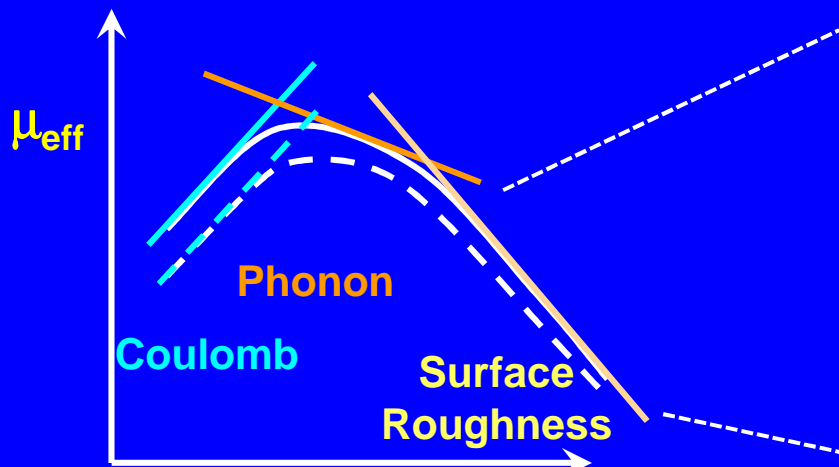
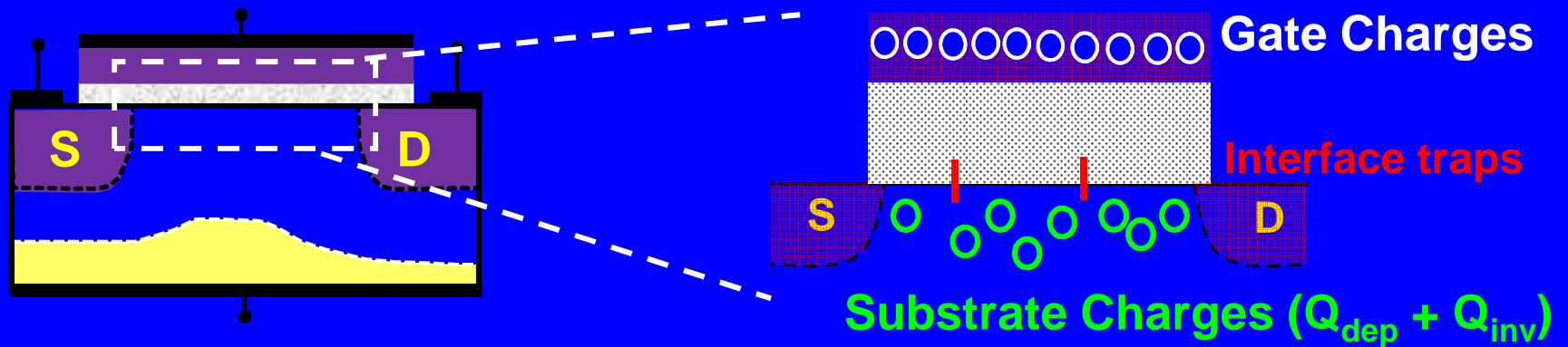
I_D should decrease ($\Delta I_D < 0$) with N_{IT}

N_{IT} -induced I_D Degradation

$$I_D \sim \mu_{eff} (V_G - V_T)$$

$$\frac{\Delta I_D}{I_{D0}} \sim \frac{\Delta \mu_{eff}}{\mu_{eff0}} - \frac{\Delta V_T}{V_G - V_{T0}}$$

$$\Delta V_T = \frac{qN_{IT}}{C_{ox}}$$



Takagi, TED '94

$$E_{eff} \sim Q_{dep} + \eta Q_{inv}$$

E_{eff} [a.u.]

N_{IT} -induced I_D Degradation

$$I_D \sim \mu_{eff} (V_G - V_T)$$

$$\frac{\Delta I_D}{I_{D0}} \sim \frac{\Delta \mu_{eff}}{\mu_{eff0}} - \frac{\Delta V_T}{V_G - V_{T0}}$$

$$\Delta V_T = \frac{qN_{IT}}{C_{ox}}$$

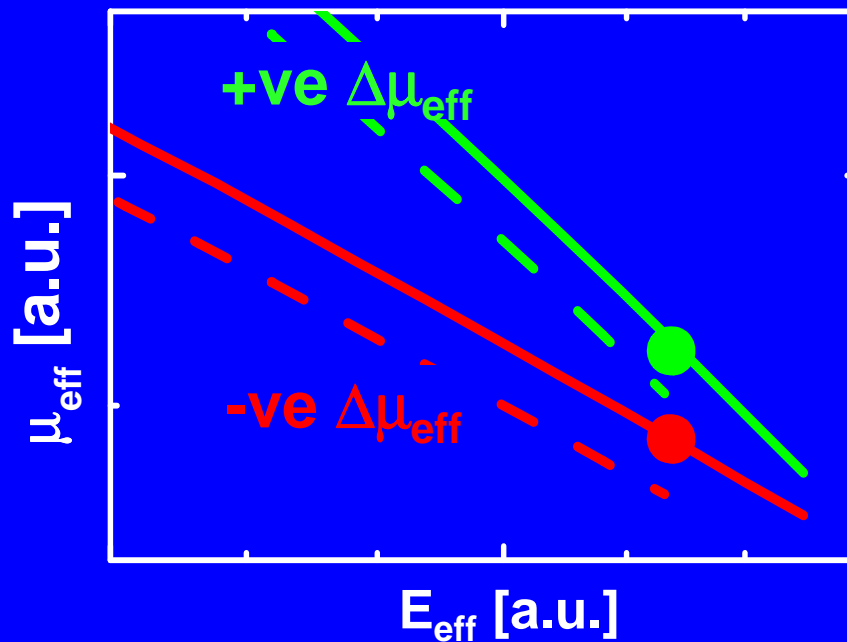
N_{IT} Generation

- Increases $|V_T|$

- Decreases μ_{eff} @ E_{eff}

- Decreases $E_{eff} \sim (V_G - V_T)$

} $\Delta \mu_{eff}$ @ V_G



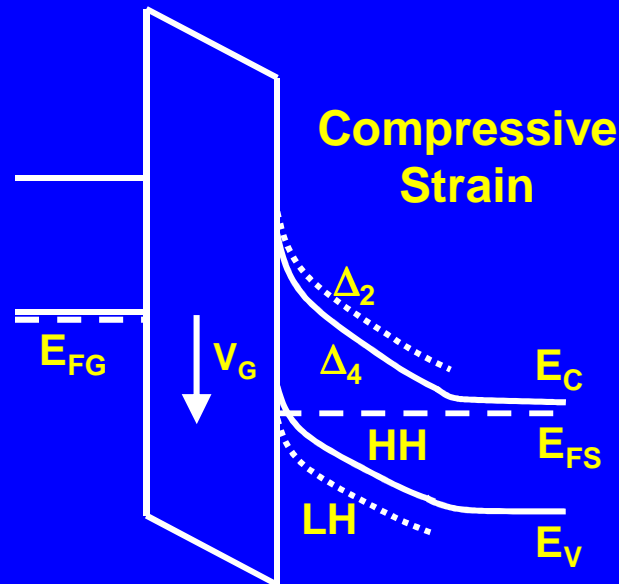
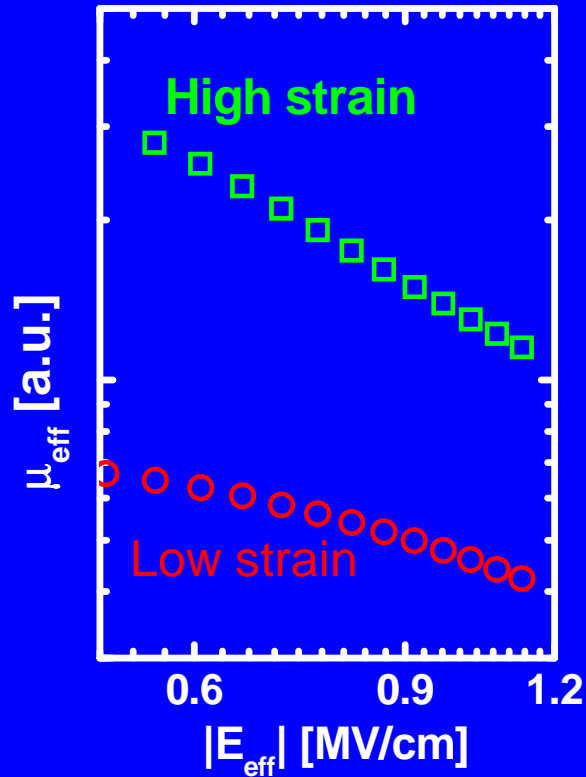
$\Delta \mu_{eff}$ @ V_G : Depends on $\mu_{eff} - E_{eff}$ steepness

Strain Dependence of ΔI_D

$$I_D \sim \mu_{\text{eff}} (V_G - V_T)$$

$$\frac{\Delta I_D}{I_{D0}} \sim \frac{\Delta \mu_{\text{eff}}}{\mu_{\text{eff}0}} - \frac{\Delta V_T}{V_G - V_{T0}}$$

$$\Delta V_T = \frac{qN_{IT}}{C_{\text{ox}}}$$



At low E_{eff} :
Reduced inter-valley scattering

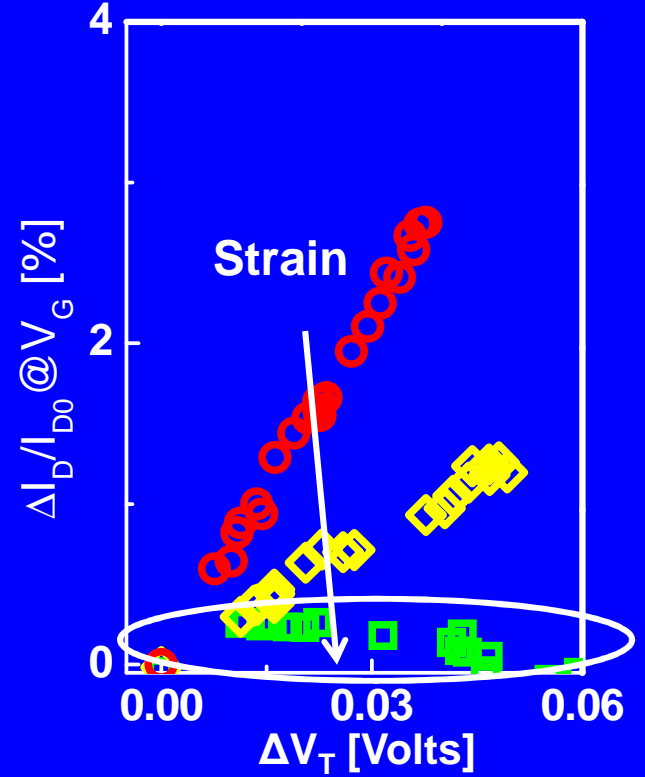
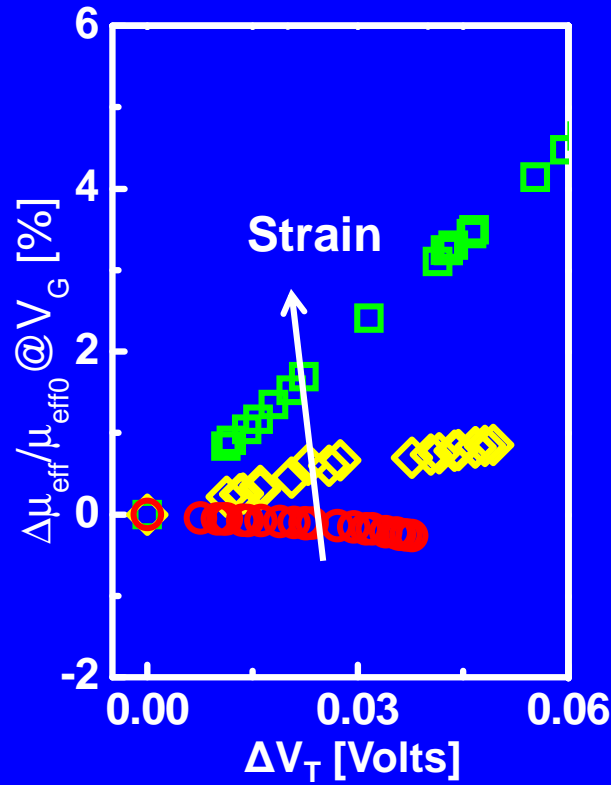
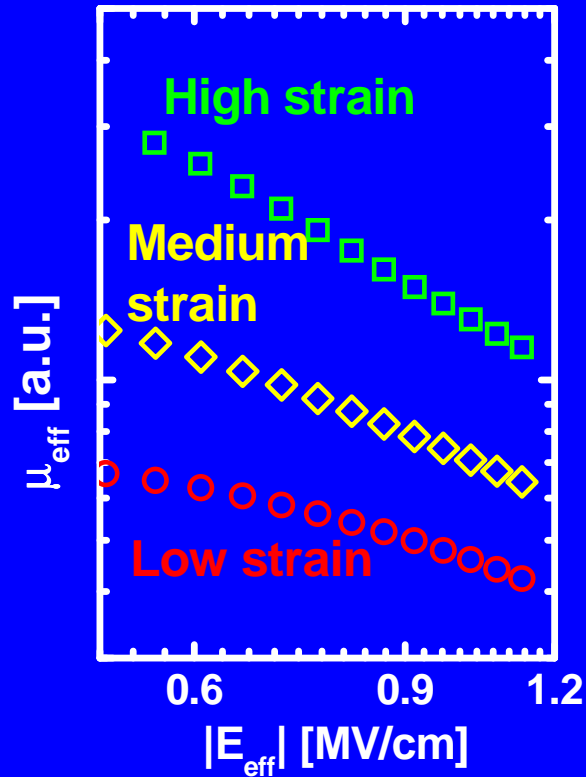
At high E_{eff} :
Surface roughness scattering

Strain Dependence of ΔI_D

$$I_D \sim \mu_{\text{eff}} (V_G - V_T)$$

$$\frac{\Delta I_D}{I_{D0}} \sim \left(\frac{\Delta \mu_{\text{eff}}}{\mu_{\text{eff}0}} \right) \frac{\Delta V_T}{V_G - V_{T0}}$$

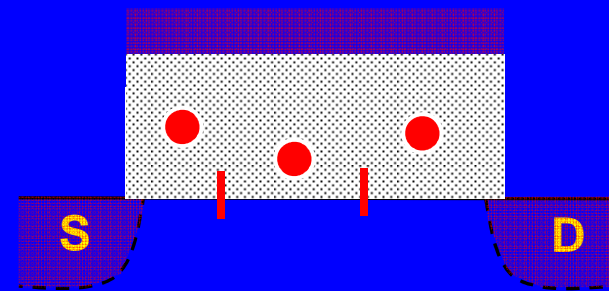
$$\Delta V_T = \frac{qN_{IT}}{C_{\text{ox}}}$$



I_D Degradation-compensated

Conclusion

- **Strain dependence of N_{IT}**
 - SiH Precursor plays negligible role
 - Depends mainly on hole tunneling rate
 - Tensile ($N_{IT}\uparrow$) Compressive ($N_{IT}\downarrow$)
- **Sufficient strain improves $\mu_{eff}(N_{IT}) \rightarrow$ Reduced ΔI_D**
 - Reduce NBTI being a concern
- **Resilient to variations!!**



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