Negative Bias Temperature Instability (NBTI) in p-MOSFETs: Characterization, Material/Process Dependence and Predictive Modeling (Part 2 of 3)

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Outline

Introduction, Basic NBTI signatures

Fast / Ultra-fast drain current degradation measurement

Estimation of pre-existing and generated defects

} Part - I

Transistor process / material dependence

Role of Nitrogen – Study by Ultrafast measurement

} Part - II

Predictive modeling

Conclusions / outlook

} Part - III

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Fast / Ultra-fast drain current degradation measurement

Estimation of pre-existing and generated defects

Transistor process / material dependence

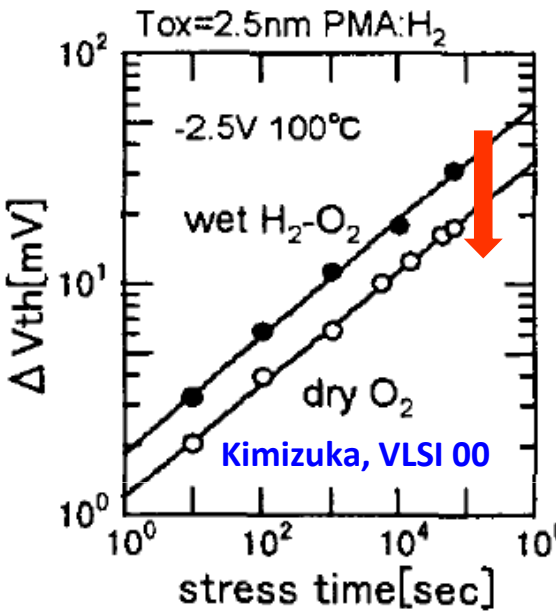
Hydrogen / water
Nitrogen
Fluorine

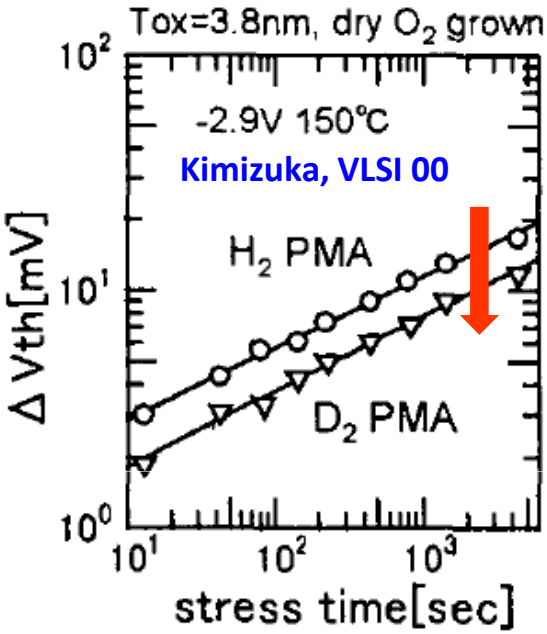
Role of Nitrogen – Study by Ultrafast measurement

Predictive modeling

Conclusions / outlook

Impact of Oxide Type and PMA

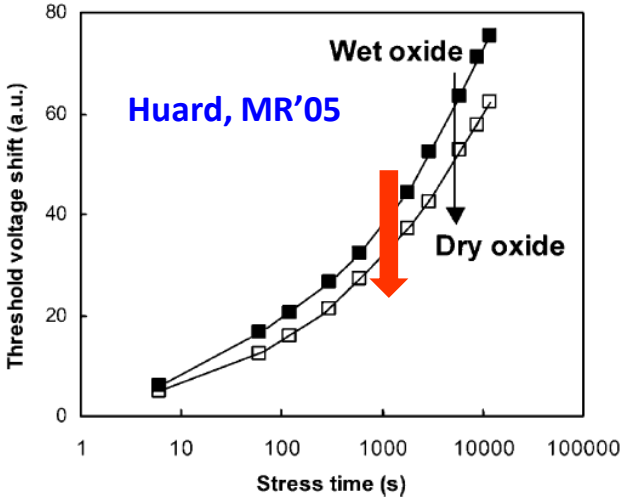


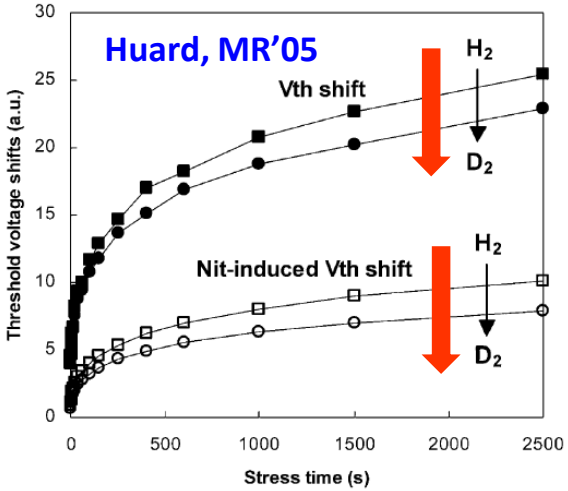


Lower NBTI for dry oxide due to lower water content

Lower NBTI for oxides with D_2 PMA

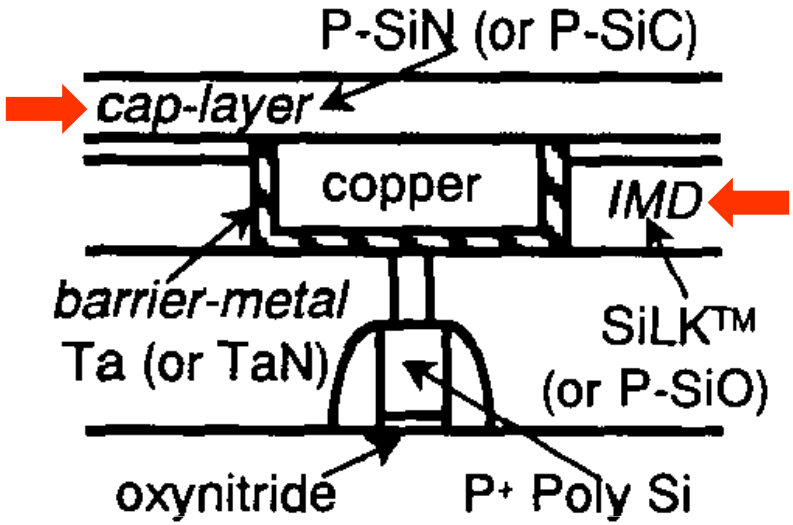
Lower interface trap generation for oxides with D_2 PMA

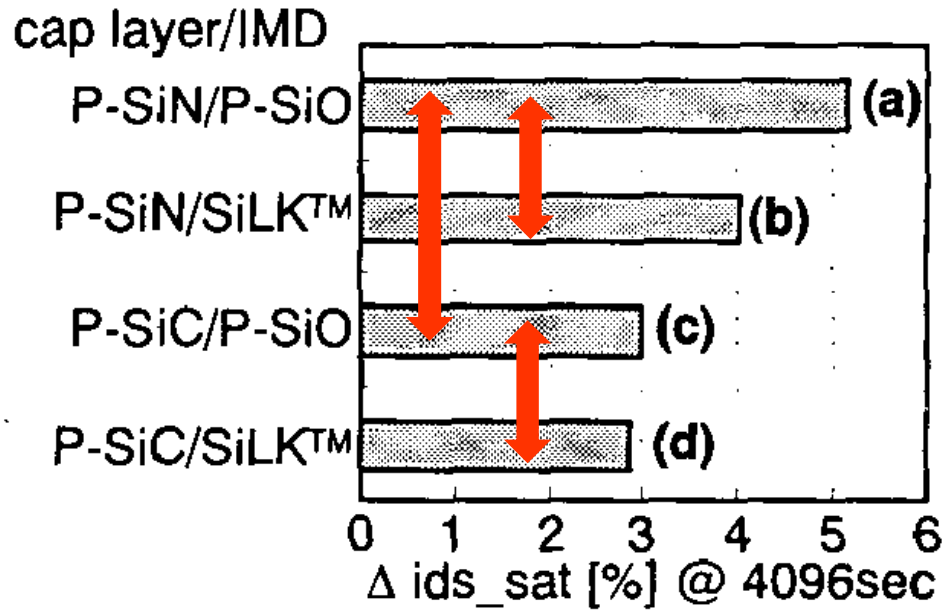




Impact of interface trap generation and role of hydrogen

Impact of Backend Processes





Suzuki, VLSI'02

Higher NBTI for P-SiN w.r.t P-SiC cap

Higher NBTI for P-SiO IMD w.r.t SiLK IMD for P-SiN cap layer

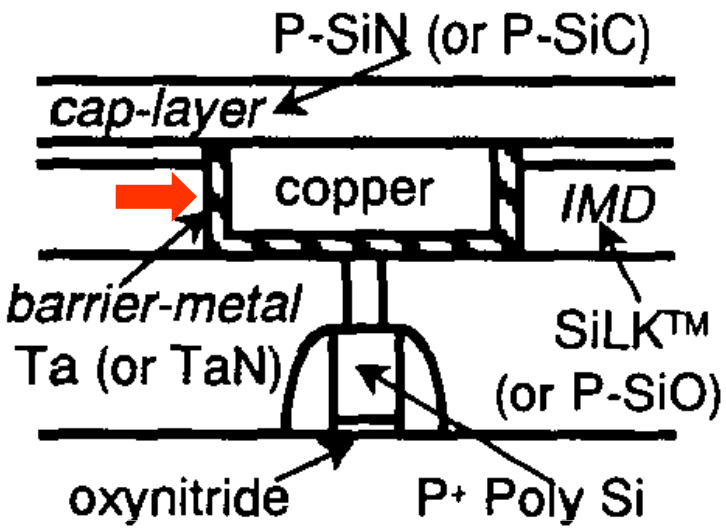
Similar NBTI for P-SiO IMD w.r.t SiLK IMD for P-SiC cap layer

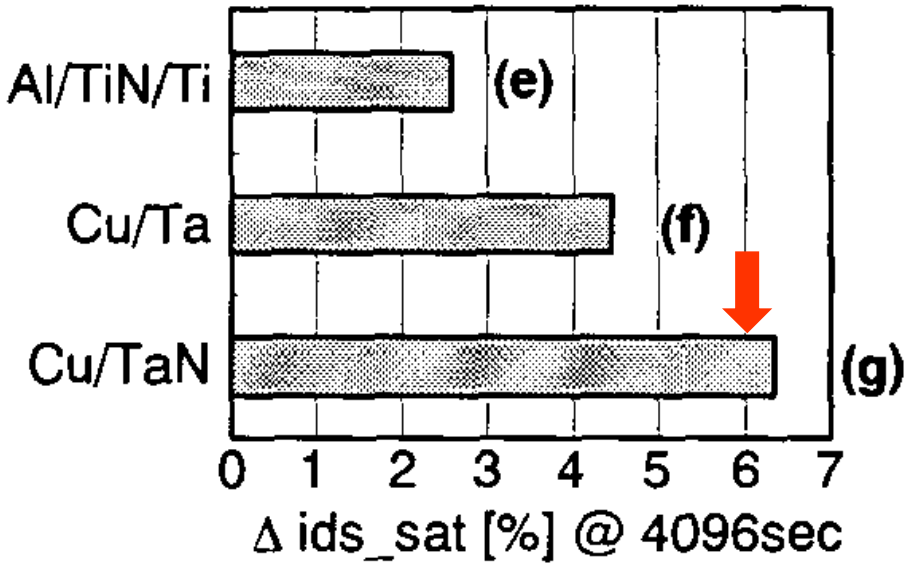
Higher water content in P-SiO compared to SiLK IMD (from TDS)

Water cannot escape to upper layers for P-SiN cap, goes down to SiON gate stack causing higher NBTI for P-SiO IMD

Escape of water to upper layers for P-SiC cap, lower NBTI

Impact of Backend Processes

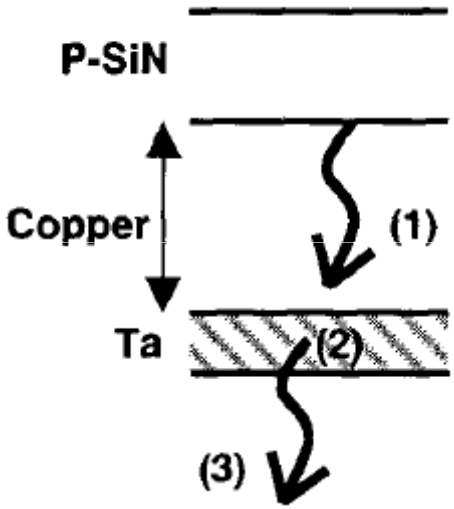




Suzuki, VLSI'02

Different barrier metals, P-SiN cap and SiLK IMD (small water content)

Large NBTI for TaN barrier metal



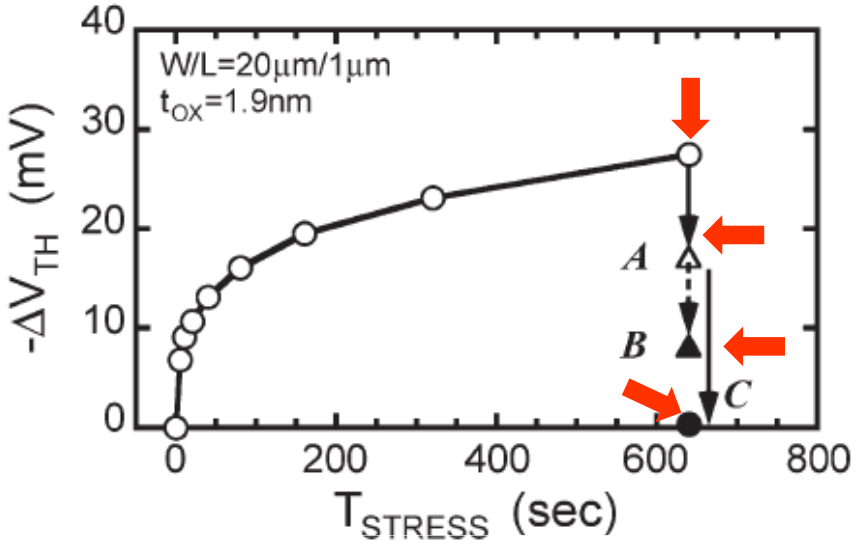
H_2 diffusion during P-SiN deposition via Cu to barrier

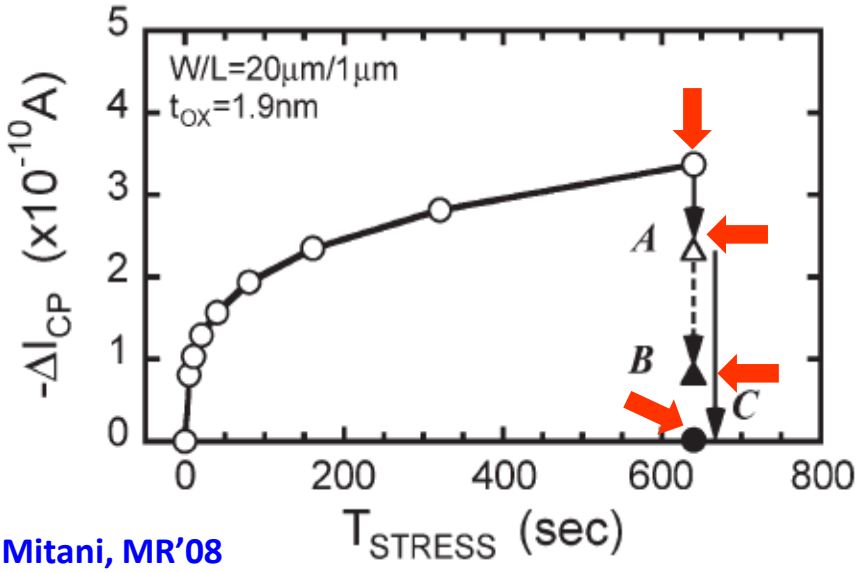
H_2 desorption during PMA and subsequent diffusion to SiON

Largest H_2 content for TaN barrier (SIMS) – highest NBTI

Enhanced NBTI for larger PMA temperature

Role of Hydrogen (NBTI Degradation & Recovery)





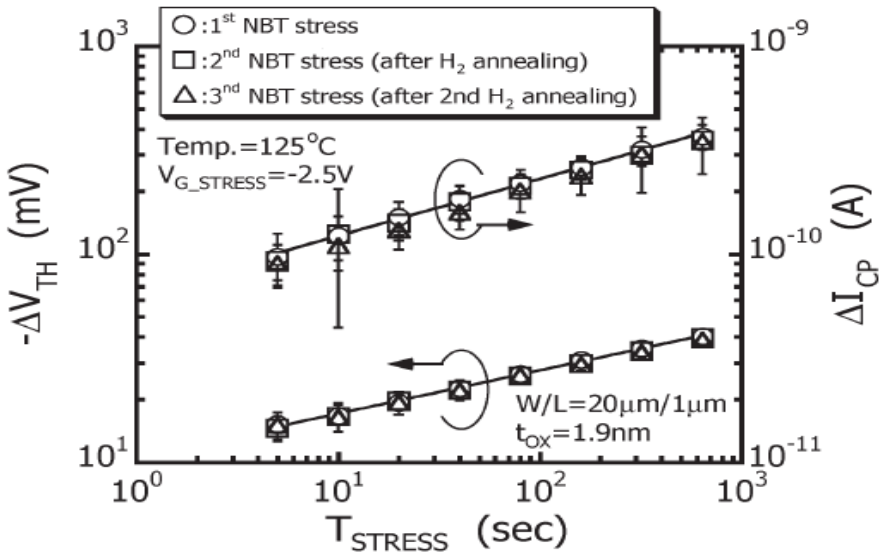
Mitani, MR'08

Degradation: Increase in V_T shift (slow MSM) and CP current

Recovery after stoppage of stress

Recovery after high T anneal in N_2

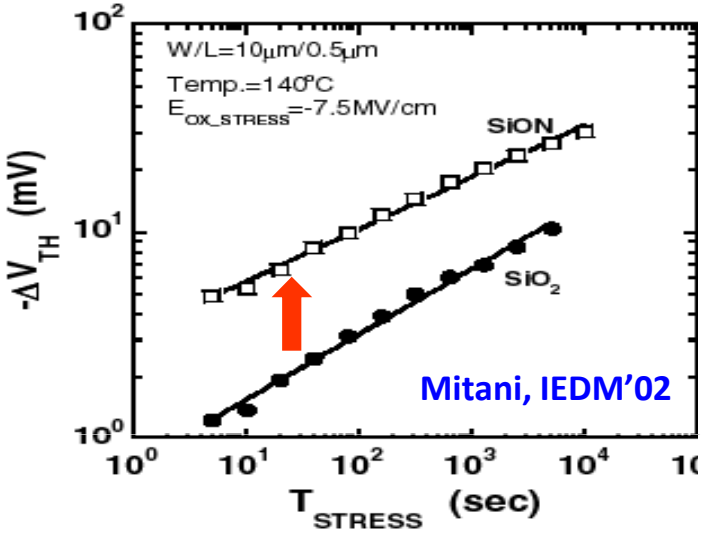
Complete recovery after high T anneal in H_2

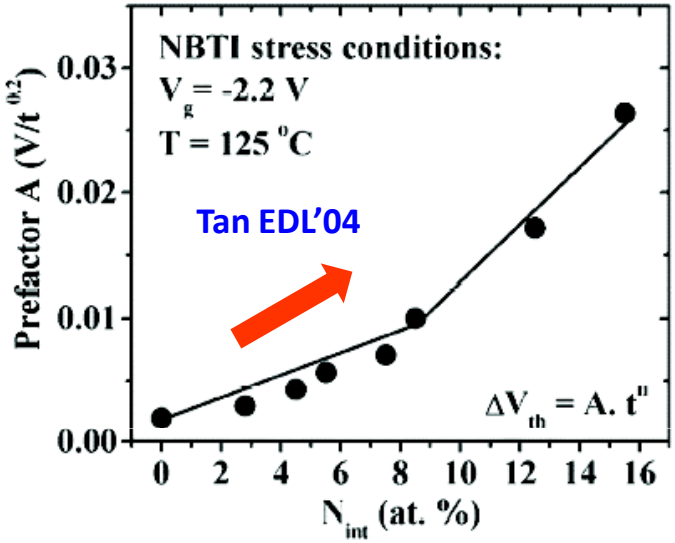


Identical re-degradation rate for ΔV_T and ΔI_{CP} after full recovery

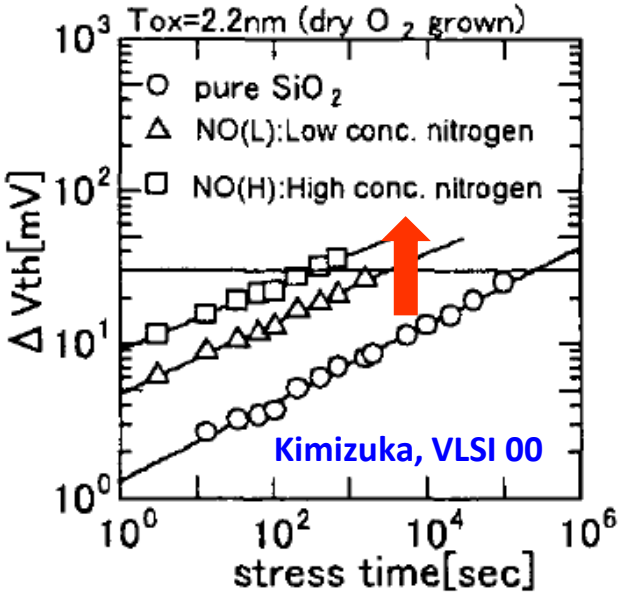
Impact of Nitrogen

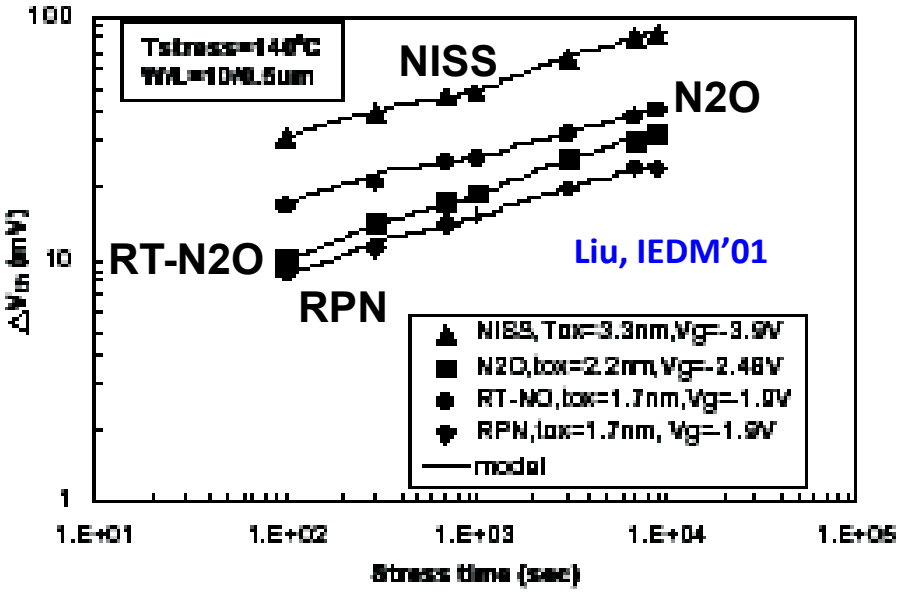
Higher NBTI for nitrided gate oxides → Increases with N_2 content





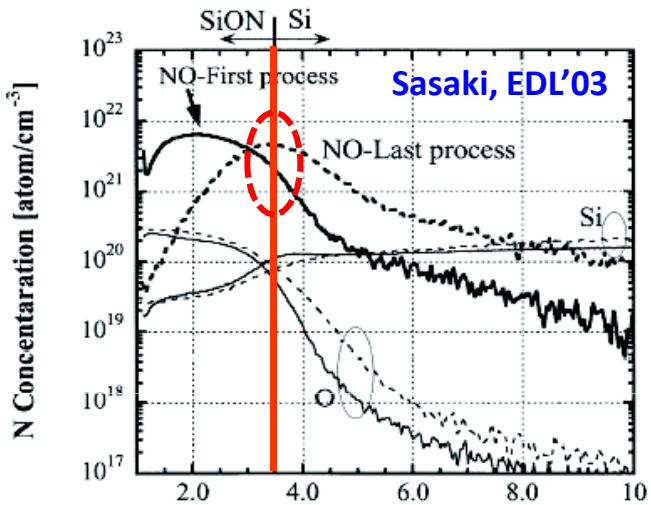
Depends on method of Nitrogen incorporation: NISS > N_2O > RT-N_2O > RPN

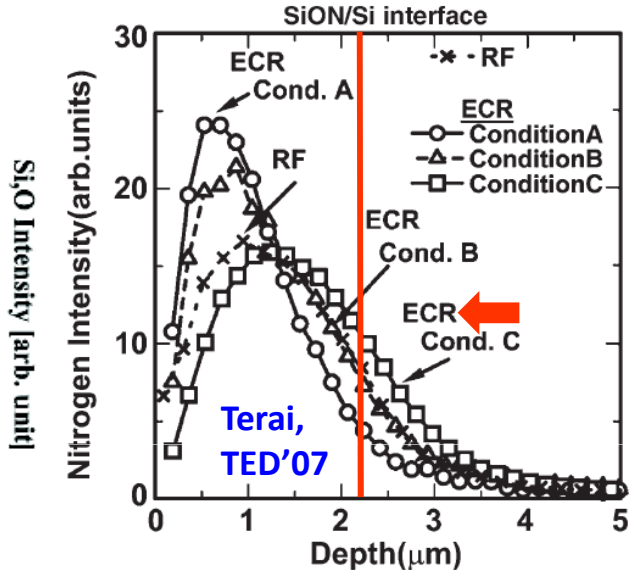


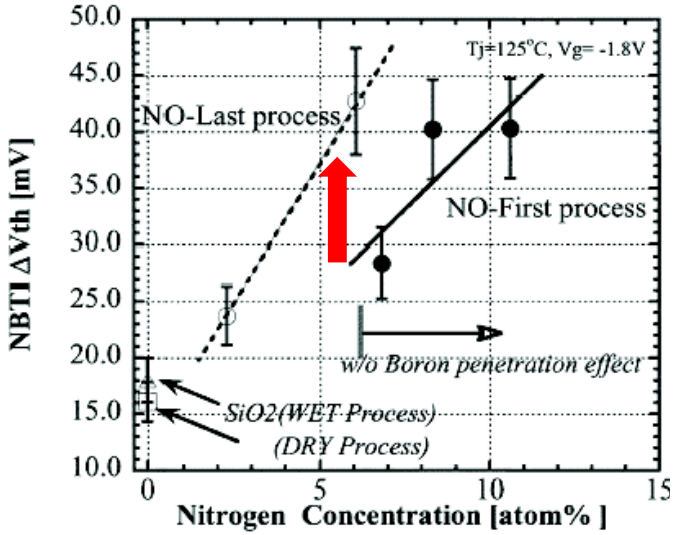


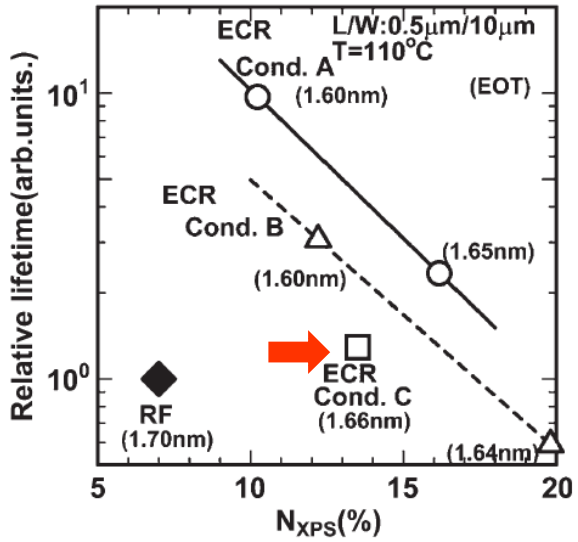
Si/SiON Interfacial N Driven NBTI

Higher Si/SiON N density for NO last process → Higher NBTI









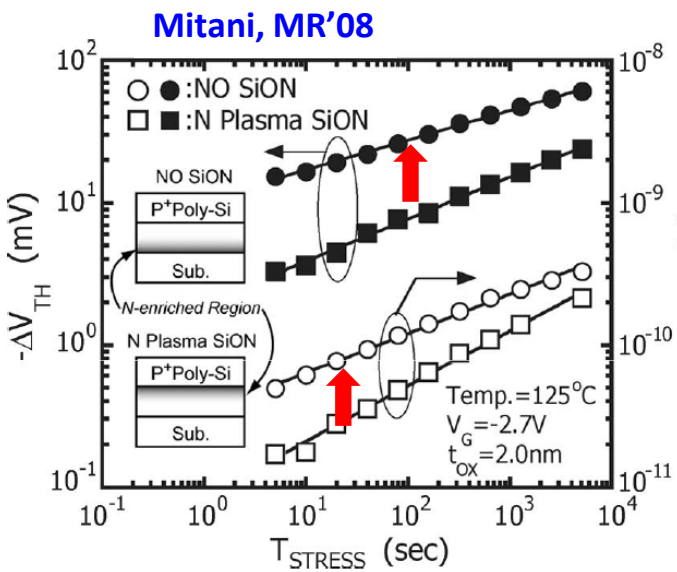
Variation in N density at Si/SiON interface by different Electron Cyclotron Resonance (ECR) plasma N process

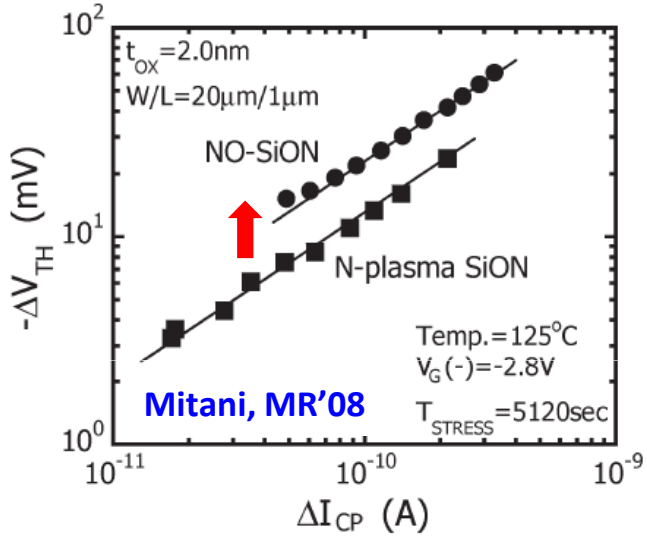
Lower lifetime (higher NBTI) for higher Si/SiON N density (ECR-C)

Role of Nitrogen

NO SiON (Type-B) shows larger V_T shift and trap generation (CP)

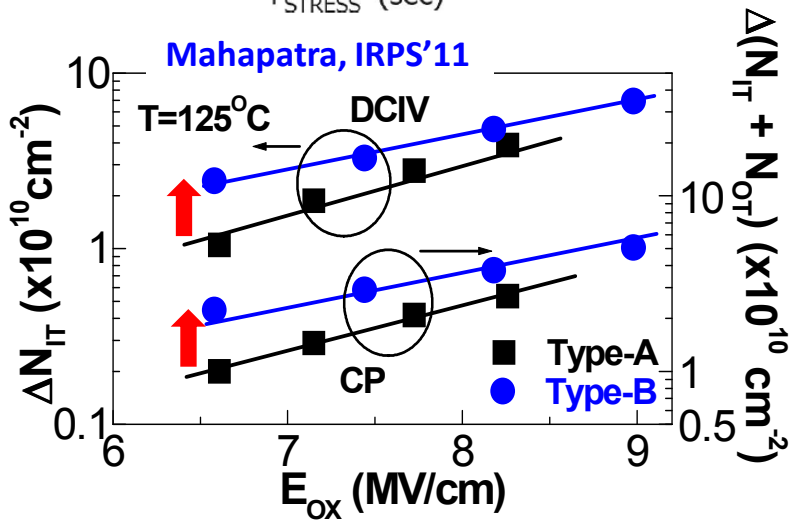
Higher trap generation in Type-B SiON – consistency in CP & DCIV data

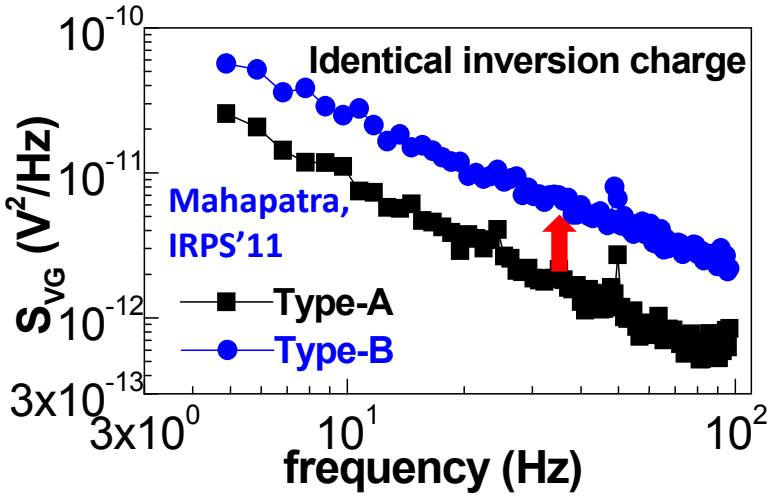




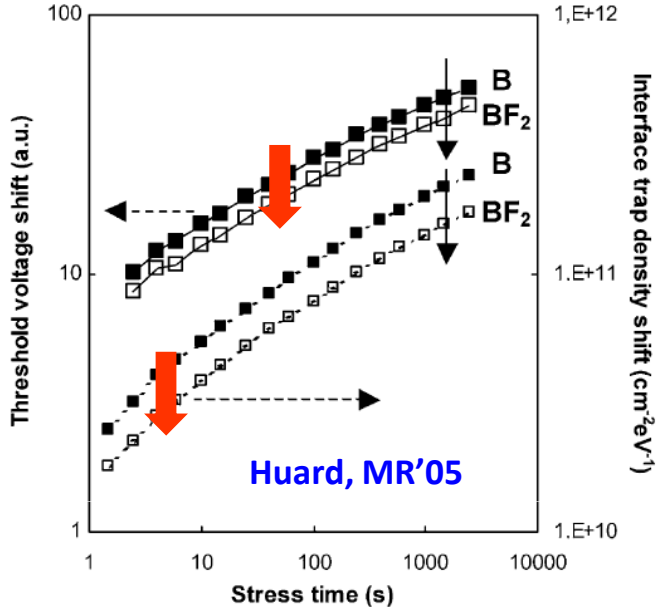
Larger V_T shift for a given trap generation for NO SiON

Larger process related traps for NO-SiON





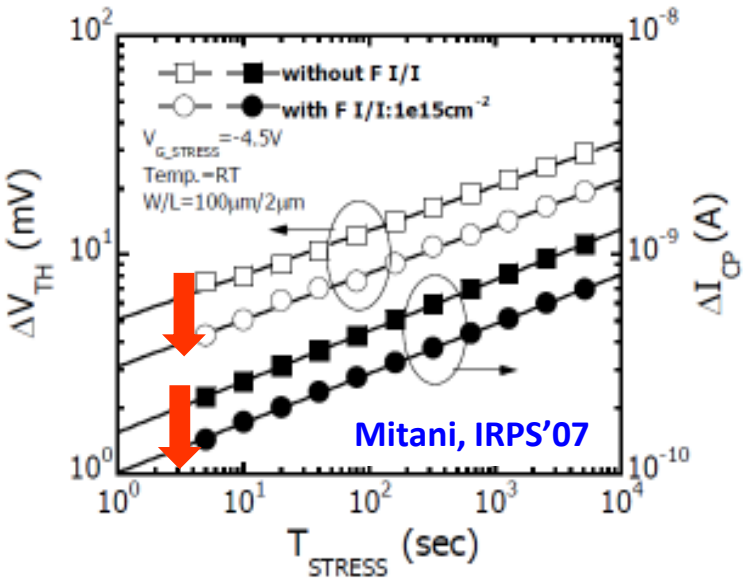
Impact of Fluorine

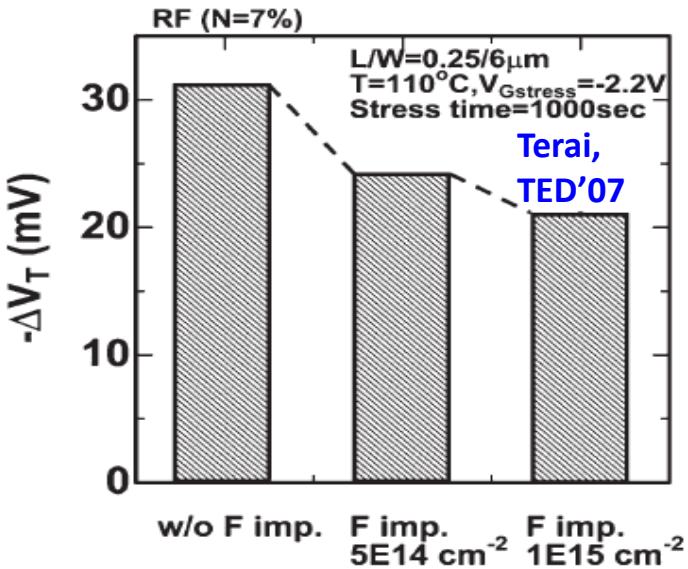


Lower V_T shift and for Fluorine incorporated samples

F incorporation causes reduction in interface trap generation

Higher reduction in NBTI for larger F dose





Summary

Increased NBTI for larger water content in gate dielectric (type of oxidation / incorporation from backend films)

Reduced NBTI for D_2 (w.r.t H_2) PMA samples – lower generation of interface traps

Increased NBTI due to N_2 incorporation in gate stack

- **Increase in trap generation**
- **Increase in trapping in process related traps**

Reduced NBTI due to F incorporation in gate stack

- **Reduction in interface trap generation**

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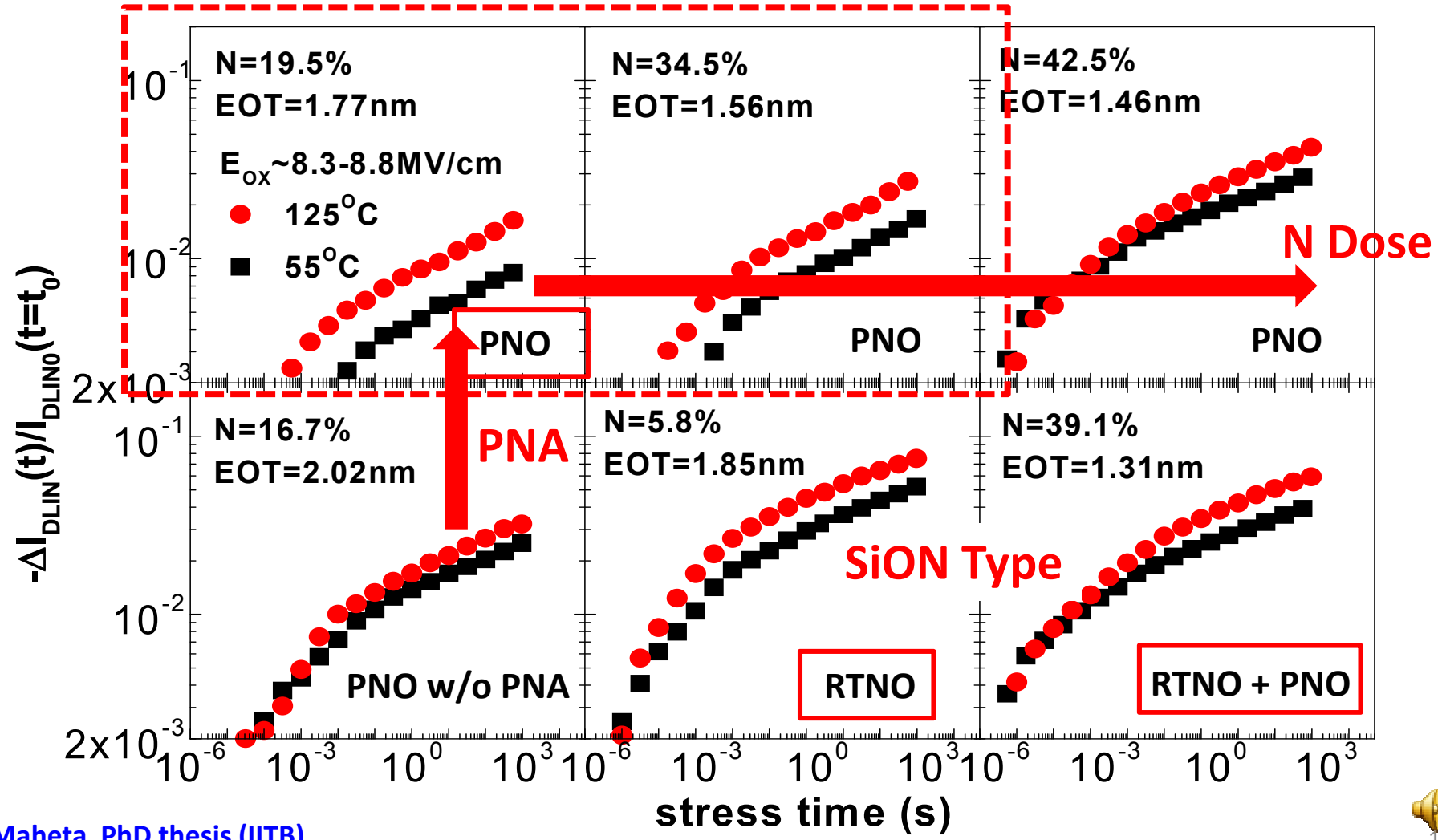
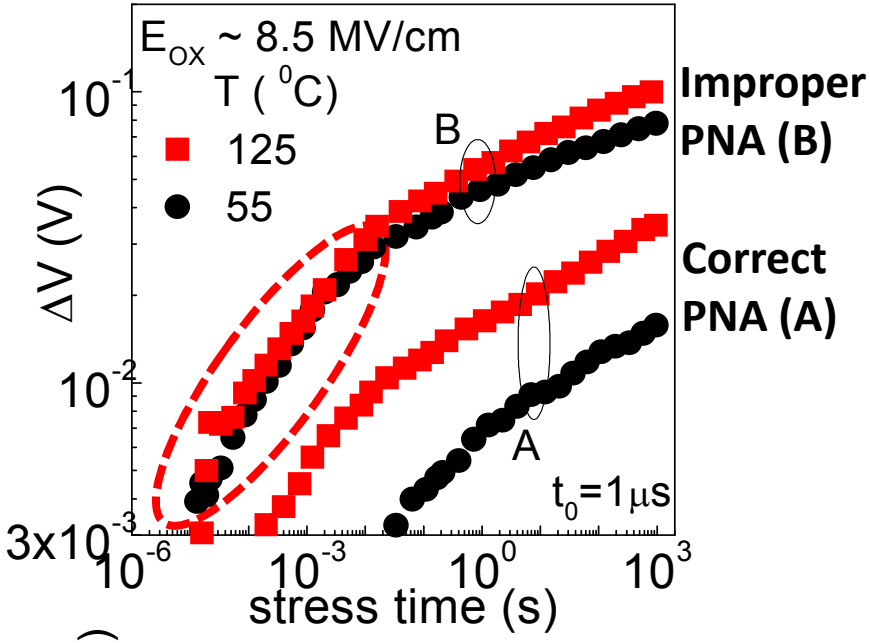
Measured UF-OTF I_{DLIN} Degradation

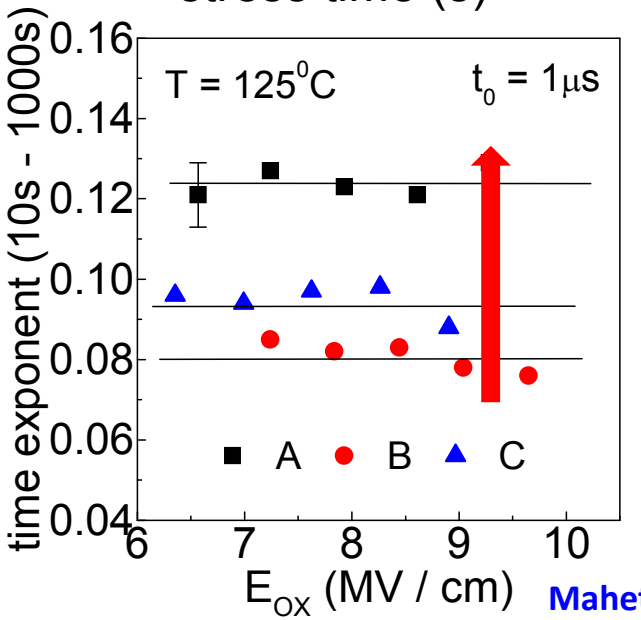
Measured degradation (magnitude, time & T dependence) strongly impacted by SiON gate insulator process



Maheta, PhD thesis (IITB)

PNO: Impact of Post Nitridation Anneal





Maheta, PhD thesis (IITB)

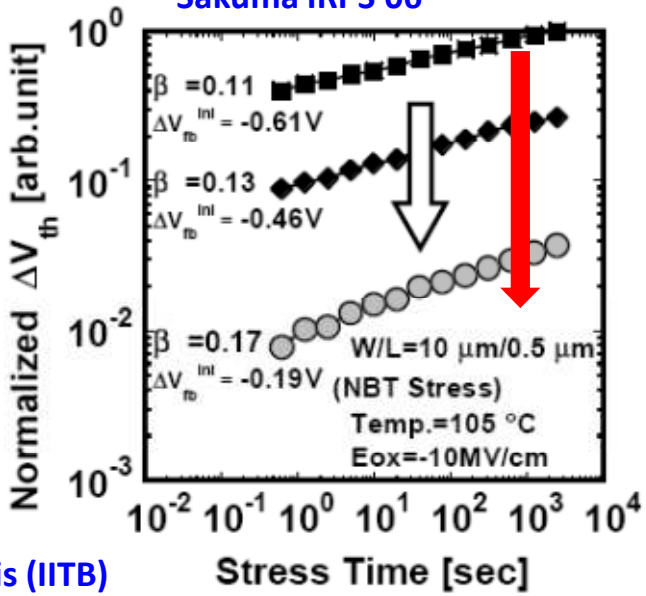
PNO with proper PNA – lower magnitude, stronger T activation

Improper PNA: Large sub-ms degradation, weak T activation

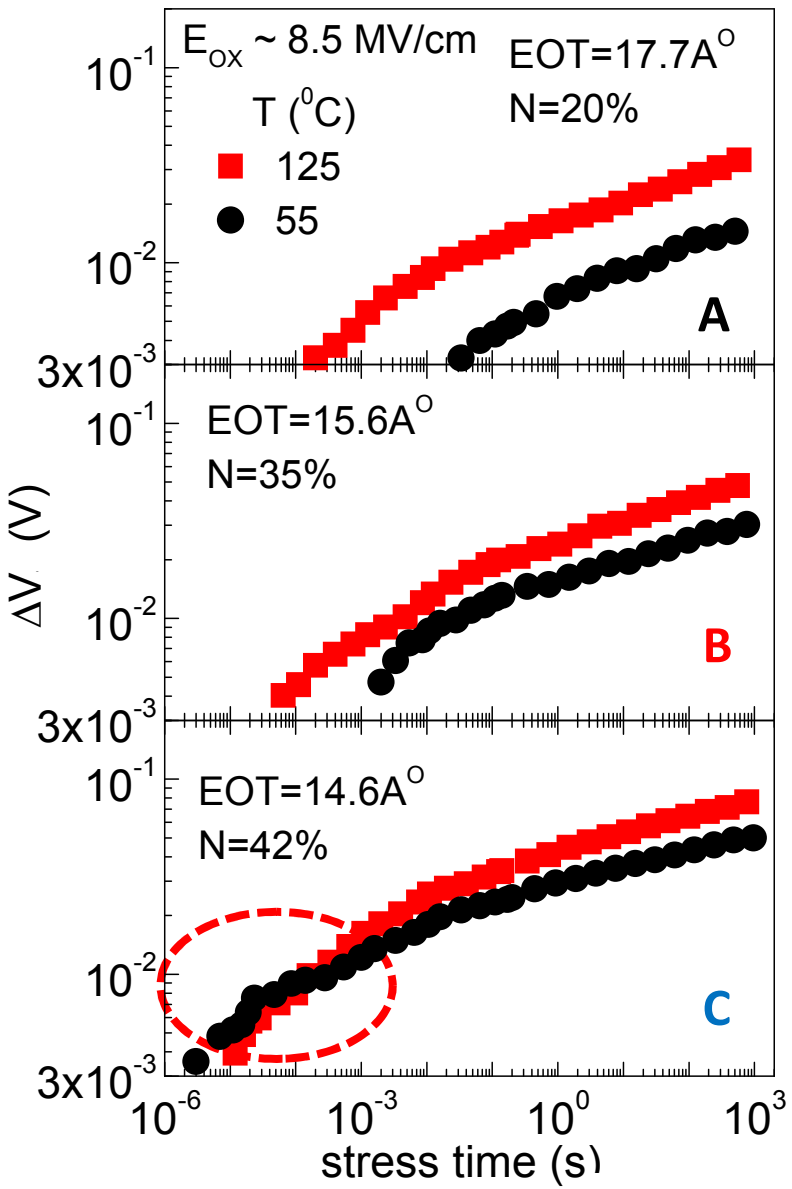
PNA: NBTI reduction, increase in n

Similar process optimization of NBTI from other group

Sakuma IRPS'06



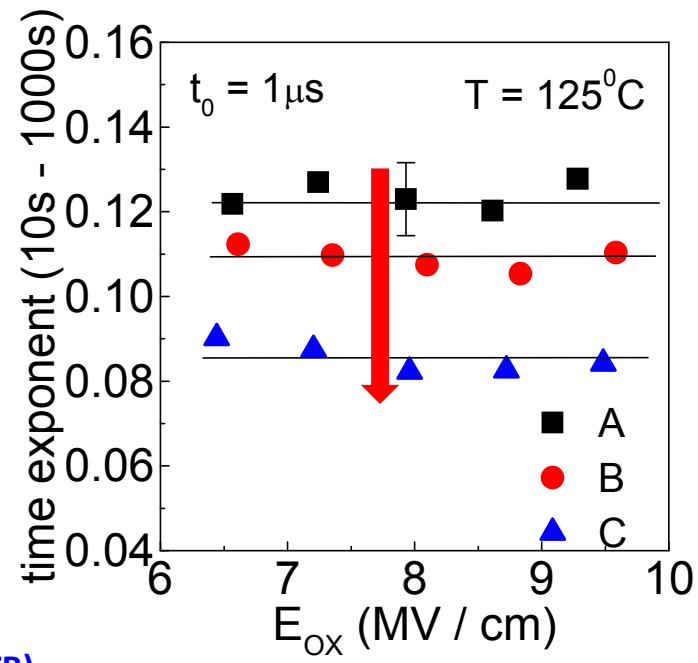
PNO: Impact of Nitridation Dose



Increased PNO N content – higher magnitude, weaker T activation

Large sub-ms degradation, negligible T activation at short time

Reduction in time exponent (n) with higher PNO dose



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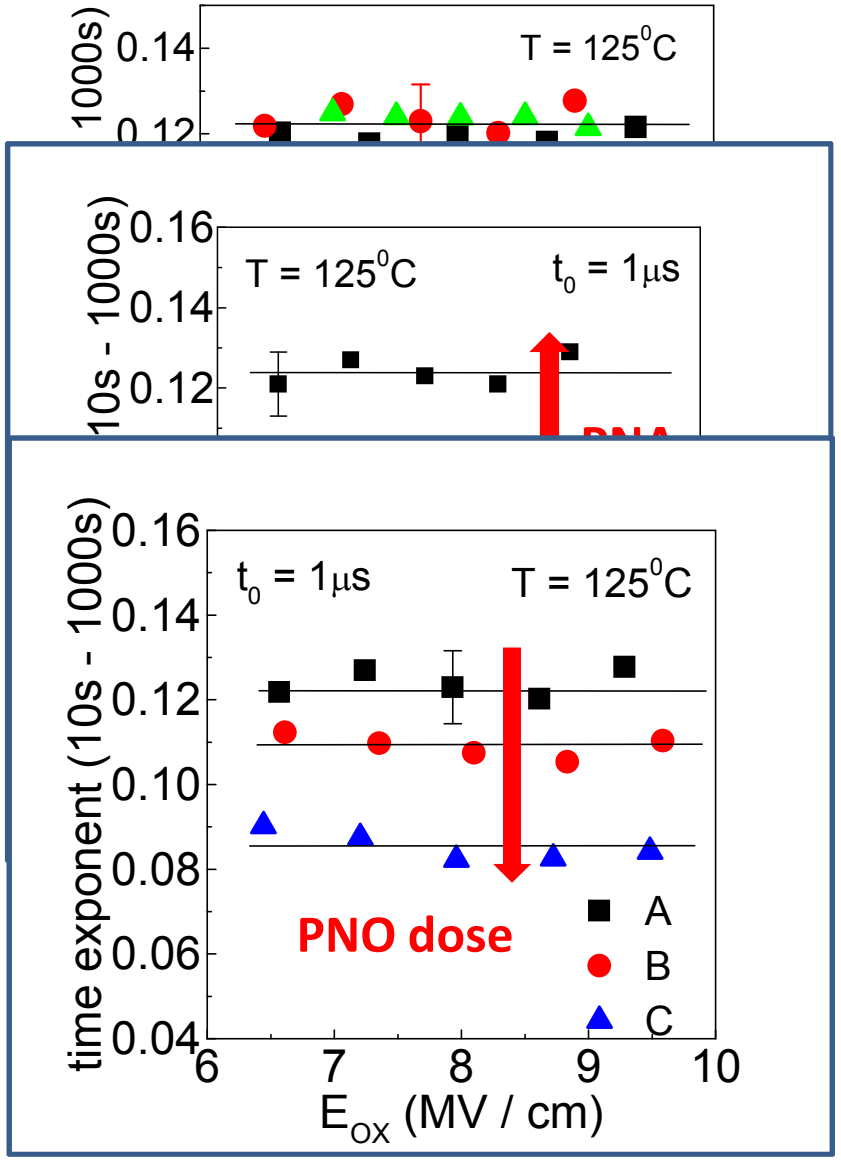
Time Exponent: Process / Material Dependence



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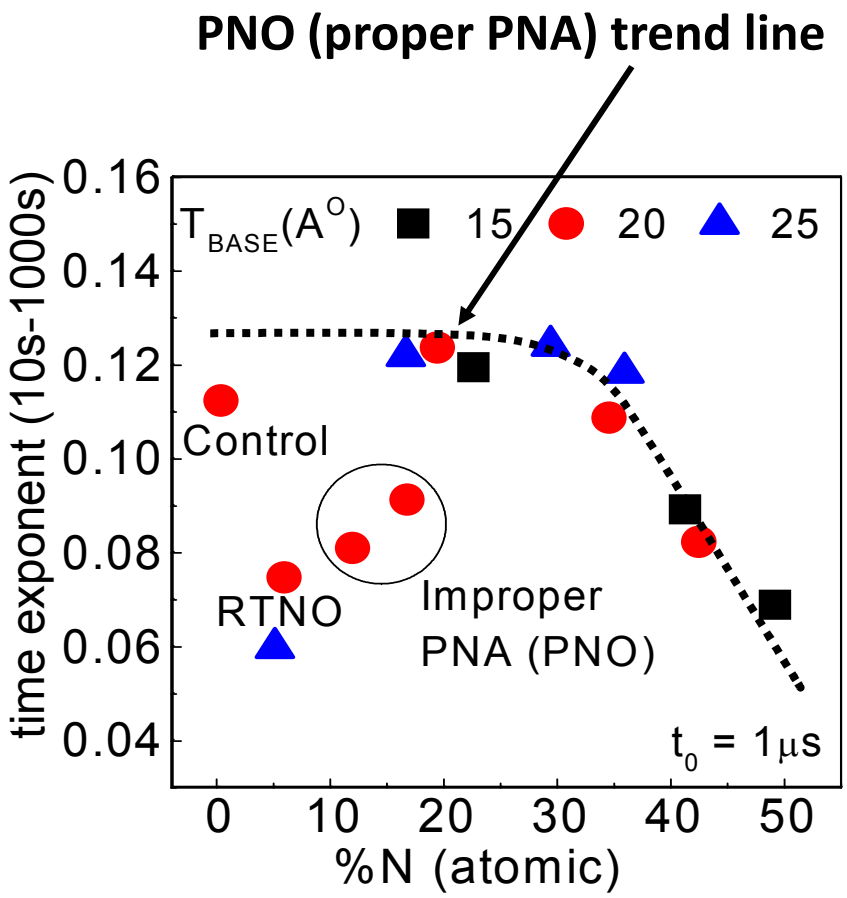
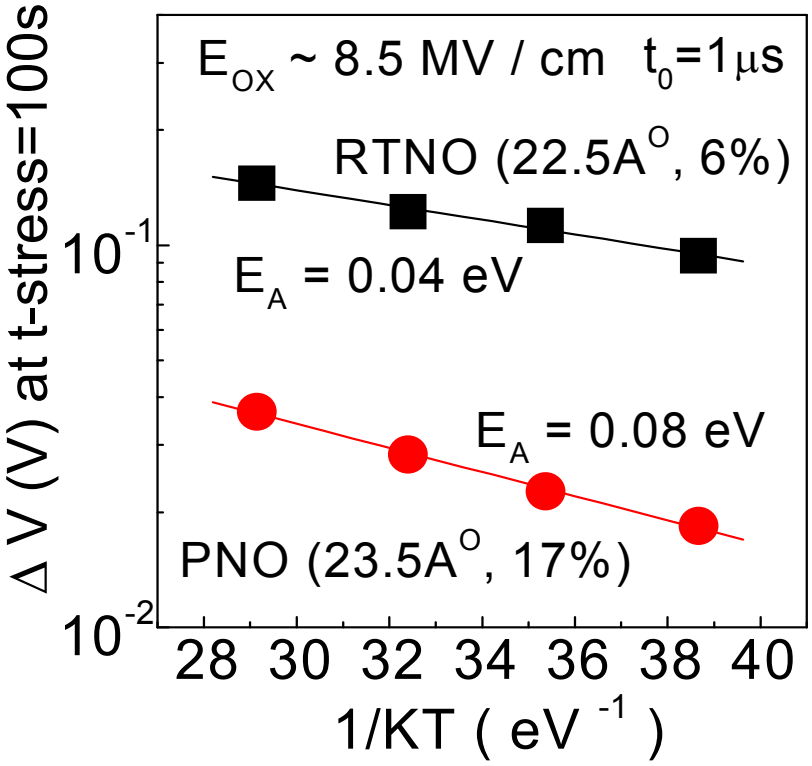


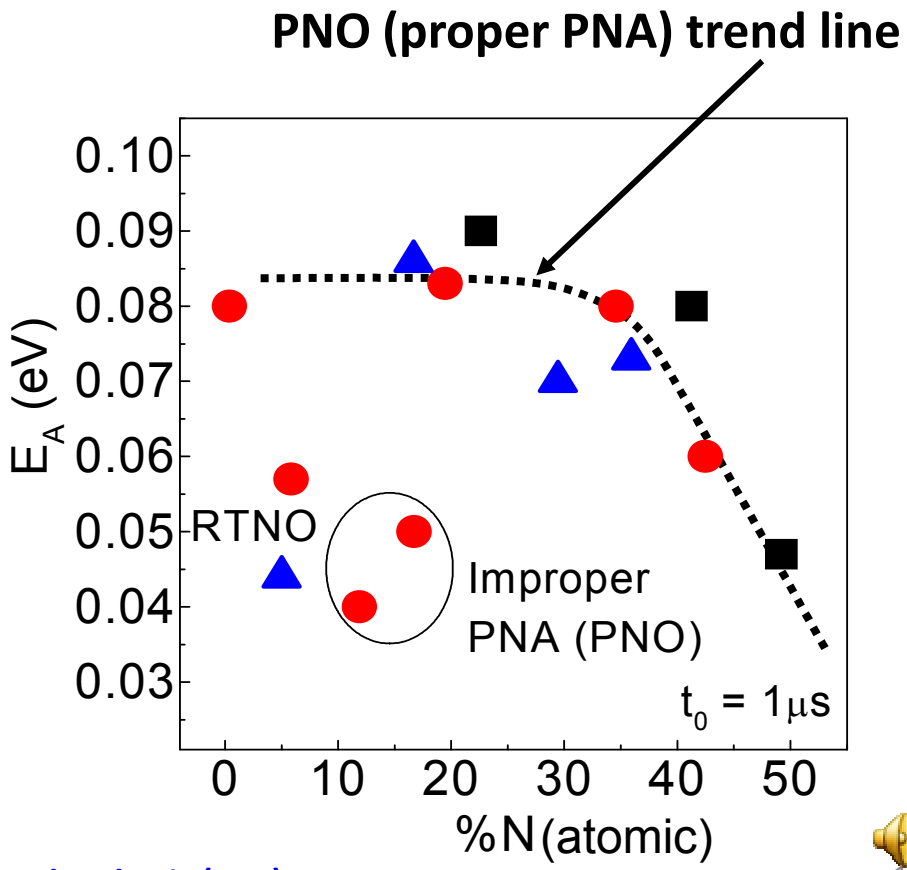
Long-time power law time exponent (n) depends on gate insulator process (PNO, PNA, RTNO) & N%

Temperature Activation of Degradation

RTNO shows higher degradation and lower E_A compared to PNO

T activation energy depends on gate insulator process (PNO, PNA, RTNO) & N%





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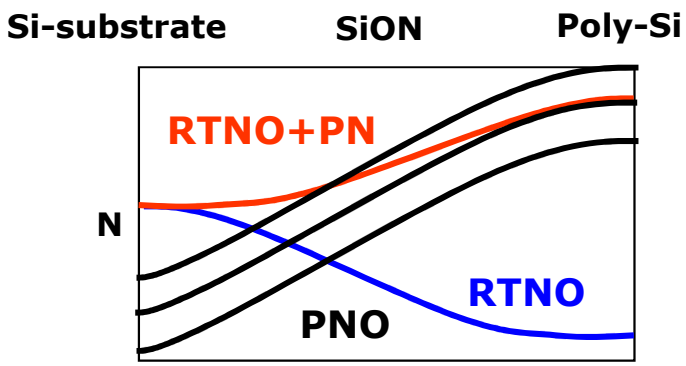
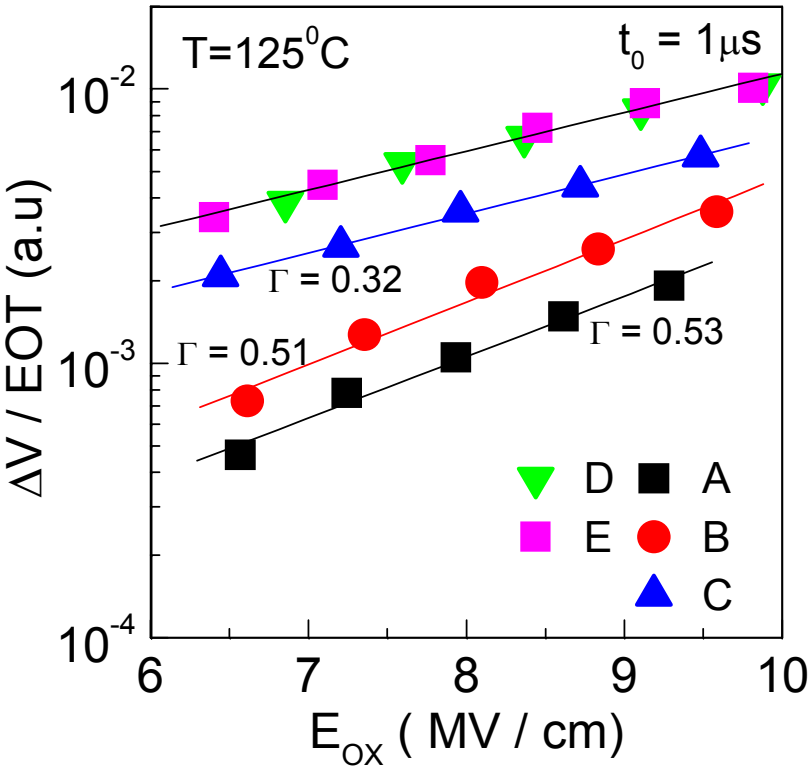
Oxide Field Dependence of Degradation



D#	N_{DOSE}($x10^{15}cm^{-2}$)	N%	EOT(Å)
A	0.0+2.9	19	17.7
B	0.0+5.3	35	15.6
C	0.0+6.8	42	14.6
D	0.8+5.1	39	13.1
E	0.8+0.0	6	18.5



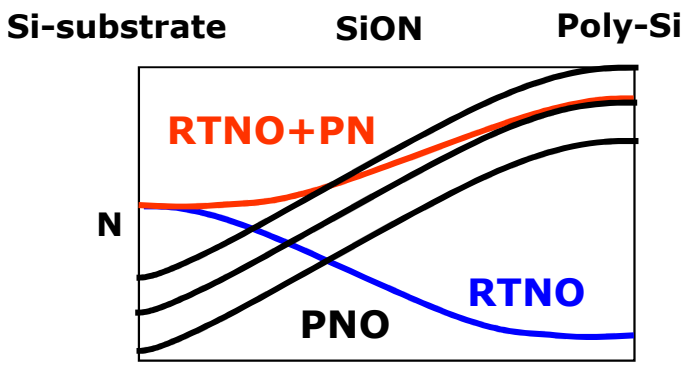
PNO: Increased degradation & lower field dependent slope for higher N%

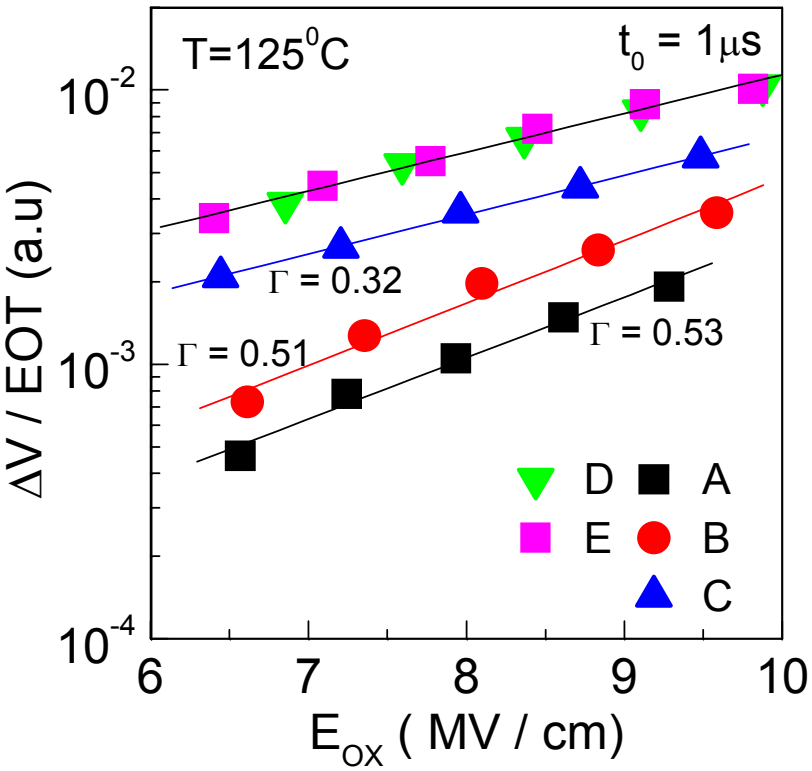
RTNO, RTNO+PN: Very high degradation and low slope

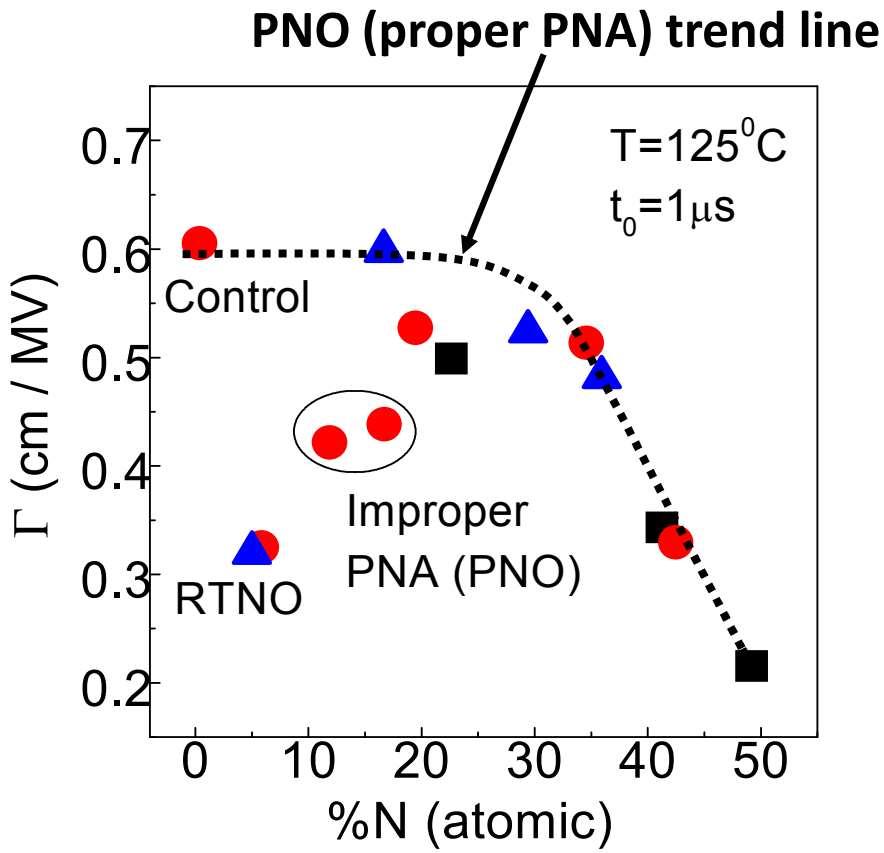
Si/SiON interface density governs overall degradation magnitude & oxide field-dependent slope

Maheta, PhD thesis (IITB)

Field Acceleration Factor: Process Dependence



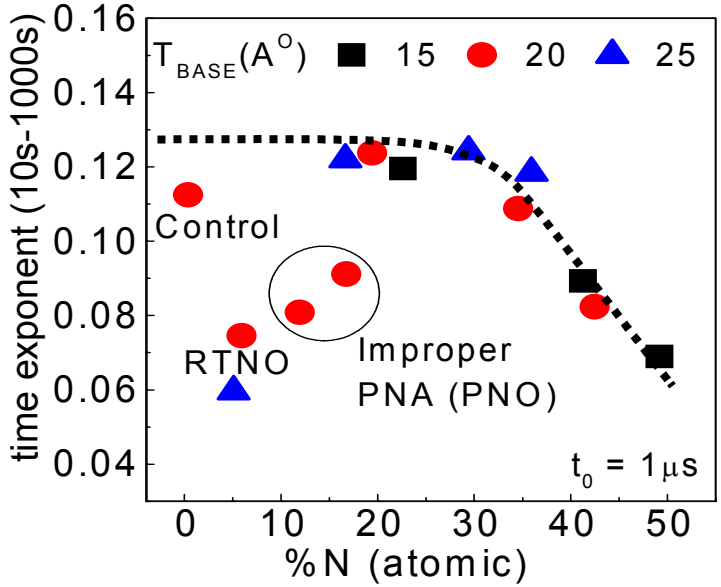


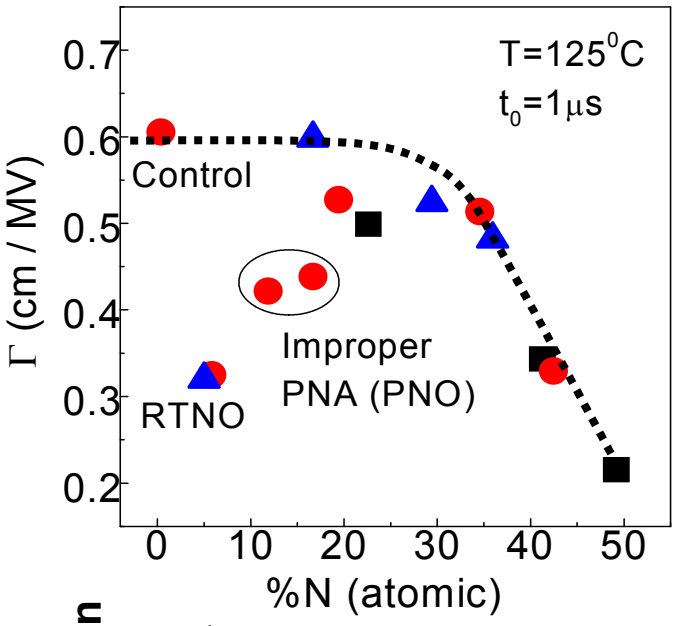


Magnitude and field acceleration govern by SiON process; more importantly by N density at Si/SiON interface

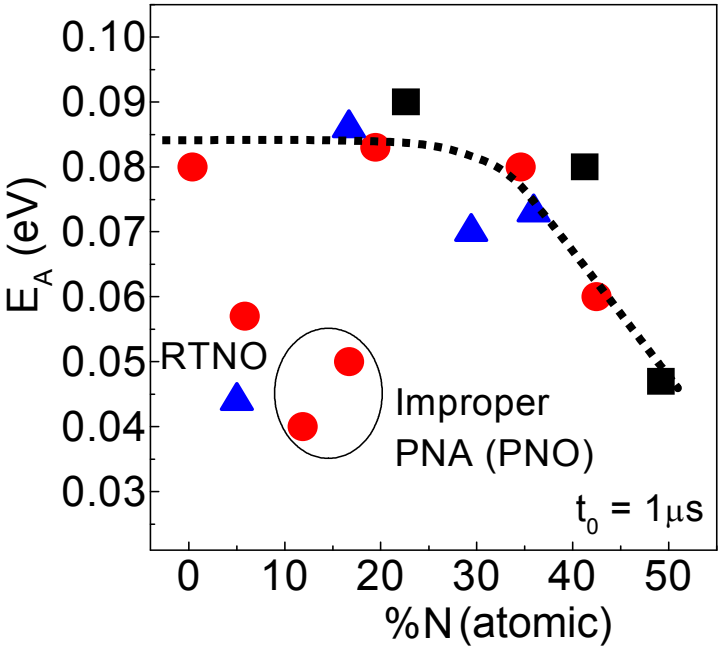
Maheta, PhD thesis (IITB)

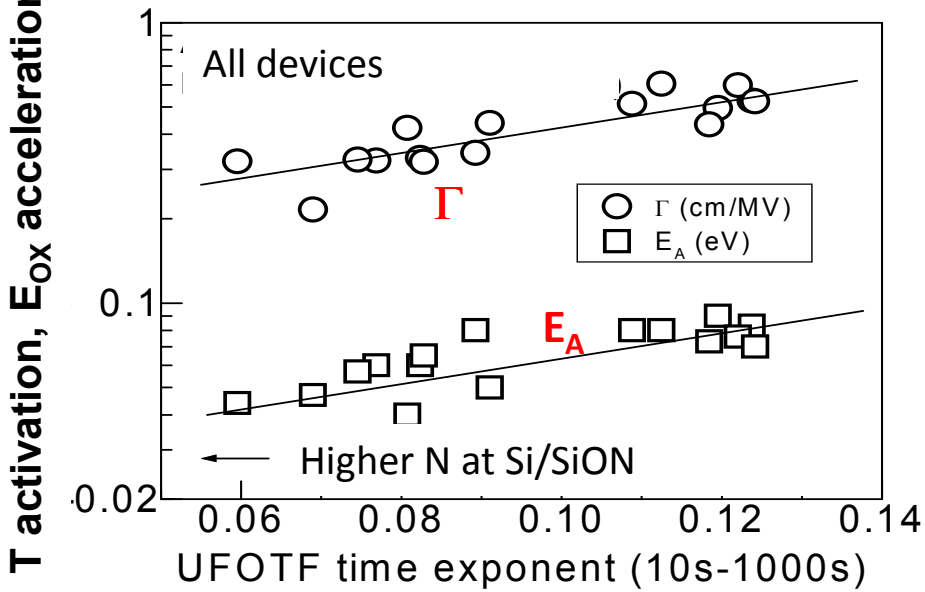
Correlation: Process Dependence of n, E_A, Γ





Strong parametric correlation across gate insulator processes

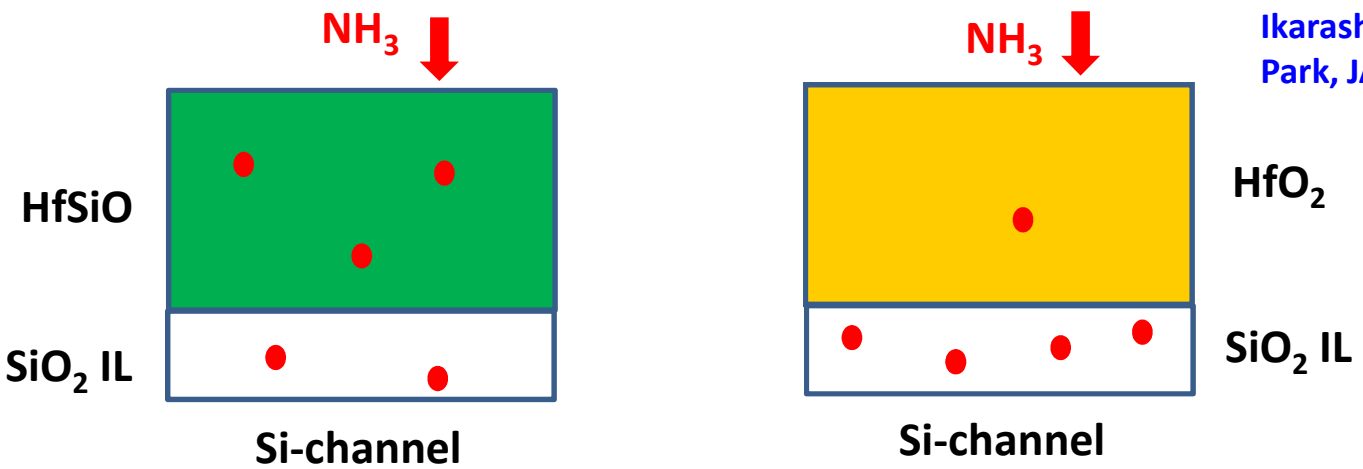




Hi-K/MG vs. SiON: Role of Nitrogen

SiON: N density at Si/SiON interface governs NBTI magnitude, time exponent, T activation, field acceleration

Hi-K/MG: IL (1nm) / HfSiO (2nm, 3nm) and IL (1nm) / HfO_2 (2nm, 3nm) stacks, NH3 anneal following Hi-K deposition

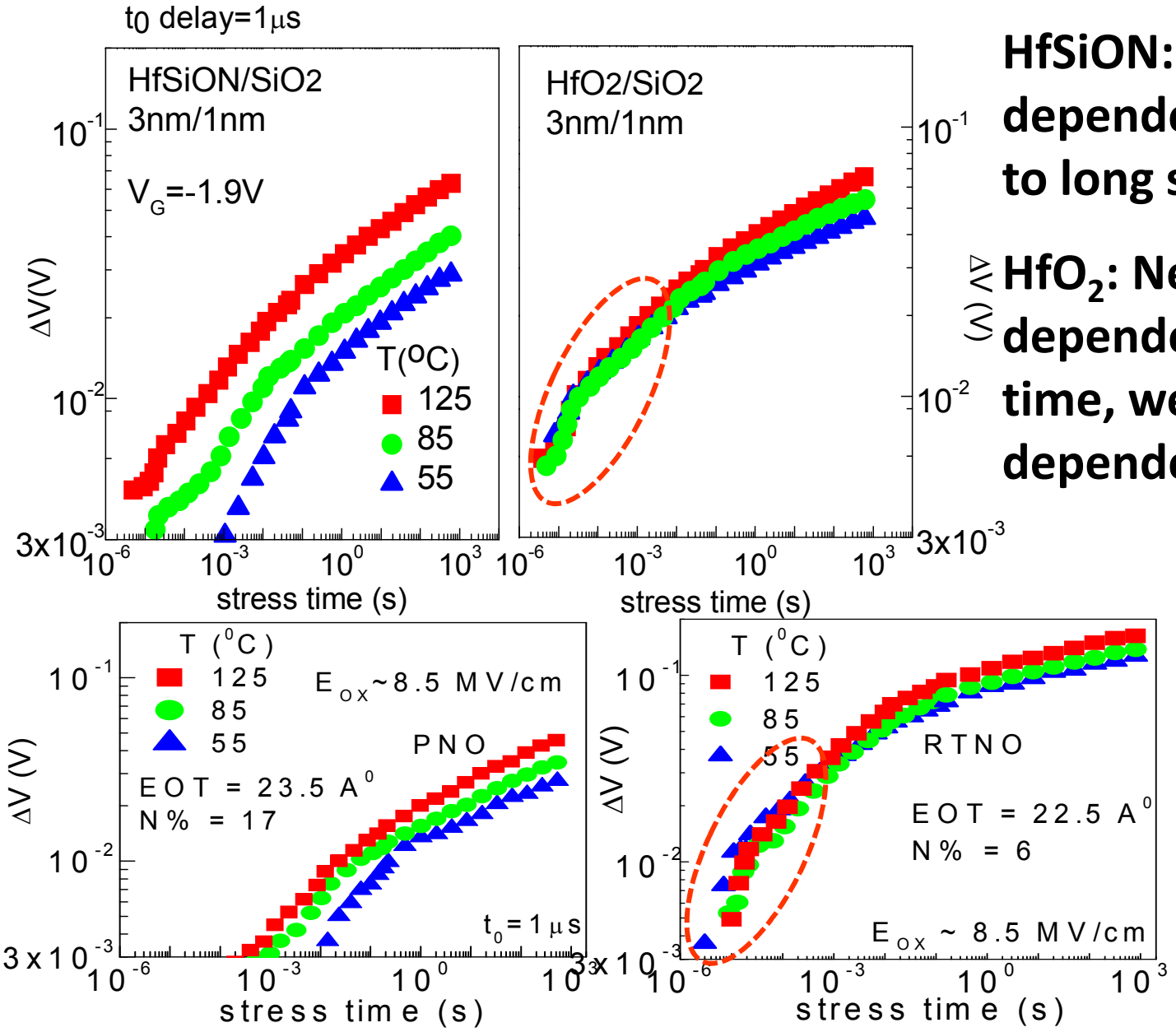


Ikarashi, JAP'06 (100, 063507)
Park, JAP'08, (104, 054101)

Presence of Si in HfSiO reduces N from entering IL (formation of Si-N bonds in Hi-K)

IL N density: 3nm HfSiO stack < 2nm HfSiO stack < HfO_2 stack (Note: Hi-K processes are *not* optimized)

Hi-K/MG vs. SiON: T Dependent Transients



HfSiON: Clear T dependence from short to long stress time

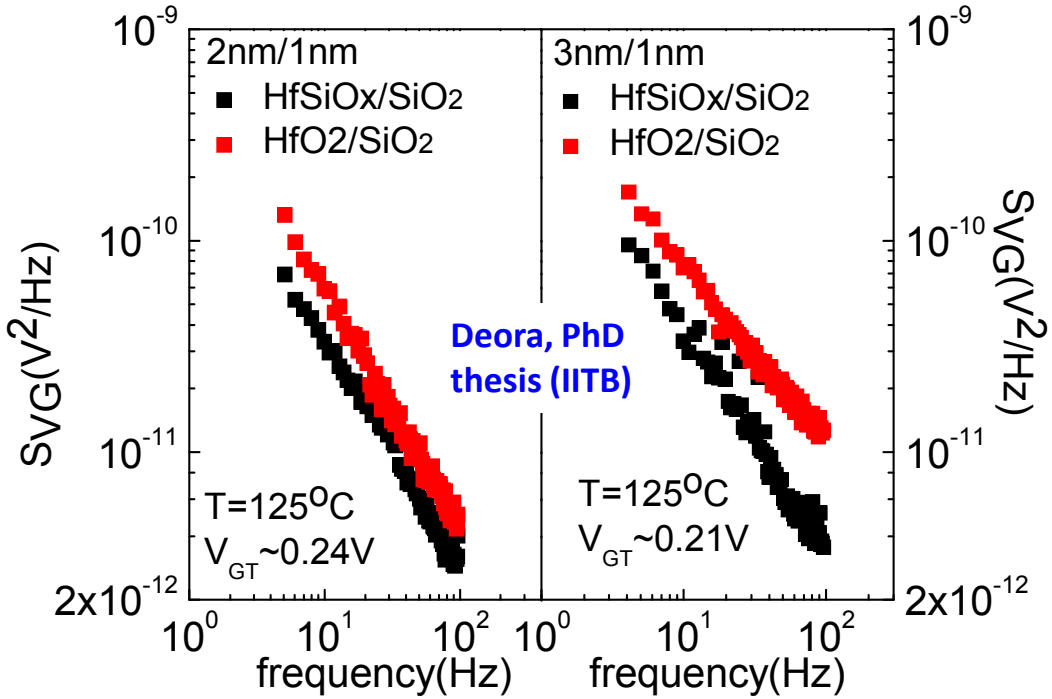
HfO_2: Negligible T dependence at short time, weak T dependence at long time

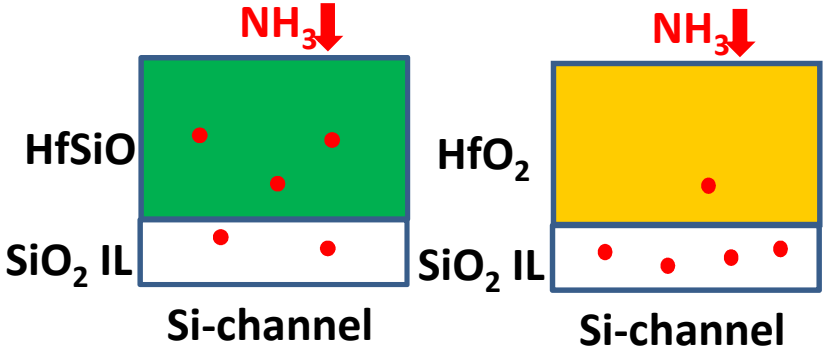
HfSiON behaves like Type-A SiON (low Si/SiO_2 N)

HfO_2 behaves like Type-B SiON (high Si/SiO_2 N)

Deora, EDL'09

Flicker Noise Measurement (Hi-K/MG)

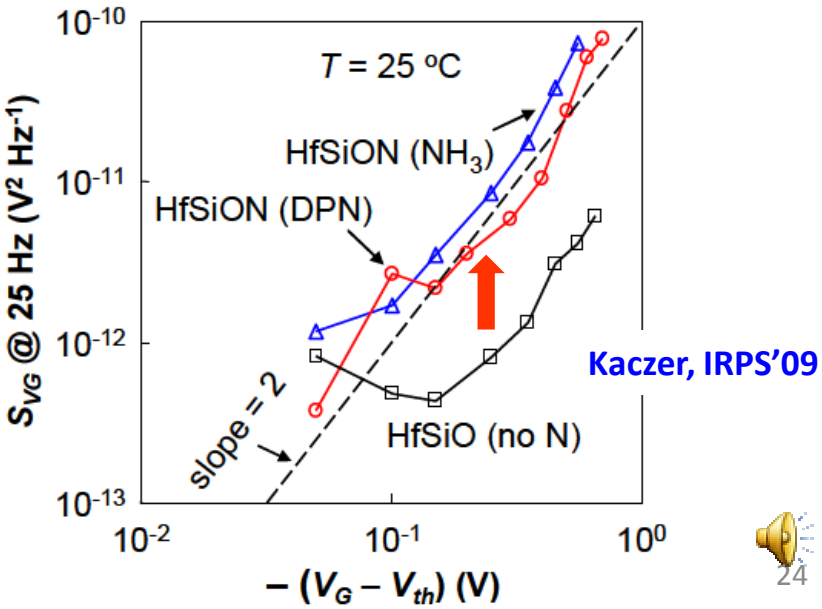




Larger noise magnitude in HfO_2 compared to HfSiON

Higher N (pre-existing hole traps) in IL of HfO_2 stack compared to HfSiON stack

Similar N related pre-existing trap increase reported by others

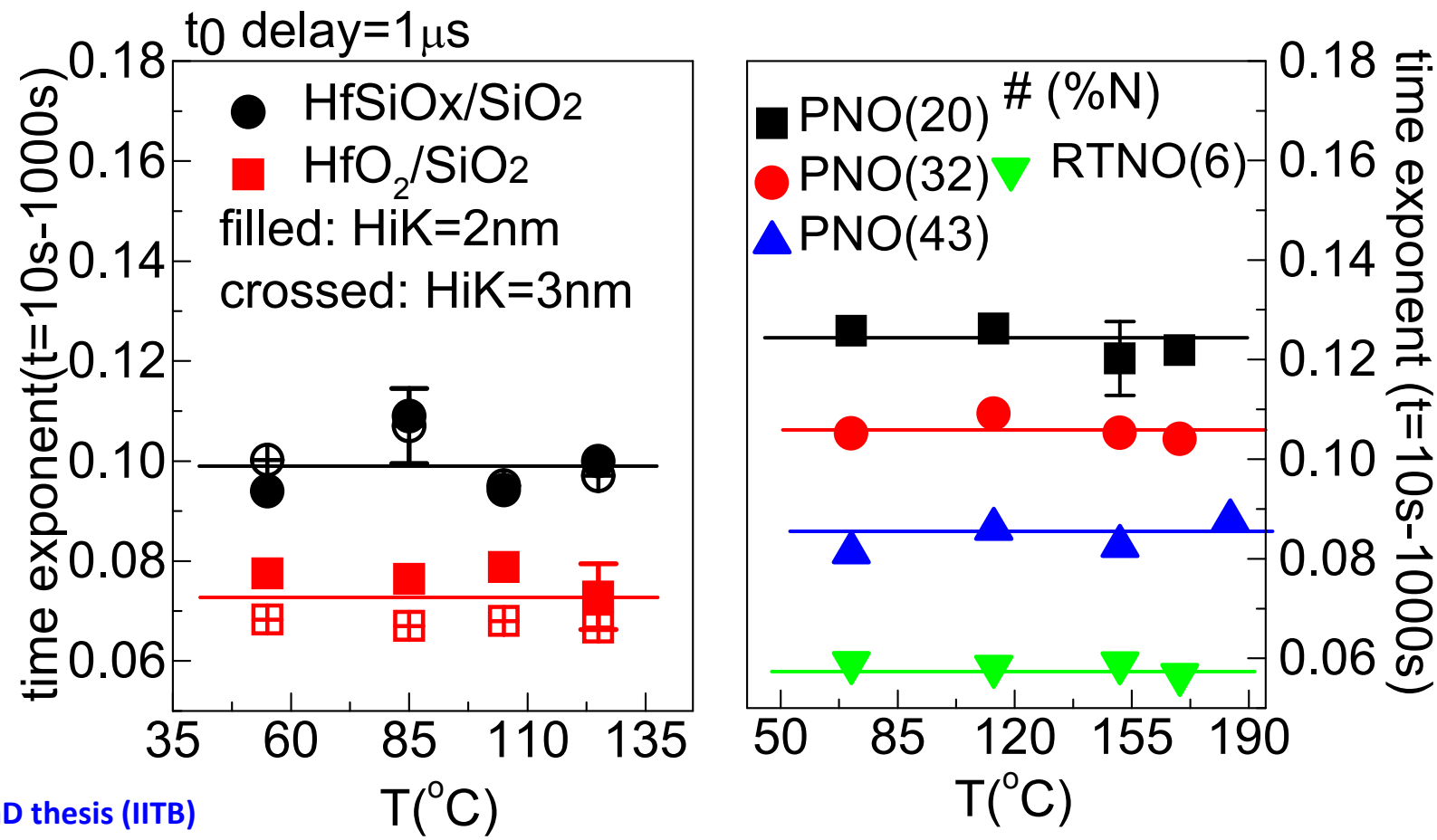


IL N density: 3nm HfSiO stack < 2nm HfSiO stack < HfO_2 stack

Hi-K/MG vs. SiON: Time Exponent (n)

Hi-K: HfSiON shows higher n compared to HfO_2, n independent of T

SiON: PNO shows higher n (reduces with increase in N) compared to RTNO

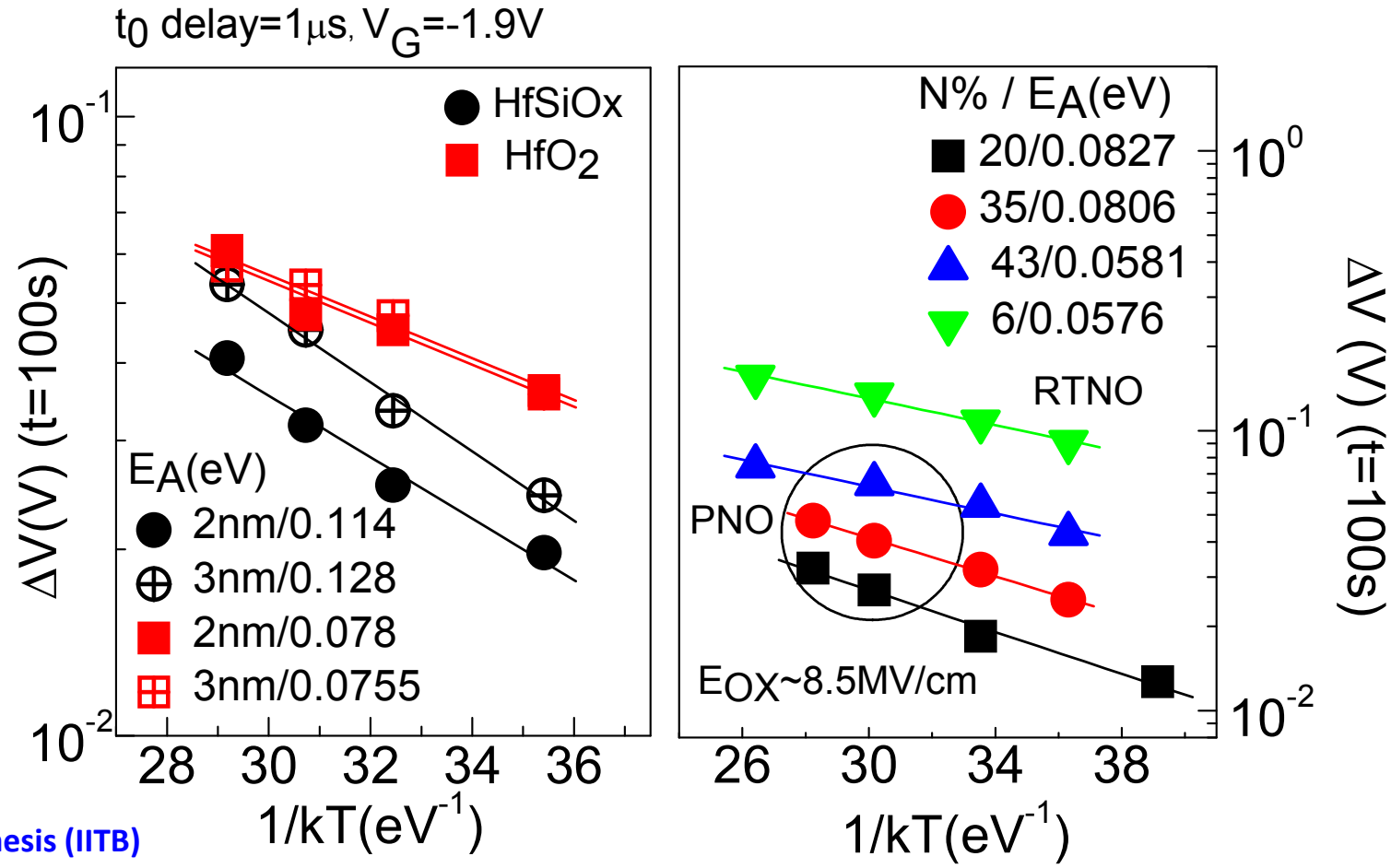


Deora, PhD thesis (IITB)

Hi-K/MG vs. SiON: Temperature Activation (E_A)

Hi-K: HfSiON shows lower magnitude and higher E_A compared to HfO_2

SiON: PNO (magnitude increases, E_A reduces with increase in N) shows lower magnitude and higher E_A compared to RTNO

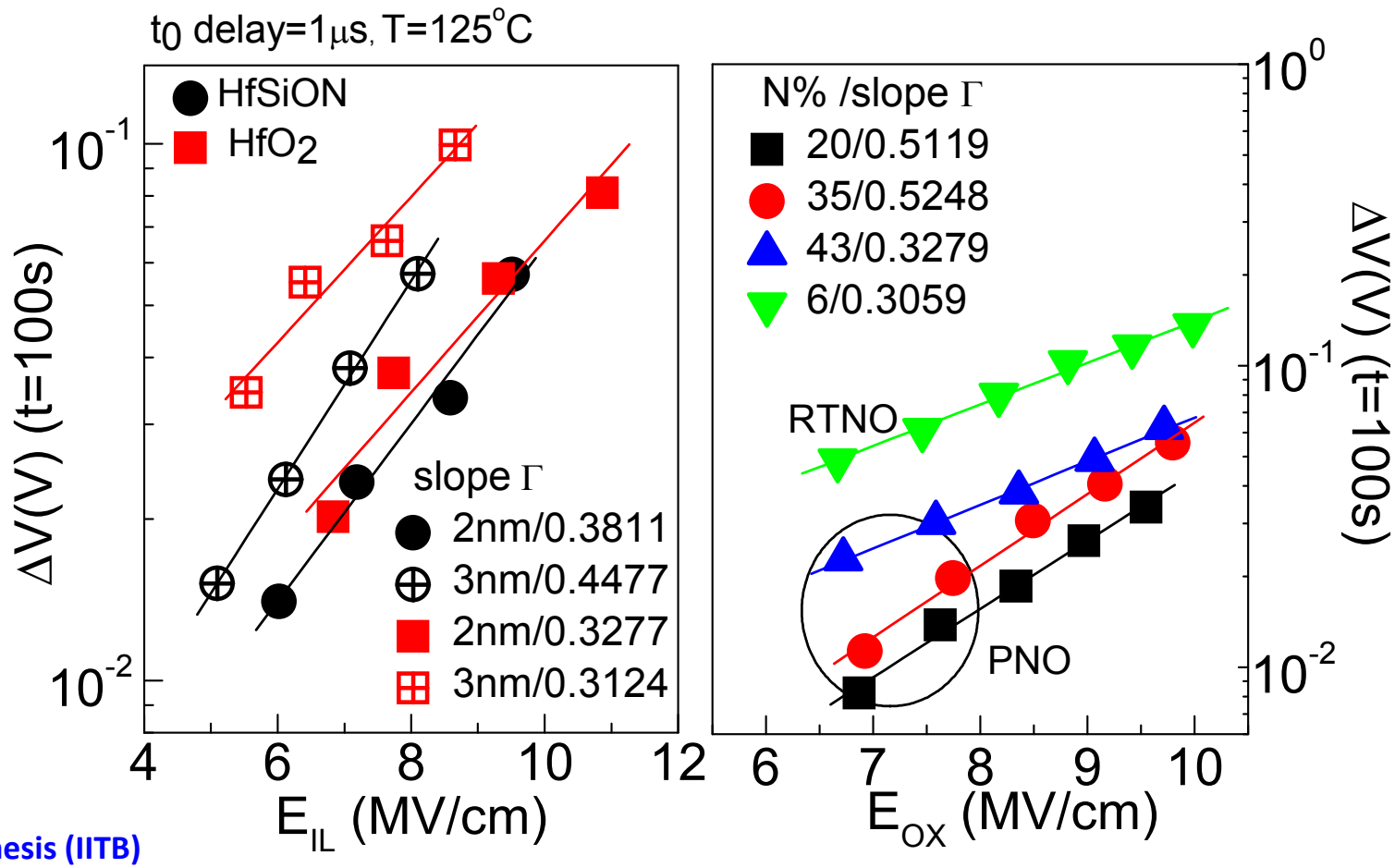


Deora, PhD thesis (IITB)

Hi-K/MG vs. SiON: Field Acceleration (Γ)

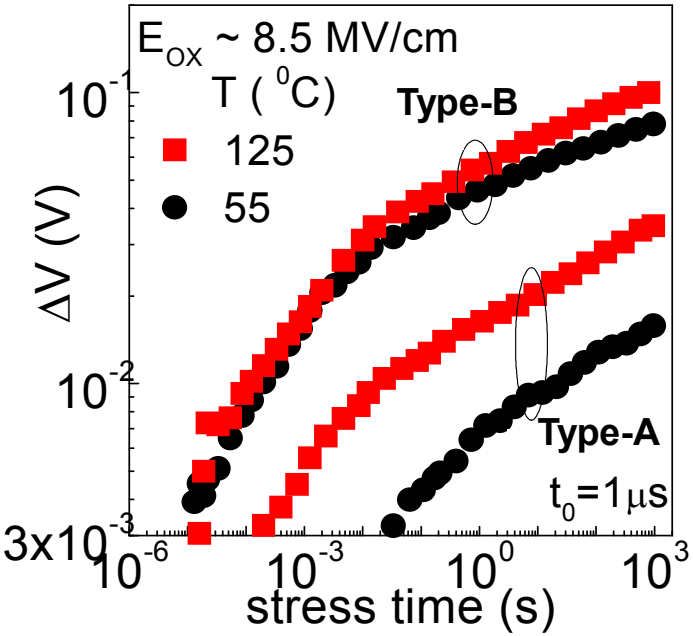
Hi-K: HfSiON shows lower magnitude and higher Γ compared to HfO_2

SiON: PNO (magnitude increases, Γ reduces with increase in N) shows lower magnitude and higher Γ compared to RTNO



Deora, PhD thesis (IITB)

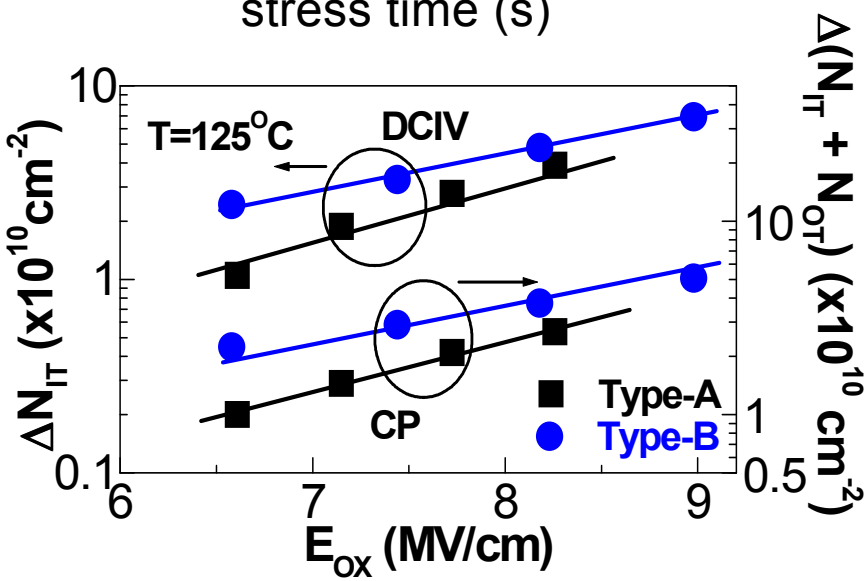
Role of Nitrogen

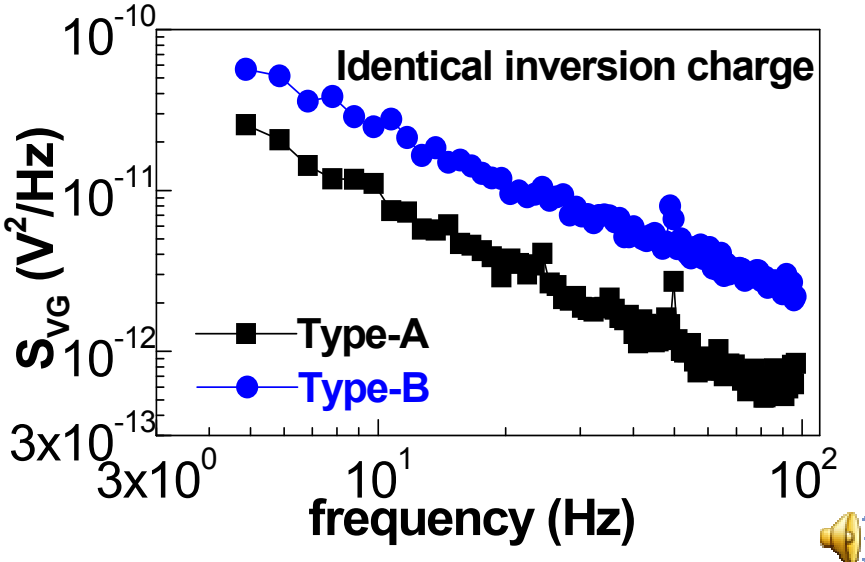


Process impact on NBTI: Higher degradation for Type-B (more N close to Si/SiON interface)

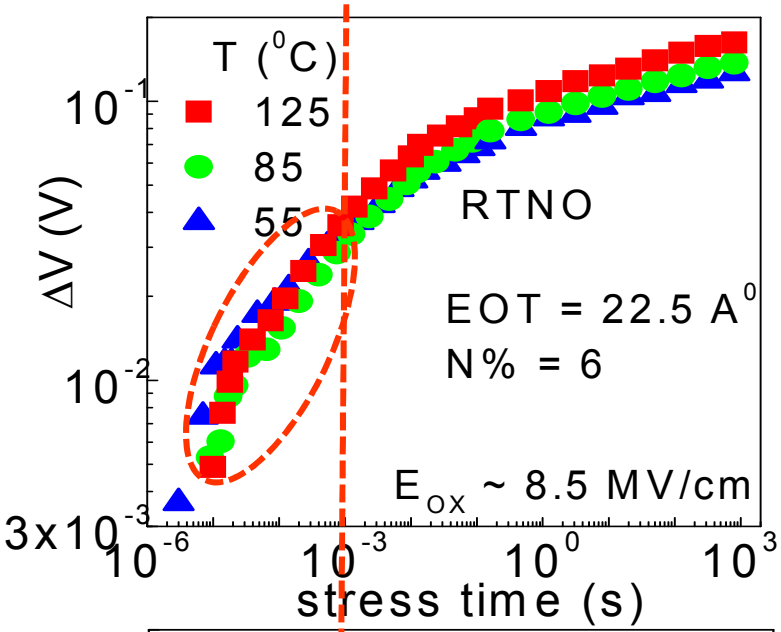
Traps are generated, small difference in generated traps (DCIV, CP)

Large difference in pre-existing traps linked to N in GOX (Flicker noise)





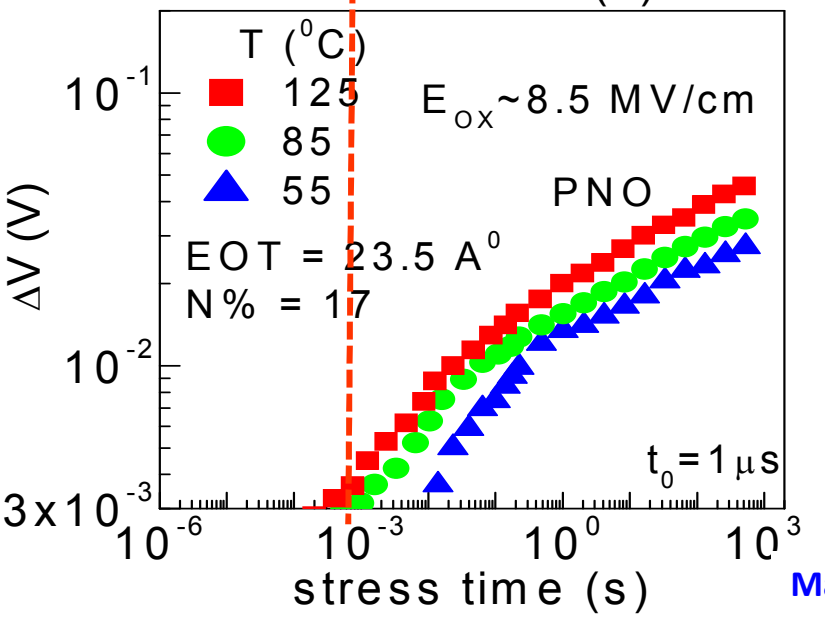
Short Time Degradation: Different Devices

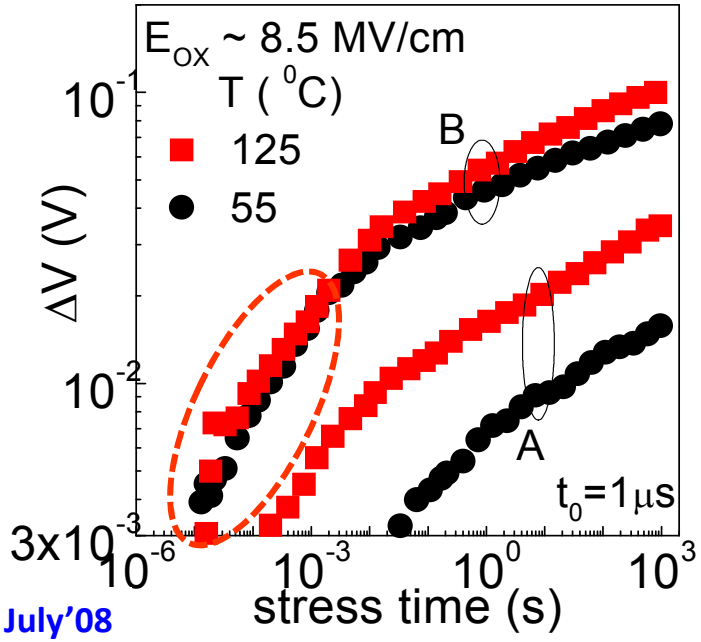


RTNO shows large sub-ms degradation that has negligible T activation

Similar observation for PNO devices with improper PNA

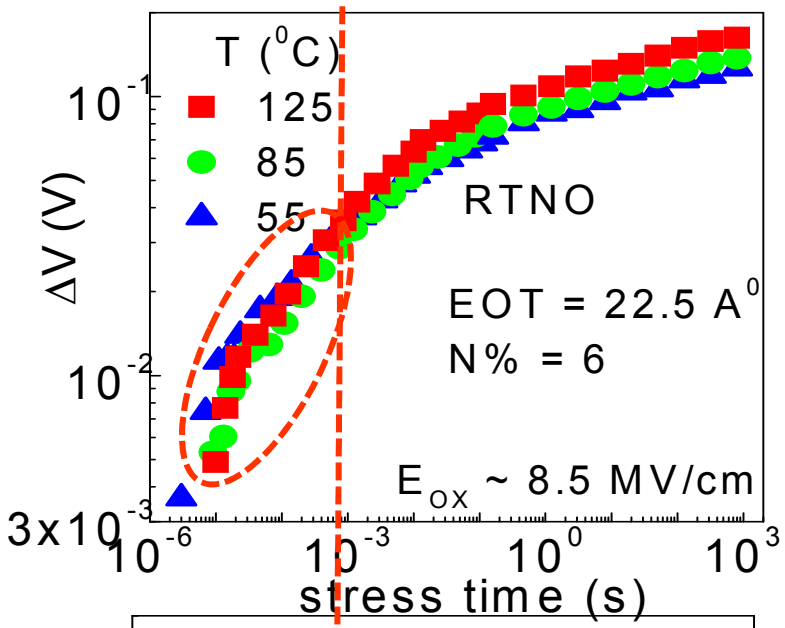
Short-time negligible T dependence - artifact due to time-zero subtraction?

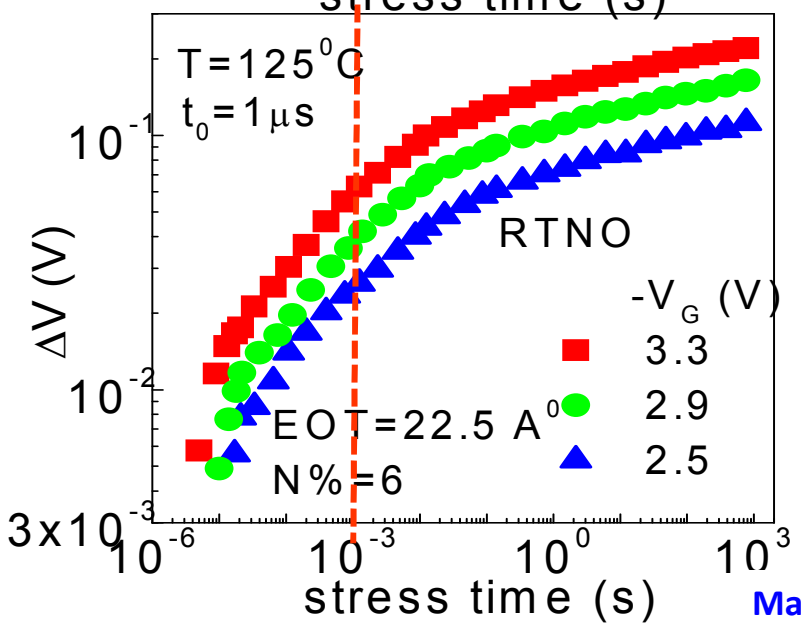




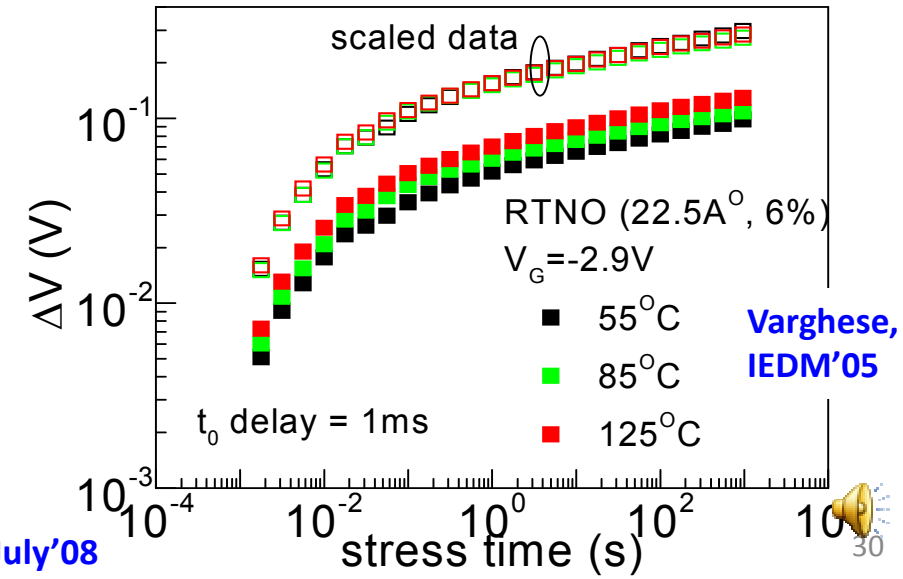
Maheta, TED July'08

Short Time Degradation: V_G and T Dependence





- T dependent data show negligible T activation especially at sub-ms time
- Bias dependent data show strong acceleration for entire stress duration
- OTF (1ms) T dependent data also shows strong acceleration
- Sub 1ms negligible T dependence – real physical phenomenon

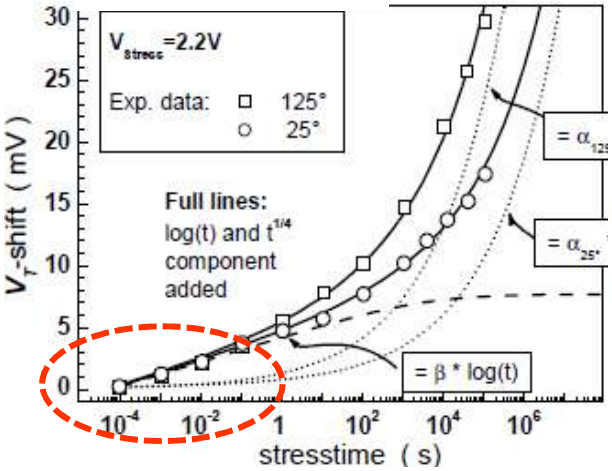


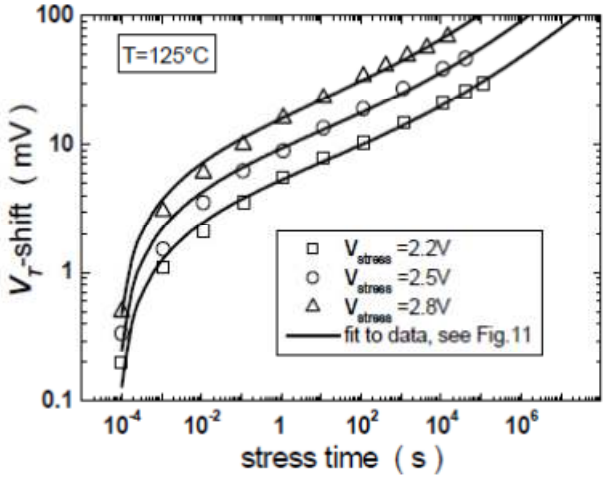
Varghese, IEDM'05

Maheta, TED July'08

Short Time Degradation: Other Measurements

Reisinger, IRPS'06



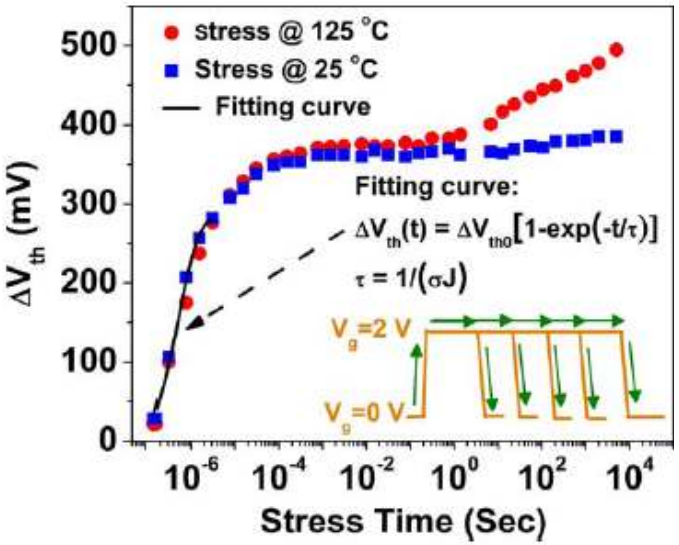


Negligible short time T dependence

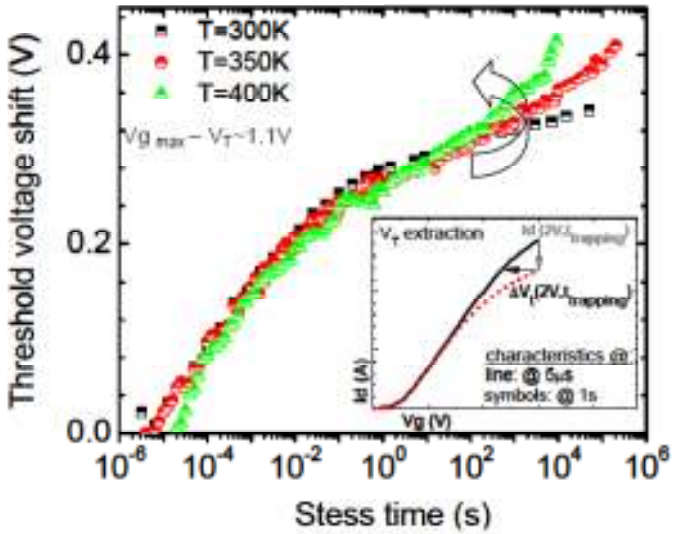
Strong short time bias dependence – no time zero subtraction issue

PBTI Examples:

Heh, EDL Feb'08



Mitrad, IRPS'06



Similar behavior of short time T independence for PBTI in Hi-K/MG

Summary

Enhanced NBTI for Type-B (poorly optimized) devices having higher N density close to Si/SiON interface

Slightly larger trap generation, significantly higher trapping in N related pre-existing traps responsible for enhanced NBTI

Only Type B devices show significant sub-ms degradation, which has negligible T activation, feature only captured by UF-OTF I_{DLIN}

Strong correlation of NBTI features and parameters across different GOX processes

More N → Larger magnitude → lower long time n, E_A and Γ

NBTI in HKMG devices governed by IL, follow similar (to SiON) N dependent signature of time, T and bias dependence

Outline

Introduction, Basic NBTI signatures

Fast / Ultra-fast drain current degradation measurement

Estimation of pre-existing and generated defects

Transistor process / material dependence

Role of Nitrogen – Study by Ultrafast measurement

Predictive modeling

Conclusions / outlook

Go to Part - III