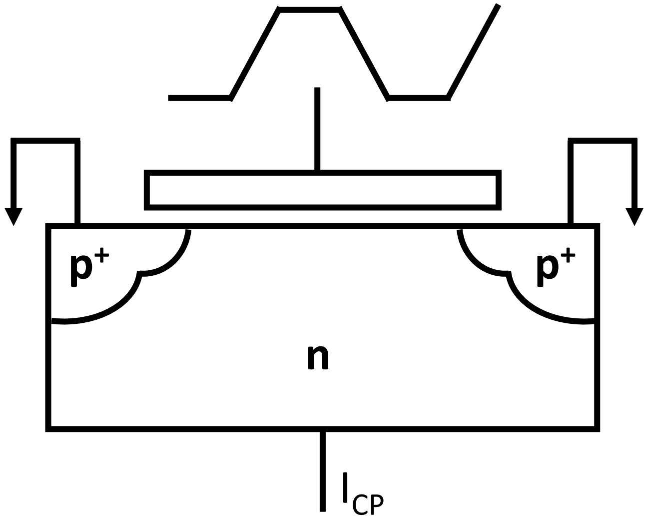
Charge Pumping (Interface Traps)



Pulse V_G repetitively from inversion to accumulation, measure I_{SUB} due to electron-hole recombination in traps at (or near) Si/SiO_2 interface

Frequency

Interface trap density (/cm²/eV)

$$I_{CP} = q * f * (WL) * (D_{IT}\Delta E)$$

I due to charge pumping

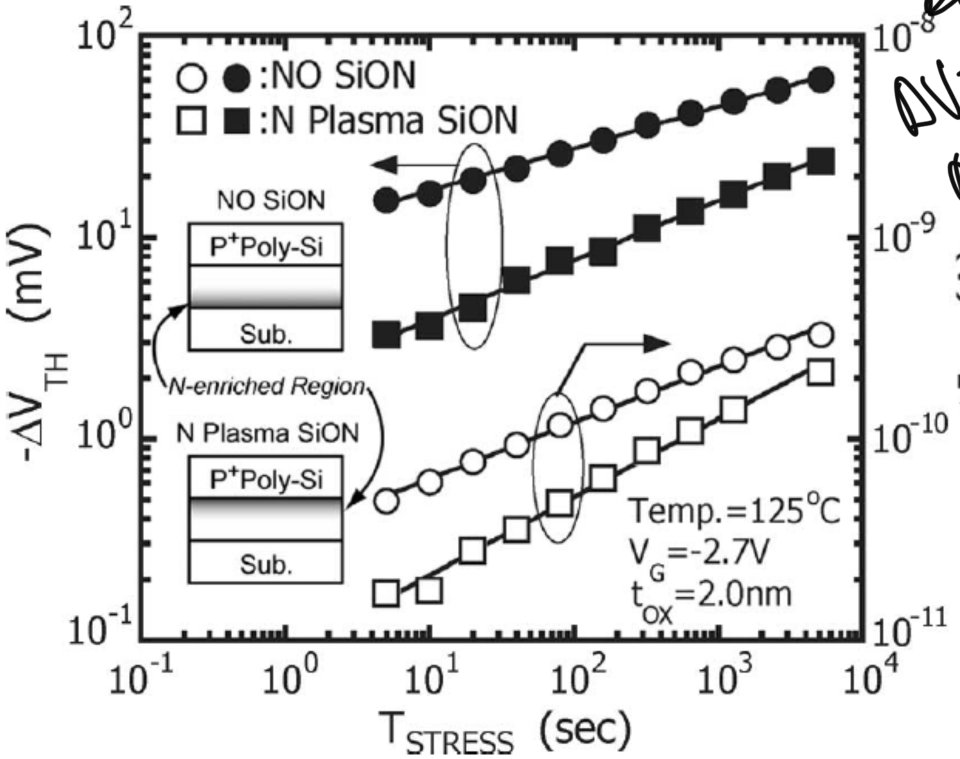
Energy zone scanned by CP

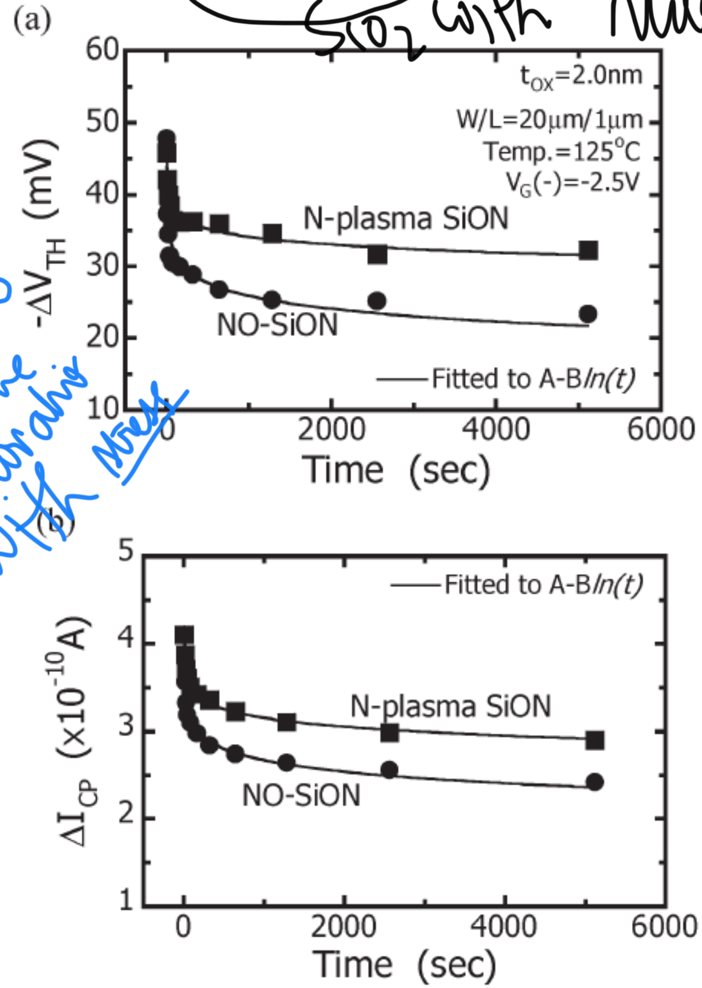
Correlation of Different Methods

Both ΔV_T (slow MSM) and ΔI_{CP} shows power law time dependence and higher degradation for NO-SiON, and recovery after stress

SiO$_2$ with nitridation

both ΔV_T & ΔI_{CP} show same variation with stress





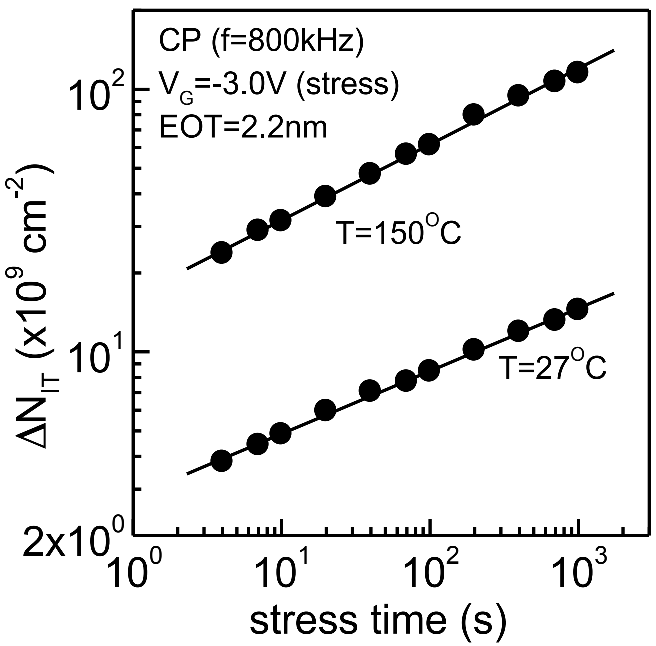
Mitani, MR'08

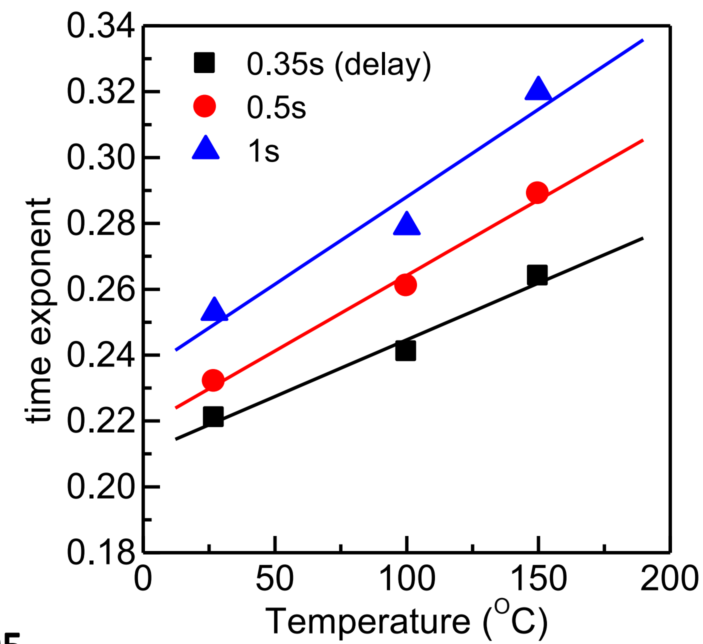
Power Law Time Exponent

CP current increase (trap generation) with stress time - power law time dependence - larger n than I_{DLIN} measurement

traps↑ ⇒ NBTI↑ ⇒ ΔV_T↑ ⇒ will degrade easily with time

Time exponent increases with delay time and stress T – recovery related artifact (need delay correction)



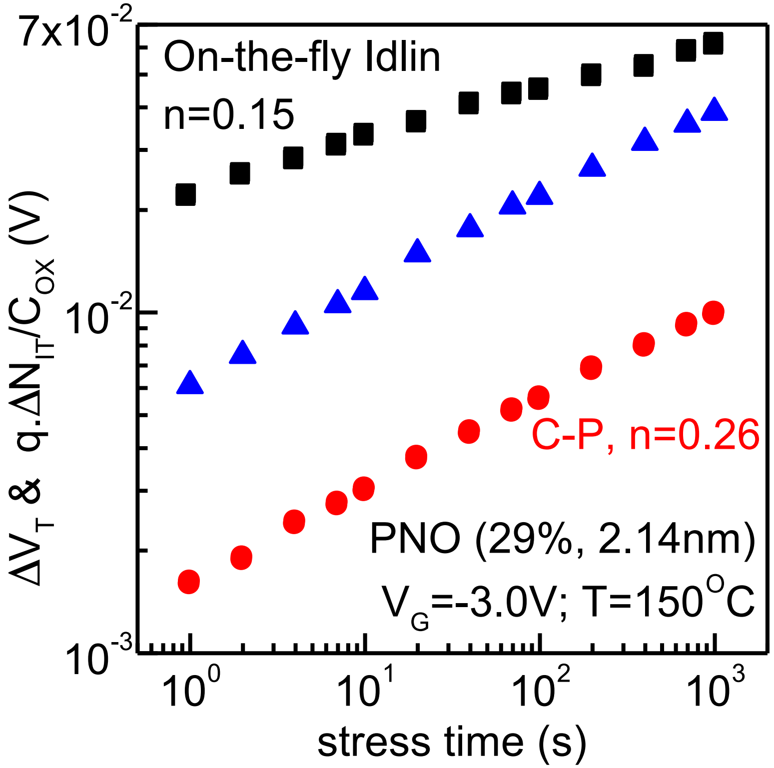


Varghese, IEDM'05

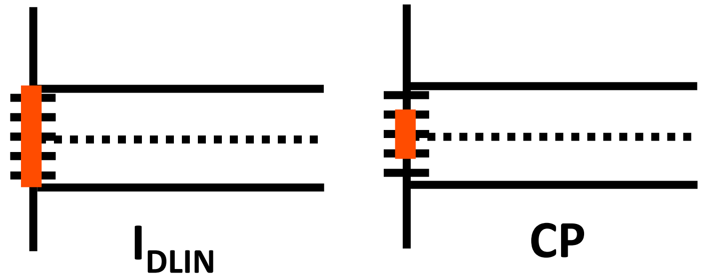
Comparison of CP and OTF-I_{DLIN} (t_0=1ms)

on the fly

As measured difference ~ 10X → NBTI not due to trap generation?



Band gap scan: Full for I_{DLIN}, partial near midgap for CP



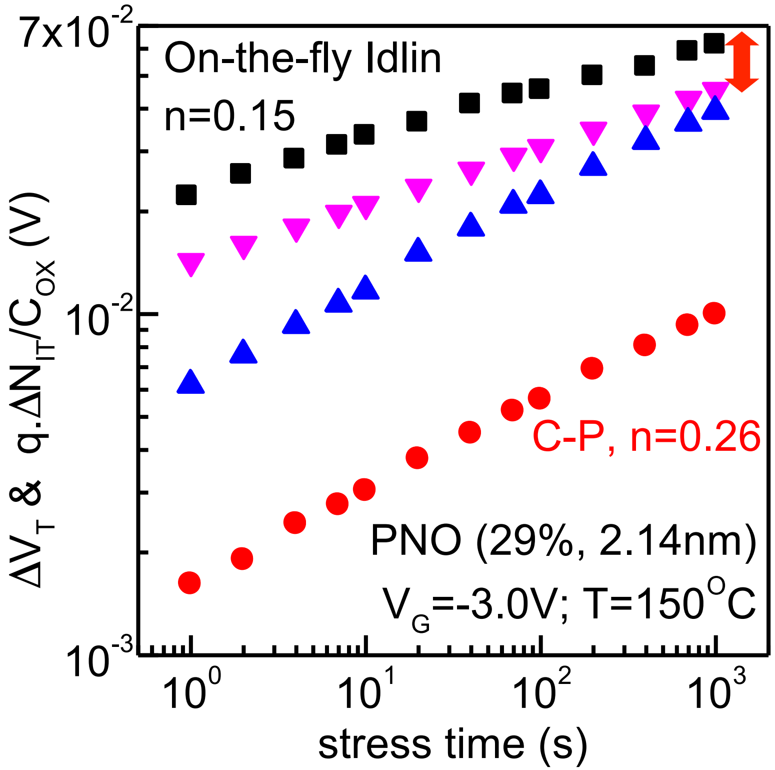
Correct for band gap difference

Mahapatra, IRPS'07

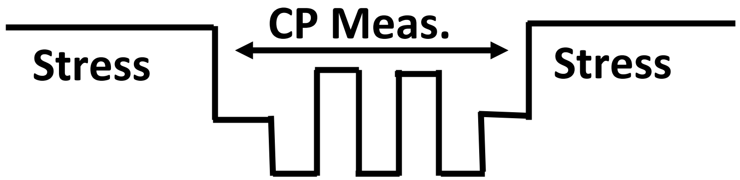
Comparison of CP and OTF-I_{DLIN} (t_0=1ms)

Final difference within ~ 20%

As we were doing MSM for the CP therefore recovery occurs



Inherent recovery for CP

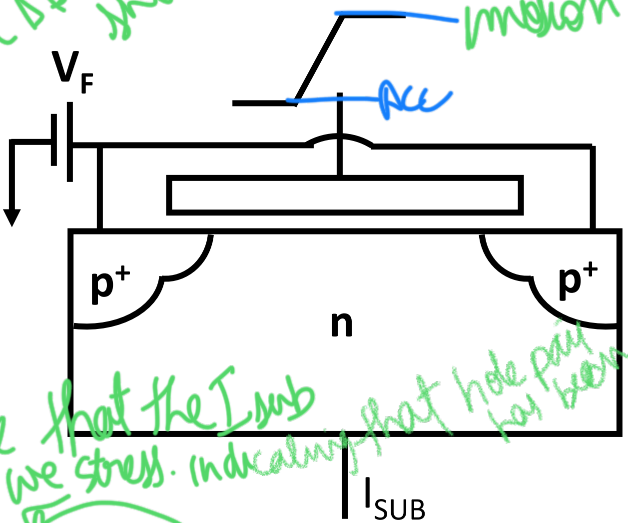


Correct for recovery

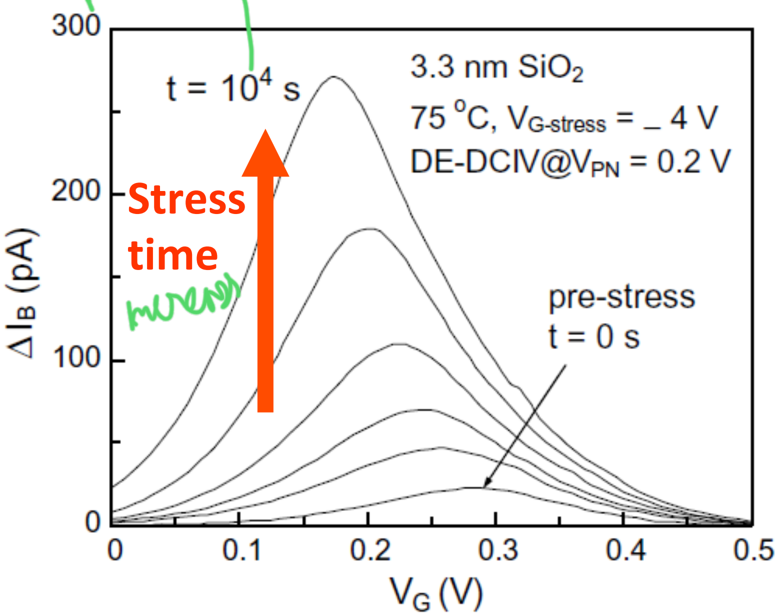
Mahapatra, IRPS'07

DCIV Measurements (Interface Traps)

Drain & Source shorted



We can see that the Isub increases as we stress. indicating that hole pair has been formed



Sweep V_G with S/D in F.B, measure I_{SUB} due to electron-hole recombination in traps at or near Si/SiO_2 interface

can be calculated from here:

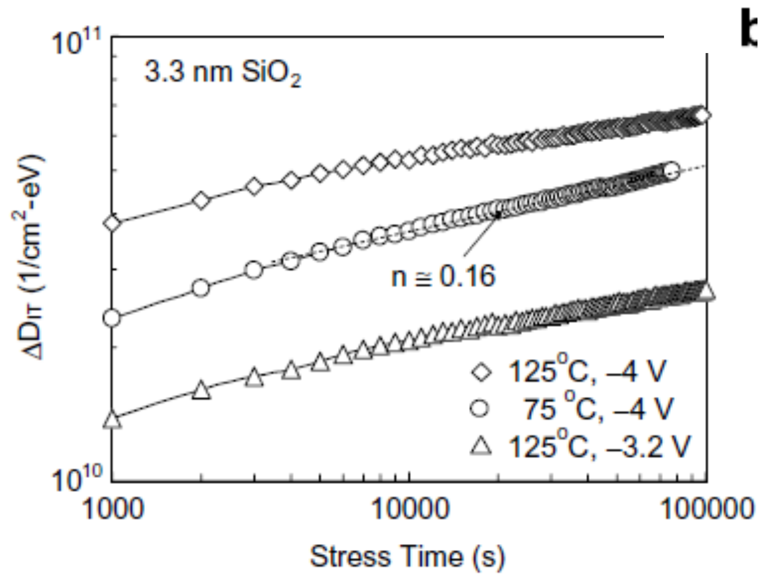
Constant

$$I_B = q * K * (WL) * D_{IT} * \exp(\frac{qV_F}{kT})$$

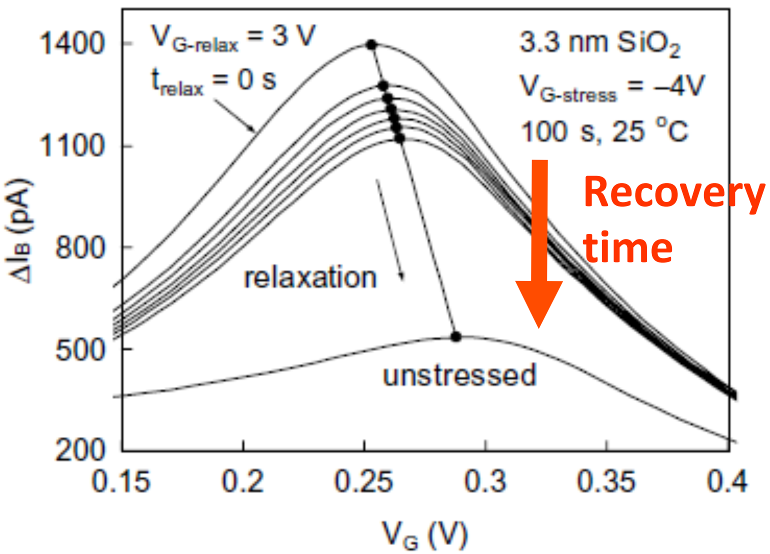
Increase in I_{SUB} due to stress: Indicates trap generation at or near Si/SiO_2 interface

Neugroschel, MR'07

DCIV Measurements (Interface Traps)



Power law time dependence (A^*t^n), with n ~ 1/6 at long stress time for different stress V_G and T

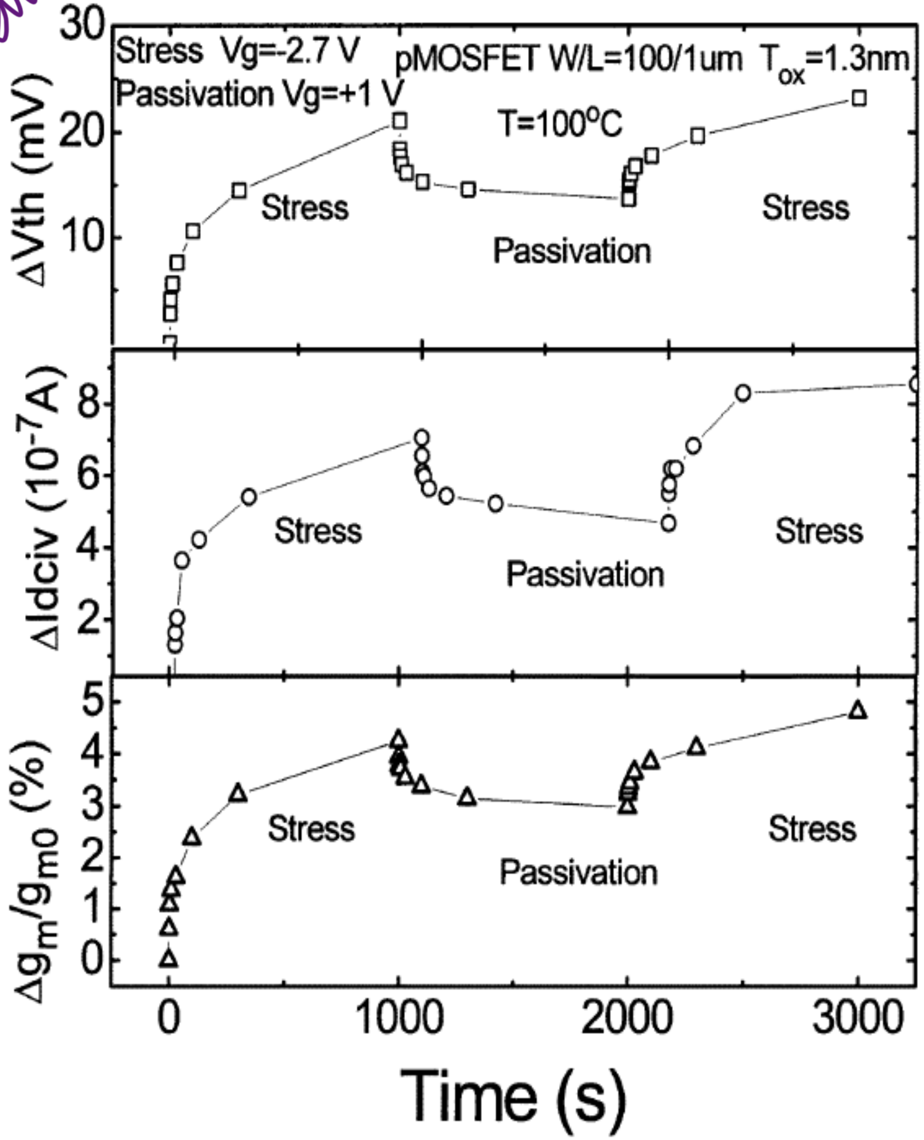


Reduction in I_{SUB} after stress seen in both SiO_2 and SiON: Indicates recovery of generated traps

Neugroschel, MR'07

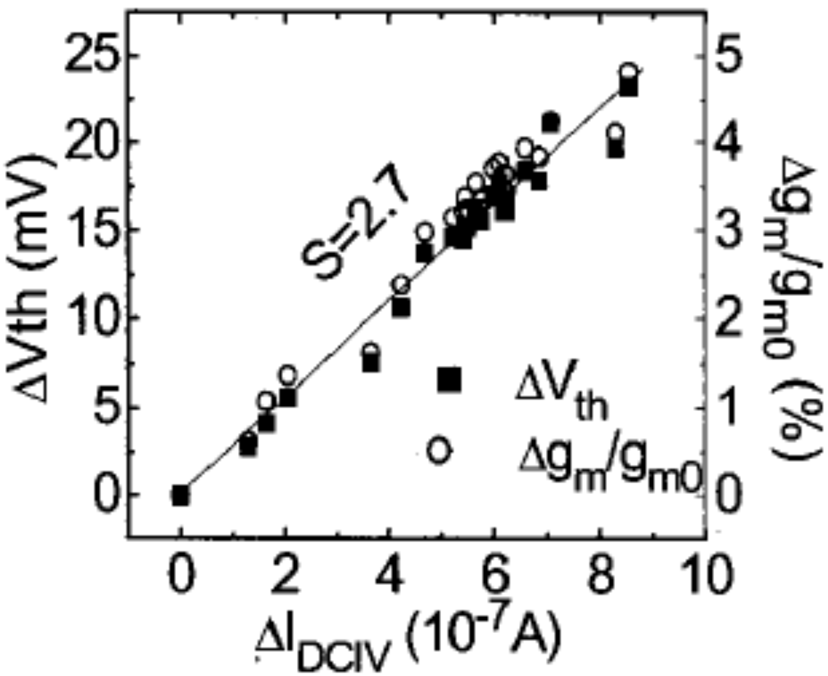
Correlation of Different Methods

We can see similar behavior among the three.

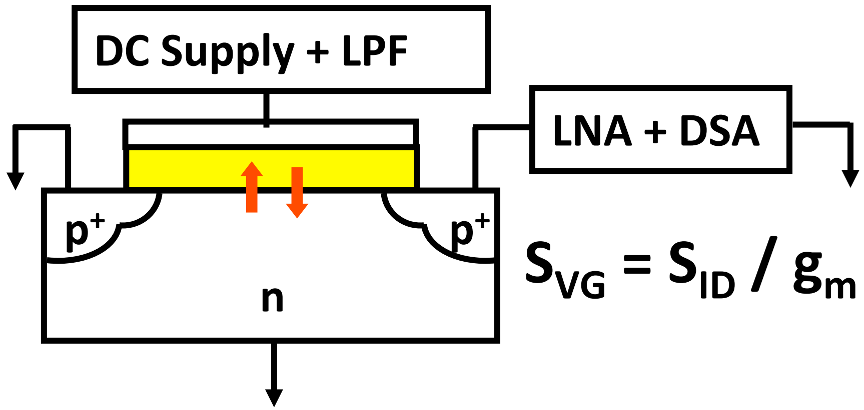


Good correlation of ΔI_{DCIV} to ΔV_T & Δg_m degradation during stress and recovery

Chen, EDL'02



Flicker Noise (Pre-Existing Traps)



LPF: Low Pass Filter
LNA: Low Noise Amplifier
DSA: Dynamic Signal Analyzer

Flicker noise due to trapping/ detrapping of channel carriers in oxide traps

Measure I_D power spectral density (how much signal at a given frequency) versus frequency at low gate overdrive

Flicker Noise (Pre-Existing Traps)

Number fluctuation → Fluctuation in channel carriers due to trapping / detrapping

Mobility fluctuation → Fluctuation in mobility due to scattering

Mixed model → Due to both

Hung, TED'90

Scattering coefficient

Inversion carrier density

$$S_{VG} = \frac{kT * q^2}{\lambda * f * (WL) * C_{OX}^2}(1+\alpha\mu N_C)^2 * N_T(E_{FN})$$

Waveform attenuation factor

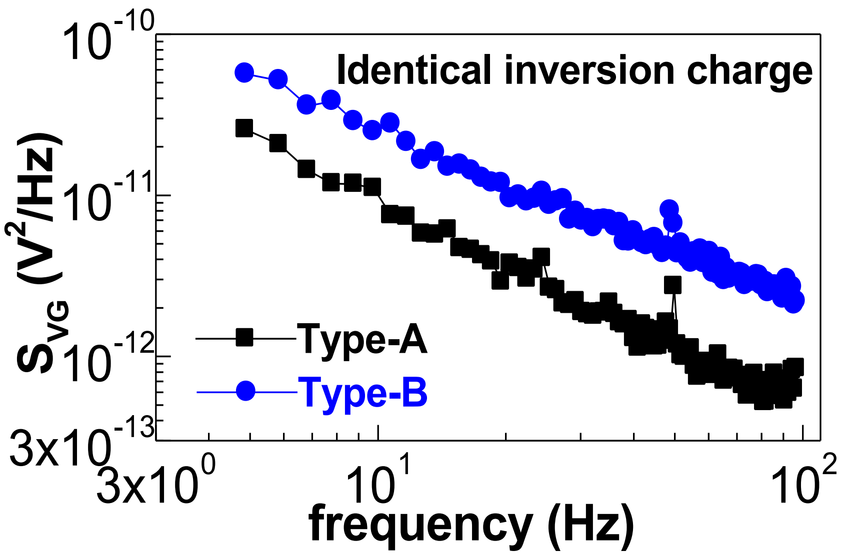
Mobility

Trap density at Fermi level

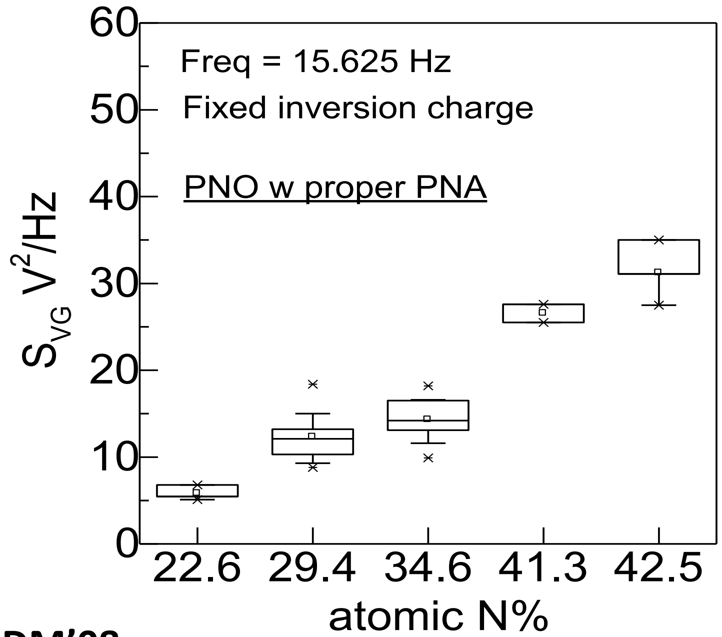
Flicker Noise (Pre-Existing Traps)

Flicker noise due to trapping/ detrapping of channel carriers in oxide traps

High pre-existing hole trap density for certain (type-B) devices

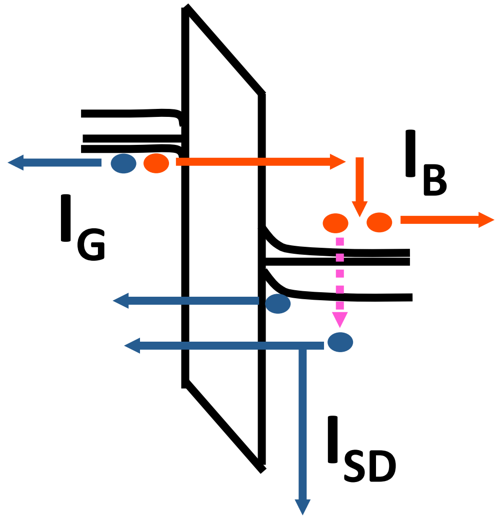


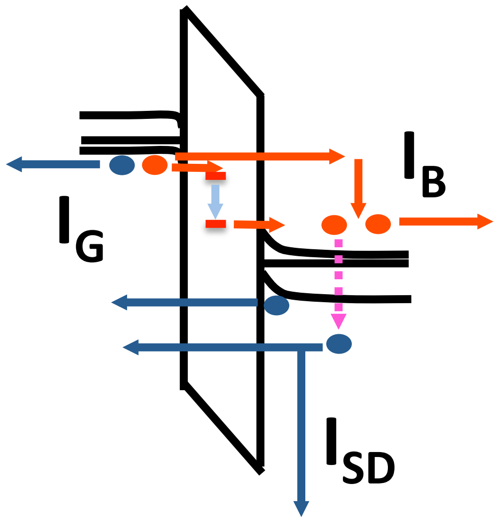
Increase in pre-existing hole trap density with N density



Kapila, IEDM'08

Gate Tunneling During NBTI (V_G < 0)





Carrier separation measurement

Electrons tunnel from gate to substrate (C.B.), holes tunnel from S/D → substrate (V.B.) to gate

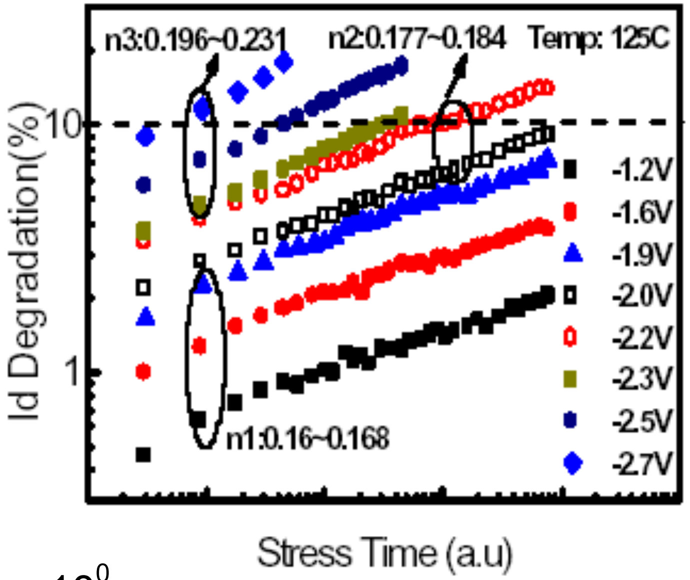
Electrons impact ionize in substrate and create EHP (high V_G and/or V_B), additional hole current to gate

electron hole pair

Stress Induced Leakage Current (SILC) → Trap assisted tunneling in the presence of bulk traps

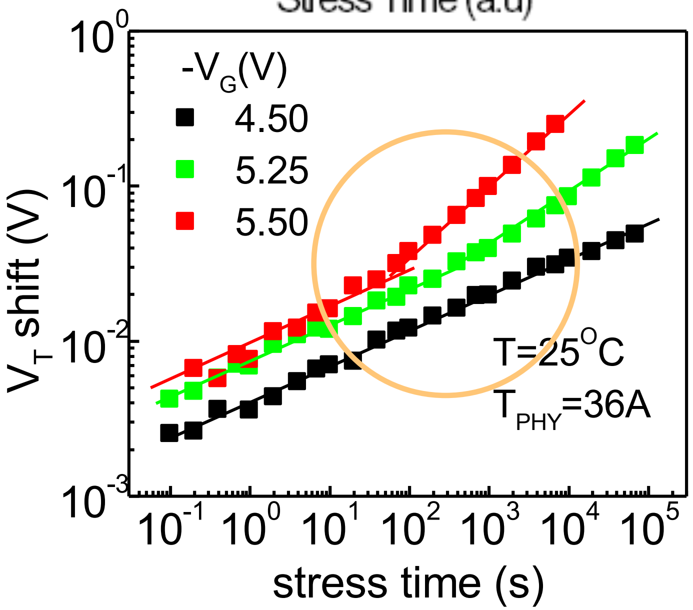
due to traps it easier for tunneling

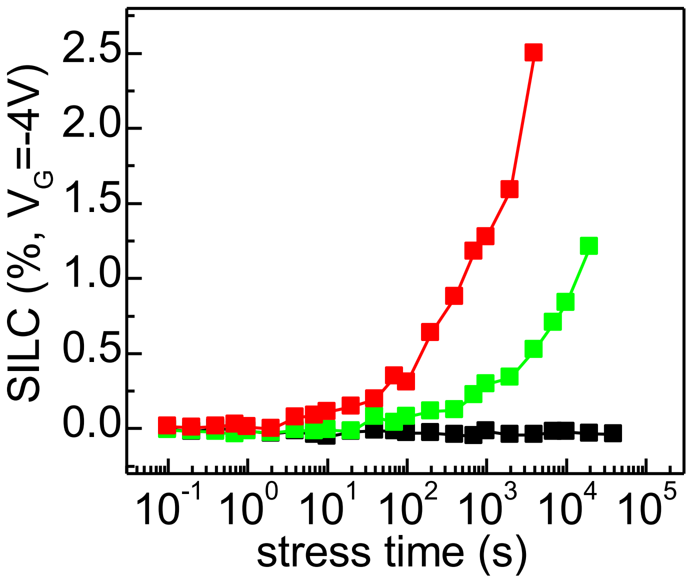
NBTI and SILC (Bulk Trap Generation)



Chen IRPS'05

Higher time slope at larger stress bias → Appearance of SILC (generated bulk traps)



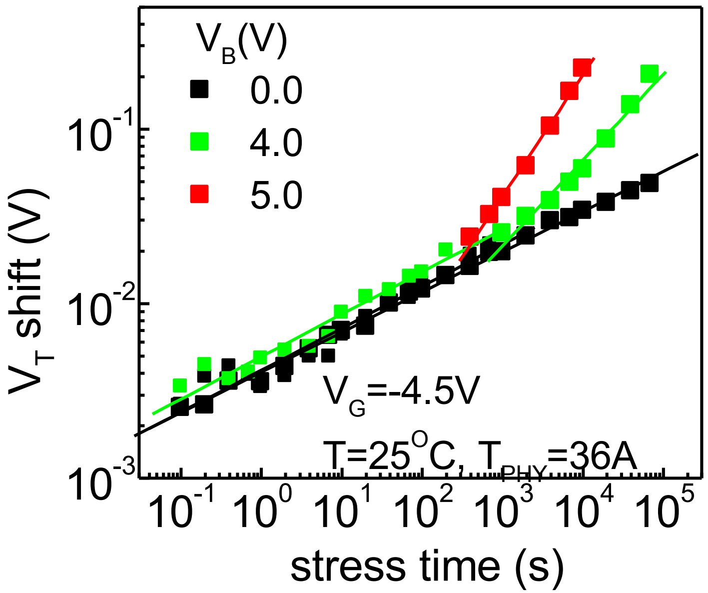


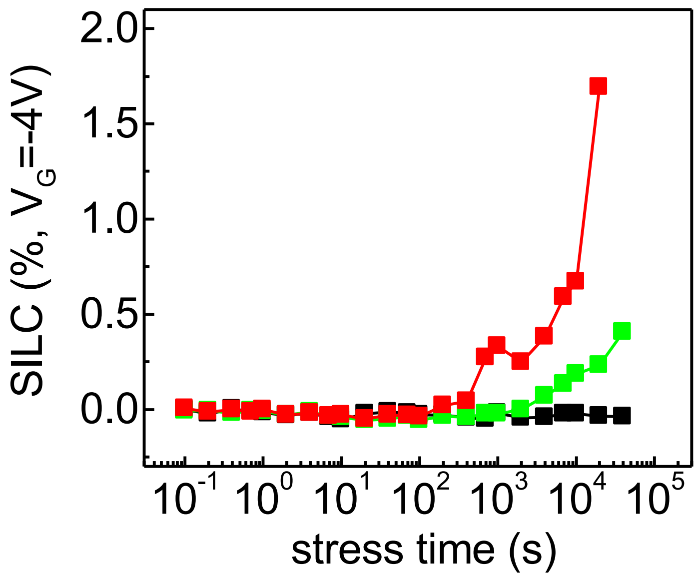
Mahapatra, IEDM'02

NBTI and SILC (Bulk Trap Generation)

Higher slope and SILC when substrate is reverse bias

High energy, not high field effect



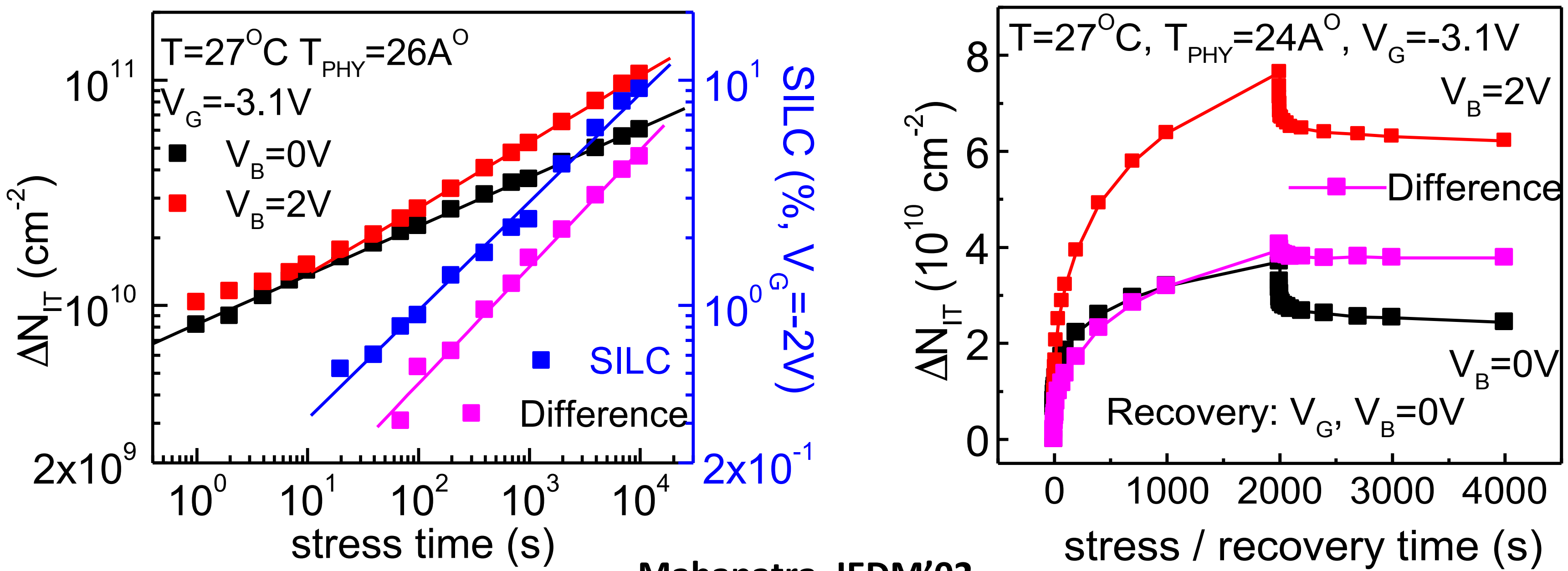


Mahapatra, IEDM'02

NBTI and SILC (Bulk Trap Generation)

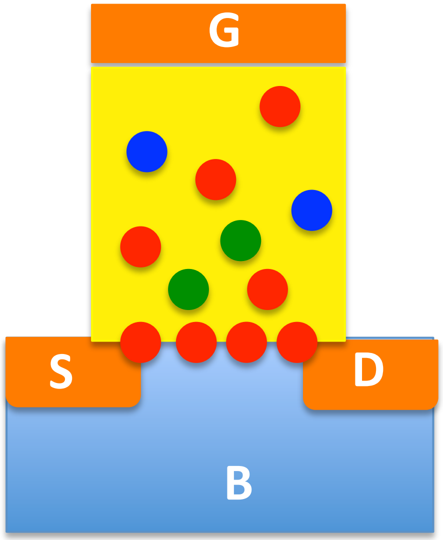
Higher slope and SILC when substrate is reverse bias, high energy, not high field effect

No recovery of additional traps



Mahapatra, IEDM'02

Summary (NBTI).....



Breaking of H passivated defects at channel/oxide interface and oxide bulk (red dots)

Hole trapping in pre-existing defects inside gate oxide (green dots), higher (relative) contribution when N is high

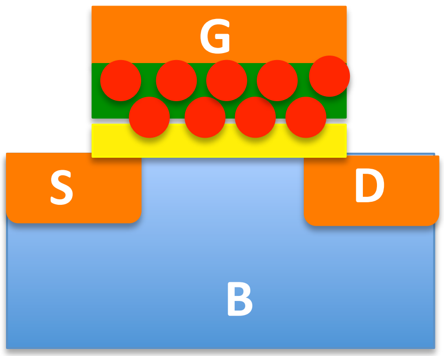
Breaking of Si-O-Si bonds in oxide bulk and generation of bulk traps

Each with unique n, VAF and E_A, determine overall NBTI

Summary (Measurement Methods)....

	Gate Stimulus	Measure	Monitor
Flicker Noise	Fixed bias close to V_T	Drain current power spectral density	Traps in IL and HK
DCIV	Sweep from accumulation to inversion	S/D current due to trap assisted electron-hole recombination	Traps near channel in IL and IL/HK transition
SILC	Fixed bias close to V_{DD}	Gate current due to trap assisted tunneling	Traps in HK and IL/HK transition layer

Positive Bias Temperature Instability



Degradation of drain current

Uniform degradation, observed for only HKMG (SiON/HfO_2) gate stacks → Now of lesser importance

Negative charges at SiO_2/HfO_2 interface and HfO_2 bulk → Positive V_T shift

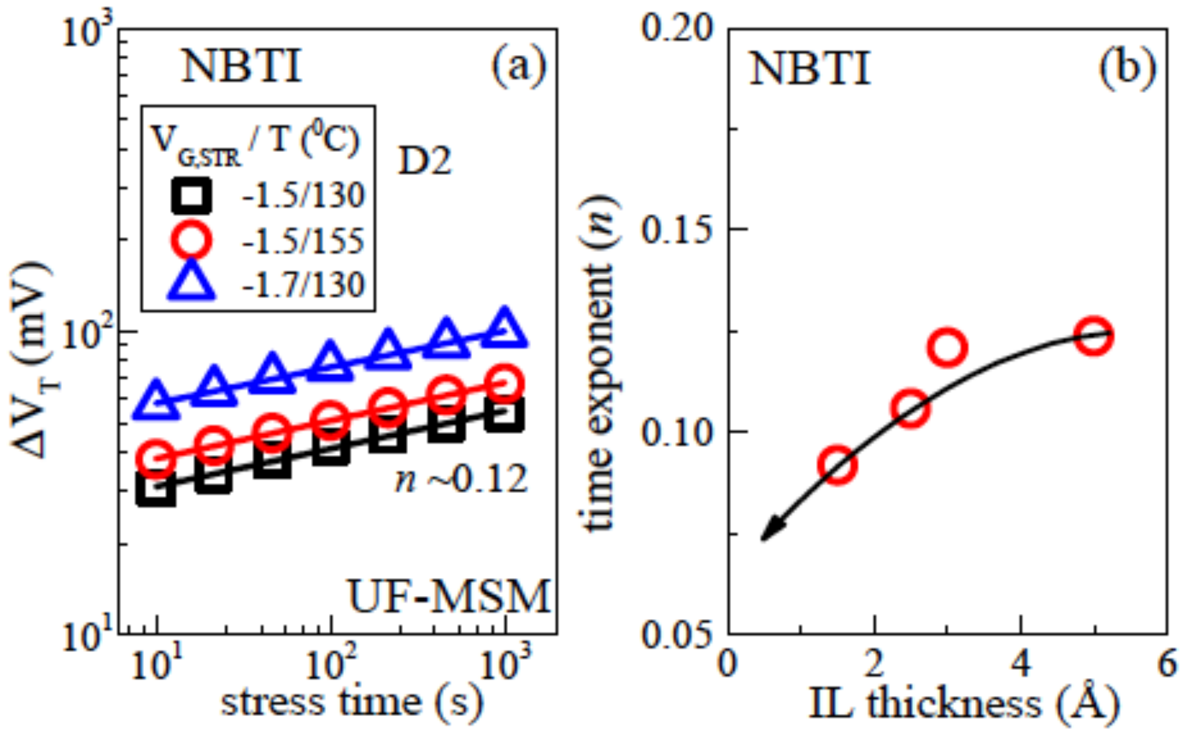
Absence of transconductance (g_m) degradation

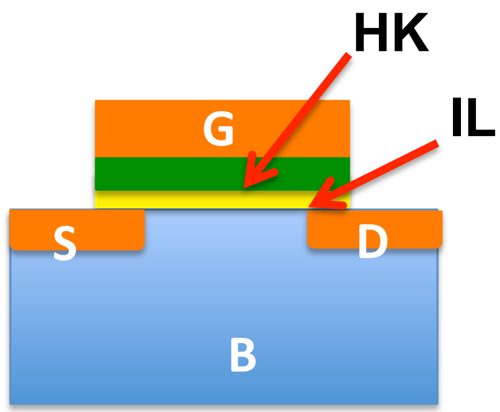
NBTI in p-MOSFET

Slides 53-75:
Mahapatra, IRPS'14
(tutorial)

Power-law time dependence

Time exponent (*n*) reduces for thinner IL

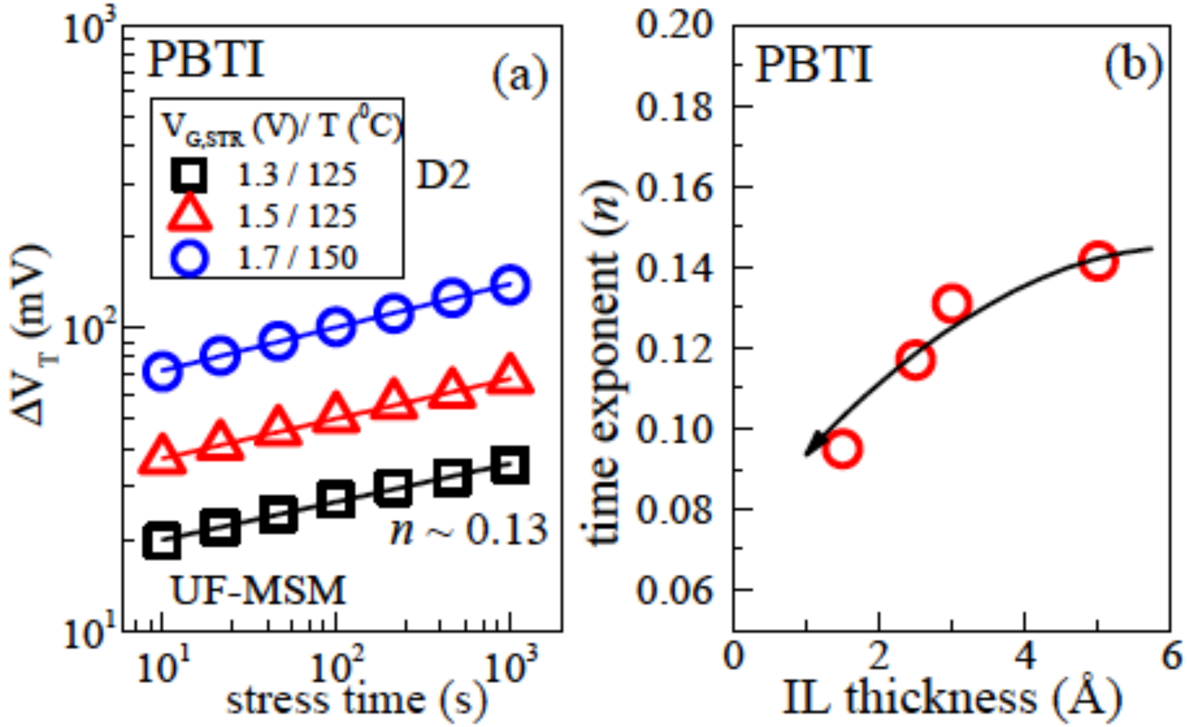




PBTI in n-MOSFET

Power-law time dependence

Time exponent (*n*) reduces for thinner IL

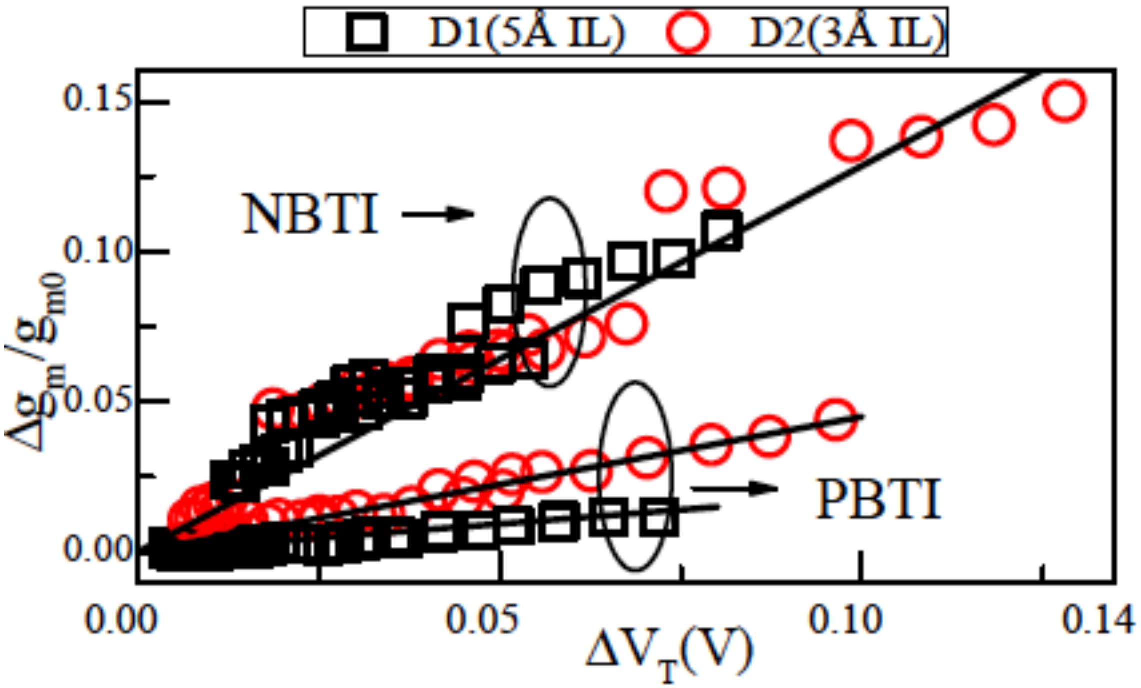


Similarity of *n* between NBTI and PBTI

Transconductance Degradation

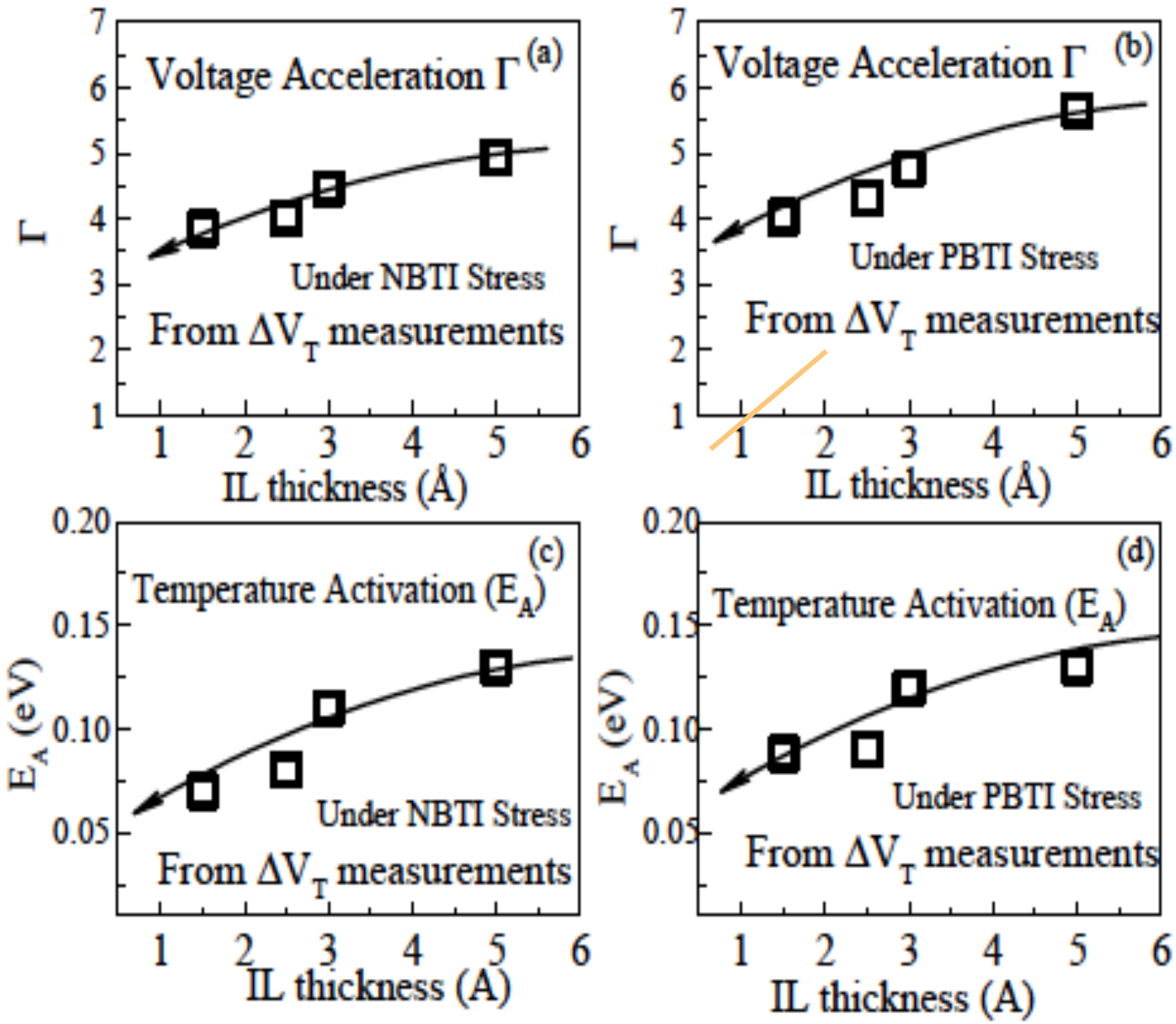
NBTI: Large g_m degradation, independent of IL thickness

PBTI: Negligible g_m degradation



NBTI defects closer to channel than PBTI

Voltage and Temperature Dependence



Similar acceleration factors for NBTI and PBTI

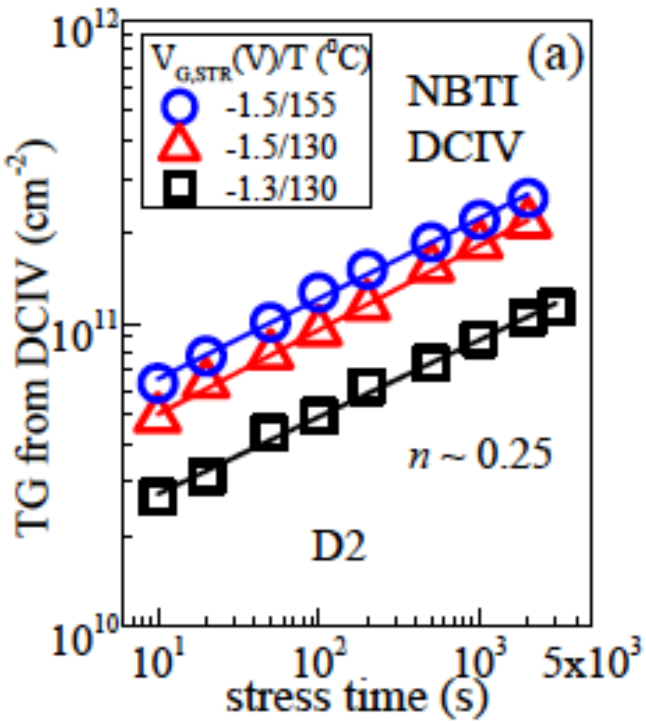
Reduction in Γ and E_A for thinner IL

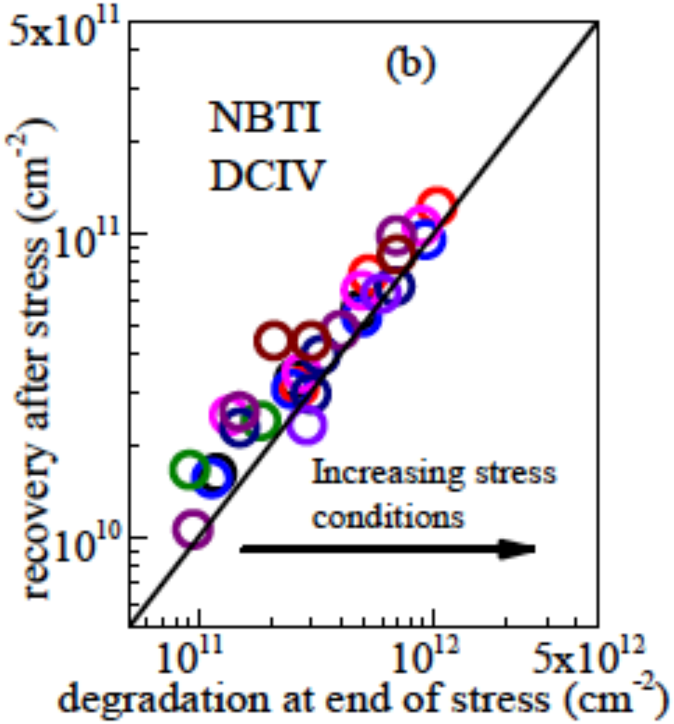
Nbti and pbti shows similar dependence on EA and Gamma

NBTI Trap Generation (DCIV)

Power-law time dependence for stress **Dc characteristics of mos fet**

Recovery of generated traps after stress



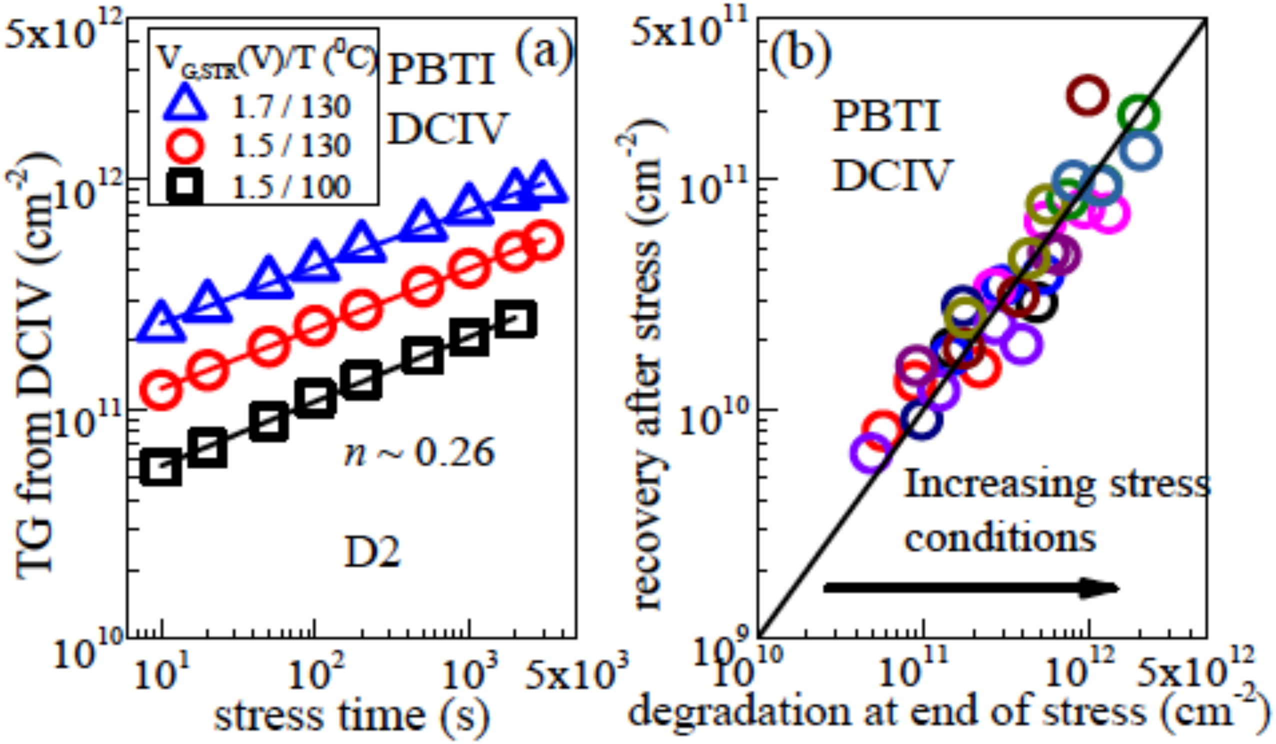


Universal correlation of generation and recovery across HKMG processes

PBTI Trap Generation (DCIV)

Power-law time dependence for stress, similar *n* as NBTI

Recovery of generated traps after stress

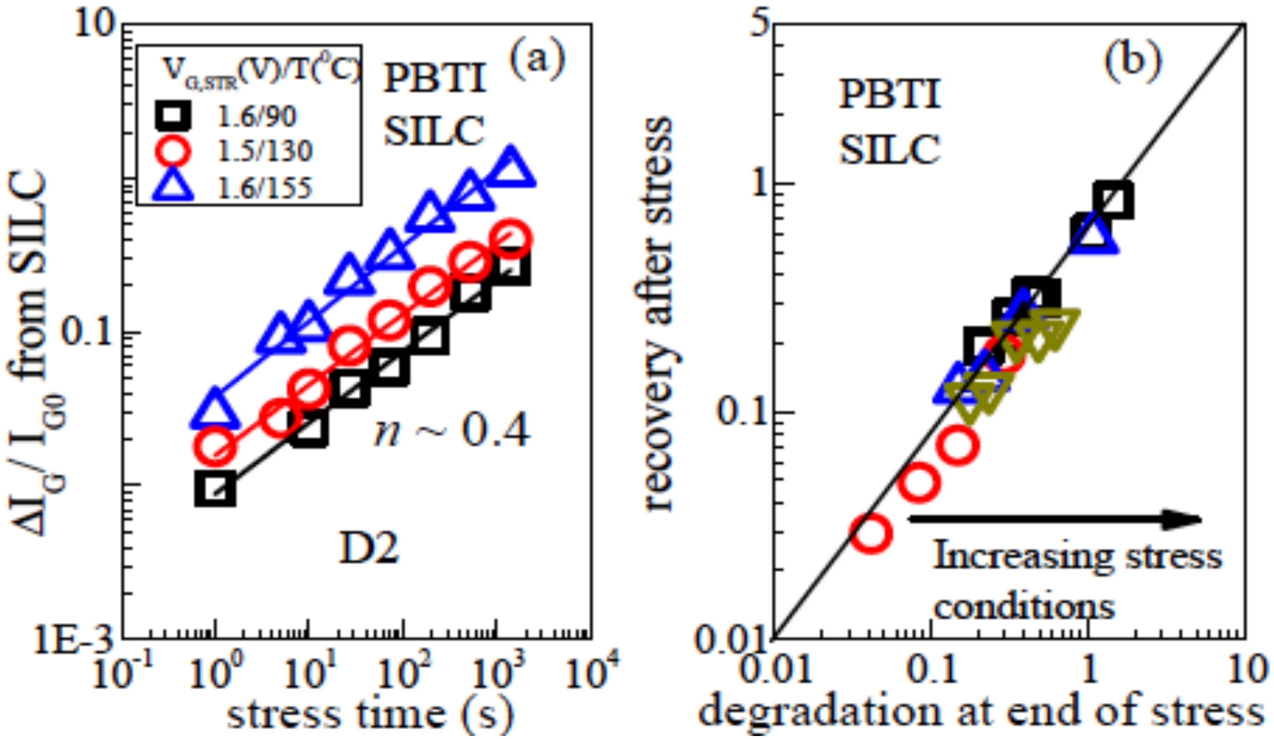


Universal correlation of generation and recovery across HKMG processes, similar ratio as NBTI

PBTI Trap Generation (SILC)

Power-law time dependence for stress, larger *n* w.r.t DCIV

Recovery of generated traps after stress

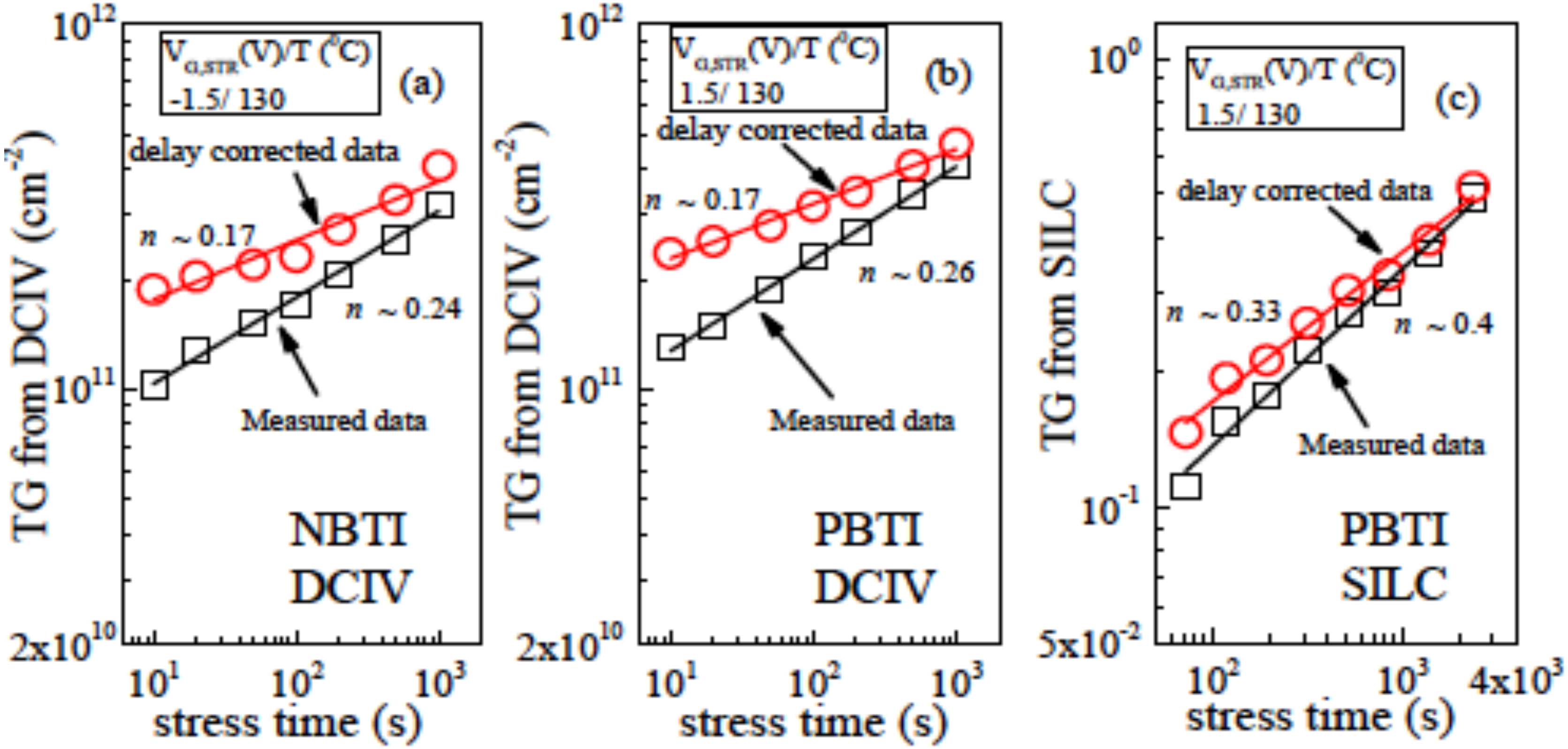


Universal correlation of generation and recovery across HKMG processes, different ratio than DCIV

Slope Correction of Slow MSM Data

Similar *n* from DCIV for NBTI and PBTI **stress induced likage current**

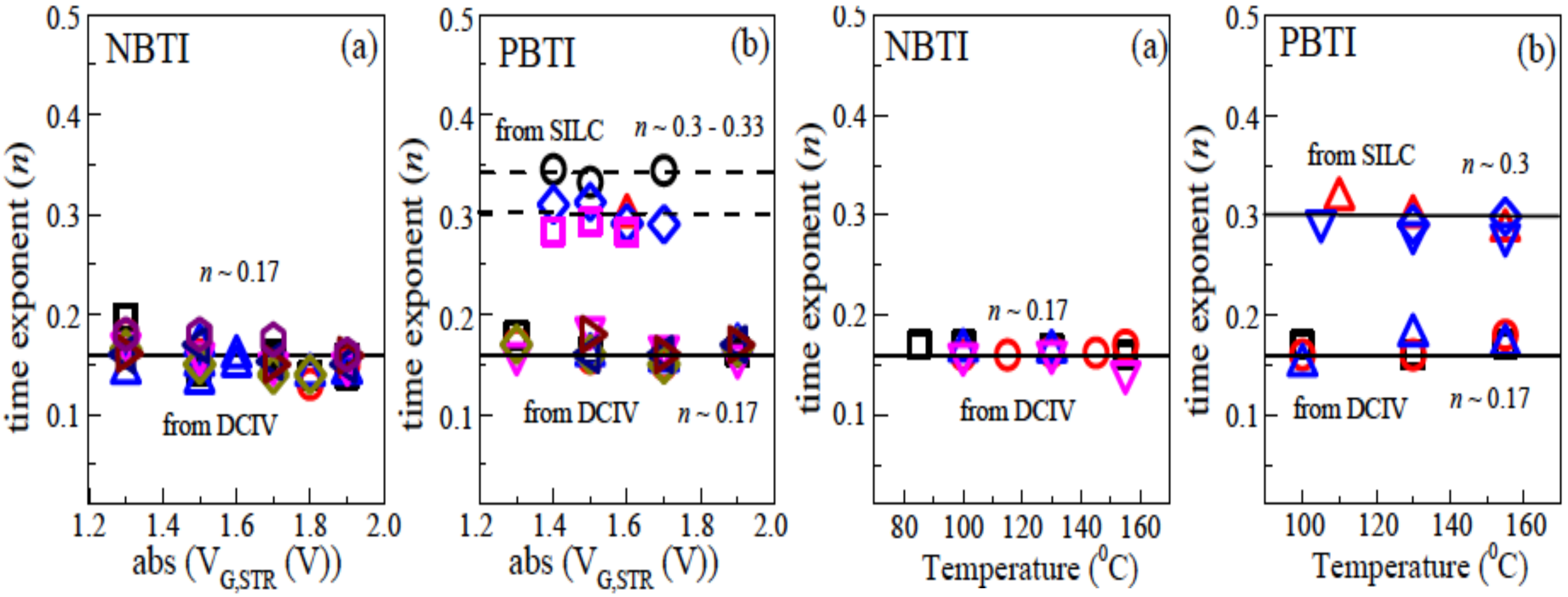
Much larger *n* from SILC compared to DCIV for PBTI



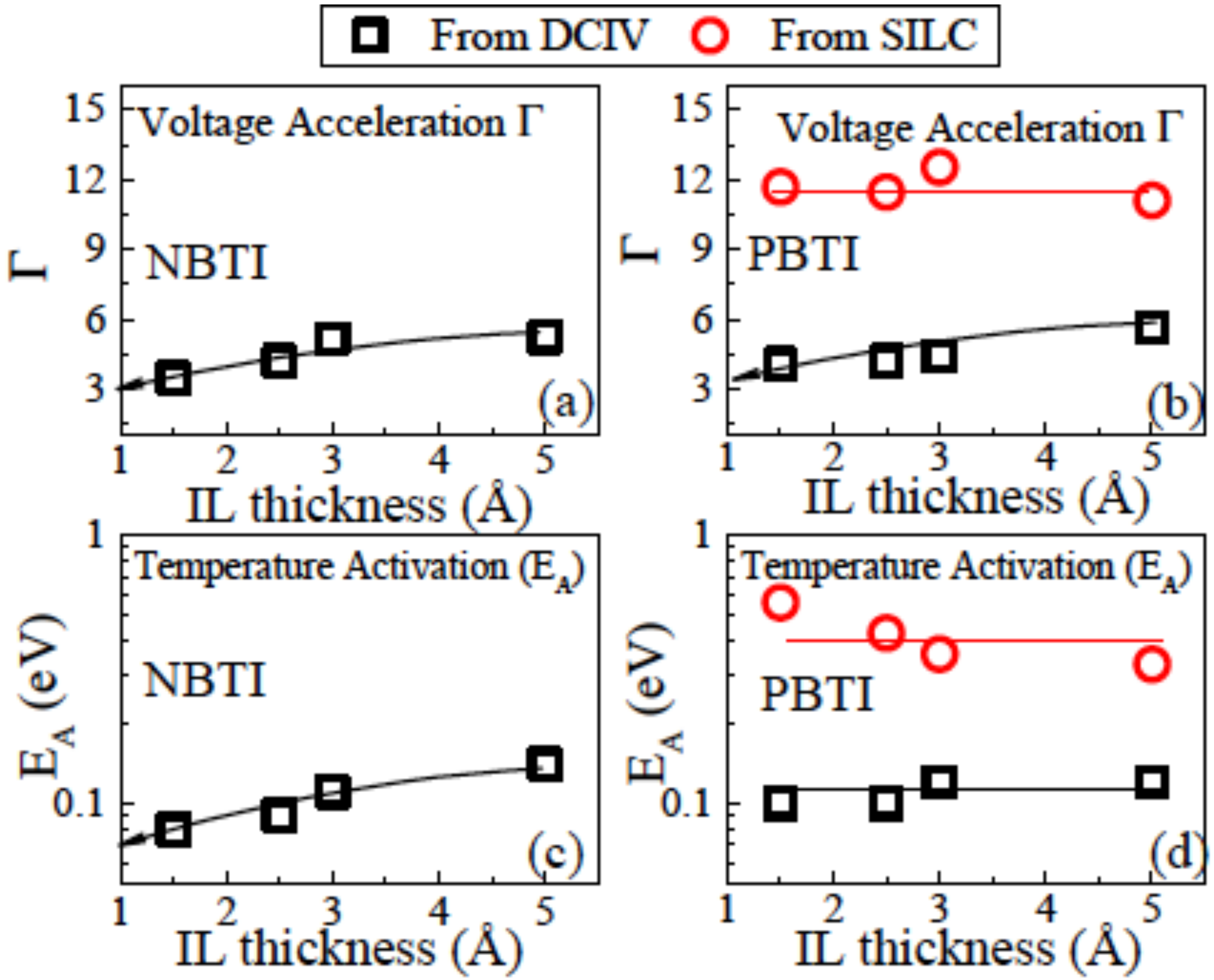
HKMG Process: Power-law Time Exponent

Similar n from DCIV for NBTI and PBTI; much larger n from SILC for PBTI

Universal feature across different HKMG processes



Voltage and Temperature Dependence



Similar acceleration factors from DCIV for NBTI and PBTI

Much larger acceleration factors from SILC for PBTI

Parameter Summary

	n (power law)	E_A (eV)	Γ (power law)
NBTI DVT	0.08 – 0.12	0.07 – 0.11	4 – 5
PBTI DVT	0.09 – 0.14	0.08 – 0.13	4 – 5.5
NBTI DCIV	0.17	0.08 – 0.13	4 – 5
PBTI DCIV	0.17	0.11 – 0.15	4 – 5.5
PBTI SILC	0.25 – 0.35	0.3 – 0.4	12

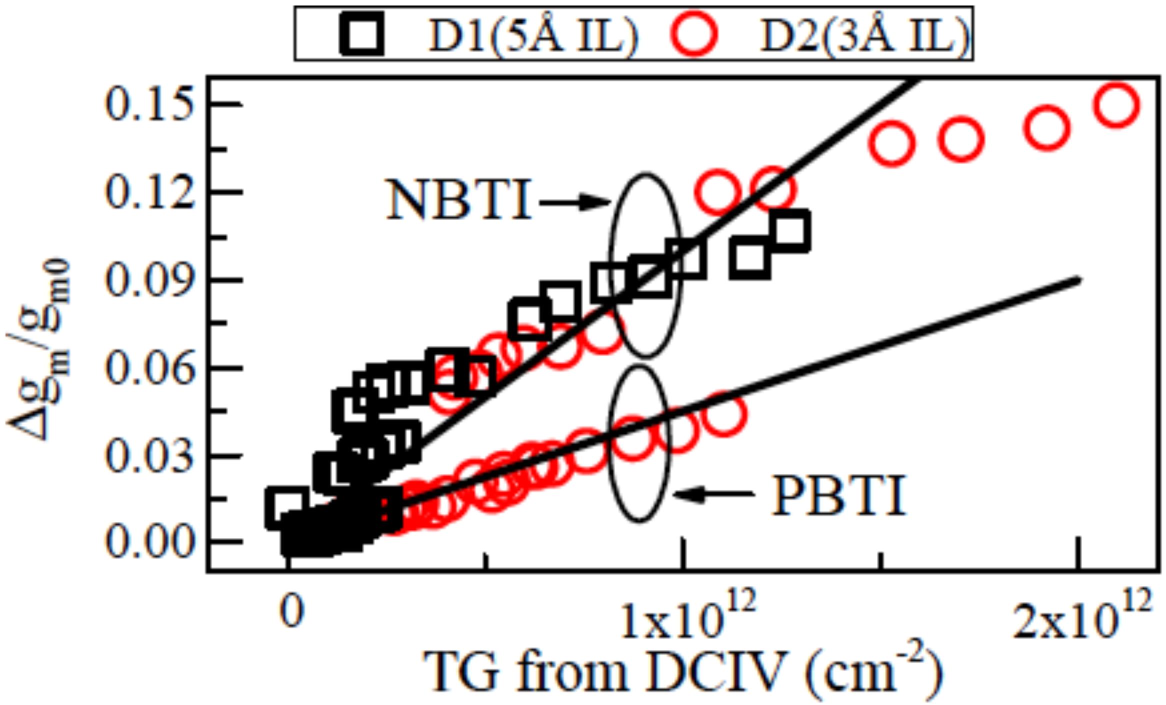
Trap generation probed by DCIV has more impact on BTI, similar dynamics for NBTI and PBTI

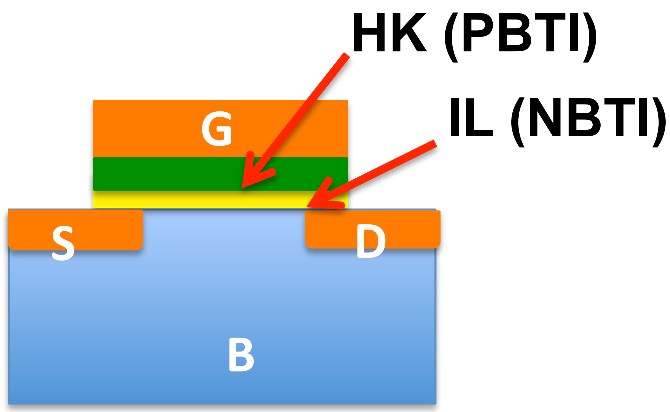
SILC and PBTI has weak (negligible) correlation

Transconductance Degradation

Generated traps results in larger g_m degradation for NBTI than PBTI

NBTI trap generation closer to channel than PBTI

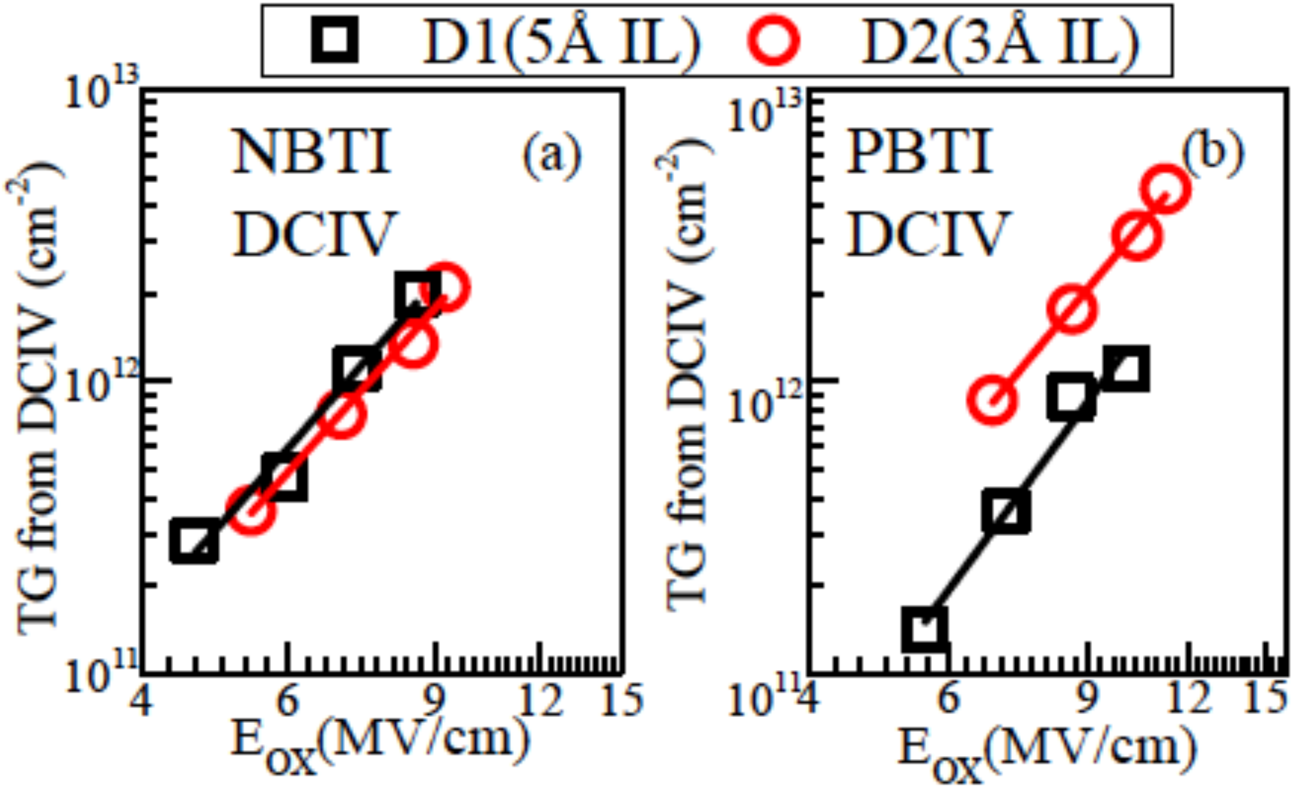




DCIV: Impact of IL Thickness

HK comes closer to channel as IL is scaled

Increase in PBTI trap generation, no NBTI impact



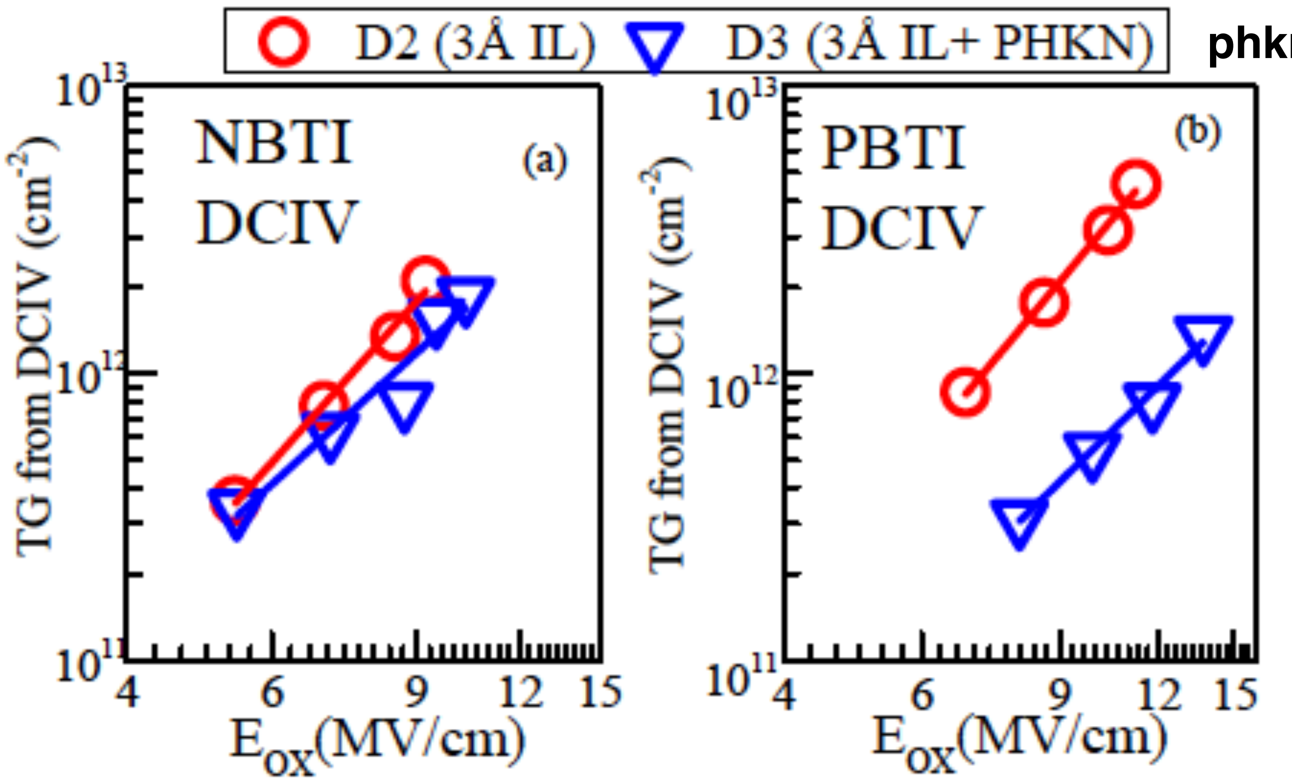
Trap generation:

NBTI → IL
PBTI → HK

DCIV: Impact of Post HK Nitridation

Larger Nitrogen in HK compared to IL

Large reduction of PBTI trap generation, no NBTI impact



phkn: post hk nitration

Trap generation:TG

impacted by

NBTI → IL

PBTI → HK

no impact of nitration on nbti

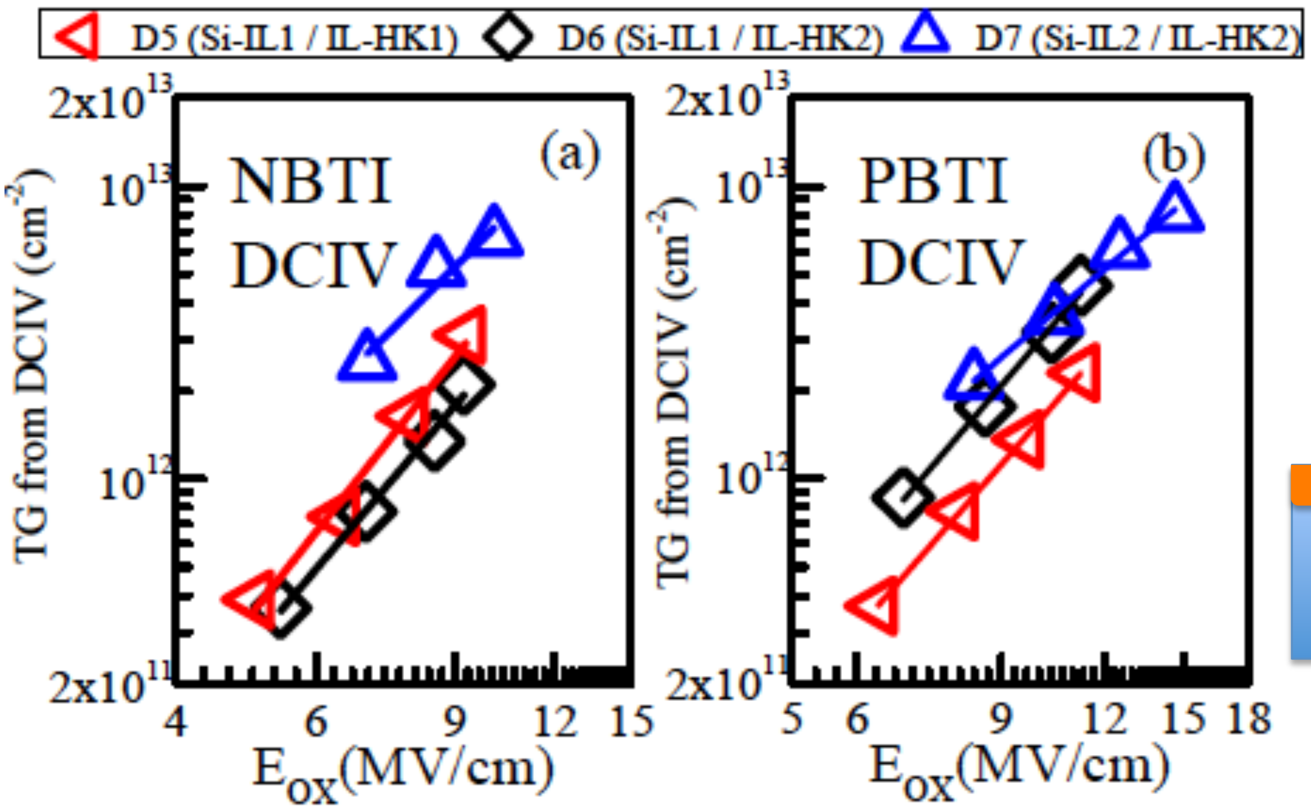
DCIV: Impact of Surface Treatment

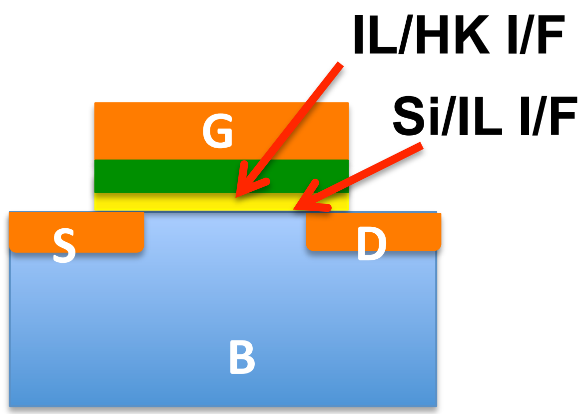
IL/HK interface: Impacts PBTI, not NBTI

Si/IL interface: Impacts NBTI, not PBTI

Trap generation:

NBTI → IL
PBTI → HK

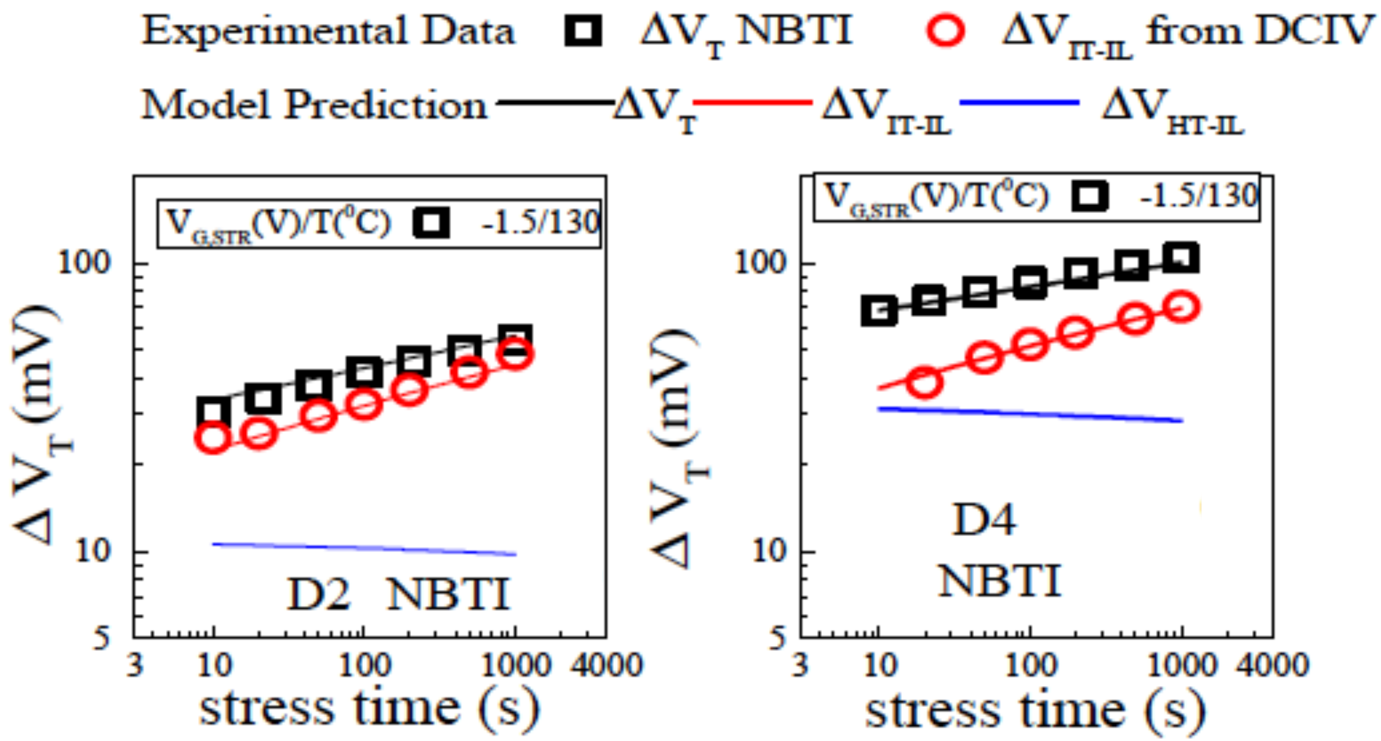




Compact Model (NBTI)

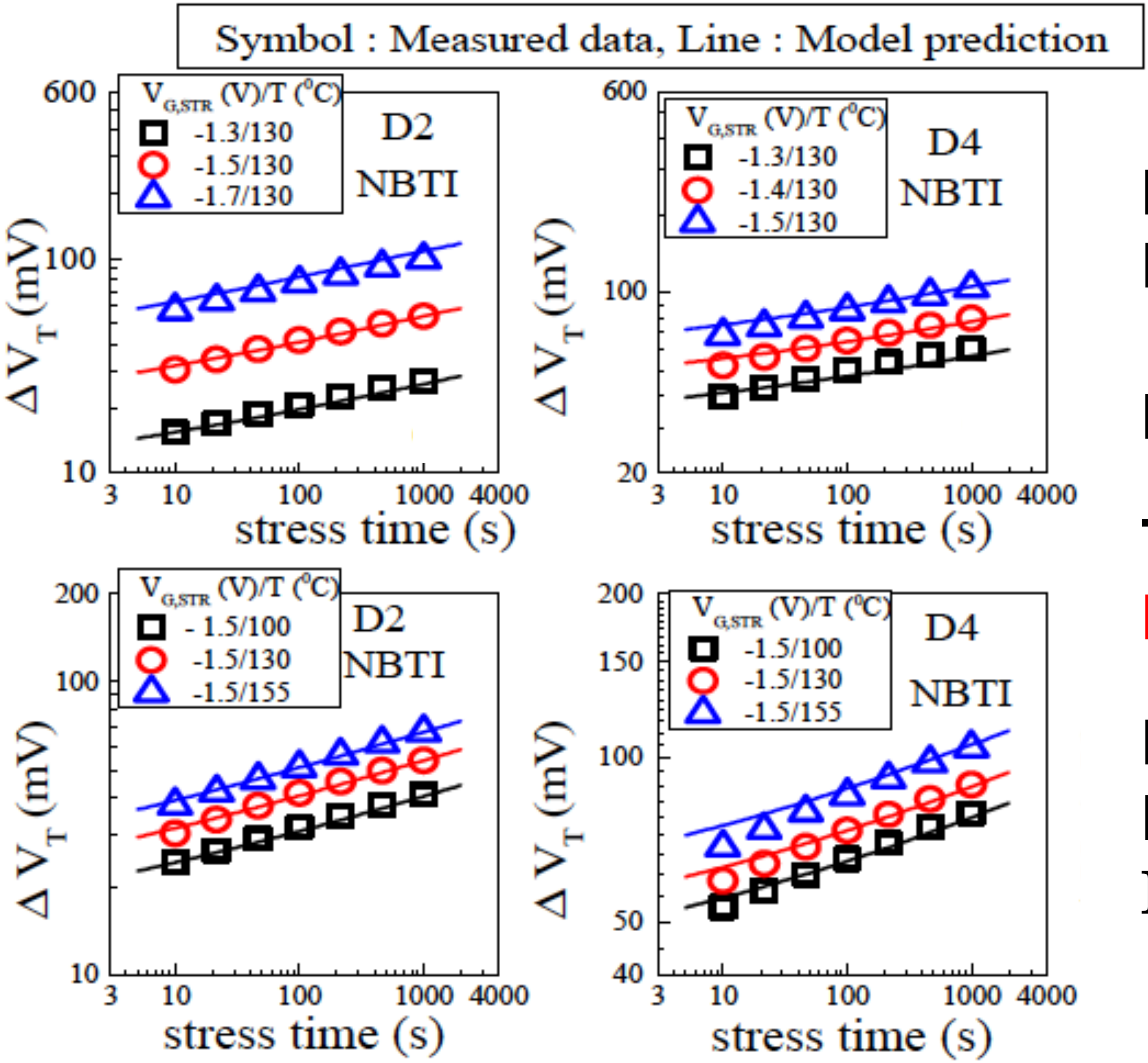
Si/IL trap generation (A*t^0.17) + IL hole trapping (B)

A, B: Arrhenius T activation; power-law or exponential E_{OX} dependence



Modeled $\Delta V_{IT\text{-}IL}$ component verified with DCIV data

Compact Model Prediction (NBTI)



D4 has higher IL Nitrogen content

Parameters (4 free):

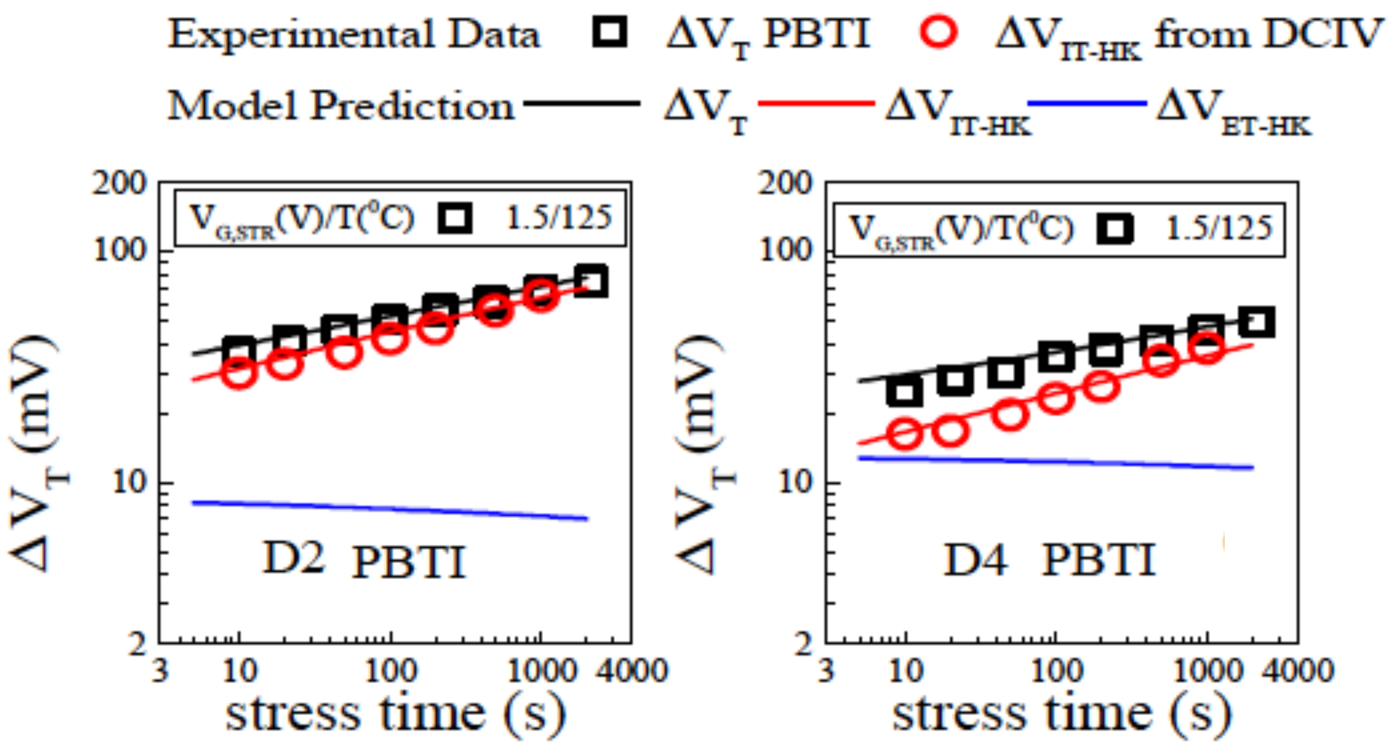
Trap generation: A, $E_{A,IT}$ and Γ_{IT}

Hole trapping: B, $E_{A,HT}$ (~0.05eV) and Γ_{HT} (=Γ_{IT})

Compact Model (PBTI)

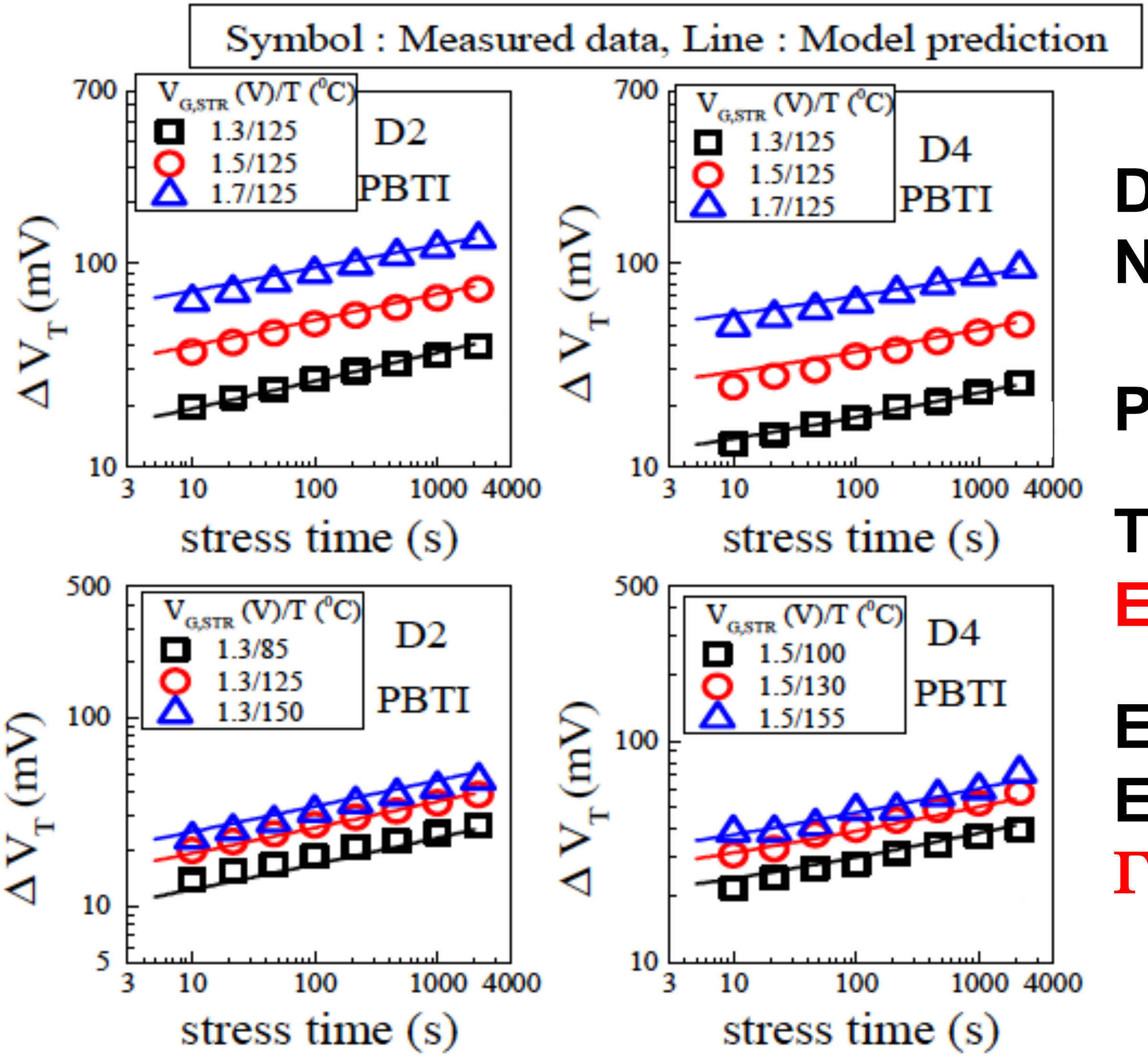
IL/HK trap generation (A*t^0.17) + HK electron trapping (B)

A, B: Arrhenius T activation; power-law or exponential E_{OX} dependence



Modeled $\Delta V_{IT\text{-}HK}$ component verified with DCIV data

Compact Model Prediction (PBTI)



D4 has higher IL Nitrogen content

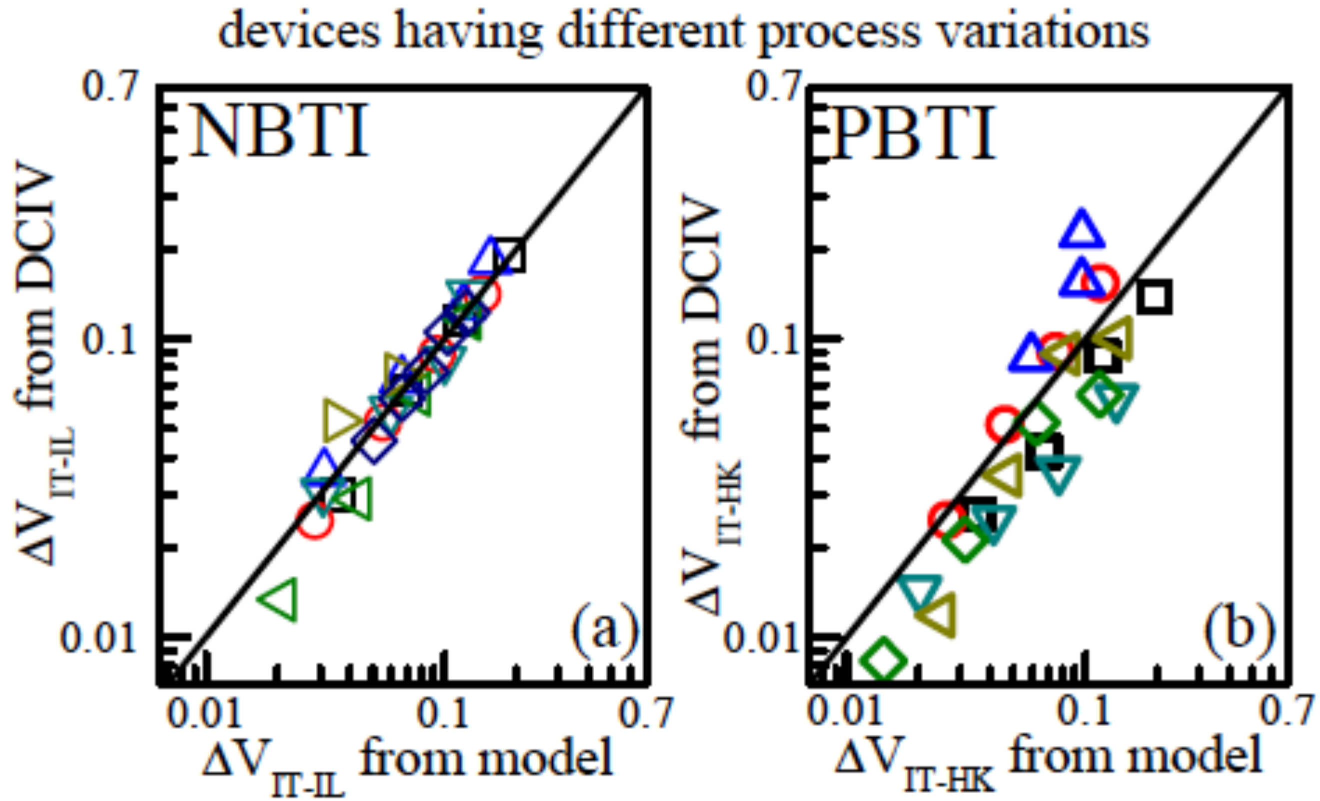
Parameters (5 free):

Trap generation: A, $E_{A,IT}$ and Γ_{IT}

Electron trapping: B, $E_{A,ET}$ (~0.05eV) and Γ_{ET}

Trap-Generation Sub-Component

Modeled trap generation sub-component is verified using DCIV measurements for different HKMG splits

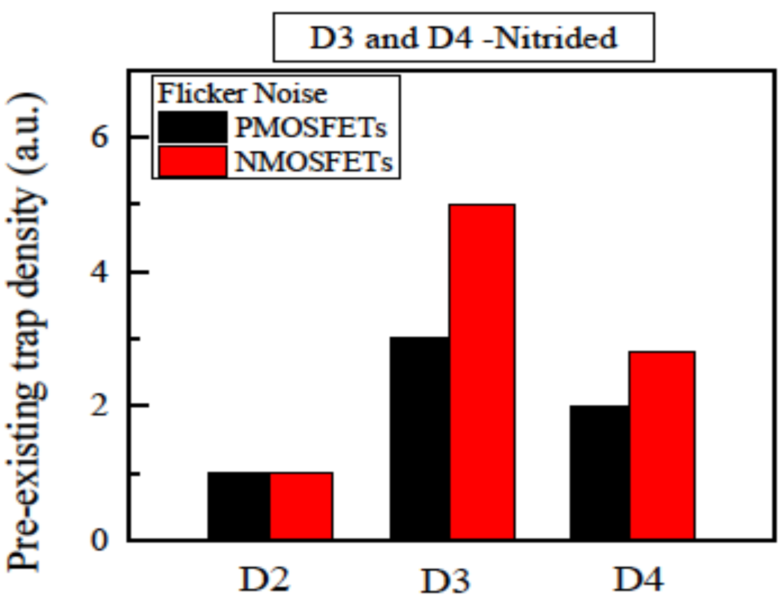


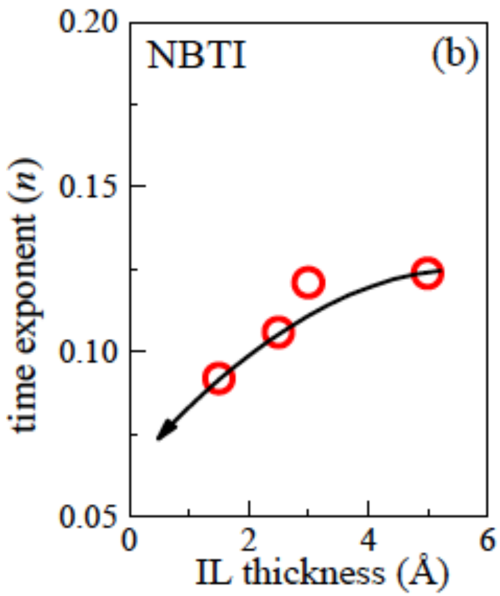
DCIV: Corrected for delay and band-gap differences

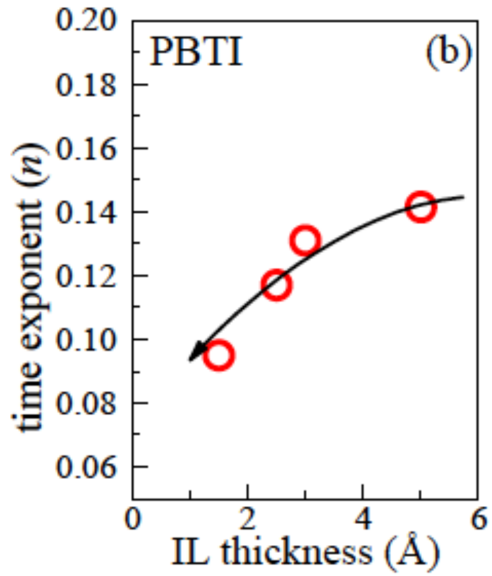
Trapping Sub-Component

Higher hole trapping (in IL) for NBTI and electron trapping (in HK) for PBTI for stacks containing Nitrogen

Trapping saturates at long time; higher trapping reduces time exponent (*n*) for Nitrogen based scaled IL stacks

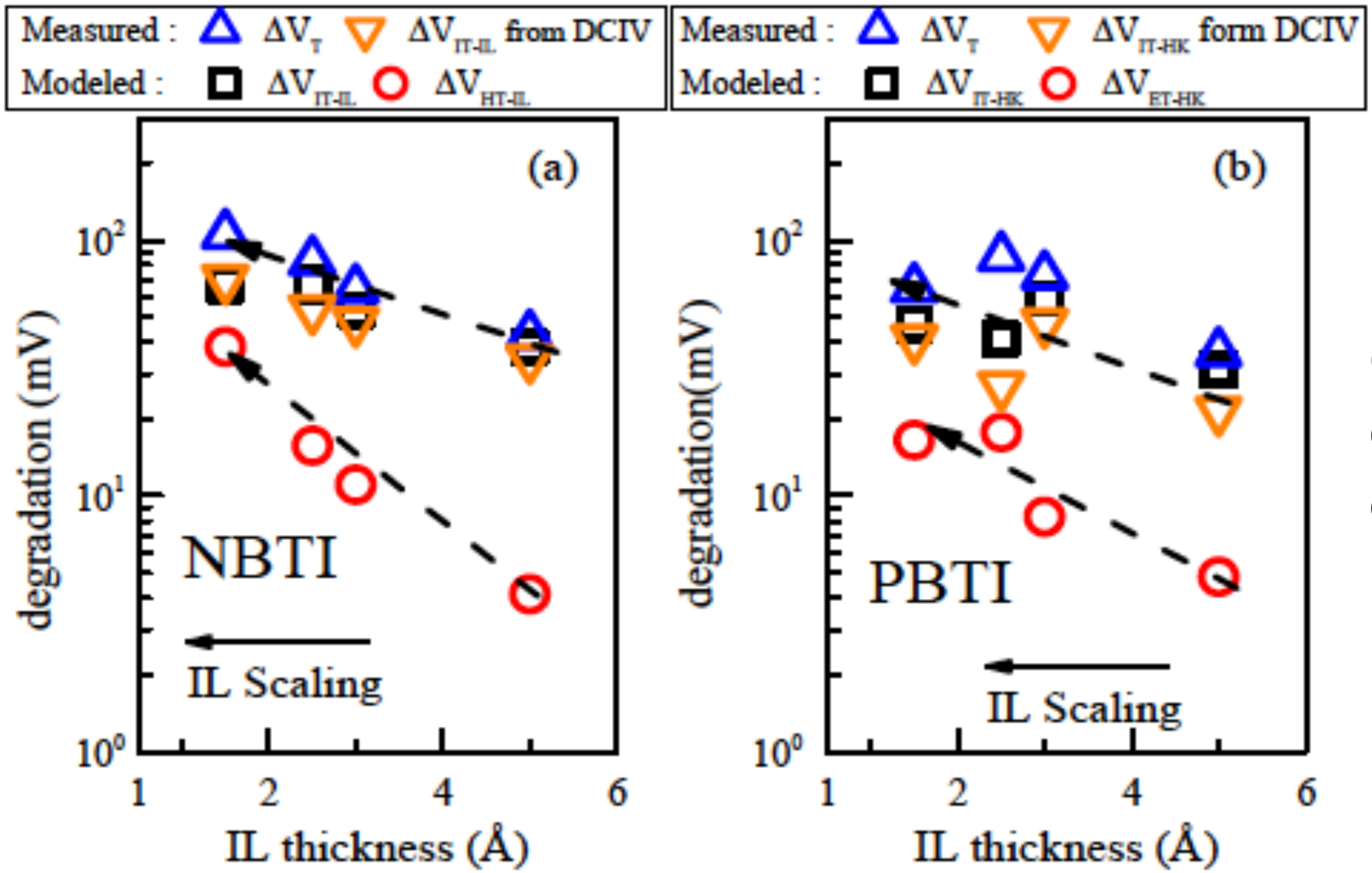






IL Scaling Impact on BTI Sub-Components

Relatively larger increase in trapping as IL is scaled



Constant gate bias overdrive

Summary – BTI Physical Mechanism

NBTI: Trap generation and hole trapping in IL

PBTI: Trap generation and electron trapping in HK

Mutually uncoupled trap generation and trapping

Similar trap generation (DCIV probe) dynamics for NBTI and PBTI

SILC has negligible correlation to PBTI

Nitridation reduces HK trap generation (PBTI), increases trapping of holes (NBTI) and electrons (PBTI)