KYOTO INSTITUTE OF TECHNOLOGY

Defect-Oriented Degradations in Recent VLSIs : Random Telegraph Noise, Bias Temperature Instability and Total Ionizing Dose

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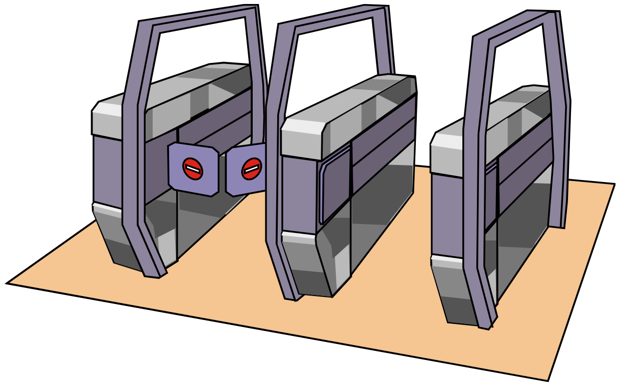
Kobayashi Lab.

Agenda

- Introduction
- RTN: Random Telegraph Noise
- BTI: Bias Temperature Instability
- TID: Total Ionizing Dose
- Summary

Dependability & Serviceability

- Our daily-life highly depends on embedded systems



Transportation

Banking

- Big problems when failures happen

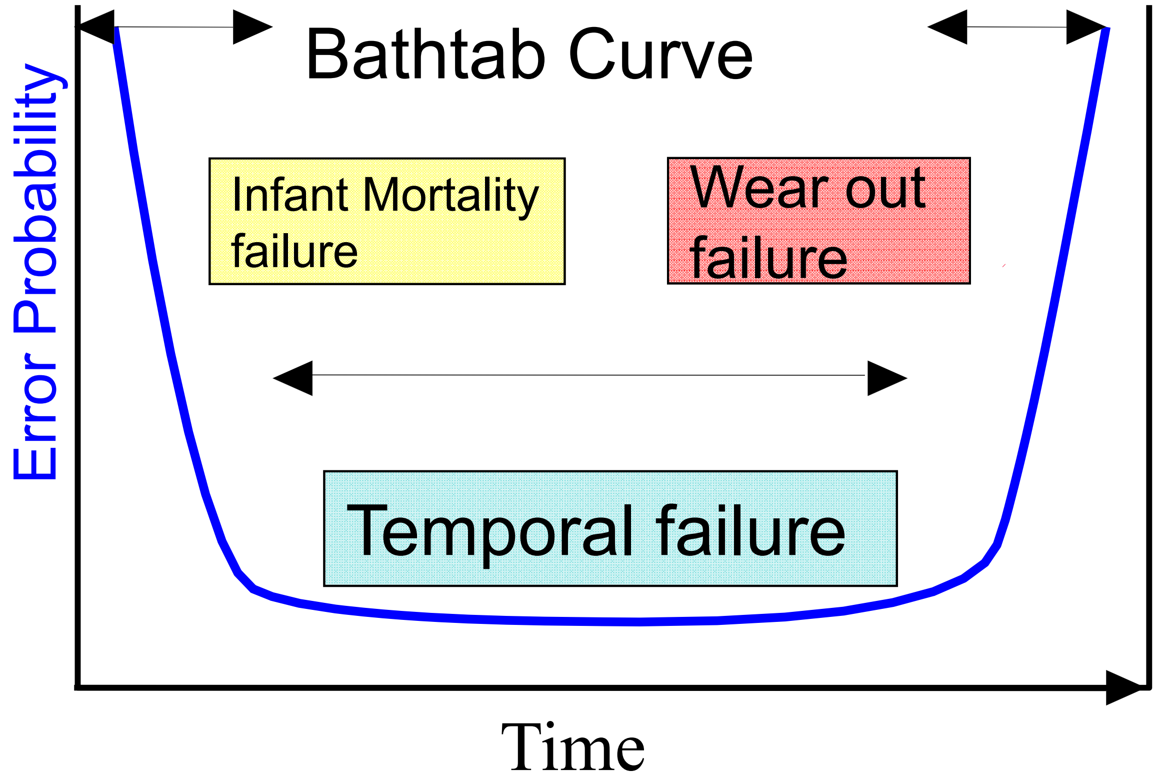
2 million affected

Dec. 2007
Trouble on a train system

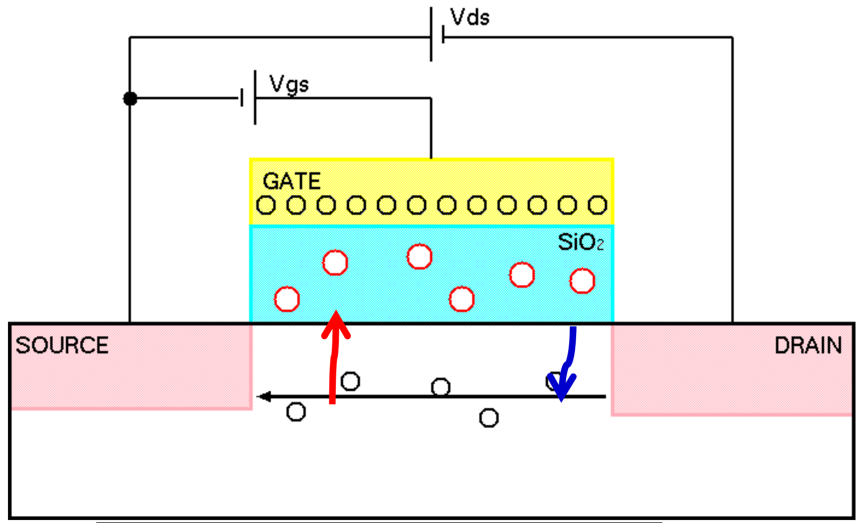
50 planes stopped

Jan 2013
Trouble on 787 airplane

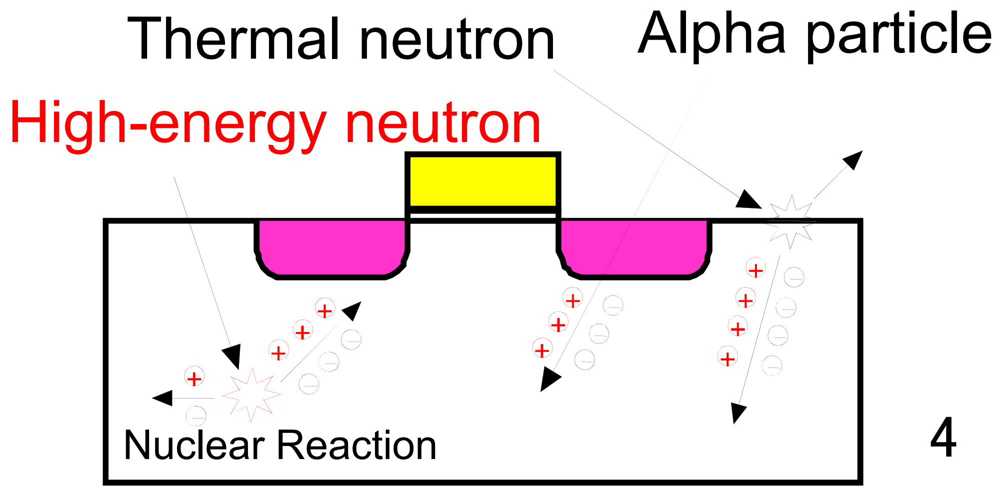
Reliability Issues in VLSIs



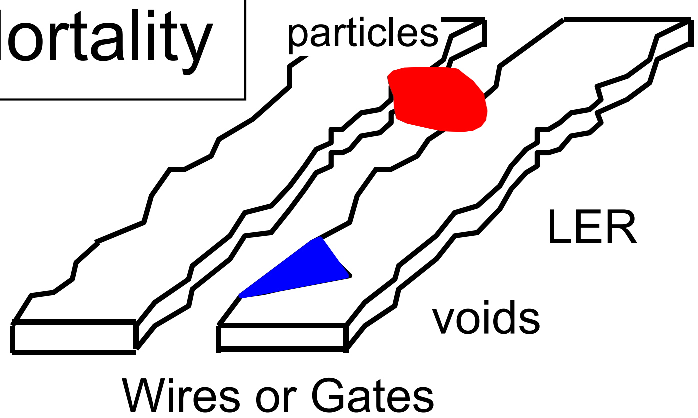
Wear Out (BTI)



Temporal (SEE)



Infant Mortality



Three Topics Related to Defects

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Bias-induced Temporal Fluctuation

- RTN
  - Random Telegraph (Signal) Noise

Stress-induced Aging Degradation

- BTI
  - Bias Temperature Instability

Radiation-induced Aging Degradation

- TID
  - Total Ionizing Dose

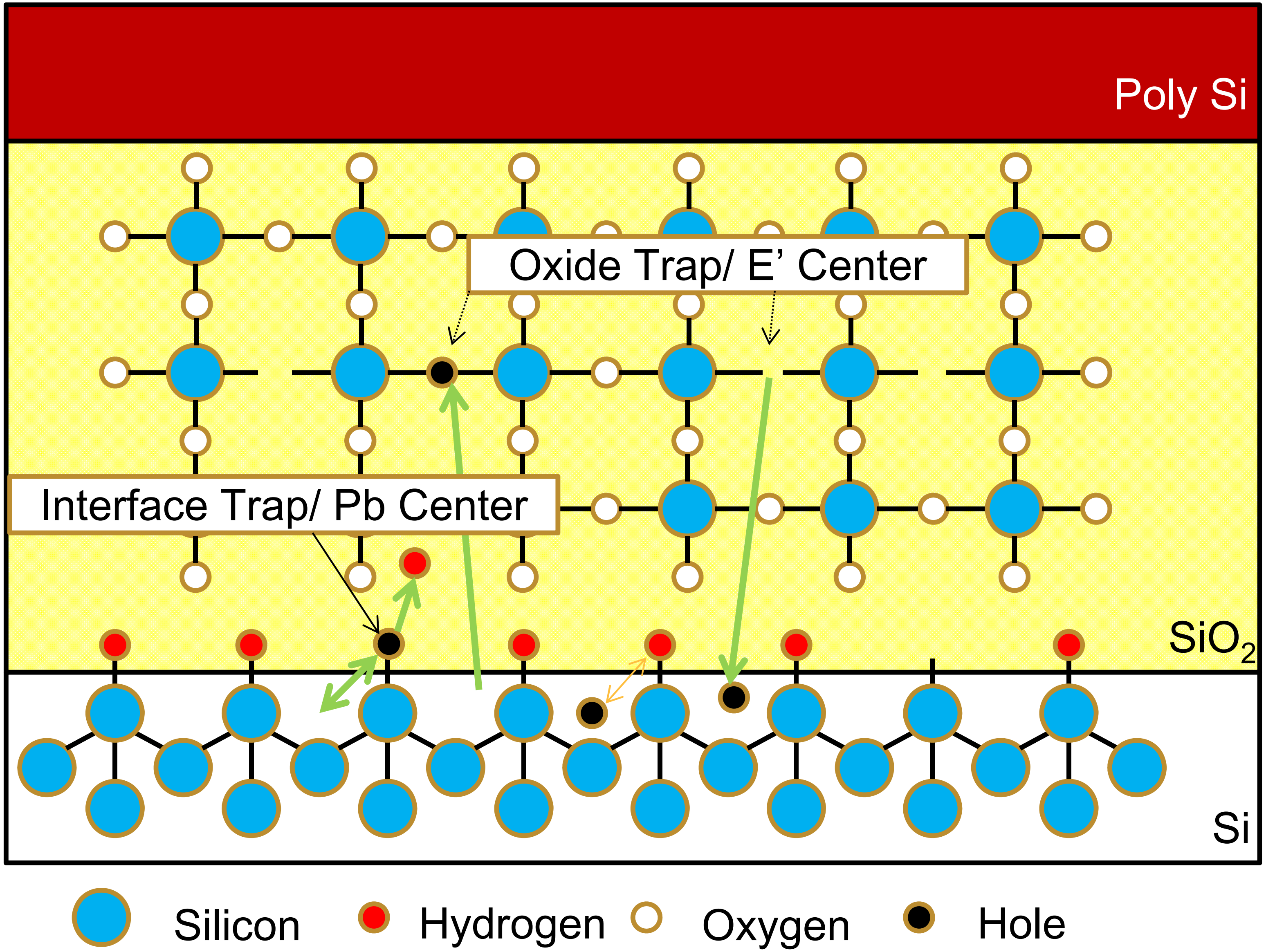
CMOS Technology Scaling

CMOS Technology Scaling					Gate Dielectrics
before 180nm	HCI				SiO_2
90 ~ 65nm	HCI	NBTI			SiON
40nm	HCI	NBTI	PBTI		High-k
32 ~ 14nm	HCI	NBTI	PBTI	RTN	High-k

HCI: Hot Carrier Injection
NBTI: Negative BTI on PMOS
PBTI: Positive BTI on NMOS
RTN: Random Telegraph Noise

- Aggressive scaling worsens reliability

Traps (Defects) in Gate Oxide



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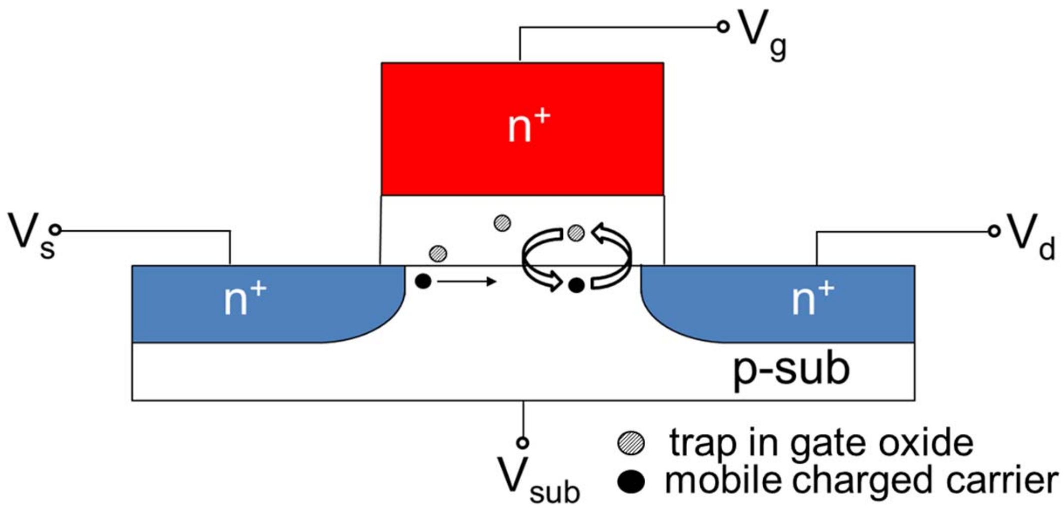
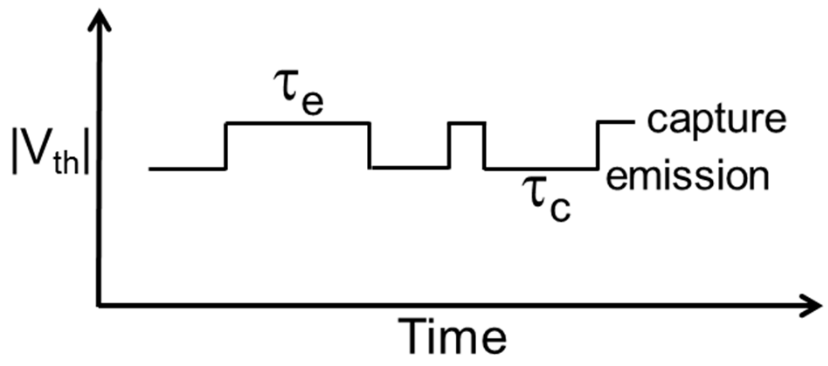
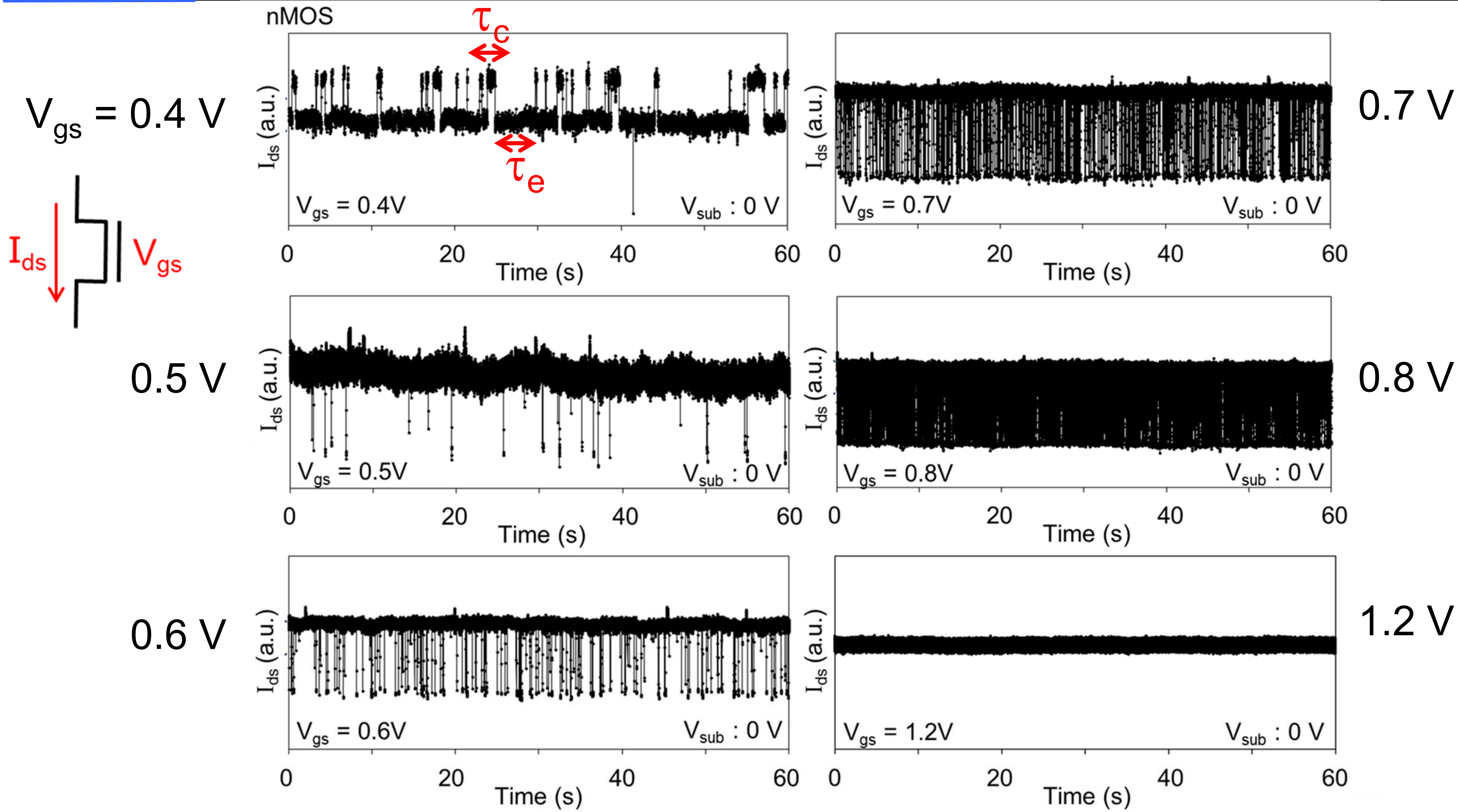
Random Telegraph Noise

- Charged carriers are captured (trapped) or emitted (detrapped) in oxide traps.
- Vth (transistor current) fluctuates temporarily.
- τ_e: time to emission , τ_c: time to capture
- Serious in CCD (Charge Coupled Device)



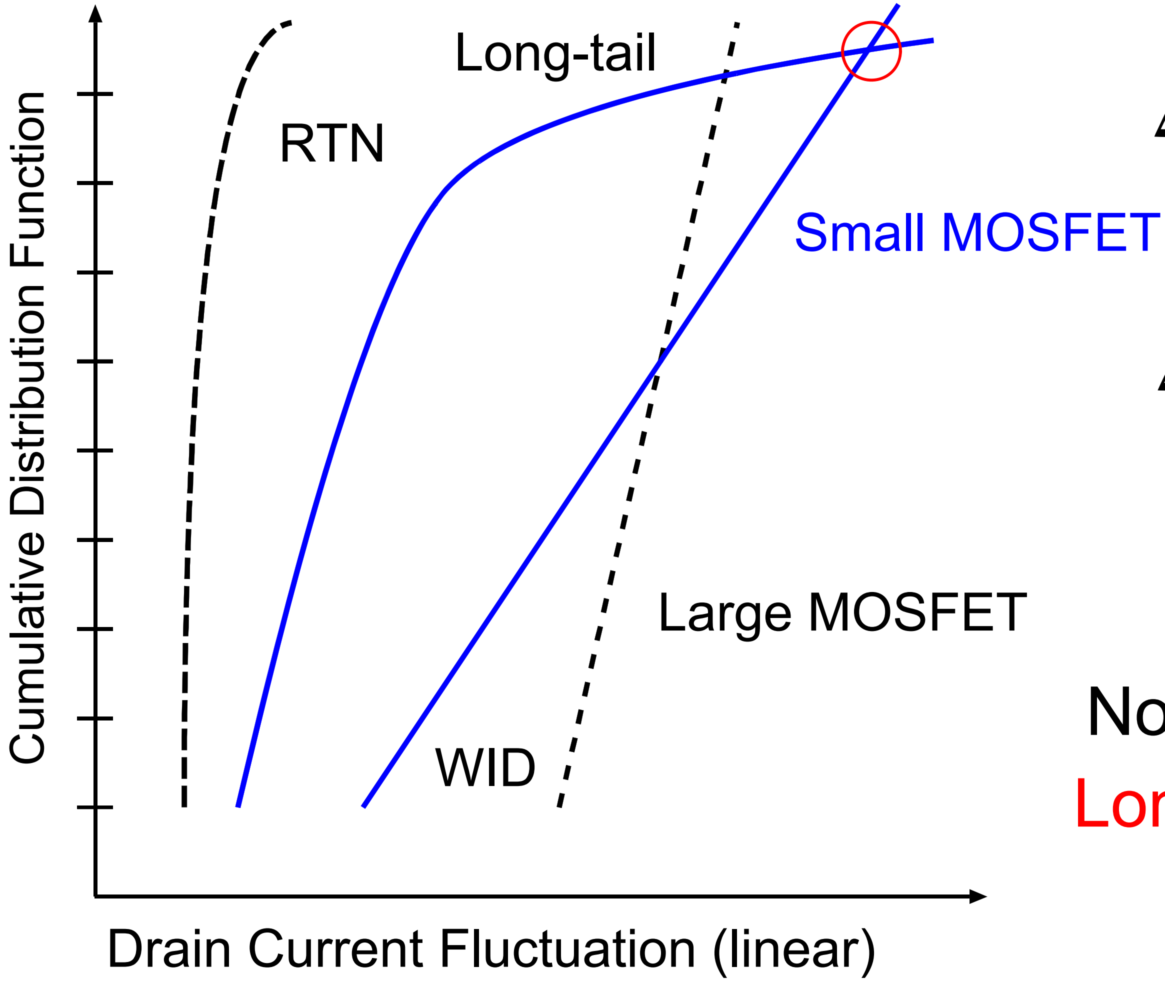


RTN-induced Drain Current Fluctuation



- Time constant (τ_c, τ_e) of RTN strongly depends on gate bias.

Process Variations vs RTN in Scaled Devices



$$\Delta V_{\mathrm{thPV}} \propto \frac{1}{\sqrt{LW}}$$

$$\Delta V_{\mathrm{thRTN}} \propto \frac{1}{LW}$$

Normal distribution for PV

Long-tail distribution for RTN

- Large MOSFET: WID variation dominates
- Small MOSFET: RTN can dominate at some realistic σ value

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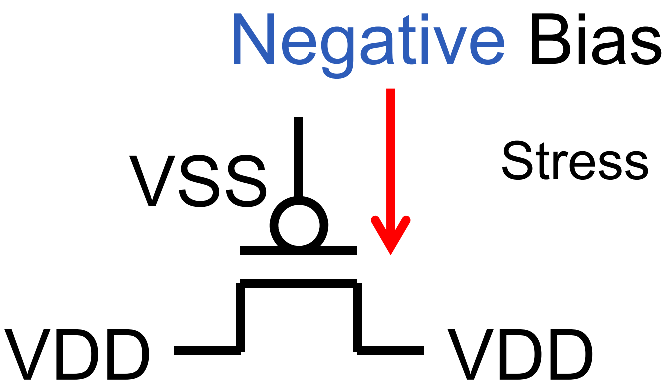
NBTI on PMOS and PBTI on NMOS

- Aging degradation by continuous stress

PMOS

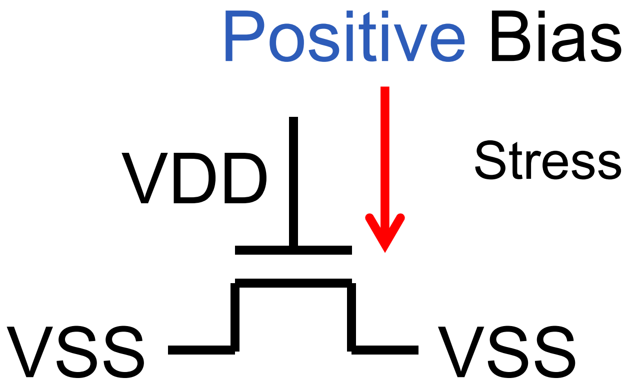
NBTI



After 65nm process
SiON gate dielectric

NMOS

PBTI



After 40nm process
Hi-k gate dielectric

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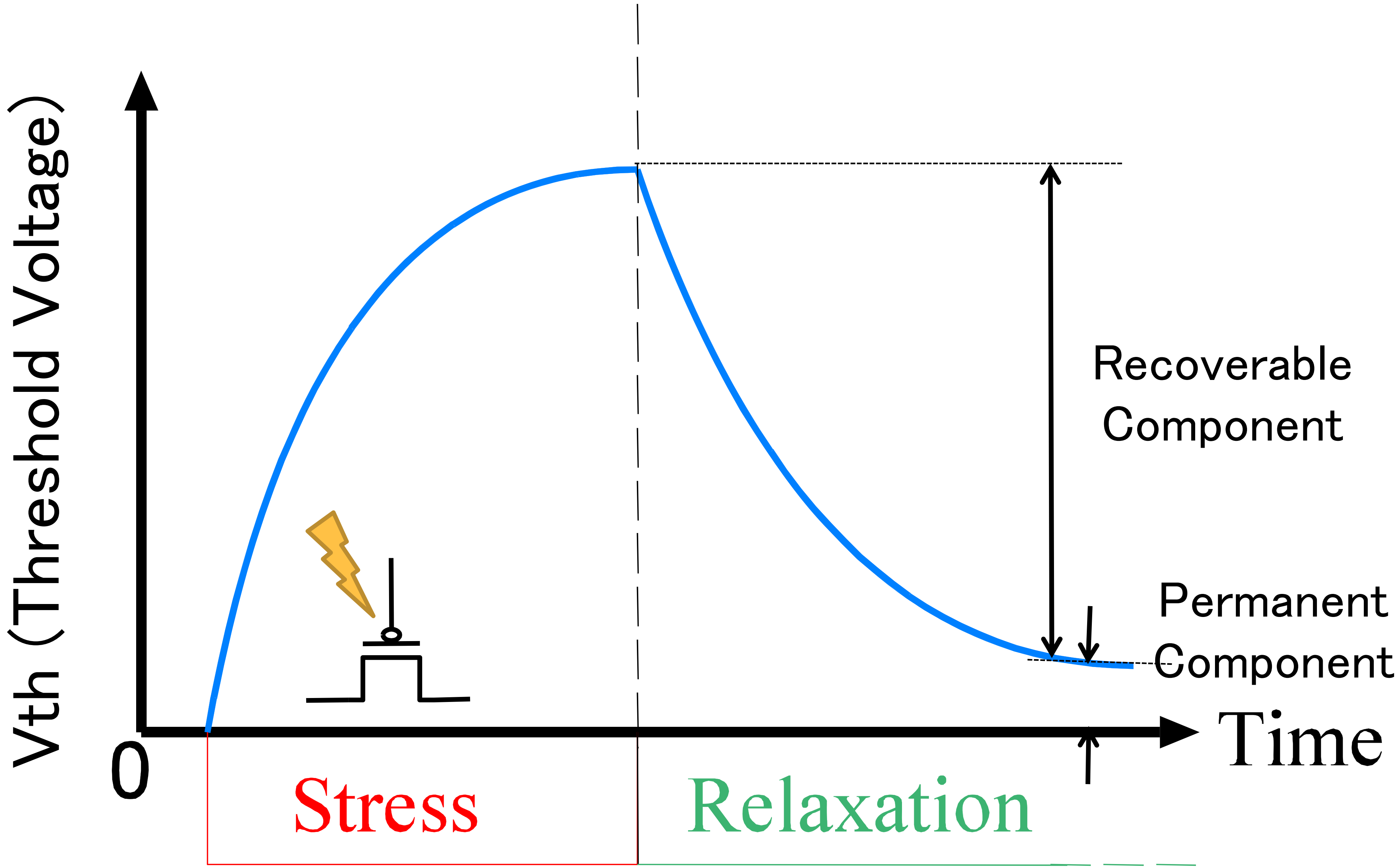
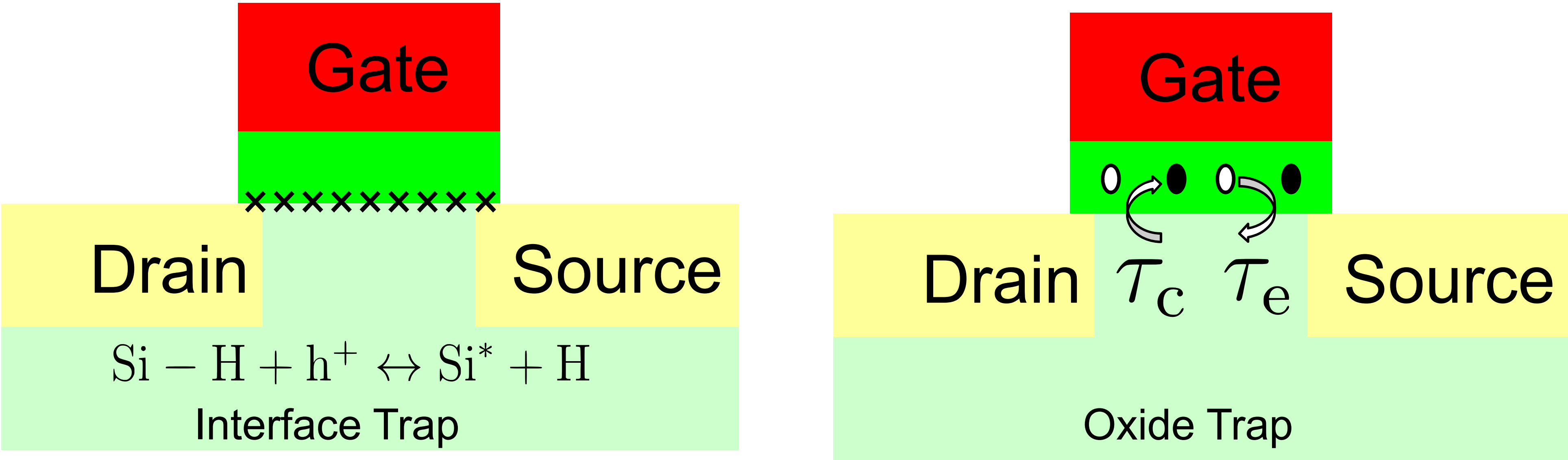
BTI (Bias Temperature Instability)



Two Models of BTI



- Reaction Diffusion Model [Alam, IEDM03]
  - Carriers are trapped by dangling bond (interface trap)
- Atomistic Trap-based Model [Kaczer, IRPS10]
  - Carriers are trapped /detrapped in oxide trap (same as RTN)
  - RTN: $\tau_c \simeq \tau_e$ Carriers repeats capture and emission
  - BTI: $\tau_c << \tau_e$ Captured carriers are never emitted

BTI Degradation Models

- Reaction Diffusion Model

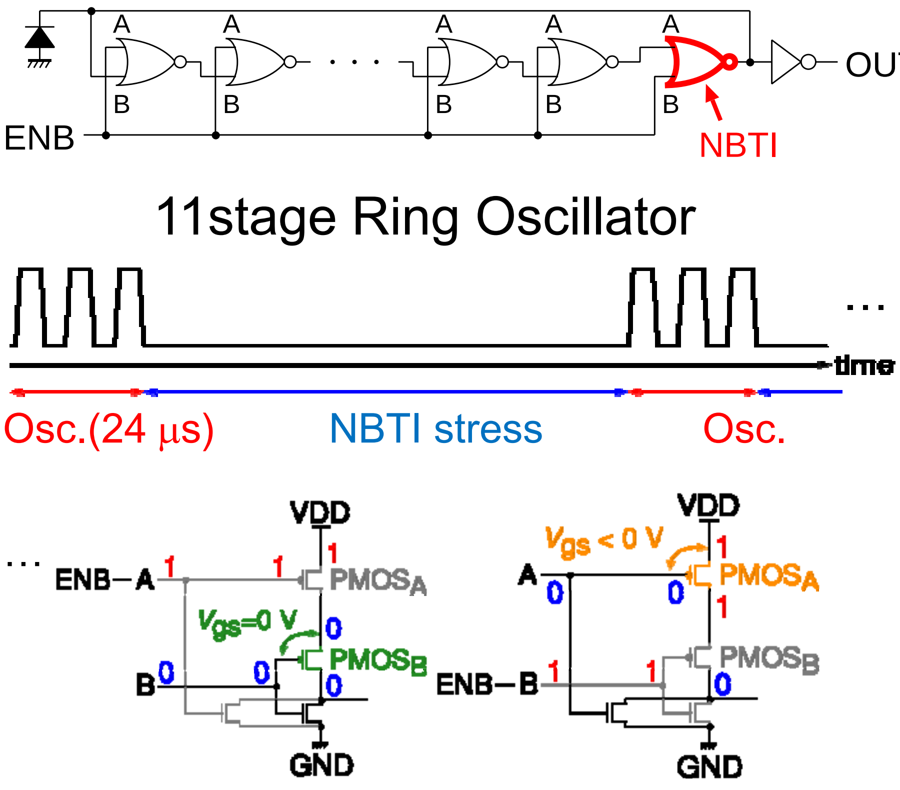
$$\Delta V_{\mathrm{TH}} \propto t^{n}$$

n=1/4: atomic H diffusion
n=1/6: H_2 diffusion

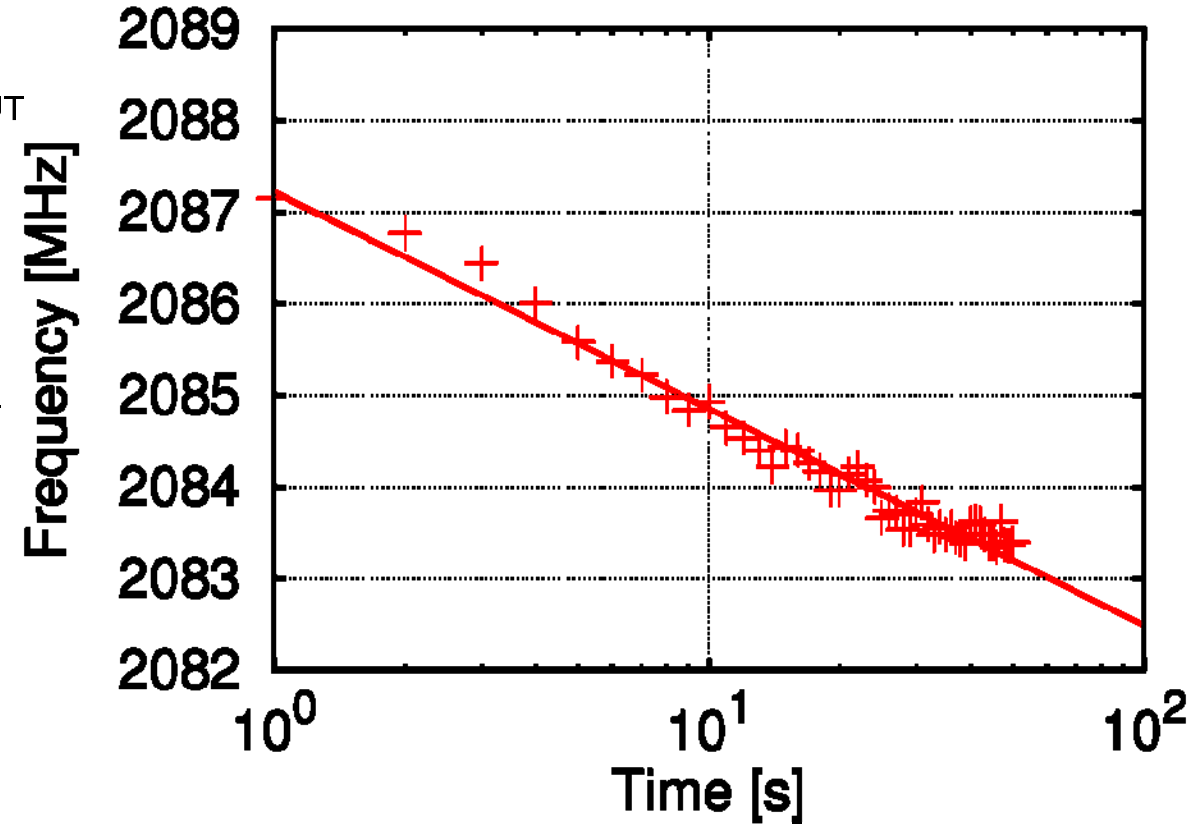
- Atomistic Trap-based Model

$$\Delta V_{\mathrm{TH}} \propto \log t$$

Measurement Results



NOR w/o NBTI Vgs=0   NOR w/ NBTI Vgs<0

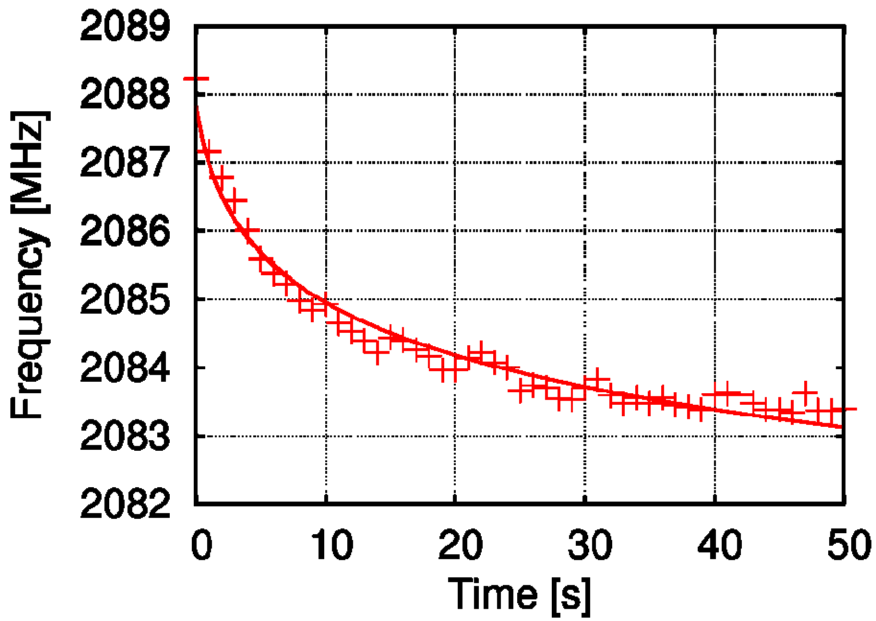


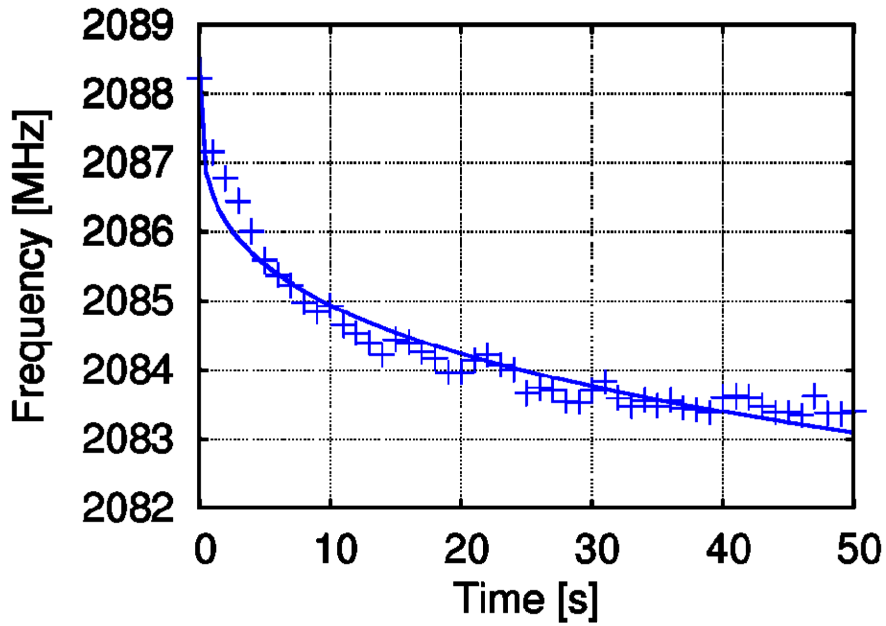
VDD 2.0V, Temperature 80℃

- Stress measurement by Ring Oscillator (RO)
  - Frequency degradation follows log(t)?

[R. Kishida et.al. IRPS 2015]

Fitting by Two Models

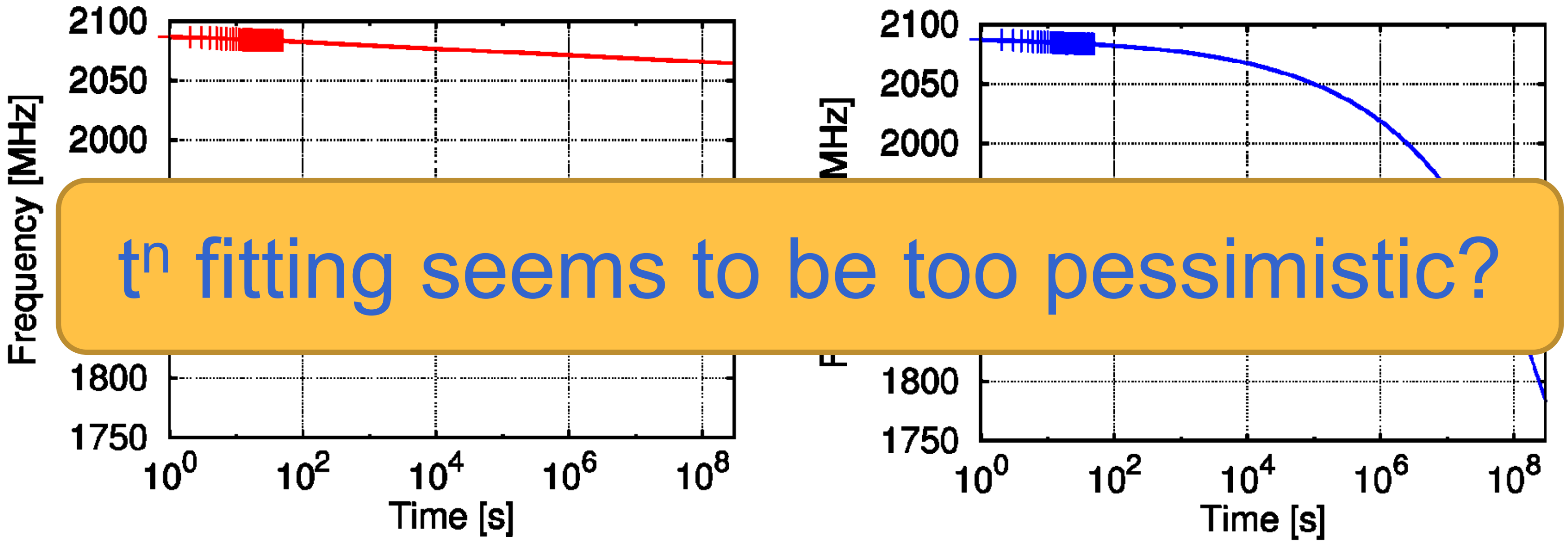




	$\log t$	t^n
Average Error	0.53%	0.02%

- Short-time measurement data matches both models

Long-term Prediction

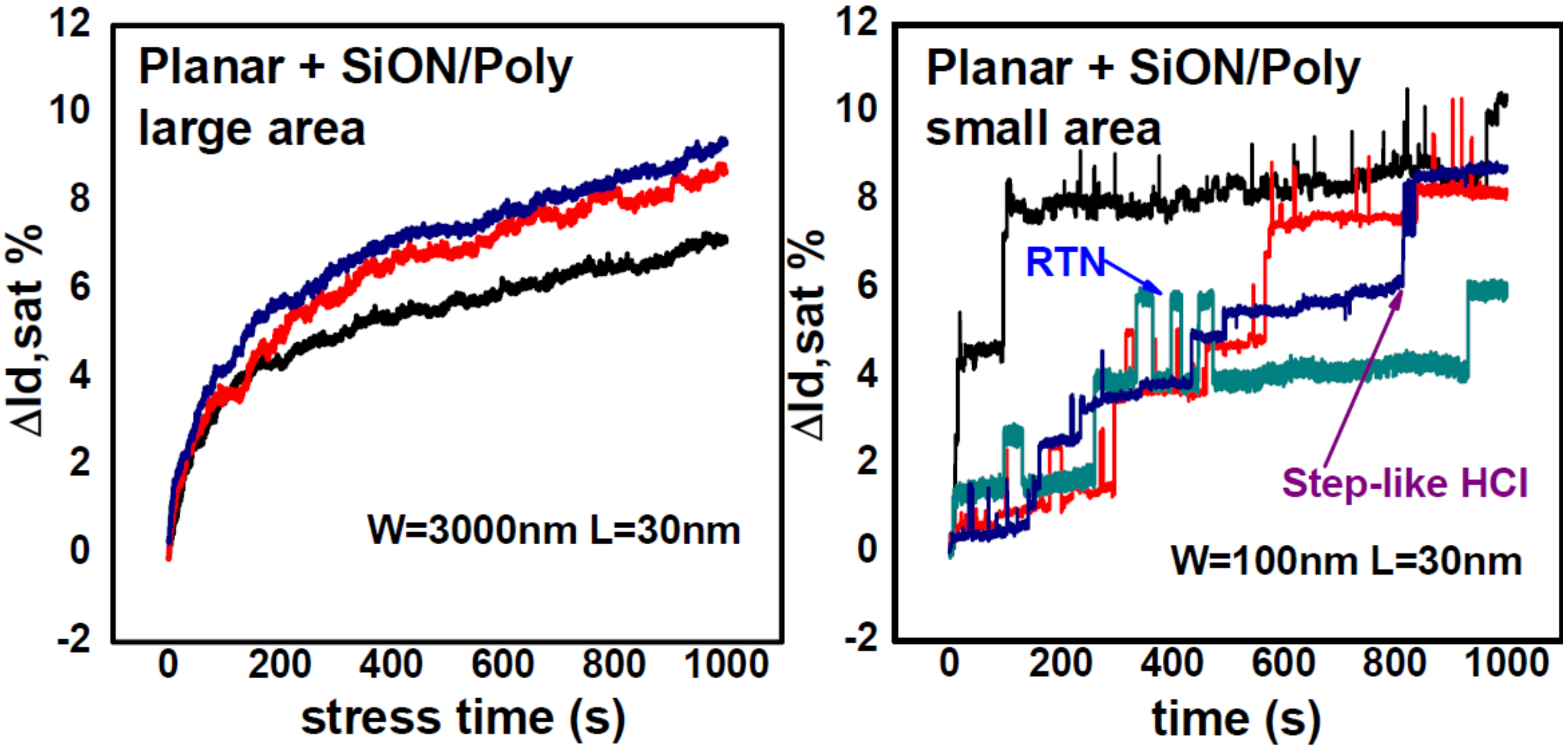


t^n fitting seems to be too pessimistic?

- $\log t$
- t^n

- After 10^8 seconds (3 years), log fitting has a few % degradation, while t^n fitting has 20% degradation.

RTN and BTI



[IEDM14, 34-6]

- Large device: smooth degradation by many traps.
- Small device: discrete degradation by several traps.

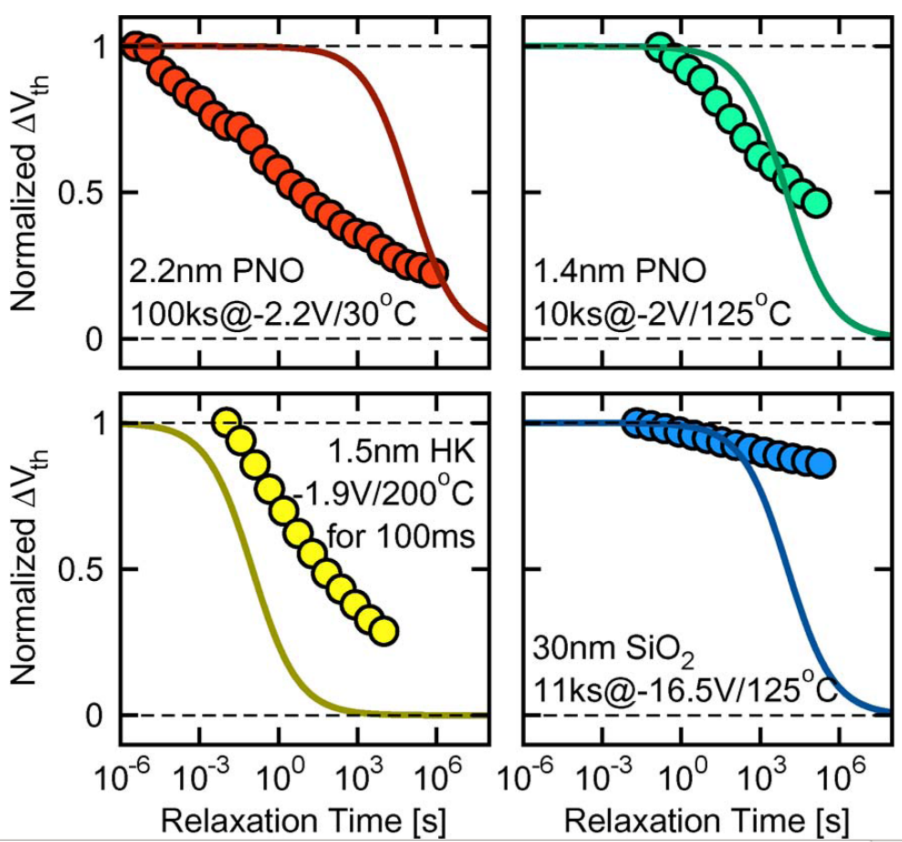
BTI is caused by oxide traps, not by interface traps

RD Model or Trap-based Model

- Hot discussions in IRPS over decades
- Recently, Trap-based model has more supporters
  - How H is diffused back to interface trap on recovery?
  - In RD model recovery depends on stress/relaxation time only

$$\frac{\Delta V_{th}(t_s)}{\Delta V_{th}(t_r)} = \frac{1}{1+(t_r/t_s)^{1/2}}$$

Recovery on RD model



Measurement data on recovery. Dots are measurement data. Lines are predicted by RD model.[Grasser, Trans. ED 2011]

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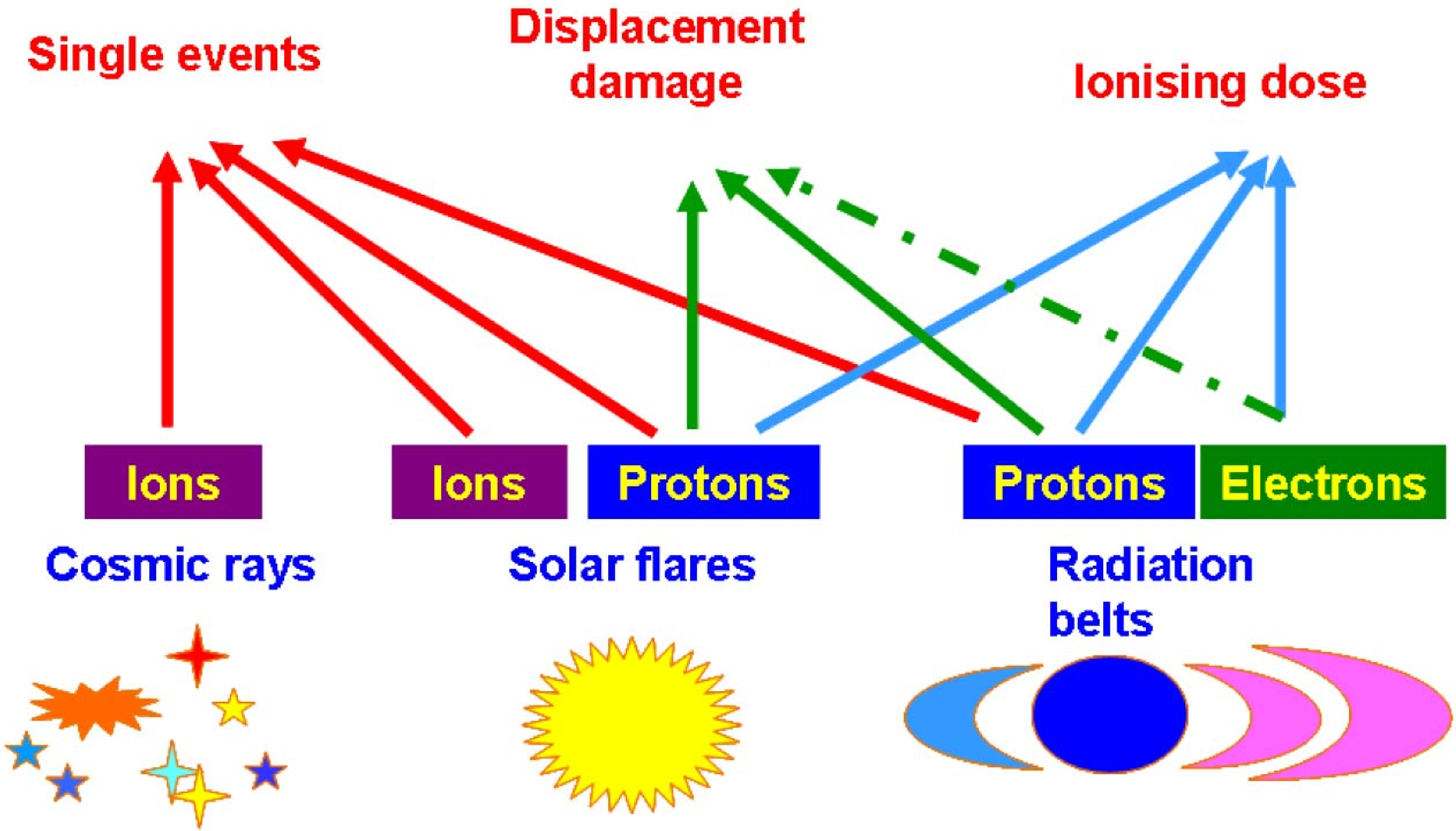
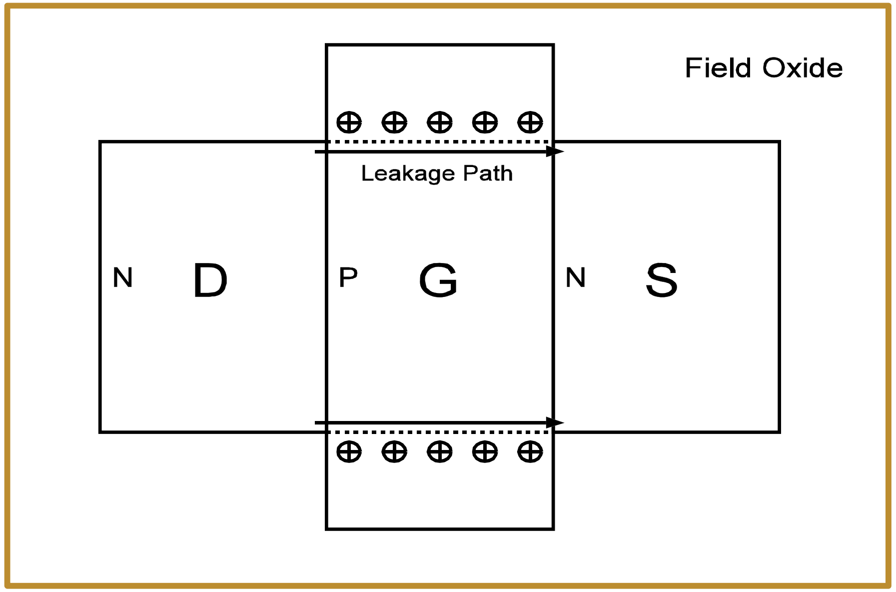
Radiation Effects in Outer Space

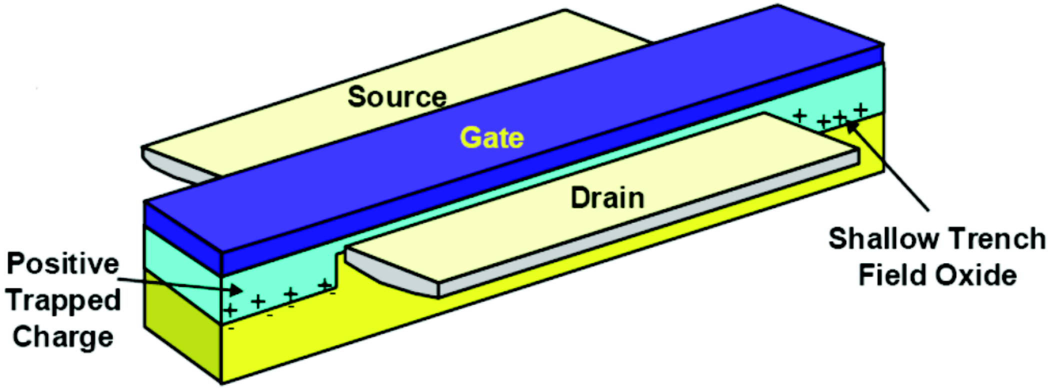


[RADECS 2015 Short Course]

TID (Total Ionizing Dose)

- Performance degradation on MOS transistors by protons and electrons
  - Thicker field oxide is damaged more than thin gate oxide
  - Leakage path between drain and source by charge in field oxide (NMOS only)
  - Vth shift like BTI (PMOS dominant)





[Ratti, Ionizing Radiation Effects in Electronic Devices and Circuits]

BTI and TID

- Both degradations are caused by traps in oxide or interface
- Thicker field oxide is dominant in TID, while thin gate oxide is dominant in BTI
  - No bias in field oxide (No BTI)
  - Thicker oxide is damaged more than thinner oxide by TID
- No confirmed theory is established
  - Interface traps vs Oxide traps
  - How hydrogen is related to degradation
  - Still in debates

Summary

- Reliability issues are hot topics in highly-scaled CMOS circuits
- Introduce RTN and BTI in terms of defects (traps)
  - Oxide traps and interface traps
- RTN is temporal fluctuation of Tr. performance
- BTI is permanent (continuous) degradation of Tr. performance. When stress is released, relaxation (recover) starts
- TID is also related to defects
  - TID is dominant in thicker field oxide
  - BTI is dominant in thinner gate oxide
- Still in debates about the correct theory

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Acknowledgement

- Our lab. members of long-term degradation group
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