Aging Effects and Modeling Researches on 22nm FDSOI MOSFETs

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Outlines

Aging effects and modeling

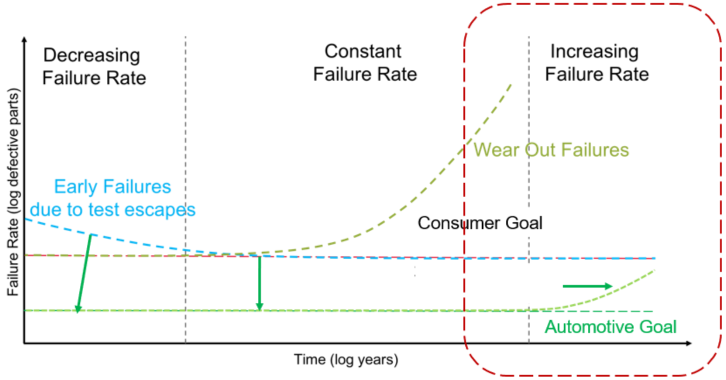
1. Backgrounds
2. Aging Effects Modeling
3. Dynamic Voltage Stress
4. SMI Simulator
5. Summary

Backgrounds

- **Reliability has become one of the most important design indicators of ICs**

	Consumer	Industrial	Automotive
Temperature	0°C → 40°C	-10°C → 70°C	-40°C → 85°C/155°C
Lifetime	1-3 years	5-10 years	> 15 years
Test Coverage	~ 95%	~99%	Target = 0 dppm
Safety Rating	-	ASIL B	ASIL C, D

***Semiconductor Requirements for Heterogenous Applications By market segment （cadence)**

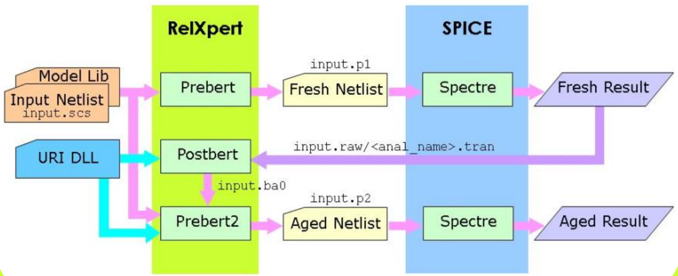


- **Multiple effects**
- **Hard to characterize**

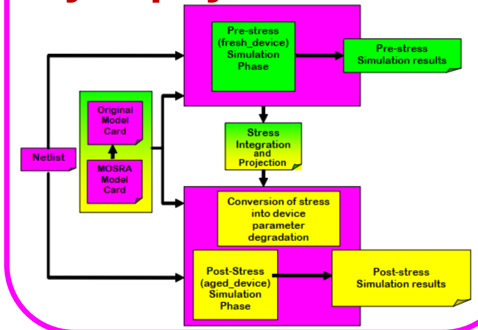
- **Automotive puts forward more stringent reliability requirements for ICs**
- **Accurate prediction of device performance vs. time**

Backgrounds

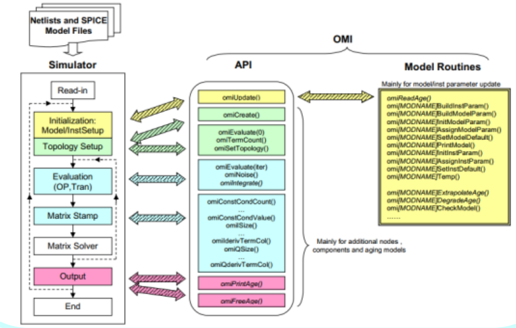
Cadence Legato



Synopsys MOSRA



TSMC TMI



Commercial reliability simulation software

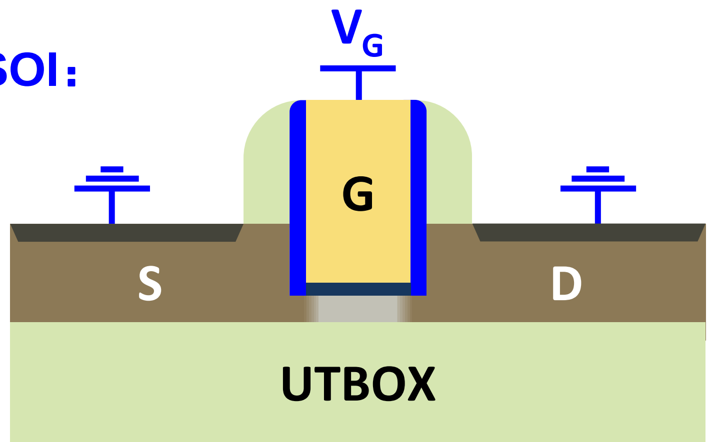
TSMC Only

Process	FAB	Kernel	Process Model	Aging Effect	Self-heating Effect
130nm PD SOI	GSMC	BSIMSOI	5 Corner /Mismatch	N/A	√
22nm BULK	HLMC	BSIMBULK	9 Corner /Mismatch/Monte Carlo	N/A	N/A
22nm FD SOI	GF	BSIMIMG	9 Corner with SOA /Mismatch/Monte Carlo	√	√
7nm FinFET	TSMC	BSIMCMG	11 Corner with SOA /Mismatch/Monte Carlo	√	√

- **No domestic alternative solutions**
- **Commercial IPs: expensive licensing fee increases the R&D cost**

Backgrounds

FDSOI:



High speed

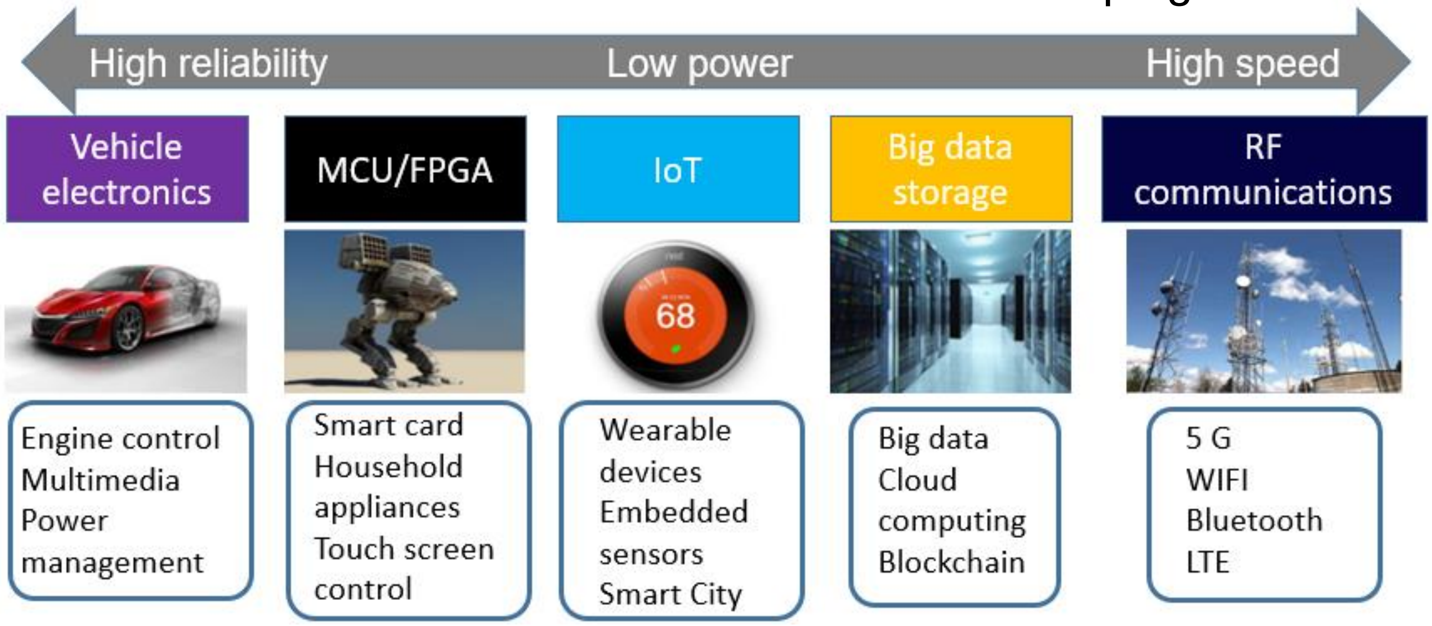
Thin oxide, low parasitic capacitance

Low power consumption

No substrate leakage

High reliability

Low random doping distribution



FDSOI is more advantageous in Vehicle electronics, IoT, and RF communications

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Characterization of Aging Effects

What is aging?

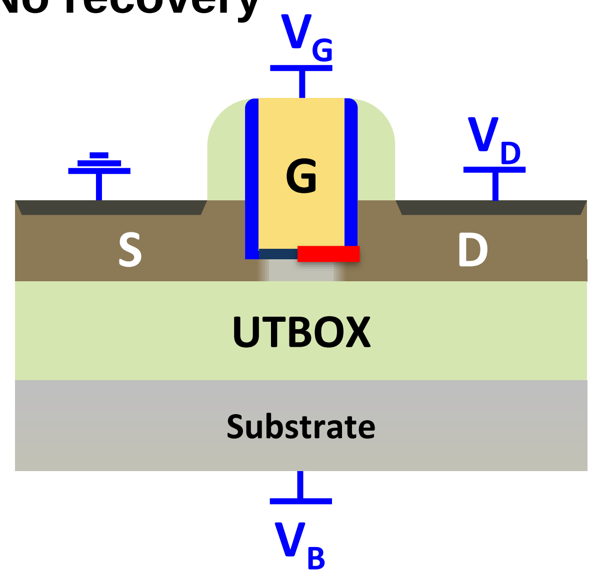
- Time dependent dielectric broken, (TDDB)
- Electron migration, (EM)

Reach lifetime limit, no need to characterize

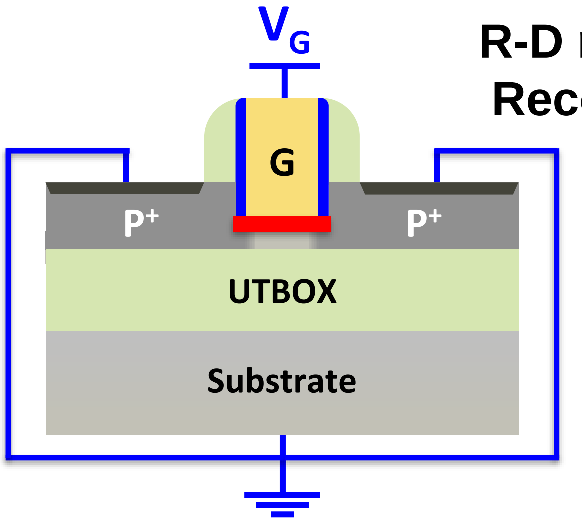
- **Bias temperature instability, (BTI)**
- **Hot carrier injection, (HCI)**

Negative / Positive

No recovery

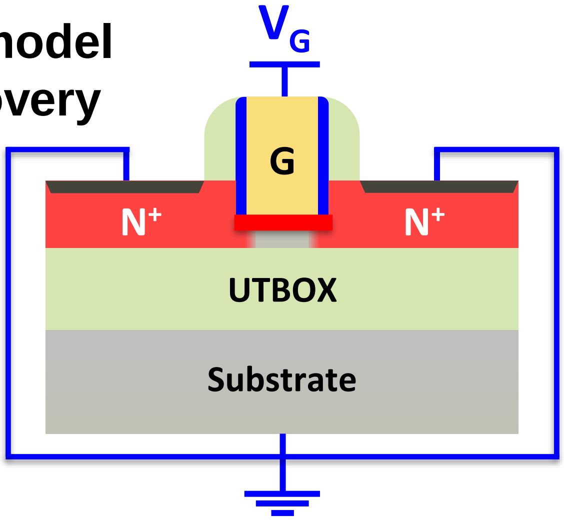


NBTI on PMOS



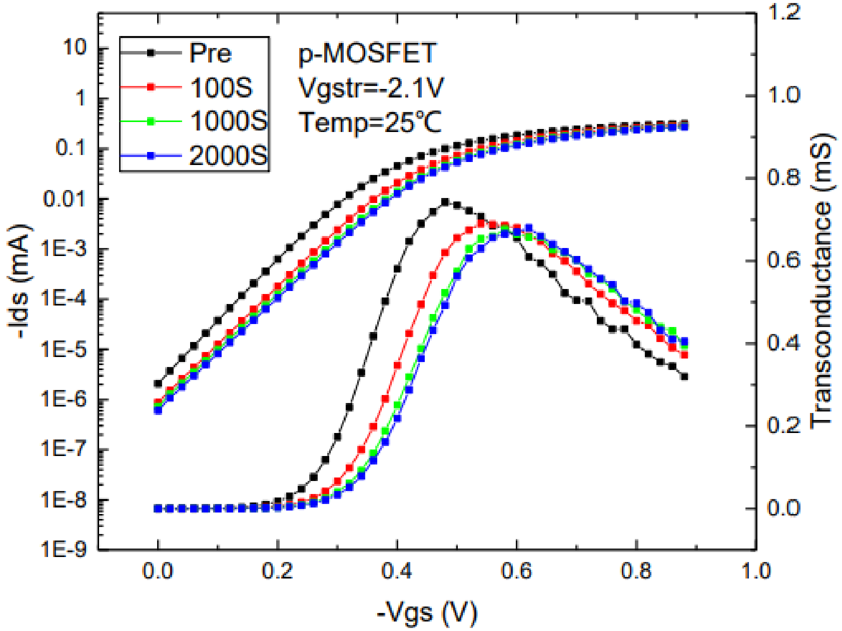
R-D model Recovery

PBTI on NMOS



Static Aging Characters

NBTI on PMOS

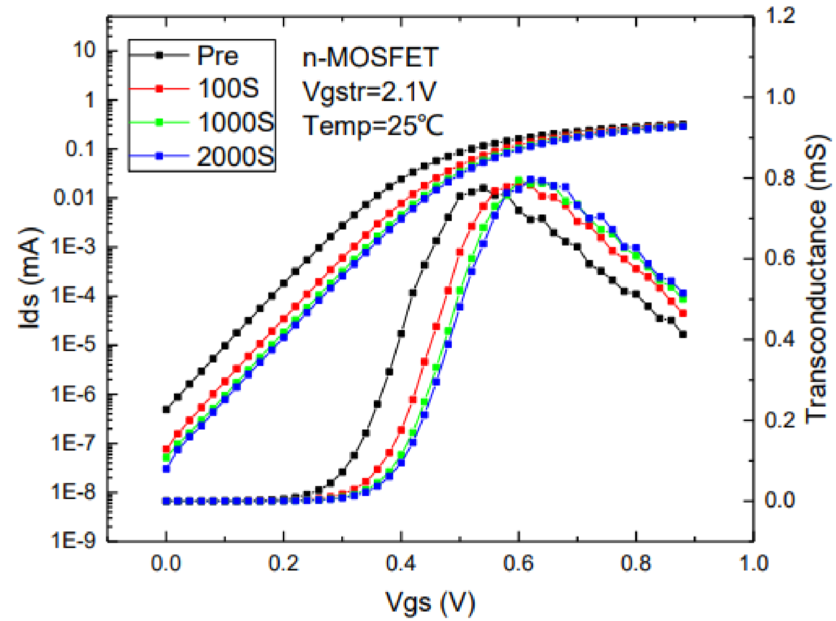


- V_{th} shift
- Gm_{max} decreases
- SS increases

Affect both Vth and mobility

Holes can be captured and released, forms equivalent interface capacitance

PBTI on NMOS



- V_{th} shift

Only affect V_{th}

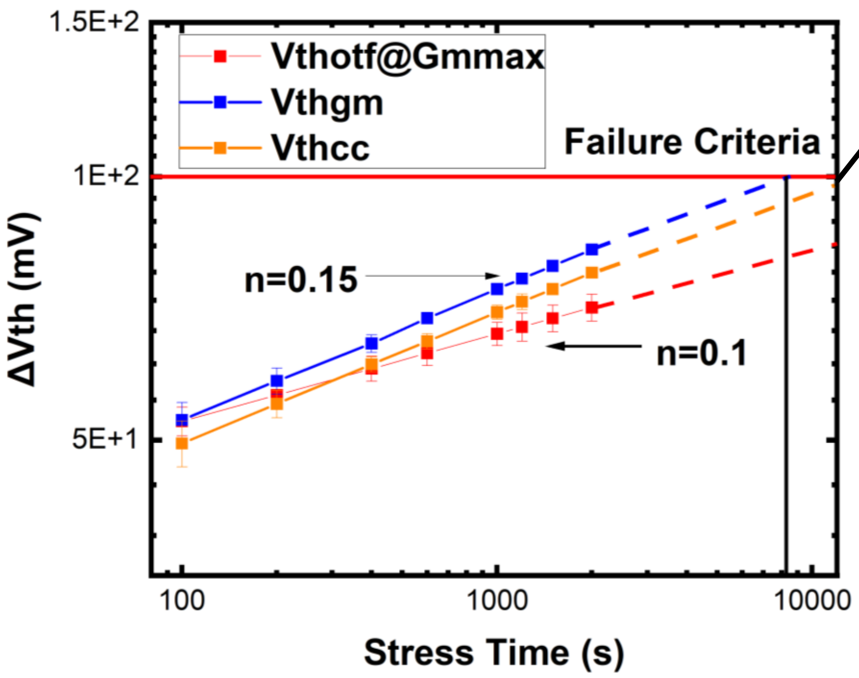
Electrons is hard to be captured, forms fixed charges

R-D model

Lifetime Prediction

3 methods to extract threshold voltage V_{th}:

- On The Fly (OTF), can be affected by mobility degradation;
- Constant current (Icon), can be affected by SS increase;
- Extrapolation in the linear region (ELR) at Gm_{max}, closest to actual physics.



$Log(\Delta V_{th}) \propto Log(T)$

Set ΔV_{th} = 100 mV as the failure criteria

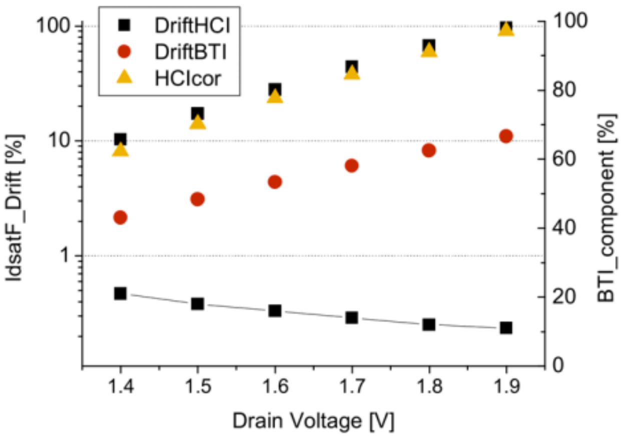
Extract method	Lifetime prediction (s)
OTF	63000
ELR	7200
Constant current	11000

Even mV error can result in multiple lifetime prediction difference

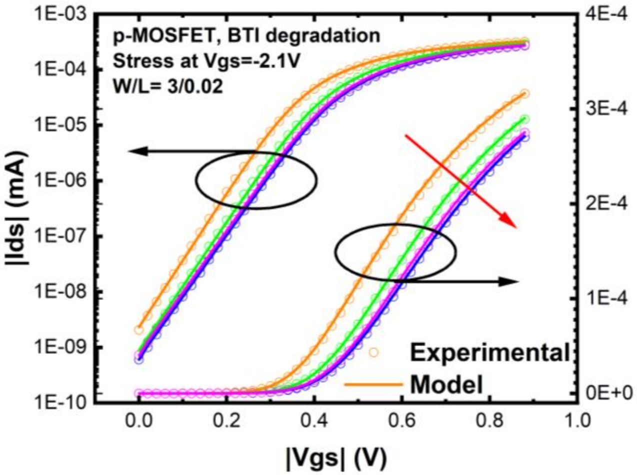
Unified Aging Model

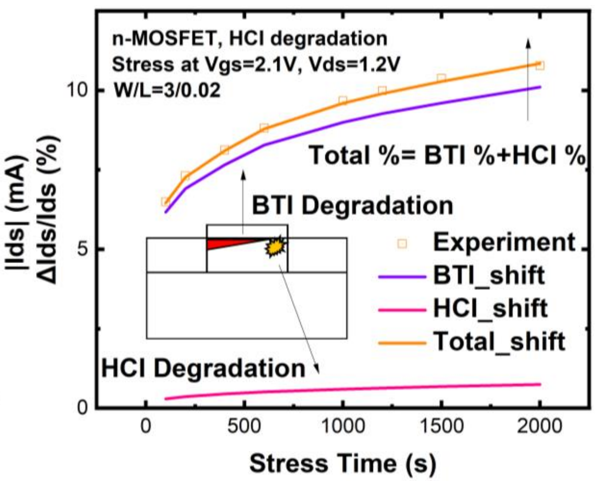
- **HCI shows correlation with BTI**

BTI: V_{th}、mobility(scattering) degradation



Federspiel X, et al.IEEE International Reliability Physics Symposium (Irps),2013.





BTI: SS degradation

HCI: intrinsic mobility degradation

$$\Delta V_{\mathrm{th,HCI}}=\Delta V_{\mathrm{th,BTI}}\cdot E^{-k\cdot \mathrm{Vd}}$$

The influence of HCI can be extracted based on proper extraction of BTI

Unified model: $$\frac{1}{u_{tot}}=\frac{1}{u_p}+\frac{1}{u_p/\alpha_{co}}+\frac{1}{u_p/\alpha_{ph}}+\frac{1}{u_p/\alpha_{ro}}$$ Matthiessen Rule

Vth and SS Modeling

- ➢Performance in subthreshold region can be described by interface charges.
- ➢**Model includes the influence of gate/drain voltage and temperature.**

V_{th} model：

$$\Delta V_{th}=\frac{q\cdot(1+k)\Delta N_{it}}{C_{ox}}$$

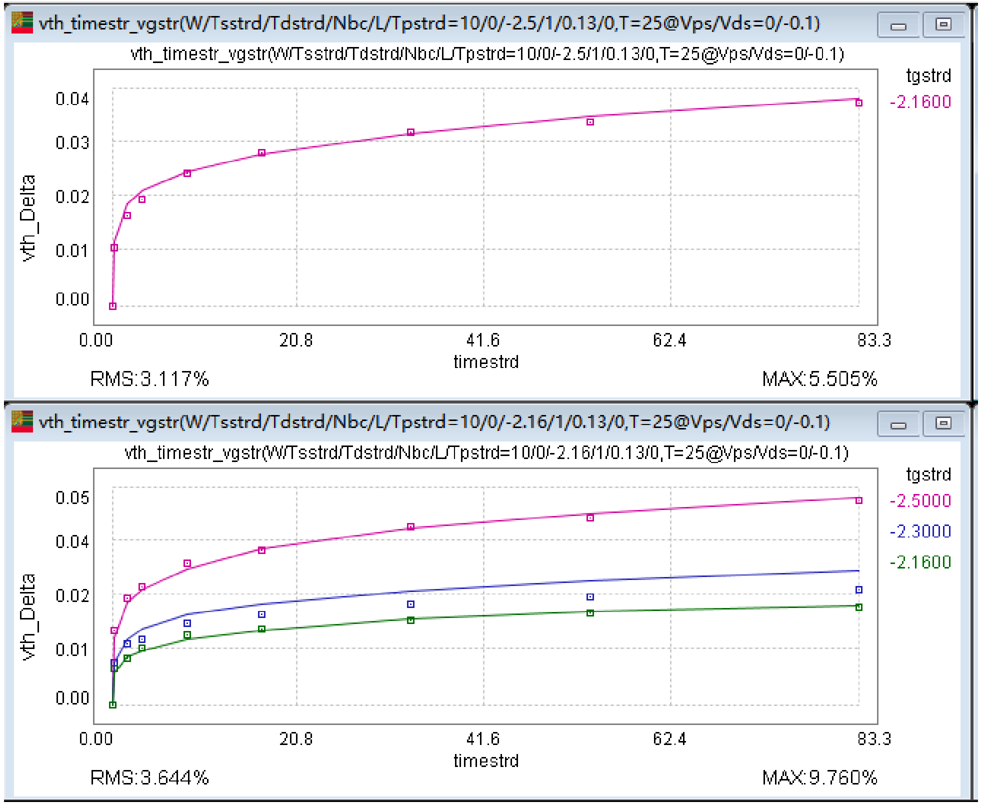
$$\Delta N_{it}=\mathrm{B}\cdot\mathrm{EXP}(\mathrm{C_g}V_{gs}+\mathrm{C_d}V_{ds}-\frac{Ea}{k_B T})\cdot t^n$$

Voltage stress 0.1 V ⇔ Temperature 50 ℃

Arrhenius equation

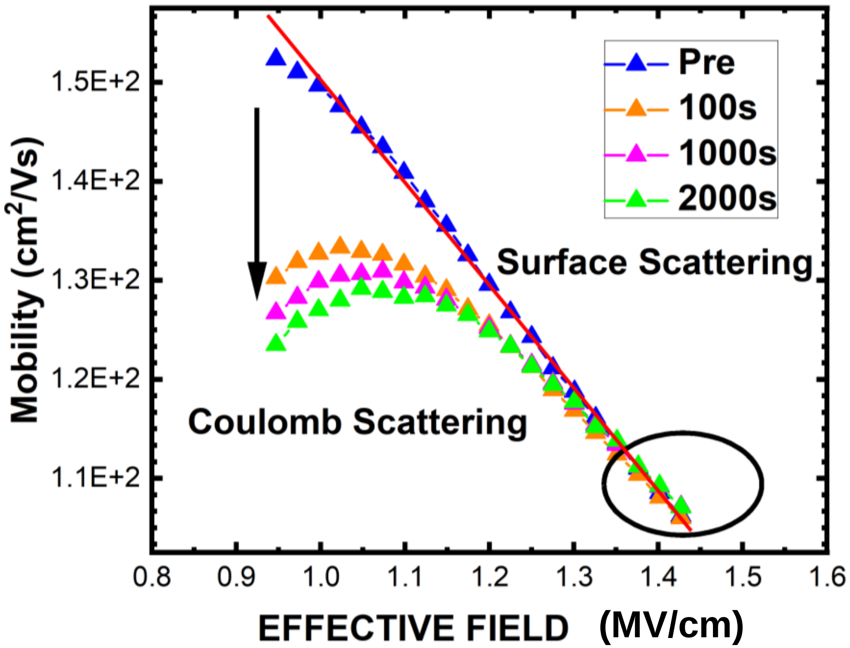
SS model：

$$\Delta SS=2.3\cdot\frac{kT}{q}\cdot\left(1+\frac{C_{dep}}{C_{ox}}+\frac{\Delta C_{it}}{C_{ox}}\right)$$

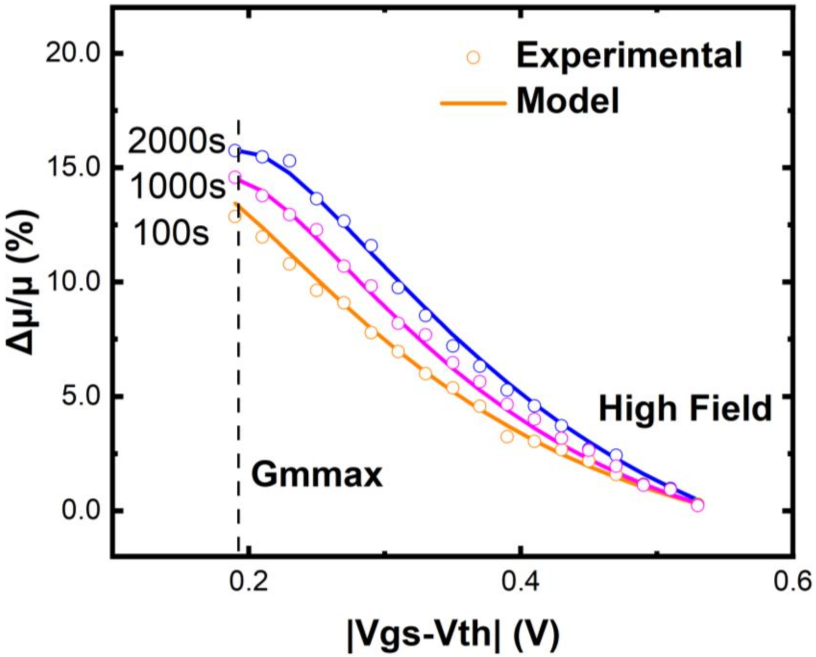


- ■ **The performance degradation in subthreshold region can be described by this model accurately**

Mobility Degradation Modeling



- Low Vg: μ decreases significantly after aging. Coulomb scattering is enhanced by interface traps
- High Vg: no evident change. Aging doesn't affect surface scattering (different with bulk).



Coulomb scattering model:

$$\mu = \mu_0/[1 + \alpha \cdot Q_{it}/(\beta + Q_{inv})]$$

Mobility approximate formula:

$$\frac{\Delta\mu}{\mu} = 1 - \frac{I_{ds,lf}}{\left[I_{ds,lf0}/|V_{gs,lf} - V_{th0}| \cdot \Delta V_{th,hf} + I_{ds,lf0}\right]}$$

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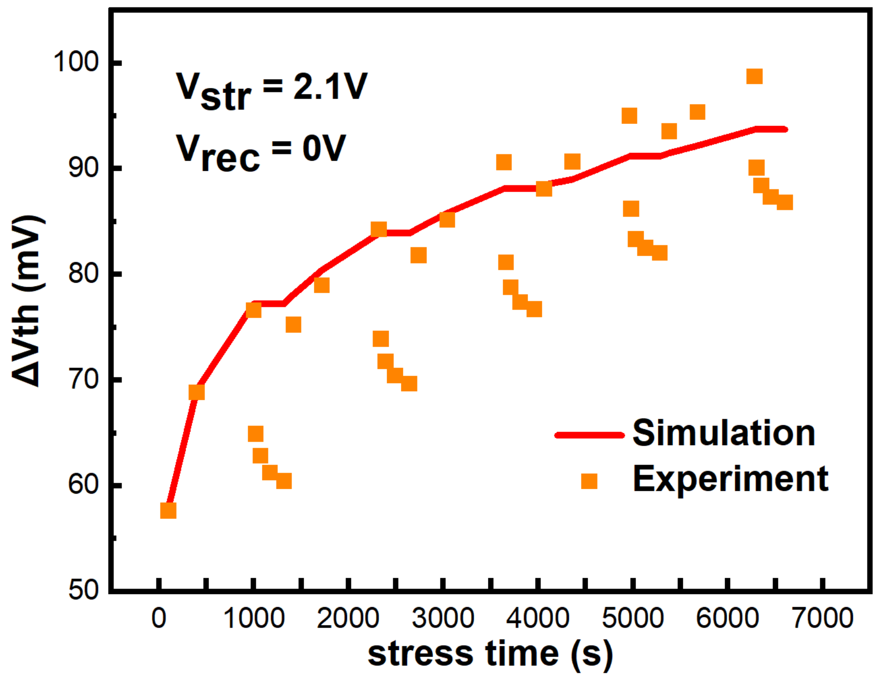
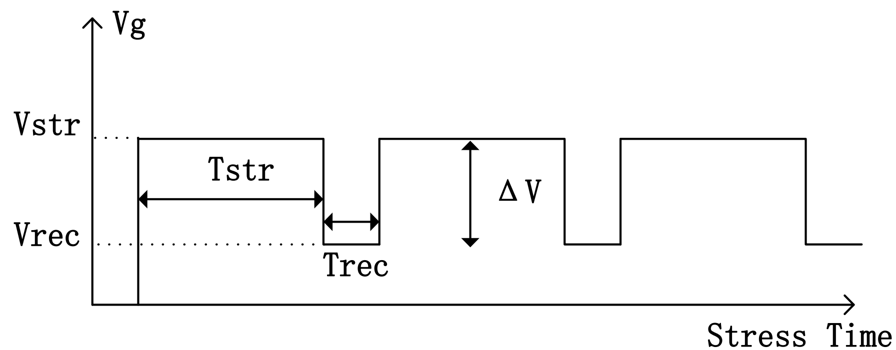
Dynamic Voltage Stress (DVS)

➢ **Static model cannot describe dynamic aging**



- **Correlation with stress sequence:** The recovery will affect follow-up aging characters
- **Correlation with bias voltage:** Voltage stress in recovery cycle may be different R-D model ✕



➢ Important factors to be considered:
Recovery voltage, recovery time, duty cycle, number of cycles, etc.

Saturation in DVS

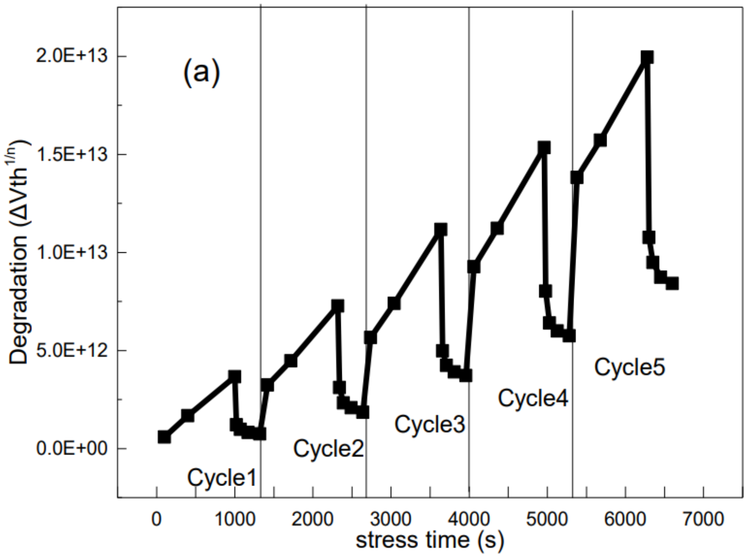
- **V_{th} degrades exponentially:**

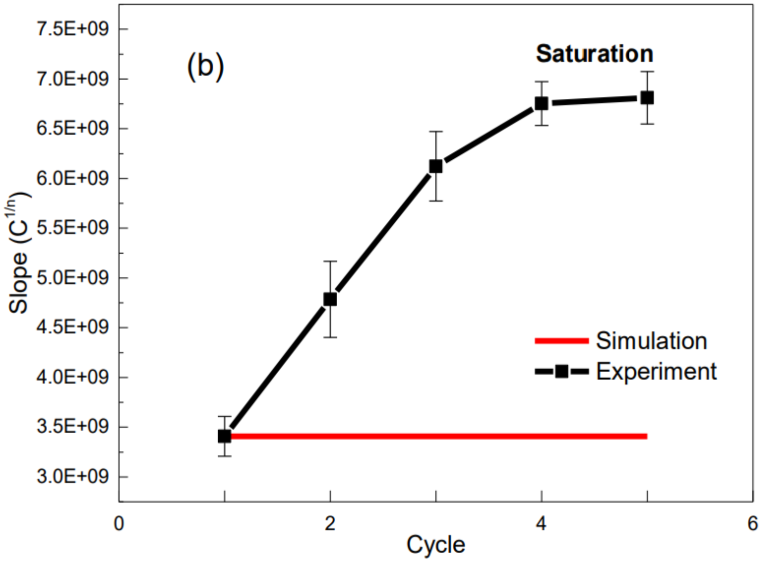
$$\Delta V_{th} = C \cdot t^n$$

$$\Delta V_{th}^{1/n} = C^{1/n} \cdot t$$

Slope

Changes linearly with time

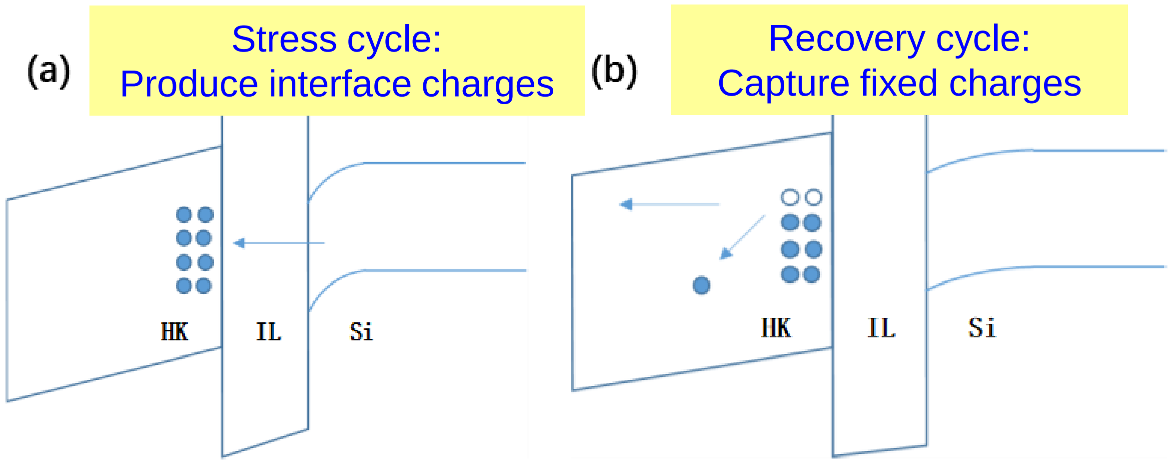




- **Recovery effects will increase the follow-up aging rate, saturates after 3 cycles**
- **No saturation in high V_{rec} (not shown)**

Make DVS model complex !

DVS Modeling



Recovery cycle：charges transfer to saturation

$Q_t \rightleftarrows Q_f$

Stress cycle：charges captured

Various charge based models have been investigated

Bias dependency × **multiple cycles ×**

Constant stress	$\Delta V_{th}(t)=\phi\cdot[A+B\log(1+Ct)]$
Random Input stress	$\Delta V_{th}(t+t_0)=\Delta_1+\Delta_2$ $\Delta_1=\varphi(A+B\log(1+Ct)),$ $\Delta_2=\Delta V_{th}(t_0)\left(1-\frac{k+\log(1+Ct)}{k+\log(1+C(t+t_0))}\right)$

Ref: K. Sutaria, A. Ramkumar, R. Zhu, R. Rajeev, Y. Ma and Y. Cao, "BTI-induced aging under random stress waveforms: Modeling, simulation and silicon validation," 2014 51st ACM/EDAC/IEEE Design Automation Conference (DAC), 2014, pp. 1-6.

V_{th} model：

$$\Delta V_{th}=(Q_t+Q_f)/C_{ox}$$

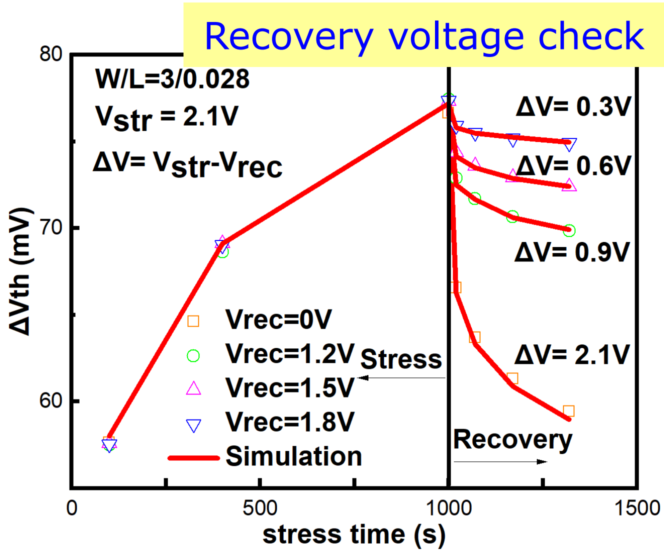
Interface charge model：

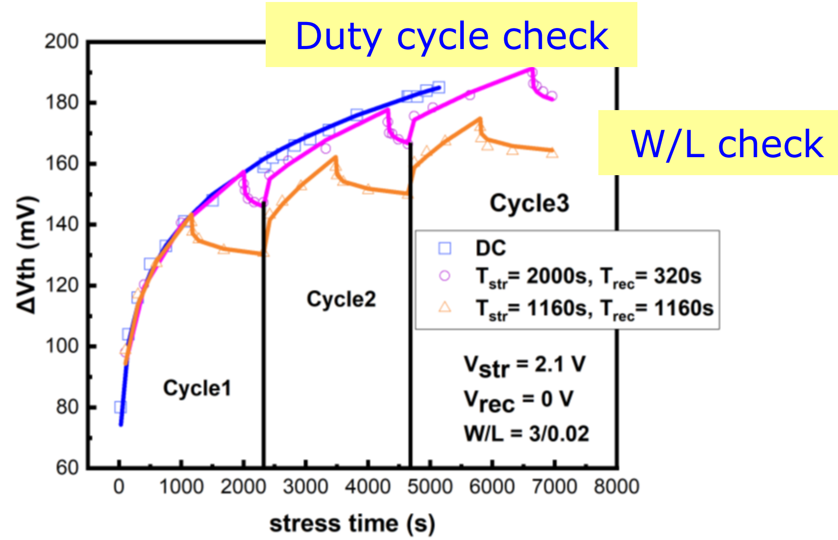
$$Q_t=(A_i+B_i Q_f)\cdot t_S^{\alpha}$$

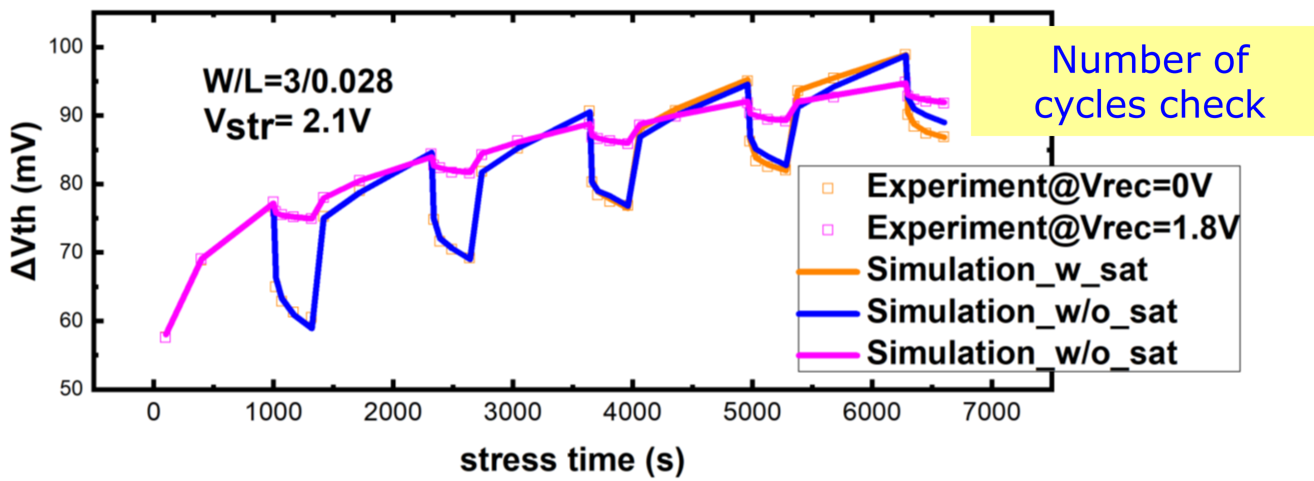
Fixed charge model：

$$Q_f=\mathrm{MIN}\left(\gamma Q_t\left[1-\Delta V\left(A_o+B_o Q_{f0}\right)\cdot t_r^{\beta}\right], Q_{fmax}\right)$$

Model Accuracy







- **DVS model can fit the experimental data under various conditions in high accuracy, reaches mV level**

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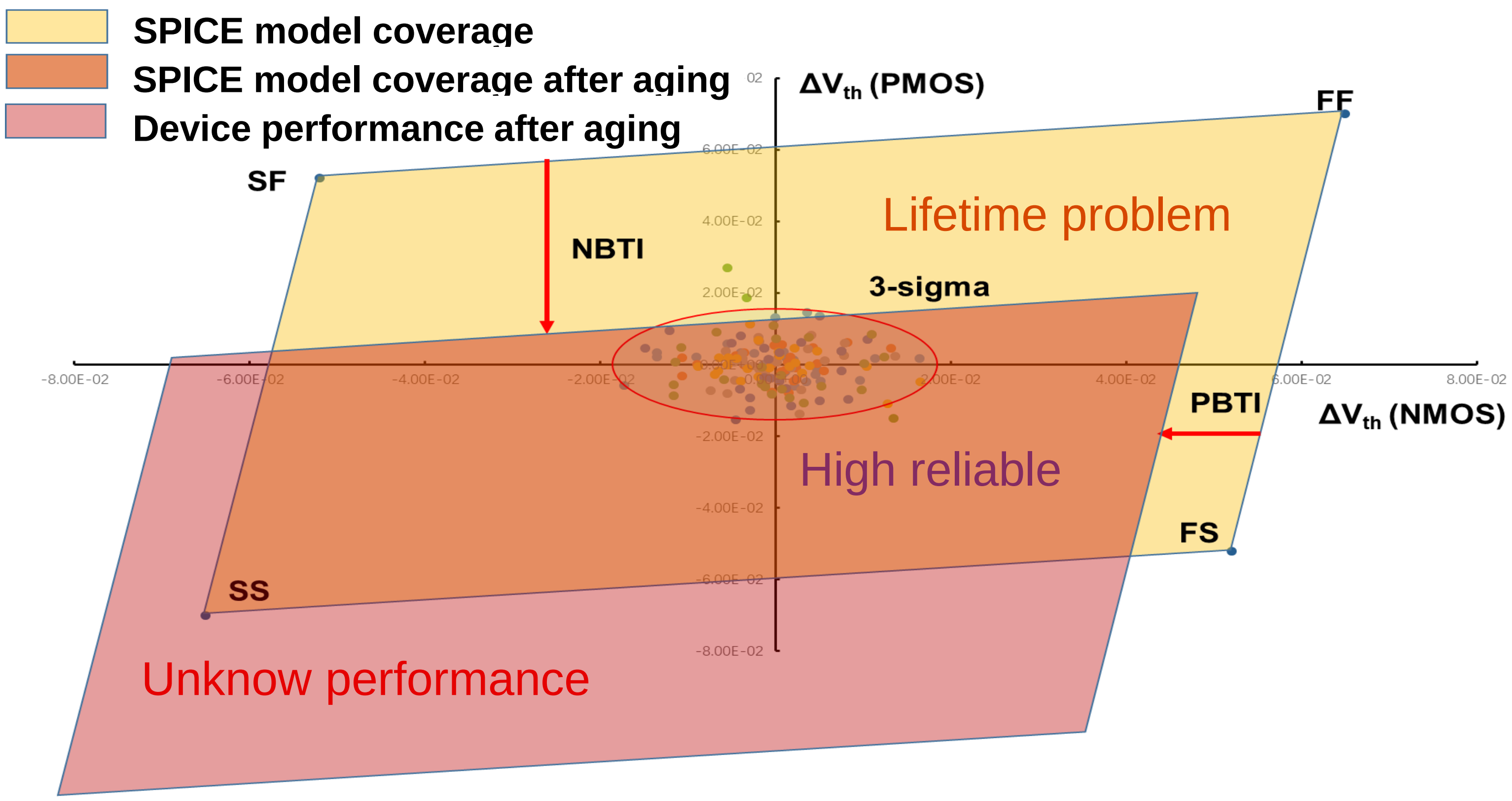
Process Variation & Reliability

- What dose the simulator do?

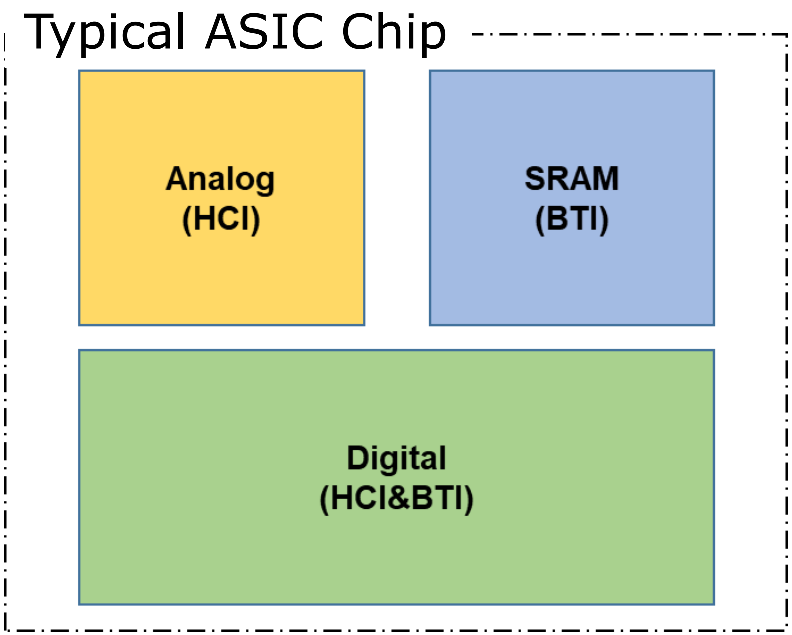


- Aging effects can cause the device performance move to SS corner
- Preciously describe aging effects → Preciously predict lifetime

Circuit Level Aging Simulation

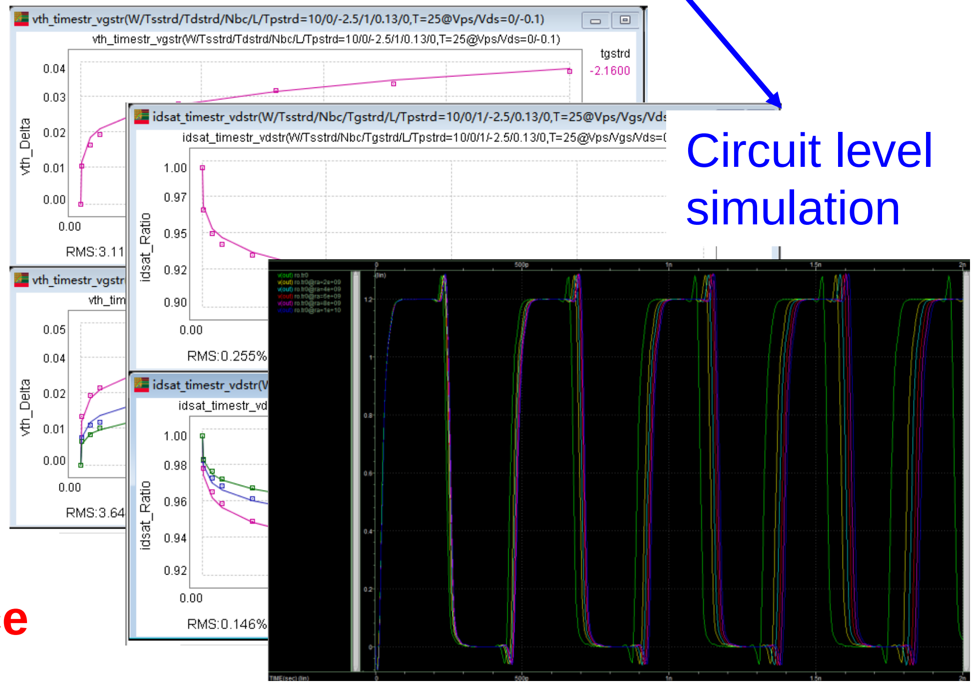
- Why we need a simulator?

1. The SPICE model cannot characterize aging effects directly
2. For circuit level applications, different function units have different aging characters



Device level simulation

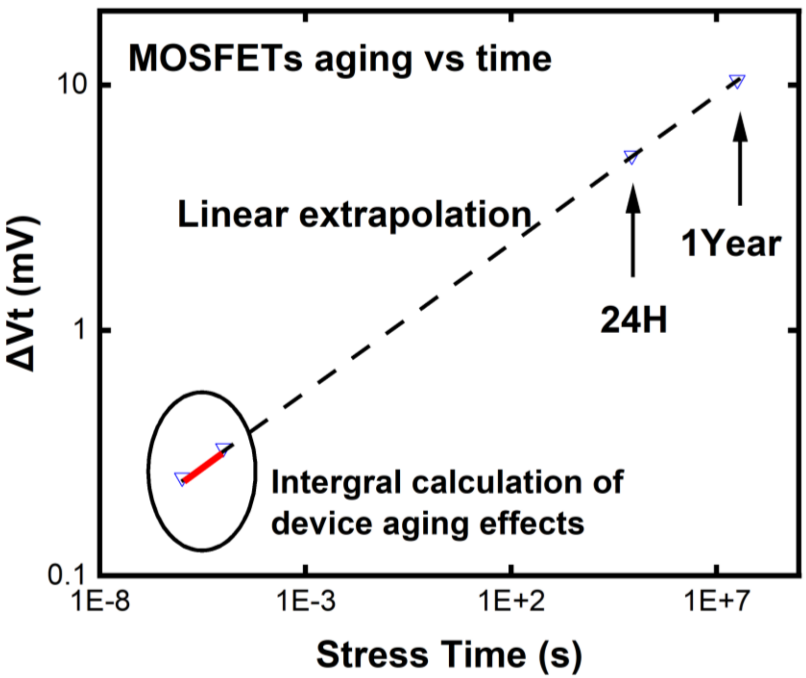
Circuit level simulation



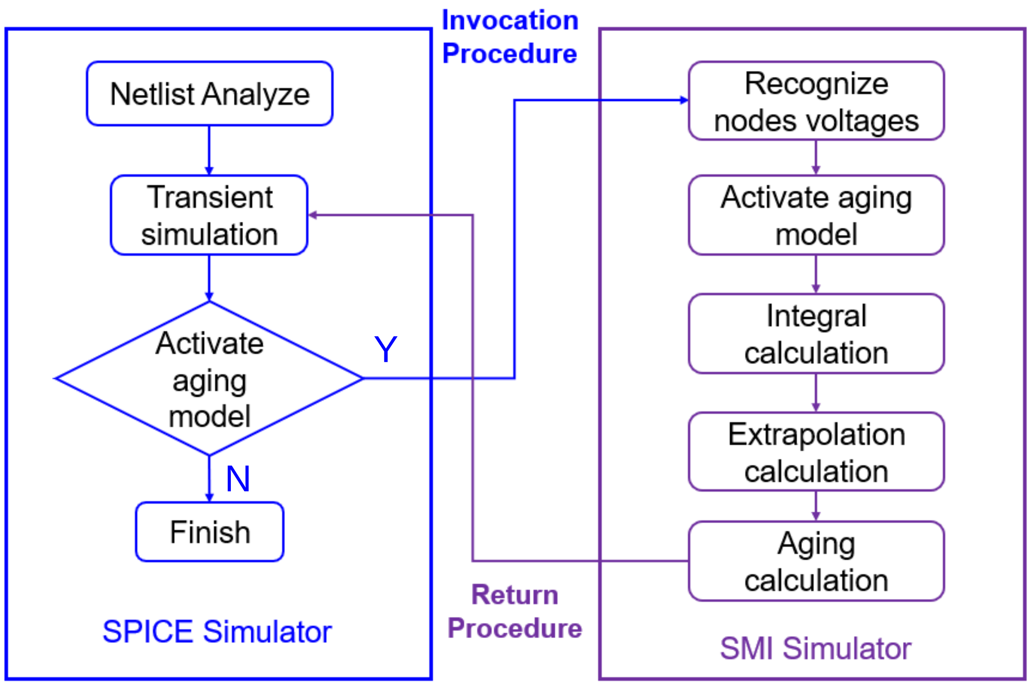
- **The aging characters of each device need to be calculated separately**

SMI Simulator

- **Local sampling and extrapolation**



Workflow

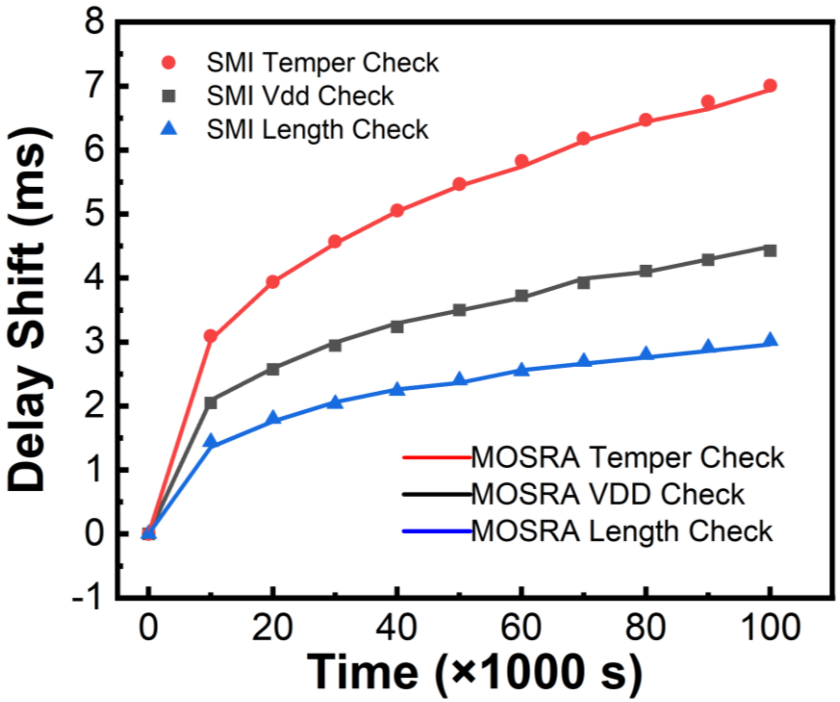


- **SMI has already been embedded into the EDA software ALPS/Xmodel of Empyrean Corporation for commercial applications**

SMI Simulator

Feature	MOSRA	SMI
Integration	√	√
Extrapolation	√	√
BTI_Core	√	√
HCI_Core	√	√
Annealing	√	√
Temperature behavior	×	√
Extraction Flow	×	√
Failure Criteria	√	√
Lifetime Prediction	√	√
Self-heating Model	×	√
DVS Model*	×	√

Ring oscillator simulation results
SMI vs. MOSRA (ps/stage)



- **Ring oscillator simulation results of SMI are highly consistent with Synopsys MOSRA under different voltages, sizes and temperatures**

Summary

1. Aging effects including BTI and HCI of 22 nm FDSOI devices were systematically studied;
2. A novel model, as well as a simulator (SMI) supporting both SVS and DVS aging conditions, were investigated;
3. This model can precisely predict key parameters of MOSFETs degrading with time in high accuracy;
4. The model accuracy is highly consistent with MOSRA and meet the industrial standard;
5. The SMI simulator has already been embedded into the EDA software ALPS/Xmodel of Empyrean Corporation and realized commercial applications.

Thank you !