BSIM4 Modeling of 90nm n-MOSFET Characteristics Degradation Due to Hot Electron Injection

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Supported by STARC

Outline

- **Purpose, Background**
- **Consideration of Degradation Equations**
- **Simulation Results and Model Parameter Extractions**
- **Summary**

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Purpose

Developed MOSFET model

- **HCI induced DC degradation model**

  Show deterioration DC characteristics of channel length dependence in simulation

- **1/f noise model**

  Show simulation of deterioration 1/f noise at DC

Background

integrated circuits

high integration, miniaturization

- **Manufacturing Variations**
- **Degradations of Circuit Performance Due to Time and Temperature**

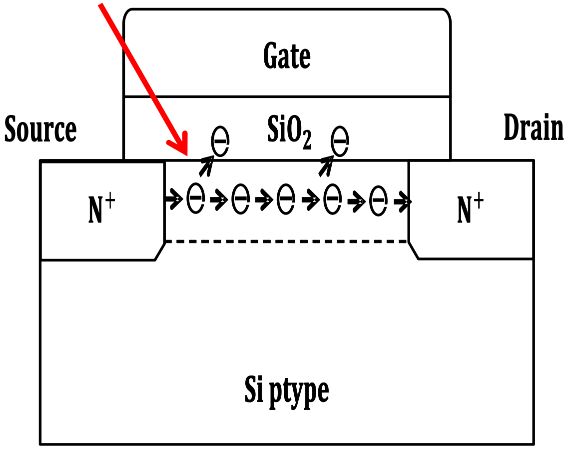
Reliability Simulation would also be performed in SPICE environment!

Generation Principle of 1/f noise

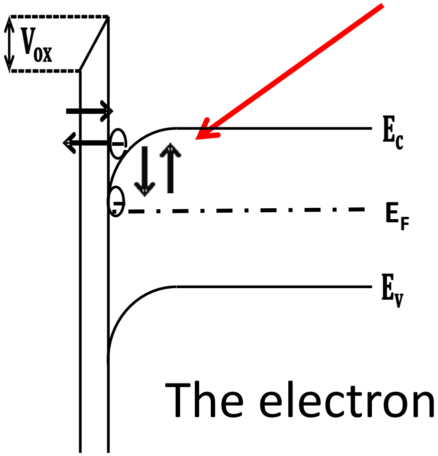
1/f noise: Occurred in all active elements such as transistors
Dominant in the low frequency

$$S_{id}(f) = \frac{KF \cdot {I_{ds}}^{AF}}{C_{OX}{L_{eff}}^{2} f^{EF}}$$

Electrons are trapped in the channel



Fluctuations in the energy levels



The electron trap by energy level

What is Modeling

- **Modeling:**

  Usually includes to develop a device model
  and to determine its model parameters

- **Model :**

  Represent the behavior by equivalent circuit
  and equations programmed with
  C or Verilog-A language in a circuit simulator

- **Parameter Extractions:**

  Since there are many variables in model equations,
  they should be accurately determined with device measurements

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Degradation Phenomena of N-MOSFETs

- **Hot Carrier Injection (HCI)**
  - Carriers with energy accelerated by the high electric field
  - Increase in threshold voltage arises from high electric field at drain area in saturation region
  - Phenomenon is similar with 1/f noise generation mechanism

More dominant than PBTI in analog circuit design

- **Positive Bias Temperature Instability(PBTI)**
  - Increase in threshold voltage arises from positive voltage stress for a long time

HCI Model

Initially introduced by Professor Hu
(University California Berkeley)

BErkeley Reliability Tools (BERT model)

↓

Reaction-Diffusion model (RD model)

correspond BSIM4

- Modeled hot carrier effect
- Represented generation of hydrogen diffusion of particles

Reaction-Diffusion Model (1)

- Number of interface trap

$$N_{H(0)}N_{it} \approx \frac{k_F}{k_R}N_0 \qquad \textbf{(1)}$$

$N_{H(0)}$	Initial value of hydrogen concentration on interface
N_{it}	Number of interface trap
k_F	Oxide–field–dependent forward dissociation rate constant
k_R	Annealing rate constant
N_0	Initial number of unbroken Si-H bonds

- Hydrogen reaction equation in channel / oxide interface

$$N_{H_x} = k_H {N_H}^{n_x} \qquad \textbf{(2)}$$

N_H	Concentration of hydrogen particles per volume
k_H	Reaction constant
n_x	Number of hydrogen atoms per hydrogen particles

- Calculate interface trap number by number of Si-H bonds

$$N_{it} = \frac{\pi W}{2A_{tot}} n_x \int_0^{\sqrt{D_{H_x}t}} \left(N_{H_x(0)}\left[r - \frac{r^2}{\sqrt{D_{H_x}t}}\right]\right) dr$$

$$= N_{H_x(0)} \frac{\pi n_x}{12L} D_{H_x}t \qquad \textbf{(3)}$$

$D_{H_x}t$	Density of N_H
A_{tot}	Total area under transistor gate
L	Channel length of transistor
W	Channel width of transistor

Reaction-Diffusion Model (2)

N_{it} is written as follows by combining (1), (2), with (3)

$$\boldsymbol{N_{it} = \left(\frac{k_F N_0}{k_R}\right)^{\frac{n_x}{1+n_x}} \left(\frac{n_x \pi k_H}{12L} D_H\right)^{\frac{1}{1+n_x}} * t^{\frac{1}{1+n_x}}} \qquad \textbf{(4)}$$

Voltage dependence represented as V_{th} shift

$$\boldsymbol{\Delta V_{th_{DEGRADATION}} = C_{HCI} \left(\frac{k_F N_0}{k_R}\right)^{\frac{n_x}{1+n_x}} \left(\frac{n_x \pi k_H}{12L} D_H\right)^{\frac{1}{1+n_x}} * t^{\frac{1}{1+n_x}}} \qquad \textbf{(5)}$$

$\boldsymbol{D_H}$	Density of hydrogen atoms
$\boldsymbol{t}$	Time
$\boldsymbol{C_{HCI}}$	Technology-dependent parameter

Proposed Model

Threshold voltage shift due to HCI is implemented to mobility model equation

↓

Modeling of mobility degradation phenomenon

Mobility Model (2)

Directly assigned *VTH0* a parameter

Extraction, optimization and simulation

MOBMOD = 2

$$\mu_{\mathrm{eff}} = \frac{\mathrm{U0}}{1+(\mathrm{UA}+\mathrm{UC}*V_{\mathrm{bseff}})\left[\frac{V_{\mathrm{gsteff}}+C_0(\boxed{\mathrm{VTH0}}-\mathrm{VFB}-\emptyset_s)}{\mathrm{TOXE}}\right]^{\mathrm{EU}}} \tag{6}$$

U0	Zero voltage carrier mobility	**VFB**	Flat-band voltage
UA	Primary factor of mobility degradation	V_{gsteff}	Effective value of V_{gs}-V_{th}
UC	Substrate effect factor of mobility degradation	V_{bseff}	Effective substrate voltage of source
TOXE	Electrical gate oxide thickness	$\emptyset_s$	Surface potential
VTH0	Threshold voltage at zero drain voltage	C_0	Constant value

Threshold Voltage Degradation

Threshold voltage shift is successfully included!

$$
\begin{aligned}
V_{th} = {} & VTH0 + \Delta V_{th,\ body\_effect} - \Delta V_{th,\ carge_{sharing}} - \Delta V_{th,\ DIBL} \\
& + \Delta V_{th,\ reverse\_short\_cannel} + \Delta V_{th,\ narrow_{width}} \\
& + \Delta V_{th,\ small\_size} - \Delta V_{th,\ pocket\_implant} \\
& + \Delta V_{th\_DEGRADATION}
\end{aligned}
\qquad (7)
$$

$$
\Delta V_{th_{DEGRADATION}} = C_{HCI}\left(\frac{k_F N_0}{k_R}\right)^{\frac{n_x}{1+n_x}}\left(\frac{n_x \pi k_H}{12L} D_H\right)^{\frac{1}{1+n_x}} * t^{\frac{1}{1+n_x}} \qquad (5)
$$

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Conditions for Our Experiments (1)

Target device:

90 nm process n-channel MOSFET

Device to be used for measurement and simulations:

• **Large**	Channel Width	**10.0µm**
	Channel Length	**10.0µm**
• **Short**	Channel Width	**10.0µm**
	Channel Length	**0.1µm**

Conditions for Our Experiments (2)

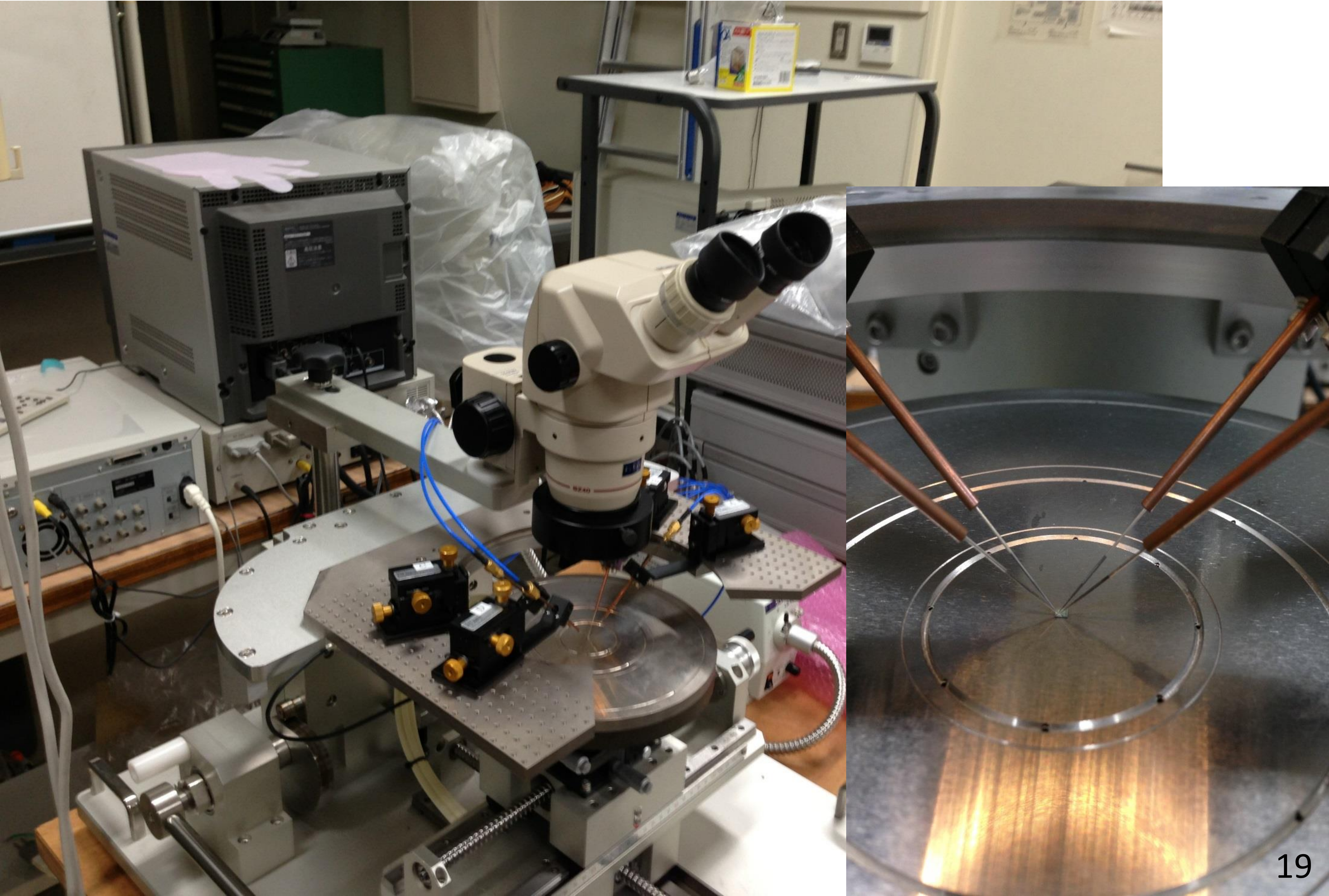
Stress condition

Degradation parameter is based on 65nm process device’s, whereas our device is fabricated with 90nm process

- Temperature **300.15 [K]**
- Time **1,000 [hours]**

**Because of our resource limitations,
degradation parameters are obtained from a paper**

Measurement Environment

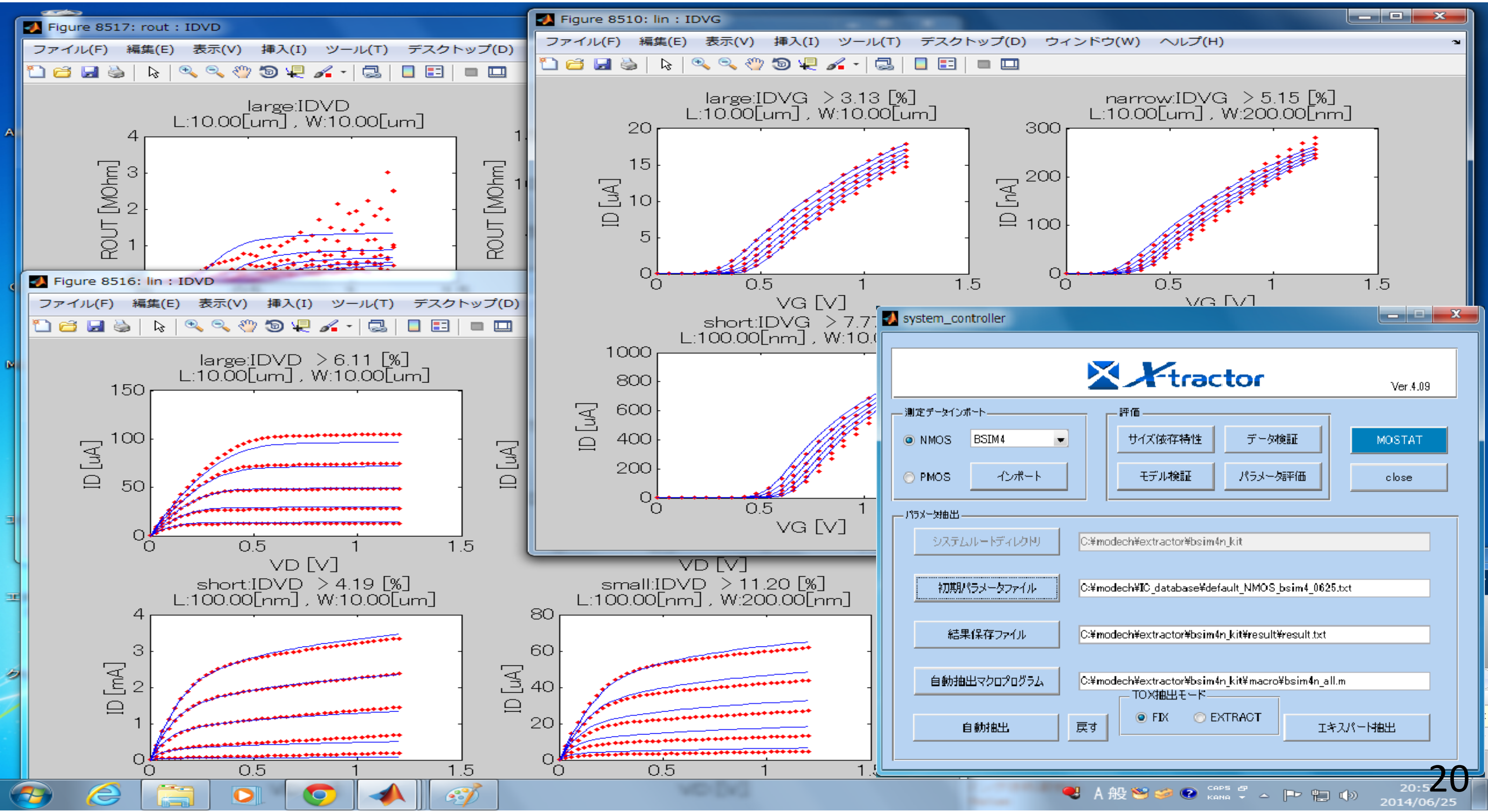


Modeling Software System

Extraction software

MoDeCH Inc.

X-tractor



● NMOS ○ PMOS

BSIM4

システムルートディレクトリ: C:¥modech¥extractor¥bsim4n_kit

初期パラメータファイル: C:¥modech¥IC_database¥default_NMOS_bsim4_0625.txt

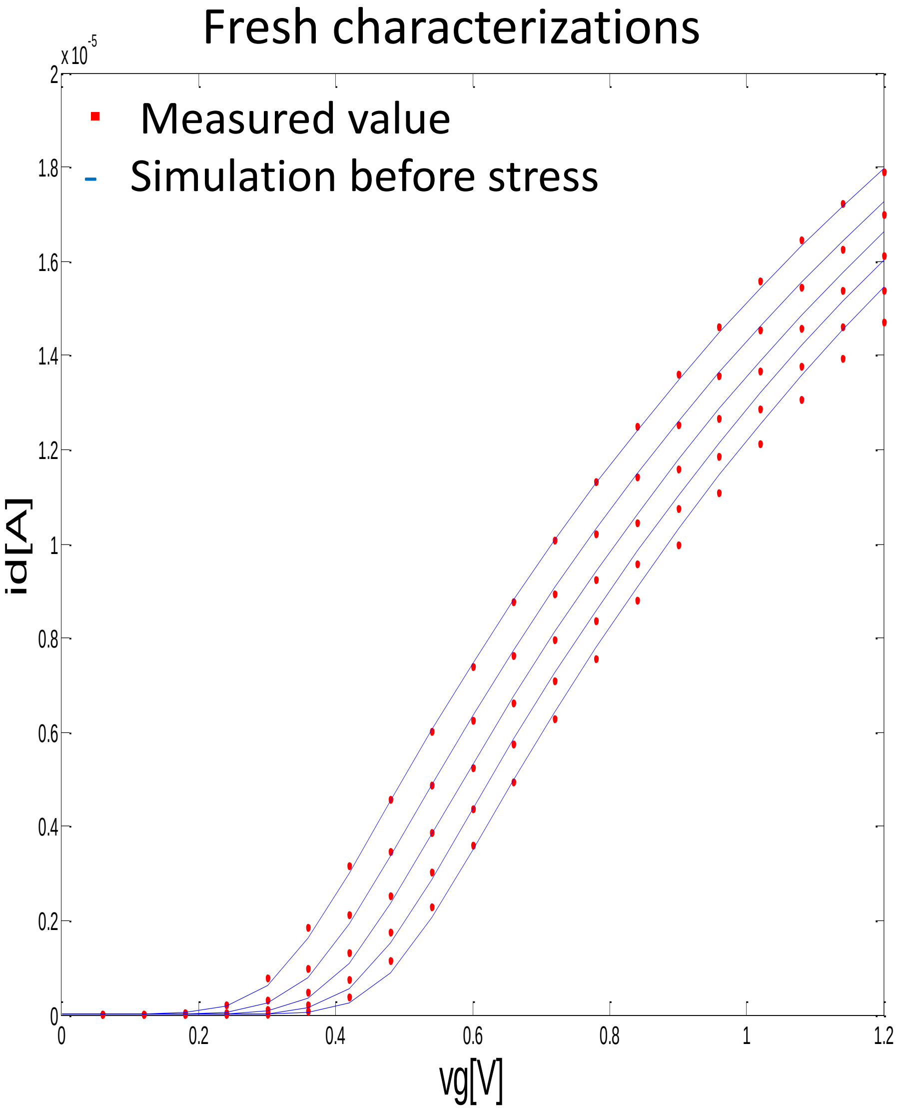
結果保存ファイル: C:¥modech¥extractor¥bsim4n_kit¥result¥result.txt

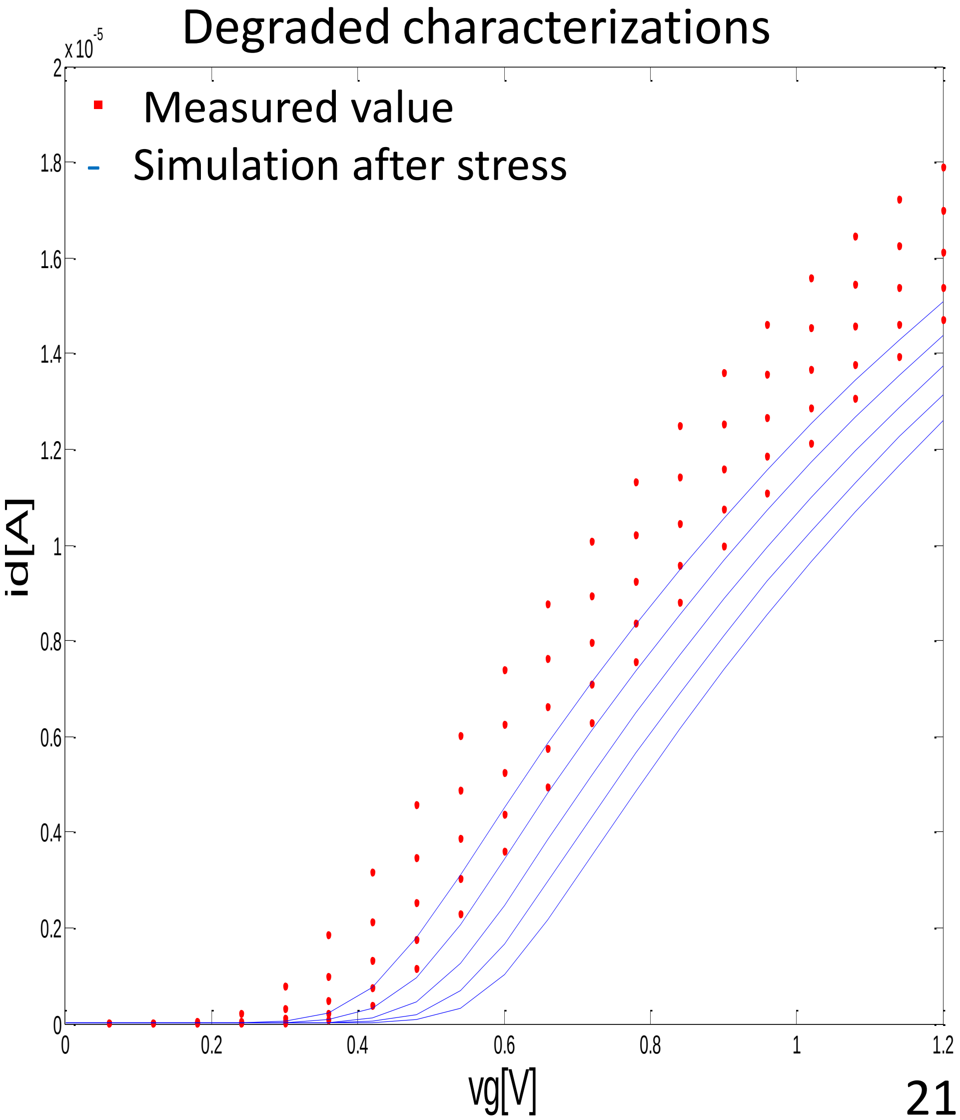
自動抽出マクロプログラム: C:¥modech¥extractor¥bsim4n_kit¥macro¥bsim4n_all.m

TOX抽出モード: ● FIX ○ EXTRACT

Large Id-Vg

Degradation 2.87E-06 [A]

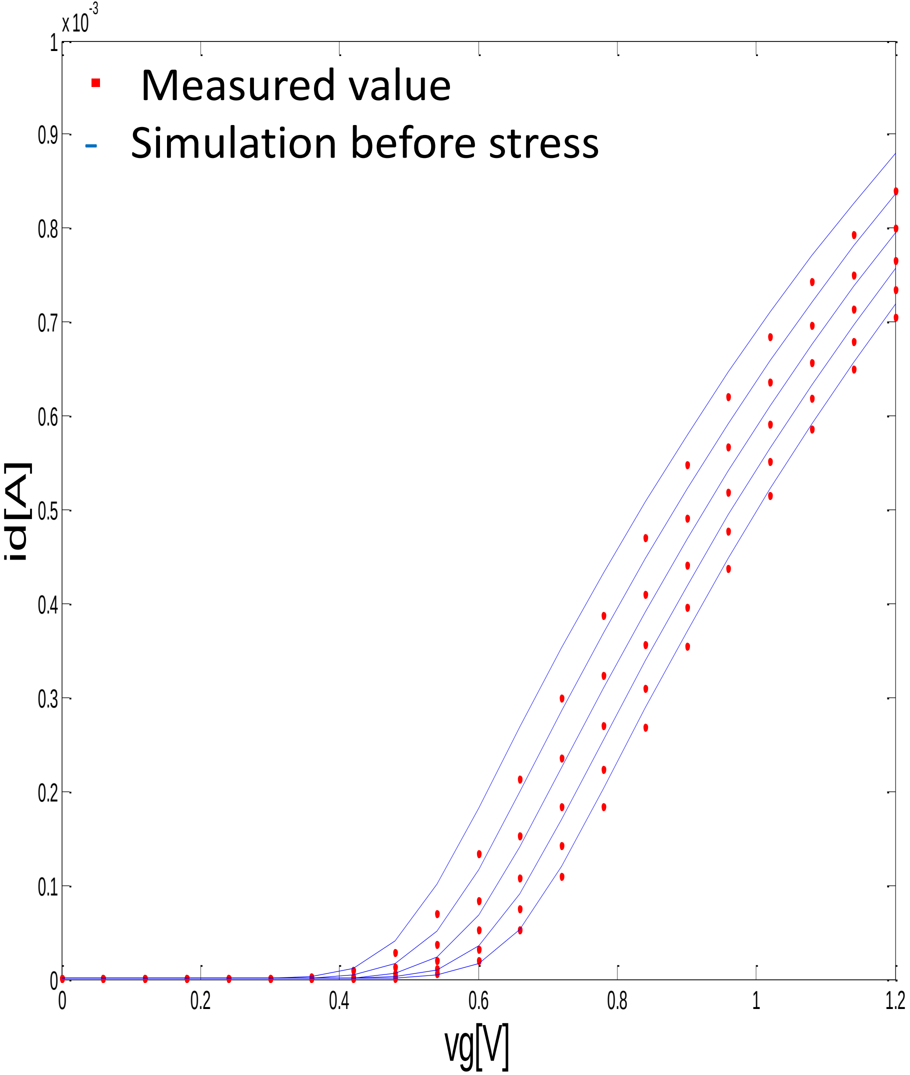




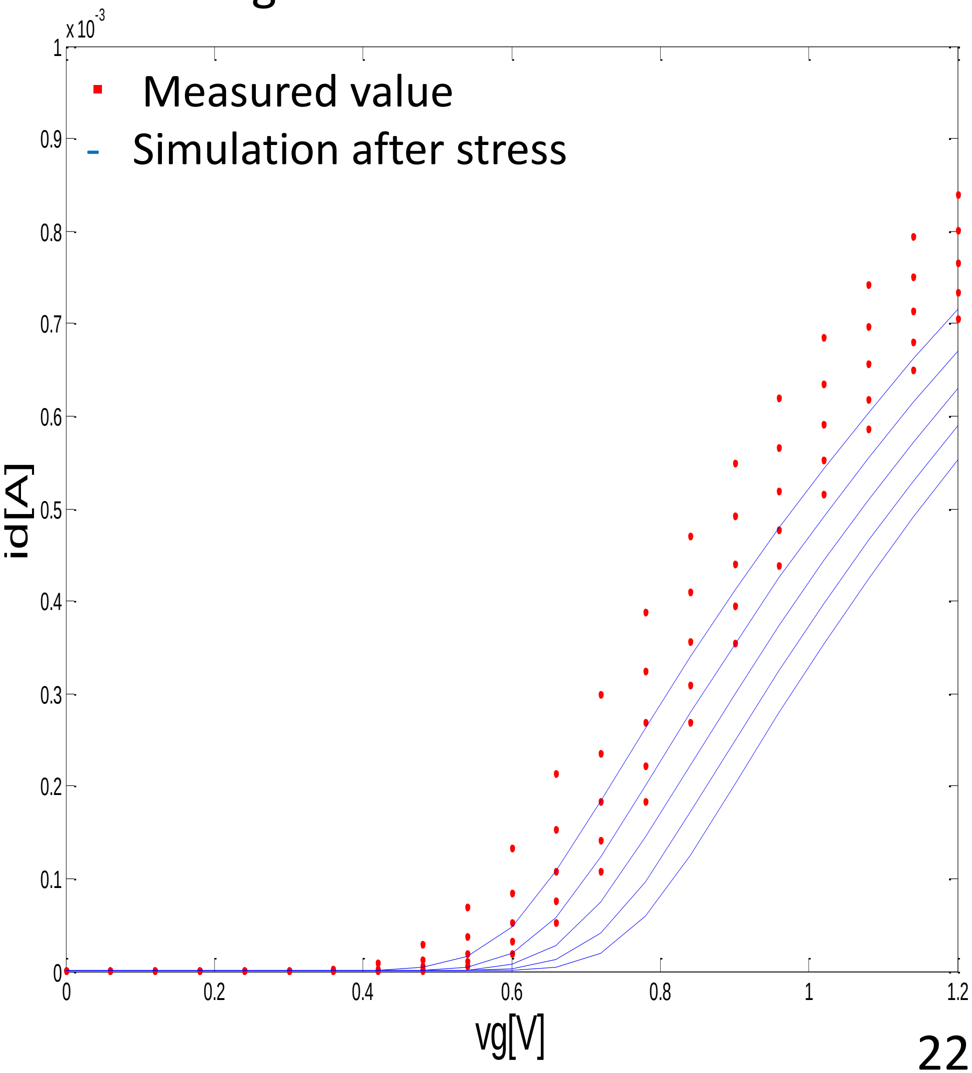
Short Id-Vg

Degradation 1.65E-04 [A]

Fresh characterizations



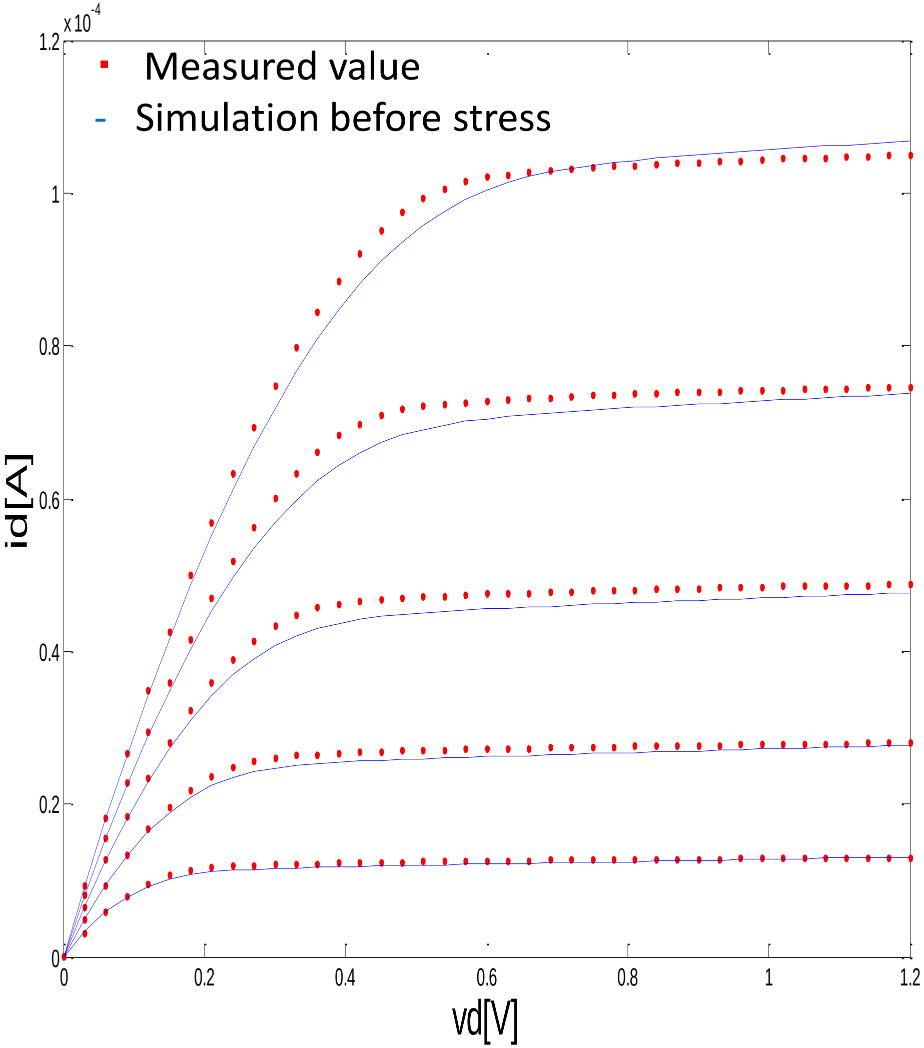
Degraded characterizations



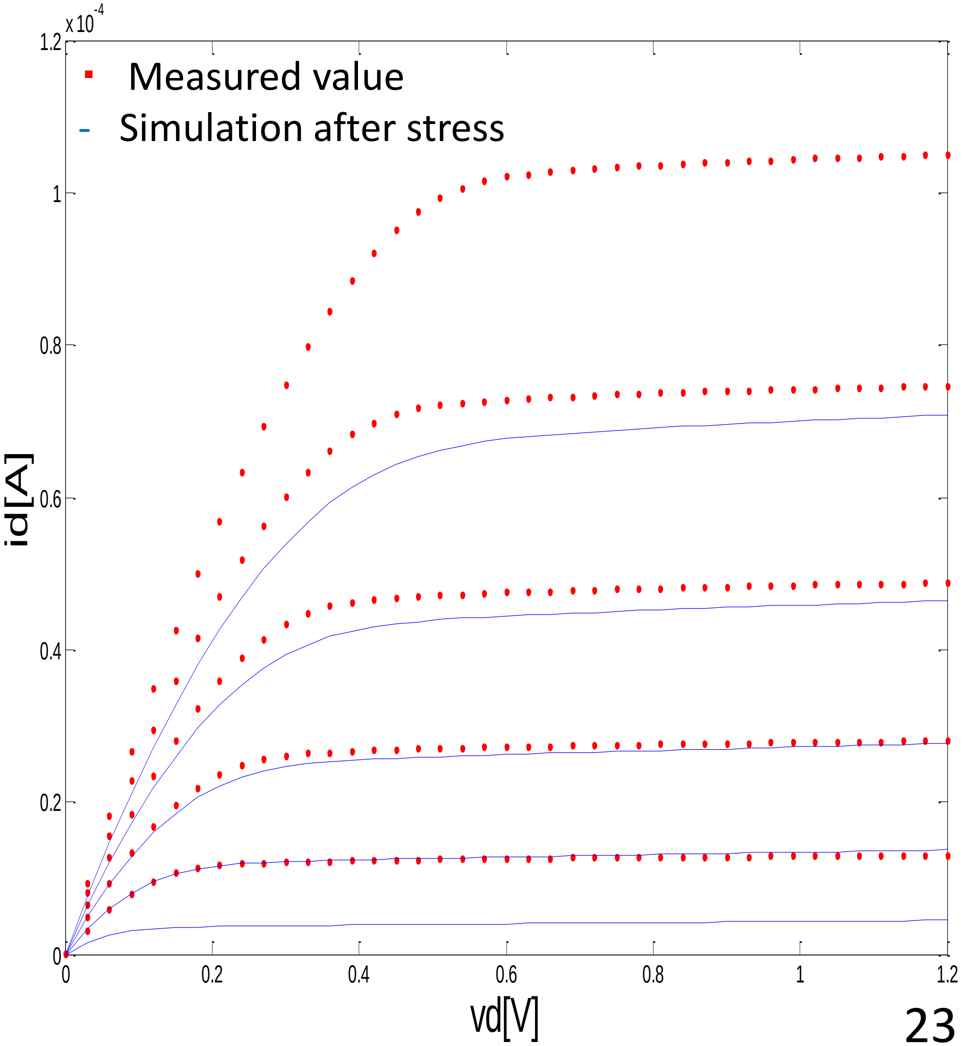
Measurement and Simulations (Id-Vd of Large)

Degradation 3.60E-05 [A]

Fresh characterizations

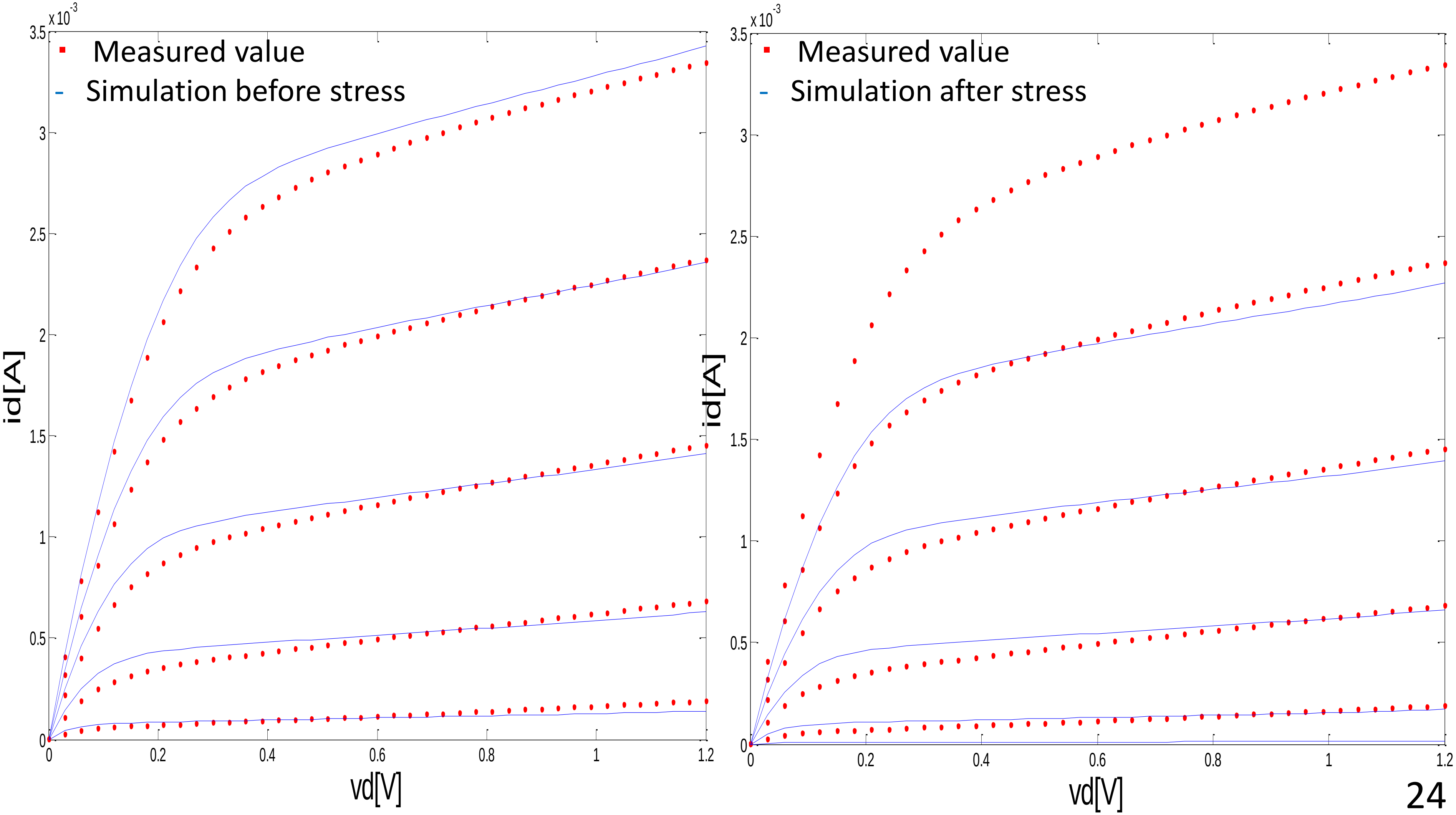


Degraded characterizations



Measurement and Simulations (Id-Vd of Short)

Degradation 1.16E-03 [A]



Fresh characterizations

Degraded characterizations

1 / f Noise Measurements

Target device

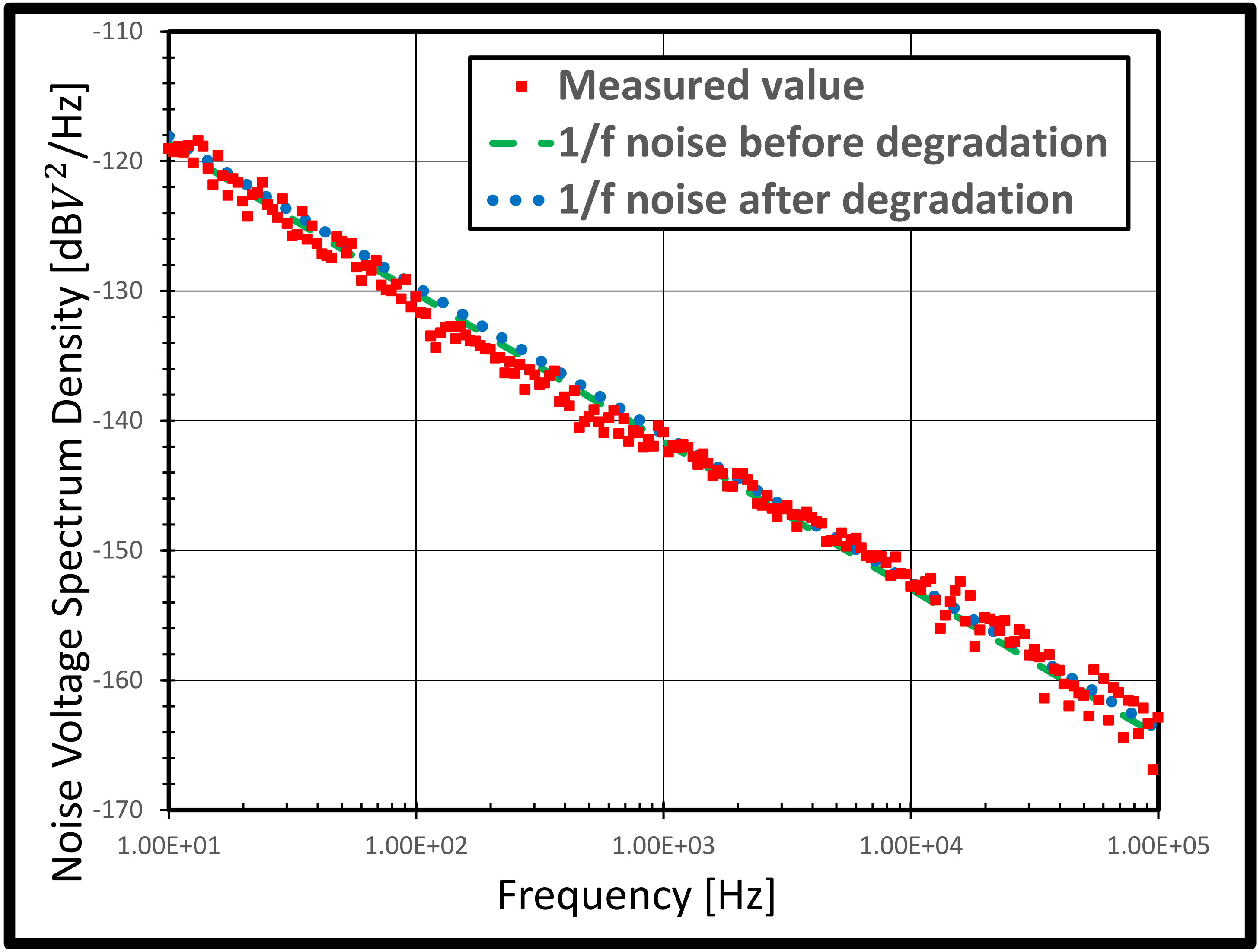
90 nm process n-channel MOSFET

Stress conditions

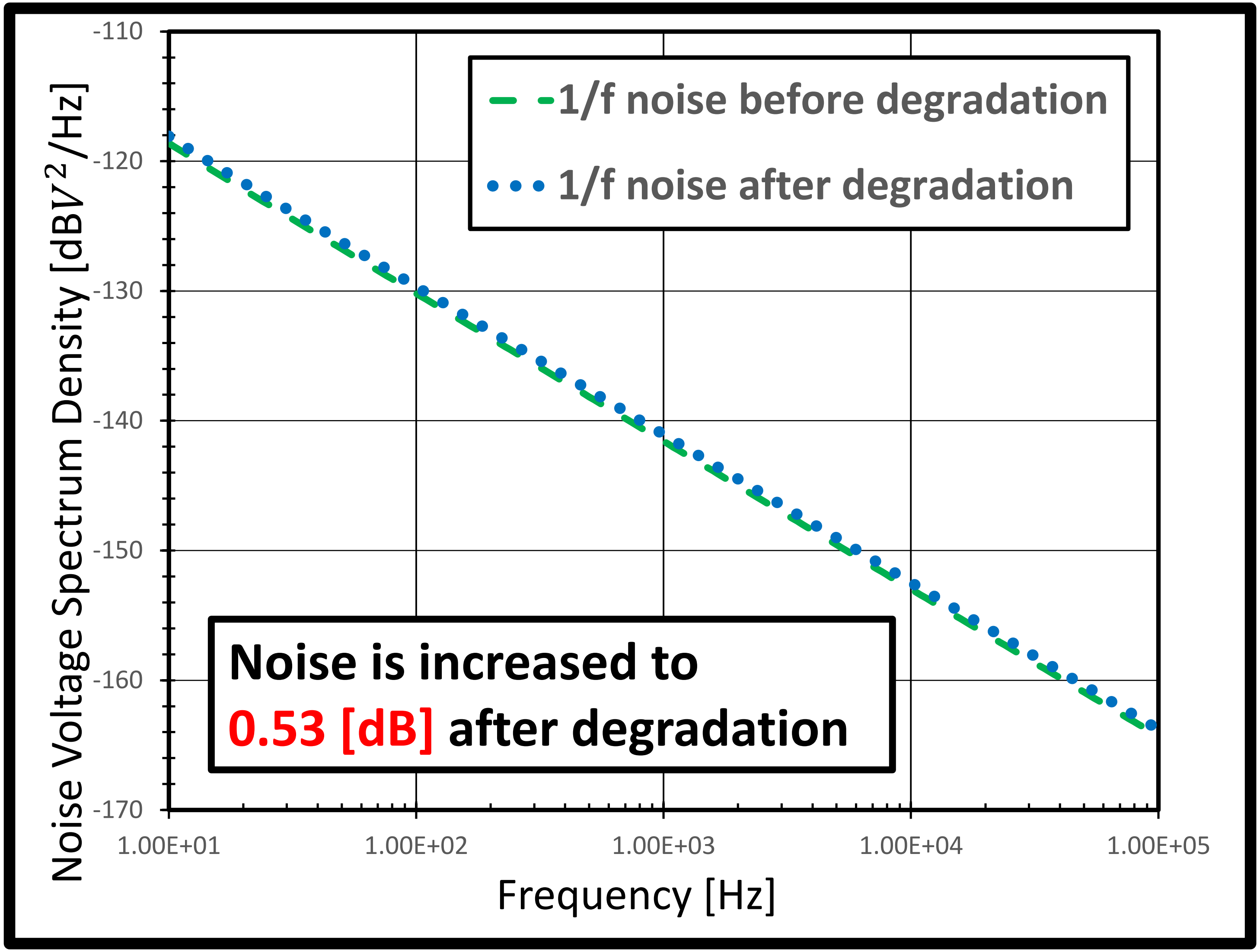
Degradation parameter is based on experimental data from 65nm process devices

• Temperature	**300.15 [K]**
• Time	**1000 [hours]**

Measurement and Simulation of Drain Output 1/f Noise Density



Simulation of Drain Output 1/f Noise Density



Noise is increased to
0.53 [dB] after degradation

1/f Noise Characteristics

why stressed device noise at drain side is not increased

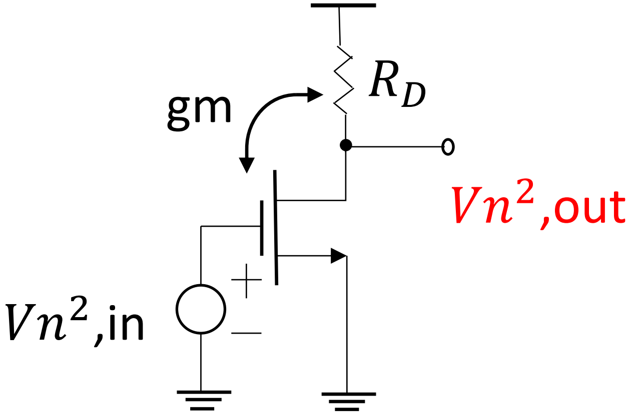
$$S_{I_D} = \frac{C_{OX} * \mu_{eff} * 2 * k * T * \alpha_{H_{nominal}} * D * e^{-(V_{gs}-V_{th})} * {I_{ds}}^{AF}}{C_{OX}{L_{eff}}^2 f^{EF}}$$

$V_{th}\uparrow \;\Rightarrow\; Ids\downarrow \;\Rightarrow\; S_{id}\downarrow$

$\alpha_{Hnormal}\uparrow \;\Rightarrow\; S_{id}\uparrow$

Input Referred Noise

$$\overline{Vn^2,\text{in}} = \frac{\overline{I_n, ds^2}}{\overline{g_m}^2} \qquad I_n, ds^2 = \frac{Vn, ds}{R_D}$$



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Summary

- HCI degradation model was studied and implemented in BSIM4 of our MDW-SPICE simulator
- BSIM4 and degradation model parameters were extracted with measurements of 90nm n-channel MOSFETs
- Simulation verifications of DC drain currents were performed with and without bias stresses
- 1/f noise model parameters were extracted with measurements
- Simulation verifications of drain output 1/f noise density were performed with and without bias stresses

質疑応答

- 劣化前後でアーリー電圧は変化しているのか

  ⇒計算していませんが、移動度が変化しているので

  　変化は起こっていると思います。
- Sパラメータの測定、抽出は行ったのか

  ⇒やっていない

- Due to HCI とするならストレス電圧をいろいろな電圧を用いてやるといいのではないか。

質問は聞き取れなかったので後で聞きにいきました。