Challenges and Opportunities for Achieving a Low-Power CMOS

Low Power → Low V_{DD}

Any Fluctuation degrades LSI Performance. S/N > 23 is required.

Total Fluctuation *N*: $N = \sqrt{V_{1/f}^2 + V_{\sqrt{n}}^2 + V_\sigma^2}$

$V_{1/f}$: Flicker Noise

$V_{\sqrt{n}}$:Quantum Noise

V_σ : Threshold Voltage Fluctuation

Si_3N_4 gate insulator & (110)-surface-orientation CMOS

10 times larger current drivability

Signal Propagation Velocity along with Interconnect is completely different from $\frac{c}{\sqrt{\varepsilon_r}}$ (*c*: Light Velocity, ε_r: dielectric constant)

Propagation velocity slows down in LSI interconnect.

The size and atomic scale expression of a MOS device

Low Power Consumption ➔ Low V_{DD}

Generation	0.18 μm	0.10 μm	0.05 μm	0.035 μm	0.025 μm
Effective Gate Oxide thickness T_{eff}	2.2 nm	1.25 nm	0.7 nm	0.55 nm	0.45 nm
Gate insulator film (ε_r)	SiO_2(3.9)	Si_3N_4(7.9)	HfO_2(30)	HfO_2(30)	HfO_2(30)
Gate insulator film thickness T_{phy}	2.2 nm	2.53 nm	5.38 nm	4.23 nm	3.46 nm
Channel impurities concentration N_A	2×10^{18} cm^{-3}	4×10^{18} cm^{-3}	1.4×10^{19} cm^{-3}	3×10^{19} cm^{-3}	6×10^{19} cm^{-3}
Power supply voltage V_{DD}	1.7 V	1.1 V	0.6 V	0.5 V	0.4 V
Required σ (threshold voltage variation) for S/N or S/σ >23	**74mV**	**48mV**	**26mV**	**22mV**	**17mV**
The number of atoms toward the gate length direction*	663	368	184	129	92
The number of atoms toward the gate insulator film thickness direction*	8	9	19	15	12
The number of impurity-atoms in a channel domain n_a	787	347	165	119	86
The number variation of impurity- atoms $sn_a=\sqrt{n_a}$	28	18	12	10	9

*The number of atoms was standardized based on the distance (0.27nm) between 2 atoms of Si crystal.

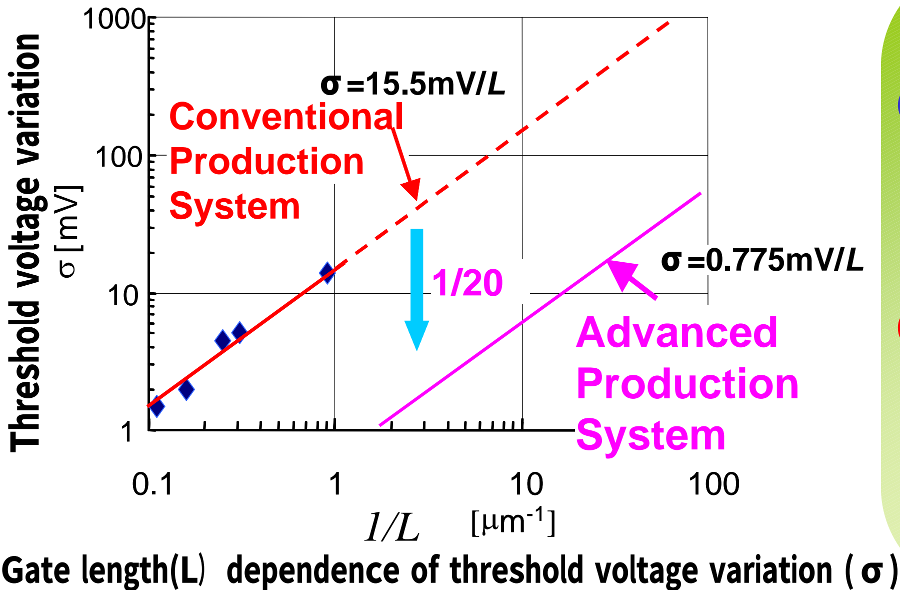
Any fluctuation degrades LSI performance.

S/N, S/σ > 23 is required for prospective high speed MPU

Degradation of S/N by the threshold voltage variation accompanied by the device scaling

S/N, S/σ > 23 is required

The case of W=L



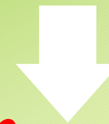
Gate length(L) dependence of threshold voltage variation (σ)

Conventional Production System : σ=15.5/L (1) *(in the case of W=L)*

0.1μm generation (L=0.1μm) **σ=155mV from Eqn.(1)**

Power supply voltage V_{DD}=1.1V

$$S/N = \frac{1.1V}{155mV} = 7.1$$



0.035μm generation (L=0.035μm) **σ=443mV from Eqn.(1)**

Power supply voltage V_{DD}=0.5V

$$S/N = \frac{0.5V}{443mV} = 1.1$$

S/N degrades to 1/7

Advanced Production System : σ=0.85/L (2) *(in the case of W=L)*

Threshold voltage variation: 1/20 of conventional production system

0.1μm generation (L=0.1μm) **σ=7.75mV from Eqn.(2)**

V_{DD}=1.1V

$$S/N = \frac{1.1V}{7.75mV} = 141$$

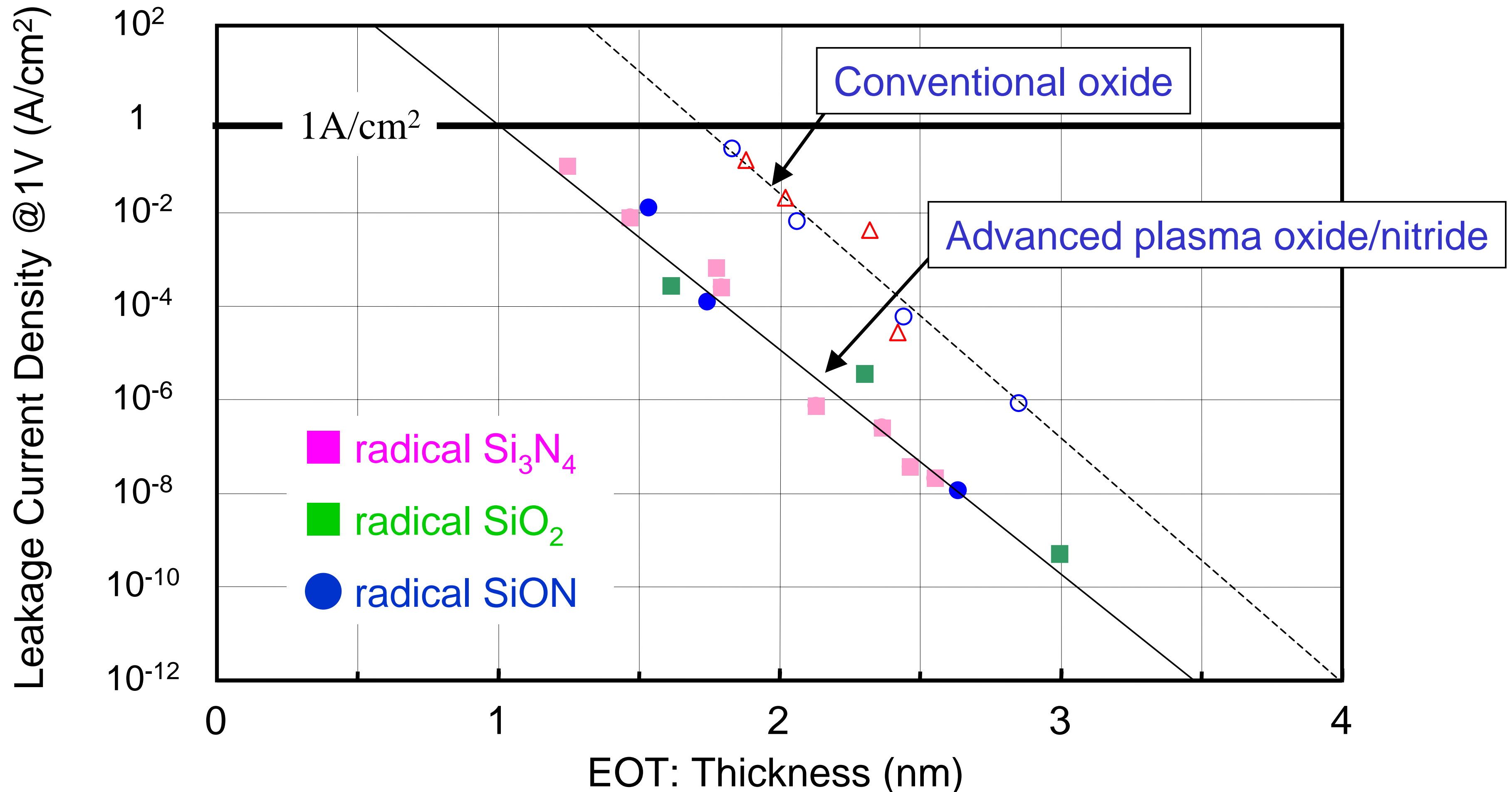
0.035μm generation (L=0.035μm) **σ=22.1mV from Eqn.(2)**

V_{DD}=500mV

$$S/N = \frac{0.5V}{22.1mV} = 23$$

S/N still be kept grater than 23 even in 0.035μm generation

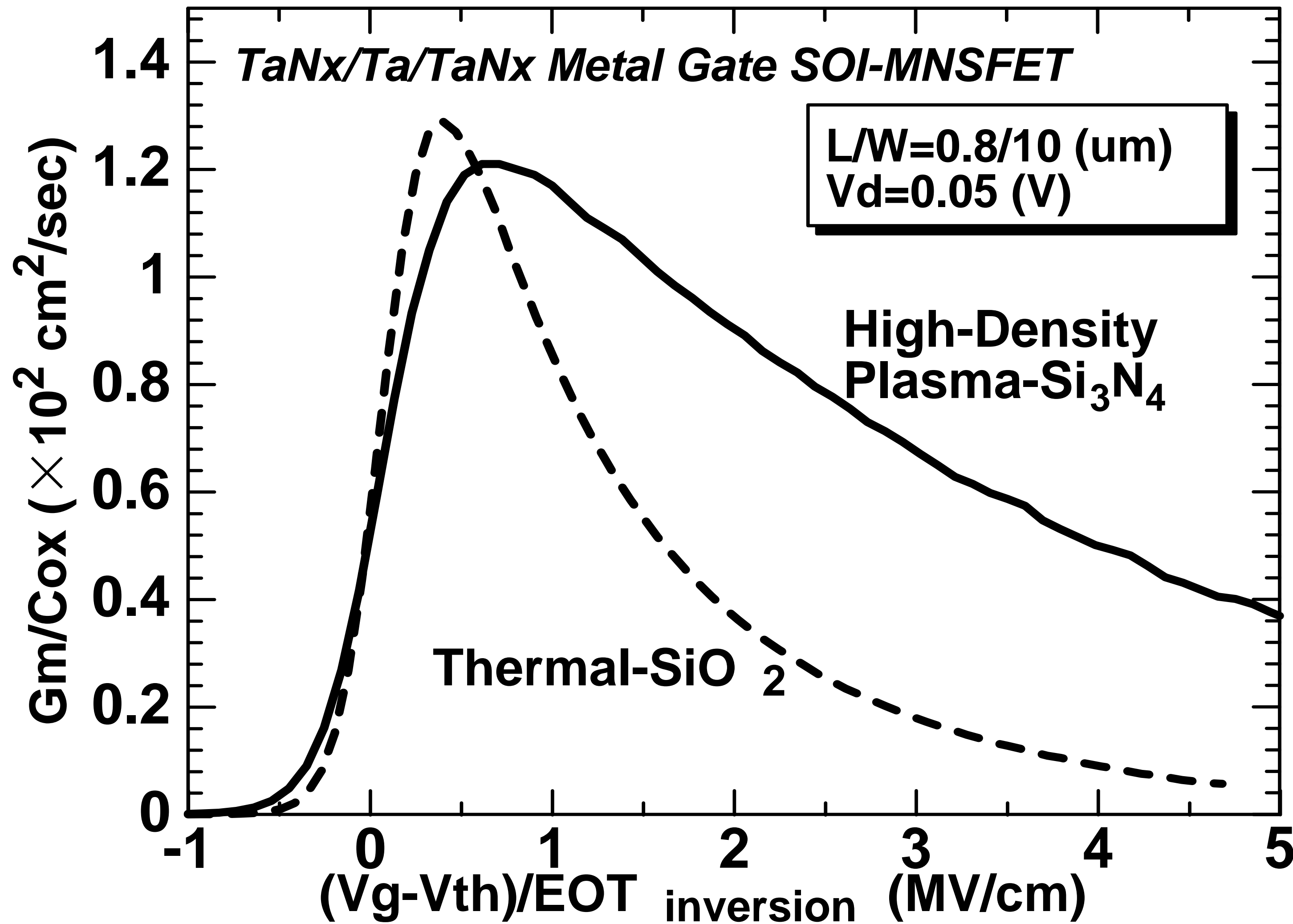
Leakage Current (@1.0V) as a function of Oxide Thickness



Si_3N_4 (~4 times) Gate Insulator & (110) surface orientation (~ 2.5 times)

➔ 1/10 of Conventional Device Power Consumption

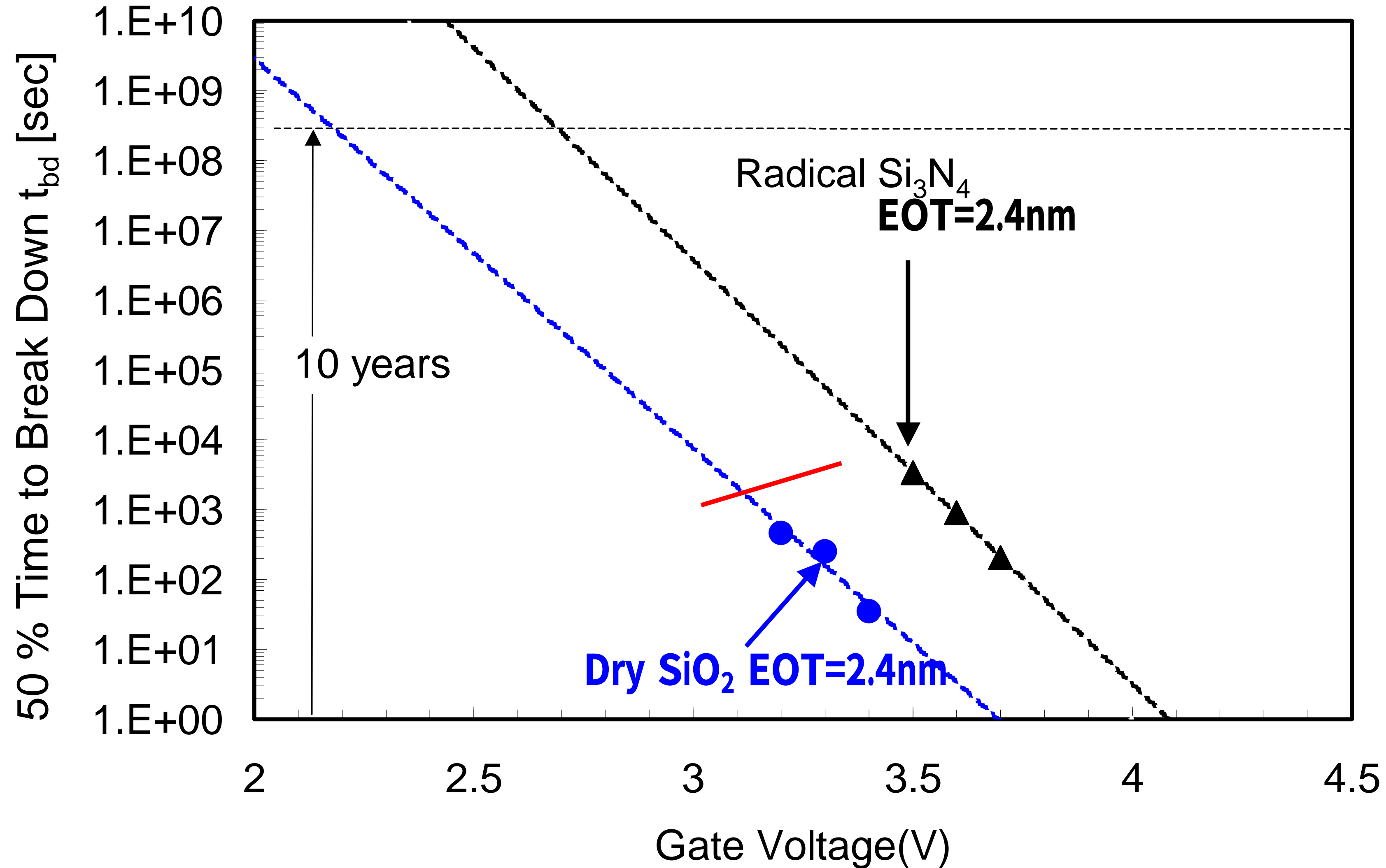
Comparison of Transconductance



Si_3N_4 (~4 times) Gate Insulator & (110) surface orientation (~ 2.5 times)

➔ 1/10 of Conventional Device Power Consumption

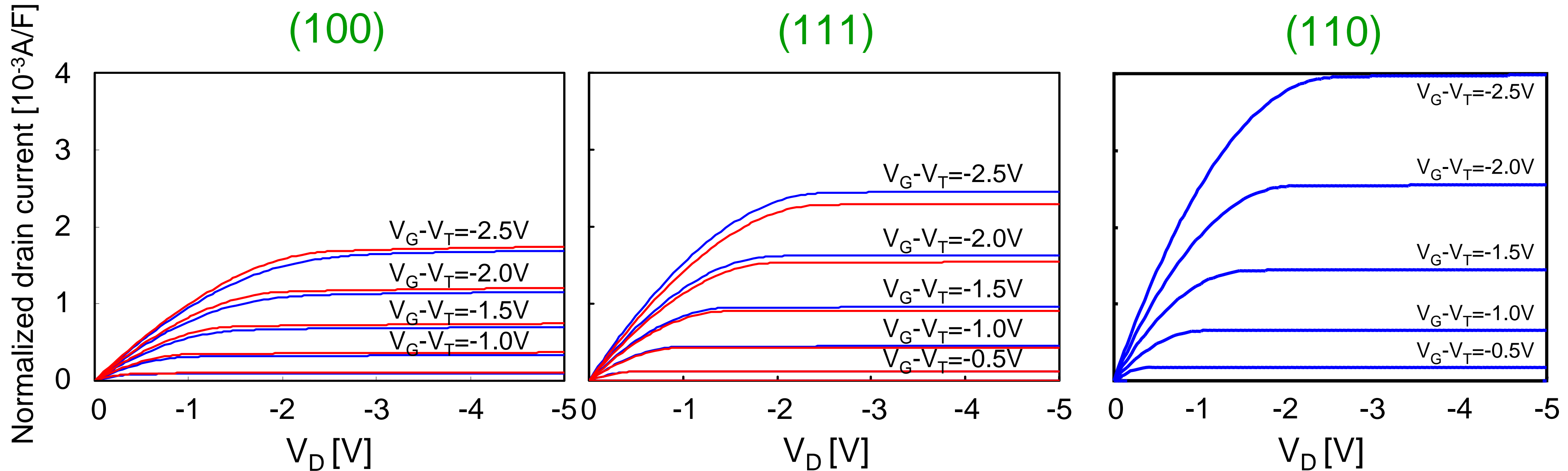
10 Year Lifetime Projection for Si_3N_4



20~30% higher gate voltage can be applied to the Si_3N_4 gate insulator

2 times larger current drivability is available.

Implement the (110)-oriented MOSFET



	(100)	(111)	(110)
Current	***1.0***	***1.3***	***2.5***

(110)-oriented MOSFET

2.5 times large current drivability

➔ 1/ 2.5 of Conventional Device Power Consumption

Interconnect Performance in LSI curcuit

Signal Propagation Velocity in Interconnect [cm/s]

10^{11}

10^{10}

10^{9}

10^{8}

1GHz Propagation

Signal velocity in SiO_2 $= \frac{c}{\sqrt{\varepsilon_r}} (= 1.5 \times 10^{10} [cm/s])$

0.3μm interconnect: 4.3×10^9 [cm/s]

0.1μm interconnect: 1.8×10^9 [cm/s]

t_{SiO2}=10μm

t_{SiO2}=1μm

LSI circuit region

100 10 1 0.1 0.01

Interconnect Width and Thickness [μm]

Interconnect in LSI
Width & Thickness
< Skin Depth

Signal energy is mainly in interconnect metal other than interlayer dielectric in LSI circuit

Signal propagation velocity slows down in LSI circuit region