Wafer-Level Extraction of BSIMSOI Low-Frequency Noise Parameters for 130 nm Partially-Depleted SOI MOSFETs

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Outline of presentation

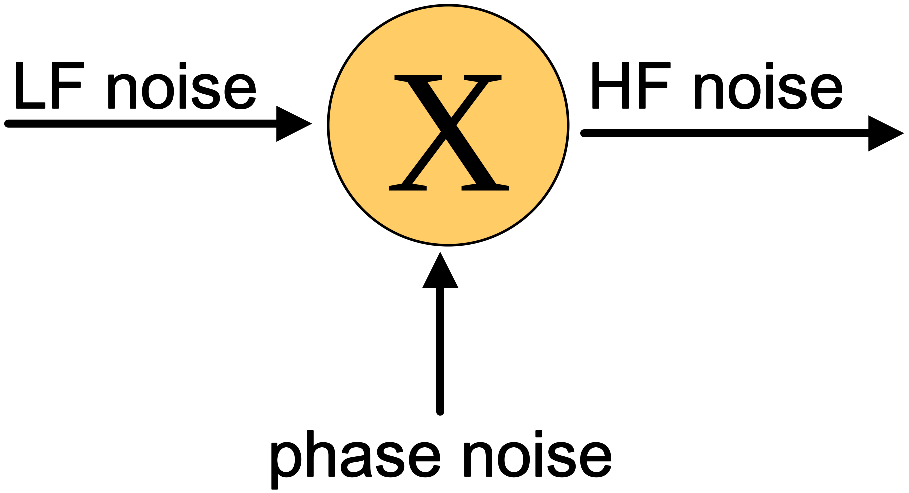
- Aim of this work
- Physical Low-Frequency Noise (LFN) models
- Extraction of LFN parameters, without simulation
- LFN models implemented in SPICE and BSIM3/4
- Experimental
- Extraction of LFN parameters, with simulation
- Discussion
- Summary and conclusion

Keywords: low-frequency noise, BSIM model, parameter extraction, analog & RF circuit design

Aim of this work

- ➢ **Design of analog and RF circuits : phase noise**

- ➢ **Need for LFN models and parameters**



Physical LFN models

- **1/f noise : σ fluctuations**

$$\sigma = q\, n\, \mu$$

- **Hooge's model (Δμ)**

$$\frac{S_i(f)_{\Delta\mu}}{Id^2} \# \frac{1}{Id}$$

- **McWhorter's model (Δn)**

$$\frac{S_i(f)_{\Delta n}}{Id^2} \# \left(\frac{gm}{Id}\right)^2$$

- **McWhorter's enhanced model (Δμ-Δn) : Ghibaudo**

$$S_i(f)_{\Delta\mu-\Delta n} = \left[1 \pm \alpha\, \mu_{eff}\, C_{ox} \frac{Id}{gm}\right]^2 S_i(f)_{\Delta n}$$

- **Total noise spectral density (without R_{access}):**

$$[S_i(f)]_{1/f} = [S_i(f)]_{McWhorter(\Delta n / \Delta\mu-\Delta n)} + [S_i(f)]_{Hooge(\Delta\mu)}$$

Extraction of LFN parameters, without simulation

- McWhorter's enhanced model ($\Delta\mu$-Δn) : N_t^* [$eV^{-1}\ m^{-3}$]

$$S_i(f)_{\Delta\mu-\Delta n} = gm^2 \frac{q^2\, kT\, N_t^*}{\gamma\, WL\, C_{ox}^2} \frac{1}{f^{EF}} \qquad \left(S_i(f)_{\Delta n} = gm^2 \frac{q^2\, kT\, N_t}{\gamma\, WL\, C_{ox}^2} \frac{1}{f^{EF}} \right)$$

- 2-parameter definitions : (N_t,α) or (A,C) with B = $2(AC)^{1/2}$

$$C_{ox} \frac{Id}{gm} \sim C_{ox}(Vg - Vt) \sim qN(x) \text{ in linear regime \& SI}$$

$$N_t^* = N_t\left[1 \pm \alpha\, \mu_{eff}\, qN(x)\right]^2 = A + B\, N(x) + C\, N(x)^2 \qquad \begin{cases} A = N_t \\ B = 2\,\alpha\,\mu_{eff}\, q\, N_t \\ C = (\alpha\,\mu_{eff}\, q)^2 N_t \end{cases}$$

➢ With (Id,gm) measurements only (n-MOSFET) :

A = 10^{23} $eV^{-1}\ m^{-3}$ ($\Rightarrow N_t = 10^{17}$ $eV^{-1}\ cm^{-3}$)

B = 9 x 10^{6} $eV^{-1}\ m^{-1}$

C = 2 x 10^{-10} eV^{-1} m

LFN models implemented in SPICE and BSIM (1/2)

- **SPICE :**

$$S_i(f) = \frac{KF\ Ids^{AF}}{WL\ C_{ox}} \frac{1}{f^{EF}}$$

  (Δμ) if AF = 1

  (Δn) if AF = { 2 when Vg < Vt or 1 when Vg > Vt }

- **BSIM : (Δμ-Δn)**

$$N_t^* = NOIA + NOIB\ N(x) + NOIC\ N(x)^2$$

- **Weak inversion : NOIA**

$$S_{wi}(f) = \frac{kT\,Ids^2}{\gamma\ WL\ [\frac{kT}{q^2}(C_{ox} + C_{dep} + C_{it})]^2} \frac{NOIA}{f^{EF}} = \frac{kT\,Ids^2}{\gamma\ WL\ N^{*2}} \frac{NOIA}{f^{EF}}$$

- **Strong inversion : NOIA, NOIB, NOIC**

$$S_{si}(f) = \frac{kT\ Ids^2}{\gamma\ WL^2} \frac{1}{f^{EF}} \int_0^L \frac{NOIA + NOIB\ N(x) + NOIC\ N(x)^2}{[N(x) \quad + N^*]^2} dx$$

LFN models implemented in SPICE and BSIM (2/2)

- **Strong inversion :** $S_{si}(f) = S_{si1}(f) + S_{si2}(f)$

$$S_{si1}(f) = \frac{q^2 \mu_{eff} kT \, Ids}{\gamma C_{ox} L^2} \frac{1}{f^{EF}} \left[NOIA \ln \frac{N_0 + N^*}{N_L + N^*} + NOIB\,(N_0 - N_L) + \frac{NOIC}{2}(N_0^2 - N_L^2) \right]$$

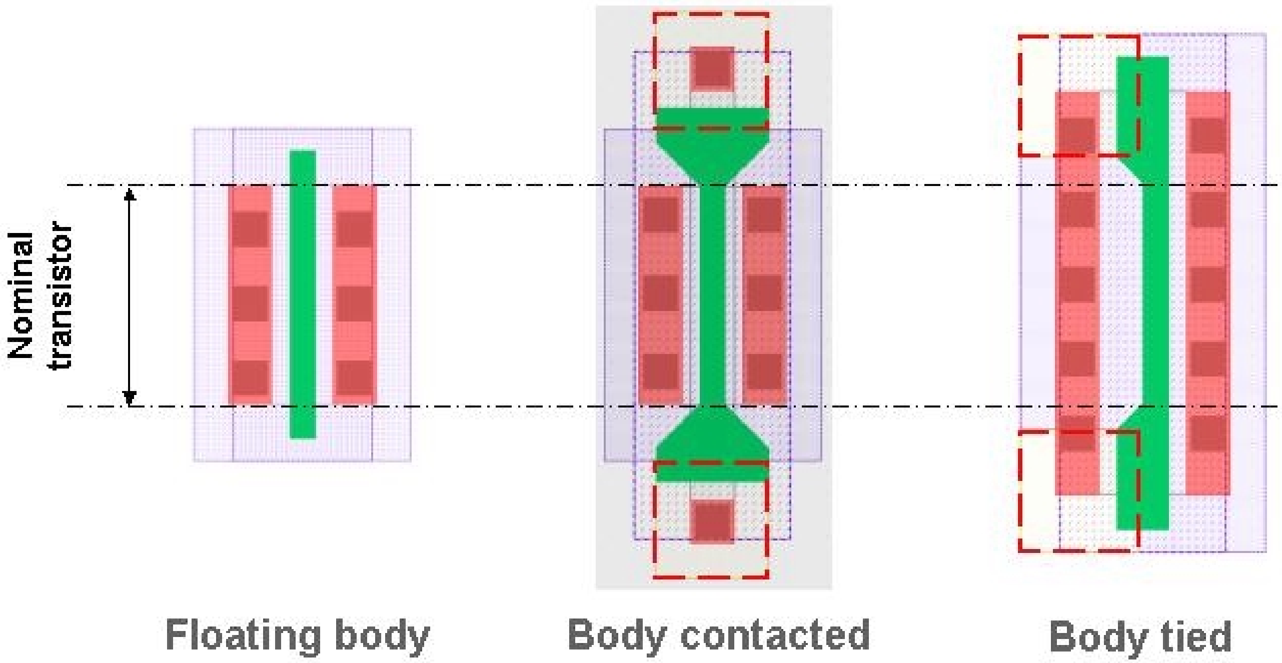
$$S_{si2}(f) = \Delta L_{pin} \frac{kT Ids^2}{\gamma W L^2} \frac{1}{f^{EF}} \left[\frac{NOIA + NOIB\, N_L + NOIC\, N_L^2}{\left(N_L + N^*\right)^2} \right]$$

- **Continuity :** $\dfrac{1}{S_i(f)} = \dfrac{1}{S_{wi}(f)} + \dfrac{1}{S_{si}(f)}$

➢ **Need for extracted DC parameters**

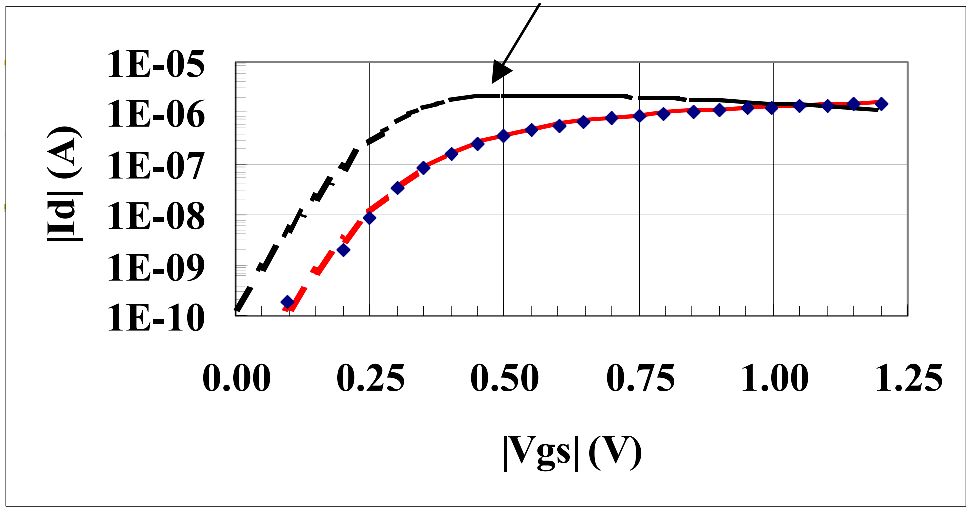
Experimental

- **Point-probe noise measurements**
- ***Noisys* : enables wafer-level LFN acquisition**
- **130 nm PD SOI MOSFETs (V_{DD} = 1.2 V, t_{ox} = 2.6 nm)**
- **FB (Floating Body)**
- **BC (Body Contacted) : T- type or H- type**

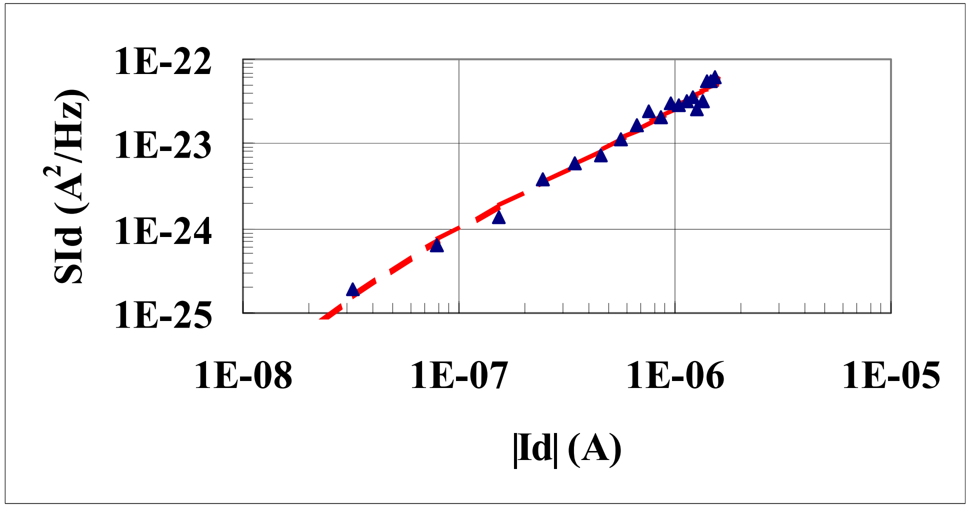


Extraction of LFN parameters, with simulation (1/2)

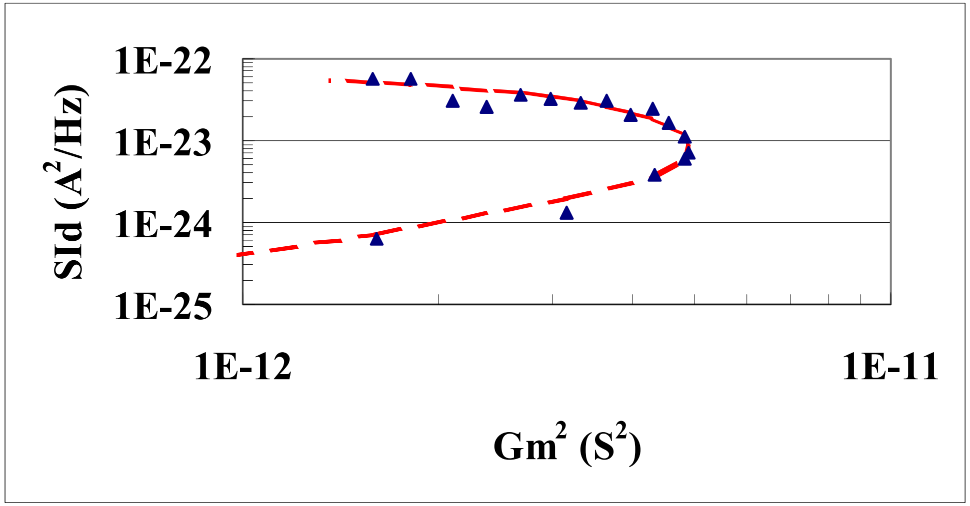
Id(Vgs), gm(Vgs)



$S_{Id}(Id)$

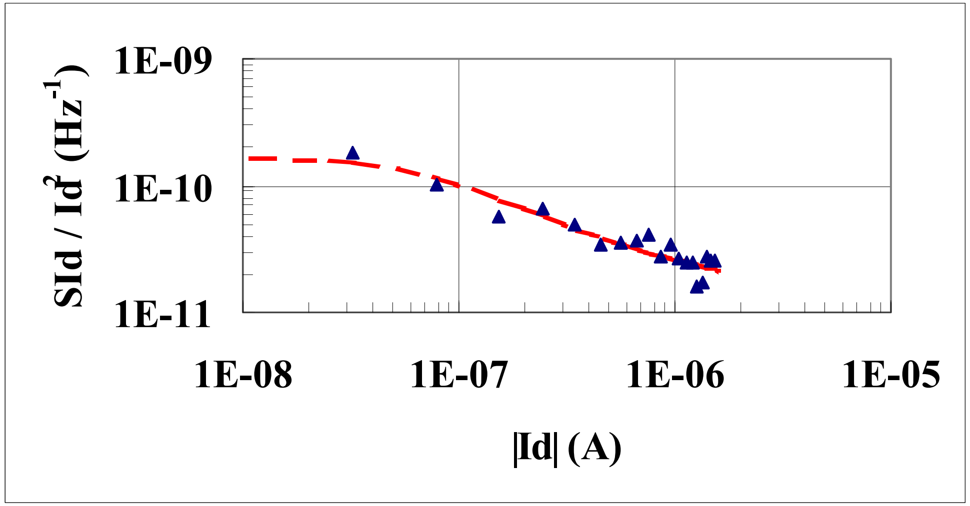


$S_{Id}(Gm^2)$



EF≈1

$S_{Id}(Id)/Id^2$



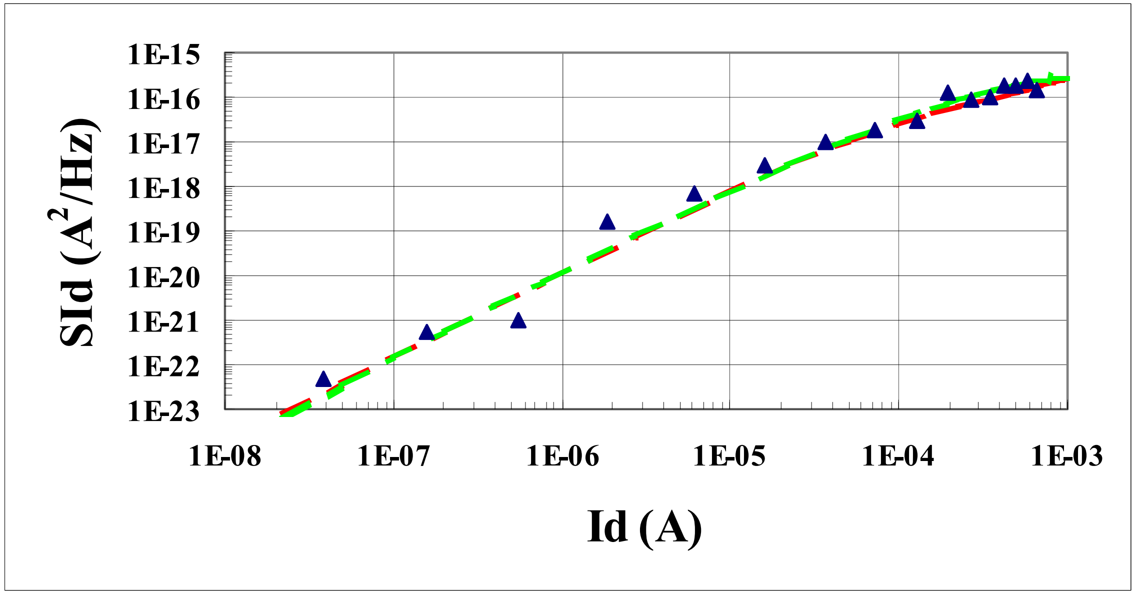
p-MOSFET BC-H W=5 L=10 [µm] @ f=10 Hz |Vds|=50 mV

Extraction of LFN parameters, with simulation (2/2)

Dots : measurements

Red line : Δμ-Δn

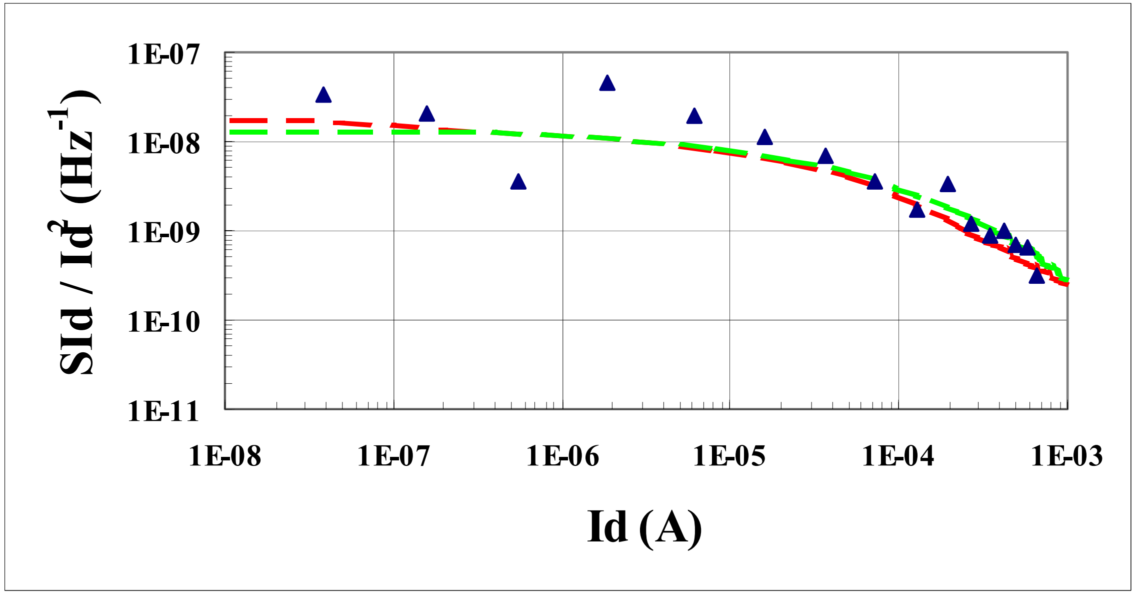
Green line : BSIMPD2.2.3



- **With DC parameters and simulation only :**

NOIA = 10^{20} eV^{-1} m^{-3}

(⇒ N_t = 10^{14} eV^{-1} cm^{-3} !)



NOIB ~ 3 x 10^{5} eV^{-1} m^{-1}

NOIC = 2 x 10^{-13} eV^{-1} m

n-MOSFET BC-T W=10 L=0.13 [μm] @ f=10 Hz Vds=50 mV

Discussion (1/2)

➢ (NOIA, NOIB, NOIC) ≠ (A, B, C) using BSIMPD2.2.3 !

x 10^{-3}

A	B	C	Results
10^{23}	9×10^{6}	2×10^{-10}	n-MOSFET
NOIA	NOIB	NOIC	Results
10^{20}	$\sim 3 \times 10^{5}$	2×10^{-13}	n-MOSFET
$eV^{-1}\ m^{-3}$	$eV^{-1}\ m^{-1}$	$eV^{-1}\ m$	units

- Why this factor ? No clear answer but …
- Change of units : since BSIM4.0.0 and BSIMSOI3.2 releases
  - $\gamma = 10^{8}$ [cm^{-1}] $\rightarrow \gamma = 10^{10}$ [m^{-1}]
  - $N^{*} = 10^{14}$ [cm^{-2}] $\rightarrow N^{*} = 10^{18}$ [m^{-2}]

C code values

Discussion (2/2)

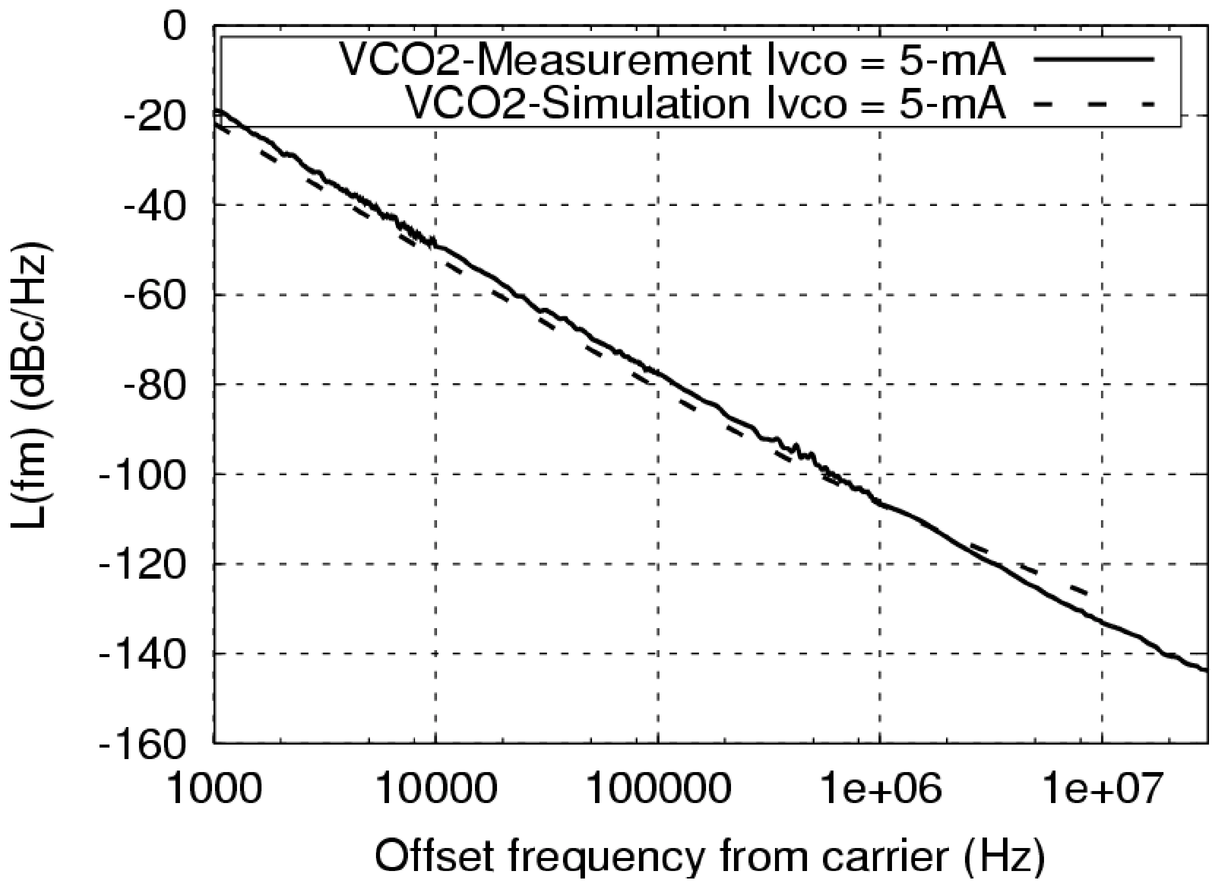
- **old :** $<$ BSIM4.0.0 (2000) or BSIMSOI3.2 (2004)
- **new :** $\geq$ BSIM4.0.0 (2000) or BSIMSOI3.2 (2004)

$NOIA^{new}$	$NOIB^{new}$	$NOIC^{new}$	Default new values
6×10^{41}	3×10^{26}	9×10^{9}	n-MOSFET
$NOIA^{new} \times q$	$NOIB^{new} \times q$	$NOIC^{new} \times q$	Default new values x q
10^{23}	5×10^{7}	1×10^{-9}	n-MOSFET
$NOIA^{old}$	$NOIB^{old}$	$NOIC^{old}$	Default old values
10^{20}	5×10^{4}	1×10^{-12}	n-MOSFET

$\times 10^{-3}$

➢ $NOIA^{old} = 10^{-3}$ A ; $NOIB^{old} = 10^{-3}$ B ; $NOIC^{old} = 10^{-3}$ C

Application : Phase noise simulations & measurements in VCO



n-MOSFETs
BC-T

« A Multi-phase 10 GHz VCO in CMOS/SOI for 40-Gbit/s SONET OC-768 Clock and Data Recovery Circuits », D. Axelrad, E. de Foucauld, M. Boasis, P. Martin, P. Vincent, M. Belleville and F. Gaffiot, IEEE RFIC 2005 Symposium, Long Beach CA, 12-14 June, 2005

Summary and conclusion

- Wafer-level LFN measurements
- 130 nm PD SOI MOSFETs
- BSIM noise model based on physical model Δμ-Δn
- Proposed extraction method without simulation
- Easier than BSIM simulation (no need for DC parameters)
- If revision < BSIM4.0.0 or BSIMSOI3.2 then factor 1000
- Compatible with Philips' MM11 model (NFA, NFB, NFC)

$$\mathrm{NFA} = \frac{q}{\gamma WL}\left(\mathrm{NOIA} + \mathrm{NOIB}\ N^*\right) \quad \left[V^{-1}\ m^{-4}\right]$$

$$\mathrm{NFB} = \frac{q}{\gamma WL}\left(\mathrm{NOIB} + \mathrm{NOIC}\ N^*\right) \quad \left[V^{-1}\ m^{-2}\right]$$

$$\mathrm{NFC} = \frac{q}{\gamma WL}\mathrm{NOIC} \quad \left[V^{-1}\right]$$

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