Measurement and modelling of specific behaviors in 28nm FD SOI UTBB MOSFETs of importance for analog / RF amplifiers

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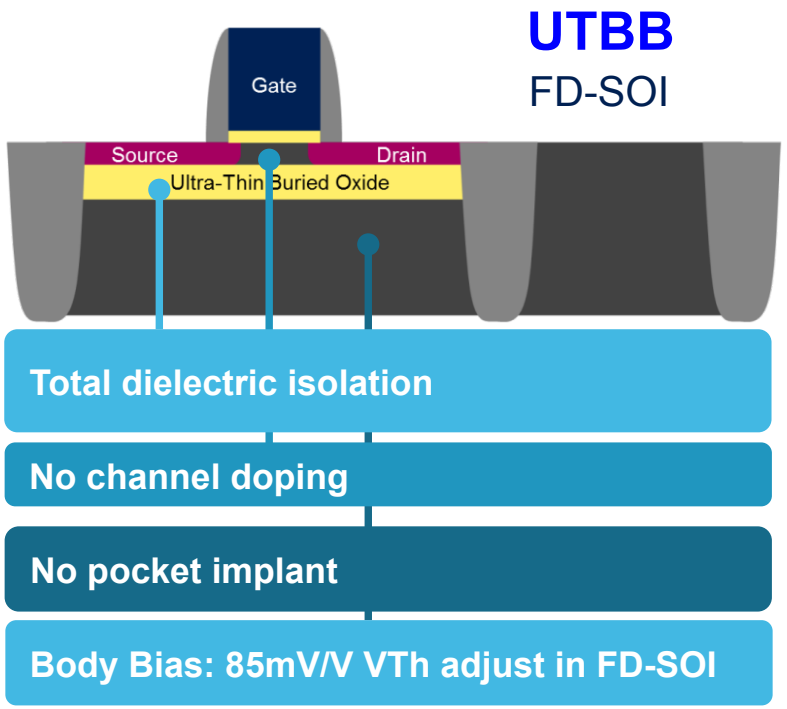
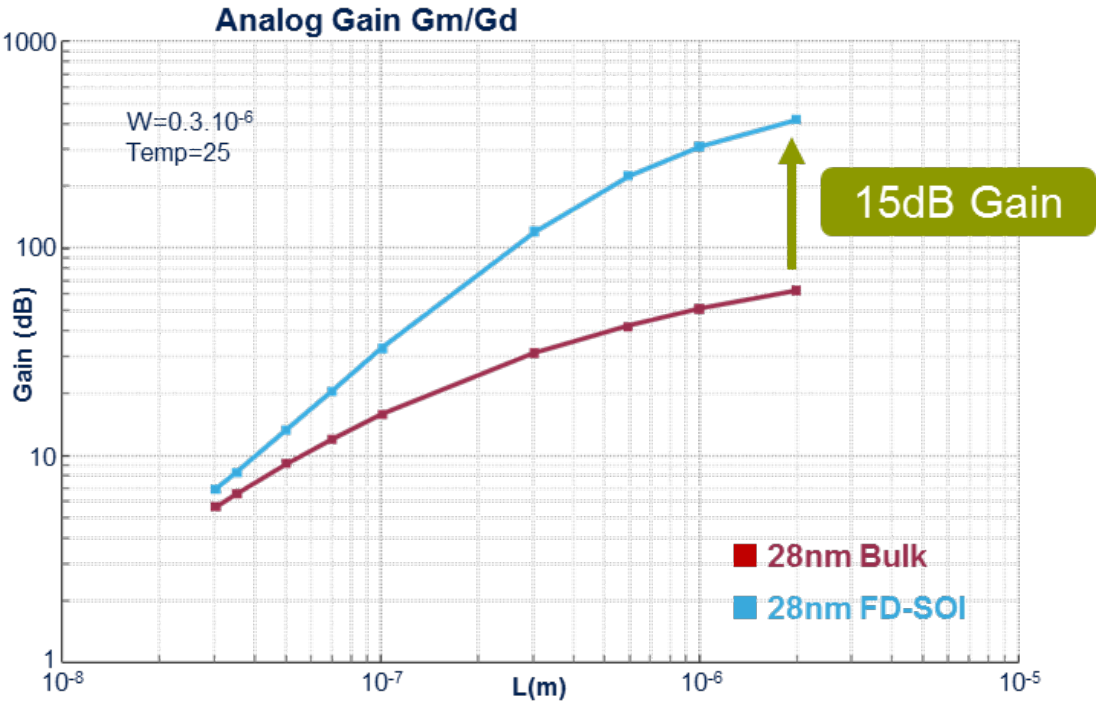
Context FD-SOI: Unique Analog design opportunity





- **New design opportunity** by controlling analog device characteristics through **back gate biasing** techniques
  - ❑ **V_T adjustment**
  - ❑ **Improved SCE control (suppression of SUB depletion)**

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→ Also better other analog performances ? And are they correctly modeled ?

Outline

- ✓ **Context**
- ✓ **Analog / RF Figures of Merit :**

  from device assessment to circuit design at low frequency
- ✓ **UTBB specificities & challenges**

  Back gate biasing & FoM variation with frequency
- ✓ **Wideband RF amplifier**

  Non-linear performance
- ✓ **Conclusions**

Analog / RF figures of merit

Key-factors

@ MOSFET-level

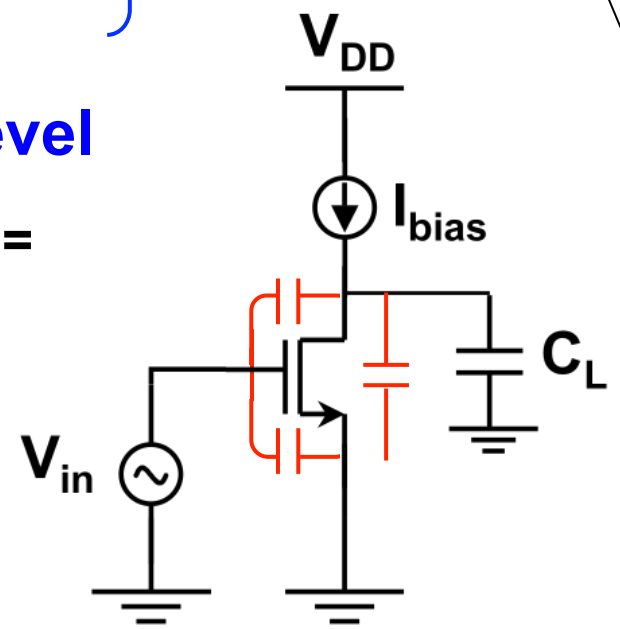
- $f_T = g_m/(2\cdot\pi\cdot C_{gg})$
- $f_{max} \propto f_T, R_g$
- $A_{v0} = g_m/g_d = (g_m/I_d)\cdot V_{EA}$ $\neq$ const (f)

⇨ *depends on*

- ❑ Transconductance g_m
- ❑ Drive current, I_d
- ❑ Output conductance, g_d
- ❑ Early voltage, V_{EA} ($V_{EA}=I_d/g_d$)
- ❑ g_m/I_d ratio
- ❑ Gate capacitance, C_{gg}
- ❑ Parasitics (C, R)

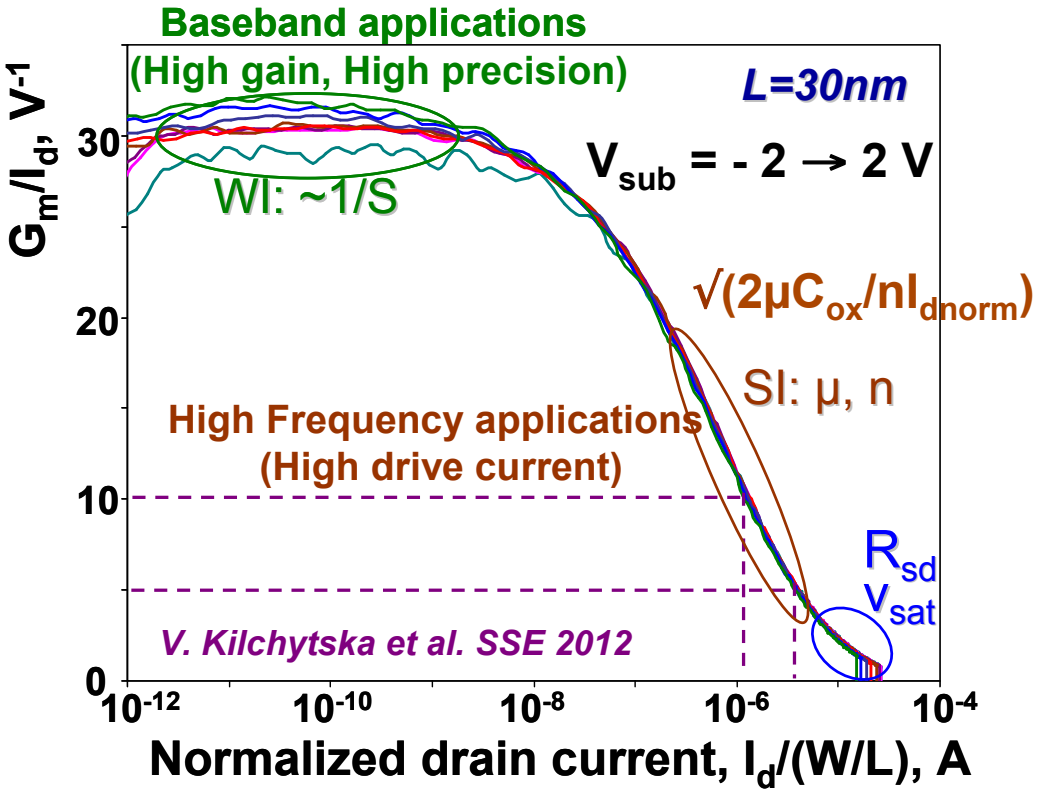
@ IC (amplifier)-level

- GBW = $g_m/(2\cdot\pi\cdot C_L)$ = = $(g_m/I_d)\cdot(I_d/(2\cdot\pi\cdot C_L))$



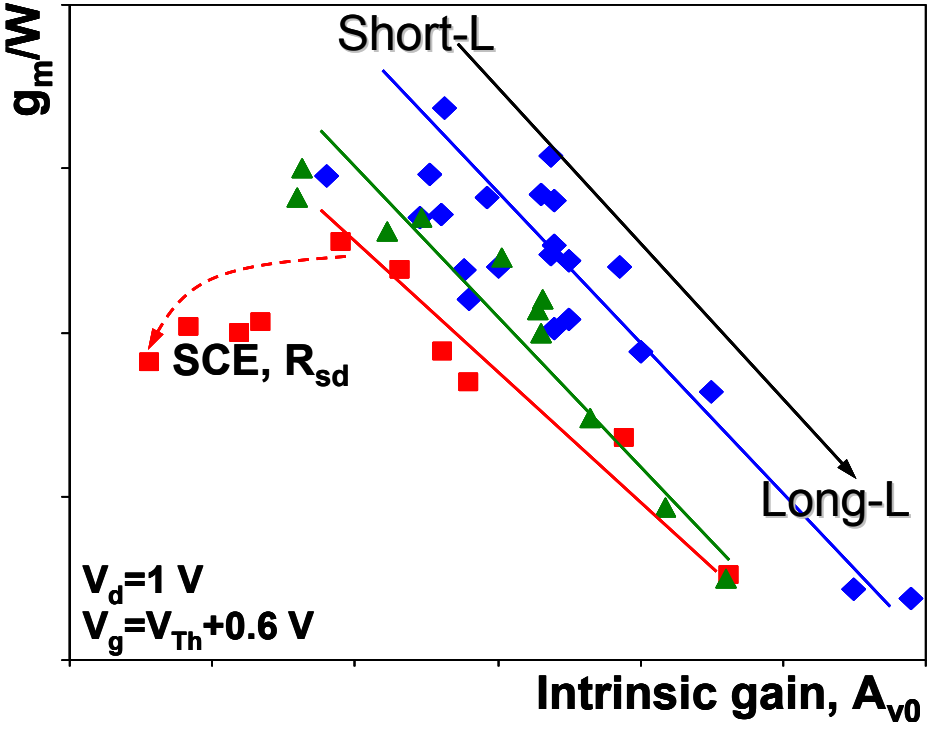
Methodology : device assessment & circuit design

g_m / I_d vs $I_{d,norm}$



- independent on V_T
- independent on L (except SCE)
- independent on V_{sub}

g_m - A_v Analog Metric

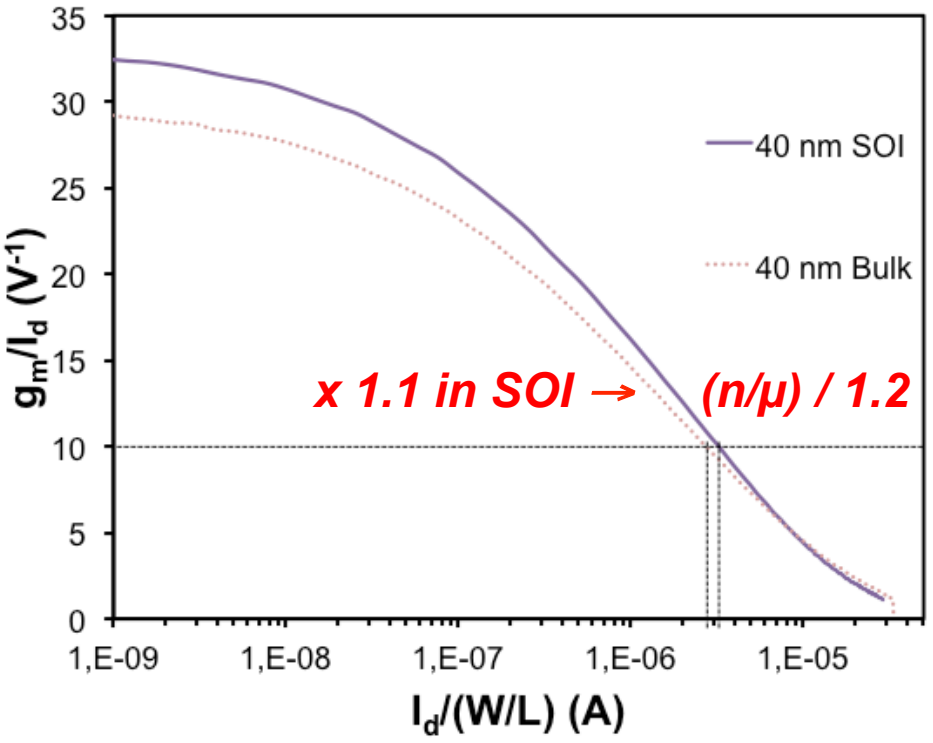


- analogue of I_{on}– I_{off} digital metric
- very visual
- independent of V_T

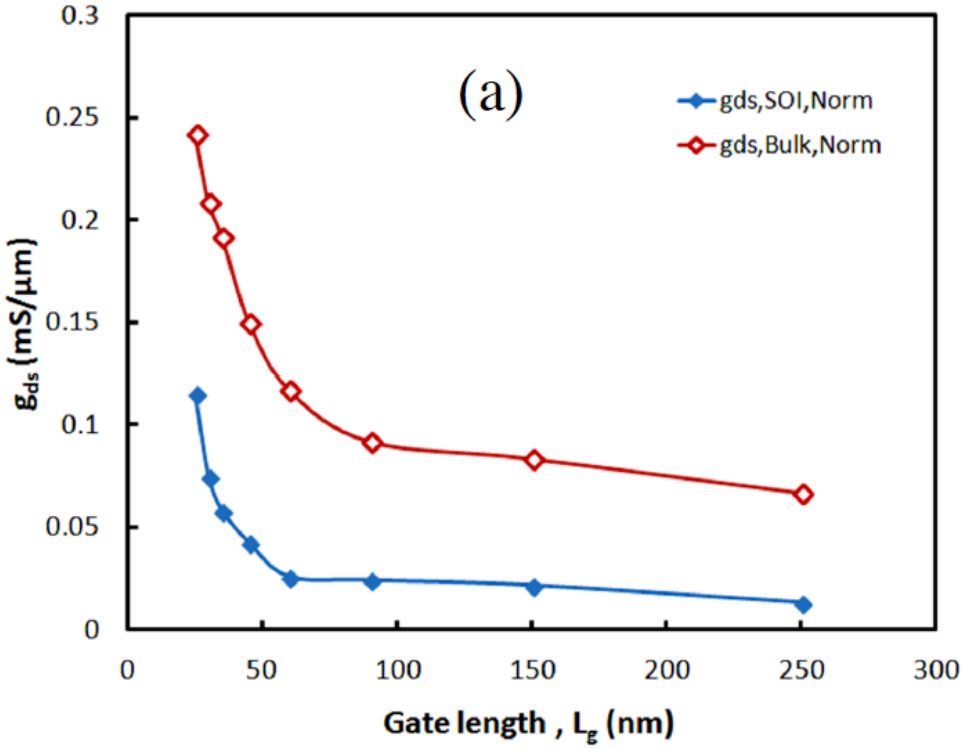
Allow fair comparison of different devices & at different conditions

Comparison of UTBB vs bulk

g_m / I_d



g_d



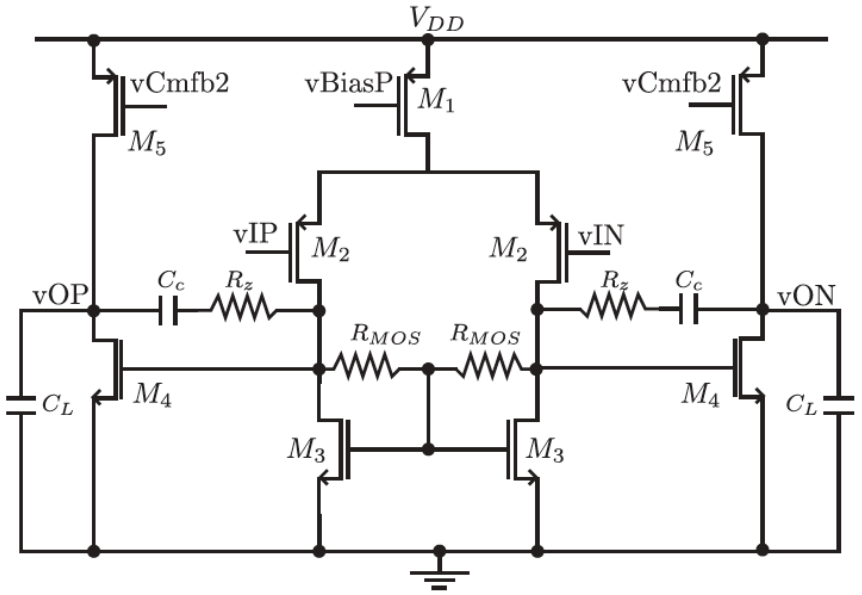
g_m/I_d ~ 10 – 20 % and g_d ~ 2 – 10 x better in UTTB than bulk

depending on length, bias, temperature and frequency conditions

Circuit validation at low frequency and power

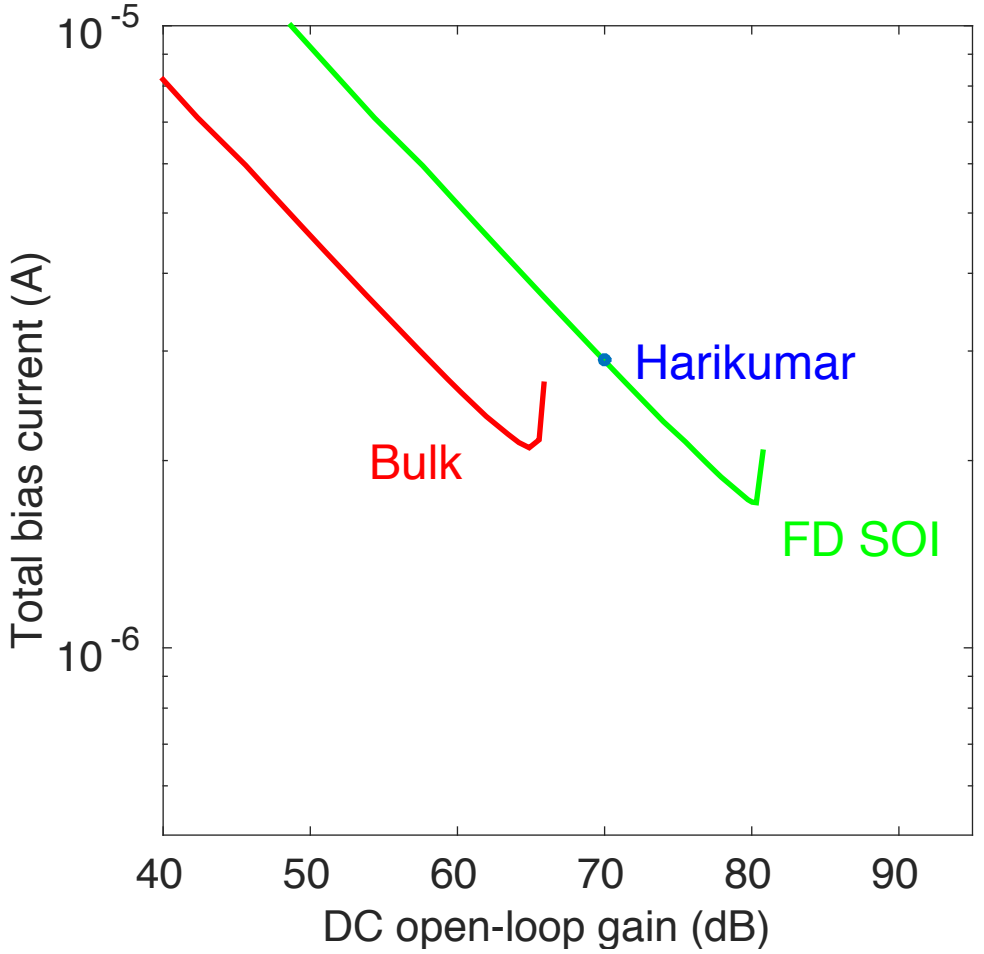
A Fully-Differential OTA in 28 nm UTBB FDSOI CMOS

Harikumar et al, ECCTD 2015



Specification	This work
Technology (nm)	28
Supply voltage (V)	1
DC gain (dB)	70
Unity-gain freq. (MHz)	4.3
Power (μW)	2.9

SPICE simulations



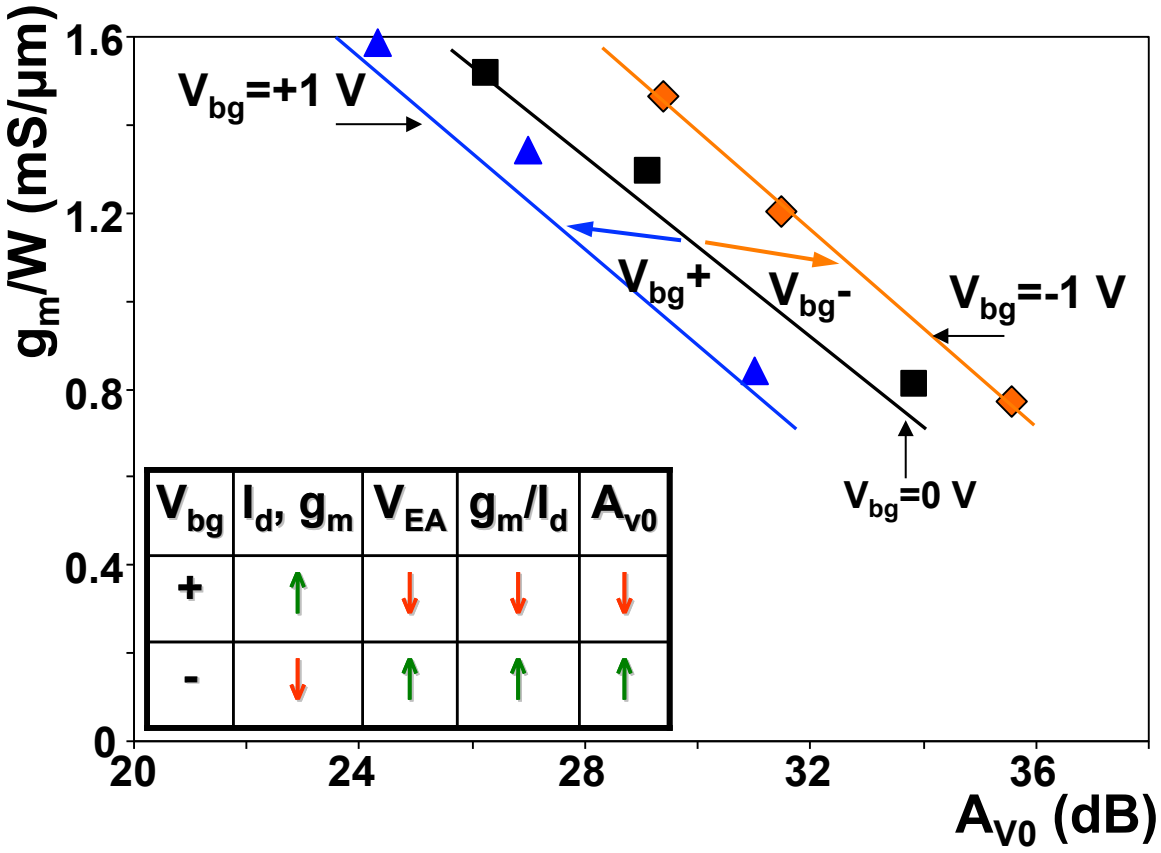
UTBB Specificities (1) : Effect of V_{sub}

V_{sub} → "–" : S↓, DIBL↓, but V_T ↑ ⇨ I_{on}↓

V_{sub} → "+": μ ↑ ⇨ $G_{m\,max}$ & I_{on} ↑

Trade-off for analog FoM ???

V. Kilchytska et al. SSE 2012

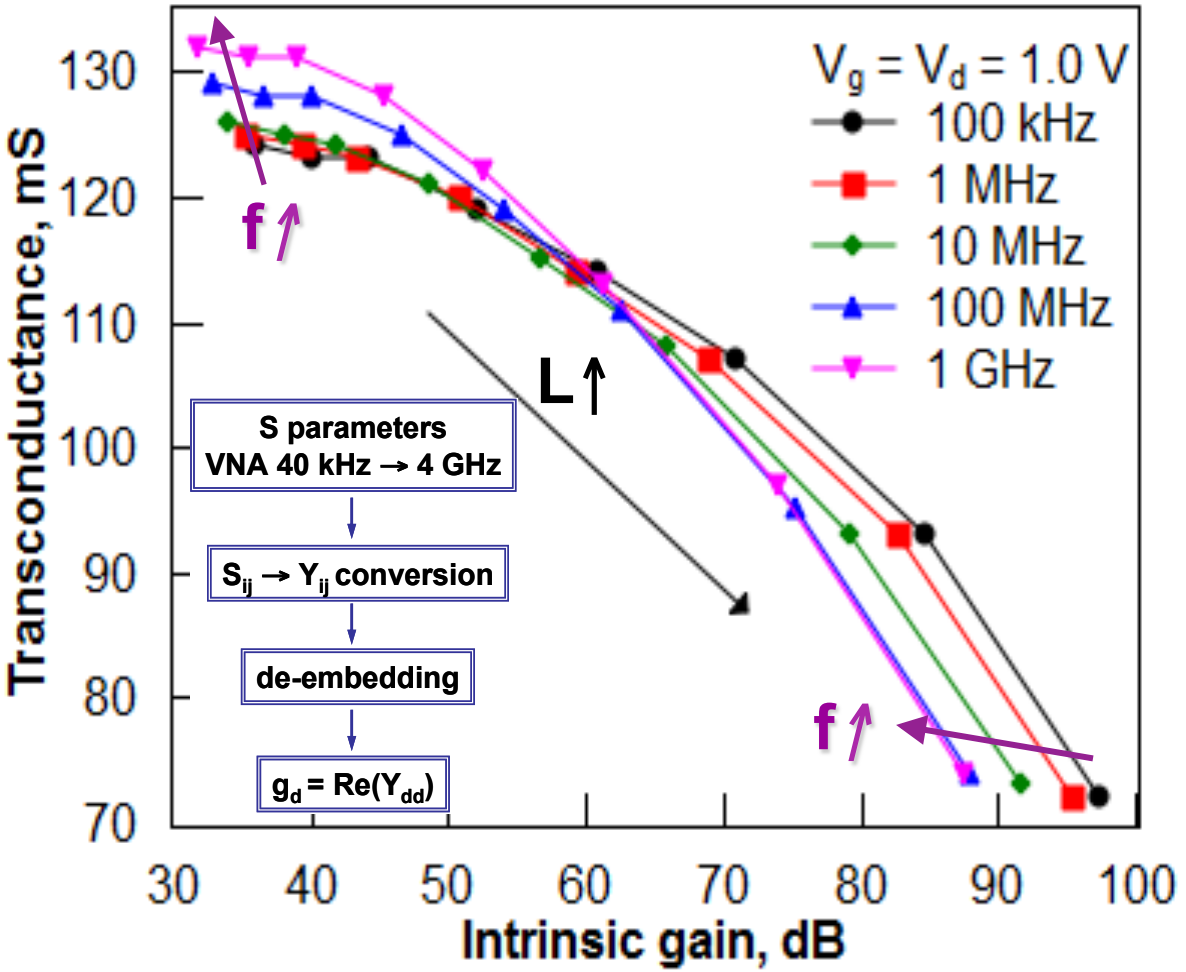


V_{bg}	I_d, g_m	V_{EA}	g_m/I_d	A_{v0}
+	↑	↓	↓	↓
-	↓	↑	↑	↑

- V_{sub} → "+"
  - ⇨ $I_{d\,norm}$↑ of 5-10% (sign of μ ↑)
- V_{sub} → "–"
  - ⇨ V_{EA} ↑ (as a result of DIBL improvement)
  - ⇨ G_m/I_d ↑ ↑ (*at low* V_g=V_d) (result of V_T shift)
  - ⇨ one can win ~ 5 dB (in max A_v range)

⇒ Choice of V_{sub} "+" or "-" depends on targeted applications (either I_d ↑ or A_v ↑)

UTBB Specificities (2) : Effect of frequency



Frequency-dependent effects:

Floating body, self-heating, substrate coupling, …

$$g_d\,(f)\ \&\ g_m\,(f) \Rightarrow \mathit{Gain}\,(f)$$

⇒ **Performance** prediction from **DC** data **is insufficient**

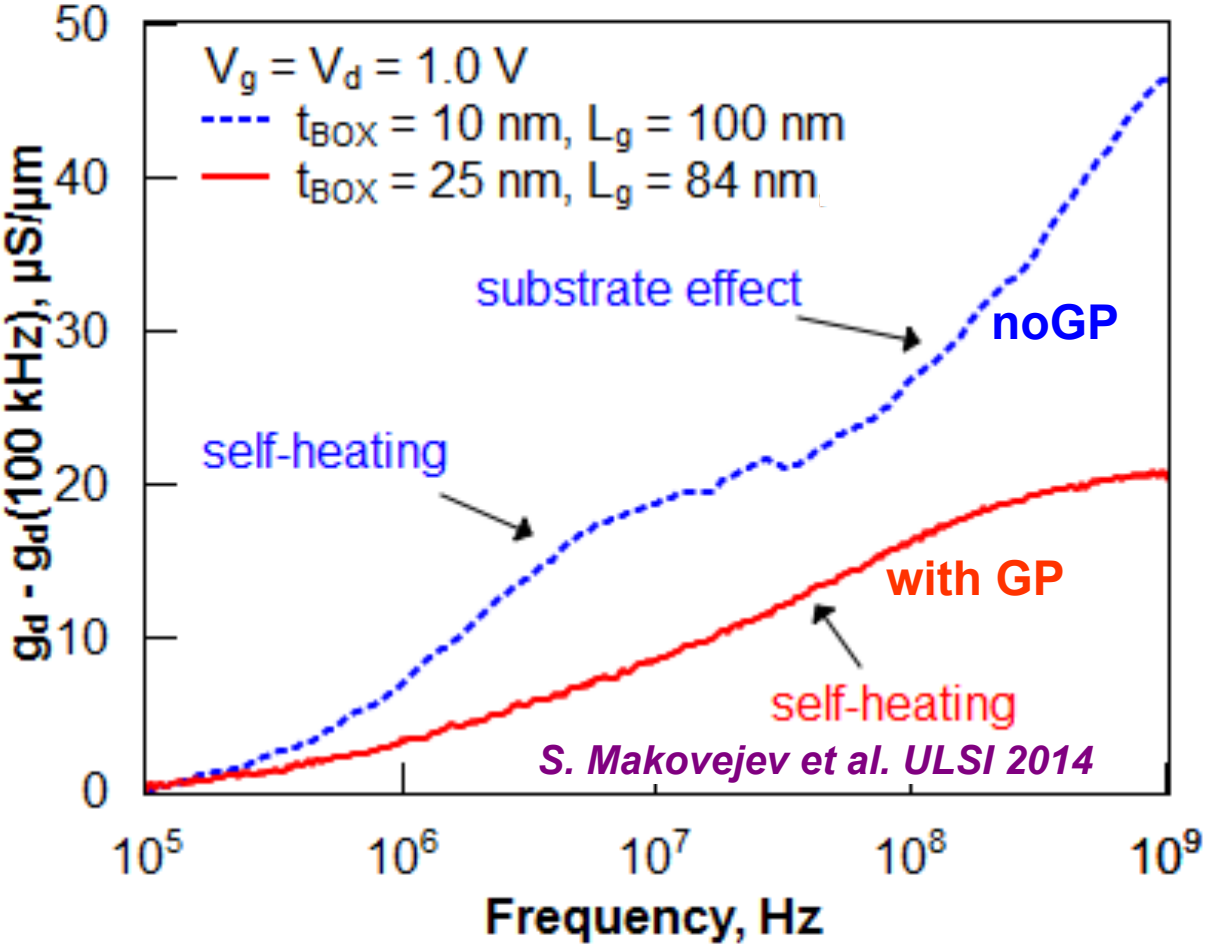
⇒ **Quest for wide-*f* characterization**

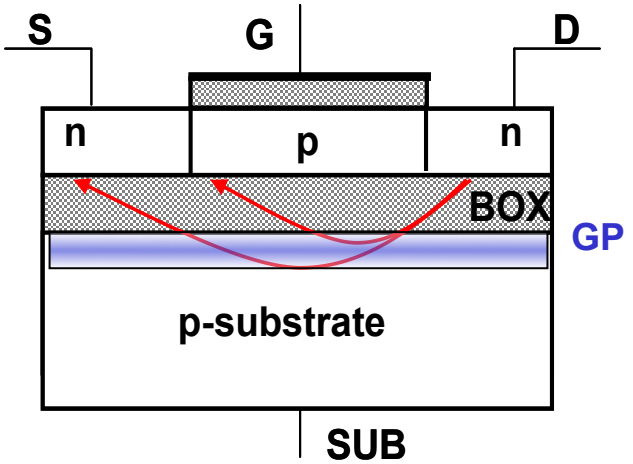
⇒ **g_m – A_v analogue metric is strongly f-dependent:**

g_m ↑, g_d ↑ ↑, A_v ↓ with f ↑

S. Makovejev et al. ULSI 2014

UTBB Specificities (3) : Effect of self-heating (SH)





⇒ **GP allows to suppress SUB-related g_d (f) variation**

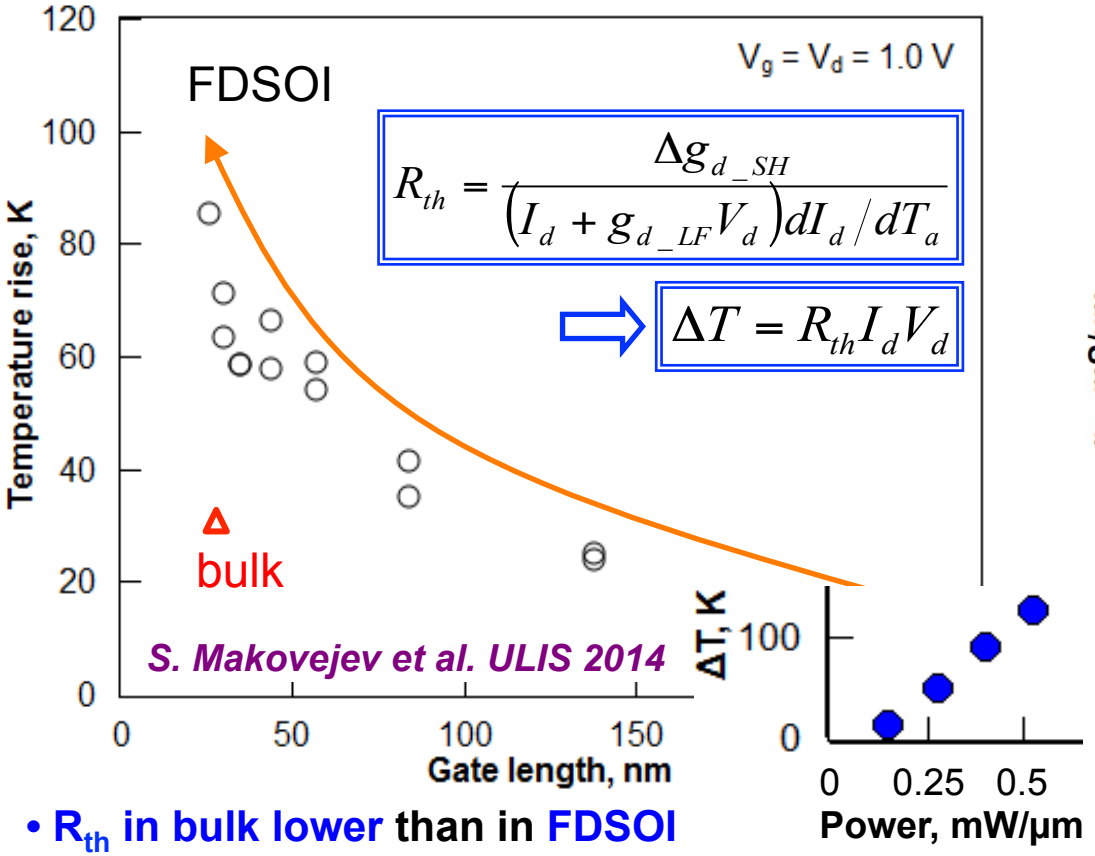
⇒ **SH is the main reason of g_d(f) variation**

$$g_d(f) = g_{intr} + \Delta g_{d_FB}(f) + \Delta g_{d_SH}(f) + \Delta g_{d_SUB}(f)$$

SH and its effect on Analog FoM in 28 FDSOI vs bulk

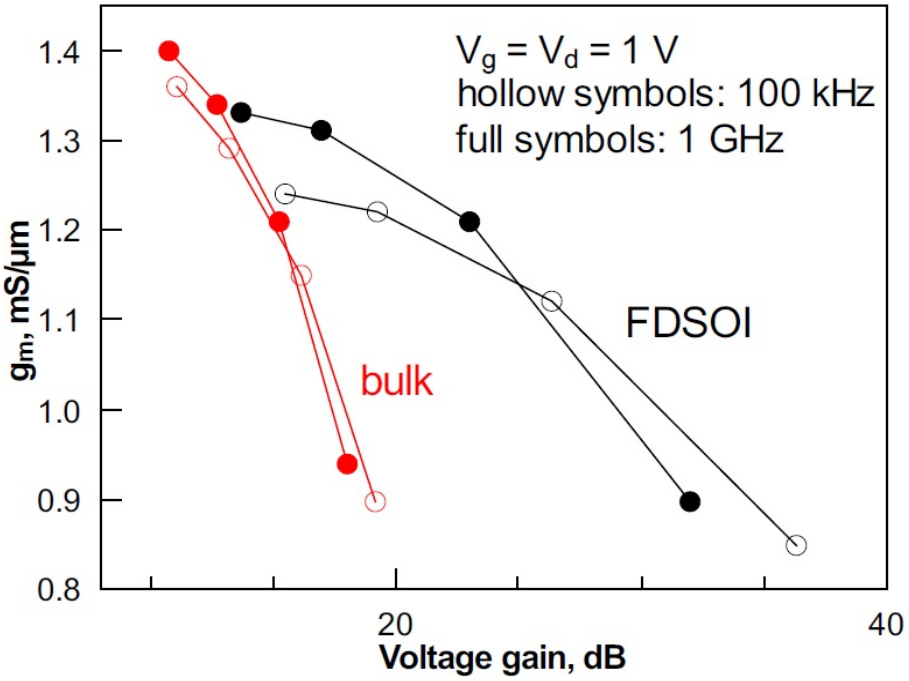
SH extraction using RF *(S-param)* method

S. Makovejev et al. EuroSOI-ULIS 2015



- R_{th} in bulk lower than in FDSOI
- C_{th} higher in bulk than in FDSOI due to larger Si volume available for generated heat
- Temperature rise due to self-heating up to ~32 K in bulk and ~87 K in FDSOI

g_m - A_v analogue metric



- In spite of stronger SH effect, FDSOI outperform bulk in terms of Analog FoM in entire frequency range
- While thermal effects are stronger in FDSOI, their influence on device parameters is limited

Outline

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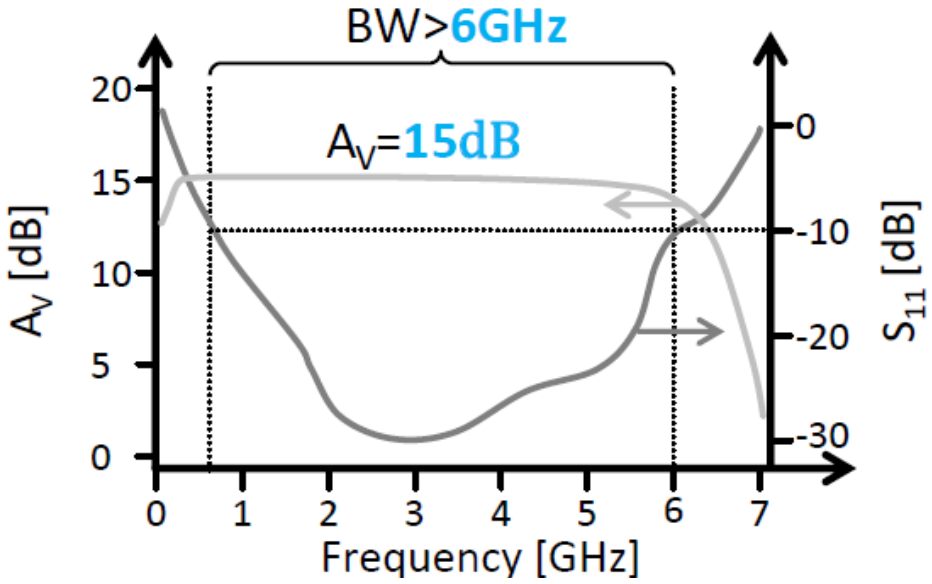
  Back gate biasing & FoM variation with frequency
- ✓ **Wideband RF amplifier**

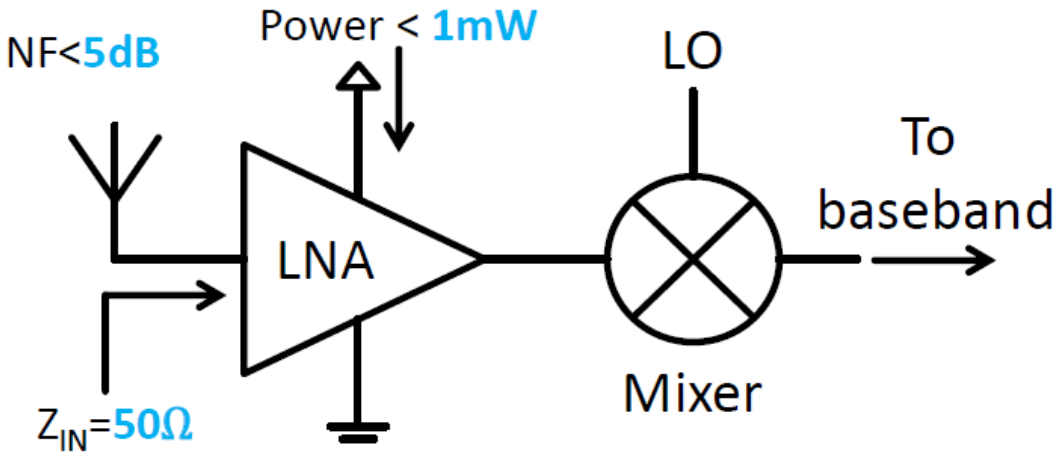
  Non-linear performance
- ✓ **Conclusions**

Wideband LNA

Crucial for efficient low-power multi-standard applications such as

- **UWB (Ultra-Wide Band)**
- **SDR (Software-Defined Radio)**

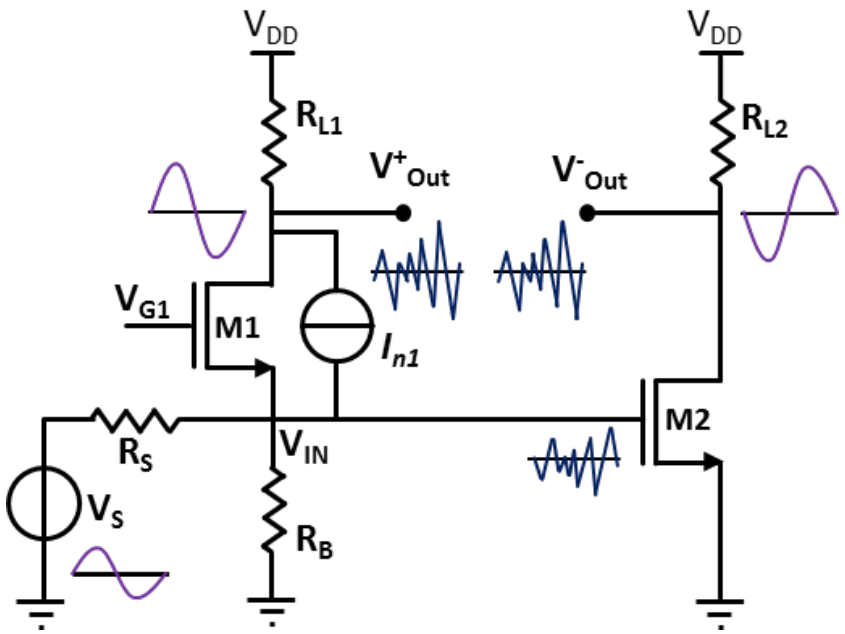




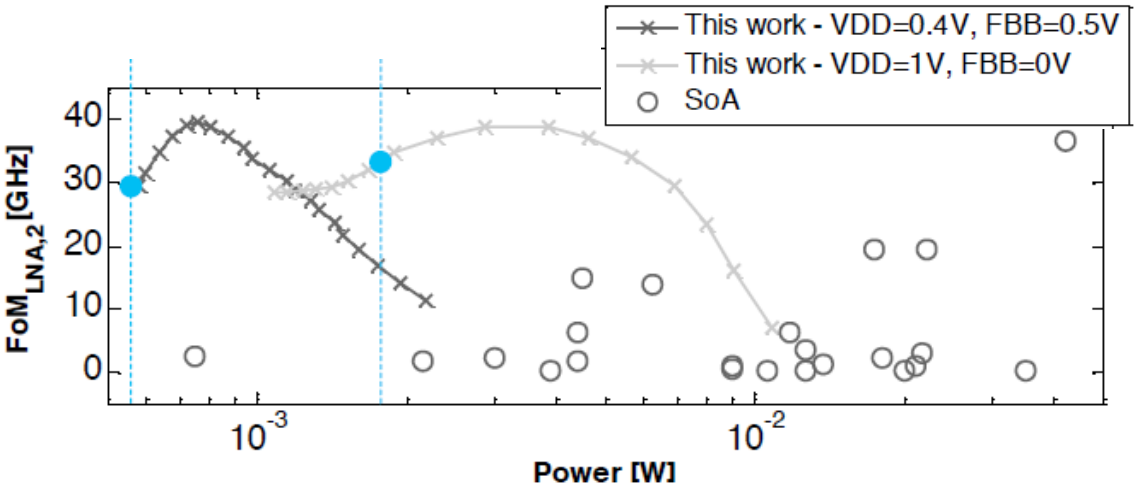
High gain up to 6 - 10 GHz +

- **impedance matching**
- **noise figure**
- **linearity**
- **low area (inductorless)**

Wideband inductor-less LNA

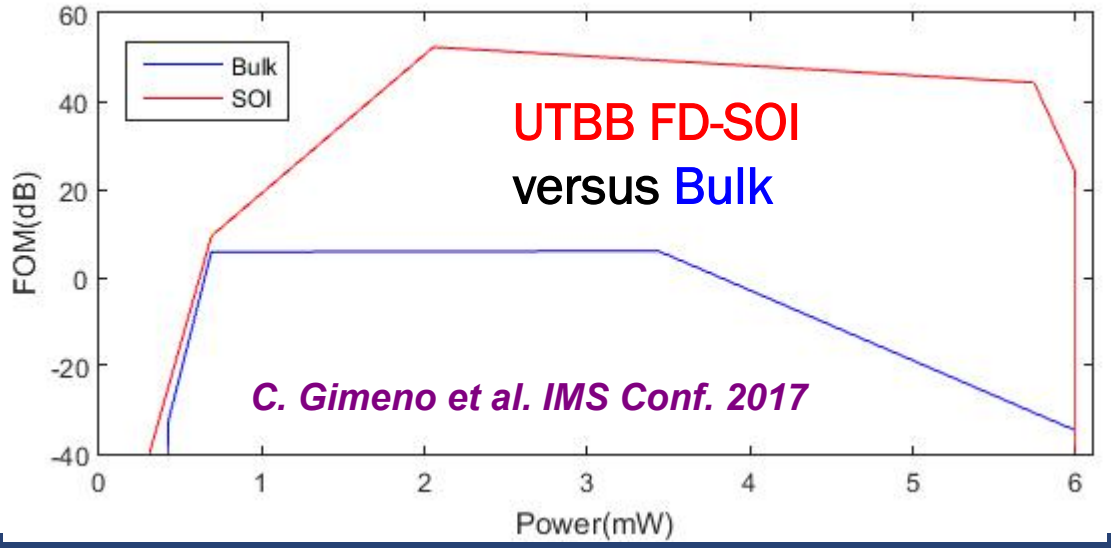


$$FOM = 20\log\left(\frac{IIP3[mW]\cdot Gain[Lin]\cdot BW[GHz]}{Power[mW]\cdot(NF[Lin]-1)}\right)$$



Noise-cancelling
Inductor-less architecture
With high linearity
For 6 - 10 GHz
Software-Defined Radios
In 28nm CMOS

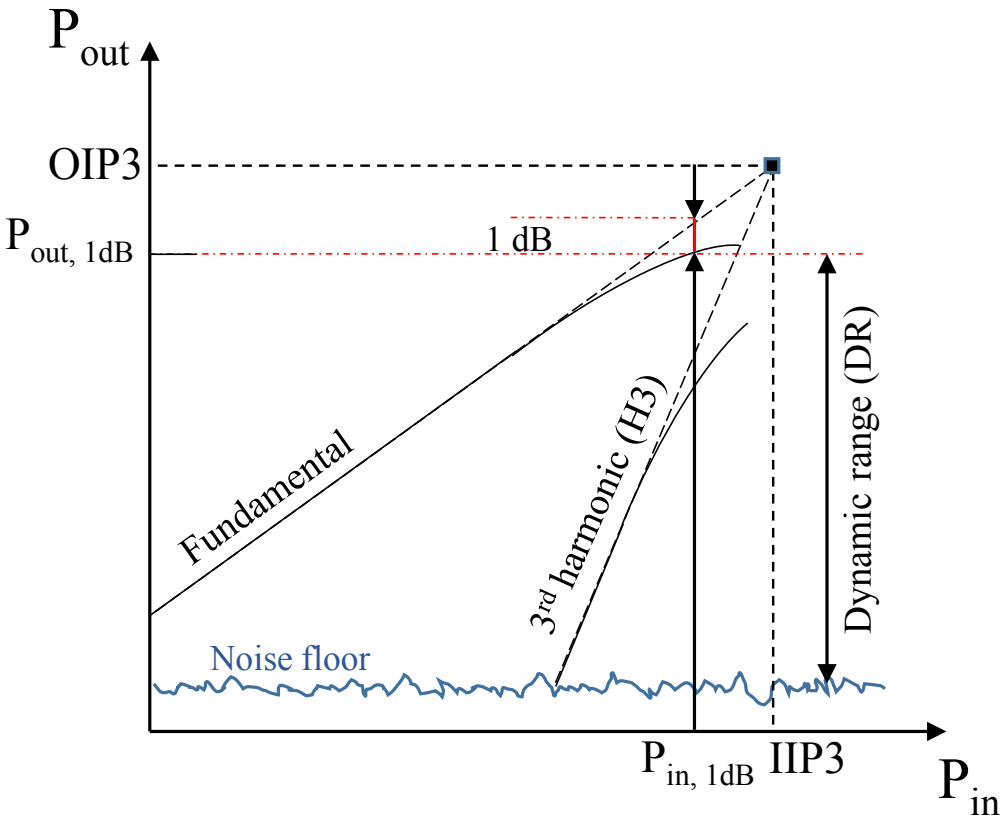
G. De Streel et al. IEEE S3S Conf. 2015



Non-linearity figures of merit

Considering a memoryless circuit excited by a sinusoidal signal with AC amplitude A

$$HD_2 = \frac{A}{2}\left|\frac{K_2}{K_1}\right| \qquad HD_3 = \frac{A^2}{4}\left|\frac{K_3}{K_1}\right| \qquad \text{with} \qquad K_n = \frac{1}{n!}\frac{d^n f}{dx^n}$$



Considering $Y = g_1X + g_2X^2 + g_3X^3$

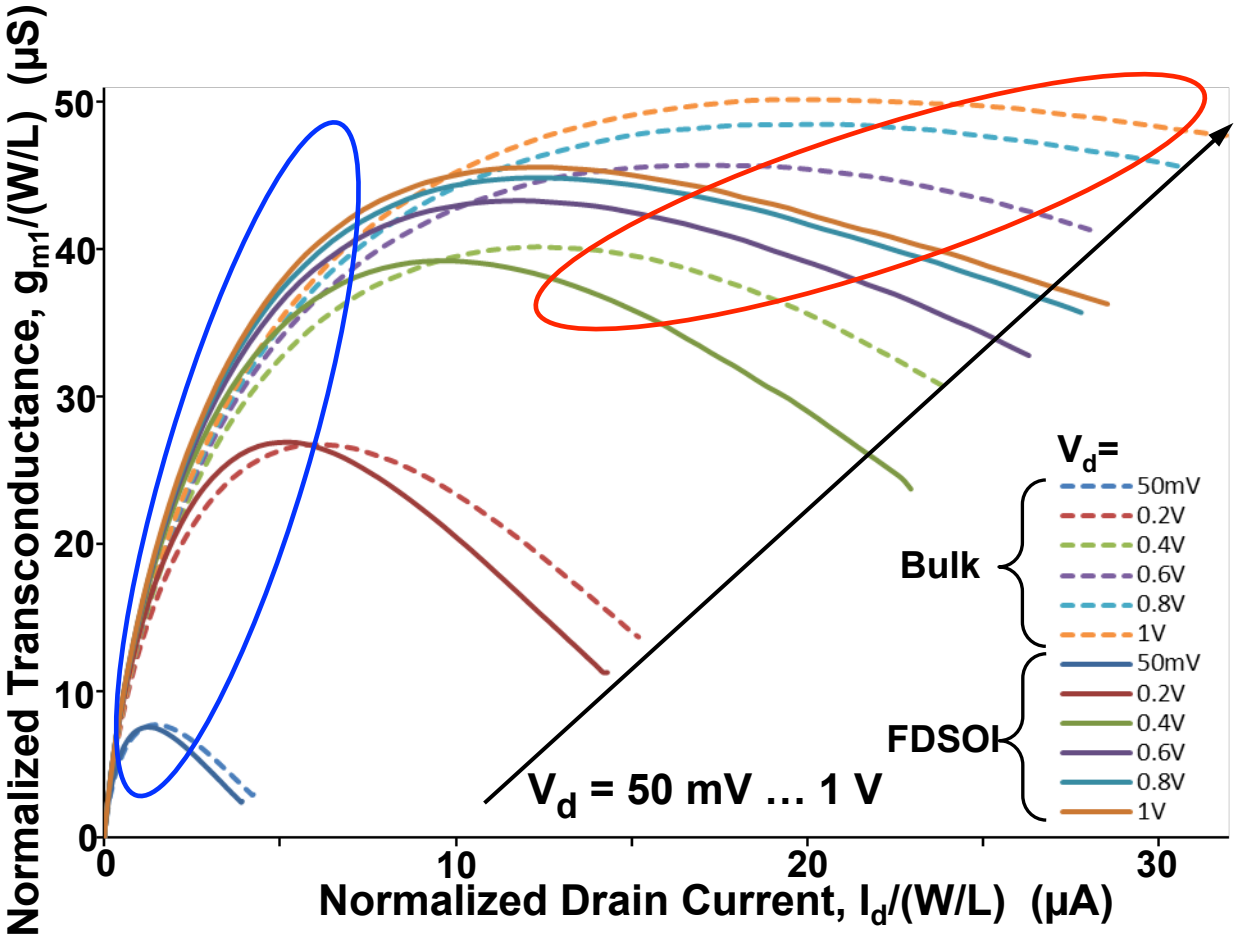
IIP3 of an amplifier in open loop is proportional to

$$(g_1 / g_3)^{1/2}$$

while in feedback

$$g_3 - 2g_2^2 / g_1$$

Transconductance : Bulk vs UTBB SOI



L=30 nm; W= 48.6 µm

- Advantage of FDSOI is very clear in below–around – V_{Th}
- $V_g > V_{Th}+0.2$ V ⇒ Bulk curves stretch out w.r.t FDSOI to higher I_d and higher g_{m1}
- Contrarily FDSOI curves quasi-saturate with V_d ↑

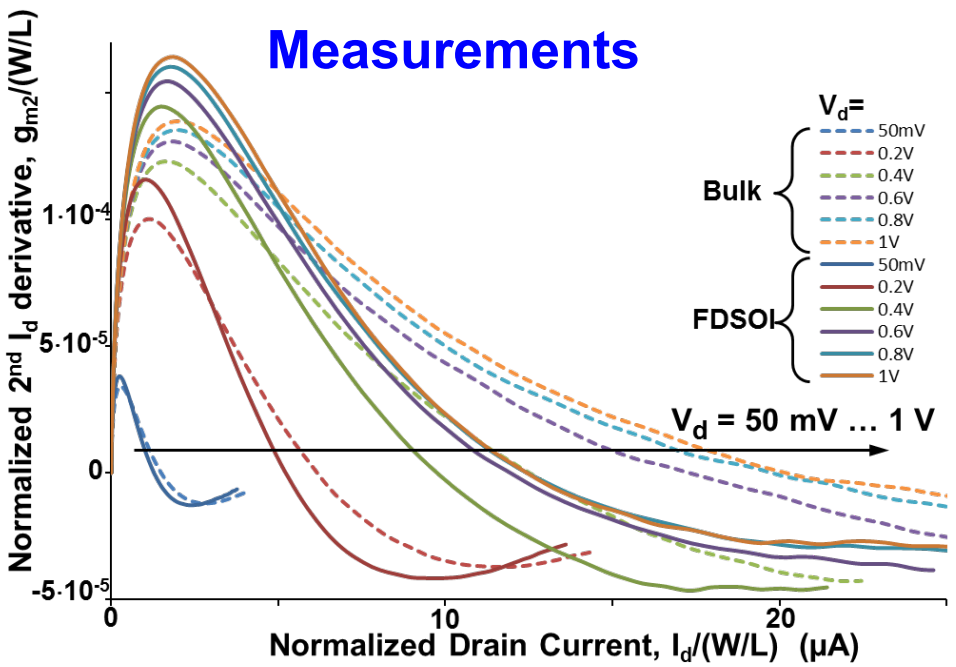
R_{sd} effect ???

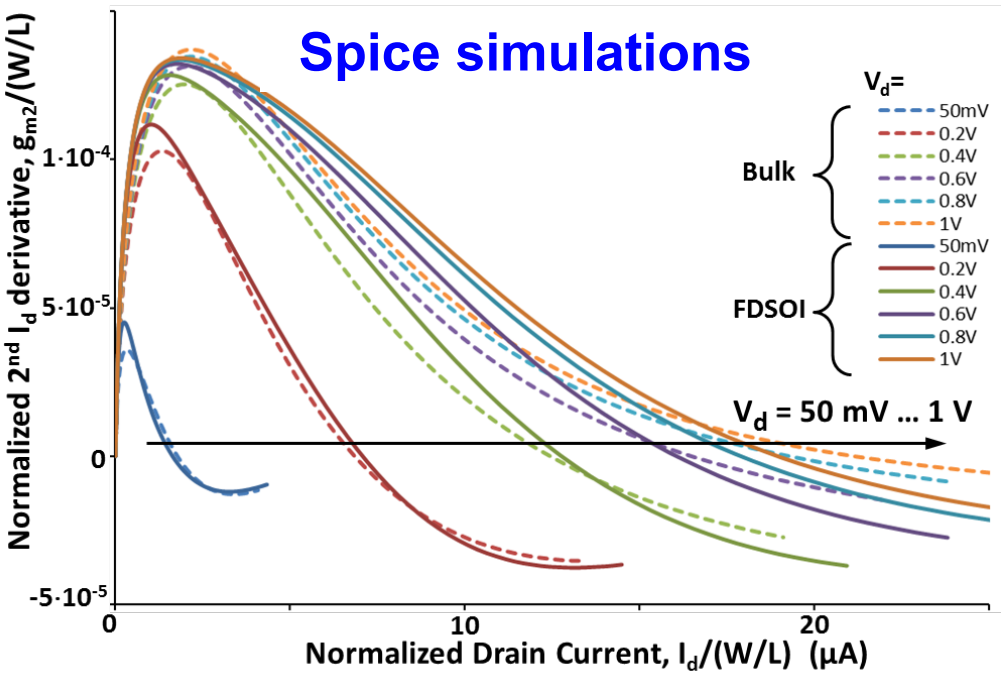
- RF measurements give : $R_{sd_FDSOI} < R_{sd_bulk}$
- I_d-V_d curves do not indicate higher R_{sd} in FDSOI

⇒ Not related to R_{sd}

V. Kilchytska et al. EUROSOI-ULIS 2017

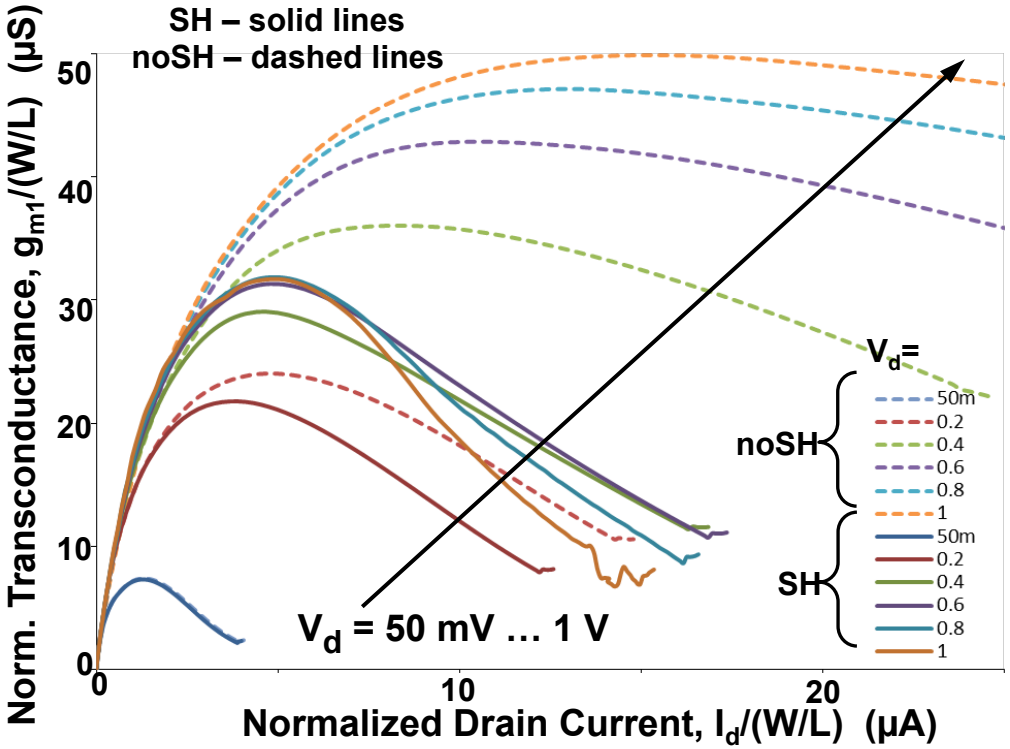
Second-derivative g_{m2} : Experiments vs SPICE

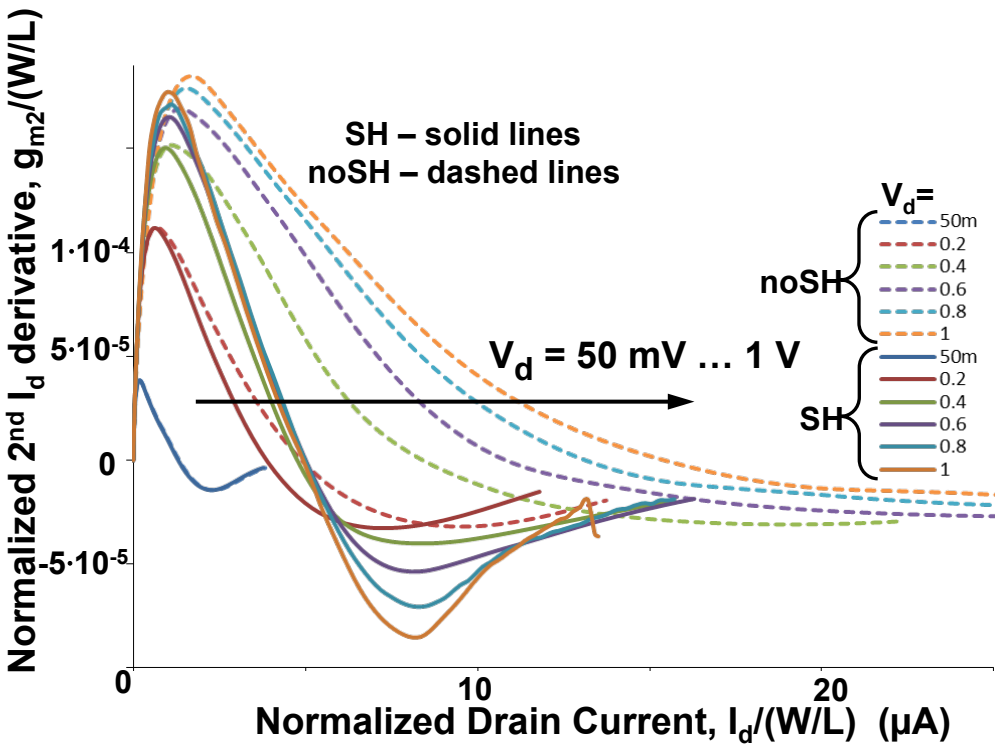




- Difference in the V_d behavior of FDSOI and Bulk devices is not well reproduced by Spice simulations
- At low V_d: Spice curves agree well for both Bulk and FDSOI devices
- With V_d ↑: discrepancy is rather strong in FDSOI device
- "Stretching" of bulk curves is well reproduced, but not "saturation" of FDSOI ones, which in Spice simulations behave in the same way as bulk

Silvaco ATLAS simulations : with SH or not





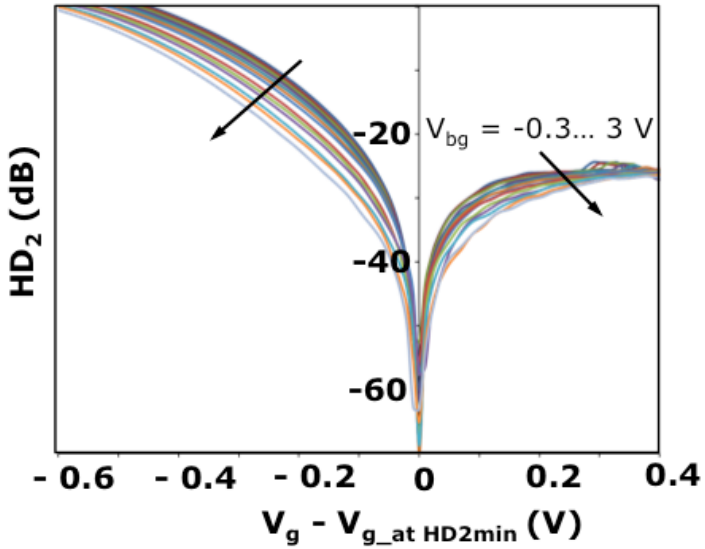
strongly suggests that the experimental difference in FDSOI vs Bulk is (at least partially) due to SH

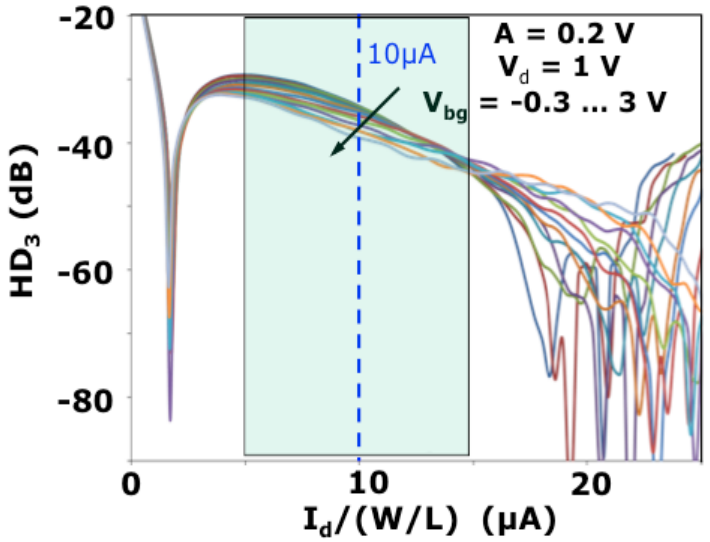
Preliminary RF experiments show similar trend

V. Kilchytska et al. EUROSOI-ULIS 2017

Impact of back-gate bias on non-linearities

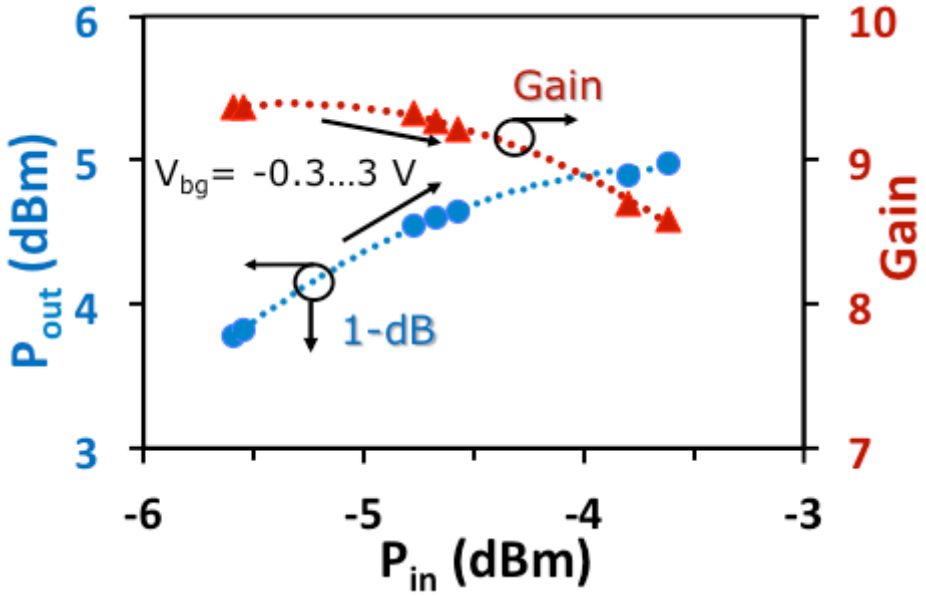
DC :

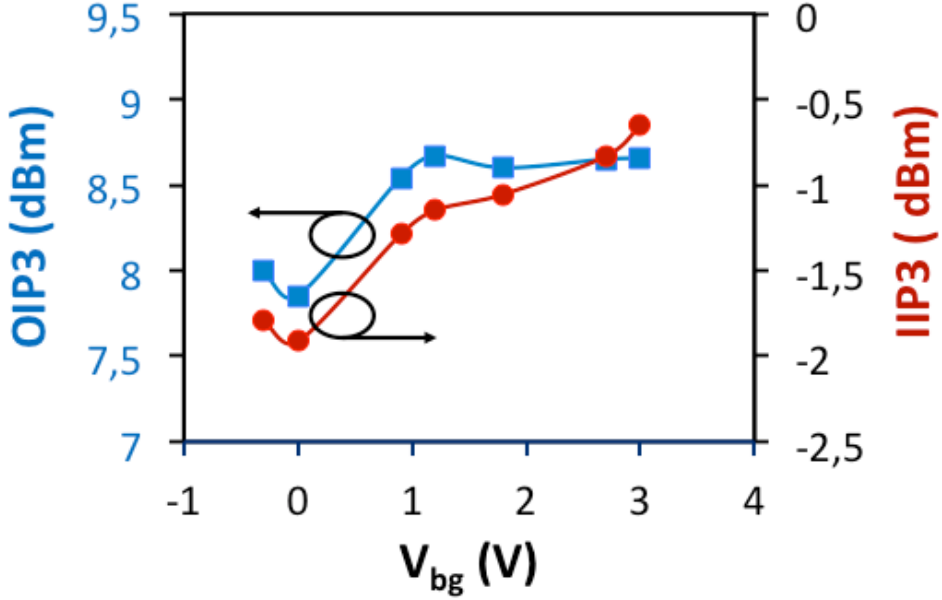




B. Kazemi et al.
ESSDERC 2017

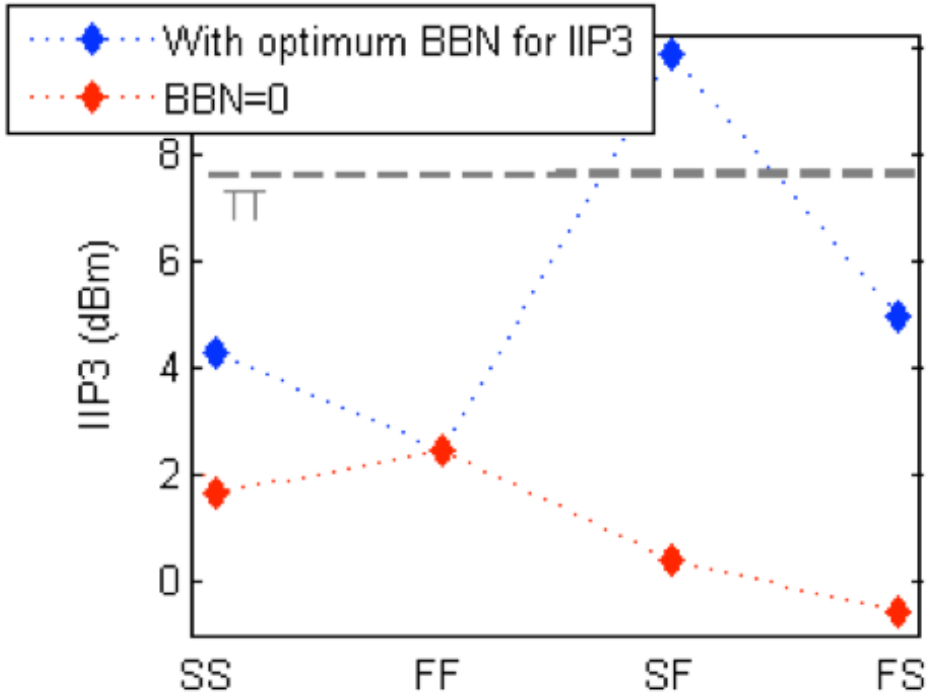
RF :

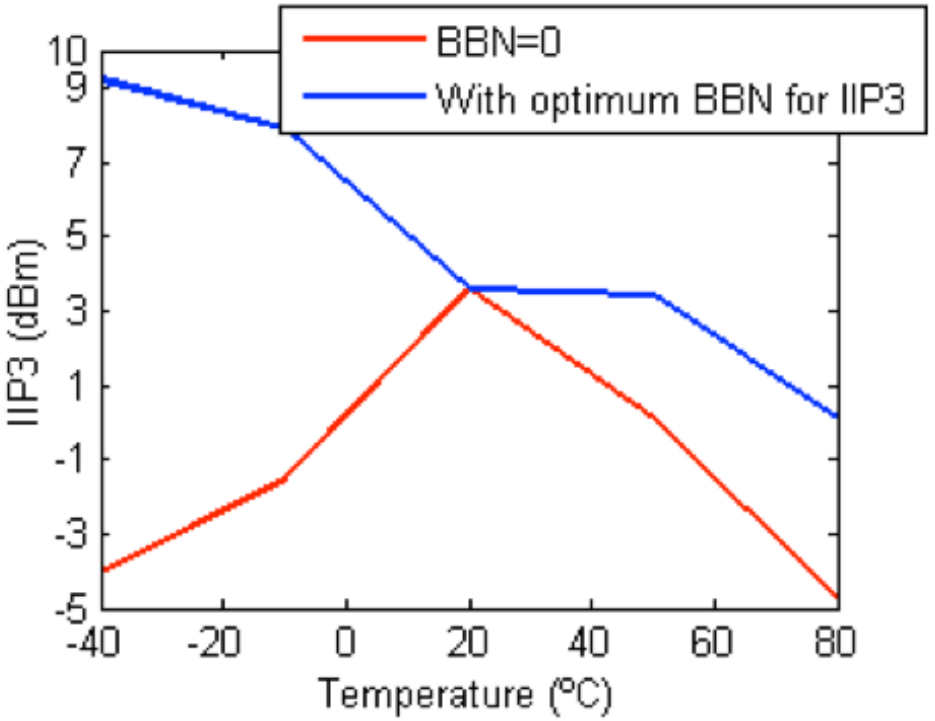




Wideband LNA SPICE simulations

Back-bias improvement also obtained in simulations over large process and temperature variations





C. Gimeno et al., IEEE S3S Conf. 2017

Conclusions

✓ **Analog / RF FoM are excellent in FDSOI to design high-performance amplifiers** (gain, bandwidth, power consumption) **but specificities require cautious modeling** (back bias, frequency, self-heating)

✓ **Non-linearities in FDSOI and Bulk MOSFETs compared by measurements and simulations :**

- Minimization at lower biases in FDSOI w.r.t bulk, which is beneficial for LP applications
- Application of a positive back-gate (or body) bias in FDSOI allows for further non-linearity reduction

✓ **Next : noise ?** (see L. Van Brandt 's presentation in this workshop)

ACKNOWLEDGEMENTS

Research projects & Major partners : STM, LETI, IMEC…

ECSEL JU

eniac JOINT UNDERTAKING

PLACES2BE

WAY TO GO FAST

WELCOME Characterization Platform (ELEN/ICTEAM/UCL):

welcome

https://sites.uclouvain.be/welcome/index.php