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This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LED.2017.2717460, IEEE Electron Device Letters

Multi-gate FinFET Mixer Variability assessment through physics-based simulation

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***Abstract*—In this paper we show that innovative physics-based simulations can be used for a comprehensive analysis of RF stages subject to random variations of technological parameters, including the computation of the average (deterministic) RF performance along with their statistical deviation. The variability analysis is addressed by means of the recently developed physics-based sensitivity analysis of AC parameters through Green's functions [1], [2]. To demonstrate the technique, we address the analysis of a FinFET mixer exploiting an innovative Independent Gates topology, showing that a careful design allows to maximize the mixer conversion gain while minimizing its variability vs. several physical parameters, such as the gate length, oxide thickness and fin width.**

***Index Terms*—FinFET, Sensitivity, Mixer**

I. INTRODUCTION

FinFETs have become the reference devices for digital applications, due to their reduced short channel effects, DIBL and smaller subthreshold slope. FinFETs are also competitive with UTB-SOI planar devices in terms of RF performance [3] and, even if concerns are raised for their larger parasitics, the full compatibility with CMOS digital applications fosters research on their AC characterization and modelling [3], [4] in the perspective of FinFET-based RF and mixed-mode circuit design [5]–[7]. While the typical FinFET is characterized by two (double gate) or even three (trigate) gates physically connected by a unique metalization, the possibility to exploit the multiple gates in an independent way (independent gates – IGs), is attractive for the possible development of novel circuit topologies [8]–[10], although it requires a more sophisticated technology to keep the gate metalizations apart [11]. Typical applications of IG FinFETs exploit, e.g., the back-gating effect [9], where one of the gates is biased in order to modulate the other gate channel and, hence, its threshold voltage.

Despite the technology optimization, FinFETs are still affected by a significant amount of variability resulting from physical parameter variations, such as geometrical dimensions, doping level or gate workfunction. Modelling such variations is very important for FinFET-based digital [12] and, even more, analog circuit design [7], [10], [13], [14]. In fact, any new circuit topology, e.g. exploiting IG FinFETs, must be investigated carefully also in terms of variability. Physics-based simulations are the ideal tool to link the uncertainty of process parameters to the spread of RF circuit performance, but a full physics-based analysis of RF stages has been addressed only sparsely [15], and is nearly prohibitive with conventional, Monte Carlo based, variability analysis tools. In this work, we demonstrate how accurate physics-based simulations can be applied to the numerically efficient variability analysis of a new promising mixer topology based on IG FinFETs [9], [11], linking its RF performance in terms of conversion gain with the corresponding process variations. We exploit a recently developed technique, based on a Green's function approach, allowing for concurrent physics-based DC, AC and sensitivity analysis of electron devices [16]. We show that, due to the peculiar structure of the mixer, the Local Oscillator (LO) and RF bias can be adjusted to achieve maximum conversion gain and virtually null sensitivity to parameter variations. This result further highlights the advantages of the IG mixer topology in terms of compactness and robustness.

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II. FINFET MIXER DESIGN

Multiple gate devices are especially convenient for mixers, since the various gates can be used to selectively supply the RF and LO signals, with inherently better isolation and easier matching with respect to single gate devices. Therefore IG FinFETs have immediately driven the attention towards mixer applications. While in typical dual gate devices (e.g. HEMTs in III-V technologies) the gates are "in series", i.e. they share the same drain current, the FinFET gates are independent and can modulate the drain current by means of the back-gating effect: this leads to a totally different kind of mixer topologies with respect to the traditional ones.

In this paper we consider an IG FinFET mixer, based on the device whose cross section is reported in Fig. 1, and whose circuit topology is sketched in Fig. 2 [9], [11], [17], [18]: the RF signal (assumed small) at the frequency of 60 GHz is applied to the front gate, which is biased to bring the corresponding front gate channel into inversion. The LO signal is instead applied to the back-gate: it must be large enough to modulate the channel transconductance of the front gate, in order to achieve frequency conversion, while keeping the back gate channel off. An in-house drift-diffusion simulator, implementing the Green's function approach to the device sensitivity analysis [1], [2], has been used for the whole mixer statistical analysis. First, DC simulations are used to investigate the FinFET behavior subject to back-gating, showing that the LO signal must be a square wave limited between $V_{G2} = -0.4$ V (lower values would drive the back-channel into accumulation) and $V_{G2} = 0.2$ V (higher values would turn-on the back-channel). AC simulations are then used to extract the nominal value of the mixer gain with varying front gate bias. The LO frequency is supposed close enough to the RF one to neglect dispersion in the down-conversion.

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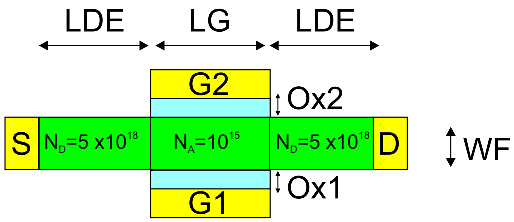

equivalent SiO_2 (OX1 & OX2)	1 nm	LG	54 nm
LDE	54 nm	WF	10 nm

Fig. 1. DG MOSFET (FinFET) structure. Green areas represent Si regions, the light blue SiO_2 and yellow the metal gates. LDE: length of the Source and Drain extensions (nm); OX1 and OX2: thickness of the lower and upper gate oxides (nm); WF: fin width (nm). The doping concentration of the Source and Drain extensions (5×10^{18} cm^{-3}) is referred to as DOP hereafter.

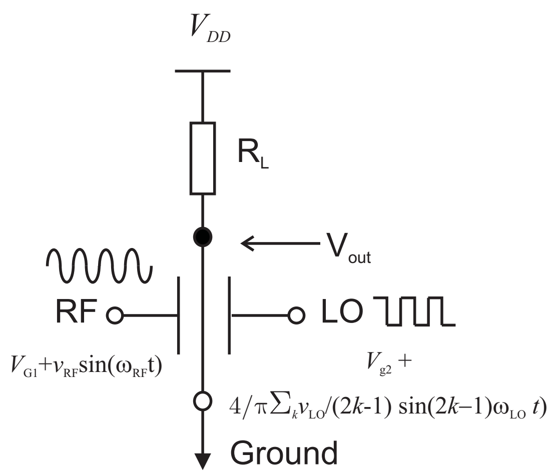

Fig. 2. Mixer topology for a dual gate FinFET.

Defining the largest and smallest values of the device transconductance with varying LO:

$$y^+ = \mathrm{Re}\left(Y_{\mathrm{D,G1}}\left(V_{\mathrm{G1}}, V_{\mathrm{G2}} = 0.2, V_{\mathrm{D}}\right)\right)$$

$$y^- = \mathrm{Re}\left(Y_{\mathrm{D,G1}}\left(V_{\mathrm{G1}}, V_{\mathrm{G2}} = -0.4, V_{\mathrm{D}}\right)\right)$$

the mixer conversion gain G_C is [9]:

$$G_C = \frac{R_L}{4}\left(y^+ - y^-\right) = \frac{R_L}{4}\Delta y \tag{1}$$

where R_L is the mixer load shown in Fig. 2.

Hence to maximize the conversion gain, the front gate bias (i.e. the bias of the mixer RF port) must be chosen to have maximum Δy. Fig. 3 reports the area where Δy is largest, ranging from $V_{G1} = 0.6$ V to $V_{G1} = 0.8$ V. Supposing a height/width fin ratio of 5, the fin height is 50 nm (notice that volume inversion has been investigated and found limited in the proposed structure and with the selected bias conditions: hence the effect of volume inversion on the effective gate width [19] has been, as a first approximation, neglected). Assuming further a stage with 200 fingers, i.e. a total width of 10 μm, and $R_{\mathrm{L}} = 500\ \Omega$ [9], the conversion gain is 1.3 dB for $V_{G1} = 0.6$ V, 5.8 dB for $V_{G1} = 0.7$ V and 1.85 dB for $V_{G1} = 0.8$ V.

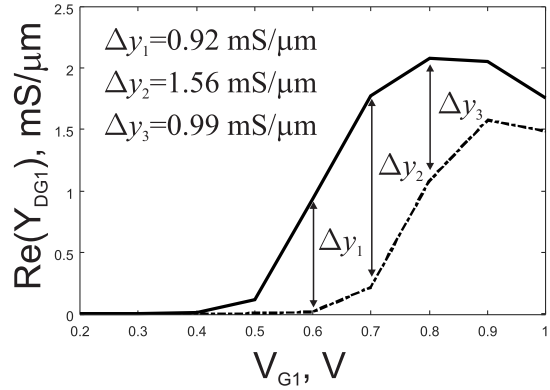

Fig. 3. Real part of the (D,G1) element of the admittance AC matrix. Solid: $V_{\mathrm{G2}} = 0.2$ V; Dash-dot: $V_{\mathrm{G2}} = -0.4$ V.

III. FinFET mixer variability

We now turn to the variability analysis of the mixer stage. We address variations of all the relevant FinFET physical parameters P, i.e. the fin width (WF), the oxide thickness of the front (OX1) and back (OX2) gates, the gate length (LG), the source/drain extension width (LDE) and source/drain doping (DOP) (see again Fig. 1). We exploit the same in-house drift-diffusion simulator as in Sec. II to extract the *sensitivity charts* [20], i.e. the bias-dependent *relative sensitivities* $S_{Y_{i,j}}$ of the (i, j) element of the AC Y matrix

$$S_{Y_{i,j}} = \frac{\partial Y_{i,j}}{\partial P} \cdot \frac{P_0}{Y_{0,i,j}} \approx \frac{\frac{\delta Y_{i,j}\cdot 100}{Y_{0,i,j}}}{\frac{\delta P \cdot 100}{P_0}} \tag{2}$$

where $Y_{0,i,j}$ and P_0 corresponds to the nominal values. Relative sensitivities are also the *percentage variations* of $Y_{i,j}$ with respect to a unit percentage (positive) variation of P.

Fig. 4 shows an example of the sensitivity chart for $\mathrm{Re}\left(Y_{\mathrm{D,G1}}\right)$ with all the considered variations. Notice that WF variations have highest impact, followed by OX1 variations.

Turning to the mixer stage, the conversion gain variation is found from (1):

$$\delta G_C = \frac{R_L}{4}\left(\delta y^+ - \delta y^-\right) \tag{3}$$

where $\delta y^{\pm}$ is the variation of $y^{\pm}$. We now define further the relative sensitivities of y^+ and y^-:

$$S^+ = S_{\mathrm{Re}(Y_{\mathrm{D,G1}})}\left(V_{\mathrm{G1}}, V_{\mathrm{G2}} = 0.2, V_{\mathrm{D}}\right)$$

$$S^- = S_{\mathrm{Re}(Y_{\mathrm{D,G1}})}\left(V_{\mathrm{G1}}, V_{\mathrm{G2}} = -0.4, V_{\mathrm{D}}\right)$$

corresponding to the relative sensitivities of Fig. 4, taken with the largest and smallest value of the LO signal. Converting the relative sensitivities into absolute variations (see (2)):

$$\delta y^+ = S^+ y^+ \frac{\delta P}{P_0};\ \delta y^- = S^- y^- \frac{\delta P}{P_0} \tag{4}$$

we have:

$$\delta G_C = \frac{R_L}{4}\left(S^+ y^+ - S^- y^-\right) \cdot \frac{\delta P}{P_0}$$

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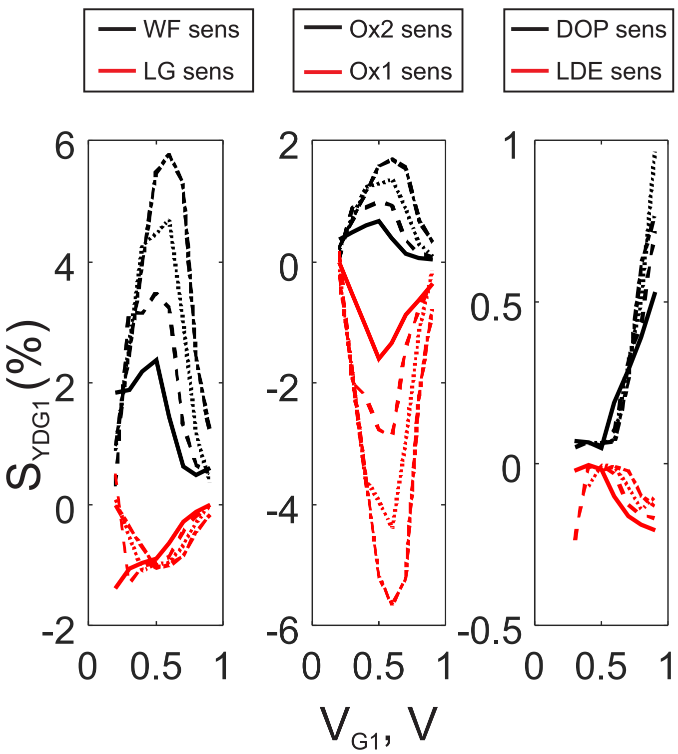

Fig. 4. Sensitivity chart of the real part of the (D,G1) element of the admittance matrix. Solid: V_{G2S} = 0.2 V. Dash: V_{G2S} = 0. V. Dot: $V_{G2S} = -0.2$ V. Dash-Dot: $V_{G2S} = -0.4$ V.

With random variations of the parameter P characterized by zero average and a normal distribution with variance σ_P^2, the conversion gain also has a normal distribution with variance

$$\sigma_{G_C}^2 = K_{G_C}\langle \delta G_C, \delta G_C \rangle =$$
$$= K_{G_C}\langle \left(S^+y^+ - S^-y^-\right)\delta P, \left(S^+y^+ - S^-y^-\right)\delta P \rangle$$

where $K_{G_C} = \left(R_L/(4P_0)\right)^2$. Finally

$$\sigma_{G_C}^2 = K_{G_C}\left(S^+y^+ - S^-y^-\right)^2 \sigma_P^2 \tag{5}$$

Notice that, since the variations of y^+ and y^- correspond to the variations of the *same parameter* P, they are fully correlated, and a cancellation in the $\sigma_{G_C}^2$ can occur when the sign of S^+y^+ and S^-y^- is the same.

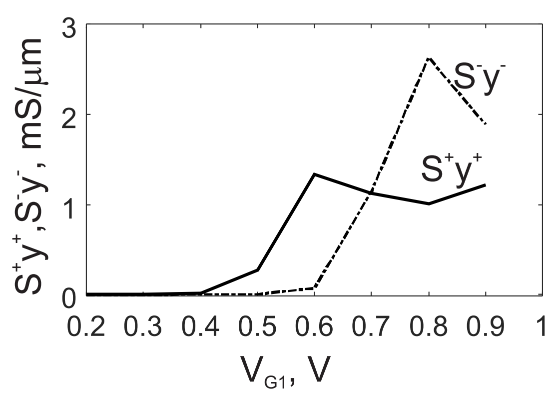

Fig. 5. Variation S^+y^+ (solid) and S^-y^- (dash-dot) for fin width variations. These quantities are used in eqs. (4) and (5).

We now finalize the mixer optimum design. Since Fig. 4 shows that the dominant sensitivity is towards WF, we first look at this parameter variations. Fig. 5 shows the contributions S^+y^+ and S^-y^- of (5). Notice that for $V_{G1} = 0.7$ V the two values are nearly coincident, therefore, according to (5), the sensitivity is close to zero, while at $V_{G1} = 0.6$ V or $V_{G1} = 0.8$ V only partial cancellation is observed. Namely, with the 10 μm total periphery and assuming σ_P of 10% with respect to the nominal fin width, (5) predicts σ_{G_C} of 14% for $V_{G1} = 0.6$ V and 16% at $V_{G1} = 0.8$ V, hence deteriorating significantly the stage conversion efficiency. At 0.7 V, instead, the conversion gain is hardly affected by WF variations; hence we conclude that this is the optimum bias for the RF terminal both for maximum conversion gain and minimum sensitivity.

IV. Conclusions

With the growing interest towards RF FinFET applications, new design concepts exploiting the peculiar features of the FinFET technology are actively investigated but need to be validated not only in terms of their RF performance but also in terms to their robustness towards technology variations. Among the possible innovative schemes, the mixer topology based on the Independent Gates FinFET technology is extremely attractive for its compactness and high conversion gain. In this paper, the recently developed efficient physics-based sensitivity analysis of FinFETs in the IG configuration has been exploited to address the variability of this novel mixer topology. We have shown that the sensitivity towards physical parameters can impair the successful design of the stage, but a careful choice of the operating conditions leads instead to a concurrent maximization of the conversion gain and minimization of its variability. This further demonstrates that IG mixers are extremely attractive for RF applications. Furthermore, new topologies for balanced or double-balanced mixers may be also developed, exploiting the peculiar structure of multi-fin IG FinFETs [9].

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