Journal of Applied Sciences

ISSN 1812-5654

science alert

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Journal of Applied Sciences 15 (5): 800-807, 2015
ISSN 1812-5654
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RESEARCH ARTICLE OPEN ACCESS

DOI: 10.3923/jas.2015.800.807

Nanoscale DGMOSFET: DC Modelisation and Analysis of Phase Noise in RF Oscillator

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ARTICLE INFO
Article History:
Received: November 19, 2014
Accepted: February 26, 2015

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ABSTRACT
A numerical model for drain and gate currents in symmetrical Double Gate MOSFET (DGMOS) including short-channel and quantum effects is developed. This modelisation in a good agreement was successfully conducted with electrical characteristics of a SILVACO software simulation. So, mixed-mode modeling of a Radio Frequency (RF) LC oscillator, built around the considered DGMOS is developed. The quantum model was applied to the device, whereas, the rest of the circuit is governed by Kirchhoff's laws. The first goal of this work is to establish the DC characteristics, the key is to achieve an analyse of quantum effect on static electrical performances of this device. The second goal is the investigation of phase noise in the considered oscillator. Then, analyse via the LTV (Linear Time Variant) model, the Impulse Sensitivity Function (ISF) of the circuit which describes carefully the sensitivity of an oscillator to any impulse current injection in any node of the circuit. Finally, the phase noise modeling, confronting some analytical developments to mixed-mode simulations was improved.

Key words: DGMOS, quantum effect, colpitts oscillator, mixed-mode simulation, ISF function

INTRODUCTION

The DG MOSFET (DGMOS) has emerged as the most promising device for circuit design in nanometer scale. This is essentially due to its excellent control of the short channel effects: Drain Induced Barrier Lowering (DIBL), subthreshold current, tunnel current and better 'ON' current (Park and Colinge, 2002; Pati *et al*., 2013; Sarkar *et al*., 2008).

To continue the downward scaling, dielectrics with higher dielectric constant are being suggested as a solution to achieve the same transistor performances while maintaining a relatively thick physical thickness in order to minimize the leakage tunneling current. A lot of studies has been done in this area (Tripathi *et al*., 2012; Chang and Shin, 2002). Hafnium oxide (HfO_2) and Zirconium oxide (ZrO_2) have a good potential for present and future CMOS application (Lim and Armstrong, 2007). On the other hand, the use of DG MOSFET in Radio frequency (RF) applications is more and more considered due to their interesting high cut-off frequency (f_t) and high maximum oscillation frequency (f_{max}) which could be getting (Videivic-Misic and Jevtic, 2004; Varadharajan and Kaya, 2005; Liang *et al*., 2008). The Voltage Controlled Oscillator (VCO) is a typical example of this applications, it is an essential part of many electronic systems such as image rejection demodulator in wireless transceivers (Li and Afshari, 2010).

The phase noise in RF oscillators is one of the most critical performance parameters for signal generators and integrated transceivers. Many works had been done using Spice-like simulations (Leeson, 1966; McNeill, 1994; Hajimiri and Lee, 1998, 1999; Hajimiri *et al*., 1999; Demir *et al*., 2000; Lee and Hajimiri, 2000; Navid *et al*., 2005). Hajimiri and Lee (1998) have proposed a time variant model (LTV) based on the so-called Impulse Sensitivity Function (ISF) to predict this phase noise. This technique provides insight into the design of oscillator. The ISF function characterizes only the stationary results of a perturbation. The purpose of this study is the modeling and the optimization of DG MOSFET for Radio frequency application. For this, a numerical modeling of this device using a 2D Poisson-Schrodinger self consistent approach was presented, taking into account the effects to the aggressive scaling of the device (SCE effects, I_{off}, $I_{Gtunnel}$). The obtained results can give helpful design guidelines for DG MOS devices for RF applications. Indeed, we 'built' an LC Colpitts oscillator around the considered device and then, present the method to calculate Impulse Sensitivity Function. These results are favorably compared with a developed analytical model.

MATERIALS AND METHODS

Device mathematical model: The mathematical model consists on a 2D solution of Poisson equation coupled to a 1D Schrödinger equation (Bella *et al.*, 2011). Usually, 2D Poisson equation describes electrostatic transport and 1D Schrodinger equation is used to handle the quantum transport. The coupling of Poisson and Schrödinger equations is necessary when the oxide thickness is decrease and the thickness of the channel takes values close to the wavelength of the electrons. This approach is justified by several results presented by Bescond *et al.* (2004) and Colinge (2008).

The Poisson (Eq. 1) and Schrodinger (Eq. 2) are given by the following equations:

$$\frac{d^2V(x,y)}{dx^2}+\frac{d^2V(x,y)}{dy^2}=-\frac{\rho(x,y)}{\varepsilon_0\varepsilon_r} \quad (1)$$

$$-\frac{\bar{h}^2}{2m^*}\frac{\partial^2}{\partial y^2}\psi(y)+qV(y)\psi(y)=E\psi(y) \quad (2)$$

where, V(x,y) is the electrostatic potential, ρ(x,y) is the charge density, ε is the permittivity of the dielectric material constant, m* is the electron effective mass, q is the electron charge, h is the Planck's constant and ψ(y) is the wave function corresponding to the eigenvalue E.

It is clearly seen that the Eq. 1 and 2 are coupled. It is therefore self consistency in their resolution. The self consistent system can be illustrated by the following one:

$$\rho(y) = S[V(y)]$$
$$V(y) = P[V(y)]$$

where, the functions S[V(y)] and P[ρ(y)] represent the Schrödinger and Poisson equations. To solve these later, the concept of the finite difference method was used (Bella *et al.*, 2011). The system equations obtained is then numerically solved by the Newton-Raphson method. The results are obtained with a precision within 10^{-9}.

Structure device: The DG MOSFET structure under analysis and related parameters values are shown in Fig. 1 and Table 1. The threshold voltage of the DG MOSFET is adjusted to be

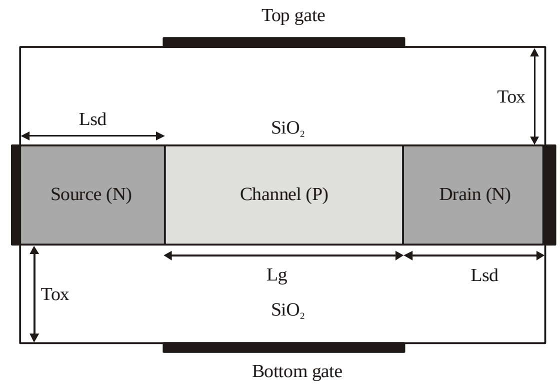

Fig. 1: Schematic of the double gate MOS transistor

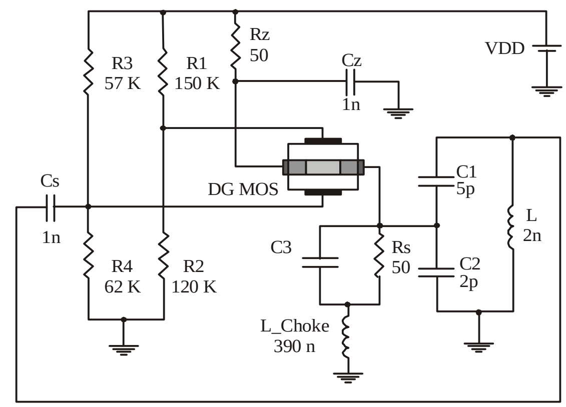

Fig. 2: Considered Colpitts oscillator

Table 1: Main parameter used in this study

Parameters	Value	Length	Value (nm)
N	10^{20} cm^{-3}	Lg	10.0
P	10^{10} cm^{-3}	Lsd	5.0
ϕ	4.25 eV	Tox	1.5

0.15 V using a gate work function (φ_m) equals to 4.25 eV corresponding to SiO_2 material. The voltages Vgs applied to the two gates are identical.

Mixed mode simulation (DGMOS oscillator)

Oscillator: An RF oscillator is 'Built' around the considered DG MOSFET. A mixed-mode analysis involve, applying a 2D Poisson-Schrodinger model to the device, whereas, the rest of the circuit used is governed by Kirchhoff's laws using the DESSIS tool in the ISE-TCAD software (ISE., 2002) (Fig. 2). In this fact, the simulator combines the device and circuit equations in one signal equation system.

In order to get a stable oscillation with a frequency oscillation f_0, the system must satisfy the Barkhausen criteria:

$$\beta(\omega_0).G(\omega_0) = 1 \quad (3)$$

where, $G(\omega_0)$ is the gain of the amplifier (DGMOS) and $\beta(\omega_0)$ is the attenuation introduced by the LC tank.

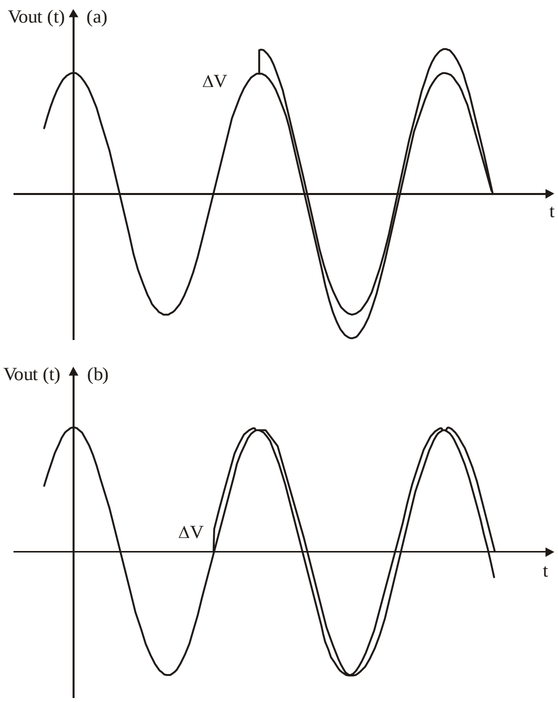

Fig. 3(a-b): Consequence of the injection of a (a) Maximum noise amplitude and (b) Zero-crossing

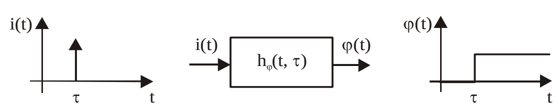

Fig. 4: Model of the phase impulse response

Then the oscillation frequency is majority determined by the LC tank resonant frequency:

$$\omega_0 = \frac{1}{\sqrt{LC_{eq}}}$$

With:

$$C_{eq} = \frac{c_1 c_2}{c_1 + c_2} + C$$

where, C is the gate substrate capacitance which is very small compared to C1/C2.

Linear Time-Variant (LTV) phase noise model: This model provides a technique for calculating the phase noise based on the study of the sensitivity of the phase of an oscillator according to the time (Hajimiri *et al.*, 1999). The idea of this model is to determine the impulse response of the phase excited by injection of low amplitude assimilated to current noise oscillator.

Usually the output of an oscillator can be written as:

$$V_{OUT}(t) = A(t),f(\omega_0 t+\varphi(t) \quad (4)$$

where, f is periodic function, A(t) is variation of the amplitude, φ(t) is phase variation.

For characterizing the phase noise of the oscillator, Hajimiri and Lee (1998) defined the Impulse Sensitivity Function (ISF). It indicates that the time (t) according to which the pulse is injected current, the phase response of the oscillator is different.

In fact, if the pulse is applied at the instant when the output signal of the oscillator has a maximum (zero-crossing), the phase variation is maximal. Conversely, if the pulse is applied at the moment the output signal has a zero, the change phase is zero (Fig. 3).

The purpose of the Hajimiri's model is to determine the impulse response of the phase hφ(t, τ) an oscillator when applying a current impulse i (t) at time τ (Fig. 4).

So, the phase noise can be characterized by an impulse response (Hajimiri *et al.*, 1999) as:

$$h_\varphi(t, \tau) = \frac{\Gamma(\omega_0 \tau)}{q_{max}} U(t-\tau) \quad (5)$$

where, U(t-τ) is the unit step function, q_{max} the maximum charge displacement, $\Gamma(\omega_0\tau)$ is the Impulse Sensitivity Function (ISF). The LTV phase noise model can predict the phase noise but it is difficult to define the ISF function by simulation.

RESULTS AND DISCUSSION

DC characteristic: In this section, the principal static characteristics (DC) of the considered DGMOS were described. They are obtained by self-consistent solution of Poisson-Schrodinger system. Short-Channel Effects (SCE) is monitored in several ways such as leakage current (I_{off}) and the Drain-Induced Barrier Lowering (DIBL).

Firstly, the electrical characteristic obtained by self-consistent model and SILVACO-TCAD software were compared successfully (Fig. 5). This later executes quantum numerical simulation using a full 2D Poisson-Schrodinger code.

Drain leakage current: One of the important problems mechanisms in off-state MOSFET's is OFF-leakage current. Several papers addressing leakage current have been published (Chang *et al.*, 1995; Roy *et al.*, 2003; Orouji and Kumar, 2006).

Figure 6 present the drain leakage current I_{off} for different gate work function. This current decrease consequently with the increased of the gate work function, this reduction of the current is related to the increase of the barrier potential. In order to maintain I_{off} very low, it is necessary to consider gate metal with higher corresponding metal work function.

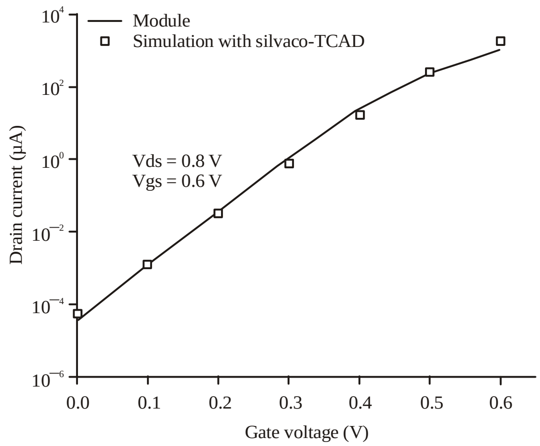

Fig. 5: Comparison of the output characteristics between present model and simulation with SILVACO-TCAD software

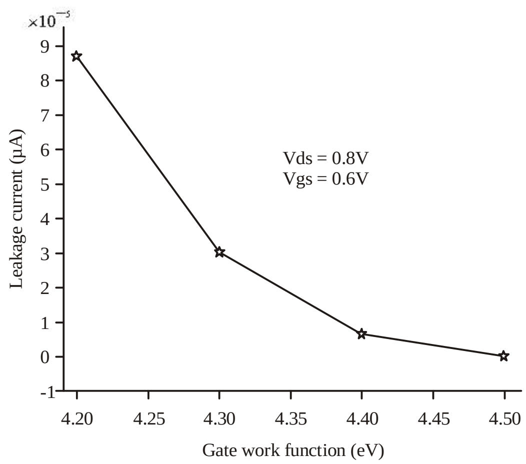

Fig. 6: Leakage current vs. gate work function

DIBL: Analysis of the characteristics Id (Vds) has identified the DIBL for different channel lengths for low and high drain polarizations.

Figure 7 represents the effect of varying the channel length on the DIBL for low (Vds = 0.1 V) and high (Vds = 1.5 V) drain bias. It can be observed that when the gate work function decreases from 4.25-4.5 eV, the DIBL is reduced. Moreover, the DIBL is lightly affected by gate work function, for the channel length greater than 12 nm.

Gate tunneling leakage current: Another parameter characterizing the short channel performance is the tunnel current. In MOS structures, the tunneling effect is characterized by the passage of the carriers through the oxide. The direct tunneling current is the dominant type of conduction in ultra-thin oxide MOS structures (<3 nm) (Lee and Hu, 2001).

Modeling of the direct tunneling current, the Wentzel-Kramers-Brillouin (WKB) approximation have been largely used. The direct tunneling current is depending

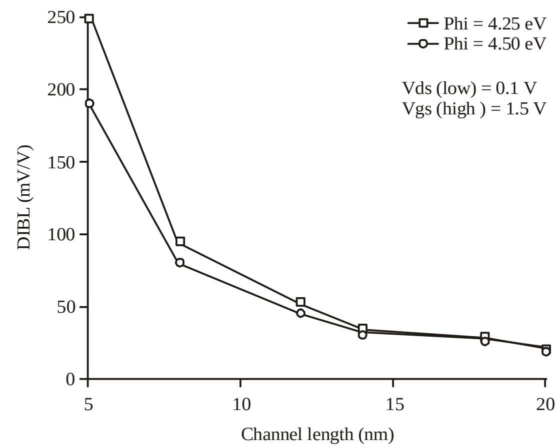

Fig. 7: DIBL vs. channel length for gate work functions

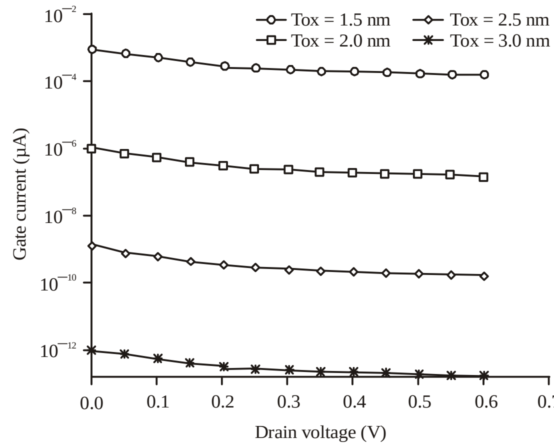

Fig. 8: Gate current vs. drain voltage for oxide thickness

exponentially on the electric field across the oxide (Mukhopadhyay *et al.*, 2007). It can be expressed by Lee and Hu (2001) in the following equation:

$$J = \left(\frac{q^3}{8\pi h V_{ox}}\right)\left(\frac{2\varphi_b}{V_{ox}}-1\right)\left(\frac{V_{ox}}{T_{ox}}\right)^2 \cdot \exp\left(\frac{-\left(\frac{8\pi\sqrt{2m_{ox}}\,\varphi_b^{3/2}}{3hq}\right)\left[1-\left(1-\frac{V_{ox}}{\varphi_b}\right)^{3/2}\right]}{V_{ox}/T_{ox}}\right) \quad (6)$$

where, V_{ox} is oxide voltage, T_{ox} is oxide thickness, m_{ox} is effective mass in the oxide, ϕ_b is the barrier height of the electron.

Figure 8 presents the gate tunneling current versus the drain voltage for different oxide thickness. Increasing the oxide thickness reduces the gate to channel tunneling. This is, because the reduction of gate oxide thickness results in an increase in the field across the oxide. The high

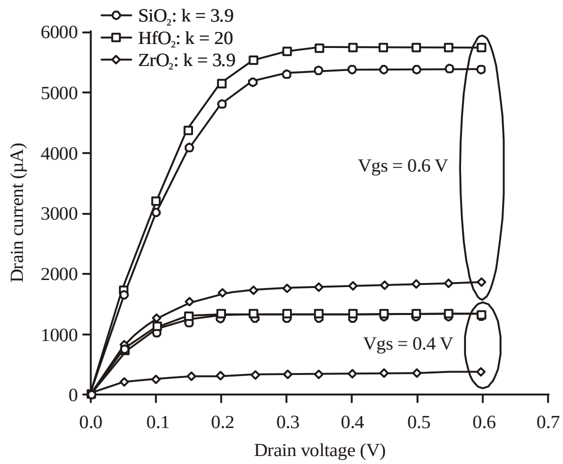

Fig. 9: Impact of the permittivity of the material to the output current

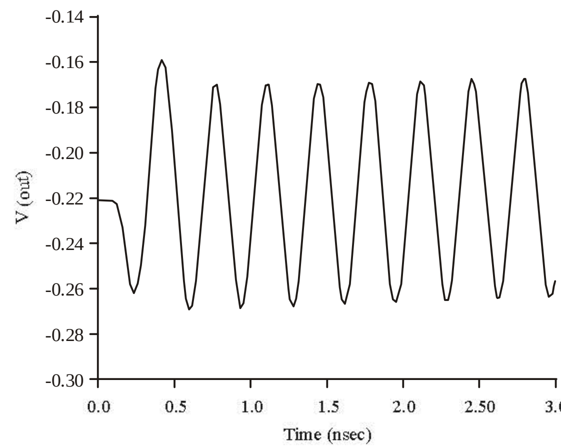

Fig. 11: A typical response of the DGMOSFET oscillator (mixed-mode simulation)

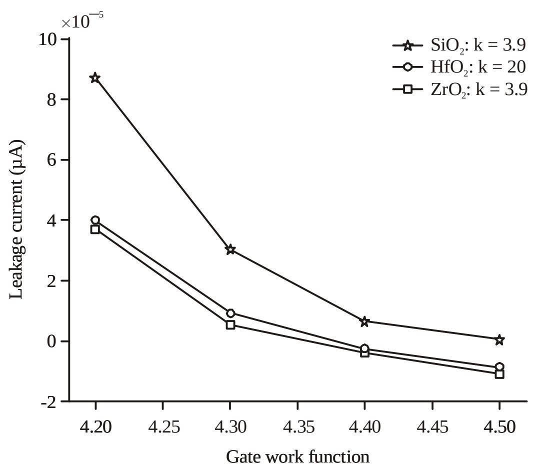

Fig. 10: Leakage current vs. gate work function for different permittivity

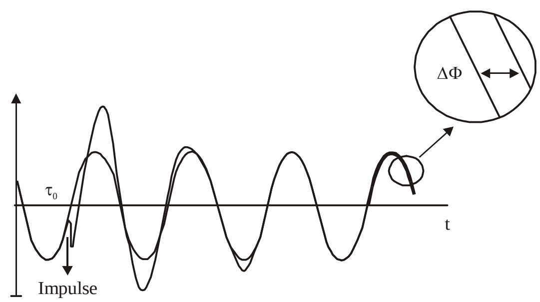

Fig. 12: Injection of an impulse at $t = \tau_0$

electric field coupled with low oxide thickness results in tunneling of electrons (tunnel current) from channel to gate.

The most promising technology to reduce the tunneling effect is High-k technology. This later is based on the change of the gate oxide SiO_2 by another insulate with a higher permittivity.

The two high-k materials widely studied are Hafnium (HfO_2) and Zirconium (ZrO_2) oxides, due to their dielectric constant evaluated between 20 and 25. Figure 9 represents the drain current versus the drain voltage for different permittivity values (SiO_2, ZrO_2 and HfO_2) for $T_{SiO2} = 1.5$ nm and $EOT_{HfO2} = 7.7$ nm, $EOT_{ZrO2} = 9.6$ nm. It can be observed that when the permittivity increases, the drain current also increases. This is because the gate tunneling current through the gate decrease (Fig. 10).

Output signal of the oscillator: The circuit generates after a very short transient regime (<1 nsec), a sinusoidal signal with a frequency oscillation in the order of 3 GHz corresponding to a period T = 335.8 ps (Fig. 11).

Analyse of the ISF function

Determination of the shift phase: Based on the LTV model and in order to determine the phase noise performance of the oscillation, we are interested in determining Φ $\Delta\Phi$. For this, a current pulse (i(t)) was injected at time τ of period T and the oscillator response for a few periods after the injection was analysed. By measuring the deviation Δt of the moment of zero crossing, it can measure the phase difference $\Delta\Phi = 2\pi\Delta t/T$, produced by the injection (Fig. 12).

The phase shift of the output signal depends on the moment where a disturbance is injected. This relationship between the phase shift and the timing of the injection pulse can be characterized using the sensitivity function (ISF). This function is used to study the sensitivity of the elements (L, C1 and C2) of the Colpitts oscillator to a current disturbance. In order to have sufficiently of measuring points to trace the ISF function, we chose a step 6.74 psec corresponding to 50 measuring point on the period T = 335.8 psec.

Figure 13a-c represents the transient simulated output waveform obtained by ISE-TCAD simulator. It can observed that the:

- ISF function depends on injection node
- ISF function is sinusoidal with a period of 2.97 GHz which is the nearly same period of the output signal

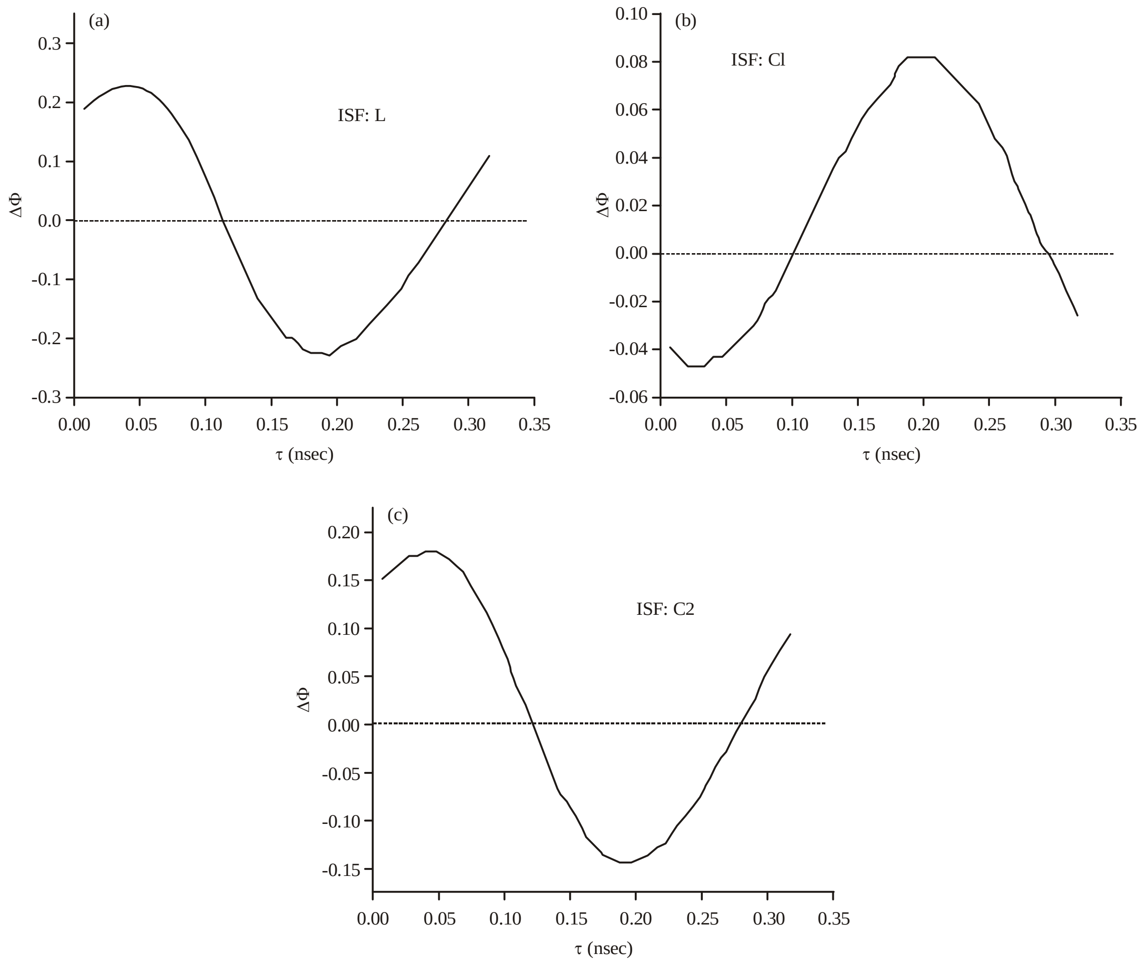

Fig. 13(a-c): ISF function for current pulses in (a) Inductance (L), (b) Capacitance (C1) and (c) Capacitance (C2)

Analytical model: Now, we would like to extend the discussion to any value of the Φ phase (Φ E [0, 2π]), not only for a small charge injection. Gontrand *et al.* (2009) have established that if we consider a parasitic pulse injection (a "dirac") at τ time, the global output voltage of an oscillator can be considered as the superposition of the permanent voltage and the response to the parasitic injection, because any time or phase shifted solution remains a solution of the harmonic oscillator:

$$\frac{1}{\omega_0^2}\frac{d^2V}{dt^2}+V=\frac{q}{C}\delta(t) \tag{7}$$

$$\begin{aligned} V_T(t) &= V_S(t)+p(t) \\ &= V_0\cos(\omega_0 t)+\frac{q}{C}\cos(\omega_0 t)u(t-\tau) \end{aligned} \tag{8}$$

where, V_T is total output voltage, Vs is output voltage of the free oscillator, C is global capacity of the Colpitts oscillator (Fig. 2).

Equation 8 can be reformulated as:

$$V_T(t) = V_{T0}\cos[\omega 0t+\phi] \tag{9}$$

With:

$$V_{T0}=\sqrt{V_0^2+\left(\frac{q}{C}\right)^2+\frac{2qV_0\cos(\omega_0 t)}{C}} \tag{10}$$

$$\varphi=\arctan\left(\frac{-q\sin(\omega_0 t)}{CV_0+q\cos(\omega_0 t)}\right)+/-k\pi \tag{11}$$

Now, from these general formulas and assuming a limited expansion of φ and considering only the first order, can be reformed by:

$$\varphi=\frac{-q\sin(\omega_0 t)}{CV_0} \tag{12}$$

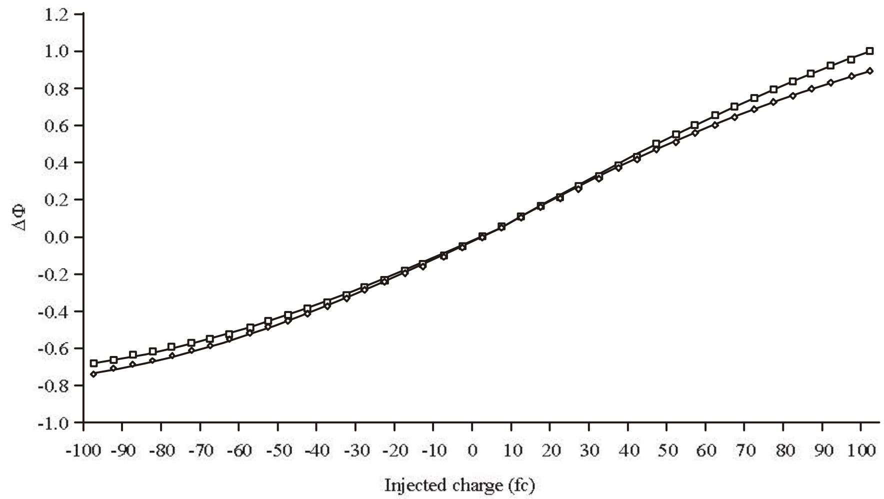

Fig. 14: Phase shift (output of transistor) versus injected charges

If the latter Eq. 12 compared to the appendices of Hajimiri and Lee (1998), the well known results can be found out: $\Gamma = -\sin(\omega_0 t)$ (Eq. 11) of Hajimiri and Lee (1998) with $q_{max} = CV_0$; this result is valid but for q very small.

The mixed-mode simulations that we have realized, have identified each time the phase deviation $\Delta\Phi$, considering $CV_0 = 100$fc. Raised these variations is reported in Fig. 14 and favorably compared with the analytical model. A good linearity is observed.

CONCLUSION

In this study, the analysis of the RF oscillator (Colpitts oscillator) built around the nanoscale DGMOS has been presented. Firstly, the SCEs (leakage currents and DIBL) in the DGMOS device was analysed; the results show that the impact of metal gate work function on leakage current and DIBL is important and must be considering to minimize SCEs. It have also note that above 12 nm, the DIBL is relatively small, but for greater channel length, significant effect of DIBL appears and must be take into account. Furthermore, the Double Gate transistor with High-k gate dielectric was analysed in order to reduce current leakage tunneling while maintaining the same value of capacitance.

Secondly, we go further on phase noise theory of such oscillator; starting with mixed mode analysis of an LC-type oscillator; some analytical solutions for the phase noise were derived, through a new lecture of the Impulse Sensitivity Function (ISF). First numerical simulation raw results are very consistent with such a numerical and analytical models; the phase shift of the output signal depends on the moment where a disturbance is injected. The method in this study don't require specific 'Artificial' noise source to be introduced at some nodes (cf. Spice-like simulations) and it is its principal originality.

ACKNOWLEDGMENT

This study was supported by UPM (Union pour la méditéranée).

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