# Study of the MOSFET’s ageing using a new techniques

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## ABSTRACT

The MOSFET’s models of SPICE 3F4 do not consider the charge pumping phenomena (CP). In this work, we have implemented the three models of the CP technique in SPICE 3F4. We have used the MOSFET level 1 of SPICE3F4, to which we added a generator of current between drain and substrate for the measurement of the CP current. This current measured versus the different levels of the gate bias, can provide many interesting results concerning the parameters of the considered MOSFET. The simulated results are in a good agreement with recent and different experimental results.

**Key words**

Spectroscopic Charge Pumping, Characterization, Modeling, SPICE3F4.

## 1. Introduction

One of the main reasons for the success of the VLSI MOS (Metal-Oxide-Semiconductor) technology has been, and still is, the high quality of the interface between the Si substrate and the $SiO_2$ gate dielectric. The quality of this interface plays an important role in the performance and the reliability of the MOSFET devices. It is, therefore, very important to dispose of a technique that allows a full and sensitive characterization of this interface quality. For this purpose, the charge pumping technique proved to be the most successful and reliable technique.

The charge pumping effect in MOS transistor was reported for the first time by Brugler and Jespers in 1969[1,2] when applying rectangular pulses to the gate of a MOSFET, while source and drain are kept at a small reverse voltage. At the substrate contact, a recombination current proportional to the $SiO_2$ interface trap density is measured. It is based on the exploitation of a repetitive process whereby majority carriers coming from the substrate recombine with minority carriers previously trapped in interface states. By taking into account the emission processes, which control the exchange of charges at the interface, information concerning the capture cross-section and the energy distribution of the interface states can be obtained [2-5]. A lot of work has been published over the last two decades in order to improve the understanding of the technique [6-10].

By adjusting the signal parameters we can calculate the average density of the interface state $<D_{it}>$ and their average cross-section $< s >$ and we also again access to the energy distribution of the state $D_{it}(E)$ and to their spatial distribution $D_{it}$ (x).

With the spectroscopic technique similar to the DLTS (Deep Level Transient Spectroscopy) [7], it is possible to define an energy window by exploiting a differential signal and that $D_{it}(E)$ and $s$ (E) are accessible by performing a temperature sweep. In [3] this technique has been coupled with static characteristic of transistor. However, because the spectroscopic technique has a lot of advantages, and it is not taken into account in electrical simulators such as SPICE3F4 (Simulation Program With Integrated Circuit Emphasis), we have simulated this experimental technique by elaborating and implementing a model in the electrical simulator SPICE3F4 [11]. This model takes into account the temperature effect on the geometrical and electrical parameters of the studied transistor.

## 2. Charge pumping theory

Groeseneken et al. [2] have developed a simple quantitative model for the charge pumping mechanism. That yields expressions of $<D_{it}>$ and of a geometrical mean value of capture cross-section. These authors thus explain all the phenomena previously not well understood. Their model takes into account the emission of holes and electrons, respectively toward the valence or the conduction band, depending on the state of the Si-$SiO_2$ interface traps.

### 2.1. Steady-state condition

When an n-channel MOSFET is pulsed into accumulation, the interface (Fg.1b) traps above the hole quasi-Fermi level are filled with the holes. These holes are emitted at a certain rate when the gate voltage $V_g$ is ramped back towards inversion. At the first, this emission process is in equilibrium with the change in the surface Fermi level, i.e., it occurs in a steady-state regime. The rate of change of the trapped interface charge is then given by [2]:

$$\left[\frac{dQ_t}{dt}\right] = -q^2 D_{it}\frac{d\psi_s}{dt} = -q^2 D_{it}\left[\frac{dV_g}{d\psi_s}\right]^{-1}\frac{dV_g}{dt} \qquad (1)$$

$D_{it}$ is the interface traps density ($cm^{-2}.eV^{-1}$), q is the elementary charge, $Q_t$ is the interface-trapped charge with respect to the area unit ($C.cm^{-2}$), and $\psi_s$ is the silicon surface potential.

When the surface is approaching the flat-band condition, the emission rate becomes insufficient to meet the equilibrium condition imposed by the surface potential sweep, from this moment, the system enters the non-steady-state emission mode [3,5].

### 2.2. Non steady-state emission

Van den Bosch et al. [5] define a non-steady-state emission function given by:

$$F(E_t, t) = e_p(E_t).[1 - f(E_t, 0)].e^{(-e_p(E_t).t)} \qquad (2)$$

where $e_p(E_t)$ is the hole emission rate ($s^{-1}$) for trap of level $E_t$ and $f(E_t,0)$ is the occupancy function of these traps when the non-steady-state condition set in (t=0).

Function $F(E_t,t)$ is sharply peaked around a certain energy level $E_{ph}(t)$, indicating that only energy level $E_{ph}(t)$ contribute to the emission process. $E_{ph}(t)$ is given by [5]:

$$E_{ph}(t) = E_{em,h}(t) = E_i + K \cdot T \ln\left[ v_{th}\sigma_p n_i t + e^{\left(\frac{E_{em,h}(0) - E_i}{K \cdot T}\right)} \right] \qquad (3)$$

$E_{em,h}(0)$ is the Fermi level at the onset (t=0) of the non-steady-state of the emission.

$\sigma_p$ is the capture cross-section of holes, $n_i$ is the intrinsic carrier concentration ($cm^{-3}$), $v_{th}$ is the thermal velocity of carriers, $K=1.38.10^{-23} j.k^{-1}$ is the Boltzmann constant, $E_i$ is the intrinsic Fermi level. In the case of electron emission, an analog reasoning, is done:

$$E_{pe}(t) = E_{em,e}(t) = E_i - K \cdot T \ln\left[ v_{th}\sigma_n n_i t + e^{\left(\frac{E_{em,e}(0) - E_i}{K \cdot T}\right)} \right] \qquad (4)$$

$E_{em,e}(0)$ is the energy level reached at the onset (t=0) for the non-steady emission of electron. $\sigma_n$ is the electron capture cross-section.

### 2.3. Calculation of emission level

A simple reasoning allows us to assess the demarcation levels. To determine level $E_{em,h}$ (Energy level reached at the end of non-steady-state emission of holes) we consider that the interface states situated between $E_{F,acc}$ (Fermi-level energy in the accumulation mode) and $E_{em,h}$ have a hole emission time constant $\tau_{em,h}$ which is small compared with $t_{em,h,}$ (the time period during which these traps can emit holes). The closer to the valence band, the easier it is for the traps to re-emit holes into it. According to the Shockley-Read-Hall (SRH) theory [2,12], $\tau_{em,h}$ can be expressed as:

$$\tau_{em,h} = \frac{1}{\sigma_p v_{th} n_i e^{\frac{E_i - E_t}{KT}}} \qquad (5)$$

with $E_t$ is the energy level of the interface trap.

Therefore, for those interface traps located between $E_{em,h}$ and $E_{F,inv}$ (Fermi-level energy in the inversion mode), the emission time constant is greater than $t_{em,h}$. Demarcation level $E_{em,h}$ is thus given by the condition $\tau_{em,h}=t_{em,h}$:

$$E_{em,h} - E_i = K.T.\ln(v_{th}.\sigma_p.n_i.t_{em,h}) \qquad (6)$$

Likewise:

$$E_{em,e} - Ei = -K.T.\ln(v_{th}.\sigma_n.ni.t_{em,e}) \qquad (7)$$

A more comprehensive analysis, can be found in [2,5] when $V_g$ is between $V_{FB}$ (Flatband voltage) and $V_T$ (Threshold voltage of the MOS transistor). The emission duration $t_{em,h}$ and $t_{em,e}$ are given by:

$$t_{em,e} = \frac{|V_T - V_{FB}|}{\Delta V_g} t_f \quad \text{and} \quad t_{em,h} = \frac{|V_T - V_{FB}|}{\Delta V_g} t_r$$

with $\Delta V_g=V_{gh}-V_{gl}$ the amplitude of the gate voltage pulse, $V_{gh}$ is the upper level of the gate voltage pulse, $V_{gl}$ is the lower level of the gate voltage pulse, $t_r$ is the rise time of the gate pulse and $t_f$ is the fall time of the gate pulse.

$$E_{em,h}(t_r) = E_i + KT\ln\left[ v_{th}\sigma_p n_i \left( \frac{|V_T - V_{FB}|}{\Delta V_g} \right) t_r \right] \qquad (8)$$

$$E_{em,e}(t_f) = E_i - KT\ln\left[ v_{th}\sigma_n n_i \left( \frac{|V_T - V_{FB}|}{\Delta V_g} \right) t_f \right] \qquad (9)$$

Equations (8) and (9) are directly dependent on temperature, physically carrier emission from the interface traps depends strongly on temperature, CP measurements are also very sensitive to temperature. When T increases, the emission processes from the traps increases while the recombinaison processes decrease [7].

Van den Bosch et al [5,7] have expressed the dependence of charge pumping current $I_{cp}$ on T by:

$$I_{cp} = -aT - bT \ln(T) + c \qquad (10)$$

where:

$$a = 2.qKfA_{eff}\langle D_{it}\rangle \ln\left[\sqrt{\sigma_n\sigma_p}\right]\sqrt{\frac{3.K}{m^*}}.K_i \frac{|V_T - V_{FB}|}{\Delta V_g}\sqrt{tr.t_f}$$

$$b = 4KfA_{eff}\langle D_{it}\rangle$$

$$c = qfA_{eff}\langle D_{it}\rangle E_G$$

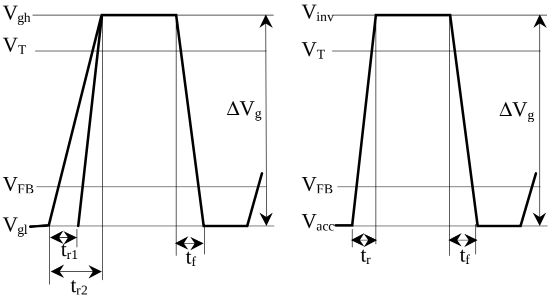
$m^*$ is the average effective mass of the carriers, $E_G$ silicon bandgap, and $K_i$ is a constant.

### 3. Spectroscopic charge pumping

The spectroscopic CP method consists in monitoring and subtracting the CP currents obtained with a trapezoidal signal for two distinct and consecutive $t_{r1}$

and $t_{r2}$ values of the rising edge of the gate pulse, while keeping the falling edge unchanged; the other parameters kept unchanged (Fig 1a). The difference between the two CP currents is due to the fact that hole emission stops earlier(i.e. $(E_{em,h}(t_{r1})<E_{em,h}(t_{r2}))$ when the rising edge is sharper (i.e. $t_{r1}<t_{r2}$).

By subtracting the two signals, we obtain a third signal whose magnitude depends on the portion of energy bandgap thus scanned. The lower half of the band gap can thus be scanned by an energy windows ( defined by $t_{r1}$ and $t_{r2}$ at constant $t_f$ ) forced to move through the bandgap by varying the sample temperature (likewise, the upper half can be scanned by using two distinct tvalues while maintaining $t_r$ constant and by varying T(Fig 2)



(a) (b)

Fig. 1. Comparaison of waveforms used in standards Spectroscopic charge pumping (a) and 2-level CP (b).

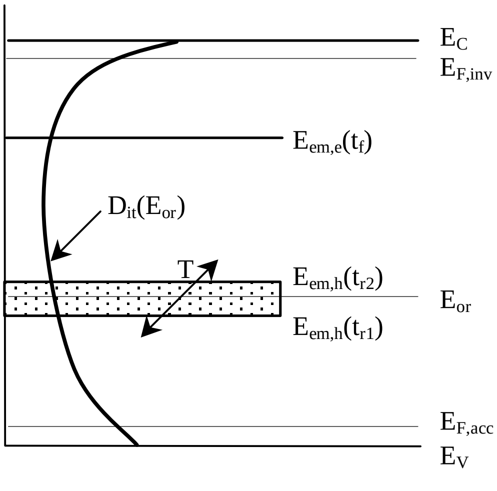


Fig.2. Distribution of interface states and domain of energy bandgap which can be explored by the SCP technique using the signal defined in (Fig.1a).

The spectroscopic signal ($S_r$) corresponds to the energy window defined by $t_{r1}$ and tr$_2$ at constant $t_f$, the differential CP current is given by:

$$S_r(t_{r1},t_{r2}) = I_{cp}(t_{r2},t_f) - I_{cp}(t_{r_1},t_f)$$
$$= qfA_{eff}\,D_{it}(E_{or})KT\ \ln\left(\frac{t_{r2}}{t_{r1}}\right) \quad (11)$$

$E_{or}$ is the mean energy level corresponding to window ($t_{r1}$,$t_{r2}$).

Likewise, the spectroscopic signal ($S_f$) corresponds to the energy window defined by $t_{f1}$and $t_{f2}$ at constant $t_r$, the differential CP current is given by:

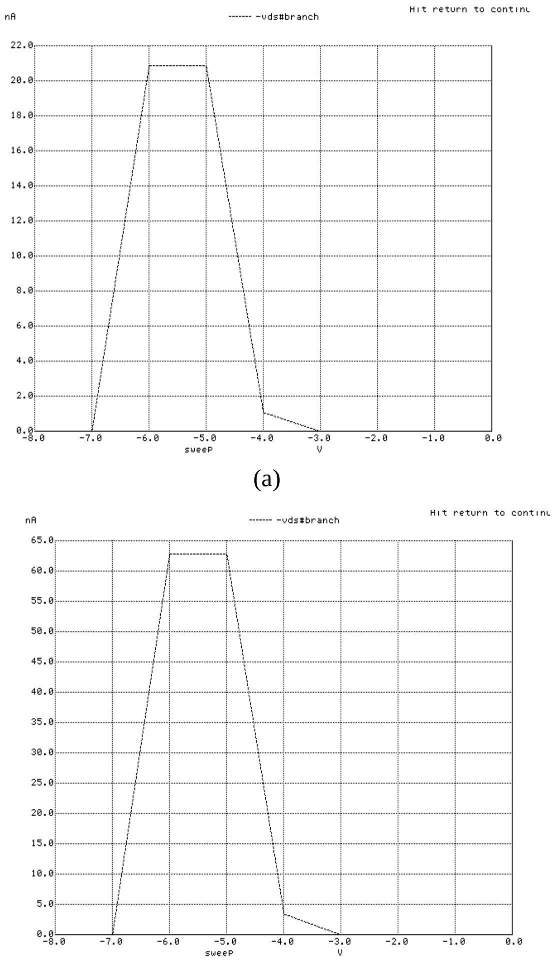
$$S_f(t_{f1},t_{f2}) = I_{cp}(t_r,t_{f2}) - I_{cp}(t_r,t_{f1})$$
$$= qfA_{eff}\,D_{it}(E_{of}).KT\ \ln\left(\frac{t_{f2}}{t_{f1}}\right) \quad (12)$$

$E_{of}$ mean energy level corresponding to windows ($t_{f1}$,$t_{f2}$).

## 4. Results and discussion

The simulations results plotted in this paper have been obtained on conventional n-channel MOSFET's. The oxide thickness is of 34nm, the channel length and width on mask are, respectively, of 0.1 and 100 µm.

Fig.3 shows the charge pumping current $I_{cp}$ as function of the base level $V_{gl}$ of the gate pulse, with the temperature as parameter. We have choose in the first case, T=300°K (Fig. 3.a) and for the second T=100°K (Fig. 3.b). We note that, as the temperature decreases, the maximum of the base-level curve increases.



(a)

(b)

Fig 3.Charge-pumping current $I_{cp}$ as a function of pulse base level, parameters: f=50Khz, $\Delta V_g$=6 v, $t_r$=$t_f$=600 ns, $<\sigma>=2.10^{-15}$ cm$^2$, $<D_{it}>=3.10^{10}$ cm$^{-2}$.eV$^{-1}$.

We can explain, physically, this phenomenon by the increase of the emission process from the traps and the decrease of the recombination processes when T increases. This last provokes an increase of the emitted holes and electrons.

In Fig.4, the maximum of the base-level CP curves is shown as function of temperature. We can note that $I_{cp}$ is well described by (10). Implying an interface trap distribution which is not strongly varying over the band. In the lower temperature range, the CP process behaves as expected from theory at least down to 77°K.

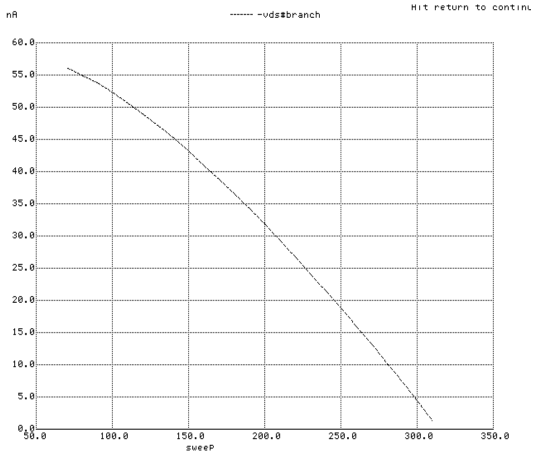
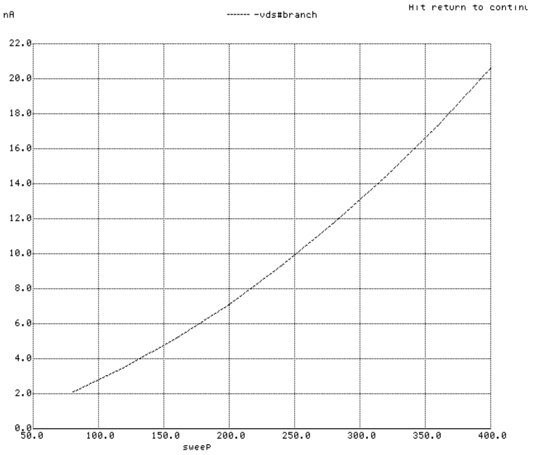


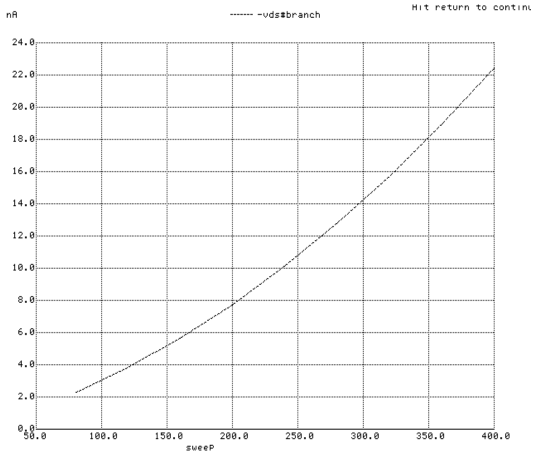
Fig.4.Maximum of $I_{cp}$ versus base level with the same parameters of Fig. 3, as a function of temperature.

Fig. 5 shows a number of spectroscopic signals plotted on nMOSFET, at temperature scan between 60 and 380 K, the gate was pulsed with a frequency of 50 kHz, between –3 and +3 V and for two different energy windows, three rise times 250, 500, 1000 µs, were applied at a fixed fall time of 1µs, and vice versa. By doing so, two edge pairs (500, 1000µs) and (1000, 2000µs), were applied at a fixed rise time of 1µs.

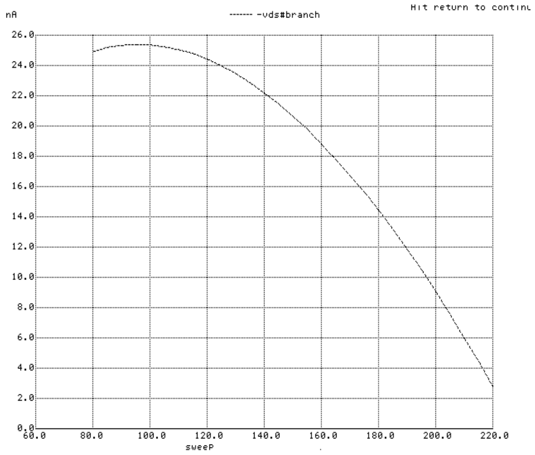
$S_r$ and $S_f$ expressed by (11) and (12) vary linearly with respect to $D_{it}$. Thus, for the given temperature, set of $t_r$ (or $t_f$) values and device parameters we can extract $D_{it}(E)$ using the $S_r$ (or $S_f$) plots.



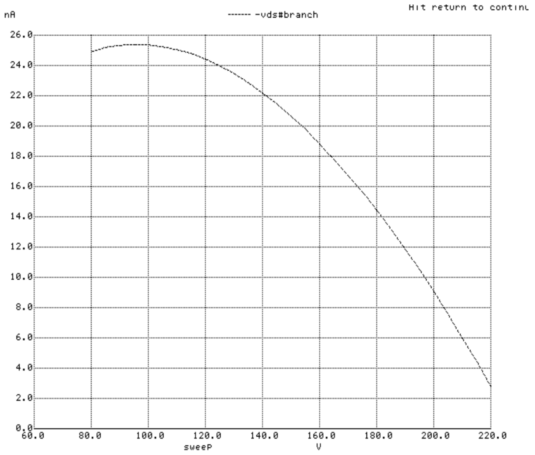
(a)



(b)



(c)



(d)

Fig.5. Spectroscopic signals plotted for n-channel transistor with different emission windows. In (a) and (b) $t_f$=1µs and $t_r$ have two distinct values. In (c) and (d) $t_r$=1µs and $t_f$ have two distinct values.

## 5. Conclusion

In this work, we have developed a spectroscopic charge-pumping model, implemented in SPICE3F4. We have plotted $I_{cp}=f(V_{gl})$ for different temperature, we have also plotted the spectroscopic signals versus the temperature for various energy windows. The simulated results are compare to other recent experimental results. The observed good concordance proves the efficiency of the developed model.

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