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► **To cite this version:**

Bogdan Cretu, Eddy Simoen, Jean-Marc Routoure, Régis Carin, M. Aoulaiche, et al.. Low frequency noise characterization in n-channel UTBOX devices with 6 nm Si film. The International Conference on Noise and Fluctuations (ICNF), 2013, Montpellier, France. 4 p. hal-00994170

**HAL Id: hal-00994170**

**<https://hal.science/hal-00994170>**

Submitted on 22 Jul 2014

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# Low frequency noise characterization in n-channel UTBOX devices with 6 nm Si film

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**Abstract**—The noise spectra of the studied n-channel UTBOX devices contain flicker noise and Lorentzian components. At room temperature it was found that the flicker noise is explained by the carrier number fluctuation model for both front and back interfaces. Due to the thin silicon film thickness a strong electrostatic coupling between front and back interface was evidenced. The evolution of the low frequency noise versus the temperature allows to identify traps in the silicon film and to make a correlation between the observed traps and some technological steps.

**Keywords**—UTBOX, thin silicon film, low frequency noise, carrier number fluctuation noise, Lorentzian noise

## I. INTRODUCTION

The increase of the integration density and the improved performances of integrated electronic circuits are made possible by the continuous evolution of semiconductor devices to smaller dimensions in new technological nodes, which on top of that implement new materials, process modules and architectures. For the development of the 16 nm technology node and below there is a growing interest in the fully depleted (FD) ultra-thin buried oxide (UTBOX), due to the enhanced performances reported in the literature, in particular related to the very thin BOX which allows an additional control of the short channel effects owing to the electrostatic coupling between gate and channel and also of the threshold voltage that can be controlled by applying a back bias voltage [1,2]. Because there is no external capacitor needed, there is an increase interest in using such devices as one-Transistor Dynamic Random-Access Memory (1T-DRAM) cells [3,4]. However, for this application, the main concerns are related to the charge retention time, which is strongly influenced by the traps present in the silicon film and the dielectric layers. A good process control is necessary in order to induce less/no traps related to the carrier generation-recombination (G-R) mechanism.

The low frequency noise measurements can be used as a non-destructive device characterization tool in order to evaluate the quality of the silicon/dielectric interface and to identify the traps in the depletion area of the transistors. The study of the G-R noise, corresponding to a Lorentzian type of spectra

allows to make the so-called noise spectroscopy when it is performed as a function of the temperature [5,6].

The aim of this work is to investigate the low frequency excess noise sources ( $1/f$  and Lorentzian spectra) versus temperature as a diagnostic tool in order to characterize the traps present at the front (back) gate oxide/Si film interface and in the depletion area (Si film) of these advanced n-channel UTBOX devices.

## II. TECHNOLOGICAL DETAILS AND METHODOLOGY

The studied devices were fabricated at imec in a FD UTBOX SOI technology on 300 mm wafers. The tested devices present a fixed mask gate length and width of 150 nm and 1  $\mu\text{m}$  respectively; a BOX thickness of about 8 nm and a silicon film thickness of about 6 nm. The gate stack consists of a high-k dielectric (SiON) on top of a 1 nm interfacial SiO<sub>2</sub>, resulting in an equivalent oxide thickness (EOT) of 2.6 nm. The low frequency noise measurements were performed directly on wafer-level using a "Lakeshore TTP4" prober. The devices were biased in the linear regime with an applied drain voltage  $V_{DS} = 50 \text{ mV}$ . At room temperature, the front (back) interface noise was investigated as a function of the applied front (back) interface voltage  $V_{GS}$  ( $V_{BS}$ ) for a fixed applied back (front) interface voltage of  $V_{BS} = 0 \text{ V}$  ( $V_{GS} = 0 \text{ V}$ ). Noise measurements from 200 K up to room temperature (step of 10 K) were performed for a fixed drain current (the front interface voltage was adjusted in order to keep the drain current constant at  $I_D = 1.5 \mu\text{A}$  for a fixed applied  $V_{BS} = 0 \text{ V}$ ). The measurement set-up allows to measure the total dynamic resistance between drain and source  $r_t$  and the transconductance  $g_m$  by applying a small signal at the source and gate nodes, respectively. Noise is calculated at the input of the device by dividing by the square of the measured voltage gain between the gate and the output and this for all different applied gate voltages.

Typical frequency normalized front interface noise spectral density is presented in Fig. 1. It can be observed that the noise behavior contain  $1/f$  and Lorentzian contributions. In order to clearly identify the excess noise parameters, i.e. the  $1/f$  noise

level and the plateau and the characteristic frequency of each Lorentzian contribution, one method is to take into account the frequency dependence of the different contributions on the total noise spectral density at the input of a MOS transistor:

$$S_{V_G}(f) = B + \frac{K_f}{f} + \sum_{i=0}^N \frac{A_i}{1+(f/f_{0i})^2} \quad (1)$$

where  $B$  presents the white noise level,  $K_f/f$  is the flicker noise, and the third term of the equation presents a sum of Lorentzian components, with  $A_i$  the plateau value and  $f_{0i}$  the characteristic frequency.

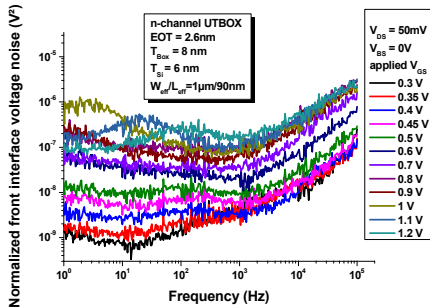


Figure 1. Typical frequency normalized front interface noise density for different applied gate voltage.

The addition in (1) assumes that these three noise sources are uncorrelated. The Lorentzian type of noise contribution is due to processing-induced traps in the thin silicon film, at the silicon film/interface and random telegraphic signals (RTS), which can be observed for small areas devices ( $< 1 \mu\text{m}^2$ ) and are commonly related to individual carrier trapping at the silicon-oxide interface. Moreover, for advanced devices with very thin  $\text{SiO}_2$  or using a high- $k$  dielectric, the  $1/f$  noise is explained by carrier number fluctuation (for n and p-channel devices), which is associated with carrier trapping/detrapping in the gate oxide. Both Lorentzian and  $1/f$  noise are so related to generation-recombination mechanisms. However, the question is whether or not they can be still considered as uncorrelated?

Situations where many G-R spectra lead to a  $1/f$  behaviour was pointed out in [7], assuming that the individual G-R spectra can be simply added and that the individual spectra have the same variance. A physical model that fulfils these assumed mathematical conditions is given in [8] where a microscopic model of carrier tunnelling into the oxide state is proposed as microscopic source of  $1/f$  noise. Considering that the semiconductor contain only two G-R centres, characterised by two relaxation times  $\tau_1$  and  $\tau_2$ , then if they are uncorrelated the noise spectrum is an addition of the two spectra. If they are correlated the noise spectrum will be a Lorentzian with a relaxation time given by  $\tau_1^{-1} + \tau_2^{-1}$ . The mathematical criterion that decides whether the spectra could be considered uncorrelated is given in [9]:  $n \gg m^*$ , where  $n$  is the total number of free electrons and  $m^*$  is defined as

$m^{*-1} = m^{-1} + (M - m)^{-1}$ , where  $M$  is the total number of trap in the oxide in the McWhorter model and  $m$  is the number of trapped electrons. Consequently, if  $n \ll m^*$ , correlated sources should be considered. In [9], based on the calculated behaviour of an  $\alpha$  parameter (defined as  $\alpha = S \cdot f/n$ ) it is pointed out that even if the McWhorter model explains the shape of the spectrum ( $1/f$ ), it not predicts the right magnitude.

Noise measurements and simulations performed on polysilicon thin film transistors (TFTs) [10] show the same  $\alpha$  parameter bell-shape-behaviour as predicted in [9]: increase from weak to moderate inversion and then a decrease from moderate to strong inversion. For the studied devices, these previous results suggest that the condition  $n \gg m^*$  seems to be fulfilled for applied gate voltages higher than the threshold voltage. However, whether or not this result can be extended for monocrystalline transistors is an open question.

For advanced MOSFET devices, the plateau  $A_{0i}$  and the time constant  $\tau_{0i} = 1/(2\pi f_{0i})$  of the observed Lorentzians were already estimated using the model of (1) for all investigated temperatures [5,6]. For traps located in the silicon film, the evolution of the Lorentzian plateau  $A_i$  versus  $\tau_i$  ( $A_i$  and  $\tau_i$  associated to the same trap) should be linear [11]. If there are correlated Lorentzian contributions, no correlations between the  $A_i$  and  $\tau_i$  should be observed. However, a linear dependency between  $A_i$  and  $\tau_i$  was already highlighted in [6] and it suggests that the considered Lorentzian contributions are uncorrelated.

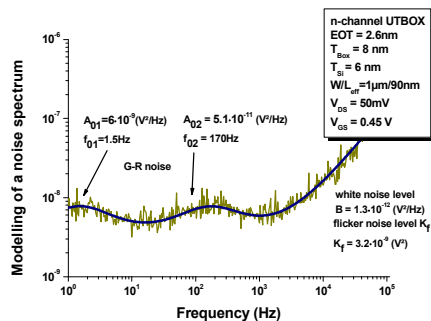


Figure 2. Comparison between noise measurement and model using (1). White noise,  $1/f$  noise and two Lorentzians were used to obtain the best agreement between the model and measurement

Assuming contributions of these three noise sources, the noise spectra of these samples can be perfectly modeled by (1), and the different noise parameters can be clearly identify, as shown in Fig. 2.

### III. LOW FREQUENCY NOISE

#### A. $1/f$ noise at room temperature

Considering uncorrelated noise sources in the channel and the source/drain regions and assuming that the drain and source access regions are symmetrical, in the framework of the carrier number fluctuation, taking into account the supplementary mobility fluctuations  $\delta\mu_{eff}$  due to the modulation of the

scattering rate induced by the interface charge fluctuations, the total voltage noise spectral density in the linear region of operation can be described by the formula:

$$S_{V_G} = \frac{(r_T - r_{access})^2}{r_T^2} S_{V_{FB}} (1 + \alpha_{SC} \mu_0 C_{ox} V_{GT})^2 + \frac{K_r r_{access}^2 I_D^2}{f 2r_T^2 g_m^2} \quad (2)$$

where  $S_{V_{FB}}$  is the flat-band spectral density,  $\mu_0$  is the low field mobility,  $\alpha_{SC}$  is the Coulomb scattering coefficient,  $C_{ox}$  is the gate oxide capacitance,  $r_{access}$  is the dynamic access resistance and  $K_r$  is the access resistance noise level.

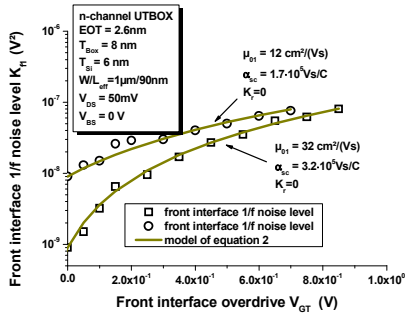


Figure 3. Typical example of the extracted front interface  $1/f$  noise level  $K_{f1}$  versus the applied front gate voltage overdrive. In this figure, the squares correspond to the noise measurements presented in Fig. 1

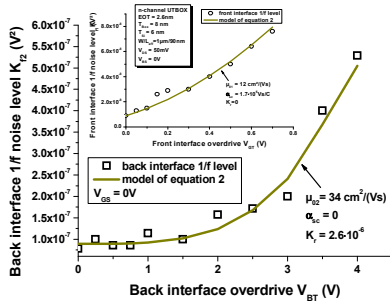


Figure 4. Typical example of the extracted front interface  $1/f$  noise level  $K_{f2}$  versus the applied back interface overdrive. In the inset are presented the corresponding  $K_{f1}$  noise levels (circles in Fig. 3)

The extracted  $1/f$  noise levels are noted  $K_{f1}$  for the front interface and  $K_{f2}$  for the back interface. Example of  $1/f$  noise behaviours with the applied gate voltage overdrive are represented in Fig. 3 and Fig. 4. The  $K_{f1}$  (and  $K_{f2}$ ) evolutions with the applied front (back) interface overdrive can be well modelled by (2). The  $K_{f2}$  noise level is found to be independent of the applied back voltage overdrive in moderate inversion. This suggests that the carrier number fluctuations dominate the  $1/f$  noise at the back interface. The increase in strong inversion of the  $K_{f2}$  can be explained by the parasitic access resistance contribution on the total  $1/f$  noise. The

increase of the  $K_{f1}$  noise level from moderate to strong inversion may only be related to the carrier number fluctuations correlated to mobility fluctuations.

An analytical model, that takes into account the coupling effect between the front and back-gate input gate voltage  $1/f$  noise, is proposed in [12] for fully depleted SOI devices, for which the carrier number fluctuations dominate the  $1/f$  noise. This model assumes that the noise sources are related to fluctuations of the front and back flat - band voltages, and if one channel is activated, the opposite channel is in the depletion or weak inversion mode. Based on the determined values of the voltage spectral density in the flat-band operation for the front and the back interfaces the slow oxide trap densities of the front interface  $N_{t1}$  and of the back interface  $N_{t2}$  can be estimated. The good quality of the front/back interfaces is evidenced for all investigated devices by the relatively low values of the traps densities:  $N_{t1}$  was found in the range of  $1.1 - 9.8 \cdot 10^{17} (\text{cm}^3 \text{eV}^{-1})$  while  $N_{t2}$  was in the range of  $1.1 - 20.4 \cdot 10^{17} (\text{cm}^3 \text{eV}^{-1})$ . For all investigated devices, a contribution of the back interface noise source in a range of 42 - 64% on the measured noise in the front channel conduction was found, while the contribution of the front interface noise source is in a range of 10 - 23% on the measured noise in the back channel conduction.

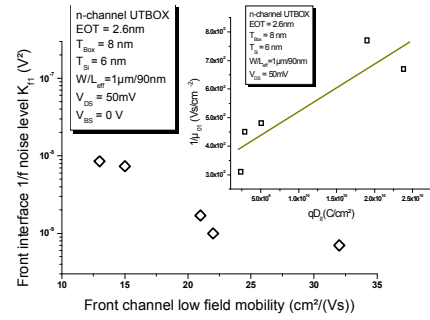


Figure 5. Correlation between the front interface  $1/f$  noise level  $K_{f1}$  and the front channel low field mobility

From Fig. 5, it can be observed that a higher (lower) front interface  $1/f$  noise level can be associated with lower (higher) low field mobility of the front channel. Such behavior has been already reported in [13] and can be explained by the impact of the charged oxide traps on both  $1/f$  and low field mobility through remote Coulomb scattering. This corroborates with results presented in the inset of Fig. 5, which shows the inverse low field mobility versus the oxide trap charge (expressed in  $\text{C}/\text{cm}^2$ ). The higher scattering coefficient  $\alpha_{SC0}$  (i.e. about  $1 \cdot 10^7 \text{ Vs/C}$ ) derived from the inset of Fig. 5 may be related to the strong coupling between the two interfaces.

### B. Noise spectroscopy

Low frequency noise measurements were also performed for one device at constant drain current of  $1.5 \mu\text{A}$  for the front channel at different temperatures. According to [11], if the characteristic frequency of a Lorentzian does not change with

the applied gate voltage, this Lorentzian can be assigned to a trap located in the depletion area (Si film). The variation of the characteristic time constant of the Lorentzians ( $\tau_i$ ) as a function of the temperature allows to plot an Arrhenius diagram; according to [14] from the slope and the y-intercept of the evolution of  $\ln(\tau T^2)$  versus  $1/(kT)$  one can extract the energy difference between the appropriate band energy and the trap energy (i.e.  $\Delta E = E_C - E_T$ ) and the capture cross section  $\sigma_n$  of the trap, respectively. The physical nature of these traps can be identified by comparing the energy level and the capture cross section of the traps with data in the literature.

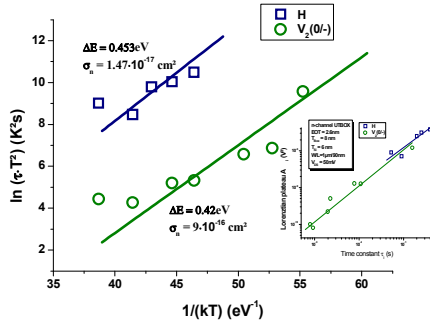


Figure 6. Arrhenius plot for UTBOX with physical gate length of 90 nm. In the inset: linear evolution of the Lorentzian plateau  $A_i$  versus the time constant  $\tau_i$  associated with the same trap

The Arrhenius diagram corresponding to this studied device is presented in Fig. 6. Two traps can be clearly identified: divacancies  $V_2(0/-)$  and traps related to hydrogen (H). The presence of divacancies could be explained by the recombination or the evolution to a stable state of the unstable defects like Frenkel pairs, which could be generated during the implantation. The traps related to hydrogen may be present due to hydrogen incorporated during the selective epitaxial growth (SEG) of the raised source/drains from the  $\text{SiH}_4$  precursors used in Chemical Vapor Deposition.

Linear evolutions of the Lorentzian plateau  $A_i$  versus  $\tau_i$  (associated to the same trap) are observed in the inset of the Fig. 6. From the slope of the  $A_i$  versus  $\tau_i$  variations, the effective trap density of each trap, defined as  $N_{\text{eff}} = \text{slope}(\tau_i, A_i) W_{\text{eff}} L_{\text{eff}} C_{\text{ox1}}^2 / q^2$  can be extracted. The effective trap density of the  $V_2(0/-)$  traps is about  $6.5 \cdot 10^9 \text{ cm}^{-2}$ , while for H traps it is about  $4.1 \cdot 10^9 \text{ cm}^{-2}$ . One should observe that the obtained values of the effective trap densities are almost 2 orders of magnitude lower compared to other non-intentionally doped channel technologies [6].

#### IV. CONCLUSION

The carrier number fluctuations dominate the  $1/f$  noise for both front and back interfaces. Contributions of the carrier number correlated to mobility fluctuation prevail from moderate to strong inversion for the total  $1/f$  noise at the front interface, while the access resistance noise contribution prevails in strong inversion for the total  $1/f$  noise of the back

interface. For all studied devices an important electrostatic coupling between front and back interface is observed: a contribution of the back interface noise source in a range of 42-64% on the measured noise in the front channel conduction was found, while the contribution of the front interface noise source is in a range of 10-23% on the measured noise in the back channel conduction. The quality of the oxidation process for the front and back interfaces was evidenced by the relatively small values of the oxide trap densities.

The analysis of the temperature evolution of the Lorentzian time constants allowed to identify two traps in the silicon film. The traps related to hydrogen may arise during the selective epitaxial growth of the raised source/drain, while the divacancies  $V_2(0/-)$  can originate from the implantation damage.

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