1/f Noise in MOS devices: Mobility or number fluctuations? (invited)
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Abstract—Recent experimental studies on $1/f$ noise in MOS transistors are reviewed. Arguments are given for the two schools of thought on the origin of $1/f$ noise. The consequences of models based on carrier-number $\Delta N$ or mobility fluctuations $\Delta \mu$ on the device geometry and on the bias dependence of the $1/f$ noise are discussed. Circuit-simulation-oriented equations for the $1/f$ noise are discussed.

The effects of scaling down on the $1/f$ noise is studied in the ohmic region as well as in saturation. In the ohmic region the contribution of the series resistance often can be ignored. However, in saturation the noise of the gate-voltage-dependent series resistance on the drain side plays a role in lightly doped drain LDD mini-MOST’s. Surface and bulk p-channel devices are compared and the differences between n- and p-MOST’s often observed will be discussed.

The relation between degradation effects by hot carriers or by $\gamma$-irradiation on the one hand and the $1/f$ noise on the other is considered in terms of a $\Delta N$ or $\Delta \mu$.

Experimental results suggest that $1/f$ noise in n-MOST’s is dominated by $\Delta N$ while in p-MOST’s the noise is due to $\Delta \mu$.

I. INTRODUCTION

A generally accepted model explaining the $1/f$ noise in all p- and n-channel MOS transistors is still lacking. The increase of $1/f$ noise through degradation by hot carriers or irradiation is often used as a proof for the surface and, hence, a number fluctuation $\Delta N$ origin of the $1/f$ noise. However, the majority of results obtained not on n-channel MOS transistors but on homogeneous semiconductors and p-MOST’s can be described by an empirical relation [1]–[3]

$$\frac{S_G}{G^2} = \frac{\alpha}{Nf}$$  \hspace{1cm} \text{(1)}

where $\alpha$ is not a constant [2] but a volume and device-length independent [3], [4] $1/f$ noise parameter between $10^{-7}$ and $10^{-3}$. A systematic study by Chang, Abidi and Viswanathan [3] of flicker noise in CMOS transistors from twelve different fabricators (in three continents) shows that for modern p-channel devices holds $10^{-7} < \alpha < 10^{-4}$. $N$ is the total number of free charge carriers in a homogeneous sample with perfect contacts, or it is a well defined reduced number in samples submitted to nonuniform fields [5] as is often the case in contacts.

The usefulness of (1) lays in the fact that a comparison in $1/f$ noise in $\alpha$-values is made independent of bias, frequency and size of the device. The misuse of (1) to calculate $\alpha$ values from experimental results by overlooking the nonuniform current densities on a microscopic scale and replacing $1/N$ by $q\mu R/L^2$, always leads to overestimation of apparent $\alpha$-values as was shown by Vandamme [2], [3], [5]. The equation $1/N = q\mu R/L^2$ with $q$ the elementary charge, $\mu$ the mobility, $R$ the sample resistance and $L$ the length between the contacts, only holds for homogeneous fields in homogeneous samples. The empirical relation (1) has been applied successfully for $p$-$n$ diodes and bipolar transistors by Kleinpenning [3], [6], [7].

The MOS transistor is an interface dominated device by excellence. The $1/f$ noise of n-MOST’s has been described successfully by carrier-number fluctuations $\Delta N$, which are caused by tunneling of free-charge carriers into oxide traps close to the Si-SiO$_2$ interface. Classical arguments in favor of the McWhorter model are the observed proportionality between trap density and $1/f$ noise [8]–[10]. Recent evidence for the $\Delta N$ origin of $1/f$ noise in MOS transistors are the change in $1/f$ noise through degradation by hot electrons [11]–[18] or by ionizing irradiation [19]–[30]. The p-MOS transistor often has a channel at a larger distance from the interface and is less noisy [4], [31], [32]. This is often easier to interpret in terms of $\Delta \mu$ than in terms of $\Delta N$ [4], [33].

Here, we discuss both points of view and explain why the $1/f$ noise in MOS transistors is still a problem that gives rise to much controversy. Therefore first, geometry and bias dependence will be discussed. From the analysis of geometry dependence we can discriminate between the contributions of the series resistance and the channel. This analysis has to be done before we can discriminate between the number fluctuation formalism and the mobility fluctuation. The $\Delta N$ or $\Delta \mu$ origin of $1/f$ noise is suggested by its gate voltage dependence. Some circuit-simulation-oriented equations for the $1/f$ noise in MOST’s are discussed in terms of $\Delta N$ or $\Delta \mu$. Then some hot carrier degradation experiments will be discussed in view of $\Delta N$ or $\Delta \mu$. At last the correlation between $1/f$ noise and radiation hardness for n-channel MOST’s will be discussed.

II. GEOMETRY AND BIAS

Dependence in View of $\Delta N$ or $\Delta \mu$

The geometry dependence of the $1/f$ noise in submicron MOST’s is a diagnostic tool to discriminate between channel
and series resistances noise. Only if series resistance contributions can be ignored, the straightforward circuit-simulation-oriented (9)-(12) can be applied successfully.

The 1/f noise parameter \( \alpha \) is used in our analysis as a figure of merit and not to suggest a \( \Delta \mu \) origin of the 1/f noise. Its value is gate-length independent for both models [4]. For the sake of simplicity, in this section we assume no series resistance or edge current problems. This results in generally accepted dependence between the 1/f noise in MOST’s and the channel area \([8]\); the dependence on oxide thickness is still under discussion. We start from the empirical relation (1) and do not suggest \( \Delta \mu \) fluctuations. The empirical relation is well found for p-MOST’s as shown by Chang et al. [3]. For n-MOST’s we still use the empirical relation but with a gate-voltage dependent \( \alpha \)-value as given by (8) in this section. From (1) and \( N = C_{ox} V_G^2 W L / q \) and the simple current-voltage equations, we find the calculated 1/f noise for MOST’s biased above threshold voltage [34], [35]. Ignoring the \( \alpha \) dependence on scattering we find:

1) Below saturation \( (V < V_s, I < I_s) \) with \( V_s \) the drain saturation voltage and \( I_s \) the saturation current, for the relative noise in the current

\[
S_I = \frac{\alpha q \mu R}{L^2 f} = \frac{\alpha q}{C_{ox} V_G^2 W L f} \times \frac{1}{W L}.
\]

Hence for different MOST’s on the same chip at a fixed gate voltage bias we expect the relative noise in current or voltage to be inversely proportional to \( 1/W L \). For \( S_I \) we find with (2) using \( I = (W/L) \mu C_{ox} V_G^2 V \) and \( R = V/I \):

\[
S_I = \frac{\alpha q \mu^2 C_{ox} V_G^2 V^2 W}{f L^3} \propto \frac{W}{L^3}. \tag{3}
\]

In the above, \( \mu \) is the mobility, \( V_G^2 \) the effective gate voltage, \( V \) the drain voltage, \( C_{ox} \) the oxide capacitance per unit area, \( W \) and \( L \) the channel width and length respectively. The Eq. (3) shows that \( S_I \) at fixed \( V_G^2 \) and \( V \) is proportional to \( W/L \). In the ohmic region \( V < V_G^2/10 \) holds, \( S_I/I^2 = S_T/I^2 = S_I/V^2 = S_N/R^2 = S_C/V^2 \). In open circuit \( S_I \) is measured and in short circuit condition (a voltage source without series resistance with the sample) \( S_I \) is measured.

2) In saturation we find a reduced free carrier number of \( 2/3 N \) with \( N \) the number of carriers at zero drain source voltage. The current noise \( S_{I_s}/I_s^2 \) is twice the value of \( S_I/I^2 \) in the ohmic region at the same effective gate voltage for the \( \Delta \mu \) model [35]. For the \( \Delta N \) model [36], provided \( N < N_l \) the ratio \( (S_{I_s}/I_s^2)/(S_I/I^2) = 2 \). We chose for a factor two in our analysis which is in agreement with both models and which is often observed. Ignoring the series resistance and body effect we expect for the saturation current in first order approximation \( I_s = (W/L) \mu C_{ox} V_G^2/2 \). The \( L \) and \( W \) dependence of the 1/f noise in the saturation current as a function of \( V_G^2 \) [35] then becomes

\[
S_{I_s} \approx \frac{2 \alpha I_s^2}{N f} = \frac{\alpha q \mu^2 C_{ox} V_G^2}{2} \frac{W}{L^3 f} \times \frac{W}{L^3}. \tag{4}
\]

For \( S_{I_s} \) versus \( I_s \) we then obtain

\[
S_{I_s} \approx \frac{2^{1/2} \alpha q \mu^{1/2} I_s^{1/2}}{W^{1/2} C_{ox} V_G^2 L^{1/2} f} \tag{5}
\]

only if \( \alpha \) is \( V_G^2 \) independent holds for an array of MOST’s biased at fixed \( I_s \), \( S_{I_s} \propto 1/W^{1/2} L^{3/2} \).

Equations (4) and (5) show the difference in \( W \), \( L \) dependence of \( S_{I_s} \), depending whether or not \( V_G^2 \) or \( I_s \) was kept constant in the comparison between different geometries. A comparison under constant \( V_G^2 \) results for both models in \( S_{I_s} \propto W/L^3 \). Under constant saturation current a different dependence is to be expected (5).

For the equivalent input noise voltage \( S_{V_{eq}} = S_{I_s}/g_m \) as a function of \( V_G^2 \) we find [35] from (4) and the simple expression for transconductance \( g_m = \partial I_s/\partial V_G = (W/L) \mu C_{ox} V_G^2 \)

\[
S_{V_{eq}} \approx \frac{\alpha q V_G^2}{2 W L C_{ox} f} \propto \frac{1}{W L} \tag{6}
\]

or for \( S_{V_{eq}} \) as a function of saturation current \( I_s \)

\[
S_{V_{eq}} \approx \frac{\alpha q I_s^{1/2}}{2^{1/2} (W C_{ox})^{3/2} (L \mu)^{1/2} f} \tag{7}
\]

only for \( \alpha V_G^2 \) independent holds at fixed \( I_s \), \( S_{V_{eq}} \propto 1/W^{1/2} L^{3/2} \).

From (3), (4), and (6) it is clear that submicron MOST’s are notorious for their 1/f noise. To minimize the device thermal noise, very large width to length ratios are used as can be seen from (20) in [10] and (2) in [31].

The 1/f noise of devices with different channel areas and \( W/L \) ratios have been compared with the proportionalities given in (2)-(7). If the devices do not suffer from important series resistance contributions [27], [28], [33], [37]-[39] or channel edge currents and the electrical dimensions \( L \) and \( W \) are used in (2)-(7) and the devices are biased at fixed effective gate voltages instead of fixed saturation currents, no deviations between calculated (2)-(4) and (6) and observed \( LW \) dependence are seen [4], [8], [31].

In Fig. 1 experimental results in support of (3) are presented. In the ohmic region, \( S_I \) is proportional to \( V^2 \) and for a fixed drain and gate voltage, \( S_I \propto W/L^3 \), at least if we take the electrical channel length into account and do not use the mask length. The \( \alpha \) value for these devices is inversely proportional to \( V_G^2 \) in the ohmic region, because \( S_I \propto \alpha V_G^2 \) coincides for two different values of \( V_G^2 \). For this LDD MOST at saturation the typical \( \Delta N \) behavior, with \( S_{I_s} \propto \alpha V_G^2 \propto V_G^2 \), is not observed possibly due to complications of nonlinear series resistance at the drain [38], [39].

To discriminate between \( \Delta N \) and \( \Delta \mu \) models, the 1/f noise must be studied as a function of gate voltage because both models predict the same dependence on \( L \) and \( W \) at fixed \( V_G^2 \). If we consider \( \Delta \mu \) here we do not have in mind the induced mobility fluctuations due to fluctuations in the oxide charge from trapping. The straightforward \( \Delta \mu \) model predicts a gate voltage independent \( \alpha \) value \((10^{-7} \lesssim \alpha < 10^{-5}) \) if there: 1) is no appreciable mobility degradation with increasing bias voltages [10], [34], [35], 2) a uniform noise source under the SiO2 can be assumed which is not always the case as can be
Physical Systems and l/f Fluctuations, St. Louis, LDD n-MOST's having the same width but different length in terms of a refined facts not on MOS transistors and some of them are well understood. These are not large "holes" to allow any result seen from Fig. 4 in [3] by Vandamme and X. Li, "l/f noise in MOS transistors due to number of mobility fluctuations," in Proc. Noise in Physical Systems and l/f Fluctuations, St. Louis, MO, pp. 345-353, 1993).

The above-mentioned conditions are based on experimental facts not on MOS transistors and some of them are well understood. These are not large "holes" to allow any result in terms of a refined $\Delta \mu$ model. The physical basis is that at least sound as a non uniform trap distribution used in refined $\Delta N$ models. These conditions are important because: 1) mobility degradation by scattering mechanism other than lattice scattering reduces the $\alpha$ parameter, as was shown for the first time by Hooge and Vandamme [1], [3], 2) reduced crystal quality results in high $\alpha$ values [3], [41], and 3) at low $V_G$ spatial field fluctuations at the interface can induce cavities in the inversion layers. The Si-O$_2$ interface roughness and spatial field fluctuations result in a "Swiss-cheese" channel. An increased interface surface due to roughness results in an increased interface trap number. A Swiss-cheese channel leads to current contractions and a marked increase in $1/f$ noise at lower $V_G$. By overlooking the nonuniform current density in the channel, an increasing apparent $\alpha$ value is obtained with decreasing $V_G$. The Swiss-cheese model easily explains 10% increase in resistance and a factor of 10 increase in $1/f$ noise, by taking an inhomogeneous current density into account in the same way as in [42]. Increasing cavity holes in the inversion layer with decreasing $V_G$ is a good alternative to explain a dependence of $\alpha \propto V_G^{-1}$ often interpreted as a proof for $\Delta N$ [10].

Here we propose to compare the outcomes of the $\Delta \mu$ and $\Delta N$ models in their straightforward form. In the straightforward $\Delta \mu$ model we ignore the consequences of an increase in $V_G$ on the $1/f$ noise parameter $\alpha$. For the straightforward $\Delta N$ model we ignore the dependence of $D_0$ on $V_G$. This is in contrast to more refined $\Delta N$ models [43], [44] explaining the dependence of $S_{\text{V}}$ on $V_G$ as a consequence of the dependence of $D_0(E_F)$ on $V_G$. The often observed peaks in $D_0(E_F)$ distribution near the band edges are apparent when using the Gray Brown [45] measuring method. Independently Declerck et al. [46] have demonstrated that spatial fluctuations in the oxide charge give apparent interface trap peaks near the band edges.

In the $\Delta N$ model we find $\alpha = \frac{q x_0 D_0 k T (x_0/x_2) e_0 c_0}{V_G^2}$, and $\alpha = \frac{E_c t_{\text{ox}}}{V_G}$, and

$$\Delta N \propto \frac{\alpha E_c t_{\text{ox}}}{V_G} \propto \frac{t_{\text{ox}} T}{V_G^2}$$

where $x_0$ is the characteristic decay length of the electron wave function ($\approx 1 \text{ Å}$), $x_0 D_0 (\approx 10^{-10} \text{ cm}^{-2} \text{eV}^{-1})$ trap density per unit area and unit energy, $x_2 (\approx 30 \text{ Å})$ the largest trapping distance resulting in a $1/f$ spectrum over 13 decades in frequency and $e_0$ the relative dielectric constant of the gate oxide. Here $\alpha$ is a reference value at a field strength of $V_G^2/t_{\text{ox}} = E_c$, which is a critical field strength. In the straightforward $\Delta N$ model $\alpha = \frac{E_c t_{\text{ox}}}{V_G}$ is independent of $V_G^2$ but $\alpha \propto 1/V_G^2$. The proportionality $\alpha \propto E_c t_{\text{ox}} / V_G^2$ from (8) should be proof of the validity of the straightforward from the $\Delta N$ model in MOS transistors. The proportionality $\alpha \propto t_{\text{ox}} / V_G^2$ has its consequences for the bias and oxide-thickness dependence of the $1/f$ noise in (2)-(7).

The expected proportionalities are summarized in Table I.

<table>
<thead>
<tr>
<th>Table I</th>
<th>Expected Proportionalities Between Noise, Geometry, $V_G$, and $T_{\text{ox}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta N$</td>
<td>$\alpha \propto \frac{t_{\text{ox}}}{V_G^2}$</td>
</tr>
<tr>
<td>$\Delta \mu$</td>
<td>$\alpha$ constant</td>
</tr>
<tr>
<td>$S_{\text{V}}$</td>
<td>$\alpha = \frac{q x_0 D_0 k T (x_0/x_2) e_0 c_0}{V_G^2}$</td>
</tr>
<tr>
<td>$S_{\text{V}}^2$</td>
<td>$\alpha = \frac{E_c t_{\text{ox}}}{V_G}$</td>
</tr>
<tr>
<td>$S_{\text{V}}$</td>
<td>$\alpha = \frac{E_c t_{\text{ox}}}{V_G}$</td>
</tr>
<tr>
<td>$S_{\text{V}}^2$</td>
<td>$\alpha = \frac{E_c t_{\text{ox}}}{V_G}$</td>
</tr>
</tbody>
</table>

In the second column and second row is described the expected geometry and effective gate voltage dependence of the relative current noise in the ohmic region $S_{\text{V}}^2 f^2$ if the straightforward $\Delta N$ model holds. In the third column and second row the proportionalities for $S_{\text{V}}^2 f^2$ are shown if the straightforward $\Delta \mu$ model holds. In the third and fourth row the proportionalities are presented for $S_{\text{V}}^2 f^2$ if the straightforward $\Delta \mu$ model holds. In both models we can scale down the oxide thickness to improve the noise performance. Liu and Huang [47] compared the noise between MOSTs with different oxide thickness and area. They [47] observed $S_{\text{V}}^2 \propto 1/WL$ as in [1], [4]. The devices with $t_{\text{ox}} = 1100 \text{ Å}$ were twice as noisy as the devices with $t_{\text{ox}} = 540 \text{ Å}$. Their results are in agreement with Van der Ziel's [48] limiting $1/f$ noise for a MOST, in which the thermal noise of the frequency-independent dielectric loss
angle $tg\delta$ in the gate oxide results in $4kTRe[Z]$ which is inversely proportional to the frequency. This $1/f$ spectrum modulates the gate voltage and the current in the MOST.

We investigated different $L$-arrays which are groups of devices with the channel length $L$ as the only variable. If the series resistance on the drain side plays a role [38, 39], the results obtained on an $L$-array at fixed saturation current are more difficult to interpret in terms of geometry dependence or type of noise source. What is a correct comparison in, e.g., $S_{V_{th}}$ for circuit analysis [30] is less useful for the point of view of noise source comparison [17].

Comparing the noise before and after degradation at fixed $I_s$ also has to be avoided for the above-mentioned reason. After degradation, a threshold voltage shift, a mobility reduction and an increase in series resistance is often observed, resulting in a different gate voltage to obtain the same saturation current. If we are interested in the evolution of the noise source through degradation, the $1/f$ noise in the ohmic region should be measured at comparable $V_G^2$ and can be expressed in $\alpha$-values in order to avoid misunderstandings [13].

The $1/f$ noise is often expressed in pragmatic circuit-simulation-oriented equations without bother about $\Delta N$ or $\Delta \mu$. We find for MOST's biased in

1) saturation, for the noise in the saturation current as a function of saturation current

$$S_{I_S} = \frac{K^* I_S^2}{f} \quad \text{with} \quad K^* = \frac{\alpha_a E_c t_{ox} q \mu}{L^2} = \frac{\alpha V_G^2 q \mu}{L^2} \quad (9)$$

or in terms of transconductance we find with $g_m = (W/L)\mu C_{ox} V_G^2 = 2I_s/V_G^2$

$$S_{I_S} = \frac{B g_m^2}{W L f} \quad \text{with} \quad B = \frac{\alpha_a E_c t_{ox} q}{2e_{o}e_{r}} = \frac{\alpha V_G^2 q \mu}{2e_{o}e_{r}} \quad (10)$$

or as equivalent input noise we obtain from (6) and (8)

$$S_{V_{th}} = \frac{AV_G^*}{C_{ox} W L f} = \frac{B}{W L f} \quad \text{with} \quad A = \frac{B C_{ox}}{V_G^2} = \frac{\alpha_\mu}{2e_{o}e_{r}} \quad (11)$$

Here $K^*$, $B$, and $A$ are the parameters often used in circuit-simulation-oriented equations.

2) In the ohmic region the following empirical expression is often used to discuss $1/f$ noise and radiation hardness of devices [19]–[29]

$$S_V = \frac{KV^2}{V_G^2}$$

with

$$K = \frac{\alpha_a E_c t_{ox} q}{e_{o}e_{r} W L} = \frac{q^2 E_c t_{ox} D_{0} k T(x_0/x_2)}{W L (e_{o}e_{r})^2} = \frac{\alpha_\mu q V_G^2}{W L C_{ox}} \quad (12)$$

An overwhelming number of publications, especially for n-channels, showed $\alpha \propto V_G^{-1}$ or its consequences in the bias dependence of the $1/f$ noise; see for example [19]–[30], [9], [10]. The straightforward interpretation lends support to the $\Delta N$ model. The noise results on n-MOST’s from 12 different fabricators Chang et al. [3] and our results [4] can be summarized with $\alpha V_G^2$ values which are now $V_G^2$ independent and are between $6 \times 10^{-5}$ V and $6 \times 10^{-4}$ V ($\alpha$ is dimensionless). Invoking an increase in inhomogeneity of current density in the inversion layer at decreasing $V_G$ is also possible to explain $\alpha \propto V_G^{-1}$ in terms of a refined $\Delta \mu$ model.

Klaassen [8] observed for p-MOST’S, $S_{V_{th}} \propto V_G^2$ which means (6) $\alpha$ gate voltage independent. This is in support to the $\Delta \mu$ model. For modern p-MOST’S holds $\alpha$ independent of gate voltage with values between $10^{-7}$ and $10^{-4}$.

Fig. 2 shows $\alpha$-values versus effective gate voltage [33] for p-MOST’S with a bulk and surface channel. The devices are enhancement types and have a slightly different effective voltage ($V_T = -0.6$ V for surface and $-0.75$ V for bulk). The main difference between the two devices is that: 1) the bulk device has a n+$^+$ polysilicon gate and the surface device a p+$^+$ polysilicon gate. 2) The bulk device has a boron implantation and the surface device a phosphorus implantation of about the same surface concentration in order to keep the difference in $V_T$ rather small. A typical $\Delta \mu$ behavior is shown with a surprisingly low noise ($\alpha \approx 3 \times 10^{-7}$) for the device with the current path away from the interface. This is in agreement with the results observed in an n-type resistor with gate electrode [40].

A $1/f$ noise model [49] for MOST’s in deep saturation based on $\Delta \mu$ and two-dimensional device simulator results showed almost no difference with the $\Delta N$-based results. The results agree with both $\Delta N$ and $\Delta \mu$ interpretations.

The proportionality between noise and temperature as predicted by the $\Delta N$ model in (8), has been observed for MOST’S biased in the ohmic region [50]. However, this is not direct proof of $\Delta N$ because the temperature dependence of $\alpha$ in the $\Delta \mu$ model also shows a reduction in $\alpha$ with decreasing temperature as shown by Hooge [3]. The temperature dependence in $S_{V_{th}}$ or $\alpha$ for p-MOST’S is higher than for n-MOST’S see Chang et al. [3].
III. HOT CARRIER DEGRADATION, PROOF OF $\Delta N$?

The $1/f$ noise has been used as a more powerful tool than dc characteristics to evaluate the quality of a MOST [38] and investigate hot-carrier degradation in devices [11]–[18]. An LDD structure is often used in modern MOST’s and the series resistance shows its influence on the dc characteristics, as well as the $1/f$ noise for submicron devices. It was shown that a series resistance with an acceptable value can be the dominant term in the $1/f$ noise behavior of an edgeless MOST [38].

Another study [37] explained how to distinguish the $1/f$ noise from the series resistance and the channel part in a MOST biased in the ohmic region. Especially in a short channel LDD device, not only the value of the series resistance $R_s$ but also its contribution to the $1/f$ noise increases significantly. At saturation the situation becomes worse by a strong increase in the noise of the series resistance on the drain side. An LDD device, as shown in the insert of Fig. 3(a), consists of a conventional MOST in series with two series resistors $R_{dsd}$ on the drain side and $R_{ss}$ on the source side [51]–[54]. Investigations [39], [53]–[56] showed that the series resistance on the drain side behaves differently from that on the source side. The assumption $R_{dsd} = R_{ss} = F(V_{gs})$ is only valid when a MOST is biased in the ohmic region. Above the ohmic region, it was found [53]–[56] that $R_{dsd} > R_{ss}$ and $R_{dsd}$ is a function of $V_{gs}$ and $V_{ds}$ (see Figs. 2–5 in [39]), although $R_{ss}$ is still only a function of $V_{gs}$. When $V_{gs}$ is constant, $R_{dsd}$ increases strongly because $V_{ds}$ increases towards the effective gate voltage $V_{g}^{*}$. Consequently, the internal drain source voltage is clamped, and the channel current is kept constant. This concept is used successfully to explain some experimental results of $S_f$ as a function of $V_{ds}/V_{g}^{*}$ [13], [39].

Fig. 3(a) shows $R_{ss}$ versus $1/V_{g}^{*}$ for a p-MOST with $L = 0.8 \mu m$ and $W = 10 \mu m$ and in Fig. 3(b) its drain series resistance is shown versus the voltage drop $V_{dsd}$ when the device is biased close to saturation.

Nowadays hot-carrier degradation of submicron MOST’s and the evolution of $1/f$ noise are often considered as a direct proof of the number fluctuation origin of the $1/f$ noise. It is thought that the $1/f$ noise increases after hot-carrier stressing due to an increase in the trap density in the oxide layer [11]–[18]. But the consequence of hot-carrier degradation in a MOST is far more complicated.

Among other characteristics, the subthreshold current voltage behavior is often investigated in MOST-degradation experiments. From the slope in the plot of log $I$ versus linear $V_{d}$ trap densities near mid gap can be derived, this is the so-called subthreshold gradient or subthreshold slope analysis. Generally speaking, the shift of the threshold voltage, the changing slope in the subthreshold region, and the decrease in the channel current are considered as degradation phenomena due to an increase of traps. It was also found after a short time of stressing, that the threshold voltage and the slope in the subthreshold region do not change [57], but that the series resistance increases especially on the drain side. Another degradation phenomenon is the reduction in effective channel length [58], [59], which implies an increase in the series resistance.

It was observed that $1/f$ noise level increased a lot in the reverse mode, but hardly changed in the normal mode after hot-carrier stressing when a MOST is biased in saturation [11], [12]. This can be explained without using the $\Delta N$ model [13]. Before stressing, a MOST should be symmetric, which means there is no difference between $1/f$ noise levels in the normal mode and in the reverse mode. A post-stressed MOST biased in the ohmic region has nonsymmetric resistance $R_{ss} < R_{dsd}$, with about the same dependence on the biasing conditions. Hence, under the same external voltages, the internal biasing conditions and $1/f$ noise remains [11], [12] at low $V_{g}^{*}$. This is independent of the normal or the reverse mode. In saturation, our results [13] showed that the series resistance on the drain side $R_{dsd}$ increases significantly with $V_{dsd}$ (see Fig. 3(b)) and
is clamping the current, the voltage drop \( V_{DD} \) across \( R_{DD} \) increases with \( R_{DD} \).

It has been observed for n-MOST's in a 0.5 \( \mu m \) technology [13], after a stress of only one hour under the bias condition of \( V_{GS} = 2 \) V and \( V_{DS} = 5 \) V, that hot-carrier degradation causes a decrease in the threshold voltage and the drain current, and a decrease in subthreshold gradient. An increase in the relative current noise and the series resistance \( R_{DD} \) on the drain side has been observed.

The hot-carrier degradation is mainly located close to the stressed drain in a 10 \( \mu m \) length channel and extends more to the whole channel in a 1 \( \mu m \) device. For the same bias conditions, the reduction in the drain current varies for different channel lengths and from normal to reverse mode. It leads to changes by at least factor two more or less in \( S_I \) for a pre and post-stressed device depending on channel length. However, when the 1/\( f \) noise is normalized for frequency, current, and the number of charge carriers, and expressed by the \( \alpha \) value, we observe a systematic increase in \( \alpha \) by factor two after stressing. The same holds for the relative noise \( f S_I/I_{DD} \) for saturation. Both the \( \alpha \) value and the relative noise \( f S_I/I_{DD} \) in our experiments increase with hot-carrier degradation.

The hot-carrier degradation is mainly located close to the stressed drain in a 10 \( \mu m \) length channel and extends more to the whole channel in a 1 \( \mu m \) device. The channel current flows nearer to the interface on the source side than on the drain side. When the damaged part is on the source side, we expect a higher 1/\( f \) noise. Therefore, a degraded device is often noisier in reverse than in normal mode. The degradation degree is determined by the current density and the electric field. These two quantities differ for devices with different geometry, even for the same bias conditions. Hence, the damaged part decreases with increasing channel length. Thus a short channel device suffers more from hot-carrier degradation than a long channel.

The processes involved in bias stress are complicated and can be summarized as follows for n-MOST's [13]:

1) Depending on the stress conditions, positive and negative shifts in threshold voltage are possible [60]; we found negative shifts in both 10 \( \mu m \) and 1 \( \mu m \) devices.
2) Owing to the nonuniform distribution of the trapped oxide and interface charges, the threshold voltage can have a nonuniform value along the channel,
3) the mobility reduction coefficient \( \theta \) changes (with \( \mu = \mu_0/(1 + \theta V_G^2) \), where \( \mu_0 \) is the low field mobility). There is an increase in series resistance \( R_{DD} \) on the drain side,
4) the position of the depth of the conducting channel on the drain side can shift with aging, so that a noisier or less noisy part of the semiconductor can be probed [40],
5) in the ohmic region, the low field mobility \( \mu_0 \) decreases 4\%o, the 1/\( f \) parameter \( \alpha \) increases by about factor two. This makes a 1/\( f \) noise analysis a more sensitive tool than a mobility or a transconductance measurement. That is at least if the results are presented in \( \alpha \) values or in relative current noise as \( f S_I/I_{DD} \).

The comparison of 1/\( f \) noise level, in conventional MOSTs and LDD devices [61] or in devices before and after stressing, should be done under the same internal biasing conditions and not in terms of equivalent input noise voltage. Otherwise the analysis leads to incorrect conclusions. It is clear that, for example, an LDD device can have less noise than the conventional MOST operated under the same terminal voltages because the drain current will be lower due to the series resistances [61].

IV. CORRELATION BETWEEN 1/\( f \) NOISE AND RADIATION HARDNESS A \( \Delta N \) ARGUMENT?

A MOS transistor undergoing ionizing irradiation shows a gradual shift in threshold voltage mainly due to an increase in the positive oxide charge. The radiation hardness of a technology is expressed in threshold-voltage shift per Krad (e.g., 3 mV/Krad) and its estimate requires a destructive testing. A strong correlation was observed in n-MOST's between the pre-irradiation 1/\( f \) noise of MOS transistors and their post-irradiation threshold-voltage shift [19],[22],[27],[29], which makes 1/\( f \) noise a useful nondestructive radiation hardness test. This is not a surprising result, because a 1/\( f \) noise that is too high is often a good indicator of poor technology or poor crystal quality [41]. (See also Figs. 2 and 3 in [3] by Vandamme.) A poor oxide is easier to degrade than a high-quality oxide and it will result in higher threshold-voltage shifts.

Ionizing radiation not only causes oxide charging, but also an increase in interface-state density. The increase in interface-state density causes a considerable decrease in channel mobility and a decline in \( g_m \) [62]. This makes explanations in terms of \( \Delta N \) or \( \Delta \mu \) possible. On the one hand, carriers in a channel which is farther from the interface could experience fewer carrier trappings with defects in the oxide, thereby reducing the 1/\( f \) noise. On the other hand farther from the interface the \( \alpha \) values can be lower due to a better crystal quality [40]. In this way we can understand: 1) the experimental results on 1/\( f \) noise in n- and p-MOST's through...
irradiation and annealing [23], 2) 1/f noise prior to and after the bias temperature stress [63].

First, [23] irradiation results in a positive charge at the interface. n-MOST’s become noisier because the channel is closer to the interface and p-MOST’s show the same or less noise. After irradiation the noise decreases during positive-bias anneals in n-MOST’s but increases during positive-bias for p-MOST’s. In the former case the channel is farther away from the interface and in the latter case the channel comes closer to the interface. Conversely, negative bias anneals, increase the noise in n-MOST’s but decrease the noise in p-MOST’s.

Second, [63] n-MOST’s after a positive bias temperature stress show a decrease in noise and after a negative bias temperature stress an increase in noise. For p-MOST’s the opposite holds. Under both temperature stress conditions an increase in interface state densities has been observed for n- and p-MOST’s [63].

All these results through irradiation and annealing together with the bias temperature treatment do not generally support the proportionality between the equivalent input noise and oxide trap density $S_{\text{eq}} \propto D_{\text{ox}}$. The results of annealing after $\gamma$-irradiation [23] and bias temperature stress [63] are summarized in Table II. The plus and minus signs in the columns indicated by $\Delta K$, $\Delta D_i$, and $\Delta S_{\text{eq}}$ indicate an increase and decrease, respectively. The results can be understood in terms of bulk 1/f noise due to mobility fluctuations with decreasing $\alpha$-values away from the interface [40], [41]. By changing the charge at the SiO$_2$-Si interface, the position of the conducting path is slightly modified. This can have large consequences on the $\alpha$-values as can be seen from Fig. 2.

Threshold-voltage shift $\Delta V_T$ after $\gamma$-irradiation [19]–[30] is attributed to an increase in oxide charge $\Delta V_{\text{ox}}$ and to a smaller extent to a change in the charge at the Si-SiO$_2$ interface traps $\Delta V_{\text{it}}$, and is given by $\Delta V_T = \Delta V_{\text{ox}} + \Delta V_{\text{it}}$. The 1/f noise observed in the ohmic region is given by (12) where $K$ is proportional to $t_{\text{ox}}^2$. Fleetwood, Meisenheimer, and Scofield [3] show that $\Delta V_{\text{it}}$ is also proportional to $t_{\text{ox}}^2$. Then we can expect that $K \propto \Delta V_{\text{ox}}$ keeping other parameters constant, which lends support to the $\Delta N$ model. All n-MOST’s in [19]–[23], [27]–[29] obey $KWL \propto |\Delta V_{\text{ox}}|$ although no proportionality has been observed with $\Delta V_{\text{it}}$. The latter does not support the $\Delta N$ model. Fleetwood et al. [20], [3] are presenting experimental support obtained on n-MOST’s for the relation between the 1/f noise before irradiation and radiation hardness. For the $\Delta \mu$ model we expect $K \propto t_{\text{ox}}$ and that increasing $K$ and $\Delta V_{\text{ox}}$ should go hand in hand but not linearly.

Fig. 5 shows the resistance noise $S_R$ versus $V_{G}$ of a p-MOST through $\gamma$-irradiation [28]. No evolution of the 1/f noise is observed in this radiation hardened devices at least if the 1/f noise is compared at the same effective gate voltage. Although a shift in $V_T$ is observed and radiation damage goes hand in hand with an increase in traps, the 1/f noise remains constant. The proportionality $S_R \propto V_{G}^{-1.4}$ points to a proportionality $\alpha \propto V_{G}^{-1.4}$. This is in agreement with the straightforward $\Delta N$ model. At higher $V_{G}$ the slope of the $S_R$ versus $V_{G}$ is less steep due to the series resistance contribution [28], [29].

The effective gate voltage should be kept constant at a low enough $V_{G}$ in order to compare the 1/f noise through irradiation [27], [28]. N-channel devices are sensitive for leakage resistance through irradiation [29]. A dramatic increase in noise says nothing about a $\Delta N$ or $\Delta \mu$ origin [17], [18], rather it says more about the creation of a noisy leakage current path. This path is situated in parallel to the channel close to the so-called bird beaks at the gate oxide rims. The creation of a noisy leakage current path is observed from the change in subthreshold characteristic and noise after degradation. The edge current problems have been investigated from a set of MOST’s all having the same length but different width and from the comparison between edgeless and open structures.

The experimentally observed 1/f noise in n-MOST’s is often in agreement with the $\Delta N$ model and oxide trap density $D_{\text{ox}}$, see Chang et al., Fleetwood et al. [3], and in [8]–[10] and [64]. However, from the results in Table II where increase in interface state density after bias temperature treatment not always goes hand in hand with an increase in 1/f noise as should be expected from (8) in the $\Delta N$-model, we see problems for interpretation. In Fig. 2 and from Chang et al. [3] we see gate voltage independent $\alpha$-values for bulk or surface channel p-MOSTs which is in disagreement with the straightforward $\Delta N$ interpretation. From Table II and Fig. 2 [23], [63], we conclude that the extraction of oxide trap density

<table>
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<th>Table II</th>
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<td>Changes in 1/f Noise After Bias Treatment</td>
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<td>Annealing after $\gamma$-irradiation [23]</td>
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or even its energy distribution based on noise measurements as proposed in [65]–[68] are very doubtful.

V. CONCLUSION

Geometry dependence is well understood with the exception of the $t_{ox}$ dependence. The width, length and $V_G^2$ dependence can be used as a diagnostic tool to trace series resistance and edge current contributions in submicron devices. In short LDD MOST's deviations from the simple bias dependence are observed especially close to saturation due to a strong increase in the series resistance on the drain side [13, 37]–[39], [61].

The $1/f$ noise parameter $\alpha$ is a perfect figure of merit to describe the $1/f$ noise in a MOST as was done by Chang et al. in a comparative study of CMOS transistors [3]. In this way we can compare different technologies and study the change in noise source through degradation independent of geometry, frequency and current passed through the sample.

Both schools of thought have their favorite devices: n-MOST's for the $\Delta N$ school and p-MOST's for the $\Delta \mu$ school. Bias dependence of the $1/f$ noise parameter $\alpha$ points to a straightforward interpretation in terms of $\Delta N$ if $\alpha \propto V_G^{-2}$, but $\Delta \mu$ is also possible [39], [40]. The gate voltage independent $\alpha$ value often seen in p-MOST's is easy to interpret in terms of $\Delta \mu$. We observed $\alpha \approx 4 \times 10^{-7}$ which is among the lowest values ever observed for bulk p-MOST's, while for n-MOST's holds $6 \times 10^{-5} < \alpha V_G^2 < 6 \times 10^{-4}$ $V^{-2}$ with $\alpha \propto V_G^{-2}$. In general n-MOST's are noisier than p-MOST's and easier to interpret in the straightforward $\Delta N$ formalism, while for low-noise p-MOST's the straightforward $\Delta \mu$ formalism holds.

Due to series resistance complications and charging of the gate oxide in hot-carrier degraded MOST's, the interpretation in terms of $\Delta N$ is not the only one. If the charging of the interface results in a channel which is farther from the interface the result is often a reduction in the $1/f$ noise [13]. This holds for n- and p-MOST's independently if the charging was provoked by $\gamma$-irradiation, hot-carrier stressing, annealing under bias treatment after irradiation or simple bias temperature stress (Table II).

$K \propto \Delta V_{on}$ is in agreement with $\Delta N$ and $\Delta \mu$. This makes the $1/f$ noise in n-MOST's before irradiation a useful non-destructive tool to characterize radiation hardness.

The irradiation-independent behavior of the $1/f$ noise up to 300 Krad, although there is a shift in threshold voltage, is more difficult to understand in terms of $\Delta N$.

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