# Very Low Frequency Cyclostationary 1/f Noise in MOS Transistors

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***Abstract*— Cyclostationary operation of the MOS transistor has been proposed in recent years as a technique for reducing the flicker noise at the device level itself. Several works report measured cyclostationary flicker noise reduction, the PSD showing a plateau below the switching frequency, but at much lower frequencies the slope resembles again the original 1/f spectrum. But current models do not correctly address the latter effect. In this work, the PSD of a DC biased transistor is first deduced using only Shockley-Read-Hall (SRH) statistics and the autocorrelation formalism. Then the analysis is extended by means of simulations and using reasonable physical hypotheses, to a cyclostationary bias condition. The results allow explaining reported experimental data in the whole frequency range. Finally the development of a specific integrated circuit aimed at switched flicker noise measurements in different types/sizes of test transistors and at different bias conditions is presented.**

***Keywords—flicker noise; cyclostationary; noise model; MOS.***

## I. INTRODUCTION

Flicker noise or simply 1/f noise is such that its power spectral density (PSD) varies with frequency in the form:

$$S(f) = K / f^{\gamma} \ , \qquad (1)$$

with $K$, $\gamma$ constants, and $\gamma \approx 1$. It is quite well accepted that the sources of flicker noise are mainly carrier number fluctuations due to random trapping–detrapping of electrons in energy states, named 'traps', in the oxide near the surface of the semiconductor [1],[2]. From some time ago, switched biasing (cyclostationary operation) has been proposed as a technique for reducing the flicker noise at physical level in MOSFETs [3],[8]. Cyclostationary operation it is not a circuit technique like chopper or autozero [4], instead just the transistor is periodically cycled between an off-state and saturation. An intuitive explanation of the noise reduction phenomenon is that periodically turning 'off' the transistor's channel, periodically forces a significant fraction of occupied traps to a known empty state, thus introducing some 'order' in the random process. Some reported (measured) cyclostationary MOS flicker noise PSDs resemble the plot in Fig. 1 [5],[6]. Usual 1/f spectrum is observed above the switching frequency $f_{sw}$, but at lower frequencies the PSD increases with a much smaller slope like a plateau. Finally, at an even lower frequency, the original 1/f spectrum shape can be observed again. The focus of this work is in this latter portion of the noise spectrum. Several authors proposed models to explain the particular behavior of Fig.1 [6]-[8] however, the exact mechanism and the statistics of the switched noise current are not yet clear. Particularly, reported models predict a plateau at lowest frequencies that do not correctly address experimental results. To start, consider the MOS transistor in Fig. 2, and a small channel element of differential area $dA = W.dx$. Defects named 'traps' inside and at the surface of the oxide generate localized states with energy $E_t$, which may capture/release carriers from the channel in a random process. Electrons/holes may tunnel to, and back from the traps generating a noise current. $N_A^{'}$ will denote the number of occupied traps per unit area in the whole oxide volume above $dA$. The ratio between

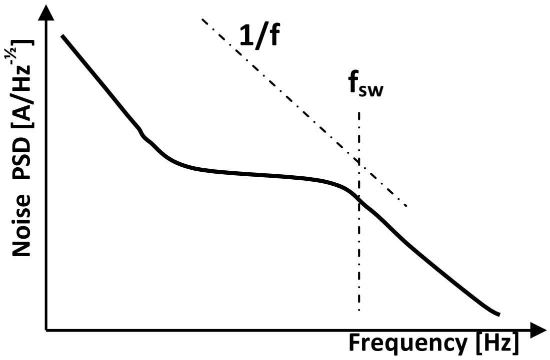


Fig. 1. Logarithmic plot of a typical MOS cyclostationary noise PSD showing a plateau in the middle. A 1/f PSD appear again at lower freqencies.

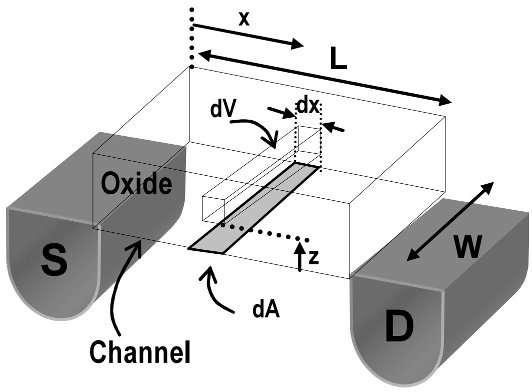


Fig. 2. Vertical cross section of a MOS transistor. Trapping-detrapping of carriers by oxide traps above $dA$, produce a noise current [2].

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the channel carrier densities named $N'$, and $N_A'$ is given by the Reimbold's coefficient [2]. To find the drain current noise, the impact on the drain current of local $N'$ fluctuations is integrated along the channel [1],[2]; the analysis can be extended to mobility fluctuations using the Mathiessen's rule [1]. Thus a physics based flicker noise model should begin finding an expression for $S_{N_A'}(f)$ (the PSD of $N_A'$) but this explicit physic deduction is most of the time omitted. This paper is organized as follows: in section II an explicit calculation of $S_{N_A'}(f)$ is presented. In section III the study is extended to the cyclostationary case using simulations, and section IV presents an integrated circuit for cyclostationary noise measurements.

## II. $N_A'$ PSD CALCULATION IN STEADY STATE (DC-BIAS)

To compute $S_{N_A'}(f)$ first a small volume $\Delta V = W.dx.dz$ is defined like in Fig. 2. $N_t'$, $N_V'[eV^{-1}\cdot m^{-3}]$, are defined respectively as the volume density of traps, and that of occupied traps inside $\Delta V$ in a small energy interval $E \le E_t \le (E+dE)$. $f_T$ will denote the probability of a single trap to be occupied (depends on the Fermi level) and $t_{ox}$ is the oxide thickness. To find the PSD of a random variable, it is necessary to compute the Fourier transform of its autocorrelation defined as $\Re(s)=\langle \delta N_V'(t), \delta N_V'(t-s)\rangle$. In a time interval *dt,* occupied traps may release their electron with a probability $e_0 \cdot dt$ while empty traps may be occupied with a probability $(c_0 n_s)\cdot dt$, where $n_s$ is the channel electron density. The expected variation of the density of occupied traps in a time interval *dt* is calculated using SRH statistics:

$$dN_V' = \left[c_0 n_s\left(N_t' - N_V'\right) - e_0 N_V'\right]\cdot dt\,, \tag{2}$$

$\left(N_t' - N_V'\right)$ is the voulme density of empty traps. At equilibrium, the average $N_V'$ must be kept constant so $c_0 n_s(1-f_t) - e_0 f_t = 0$. But $N_V'$ is not at equilibrium in (2). $N_{Veq}' = f_t N_t'$ denotes the equilibrium value, and $\delta N_V'(t) = \left(N_V'(t) - N_{Veq}'\right)$ the fluctuations of $N_V'$. If variations of $n_s$ with $N_V'$ are neglected follows:

$$\frac{d\left(\delta N_V'\right)}{dt} = -\left(c_0 n_s - e_0\right)\delta N_V'\,. \tag{3}$$

Eq. (3) is a first order differential equation with a solution:

$$\delta N_V' = \delta N_V'\Big|_{t=0}\cdot e^{\frac{-|t|}{\tau}}\,, \tag{4}$$

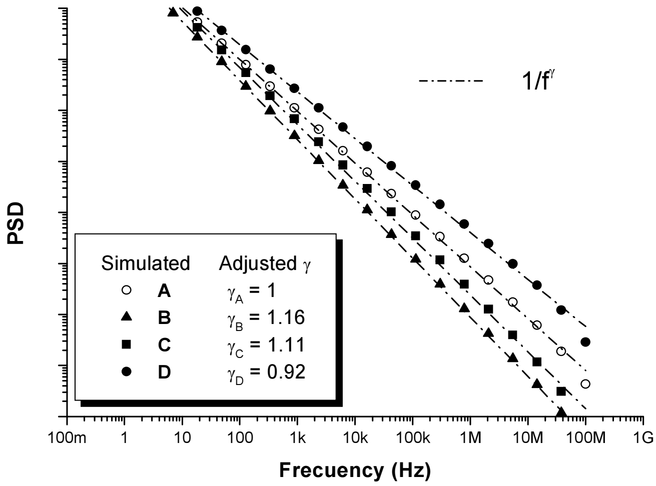


Fig.3. Simulated PSD , γ estimations for different spatial trap distributions.

where $\tau = 1/\left(c_0 n_s + e_0\right)$. To find the autocorrelation of the process it is necessary to integrate in all possible values of the random variable $\delta N_V'$ considering also a $p\left(\delta N_V'\right)$ probability:

$$\Re(s) = \int_{-\infty}^{\infty} \delta N_V' \cdot p\left(\delta N_V'\right)\cdot \delta N_V' \cdot d\delta N_V' = e^{-\frac{|s|}{t}}\cdot\left\langle \delta N_V'^{\,2}\right\rangle \tag{5}$$

The variance $\left\langle \delta N_V'^{\,2}\right\rangle = N_t'\cdot\Delta E\cdot f_t(1-f_t)/\Delta V$ is known since the number of occupied traps has a binomial distribution. $S_{\delta N_V'}(\omega)$ is calculated with a Fourier transform of (5):

$$S_{\delta N_V'}(\omega) = \frac{N_t'\cdot\Delta E\cdot f_t(1-f_t)}{\Delta V}\cdot\frac{4\tau}{1+\omega^2\tau^2}\,, \tag{6}$$

$\omega = 2\pi f$. Integrating (6) in the z coordinate and in the energy:

$$S_{\Delta N_A'}(\omega) = \frac{1}{\Delta A}\int_{E_C}^{E_V}\int_0^{t_{ox}} N_t' f_t(1-f_t)\cdot\frac{4\tau}{1+\omega^2\tau^2}\cdot dz\cdot dE \tag{7}$$

Note the integration boundaries in (7) are $E_C$, $E_V$ (valence and conduction band's energy limits) instead of $\pm\infty$. This approximation is supported by the fact that the product $N_t' f_t(1-f_t)$ is sharply peaked. From a physical point of view, an electron gaining extra energy (i.e. from a phonon) that could tunnel to a trap with energy $E_t \ge E_C$, will find in the conduction band practically infinite states with such energy thus it is very unlikely that it would jump to the trap. Therefore, the probability of an electron tunneling to a trap is negligible outside ($E_C$, $E_V$) range where the trap competes with a continuum of empty energy states. Classical approximations to solve (7) assume $\tau$ depends only on the distance z, and $N_t'$, $f_t$ on the energy *E*. It is possible to integrate (7) in the distance assuming a high dispersion in $\tau$ values, and in the energy with a probability balance generalized to both electrons and holes, the result being:

$$S_{\Delta N'_A}(\omega)=\frac{1}{\Delta A}N'_t kT\lambda\cdot\frac{1}{f}=\frac{N_{ot}}{\Delta A}\cdot\frac{1}{f} \quad (8)$$

The result in (8) exhibits the classical 1/f dependence of flicker noise. $N_{ot}=N'_t kT\lambda$ in (8) is the equivalent density of oxide traps, a technology parameter to adjust. The PSDs in (7),(8) are either the starting point to derive a consistent, physical, compact, all-regions flicker noise model in reference [2].

### *A. The variations in $\gamma$ coefficient*

It is a known that γ in (1) is not exactly 1. The variations in γ are sometimes attributed to a non-uniform trap distribution along the oxide thickness. To evaluate the influence of a non-uniform trap distribution eq.(7) was numerically integrated assuming $N'_t f_t(1-f_t)=\eta(z)$ depends only on z for the following cases: A) $\eta(z)$ constant; B) $\eta(z)$ positive exponential; C) $\eta(z)$ linear; D) $\eta(z)$ negative exponential. The results are shown in Fig. 3. The picture demonstrates that the model in (1) is still valid in all cases for several frequency decades, just adjusting a different γ coefficient.

## III. Cyclostationary Flicker Noise

The periodically varying effect of turning 'on' and 'off' a MOS transistor shall be considered to extend the analysis of section II to the cyclostationary case. When the $V_{GS}$ voltage is reduced the channel carrier density is reduced as well, changing the probabilities of capturing and emitting electrons by the oxide traps. When $V_{GS}$=0, only a few carriers are present in the channel and the probability of a substantial part of them jumping to traps is negligible (and will be considered null in this work). On the other hand, the probability of the emission of a trapped electron increases. A factor, *m* will be used to describe the emission probability change:

$$e_{0OFFemission}=m\cdot e_{0ONemission} \quad (9)$$

Eq.(9) is similar to the model proposed by van der Wel et al in [6] but simpler because no electron is captured during the 'off' state. The work by Tian and El Gamal in [7] takes the same hypothesis but utilizing just m = ∞, and predicts the flicker noise PSD will remain constant at frequencies lower than the switching frequency $f_{sw}$. But reported measurements show that although noise is reduced, its PSD is still proportional to 1/f at the lowest frequencies. In theory, using (9) and taking discrete time intervals to calculate the autocorrelation of (5), the same formalism of section II can be applied to the cyclostationary case. But in the practice the calculations became too complex to develop an analytical model for the cyclostationary noise PSD. On the other hand a numerical model can be developed just by simulating the random process described by (2) in the time domain for an enough large number of distributed traps along the oxide. Then the Fourier transform of the simulated number of occupied traps can be used to estimate an approximated $S_{\Delta N'_A}(f)$. Different spectral power estimation techniques are required in this case due to the large time series necessary to estimate a continuous PSD. Instead, better results (converge to a 'clean' PSD with a shorter time series) were

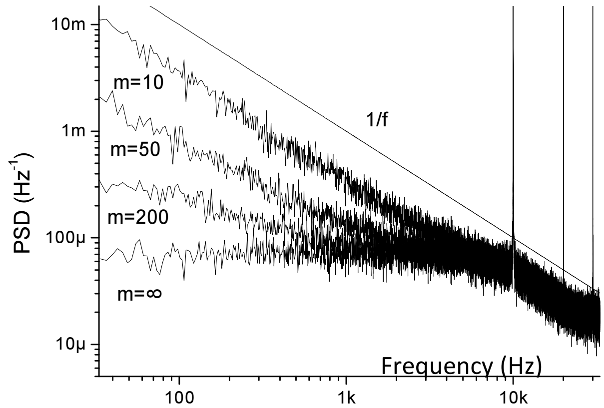


Fig. 4. Simulations of 1/f cyclostationary noise while varying m of eq.(9) using 30 traps and a time domain simulation of the random process.

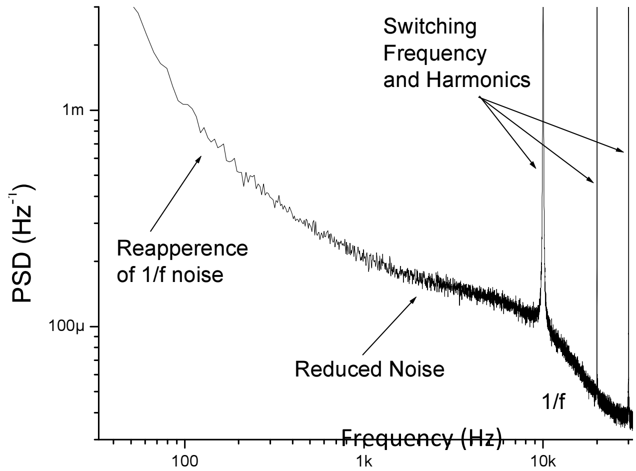


Fig. 5. Simulation using different m factors for traps as proposed in eq.(10). The resurgence of 1/f noise at lower frequencies can be observed.

obtained using the autocorrelation formalism also for the numerical PSD estimation. In the latter, $\Re(s)$ was first obtained from a full time series simulation, and then the $S_{\Delta N'_A}(f)$ PSD is calculated with a single Fourier transform. In Fig. 4 different simulated PSDs for different *m* values in (9) are shown. Cyclostationary flicker noise reduction is evident, but note the behavior is still similar to reported model for *m*=∞. It is still necessary to explain the lowest frequency side of Fig. 1.

### *A. Resurgence of 1/f noise for lower frequencies*

The reduction of flicker noise inherent to cyclostationary operation of the MOSFET was simulated in Fig. 4, but the reappearance of 1/f spectrum for even lower frequencies as reported in [5],[6] was not. The starting assumption in the previous section was in (9) that the emission probabilities of all the traps are affected by variations of $V_{GS}$ in the same way. But remembering section II-B, where a non-uniform spatial distribution of the traps result in different noise PSD γs, a non uniform spatial *m*-factor for eq.(9) can be considered in the cyclostationary case. There is no reason for *m* to be constant, and a reasonable hypothesis is to assume that the occupied traps which are farther from the channel surface are less affected by the channel depletion. To be more accurate, eq.(9)

will be related to the each trap time constant instead to the distance. Traps far from the semiconductor-oxide interface are said to be 'slow' traps. Let $\tau_c$ denote the mean time before an electron is captured by a trap in the continuous time case, and $\tau_e$ the mean time before it is emitted [6] ($\tau_c = 1/c_0 n_s$ , $\tau_e = 1/e_0$ ). A corner frequency $f_c$ is sometimes defined for a single trap: $2\pi \cdot f_c = (1/\tau_c + 1/\tau_e)$. In the simulation showed in Fig. 5, a simple, but non-distribution of $m$ was selected to substitute in (9):

$$m(f_c) = \{100 \; if \; fc > K \;\; ; \; 10 \; if \; fc < K\} \tag{10}$$

with $K$ selected, so that only 5/30 traps in the simulation will be the less affected. The result of this new simulation shows the expected behavior of 1/f noise at lower frequencies. Although the selected distribution is arbitrary, it demonstrates a possible physical mechanism to explain the observed measurements.

## IV. AN ASIC FOR THE CHARACTERIZATION OF CYCLOSTATIONARY FLICKER NOISE.

Section III brings a possible explanation to the behavior cyclostationary flicker noise, but it is not conclusive. A different explanation may be just another physical random process with 1/f noise PSD affects the MOSFET but is only visible when the larger PSD of the trapping-detrapping mechanism is drastically reduced in cyclostationary operation. Complimentary measurements while varying some parameters like $t_{ox}$, $V_{GS}$, the inversion region, $f_{sw}$, or the duty cycle are necessary to validate the model of section III. But very low frequency noise measurements are difficult; thus a specific integrated circuit was designed for the characterization of cyclostationary flicker noise. The proposed circuit is shown in Fig. 6, it was designed in a 0.6µm HV technology, with two different oxide thicknesses available. 16 NMOS and 16 PMOS different size and type of Device-Under-Test (DUT) transistors starting at minimum $W_{min}/L_{min}$=0.8µm/0.6µm are connected by means of a transmission gate switch matrix to a symmetrical Output Transconductance Amplifier (OTA) (Fig.6-top). $M_{2,3,4}$ are medium sized W/L = 30µm/30µm transistors to reduce their flicker noise. But to further reduce the noise of the mirrors, the OTA is connected in a chopper configuration like in Fig.6-bottom. This topology was demonstrated in [9], but in the present embodiment four phases are utilized: during $\phi_2$, $\phi_4$, the DUTs are in 'off' state, during $\phi_1$ them are in 'on' state as well as in $\phi_3$ but in the latter the connection of the switch matrix of Fig. 6 is flipped. Flipping the DUTs can be associated to flicker noise modulation, which is demodulated back in the output capacitors (chopper principle [4],[9]).

## V. CONCLUSIONS

An explicit deduction for flicker noise PSD was presented using SRH statistics and the autocorrelation formalism in the case of a DC biased transistor The fluctuation of the $\gamma$ coefficient originated by non-uniform trap spatial distribution was investigated. The impact on noise of the cyclostationary operation of the MOS transistor was investigated using simulation tools. A space-dependant $m$ factor relating emission probabilities during 'on' and 'off ' states was introduced to

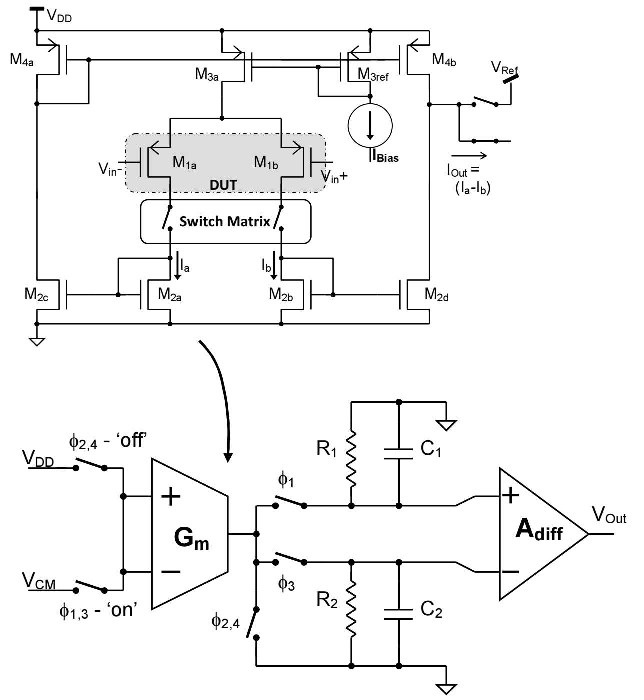


Fig. 6. The proposed integrated circuit for cyclostationary noise measurements (PMOS embodiment).

explain an increasing PSD at the lowest frequencies resembling the original 1/f spectrum. An integrated circuit was presented for accurate cyclostationary flicker noise measurements in a wide range of MOSFET operating regions, for different transistor size/types. This integrated circuit takes advantage of OTA-C chopper operation to avoid undesired flicker noise spectrums to contaminate that of the devices under test.

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