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Enhanced statistical detection of Random Telegraph Noise in frequency and time domain

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1. Abstract

In this work, a new statistical detection method of Random Telegraph Noise (RTN) in the frequency domain is presented. An algorithm for the automated detection of Lorentzian spectra in the noise power spectral density (PSD) of a device is proposed, which enables the processing of a large amount of experimental data. Using 40 nm Bulk CMOS technology as a test vehicle, we demonstrate that the detection of Lorentzian spectra in the noise PSD allows an easier, faster, and often more precise detection of RTN presence compared to the time domain detection.
Keywords-Random Telegraph Noise, Lorentzian noise, detection algorithm, statistical analysis, CMOS transistor

2. Introduction

With the downscaling of the devices area in CMOS technologies, higher levels of low-frequency noise are introduced, and Lorentzian spectra appear around the observed *1/f*-like mean spectrum [1], as shown Fig. 1 and Fig. 2b. The presence of a Lorentzian component in the power spectral density (PSD) may originate either from carrier trapping-detrapping near the oxide interface that cause random telegraph noise (RTN) in the time domain [2] as represented in Fig. 2a, or from generation-recombination (G-R) noise from defects in the semiconductor channel. While RTN is usually studied in the time domain, its statistical study requires much effort and can suffer some inaccuracies because of the diversity of the random telegraph signals (RTS) encountered. Detection of RTN in the frequency domain is not common [3-5], but it provides information on several frequency decades in only one measurement, is faster than a time domain analysis and can be useful to supply noise models where only the frequency analysis is required [4,5]. In this work, an assessment of the statistical detection of RTN in the frequency domain is presented, with first a description of a Lorentzian spectrum detection algorithm, followed by a comparative study showing that the number of detected RTS can be increased using the detection of Lorentzian components of a spectrum, called in this paper Lorentzians.

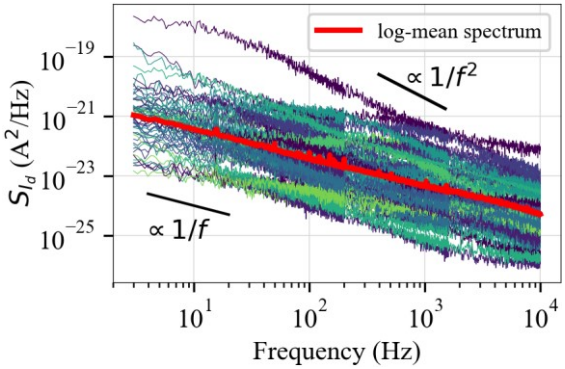


Figure 1: Measurement example of drain current noise spectra for 59 n-MOS transistors and the associated *1/f* log-mean spectrum (red line).

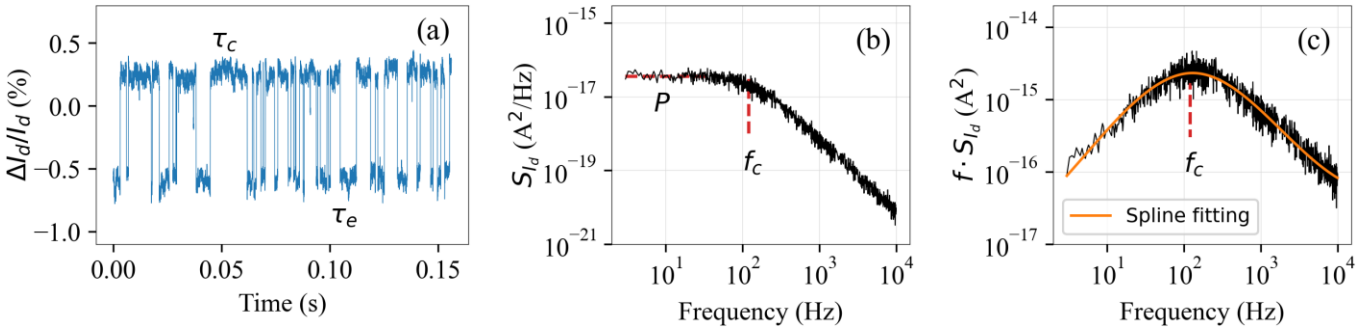


Figure 2: (a) Time domain measurement exhibiting RTN. (b) Associated Lorentzian spectrum with cut-off frequency f_c and plateau P. (c) Spectrum multiplied by the frequency.

3. Experimental setup and measured devices

Drain current noise, S_{Id}, measurements were performed on 59 n-MOS and p-MOS transistors of different channel geometries from a Bulk Si 40 nm CMOS technology, with the analysis focusing on devices with channel width $W = 0.3$ µm and length $L = 40$ nm, for various gate voltage bias in the linear regime ($V_d = 0.05$ V). Time and frequency domain noise measurements were done using a current-to-voltage amplifier and the HP35670A spectrum analyzer. Four acquisitions of different maximum frequencies, corresponding to four time windows, are concatenated to obtain a spectrum bandwidth of four decades, from 3 Hz up to 50 kHz.

4. Detection Algorithm

4.1. Lorentzian spectrum detection

A Lorentzian spectrum exhibits a plateau at low frequencies and a *1/f²* dependency above its cut-off frequency, f_c, which is related to the trap time constant, τ, through equation (1):

$$f_c = \frac{1}{2\pi\tau} = \frac{1}{2\pi}\left(\frac{1}{\tau_c} + \frac{1}{\tau_e}\right) \quad \#(1)$$

where τ_c and τ_e are the average capture and emission times of the trap respectively, in the case of a trap inducing a RTS. An experimental spectrum with N Lorentzians in it can be modeled by a hybrid Lorentzian-$1/f^\gamma$ function, with γ varying between 0.7 and 1.3, as in (2):

$$S(f) = \sum_{i=1}^{N} \frac{P_i}{1 + \left(\frac{f}{f_{c,i}}\right)^2} + \frac{K}{f^\gamma} + C \#(2)$$

where P_i and $f_{c,i}$ are respectively the i-th Lorentzian plateau and cut-off frequency, K the amplitude of the $1/f^\gamma$ component at f = 1 Hz, and C the constant white noise component associated with thermal and extrinsic noises. The parameter γ in equation (2) considers the cases where an inhomogeneous distribution of traps across the oxide/semiconductor interface leads to a *1/f*-like spectrum with a slope different from -but close to- 1. To automatically detect Lorentzians in a spectrum and extract P and f_c, the detection is accomplished in two steps: 1) Possible peaks are detected in the quantity $f \cdot S_{Id}$ illustrated in Fig. 2c, which, in the presence of Lorentzians, exhibits local maxima at each cut-off frequency, revealing the possible presence of RTN or G-R noise. 2) Around each local maximum, a curve fitting algorithm is attempted using (2).

4.2. RTS detection in the time domain

The RTS detection algorithm in the time domain uses the histogram of the signal to detect the various levels between transitions [6]. A kernel density estimation (KDE) is then applied to efficiently smooth the histogram and to remove any parasitic peaks that can lead to an overestimation of the number of levels detected in the signal. This method gives similar results to weighted time-lag plots [7], as the diagonal of the weighted plot is comparable to the smoothed histogram weighted by the KDE. One RTS is counted if two peaks are detected in the histogram. When more than two peaks are detected, we consider multi-level RTS issued from more than one trap. A measurement is considered to contain RTS if at least one of its four time domain acquisitions has a RTS detected in it.

5. Results and discussion

5.1. Lorentzian noise statistical analysis

The percentages of dies with detected Lorentzians for selected gate bias voltages are illustrated in Fig. 3. For a small geometry like the one chosen for the analysis, most of the devices show the presence of one Lorentzian or more in their noise spectrum. The fact that the number of Lorentzians is roughly independent on the polarization reveals a uniform energy distribution of traps. The slight variation with polarization is the result of a higher frequency bandwidth at high currents, which facilitates the Lorentzian detection at higher frequencies.

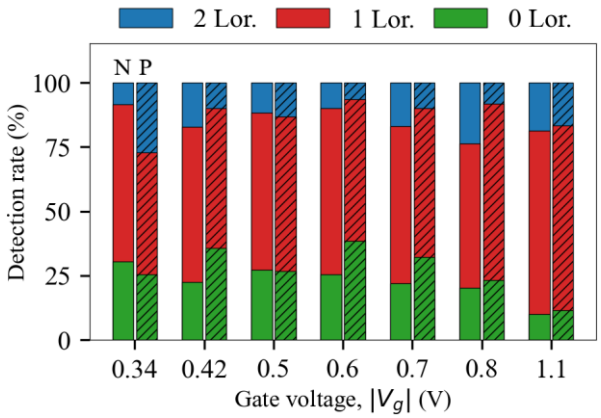


Figure 3: Detection rates of the presence of Lorentzians in the noise spectra of 59 n-MOS (left bars) and p-MOS (right hashed bars) transistors of geometry W = 0.3 µm, L = 40 nm for different gate voltages $|V_g|$.

A comparison is made in Fig. 4 between n-MOS transistors with the smallest studied geometry and a larger one (W = 10 µm and L = 0.3 µm) by plotting the average detection rate for all gate voltages. There are almost two times less Lorentzians detected for the larger geometry, traps inducing RTS and Lorentzian spectra are thus less frequent for larger devices, as expected according to the carrier number fluctuation theory, which predicts more 1/f-like spectra for large oxide areas [8]. This type of analysis can give a quick, yet reliable, insight on the activity of traps inducing RTS while staying in the frequency domain, without implementing demanding extraction methods in time domain and storing large amount of data.

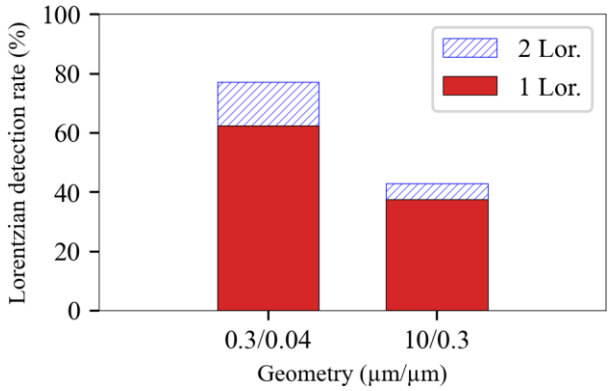


Figure 4: Average detection rates of the presence of Lorentzians in n-MOS transistors of geometries W = 0.3 µm, L = 40 nm and W = 10 µm, L = 0.3 µm

5.2. Revealed RTN with Lorentzian spectrum detection

As shown in Fig. 5, where the detection rates of Lorentzians in the frequency domain and RTS in the time domain are compared, it seems that for a significant number of cases, no RTS is detected in the signal, while a Lorentzian spectrum is measured. This could occur when RTS remains hidden behind *1/f* or white noise because its amplitude is too small to be detected in the time domain, whereas the signal may still have a specific time correlation leading to a visible Lorentzian spectrum.

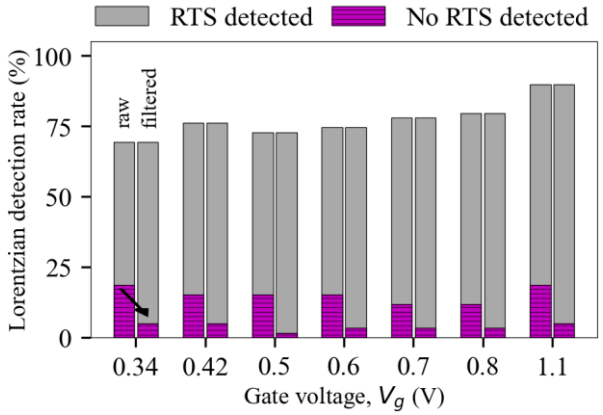


Figure 5: Detection rates of the presence of RTS within the 59 n-MOS spectra showing Lorentzians before (left bars) and after time-domain filtering (right bars) for different gate voltages V_g.

Fig. 6 shows a simulation example where the RTS is hidden behind a large background white noise. Typical detection methodologies using histograms or time-lag plots are unable to predict the presence of the RTS. Nonetheless, its spectrum exhibits a Lorentzian that is detectable at low frequencies.

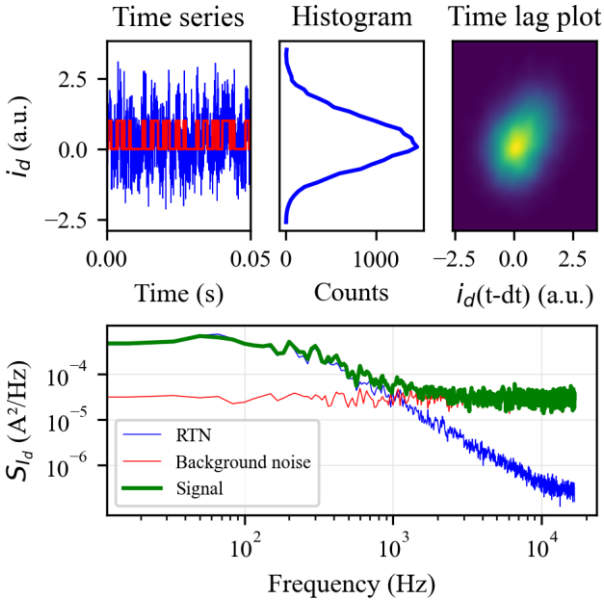


Figure 6: Simulation example of RTS hidden behind a background noise such as its histogram and time-lag plot show no significant RTS trace. The processed spectrum still shows a Lorentzian followed by the constant PSD of the background white noise (C in equation (2)).

The information contained in the spectrum could then predict the presence of a RTS with a greater sensitivity than in time domain: Fig. 7a shows a measurement example of a signal where no RTS was detected in its histogram (Fig. 7b), but a Lorentzian is found in its spectrum (Fig. 7c). However, after a moving average filter is applied, a RTS is revealed with extracted τ_e and τ_c matching the extracted f_c of the detected Lorentzian using (1), showing that RTS could be missed if simply looking at the histograms or time-lag plots. Fig. 5 shows the ratio of detected RTS before and after applying a moving average filter when Lorentzians are detected. The number of detected RTS has increased more than two times, indicating that many detected

Lorentzians are associated with hidden RTS. Lorentzian spectra can thus notify the presence of more RTS when targeting a statistical detection of RTN. Moreover, Lorentzians detection is rather straightforward as the PSD of a noise signal can be easily obtained from a Spectrum Analyzer or a FFT of the time domain measurement.

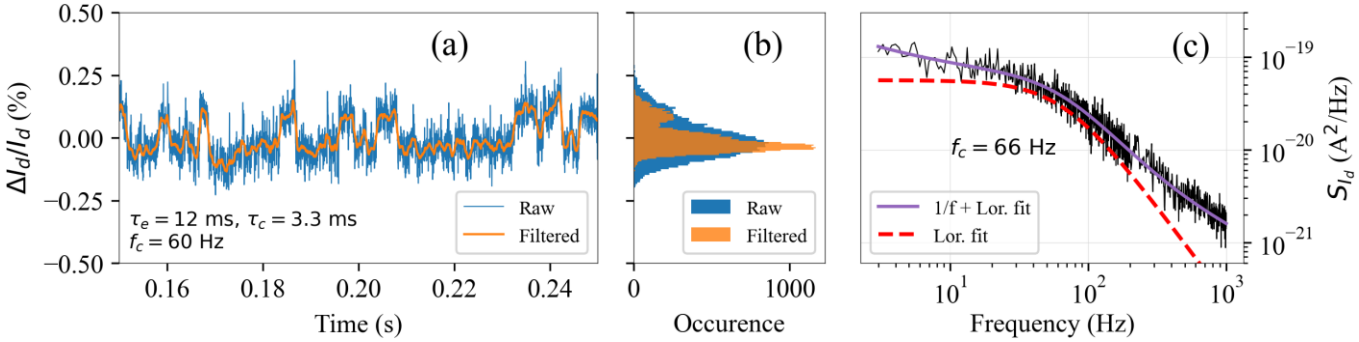


Figure 7: (a) Noise measurement before (blue lines) and after filtering (orange lines). (b) Associated histograms. (c) Noise spectrum of the raw signal fitted with the hybrid Lorentzian-*1/f*$^\gamma$ model (purple line) and the Lorentzian model (red dashed line).

6. Conclusion

A statistical RTN detection methodology through Lorentzian spectra has been presented. First, a new statistical analysis of the presence of Lorentzian components in the noise spectra for different polarizations was presented. Then, it was demonstrated that the presence of a Lorentzian component in a noise spectrum can reveal a RTS that may not have been detected by direct time domain monitoring. We show that the automatic detection of Lorentzian spectra can improve the RTS detection and enable a thorough statistical detection of RTN, with much less data processing and allocated memory.

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