Separation of Random Telegraph Signals from \(1/f\) Noise in MOSFETs

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Abstract— The low-frequency noise power spectrum of small dimension MOSFETs is dominated by Lorentzians arising from Random Telegraph Signals (RTS). The low-frequency noise is observed to decrease when the devices are periodically switched “off”. The amount of noise reduction is observed to be dependent on the amplitude of the switching gate signal. The time-domain technique of determining the statistical lifetimes and amplitudes of the RTS by fitting the signal level histogram of the time-domain record to two-Gaussian histograms is used for analysing the ‘noisy’ RTS along with the device background noise. The device background noise or \(1/f\) noise of the device can then be separated from the RTS using this procedure. In this work, the RTS and the corresponding \(1/f\) noise observed in MOSFETs, under both constant and switched biased conditions, have been investigated. Also, the noise reduction as a function of gate-switching amplitude during switched biased conditions is investigated.

Keyword — \(1/f\) noise, MOSFETs, LF noise.

I. INTRODUCTION

The low-frequency noise is very important for analog and RF applications in advanced CMOS technologies. As device dimensions shrink the low-frequency noise increases. In such devices, the low-frequency noise performance is dominated by Random Telegraph Signals (RTS) on top of the \(1/f\) noise. The origin of such an RTS is attributed to the random trapping and de-trapping of mobile charge carriers in traps located in the oxide or at the interface. An RTS has two distinct levels and it switches between the two states at random moments. The RTS is observed in MOSFETs as a fluctuation in the drain current. The most common way of an RTS analysis is measuring the averaged power spectral density in the frequency domain. A pure two-level RTS is represented in the frequency domain by a Lorentzian spectrum [1]. However, the spectral measurements do not provide us with complete information about the RTS. The spectral measurements provide only the value of the corner frequency, the frequency above which the spectral density rolls off as \(f^{-2}\) and does not give the average lifetimes in the individual states, but only the harmonic mean of these two characteristic time constants. A time domain measurement can be useful in extracting all the RTS parameters. The standard procedure for the analysis of RTS in time domain consists of directly finding from the time record the time instances at which the signal is in the distinct state. Using a simple level-crossing algorithm one can then determine the instances of the ‘high’ and ‘low’ states of the RTS. This simple procedure can be used effectively for a clean RTS, where the ratio of the RTS amplitude to background noise is high. Another procedure for analysing RTS in the time domain is based on the analysis of the signal level histogram of the measured signal and the separation of the data points into two records each corresponding to one of the RTS levels [2]. Using this procedure it is possible to separate out the RTS from the background noise.

The RTS noise decreases when the gate bias is periodically alternated between an ‘on’ state where the device is in strong inversion and saturation and an ‘off’ state where the \(V_{GS}\) (gate-to-source voltage) is well below the threshold voltage of the device [3-6]. The amount RTS noise reduction is proportional to the ‘off’ level of the periodic gate signal.

In this paper, we analyse the RTS observed in MOSFETs, under constant and switched bias (cyclo-stationary) conditions. The time domain procedure in [2] is then used to separate the RTS from the background noise under both conditions. The RTS parameters are also extracted during constant bias and switched bias conditions, with varying ‘OFF” levels of the gate signal.

II. RTS MEASUREMENT IN TIME DOMAIN

A. Measurement Setup

The measurement setup used for the noise measurements is the same as that used in [6]. A digital oscilloscope (TDS7404) is used for recording the time domain RTS data. Large time frames of the RTS are obtained in an automated manner using LabVIEW and TekVISA. Under ‘switched bias’ conditions the device is periodically switched ‘off’, by applying a square wave with a 50% duty cycle at the gate of the device. The switching frequency is much higher than the RTS corner
frequency. The ‘switched biased’ output is then sampled only in the ‘on’ state of the MOSFET. These ‘on’ states are then joined together to form a ‘switched biased’ RTS. Figure 1, shows a schematic of the ‘switched biased’ RTS.

The measurement setup [6], along with an RTS parameter extraction procedure [7], can be used successfully to extract the RTS parameters under constant and switched bias conditions. The ‘OFF’ level of the switching gate signal is varied and the RTS parameters are extracted for each condition to investigate the effect of the ‘OFF’ level on the RTS parameters and the RTS spectrum. The extracted parameters are used in Machlup’s analytical noise-power expression [1], and compared with the noise power measured using a spectrum analyser.

B. Separation of RTS and Background noise

The procedure for analysing the background noise and the RTS is based on the analysis of the signal level histogram of the measured signal and the separation of the data points into two sub-records each belonging to an RTS level [2]. The procedure assumes that the RTS is a two-level signal, whose amplitude distribution is characterised by two peaks each denoting the RTS level. The procedure assumes that the distributions of the experimentally measured signal amplitudes around each peak are due to Gaussian noise. The separation of the background noise from the distinct two level RTS is then a three step process. Figure 2, explains the procedure for separating background noise from the RTS.

The first step is to build the signal level histogram of the time domain signal. This can be fitted with two Gaussian distributions, the peak of each corresponding to the ‘high’ and ‘low’ level voltage amplitude of the RTS. The amplitude of the RTS can thus be determined. The second step is to determine the separation level (amplitude) which separates the data points into two distinct sub-records corresponding to the two levels. In our setup this separation level was determined intuitively. A more detailed analysis of this separation procedure is available in literature [8], from which it is also possible to estimate the error made in the separation. Finally, the third step is to subtract the RTS amplitude difference between the two RTS levels (obtained from step 1) from the data points in the ‘high’ state, thus obtaining a noisy signal without RTS jumps. This completes the background noise and RTS separation procedure. The power spectrum of each can then be calculated using an FFT to determine the noise power due to the RTS and the noise power due to the background noise, both for the constant bias and the switched bias conditions.

III. RTS MEASUREMENT RESULTS

The devices under test are p-channel MOSFETs, with a W/L=10/0.3 (µm), with a gate oxide thickness of 10nm. The setup measures the drain current noise power spectral density (PSD) of the device under test (dB V²/Hz). The devices selected for the measurement show a clear RTS on top of background noise. The background noise is observed to be well above the noise floor of the measurement setup, which indicates that this background noise is from the device under test. The RTS separation procedure is employed to obtain the device background noise data in time domain. The PSD of this data is the device background noise power. The first step of the noise separation procedure is shown in Fig. 3 for a device under constant bias. Figure 3 shows two distinct peaks each corresponding to the RTS level surrounded by the device background noise with a Gaussian distribution. The data points are then grouped into two levels. The RTS amplitude (difference between the two
Gaussian peaks) is then subtracted from the ‘high’ level to give the device background noise data.

The PSD of the device background noise is then calculated. Figure 4 shows the PSD of an RTS measured under constant bias conditions using a spectrum analyzer. Also shown is the PSD of the device background noise extracted using the above procedure. A line with a slope of $1/f$ (10dB/decade) is then fitted to the PSD of the device background noise. From Fig. 4, it can be seen that the slope of the noise is $1/f$.

The Hooge parameter for the extracted $1/f$ noise was then calculated to be $\alpha_H = 6.8 \times 10^{-6}$.

The same device is then periodically switched ‘OFF’ with a frequency of 10 kHz and a 50% duty cycle. The switched biased RTS time domain data is obtained using the technique in Fig. 1. Figure 5 shows the measured PSD of an RTS on a p-MOSFET under switched bias conditions. Also shown are the calculated PSD of the switched biased RTS, and the device background noise for the switched bias case.

The calculated PSD of the switched biased RTS is higher than the measured PSD because the switched biased RTS is obtained only by sampling the ‘on’ states of device. The measured PSD, on the other hand is got by sampling both the ‘on’ and ‘off’ states of the device. The PSD of the device background noise under switched bias conditions is also fitted with a line of slope $1/f$ (10dB/decade) From Fig. 5 it can be seen that the device background noise for the switched bias case is also $1/f$ in nature.

The RTS time constants are observed to change under switched bias conditions. The RTS amplitude remains constant for the switched conditions.
The ‘off’ level of the switching gate signal is varied in steps to investigate its effect on the noise PSD of the RTS under study. From Fig. 6 it can be seen that changing the ‘off’ level causes the RTS noise PSD to decrease. This decrease is due to the change in the RTS parameters under switched bias conditions. The RTS parameters extracted under the switched conditions with varying ‘off’ levels are used in Machlup’s expression and matched with the measured noise PSD.

IV. DISCUSSIONS

The results of the time domain separation method verify the assumption of the dominating two-level RTS on top of the $1/f$ noise in MOSFETs. Also the PSD of the device background noise is $1/f$ in nature for both the constant and switched bias conditions. The extracted Hooge parameter $\alpha_H=6.8\times10^{-6}$, for the device under constant bias conditions, is quite a normal value for these type of devices [9]. Our results show that the time domain analysis of an RTS is not only useful in extracting the RTS parameters, but also in extracting the $1/f$ noise of the device using the separation procedure. The noise PSD of the RTS decreases by changing the ‘off’ level of the switching signal, under switched bias conditions. This decrease is because of the change in the RTS time constants under switched conditions. The RTS time constants are a function of the Fermi level in the device. By changing the ‘off’ level, the Fermi level within the device is changed which in turn causes the RTS time-constants to change. An important observation is that the RTS amplitude does not change when the device is periodically switched from an ON state to an OFF state, indicating that we are still looking at the same trap causing the RTS.

V. CONCLUSIONS

Time domain analysis of RTS observed in MOSFETs, under constant and switched biased (cyclo-stationary) conditions has been presented. The time-domain procedure in [2] has been used to separate out the two-level RTS from the device background noise under both conditions. Measurement results indicate that this noise is $1/f$ in nature ($\alpha_H=6.8\times10^{-6}$). RTS time constants change with changing ‘off’ levels of switching signal, leading to a reduced RTS noise PSD.

ACKNOWLEDGEMENTS

This work is supported by the Dutch Technology Foundation (STW), applied science division of NWO, and the technology program of the ministry of Economic Affairs.