New Weighted Time Lag Method for the Analysis of Random Telegraph Signals

Javier Martin-Martinez, Javier Diaz-Fortuny, Rosana Rodriguez, Montserrat Nafria, and Xavier Aymerich

***Abstract*—A new method for the characterization of random telegraph signals (RTSs) is presented. The method, which is based on the time lag plot, is illustrated using Monte Carlo generated RTS traces and applied to identify the contribution of defects in multilevel RTS measured in a pMOS transistor. The results show that the new method provides a powerful and easily implementable technique to obtain the parameters of the defects responsible of multilevel RTS, even when the background noise is relevant.**

***Index Terms*—Random telegraph signals, noise, CMOS, parameter extraction, characterization.**

I. Introduction

The increasing interest in the study of Random Telegraph Signals (RTS) in deeply CMOS scaled technologies is justified by their negative consequences on the devices reliability [1], [2]. Moreover, the study of RTS, since associated to the charge trapping/detrapping in/from defects, provides a highly valuable device physics information [3], [4]. Several methods have been proposed to analyse the defects involved in RTS accurately [5]–[7]. However, if the background noise (i.e., noise that comes from measurement equipment or other sources inside the device under study) is relevant when compared with the current/voltage steps in the RTS, the precise defects detection and their parameters extraction can be difficult. In this work, a new method for the RTS analysis, which extends the Time Lag Plot (TLP) procedure [6] is presented. This new method is easily implementable and robust even when the background noise is large. The method is explained and illustrated using as example numerically generated RTS caused by only one defect. After that, the new method is applied to identify the contribution of defects related to experimental multilevel RTS.

II. The Weighted Time Lag Method

To illustrate the method, Monte Carlo simulations of two level RTS waveforms were performed considering two-state Markov processes [8]. The black line in Fig. 1(a) shows an example of a simulated current RTS without noise with levels I_L = 3 nA and I_H = 5 nA. Assuming that the responsible defect of this RTS is occupied at I_L and empty at I_H, its mean emission and capture times were chosen to be $\langle\tau_e\rangle$ = 6.6s and $\langle\tau_c\rangle$ = 10 s, respectively. Dots in Fig. 1(a) show the waveform obtained when a Gaussian noise with standard deviation σ = 0.9 nA (that reproduces the experimental background noise) is added to the RTS. Due to the large unfavorable ratio between the noise and the RTS amplitude, an accurate identification of I_L and is unfeasible from Fig. 1(a). The RTS histogram [dots in Fig. 1(b)], cannot help, because the two peaks associated with I_L and I_H are hidden by the background noise [5]. Another solution is to draw the TLP [Fig. 1(c)], which is constructed by plotting the i-th point of the RTS in the x-axis and the (i+1)-th point in the y-axis for the full RTS trace [6]. If the background noise is low, using the TLP, the RTS levels can be identified as populated regions in the diagonal, while populated regions outside the diagonal are related to the transitions between states [6] (these regions are indicated with crosses in Fig. 1(c). However, in the TLP constructed from the RTS trace in Fig. 1(a), these regions are again overlapped because of the background noise.

The weighted time lag method presented here tries to extend the TLP by minimizing the effect of the noise in the RTS and

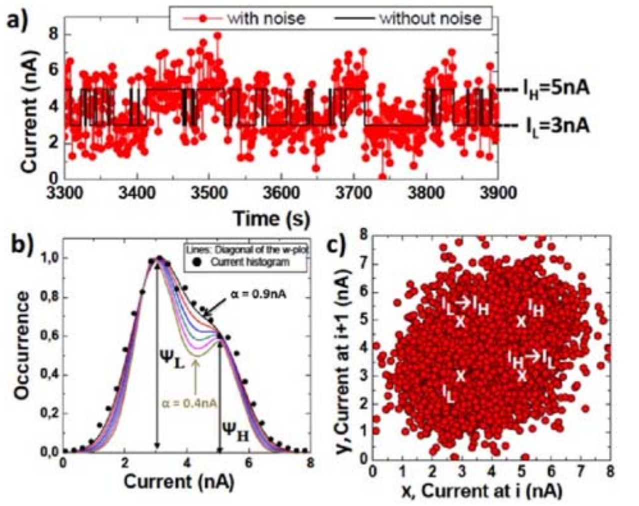

Fig. 1. (a) Monte Carlo generated RTS with and without noise; the sample rate considered was 1 s and the number of points in the RTS 10.000. (b) Dots indicate the current probability distribution obtained directly from the RTS; lines correspond to the diagonal of the w-TLP (Fig. 2(c) obtained for α values ranged between 0.3 nA and 0.9 nA. (c) TLP of the RTS; the background noise hides the current levels and transition regions (marked with crosses).

Manuscript received January 9, 2014; revised January 31, 2014; accepted February 1, 2014. This work was supported in part by the Spanish MINECO under Grant TEC2010-16126 and in part by the Generalitat de Catalunya under Grant 2009SGR-783. The review of this letter was arranged by Editor S. Hall.

The authors are with the Department of Electronic Engineering, Universitat Autonoma de Barcelona, Bellaterra 08193, Spain (e-mail: javier.martin.martinez@uab.es).

Digital Object Identifier 10.1109/LED.2014.2304673

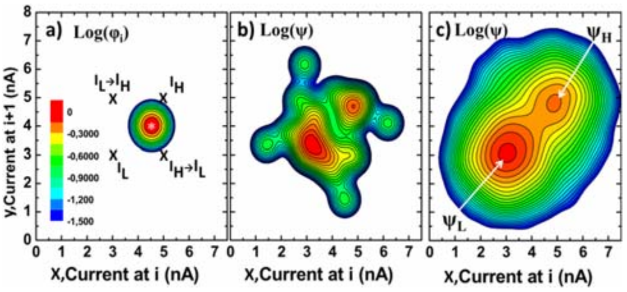

Fig. 2. (a) Representation of Log (ϕ_i), normalized to its maximum value, obtained for one point of the noisy RTS in Fig. 1(a). The position of this point in the TLP is marked with * and the levels and transitions regions with crosses. (b) Representation of Log () using the first 30 points of the RTS and (c) the full RTS trace.

allows more accurate defect parameters extraction. We depart considering a point of the plotted TLP with coordinates (Ii, Ii+1). For this point we define the ϕi function as:

$$\varphi_i(x,y) = \frac{1}{2\pi\alpha^2}\exp\left(\frac{-[(I_i - x)^2 + (I_{i+1} - y)^2]}{2\alpha^2}\right) \quad (1)$$

where x and y are the coordinates of the space where the TLP is considered. Note that ϕ_i is a normal bivariate distribution with standard deviation α and correlation coefficient 0. Then, $\phi_i(x,y)$ represents the probability that the point with coordinates (I_i, I_{i+1}) corresponds to a level or to a transition in the location (x,y) of the TLP space. Fig. 2(a) shows the plot of $\phi_i(x,y)$ in log scale for a single point of the TLP. After the ϕ_i definition, we define the weighted time lag function as:

$$\Psi(x,y) = K\sum_{i=1}^{N-1}\phi_i \quad (2)$$

being K a normalization constant chosen to get the maximum value of Ψ equal to 1 and N the number of points in the RTS. If Ψ is plotted for few points [Fig. 2(b)] two local maximums are roughly defined whose values are closer to I_L and I_H.

To understand why these peaks are revealed, we have to note that the contribution of each point of the TLP, which results in Ψ, is weighted by the distance between the position of this point and (x,y). Therefore, the Ψ function takes higher values in the most populated regions of the TLP. This is more evident in Fig. 2(c) where the Ψ function is plotted for all the points of the TLP. In the following, we will refer to the plots of the type of Fig. 2(c) as weighted TLP (w-TLP). In the diagonal of the w-TLP of Fig. 2(c) two well defined local maximums can be detected (Ψ_L and Ψ_H) in the positions 3.05nA and 4.89nA. These values correspond to the two levels of the RTS, which are very close to the nominal I_L and I_H values introduced during the generation of this signal [Fig. 1(a)]. Then, the construction of the Ψ function is valid to detect levels of the RTS that cannot be determined from conventional methods, such as the RTS histogram [Fig. 1(b)] or the TLP [Fig. 1(c)], when the background noise is relevant. The ratio τ_e/τ_c, which, in most of the cases, is enough to obtain the relevant physical information of the defect [9], can be easily calculated from the w-TLP by the evaluation of the ratio of the two local maximums found in the w-TLP Ψ_H/Ψ_L). In this case we obtain

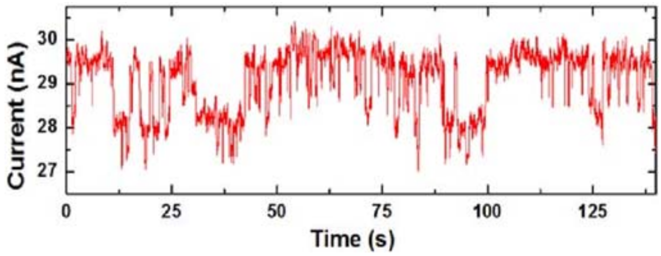

Fig. 3. Experimental multilevel RTS in the drain current of a pMOS transistor.

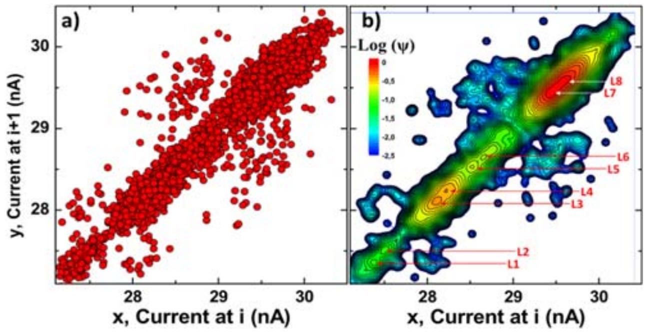

Fig. 4. Conventional TLP (a) and w-TLP (b) obtained from the RTS of Fig. 3.

$\Psi_H/\Psi_L = 0.63$, which is close to the nominal value imposed during the generation of the RTS ($\tau_e/\tau_c = 0.66$).

In the weighted time lag method, the chosen value of α (the standard deviation of ϕ_i), which is the only fitting parameter in the method, is a key point to correctly identify the levels of the RTS. Lines in Fig. 1(b) show the cross section through the diagonal of the w-TLP obtained when Ψ is constructed using different α values between 0.3 nA and 0.9 nA. For high α values, only one peak [as in the case of the histogram, dots in Fig. 1(b)] appears, and the two peaks are only revealed when α is decreased. However, if α is very low, this procedure fails because each point only contributes to Ψ in a region very close to it, leading in the limit, to a conventional histogram with a small bin size. Then, the proper selection of α is crucial to correctly determine and identify the defect in the RTS.

III. Application to Multilevel RTS

The method can be applied to multilevel signals without any change. To show this point we have applied the method to a experimental RTS obtained with a sample rate of 34.2 ms in the drain current of a pMOS transistor when a gate voltage of −0.6 V and drain voltage of −200 mV are applied for 140 s. The obtained current trace (Fig. 3) shows a clear RTS where at least two discrete steps can be detected, which indicates that two or more defects are active in this device. However, the background noise makes difficult the accurate identification of the resulting current levels. Moreover, defects that could provoke smaller current steps would be hidden by the noise.

Fig. 4(a) shows the TLP of the RTS plotted in Fig. 3. Note that, when using the TLP, the current levels of the signal are difficult to be distinguished. However, with the w-TLP

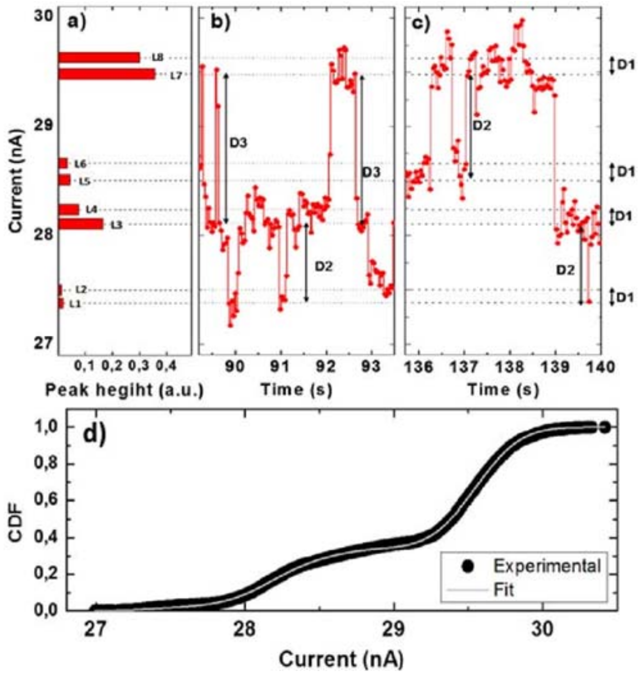

Fig. 5. (a) Position and height of the peaks detected in the diagonal of the w-TLP in Fig. 4(b). (b) and (c) Zooms of the experimental RTS trace in Fig. 3. Switchings of the three defects are indicated. D2 and D3 are evident but those of D1 cannot be clearly appreciated because of the background noise of the signal. (d) Experimental cumulative distribution function of the RTS in Fig. 3 and the fitting obtained from the data in Fig. 5(a).

[Fig. 4(b)] eight local maximums (L1-L8) can be detected. This suggests the existence of eight current levels in the RTS, and therefore, at least three active defects in the device. The position and height of the eight current levels observed in the w-TLP are plotted in Fig. 5(a). Attending to the position of the current levels, three defects with different switching amplitudes in the RTS have been identified (D1, D2, and D3). The current shift between the levels associated to D2 and D3 are large enough to detect the transition regions in the TLP and w-TLP (regions outside the diagonal in Fig. 4), and also can be detected in a zoom of the RTS [Fig. 5(b) and (c)]. However, the small current shift associated to D1 compared to the amplitude of the background noise impedes the correct D1 identification directly from the RTS or the TLP, whereas it can be clearly detected if the w-TLP is used. Moreover, using the w-TLP an additional analysis of the RTS can be done. In Fig. 5(b) and (c) can be appreciated that the current shift of D2 is different depending on the D3 state. However, the current shift of D1 does not depend significantly on the D2 and D3 states. This indicates that there is an interaction between D2 and D3 whereas is not the case of D1.

Finally, continuous line in Fig. 5(d) shows the cumulative distribution Function (CDF) of the experimental RTS (symbols) which can be well reproduced using the data of Fig. 5(a). This fitting is done by associating a normal distribution to each current level detected in the w-TLP. The mean value of the normal distributions corresponds to the current level position; their height corresponds to the relative peak height obtained from the w-TLP. The standard deviation ($\sigma = 0.22$nA) is chosen to be the same for all the current level distributions since it is related to the experimental background noise. The good fitting of the experimental data allows concluding that the Weighted Time Lag method is an efficient procedure to identify defects in the device and obtain an accurate description of the resulting RTS.

IV. Conclusion

A new method, namely Weighted Time Lag method, is proposed as a procedure to analyze Random Telegraph Signals (RTS). The method is easily applicable to conventional RTS and allows an accurate extraction of defect parameters, even when the background noise is elevated or multilevel signals are considered. The new Weighted Time Lag method can improve the characterization and analysis of RTS coming from ultrascaled devices.

References

[1] A. Ghetti, C. Compagnoni, F. Biancardi, *et al.*, "Scaling trends for random telegraph noise in deca-nanometer flash memories," in *Proc. IEEE IEDM*, Dec. 2008, pp. 835–838.

[2] N. Ayala, J. Martin-Martinez, R. Rodriguez, *et al.*, "Unified characterization of RTN and BTI for circuit performance and variability simulation," in *Proc. ESSDERC*, 2012, pp. 266–269.

[3] C. Monzio Compagnoni, R. Gusmeroli, A. S. Spinelli, *et al.*, "RTN V_T instability from the stationary trap-filling condition: An analytical spectroscopic investigation," *IEEE Trans. Electron Devices*, vol. 55, no. 2, pp. 655–661, Feb. 2008.

[4] T. Grasser, H. Reisinger, W. Goes, *et al.*, "Switching oxide traps as the missing link between negative bias temperature and random telegraph noise," in *Proc. IEEE IEDM*, Dec. 2009, pp. 1–4.

[5] Y. Yuzhelevski, M. Yuzhelevski, and G. Jung, "Random telegraph noise analysis in time domain," *Rev. Sci. Instrum.*, vol. 71, no. 4, pp. 1681–1688, 2000.

[6] T. Nagumo, K. Takeuchi, S. Yowogawa, *et al.*, "New analysis methods for comprehensive understanding of random telegraph noise," in *Proc. IEEE IEDM*, Dec. 2009, pp. 32.1.1–32.1.4.

[7] F. M. Puglisi, P. Pavan, A. Padovani, *et al.*, "Random telegraph noise signal noise properties of HfO_x RRAM in high resistivity state," in *Proc. ESSDERC*, 2012, pp. 274–277.

[8] C. Monzio Compagnoni, R. Gusmeroli, A. S. Spinelli, *et al.*, "Statistical model for random telegraph noise in flash memories," *IEEE Trans. Electron Devices*, vol. 55, no. 1, pp. 388–395, Jan. 2008.

[9] K. Abe, A. Teramoto, S. Shigetoshim, *et al.*, "Understanding of traps causing random telegraph noise based on experimentally extracted time constants and amplitude," in *Proc. IRPS*, 2011, pp. 4A.4.1–4A.4.6.