Extracting statistical distributions of RTN originating from both acceptor-like and donor-like traps

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Abstract
The impact of Random Telegraph Noise (RTN) on devices increases, as the device sizes are downscaled. Against a reference level, it is commonly observed that RTN can fluctuate both below and above this level. The modelling of RTN, however, was typically carried out only in the direction where drain current reduces. In reality, this current reduction can be compensated by simultaneous current increases. This calls the accuracy of the one-directional RTN modelling into questions. Separating the fluctuation in one direction from the other is difficult experimentally. In this paper, we review the recently proposed integral methodology for achieving this separation. In contrast with early works, the integral methodology does not require selecting devices with fluctuation only in one direction. The RTN in all devices are measured and grouped together to form one dataset. It is then statically analyzed by assuming the presence of fluctuation in both directions. In this way, the separation is carried out numerically, rather than experimentally. Based on the maximum likelihood estimation, the popular statistical distributions are tested against experimental data. It is found that the General Extreme Value (GEV) distribution agrees best with the experimental threshold voltage shift, when compared with the Exponential and Lognormal distributions.

1. Introduction

As devices downscale, they increasingly suffer from Random Telegraph Noise (RTN) [1-11], in addition to ageing [12-18]. When there is only one trap in gate dielectric, Fig. 1(a) shows it can capture and then emit a charge carrier, resulting in RTN in Fig. 1(b). For a nMOSFET, early works [1-7] focused on acceptor-like traps in gate dielectric, which capture electrons, become negatively charged, and leads to a reduction of drain current, Id. Similarly, for a pMOSFET, attentions were focused on donor-like traps, which capture holes, become positively charged, and result in a reduction of the magnitude of Id. The fluctuation in Id was typically measured as ΔId/Id, where ΔId can be defined as,

$$\Delta Id = Id,ref - Id. \qquad (1)$$

The Id,ref is typically measured from the average of the first several points before the traps become electrically active and the RTN transition starts, as shown by the blue line in Fig. 2. By the definition in Eq.(1), a positive ΔId/Id represents a reduction of Id after filling a trap. Early works [1-7] focused on modelling ΔId/Id>0. When Id was monitored against time under constant Vg and Vd, however, ΔId/Id can be either positive or negative and one example is given in Fig. 2. Fig. 3 shows that there is little correlation between the positive and negative ΔId/Id, so that the model developed for one cannot be used for the other. For a RTN model to be applicable to generic devices, it must cover both ΔId/Id>0 and ΔId/Id<0. The aim of this work is to review the recent proposed integral methodology that models ΔId/Id in both directions.

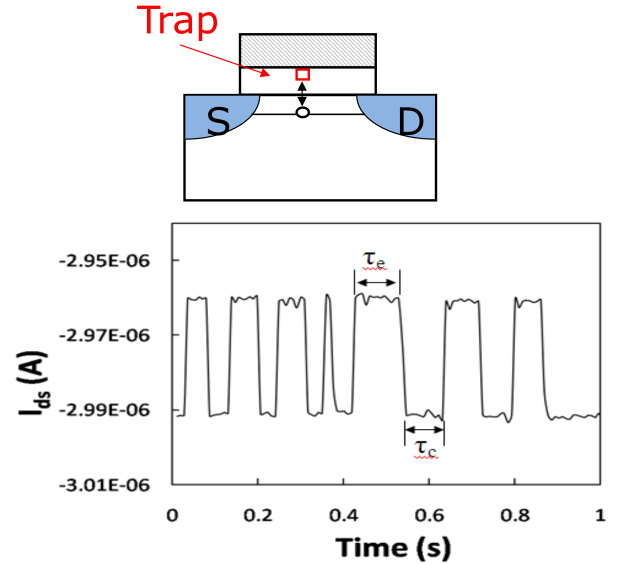

Fig. 1. (a) An schematic illustration of capturing and emitting charge carrier by a trap in gate dielectric. (b) A typical two level RTN.

2. Methodology

For a nMOSFET, it is generally agreed that ΔId/Id>0 originates from acceptor-like electron traps, which

capture electrons from the channel, form negative charges in gate dielectric, and reduce Id. There are different interpretations for ΔId/Id<0. One of them is that they originate from donor-like hole traps, which form positive charges and increase Id. The other is that, when Id,ref was measured, some acceptor-like traps were already filled with electrons. These traps then emit electrons, resulting in the observed ΔId/Id<0. Our test results do not conclude which interpretation is correct. For the convenience of presentation, we will use the terms of acceptor-like and donor-like traps, thereafter.

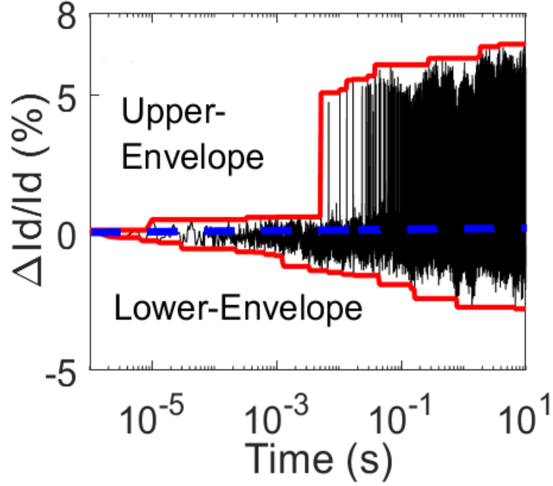

Fig. 2. Raw data of the measured RTN (Black lines). The envelopes are represented by the red lines. [19].

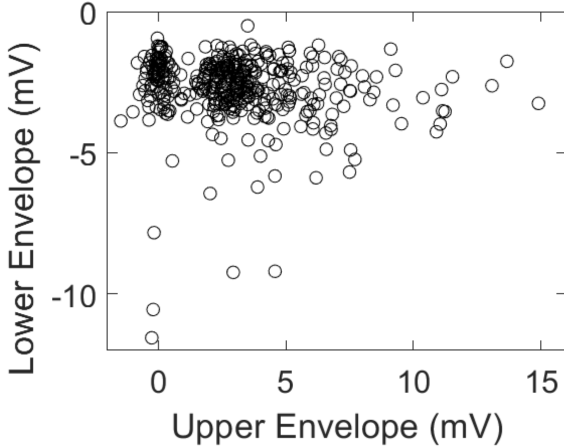

Fig. 3. The lower envelope has little correlation with the upper-envelope. [19].

The RTN can cause fluctuation in both Id and threshold voltage, Vth. Early works [4,5,11] often converted ΔId to ΔVth by,

$$\Delta Vth = \frac{\Delta Id}{gm}, \qquad (2)$$

where gm is the transconductance. When compared with the ΔVth directly measured from the pulse Id-Vg at Vg=Vth, Fig. 4 shows that the Eq. (2) is accurate only when the Vg is close to Vth. To simplify the test procedure and to minimize the inaccuracy, the ΔId will be measured at Vg=0.5 V, which is sufficiently close to Vth=0.45 V that the Eq. (2) is applicable. The gm was measured for each device from a pulse Id-Vg before starting the RTN test. We will present our model in terms of ΔVth, hereafter.

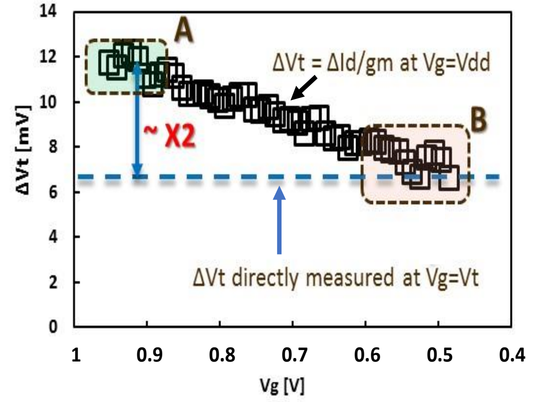

Fig. 4. A comparison of the ΔVth evaluated from ΔId/gm at different Vg with the ΔVth measured at Vg=Vth.

There are theoretical and experimental difficulties for modelling both ΔId/Id>0 and ΔId/Id<0 simultaneously. Theoretically, the well-known statistical distributions, such as Exponential and Lognormal distributions, require ΔVth to be positive only [19], which corresponds to charging acceptor-like electron traps in nMOSFETs. In order to model both positive and negative ΔVth, we will use two statistical distributions: one for the positive ΔVth_A and the other for the magnitude of the negative ΔVth_D, $|\Delta Vth_D|$, where the subscript 'A' and 'D' represents acceptor-like and donor-like traps, respectively. The total ΔVth can then be evaluated from,

$$\Delta Vth = \Delta Vth_A + \Delta Vth_D, \quad (3)$$

Experimentally, one can only measure the combined effect of acceptor-like and donor-like traps. As they compensate each other, the measured ΔVth cannot be attributed to one type of traps. As a result, it is difficult to separate these two types of traps experimentally.

To overcome the above challenges, an integral methodology has been developed which does not require separating acceptor-like from donor-like traps experimentally [19,20]. Instead, the ΔVth measured from each device will be grouped together to form a data set. At a given time, one ΔVth=ΔId/gm is taken for each device from the raw measured data like those shown in Fig. 2. By repeating the measurement on 402 devices, we have 402 ΔVth, as shown in Fig. 5.

To model the cumulative distribution function (CDF) of ΔVth in Fig. 5, it is assumed that the number of both acceptor-like traps, N_A, and donor-like traps, N_D, per device follows the Poisson distribution. The impact of one trap on the device, δVth, follows one of: Exponential, Lognormal, or General Extreme Value (GEV) distributions [2,7]. It should be pointed out that δVth is the shift per traps, which is different from the shift per device ΔVth, as multiple traps can contribute to ΔVth. In addition, the thermal noise is also taken into account by using a normal distribution with zero average value. The parameters in these distributions will be extracted by the Maximum Likelihood Estimations. In this way, the measured ΔVth is separated into contribution of individual traps numerically and statistically, rather than experimentally.

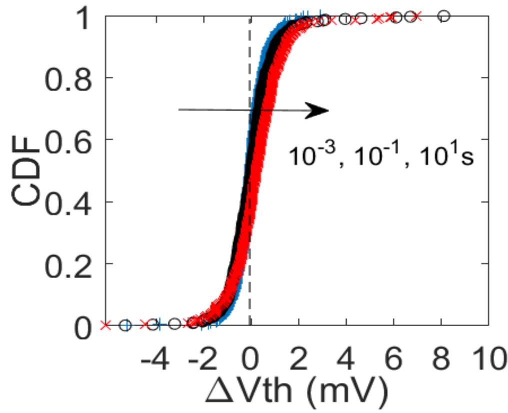

Fig. 5. A comparison of the CDF of ΔVth at different time. [19].

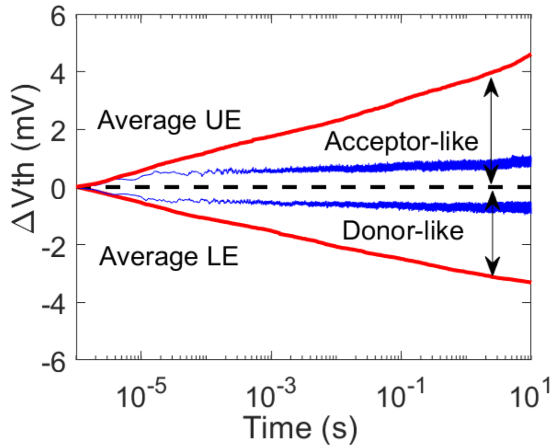

Fig. 6. A comparison of the average envelope with the average values of ΔVth>0 and ΔVth<0. [19].

Early works [6,21-27] studied the envelopes of the RTN induced fluctuation in Fig.2. In this work, however, we model the ΔVth itself, rather than its envelope. For one device, Fig. 2 shows that ΔVth (black lines) at a given time point can be substantially lower than its envelope. The upper-envelope in Fig. 2 represent the maximum $ΔVth_A$ up to that time point, when acceptor-like traps are charged. Most of the time, however, some acceptor-like traps are neutral due to emission, so that most of measured ΔVth is below the envelope. In another word, ΔVth only hits its envelope occasionally, when there are multiple traps in a device. Similarly the lower envelop represents $ΔVth_D$ when donor-like traps are charged.

To statistically compare the envelope with the average ΔVth, Fig. 6 plots the average envelops measured on 402 devices with the average ΔVth>0 and ΔVth<0 of these devices. It can be seen that the average ΔVth>0 is less than half of the average envelop. As a result, using the envelop will substantially overestimate RTN.

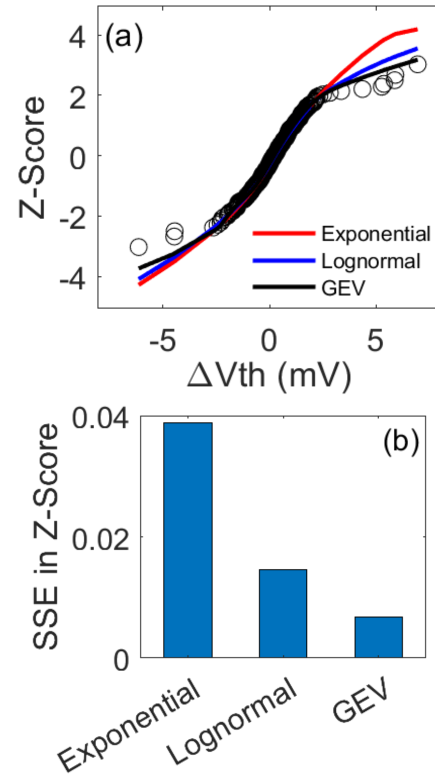

Fig. 7. (a) A comparison of the CDFs computed from the extracted distributions in Table I with the test data. (b) The Sum of Squared Errors of different distributions. [19].

3. Results

The parameters for different distributions were extracted based on the Maximum Likelihood Estimation and their values are given in Table I. Fig. 7(a) compares the CDF computed from these distributions with the experimental data. It can be seen that the GEV distribution agrees best with test data, while Exponential the worst. To enable a quantitative comparison, the sum of squared errors (SSE) per device is given in Fig. 7(b).

To explain why the GEV distribution agrees best with the measured ΔVth, it should be pointed out that GEV generally has longer distribution tails than the Exponential and Lognormal distributions. This makes it better suited to describe the widespread statistical events. Under Vg=Vth, the current flow follows percolation paths. The traps on top of these paths will have substantially larger impact than the traps away from them, giving a long distribution tail and matching the GEV distribution best.

Table I. Probability distribution functions (pdf) and their extracted parameter values. [19].

	PDF of δVth	Acceptor	Donor
Exponential	$\frac{1}{\eta}e^{-\frac{\delta Vth}{\eta}}$	$\eta = 0.56$	$\eta = 0.48$
Lognormal	$\frac{1}{\delta Vth\theta\sqrt{2\pi}}e^{(-\frac{(\ln(\delta Vth)-\epsilon)^2}{2\theta^2})}$	$\epsilon = -0.43$ $\theta = 0.12$	$\epsilon = -0.71$ $\theta = 0.16$
GEV	$\frac{1}{\beta}(k)^{\xi+1}e^{-k}$ $k = \left(1+\xi\left(\frac{\delta Vth-\alpha}{\beta}\right)\right)^{-\frac{1}{\xi}}$	$\xi = 0.35$ $\alpha = 0.43$ $\beta = 0.34$	$\xi = 0.42$ $\alpha = 0.59$ $\beta = 0.19$
Thermal	$\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{\Delta Vth}{\sigma}\right)^2}$	$Exponential, \sigma = 0.11$ $Lognormal, \sigma = 0.13$ $GEV, \sigma = 0.13$	

4. Conclusions

This work reviews the recently proposed integral methodology for modelling RTN. Early works only modeled RTN fluctuation in one direction and had to remove the devices with fluctuation in both directions. In contrast, the integral methodology does not select devices and can be used to model RTN fluctuation in both directions. It is assumed that both acceptor-like and donor-like traps exist simultaneously, which are responsible for positive and negative Vth shift, respectively. Instead of analyzing individual defects, the ΔVth measured on different devices are integrated together to form a dataset for statistical analysis. Based on the Maximum Likelihood Estimation, the parameters for different distributions have been extracted. It is found that the GEV distribution agrees best with the measured ΔVth.

Acknowledgments

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