New Understanding of State-Loss in Complex RTN: Statistical Experimental Study, Trap Interaction Models, and Impact on Circuits

Jinbin Zou1, Runsheng Wang1,2,*, Shaofeng Guo1, Mulong Luo1, Zhaqing Yu1, Xiaobo Jiang1, Pengpeng Ren1, Jianping Wang2, Jinhua Liu2, Jingang Wu2, Waisum Wong2,3, Shaofeng Yu2,3, Hanming Wu2,3, Shiu-Wuu Lee2,3, Yangyuan Wang1,3, Ru Huang1,3,*

1Key Laboratory of Microelectronic Devices and Circuits (MOE), Institute of Microelectronics, Peking University, Beijing 100871, China.
2Semiconductor Manufacturing International Corporation (SMIC), Shanghai 201203 and Beijing 100176, China.
3Innovation Center for MicroNanoelectronics and Integrated System, Beijing 100871, China

*Email: ruhuang@pku.edu.cn; r.wang@pku.edu.cn

Abstract

In this paper, the statistical characteristics of complex RTN (both DC and AC) are experimentally studied for the first time, rather than limited case-by-case studies. It is found that, over 50% of RTN-states predicted by conventional theory are lost in actual complex RTN statistics. Based on the mechanisms of non-negligible trap interactions, new models are proposed, which successfully interpret this state-loss behavior, as well as the different complex RTN characteristics in SiON and high-κ devices. The circuit-level study also indicates that, predicting circuit stability would have large errors if not taking into account the trap interactions and RTN state-loss. The results are helpful for the robust circuit design against RTN.

Introduction

The random telegraph noise (RTN) has emerged as a critical concern for modern VLSI design [1-8] due to its increasing amplitude as device scaling, which leads to severe time-dependent variations in nanoscale technology nodes. It is understood that single oxide trap behavior causes RTN with 2 distinct current-state variations; and multiple traps accounts for the more-frequently-observed cases of complex RTN with more states [5-7]. Conventionally, complex RTN is treated as the superposition of individual traps independently (i.e. n traps lead to 2^n RTN states). On the other hand, the trap interaction can be significant in complex RTN, as we have found in 2-trap (4-state) RTN experiments recently [7]. However, rather than limited case-by-case studies of individual RTN, the characteristics of complex RTN with more states needs to be further investigated from statistical experiments, for deep understanding of the trap interaction behavior and its practical impact on circuit stability.

Therefore, in this paper, the statistical characteristics of complex RTN are experimentally studied for the first time. It is observed that lots of RTN states predicted by the conventional theory are lost, due to the non-negligible trap interaction behaviors. Process dependence (SiON or high-κ) and frequency dependence (DC or AC RTN [8]) of the RTN state-loss are also discussed. According to the balancing degree of trap interactions, theoretical models based on inheritance hierarchical and non-hierarchical systems are proposed for multiple traps, which can well explain the experiments and provide guidelines for circuit analysis. The results are helpful for the understanding of trap behaviors and the future robust design against RTN.

Devices and RTN Characterization

Devices used in this work are with high-κ/metal-gate (HKMG) or SiON/Poly-Si gate stacks. The statistics of all the device drain current with RTN (2-state and complex cases) and without RTN (i.e., 1-state) were characterized. More than 270 devices were measured. Fig. 1(a)&(d) show two examples, with histogram as Fig. 1(b)&(e). With Gaussian Mixture Model and EM algorithm [9] as RTN/current state extraction method, these two examples show 4 distinct RTN states respectively, which is believed to be caused by 2 discrete traps by common understanding. Current variations under both DC and AC RTN cases can be analyzed in the same way, as shown in Fig. 2. Fig. 2 (c)&(d) represents current-state statistics of (a)&(b), which indicates that the RTN time constant statistics change largely under digital circuit operations [8]. More interestingly, Fig. 2 (e)-(h) shows that AC signals can stimulate additional RTN state. This is because that slow trap can be activated with increased frequency [7, 8].

Results and Discussions

A. New observations on complex RTN statistics

Trap number per device is believed to be Poisson distributed [10] (as the inset of Fig. 3). The conventional understanding of trap-number and RTN-state-number relationships predicts that n traps induce 2^n state, which results in the ideal RTN state number distribution with peaks on particular positions of 2, 4, 8, etc., as shown in Fig. 3. However, the statistical experimental results exhibit irregular RTN state distribution for both SiON and high-κ cases in Fig. 4, with only one clear peak on distribution and sharp drop towards the higher state number. Besides, HKMG devices show more states, i.e. more traps per device than SiON case. The most likely reason of the mismatch between experiments and the ideal cases is that the activities of some traps are impacted by the occupation of other certain traps, i.e., n traps in one device cannot lead to all possible 2^n variation states in drain current, due to trap interactions that change the trap physical properties. There are two microscopic
mechanisms of trap interaction: one is the Coulomb repulsion effect between each traps (Fig. 5), the other is the channel percolation effect induced local carrier density perturbation [11] beneath each trap (Fig. 6). By studying a 4-state (2-trap) RTN case, strong trap interactions can be observed in Fig. 7: one filled trap degrades the occupancy rate of the other one by 10%~60%. With the physical property of certain traps being largely affected by some filled traps, it is reasonable to understand the RTN state-loss in Fig. 4. It is worth noticing that, channel percolation effect can cause unbalanced trap interactions between each other, as shown in Fig. 6; while the interactions by Coulomb repulsion effect are balanced or “equal” for each trap. Thus, the trap interaction behavior should be modeled with regards to different balancing degrees of interactions, for deeper understanding of complex RTN statistics and RTN state-loss. 

B. Theoretical Modeling of Trap Interaction Mechanism

In single nanoscale device with few oxide traps, where dominant trap interaction mechanism is channel percolation effect, multi-trap exhibits an unbalanced hierarchical priority. As shown in Fig. 8, an inheritance hierarchical system (model HS) is proposed to describe trap interaction behavior with an average degradation rate of $\lambda$, to represent the observed trap interactions (e.g., as in Fig. 7). On the other hand, for the case of much more traps in one device, Coulomb repulsion effect prevails as dominant interaction mechanism, due to the fact that traps are closer and more traps can average the percolation effects to some extent. In this case, trap interactions are balanced due to the nature of Coulomb repulsion, and interactions will be stronger with reduced trap distance. Thus, the more-trap case suits a non-hierarchical system (model NHS) considering all traps equally as shown in Fig. 9. Fig. 10 gives the results of Model HS with various trap number and $q$. Only a few states can be frequently observed, and the state-loss is more than 50%, especially for the stronger trap interaction cases. If further including Poisson distribution of trap number, the correlation between experimental results and theoretical calculations are plotted in Fig. 11, as a function of average trap number ($\bar{\lambda}$) and $q$. Model NHS results in Fig. 12 reveals that under AC operations, some additional traps per device (i.e., larger $\bar{\lambda}$) are activated. Fig. 13 compares the experimental statistics of complex RTN with both models. Note that, $\bar{\lambda}$ and $q$ are self-consistently solved and have unique solution in each model. It can be observed that model HS fits the SiON devices well with a lower $\bar{\lambda}$ (~1.4) and weaker trap interactions ($q$~0.7), while model NHS better describes the HKMG devices with a higher $\bar{\lambda}$ (~3.5) and stronger trap interactions ($q$~0.3). This is exactly consistent with the expectations above that the process with more traps per device has balanced but stronger trap interactions.

C. Impacts on Digital Circuits

With the above new understanding of trap interactions, the complex RTN impact on circuit can be precisely predicted. As shown in Fig. 14, A 5-stage ring oscillator (RO) is adopted in the study as typical digital circuit. RTN states with particular trap-filling combinations are applied as a result of the above trap interaction models. Transient circuit simulations of RTN are performed on our recently-developed platform [12]. Monte Carlo simulations with random RTN amplitude ($\Delta V_{th}$) are repeated many times for average, as shown in Fig. 15. It is found that, the RTN state-loss results in the non-Gaussian distribution of RO frequency ($f$) degradation (Fig. 16), which distinctly differs from the Gaussian distributions predicted by conventional theory. The overall distribution of $\Delta f/f$ from the conventional prediction and the proposed new models are shown in Fig. 17. Although they all present exponential trends at the tail, new models show steeper probability drops at higher degradation range, due to the fact that larger variations caused by many traps being filled at the same time will not frequently appear in the presence of strong trap interaction. For the same set of experimental data extraction, Model NHS (thus high-k technology) tends to have smaller variation than HS (thus SiON technology) at high-$\sigma$, due to more balanced trap interactions. Fig. 18 shows Weibull plot of ideal non-interaction case and interaction cases. The 3-$\sigma$ and 6-$\sigma$ of RO $f$ degradation are extracted in Fig. 19. Without considering trap interactions, circuit instability due to complex RTN will be largely overestimated by 48%~72%.

Summary

The state-loss in complex RTN statistics are observed for the first time, which cannot be interpreted by conventional theory. New models based on non-negligible trap interactions are proposed. The process (SiON vs. high-k) and frequency (DC vs. AC) dependence of complex RTN statistics are also found. The results indicate that, precise prediction of practical RTN impacts on circuit stability should be with the new understanding of state-loss induced by trap interactions.

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Fig. 1. (a)(b)(d)&(e) Device currents and the histogram plots. (c)&(f) Current-variation or RTN-state extraction by Gaussian Mixed Model based on EM algorithm.

Fig. 2. (a)–(d) and (e)–(h) are two sets of experimental results. Under AC operating condition (b), RTN time constants can be largely different from the DC case (a). AC signals can also stimulate additional RTN state (f) compared to (e), indicating more traps are activated.

Fig. 3. Ideal RTN state distribution follows discrete distribution with peaks at $2^n$ positions, where trap number $n$ follows Poisson distribution as inset figure.

Fig. 4. Measured RTN-state distributions show sharp trends for both SiON and HKMG devices. No discrete peaks (like Fig. 3) are observed. Lots of RTN states predicted by conventional theory are lost under both DC and AC operations. HKMG devices show more states, indicating more traps per device, as expected.

Fig. 5. Coulomb repulsion effect as the trap interaction mechanism: capture of trap A changes capture & emission barrier of trap B due to additional Coulomb barrier. Fig. 5. Ideal RTN state distribution follows discrete distribution with peaks at $2^n$ positions, where trap number $n$ follows Poisson distribution as inset figure.

Fig. 6. Another mechanism of trap interaction behaviors (by atomistic simulation): traps on the same percolation path will have different and unbalanced impact on each other.

Fig. 7. Experimental observation of trap interactions in a 4-state RTN case-study: capture of one trap degrades the other’s occupancy rate by 10%–60%.

Fig. 8. Inheritance hierarchy system model for traps (model HS): multiple traps are considered to be interacting with a hierarchical priority map (left figure). If one higher-level trap (A) is trapped, the occupancy rate of the lower-level ones (B, C, D, E) adopts a degeneration rate of $q$. Lower $q$ means stronger interactions. Lower-level trap inherits all impact from higher ones. Right charts show an example of occupancy probability for a three-trap system.

Fig. 9. Non-hierarchical interaction system for traps (model NHS): each trap is considered to be equal and share the mutual influence. The RTN states transition map could be described by Markov Chain as shown on right. The filled traps (number of $N$) give a $q^N$ impact on all other ones.

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Fig. 10. (a) Practical statistics of trap-number and RTN state-number relationships calculated by model HS. (b) The stronger interaction between traps (lower \( q \)), the less states will be observed. (c) The proportion of the RTN state-loss.

Fig. 11. Correlation between model HS and experimental results as a function of \( q \) and \( \lambda \): for a particular set of results, a medium degeneration rate of \( q \) is found.

Fig. 12. Correlation between model NHS and experimental results as a function of \( \lambda \): in AC RTN case, average trap number is increased.

Fig. 13. (a) & (b) Model HS is more suitable for describing SiON devices (with \( \lambda \sim 1.4 \) and \( q \sim 0.7 \)). (c) & (d) Model NHS better fits HKMG devices (with \( \lambda \sim 3.5 \) and \( q \sim 0.3 \)), which means more traps & stronger trap interactions. Note that, \( \lambda \) and \( q \) are self-consistently solved and have unique solution in each model.

Fig. 14. 5-stage RO & RTN-induced jitter noise schematics. Practical trap filling combinations are applied.

Fig. 15. \( \Delta V_{TH} \) follows exponential distribution. Simulations are repeated many times to average \( f \) degradation.

Fig. 16. 2-trap & 3-trap at each stage of RO cases: w/o consideration of trap interaction, \( f \) degradation and jitter variation is larger; while w/ trap interaction case shows non-Gaussian distributions.

Fig. 17. With trap number following Poisson distribution & \( \Delta V_{TH} \) as exponential distribution, PDF of \( f \) degradation can be obtained.

Fig. 18. Weibull plot of \( f \) degradations for (a) SiON and (b) HKMG cases. Compared to w/o trap interaction, trap interaction models shows less degradation due to that many possible RTN states are concealed by trap interaction behaviors.

Fig. 19. If applying the conventional prediction (w/o interaction), there is an overestimation of 48%–72% for RO frequency variation.