# An Electric-Based Model for Coupling Traps Effect on Random Telegraph Noise

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*Abstract*— **In this work, we present a novel understanding about the anomalous Random Telegraph Noise (aRTN), asserting the existence of coupling effect among multiple traps regarding current amplitude deviation. Based on the examination in the literature of anomalous current fluctuation, we propose a model able to describe the equivalent filament resistance changes due to this process. Notwithstanding, the results obtained with our model fits with experimental current over time observations presented on literature. Given that RTN is still a concern for different technologies, such as MOSFETs, FinFets and ReRAMs, the model can be applied to understanding the dynamics of filament distribution and the trapping de-trapping activity.**

*Index Terms*— **Random Telegraph Noise; Coupling Traps; Resistive Coupling Model.**

## I. Introduction

Promising devices, such as Resistive Random Access Memory (ReRAMs), have received attention in the past decade since the semiconductor's industries are concentrating efforts on improving the system's capability to store and process large amounts of information. In terms of future applications, ReRAM devices are also considered the most promising choice to play the role of synapses in nowadays neuromorphic circuits [1]. However, ReRAMs consistently face reliability issues.

In this work, we examine Random Telegraph Noise (RTN), which is the most significant form of noise in ReRAMs devices and was also widely explored and observed in traditional MOSFETs. As ReRAMs operation principles are based on electrical applied pulses that modify the defects structure in such arrangement, the RTN behavior can also be leveraged as a tool to assess the impact of defects on materials and production processes yield [2]. Thereby, embracing these effects on the analysis of resistive switching mechanisms is critical to better comprehend the physics of ReRAM devices [3].

RTN signals are usually expressed by a random fluctuation of a detectable quantity, (e.g. current, voltage, impedance) between two discrete states, and characterized by the charge trapping/emission processes into/from a trap [4]. It can also be found as a multi-level RTN signal, which is often modeled by the activity of multiple and independent defects, that results in the superposition of independent two-level RTN signals. Such signals are commonly analyzed by the Factorial Hidden Markov Model [5].

Additionally, experimental RTN signals measured in ReRAM devices have shown anomalous RTN (aRTN) behavior, i.e., where defects may have different charge states that vary a trap statistical-parameter temporarily and randomly. Sometimes, RTN components resulted from different defects present some degree of correlation. This aRTN behavior, also seen in traditional MOSFETs, cannot be modeled as a simple sum of independent two-level RTN discrete fluctuations [6].

In this work we refine the understanding of aRTNs, asserting the existence of a *coupling effect* among multiple traps regarding current amplitude deviation, meaning that the current deviation of one component of the RTN signal at a given instant of time is also dependent on the state in which other components are found, that is, presenting a *coupling effect*. This electric model has not been covered by previously cited two-level, multi-level, and aRTN fluctuations [6]. We modeled this behavior (*coupling effect*) as trapping de-trapping activity of different defects that modify series and parallel effective resistance of an equivalent conductive filament.

## II. Coupling Trap Model

In this work, the physical mechanisms of the trap coupling effect on RTN amplitudes are studied based on experimental results from the literature [7, 8]. The goal is to propose a simple model for trap coupling in conduction paths. In devices where the current conduction channel is not homogeneous, current may flow preferably over paths of lower electrical resistance. This is the usual situation in current flow over dielectrics such as the ones employed in ReRAMs. It may also be the situation in MOSFETs and FinFETs where Random Dopant Fluctuations (RDF) and Random Traps play a role, as discussed below [9].

Considering ReRAMs, the electrical field may not be constant over the dielectric. Then electrical potential at the trap site is not solely a function of trap distance from the electrodes, as sometimes assumed in the literature. A similar situation may appear in MOSFETs, and current may percolate preferably over paths with lower electrical resistance. Paths of different electrical resistance may result from RDF. In the literature results, it is observed that the activity of one trap may interfere (couple) with the activity of another trap. There are also observations of trap coupling on different devices, such as FinFETS and planar MOSFETs [6], [10].

In this work, we investigate RTN with coupled amplitude, which means, when the amplitude of one trap can be altered if another trap stayed in its occupied state. If the trap amplitude increases, we consider it to be *positive coupling*. If the trap amplitude decreases, we consider it to be *negative coupling*. In the literature, both the positive and negative coupling have been observed.

If the conduction channel is not homogeneous, percolation paths may be established, originating paths of lower electrical resistance connecting one electrode to the other. This may be considered as a network of electrical resistances. Considering a given branch that connects one electrode to the other, the electrical field and electrical potential at a given

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position of the branch may be affected by the activity of traps located along the branch. If a trap switches its state, capturing or emitting a charge carrier, it may change the resistance at its position, changing the electrical potential at other positions along the branch. When considering a network of electrical resistors, trap activity dynamically changes its values.

If the voltage at the terminal of a resistor network is kept constant, and the value of a resistor in a series arrangement is increased, the potential drop over the other resistors in series with it will decrease. On the other hand, if the value of a resistor in a parallel branch of the network is increased, the equivalent resistance of the parallel branch will increase, leading to an increase of the potential drop over the parallel resistors. Considering that, trap activity changes the values of resistors in the network, and that trap amplitude depends on the voltage drop (electrical potential) at the path where the trap is located, it will be shown below that both positive and negative trap coupling may be observed.

Note that if a serial trap drastically increases the electrical resistance at its position, it may almost block the current flow along the whole branch. In this case, a second trap eventually located downwards or upwards the branch may have a negligible effect on current conduction. This may lead to apparent 3-level RTN or transient RTN, where the activity of one trap is visible only when the other trap allows current flow over its location. Similarly, if a serial trap resistance is significantly greater than a parallel branch under trap activity this may also lead to apparent 3-level RTN or transient RTN.

In the next section, literature results presented in [7] and [8] showing the coupling of two traps in ReRAM devices are discussed in the framework of the model here presented. Please note that the modeling framework here proposed is not restricted to the case of two traps and ReRAM devices.

## III. Case Study

### A. *Series Coupling Traps Model*

To understand the negative coupling amplitude effect, we propose a coupling model considering traps on conductive filaments. Particularly, different filaments branches may be arranged in parallel or in series, whereas the traps are always arranged in series in this model (observe traps $T_{S1}$ and $T_{S2}$ highlighted in Fig. 1). The states of $T_{S1}$ e $T_{S2}$, modify the filament resistances $R_{S1}$ and $R_{S2}$, for both Low Resistive State (LRS), defined by a state of higher conductivity after a set process, in which trap activity is caused by a Coulomb blockade of a portion of the filament, and High Resistive State (HRS), assuming a MP-trap-assisted tunneling mechanism [11, 3]. For instance, the resistance $R_{S1.EMP}$, related to $T_{S1}$ in its empty state, is lower than $R_{S1.OCC}$, related to $T_{S1}$ occupied, the same occurs for $T_{S2}$ and the associated resistance $R_{S2}$. Let us now assume $T_{S1}$ switches faster than $T_{S2}$ for analysis purposes. When $T_{S2}$ changes from *EMP* state to *OCC* state, $R_{S2}$ increases, as also its applied voltage ($VR_{S2}$). At the same time, this decreases the total current in the filament, as also the applied voltage in $R_{S1}$ ($VR_{S1}$). Therefore, the current deviation produced by $T_{S1}$ is impacted by $T_{S2}$ activity and is less significant when $T_{S2}$ is occupied, modeling the negative coupling amplitude effect.

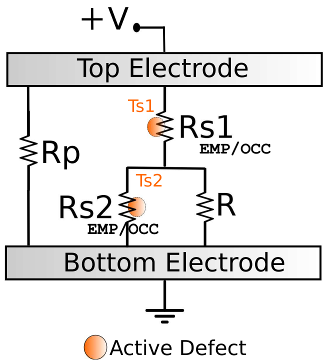


Fig. 1: Series Coupling Traps Model. Note that the resistances could be also arranged as in Fig. 4, resulting in a serial coupling since an active trap was also located at resistance Rs.

The described behavior appears in Fig. 2, obtained in [7], where is assumed the current varying over 3 different well-defined levels (Fig. 2). This aspect is nonconforming with the established multi-level RTN definition [11], where is expected $2^N$ different levels. In [7] such behavior is modeled by charges diffusion resulting in a physical interaction between oxygen vacancies (Vo) and neutral oxygen interstitial (NOI). The assumption is that the activity of a fast defect, such as Vo, could be suddenly interrupted by a Coulomb blockade effect, caused by the occupied NOI. In this work, we show that this behavior can also be modeled by a simple series trap arrangement, such as presented in Fig. 1. In this case, Level 1 can be the result of a negative coupling, when the amplitude of a trap decreases if another trap stayed in its occupied state.

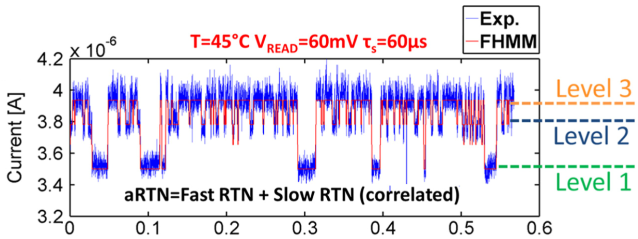


Fig. 2: Experimental Anomalous RTN in a $HfO_2$ based sample under a constant 60mV applied voltage. Adapted of [7].

The equivalent resistances (Req), measured between the top and bottom electrode, are obtained by the relation between the applied voltage, V, and the current levels approximated by Fig. 2: $I_{EMP/EMP}$ = 3.9 $\mu$A, $I_{EMP/OCC}$ = 3.8 $\mu$A, $I_{OCC/EMP}$ = 3.56 $\mu$A, and $I_{OCC/OCC}$ = 3.55 $\mu$A. Note that the resistance R is included just for model compatibility purpose, considering the Parallel Coupling Traps Model, presented in the next section. To simplify the analysis, R can be assumed as an open circuit, $R -> \infty\ \Omega$. The parameters are estimated as follows:

$$I_{StateS1/StateS2} = \frac{V}{Req_{StateS1/StateS2}} = \frac{V}{(R_{S1.(EMP/OCC)} + R_{S2.(EMP/OCC)})//Rp} \tag{1}$$

The equation system composed by the four possible states derived of (1) is numerically solved. Please note that multiple solution exists. In Table I, two examples of solution sets are presented. Even though a unique solution set is impossible, we remark that in this case, $R_{S2.OCC}$ is always orders of magnitude larger than Rp, which always converges to a similar value that corresponds to the higher equivalent resistance level, related to LEVEL 1. Values presented in Solution 1, with a mean error $\varepsilon$M= 100$\Omega$, are the ones used to fit data to model, not meaning they are better than the other possible solutions.

Table I. Parameters Solution

| Parameter | Solution 1 | Solution 2 |
|---|---|---|
| Rp | 17 KΩ | 17 KΩ |
| $R_{S1.EMP}$ | 102,7 KΩ | 149 KΩ |
| $R_{S1.OCC}$ | 160,0 KΩ | 209 KΩ |
| $R_{S2.EMP}$ | 57.9 KΩ | 12.9 KΩ |
| $R_{S2.OCC}$ | 1.75 MΩ | 2.42 MΩ |

From the extracted parameter it was possible to plot the current over time model fitting curve, Fig. 3, that corresponds in terms of amplitude fluctuation with the experimental data observed in Fig. 2. In this work, the time constants were arbitrarily approximated considering a fitting standpoint and assumed to be in an exponential distribution as described by [12], making $T_{S2}$ emission/capture time constants (3 ms/ 16 ms) greater than $T_{S1}$ ones (165 ms/ 66 ms). Although it is known that the RTN also exhibits a Lorentzian when observed in the frequency domain [12], such analysis is not addressed in this work.

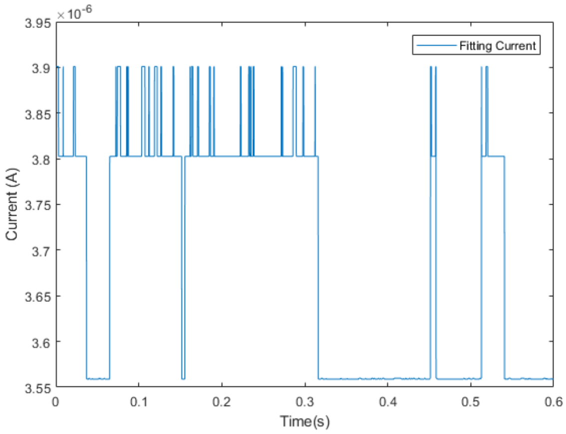


Fig. 3 Series Coupled Traps Model Current Fitting

### B. Parallel Coupling Traps Model

To understand the positive coupling amplitude effect, we propose a coupling model considering traps on conductive filaments. In this model, the traps are always arranged in parallel branches (observe traps $T_{P1}$ and $T_{P2}$ highlighted in Fig. 4). The states of $T_{P1}$ e $T_{P2}$, modify the filament resistances $R_{P1}$ and $R_{P2}$ for both LRS and HRS [11, 3]. For instance, the resistance $R_{P1.EMP}$, related to $T_{P1}$ empty state, is lower than $R_{P1.OCC}$, related to $T_{P1}$ occupied, the same occurs for $T_{P2}$ and the associated resistance $R_{P2}$. Let us now assume $T_{P1}$ switches faster than $T_{P2}$ for analysis purpose. When $T_{P2}$ changes from *EMP* state to *OCC* state, $R_{P2}$ increases, as also its applied voltage ($VR_{P2}$) which is the same in $R_{P1}$ ($VR_{P1}$). Therefore, the current deviation produced by $T_{P1}$ is impacted by $T_{P2}$ activity and is more significant when $T_{P2}$ is occupied, modeling the positive coupling effect.

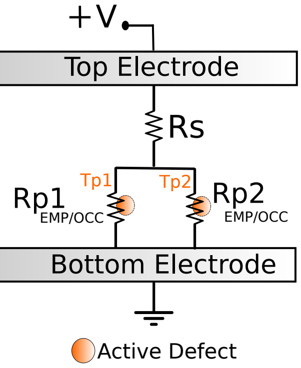


Fig. 4: Parallel Coupling Traps Model. Note that the resistances could be arranged as in Fig. 1, resulting also in a parallel coupling since an active trap was located at resistance R.

The described behavior is exemplified by a measurement presented in [8] for a TMOx-based resistive switching memory (TMOxRAM), shown in Fig. 5. The positive coupling amplitude effect is verified since ΔI1, here called ΔILow, is more significant than ΔI2, here expressed as ΔIHigh. In short, ΔILow > ΔIHigh. Once again, this difference is nonconforming with classical multi-level RTN definition.

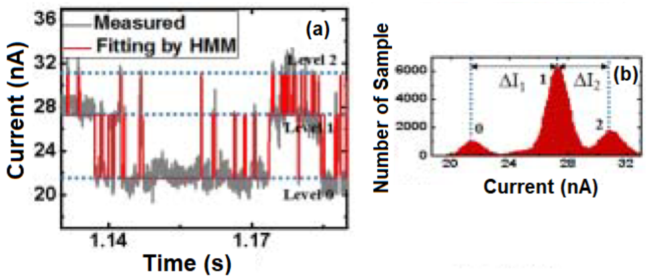


Fig. 5: (a) Experimental Anomalous RTN in a TMOxRAM based sample under a constant 100mV applied voltage and (b) the respective current discrete levels. Adapted of [8]

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Similarly, the estimated equivalent resistances states values are obtained by the relation between the applied voltage, V, and the current levels approximated by Fig. 5: $I_{EMP/EMP}$ = 3.1 nA, $I_{EMP/OCC}$ = 2.8 nA, $I_{OCC/EMP}$ = 2.805 nA, and $I_{OCC/OCC}$ = 2.1 nA, as follows:

$$I_{StateS1/StateS2} = \frac{V}{Req_{StateS1/StateS2}} = \frac{V}{R_S + (R_{P1.(EMP/OCC)} // R_{P2.(EMP/OCC)})} \quad (2)$$

The equation system composed by the four possible states derived of (2) is numerically solved. Please note that multiple solutions exist. Values presented in the Solution 1 of Table II, with a mean error $\varepsilon$M= 1 $\mu\Omega$, are the ones used to fit data to model, not meaning they are better than the other possible solutions. From the aforementioned process, we obtained two possible solution intervals: one showing $\Delta R_{P1}$ = ($R_{P1.OCC}$/$R_{P1.EMP}$) > $\Delta R_{P2}$ = ($R_{P2.OCC}$/$R_{P2.EMP}$))

and other considering $\Delta R_{P2} > \Delta R_{P1}$. Even though a unique solution set is impossible, we remark that in this case, $\Delta R_{P1}$ and $\Delta R_{P2}$, present similar orders of magnitude in the two counterpart intervals. Also, the algorithm always converges to the same Rs. From the extracted parameter was possible to plot the I-t fitting curve, Fig. 6, that corresponds in terms of amplitude fluctuation with the experimental data observed in Fig. 5 making $T_{P2}$ emission/capture time constants (3 ms/ 16 ms) greater than $T_{P1}$ ones (165 ms/ 66 ms).

Table II. Parameters Solution

| **Parameter** | **Solution 1** | **Solution 2** |
|---|---|---|
| Rs | 2.61 MΩ | 2.61 MΩ |
| $R_{P1.EMP}$ | 1.74 MΩ | 963 KΩ |
| $R_{P1.OCC}$ | 4.46 GΩ | 5.15 MΩ |
| $R_{P2.EMP}$ | 957 KΩ | 1.72 MΩ |
| $R_{P2.OCC}$ | 2.15 MΩ | 2.63 GΩ |

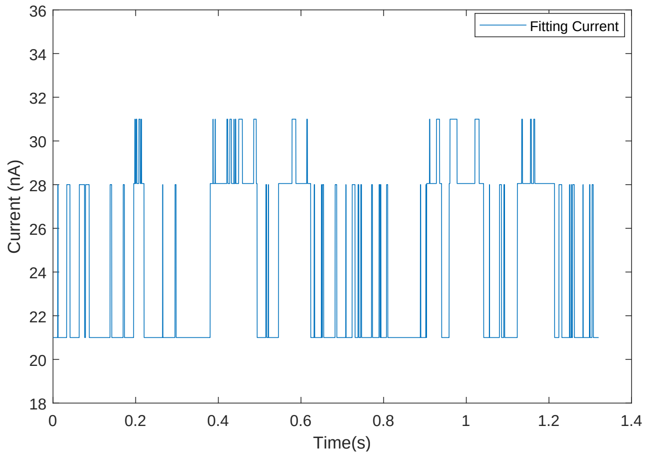


Fig. 6 Parallel Coupled Traps Model Current Fitting

## IV. Conclusion

The electric models presented in this work refine the understatement of RTNs in ReRAMs, asserting the existence of a *coupling effect* among multiple traps regarding current amplitude deviation. We propose a coupling model considering traps on conductive filaments. Particularly, different filaments branches may be arranged in parallel or in series, whereas the traps are arranged once in parallel resulting in a positive coupling amplitude, $\Delta$ILow $>$ $\Delta$IHigh, behavior or in series resulting in a negative coupling amplitude, $\Delta$IHigh $>$ $\Delta$ILow, behavior. Experimental literature study of case data fits with the models assumptions. Considering this anomalous current fluctuation, RTN signals could not be evaluated by traditional techniques and a novel method, assuming the possibility of trapping *coupling effect*, should be proposed.

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