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Application of the defect clustering model for forming, SET and RESET statistics in RRAM devices

Nagarajan Raghavan *

Engineering Product Development (EPD) Pillar, Singapore University of Technology and Design, 487 372, Singapore

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ABSTRACT

The choice of the right statistical model to describe the distribution of switching parameters (forming, SET and RESET voltages) is a critical requirement for RRAM, as it is used to analyze the worst case scenarios of operation that have to be accounted for while designing the cross-bar array structures, so as to ensure a robust design of the circuit and reliable data storage unit. Several models have been proposed in the recent past to characterize the voltage variations in V_{FORM}, V_{SET} and V_{RESET} using the percolation framework. However, most of these models assume defect generation to be a Poisson process and apply the standard Weibull distribution for parameter extraction and lifetime extrapolation. Recent dielectric breakdown studies both at the front-end as well as back-end have shown that the Weibull statistics does not describe the stochastic trends well enough, more so in downscaled structures at the low and high percentile regions given the possibility of defect clustering which is either physics-driven or process quality-driven. This phenomenon of defect clustering is all the more applicable in the context of resistive random access memory (RRAM) devices, as switching occurs repeatedly at ruptured filament locations where defect clusters pre-exist. This study examines the validity of the clustering model for RRAM switching parameter statistics (time/voltage to FORM, SET and RESET) and presents a physical picture to explain the origin of clustering in RRAM. A large set of data from various published studies has been used here to test the suitability and need for a clustering model based reliability assessment. Dependence of the clustering factor on temperature, voltage, device area, dielectric microstructure and resistance state has also been examined.

1. Introduction

Spatial and temporal patterns of defect nucleation, transport and growth during electrical/thermal stresses on dielectric thin films play a critical role in determining the lifetime of many nanoelectronic devices, one of which is the resistive random access memory (RRAM). As a potential non-volatile memory (NVM) technology for the future, RRAM operates as a binary storage device through repetitive breakdown and recovery of the dielectric, depending on the applied voltage stress magnitude and polarity. The role of oxygen vacancy/metal ion defects is crucial in the functioning of RRAM as they influence the stochastics of forming, SET and RESET events in the stack. In the past, defect nucleation was by default assumed to follow the Poisson process [1] wherein there is no spatial preference for the evolution of defects and eventual percolation occurs when a cluster of closely spaced defects forms a chain shorting the two electrodes on either side of the oxide layer [2,3]. This led to the widespread use of the Weibull distribution to model the time to breakdown trends in logic devices [4] as well as switching statistics in NVM technology [5].

However, recent studies on time-dependent dielectric breakdown (TDDB) by Wu et al. [6,7], Yokogawa et al. [8] and Shimizu et al. [9] reveal that the Weibull model fails to describe the failure data well especially at the extreme percentile regions. The existence of process-induced defects as well as intrinsic dimensional (geometric) variations in the patterned features of highly downscaled devices was proposed to be the origin of the non-Weibullian trends observed. Taking cue from yield models that talk about non-homogeneous defect density distributions in space and time [10,11], a failure model was developed in Ref. [6] that accounted for the spatial distribution of defects and its impact on the mean and variation in breakdown lifetime. This is referred to as the clustering model and its validity for FEOL, MEOL and BEOL technologies has been adequately demonstrated [7]. However, in spite of its relevance to the switching stochastics and the commonalities between dielectric breakdown (SBD, HBD) and resistance switching (oxygen vacancies, metal filaments), the cluster model has yet to be advocated for better representation of the distributions of forming voltage (V_{FORM}), SET (V_{SET}) and RESET (V_{RESET}) voltages. The aim of this study is to do just that.

There are multiple reasons why the clustering model might be a suitable one for modeling the statistics of switching in RRAM. In recent times, first principle studies by Bradley et al. [12,13] have suggested that the presence of a vacancy defect at a certain location makes it favorable for additional defects to nucleate in its neighborhood with lower

* 8 Somapah Road, Singapore University of Technology and Design, 487 372, Singapore.
E-mail address: nagarajan@sutd.edu.sg.

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activation energy. The nucleation of additional defects in the vicinity becomes increasingly thermodynamically favored when the existing defect cluster tends to grow in size as the collection of vacancies has a stronger binding energy per vacancy [13]. It is also possible for vacancies to diffuse/drift and segregate/aggregate along fault lines such as grain boundaries/dislocations in polycrystalline dielectric stacks (microstructure in the post-anneal stage) [14,15]. These non-idealities have not been captured by recent statistical models and as a result, the fit to the forming and SET voltage distributions tend to be inaccurate when the standard Weibull model is used [16,17].

In this study, we will use the clustering model to fit a wide variety of data extracted from various literature reports pertaining to V_{FORM}, V_{SET} and V_{RESET} at different voltage and temperature stress conditions. The dependence of the clustering effect on the above stress factors as well as device area, dielectric microstructure and resistance state level will be examined and the physical mechanism underlying the clustering trends shall be qualitatively explained.

This work is organized as follows. Section 2 introduces the clustering model (CM) and its underlying formulation. In Section 3, CM is used to fit the V_{FORM} distribution for both amorphous and polycrystalline microstructure dielectrics. Section 4 analyzes the validity of CM for SET at different temperature and voltage stress conditions as well as device areas. The RESET process is examined in Section 5 and CM is used to fit two very different low resistance states (LRS) with thin and thick filaments to observe the differences in the optimum model parameter values. Finally, Section 6 concludes with a summary of the results and presents key ideas worth investigating further.

2. Defect clustering model

The cumulative density function for failure (yield loss) using the clustering model can be expressed by Eq. (1), where λ is the average number of defects and α is the clustering factor. The value of α ranges between $(0, \infty)$ with $\alpha \to \infty$ implying perfectly random defect generation, taking us back to the Poisson process. Low values of α closer to zero are indicative of high clustering effect. In the case of constant and ramped voltage stress, from a reliability standpoint, the expression for λ may be given by Eqs. (2) and (3) in the form of a power law, where η and β represent the mean time (voltage) to failure and the Weibull shape parameter, respectively, while RR is the ramp rate. The parameter λ, in the reliability context with time dependency, can be interpreted as the probability of defect generation which can be assumed to follow power law for the low percentile/early failure scenarios, as is usually the case in percolation models [18,19].

$$F_{CLUS} = 1 - \left(1 + \frac{\lambda}{\alpha}\right)^{-\alpha} \tag{1}$$

$$\lambda = \left(\frac{t}{\eta_{CVS}}\right)^{\beta_{CVS}}; \lambda \ll 1 \tag{2}$$

$$\lambda = \left(\frac{V}{\eta_{RVS}}\right)^{\beta_{RVS}} = \left(\frac{RR \cdot t}{\eta_{RVS}}\right)^{\beta_{RVS}}; \lambda \ll 1 \tag{3}$$

3. Statistics of forming voltage (V_{FORM})

Fig. 1 shows the results of a fit of the cluster model to forming voltage measurements on a 5 nm HfO_x MIM stack with device area of 40×40 nm^2. The data was extracted from the work of Govoreanu et al. [20]. Two different microstructures were considered – one amorphous and the other polycrystalline. When the two sets of data are fit using the maximum likelihood estimate (MLE) algorithm, the value of $\alpha_{POLY} = 0.4 < \alpha_{AMOR} = 0.6$. This suggests that the clustering effect could be more pronounced in the case of polycrystalline thin films.

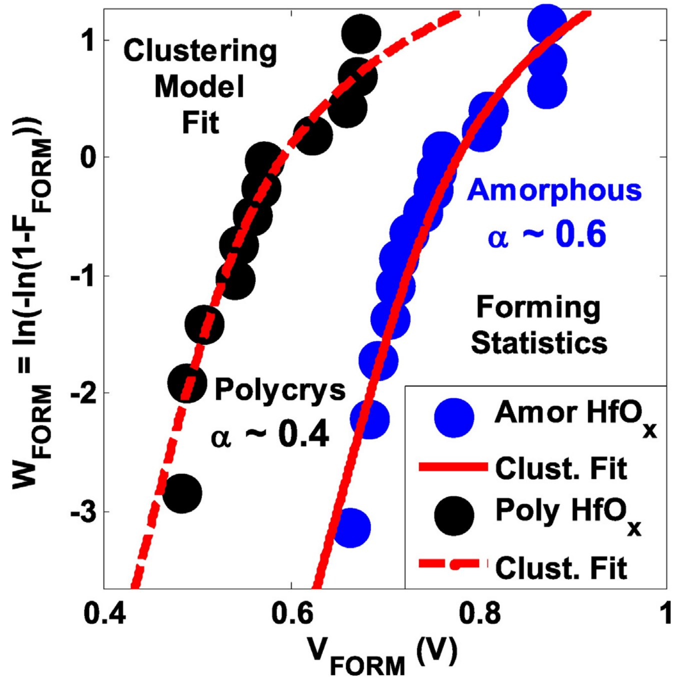

Fig. 1. Weibull plot of the forming voltage (V_{FORM}) distribution with a cluster model fitting to the data for both amorphous and polycrystalline dielectric thin films. The value of α is lower for polycrystalline stack indicative of more preferential clustering effect in and around the grain boundaries.

This is in line with theoretical [14,15] and experimental [15] studies that point to the grain boundaries (GB) acting as a sink for oxygen vacancies. The overall system free energy is lowered when the vacancies in the grain region migrate and segregate along the GB contours. Fig. 2 illustrates this scenario comparing the two different microstructures.

4. Statistics of SET events for different conditions

The SET process occurs in partially ruptured filaments with one or many defect clusters or at least a certain localized arrangement of

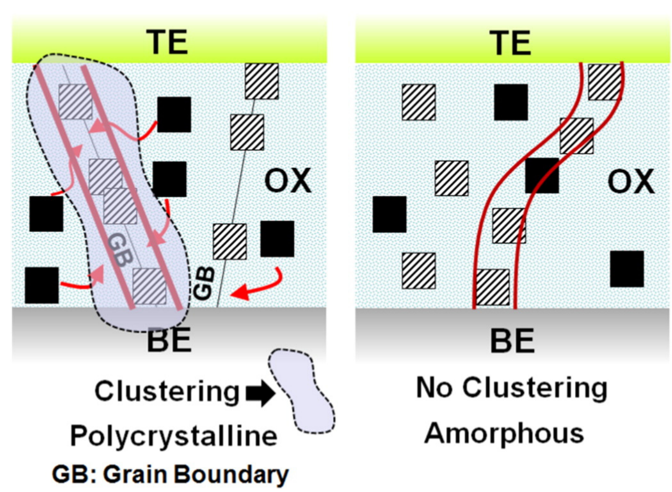

Fig. 2. Illustration showing the defect clustering process for polycrystalline and amorphous dielectric RRAM stacks. There is a higher probability for clustering to be dominant in polycrystalline thin films as the grain boundaries serve as a thermodynamic sink for vacancies to segregate to. The shaded squares represent pre-existing defects while the dark squares denote the new forming-stress induced defects. Red arrows represent the preferred vacancy migration direction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)