# Understanding on Current-induced Crystallization Process and Faster Set Write Operation Thereof in Non-Volatile Phase Change Memory

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**ABSTRACT**

We experimentally demonstrate that the crystallization process of Ge-Sb-Te crystallites during the set operation in non-volatile phase change memory commences after threshold switching event. It is also shown that the nucleation and growth rates have opposite behaviors with the increase of set operation power: the incubation time in nucleation stage can be minimized at higher power whereas the percolation time in growth stage is smaller at lower power. Based on this observation, we introduce a two-step set pulse making set write operation ~5 times faster than conventional simple rectangular or slow-quenched form.

**Key words: Incubation, Nucleation, Percolation, Growth, Two-step set pulse**

## 1. INTRODUCTION

Non-volatile phase change memory encodes binary information into Ge-Sb-Te-based phase change materials through a current-driven Joule heating: a higher and shorter pulse induces a phase change material to melt and quench to make a high-resistive amorphous state (reset operation) while a lower and longer pulse makes the material crystallize to have a low-resistive crystalline state (set operation). Meanwhile, stored data are nondestructively sensed by the difference in electrical resistance between two states.

On increasing revenue in conventional Flash memory markets, phase change memories are strongly required about the improvement of programming performance for high-speed applications toward RAM-type memory systems. The programming performance is mainly limited by the set operation because it encompasses a relatively sluggish crystallization process. Thus it is critical to understand the detailed process of current-induced crystallization of Ge-Sb-Te phase change material. Nonetheless, there are some uncertainties in crystallization process during set operation. Before three decades ago, Ovshinsky[1] has interpreted the resistance decrease after set operation in memory-type switching devices as a result of crystallization process of chalcogenide semiconductor materials accompanied with threshold switching phenomenon. Two recent experimental studies[2,3] on the set operation of phase change memory device showed that crystallization process proceeds with finite time delay after the event of threshold switching. On the other hand, Karpov et al.[4] propose a nucleation switching model where they assume a filament embryo at threshold switching in amorphous matrix and successively, they describe a crystallization process of phase change material as field-assisted growth of this longish embryo. In addition, Yeo et al.[5] also speculated from resistance changes and current waveforms of phase change memory device that the nucleation of phase change material might occur simultaneously with threshold switching.

In this study, it is experimentally demonstrated that the nucleation of Ge-Sb-Te is rarely probable before or on threshold switching but it needs a finite power-dependent incubation time right after threshold switching. Then, we systematically investigate electrical power dependencies of nucleation and growth processes of Ge-Sb-Te phase change material and those kinetic behaviors. Finally, based on these results, we introduce a two-step set pulse to speed up the crystallization.

## 2. TIME-RESOLVED ANALYSIS OF SET PROCESS

Figure 1(a) presents a typical example of device voltage waveform during set operation and superimposed low-field resistance after pulsing at fixed pulse voltage of 0.9V with various pulse widths, showing a pre-threshold time $t_{pre\text{-}th}$ of 260ns, an apparent incubation time for crystallization $t_{inc,app}$ of 400ns (at which the low-field resistance begins to decrease) and a complete set time $t_{set}$ of 440ns (at which the resistance decrease is significantly retarded). It has been thought from our previous study [3] that $t_{pre\text{-}th}$ is attributed to a parasitic RC delay, $t_{inc,app}$ is clearly related with the nucleation process of Ge-Sb-Te nuclei, and $t_{set}$ can give an information about their growth behavior, respectively.

Firstly, simple repetition test of set operation (at the fixed height of 0.9V) without intervening reset operation may answer a fundamental question of "*When crystalline Ge-Sb-Te embryos for nucleation start to form in the set*

*operation of electrical phase change memory*?" of which should be the starting point for understanding overall kinetics of set crystallization process. Regardless of repetition period (1s ~ 60s), pre-threshold set operations with smaller width (200ns and 250ns) than $t_{pre\text{-}th}$ (260ns) fail to reduce (set) the resistance of phase change memory device even up to 100 repetitions where a total accumulated time is as long as 20us~25us whereas post-threshold set operations with larger width than $t_{pre\text{-}th}$ enable to abruptly reduce device resistance only four times of 300ns and twice of 400ns, respectively, as seen in Fig. 1(b).

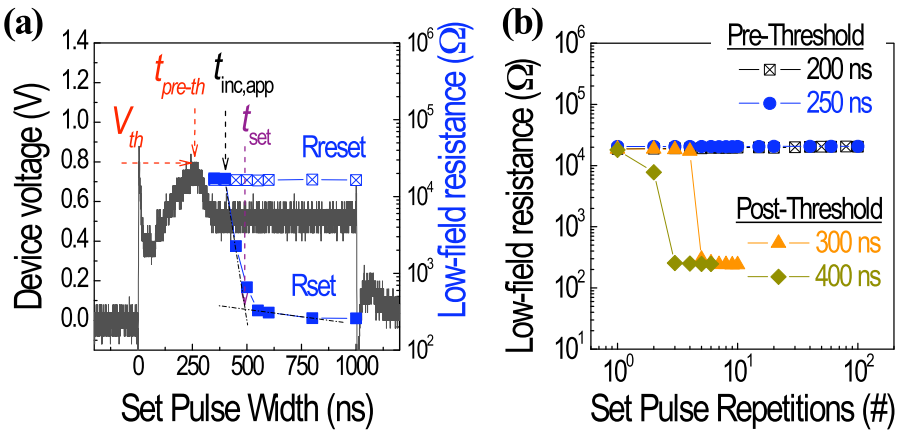


Figure 1 (a) Device voltage waveform at the set pulse voltage of 0.9 V and the set pulse width of 1us, where changes in low-field resistance at various set pulse widths are superimposed in order to show three characteristic times. As commented in ref. 2, subtle peak at both ends of the wave forms are artifacts. (b) Changes in low-field resistance with the increase of set overwrite up to 100 counts (repetition period=60s) at two pre-threshold and two post-threshold set pulse widths.

An important finding from these experiments is that Ge-Sb-Te embryos were unstable before threshold switching but they need a finite time for evolving into stable crystalline nuclei. Now, we can extract two characteristic times ($t_{inc}$ and $t_{gro}$) of crystallization process from Fig. 1(a). Here, $t_{inc}$ means true incubation time indicating a time needed to form stable Ge-Sb-Te nuclei right after threshold switching, which can be given by $t_{inc,app} - t_{pre\text{-}th}$ while $t_{gro}$ means the growth time for which Ge-Sb-Te nuclei are connected to have at least one electrical shunting path (percolation) making a low-resistive state which can be expressed by $t_{set} - t_{inc,app}$.

In case of a current-induced crystallization, it is most critical for its kinetic approach to investigate power dependencies of characteristic times of $t_{set}$, $t_{inc}$ and $t_{gro}$ since an electric power instead of temperature can be regarded as an accelerating factor in thermal-activated crystallization process. Thus we carried out set operations with different set pulse voltages (0.76V~1.80V) and monitoring real-time current levels to obtain corresponding power values. Simultaneously, voltage wave forms across device are correlated with low-field device resistances measured separately for varying set pulse widths from 100ns to 1us in order to extract characteristic times at each set operation, as shown in Fig. 2. The device was always reset with 2.0V and 100ns pulse (20mW) before each set operation for consistency. The time-averaged power during set crystallization $\overline{P}_{cryst}$ can be given by Eq. (1):

$$\overline{P}_{cryst} = \frac{t_{inc}}{t_{cryst}}\overline{P}_{nuc} + \frac{t_{gro}}{t_{cryst}}\overline{P}_{gro} \qquad (1)$$

And $\overline{P}_{nuc}$ and $\overline{P}_{gro}$ are time-averaged powers during nucleation and growth processes, respectively and are also expressed by

$$\overline{P}_{nuc} = \frac{\int_{t_{th}}^{t_{inc,app}} V_{dev}(t) I_{dev}(t) dt}{t_{inc}} \qquad (2)$$

$$\overline{P}_{gro} = \frac{\int_{t_{inc,app}}^{t_{set}} V_{dev}(t) I_{dev}(t) dt}{t_{gro}} \qquad (3)$$

where, $V_{dev}$ and $I_{dev}$ are time-dependent voltage and current through a phase change memory device and are monitored at oscilloscope during the set operation [3].

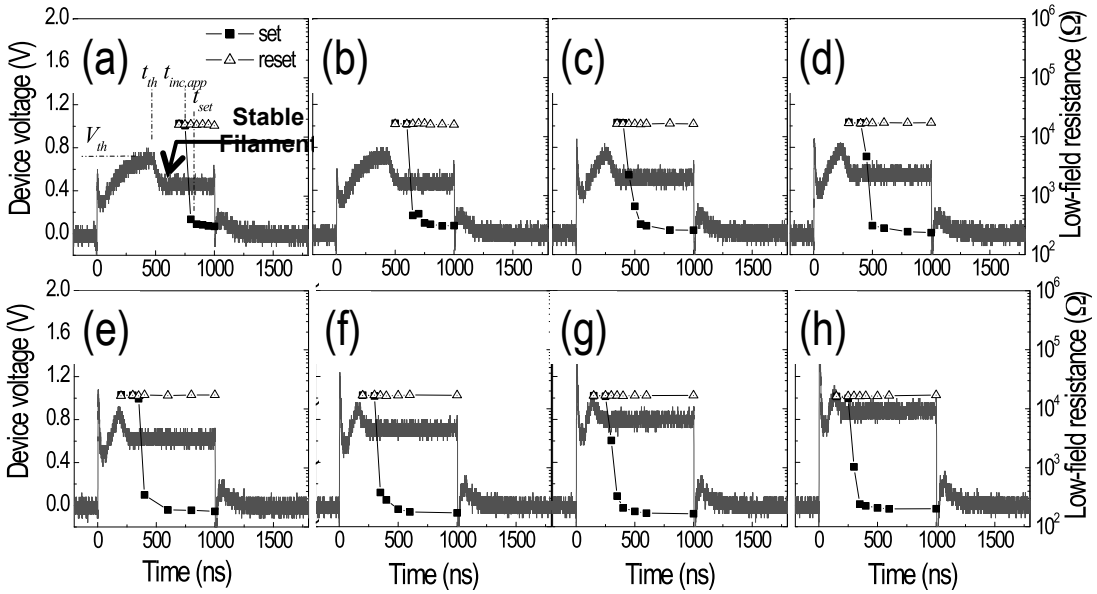


Figure 2 Device voltage waveforms superimposed by time-resolved low-field resistances at the set voltages of (a) 0.76V (b) 0.8V (c) 0.9V (d) 1.0V (e) 1.2V (f) 1.4 V (g) 1.6V and (h) 1.8 V. The device was always reset with 2.0V and 100ns pulse (20mW) before each set operation for consistency.

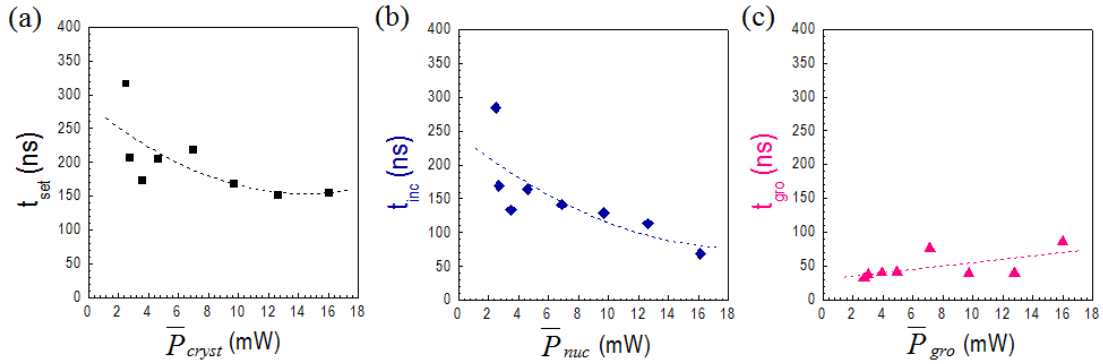


Figure 3 Set power dependencies of (a) the incubation time $t_{inc}$ and (d) the growth time $t_{gro}$ in the current-induced crystallization.

When plotting the measured values of these characteristic times as functions of above-calculated power, their power dependencies can be found out. First of all, total set time $t_{set}$ is initially decreased and becomes saturated with respect to set power but it reversely starts to increase as set power gets close to reset power (20mW) as plotted in Fig. 3(a). Interestingly, this power dependency of current-induced crystallization time is quite similar to a conventional T-T-T (Time-Temperature-Transformation) curve saying that there is a temperature showing the minimum crystallization time between crystallization temperature ($T_x$) and melting temperature ($T_m$). It is found out that such power dependency is resulted from different behavior of two gradient times of $t_{inc}$ and $t_{gro}$ on the respective power, as seen in Figs. 3(b) and 3(c). In other words, the incubation time is inversely proportional to power whereas the growth time monotonously increases with power.

According to Monte Carlo model on phase change memory by Russo *et al.*[6], it is not until the nucleation and percolation processes are electrically sensed when crystalline volume fractions reach 10% and 35%, respectively. When temperature profiles during set operation at various powers and typical T-T-T (Transformation-Time-Temperature) diagram of Ge-Sb-Te material [7] are considered together, such behaviors of characteristic times with respect to input set power can be easily understood. For this, we first draw 10% and 35% transformation curves in T-

T-T diagram, which indicates the starting point of electrical-sensible nucleation and percolation processes at various temperatures and times. Next, a temperature profile generated by electrical set pulse is overlapped to these transformation curves, as depicted in Fig. 4. Accordingly, we cannot only estimate $t_{inc}$ and $t_{gro}$ times from the intersections of 10% and 35% transformation curves and temperature profile at a given set power, respectively but also interpret their behaviors as the electric power that is, evolving temperature profile are changed. Intrinsically, $t_{inc}$ is continuously decreased as the electrical power is increased since it is approaching to the nose of 10% transformation curve which is theoretical minimum of incubation time. On the contrary, $t_{gro}$ is somewhat complicated; at low power, it may increase or decrease according to the intersection point of 35% transformation curve and temperature profile but at higher power, it is definitely increased because the intersection point is drastically increased to longer time, as schematically described in Fig. 4. Despite this explanation is quite qualitative, it is well consistent with experimental results of Fig. 3.

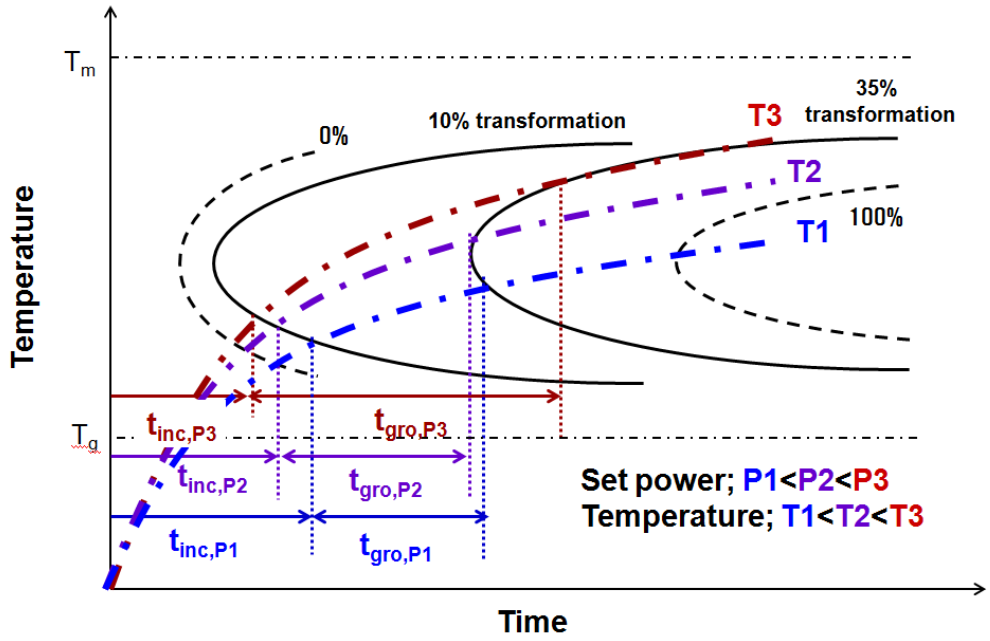


Figure 4 Temperature profiles increased by electrical set pulse various powers and typical T-T-T (Transformation-Time-Temperature) diagram of Ge-Sb-Te material.

## 3. MODEL OF SET CRYSTALLIZATION PROCESS

We model the set operation as sequential processes of threshold switching in amorphous Ge-Sb-Te matrix, the nucleation and percolation of Ge-Sb-Te nuclei. In order to calibrate our damascene-type phase change memory cell, we modify Peng's equations for the nucleation and growth of $Ge_2Sb_2Te_5$ glass as follows [The detailed description on the modeling will be available in other publication]; Thus, we can model the set operation as sequential processes of threshold switching of amorphous Ge-Sb-Te, the nucleation and the growth of Ge-Sb-Te nuclei, as depicted in Fig. 5. As a result of threshold switching, a high-conductive filament is generated in amorphous matrix and it is soon or later heated via current-induced Joule heating [Fig. 5(a)]. When the filament reaches a crystallization temperature $T_x$ (150°C~200°C in case of Ge-Sb-Te material), Ge-Sb-Te nuclei are generated within filament [Fig. 5(b)]. It needs some finite time for ramping up a filament temperature above $T_x$ and for making a Ge, Sb, or Te atoms diffuse to become thermodynamically stable nuclei, which corresponds to aforementioned incubation time $t_{inc}$. Then, nuclei are grown to coalescence to make a high-conducting crystalline path between electrodes [Fig. 5(c)]. Likewise, the time required to make a shunting path is said to be aforementioned percolation time $t_{gro}$.

Figure 5 Schematics of nucleation and growth process during the set operation in phase change memory.

## 4. NOVEL SET PULSE DESIGN

This simple set process model not only makes conceptual understanding on power dependencies of measured set characteristics times but informs how set pulse should be designed to accomplish nucleation and growth processes as rapid as possible. With concept of set pulse design [as depicted in Fig. 6] for maximizing the set operation speed of higher set power at the nucleation (incubation) stage and lower set power at growth (percolation) stage in tandem during set operation, we apply a two-step pulse in order to set the phase change memory device and compare with conventional simple rectangular and slow-quenched forms, as shown in Fig. 7. It turns out that novel two-step pulse is very effective to improve the operation speed by reducing the minimum pulse width to satisfy the upper resistance limit of set state by ~1/5 times [Fig. 8].

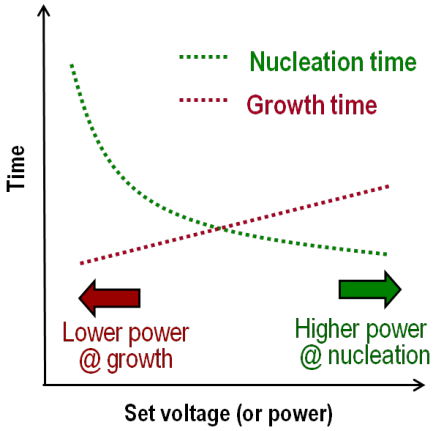


Figure 6 Concept of set pulse design for maximizing the set operation speed: higher set power at the nucleation stage and lower set power at growth (percolation) stage in tandem during set operation.

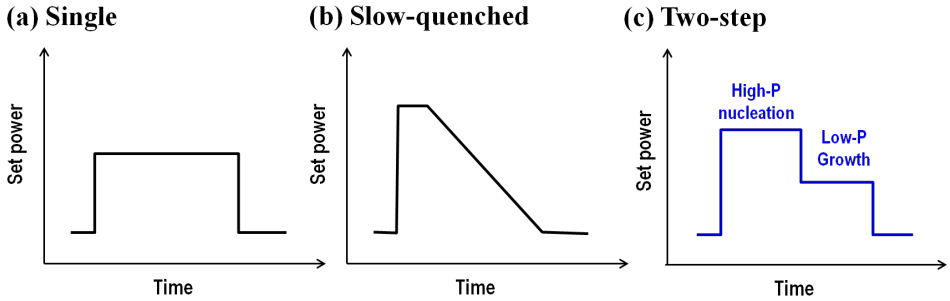


Figure 7 (a) single set pulse form, (b) slow-quenched form, and (c) two-step pulse form.

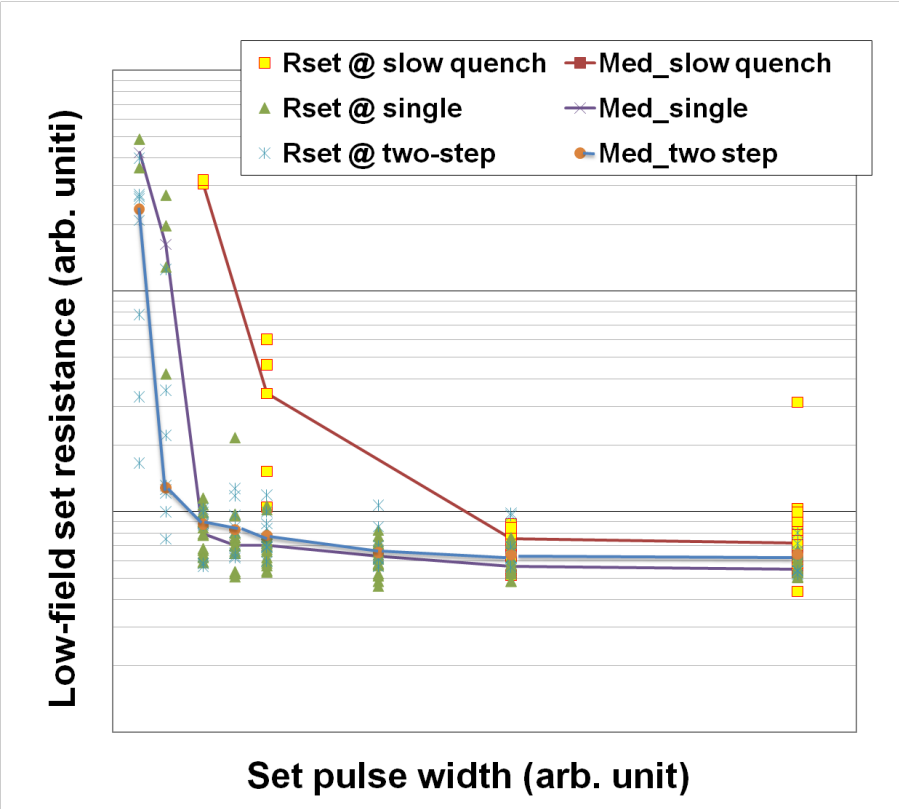


Figure 8 Resistance behaviors with respect to the set pulse width in conventional pulse and a two-step pulse (in this study), which shows that a novel set pulse improves the operation speed by ~5 times than conventional ones.

## 5. CONCLUSION

With Nucleation and growth of Ge-Sb-Te crystallites are thought to commence after threshold switching event and the related characteristic times of $t_{inc}$ and $t_{gro}$ have different dependencies on input set power from each other. A two-step set pulse consisting of high-power nucleation and lower-power growth is very effective to speed-up the set write operation in non-volatile phase change memory.

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**Biographies**

Dr. Dae-Hwan Kang was born in 1968. He received a B.E in Materials Science and Engineering from Pohang University of Science and Technology, Korea. And he received an M.E and Ph.D. degree in Materials Science and Engineering from Seoul National University, Seoul, Korea, respectively. He was a senior researcher at KIST (Korea Institute of Science and Technology) working on the material design for developing low-power and high-speed phase change memory and *in-situ* electrical evaluation of the threshold switching and crystallization processes of amorphous chalcogenide semiconductors. Then he joined phase-change random access memory (PRAM) development team at Samsung Electronics in 2005 and he has been a principal engineer working on mass production of world-first 512Mb PRAM with 82nm technology and on the development of low-power and high-speed cell technologies for next-generation phase change memory device.