Book Chapter

Reliability Degradation of Resistive Switching Memory Cells due to Thermal Cross-Talk

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Abstract

When a memory cell of a ReRAM crossbar array is switched repeatedly a considerable amount of Joule heat is dissipated in the cell and the heat may spread to neighboring cells that share one of the electrode lines with the heat source device. The remote heating of a probed memory cell by another cell allows separating the influence of temperature effects from the impact of the electric field on the resistive switching kinetics. We find that the cell-to-cell heat transfer causes severe degradation of electrical performance of the unheated neighboring cells. A metric for the thermal degradation of the I-V characteristics is established by a specific conditioning of a so-called “marginal” device used as a temperature-sensitive probe of electrical performance degradation. We find that even neighboring cells with no common metal electrode lines with the heated cell, suffer substantial electrical performance degradation provided that intermediate cells of the array are set into a conductive state establishing a continuous thermal path via nanofilaments between the heated and probed cells. The cell-to-cell thermal crosstalk poses a serious electro-thermal reliability problem for the operation of a memory crossbar array requiring modified write/erase algorithms to program the cells (a thermal sneak path effect). The thermal crosstalk appears to be more severe in nanometer sized memory arrays even if operated with ultra fast, nanosecond wide voltage/current pulses.

Keywords

Nanofilament; Nanofilament Formation; Diffusive Dissolution; Thermal Stability; Thermal Crosstalk

Introduction

Traditional non-volatile memory based on floating gate MOSFET transistor has reached its scaling limits, and, hence, the development of alternative memory cells has become imperative. Resistive Random Access Memory (ReRAM) is one of prime candidates to replace the current non-volatile technology due to its simple architecture, excellent scaling potential, low power

consumption, high switching speed, large on/off ratio and good retention, and endurance properties [1-3]. Resistive memory cells hold also promise for neuromorphic applications [4,5]. The resistive switching device is a two-terminal device, such as Cu/TaO_x/Pt, composed of a solid electrolyte insulating layer (here TaO_x) sandwiched between two metal electrodes. The solid electrolyte layer displays a change between high and low resistance states in response to a suitably applied electric field. In so called bipolar resistive devices, the transition from a low resistive state (LRS), characterized by the resistance R_{on} , to a high resistance state (HRS), characterized by the resistance R_{off} , occurs at an opposite polarity than the switching from HRS and LRS. The resistance switching effect is ascribed to the formation and rupture of conductive nano-filaments (CF) in the insulating material matrix due to ionic and charged defect electromigration as well as to the thermal effects [6]. In the case of so called electrochemical metallization [7] responsible for the formation of a metal atom CF, metal cations of the active electrode (here Cu) drift in the electric field towards the counter, called also inert, electrode (here Pt), where they are stopped and neutralized. Over time, the Cu metal atoms pile up on the Pt interface and form a metal nanofilament between the two electrodes. This process constitutes the so-called SET operation. In contrast, when a negative voltage is applied to the active electrode a large current is flowing through the filament depositing Joule heat and causing the Cu atoms to diffuse out leading to the rupturing of the filament at a critical current I_{reset} . The rupturing of the filament is called the RESET operation. In both, SET and RESET operations, Joule heating is of crucial importance. It has been amply demonstrated [8-12] that the RESET process is dominated by Joule heating. The self-heating effects associated with the switching of the cell lead to the deterioration of the R_{off}/R_{on} ratio [13] since for the off-state associated with a semiconductor behavior, i.e. resistance R_{off} decreases as the temperature increases, while the on-state exhibits metallic behavior with the resistance R_{on} increasing with increasing temperature. Walczyk et al [13] found that the R_{off}/R_{on} ratio decreased from a value of 20 to approximately 5 over the temperature interval of 213K-413 K. Such changes in R_{on} and R_{off} of ReRAM cells also cause significant degradation in the

computational accuracy of ReRAM based neuromorphic computing systems [5]. Specifically, a hotter cell is more susceptible to generate an incorrect output. The thermal reliability of ReRAM is also a concern for embedded memories for automotive applications [14]. Chang et al [12] found two different modes of resistive switching for identical devices with the exception of a different thickness of the bottom Pt electrode. The difference in switching behavior has been explained in terms of the temperature-dependent stability of the CF. Thinner thickness of the bottom electrode makes the dissipation of Joule heat less efficient and hence the filament will be heated to a higher temperature and become more unstable at the same operation conditions.

Switching of a cell repeatedly leads to an increasing deposition of Joule heat in the device. Our results demonstrate that this Joules heat is transported preferentially along the electrode metal lines affecting the neighboring cells disposed along the same electrode lines and causing the deterioration of their electrical properties. Due to this non-local cell heating configuration, the influence of temperature by dint of remote Joule heating of a heated cell and of the electric field on the switching kinetics of its neighbor cell could be separated. We have found that even cells with no common metal lines with the heated cell are liable to thermal degradation provided that the intermediate cells are set into an on-state establishing thus a continuous thermal pathway between the heated cell and the probed neighbor cell. A preliminary report of this work has been submitted the MRS Spring 2019 conference [15].

Figure 1: (a) Optical micrograph of the crossbar architecture of Cu/TaO_x/(Pt and Ru) devices. (b) cross-section of the device with relevant layer thicknesses indicate

Device Fabrication and Electrical Characterization Methodology

In the most common architecture, ReRAM cells lie at the intersection of perpendicular metal electrode lines in a crossbar array as shown in Fig.1 (a). The Cu/TaO_x/Pt/Ti resistive RAM cells have been fabricated in a crossbar array on a thermally oxidized Si wafer [3] with a SiO₂ layer 730 nm thick. The cross-section of the resistive switching cell manufactured on an oxidized Si wafer is shown in Fig. 1(b). Cu (150 nm), Pt (50nm), and Ti (20nm) layers have been deposited in a Kurt Lesker e-beam PVD-250 chamber and patterned by lift-off technology with a photoresist thickness of 2 μm to make sure that the sidewalls are sloped gently. A thin Ti layer of 20 nm was used between Pt and SiO₂ to improve the adhesion of the Pt layer. The thickness of TaO_x was 25 nm. The thickness of the TaO_x on the sloped sidewalls of Pt line is 98% of the planar thickness as confirmed by Ta₂O₅ atomic layer cells manufactured with Ta₂O₅ deposition by atomic layer deposition (ALD) [16]. The oxygen-deficient TaO_x (x≈1.9) was deposited also in the PVD-250 chamber by evaporating Ta₂O₅ pellets without O₂ injection into the evaporation chamber. The details of the sample manufacturing process has been given in [16] where the role of the parameter x in TaO_x (as opposed to the stoichiometric Ta₂O₅) on resistive switching properties has been discussed in detail.

The width of metal lines varies between $5\mu\text{m}$ and $35\mu\text{m}$ resulting in rectangular device areas of the device in the range of $(5 \text{ to } 35) \times (5 \text{ to } 35) \mu\text{m}^2$. The neighboring line pitch is between $150 \mu\text{m}$ and $185\mu\text{m}$. The memory cells used in this investigation are described in much detail in [17,18]. The electrical characterization was performed at 300K on a probe station equipped with Keithley 4200-SCS. Before a measurement is taken the two grounded needles are placed on the cell contacts for at least 20s to make sure that the cell capacitor is fully discharged. Then, for the SET operation, the voltage of the Cu electrode starting at 0V is ramped at a ramp rate (rr) ranging from 0.02V/s to 2.00V/s. During the SET operation, a compliance current (I_{cc}) of 5 μA to 1 mA has been imposed without an off-chip resistance lest the device be damaged. A Cu conductive filament (CF) is established at a critical positive voltage V_{set} and the conductive filament is ruptured at a negative voltage bias, when a critical voltage, denoted by V_{reset} has been reached. Typical I-V characteristics for a single cell are shown for the SET and RESET operations in Fig. 2.

Figure 2: Even cycles of a typical first 12 switching set and reset cycles of a Cu/TaO_x/Pt device.

Thermal Cell-to-Cell Cross-Talk Effects in ReRAM Array

During the electrical characterization of the memory cells, it has been noticed that the electrical switching of a fresh cell A has been degraded when a direct neighbor of cell A, a cell B, has been heated by repeated SET-RESET cycles. The degradation manifested itself by the onset of volatility after the device has been cycled only a few times. This degradation of electrical properties disappeared when the cell A was tested again after 10, 15, 20 minutes or a longer cool-off time period. We assume that the thermally induced degradation subsides after times smaller than 5-7 min. Tests between various Pt and Cu line proved that there are no sneak paths [19]. We hypothesize that the degradation of cell A is due an inter-cell thermal cross talk, which subsides within a few minutes when the heat is dissipated to the ambient.

Definition of a “Marginal” Device as a Probe into Cross-Talk Effects

In order to quantify the thermal cross talk we fashioned so called “marginal” memory cell. By a cell being “marginal” we mean following cell’s behavior after being subject to a specific SET condition. We set a device at an I_{cc} of only 10 μA and a voltage ramp rate $rr=1.1V/s$. When the cell is set at such conditions the cell becomes volatile after a limited number of sequential SET-RESET switching cycles. One manifestation of volatility is spontaneous RESET events. The marginality of the device is demonstrated further when the device is set at slightly lower and slightly higher I_{cc} . When applying $I_{cc} < 7\mu A$, the device cannot be set permanently in a LRS state. When the same device is set at higher compliance currents of 8-10 μA , the LRS state is stable although only for a very small number of sequential switching cycles, typically 11-14, after which the cell becomes volatile, eventually. A test has been applied to ~ 100 cells set at $I_{cc}=10 \mu A$ and a maximum of consecutive switching cycles has been determined. We obtain a mean of $M_x=12.7$ cycles and standard deviation $\sigma=1.3$. A low $rr=0.1V/s$ has been applied during the RESET operation to allow for a long heating time. For a low rr ,

the current lingers for a long time and hence low r_r maximizes heat dissipation. When the maximum number of switching cycles (M_x) is reached the device is driven to highly unstable performance. On the other hand, a device set at $I_{cc}=40-100 \mu A$ can be switched repeatedly more than hundred of times. Thus, a “marginal” device demarcates the boundary between stable and unstable (volatile) behavior of the cell. Hence, a “marginal” device set at $I_{cc}=10 \mu A$ is our “canary in the coal mine” and the maximum number of switching cycles, M_x , is our metric to quantify the degree of the thermal cross talk. We find that such a marginal device when heated remotely by another cell will have a maximum number of switching cycles smaller than $M_x=13$, depending by the amount of heating experienced by the cell. Thus, the measure M_x defines the onset of the cell’s volatility in response to the local temperature of the cell. The volatility is caused by the accumulated Joule heat during its consecutive switching. When such a probed cell is heated remotely from another (heated) cell the temperature at which the cell becomes unstable should be reached after a fewer own I-V cycles. Thus the remote heat superposes on the heat generated locally by the switching of the cell itself. In our experimental setup the time between heating the cell B and characterization of the probed cell A is about 50s - the time required to replace the needles on the probe station.

Figure 3: Location of neighbor cells relative to the heated cell marked by a red dot. Initially the cells are set in an Off-state. (a) heat transport from the heated cell to its neighbors located on the Pt electrode. (b) heat transport to its neighbors on the Cu electrode. (c) heat transport to its neighbors located diagonally with respect to the heated cell. (d) heat transport to its neighbors on diagonal locations with intermediate cells (marked by green crosses) in the ON-state. (e) thermal path from the heated cell to 1st cell via the cell Y. (f) thermal path from the heated cell to 1st cell via the cell X.

When testing in such a way the 1st, 2nd, 3rd, and 4th neighboring cell, we find that 1st neighbor suffers the highest degree of degradation yielding at most a M_x of 0-3 switching cycles while the 3rd and 4th neighbor are degraded only slightly showing M_x of 9-11 compared with a mean of 13 for a fresh or thermally unaffected cell.

Dissipation and Transport of Joule's Heat in ReRAM Arrays

At this point it is instructive to estimate the heat dissipated in the cell during a single reset operation, characterized by a reset current $I_{res} = V_{res}/R_{on}$. Here R_{on} is the resistance of the LRS state. The reset current is typically $1\text{mA} < I_{res} < 6\text{mA}$. For a cell to which

a constant voltage ramp rate is applied the Joules heat Q_{JH} can be calculated by eq. (1)

$$Q_{JH} = \int_0^{t_{res}} \frac{V^2(t)}{R_{on}} dt = \int_0^{V_{res}/rr} \frac{rr^2 \times t^2}{R_{on}} dt = \frac{V_{res}^3 \times I_{cc}}{3 \times rr \times K} \quad (1)$$

Here the reset time at an applied voltage ramp rate rr is given by $t_{res}=V_{res}/rr$ [20,21]. In eq. (1), the well known relation between R_{on} device is described in terms of experimentally measurable parameters, namely, the compliance current I_{cc} , the voltage ramp rate rr , and the reset voltage V_{res} . It has been shown [22] that R_{on} depends on I_{cc} via $R_{on}=K/I_{cc}^n$ with $n \approx 1$ and $K \approx 0.2V$ for Cu/TaO_x/Pt devices. Depending on the chosen values for I_{cc} and rr , Q_{JH} can vary from 3 to 60 μJ . When the cell is switched N times on and off repeatedly and in a quick succession (50s idle time between the set and reset operations), the total heat deposited in the cell will be $Q_{tot}=N \times Q_{JH} \times f$, where f is a dimensionless, positive number, less than unity, accounting for the heat removal out of the device between the subsequent switching events. We estimate f to be between 0.6 and 0.85. The heat transferred to a neighboring cell, as shown in Fig. 3 (a) and (b), is then $Q_{tran}=N \times Q_{JH} \times f \times t_{tran}(n)$, where the coefficient $t_{tran}(n) < 1$ describes the efficiency of thermal transfer from the heat source cell B to n -th neighboring cell A along one of the shared electrodes (Fig. 3). Of course, $t_{tran}(n) < t_{tran}(n+1)$. Since the thermal conductivity of Cu (390 W/(mK)) and Pt (72 W/(mK)) is at least two order of magnitude higher than the thermal conductivity of TaO_x of 0.7 (W/(mK)) [23], it is clear that the dominant transport path to dissipate Joule heat takes place via the metallic connections within the crossbar array. Also, due to the thickness of top Cu electrode of 150 nm (vs 50 nm of the Pt electrode) and the finite size of the cell, the low thermal convection through air is very inefficient in dissipating the heat. Since the memory array has been manufactured on a Si wafer with a grown field oxide of 650nm thickness, it is reasonable to assume that the main heat transfer is achieved mainly via the metal electrode lines. The Cu filaments in the cells set into the on-state complement the network of electrode lines. I_{cc} imposed at the SET operation can modulate the heat transport efficiency

through the filament. High I_{cc} leading to a low resistance filament will provide a highly conductive thermal path between the Cu and Pt electrode. A low I_{cc} will provide an inefficient heat transport path because of the thinness of the filament and on account of a small thermal contact area with the Cu electrode.

Several thermal models exist in the literature describing the temperature distribution in ReRAM cells. Mickel et al [24] established a geometrically equivalent circuit to describe the heat flows through a conductive filament, yielding temperature distribution of the memory cell. The critical temperature responsible for the rupturing of a filament is calculated to be $\sim 1225^\circ\text{K}$. In another work, Mickel et al [25] proposed a set of constitutive equations describing the evolution of the heat transport. Based on this work, the temperature responsible for the rupturing of the filament can be as high as $\sim 1500^\circ\text{K}$. Sun et al [26] also found that the peak temperature of the filament is somewhere between 600°C and 900°C [26]. Thus there is a broad consensus that the local temperature of the filament is very high and this temperature can increase only further when the cell is switched on and off sequentially and frequently.

Since a weak filament is highly resistive with a constriction at the tip of the truncated cone shaped filament, the area of contact formed with the Cu electrode is smaller than the area of contact with the Pt electrode (see Fig. 4(a)). Hence, one would expect a more efficient heat transport from the filament to the Pt line rather than to the Cu line despite the more than five times larger thermal conductivity of Cu than that of Pt. Hence, based on this argument, one would expect cells neighboring the heated cell and disposed on the Pt line should experience a larger heat transfer than the neighbors disposed along the Cu line. However, experimental data discussed below contradict such a conjecture.

Degradation of Electric Performance of Cells sharing the Pt Electrode

We begin the discussion of the electrical degradation of the neighbor cells disposed along the Pt electrode line. They are characterized, one by one, immediately after heating by the

heated cell marked by a red dot after in Fig. 3. The metric for degradation is established customarily by degradation defined in this context as

$$D = \frac{M_x(\text{unheated cell}) - N(\text{heated cell})}{M_x(\text{unheated cell})} \quad (2)$$

The mean of M_x for an unheated cell has been found to be 13 SET-RESET cycles, as mentioned before. The cell degradation results for cells disposed along the Pt electrode are shown in Table 1 based on 66 devices measured. It can be seen that for the nearest neighbors the degradation is about $D=67\%$. In contrast, the degradation of the 4th device located on the Pt electrode is much smaller, $D=13\%$. The results could be explained by the heat transfer over a distance of $n \times 160 \mu\text{m}$ where $n=1,2,3,4$, corresponding to the 1st, 2nd, 3rd, 4th neighboring cell.

The switching behavior of a cell A is impacted whenever a neighboring cell B (heat source device) went through a repeated switching cycles. This means, quite surprisingly, that the thermal cross-talk is effective over distances of multiple integers of $150 \mu\text{m}$. At the same time, this means that the electrode lines cannot be assumed to be effective heat sinks even for devices subject to no electrical stress. The heat transport over such large distances is further supported by the experimental dependence of the degradation effect on the width of the metal lines. For wider Pt line ($35 \mu\text{m}$) the 1st neighbor is degraded much less $M_x=6$ or $D=(13-6)/13=54\%$ than for a narrow Pt line ($10 \mu\text{m}$) cell, $M_x=3$ or $D=(13-3)/13=77\%$, as the heat is dissipated faster along the wider $35 \mu\text{m}$ than along a $10 \mu\text{m}$ Pt line.

Degradation of Electric Performance of Cells sharing the Cu Electrode

We turn our attention to the degradation behavior of the cells A located along the Cu electrode that are neighbors of the heat source cell B. The neighbor cells of the heated memory cell disposed now along the has Cu electrode (Fig.3 (b)) are characterized analogously. The degradation results are

summarized in Table I (Cu electrode) based on 53 tested cells. The degradation in terms of M_x for cells located on the Cu line is significantly larger than of those cells disposed on the Pt electrode. It can be observed that for the Cu line, the distant neighboring cells are more severely degraded than those for the Pt electrode. Comparison of the 4th cell on the Pt electrode with the 4th cell on the Cu electrode shows that the degradation of is 5 fold larger for the Cu electrode. This appears to be consistent with the much better heat conductivity of Cu (385W/(mK) and 150 nm thick) lines than Pt (72 W/(mK) and 50 nm thick) lines, but is at odds with the assumptions of much larger contact area of the Cu filament with the Pt than with the Cu electrode, see Fig. 4 (a). As a general trend, we find for Cu line cells the same line width dependence as for the Pt lines discussed above: for a wide Cu line of 35 μm the next neighbor is degraded much less than for a narrower Cu line of 10 μm . We also find that the coefficient t_{trans} for the Cu line is larger than for the Pt line due to larger thickness and due to higher thermal conductivity of the Cu line than those of Pt line.

Figure 4: Different geometrical shapes approximating the actual form of a Cu filament: (a) conventionally assumed shape of a truncated cone. (b) an hourglass-shaped filament formed at low I_{cc} . (c) an hourglass-shaped filament formed at high I_{cc} .

Table 1: Degradation D of the neighbor cells of the heated device.

Neighbor Cell to the Heated Cell Along Pt Metal Line					Neighbor Cell to the Heated Cell Along Cu Metal Line			
#neighbor	1 st	2 nd	3 rd	4 th	1 st	2 nd	3 rd	4 th
D [%]	67	53	40	13	80	75	70	67

Degradation of Electric Performance of Cells with no Common Electrodes with the Heated Cell

Finally, we investigate the neighboring devices A that have neither Pt nor Cu electrode lines in common with the heated cell B. Fig. 3(c) shows such three neighbor cells of the heated device that do not share any the Pt and Cu electrodes with it. The cells in Fig. 3(c) are electrically characterized under two different conditions: 1) the intermediate cells between the heated cell B and the tested cell A are in a non-conductive off-state, and 2) the intermediate cells are preset to a conductive on-state at $I_{cc}=100\mu A$ shown in Fig. 3(d) by the green crosses. The $I_{cc}=100\mu A$ applied to the cells marked by green crosses, ensures that a low resistance Cu filament is formed with R_{on} typically between 450 and 550 Ω . Such a low resistance, robust filament is assumed to provide a path of high thermal conductivity between Pt and Cu electrodes.

In the first case, as could be expected, we find no degradation of maximum switching cycles M_x for any of the diagonal neighbors of the heated device. This could have been expected since there is no thermally (metallic) conductive path between the heated cell B and the probed cell A. When, however, the cells marked by green crosses are preset to a conductive, i.e. LRS, state (see Fig. 3(d)), the (diagonal) neighboring cell is found to be degraded considerably. A degradation of $D=19\%$ is found for the 1st diagonal neighbor. The product of degradation $0.67 \times 0.80 = 0.53 = 53\%$ (see Table I) being larger than 0.19 indicates that the Cu filament despite its nanometer cross-section but, apparently by virtue of its small length of 25nm provides an efficient conduit for the heat transport. It may be, therefore, concluded that the thermal cross-talk along the Cu electrode is 15 fold more efficient than along the Pt electrode.

It is known that the heat transport is proportional to the temperature gradient, to the wire cross-section, to the thermal conductivity of the material, and inversely proportional to the length of the wire. The higher heat transport over the Cu line would indicate that the high conductivity of the Cu line more than compensates for the small contact area between the filament and the Cu electrode. The diameter of the filament, assumed to be of cylindrical shape, is about 15 nm. When the thermal conductivity of the Cu filament is assumed to be roughly half of the thermal conductivity of bulk Cu, ie. around 190 W/mK then one could conclude that the heat transport via Cu filament 25 nm long is comparable with the heat transport along the Pt electrode over a distance of $\sim 150\text{ }\mu\text{m}$, assuming similar contact areas with the Cu and Pt electrodes.

Inference of the Nanofilament Shape

A more cogent explanation of the more efficient heat transport over the Cu line can be achieved assuming a revised shape of the Cu CF. Rather than a truncated cone shape, an hourglass shape is hypothesized for the Cu CF. A modified shape of the filament is shown in Fig. 4 (b) and (c). For low I_{cc} the hourglass shape has a large base with Pt electrode and a small base with the Cu electrode (Fig.4 (b)). As the I_{cc} increases the base with Cu grows while the base with Pt stays more or less constant (Fig. 4(c)). The hourglass-shaped filament would be more consistent with our data as it provides now a larger contact area with the Cu electrode and would thus explain the large heat transport from the filament along the Cu electrode line to the neighboring cells along the Cu electrode. In the hourglass shape of the filament, its base with Pt electrode is likely to be weakly dependent on the applied compliance current I_{cc} , while the base of the hourglass with the Cu electrode should be a strong function of I_{cc} .

Analysis and Implications for high-pitch Nanometer-sized Commercial Arrays

It should be noted that in case of the 1st diagonal device as shown in Fig. 3(d) there exist two thermal conduction paths between the

heated cell and the 1st diagonal cell. Evaluation of the electrical degradation of the 1st diagonal cell with intermediate cells partly in LRS and partly in HRS states as shown in Fig. 3(e) and Fig. 3(f) reveal that the two individual paths contribute differently to the probed diagonal device's electric degradation. The path first along the Cu and then along the Pt electrode (Fig. 3(e)) causes a more severe degradation of the 1st diagonal cell than the conductive path first along Pt and then along the Cu electrode as shown in Fig. 3(f). In case of Fig. 3(e), the degradation of the 1st diagonal cell is 7%; and in case of Fig. 3(f) the degradation of the 1st diagonal device is 11%. This can be compared to the degradation of the 2nd cells along Cu and Pt line, which are 75% and 53%, showing that the thermal connection via the Cu filament poses a heat transfer bottleneck when compared with the heat transport along the comparatively massive electrode lines. It is seen also that the two paths contribute constructively (additively) to the overall degradation of $(7\%+11\%) \approx 19\%$. These results demonstrate that a low resistance Cu filament in the cells X and Y provides an efficient thermal path to transmit the Joule heat to the diagonal cell. Testing the degradation of the neighbor cells as a function of the width of the metal lines, which in our case vary between 5 nm and 35 nm, we find that it takes the Joule heat less time for the Joule heat to reach the 4th neighbor cell A for a 35 nm Cu line than for 5 nm or 10 nm Cu lines. This indicates that the heat is transmitted faster over or large distance of 700 nm by a wider than by a narrow Cu electrode line.

At this point the question arises how the present results apply to commercial ReRAM arrays that are a factor 1000 smaller in geometrical dimensions with correspondingly much tighter pitch to boot and the SET and RESET operations are performed with voltage and current pulses and not by the relatively slow voltage or current ramps taking up to several seconds to complete successfully the operations. In commercial applications a RESET voltage pulse is typically 5V height with a pulse width of a typically 200 ns [27]. Assuming a representative value for $R_{on}=2000 \text{ Ohm}$, the Joule heat dissipated at the RESET $Q_{JHpulse}=200 \text{ ns} \times 5^2 \text{ V}^2 / 2000 \Omega = 2.5 \text{ nJ}$. This is four orders of magnitude smaller than the Joule heat Q_{JHramp} dissipated at a

ramped voltage given by eq.(1) which is typically 25 μJ . However, the commercial arrays are much smaller with a much tighter pitch. Therefore, considering the Joule heat *density* for both array cases can make a meaningful comparison. For a commercial ReRAM array, we assume that for an electrode thickness 50 nm and width 50 nm, and a pitch of 100 nm. From these dimensions we obtain a typical array unit volume of $2.5 \times 10^{-16} \text{ cm}^3$. We can now calculate the heat density for the commercial array in the vicinity of a reset cell: $q_{\text{com}} = 2.5 \text{ nJ} / 2.5 \times 10^{-16} \text{ cm}^3 = 10^7 \text{ J/cm}^3$. In our academic memory arrays used in this work, the thickness and width of the Cu electrode are 150 nm and 10 μm , respectively, with a pitch of 160 μm that leads to a corresponding volume of $2.4 \times 10^{-10} \text{ cm}^3$, six orders of magnitude larger than the corresponding volume for commercial memory arrays. With a switching Joule heat of 25 μJ we obtain a heat density of $\sim q_{\text{ac}} = 10^5 \text{ J/cm}^3$. Thus, the Joule heat density in commercial cutting edge arrays is two orders of magnitude higher than in our memory arrays.

This calculation indicates that for commercial memory arrays despite much lower switching Joule but because of the much smaller dimensions, the cell-to-cell thermal crosstalk poses a serious conundrum. There are two ways to mitigate the high heat density issue. Either by reducing the generated Joule heat, so to speak at the origin of the problem, by lowering the reset current [28] or by using ultra-fast pulses of sub ns widths [27]. The other possibility is an enhanced ability to remove the heat from the arrays quickly and efficiently. The heat dissipation could be increased by usage of metallic materials for the electrodes with higher thermal conductivity. One possibility would be to integrate the metal electrodes with graphene [29] which boasts a thermal conductivity of 3000-5000 W/(mK). However, higher thermal conductivity of the electrodes leads to another tradeoff: an electrode material of high thermal conductivity would induce a quicker heat dissipation of the heated device and allow a quicker return to non-degraded switching operation than an electrode material characterized by low thermal conductivity. Higher thermal conductivity material, on the other hand, would transport the heat faster to the more distant cells in the crossbar array which then, in turn, would be affected more than in the

case of low thermal conductivity electrode material. Finally, we wish to mention that in terms of heat transport modeling, our results indicate that the electrodes of the ReRAM cell cannot be treated as perfect heat sinks [8,30,31]. Our results indicate that the local temperature of the metal electrode lines may exceed considerably the ambient room temperature assumed frequently in many thermal models of the nanofilament heating.

Conclusions

In conclusion, we have found that the heat deposited in a cell stressed by frequent switching is transported to the neighboring cells causing their serious degradation in terms of electrical performance. Since the degradation of the cell performance occurs only when a cell nearby undergoes repeated switching cycles, its observed degradation, in absence of other discoverable factors, has been attributed to the impact of the heated cell in which heat is being dissipated over a number of switching cycles.

The neighbor cells disposed along one of the electrodes common with the heated device degrade most. Cells with no electrode lines in common with the heated cell experience electrical degradation in terms of maximum switching cycles only in the case when an uninterrupted thermal (and by the same token electrical) path is provided between the probed neighbor and the heated cell. This occurs when the intermediate cells along the Cu and Pt line shared with the heated device (similarly as in the electric sneak path problem) are set into an LRS state. The electrical performance of a memory cell conditioned properly can be used as a probe into heat transfer phenomena. We find that the cell performance degradation is potentially more severe in nanometer-sized memory arrays despite much lower switching heat delivered by voltage pulses of ns widths.

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