On the Effect of Cell Geometry on the Amorphization Process in Phase-Change Memories

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Abstract—In phase change memories, the crystalline to amorphous phase transition is strongly affected by the cell geometry. In this paper, we study the amorphization process by analyzing the effects of amorphizing (RESET) pulses on the phase distribution inside the active chalcogenide portion of the memory cell. The purpose is to investigate how the shape and the volume of the amorphous cap are affected by the cell structure. In particular, the analysis is carried out considering two of the most popular cell architectures, namely, the Lance and the Pillar structures.

Index Terms—Pillar cell, Lance cell, amorphization model, phase-change memory.

I. INTRODUCTION

Phase change memories (PCMs) are gaining increased attention among non-volatile memories as promising alternatives to Flash technology [1]. This is primarily due to fast read access, short programming time, bit-level programming granularity, high endurance, good compatibility with standard CMOS fabrication processes, and potential of scalability beyond Flash technology limits. The working principle of a PCM cell relies on the physical properties of chalcogenide materials, typically Ge$_2$Sb$_2$Te$_5$ (GST), that can switch from the amorphous to the crystalline phase and vice versa by means of suitable electrical pulses. These two phases feature a large difference in their electrical resistivity, which allows an information bit to be stored by controlling the phase (or, state) of a portion of the cell GST material (referred to as the active GST). Readout is achieved by measuring the cell resistance. In the amorphous state, which is also referred to as RESET state, the cell shows a high resistance, while in the crystalline (or SET) state the cell resistance is significantly lower. Since phase transitions are thermally assisted, in PCM devices Joule heating is exploited to raise the temperature inside the chalcogenide material to the required value. The crystalline to amorphous phase transition is obtained by applying a suitable electrical pulse to the cell, so as to bring the temperature of the active GST material above the melting point $T_{\text{melt}}$ (600 °C), and then quickly cooling the cell in order to freeze the GST material into a disordered (i.e., amorphous) structure. The amorphous to crystalline phase transition is obtained by applying an electrical pulse with a longer time duration and a lower amplitude. In this case, the amorphous material is heated above the crystallization temperature but below the melting point and the thermal energy is used to obtain the crystalline lattice.

Since the RESET-state resistance is about 2-3 orders of magnitude larger than the SET-state resistance, multilevel programming [2] is a feasible approach to increase the bit density, thus reducing the cost per bit. Two multilevel programming approaches have been proposed in the literature, namely, programming from the RESET to a partial SET state [2] and programming from the SET to a partial RESET state [3]. An important difference between these two methods is the shorter programming time that the second approach can theoretically ensure. In fact, the SET to partial RESET programming can be achieved via a single RESET pulse, which is shorter than the typical SET pulse, due to the fast dynamics of the amorphization process. Another key issue is the phase configuration, that is the distribution of amorphous phase and crystalline phase inside the active GST material, since it remarkably affects data retention of the cell [4]. Such a distribution mainly depends on the initial state of GST material as well as on the applied programming pulse, and on the structure of the cell.

In this paper, the impact of cell geometry on the amorphization process is analyzed, in order to point out how a specific PCM cell structure can lead to different phase distributions during the programming of the cell resistance from the SET to a partial RESET state. In particular, among the cells proposed in the literature, we will consider two different cell structures, namely, the so called “Pillar” [5] and “Lance heater” [6] cells.

The paper is organized as follows. Section II describes the geometrical properties of the considered cell structures. Section III presents an electro-thermal model developed to analyze the crystalline to amorphous phase transition, and Section IV presents the performance comparison, based on the results obtained with the proposed model. Conclusive remarks are drawn in Section V.

II. PILLAR AND LANCE CELL ARCHITECTURES

Basically, a PCM cell is composed of a thin GST film, a resistive contact called heater, and two contact electrodes, i.e., the top electrode contact (TEC) and the bottom electrode contact (BEC). The 3D physical models of the two architectures considered in this work are shown in Fig. 1. The physical sizes of the two structures have been obtained from published data. More specifically, the sizes of the Lance cell were directly extracted from the literature [6], [7], while the dimensions of the Pillar cell were modified with respect to the published values [5]. Indeed, as opposed to the case of the Lance cell architecture, the heater and the GST element in the Pillar cell have the same shape and the same physical sizes. To
TABLE I
SIZES OF CELL ELEMENTS

<table>
<thead>
<tr>
<th></th>
<th>Lance cell</th>
<th>Pillar cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>GST thickness</td>
<td>70 nm</td>
<td>70 nm</td>
</tr>
<tr>
<td>Contact area</td>
<td>3000 nm²</td>
<td>2400 nm²</td>
</tr>
<tr>
<td>Heater height</td>
<td>230 nm</td>
<td>70 nm</td>
</tr>
</tbody>
</table>

TABLE II
ELECTRICAL AND THERMAL PROPERTIES OF CELL MATERIALS

<table>
<thead>
<tr>
<th>Element</th>
<th>Material</th>
<th>Thermal conductivity $\kappa$ (W/m°C)</th>
<th>Heat capacity $C$ (J/m³°C)</th>
<th>Electrical conductivity $\sigma$ (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulator</td>
<td>SiO₂</td>
<td>1.1</td>
<td>1.5 M</td>
<td>$10^{-14}$</td>
</tr>
<tr>
<td>GST layer</td>
<td>Amorphous GST</td>
<td>0.3</td>
<td>1.25 M</td>
<td>$10^4$</td>
</tr>
<tr>
<td>GST layer</td>
<td>Crystalline GST (low-field)</td>
<td>0.5</td>
<td>1.25 M</td>
<td>$10^5$</td>
</tr>
<tr>
<td>GST layer</td>
<td>Crystalline GST (high-field)</td>
<td>0.5</td>
<td>1.25 M</td>
<td>$10^5$</td>
</tr>
<tr>
<td>TEC</td>
<td>Ti</td>
<td>20</td>
<td>3.5 M</td>
<td>0.7 M</td>
</tr>
<tr>
<td>BEC</td>
<td>W</td>
<td>167.2</td>
<td>2.6 M</td>
<td>20 M</td>
</tr>
<tr>
<td>Heater</td>
<td>TiN</td>
<td>12</td>
<td>3.5 M</td>
<td>10 k</td>
</tr>
</tbody>
</table>

provide the same read margin for the two cells, hence allowing a fair comparison, in our analysis, the Pillar cell was resized in order to obtain, approximately, the same total low-field SET resistance (about 3.5 kΩ, equal to the sum of the GST and the heater contributions) as for the Lance cell. The dimensions of the Lance and the Pillar cells are summarized in Table I.

We assume that the two cells are made with the same materials, namely, doped titanium nitride for the heater, tungsten for the BEC, titanium for the TEC, and GST for the active material. Both cells are surrounded by electrical insulating material (SiO₂). The physical properties of the above materials are summarized in Table II. Particular attention must be paid to the electrical properties of the GST material, which are strongly dependent on the value of the electrical field [8]. When a high-voltage RESET pulse is applied to the cell and, hence, a high electrical field is present within the GST, the resistance of the GST layer is negligible as compared to the heater resistance: for simplicity, we assumed the high-field crystalline GST resistivity to be in the order of $10^{-5}$ Ωm. In this case, the total cell resistance ($R_{ON}$) is approximately equal to the heater resistance, and is therefore different for the two structures even though their low-field SET resistances are equal. In particular, for the Lance cell $R_{ON} \approx 2.3$ kΩ and for the Pillar cell $R_{ON} \approx 900$ Ω. Hence, for a fair comparison of the considered cells, electrical power must be considered rather than the voltage or the current applied to the PCM cell. On the other hand, when a low electrical field is present inside the GST, such as during read operation, the GST layer resistance is not negligible as compared to the heater resistance. In this case, we took the dependence of the amorphous and the crystalline GST resistivity on the electrical field into account, as presented in the literature [9]. Notice that the read voltage is kept low so as to prevent the risk of electronic switching [8], in order to maintain the temperature inside the GST film below the crystallization value.

III. ELECTRO-THERMAL MODEL

The electro-thermal model developed to analyze the crystalline to amorphous phase transition consists of a set of equations that are sequentially solved in a finite-element environment. In our case, we considered the GST to be initially in its crystalline state. The crystalline material cannot undergo crystalline to amorphous phase transition as long as the temperature inside the GST is below the melting point. As soon as the programming current is high enough to allow the melting temperature to be reached, the transition from the crystalline to the amorphous phase begins to take place. We assumed, as a good approximation, that, when the GST material melts, its electrical conductivity is equal to the high-field conductivity of the crystalline state.

From the above considerations, we first applied a RESET voltage to the cell structures under analysis and, hence, we calculated the generated Joule heating by using an electrical model of the GST film. Then, the temperature inside the PCM cell was evaluated through the developed thermal model. Notice that, since we used RESET pulses with very short fall and rise times, no expressions were introduced in the model to exactly take amorphization dynamics into account. In fact, once the GST material melts (as soon as the melting temperature is reached), the melted to amorphous phase transition takes place provided that the melted material is rapidly cooled [10], [11] as it is the case in our simulations. The width of the RESET pulses was set to 40 ns.

After the RESET programming pulse, the read voltage (400 mV) is applied to the cell, and the cell resistance different for the two structures even though their low-field SET resistances are equal. In particular, for the Lance cell $R_{ON} \approx 2.3$ kΩ and for the Pillar cell $R_{ON} \approx 900$ Ω. Hence, for a fair comparison of the considered cells, electrical power must be considered rather than the voltage or the current applied to the PCM cell. On the other hand, when a low electrical field is present inside the GST, such as during read operation, the GST layer resistance is not negligible as compared to the heater resistance. In this case, we took the dependence of the amorphous and the crystalline GST resistivity on the electrical field into account, as presented in the literature [9]. Notice that the read voltage is kept low so as to prevent the risk of electronic switching [8], in order to maintain the temperature inside the GST film below the crystallization value.

Fig. 1. 3D Models of the Pillar cell (left) and Lance cell (right).

Fig. 2. Simulated (solid line) and experimental (black circles) programming curve for the Lance cell.
is calculated by using a low-field resistivity model for the GST material. The general electrical model is based on the time-independent continuity equation

$$\nabla \cdot \mathbf{J} = 0,$$

where \( \mathbf{J} \) is the current density, which can be expressed as

$$\mathbf{J} = \sigma \mathbf{E} = -\sigma \nabla V.$$

In the above equation, \( \sigma \), \( \mathbf{E} \), and \( V \) denote the electrical conductivity, the electrical field, and the electrical potential, respectively. Since thermal conduction is the key mechanism for heat transfer, the thermal model is based on the well-known heat equation

$$C \frac{\partial T}{\partial t} - \nabla \cdot (\kappa \nabla T) = Q_j,$$

where \( T \) is absolute temperature, \( C \) is the volumetric heat capacity, \( \kappa \) is the thermal conductivity, and \( Q_j \) is Joule power density, which couples the electrical and the thermal domain.

**IV. SIMULATION RESULTS**

To evaluate the accuracy of the developed model, the simulation results of a crystalline to amorphous phase transition were compared to the experimental programming curve (programmed cell resistance as a function of the programming current) presented in the literature for the Lance cell [6], [4]. The simulated curve and the experimental data (Fig. 2) show a very good agreement.

The simulated programming curve for the Pillar cell is shown in Fig. 3. Notice that the cell conductance/resistance is now plotted as a function of programming Joule power. The cell conductance decreases as programming Joule power increases in the range from 0.5 mW to 0.8 mW. The two phase distributions of the chalcogenide material after two RESET pulses of different amplitude are shown in Fig. 4. The phase configuration is parallel (i.e., the amorphous and the crystalline phases are placed in parallel) if the programming power is less than about 0.7 mW. Above this value, no parallel crystalline path from the TEC to the heater remains. The maximum value of the cell resistance, which is approximately 3.5 MΩ, is achieved when the programming power is larger than about 0.85 mW.

The simulated programming curve for the Lance cell is shown in Fig. 5. In this case, the cell resistance increases at a higher rate for RESET pulses corresponding to a programming power from 0.7 mW to 0.9 mW. As the RESET pulse power increases, the slope of the programming curve decreases. This effect is essentially ascribed to the fact that an increase in the maximum temperature inside the GST (which is close to the heater-GST interface) does not lead to a proportional increase of the amorphous cap thickness, since the TEC acts as a thermal ground. Anyway, even for lower-amplitude RESET pulses, a series type phase distribution is obtained, in contrast to the case of the Pillar cell.

Notice that the cell geometry is responsible for the phase configuration obtained after a RESET pulse: the Pillar cell geometry favors a parallel-type phase configuration while the Lance cell geometry leads to a series-type phase distribution. This is due to the fact that the cell geometry impacts on the ratio between the lateral and the vertical heat flow, thus leading to different temperature distributions, which affect the shape of the amorphous volume.

From simulations, it was also possible to extract a lumped
equivalent thermal model of the PCM cell. In this case, the maximum temperature inside the GST can be expressed to a good approximation as

\[ T_{\text{max}} = T_0 + R_{\text{th}}Q, \]  

where \( T_0 \) is the thermal ground temperature (27 \( ^{\circ}\)C), \( R_{\text{th}} \) is the equivalent thermal resistance as seen from the highest temperature point inside the GST (i.e., from the heater-GST interface), and \( Q \) is the programming Joule power. If a voltage \( V \) is applied across the cell, then \( Q = \frac{V^2}{R_{\text{ON}}} \), \( R_{\text{ON}} \) being the effective electrical resistance during the program pulse, that is the heater resistance. For any fixed value of programming power, the maximum temperature inside the GST material can be remarkably different for the considered cell types. In fact, the geometrical properties of a PCM cell also affect its thermal resistance. The equivalent thermal resistance \( R_{\text{th}} \) of both cells can be estimated by simply dividing \( T_{\text{mealt}} - T_0 \) by the programming power corresponding to the minimum RESET voltage, under the simplifying approximation that the whole Joule power is generated at the heater-GST interface. For the Lance and the Pillar cell, we obtained \( R_{\text{th}} \approx 900 \text{ k}\text{C}/\text{W} \) and \( R_{\text{th}} \approx 1 \text{ M}\text{C}/\text{W} \), respectively. Notice that the two cells show an almost equal equivalent thermal resistance in spite of the much longer length of the Lance heater. This is mainly ascribed to the fact that the equivalent thermal resistance is referred to the heater-GST interface, but the maximum temperature in the Lance cell is actually obtained inside the heater element (Fig. 7). This results in a waste of power, which leads to a decrease of the equivalent thermal resistance. On the contrary, the maximum temperature in the Pillar cell is obtained at the heater-GST interface, as shown in Fig. 8.

The thermal resistance, as seen from the heater-GST interface, can also be estimated via hand calculations by considering the parallel connection of the thermal resistance of the heater and of the GST layer. Anyway, since Joule power is uniformly dissipated inside the heater, the calculated thermal resistance is higher than the equivalent thermal resistance obtained by simulation. In fact, the fraction of power generated near the TEC (Pillar cell) and the BEC (Lance cell) is much more easily evacuated than the power generated close to the heater-GST interface.

V. CONCLUSIONS

In this paper, the amorphization behavior of the Lance and the Pillar cell has been investigated.

The Lance cell shows a series-type phase distribution, even for low-intensity RESET pulses. The electrical resistance of the cell is proportional to the amorphous cap thickness, which increases with increasing RESET pulse amplitude.

The lateral electrical confinement of the chalcogenide material in the Pillar cell adds a degree of freedom (i.e., the choice of the insulating material) which impacts on the amorphization process. For the insulating material considered in this work (silicon dioxide), the cell shows a parallel-type phase distribution after a RESET pulse. The choice of a different insulating material can notably change the amorphization process by modifying the vertical to lateral heat flow ratio. In particular, the parallel phase distribution can be emphasized by increasing the thermal conductivity of the electrical insulating material. On the other hand, the choice of an insulating material having a lower thermal conductance will result in a series-type phase distribution.

REFERENCES