Thermal investigation of a phase change memory device at the nanoscale

Jean-Luc Battaglia1, Indrayush De1, Abdelhak Saci1, Andrzej Kusiak1, Véronique Sousa2

1I2M Laboratory, University of Bordeaux, UMR CNRS 5295, 351 cours de la libération 33405 Talence cedex, France
2CEA-LETI, MINATEC, 17 rue des Martyrs, F-38054 Grenoble Cedex 9, France

E-mail: jean-luc.battaglia@u-bordeaux.fr

Abstract. New technologies in non-volatile memories have been developed for several years based on phase-change alloys out of which, the most known is the Ge2Sb2Te5. The thermal investigation of the microelectronics device at cell scale is relevant since the heat transfer is the main limiting aspect for the optimal functioning of the device. More particularly, the thermal resistance at interfaces between the constitutive materials is of primary importance. We implemented a scanning thermal microscopy experiment in the 3 mode that allowed to fully characterizing the thermal properties of the cell at the nanoscale. The results lead to understand the 3D heat diffusion in the cell and more particularly the role of the vertical and horizontal interfaces.

1 Introduction

The phase change memory technology involves the use of a phase change material (PCM) and the alloy mostly used so far is the Ge2Sb2Te5 (GST 225) one [1]. This alloy demonstrates a rapid and reversible phase-change switching from amorphous (α) to face centered cubic (fcc) metastable and hexagonal close packed (hcp) stable crystalline phases. The amorphous-to-crystalline transition is achieved by heating the GST above the glass transition temperature that is 130°C for α to fcc transition while it is around 300°C for the fcc to hcp transition. A remarkable, and one of the most interesting features concerning the practical implementation of the PCM in microelectronics, is that the GST electrical resistance varies along decades according to the crystalline state [2, 3]. In the crystalline state (SET mode), the electrical conductivity of the GST alloy is high, leading to a low electrical resistance measured between the top electrode contact (TEC) and the bottom electrode contact (BEC) surrounding the PCM layer. To reset the PCM into the amorphous phase, the material is first melted and then quenched rapidly by applying a large electrical current pulse for a short time period. Doing so leaves a region of amorphous and highly resistive material. This amorphous region, the programming region, is in series with any crystalline region of the PCM and effectively determines the resistance of the PCM cell between the TEC and the BEC. For the GST, amorphization occurs when an electrical pulse is high enough to reach the melting temperature (680°C) and its falling edge is quick enough to quench the molten alloy (cooling within a few tens of ns). To set the PCM cell into the crystalline phase, a medium electrical current pulse is applied to anneal the programming region at a temperature between the crystallization temperature and the melting temperature for a time period long enough to crystallize. To read the state of the programming region, the resistance of the cell is measured by passing an electrical current small enough not to disturb the current state. Several technologies have been tested so far to implement the GST in microelectronics structures in order to reach stable, reliable and fast phase-change in the effective device. The reader could refer to an abundant literature reviewing all the investigated technologies [4]. In this paper, the scanning thermal microscopy (SThM) is used to assess the thermal properties at the nanoscale of a μ-trench technology phase change memory cell. This technique has been used already to measure the thermal conductivity of materials at the nanoscale but its use for the measurement of thermal boundary resistance (TBR) at the interfaces between layers at the scale of a microelectronic device has not been reported yet. Indeed it was demonstrated that interfaces play a key role in the heat transfer within the device during the SET and RESET modes regarding the amount of heat required to reach the
prescribed phase-changes temperatures from amorphous to crystalline and vice versa. Interfaces are also responsible of the cross-thermal talk between neighbour cells that need to be avoided in order to monitor a single cell during its heating.

2 Device configuration

The studied device is represented in Fig. 1. The structure is quite complex since it is based on the juxtaposition of different thin films as well as on a specific implement of the PCM in the shape of a narrow μ-trench. All the dimensions are reported in the figure. Thermal properties (thermal conductivity, density and specific heat) of the materials have been the subject of previous analysis and they are reported in Tab. 1 (values are given for room temperature only). It must be emphasized that the thermal characterization of the device performed in this paper does not lead to a phase-change of the PCM since temperature change remain very small during the thermal inspection using the SThM probe.

![Figure 1](image)

**Figure 1.** Geometry of the phase change memory cell (cross-section view and top view). Thickness of the GST trench is 30 nm.

| Material     | \(k\) (W.m\(^{-1}\).K\(^{-1}\)) | \(\rho\) (kg.m\(^{-3}\)) | \(C_p\) (J.kg\(^{-1}\).K\(^{-1}\)) |
|--------------|-------------------------------|--------------------------|-------------------------------|
| Si           | 131                           | 2329                     | 700                           |
| SiO\(_2\) [7]| 1.4                           | 2200                     | 787                           |
| AlCu         | 238                           | 2700                     | 900                           |
| Ti [5]       | 13                            | 4500                     | 540                           |
| TiN [5]      | 33.6                          | 5400                     | 220                           |
| GST (\(\alpha\)) [3]| 0.18                     | 5870                     | 218                           |
| Si\(_3\)N\(_4\) [6, 7]| 2.1                      | 2900                     | 300                           |

The Ti layers are thin enough to be considered as pure thermal boundary resistance. The TBR at the interface between TiN and AlCu is about \(5 \times 10^{-9}\) K.m\(^2\).W\(^{-1}\) as reported in the literature [8]. The TBR at the interface between TiN and GST (\(\alpha\)) layers has been also the subject of previous studies and it was reported to be \(3-5.5 \times 10^{-8}\) K.m\(^2\).W\(^{-1}\) [5, 8]. Therefore, the TBR at the vertical interface between GST and SiN remains the one that needs to be identified.

3 Scanning Thermal Microscopy (SThM) technique

The SThM has been developing for several years starting from the Wollaston wire technology. Although this technique was already attractive, it did not allow reaching the sub-micrometre spatial
resolution required to assess the thermal properties of microelectronics structure. A huge technological effort has been done more recently that gives rise to new probes with less that 100 nm spatial resolution accuracy [9]. In addition, 4-pads probes have been developed that allow implementing the 3ω technique in a very efficient way [10]. Finally, it was reported more and more use of vacuum conditions leads to avoid the water meniscus formation at the tip of the SThM probe, at the interface with the investigated surface [10].

In this study, the SThM probe has a curvature radius at the tip of \( r_c = 100 \) nm. The central element is a narrow palladium (Pd) strip deposited at the sharp tip of a 400-nm-thick Si₃N₄ substrate, which plays the role of a reflecting mirror and a cantilever. The Pd strip simultaneously acts as a heater and a thermometer. The contact force between the probe and the sample is accurately controlled using a feedback-closed loop on a piezo-element, which ensures the displacement in the z direction with precise steps of 1 nm. A periodic current \( i = i_0 \cos(\omega t) \) with angular frequency \( \omega = 2 \pi \) f., generated from a function generator, flows in the Pd strip. Consequent Joule heating \( P_{2\omega} = P_0 (1+\cos(2\omega t)))/2. \) with \( P_0 = R_0 i_0^2 \), occurs, which results in a temperature increase \( \Delta T = \Delta T_{\text{DC}} + \Delta T_{2\omega} \cos(2\omega t+\phi) \). The Pd electrical resistance is thus varied as \( R = R_0 (1 + \alpha_\text{P} \Delta T) \), where \( R_0 \) denotes the electrical resistance at room temperature and \( \alpha_\text{P} = 1/R_0 \)\( \frac{\partial R}{\partial T} \) is the thermal coefficient. The voltage drop at the Pd strip ends is expressed according to \( \Delta V = \Delta V_{\text{DC}} + \Delta V_{2\omega} \cos(2\omega t) \). The third harmonic is related to the transient contribution of the temperature change as \( \Delta T_{2\omega} = 2 U_{\text{tot}} / R_0 i_0 \alpha_\text{P} \). The third harmonic contribution is measured using a differential stage coupled with a lock-in amplifier. The thermal coefficient of the Pd strip was calibrated by measuring the change in sensor resistance as a function of temperature and is \( \alpha_\text{P} = (0.97 \pm 0.2) \times 10^{-3} \) K⁻¹. Heat transfer in the probe and the investigated material in the contact mode configuration is described in Fig. 2 using the formalism of thermal impedances. The average temperature \( T_p(\omega) \) of the Pd strip is related to the total heat flux \( P_{2\omega} (\omega) \) generated by the Joule effect as \( T_p(\omega) = T_0(\omega) P_{2\omega} (\omega) \). The thermal contact resistance at the interface between the probe and the sample is denoted by \( R_c \), and the heat flux on the contact area is assumed to be uniform. The thermal resistance \( R_\text{c} \) at the interface between the probe and the investigated surface has been measured in a previous study and it was found that \( R_\text{c} = (3.87 \pm 0.4) \times 10^6 \) K.W⁻¹. On the other hand, the contact radius between the probe and the surface has been measured to be close to the tip curvature, i.e., \( r_0 = 120 \pm 15 \) nm. This leads to consider that the maximum investigated depth by the probe is about \( 4 r_0 = 480 \) nm.

The thermal impedance \( Z_p(\omega) \) of the probe, which relates the heat flux \( \phi_p(\omega) \) through the probe to the measured average temperature \( T_p(\omega) \) of the Pd strip, can be expressed as \( Z_p(\omega) = A_p(\omega) \exp(i \delta_p(\omega)) \). To address the complexity of the tip, we proposed to identify \( Z_p \) from the measurement of the amplitude \( A_p(\omega) \) and phase \( \delta_p(\omega) \) in the out-of-contact mode. Indeed, we consider that the model bias from this “system identification” approach is much smaller than that obtained from an analytical solution based on a simplified geometry of the probe. Moreover, the FEA showed that the complexity of the probe couldn’t be accounted fully within the complete model. Therefore, we found the most appropriate model for \( Z_p \) as:

\[
Z_p(\omega) = \frac{a_0}{1 + b_1 \sqrt{j \omega + b_2 j \omega}}
\]
Figure 2. Heat transfer in the Non-Contact and Contact modes using the thermal impedances formalism. The SThM probe used in the present study is a 2-pads contact configuration (photo presented on the lower left).

In out-of-contact mode, measurements of $A_p(\omega)$ when $\omega \to 0$ (DC mode) leads to the thermal resistance $R_p$ of the probe. This means that: $$\lim_{\omega \to 0} A_p(\omega) = T_{p,DC} = a_0 P_0$$

$\tilde{a}_0 = R_p = T_{p,DC}/P_0 = 1.868 \times 10^6 \text{K.W}^{-1}$. Parameters $b_0$ and $b_1$ are identified by minimizing the quadratic gap: $$J = \sum_1^N (\tilde{A}_p(\omega_i) - \tilde{|Z_p(\omega_i)} P_0)^2$$, where $\tilde{A}_p(\omega)$ denotes the measured amplitude within the non-contact mode at frequency $\omega$. The minimization is achieved by using the Levenberg-Marquardt algorithm. It is then found: $b_0 = (1.4 \pm 0.16) \times 10^{-3}$ and $b_1 = (1.32 \pm 0.13) \times 10^{-5}$.

The thermal impedance $Z_m$ of the investigated material can be expressed as an analytical expression within specific configurations involving symmetry and homogenous layers. In the present case, the FEA technique has been implemented in order to simulate the heat transfer within the investigated device in the periodic mode. This requires a lot of attention regarding the mesh of the domain according to the experimental frequency range in order to capture well the surface diffusion.

In the present study, experiments have been done under inert atmosphere (Ar). Primary vacuum is first obtained and then the Ar fills the chamber where the SThM setup is enclosed.

4 Results and analysis

Figure 3. (a) AFM image, (b) Amplitude (SThM) and (c) phase (SThM) measured at 3123 Hz.
Using the AFM mode, it was first possible to determine that the maximum roughness at the surface did not exceed 2 nm. The measured amplitude and phase at a frequency of 3123 Hz are reported on Fig. 3. It was clearly identified the PCM μ-trench despite the fact that the spatial accuracy, determined by $r_0$, was higher that the trench width (30 nm). This result is visible either on the amplitude and the phase measurements.

Performing the probe sweep in the vicinity of the trench, we obtained the results presented in Fig. 4. It is demonstrated on the figure that the temperature on both sides of the GST trench is clearly influenced by the low thermal conductivity of the amorphous GST as well as the heat confinement when the probe is located inside the cell. The maximum temperature is reached at $r=0$, at the center of the cell. The simulated data along the Δ line are represented in Fig. 5 considering two values of the TBR at the vertical interfaces between the GST and Si₃N₄. The agreement with experimental data (Fig. 4) is fair when the value of the TBR is close to $5 \times 10^{-8}$ m².K/W, that is the value at the interface between TiN and GST. It is clear on the figure that, despite of the already low thermal conductivity of the α-GST, the TBR at interface has still a significant contribution. A higher sensitivity would be expected for the GST in the crystalline state.

Figure 4. Topography (AFM mode) and SThM scan (Amplitude and Phase) in the vicinity of the GST μ-trench.

Figure 5. Right: simulated amplitude along the Δ line (left image) considering three values of the TBR at the vertical interface and comparison with measurements along the Δ line.
5 References

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