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Thermal deformation and failure analysis of phase change random access memory

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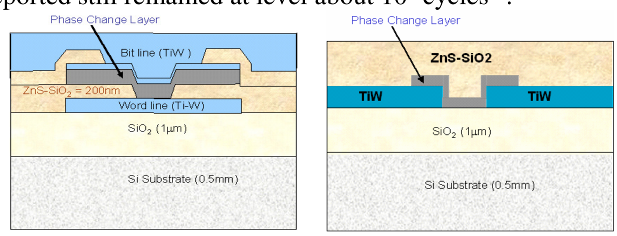
1. Introduction

Phase change random access memory (PCRAM) is one of the best candidates for the next-generation nonvolatile memory (NVM) due to its near-ideal advantages: fast access time, low power, low cost, high endurance, high scalability and good data retention[1-2]. The reversible phase change can be induced by electric pulse between amorphous and crystalline states[3-6]. But all the phase change mechanism reported were based on the assumption of no change in lattice constant of phase change material. This was only an approximation of small deformation in phase change layers. Actually, researchers had found that large deformation would cause the lattice constant and other parameters change a lot in some materials[7-8]. These change degraded the stability of phase change material cause PCRAM breakdown. That means large deformation may cause phase change phenomenon disappear in phase change material and make PCRAM breakdown.

In this paper, ovonic unified memory (OUM) and lateral PCRAM had been chosen to compare the thermal deformation in phase change layer and working performance. OUM is a vertical structure, with electrode on bottom and top of phase change material. With many year's development, OUM (as shown in Fig.1 (a)) had been reported with good stability and high endurance (10^9 ~ 10^{12} cycles). Lateral PCRAM is a lateral structure, with electrode from left and right side (Fig.1 (b)). With the simplicity of fabrication process, easy to integrate into CMOS and much lower reset current, lateral PCRAM was gained more attentions recently[9-12]. Although many phase change materials have been applied in lateral PCRAM, the highest endurance reported still remained at level about 10^6 cycles[12].

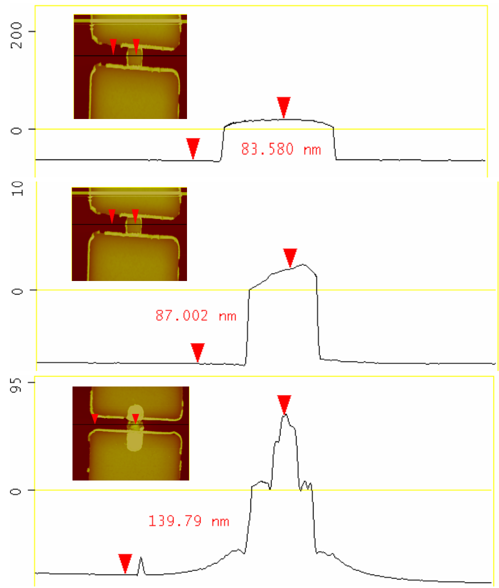


(a) (b)

Fig.1 Structure of (a) OUM and (b) lateral type PCRAM

2. Experiment design and result

Both OUM and lateral PCRAM with Ge2Sb2Te5 were fabricated and the thermal deformation of them was measured with Atomic Force Microscopy (AFM) after similar level endurance cycles. The OUM and lateral devices shown in Fig.1(a) and (b) were fabricated on silicon wafer with 1um thermal SiO2 on the top. The feature size is 0.5μm for both OUM and lateral PCRAM. The layer of phase change material $Ge_2Sb_2Te_5$ is 50nm thick. Both OUM and lateral PCRAM can be set and reset with proper pulse width and amplitude. With these conditions, the OUM and lateral PCRAM were tested with the endurance cycle (Seen in Fig.3). The endurance cycle of OUM exceeds 10^6. But the lateral PCRAM last only around one hundred times and then die. To check the effect in lateral PCRAM, the set and reset pulse still applied after the lateral PCRAM die. The thermal deformation of OUM and lateral PCRAM had been measured after 0, 10^3 and 10^6 overwriting times. For OUM, the thermal deformation is very small after 10^6 endurance cycles. While for lateral PCRAM, the thermal deformation reached about 4nm after 10^3 overwriting and the surface of phase change material was not flat. After 10^6 overwriting, the surface on top of phase change material was extremely rough and the thermal deformation reached several tens of nm (Detail can be seen in Fig.2). It was found that the thermal deformation of OUM PCRAM was very small over 10^6 cycles, while the thermal deformation of lateral PCRAM was significant after 10^3 cycles. If the lattice structure still remained, the lattice constant expanded 10% after 10^3 overwriting and 100% after 10^6 overwriting in phase change layer of lateral PCRAM. The large change in lattice constant and other parameters may seriously change the characteristics of phase change material and make lateral PCRAM fail to work any more.

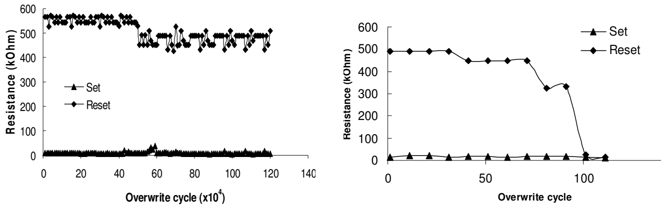


(a)

(b)

(c)

Fig. 2 Shape of measured phase change line for lateral PCRAM for (a) 0 times (b)10^3 times (c) 10^6 times overwriting



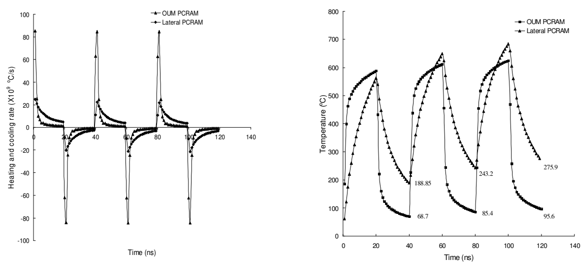
(a) (b)

Fig.3 Overwrite cycle comparison in (a) OUM and (b) lateral PCRAM

3. Thermo-mechanical modeling and simulation results

To find out the factor dominating the thermal deformation in PCRAM, thermo-mechanical modeling and analysis had been done with finite element method (FEM). The thermo-mechanical modeling of phase change optical disks have been reported by Yang et al[13]. But that model described the thermal deformation in phase change material by laser irradiation. For PCRAM, the heat comes from Joule heat. The thermo-mechanical model is same as reported before[13].

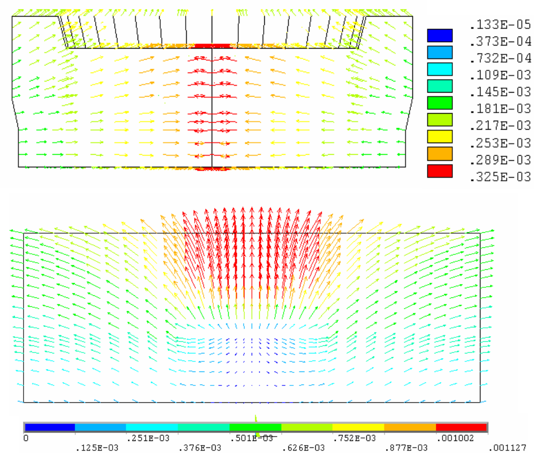
The simulation had been conducted based on above mechanism. To simplify the model, the 1 overwriting cycle has been defined as 50ns reset pulse and 50ns cooling time. Three times overwriting had been simulated for OUM and lateral PCRAM. The heating cooling rate and temperature of active region had been compared between the OUM and lateral PCRAM. Figure 4 shows the result. It was found that the heating and cooling rate of OUM was about 4 times of that of lateral PCRAM. This was mainly caused by the different structures. For OUM, the active region of phase change material sandwiched by metal layers, which has better thermal conductivity and can conduct the Joule heat faster. For lateral PCRAM, the distance between active region and metal electrode is much larger and the Joule heat mainly dissipated into top and bottom dielectric layers[10]. The thermal conductivity of dielectric material is much smaller than that of metal electrode. This is the main reason that heating and cooling rate of OUM was about 4 times of that of lateral PCRAM. With much higher heating and cooling rate, the temperature profile in OUM was very uniform during overwriting. But for lateral PCRAM, the heat can not conducted away so fast that more heat accumulated made the temperature increase with more overwriting cycles.



(a) (b)

Fig.4 Comparison of (a) temperature and (b) heating cooling rate in active region between OUM and lateral PCRAM for 3 overwriting cycles

To compare the thermal deformation in OUM and lateral PCRAM, the temperature of active region was set at melting point 600°C. The result was shown in Fig.5. It can be observed that the thermal deformation of active region in lateral PCRAM was about 3 times of that of OUM. And the deformation direction in OUM was in plane while cross plane in lateral PCRAM. This can be explained that the elastic modulus of TiW metal electrode was much larger than that of dielectric ZnS-SiO2[14]. That implied that phase change material was covered by hard material in OUM while soft material in lateral PCRAM. With more times overwriting, the accumulated thermal deformation in lateral PCRAM will be much lager than that in OUM. This result coincided with experiment results.



(a)

(b)

Fig.5 Deformation flux in (a) OUM and (b) lateral PCRAM

4. Conclusions

The thermal deformation of OUM and lateral PCRAM had been analyzed by the experiment measurement and simulation analysis. Both experiment and simulation results showed thermal deformation of lateral PCRAM was much larger than that of OUM during overwriting. The huge deformation may cause the phase change material change a lot in the lattice constant and other parameters, which made phase change material lose phase change stability. So the thermal deformation may be one main reason for PCRAM to breakdown. Control on the thermal deformation in phase change material effectively may extend the lifetime of PCRAM. More results will be reported in the conference.

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