Fatigue measurement system designed for a chalcogenide-based device using a homemade heater tip

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A fatigue measurement system is designed using a homemade tungsten (W) heater tip. This system is composed of a pulse generator and an atomic force microscope with the W heater tip attached. Also included are a parameter analyzer and control devices. The entire measurement process is controlled by a designed program without communication errors. Additionally, a process to fabricate the sharp W heater tip that applies an electrical pulse and evaluates the electrical properties is introduced. The analysis of the tip, carried out by scanning electron microscopy and electron backscattering diffraction, shows that the tip has high thermomechanical stability. Using this fatigue measurement system, the resistance of the Ge$_2$Sb$_2$Te$_5$ (GST) cell was successfully measured as a function of the number of set/reset cycles. The specific area (both program area and failure area) was easily observed. It is expected that the expansion of GST is a source of information regarding the fatigue of a GST cell. © 2008 American Institute of Physics. [DOI: 10.1063/1.3010380]

Current information technology, computer and wireless communication systems are strongly connected to the advancements in data storage technology. Data storage systems require great efforts to develop next-generation memories characterized by low power consumption, fast read/write speeds, nonvolatility, and that a high density in comparison with existing memories (flash, static random access memory, and dynamic random access memory). Phase change random access memory (PRAM) is regarded as one of the most promising candidates of next-generation memories. PRAM stores data using the distinct status of the resistance difference between the amorphous state and the crystalline state of chalcogenide materials. While writing/erasing data, PRAM uses an electrical pulse to create a phase transition in the commercial tip. The manufacturing process of the homemade W heater tip is as follows: First, an omniprobe is connected to the tungsten wire via platinum deposition on their joints. A focused ion beam is then utilized to cut the wire to an adequate size for manipulation. The end of the tungsten wire is then placed in the hole of the cantilever. Platinum deposition is carried out again to connect the cantilever and the tungsten wire. One concern is that Pt in FIB is not element Pt and a focused carbon, (not element Pt), which might become instable or degrading through long-time repeated heat-up. However, we did not experience the degradation of the cantilever through long-time repeated heat-up, which was confirmed by electron backscattered diffraction (EBSD) results. After cutting the connection with the omniprobe, the wire is trimmed into a pyramidal shape. The sample should be rotated or tilted three dimensionally during manufacturing.

The PRAM fatigue tool includes (a) a pulse generator that generates set and reset pulses repeatedly in turn, (b) an AFM that receives the voltage and makes phase changes in the chalcogenide GST cell, (c) a parameter analyzer that measures a wide variety of parameters in accordance with phase changes in the GST cell (with the voltage of the phase-changed substances and the resistance values calculated from the current-voltage curve being analyzed), and (d) control devices that interface and control each of the devices. The pulse generator, AFM, and parameter analyzer are characterized by being interfaced with each other and automated by a general purpose interface bus. This study uses the Agilent Vee' program as an interface/automation system. Figure 2 shows a schematic that illustrates the devices that constitute...
the PRAM fatigue tool and the links between them. This device is comprised of a pulse generator, an AFM, a parameter analyzer, and a controller; the I-V curve and resistance analyzed by the parameter analyzer are visualized as a graph in the display. When the applied voltage and pulse width, which are required for set/reset phase changes previously set up in the controller, are put in, the corresponding signals are generated by the pulse generator. This pulse-type voltage is generated as Joule heat by the heater tip within the AFM and transforms the phase of the GST substance touching the heater tip into either a crystalline or amorphous phase.3–5 The permissible voltage is outputted rapidly by the unit in dozens or hundreds of nanoseconds, and the phase-change substance of the PRAM device accordingly goes through rapid phase changes. The current value, which is subject to phase changes in the amorphous or crystalline state, is outputted within the parameter analyzer according to the permissible voltage, and the resistance value is calculated in parallel. This process is repeated within the preset period of measurement or according to the number of measurement cycles when conducting the fatigue test. In order to measure the I-V and R values of the phase-changed cell using the parameter analyzer, the voltage value (V′_in) outputted by the parameter analyzer should be put into the AFM (V′_in) so that the current value can be measured by the phase-changed GST area. Therefore, the voltages outputted from the parameter analyzer and pulse generator should be controlled via the Agilent Vee program to prevent possible clashes as these two voltages are permitted into the voltage input part within the AFM (V′_in).

Figure 3 is a flowchart of the program that controls each device of the PRAM fatigue tool. At the stage of Number-Valid Check, the validity of the input values from the devices in the PRAM fatigue measurement system is checked. At the stage of the IDLE process, the pulse generator is used to adjust the voltage and pulse width required between actual measurement cycles; this stage consists of an amorphous state process followed by a crystalline state process. In the amorphous state process, the pulse generator produces the pulse-type voltages needed for phase changes into the amorphous state; it is the process of these voltages inputted from the pulse generator to the AFM. In the crystalline state process, the pulse generator produces the pulse-type voltages that are needed for phase changes into the crystalline state; this represents the entire process of these voltages as they are inputted from the pulse generator to the AFM. Both the amorphous and crystalline state processes use the same set/reset reading process. This includes the following stages: (a) The parameter analyzer generates voltages and reads currents within the scope of the voltage required for the I-V curve, (b) the I-V curve is drawn, and (c) the two aforementioned processes are repeated until the suspend voltage is reached. Once the suspend voltage is reached, the measured current-voltage data are utilized to display the set/reset resistance on the graph. Linear fit processing is a process in which the parameter analyzer outputs voltages without any conflicts upon the necessary voltage for the phase change are displayed and the analyzed results of the measurement are updated on the main screen. The measurement is later completed when the stage of suspend condition processing is reached.

Figure 4 shows the screen required to run the PRAM fatigue tool control program with the AFM with the homemade W heater tip applied. Figure 4(a) is the main screen. It
illustrates the final form of the programming of the control program; one part (left) provides the parameters that are needed for the actual measurement while the other (right) shows the measured data. The variables set on the main screen are the voltage and pulse width needed for the phase change into the amorphous state; the voltage, pulse width, and set/reset pulse delay needed for the phase change into the crystalline state; and the reference value and permissible error (limit) of resistance in accordance with the set/reset phase change. For variable values, either those tested on the configuration screen are applied or the user can input values directly on the main screen. Displayed on the main screen are the results of the resistance measured by the phase change, calculated into such values as the average, standard deviation and maximum/minimum values; the results of the measurement are saved in the form of a file. When any given numbers are entered for “total cycles” and the “number of save cycles,” the save point will be calculated automatically and the experiment will be conducted on this basis. The I-V curve and resistance in the graph on the main screen are displayed in linear and log scales, respectively. Proceeding with the experiment, the point of time when the measurement begins, the estimated time of the completion of the measurement, the number of cycles (or points) when the process is completed, and the rate of progress (%) may be displayed for the monitoring of the rate of progress. Figure 4(b) shows the configuration screen that is used to check whether each of the devices is connected to each other without communication errors. This screen also includes the areas where the conditions for measurement suspension—set by the combinations of “and,” “or” and “no stop condition”—are displayed.

In order to perform a fatigue test, the GST cell is fabricated. In this process, it is very important to isolate the GST to assess the electronic properties at a vertical electrode and to conduct research on transmission electron microscopy (TEM) by applying the scanning probe microscopy (SPM) tip to the top TiN electrode. The TiN (100 nm)/Ti (20 nm) bottom electrode is deposited by a sputtering method onto Si thin film, where 1500 Å oxidation is utilized in a dry thermal method. The GST thin film is subsequently deposited at a thickness of 100 nm at room temperature. On top of that, a two-dimensional array of a GST cell with a size of 20 × 20 μm² is fabricated using photopatterning, and these patterns are utilized for isolating the GST. A wet etching process of the GST is performed using an aqueous solution of 20% nitric acid (HNO₃). It has been found that this etching is more equally and consistently finished when the GST thin film is amorphous compared to when it is crystal; the rate of etching in this case is 4.6 nm/s. Subsequently, SiO₂ is deposited to achieve GST isolation and to ensure a heatproof layer. On a GST specimen prepared as described...
above, pattern alignment for the top electrodes is carried out using patterns that are $2\,\mu m$ smaller than existing GST etching patterns, i.e., $18\,\mu m$. To minimize the impact of the GST in the phase generation, TiN as a top electrode\textsuperscript{19,20} is deposited at room temperature.

Figures 5(a) and 5(b) illustrate SEM images of the homemade W heater tip before and after the $10^8$ cycle test. The tip is suitably defined at $20\,\mu m$ in length. Although the surface shows remarkable roughness, a sharp tip can be seen in the apical zone, featuring a radius of curvature of $\sim 50$ nm and pyramidal shape. Figure 5(c) shows the set (red-dot line) /reset (black-dot line) cycling performance of the GST cell when 5 V, 300 ns was applied for set, (10 V, 50 ns reset), respectively. The resistance ratio ($R_{\text{reset}}/R_{\text{set}}$) of the GST cell decreased slightly to approximately 100 [Fig. 5(e)], indicating that the GST cell had degraded slightly. A TEM observation of the program region was carried out in a pre-
To accelerate the fatigue behavior of the GST cell, the power was increased (9 V, 300 ns set). Figure 5(d) shows the set/reset cycling performance of the GST cell power was applied (9 V, 300 ns set), (10 V, 50 ns reset), respectively. The resistance ratio ($R_{\text{reset}}/R_{\text{set}}$) of the GST cell was drastically degraded to 10 [Fig. 5(e)]. Recently, Ryu et al. and Park et al. reported another important issue regarding compositional alteration of GST (2/2/5) during operation. In their report, GST (2/2/5) phase is not stable and has changed to GST (15/47/38). $T_c$ (crystalline temperature) and $T_m$ (melting temperature) values of the GST (15/47/38) are 205 and 550 °C, respectively, which is about 40 °C higher than the $T_c$ and 70 °C lower than the $T_m$ of GST (2/2/5). Such rapid degradation is possible due to nonuniform distribution of elements results from repeated heat-up and cool-down of GST. Of course, the effect of delamination damage at the interface between TiN top electrode and GST film could not be excluded, as shown in TEM image [Fig. 5(f)]. Figure 5(f) shows a cross-sectional TEM image of the GST cell after the $10^8$ cycle test. The TiN top electrode disappeared and delamination of the GST layer on the TiN bottom electrode can be observed. An expansion of the GST layer toward the top electrode appeared to have occurred. In a previous paper, the authors reported that a TiN mound formed due to the volume expansion of amorphous GST under the top electrode. However, the homemade W heater tip maintained its original shape regardless of the number of the number of heating trials [Fig. 5(b)]. Figure 6 shows the results of the homemade W heater tip after the $10^8$ cycle test with the W wire. Thermal stability of SPM tip is great concern in this research because SPM tip has to endure temperature to 632 °C or over. It is suspected that microstructure and preferred orientation of tungsten could be changed with concentration of heat although the tip continued normal operation. First of all, cross-sectioned microstructure of 18 μm tungsten wire was observed by using SEM and EBSD. The preferred orientation maps of the W wire [Fig. 6(a)] and the homemade W heater tip [Fig. 6(b)] provide evidence of identical orientations. In general, as drawn tungsten wire [Fig. 6(a)] has {110} preferred orientation along the drawing direction, the same result is also observed in Fig. 6(b). The {110} direction is characterized by green color; it is found that {110} preferred orientation is over 95% dominant in this drawn wire. Misorientation map and histogram display grain boundary and subgrain boundary in tungsten wire. The thin red lines are subgrain boundaries which has misorientation angle between 3° –15°. The thick black lines are grain boundaries which has misorientation angle more than 15°. The amount of subgrain boundaries correspond to the left peak in misorientation histogram, and the amount of grain boundaries correspond to the rest peaks. It is expected that tungsten wire got through severe thermal fatigue during the tip operations, this misorientation map and histogram would be changed because of subgrain or grain boundary migrations or grain growth. However, it is found that microstructure and preferred orientation of homemade W heater tip was not greatly changed after tip operation. Thermal stability of homemade heater tip was very reliable; it explains how the tip operation could go $10^8$ cycles without failure. These results indicate that the homemade W heater tip has excellent thermomechanical stability with no increase in the grain size.

In summary, this study introduces a method to produce a sharp W heater tip for application with the electrical pulse for a phase transformation of a GST cell and to evaluate the electrical property of a GST cell simultaneously. The homemade W heater tip maintains its sharp feature even after $10^8$ set/reset tests and shows exceptional thermomechanical stability. The fatigue measurements system in this study is composed of a pulse generator, an AFM with a W heater tip and a parameter analyzer. Integration of an experiment and analysis is realized; set and reset operations and evaluations of the I-V characteristics were carried out on precisely the same area without the need for probe relocation. Thus, this system allows a straightforward observation of a specific area (for example, program area) via TEM. In practice, it was possible to observe the program and failure area using this system.

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