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Nanosecond switching in GeTe phase change memory cells

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The electrical switching behavior of GeTe-based phase change memory devices is characterized by time resolved experiments. SET pulses with a duration of less than 16 ns are shown to crystallize the material. Depending on the resistance of the RESET state, the minimum SET pulse duration can even be reduced down to 1 ns. This finding is attributed to the increasing impact of crystal growth upon decreasing switchable volume. Using GeTe or materials with similar crystal growth velocities, hence promises nonvolatile phase change memories with dynamic random access memorylike switching speeds. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3191670]

Phase change materials possess a unique portfolio of properties that holds considerable promise for applications in data storage.[1] They can be rapidly and reversibly switched between the amorphous and crystalline states, which differ substantially in their properties. While the principle of a phase change random access memory (PCRAM) was already demonstrated in the 1960s,[2] only in the last two decades materials such as $Ge_2Sb_2Te_5$ (Ref. 3) and Ag and In doped Sb_2Te [4] were discovered that crystallized rapidly enough to enable competitive solutions for rewritable optical data storage. Recently, however, the main focus of attention has shifted to the use of phase change materials in nonvolatile electronic memories. This application benefits from the resistance contrast of up to five orders of magnitude between the amorphous and crystalline state.[5] The large contrast promises to facilitate the development of multilevel storage concepts.[6] Other attractive attributes include high switching speed, flash memorylike retention, and superior endurance. Hence there is a significant interest to develop a nonvolatile memory based on this material class. One of the crucial characteristics is the switching speed between the two distinct resistance states. Crystallization of the amorphous regions is the slowest process and hence will determine the maximum speed. In recent years a number of authors have reported crystallization times of less than 60 ns.[7–9] This transformation time is already much faster than the write speed of about 10 μs for flash, presently the dominant solution for nonvolatile memory applications. Attractive market opportunities would arise, however, if nonvolatile memories could be developed that reach dynamic random access memory (DRAM)-like switching speeds of around 10 ns.

In this report we present data for GeTe that demonstrate such speeds and provide a high resistance contrast. The determination of such short crystallization times puts severe constraints on the experimental setup. Hence, for a reliable exploration of the speed limits of PCRAMs a high frequency impedance matched setup is crucial. For this analysis, a fast pulse generator and oscilloscope are combined with a custom made contact board including a low noise amplifier in close proximity to the wafer. The pulse generator allows pulses down to a plateau length of 1 ns with rise/fall times of 2 ns. Voltage pulses with a plateau length between 1 and 128 ns were applied to individual phase change memory cells in the classical bottom heater geometry.[10] A titanium nitride heater with a diameter of 60 nm is embedded in an isolating silicon nitride layer and covered by a 20 nm thick GeTe layer deposited from a stoichiometric target by dc magnetron sputtering. The resulting film composition was determined to $Ge_{53}Te_{47}$ by laser ablation inductively coupled plasma mass spectrometry (ICP-MS). Subsequently, a 3 nm titanium adhesion layer and a 20 nm thick TiN top electrode layer have been sputter-deposited and patterned by a lift-off process. Finally the phase change material was crystallized in argon atmosphere at 250 °C resulting in a cell resistance of approximately 3 kΩ.

The switching properties of several cells were electrically characterized using dynamic stimulation. In Fig. 1, the typical *R-I* switching curves for cell resistance versus pulse current are presented for different pulse lengths in the range of 1–16 ns (defined as the time between reaching and leaving 90% of the pulse maximum). For all pulse lengths down to 1 ns, a successful set operation to cell resistances <15 kΩ is possible for currents between 400 μA and 1.1 mA. However, the lowest cell resistance of 3 kΩ is only reached with the longer 16 ns pulses. For currents exceeding 1.2 mA, the highly resistive reset state is recovered.

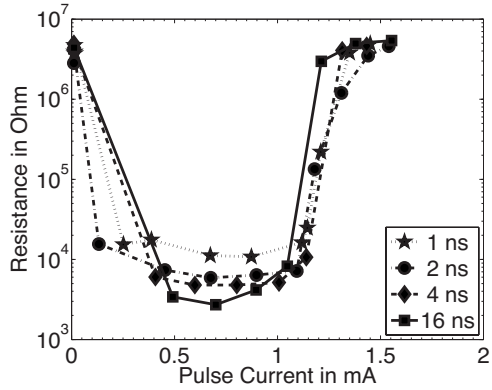

FIG. 1. Cell resistance vs pulse current for applied reset and set pulses in the range from 1 to 16 ns.

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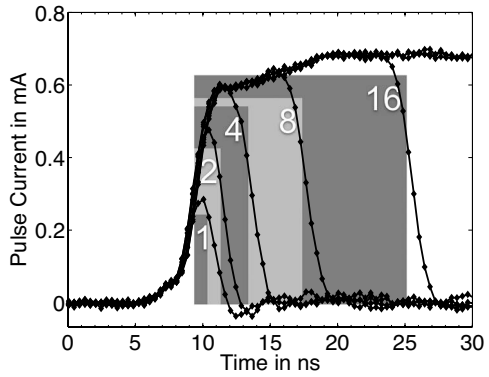

FIG. 2. Time resolved measurement of the pulse current. The pulse generator output was programmed to 1.2 V and pulse lengths were varied between 1 and 16 ns. With increasing pulse length the maximum current increases and saturates at 0.7 mA. Grey boxes indicate the pulse length.

In Fig. 2 the current amplitude of voltage pulses of 1.2 V through the memory cell is displayed for different pulse lengths. A strong dependence of pulse amplitude on pulse width is present. This amplitude loss for short pulses results in an increase in the reset voltage for pulses <4 ns. The resistance of the reset state depends on the pulse current. Hence, the resistance value of the reset state can be controlled in the range of 2–7 MΩ by adjusting the pulse amplitude. The data presented in Figs. 1 and 2 unequivocally demonstrate that GeTe-based phase change memory cells can be symmetrically set and reset with pulses as short as 1 ns. Such behavior is a prerequisite for DRAM-like applications of phase change materials.

In order to further investigate the high speed set properties of the GeTe memory cells, the influence of set pulse length and amplitude on the resulting cell state was investigated in more detail. Figure 3 shows the cell state after the applied set test pulse in a two-dimensional crystallization diagram. To ensure a uniform and reproducible initial state for this experiment, each test pulse was preceded by both a full set (3 kΩ) and a subsequent reset to the amorphous state (6 MΩ). By this technique, the cell can be repeatedly programmed to precisely defined resistance states. At the optimum pulse amplitude around 1.3 V, crystallization starts at pulse lengths of 2.8 ns. The set state with the lowest resistance is reached for pulses longer than 8 ns. For pulses below

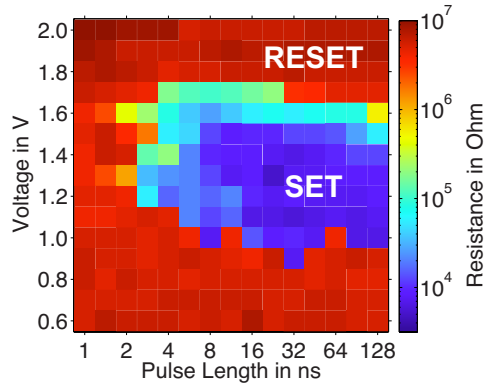

FIG. 3. (Color online) Cell resistance after application of set pulses with different amplitude and length, each starting from the amorphous reset state. The color of each data point represents the cell resistance after the test pulse. For pulses longer than 4 ns a broad crystallization window opens between 1.0 and 1.5 V.

0.9 V, no lowering of the cell resistance is observed. This is due to the threshold voltage V_{th} of the investigated reset state, which lies between 0.9 and 1.0 V, resulting in negligible current flow below this voltage. For amplitudes between 1.0 and 1.5 V, a well defined set window is observed for pulses longer than 4 ns. Pulses of 1.6 V and above force currents of 1 mA or more, which are sufficient to locally melt the cell resulting in a highly resistive amorphous state upon fast cooling. This more detailed characterization confirms the set performance derived from Fig. 1 and demonstrates the reliable and fast program and erase operation of this particular material.

The high recrystallization speed in the range of 1–5 ns of our GeTe-based electrical memory cells is quite remarkable in light of the earlier data from research on materials for optical data storage. For GeTe, laser induced recrystallization times of around 30 ns have been reported.[11,12] It is commonly accepted that the recrystallization process is a thermal process that proceeds once a material is heated for a sufficiently long time to elevated temperatures. Hence recrystallization should proceed with similar nucleation and growth rates in both cases. A possible reason for the pronounced decrease in recrystallization time observed here could be due to the difference in the size of the amorphous regions. While an amorphous mark in a typical laser annealing experiment has a diameter of around 1 μm, in our phase change memory cell the size of the amorphous region is controlled mainly by the heater size and falls in the range of 20–60 nm. Phase change materials are often divided into two different categories depending on the recrystallization mechanism.[11] In growth dominated crystallization, the transformation of the amorphous region is dominated by growth of the crystalline phase from the crystalline rim surrounding the amorphous region. On the contrary, in nucleation dominated crystallization many crystalline nuclei are formed. Growth dominated recrystallization is characterized by a strong dependence of recrystallization time upon the size of the amorphous region, in contrast to nucleation dominated recrystallization, which is practically independent of mark size. Hence the fast recrystallization times we observe could be explained by GeTe recrystallizing predominantly via crystal growth in our cells. This is in line with studies for rewriteable optical data storage, where average grain sizes larger than 100 nm have been observed in crystallized thin films of GeTe.[13] To check this hypothesis of growth dominated recrystallization it has been studied how the speed of the set operation depends upon the initial amorphous state (reset) of the memory cell.

Figure 4 shows a systematic analysis of the crystallization diagram for different initial reset resistances. The bottom row shows the cell resistance after application of the test set pulse as a function of the pulse generator voltage, whereas the top row plots the resistance versus the pulse current. Starting from the 2.3 MΩ reset state, voltage pulses of 0.6 V stay below the threshold voltage and do not lead to significant currents. Currents around 0.8 mA seem to be optimal to recrystallize the amorphous mushroom. Even the minimum pulse length of 1 ns is sufficient to recrystallize enough material to restore a set state below 15 kΩ. In the experiments, testing higher reset states such as 4.2 or 5.2 MΩ the shortest pulses cannot fully restore the set state, but decrease the resistance significantly. For these reset states 16 ns pulse length are necessary to fully set the cell. The highest tested

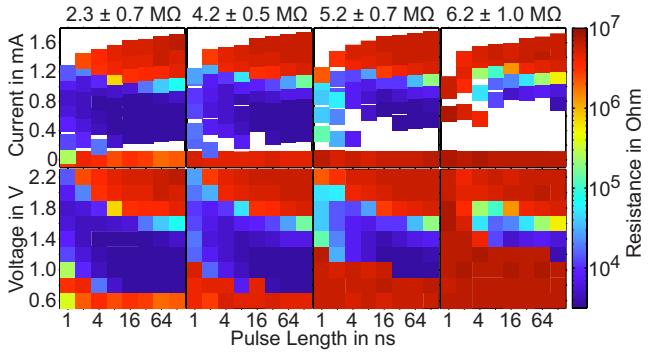

FIG. 4. (Color online) The crystallization behavior of GeTe was tested for four different reset states (Same color code as in Fig. 3). Top: current vs pulse length. Moderate currents (<0.9 mA) can crystallize the cell while higher currents (>1.1 mA) reamorphize the cell. Bottom: voltage vs pulse length. The lower border (from red to blue) shows how the threshold voltage depends on the reset resistance.

reset state 6.2 MΩ shows no effect after 1 or 2 ns pulses, but 16 ns can recrystallize this larger region, too. With increasing reset resistance the threshold voltage increases as well. Therefore medium currents between 0.1 and 0.8 mA are not available for the set of measurements starting with the highest initial resistance. At 1.6 V increasing the pulse length leads to reamorphization of the test cell. This indicates a temperature increase in the cell during long pulses, which leads to melting and subsequent melt quenching.

It is obvious from Fig. 4 that the recrystallization phenomena are much faster for amorphous regions with lower resistance. It is very tempting to relate differences in the resistance of the reset state with differences in the size of the amorphous region. This indicates that smaller amorphous regions recrystallize faster than larger amorphous regions. Similar results have recently been reported for the switching characteristics of memory cells containing $Ge_2Sb_2Te_5$,[7] a phase change material employed in optical storage applications. In this study the duration of set and reset pulses also decreased with a smaller switchable volume, obtained by reducing the absolute cell size. Such a behavior is expected for growth dominated recrystallization.[14] At the same time for the larger amorphous marks in optical storage media, nucleation dominated recrystallization has been observed for GeTe.[11] This implies that the crystallization mechanism can change with decreasing size of the amorphous region. Such a conclusion is quite reasonable since the number of nuclei formed within the amorphous region during a pulse will decrease with the shrinking size. On the contrary the significance of growth will increase with shrinking size, since the interface to volume ratio increases. Hence this is a reminder that differences in recrystallization behavior are expected upon pronounced changes of cell size.

In summary, it has been demonstrated that GeTe can be a very fast phase change material with DRAM-like switching speeds down to at least 1 ns for both set and reset operations. Together with the high resistance change upon crystallization and the nonvolatile retention this particular material is hence very promising for memory applications. At 55 °C, crystal growth would lead to a shift in the interface by only 2 nm in 10 yr, as can be estimated from data we measured for the crystal growth velocity. It was also shown that the set operation became faster with decreasing value of the reset resistance. This is presumably linked with the size of the amorphous region and provides evidence that at these small dimensions GeTe shows growth dominated recrystallization.

The high set speeds we observe are very encouraging for memory applications. It is expected that in the near future the cell size will approach 20 nm promising even faster switching behavior. Already during the optimization of phase change materials for optical storage a number of alloys were found that demonstrate growth speeds of 30–50 m/s.[15] With such fast growth speeds, subnanosecond switching could become a reality.

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