Employing advanced characterization tools for the study of phase change materials

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ABSTRACT

Phase change materials display a property portfolio which is highly attractive for memory applications. Of particular interest is the use of phase change materials in non-volatile electronic memories. To compete with ongoing developments in DRAM and Flash technology, phase change memories have to meet stringent requirements in terms of scaling, speed and power consumption. Hence it is mandatory to investigate which materials possess the most desirable properties for memory applications. These properties include both electronic characteristics which govern charge transport, as well as the transformation kinetics which define the limits of data transfer rates. Measuring fast transformations as well as the electronic properties with very high accuracy creates significant challenges in the design of advanced measurement tools.

Novel set-ups will be presented which have been designed to identify the limits of transformation speed as well as the charge transfer mechanisms in the amorphous and crystalline phase. We will demonstrate that an investigation of electronic switching within one nanosecond has been enabled by careful design of high speed electronics. This result demonstrates that this new memory technology has not only an impressive scaling performance but also huge potential in terms of writing speed.

Keywords: Phase change materials, phase change memories

1. INTRODUCTION

Since Ovshinsky et. al. [1] first showed the feasibility of phase change materials for electronic data storage the area has attracted much interest. Recent work has demonstrated unequivocally, that phase change memories show very attractive scaling properties [2]. To determine the full potential of this storage technology it is equally important to determine the data transfer rate of phase change memories. This is the focus of our present activities. If it would be possible to realize very fast write and read times together with low power consumption it might even be possible to replace dynamic random access memories (DRAM) by a phase change memory.

For the investigation of the switching speed of the phase change materials a set-up was developed which employed careful impedance matching. In addition the tester can precisely determine the cell resistance before and after a cell switch as demonstrated by the measurement of the resistance drift of an amorphous phase change cell.

2. EXPERIMENTS

Novel set-up and measurement scheme

Many measurement schemes have so far be proposed for the measurement of phase change memory single cells. A good overview can be found in [3]. The present set-up has been designed to measure cells with both contacts floating. This allows forcing the voltage on the cell on one 'driving' contact while measuring the current through the cell with a shunt resistor on the other 'sensing' contact against ground. Hence the current signal is directly ground-referenced. Both circuitries, the driving and the sensing, were moved as close as possible to the sample. A printed circuit board was designed to fulfill these demands and to adapt the impedance of the source to the phase change memory cell. The

driving signal is generated by a HP 81110A pulse generator which is capable of generating single pulses with rise/fall times of down to 2.5 ns and 1 ns plateau length.

A Rohde&Schwarz ZVL 3 vector network analyzer was used to check that the impedance matching condition is fulfilled and the signal from the pulse generator is driven to the needle and measured in the scope without unwanted reflections or other artifacts up to the scope bandwidth of 500 MHz. The sensing circuitry is also implemented on the same circuit board where the current is measured by a sense resistor. A high-bandwidth, low noise amplifier is used to amplify the signal before it is recorded in the scope. This way the whole current measurement system has a -3 dB bandwidth exceeding 300 MHz. Overall, this high speed measurement scheme was designed to be capable of applying voltage-controlled pulses to a phase change memory cell with down to 1 ns plateau length. Both voltage and current can be recorded with more than 300 MHz system bandwidth. Current rise times down to 1 ns, e.g. caused by a sudden threshold switch of the cell, can be resolved.

To be able to measure the cell resistance before and after the switching experiment, a small 1 kHz sinusoidal signal of 10 mV is superimposed on the driving needle. This small signal causes a current variation on the sensing needle. Even though this signal causes voltages in the range of nV on the shunt resistor, its magnitude can be determined by using a lock-in amplifier. This allows the precise measurement of cell resistance without switching contacts, neither mechanically nor electronically.

All experiments were performed on phase change memory cells following the bottom heater design [4]. The cells consist of a TiN heater of 60 nm diameter embedded in dielectric. A uniform GeTe layer is then deposited on this heater and an additional Ti and TiN Layer above act as one contact pad. A second contact pad is in contact to the heater below the surrounding dielectric. The resulting film composition was measured to be $Ge_{53}Te_{47}$ by laser ablation inductively coupled plasma mass spectroscopy (LA-IPC-MS).   After deposition the active material was crystallized in argon atmosphere at 250°C resulting in approx. 3 kΩ cell resistance.

Test experiment

The capabilities of the novel set-up were first tested by applying voltage pulses to special ohmic test cells. Those were fabricated by replacing the phase-change layer by titanium. This lead to ohmic cells having approximately the heater resistance of 1.2 kΩ. Fig. 1 shows the current and voltage curves recorded for 2 ns and 8 ns plateau length with 2.5 ns rise/fall time. While there is a delay between the current and voltage, which is caused by the signal propagation speed through the current signal preamplifier and differences in cable length, the shape of the curves is very similar. This clearly shows that the ohmic behavior of the test cell can successfully be measured even with very short pulses. Also the sharp rising and falling edges of the pulses created no significant overshoot of the current signal. Therefore parasitic capacitances had no significant influence on the cell current.
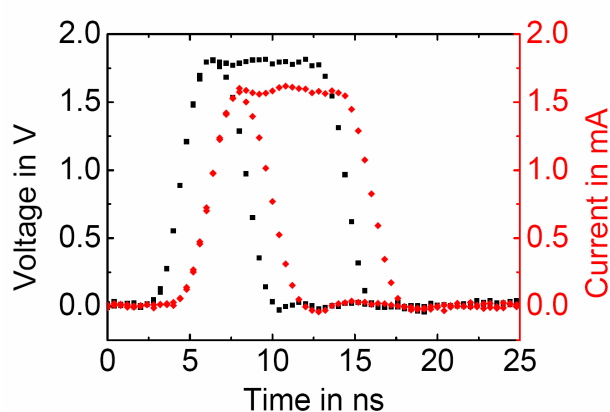

Fig. 1: Voltage and current curves for voltage pulses with 2 ns and 8 ns plateau length applied to an ohmic test cell.
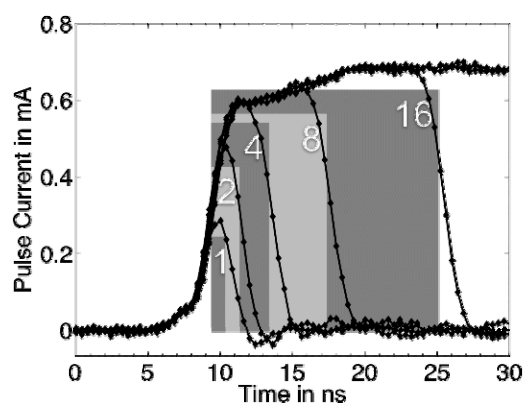

Fig. 2: Time resolved pulse current. The plateau length of a 1.2 V pulse applied to an amorphous GeTe phase change memory cell was varied between 1 and 16 ns. The cell was set and reset between each pulse.

3. RESULTS & DISCUSSION

Switching experiments on GeTe phase change memory cells

After these test experiments, cells with GeTe as active material were measured. To ensure the reproducibility of the experiment, the cell were put in the same initial state before each pulse. This was done by first applying a set pulse on the cell which lead to approx. 3 kΩ cell resistance and afterwards fully resetting the cell to 6 MΩ. These experiments, which are described in more detail in [5], showed that the set-up is capable of measuring the low currents in phase change memory cells with high resolution. More importantly, the data prove that such short pulses can significantly change the cell resistance and therefore be used for writing data. Fig. 2 shows the time-resolved current for pulses from 1 ns to 16 ns plateau length and 1.2 V applied voltage, starting from an amorphous cell state. Both the rise in peak current from 1 ns to 4 ns plateau height, which is indicative for threshold switching, and the trend from 4 ns to 16 ns were precisely resolved. The common parts of the curves measured lie perfectly on top of each other which shows the reproducibility of the experiment.
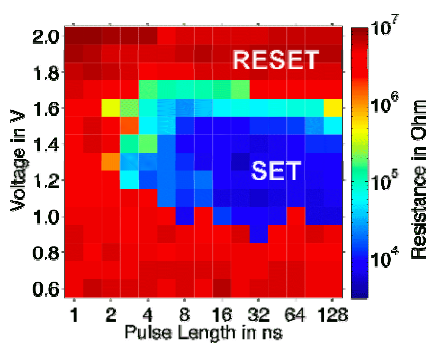

Fig. 3: Cell resistance (color code) after a test pulse in dependence of pulse voltage and width. Before each pulse the cell was reset to approx. 6 MΩ.
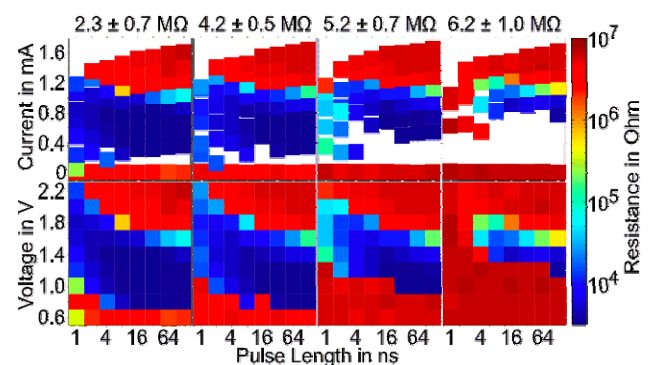
Fig. 4: Cell resistance (color code) after test pulses in dependence of pulse current or voltage (y-axis) and pulse length (x-axis). The cell was initialized to four different reset-state resistances (columns).

Using these new possibilities allowed systematically investigating the cell behavior as a function of pulse voltage and plateau width. Starting every time from a well defined amorphous cell state (6 MΩ), the effect on the cell resistance was measured in dependence of these parameters. In Fig. 3 every dot corresponds to one pulse with the parameters described on the axis. The color code indicates the cell resistance measured after the pulse. Below 0.9 V no effect can be observed since the threshold voltage of the measured cell was between 0.9 V and 1.0 V. Above 1.8 V the active material always reached the melting temperature which resulted again in an amorphous state after the pulse. With pulses longer than 4 ns the cells were successfully switched into the crystalline state within a broad window of pulse voltages between 1.0 V and 1.5 V.

As a third parameter the initial reset resistance before the pulse was varied. Fig. 4 shows the same experiment with different preconditions. The initial reset resistance was set to values from 2.3 MΩ to 6.2 MΩ in four steps. For each step the two-dimensional parameter space of voltage and pulse plateau length was scanned. In the upper row the resistance is plotted against the measured peak current. In contrast, in the lower row, the resistance is plotted against the applied voltage to the cell. From these plots it is obvious that the recrystallization speed increases coming from a lower reset resistance. This is indicative of growth dominated recrystallization.

To show the possibilities of this technique, the R-I switching curves for the case of an initial resistance of 2.3 MΩ are plotted (Fig. 5). Within this experiment a pulse plateau length of 1 ns was sufficient to change the cell resistance by

more than two orders of magnitude. Switching back and forth between the amorphous and crystalline state was possible by just applying this short pulse with different voltages.

Compared to laser crystallization experiments where the fastest crystallization time so far was reported to be around 30 ns [6,7] this speed is quite remarkable. A possible reason for this difference could be the size of the amorphous region. While typical mark sizes in optical experiments are around 1 μm, the active region here does not significantly exceed the heater diameter of 60 nm. Hence the probability of a nucleation event in the cell decreases significantly. From earlier experiments [8] it is observed that GeTe forms, compared with other phase change materials, quite large grains with sizes often larger than 100 nm. Comparing this grain size with the bit dimensions in optical and electronic memories, we expect nucleation dominated crystallization for the laser mark, since for the 1 μm spot one would expect several nuclei to be formed. This is in line with the experimental results [6]. On the other hand, for the electrical switching of the phase change cell, we expect growth dominated crystallization [9] since the probability for a nucleation event in this small cell is considerably reduced. Such a growth dominated scenario could explain the fast crystallization, since crystal growth starting from the crystalline surrounding of the amorphous active region could crystallize the area over the heater very rapidly due to the small dimensions.
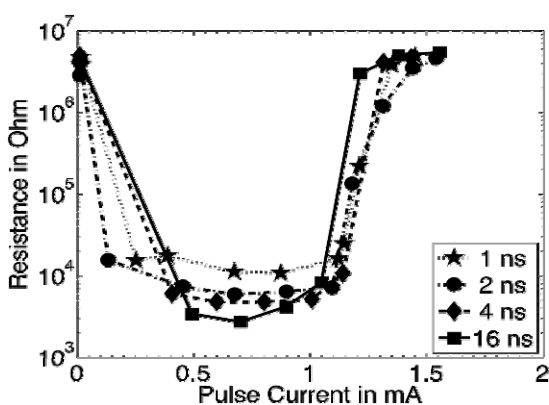

Fig. 5: Cell resistance versus pulse current for an initial cell resistance of 2.3 MΩ. The pulse plateau length was varied from 1 to 16 ns.
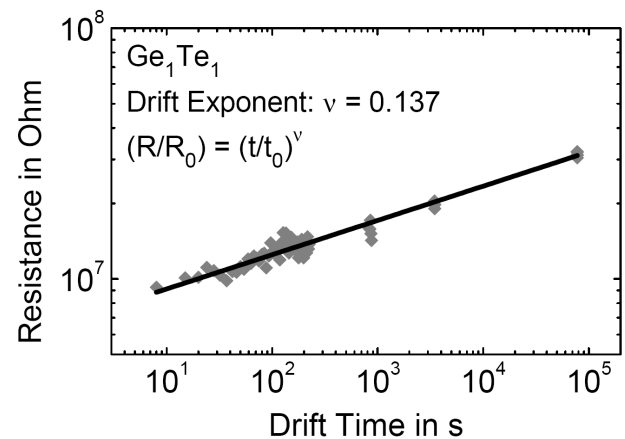
Fig. 6: Resistance drift measured on an amorphous GeTe phase change memory cell.

It is very likely that the size of the amorphous region is directly related to the reset-state resistance. Hence the smaller amorphous region of cells with lower reset-resistance in Fig. 4 enable the crystal growth from the crystalline surrounding to reach the heater area in less time and therefore reach the set-state faster. This would explain the relationship between minimum set-pulse length and reset-state resistance. Such experimental results were also reported by [10] on cells containing $Ge_2Sb_2Te_5$ as active material. A third study [11] observed larger time constants, but this finding might be attributed to the larger cell diameter of approximately 1 μm.

Measurement of cell drift in the amorphous state

The precise lock-in measurement of the cell resistance enabled the measurement of the resistance drift of cells over time. Fig. 6 shows the result of a resistance drift experiment on a GeTe cell. The cell was switched in the amorphous state at t=0 and then the cell resistance was measured up to $t=10^5$ seconds. In order not to block the set-up, the sample was removed and reinserted into the set-up for the data points at 10^4 and 10^5 seconds. The resistance showed clearly

the usual trend of resistance drift, which can be fitted with the empiric formula $\dfrac{R}{R_0} = \left(\dfrac{t}{t_0}\right)^\nu$ leading to a drift

exponent of 0.137. This shows that this novel measurement configuration is not only capable of switching cells within very short timescales but also enables very precise measurements of the cell resistance without any compromise by switching between two configurations.

4. CONCLUSION

We have shown that by carefully designing high-speed electronics the measurement limit for single phase change memory cells can be shifted to single ns and measurement bandwidths exceeding 300 MHz. This was possible while still recording both voltage and current in the cell. In addition to these new opportunities, precise non-influencing resistance measurements are possible without any configuration switch, neither mechanically or electronically. This opens up new possibilities for the measurement of memory cells, their switching speed and their resistance drift. These experiments demonstrate that cells can be easily switched in just a few nanoseconds, opening up possibilities for their use, e.g. as a non-volatile DRAM replacement.

The measurement concept leaves still room for improvement and further gain in speed. Being able to track the behavior of a single cell with even higher temporal resolution would allow to further investigate the ultimate limits in terms of the kinetic memory switching process as well as the time-dependent investigation of threshold switching. On the other hand, different cell geometries and active materials can be tested and optimized for their performance in terms of reproducibility, achievable resistance contrast and speed.

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REFERENCES

1. S. Ovshinsky, Phys. Rev. Lett. 21, 1450 (1968)
2. Y. Zhang et. al., J. Appl. Phys. 104, 074312 (2008)
3. S. Raoux (ed.), M. Wuttig (ed.), "Phase change materials: science and applications", Springer (2008)
4. S. Lai and T. Lowrey, Tech. Dig. – Int. Electron Devices Meeting. 2001, 36.5.
5. G. Bruns et. al., Appl. Phys. Letter 95, 043108 (2009)
6. J. Coombs et. al., J. Appl. Phys. 78, 4918 (1995)
7. M. Chen et. al., Appl. Phys. Lett. 49, 502 (1986)
8. E. Huber and E. Marinero, Phys. Rev. B 36, 1595 (1987)
9. J. Kalb et. al., J. Appl. Phys. 98, 054910 (2005)
10. W. J. Wang et. al., Appl. Phys. Lett. 93, 043121 (2008)
11. E. G. Yeo et. al., Appl. Phys. Lett. 94, 243504 (2009)

Biography

Carl Schlockermann started his studies in the field of communication engineering 1999 at the University of Applied Sciences in Munich, Germany. From 2001 on he also took courses in the field of industrial engineering with the specialization on information technology. After finishing his diploma in communication engineering he worked 12 months at Bell Labs (Lucent Tech.) at NJ, USA in the field of near field optics, surface plasmons, AFM/NSOM microscopy and nanostructuring. Back in Munich he continued his studies in industrial engineering as well as his work on surface plasmons. After finishing his second diploma in 2006 he joint the group of Prof. Dr. Wuttig at RWTH Aachen for a Ph.D. thesis in the field of phase change materials, focusing on new measurement methods and set-ups for the characterization of electronic and kinetic properties.