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Comparison of new and old generations of the phase change memory chalcogenide materials and devices

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A comparison of the two generations of the phase change memory cells was made. Advantages and disadvantages of the new generation of the phase change memory were formulated from the point of view of an electronic-thermal theory. The phase change memory technology was compared with the flash memory technology.

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1. Introduction

The first generation of the phase change memory (PCM) cells (old cells), based on a "glass-crystal" phase transition in chalcogenides was made in the 1970s. However, because of a low endurance, this generation of PCM cells was not successful. The new generation of memory cells (new or modern cells) was made at the beginning of this century and may be characterized by a very high endurance. The purpose of this paper is to compare new and old generations of the phase change memory devices and respective chalcogenide materials in order to find out the reasons of the success.

The second purpose of the paper is to discuss the reasons for the current interest to PCM. What happens in microelectronics and why scientists and technologists start consider the PCM as an alternative to silicon-based flash memory devices?

At the beginning, we will make a short review of switching and memory effects in chalcogenide glassy semiconductors. Then the properties of the "off" and "on" states will be analyzed within the framework of an electronic-thermal model. Finally, a comparison of silicon based flash memory and chalcogenide based PCM will be made.

2. Experimental data

The discovery of the phase-change memory in chalcogenide glassy semiconductors (CGS) [1] was not accidental, but was based on the discovery of semiconductor properties of chalcogenide glasses in the Ioffe institute [2]. It is well known that a switching effect is a predecessor of a memory effect. The switching effect (SW) and the memory effect (MEM) in CGS are sketched on the Fig. 1.

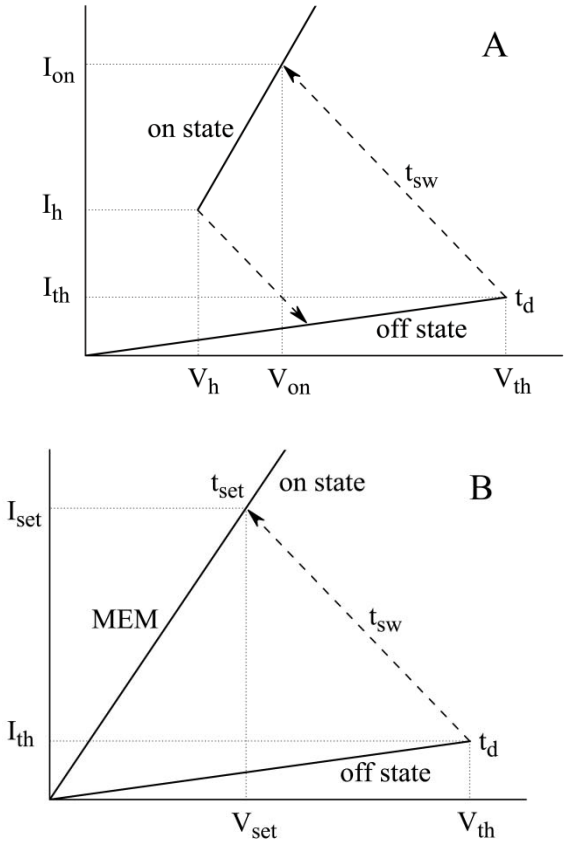

Fig. 1. A schematic view of switching (A) and memory (B) current voltage characteristic. Explanation in the text.

Each point of a high-resistive (off-state) CVC branch on the Fig. 1 corresponds to the applied voltage $V \leq V_{th}$, where V_{th} is a threshold voltage. If the applied voltage is higher than the threshold voltage V_{th}, the switching effect occurs i.e. after a delay time t_d a transition from a highly resistive off-state to low-resistive on-state occurs. The

switching time t_{sw} is very small in comparison with the delay time, $t_{sw} << t_d$. The delay time t_d strongly (exponentially) depends on the overvoltage V-V_{th} and chalcogenide film thickness L. For devices with a large radius, the current distribution in the on state is not uniform, a narrow current filament with a high current density forms. If the circumstances inside the filament do not satisfy the crystallization conditions (e.g. low crystallization ability, low temperature of the filament, small time in the on-state t_{on}, etc.), then the device reversible returns to the off-state. This is called a reversible switching effect (Fig. 1A).

If the crystallization conditions are satisfied, the device does not returns to the off-state, after a set time t_{set} a part of the filament changes its resistance due to crystallization and remains in the crystalline state after the voltage is removed. This is called a memory effect (Fig. 1B).

Let us consider the memory effect, i.e. amorphous to crystalline transition (set process) and crystalline to amorphous transition (reset process) in details. A schematic view of old and modern memory cells and its current-voltage characteristics are presented in Fig. 2 and Fig. 3 respectively.

To obtain the set (crystalline) state one has to use current and voltage from the set region of Fig. 3 (left) in order to reach the crystallization temperature T_c, which is of the order of the softening temperature T_g (Fig. 3 right). Moreover, the set pulse duration must be long enough for the crystallization to complete. For the reset process (amorphization) a shorter pulse (Fig. 3, right) with a higher current density (Fig. 3, left). is used The reset pulse heats the active volume up to the amorphization temperature T_a, which is close to the melting temperature T_m . The reset pulse must be short with a sharp trailing edge in order to achieve rapid cooling and therefore an amorphous state (Fig. 3, right).

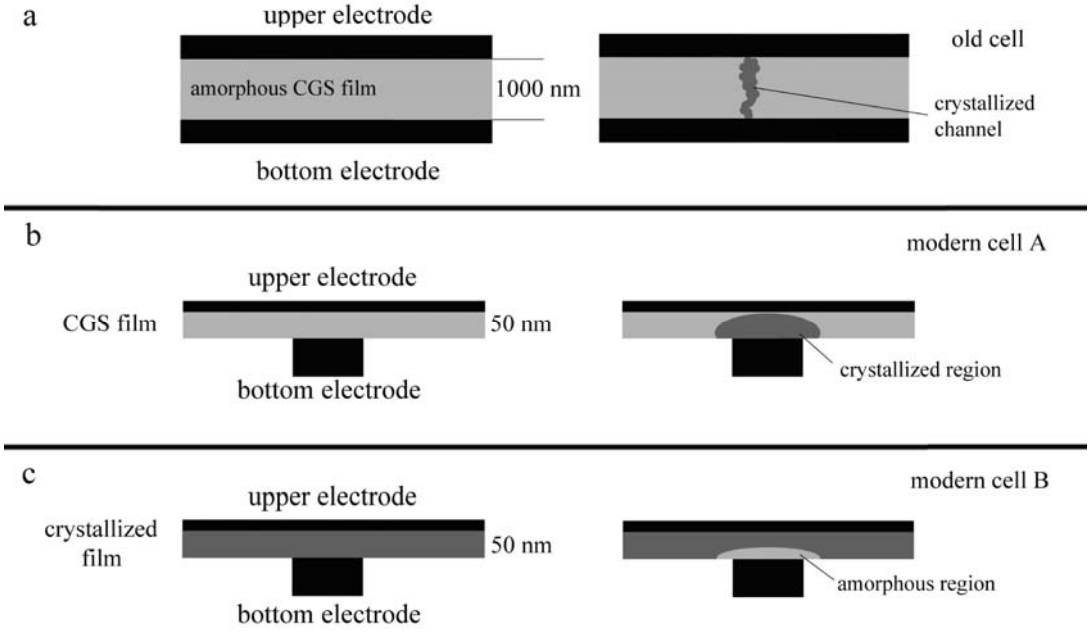

Fig. 2. Old and modern memory cells.

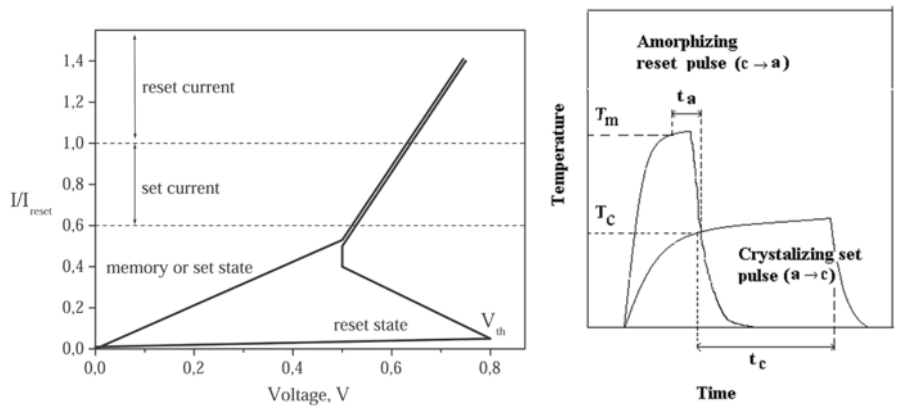

Fig. 3. Current-voltage characteristic of a memory cell and set-reset pulses.

3. Properties of the off-, on- and memory states

Table 1 shows the most important optical and low-field electrical properties of $Ge_2Sb_2Te_5$ (GST) compound [3].

Table 1. Optical end electrical properties of GST.

GST properties by T. Kato and K. Tanaka [3]							
	E_g, eV	E_μ	E_n	$E=E_n+E_\mu$	n, cm^{-3}	μ, $cm^2/V\cdot sec$	ρ, Ohm·cm (300 K)
Chalcogenide glassy semiconductor (amorphous)	0.74	0.25	0.2	0.45	10^{17-18}	10^{-2}	10^4
Crystalline semiconductor, cubic phase	0.5	0	0.14	0.14	10^{16}	10^2	1
Crystalline semimetal, hexagonal phase	0.5				$5\cdot10^{20}$	20	10^{-3}

Where E_μ and E_n are the activation energies of mobility (μ) and concentration (n).

Our investigation has shown that information recording, based on the glass-crystal phase transition, induced by an electric pulse in old cells, has the following peculiarities: memory state arises not from semiconductor but from metallic-type state. This state is due to switching effect in thin films, which have a strong non-linearity of the current-voltage characteristic.

In the off-state in a high field CGS are semiconducting glasses, the conductivity is specified by the relation $\sigma = \sigma_0 \exp(-E^*/kT)$ with an effective activation energy $E^* = (E - f(V/V_0))$, which depends on the electric field. In the on-state E^* is approximately equal to zero so the phase transition from a semiconductor to a metal conductivity $\sigma = \sigma_0$ occurs. While crystallization or set process the conductivity changes $\sigma_0 \rightarrow \sigma_C$. In other words, the conductivity of the memory state differs from the conductivity of the on-state. In a strong electric field about 10^5 V/cm the temperature T_{tr} of the phase transition from a semiconductor to metal conductivity $\sigma = \sigma_0$ is approximately equal to 450-600 K for $Si_{12}Te_{48}As_{30}Ge_{10}$ and As_2Se_3-$4As_2Te_3$ compounds [4]. Unfortunately, there are no available experimental data on the transition temperature in new GST materials.

Comparison of new and old PCM

In the Table 2, one can see the comparison of old and modern PCM cells.

Table 2. Dependence of the phase transition temperature T_{tr} and reversibility or endurance on the composition of the CGS. The first four lines from [4]. The last line: endurance [5] and E_g [3]

composition	T_{tr}, K	endurance	E_g, eV
As_2Se_3 – 4 As_2Te_3	450	10^4	0.91
As_2Se_3 – As_2Te_3	630	10^2	1.17
3 As_2Se_3 – As_2Te_3	1000	1	1.37
As_2Se_3	1500	1	1.90
$Ge_2Sb_2Te_5$		10^{11}-10^{12}	0.74

As one can see, modern materials show sufficiently higher endurance. Let us formulate the main reasons for it:

- In modern cells, the initial state of the CGS film is crystalline (see fig. 2c, left side). Therefore, the size of the amorphous region is equal to the size of the small bottom electrode heater. This method allows to amorphize a small volume near the heater (see Fig. 2c, right side). Because of a large difference in resistivity between amorphous and

crystalline phases (see Table 1), it is enough to obtain the reset state.

- The phenomenological electronic-thermal theory of switching and memory effects [4] predicts that the size of the current filament is not less than several microns. The size of the memory cell in modern devices is many times smaller, therefore we believe that the current is distributed uniformly within the memory cell, and the filament does not forms. It has been shown [6] that the current-voltage characteristic (CVC), which has been calculated within the framework of an electronic-thermal theory with a homogeneous current distribution coincides very well with the experimental data on a famous $Ge_2Sb_2Te_5$ compound, which represents the new generation of the phase change materials.
- New memory cells display a non-pronounced S-shaped CVC. Therefore current and voltage do not change significantly while switching from off to on states (Fig 1A).
- A small active volume allows reaching a very high cooling speed and therefore obtaining materials with a facility for rapid crystallization, namely GST, in amorphous state.
- Such materials display not only high recording speed but also a large endurance, which is inversely proportional the reset pulse power [5].
- From the point of view of an electronic-thermal theory [6] the nonlinearity of the current-voltage characteristic decrease an effective activation energy of conductivity $\Delta E^* = (-\Delta E + f(V/V_0))$ and the temperature in the on-state: if we use a simple approximation $f(V/V_0)=V/aT$, the threshold temperature for a low pronounced S-shaped CVC is equal to $T_{th} \sim T_{on} \sim 2T_0$

All these advantages allows PCM to compete with Si-based flash memory (FM) cells as one can see below.

Comparison of Si based flash memory and Chalcogenide based memory cells

Let us compare the parameters of the new generation PCM cells and Si-based Flash memory cells in more detail

Table 3.Comparison of PCM and flash-memory.

	PCM	Flash
Endurance	10^{11}	10^5
Dimensions	3×20 nm	22 nm
Set time	10^{-7} sec	10^{-3} sec

Advantages of PCM:

1. Information retaining due to positions of heavy atoms not to the light electrons
2. Simplicity of PCM cell preparation – only one chalcogenide layer between contacts
3. PCM or PRAM has higher performance both because the memory element can be switched more quickly and also because single bits may be changed to either 1 (crystal) or 0 (amorphous) without need to erase an entire block of cells first.

Disadvantages of PCM:

1. The most important disadvantage of PCM is the a high density of the programming current ~ 10^7 A/cm^2. For a typical transistor this value is ~ 10^5 -10^6 A/cm^2
2. The second PCM problem is the contact between the hot phase-change region and the adjacent dielectric and metal with different expanding properties.
3. The one more challenge for PCM is its small long-term resistance and threshold voltage drift (~ $t^{0.1}$)

4. Conclusion

A comparison of the two generations of phase change memory cells has shown that nanoscale dimension of modern PCM cells and modern materials with a facility for rapid crystallization result in a success of the PCM technology. Advantages and disadvantages of the new generation of the phase change memory were formulated from the point of view of an electronic-thermal theory. As compared to the flash memory, phase change memory technology shows a considerably faster read and write speed and a higher scaling potential.

Acknowledgements

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