Performance of an optical non-volatile Ge\textsubscript{2}Sb\textsubscript{2}Te\textsubscript{5}-based storage element

M Makarov\textsuperscript{1,2}, A Sapegin\textsuperscript{1,3}, M Barabanenkov\textsuperscript{1,2} and A Italyantsev\textsuperscript{1}

\textsuperscript{1}JSC Molecular Electronics Research Institute, Moscow 124460, Russia
\textsuperscript{2}Institute of Microelectronics Technology and High-Purity Materials of the Russian Academy of Sciences, Chernogolovka 142432, Russia
\textsuperscript{3}Moscow Institute of Physics and Technology, Dolgoprudny 141701, Russia

Abstract. Considerable growth in data exchange leads to enhanced requirements for computing, storage, and transmitting devices. Promising solutions to this challenge can be found in the use of phase-change materials. This paper is devoted to evaluating the frequency response of a non-volatile storage element with optical recording and readout. The evaluation shows that it is possible to reduce the device’s operating cycle time and improve its performance.

1. Introduction

An increase in the volume of transmitted and processed data leads to increased requirements for computing devices [1]. Although most modern computers are based on von Neumann architecture, which provides separation of central processor unit (CPU) and memory unit, such a computer configuration leads to delays in the transfer of information between the CPU and the memory in each cycle of calculations. One way to solve this problem is to use non-volatile memory devices [2] and neuromorphic architecture [3]. Such devices can be created based on phase change materials (PCM). Microelectronic solutions reach their fundamental physical limit [4]; therefore, several large companies (IBM, Intel, Fujitsu) use an approach based on silicon photonics technologies [5].

This paper is devoted to an optical non-volatile storage element based on Ge\textsubscript{2}Sb\textsubscript{2}Te\textsubscript{5} (GST), hereinafter referred to as a photonic storage element. The photonic storage element retains the advantages of electronic non-volatile memory and has additional benefits associated with photonics such as low power dissipation and a high-frequency threshold of dispersion signal blur.

2. Operation principle

The photonic storage element consists of a silicon strip waveguide with a thin GST layer on its top (Figure 1). The logical state of the element is stored as a phase state of GST and can be distinguished by the level of light transmission. A low transmission level corresponds to “0” in binary notation and the crystalline state of GST, and a high one corresponds to “1” and the amorphous state of GST. There are three functions of this device: recording, readout, and erasing. All of them are performed by light with a wavelength of 1.55 um. Consider each of them in more detail.

It is well known that the imaginary part of the refractive index of crystalline GST is almost 20 times higher than that of amorphous [6]. The readout operation is carried out by transmitting a low-intensity light signal, which does not affect the photonic storage element’s logical state. The duration of this operation is limited by the speed of light propagation in the waveguide and the operation frequency of the receiving device.
The duration of recording and erasing of the logical state is determined by the heating rate upon absorption of light and the cooling rate of the region with the GST layer. The recording operation includes the melting process of crystalline GST, followed by rapid cooling. Such a thermal cycle leads to the switching of the GST phase from crystalline to amorphous. This cycle’s duration mainly depends on the heating rate provided by the light source and the cooling rate. The erasing operation includes the reverse change of the GST state from amorphous to crystalline. This phase transition is performed by solid-state recrystallization of GST. One of the possible models describing the recrystallization of amorphous GST without a crystalline seed in the form of an underlying crystal with crystallography consistent with the GST layer is the adapted JMAK model, which is presented in [9]. The model describes the growth dynamics of the GST crystalline phase in amorphous media. The model provides crystalline nuclei formation with certain incubation time, during which they are stable. The temperature dependence of the crystallization rate of GST was not considered in works devoted to similar devices [7, 8]. However, the adapted JMAK model reports that the maximum crystallization speed of GST is achieved in the temperature range near the melting point. The use of this temperature range reduces the duration of the erasing operation and, therefore, improves the photonic storage element’s performance.

The following are the quantitative recording and erasing times estimates—which, so far, have not been available in the literature—of the photonic storage element in question.

3. Device simulation

The performance evaluation of the photonic storage element was performed in two stages using Comsol Multiphysics. At the first stage, the absorption of light with a wavelength of 1.55 um was calculated for the crystalline and amorphous states of the GST layer. As a result of the calculation, two transmission levels were obtained corresponding to the logical levels “0” and “1”. Figure 2 shows the field distribution of the waveguide mode in the longitudinal section of the photonic storage element.
The intensity of the guided light remains almost unchanged in the case of the amorphous GST layer (Figure 2a) and significantly decreases in the case of the crystalline GST layer (Figure 2b). The transmittance is about 99% and 70%, respectively.

At the second stage, thermal calculations of the erasing and recording operations were carried out. The following parameters were used in the calculations. The waveguide height was 220 nm, the width was 500 nm, the thickness of the GST layer was 10 nm, the length was 1 μm. As a result, the duration of these operations was obtained.

Figure 3 (a, b). Non-linearity in the heat capacity coefficient of Ge²Sb²Te₅ used to simulate the transition to a liquid state (a); solid-state transition time between the amorphous and crystalline states of Ge²Sb²Te₅ according to the adapted JMAK model (b).

The calculation of thermal dynamics during the recording operation was divided into three parts corresponding to the processes of heating, melting, and cooling. The duration of melting was taken into account using the non-linearity of the heat capacity coefficient of GST (Figure 3a). This non-linearity corresponds to the volume latent heat of 126*10^3 J/kg [10].

The erasing operation was also divided into three parts for calculation. In the first part, the heating required to reach the optimal temperature range according to the adapted JMAK model was calculated. The second part was devoted to the recrystallization of GST, during which the temperature was stable. In the third part, the cooling duration was obtained. The operation was considered completed when the temperature in the center of the GST layer dropped below 418K [11]. Figure 3b shows the temperature dependence, which determines the crystallization time of GST. The minimal crystallization time (~10 ns) can be obtained in the temperature range near the melting point.

Figure 4 (a, b). Temperature dependence during (a) the recording operation; (b) the erasing operation.
Based on the calculation results, the regimes of the light source were selected and the temperature dependences corresponding to the recording and erasing operations were obtained (Figure 4). The best regime of the light source for the recording operation is high-intensity light pulse (Figure 4a). Such a pulse provides fast heating and melting of the GST layer and minimizes the effect of heat sink. The result time of the recording operation is near 25 ns.

The combination of two laser pulses with different amplitudes was selected for the erasing operation (Figure 4b). The first pulse provided heating of the GST layer to the optimal temperature for crystallization, and the second pulse maintained the temperature stable during the crystallization time in accordance with the adapted JMAK model. As a result of the calculations, the duration of the erasing operation was 75 ns, and the entire operation cycle (recording/erasing) of the photonic storage element took 100 ns.

4. Conclusion

The work presents a model of functioning of the photonic storage element based on Ge$_2$Sb$_2$Te$_5$. Thermal calculations were carried out, and the dynamics of the Ge$_2$Sb$_2$Te$_5$ transition was analysed. The calculations showed that the entire operation cycle of the photonic storage element took 100 ns. The durations of the erasing and recording operations were 75 ns and 25 ns, respectively. The possibility of reducing the duration of the erasing operation by using the temperature range near the melting point of Ge$_2$Sb$_2$Te$_5$ is confirmed.

Acknowledgments

This study was supported by the Russian Foundation for Basic Research, project No.19-29-03040.

References

[1] Editorial 2018 Big data needs a hardware revolution Nature 554 pp 145–6
[2] Philip H S Wong and Sayeef Salahuddin 2015 Memory leads the way to better computing Nature Nanotechnology 10 pp 191–4
[3] Mohammed A Zidhan, John Paul Strachan and Wei D Lu 2018 The future of electronics base on memristive systems Nature Electronics 1 pp 22–9
[4] Krasnikov G Ya and Zaitsev N A 2009 Nanoelectronics: status, challenges and prospects Nano- and Microsystems Technology 1 pp 2–5
[5] John Caulfield H and Shlomi Dolev 2010 Why future supercomputing requires optics Nature Photonics 4 pp 261–3
[6] Matthias Stegmaier, Carlos Rios, Harish Bhaskaran and Wolfram H P Pernice 2016 Thermo-optical effect in phase-change nanophotonics ACS Photonics 3 pp 828–35
[7] Xuan Li, Nathan Youngblood, Carlos Rios, Zengguang Cheng, David Wright C, Wolfram H P Pernice and Harish Bhaskaran 2019 Fast and reliable storage using a 5 bit, nonvolatile photonic memory cell Optica 6 pp 1–6
[8] Carlos Rios, Matthias Stegmaier, Peiman Hosseini, Di Wang, Torsten Scherer, David Wright C, Harish Bhaskaran and Wolfram H P Pernice 2015 Integrated all-photonic non-volatile multi-level memory Nature Photonics 9 pp 725–32
[9] Wright C D, Armand M and Aziz M M 2006 Terabit-per-square-inch data storage using phase-change media and scanning electrical nanopores IEEE Transactions on Nanotechnology 5 pp 50–61
[10] Zhaohui Fan and David E Laughlin 2003 Three dimensional crystallization simulation and recording layer thickness effect in phase change optical recording Japanese Journal of Applied Physics 42 pp 800–3
[11] Pengfei Guo, Andrew M Sarangan and Imad Agha 2019 A review of germanium-antimony-telluride phase change materials for non-volatile memories and optical modulators Applied Science 9 p 530