ANNOTATION

dissertation for the degree of Doctor of Philosophy (PhD) in the specialty «6D072300 – Technical Physics»

ZHAKYPOV ALIBEK SERIKULY

Elements of non-volatile memory for optical and electrical information recording based on modified GST films

General description of work. The dissertation work is devoted to experimental studies of non-volatile memory elements based on a $Ge_2Sb_2Te_5$ functional layer modified with silver for optical and electrical recording of information.

Relevance of the research. In the modern era of rapidly increasing volumes of digital information, the demand for memory devices capable of storing and transferring large data flows is constantly growing. Despite the high growth rates and large production volumes, the efficiency of information processing cannot be ensured by traditional technologies.

Next generation embedded non-volatile memory (eNVM) is characterized by excellent scalability, low power consumption, a large number of rewrite cycles, and in the near future may replace traditional memory devices. Phase Change Memory (PCM), a type of non-volatile memory, is one of the potential technologies considered for the implementation of next-generation memory devices. PCM technology is based on a reversible phase transition of the material between the amorphous and crystalline states under the influence of laser radiation pulses or an electric field.

n comparison with traditional technologies such as Flash memory (NOR, NAND), dynamic (DRAM) and static (SRAM) random access memory, as well as several developing next-generation memory technologies including spin-transfer torque memory (STT-RAM) and resistive memory (ReRAM), PCM technology is characterized by relatively high read speed (~10 ns) and write speed (≥50 ns), low write power consumption (~0.1 pJ/bit), and a large number of possible rewrite cycles (10^8–10^{15}).

The basis of PCM-type memory storage devices is chalcogenide glassy semiconductors (CGS). These materials belong to the class of non-crystalline semiconductors and possess unique properties such as photostructural transformations, switching effect, and memory effect. These properties of chalcogenide semiconductors are due to the lability of their atomic structure, as the atoms contain lone electron pairs. In addition, CGS are characterized by a high density of localized electronic states caused by intrinsic charged structural defects, which pin the Fermi level in the middle of the bandgap.

When strong electric fields are applied to thin amorphous films of CGS, a rapid abrupt decrease in their electrical resistance is observed, followed by restoration of the initial state after the removal of the external electric field, which was later called the switching effect. If, after the switching effect, a rearrangement of the local structure of CGS occurs, resulting in crystallization and the low-resistance state is retained even in the absence of an external electric field, this effect is called the memory effect. The materials used in modern phase-change memory (PCM) devices are chalcogenide semiconductors of complex compositions located on the quasi-binary line of the $GeTe–Sb_2Te_3$ system. Among them, well-studied thin films of $Ge_2Sb_2Te_5$ (GST) composition are considered the most promising functional layers for use in such devices. The main disadvantages of GST functional layers are the limited number of write/erase cycles, relatively slow switching speed between phase states, and sensitivity of parameters to temperature changes. Controlling the structure and electronic properties of these materials can not only enhance the performance of non-volatile memory devices but also significantly expand the range of their possible applications.

One of the effective methods for improving the above-mentioned properties of GST functional layers is the method of structural and impurity modification of electronic properties. The structural modification method consists in controlling the structure of GST using different

fabrication techniques without changing the material composition. The peculiarity of impurity modification of GST lies in the use of methods that ensure the preservation of their amorphous structure at high impurity concentrations.

To date, the method of ion-plasma high-frequency magnetron co-sputtering of GST and the impurity allows the implementation of both of the above-mentioned approaches and enables wide-range control of the electronic properties of the modified GST layers. In addition, this method makes it possible to obtain functional layers of complex compositions with a specified ratio of components.

Silver, along with other impurities, is used as a modifying impurity for the functional layers of GST. In silver-modified GST layers, an increase in crystallization temperature and speed, a decrease in switching time under the action of an electric pulse, and changes in optical properties are observed. In addition, the high diffusion ability of silver impurity atoms leads to a fairly uniform distribution of the impurity in the functional layers of phase-change materials.

However, despite numerous studies of silver-modified functional GST layers, such important processes for information recording as the kinetics of structural transformation under laser irradiation and the effect of silver impurity on the switching effect in memory cells remain unexplored.

The dissertation work aims to experimentally investigate the functional layers of non-volatile memory based on silver impurity modified $Ge_2Sb_2Te_5$ functional layers for optical and electrical information recording.

To achieve the stated aim, the following logically interconnected and sequential tasks were set:

1. To develop the technology for obtaining phase-change functional layers with an amorphous structure and a specified composition based on silver-modified $Ge_2Sb_2Te_5$ ($Ge_2Sb_2Te_5$<Ag>) using the method of ion-plasma high-frequency magnetron co-sputtering;

2. To study the optical properties of modified phase-change functional layers of $Ge_2Sb_2Te_5$, to determine the effective penetration depth of laser radiation and the spectral distribution of optical contrast in GST in the visible region of the spectrum, to investigate the in situ kinetics of structural transformation of functional layers of $Ge_2Sb_2Te_5$ and $Ge_2Sb_2Te_5$<Ag> under the action of laser radiation;

3. To investigate the influence of silver impurity on the electrical characteristics and parameters of memory cells based on the developed modified phase-change functional layers of $Ge_2Sb_2Te_5$<Ag>.

The objects of research are phase-change functional layers based on the composition $Ge_2Sb_2Te_5$ modified with silver impurity, obtained by the method of ion-plasma high-frequency magnetron co-sputtering in an argon atmosphere.

The subject of research is the composition, structure, kinetics of structural transformation under the influence of electromagnetic radiation, and optical properties of functional layers $Ge_2Sb_2Te_5$<Ag>, as well as the study of current-voltage characteristics of memory cells based on them.

Research Methods.

To achieve the goal of the dissertation work and successfully accomplish the assigned tasks, the following experimental methods were used to study the modified functional layers: the structure and composition of the functional layers were investigated using analytical equipment such as the X-ray diffraction method (Rigaku MiniFlex 600), scanning electron spectroscopy method (Quanta 3D 200i), energy-dispersive analysis method (Quanta 3D 200i with EDAX attachment in high vacuum mode), and Raman spectrometer (Solver Spectrum 600/600 with He-Ne laser (λ = 633 nm)). The investigation of structural transformation was carried out by step-by-step thermal annealing using a temperature controller (Omron E5CZ), a power supply (Tektronix PWS2326), and a picoammeter (Keithley 6485, PC), and laser irradiation using the Raman scattering method (Solver Spectrum 600/600 with He-Ne laser (λ = 633 nm)). The study of optical and electrical properties of the functional layers was performed using an optical spectrophotometer

(Shimadzu UV2000) and methods for studying current-voltage characteristics with the use of a pulse generator (Aktakom ANR-1011) and an oscilloscope (Gwinstek GDS-71062A).

Scientific novelty of the work

1. For the first time, the effect of the power and duration of laser radiation (λ = 633 nm) on the kinetics of structural transformation of phase-change modified functional layers of $Ge_2Sb_2Te_5$<Ag> was studied using the in situ Raman spectroscopy method, and the features of phase transitions controlled by laser radiation power and impurity concentration were identified.

2. For the first time, a significant increase in the optical contrast of phase-change functional layers of $Ge_2Sb_2Te_5$ in a wide spectral range from 300 to 650 nm was established upon their modification with silver. The most substantial increase in optical contrast (up to 60%) occurs in functional layers with a concentration of 12.3 at.% silver.

3. For the first time, the influence of silver impurity on the parameters of electrical information recording in memory cells based on phase-change modified functional layers of $Ge_2Sb_2Te_5$ was studied. It was established that with an increase in impurity concentration, the threshold voltage and switching time decrease. The lowest power consumption is observed in memory cells based on the composition $Ge_2Sb_2Te_5$<Ag 7.0 at.%>.

Statements submitted for defense

1. By the method of ion-plasma high-frequency (13.56 MHz) magnetron sputtering of a combined target made of polycrystalline semiconductor composition $Ge_2Sb_2Te_5$ and Ag, it is possible to obtain phase-change functional layers $Ge_2Sb_2Te_5$<Ag> with an amorphous structure, with Ag impurity content up to 12.3 at.% and an increased crystallization temperature (280 °C).

2. The effect of laser radiation (λ = 633 nm) on phase-change functional layers of $Ge_2Sb_2Te_5$<Ag> leads to a phase transition of their structure from the amorphous to the crystalline state (optical information recording), the features of which (presence or absence of an intermediate phase) are determined by the power and duration of the radiation and are controlled by the concentration of the Ag modifying impurity. The optical contrast of $Ge_2Sb_2Te_5$<Ag> functional layers significantly increases with an increase in Ag impurity concentration for all laser radiation wavelengths used in practice for information recording.

3. The parameters of electrical information recording in memory cells based on phase-change functional layers of $Ge_2Sb_2Te_5$<Ag> are controlled over a wide range by the concentration of the Ag modifying impurity. As the silver concentration increases from 0 to 12.3 at.%, the threshold voltage and switching time decrease from 1.74 to 1.06 V and from 70 ns to < 50 ns, respectively. The minimum recording power is achieved at an Ag concentration of 7.0 at.% in $Ge_2Sb_2Te_5$.

Theoretical and practical significance of the work

The obtained results represent both technological and practical value for the development of semiconductor material technologies, the design and fabrication of non-volatile memory elements for optical discs and electrical memory cells based on new promising functional phase-change layers of $Ge_2Sb_2Te_5$<Ag>. In addition, the research results are important for the educational process of training master's and doctoral students in the field of technical physics.

Research aimed at improving the speed and reliability of data recording in functional layers based on phase-change materials can have a significant impact on modern digital technologies and artificial intelligence.

The reliability and validity of the obtained results are ensured by the use of modern research methods and equipment. In addition, the reliability of the results is confirmed by the presence of publications in high-impact-factor scientific journals of far-abroad countries, as well as in publications recommended by the Committee for Quality Assurance in the Field of Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan (CQAFSHE MSHE RK), and in the proceedings of international scientific conferences of both near and far-abroad countries.

Author's personal contribution

The development of the technology for obtaining phase-change functional layers of $Ge_2Sb_2Te_5$ and $Ge_2Sb_2Te_5$<Ag> compositions was carried out by the author using the method of ion-plasma high-frequency magnetron sputtering. The acquisition, processing, and analysis of the results of optical and electrical characteristics studies were performed independently.

Publications

Based on the materials of the dissertation work, 12 printed works were published, including 2 articles in journals indexed in the Scopus and Web of Science databases, 2 articles in publications recommended by the CQAFSHE MSHE RK, and 8 conference abstracts in the proceedings of international scientific conferences.

Approbation of the dissertation work

The results obtained during the dissertation work were reported and discussed at the following international conferences – V International Scientific Conference "Modern Problems of Condensed Matter Physics, Nanotechnology and Nanomaterials," May 17–18, 2018, Almaty, International Conference on Amorphous and Nanostructured Chalcogenides, June 30 – July 4, Chisinau, Republic of Moldova, 2019, The 7th International Conference on Nanomaterials and Advanced Energy Storage Systems (INESS), August 7–9, Almaty, 2019, International Scientific Conference of Students and Young Scientists “FARABI ÁLEMI” Almaty, Kazakhstan, April 6–9, 2020, The 8th International Conference on Nanomaterials and Advanced Energy Storage Systems (INESS-2020), August 6, Nur-Sultan, 2020, International Scientific Conference “Amorphous and Microcrystalline Semiconductors,” November 19–21, 2021, Saint Petersburg, Russia, The 10th International Conference on Nanomaterials and Advanced Energy Storage Systems (INESS-2022), August 4–6, 2022, Nur-Sultan, International Scientific Conference “Amorphous and Microcrystalline Semiconductors,” July 3–5, 2023, Saint Petersburg, Russia.

Articles with impact factor included in the international scientific databases Scopus and Web of Science:

– O.Yu. Prikhodko, G.A. Ismailova, **A.S. Zhakypov**, A.V. Kolobov, K.N. Turmanova, R.R. Nemkaeva, S.Ya. Maksimova, Zh.K. Tolepov, S.L. Peshaya. Structural transformation of thin $Ge_2Sb_2Te_5$<Ag> films produced by ion-plasma co-sputtering under laser irradiation // Journal of Electronic material. – 2023. – 52(4). – P. 2492-2498.

– S.L. Mikhailova, O.Yu. Prikhodko, Y.S. Mukhametkarimov, K. Dautkhan, U.A. Doseke, S.A. Kozyukhin, G.A. Ismailova, S.Ya. Maksimova, A.Yu. Tarapeyeva, **A.S. Zhakypov**. Thermal stability of the structure and optical properties of nanostructured TiO_2 films // Russian Physics Journal. – 2021. – 63(12). – P. 2045-2051.

Articles in publications recommended by the CQAFSHE MSHE RK:

– **A.S. Zhakypov**, Zh.K. Tolepov, G.A. Ismailova, S.L. Peshaya, M.N. Ualkhanova. Structural changes of nanoscale amorphous $Ge_2Sb_2Te_5$<Bi> films under laser irradiation // Bulletin of D. Serikbayev East Kazakhstan Technical University. – 2022. – No. 3. – P. 104–111.

- S.A. Fefelov, L.P. Kazakov, N.A. Bogoslovsky, A.B. Bylev, E.V. Gushchina, Zh.K. Tolepov, A.S. Zhakypov, O.Yu. Prikhodko. Influence of Bi impurity on the main parameters of the current-voltage characteristics of the phase-change semiconductor $Ge_2Sb_2Te_5$ // Physics of the Solid State. – 2024. – Vol. 58, No. 8. – P. 443–447.

Relation of the work topic to the plans of scientific works

The dissertation work was carried out in accordance with the plans of the research project No. AP05133499 "Structure and electronic properties of nanoscale films of metal-modified chalcogenide semiconductors with phase memory in glass-crystal states" (2018-2020).

Scope and structure of the dissertation

The dissertation work contains a list of symbols and abbreviations, an introduction, a main part consisting of 4 sections, a conclusion, and a list of references. The work is presented on 111 pages, contains 58 figures, 11 tables, and 181 bibliographic references.