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Strategic Investment in the Research and Development of Memristor Technology in the Republic of Serbia

Abstract: The rapid advancement of Artificial Intelligence (AI) has significantly impacted both high technology development and economic and social progress. The Republic of Serbia has been strategically supporting research and development of in the field of AI. Given the dramatic dynamic development of AI, the aim of this paper is to identify and describe memristor technology as currently very relevant and attractive, in order to achieve technological innovation, socio-economic benefits, and potentially global breakthroughs. The paper presents an overview of literature to analyze theoretical concepts, current research outcomes in AI, and possible applications of memristors. The analyses indicate that adoption and development of memristor technology in Serbia can position the country as a leader in AI hardware innovation, attracting international partners and fostering a technologically advanced industrial system. Therefore, this paper suggests that future research should focus on overcoming practical challenges in the production of memristors, developing hybrid architectures, and formulating advanced neuromorphic algorithms.

Keywords: memristors, neuromorphic computing, technological innovation, strategic positioning, global breakthrough

Introduction

AI has rapidly transformed from a narrow field of computing sciences to an important factor which shapes economy and society worldwide. Since we are at the threshold of a new technological revolution, it is necessary to identify a specific field within AI in order to direct resources into investment and development, with the aim of achieving technological progress and socio-economic benefits. Some of the more relevant steps taken by the Republic of Serbia in order to support development in this field are

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the adoption of the Strategy for the Development of Artificial Intelligence for the period 2020-2025, the foundation of the institute dedicated to AI research and development, the adoption of the guidelines for ethical development of AI, and the establishment of a legal framework for autonomous driving (Strategy, 2020; IVI, 2022; Etika, 2023; Auto, 2023). Regarding this field, the Republic of Serbia has the advantage over many countries in the world thanks to its geopolitical position, strong academic institutions and the scientific- technological system.

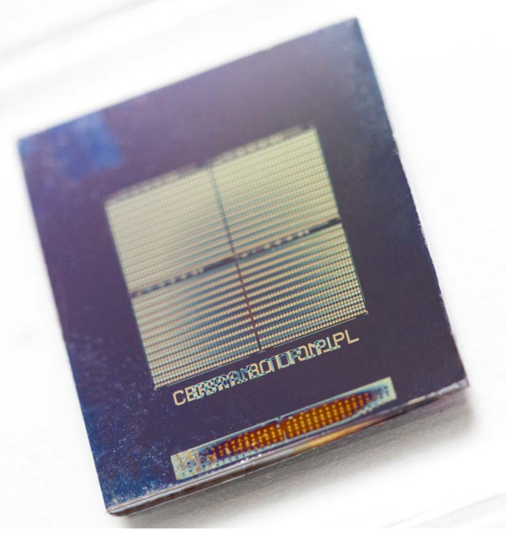
The main question to be considered in this paper is the manner in which the strategic investment of the Republic of Serbia in the field of AI may lead to technological innovation. With the dynamic development of AI, apart from the areas already identified in the valid Strategy for the Development of AI, as well as the favourable geopolitical position for establishing a forum which would work on global solutions for regulation and ethics of AI (Bojic, 2024; Bojic, 2022), memristor technology appears as interesting because of the expectations that it would solve a problem of vital importance, namely the high consumption of electric power of AI systems, such as large language models (ChatGPT) (Bojic et al., 2024, Talanov et al., 2024). This is of particular importance because big technological companies develop general-type artificial intelligence which will be applied through different solutions and services in all aspects of society. Therefore, this paper primarily considers the possibility of the development of memristors, proposing that the Republic of Serbia should begin investing in this type of technology, which is expected to enable the development of a new generation of neural networks and lead to a revolution in AI.

Memristors are the third generation of neuron networks which provide greater efficiency and the possibility of energy saving in AI computing processes. Because of the ability of memristors to emulate the functions of brain synapses, memristor technology is suitable for the application in artificial intelligence.

Memristors and neural networks of the third generation

The paper by Leon Chua from 1971 presents the theoretical basis about memristors, where they are described as an element of electric circuits with the commonly known elements – resistors, capacitators and inductors. Chua explains that memristors can store and process information similarly to the activities of brain synapses. This technology connects in a unique manner electric voltage and magnetic flow, thus enabling a non-linear connection between voltage and electricity. This connection enables memristors to keep memory without constant power supply, which is a characteristic that reminds of the functioning of brain synapses.

Memristor technology was a mere theoretical construct until as late as 2008, when it was constructed with the aid of titanium- dioxide nanometre coating (Strukov et al., 2008). This invention confirmed



Memristor, developed by the University of Illinois and National Energy Technology Laboratory of the USA, invented by Leon Chua in 1971.
Photo: Wikipedia

Leon Chua's assumptions and opened up the road for further research functionality of memristor technology derives from its characteristic of changing resistance based on the history of voltage. This property is known as hysteresis and it emulates the synaptic plasticity of biological neuron networks in which synaptic power varies depending on neuron activity.

Since nanometre coatings are used in the construction of memristor technology, it is possible to substantially reduce energy consumption as compared to traditional silicon resistors. Since they enable fast and efficient information processing, the devices in which memristors are used can create more capable AI systems, and also be applied in different fields, from robotics to data analysis in real time. Recent research points to the application of neuron networks based on memristors in solving tasks of pattern recognition (Prezioso et al., 2015), which corroborates the fact that memristors technology systems can autonomously learn and solve problems in a similar way to biological systems.

Technological achievements and challenges in the construction of memristor technology

The most relevant field of research related to memristor technology refers to the materials used for the construction of memristors. As it has already been mentioned, titanium-dioxide was first used in its production. Later on, other materials were used, such as hafnium-oxide, graphene-oxide and organic compounds. Each of these materials has unique properties which affect the performances and production costs of memristor technology (Adhikari et al., 2012). Graphene-oxide is a suitable material because of its electric conductivity, mechanic stability and flexibility. Research shows that memristor technology based on graphene-oxide is characterized by durability and a great switching speed function, which is quite important in the application in AI. However, there are still problems in relation to the achievement of uniformity in production. Variability of the properties of materials leads to uneven performances of memristor technology. That is why new techniques of its production, such as atomic deposition and chemical deposition of coating layers from the steam phase, the subject of research, with the aim of improving reproductivity of devices which use memristor technologies (Chang, Jo, Lu, 2011).

The application of memristors in traditional computer systems requires innovative approaches in the design of electric circuits. Unlike conventional transistors, non-linear functioning of memristor technology requires new architectures of electric circuits. Hybrid circuits in which memristors supplement traditional transistors can contribute to the efficiency of computing processes (Wang et al., 2017). An important step forward in the development are crossbar arrays in which memristors are distributed on the network structure. Crossbar arrays ensure great density of memory storage and parallel computing procedures. Research shows that it is possible to apply crossbar arrays in neuromorphic systems with the ability of pattern recognition and autonomous learning (Prezioso et al., 2015). It should be noted that designing efficient mechanisms for reading and writing circuits which are based on memristors is necessary for the application of these circuits. That is why reading and writing algorithms are explored, as well as error correction techniques in order to improve the reliability of the memory systems which use memristor technologies.

By emulating the plasticity of the synapses, memristors can facilitate synaptic weighting and adaptation (Yang et al., 2013). Memristor-based accelerators go beyond traditional systems based on graphics processing units (GPUs). With the expansion of the *Internet of Things*, there is an increasing need for efficient edge computing, in which data are processed locally instead of relying on remote servers. Memristor-based systems are suitable for application in edge computing, as well as in edge AI (Ambrogio et al., 2018). These systems can be applied in smart networks and autonomous vehicles, for example, which are only some of the numerous possibilities of the memristor technology application.

Applications of memristor technology in different industries

The applications of memristor technology are diverse and promise revolutionary changes in different industries, from healthcare and agriculture to energy and automobile industry. Thanks to its ability to increase energy efficiency and enable advanced computing processes, memristor technology is considered the key bearer of innovation and technological progress. In this chapter we will analyze the most relevant applications of memristors in different fields, as well as their advantages and challenges.

Memristor technology can substantially improve medical diagnostics and therapy. Neuromorphic systems based on memristors ensure advanced methos of medical image analysis and pattern recognition in complex biomedical data. These systems can help doctors in making more precise diagnoses in a shorter period of time.

One of the innovative applications of memristor technology is in the development of implantable medical devices, such as neurostimulators and pacemakers. Memristors can share energy requirements of these devices, thus reducing the need for frequent replacement of batteries or for charging these devices. Moreover, these devices might be able to adapt to individual patients' needs thanks to their ability of self-learning.

Agriculture is facing huge challenges in terms of sustainability and efficiency. Memristor technology can contribute to the resolution of these problems through the development of smart mechanisms for irrigation and resource management. Memristor-based systems may analyze a huge amount of data in real time, including soil moisture, weather conditions and the condition of crops, in order to optimize the use of water and other resources.

Moreover, memristor technology enables the development of autonomous robots which can perform agricultural activities such as sowing, harvesting and pest control. These robots might use advanced algorithms for autonomous learning and adaptation to different conditions, thus substantially increasing the efficiency of agricultural processes.

Energy industry can also benefit largely from memristor technology. One of the most promising applications is in the development of smart grids. These grids can use memristors for storing energy and managing its flow in an efficient manner. Memristors can ensure fast data processing and decision-making in real time, which is crucial for the optimization of electricity consumption and integration of renewable energy sources, e.g., solar and wind-electric systems.

In addition, memristor technology can play an important role in the development of energy-efficient devices and systems for energy storage. Great density of memory storage and small energy consumption make memristors ideal for the application in new-generation batteries and other systems for storing energy.

Automobile industry is preparing for a revolution with the development of autonomous vehicles. Memristor technology can significantly improve the possibilities of these vehicles through advanced systems of data processing and autonomous learning. Autonomous vehicles require fast and accurate processing of large amounts of data coming from sensors and cameras, and memristors could ensure substantially greater efficiency in processing these data as compared to traditional computer systems

Memristors can also contribute to the development of energy-efficient systems for storing energy in electric cars. Reduced energy consumption and increased density of memory storage may improve battery performances and extend the time of vehicle functioning between the charging periods.

The Internet of Things (IoT) is increasingly becoming part of everyday life, while memristor technology can ensure substantial improvements in this field. Memristor-based devices can process data directly at the source (edge computing), which reduces dependence on central servers and clouds and ensures faster and more efficient decision-making. The application of memristors in IoT devices can include smart sensors for monitoring the environment, energy management in smart homes and the development of autonomous robots and drones. Memristor technology is ideal for this application thanks to its small energy consumption and the abilities of autonomous learning and adaptation.

Although memristor technology offers a large number of advantages, there are also challenges in relation to ethical and security aspects of its application. The development of the systems which may autonomously learn and make decisions raises questions of responsibility and transparency. There is a need for the development of ethical standards and regulatory frameworks which will ensure that the use of memristor technology is in line with the principle of social responsibility and privacy protection.

Security challenges also include protection of memristor-based systems from malicious attacks and manipulations. Securing data and integrity of the systems must be a priority in the development and application of memristor technology.

The applications of memristor technology in various industries have the potential of bringing important innovation and improving the efficiency and sustainability of different systems. No matter whether it is healthcare, agriculture, energy, automobile industry or the Internet of Things, memristors provide the base for the development of advanced and efficient technological solutions.

However, successful application of memristors also depends resolving challenges in relation to their reliability, production costs and ethical aspects. Cooperation of the academic community, economy and the state can encourage accelerated development and broad acceptance of memristor technology, which would position Serbia as the leader in the field of technological innovation.

Conclusion

Investing in AI research and development can position Serbia at the very top of technological innovation and economic growth. By directing research towards memristor technology, as the third generation of neural networks, the Republic of Serbia may use its unique geopolitical and economic advantages to become relevant at the global level of AI research.

Investing in AI and memristor technologies should contribute to economic growth, as well as to the welfare of society on the whole. Memristor technology should lead to a revolution in AI technology and make computing technology more efficient, more energy-efficient and usable. By emulating synaptic functions of biological neural networks, memristors ensure neuromorphic computing and advanced application of AI. The applications of memristor technology in neuromorphic systems and edge computing enable efficient resolution of social problems and improvement of the quality of life. According to the conclusions listed in this paper, future research should be directed towards advanced materials, hybrid architectures, neuromorphic algorithms and resolution of problems of changeability and reliability of memristor technology in order to realize all the potentials of memristor technology.

Cooperation between the academic community, economy and the state can encourage the development and application of memristor technology. Its development and application in AI systems in healthcare, agriculture and edge computing, for example, apart from contributing to the welfare of society, should further direct research and development. By strategically investing in the research and development of memristor technology, Serbia can use the transformative potential of this technology.

References

Adhikari, S. P. et al. (2012). Memristor bridge synapse-based neural network and its learning. *IEEE Transactions on Neural Networks and Learning Systems*, XXIII (9), 1426–1435. https://doi.org/10.1109/TNNLS.2012.2204770

Ambrogio, S. et al. (2018). Equivalent-accuracy accelerated neural-network training using analogue memory. *Nature*, DLVIII (7708), 60–67. https://doi.org/10.1038/s41586-018-0180-5

Auto (2023). *New steps in the development of the legal framework for autonomous driving*. Available at: http://www.ai.gov.rs/vest/sr/771/novi-koraci-u-razvoju-pravnog-okvira-za-autonomnu-voznju.php

Bojic, L. (2022). Metaverse through the prism of power and addiction: What will happen when the virtual world becomes more attractive than reality? *European Journal of Futures Research*, 10 (1), 22. https://doi.org/10.1186/s40309-022-00208-4

Bojic, L. (2024). AI alignment: Assessing the global impact of recommender systems. *Futures*, CLX, 103383. https://doi.org/10.1016/j.futures.2024.103383

Bojic, L. et al. (2024a). AI and Energy Consumption: Social Aspects, 1-4. DOI: 10.23919/SpliTech61897.2024.10612493.

Chang, T., Jo, S.-H. & Lu, W. (2011). Short-term memory to long-term memory transition in a nanoscale memristor. *ACS Nano*, V (9), 7669–7676. https://doi.org/10.1021/nn202983n

Chua, L. (1971). Memristor-The missing circuit element. *IEEE Transactions on Circuit Theory*, XVIII (5), 507–519. https://doi.org/10.1109/TCT.1971.1083337

Etika (2023). *Adopted ethical guidelines for the development and use of artificial intelligence*. Available at: https://www.srbija.gov.rs/vest/692988/usvojene-eticke-smernice-za-razvoj-i-upotrebu-vestacke-inteligencije.php

IVI (2022). *Artificial Intelligence Research and Development Institutes*. Available at: https://ivi.ac.rs/

Prezioso, M. et al. (2015). Training and operation of an integrated neuromorphic network based on metal-oxide memristors. *Nature*, DXXI (7550), 61–64. https://doi.org/10.1038/nature14441

Strategy (2020). *Strategy for the Development of Artificial Intelligence*. Available at: https://www.srbija.gov.rs/tekst/437277/strategija-razvoja-vestacke-inteligencije.php

Strukov, D. B. et al. (2008). The missing memristor found. *Nature*, CDLIII (7191), 80–83. https://doi.org/10.1038/nature06932

Talanov, M., Vallverdu, J., Bojic, L. (2024b). Neuropunk revolution: memristive spinal CPG learning approach. *9th International Conference on Smart and Sustainable Technologies (SPLITECH)*, June 25–28, 2024, Split, Croatia.

Wang, Z. et al. (2017). Memristors with diffusive dynamics as synaptic emulators for neuromorphic computing. *Nature Materials*, XVI (1), 101–108. https://doi.org/10.1038/nmat4756

Yang, J. J., Strukov, D. B., Stewart, D. R. (2013). Memristive devices for computing. *Nature Nanotechnology*, VIII (1), 13–24, https://doi.org/10.1038/nnano.2012.240