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# Memristors: a Short Review on Fundamentals, Structures, Materials and Applications

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***Abstract*—The paper contains a short literature review on the subject of special type of thin film structures with resistive-switching memory effect. In the literature, such structures are commonly labeled as "memristors". The word "memristor" originates from two words: "memory" and "resistor". For the first time, the memristor was theoretically described in 1971 by Leon Chua as the 4th fundamental passive electronics element with a non-linear current-voltage behavior. The reported area of potential usage of memristor is enormous. It is predicted that the memristor could find application, for example in the domain of nonvolatile random access memory, flash memory, neuromorphic systems and so forth. However, in spite of the fact that plenty of papers have been published in the subject literature to date, the memristor still behaves as a "mysterious" electronic element. It seems that, one of the important reasons that such structures are not yet in practical use, is unsufficient knowledge of physical phenomena determining occurrence of the switching effect. The present paper contains a literature review of available descriptions of theoretical basis of the memristor structures, used materials, structure configurations and discussion about future prospects and limitations.**

***Keywords*—memristors, materials, electronics, applications**

## I. Introduction

AN intensive development in micro- and nanotechnology observed in the recent years and demanding for electronics components with better performance resulted in searching for new materials and devices. One of still unexplored field in the electronics is connected with a memristor and this task have become now more and more popular [1]. The memristor is another, fourth (beside resistor, capacitor and inductor) fundamental passive electronic element that was theoretically predicted by Leon Chua in 1971 [2]. During the analysis of dependencies between the basic electronic elements, Chua noticed that there is no dependency between the electric charge and the magnetic flux. The definition formulated by Chua [3] is that: "memristor is a nonlinear, passive and two-terminal element, which combines functional time dependence between voltage and current". Main feature of the memristor is the ability to remember the state of the resistance (high state/low state) [4]. The principle of operation of the memristor is that, if the current flows in one direction, the value of resistance is increasing, whereas if the current is starting to flow in the opposite direction, the value of resistance starts to decrease. If the current stops flowing, the structure maintains the value of its resistance. When the current is not flowing across the structure, the value of resistance will be the same as the value of resistance at the last moment when the current was flowing. Therefore the memristor behaves like non-linear resistor with the ability to remember its states of the resistance [5]. It could be said, that memristor is a non-linear resistor with feature that allows it to change its resistance in time based on the amount of the current that flows through the structure. In 1976, Leon Chua and Sung Mo Kang expanded the concept of memristors and proposed wider classification for memristor devices [6]. However, first reports on physical realization of the memristor came not before than 2008. In 2008 Strukov et al. from HP LABS reported about observed memristor effect in nanogrid memory array structure fabricated with very thin layer of titanium dioxide [5]. After 2008 plenty of similar papers have been published that reported finding memristor-like effects in different structures (Fig. 1). Simultaneously, due to expected wide area of new applications many groups started to focus their efforts on fabrication and optimizing the memristors [7]. Performed experimental evidences were supposed to prove the existence of 4th missing basic circuit element, which would open enormous areas of possible applications for the memristor, especially in many different fields from chaotic systems to commercial nanodevices. However, it seems that currently, discovery of the memristor by HP has been verified and at present the real, ideal memristor, still has not been found [8]

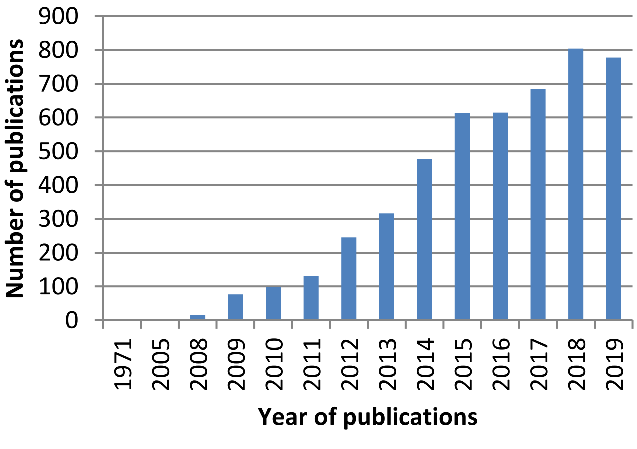


Fig. 1. Number of publications vs. year of publications from Web of Science, searched word: memristor.

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Among emerging idea of memristor, various types of the RAM memories, resistive RAM memory (ReRAM) are gaining more and more interest due to possibility of high density of packaging and high speed of operation. Therefore, the search for materials based on oxides, especially including such transition metal oxides (TMO) as ZnO or $TiO_2$ which exhibit resistive switching (RS), has started [9]. First mention about resistive switching mechanisms was published as early as in 1962 [10], that is yet before the theoretical prediction of the memristor by L. Chua. Up to now, the RS mechanisms have been observed in many layered metal-oxide-metal structures.

The present paper contains a short literature review on theoretical basis of operation of the memristor structures, review of used materials and structure configuration and the mathematical models used for modeling of the memristor structures.

## II. FUNDAMENTALS

### 1) *Principle of operation of memristive devices*

Understanding the memristor, requires analysis of basics of operation of the three fundamental electronic elements: capacitor, inductor and resistor and the dependencies between them [11]:

– voltage *V*, defined as a change of the magnetic flux ($\phi$) in time (*t*):

$$V = d\phi/dt \tag{1}$$

– current *I*, defined as a change of the electric charge ($q$) in time (*t*):

$$I = dq/dt \tag{2}$$

– resistance *R*, described as a linear dependency between the voltage (*V*) and the current (*I*):

$$R = dV/dI \tag{3}$$

– capacitance *C*, described as a linear dependency between the voltage (*V*) and the electric charge (*q*):

$$C = dq/dV \tag{4}$$

– inductance *L*, described as a linear dependency between the magnetic flux ($\phi$) and the current (*I*):

$$L = d\phi/dI \tag{5}$$

So far, only magnetic flux ($\phi$) and electric charge ($q$) do not have defined dependency between them. Leon Chua [2] stated that from the mathematical point of view there should be a dependency, which describes this two quantities:

$$d\phi = Mdq \tag{6}$$

where: $M$ – is a memristance.

Equation (6) describes relation, which occurs in the 4th electronic element called memristor. In addition, Chua distinguish two types of memristor: charge-controlled and flux-controlled. Electrical voltage in a charge-controlled memristor is therefore defined by equations:

$$V(\mathrm{t}) = M\big(q(\mathrm{t})\big)I(\mathrm{t}) \tag{7}$$

$$M(\mathrm{q}) = d\phi(\mathrm{q})/dq \tag{8}$$

Whereas, current in a flux-controlled memristor is defined by:

$$I(\mathrm{t}) = W\big(\phi(\mathrm{t})\big)V(\mathrm{t}) \tag{9}$$

$$W(\phi) = dq(\phi)/d\phi \tag{10}$$

where: *M(*q*)* and *W(*ϕ*)* are expressed in the units of resistance (Ω) and conductance (S) [6].

Moreover, in order to be called a memristor, the device must fulfil three characteristic conditions [6,12]: device must show pinched hysteresis loop in the I-V plane for every bipolar excitation signal, hysteresis lobe area should decrease monotonically with an increasing in excitation frequency, hysteresis loop should shrink to a single-valued function as the excitation frequency tends to infinity. An example of theoretical characteristic of a memristor in the I-V plane is shown in Fig.2.

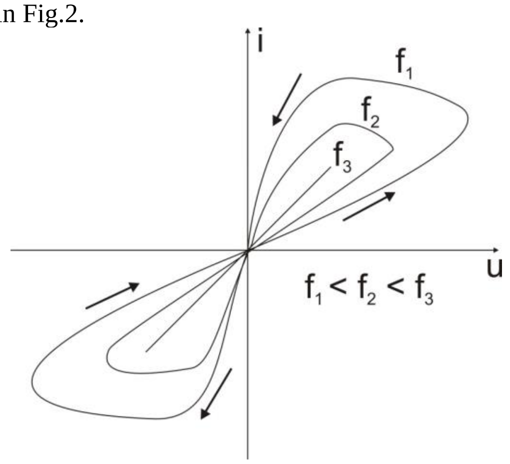


Fig. 2. Exemplary theoretical characteristic of a memristor.

Chua predicted that using charge-controlled or flux-controlled mechanism resistance could be memorized infinitely. If technology of such structures would be commercially available it would open a plethora of different non-volatile memory-based applications.

### 2) *Types of resistive switching mechanisms*

As is was mentioned earlier, resistive switching is another memory behaviour observed in oxide structures that focuses the research interest of many groups since late 1960s [e.g. 13–20]. There are two main types of RS that can be distinguished: bipolar switching and unipolar switching. Additionally, three possible types of mechanisms for RS are reported resulting from thermal, electrical or ionic effects [19]. For specific kind of structures, additionally a forming process has been observed, too. This forming process is often being called electroforming. Types of observed mechanisms are dependent on many factors, including: type of material used for fabrication of structure and dominance of particular effect (thermal, electric, chemical) [15].

Typical resistive switching effect is based on thermal effects and exhibits unipolar characteristic. It is initiated by partial voltage breakdown of thin dielectric layer placed between two metal electrodes. As a result of the Joul'e heat, a weak conducting path with controlled resistance is formed. Such conducting filament (CF) may consist of material from metal electrode, which penetrates to the isolating layer. Formation of the conducting filaments is known as the "SET" process to the low resistance state (LRS). Switching back to the high resistance state (HRS) – the "RESET" process is preceded by the rupture of the filaments due to the created heat.

Unipolar mechanism is observed in many non-conductive oxides like binary oxides [17]. The filament nature of conducting paths during LRS state have been confirmed already in 2006 for NiO and $TiO_2$ materials [19]. It is worth to notice, that RESET process does not restore the initial value of resistance (resistance of newly fabricated structure) of MIM structure but only a value of an resistance after the first forming process. This phenomena indicates on deep level structural changes occurring during forming process. Another evidence is the higher value of voltage needed during forming process than value of voltage needed to switch between LRS and HRS states [15].

Bipolar switching requires opposite polarization for transition between LRS and HRS states. In the bipolar mechanism the electrical effect are dominant [15].

Bipolar mechanism occurs in many such semiconducting oxides, like e.g. complex perovskite oxides.

Additionally, classification of the types of the switching mechanisms has been introduced based on the type of conducting filament. First type of conducting filament is called "formation and rupture". This method is based on forming and then rupturing of the conducting filaments located in the insulating layer. This kind of conducting filaments may occur both in bipolar and in unipolar switching mechanism. Second type of conducting filaments is called interfacial switching [21]. In this type, the filaments are being formed at the interface between metal electrode and oxide layer. Switching mechanism in interfacial type has been interpreted as changes of the height of the Schottky barrier between the metal electrode and the switching material. This kind of filaments occurs only in the bipolar mechanism and it is very characteristic for the semiconducting perovskite oxides [22] and is strongly dependent on the type of used metal for electrical contact.

## III. MATHEMATICAL MODELS

This chapter contains a review of the basic mathematical models used for theoretical analysis of electrical properties of memristive structures. First practical model of the memristor was described by the HP LABS in 2008 [4]. Later on, a several other models were developed such as: linear ion drift model (chapter III.3), nonlinear ion drift model (chapter III.4), Simmons tunnel barrier model (chapter III.5) and threshold adaptive (TEAM) model (chapter III.6) [6].

### *3) Linear Ion Drift Model*

Memristor structure (Fig. 3) can be represented by semiconducting oxide thin-film with overall thickness D placed between two metal contacts. It is assumed that the thin film consists of doped and undoped region as its shown in the Figure 3.

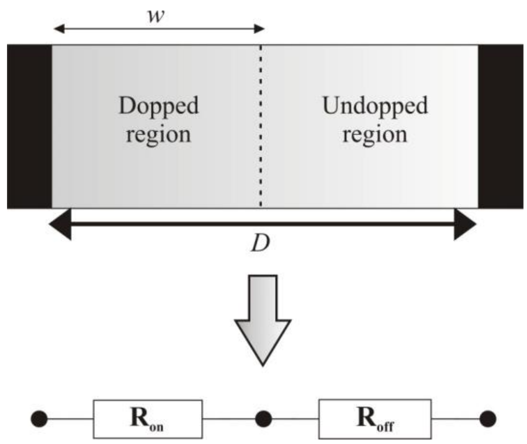


Fig. 3. Schematic view of the memristor structure used in Ion Drift Model.

The length of the doped region with low resistance in comparison to undoped region is determined by the internal state variable (w). Value of the w variable and consequently the total value of resistance of the structure, can be changed by applying external voltage to the structure [5]. Taking boundary conditions into assumptions, that (a) electric field across the device is uniform and (b) there is a linear relationship between drift-diffusion velocity and the net electric field, memristive element in which the pinched hysteresis loops occurs in the voltage-current plane can be described by [6]:

$$V(\mathrm{t}) = \left(R_{on}\frac{w(\mathrm{t})}{D} + R_{off}\left(1 - \frac{w(\mathrm{t})}{D}\right)\right)i(\mathrm{t}) \qquad (11)$$

According to this model, memristor could be modeled as a variable-resistor, where $R_{on}$ and $R_{off}$ denote the value of the resistance of the memristor, when the element is in the low or high resistance state, respectively. The internal state variable ($w$) is described by the equation:

$$\frac{dw(\mathrm{t})}{dt} = \frac{\mu_V R_{on}}{D} i(t) \qquad (12)$$

where $\mu_v$ – is the electrical charge mobility.

This model is simplified on the assumption that the oxygen deficiencies could move freely across the structure, which is not accurate [6]. The vacancies slows down on the edge of the structure, because of the vacancies could move freely across the structure, it would mean lack of physical oxide vacancies, so the length of doped region would be zero. Similarly, the doped region could not be all across the structure, because the undoped region would not exist and the element would not work. In order to deal with these boundary conditions the window function f(w) is also introduced and added to the internal state variable [4,6,23].

Ion drift model is simplified and has underlying limitations in electrodynamics. Many different experiments proves that operation of the memristive devices is quite nonlinear. It means, that the accuracy of linear ion drift model is very poor.

### *4) Nonlinear Ion Drift Model*

Nonlinear ion drift model assumes that memristor is controlled by the voltage and the dependence between internal state variable and voltage is nonlinear [6,20,24]. Moreover, the asymmetric switching between the states of the memristor is taken into consideration. The relationship between voltage and current is described by the equation:

$$i(\mathrm{t}) = w^n(\mathrm{t})\beta\sinh\big(\alpha v(\mathrm{t})\big) + \chi[\exp\big(\gamma v(\mathrm{t})\big) - 1] \qquad (13)$$

The internal state variable is now expressed by:

$$\frac{dw(\mathrm{t})}{dt} = a v^m(\mathrm{t}) f(\mathrm{w}) \qquad (14)$$

where: $\alpha$, $\beta$, $\gamma$, $\chi$, $a$ i $m$ are the parameters determined experimentally. $N$ determines, how the internal state variable influences the current [6]. In this equation the internal state variable $w$ is normalized in the interval {0, 1}. This model describes asymmetric nature of switching between states of the memristor. During the LRS, the curve in the I-V graph is interpreted as tunneling process (sinh part) whereas during the HRS the I-V characteristic behaves like the I-V characteristic for the conventional p-n junction (exponential part) [6]. Nonlinear ion drift model ensure better accuracy for the description of real memristive structure. Flexibility of this model gives a high level of sensitivity for the voltage levels, which was not considered in the linear ion drift model. Also this model combines the stability of the read process with the fast speed of the write process.

*5) Simmons Tunnel Barrier Model*

Memristive device in the Simmons tunnel barrier model is modeled as a resistors connected in series with the effect of electron tunneling through potential barrier. In Ion Drift models (equations 11, 12), memristive device was modeled as a two resistors connected in series: one resistor represents doped oxide region, whereas the second one - undoped (insulating) oxide region. Simmons tunnel barrier model assumes nonlinear and asymmetric switching of states resulting from exponential dependency of movement of ionized dopants. Additionally, this model exhibits nonlinear and asymmetric characteristics [6,25–27]. The relationship between voltage and current is described by the equation:

$$i(\mathrm{t}) = \tilde{\mathrm{A}}(\mathrm{x}, \mathrm{v_g})\phi_1(\mathrm{v_g}, \mathrm{x}) \times \exp\left(-\mathrm{B}(\mathrm{v_g}, \mathrm{x})\phi_1^{0.5}(\mathrm{v_g}, \mathrm{x})\right) - \tilde{\mathrm{A}}(\mathrm{x}, \mathrm{v_g})\left(\phi_1(\mathrm{v_g}, \mathrm{x}) + e|v_g|\right) \times \exp\left(\mathrm{B}(\mathrm{v_g}, \mathrm{x})(\phi_1(\mathrm{v_g}, \mathrm{x}) + \mathrm{ev_g})^{0.5}\right)$$

$$v_g = v - i(\mathrm{t})R_s \qquad (15)$$

The internal state variable is described by the equation:

$$\frac{dx(\mathrm{t})}{dt} = \begin{cases} C_{off}\sinh\left(\frac{\mathrm{i}}{\mathrm{i_{off}}}\right)\exp\left[-\exp\left(\frac{\mathrm{x}-\mathrm{a_{off}}}{\mathrm{w_c}} - \frac{|\mathrm{i}|}{\mathrm{b}}\right) - \frac{x}{w_c}\right] & i > 0 \\ C_{on}\sinh\left(\frac{\mathrm{i}}{\mathrm{i_{on}}}\right)\exp\left[-\exp\left(\frac{\mathrm{x}-\mathrm{a_{on}}}{\mathrm{w_c}} - \frac{|\mathrm{i}|}{\mathrm{b}}\right) - \frac{x}{w_c}\right] & i < 0 \end{cases} \qquad (16)$$

where: $C_{off}$, $C_{on}$, $a_{off}$, $a_{on}$, $i_{off}$, $i_{on}$ and *b* are the coefficients of matching. The variable state *x* determines the width of Simmons tunnel barrier. $C_{off}$ and $C_{on}$ influence the magnitude of change of the variable *x*. $i_{off}$ and $i_{on}$ limits threshold voltage, which may find the usage in the digital electronics. The value of $a_{off}$ and $a_{on}$ limit upper and lower boundary of variable *x*, and thanks to that, there is no need for applying window function in this model. Simmons tunnel barrier model is the most accurate model for the description of the memristor. However, this model has some disadvantages: it is very complicated, it is not a general model (describes only specific type of memristor) and the relationship between voltage and current is not clear [6,25–27].

*6) Threshold Adaptive Model (TEAM)*

Threshold adaptive model (ThrEshold Adaptive Memristor model - TEAM) was developed in order to simplify analysis and to improve computing efficiency [28]. The assumptions for this model are as follows: below certain threshold there is no change of state variable *x*, and instead of exponential relationship, there is polynomial relationship between current of the memristor and derivative of internal state variable [6,29]. The relationship between voltage and current is described by the equation:

$$v(\mathrm{t}) = \left[R_{on} + \frac{R_{off}-R_{on}}{x_{off}-x_{on}}(x - x_{on})\right]i(\mathrm{t}) \qquad (17)$$

or

$$v(\mathrm{t}) = R_{on} * \exp\left(\frac{\lambda}{\mathrm{x_{off}}-\mathrm{x_{on}}}(\mathrm{x} - \mathrm{x_{on}})\right)i(\mathrm{t}) \qquad (18)$$

The derivative of internal state variable is given by:

$$\frac{dx(\mathrm{t})}{dt} = \begin{cases} k_{off}\left(\frac{i(\mathrm{t})}{i_{off}} - 1\right)^{\alpha_{off}} * f_{off}(\mathrm{x}) & 0 < i_{off} < i \\ 0 & i_{on} < i < i_{off} \\ k_{on}\left(\frac{i(\mathrm{t})}{i_{on}} - 1\right)^{\alpha_{on}} * f_{on}(\mathrm{x}) & i < i_{on} < 0 \end{cases} \qquad (19)$$

where: $k_{off}$, $k_{on}$, $\alpha_{off}$, $\alpha_{on}$ are constants ($k_{off} > 0$, $k_{on} < 0$), $i_{off}$ and $i_{on}$ represents the values of threshold voltage, and *x* is the internal state variable. Functions $f_{off}(x)$ and $f_{on}(x)$ are like window functions, limits *x* to the boundaries $[x_{on}, x_{off}]$. In relation (17), memristance is linearly proportional to the state variable *x*, which is in agreement with two previous models (linear/nonlinear ion drift model). In the relation (18), memristance is exponentially proportional to the state variable *x*, where $\lambda$ is a matching parameter and should fulfill the condition $\lambda = \ln\left(\frac{\mathrm{R_{off}}}{\mathrm{R_{on}}}\right)$, which characterize Simmons tunnel barrier model. $R_{on}$ and $R_{off}$ represents effective memristance on boundries $x_{on}$ and $x_{off}$. TEAM model has sufficient accuracy and moreover TEAM fulfills the convergence conditions, computing effectivity needed for simulation engines and requirements for memristive systems [6].

## IV. Materials and devices

Diversity of materials in which memristive effect (pinched hysteresis loop) is observed is very wide. Due to the wide possibility of applications in memory devices, the metal oxides such as: nickel oxide, zirconium oxide [30,31], zinc oxide [1,32], hafnium oxide [33,34], titanium oxide [28,35,36] gained special attention. Table I summarize types of switching mechanisms occurring in the most common materials used as active layer in the memristive devices.

TABLE I
REVIEW OF OXIDES USED AS ACTIVE LAYER IN THE MEMRISTORS STRUCTURES. THE DENOTATIONS ARE FS - FILAMENTARY SWITCHING AND IS - INTERFACIAL SWITCHING

| Oxide type | Switching mechanism | Literature |
|---|---|---|
| $TiO_2$ | FS | [13,14,36–42] |
| | IS | [4,14,21,35,40,43,44] |
| ZnO | FS | [2,32,45] |
| $HfO_2$ | FS | [18,21,33] |
| | IS | [34] |
| $ZrO_2$ | FS | [30,46] |
| $LiNbO_3$ | FS | [47] |
| $Ta_2O_5$ | FS | [48–50] |
| | IS | [51,52] |
| CuO, $Cu_2O$ | FS | [53–56] |
| NiO | FS | [57–60] |

*7) $TiO_2$*

The most popular material used as an active layer in the memristor structures is the titanium dioxide ($TiO_2$) [2,6,35,43]. Fabrication of thin-film layers of the $TiO_2$ may be realized using different chemical or physical methods. First HP memristor, which caused increased attention to the memristance effect, was made on the basis of the doped and undoped titanium oxide layers [6]. By applying positive voltage to the top (platinum) electrode, the electric field repels oxygen vacancies from $TiO_{2-x}$ layer (doped region) deep into the layer of pure $TiO_2$ (undoped region). This results in an increase of the width in the $TiO_{2-x}$ region and simultaneously a decrease of the width in the $TiO_2$ region. Applying negative voltage to the electrode results in inverting the effect, where oxygen vacancies are attracted to the electrode, widening the undoped region and at the same time narrowing the doped region [6].

The mechanism of resistive switching in the $TiO_2$ layer is often believed to be based on creation of conducting filaments [38]. According to the theory of the filaments, resistive switching mechanism consists in forming and destroying of conducting filaments, which may be realized by electromigration or thermal diffusion of such defects as oxygen vacancies.

*8) ZnO*

Another material widely used for fabrication of memristive devices is zinc oxide (ZnO) [1,32]. It exhibits very good electrical and mechanical properties. Additionally, this material could be fabricated by the relatively inexpensive techniques like hydrothermal growth. For example, the memristive device proposed by Y. Han et al. [32] consists of two PCBs connected together by flip-chip technology. On the middle side of the board, there is a narrow path of copper on which the ZnO in the form of nanotubes are deposited by using the hydrothermal growth method. After the connection of PCBs, the ZnO nanowires are in direct contact with each other. RAM memory device with resistive switching (RRAM) effect has also been fabricated in the form of Au/ZnO/ITO structure deposited on glass substrate [32]. This kind of semi-transparent device might be used in the field of transparent electronics. The structure was made by using the RF sputtering. HRS state was achieved, when the DC voltage was swept in the range from -2 V to 4 V, while LRS state was achieved in the range from 0 V to -2 V. Conducted endurance tests of the switching from HRS to LRS and durability test of maintaining level of the resistance, showed that resistive switching of the prepared ZnO-based RRAM devices endures over 100 cycles and maintaining its resistance level for about 10 years of constant working.

*9) $HfO_2$*

Hafnium oxide is another material, which may be used in applications connected with RRAM [33], however nowadays, the structures with hafnium oxide are still in experimental phase. An example of memristive structure based on hafnium oxide is TiN/$HfO_x$/TiN was described in [47]. Such memory device exhibited high susceptibility on self-reseting (during formation, the device automatically get HRS state). It was observed that during sweeping with negative voltage, the structure was showing SET process, instead of RESET process, which could be observed during typical bipolar switching mechanism). Surprising was the fact that self-reseting behavior of the structure could be limited by depositing thin-film of $Al_2O_3$ placed between TiN and $HfO_x$ or could be totally eliminated by replacing the TiN electrode with the Pt electrode. RRAM devices based on $HfO_x$ are commonly classified as the „filament-type" devices, because firstly they require a forming process. During the forming process, the conducting filament is formed between two electrodes. Bipolar switching exists until the range of voltage is limited. Increasing the range of positive voltage uncovers complete resistive switching mechanism (CRS). As it is reported in [47] CRS mechanism may results from the exchange of oxygen vacancies between two layers TiN and $HfO_x$.

*10) $ZrO_2$*

Another material used in the RRAM applications is the zirconium oxide $ZrO_2$. This material is commonly used in the MIM structures as isolating layer and is being researched for scalability of the resistive switches. An example of the Ag/$ZrO_2$/ITO structure was described in the paper [30]. The structure was fabricated by the electrohydrodynamic atomization method. This method is efficient, adapted to mass scale production, free from harmful radiation and the time of fabrication of the structure is short. I-V characteristics were measured by applying double voltage sweep of the range from 3V to – 3V. The difference of the resistance in HRS state was less than 3Ω and in the LRS state is less than 5Ω.

*11) $LiNbO_3$*

Among the all previous materials, the $LiNbO_3$ is potential candidate for neuromorphic applications. The paper [47] describes the fabrication and the measurements for the memristor made of lithium niobate. The structure of the memristor consists of Ti/Pt/$LiNbO_3$/Ti/Pt, where the thickness of the lithium niobate layer equals to 42 nm. The switching $LiNbO_3$ layer was prepared by the PLD method. Bottom electrode was made of 10 nm of titanium and 50 nm of platinum, whereas the top electrode was made of 10 nm of titanium and 80 nm of platinum. The silicon substrate was used on which the 2 μm layer of silicon oxide was deposited by the PECVD method. In this structure the titanium is an active metal similar to the Ag i Cu. The top electrode was made of titanium and it probably promoted the movements of the oxygen vacancies inside the layer, which result in memristive effect. The measurements of the structure was made by the cyclic change of the voltage in the room temperature. Before the main measurements, each devices needed the forming process by applying the pulse voltage between 3 – 4 V. The main measurements were made by applying sweeping voltage of the range from -3 V to 3 V. The repeatable hysteresis loops were achieved. Memristor exhibits bipolar resistive switching mechanism.

*12) $Ta_2O_5$*

Tantalum oxide is another type of material that could play very important role in the resistive switching mechanism occurring in memristor structures as a layer responsible for fully controlled limitation of resistance states resulting from the non-uniform switching [48]. Moreover, according to the [51,52] it is possible to fabricate memory system with 162 Gbit in density crossbar array based on nanoporous $Ta_2O_{5-x}$, that would satisfy the requirements for highly scaled memory devices. As it shown in [51] the tantalum oxide in such memory system is responsible for high uniformity in the resistance switching and additionally provides the low power consumption for the memory system, as its play a role of a memristor.

## V. Applications of the memristive devices

The area of potential applications for the memristor devices is enormous. Memristor has potentially very wide usage in the fields of nonvolatile RAM memories, DRAM, flash memories, neural networks, image processing and in the field of artificial intelligence [35]. The main division of the memristive devices is on the discrete elements and on the crossbar arrays. In discrete devices applications, the memristors are used due to their nonlinear characteristic and their controllable change of resistance. On the other hand, in the crossbar arrays applications, the memristors gains attention thanks to the possibility of their size reduction while maintain their properties [10]. Thorough analysis of the taxonomy shows another division of the applications of the memristors between usage in digital electronics and in analog circuits. From this level of taxonomy more specific usage of the memristor is resulting.

### *13) Analog circuits*

Applications of the memrisotrs in the field of analog circuits improves operation of certain circuits such as: oscillators, adaptive filters, programmable circuits, neuromorphic networks or chaotic systems. In order to improve operation of different devices memristors are usually used instead resistors. Several examples of such devices have been demonstrated, e.g. in [6,11]. Memristors also found applications as switches in the radio frequency (RF) antennas [11]. Programing mode and resistive mode were separated through the difference of the signals frequencies.

One of the important applications of the memristors is the field of programmable circuits [11]. In many analog circuits like filters or amplifiers, resistors need to be specifically programmed in order to adjust operation of the circuits to the specific applications. Programmable resistor with a good resolution is very useful in the differential circuits in analog and RF range. Applications of this type of resistors may be found in programmable amplifiers or programmable filters. The most popular realization of programmable resistors is the circuit of resistors controlled by switches realized by array of weighted resistors and switches. However, this kind of circuits has great disadvantage, because of the high value of parasitic resistance and parasitic capacitance introduced by the switches. The state of the switch influencing the parasitic values, which leads to limitation of the resolution and of the number of bits in resistor switches. This mechanism causes long-term problems with the reliability of the circuits.

Moreover, some other programmable analog circuits were investigated, such as: programmable threshold comparator, programmable amplifier or programmable relaxation oscillator. The results from the experiments gathered in the paper [6] shows good and promising results of working of the memristor as the gain enhancer element in the field of amplifiers.

Memristors may be also used in realization of logic operations. Memristors could represents many different logic states, not only the “on” or “off” states [5]. This feature indicates on the possibility of creation new type of computing models and analog computers. In order to realize mathematic operations (e.g. addition, subtraction, multiplying, division) the representation of two arguments are necessary. Nowadays, in the most working logic circuits the values of the signal are represented by values of voltage or values of current [5]. Total memristance of two memristors connected in the series represents the addition operation (M1+M2). Subtraction operation (M1−M2) may be realized as M1+ (−M2). In case of subtraction, memristors should be connected in series, where memristance of one of them is –M2. Simple inverting amplifier based on operational amplifiers is the memristance divider (M2/M1).

The most fascinating applications of memristors is in the field of neuromorphic systems [61]. Accurate definition of such systems is described in the paper [6] and states that "neuromorphic system is a connection of analog-digital systems, whose responsible for imitating the architecture of neuron system, creating new neurons patterns during computing in real time, simulating and emulating nerve system of a man". Simulation of nerves connection consisting of neurons and synapses (connection between neurons) as an electronic circuit requires implementation of elements of low power consumption. Synapses represented by the electronic circuits are very difficult to achieve, because of requirement that capacity of the memory must be elastic and dynamic at the same time [6]. Up to date, the scientists have simulated with good results the work of brains of little pets (cat, rat and spider). The problem in this types of simulations is that: memory of the computer is required at higher level than terabytes. Due to that, memristors may play significant role, because they could represent synapses and having the low power consumption at the same time. Practical implementation of learning circuits was demonstrated by using pattering scheme of learning of amoeba-like cells in memristive systems [6].

Another important field of applications in which memristors might be useful are chaotic systems. Due to randomness of chaotic systems, memristors as a nonlinear elements are great solution for encryption and for the random number generators. Thanks to the features of the memristors there is a possibility of gaining better control and to simplify chaotic circuits [6].

### *14) Digital circuits*

As was mentioned earlier, logic operation could be represented by the analog or digital circuits. Memristor may be used as basic element for building an logic gate. Memristor logic gate may be implemented for all binary operation of two variables. Realization of material implication was achieved by Borghetti in [6], which leaded to realization of all fundamental Boolean operations.

The most significant and future usage of the memristors is their applications in the fields of nonvolatile memories. In the literature resources, there are many ideas of how to improve present standard of the RAM memories. Nonvolatile memory (NVM) is in the research state for the long time, because the scientists predicted that flash memory will stop developing due to the limitations connected with miniaturization [10].

A great potential of memristors in the field of nonvolatile memories (NVM) due to showing memory effect, does not need continuous power supply and requires only small physical space [11]. Representation of one bit of information is achieved by the two states (HRS and LRS) occurring in the memristor, which represent logical 0 and 1. In order to store this bit of information only single memristor is needed. For writing of the bit, the DC voltage is applied, whereas for reading the bit, the AC voltage is applied. Using the AC signal provides protection from data loss [11]. Memristors could act as associative memories. New kinds of NVM, which are still in the development, are: resistive random access memory (RRAM), phase-change random access memory (PCRAM), ferroelectric memory (FeRAM), magnetoresistive memory (MRAM) [6,10,11].

Resistive random memory access (RRAM) is two terminal device, where the switching layer is placed between electrodes. Exemplary realization of the RRAM device fabricated of trilayer of $Al_2O_3/HfO_2/Al_2O_3$ deposited on the Si substrate with the $SiO_2$ layer coated with TiN by ALD method was shown in [18].

Resistance of RRAM may be modulated by applying voltage or by flow of current through the structure. Moreover, the changes in electrical nonvolatile resistance was observed in the FeRAM, MRAM, PRAM memories. Common method used to the integration of RRAM cell with CMOS system is called 1T1R (1 transistor + 1resistance switching element). Transistor is responsible for the control of location of the switching element, which access is required at the moment. Disadvantage of this method is using one transistor for one switching element so the package density is still dependent on scalability of the transistor [6]. Resistive switching effect of the memristor results from the configuration of metal-isolator-metal (MIM). Memristor in comparison to the flash memory requires very little energy in order to work properly. HP Lab experimentally demonstrated nonvolatility of the memristors and also their features such as compatibility in CMOS system, fast response time and low power consumption [6]. Thanks to the possibility of nonvolatility of memory of memristor, it will be possible to turn on computer without the need of reloading operation system, moreover physical RAM memory will be not needed. Even in the field of mobile applications, the research on the static random access memory (SRAM) are being conducted in order to improve write/read of data, lowering power consumption and decreasing the physical size of the devices [6].

The research on phase-change memory (PCRAM) has been started before the discovery of the memristor by HP Labs. In near future, PCRAM probably will be commercially available. The working principle of PCRAM is based on the change of phase of the materials (PCM) between crystalline state (state of low resistance) and the amorphous state (state of high resistance) by applying current to the structure [10].

In the RAM memories based on redox reaction, there are 3 types of switching mechanisms: memory effect of the valance change (VCM), thermoelectric memory effect (TCM) and memory effect of electrochemical metallization (ECM). Memory effect of the valance change is an redox reaction caused by valance change of cation sublattice and sudden change of electrical conductivity known as isolator-metal transition. Thermoelectric memory effect depends on the gradient of the temperature between conducting filament and the surrounding material, which is responsible for the switching. Lastly, memory effect of electrochemical metallization is based on electrochemical oxidation of electrochemically active material (np. Ag or Cu) [10]. On the other hand, there are a few problems with the memristor usage in the memory applications. For instance, in the crossbar memory structure there could be effects like: nonuniform distribution of resistance across the structure or resistance drift. As the memristor is gaining more and more attention, the scientists are intrigued of potential possibilities of these devices. It is expected, that new areas of applications of the memristor will arise thanks to the precise computer models for the memristors [10].

## CONCLUSIONS

On the basis of the review of the literature, it can be stated that memristive structures may be a breakthrough discovery in the field of modern basic and advanced electronics. It is expected that the application of fourth "missing" electronic element would result in improvement of reliability of the systems, computing power, lower power consumption and it will allow to scale electronic devices to the nanoscale. The most promising domain of applications of the memristors seems to be such fields like: nonvolatile memories, chaotic systems and bionic and neuromorphic systems. On the other hand, the complexity of the physical phenomena occurring in the memristive structure are still not thoroughly investigated. Future perspectives for the memristor is very promising, especially in the field of decreasing power consumption of the memory devices, whereas maintaining and even increasing the data possible storage, thanks to the capability of high density of the memristors devices, and their functioning without the need of 1T1R system to maintain one bit of a memory. Discovering a truly memristor devices could be an enormous breakthrough in the field of the nowadays electronics.

Despite of many published scientific papers on the subject of resistive switching, the complete model describing resistive switching phenomenon is still missing [8]. Memristors based on hafnium and tantalum oxides are commercially available, even though the resistive switching mechanism is not thoroughly understood.

The elements of electronic circuits, which may store the information without the need of continuous supplying would introduce new paradigm to the field of electronics. It may be concluded that the conception of a memristance, despite of its name, does not necessarily have to relate only to resistance, but also to capacitance and inductance. Memcapacitance and meminductance circuits will provide new functionality to the world of electronics. Regardless of the mechanisms that occur during the switching of the resistance, it can be determined that at very low frequencies, the system has sufficient time to adjust the resistance to the momentary value of the controlled parameter (current or voltage). Due to that fact circuit is behaving like nonlinear resistor. However, when the frequency is very high, the circuit does not have sufficient time to adjust resistance to the periodic oscillation of the controlling parameter. In that case the circuit starts to behave like linear resistor. Lastly, in the microscopic scale, local dipole of resistance has been forming. In other words, self-formation of the resistance dipoles in the structure means that there is accommodation of charge which leads to capacitance in the circuits. In the nanoscale, memristive behavior of the structure is connected with the accommodation of the charge which causing that the hysteresis loop is not pinched [62].

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