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Study of Forming Process in Memristive Devices using Rectangular Waves

Abstract. *This work focuses on the study of behavior of memristors during the process of forming, i.e., setting the resistance of the element and testing the stability of the resistance. Two types of BS-AF memristive elements are selected for laboratory experiments. The goal of the research is to investigate the conditions under which the resistance of the element is changed when voltages of different levels, duration and polarization are applied. In particular, we are interested in finding the threshold voltage value which is needed to modify of state of the element. Such a value defines the voltage level below which one can safely measure instantaneous value of memristor's resistance (data read operation) without changing this value. The results obtained show that the threshold value depends on the polarization of the applied voltage. Memristors under study are much more sensitive to applying a negative voltage. This means, that a significantly smaller value of the voltage is needed to switch from low to high resistance level than to switch from high to low resistance level. It has also been observed that the final value of the memristor's resistance depends on the number and level of applied voltage impulses. This study confirms that BS-AF memristors can operate in more than two states in a stable way, which can be beneficial when using memristors in memory structures or for neuromorphic applications.*

Streszczenie. *W pracy opisano wyniki badań nad procesem formowania memrystorów, tzn. programowaniem poziomu rezystancji chwilowej elementu oraz stabilnością uzyskanej wartości. W części pomiarowej wykorzystano dwa rodzaje elementów memrystorowych z grupy BS-AF. Celem badań było określenie warunków niezbędnych do zmiany rezystancji memrystora podczas wzbudzania napięciami o różnych poziomach, czasie trwania i polaryzacji. W szczególności poszukiwano wartości progowej napięcia zasilającego potrzebnej do modyfikacji stanu memrystora. Wartość taka definiuje poziom napięcia, poniżej którego możliwy jest pomiar wartości chwilowej memrystancji (operacja odczytu danych), bez zmiany opisywanej wartości. Uzyskane wyniki wskazują, że wartość ta zależy od polaryzacji przyłożonego napięcia. Badane memrystory są znacznie bardziej czułe na napięcie ujemne. Oznacza to, że znacząco niższy poziom napięcia jest potrzebny aby przełączyć memrystor ze stanu niskiej do wysokiej rezystancji niż odwrotnie. Zaobserwowano również, że ostateczna wartość rezystancji chwilowej memrystora zależy od liczby i poziomu impulsów napięciowych. Eksperyment ten potwierdza, iż memrystory typu BS-AF mogą uzyskiwać więcej niż dwa poziomy rezystancji chwilowej w stabilny sposób, co może być kluczowe dla wykorzystania ich w strukturach pamięci lub systemach neuromorficznych.* ***(Formowanie elementów memrystorowych napięciowymi sygnałami prostokątnymi)***

Keywords: memristor, memristive device, memristor forming, memory structures, nonlinear systems
Słowa kluczowe: memrystor, element memrystorowy, formowanie memrystorów, struktury pamięci, obwody nieliniowe

Introduction

Theoretical definition of memristor was formulated in [1, 2]. The memristor is defined as an element in which the resistance depends on the history of flux or charge of the element. Memristors are capable of changing the resistance after application of an appropriate voltage or current signal. The value of the resistance can be measured by applying a relatively much smaller sensing signal [3].

The discovery of the element, which exhibits electrically controllable state-dependent resistance was reported in [3, 4]. It was a turning point in research on memristive devices. The most crucial property of memristor is the fact, that it can take two significantly different values of resistance in a stable way. This explains, why this topic became very popular for scientists specializing in electronics, memories, logic circuits and neuromorphic systems [5].

When a sinusoidal voltage is applied to the element a characteristic pinched hysteresis loop (also called the bow-tie curve) in $v-i$ relation is observed (see Fig. 1). This $v-i$ hysteresis loop always passes through the origin for any bipolar periodic input voltage. The pinched hysteresis loop narrows down when the frequency f is increased and the area of the loop converges to zero when f grows to infinity [6].

The main aim of this work is the study of memristors during the procedure of forming the element, i.e. setting the proper resistance level and consequently testing the stability of that resistance level. The process of memristor forming using rectangular waves as input signals is considered. The influence of the amplitude, the polarization, the width, and the number of input pulses on the behavior of memristors is investigated. In particular, the effects of applying specific rectangular waveforms on the resistance of memristors is studied.

Existing literature on memristor forming focuses on physical phenomena inside memristive elements during resistance switching process [8, 7], than on the properties of the input signal such as the duration, the amplitude or the number of pulses required to achieve the desired value of memristance.

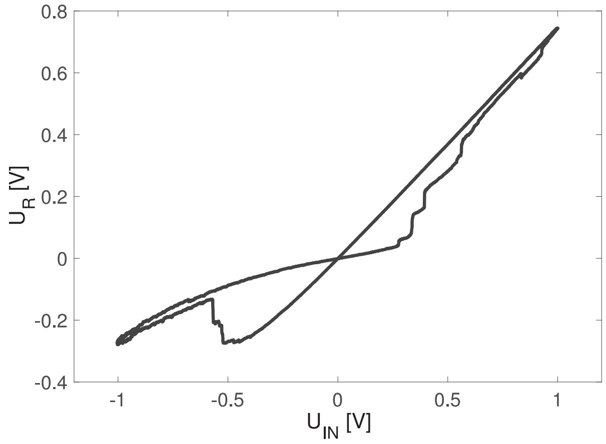

Fig. 1. Hysteresis loop observed for a BS-AF-W memristor, input signal frequency is $f = 100\ \mathrm{Hz}$.

Measurements

In this section, the measurements details are described. Tests are carried out with 16-pin chips each containing 8 memristors. Two types of memristors are considered: BS-AF-W and DM8-16DIP-BS-AF. Measurement circuit bases on Analog Discovery 2.0 device - portable oscilloscope set with two-channel periodic signals generator integrated (see Fig. 2).

The memristive element is connected in series with a resistor to measure the current flowing through the element. The value of the resistance $5\ \mathrm{k\Omega}$ is selected to protect the element under study by limiting the current. The simplified diagram of the circuit considered in tests is shown on Fig. 3. The WaveForms software package is used to define the input signal and save the results.

The input signal applied is a rectangular wave. An example of the input signal with the amplitude $0.5\,\mathrm{V}$, the period $1\,\mathrm{s}$ and the duty cycle 10% is shown in Fig. 4. The duration of the signal is limited to $10\,\mathrm{s}$.

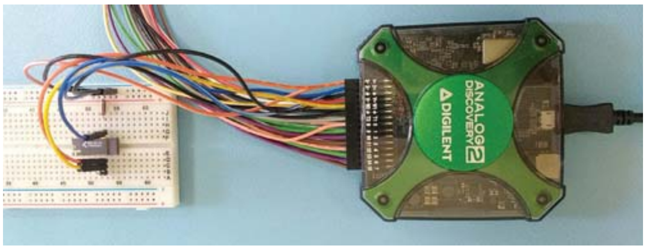

Fig. 2. Test circuit: a series connection of the on chip memristor and a linear resistor $5\,\mathrm{k\Omega}$, measurements done using the DIGILENT oscilloscope.

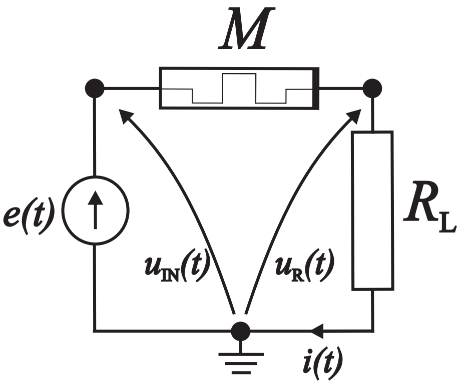

Fig. 3. Diagram of the test circuit.

The experimental setup permits to apply the input signal U_{IN}, measure and record the input voltage U_{IN} and resistor voltage U_{R}. Using these measurements and the value of resistance R_{L} one can calculate the resistance R_{M} of the memristor using the following formula:

$$R_{\mathrm{M}} = \frac{U_{\mathrm{IN}} - U_{\mathrm{R}}}{U_{\mathrm{R}}} \cdot R_{\mathrm{L}}. \tag{1}$$

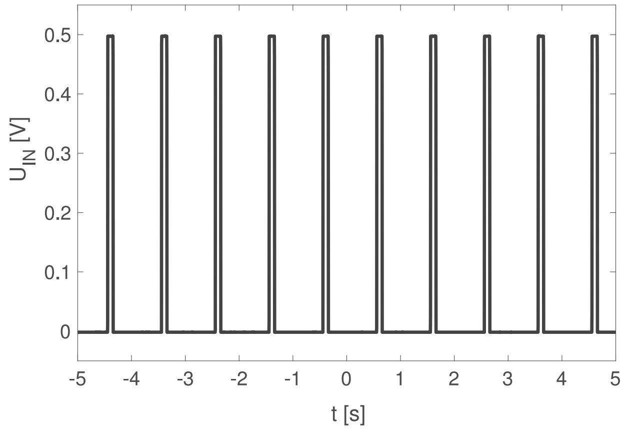

Fig. 4. Example of an input voltage signal.

Results

At the beginning of each experiment it is verified whether a device under study operates as a memristor. To this end the sinusoidal voltage signal of amplitude 1V and frequency 100Hz is applied to the element and the $v-i$ characteristics is recorded. If the observed characteristics forms a pinched hysteresis loop (compare Fig. 1) then it is assumed that a selected element works as a memristor and can be used for testing. Two types of memristive elements were tested: BS-AF-W and DM8-16DIP-BS-AF.

BS-AF-W Memristors

The first set of experiments is carried out using memristors of type BS-AF-W. The input voltage signal shown in Fig. 4 is applied to the test circuit. The observed resistance R_{M} of the memristor is plotted in Fig. 5. When the input signal is zero then there is no current flowing in the test circuit and in consequence one cannot compute the resistance R_{M}. Therefore, in this and in subsequent figures when the input signal is zero the value $R_{\mathrm{M}} = 0$ is plotted. One can see that when the input signal is positive then the resistance of the element decreases. This behavior corresponds to the OFF-ON switching in which the memristor's resistance changes from a high value to a low value. It is expected that when the input signal is zero the resistance R_{M} remains constant. The results show that this is not always true. Usually, the value of R_{M} at the beginning of a given pulse is larger than at the end of the previous one.

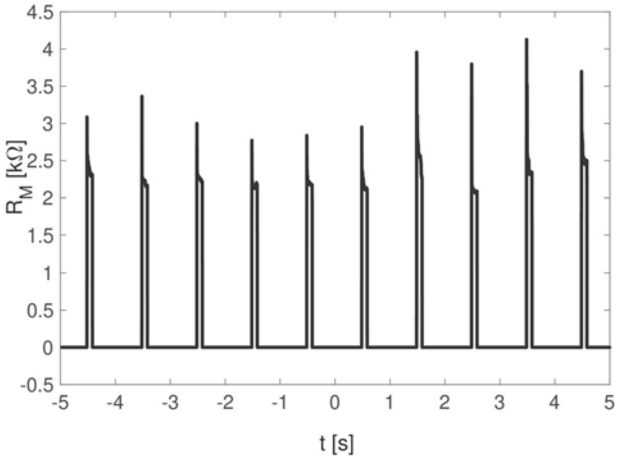

Fig. 5. The resistance of a BS-AF-W memristor; input signal: 10 pulses $U_{\mathrm{IN}} = 0.5\ \mathrm{V}$ of length $t = 0.1\,\mathrm{s}$.

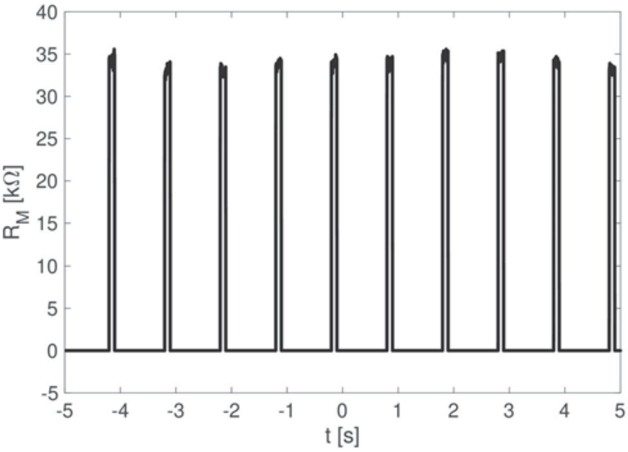

Fig. 6. The resistance of a BS-AF-W memristor; input signal: 10 pulses $U_{\mathrm{IN}} = -0.5\ \mathrm{V}$ of length $t = 0.1\,\mathrm{s}$.

In the second test the polarization of input signal is reversed. This is done to study the phenomenon of the ON-OFF switching in which the memristor's resistance changes from a low value to a high value. The absolute value of the input voltage is the same as in the first experiment. The results are shown in Fig. 6. One can see that applying the negative voltage $U_{\mathrm{IN}} = -0.5\ \mathrm{V}$ causes an almost immediate switching to high resistance state. In the following experiments it is confirmed that the ON-OFF and OFF-ON switchings take place at different levels of the absolute value of the input signal.

The purpose of next experiment is to determine the influence of the amplitude of the input signal on the OFF-ON switching process and the obtained value of the resistance of the element. The amplitude of the input signal is increased to $U_{\mathrm{IN}} = 1.0\,\mathrm{V}$. In this case the switching takes place during the first two pulses and then the resistance stabilizes (see Fig. 7). The final value of the resistance $R_{\mathrm{M}} \approx 1.2\ \mathrm{k\Omega}$ is approximately two times smaller than in the first experiment ($R_{\mathrm{M}} \approx 2.5\,\mathrm{k\Omega}$ for $U_{\mathrm{IN}} = 0.5\ \mathrm{V}$).

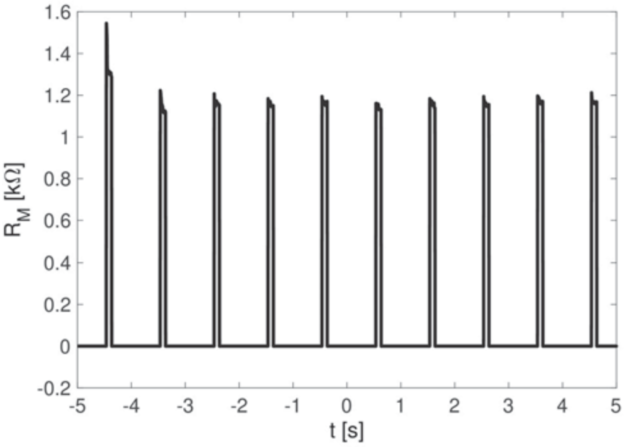

Fig. 7. The resistance of a BS-AF-W memristor; input signal: 10 pulses $U_{\mathrm{IN}} = 1.0\ \mathrm{V}$ of length $t = 0.1\ \mathrm{s}$.

In the last experiment concerning a BS-AF-W memristor the negative input voltage signal with the amplitude $U_{\mathrm{IN}} = -0.2\ \mathrm{V}$ is applied. During the first 10 pulses the resistance of the memrisive device does not change. The results of applying the next 10 pulses with the same amplitude are shown in Fig. 8. The switching occurs during the sixth voltage pulse. It is interesting to note that the memristor resistance changes to a much higher level $R_{\mathrm{M}} \approx 70\ \mathrm{k\Omega}$ than in the case $U_{\mathrm{IN}} = -0.5\ \mathrm{V}$ (compare Fig. 6).

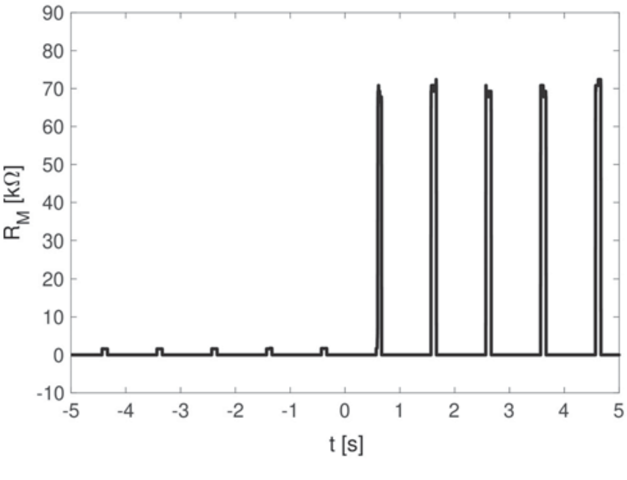

Fig. 8. The resistance of a BS-AF-W memristor; input signal: 10 pulses $U_{\mathrm{IN}} = -0.25\ \mathrm{V}$ of length $t = 0.1\ \mathrm{s}$.

From these experiments it follows that the behavior of BS-AF-W memristors under pulse input signal is somewhat unpredictible. For low amplitudes, it is difficult to predict how many impulses are needed to change the resistance of the element and the final value of the resistance.

DM8-16DIP-BS-AF Memristors

In this section results concerning DM8-16DIP-BS-AF memristors are presented. Elements of this type are supposed to have a much higher quality than BS-AF-W elements.

The first experiment was carried out for the input signal composed of 10 voltage pulses with the amplitude $U_{\mathrm{IN}} = 0.5\ \mathrm{V}$ and the duration $t = 0.1\ \mathrm{s}$. The time plot of the resistance R_{M} is presented in Fig. 9. Let us note that during the first four pulses the value of R_{M} increases. For the remaining pulses the resistance decreases, as expected.

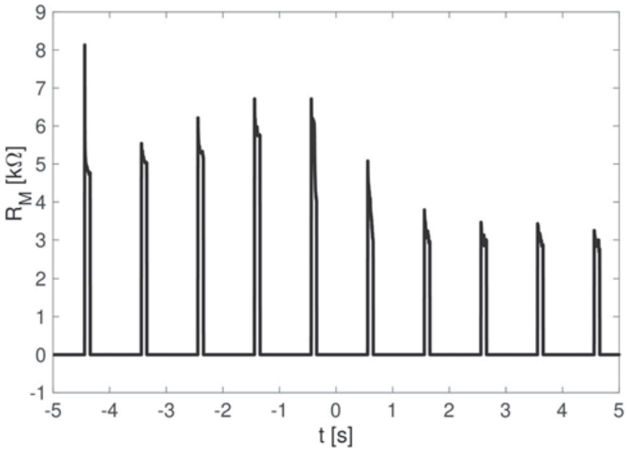

Fig. 9. The resistance of an DM8-16DIP-BS-AF memristor; input signal: 10 pulses $U_{\mathrm{IN}} = 0.5\ \mathrm{V}$, duration time $t = 0.1\ \mathrm{s}$.

The experiment carried out for the negative input voltage $U_{\mathrm{IN}} = -0.3\,\mathrm{V}$ leads to similar results as for BS-AF-W memristor. The element switches to a high resistance state during the first two pulses and than the resistance of the element stabilizes. An interesting observation is made for the input signal with the amplitude $U_{\mathrm{IN}} = 1.0\ \mathrm{V}$. In this case R_{M} does not stabilize after 10 impulses. To further investigate this phenomenon the behavior of the element under a DC signal is studied. Fig. 10 presents input and output voltages versus time. Red line indicates output voltage U_{R}. The value of that voltage increases slightly during the whole period of existing DC input signal. This is equivalent to the decrease of the resistance R_{M}. This experiment is repeated three more times, after which the resistance stabilizes.

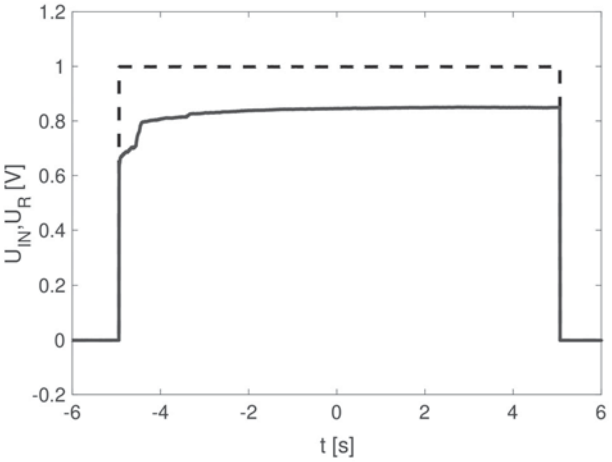

Fig. 10. Forming an DM8-16DIP-BS-AF memristor with the DC signal.

The goal of the last set of experiments is to determine the threshold value of the ON-OFF switching for DM8-16DIP-BS-AF memristors. Fig. 11(a,b) presents results of the tests for the amplitudes $U_{\mathrm{IN}} = -0.25$ V and $U_{\mathrm{IN}} = -0.3$ V. One can see that in the first case the resistance is slowly increasing in time during the whole experiment. For the larger amplitude of the input signal $U_{\mathrm{IN}} = -0.3$ V the ON-OFF switching takes place much faster—already during the first pulse the resistance reaches $100\ \mathrm{k\Omega}$ and after the second pulse the resistance stabilizes around $125\ \mathrm{k\Omega}$. It follows that by setting the amplitude of the pulses at the correct level (in this case $U_{\mathrm{IN}} = -0.25\,\mathrm{V}$) one can easily form the memristor to achieve the desired resistance. For larger voltages the switching process is much faster and it is difficult to control the final state of the memristor.

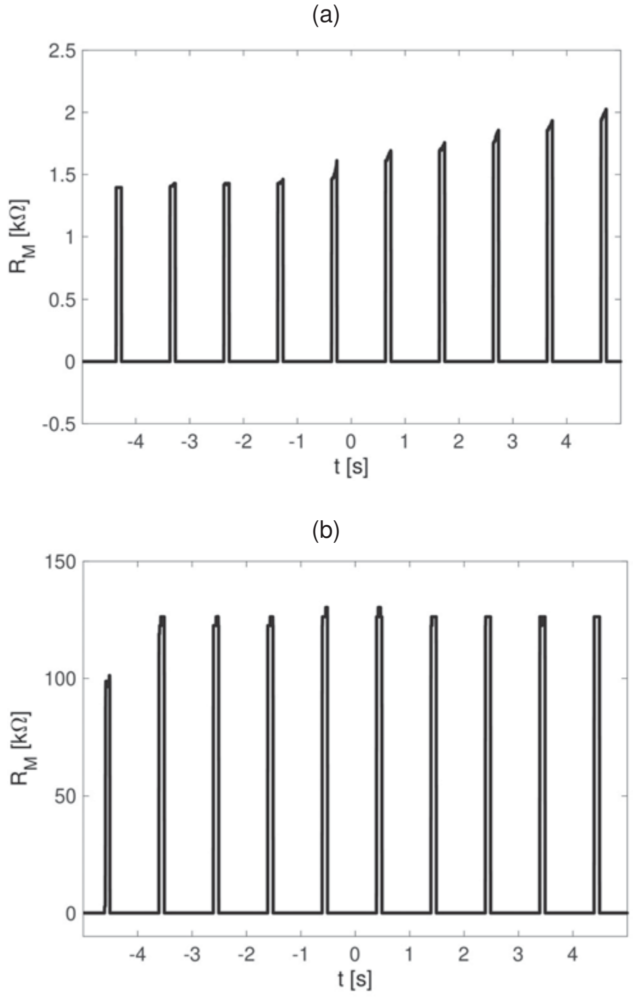

Fig. 11. The resistance of an DM8-16DIP-BS-AF memristor, (a) input signal: 10 pulses $U_{\mathrm{IN}} = -0.25\,\mathrm{V}$, duration time $t = 0.1\,\mathrm{s}$, (b) input signal: 10 pulses $U_{\mathrm{IN}} = -0.3\,\mathrm{V}$, duration time $t = 0.1\,\mathrm{s}$

Conclusions

The behavior of two types of memristive elements driven by rectangular waves have been studied and the observed switching process has been analyzed. It was shown that both the amplitude of the signal and number of pulses influence the final state of memristors. One can conclude that the elements under study are much more sensitive to negative input voltages. Slight change of the amplitude of the input signal can cause an immediate ON-OFF switching of the device. It was also shown that by a proper selection of the amplitude of the input signal one can easily obtain a required value of the resistance and that memristive elements can take more than two resistance values in a stable way.

The authors plan to carry out more comprehensive tests involving longer rectangular pulse trains with various duty cycles and also using trains of triangular pulses. This may permit a better characterisation of the memristor forming process.

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