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Research Article

Examination of the Reliability of a Robustness Test for the Self-Directed Channel Carbon-Based Memristors by Reading Their DC Resistance

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ABSTRACT

An ideal memristor that has been theoretically predicted almost a half-century ago is a nonlinear power dissipating circuit element. Nowadays, memristive systems such as thin films which are not ideal memristors are also called memristors. Such systems have current-dependent behavior and nonlinear charge-dependent electrical resistance. Self-directed channel Carbon-, Tungsten-, Chrome-, and Tin-based memristors have become commercially available nowadays and they are used for research purposes. All circuit components must be tested before their usage. It is expected that memristors will become commonly used in electronic circuits in the future. However, the literature has just a few memristor tests reported. To the best of our knowledge, there is not a suggested robustness test for the self-directed channel Carbon-based memristors in the literature. In this study, A recently suggested memristor robustness test which could be made using just a multimeter is modified using a series resistor. The test is tried on the Self-Directed Channel Carbon-Based memristors. Unfortunately, the test is found unreliable and invalid for the self-Directed Channel Carbon-Based memristors.

Keywords: *Memristor, Component test, Knowm memristors, Carbon-based memristors*

Kendiliğinden Kanal Oluşturmalı Karbon Tabanlı Memristörler İçin DC Dirençlerini Okuyarak Yapılan Bir Sağlamlık Testinin Güvenilirliğinin İncelenmesi

ÖZ

Neredeyse yarım yüzyıl önce varlığı teorik olarak tahmin edilen ideal memristör, doğrusal olmayan ve güç tüketen bir devre elemanıdır. Günümüzde, ideal memristör olmayan ince filmler gibi memristif sistemler de memristör olarak isimlendirilmektedir. Bu tür sistemler akıma bağlı davranışa ve doğrusal olmayan yüke bağlı elektrik direncine sahiptir. Kendiliğinden kanal oluşturmalı (KKO) Karbon, Tungsten, Krom ve Kalay tabanlı memristörler günümüzde ticari olarak temin edilebilir hale gelmiştir ve araştırma amacıyla kullanılmaktadır. Tüm devre elemanları kullanılmadan önce test edilmelidir. Gelecekte memristörlerin elektronik devrelerde yaygınca kullanılması beklenmektedir. Bununla birlikte, literatürde rapor edilmiş az sayıda memristör testi mevcuttur. Bildiğimiz kadarıyla, literatürde Kendiliğinden Kanal Oluşturmalı Karbon Tabanlı memristörler için önerilmiş bir sağlamlık testi yoktur. Bu çalışmada yakın zamanda önerilen sadece bir multimetre kullanılarak yapılabilen bir memristör sağlamlık testi bir seri direnç kullanılarak modifiye edilmiştir. Bu test Kendiliğinden Kanal Oluşturmalı Karbon Tabanlı memristörler üzerinde denenmiştir. Ne yazık ki, bu test Kendiliğinden Kanal Oluşturmalı Karbon Tabanlı memristörler için güvenilmez ve geçersiz bulunmuştur.

Anahtar kelimeler: *Memristör, Eleman testi, Knowm memristörler, Karbon tabanlı memristörler*

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I. INTRODUCTION

A memristor is a nonlinear charge-dependent circuit element. It has been predicted to exist in 1971 [1]. Memristive systems have been described in 1976 [2]. A TiO_2 thin-film has been shown to behave as a memristor in 2008 in [3]. Even though there are no ideal memristors found yet [4], nowadays, memristive systems are also called memristors [5-7]. Memristor has emerged as a popular research area [5-10]. It may be used in not only analog but also digital applications [8-10]. Companies are trying to make memristor commercially available in the market [11, 12]. The self-directed channel (SDC) Carbon-, Tungsten-, Chrome-, and Tin-based memristors are already on the market [12]. The SDC memristors have already been used in chaotic circuit applications recently [13-15]. In the future, more memristor-based analog circuit applications such as programmable oscillators, amplifiers, and comparators examined in [10,16] are expected to appear. When it happens, such memristor-based circuits or memristors will need test devices or testing methods. A test for memristor-based memories is suggested in [17]. A simple test for ideal memristors has been suggested in [18]. A robustness test is suggested for non-ideal memristors having a high R_{OFF}/R_{ON} ratio (Off-state resistance to on-state resistance ratio) in order to learn whether such a device is broken or not [19]. The test was so simple that it could be made using just a multimeter or an ohmmeter. However, some memristors or memristive systems have bipolar characteristics such as Complementary Resistive Switches (CRSs), discharge lambs, ZnO-based memristive systems, and diacs [20-27] and such a test may not be used to test memristive systems with bipolar resistive switching or CRS switches [20-27]. They obtain ideally the same resistance values for each polarity when excited with a DC source for a duration greater than its memristive or resistive switching time [28, 29]. The structure of the SDC Carbon-based memristors is similar to the bipolar or the CRS resistive switches. In this paper, the test suggested in [19] is used with a modification on the SDC Carbon-based memristors to verify whether such a memristor is broken or not. Considering the saturation mechanism of the SDC Carbon-based memristors and their required protection resistance, the simple test in [19] is modified. The resistances of an SDC Carbon-based memristor are measured using different series resistors in both forward and reverse directions just using a multimeter. Based on the data obtained from the experiments performed, the test is evaluated.

The study is structured as follows. The definition of memristor and memristive systems is given, the SDC Carbon-based memristors are briefly told, and a simple robustness test is presented in the second section. The experimental results are given in the third section. The study is concluded with the last section.

II. MATERIALS and METHOD

In this section, first, the description of Memristor and Memristive Systems is given to remind us how the resistance of the memristors changes, the SDC carbon-based memristors are introduced, and then the suggested test is described.

A. Memristor and Memristive Systems

In this section, memristive system equations are given first. In [2], Chua et al. have described an n^{th} degree voltage-controlled memristive system as

$$v(t) = R(x(t), v(t), t)i(t) \tag{1}$$

$$\frac{dx}{dt} = f(x(t), v(t), t) \tag{2}$$

where $R(x(t),v(t),t)$ is the electrical resistance or the memristance of the system, $v(t)$ is the system voltage, $i(t)$ is the system current, and $x(t)$ is the set of nth state variables used to describe the internal state of the system.

Nonlinear dopant drift memristor models do already exist in the literature [30-32]. They have window functions to model nonlinear drift speed within the TiO_2 region. The window function shows how a memristor deviates from being an ideal memristor. Their resistance value starts varying when the window function is different from zero. The memristor model in [30] is given as,

$$v(t) = R(x)i(t) \tag{3}$$

$$\frac{dx}{dt} = \frac{\mu_v\, i(t) R_{ON}}{D^2} g(x,i) \tag{4}$$

where $g(x,i)$ is the window function of the memristor, μ_v is the mobility constant, and $x(t)$ is the state variable of the memristor.

In literature, there are many different window functions used to model nonlinear drift phenomena. For example, the one suggested in [13] is given as

$$g(x,i) = 1 - (x - stp(i))^{2p} \tag{5}$$

where p is a shaping constant.

The memristance of such a memristor is given as

$$R(x) = R_{ON}x + R_{OFF}(1 - x) \tag{6}$$

Its resistance stays between the minimum and the maximum value, R_{ON} and R_{OFF}:

$$R_{OFF} \geq R(x) \geq R_{ON} \tag{7}$$

The CRS memristors have also been examined in the literature, especially for their usage in computer memories [23, 26]. More information about them can be found in [21-23, 33-34]. For the CRS memristors, their equivalent resistance for both polarities is almost the same after resistive switching completes since they are connected in anti-series [21-23, 26].

Therefore, the following is true:

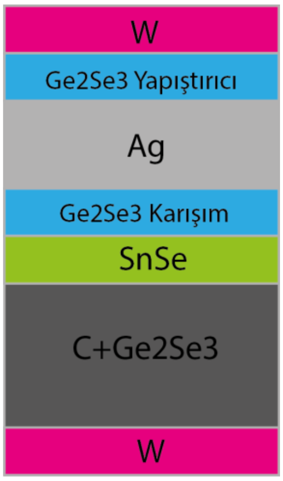
$$R_{OFF} \cong R_{ON} \tag{8}$$

In [19], a simple test is suggested to test using just an AVOmeter or a multimeter, or an ohmmeter to check whether a memristor with a high R_{OFF}/R_{ON} ratio or not. The memristor models given in [26-28] are not sufficient to model the SDC memristors due to their complex and bipolar-like characteristics. More information about the SDC memristors is given in the following section.

B. The Self-directed Channel Carbon-based Knowm Memristors

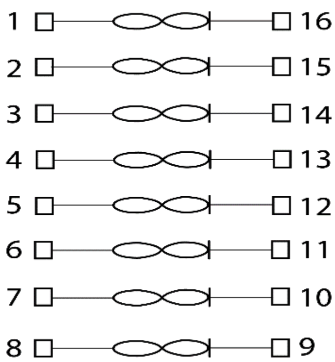
In this section, the SDC Carbon-based memristors produced by Knowm company [12] are briefly told. Its topology is shown in Figure 1.a. The SDC Carbon-based memristor circuit element has been tried to be optimized with various additives. Memristor channels formed within the material layers, used to change device resistance, rely on the movement of Ag^+ ions inside the active layers. These layers of material form a metal ion conducting device and are often referred to as an electrochemical metallization cell. The forward voltage applied to the memristor will create a channel with the movement of Ag^+ ions and will bring the device from the low conductivity state to the high conductivity state. If a reverse voltage is applied, the device whose resistance value will increase considerably will become less conductive. Knowm company defines the natural direction, i.e. forward direction, as the direction in which the resistance value decreases and the conductivity increases in its memristors. The opposite or the reverse direction defines the direction where the resistance value increases and the conductivity decreases. Photographs of the SDC Carbon-based memristor integrated circuits are given in Figure 1.b. The integrated circuit has 16 pins and 8 SDC memristors. The leg connections of these integrated circuits are given in Figure 1.c.

According to the information given in [12], the SDC Carbon-based memristor used in this study has been defined as the most suitable device for low-power binary switching. One of the memristors in the integrated circuit is chosen and excited with a sinusoidal signal and the acquired hysteresis curves of the memristor are given in Figure 2 for two different frequencies. As it can be seen in these figures, the area of the zero-crossing hysteresis loop of the memristor gets smaller when the frequency increases as described in [2]. More detailed information about Knowm memristors can be found in [12].



a)

b)



c)

Figure 1. *a) The SDC Carbon–based Knowm Memristor topologies [12], b) The SDC Carbon-based Knowm Memristor Integrated Circuits having 8 memristors [12], and c) The Pin connections of the Knowm memristor Circuits [12]*

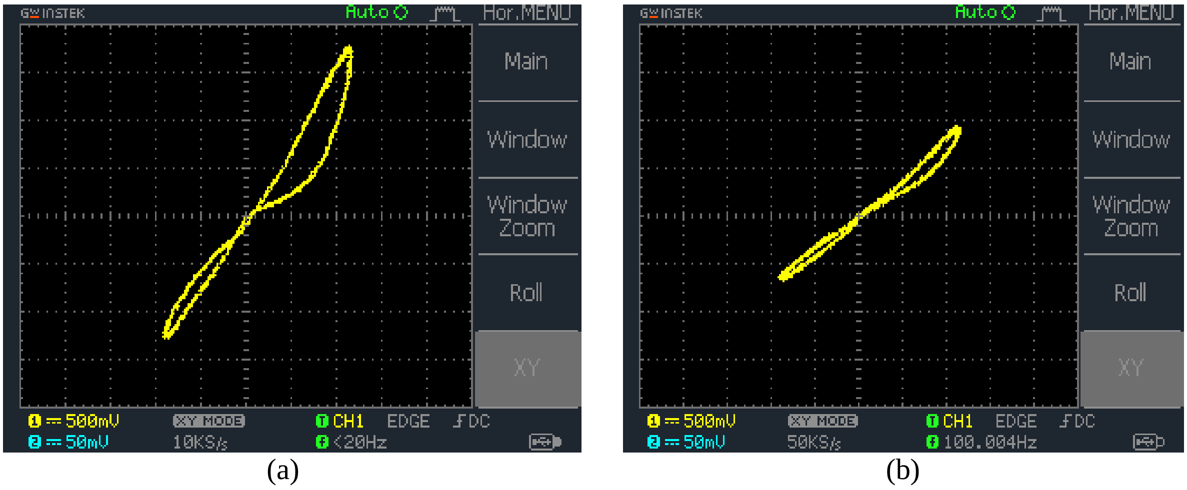


Figure 2. *The Hysteresis curves of an SDC Carbon-based memristor observed at a) 20 Hz and b) 100 Hz under a sinusoidal voltage*

C. A Simple Test for the SDC Carbon-based Knowm Memristors

Tests are commonly used for semiconductor circuit elements. A test that has been given in [19] can be easily adapted to an SDC Carbon-based memristor. Considering the protection resistor, the test given in [19] is modified a bit for the SDC Carbon-based memristors. The following test which can be done to learn whether it is good (working) or bad (failed) is summarized below:

- A protection resistor whose resistance is between 50 kOhms and 100 kOhms should be put in series with an SDC Carbon-based memristor as suggested in its datasheet. Such a series resistor is not needed in [19]. In this study, the protection resistors whose values range from 50 kOhms to 350 kOhms are used in the experiments. Then, a measurement device, which can be a multimeter or an AVOmeter, or an Ohmmeter, is used to read its resistance in experiments. Such a measurement device provides the voltage needed for the resistive switching of an SDC Carbon-based memristor to occur.

- If an SDC Carbon-based memristor is not broken, i.e., it keeps showing the zero-crossing hysteresis curve shown in Figure 2. When it is read with an ohmmeter or multimeter as shown in Figure 3, and the memristor is forward-biased, i.e., with positive DC voltage applied by the measurement device for a sufficient time for its resistive switching to occur in this direction [28]. Then, this forward-biased resistance value is measured with the device used. Several series resistors are used to examine how the resistance of the memristor varies with the resistance of the series-connected resistor used.

- Then, if the memristor is not broken, when it is read with the device used, as shown in Figure 3, and the memristor is reverse-biased, i.e., with negative DC voltage applied by the measurement device for a sufficient time for its resistive switching to occur in this direction. Then, that reverse-biased resistance value is also measured for the several series protection resistors.

- If the reverse-biased resistance is quite different from the forward-biased resistance, the memristor model is similar to the HP memristor model and, in this case, the memristor can be regarded as operational or not broken. More on this can be found in [19].

- If the reverse-biased resistance is almost the same but not equal to the forward-biased resistance, such a memristor has a bipolar characteristic, and, in this case, the memristor can be regarded as operational or not broken.

- If the same resistance value is read in both polarities, using a different resistor, the forward- and reverse-biased resistances of the memristor are read again with a different series resistor. If they are not the same, the memristor is not broken.

- For an SDC Carbon-based memristor with threshold voltages to switch in the forward and reverse directions, it must be supplied with a voltage whose absolute magnitude is higher than its threshold voltage. Under DC or low frequency (0-10 Hz), their forward polarity threshold voltages range from 0.15 V to 0.35 V and their reverse polarity threshold voltages range from -0.27 V to -0.05 V. The measurement device should be able to provide the polarity-dependent threshold voltages required but not a voltage high enough to destroy the memristor in the resistance measurement range. That's why protection resistors are needed.

The suggested test is performed and its experimental results are given in the following section.

III. RESULT and DISCUSSION

In this section, the experimental results are given and interpreted. The experiments are done with the Knowm SDC Carbon-based memristors, eight different resistors, and just using a multimeter for resistance measurement. The circuit given in Figure 3 is used for the experiments. The resistors whose values are given in Tables 1-3 are used in the experiments. At the time of the experiment, only two of the memristors (Memristor 1 and Memristor 3, the first one and the third one from the upside of the integrated circuit shown in Figure 1.c) in the memristor integrated circuit are operational, i.e., only two of them have shown proper hysteresis loops similar to the one in Figure 2 before and after the resistance measurement and used in the experiments. The ones that do not show zero-crossing hysteresis loops are not operational, i.e., broken and that's why the test is not performed on them. The SDC Carbon-based memristor resistances are measured for both of the memristor polarities using the multimeter which is first dialed to its suitable resistance range. The resistances of the memristors measured are given in Tables 1 and 2. During reading, the resistance values of Memristor 1 and Memristor 3 varied and became fixed after almost a minute in the forward and reverse directions.

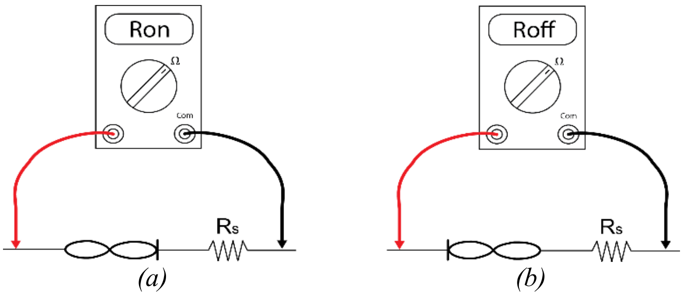


Figure 3. *Memristor test with a multimeter: a) Forward resistance reading or Forward test and b) Reverse resistance reading or Reverse test*

As can be seen from Table 1, Memristor 1 has almost the same resistance value for both of the polarities. The measured resistances of Memristor 1 are dependent on the resistance of the series protection resistor. However, there is a difference between them and its reverse resistance is higher than its forward resistance. It was observed that the difference between them increases as the resistance value of the series resistor used increases. During reading, the resistance values of Memristor 3 have kept increasing in both directions. The forward resistance value is read after a minute and recorded in Table 2. In the forward direction. the resistance value of the Memristor 3 is higher than 2 MOhms, which is out of the range for the multimeter since the device used can only read resistance up to 2 MOhms. However, the reverse resistance kept increasing to a level the device cannot measure. That's why the reverse resistance of the Memristor 3 is recorded as greater than 2 MOhms. The reverse resistance values are read after almost a minute and put in Table 2. The measured forward resistance of the memristors is also dependent on the resistance of the series protection resistor. Its forward resistance is higher than its reverse resistance. That is the opposite of Memristor 1. Comparing Tables 1 and 2, it can be seen that the same test gives different results for the memristors even though both of the memristors still have zero-crossing hysteresis loops after the tests.

For Memristor 3, the data given in Table 3 was acquired in the previous experiments done one year ago. The data in Table 3 was starting point of this study since the memristor can be thought of as having bipolar characteristics due to the resistance value being almost the same but different in both directions As can be seen from Table 3, the forward resistance is just a little below the reverse resistance except for just the data point obtained for the series resistance of 234 kOhm which can be due to an experimental error. Such is the case for the memristors or memristive systems with bipolar characteristics given in [21-28, 33-34]. According to the results of the experiments done one year ago and recently, it is found that the resistance values read are not stable and keep varying even though they continue being able to show zero-crossing hysteresis loops after the experiment is performed. More importantly, for the same memristor, Memristor 3, the data read at one year ago and the current data are different even though the same experiment is performed. The resistance values in Table 2 are in the order of MOhms while those in Table 3 are in the order of kOhms. Memristor 3 still shows the three fingerprints of a memristor and this means it is operational not broken. This shows that the test method suggested in this study is unfortunately not reliable. That's why such a test method is not suitable for the Knowm SDC Carbon-based memristors.

Table 1. *The forward and reverse resistance values of Memristor 1 measured recently*

Serial Resistance (Ohm)	$R_{forward}$ (Ohm)	$R_{reverse}$ (Ohm)
49.7k	1.203M	1.365M
77.1k	1.243M	1.384M
99.9k	1.248M	1.408M
127.3k	1.259M	1.487M
198k	1.291M	1.512M
225k	1.338M	1.559M
297k	1.394M	1.634M

Table 2. *The forward and reverse resistance values of Memristor 3 measured recently*

Serial Resistance (Ohm)	$R_{forward}$ (Ohm)	$R_{reverse}$ (Ohm)
49.7k	>2M	1.021M
77.1k	>2M	1.334M
99.9k	>2M	1.435M
127.3k	>2M	1.479M
198k	>2M	1.608M
225k	>2M	1.617M
297k	>2M	1.637M

Table 3. *The forward and reverse resistance values of Memristor 3 measured one year ago*

Serial Resistance (Ohm)	$R_{forward}$ (Ohm)	$R_{reverse}$ (Ohm)

49.9k	119.6k	120.6k
59.9k	125.3k	126.7k
99.9k	170.7k	172.3k
118.3k	183.4k	185.6k
168.7k	234k	236k
199.6k	267k	268k
234k	236k	235k
353k	354k	354k

IV. CONCLUSION

In the future, it is expected that memristor will emerge as an off-the-shelf circuit element in the market for not only analog but also digital circuit applications. When this happens, the circuit designers will need new test methods to verify whether a memristor works properly or not. The Knowm memristors can already be bought in the market [12]. In this study, the usability of a simple robustness test for an SDC carbon-based memristor with a multimeter is examined. This test is different from the test given for the memristors with a high R_{OFF}/R_{ON} ratio in [19] since it requires at least a series-connected resistor. Only two memristors that show a proper zero-crossing hysteresis loop have been used in the experiments. Unfortunately, due to not having additional operational Knowm memristor integrated circuits and/or functional memristors with proper hysteresis loops, more experiments for different memristors could not have been performed. The suggested test has been simple enough and could have been easily made by connecting the memristor in series with a few different resistors and using just an Ohmmeter or AVOmeter, or multimeter. The experimental data are different for each memristor. Even the resistance data measured at different times are not the same for the same memristor. It should have been the same considering the resistive switching phenomenon. Therefore, the test is not validated when the recent experimental results are compared with the previous ones and found to be unusable for the SDC carbon-based memristors. More sophisticated tests should be employed for such memristors. Perhaps, they may be based on dynamic reading with a microcontroller.

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