Appl Phys A
DOI 10.1007/s00339-013-7615-5

Applied Physics A
Materials Science & Processing

An electronic implementation of amoeba anticipation

Martin Ziegler · Karlheinz Ochs · Mirko Hansen · Hermann Kohlstedt

Received: 25 October 2012 / Accepted: 4 February 2013

Abstract In nature, the capability of memorizing environmental changes and recalling past events can be observed in unicellular organisms like amoebas. Pershin and Di Ventra have shown that such learning behavior can be mimicked in a simple memristive circuit model consisting of an LC (inductance capacitance) contour and a memristive device. Here, we implement this model experimentally by using an Ag/TiO_{2-x}/Al memristive device. A theoretical analysis of the circuit is used to gain insight into the functionality of this model and to give advice for the circuit implementation. In this respect, the transfer function, resonant frequency, and damping behavior for a varying resistance of the memristive device are discussed in detail.

1 Introduction

Memristive devices are two-terminal circuit elements which are able to remember the history of applied electric potentials and feature a device characteristic that cannot be emulated by one of the other basic two-terminal circuit elements (resistance, inductance, and capacitance). In this respect, recent investigations have recognized the analogue to the memristor [1], which has been theoretically predicted by Leon O. Chua in 1971 [2].

Although memristive phenomena have been studied intensively for decades [3, 4], a renewed interest in resistive switching led to a world-wide renaissance of this research topic [5]. In particular, memristive switching devices are considered as promising candidates for future non-volatile memory applications and neuromorphic analogue circuits [6–9].

An emerging task in neuromorphic engineering is to mimic neural pathways via elegant technological approaches to close the gap between biological and digital computing [9]. While the von Neumann architecture induces a strict separation of serial digital processing and storage in digital computing [10], data processing and storage are inseparably linked in the human brain. In nature, memory and learning alter the function and structure of neurons and their interconnection strength [11].

To mimic basic features of biological computing in electronic circuits and to improve the circuit design flexibility combined with a reduced circuit complexity, recent experimental studies of synaptic properties of memristive devices have gained considerable attention [8]. However, so far most of the investigations focused on synaptic potentiation in single memristive cells [12, 13], while bio-inspired circuits comprising memristive devices are less studied [14–16]. In particular, the non-linearity in the resistance change of the memristive devices, as well as their reliability, retention, fatigue, and parameter spreads are only some examples, which actually complicate the implementation of memristive devices as a part of complex circuits.

As a first step to mimic learning behavior with electronic memristive circuits, an anticipation event observed in unicellular organisms has been described in the framework of a memristive model [14]. For unicellular organisms like amoebas it was shown that even such simple organisms can learn from stimulation patterns, reflecting the environment adjacent to the unicellular organism [17]. In the model of Ref. [17], this behavior is described in terms of an internal

M. Ziegler (✉) · M. Hansen · H. Kohlstedt
Nanoelektronik, Technische Fakultät,
Christian-Albrechts-Universität zu Kiel, 24143 Kiel, Germany
e-mail: maz@tf.uni-kiel.de

K. Ochs
Lehrstuhl für Digitale Kommunikationssysteme, Ruhr-Universität Bochum, 44780 Bochum, Germany

Published online: 16 February 2013

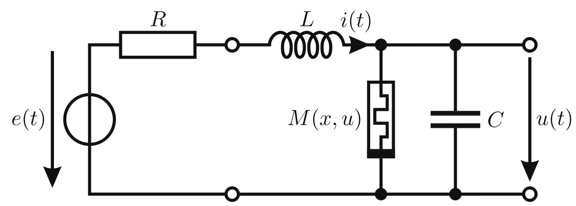

Fig. 1 Schematic of the LC circuit used to mimic amoeba anticipating events according to Ref. [14]. The circuit consists of an ohmic resistor R, an inductor L, a capacitor C, and a memristive device M. The input signal $e(t)$ is supplied by a voltage source and the voltage $u(t)$ across the memristive device is used as the output signal

biological oscillator with a natural frequency. Varying environmental conditions may be different from this frequency so that amoebas can recognize patterns and predict events. Pershin et al. [14] mimicked amoeba anticipation with an electric LC circuit model including a memristive device. Moreover, these authors were able to expand the model of Ref. [17] by a memory effect due to the memory behavior of memristive cells.

In this article, we implement the electric circuit model of Ref. [14] consisting of an LC contour and a memristive device. From a theoretical analysis of the electronic circuit, important information about the transfer characteristic, resonant frequency, and damping behavior depending on the resistance state of the memristive device is obtained. Our analysis gives design conditions for the experimental implementation of this circuit. Besides the anticipation abilities of this circuit, its application as an adaptive memristive filter has been discussed recently [15]. In this respect, the implementation of this circuit with state-of-the-art memristive devices is of general interest in bio-inspired data processing and information storage.

2 Theory

The starting point of our theoretical analysis is the electronic circuit shown in Fig. 1. Therein, an LC contour with a memristive device is shown, which is essentially an oscillator with memory $M(x, u)$. In particular, the memory behavior is introduced by a state variable x according to the definition of memristive devices in Ref. [18]. Further, the input signal (labeled as $e(t)$ in Fig. 1) is assumed to be supplied by an ideal voltage source, while the voltage $u(t)$ across the capacitor (and memristive device) is used as the output signal of the circuit. In the following analysis and experimental investigation, the memory capacitance of the memristive device is neglected. Further, the resistance R, inductance L, and capacitance C are positive constants, where the memristive device introduces the memory behavior of the circuit.

In order to analyze the LC contour in more detail and to give specific advice for an electronic implementation, the state-space equations are deduced in a matrix representation. Therefore, the current through the inductor and the voltage across the capacitor are chosen as state variables of the circuit.

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} i(t) \\ u(t) \end{pmatrix} = \mathbf{A}(M)\begin{pmatrix} i(t) \\ u(t) \end{pmatrix} + \begin{pmatrix} 1/L \\ 0 \end{pmatrix} e(t), \tag{1}$$

with

$$\mathbf{A}(M) = \begin{pmatrix} -R/L & -1/L \\ 1/C & -1/MC \end{pmatrix}. \tag{2}$$

The before-claimed memory of this circuit can be directly fetched from this differential equation by regarding its system matrix $\mathbf{A}(M)$. In particular, $\mathbf{A}$ depends on M and thus on the state variable x, as well as on the voltage drop across the capacitor (and memristive device) $u(t)$. This inhibits the solving of the differential equation system analytically and hinders an obvious prediction of the system behavior during voltage application.

Nevertheless, under particular boundary conditions, one can get a general insight of the circuit functionality. In the case of a constant memristance M, the relationship between the input signal $e(t) = E\mathrm{e}^{pt}$ and the output signal $u(t) = U\mathrm{e}^{pt}$ reads

$$U = H(p, M)E, \tag{3}$$

with

$$H(p, M) = \frac{1}{1 + [R + pL][pC + 1/M]}. \tag{4}$$

Here, p is the complex frequency and $H(p, M)$ is the transfer function, which depends on the memristance M. In Fig. 2, the absolute value of $H(p, M)$ is plotted for four different resistance states of the memristive device, which correspond to the ON resistance of $M = 2\ \mathrm{k}\Omega$, a resistance of $M = 10\ \mathrm{k}\Omega$, the later-on-used resistance to mimic amoeba anticipation of $M = 100\ \mathrm{k}\Omega$, and the OFF resistance of $M = 2\ \mathrm{G}\Omega$ (further device properties will be discussed below). From this plot the filter characteristic discussed in Ref. [15] of this circuit is clearly visible. In detail, a prominent sharp peak at the resonant frequency ω_0 of the ideal LC circuit is observed, which is damped and additionally broadened if the resistance of the memristive device decreases.

To quantify the discussed behavior of $H(p, M)$ in more detail and to give advice for an experimental implementation of the electronic circuit, we take from the denominator of the transfer function the characteristic polynomial

$$p^2 + 2\sigma p + \omega_1^2 = \frac{\omega_0^2}{H(p, M)} = 0, \tag{5}$$

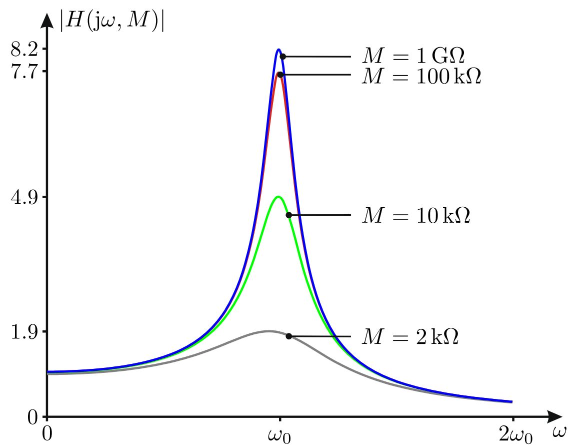

Fig. 2 Transfer function $H(j\omega, M)$ of the circuit for four different resistance states of the memristive device. Here, $M = 2$ kΩ and 1 GΩ are the limit ON and OFF resistance states of the memristive cell, respectively

with

$$2\sigma = \omega_0\left[\frac{Z}{M} + \frac{R}{Z}\right], \qquad \omega_1^2 = \omega_0^2\left[1 + \frac{R}{M}\right]. \tag{6}$$

Here, σ and ω_1 are positive parameters, which are formulated in dependence on the resonant frequency and impedance

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad \text{and} \quad Z = \sqrt{\frac{L}{C}}, \tag{7}$$

respectively. In particular, ω_1 is the frequency of the input signal, while σ describes the decay of the circuit-induced oscillation over time. Regarding σ, a damping of the circuit-induced oscillation occurs weakly for high resistances of the memristive device, but it is strongly enhanced if M decreases. Thus, the oscillatory behavior of the LC circuit is very sensitive to the resistance of the memristive device.

Besides the decay behavior of the circuit-induced oscillation, the change in the resonant frequency is of interest. Therefore, the solution of the characteristic polynomial can be determined under the assumption $\sigma < \omega_1$

$$p_1 = p_2^* = -\sigma + j\omega_r, \tag{8}$$

with

$$\omega_r^2 = \omega_1^2 - \sigma^2 = \omega_0^2 - \frac{\omega_0^2}{4}\left[\frac{1}{m} - r\right]^2. \tag{9}$$

Here, m and r are the normalized memristance $m = M/Z$ and resistance $r = R/Z$. The main result of this equation is that the resonant frequency ω_r is very close to the resonant frequency ω_0 of the ideal LC circuit if the memristive device resistance is in a high-ohmic state. In fact, even for a device resistance of 10 kΩ the resonant frequency shifts only by a factor of 0.2 % (see Fig. 2). Hence, for the following experimental condition we may assume that the resonant frequency of the electronic circuit is virtually unaffected by the memristive device if the ON resistance is above 10 kΩ. For this, it is important to bear in mind that σ and ω_r are functions of the memristance, where the above given transfer function is only valid with a fixed memristance.

3 Experimental

The memristive devices were fabricated as planar capacitor structures with a layered Ag/TiO_{2-x}/Al sequence (a sketch of the material stack is shown in the inset of Fig. 3a). The 50 nm Ag bottom electrode was deposited by thermal evaporation on a thermally grown SiO_2 layer (400 nm) on the Si substrate. Standard optical lithography was used to define 50 μm × 50 μm windows. Afterwards, a 20 nm thick TiO_{2-x} layer was deposited by reactive sputtering, followed by the deposition of a 16 nm Al top electrode and a subsequent lift-off in acetone.

Current–voltage measurements (I–V curves) were obtained using an Agilent E5260 source measurement unit by sweeping the applied voltage and measuring the device current simultaneously. An HP 33120A function generator and a Tektronix TDS 7104 oscilloscope were employed to measure the transient amoeba anticipation circuit. Rectangular voltage pulses were applied to the circuit and the oscilloscope was used to record the voltage response across the circuit elements.

4 Results and discussion

The electronic circuit of Fig. 1 was realized using different resistance states of Ag-doped TiO_{2-x}-based memory devices as a function of the applied voltage across the device. For further details about the operation mechanism of the device, the reader is referred to Ref. [19] (see also references therein). Typical current–voltage characteristics (I–V curves) of the device for three different current compliances are depicted in Fig. 3a. Starting from the initial OFF resistance state of the device, different resistances were achieved by sweeping the voltage and using appropriate settings for the current compliance. While the OFF resistance is in the range of several GΩ, the ON resistance can be precisely adjusted by choosing appropriate values for the current compliance, as shown in Fig. 3b. For this, a 50 μA current compliance, resistive switching from the OFF resistance to the ON resistance state is observed for positive bias at a set voltage of $V_{th}^{p} = 0.35$ V and vice versa for negative bias (reset

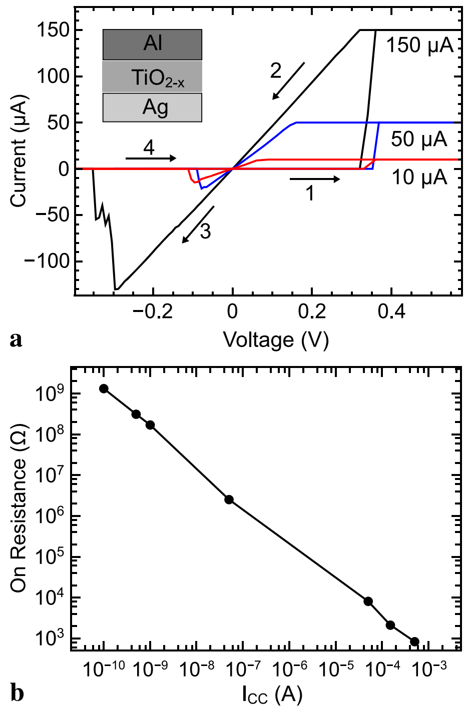

Fig. 3 (**a**) I–V curves of an Ag-doped TiO_{2-x}-based memristive device with three different settings of the current compliance I_{CC}. (**b**) The ON resistance as function of the compliance currents used. *Inset*: schematic of the Ag-doped TiO_{2-x}-based memristive device

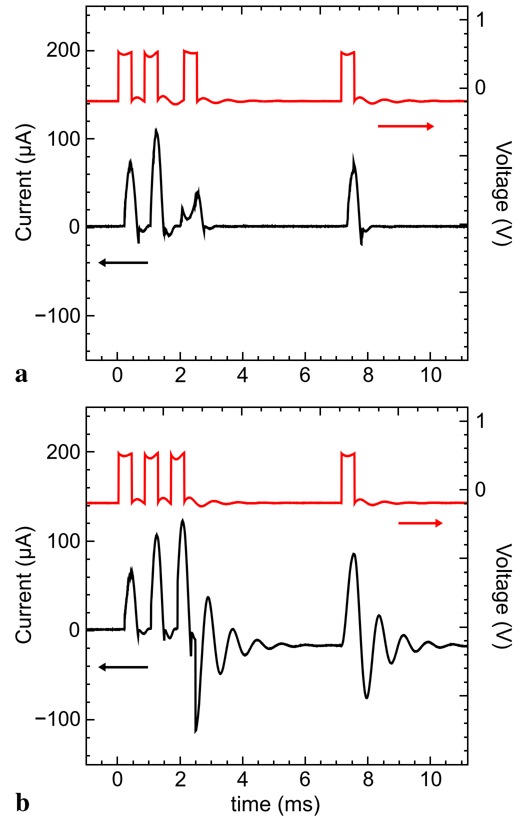

Fig. 4 Experimental demonstration of amoeba anticipation within the memristive circuit of Fig. 1. (**a**) Arbitrary pulse sequence, (**b**) learning pulse sequence. If a periodic sequence of three pulses is applied, the circuit learns and will react more efficiently to later voltage pulses (see (**b**)). For an arbitrary pulse sequence the circuit has not learned and its response to a later voltage pulse is less efficient (see (**a**)). Parameters used for the circuit: $R = 100\ \Omega$, $C = 150$ nF, and $L = 100$ mH

voltage) of $V_{th}^{n} = -0.1$ V. In the LC circuit, the current compliance is implemented by connecting a current-limiting resistor in series with the memristive device and in parallel with the capacitor. This ohmic resistor will not affect the circuit dynamics, but ensures a defined ON resistance of the memristive cell. In the following measurements a 100 kΩ resistor was used.

For the device parameters of the resistor, capacitor, and inductor important conditions can be derived from Eq. (9). In particular, we can conclude that

$$\frac{1}{m} - r = 0 \tag{10}$$

has to be fulfilled so that the electronic circuit is at ω_0 in resonance. This equation suggests that for a high-ohmic resistance of the memristive device ($m \gg 1$), as well as for $R \ll Z$ ($r \ll 1$), the circuit behaves like an ideal LC contour and will be damped if the resistance of the memristive device is decreased. If we consider that the circuit is at the OFF resistance of the memristive device in resonance, then R, L, and C can be freely chosen (apart from L being larger than C to fulfill Eq. (10)). To fulfill this condition, we are using the transition from the OFF to the ON resistance state to mimic the anticipation behavior observed in amoebas in contrast to Ref. [14], where the transition from the ON to the OFF resistance state is used. As we will show below, this choice will not restrict the learning behavior of this circuit, but will simplify the circuit parametrization. In particular, we use a resistance of $R = 100\ \Omega$, a capacitance of $C = 150$ nF, and an inductance of $L = 100$ mH to implicate an ω_0 of 8.16 rad/s.

To mimic the anticipation events observed for amoebas, we applied two different voltage trains to the circuit. The first voltage train consist of two voltage pulses in series at the resonance frequency followed by a separated third voltage pulse as depicted in Fig. 4a (red graph). The second stimulus consists of three voltage pulses in series, which matches the resonant frequency (cf. red graph in Fig. 4b). The line shape of the voltage pulses shows a non-perfect rectangular form associated with the non-ideal voltage source behavior of the function generator. However, this influence will not restrict the following findings. Regarding both stimulus trains, in the current response of the circuit it can be recognized that the amplitude of the current oscillation at the memristive device is increased in the case of a periodic stimulation. In fact, at each voltage pulse the current amplitude through the memristive device increases, where at some point the memristive device undergoes the transition from the OFF to the ON resistance state. As a consequence, the voltage oscillation across the capacitor is damped and the memristive device has learned about the input voltage pattern.

The learning ability of the circuit can be shown by using a fourth pulse following the learning pulse sequences, as shown in Fig. 4. The resulting oscillation obtained for the fourth voltage pulse is much more pronounced in the case of a periodic pattern compared to an arbitrary pulse sequence (see red curves in Fig. 4). In biological terms, we may say that the circuitry has learned about a stimulation map and can react afterwards more efficiently. Finally, we would like to remark that it was important for the anticipation process to guarantee that the decrease in the resistance of the memristive device is restricted in such a way that the resonant frequency of the circuit is unaffected and the circuit still reacts to the fourth voltage pulse (cf. Fig. 2).

In Ref. [14], this behavior has been compared to experimental data, where the amoeba was exposed to three intervals of unfavorable conditions (low temperature and humidity) [17]. In the experimental investigation, it has been found that at each time the locomotive speed of amoebas was decreased. After the learning intervals, a single interval of unfavorable conditions was sufficient to spontaneously slow down the amoeba movement even though the amoeba was exposed to favorable conditions in the meantime. This behavior may be interpreted as a form of primitive intelligence, as discussed in Ref. [14]. Therefore, positive applied voltages correspond to unfavorable conditions, while negative applied voltages are used to mimic favorable conditions for amoebas within the LC circuit. In this respect, we would like to remark again that in our experimental investigation the transition from the OFF resistance state to the ON resistance state of the memristive device is used in contrast to Ref. [14], where the transition from the ON to the OFF resistance state has been studied. Thus, in our investigation the voltage across the memristive device is damped, but the oscillatory response in the current signal through the memristive device is enhanced.

In nature, a learned pulse sequence might be extinguished if the amoeba was exposed to favorable conditions for a longer time. To mimic such behavior, the base level of the input signal train can be used. In particular, the amplitude of the (negative) base level can be used to define the extinction rate of the process. In Fig. 5, we show the extinction process of our electronic circuit using a base level of −0.19 V. In the result, this base level effects that the memristive device returns to its OFF-resistance state after 20 ms. In other words, if no unfavorable condition pulse is applied within 20 ms after the last pulse the amoeba extinguishes its before-learned behavior.

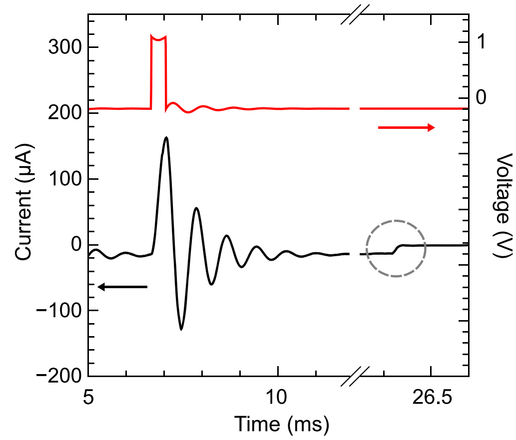

Fig. 5 Mimic of the extinction process with the circuit of Fig. 1. The base level of the input signal is shifted to −0.19 V, which enables the circuit to extinguish before the trained anticipation within 20 ms after the last voltage pulse was applied

5 Conclusions

In conclusion, the memristive model of amoeba anticipation events of Ref. [14] has been implemented experimentally using an Ag/TiO_{2-x}/Al memristive device. A theoretical analysis of the circuit was used to gain insight into the functionality of the circuit model. From this, important advice for the circuit implementation has been derived. In particular, the transfer function of the circuit shows a pronounced peak at around the resonant frequency, which is drastically decreased with a decreasing resistance of the memristive device. While the shift in resonant frequency can be neglected in the high-resistance OFF state of the memristive device, at the low-ohmic ON resistance state of the memristive device the circuit is strongly damped, broadened, and the resonant frequency is shifted. By using this damping behavior, the anticipation behavior observed in amoebas has been presented.

References

1. D.B. Strukov, G.S. Snider, D.R. Stewart, R.S. Williams, Nature **453**, 80 (2008)
2. L.O. Chua, IEEE Trans. Circuit Theory **18**, 507 (1971)
3. T.W. Hickmott, J. Appl. Phys. **33**, 2669 (1962)
4. G. Dearnaley, A.M. Stoneham, D.V. Morgan, Rep. Prog. Phys. **33**, 1129 (1970)
5. A. Beck, J.G. Bednorz, Ch. Gerber, C. Rossel, D. Widmer, Appl. Phys. Lett. **77**, 139 (2000)
6. K. Szot, W. Speier, G. Bihlmayer, R. Waser, Nat. Mater. **5**, 312 (2006)
7. R. Waser, M. Aono, Nat. Mater. **6**, 833 (2007)
8. S.D. Ha, S. Ramanathan, J. Appl. Phys. **110**, 071101 (2011)
9. C. Zamarreño-Ramos, L.A. Camuñas-Mesa, J.A. Perez-Carrasco, T. Masquelier, T. Serrano-Gotarredona, B. Linares-Borranco, Front. Neurosci. **5**, 26 (2011)
10. J. von Neumann, The general and logic theory of automata, in *Cerebral Mechanism in Behavior, the Hixon Symposium*, ed. by L.A. Jeffress (Wiley, New York, 1951)

11. E.R. Kandel, *Cellular Basis of Behavior—An Introduction to Behaviour Neurobiology* (Freeman, New York, 1976)
12. S.H. Jo, T. Chang, I. Ebong, B.B. Bhadviya, P. Mazumder, W. Lu, Nano Lett. **10**, 1297 (2010)
13. T. Ohno, T. Hasegawa, T. Tsuruoka, K. Terabe, J.K. Gimzewski, M. Aono, Nat. Mater. **10**, 591 (2011)
14. Y.V. Pershin, S. La Fontaine, M. Di Ventra, Phys. Rev. E **80**, 021926 (2009)
15. T. Driscoll, J. Quinn, S. Klein, H.T. Kim, B.J. Kim, Yu.V. Pershin, M. Di Ventra, D.N. Basov, Appl. Phys. Lett. **97**, 093502 (2010)
16. M. Ziegler, R. Soni, T. Patelczyk, M. Ignatov, T. Bartsch, P. Meuffels, H. Kohlstedt, Adv. Funct. Mater. **22**, 2744 (2012)
17. T. Saigusa, A. Tero, T. Nakagaki, Y. Kuramoto, Phys. Rev. Lett. **100**, 018101 (2008)
18. L.O. Chua, S.M. Kang, Proc. IEEE **64**, 209 (1976)
19. W. Lu, D. Jeong, M. Kozicki, R. Waser, Mater. Res. Soc. Bull. **37**, 124 (2012)