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# SPIN-BASED MEMORY: MEMRISTIVE DEVICES AND ITS APPLICATIONS

***Raj Kumar Singh, PhD***
Department of Electronics and Telecommunications, Politecnico di Torino, Italy. Department of Physics, R. L. S. Y. College, Ranchi University, Ranchi, India
***Kumari Mamta, PhD***
Department of Electromagnetic Engineering, Politecnico di Torino, Italy. Department of Physics, Jharkhand Rai University, Ranchi, India

## Abstract

We present, a none exhaustive one, the current state of the progress in memristive devices and their applications in electronic, spintronic and biological neural network domain starting from the proposition by Leon O. Chua, the father of the concept of memristive devices, to the current state of the work in this field. Starting from the general definition, we have surveyed upon various devices exhibiting memristive behavior viz. thermistors (whose internal state depends on the temperature), spintronic device (whose resistance varies according to their spin polarization) and a biological model, including the Hewlett-Packard (HP) memristor (where the change in resistance is realized by the ionic motion of oxygen vacancies activated by current flow), the first realized memristive device in the laboratory. Memristor and memristor based circuits finding application in analog memory and computing, analog devices, temperature sensor, superconducting emulator and mazes problem solver have been reported.

**Keywords**: Spin memory, memristor, memristive device, pinched hysteresis

## Introduction

Memory means recalling past experiences in human being and in the field of information technology, it is the ability to store and retrieve digital information for use in computation. Interestingly, memory state of a system is related to some of the dynamical properties of electrons and ions, indeed, related to their rearranging behavior under the effect of external perturbations. Further, such a change of state of electrons and ions is not instantaneous, and it has something to do with their the past dynamics (Di Ventra, M , 2008). This means that the resistive, capacitive and/or inductive properties of (nanoscale) systems depend on the past states through which the system has evolved.

Recent discovery of the memristor has paved way to new directions in optimization and revolutionizing analog circuit design, marking a new era for the advancement of analogue applications. In 1971, Leon Chua (Chua, L.O, 1971) postulated the existence of the fourth '*missing*' two-terminal passive fundamental circuit element, called the memristor, short for memory-resistor. This device, as observed by Leon Chua, provides a functional relationship between the time integrals of voltage and current. The uniqueness of memristor is its ability to remember its history by way of time evolution of some internal state variable $x$ of the device. As the present day CMOS technology is approaching the nano-scale floor over riding the Moore's law, the dimensionality, the power management and the dynamic nonlinear response of memristive devices qualifies them as a hot research entity.

The outline of paper is as follows: The next section, Section 2 introduces the concept and properties of memory circuit elements with special reference to memristor and memristance : the main objective of the present study. In section 3 we pick up the case of various systems exhibiting memristive behavior like thermistor, HP memristor, semiconductor/half metal junction and biological neural network to discuss how memristive behavior comes to them naturally. In section 4 we discuss various possible application of memristors in realizing electronic, spintronic, neural network devices. Concluding remarks can be found in section 5.

## General definition: memory circuit elements

We know from classical circuit theory that there are three fundamental circuit elements (R, C and L) associated with four basic circuit (charge, voltage, current and flux). For linear elements these relations take the following forms:

$$V = RI \tag{1}$$

for a resistor of resistance R, given the current I and the voltage response V .

$$q = CV_C \tag{2}$$

for a capacitor of capacitance C that holds a charge q and sustains a voltage $V_C$ and

$$\phi = LI \tag{3}$$

When the flux $\phi$ is generated by an inductor of inductance L when a current I flows across it.

In the equations (1-3), the constants R, C and L describe the linear response of the resistor, capacitor and inductor and hence are the response function.

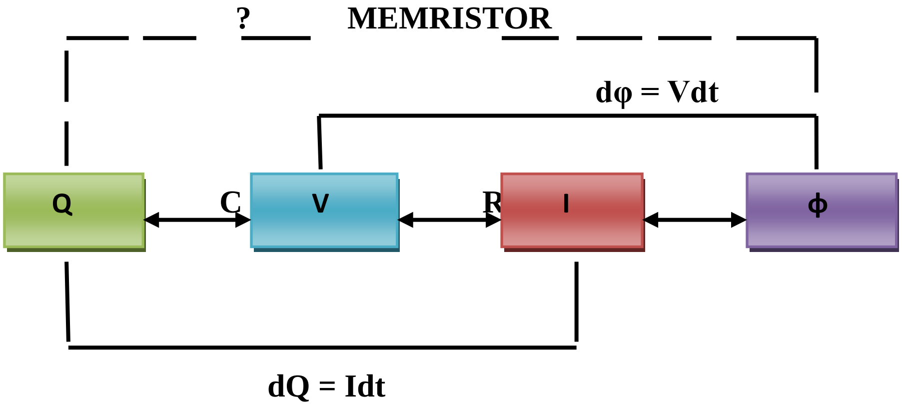


Fig. 1. Four fundamental circuit elements: Resistance (V=RI), capacitance (Q=CV) , inductance(φ=LI) , and memristance (φ=Mq) which is the missing link as suggested by Chua.

Leon Chua was the first to find the missing link between the flux and charge in 1976 (see fig. 1and fig. 3 for typical flux Vs. charge relation).

We can generalize the above definition to time dependent and non-linear responses as well, which may have memory dependence on other state variables also. If $u(t)$ and $y(t)$ are any two complementary constitutive circuit variables (current, charge, voltage, or flux) denoting input and output of the system, respectively, and $x$ is an n-dimensional vector of internal state variables, we may then postulate the existence of the following nth-order $u$-controlled memory element as that defined by the equations (Pershin, Y. V, and M. Di Ventra, 2009).

$$y(t) = g\,(x, u, t)\, u(t) \qquad (4)$$

$$\dot{x} = f\,(x, u, t) \qquad (5)$$

Here, $g$ is a generalized response, and $f$ is a continuous n-dimensional vector function.

A distinctive signature of memory devices is a hysteresis loop which follows when the response function $g(t)$ or the function $y(t)$ (or both) are plotted versus $u(t)$. The shape of a loop is determined by both the device properties and the input $u(t)$ applied. For well-defined generalized response functions $g$, the function $y(t)$ hysteresis loop passes through the origin ($y$ is zero whenever $u$ is zero and vice versa). This is called a “*pinched*" hysteresis loop. A pinched loop may be “self-crossing- type I crossing behavior " or “not self-crossing- type II crossing behavior"(see figure 2).

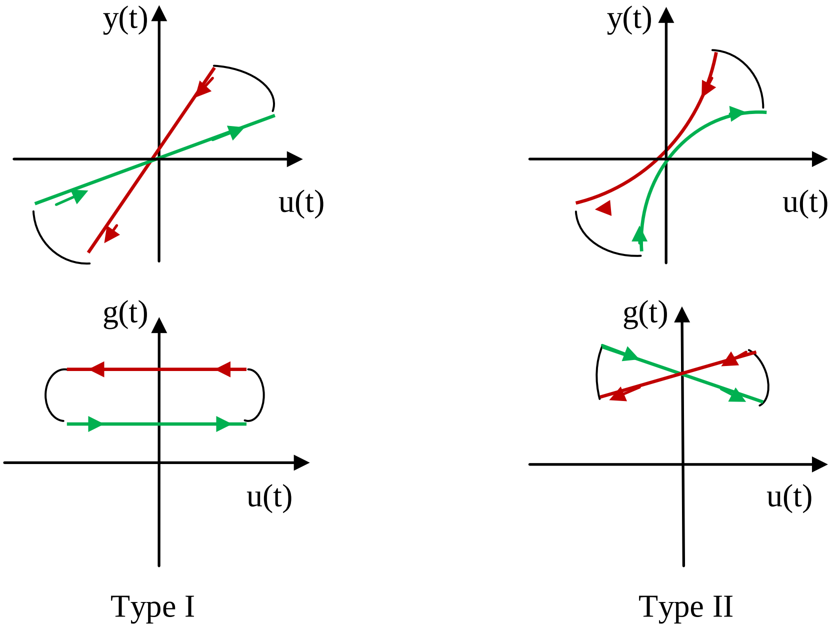


Fig. 2 Schematic pinched hysteresis loop of memory elements when subject to a periodic stimulus can be "self-crossing" (type I) or not (type II). The latter property often (but not always) arises when the state dynamics function *f* and the response function *g* are even functions of the input variable *u*.

## Memristor and memristance

*Memristor*, the contraction of ―memory resistor, is a passive device that provides a functional relation between charge and flux. It is defined as a two-terminal circuit element in which the flux between the two terminals is a function of the amount of electric charge that has passed through the device (Yu. V. Pershin and M. Di Ventra, 2008). A memristor could be charge-controlled or flux-controlled. It is said to be charge-controlled if the relation between flux and charge is expressed as a function of electric charge and is said to be flux-controlled if the relation between flux and charge is expressed as a function of the flux linkage (Chua, L.O, 1971).

For a charge-controlled memristor,

$$\phi = f(q) \tag{6}$$

Differentiating equation (6) yields

$$\frac{d\phi}{dt} = \frac{df(q)}{dq} \times \frac{dq}{dt} \tag{7}$$

Or,

$$v(t) = M(q)\, i(t) \tag{8}$$

where,

$v(t) = d\phi/dt$ is the voltage

and

$$M(q) = df(q)/dq \tag{9}$$

$M(q)$ is called as memristance, and it has the units of resistance. It defines a linear relationship between current and voltage, as long as the charge does not vary. Thus if $M$ is constant, a memristor behaves as a resistor. Memristance is a property of the memristor. When the charge flows in one direction through a circuit, the resistance of the memristor increases, and its resistance decreases when the charge flows in the opposite direction in the circuit. If the applied voltage is turned off, thus stopping the flow of charge, the memristor "remembers" the last resistance that it had. When the flow of charge is started again, the resistance of the circuit will be what it was when it was last active. A useful analogy for a memristor is to think of its behaviour as being like the flow of water through a pipe whose diameter expands or shrinks depending on the direction and amount of water that has flowed through it. When the water flow is turned off, the pipe retains its current diameter, thus 'remembering' the amount of water that has passed.

For a flux-controlled memristor,

$$q = f(\phi) \tag{10}$$

Differentiating equation (10) yields

$$\frac{dq}{dt} = \frac{df(\phi)}{d\phi} \times \frac{d\phi}{dt} \tag{11}$$

or

$$i(t) = W(\phi)v(t) \tag{12}$$

where

$i(t) = dq/dt$ is the current

$W(\phi) = df(\phi)/d\phi$, called as memductance ( the reciprocal of memristance) and it has the unit of conductance.

For non-linear response system with memory dependence on some state variable $x(t)$ where the time evolution of $x$ is known to be

$$dx/dt = f(x, I, t) \tag{13}$$

where $f$ is a continuous n-dimensional vector function, the relation between voltage and current can then be written as

$$V(t) = R_M(x, I, t)I(t) \tag{14}$$

and needs to be solved together with equation (13) for the state variables dynamics. These systems (with $f$ and or $R_M$ depending on $I$ have been called current-controlled memristive systems (Chua, L. O. and S. M. Kang, 1976). The voltage-controlled ones are those that satisfy the relations

$$I(t) = G(x, V, t)\, V(t) \tag{15}$$

$$\dot{X} = f(x, V, t) \tag{16}$$

where $G$ is called the memductance (for memory conductance).

## Properties of memristors and memristive systems

Memristive devices are passive for all R>0.

A memristive system can't store energy, like a capacitor or an inductor. This is quite obvious from the fact that V= 0 whenever I = 0 , and vice versa.

The most important one is the appearance of a "pinched hysteretic loop" (see fig. 4) in the current-voltage characteristics of these systems when subject to a periodic input (Chua, L. O. and S. M. Kang, 1976). During each period of the input voltage the I - V curve is a simple loop passing through the origin, namely there may be at most two values of the current I for a given voltage V , if we consider a voltage controlled device, or two values of the voltage V for a given current I, for a current-controlled system.

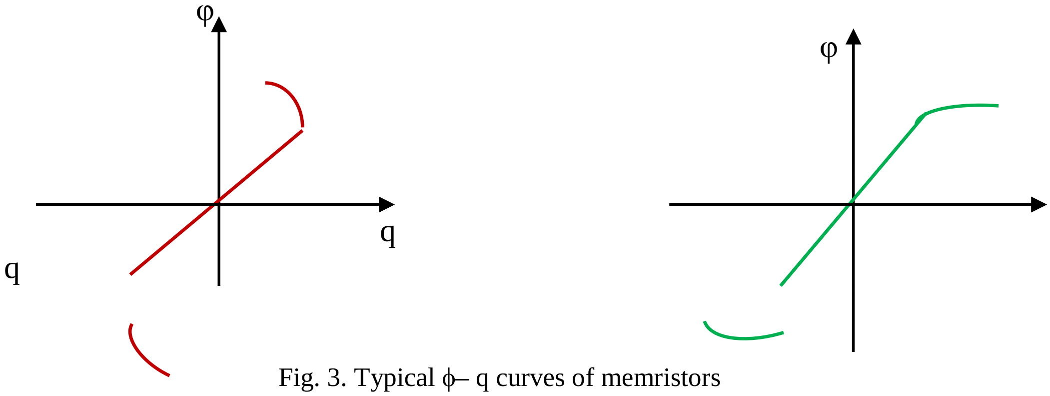


Fig. 3. Typical ϕ– q curves of memristors

A memristive system behaves as a linear resistor in the limit of infinite frequency and as a non-linear resistor in the limit of zero frequency. At very low frequencies, the system has enough time to adjust its value of resistance to a momentary value of the control parameter (either current or voltage), so that the device behaves as a non-linear resistor. On the other hand, at very high frequency, there is not enough time for any kind of resistance change during a period of oscillations of the control parameter, so that the device operates as a usual (linear) resistor.

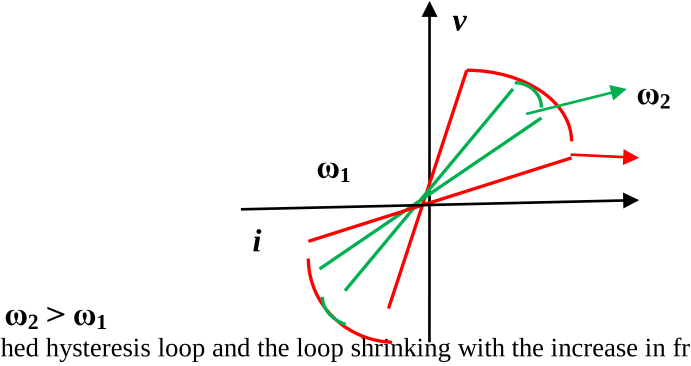


Fig. 4. The pinched hysteresis loop and the loop shrinking with the increase in frequency.

Memristive behavior has been observed in thermistors (M. Sapoff and R. M. Oppenheim, 1963), molecular systems (Y. Chen et al, 2003), spin electronic devices (Yu. V. Pershin and M. Di Ventra, 2008) and nanostructures due to thin films (D. B. Strukov et al , 2008, J. J. Yang et al, 2008, T. Driscoll et al, 2009), as well as various examples mentioned in (L. O. Chua, 1976).

## Memristive systems

### Thermistor

One of the first identified memristive systems is the thermistor: a temperature sensitive resistor. Thermistors are built of semiconducting materials that are especially sensitive to temperature, such as different oxides of metals including manganese, iron, nickel, cobalt, copper, and zinc. Memristive properties of thermistors are based on self-heating and were noticed by Chua (L. O. Chua, 1976).

Consider a thermistor with negative temperature coefficient that is described by the current-voltage relation (Sapoff, M. and R. M. Oppenheim, 1963)

$$V = R_0 e^{\beta(1/T - 1/T_0)} I$$

where the constant $R_0$ is the resistance at a temperature $T_0$, T is the absolute temperature of thermistor and $\beta$ is a material-specific constant. Resistance of negative temperature coefficient thermistor decreases with temperature. The time evolution of thermistor temperature is given by the heat transfer equation

$$C_h \frac{dT}{dt} = V(t)I(t) + \delta(T_{env} - T)$$

where $C_h$ is the heat capacitance, $\delta$ is the dissipation constant of the thermistor [13], and $T_{env}$ is the ambient temperature. Temperature $T$ of the thermistor plays the role of the internal state variable.

### Hewlett-Packard (HP) memristor device

The Hewlett-Packard (HP) memristor was realised on the concept of drifting the dopant between doped and undoped portion of the material, which models the memristive property.

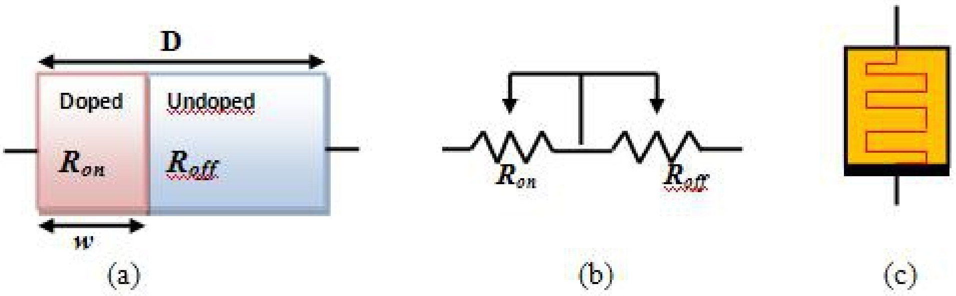


Fig. 5. (a) Memristor device structure. (b) Equivalent circuit model. (c) Memristor symbol (Y N Joglekar and S J Wolf , 2009).

Fig. 5(a), (b) and (c) show the physical structure of a memristor device along with its equivalent circuit model and symbol (Strukov D. B. et al, 2008). The device is an electrically switchable semiconductor thin film sandwiched between two metal contacts. There are two layers in the titanium dioxide film. The semiconductor thin film has a certain length , and consists of double layers of titanium dioxide films. One is highly resistive pure $TiO_2$ (undoped layer), and the other is filled with oxygen vacancies, which makes it highly conductive (doped layer). The state variable *w* represents the width of the doped region ($TiO_{2-x}$ layer). The doped region has low resistance while that of the un-doped region is much higher. The boundary between the doped and undoped regions, and therefore the effective resistance of the thin film, depends on the position of +2 mobile dopants. It, in turn, is determined by their mobility *(*$\sim 10^{-10}$ cm$^2$ V$^{-1}$ s$^{-1}$*)* (Yu. V. Pershin and M. Di Ventra, 2008) and the electric field across the doped region.

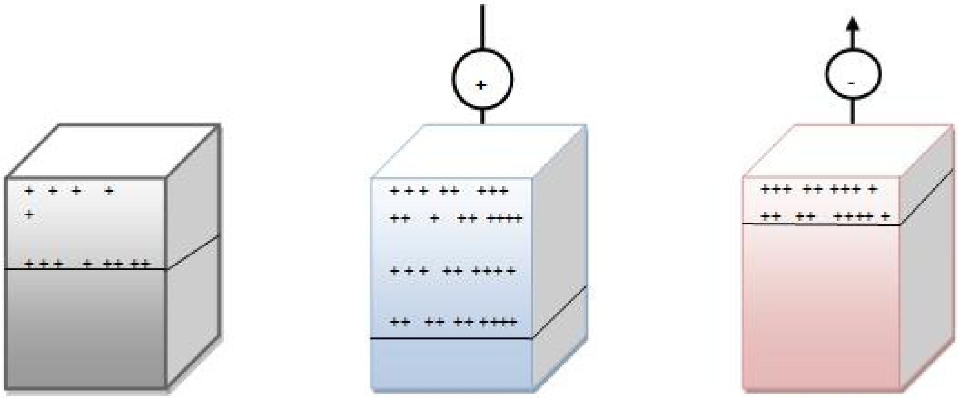


Fig.6. Change in *w*, the width of doped region, of HP memristor when the external bias *v* is applied across it. + symbol represents oxygen deficiencies.

As an external voltage bias *v* is applied across the device, the electric field will repel positively charged oxygen vacancies in the doped layer into the pure $TiO_2$ layer resulting the length $w$ changed (J. J. Yang et al, 2008) (see fig. 6). Hence, the device's total resistivity changes. If the doped region extends to the full length $D$ $(w=D)$, then $w/D=1$, the total resistivity of the device would be dominated by the low resistivity region, with a value measured to be $R_{on}$. Likewise, when the undoped region extends to the full length $D$ $(w=0)$, i.e. $w/D=0$ , the total resistance is denoted as $R_{off}$ . According to Chua (Chua, L.O, 1971), the memristor has memory effect since the device maintains its resistivity even if the power goes off. According to the reported device characteristics (Chua, L. O. and S. M. Kang, 1976), oxygen vacancies do not move around by themselves. They become absolutely immobile until voltage is applied again. This unique characteristic makes the memristor standout from other devices such as diode.

The mathematical model for memristive device resistance can be described as

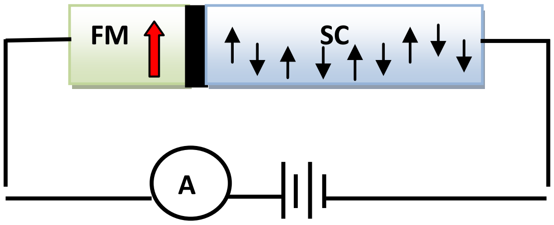
$$R(w) = R_{off} - (R_{off} - R_{on}) \times w/D$$

$$\text{where } 0 \leq w \leq D$$

$R_{on}$ $(\sim 1\ k\Omega)$ (T. Driscoll et al, 2009) corresponds to memristor state $w=D$. $R_{off}$ corresponds to memristor state $w=0$. The device resistance is bounded between $R_{on} \leq R(w) \leq R_{off}$.

## Semiconductor/half-metal junction

The use of the electron spin degree of freedom allows for the realization of memristive behavior. This fact is exploited through semiconductor/half-metal junction. Half metals are the ferromagnet with 100% spin polarization at the Fermi level and act as perfect spin filters. The principal role in realizing the memory effect is played by electron-spin diffusion and relaxation processes which drives the system to equilibrium.



**a**

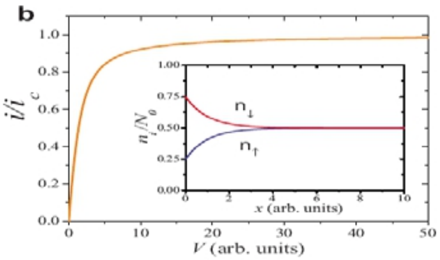


Fig 7.Semiconductor/half-metal junction. (a) Schematic representation of the circuit made of an interface between a semiconductor and a half metal. (b)Typical dc current-voltage characteristics. Inset: spin-up and spin-down densities in the semiconductor region as a function of the distance from the contact (Pershin, Y. V. and M. Di Ventra, 2008).

In a work by Yu. V. Pershin and M. Di Ventra (Yu. V. Pershin and M. Di Ventra, 2008) it has been shown that the spin blockade at such junctions leads to a saturated *i*-*V* curve (Fig. 7b) that such a system has all the necessary components to exhibit memristive behavior. The physics of the spin blockade lies in the perfect spin filter property of half metal: the half metal accepts electrons of only one—say up— spin direction. Spin-down electrons cannot enter the half metal and, therefore, form a cloud near the contact when a current flows through the system. This cloud increases with increasing current. At a critical current density the density of spin-up electrons near the contact becomes insufficient to provide a further current increase. In other words, transport of spin-up electrons through the contact is blocked by the cloud of spin-down electrons near the contact. It was predicted by Yu. V. Pershin and M. Di Ventra (Yu. V. Pershin and M. Di Ventra, 2008) that the spin blockade leads to a saturated *i*-*V* curve (as that shown in Fig. 7b). Figure 8 is the transverse voltage as a function of applied electric field at different applied field frequencies.

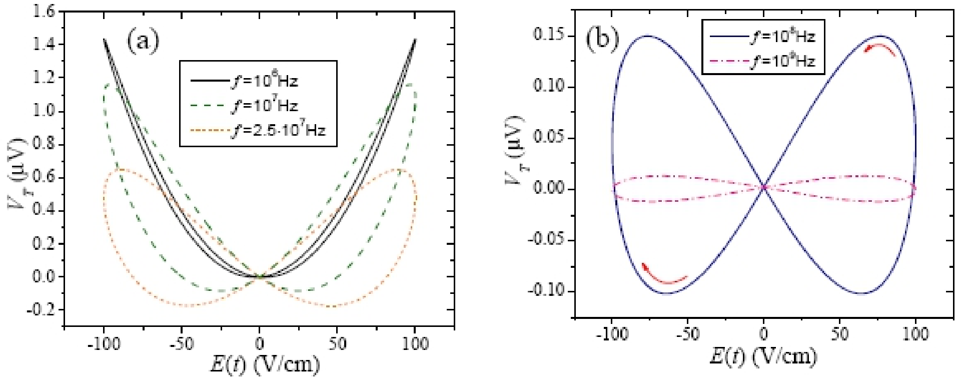


Fig 8. Spin memristive effects in a semiconducting system with inhomogeneous electron density in the direction perpendicular to main current flow (Pershin, Y. V. and M. Di Ventra, 2009). Shown in this figure is the transverse voltage as a function of applied electric field at different applied field frequencies as indicated. From (Pershin, Y. V. and M. Di Ventra, 2009).

## Biological neural network

Another important memristive system pertains to biological neural networks-functioning of membranes in axon cells. In fact, in 1952 Hodgkin and Huxley suggested a model of action potentials (Hodgkin, A. L., and A. F. Huxley, 1952) in neurons that employs history-dependent channel conductances that are essentially memristive. This model is one of the most significant conceptual achievements in neuroscience (Wang, X. Y. et al, 2000). The nerve membrane was described by three types of ion channels:

leakage channels (primarily carrying chloride ions), Na channels and K channels.

Leakage channels have a relatively low constant conductance and are the source to the resting membrane potential. The conductance of Na channels and K channels depends and changes as a function of time and voltage, and herein lies the memristive behavior. Hodgkin and Huxley have demonstrated that the step depolarization initiates a rapid inward current across the membrane carried by Na+ ions, followed by an outward current due to K+ ions. For quantitative understanding, they have suggested an equivalent circuit model of the membrane. (see fig. 9). Mathematically, the membrane current is written as (Hodgkin, A. L. and A. F. Huxley, 1952).

$$I = \frac{C_m dV_m}{dt} + M_{Na}^{-1}(V_M - E_{Na}) + M_K^{-1}(V_M - E_K) + R_l^{-1})(V_M - E_l) \qquad (17)$$

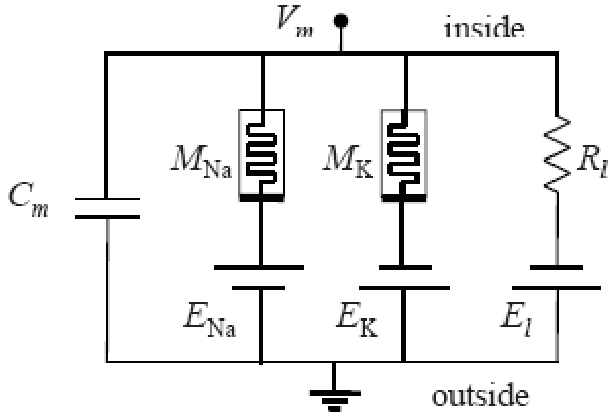


Fig .9: Equivalent electrical circuit for a short segment of squid axon membrane (modified from reference (Hodgkin, A. L. and A. F. Huxley, 1952). Here, $C_m$ is the membrane capacitance, $V_m$ is the membrane potential, $M_{Na}$ and $M_K$ are memristive systems describing conductivity of Na and K channels, respectively, $R_l$ is the leakage resistance, $E_{Na}$, $E_K$ and $E_l$ are reverse ion channel potentials, and the terms “inside" and “outside" reflect the interior of the axon.

where the memory conductances $M_{Na}^{-1} = g_{Na} m^3 h, \quad M_K^{-1} = g_K n^4, M_{Na}^{-1} = g_{Na}$ with $g_{Na}$, $g_K$, constants, $R_l$ describes the leakage resistance, and all other circuit quantities. The time-dependencies of voltage-dependent gating variables *n*, *m* and *h* are

$$dn/dt = \alpha_n (1-n) - \beta_n n \quad (18)$$

$$dm/dt = \alpha_m (1-m) - \beta_m m \quad (19)$$

$$dh/dt = \alpha_h (1-h) - \beta_h h \quad (20)$$

where $\alpha_n(m, h)$ and $\beta_n(m, h)$ are voltage-dependent constants (Hodgkin, A. L. and A. F. Huxley, 1952) defined as

$$\alpha_n = \frac{0.01(V_m + 10)}{e^{(V_m+10)/10} - 1} \quad (21)$$

$$\beta_n = 0.125e^{V_m/80} \quad (22)$$

$$\alpha_m = \frac{0.1(V_m + 25)}{e^{(V_m+25)/25} - 1} \quad (23)$$

$$\beta_m = 4e^{V_m/18} \quad (24)$$

$$\alpha_h = 0.07e^{V_m/20} \quad (25)$$

$$\beta_h = \frac{1}{e^{(V_m+80)/10} + 1} \quad (26)$$

In the above equations, the voltage is in *mV* and time is in *ms*. Time evolution of channels' conductance *n, m* and *h* values between 0 and 1. It follows from the expressions for $M_{Na}$ and $M_K$ (given in equation (17)) and equations (21-23) that the potassium and sodium channels can be classified as first-order and second-order voltage-controlled memristive systems (Chua, L. O. and S. M. Kang, 1976). In figures 10 and 11 we present simulations of potassium and sodium channel memristive systems biased by ac-voltage due to Yuriy V. Pershin and Massimiliano Di Ventra (Yuriy V. Pershin and Massimiliano Di Ventra, 2010). These plots demonstrate frequency-dependent I- V curves typical of memristive systems.

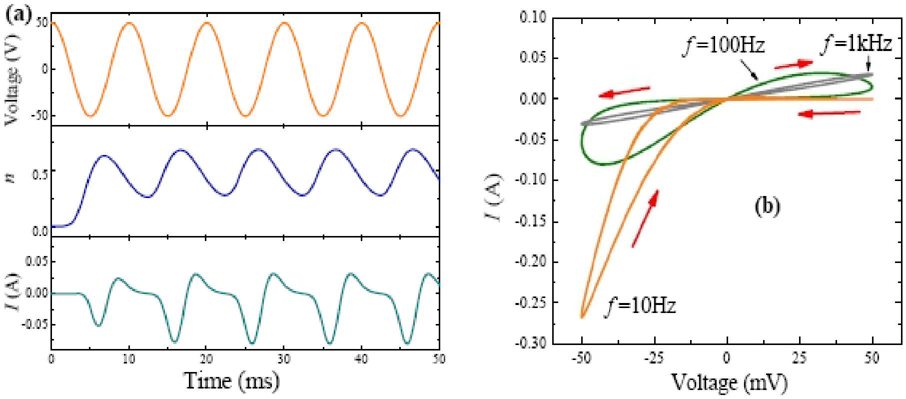


Fig 10. Simulations of the potassium channel memristive system ($M_K$) response. We have used $g_K$ = 10mS. The applied voltage is $V(t) = V_0 \cos(2\pi f t)$ with $V_0 = 50mV$ and $f = 100Hz$ in (a). After (Yuriy V. Pershin and Massimiliano Di Ventra, 2009).

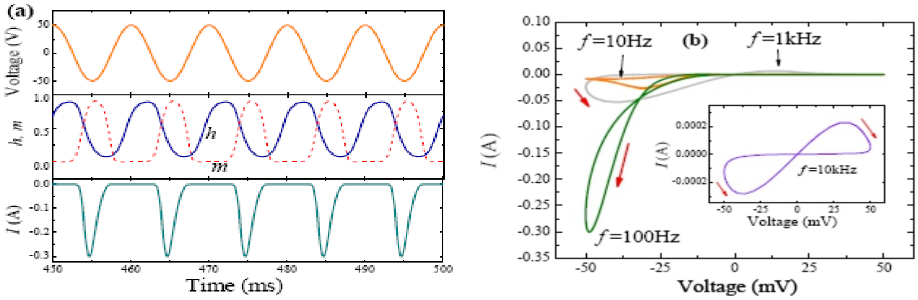


Fig 11**.** Simulations of the sodium channel memristive system ($M_{Na}$) response. We have used $g_{Na}$ = 33mS. The applied voltage is $V(t) = V_0 \cos(2\pi ft)$ with $V_0 = 50mV$ and $f = 100Hz$ in (a). After (Yuriy V. Pershin and Massimiliano Di Ventra, 2009).

## Applied memristor

### Associative memory

Yuriy V. Pershin and Massimiliano Di Ventra (Yuriy V. Pershin and Massimiliano Di Ventra, 2010) have shown, through their memristor emulator, that an artificial synaptic function can be achieved by the use of memristor. It is worth mentioning here that synapses are at the core of computation and information storage and retrieval in neural systems. The emulator is capable of retaining past events/memories and storing a continuous set of states, at the same time it simulates to behave as good as 'plastic' as per the requirement of synaptic dynamics. Further, they have showed successfully that two memristor emulator synapses connected by simple neural network leads to the formation of associative memory, an important function of the brain. This way memristor finds application in reproducing complex learning and adaptive behavior, like that of human brain.

### Read operation of memory

Affan Zidana *et al*, have demonstrated the read operation capability of memristors in one of their work (Mohammed Affan Zidana et al, 2012). The sneak paths problem has been analyzed with different memory array sizes, data sets, and architectures and following this a noise margin metric has been proposed successfully to compare the various available solutions. Memristor-based memory arrays has been used to assess the power consumption associated with the solutions and promising results have been obtained highlighting the important role played by memristors in solving sneak paths problems.

### Analog memory

Mika Laiho and Eero Lehtonen (Mika Laiho et al, 2010) have highlighted the hidden potential of memristors in analog memory and computation through programming and comparison. Memristor has been programmed, at a fixed voltage, to achieve the desired conductance level. Further, the devices based on memristor can be reconfigured to perform the arithmetic operations viz. addition and subtraction of analog conductances of dual polarity. A model of memristor with nonlinear programming feature has been proposed that automatically stops the programming upon reaching the correct conductance value by way of a cyclical programming. Thus, arithmetic operations with memristor-based analog memory is going to become a reality very soon.

**Analog devices**

Several works on memristor have been reported discussing the realization of analog devices based on memristor.

*Op-amp.* Qin Yu *et al* (Qin Yu et al, 2010) have studied the small signal transmission characteristics of a monotone-increasing and piecewise-linear memristor-based inverting and non inverting op-amp circuits and have realized the respective voltage gain.

*Filter.* Filter characteristics based on memristor has been reported by Wei Wang *et al* (Wei Wang, Q, 2009).

*Adaptive filter.* Memristive adaptive filters has been studied by T. Driscoll *et al* (T. Driscoll, 2010) in one of their works. They have demonstrated an adaptive ("learning") filter based on memristor. This filter responds to pre-specified signals by sharpening the quality factor of its response. Further, they claim to model the learning patterns observed in biological organisms through this adaptive filter. The analog functionality of memristive components is supposed to allow combination of signal processing in storage and fuzzy logic. The adaptive filter circuit consists only of passive basic circuit elements which is different from the other method of realizing adaptive filtering with combinations of transistors. Further, this device offers advantages in device density and power consumption.

*Oscillator.* Li Zhi-Jun and Zeng Yi-Cheng (Li Zhi-Jun and Zeng Yi-Cheng, 2013) have modeled, an inductance-free chaotic circuit based on a twin-T oscillator and memristor, by coupled first-order differential equations. The circuit evolves into different orbits, chaos, and hyperchaos upon change of control parameters. To observe the chaotic behaviors in the circuit, they designed an analog realization of the piecewise-linear flux controlled memristor with conventional electronic devices. The circuit can find application in chaos-based communication and electronic measurement systems.

*Phase shift oscillator.* A. Talukdar *et al* (A. Talukdar et al, 2012) have reported the good potential application for parametric oscillation of the memristor in conventional phase shift oscillator. The effects of using the memristor in place of a conventional resistor have been described mathematically and are verified by the simulation results. The said systems qualifies as an autonomous parametric oscillatory system where the memristor sets its resistance as a periodically changing parameter. The oscillating resistance, operating frequency range, and the dynamic poles are expected to redefine the conventional concept.

*Relaxation oscillator.* A. G. Mosad *et al* (A. G. Mosad et al, 2013) have introduced a memristor-based relaxation oscillator free from any reactive components. They have obtained higher oscillation frequency over a wide range of resistance compared with that of existing reactance-less oscillators. The circuit can be operated with positive as well as and negative supplies meeting the oscillation condition. Authors strongly believe that the proposed oscillator provides a suitable solution for low frequency applications such as the biomedical and embedded systems applications.

## Spintronic temperature sensor

Spintronic memristor based temperature sensor has been proposed by Xiaobin Wang *et al* (Xiaobin Wang et al Sebastiano Peotta and Massimiliano Di Ventra, 2010) exploiting the rich dynamic behavior of memristor upon excitation with dynamic current/voltage profile. The sensor property is based on the domain-wall motion in magnetic strip in a spin-valve structure. The device temperature operating range can be configured by varying domain-wall thickness through the tuning magnetic material properties. TMR stack or magnetic stack with high GMR can improve the linearity or the resolution of the sensor.

## Superconductivity

Sebastiano Peotta and Massimiliano Di Ventra (Sebastiano Peotta and Massimiliano Di Ventra , 2013) had an attempt to realize a superconducting memristor based on the phase-dependent conductance present in Josephson junctions. Superconducting memristor may have switching time in few picoseconds and this makes them extremely fast. A unique feature of this superconducting memristor is that it does not violate the Landauer bound on the minimum energy cost for reversible computation which do happen in case of irreversible computation with an ideal memristor and with other superconducting circuits.

Superconducting memristors offer new venues for neuromorphic computation since they can be readily integrated with existing circuits with extremely fast operating frequencies.

## Miscellaneous

Yuriy V. Pershin and Massimiliano Di Ventra (Yuriy V. Pershin and Massimiliano Di Ventra, 2011) have shown how a network of memristors solve mazes in a massively-parallel way by way of implementation on a computer. They claim that hardware implementation of the memristive processor is superior to any existing maze solving methods and hence will be the best choice when the complexity of the maze increases. Further, it is assumed that the memristive processor can facilitate the solution of many other computational problems for example the traveling salesman problem, graph theory problems, etc. The memristive processor have the potential that they can then be used as a complete computational device, or as a supplemental tool for traditional computing hardware. Thus memristors are expected to affect the basic sciences and technology in a diverse manner.

## Conclusion

In this paper an attempt has been made to review the research and development in the field of memristive devices and the various applications of them in real electronic, spintronic and neural network domain. The study spans from the proposition on memristive devices by Leon O. Chua to the first development of memristor in the laboratory by a group of HP scientists in the year 2008. Other examples of memristive behavior showing models are on thermistors, spintronic device, and a biological model on neural network. A separate section has been devoted to the various possible uses of memristor and memristor based circuits finding application in analog memory and computation, analog devices, associative memory, maze solver, temperature sensor and superconducting memristor.

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