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Nonlinearity in Memristor Materials - A Review

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Abstract

To meet the ever-increasing demand for smart gadgets in the mining industry, the requirement for micro and nanodevices also increases exponentially. In the field of electronics, the memristors will create a revolution by replacing transistor technology shortly due to its size, low energy consumption, reliability and memory capacity in the near future. Memristors are made up of different materials based on applications. They are variable resistors and can be used for non-volatile memory-based low-power analogue circuits. Memristor has nonlinear frequency characteristics based on different components silicon-based Op-Amps have nonlinear frequencies varying from 1kHz to 16kHz, whereas $CuSO_4$ with Cu electrode holds from 0.1Hz to 10 Hz and carbon nanotubes have the same less than 1 Hz. The modification of extraction methods or source identification techniques needs advanced tools to predict the presence of transition metals. The miners of transition metals will be burdened more to process the origin form of metals towards the fabrication of memristors. In this paper, the memristor behaviour with different biological components, transition metals and oxides and their electrical specifications are discussed along with the potential use of the same. The study has been done to identify the suitable selection of metal for memristor construction.

Keywords: Memristor, Metal Oxides, Non-Volatile Memory, Oxides, Transition Metals

1.0 Introduction

In today's times, life without metals is beyond imagination. Along with the constraints of size, weight and performance, there is a paradigm shift from traditional electronic devices to compact-sized smart devices. To meet these ever-growing demands, many devices/elements are being evolved in recent years. In the context of material or device development, memristors have attracted much attention due to their promising applications in nonvolatile memory and unconventional computing. The resistance of the memristor depends on the amount of charge through the element which in turn depends on the physical properties of metal oxide chosen. According to Chua, the fingerprints of the memristor are said to possess pinched hysteresis characteristics, zero crossing and frequency dependence on nonlinearity (component specific)[1]. Hence, the memristor is a nonlinear resistor as it has a pinched hysteresis nature of voltage-current characteristics. The resistance value will remain until the supply is given again, as it possesses a nonvolatile memory. It will find many applications in a communication circuit as it proves its nonlinearity only at very low values and linearity at high values of frequencies. The nonlinearity will be realised with the hysteresis loop, which depends on the applied voltage and frequency[2]. By 2008, Williams and his team of HP labs, invented a Nano-scaled physical memristor made up of doped and undoped titanium oxide films between platinum electrodes[3]. However, for the past 45 years, the memristor has not been significant even in the circuit model. The introduction of a physical memristor into the commercial world is difficult due to many technical complications. Hence, circuits imitating the memristor properties have evolved to identify the possibilities for application in various disciplines. Memristive circuits are built with electronic components,

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tree leaves, human skin, discharge lamps, mismatched metals, programmable circuits, etc. Due to its favourable characteristics, properties and vast applicability, it seeks attention from researchers in different fields. Researchers have developed interests in different manufacturing techniques and materials and thus explored various levels of implementation.

In literature, memristors based on ultrathin anion-strained multi-walled carbon nanotubes, Ta_2O_5-based memristors using indium tin oxide in the buffer layer, and Hf0.5Zr0.5O_2-based ferroelectric memristor with multilevel storage potential are carried out. The transformation of various metal forms using advanced metallic frameworks is used to save time in the extraction of transition metals. This paper focuses on the nonlinear behaviour of memristors with different materials and their applications.

2.0 Materials and Methods

Since its innovation, due to the unavailability of the memristor as a single IC or any other form, memristive circuits using various components are being developed. All the circuits are carefully designed to realise most of the memristor properties. The extraction of transition metals by preliminary treatment, molten form, and refinement procedure may lead to the use of advanced extraction technologies to meet memristor requirements.

2.1 Evolution

The memristive circuit works from 0.1V up to 5V, possessing a few ohms to kilo ohms. The current ranges from a few μA to Amperes. The size of the circuit varies from a few nanometers to meters depending on the component used. Most circuits emulate memristive properties, but a few fail to have the nonvolatile property. Depending on the application requirement, the circuit design is chosen. The validation of the circuit characteristics is based on the HP memristor[4].

The voltage across the HP memristor shown in Figure 1 is given as

$$v(t) = i(t)\left[R_{ON}\frac{W}{D} + R_{OFF}\left(1 - \frac{W}{D}\right)\right] \quad (1)$$

where μ_V represents dopant mobility, R_{ON} and R_{OFF} represent the limits of memristance, W represents the width of the device, and D represents the width of the doped region.

$$W = \frac{q\mu_V R_{ON}}{D} \quad (2)$$

$$M(q) = R_{OFF}\left(1 - \frac{q\mu_V R_{ON}}{D^2}\right) \quad (3)$$

Memristive circuits have found many applications due to their nonlinear behaviour. They can be used as a resistive load, switch, relay, oscillator, etc. The memristive circuits can be categorised based on control variables such as flux and charge[5,6].

In a flux-controlled memristor, the magnetic flux between its terminals is a function of the electric charge that passes through it. The memductance $W(\varphi)$ gives the rate of flux-dependent change of charge as

$$W(\varphi) = \frac{dq(\varphi)}{d\varphi} \quad (4)$$

The current through the memristor is given by

$$i(t) = W(\varphi)v(t) \quad (5)$$

The circuits developed using off-the-shelf components are unable to exhibit all the memristor characteristics due to their inherent stray inductance and capacitance effects. Similarly, in a charge-controlled memristor, the memristance M(q) and the voltage across it are given by the following equations:

$$M(q) = \frac{d\varphi(q)}{dq} \quad (6)$$

$$v(t) = M(q)i(t) \quad (7)$$

In these memristive circuits, shaping circuits are needed to achieve nonlinearity[7].

Memristive circuits are classified according to the frequency ranges as per the requirements. The value of memristance depends on the duty cycle, duration, amplitude, and frequency of the applied signal[8,9]. As the oxygen vacancies move with the changes in input voltage magnitude, the resistance of the device changes accordingly

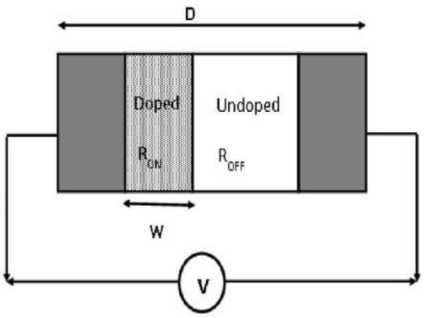


Figure 1. Hewlett Packard memristor.

in the HP memristor. The longer the duty cycle and the signal duration, the lesser the memristance and vice versa.

Following the invention of HP's memristor, several models are being recommended to identify the potential applications of memristive circuits. New designs, simulation models, the innovative combination of materials at the nano dimension, and new theories are being suggested to develop memristors for industrial applications. The following models are widely accepted to analyse the performance[10].

(a) Linear ion drift.
(b) Nonlinear ion drift.
(c) Simmon's tunnelling barrier.
(d) Threshold adaptive memristor.

Nonlinear ion drift and Simmon's tunnel barrier models expressed the relation between the voltage and current of the charge-controlled memristors. Whereas linear ion drift and TEAM models define the current-voltage relation of the flux-controlled memristors. To consider state variable limits and the nonlinearity at boundaries, a window function is included in the derivative term of the state variable. Joglekar, Biolek, Prodromakis and Piecewise window functions fit linear, nonlinear ion drift and TEAM models. Whereas team function fits only with the TEAM model.

2.2 Components/Metals/Oxides

The memristive circuits can be developed using electronic components, biological components, and chemical components. Memristor properties are identified earlier in thermistors, binary oxides, ionic systems, etc., in their hysteric behaviour or resistive switching mechanisms. The electronic components used are Op-Amps, voltage multipliers, Metal Oxide Semiconductor Field Transistor (MOSFET) transistors, resistors, grounded capacitors, floating capacitors, Junction Field Effect Transistors (JFETs), Zener diodes, Bipolar Junction Transistor (BJTs), diodes, microcontroller units, Digital Signal Processor (DSP) to digital converters, digital to analogue converters and differential difference current conveyors. The dependency of pinched hysteresis on the magnitude and frequency of source voltage has been illustrated in Figures 2 and 3, respectively.

The biological components are human skin, plant leaves, etc. The electro-osmotic transport of fluid through pores in the skin like sweat ducts constitutes a memristive property during its electrical response. The stimulation of aloe vera using bipolar periodic waves through platinum electrodes generates electrical responses like memristors at 10^{-3} Hz and becomes linear at 1000Hz. The potassium ions of the Venus flytrap with silver electrodes when stimulated under bipolar excitation responded as memristors.

The chemical component for a memristor should be the combination of an oxide with an imperfect metal[13]. The metals which undergo unipolar, bipolar, or mixed switching behaviour are appropriately sandwiched with appropriate oxides to emulate the memristor properties. The transition metal oxides can be HfO, NbO, MoO, MnO, WO, NiO, CuO, ZnO, TaO, TiO_2, etc., and the electrodes can be Cu, Al, Pt, Au, Fe, etc. The switching behaviour of memristors depends upon the properties of the electrode metals. The affinity of the oxygen atoms, work function, and surface factor determine the switching as well as dynamic behaviour, withholding capacity, reliability, operating voltages and ROn/ROff ratios of the devices. A buffer layer with Indium tin oxides helps to develop heterogeneous double-layer devices to achieve enhanced

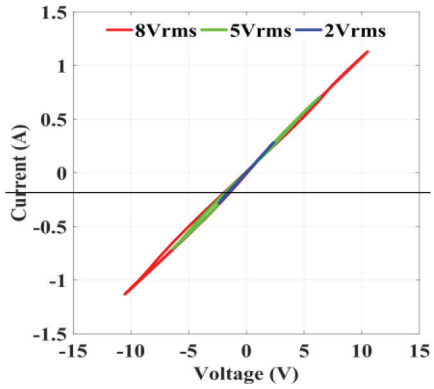


Figure 2. Pinched hysteresis of JFET circuit[11] when simulated using MULTISIM software.

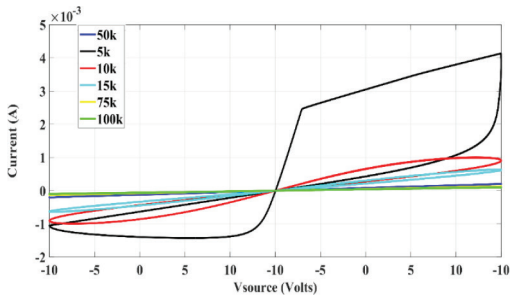


Figure 3. Pinched hysteresis of OPAMP circuit[12] when simulated using PSPICE software.

Table 1. Nonlinear frequency ranges of memristor components

Component	Applied Voltage	Current	Nonlinear Frequency	References
Op-Amps	0.8V	20 mA	1 kHz-16 kHz	11,10,24,25
JFETs	3V	50 mA	1 kHz-10 kHz	
MOSFETs	1.2 V	30 µA	1 mHz-1 MHz (floating) 1 mHz-10 MHz (grounded)	
Arduino	3.3 V	60 µA	100 Hz-1 kHz	
Human skin	10 V	20 mA	Pulse	26
Venus flytrap with Ag/AgCl electrode	1.5 V	8 µA	10^{-3} Hz- 1kHz	27
Aloe vera	4 V	8 µA	1 mHz- 1 kHz	
ZnO with electrode	0.8 V	20 mA	100Hz	28,29
TaO with electrode	0.8 V	5 mA	1Hz	30
TiO_2 with Platinum electrode	1.5 V	2 mA	1 kHz	1,2
$CuSO_4$ with Copper electrode	1 V	1 mA	0.1 Hz- 10 Hz	31
Carbon Nano Tube (CNT)	0.75 V	47 nA	<1Hz	16,32
Coherer setup (Iron filling/ chain form, Iron-Mercury)	0.5 V	2.5 mA	Bipolar pulse	13
Electric Arcs	35 V	22 A	-9 kHz	33

stability and symmetry in terms of potentiation and depression characteristics[14]. Photo-memristive devices based on graphene and its oxide, bismuth oxy-selenide and dichalcogenides of transition metals are chosen for image recognition in autonomous applications[15]. The extraction of transition metals with wastewater treatment includes processes such as metal adsorption, cementation, filtration, electro-dialysis, and photo-catalysis along with concentrations of metal and pH factors.

Non-volatile memory applications use memristor configurations with multi-walled carbon nanotubes and tungsten electrodes for excellent switching characteristics under vacuum[16]. Temperature change will be a constraint for these chemical memristors[17]. Some of the auto-recoverable coherers used during the World War also have memristor properties. The nonlinearity of various component-based memristive circuits is summarised in Table 1. Based on the application requirement, the memristor component can be chosen. The chemical and biological memristors possess suitable memory properties.

2.3 Research Perception

Memristive circuits have been developed as a nonlinear load, comparator, ADC or DAC circuit, voltage divider, switch, oscillator, relay, etc.[19-20]. A combination of a universal memristive circuit and mutator generates meminductor and memcapacitor circuits[21]. Different combinations of memristor, meminductor and memcapacitor in an incremented or decremented manner can also be generated[22]. A single memristor can replace around 15 transistors and other passive elements. Hence, it will replace Non-Volatile Randon Access Memory (NVRAM) devices, Field Programmable Gate Array (FPGA) and programmable systems as it has already started to mimic a brain with its memory property[23]. The circuits can be categorized as a load, switch, synthesiser and memory device.

A need for alternatives to scaled-down sizes of programmable devices and analogue modules with memory will be satisfied and have a remarkable future with memristors. Memristor-embedded DSP processors with high memory density may enhance their performance. A mixture of transistors and memristive circuits may have boundless digital applications[24].

3.0 Future Applications of Memristors in Mining Industries

With the development of memristors or emulators, the nonlinearity will be examined based on the physical and chemical properties of the components used[25-28].

Identification of various transition metals or metal oxides suitable to fabricate memristors will be an interesting research area[29,30]. Characterising the metal complex structure, identifying new materials and removing any unwanted or toxic metal within ore has helped in advanced extraction technologies[31-33]. Machine learning-based extraction tools help to avoid iterations on a particular ligand or limitations on local chances. The mining of these metals may help to identify memristive properties with different sizes, capacities and models. With the advanced technologies in the mining industry, the metal properties can be identified, processed and fabricated by the device so that it will find its applications in emerging areas of biology, chemistry, physics, etc. The development of memristors on different metal combinations will lead to their use in various voltage-level applications in the future[34]. The synthesis of transistors and memristors further contributes to innovative circuit designs. Memristors are expected to play pivotal roles in devices related to smart metering, self-monitoring, memory and control circuits[34]. The inherent nonlinearity of memristors offers the potential to act as a damper device for device protection[35]. Additionally, the programmable switching ability of memristors is harnessed in RF/microwave applications[36]. The memory property of mem elements is poised to enhance the usage of electronic circuits[18,23]. Furthermore, the distributed mem capacitance of a reconfigurable transmission line is capable of performing signal analysis through its programming pulses[37]. These advancements underscore the multifaceted potential of memristors in shaping the landscape of future electronic applications.

4.0 Conclusion

The upcoming memristor technology promises many applications through its emulation circuits. Much research on memristive circuits can be attempted through a synthesis of different metal combinations. The advancement of memristor technology is poised to supplant conventional passive elements through the integration of cutting-edge mining technologies, showcasing superior performance. This paper diverges from prior research, emphasising the utilisation of not only commercial off-the-shelf components but also incorporating biological and chemical elements in certain circuits. The discussion systematically categorizes existing memristive circuits based on control signal, frequency, components, and applications. Furthermore, the paper delves into prospective applications of memristors, spanning diverse fields like electronics, biochemistry and biophysics, underscoring their versatility. The synthesis of hybrid circuits is also explored, emphasising the potential roles of either memristors or their emulator circuits in shaping the future landscape of technological innovation. Though the effort to identify the emulation of memristor according to the requirement of emerging research area has been made in a brief version, this might help the researchers to begin an impressive work. There might have been many discoveries on memristor properties of different existing metals or new combinations of metals and oxides before this publication.

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