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Investigating conduction mechanism and frequency dependency of nanostructured memristor device

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ABSTRACT

The present paper depicts the simulation of conduction mechanism and frequency dependency of nanostructured memristor device. The simulation of memristor is carried out using linear drift model of memristor. Further effect of various frequencies on memristor device has been investigated. We present the simulation proof of Limiting Linear Characteristics theorem or Frequency Dependent Theorem of memristor device. Moreover, the nanoscopic conduction mechanism of memristor device is simulated and it is found that the Low Resistance State (LRS) of memristor device follows the Ohmic conduction mechanism. The conduction mechanism in the High Resistance State (HRS) is found to be very complex one and follows the space charge limited current (SCLC) theory.

1. Introduction

The memristor is a fourth fundamental circuit element along with resistor, inductor and capacitor. The existence theory of memristor was postulated in 1971 [1] and its first physical realization was confirmed in 2008 [2]. Regarded as memory+resistor, the device is supposedly ability of remembrance of the last applied states and it switches from Low Resistance State (LRS) to High Resistance State (HRS) with proper bias and frequency. This unique attribute has led to many potential applications in the area of resistive memory, chaos theory, biomedical application, neuromorphic application, and many more [3–5]. The pinched hysteresis loop in current–voltage (I–V) plane and nonlinear, continuously differentiable, and monotonically increasing relation between charge (q) and magnetic flux (φ) are the two fingerprint properties of memristor devices, which are useful for many applications [1]. Interestingly the above referred pinched hysteresis loop can be found in many areas ranging from human skin [3] to nanostructured metal–insulator–metal (MIM) structure [4,5].

There have been many interesting offshoots of the memristor phenomenon from various view points, significant amongst them for us is their properties from applications in electronics engineering. In this regard, recently Soltiz et al. reported the memristor-based neural logic blocks for realization of biologically inspired reconfigurable hardware [6]. Emboras et al. reported the memristor based RRAM integrated with a plasmonic waveguide [7]. Gao et al. proposed hybrid CMOS-memristor structure for programmable threshold logic gate [8]. Dongale et al. reported effect of device size on memristor based Resistive Random Access memory (RRAM) [9]. The inherent resistive switching mechanism of memristor device is depending upon many internal and external parameters or variables; hence the study of this parameters have great scientific importance.

Following this emerging direction, in this study, we investigate the nanoscopic conduction mechanism and frequency dependency of memristor device. The proposed investigation is based on HP memristor model, where drift

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of oxygen vacancies are considered as a state variable [2]. The rest of paper as follows: Introductory information about memristor device and its applications have already been well placed by the way of introduction. This is followed by Section 2 discusses the modelling of memristor. The simulative study of frequency dependency and conduction mechanism of memristor is carried out in Section 3 which is followed by the results and discussions.

2. Modelling of memristor

At the outset, brief introduction of linear drift model has been put in place in this section. This is followed by simulation in the MATLAB paradigm based on the above model. Then after simulation interpretation as regards to the conduction mechanism has been presented.

2.1. Linear drift model of memristor

The memristor is widely known as a passive and nonlinear circuit element [1] and it is defined in terms of nonlinear relationship between charge (q)–magnetic flux (φ) curve and pinched hysteresis loop in I–V plane. The memristor is defined either current controlled or voltage controlled device based on charge or flux as a state variable. The detailed information can be found in Ref. [4]. The HP memristor which is solely used in the present work, considers the drift of oxygen vacancies as a state variable in the Pt/TiO_2/Pt structure. The typical structure of HP memristor is depicted in Fig. 1.

The reported memristor comprises of Pt/TiO_2/Pt structure in which TiO_{2-X} is oxygen rich doped conductive layer used for state variable formulation and the 'D' is a thickness of active sandwich structure. The movement of TiO_{2-X} is oxygen rich region can be controlled by proper bias and frequency. The doped layer having low resistance whereas, undoped region has very high resistance. The TiO_{2-X} doped region or state variable (w) moves between upper and lower boundaries of device. If state variable reaches to upper boundary, then device goes in the Low Resistance State (LRS) and if state variable is goes to its lower limit then undoped region will dominates which results memristor switches to High Resistance State (HRS).

In HP Model, drift velocity of oxygen vacancies are proportional to applied electrical field hence this model is popularly known as the Linear Drift Model of Memristor [2]. Considering the linear ionic drift with the average drift velocity of oxygen vacancies μ_v, then memristor current and voltage relation can be represent as following mathematical Eq. (1) [2]:

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

where state variable 'w' can be represented as,

$$\frac{dw(t)}{dt} = \eta \frac{\mu_v R_{ON}}{D} i(t) \tag{2}$$

Integrating Eq. (2) *w. r.* to 't' we get,

$$w = \eta \frac{\mu_v R_{ON}}{D} q(t) \tag{3}$$

Eq. (3) clearly indicates that memristor state variable is directly proportional to the flow of charges through the device which is a basic assumption for linear drift model of memristor device. The parameter 'η' indicates the polarity of memristor. Substituting Eq. (3) into (1) we get memristance $M(q)$, if $R_{ON} \ll R_{OFF}$ or LRS $\ll$ HRS, [2]

$$M(q) = R_{OFF}\left(1 - \frac{\eta \mu_v R_{ON}}{D^2} q(t)\right) \tag{4}$$

Eq. (4) clearly indicates that the memristance $M(q)$ is directly proportional to drift velocity of oxygen vacancies 'μ_v' and inversely proportional to memristor device thickness 'D'. This signifies that memristance is higher if and only if higher the drift velocity of oxygen vacancies and lower the film thickness. This equation also suggests that typical memristor characteristics distinctly observed in nanometer range [2].

Fig. 2 represents the simulation of memristor in the MATLAB environment. For the present simulation the state variable is limited to the interval [0, D]. For the present simulation following parameter are kept constant: Input sinusoidal signal—V_M *sinwt*, where $V_M = 2$ V, frequency of applied signal = 5 Hz; Drift Velocity of oxygen vacancies = $\mu_v = 10^{-14}\ m^2\ V^{-1}\ s^{-1}$; $D = 10$ nm; $w = 2$ nm; $R_{ON} = 120\ \Omega$; $R_{OFF} = 20\ k\Omega$; M-efficiency factor (R_{OFF}/R_{ON}) = 166.

2.2. Nanoscopic conduction mechanism in the memristor device

The memristor device is similar to metal–insulator–metal (MIM) structure in which insulator plays an important role for resistive switching. The typical MIM structure is shown in Fig. 3. The structure consists of two electrode and one insulator layer. The insulator layer is sandwiched between two electrodes. In HP memristor platinum (Pt) worked as electrode and TiO_2 worked as insulator layer. The Space Charge Limited Current (SCLC) type charge carrier electronics transport has been observed in many of the memristor or RRAM type structure [10,11]. In the absence of any trapping effects the current density (J_{SCLC}) and electric field distribution ($E(x)$) of the device is given by Mott–Gurney law such that, [12]

$$J_{SCLC} = \frac{9\mu_0 \varepsilon_r \varepsilon_0 V^2}{8L^3} \tag{5}$$

$$E(x) = \sqrt{\frac{2J_{SCLC}\,x}{\mu_0 \varepsilon_r \varepsilon_0}} \tag{6}$$

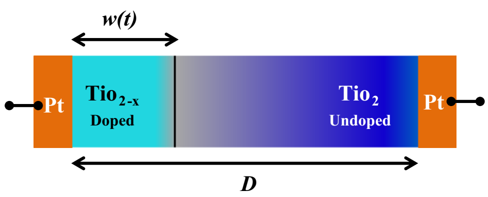

Fig. 1. Structure of memristor reported by HP Lab redraw from [2].