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Memristive Behavior in Magnetic Elements Separated by Thin Non-Magnetic Spacer Layer

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Abstract:Memristance due to domain wall displacement following spin polarization of current through two magnetic elements with a thin non-magnetic spacer layer in between has been studied in this paper. A domain wall is a type of spin structure appearing between two magnetic domains. When spin polarized current interacts with the second layer it produces a change of resistance which depends on the relative orientation of the magnetic moments in layers. Analytical simulation results on 10 nm sample size domain wall have been obtained under the impression of magnetic field and spin polarization of current. The non-linear pinched hysteresis loop obtained as current-voltage characteristics shows linearity at high frequencies.

Keywords: Memristance, domain wall, pinch hysteresis, spin polarization.

I. INTRODUCTION

In circuit theory, the three fundamental two-terminal devices resistor,capacitor and inductor have been excellently explored. They are expressed as the relation between two out of the four fundamental circuit variables (*current*, *voltage*, *charge* and *flux)*. Time rate of change of charge defines the current. Faraday's law defines the voltage as the time rate of change of the flux. Resistor comes a proportionality constant between voltage and current, the capacitor as a proportionality constant between charge and voltage and the inductor is defined by the relationship between flux and current. Out of the six possible combinations of the four fundamental circuit variables, five are defined. But nowhere is mentioned the relation between the *flux* and *charge.* In 1971, Leon Chua [1] postulated, purely on mathematical ground, the existence of the fourth missing fundamental circuit element called the *memristor*, short for memory-resistor. This device was shown to provide a functional relationship between the time integrals of voltage and current. A memristor is charge-controlled if the relation between flux and charge is expressed as a function of electric charge. Otherwise, for the flux-controlled type the relation between flux and charge is expressed as a function of the flux linkage.

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After the first time the concept of memristor was reported, Chua and Kang [2] extended it to memristive systems. A memristive system behaves as a linear resistor for infinitely large frequencies and as a non-linear resistor for zero frequency [3-5]. Electron spin degree of freedom can be used to realize memristive behaviour. This fact has been exploited in semiconductor/half-metal junction. Half metals are known to behave as perfect spin filters because they have 100% spin polarization. Y. V. Pershin and M. Di Ventra [6,7] have shown that the spin which is not identically matched produces blockade at the said junctions and memristive behaviour is realizable for such junctions.Functioning of biological neural networks has been found to simulate the memristive behaviour [8].
Spin degree of freedom of electron can be exploited to obtain the memristivesystems. Spin torque is found to work on the current through two magnetic elements filled with a thin non-magnetic layer in between. Current becomes spin polarized after transmission or by reflection from the first magnetic layer upon which it is incident. The currentmanages the spin polarization as it allowed to pass through the non-magnetic layer. This is followed by its interaction with the second ferromagnetic layer. This interaction of current with the second layer magnetization produces noticeable change in resistance. This change in resistance depends on the relative orientation of the magnetic layers. This give rise to giant magnetoresistance (GMR) [9]. For parallel alignment of magnetic moments, GMR is the lowest and it becomes highest when magnetic moments are anti-aligned (figure 1). The current through the layers can either be perpendicular or parallel to the interfaces [10]. Transfer of angular momentum takes place from the polarized current to the free layer magnetization resulting in spin transfer torque (STT). This change in resistance can be exploited in realizing memristive system. The spin torque produces domain wall displacement which is function of the angle between the two magnetization states. The available range of domain wall displacement is taken as unity. If the DW has a displacement of w (corresponding to R_{ON}) then undisplaced part $(1-w)$ corresponds to R_{OFF}. The DW displacement fits into the nonlinear ion drift model.

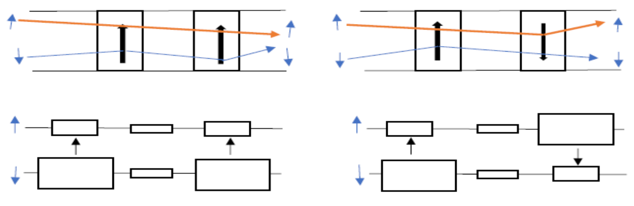

Figure 1: (a) Current flowing through two magnetic elements separated by a thin non-magnetic spacer layer.

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Electron trajectories: Parallel, P (left) and anti-parallel, AP (right) orientation of magnetization.**(b)** Equivalent circuit: parallel (left) and anti-parallel (right) orientation of magnetization. Size of the blocks are in direct proportion to the magnitude of resistances.D = 10nm, $R_{on} = 100\Omega$, $R_{off} = 16k\Omega$, $V_0 = 1V$, $\mu = 10^{-10}$ units, r =160

1.1 Domain wall distortion

Domain wall distortion is characterized by ϕ(t) and is given by

$$\varphi(t) = tan^{-1}\left[anti\ log\left\{1 + \left(\frac{\alpha b_J^2 M_s}{2A\gamma\theta^2}\right)t\right\}\right] \quad 1$$

Deformation of DW is function of time and spin torque. It attains a saturation value for higher spin torque which may correspond to crossover from transverse character of wall to vortex type.

1.2 Domain wall velocity

At t = 0, if domains have head-to-head magnetization (standard in-plane Neel Wall), then its velocity is defined by

$$v(t) = -b_J\, cos^2\, \varphi \quad 2$$

The velocity of current driven wall motion decreases with time. For small spin torque (b_J = 200 m/s) it increases to a maximum value and then decreases to zero showing resonance effect. At higher spin torque DW velocity becomes negative which could be probably associated with magnetization reversal and the formation of 'vortex' wall. Further, vortex wall changes to 'transverse' wall, as the wall velocity becomes positive.

1.3 Domain wall width

Thickness of domain wall depends on the sample nature and shape. Typically, for 3d transition metals thickness of domain wall is of the order of 500 to 1000 °A.

$$w(t) = \frac{-2A\gamma}{\alpha b_J M_s} \qquad i.e., w(t)\alpha\frac{1}{b_J} \quad 3$$

Domain wall width decreases with spin torque and becomes minimum for higher spin torque.

1.4 Domain wall displacement

It is assumed that the length available for DW displacement is D. This length is divided into two parts: one part of length w is the length to which DW has grown and $D - w$ the length available for DW growth. The region of width w has lower resistance and the available width $D - w$ has higher resistance. The memristor resistanceis given by the sum of the resistances of the two regions. Memristor dynamics is based on the width of doped region which itself varies with the time.

The current displaces the wall as well as distorts the internal structures. At higher spin current wall displacement is maximum and is given by

$$x(t) = \frac{b_J^3 \alpha M_s}{8A\gamma}(sin\, 2\,\varphi)^2 t^2 \quad 4$$

II. THE MEMRISTOR MODEL

The sinusoidal applied voltage is $V(t) = V_0 sin(\omega t)$. The corresponding flux will be

$$\Phi(t) = \int_0^t V_0 sin(\omega t)dt = \frac{V_0}{\omega}(1 - cos\omega t) \quad 5$$

The minimum and maximum values of flux are 0 and $2V_0/\omega$. We assume that the initial values of charge and flux being zero.

In the non-linear drift formulation

$$V(t) = (R_{on}\frac{w(t)}{D} + R_{off}(1 - \frac{w(t)}{D}))i(t) \quad 6$$

Where $w(t) = \frac{2A\gamma}{\alpha b_J M_s}$

with A = Anisotropy constant,

$\gamma = gyromagnetic\ ratio, b_J =$ $adiabatic\ spin\ transfer\ torque$ and M_s=saturation magnetization

Following the definition of memristor, the terms in the bracket represent the memristor given by

$$M(q) = R_{on}\frac{w(t)}{D} + R_{off}(1 - \frac{w(t)}{D}) \quad 7$$

Expressing the current voltage relationship in terms of first order term of flux

$$i(t) = \frac{V(t)}{R_{off}(\frac{\mu D}{rD^2})\varphi(t)} \quad 8$$

Where $r = \frac{R_{off}}{R_{on}}$. Let the current through the system is described as

$$i(t) = \sin(\omega t) + \sin(2\omega t) + \sin(3\omega t) \quad 9$$

This gives the charge variation with respect to time as

$$q(t) = -\frac{1}{\omega}[\cos(\omega t) + \cos(2\omega t)/2 + \cos(3\omega t)/3] \quad 10$$

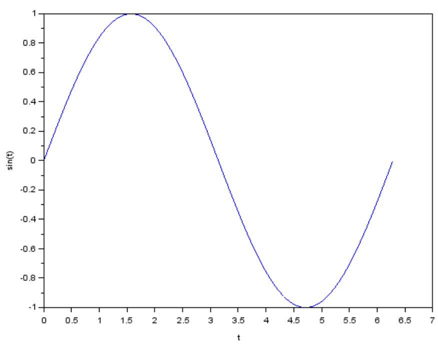
Setting $V_0 = \omega = 1$

$$q(t) = -[\cos(t) + \cos(2t)/2 + \cos(3t)/3] \quad 11$$

$$\varphi(t) = (1 - \cos(t)) \quad 12$$

III. SIMULATION AND MODELLING

Following parametric values are used for simulation:



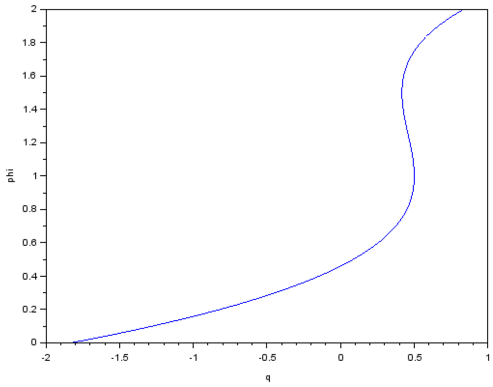


Figure 2: Input sinusoidal voltage and charge variation with the flux.

Input voltage variation with time and flux against charge is plotted in figure 1.

Variation of memristor with the relative growth of DW is shown in figure (3). It can be observed that the system offers less resistance as more and more available area for the DW is covered

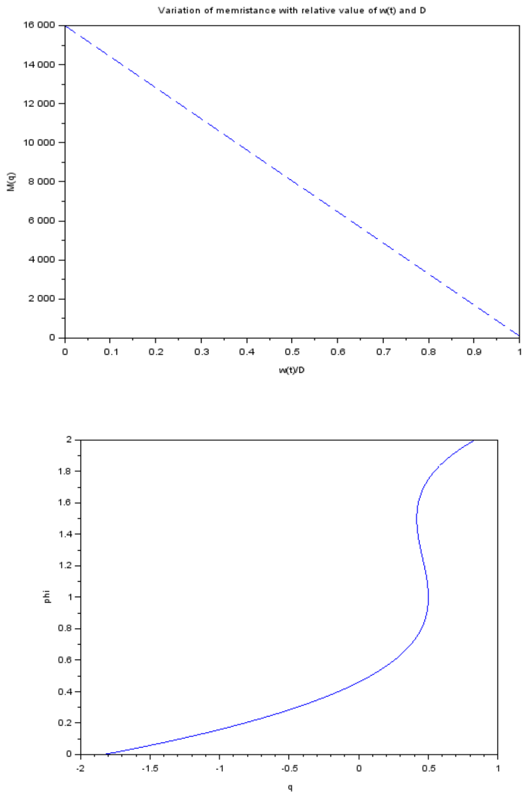
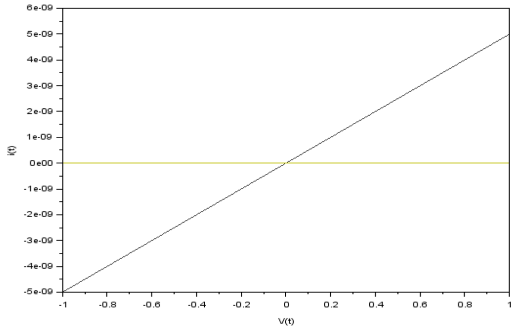
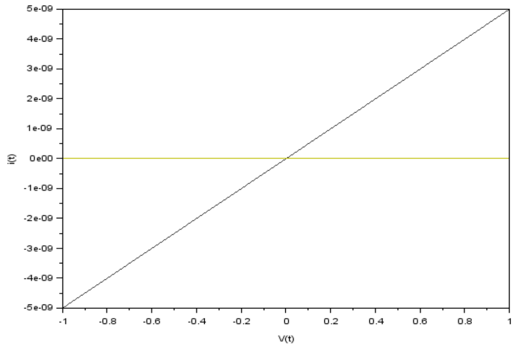


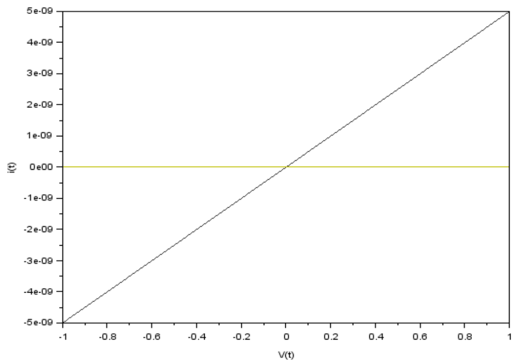
Figure 3: Variation of memristance with the relative growth of DW and the flux vs. charge limited to first order variation of flux. Parameters used for the simulation are D = 10nm, $R_{on} = 100\Omega$, $R_{off} = 16k\Omega$, $V_0 = 1V$, $\mu = 10^{-10}$ units, r =160

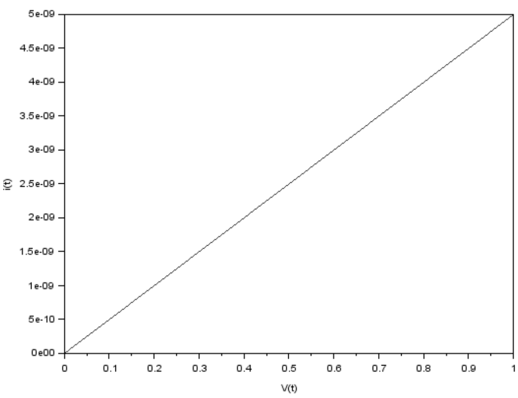
A pinched hysteresis loop is obtained as the loci of (i(t), v(t)) on 2D I-V plane. The loop is found to be pinched at the origin (0,0). This is an important feature of memristor. The I-V plots have been obtained at the frequencies ω, 3ω and 5ω and for the voltage waveform of the type $\pm V_0 \sin^2(\omega t)$. At higher frequencies, the pinch character of hysteresis loop is lost and the memristor becomes linear in its response. At very low frequency, the material has enough time to adjust its resistance to that of control parameter and the device performs like a non-linear resistor. Whereas at very high frequency, there is insufficient time for resistance change in tune with the control parameter and the device operates as a linear resistor.

Current-voltage characteristics of the memristor with current is plotted in figure 4.









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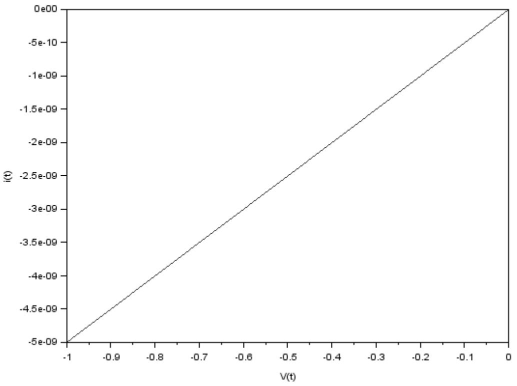

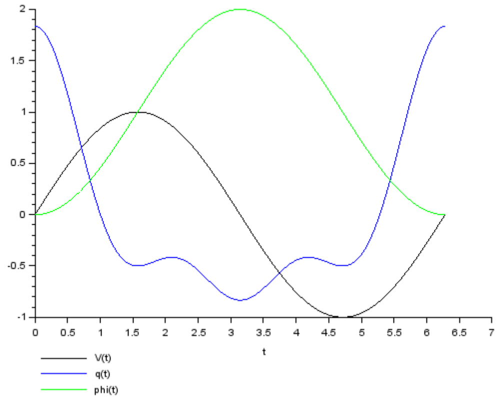

Figure 4: Current-voltage characteristics of the memristor with current given by equation (9) for the parameter values D = 10nm, $R_{on} = 100\Omega$, $R_{off} = 16k\Omega$, V_0 = 1V, $\mu = 10^{-10}$ units, r =160

IV. RESULT AND DISCUSSION

In this paper we have studied the memristive system realizable from the resistance change effect following the spin polarization of current in two magnetic layers separated by a non-magnetic spacer layer. Resulting domain wall motion provides a way to switch resistance between R_{on} to R_{off}. Spin torque produces domain wall displacement w, and the displacement is function of the angle between the two magnetization states. The available range of DW displacement is taken as unity. If the DW has a displacement of w (this corresponds to R_{ON}) then undisplaced part $(1 - w)$ corresponds to R_{OFF}. The DW displacement fits into the nonlinear ion drift model. It is assumed that the length available for DW displacement is D. This length is divided into two parts: one part of length w is the length upto which DW has grown and $(D - w)$ the length available for further growth of DW. The region of width w has lower resistance and that of width $(D - w)$ has higher resistance. The system offers less resistance as more and more available area for the DW is covered. Pinched hysteresis loops, a typical of memristor, have been obtained in the i-V plane for different input frequencies of the current. It has been observed that at higher frequencies, the pinch character of hysteresis loop is lost and the memristor becomes linear in its response- this is also in conformity with a typical memristive system. Further it will be interesting to see the behaviour of system as the DW reaches the boundary.

V. CONCLUSION

The memristive system realizable from the resistance change effect following the spin polarization of current in two magnetic layers separated by a non-magnetic spacer layer is the core issue of this study. Analytical simulation results have been obtained on a10 nm sample size domain wall under the impression of magnetic field and spin polarization of current. The I-V plots have been obtained at the frequencies ω, 3ω and 5ω with standard alternating input voltage.Pinched hysteresis loop which narrows down to linear type response at higher frequencies is a clear indication of the memristive features.Memristors have great potential to be used in ROM, Analog memory, Analog devices, Spin temperature sensors etc.

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