**An Overview of Fourth Fundamental Circuit Element- ‘The Memristor’**

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**Abstract**- The fourth fundamental circuit element- Memristor, was mathematically predicted by Prof. Leon Chua in his seminal research paper in *IEEE Transaction on Circuit Theory* on the symmetric background. After four decade in 2008, researchers at the Hewlett–Packard (HP) laboratories reported the development of a new basic circuit element that completes the missing link between charge and flux linkage, which was postulated by Chua. The new roadmap in the field of circuit designing, soft computing, memory technology and neuromorphic applications are emerged out very quickly in scientific community due to memristor. However the commercial device level memristor is not realized and reported in the literature until now. This paper overviews the some of the pioneer and state of art development in the view of memristor. The criticism constrains about memristor in scientific fraternity are also discussed.

**Keywords**- Forth Circuit Element, Memristor, Neurocomputing, Material Implication, Criticism

**Introduction**

The circuit theory suggest, there only three; two terminal; passive elements namely resistor, capacitor and inductor are available. These elements are defined in terms of the relation between fundamental circuit variables, such as current (*i*), voltage (*v*), charge (*q*) and flux (φ). In 1971, Prof. Leon Chua predicted that there should be a fourth fundamental circuit element to set up the *relation between charge and magnetic flux without an internal power supply* *Theory* on the symmetric background [1-2]. After four decade in 2008, researchers at the Hewlett–Packard (HP) laboratories published a seminal paper in Nature reporting the development of a new basic circuit element that completes the *missing link between charge and flux linkage*, which was postulated by Chua [3-4].

The nano-device memristor consider as passive element with property of remembrance of last applied state. This unique property make it valuable circuit element for many application such as resistive memories, soft computing, Neurocomputing, FPGAs etc. The memristor is an element (or *class of Memristive element*) that changed its resistance depending on how much charge flowed through it. The memristor behaves like a *linear resistor with memory* but also exhibits many interesting nonlinear characteristics. The several electronic models have been presented to describe the electrical behaviour of memristor devices such as, the linear ion drift model, the nonlinear ion drift model, Simmons tunnel barrier model, and the ThrEshold Adaptive Memristor (TEAM) model [1, 3, 5-7]. However, the memristor devices are not commercially available, good physical model-to-hardware correlations have not been yet been reported in the published literature [8]. There are also several research groups presented SPICE macro models of memristor [9-13] and MATLAB model [14]. The memristive class consist of the memristive (MrS), memcapacitative (McS) and meminductive (MiS) subsystem. These elements are considering as one port element whose property is depends upon the time derivative of charge and flux linkage [4]. The fig. 1 shows relationship between fundamental circuit elements and also completes the missing link between charge and flux linkage.

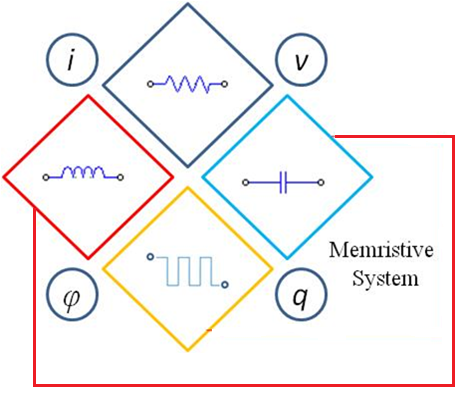


Fig. 1: Relationship Between Four Fundamental Circuit Elements: Resistor, Capacitor, Inductor and Memristor. This ‘MEM-System’ consists of memristive (MrS), memcapacitative (McS) and meminductive (MiS) subsystem, which are controlled by current (CC), voltage (VC), charge (QC), and flux (FC) respectively.

**Mathematics and Physics behind Memristor**

The memristor was predicted according to symmetry principles of two of four fundamentals electrical quantities such as current (i), voltage (v), charge (q) and flux (φ), In the history few principle are also predicted using symmetry principles e.g. the displacement current in Maxwell’s equations, a positron and a magnetic monopole. The first two have been experimentally observed; while the third one remains mysterious [15]. The lot of mathematical and simulative modelling and related work regarding with the memristor is carried out by O. Kavehei [4], Strukov. D. B [3] and Prof. L. Chua [1].

Memristor is a semiconductor thin film sandwiched between two metal contacts with a total length of D of TiO2 film and it is consists of *doped low resistance* and *undoped high resistance* regions [13]. The physical structure with its equivalent circuit model is shown in Fig. 2 [3]. The memristor possess the increases resistance in one direction of current and decreases the resistance in other direction. When applied external potential is removed then memristor remains in the last state i.e. memristor possess resistive memory [1]. In another words, memristor is nothing but an analog resistor which resistance can be change by changing direction of applied voltage or current [13]. Fig.2. shows the basic geometrical structure of a memristor. The present simulations model of memristor is carry out in MATLAB environment. The simulation results are shown in fig. 3 and 4. Thickness of the whole component is marked with D, the thickness of the doped layer with w [14]. It is necessary to present a mathematical memristor model to explain the substance of the models and simulation clearly [16].

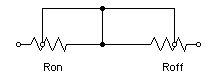
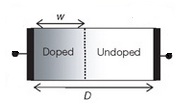


Fig. 2: Structure of Memristor Reported by HP Laboratory and Its Equivalent Model [2]

The memristor acted like a memory resistor, by relating the voltage over the element and the current through it as follows,

……………………………… (1)

The memristance M acts the same as a resistance, except that it depends on a parameter w, which in Chua’s derivations was either the charge q or the flux φ. Since the charge and current are related as follows,

……………………………………………… (2)

M depends on the complete history of current passing through the element, which makes the memristor act like a resistor with memory. The non linear memristance (M) is a function of charge (q), there is no combination of RLC element which mimics or duplicates such type of property, and hence it is a fundamental circuit element. Chua later showed that memristor are part of a broader class of systems called memristive systems described by,

**....................................................** (A)

Where, w can be any controllable property [16]. Equations (A) will represent the hysteresis loop of memristor. Equation (3) and (4) describe the ideal mathematical Model of memristor [3].

..................................................... (3)

..................................................... (4)

**Modelling of Memristor**

The chaotic characteristics are present in the memristive system hence there should be more accurate design modelling is necessary. The Monte Carlo simulation is best suited for such type of implication. The Monte Carlo simulation provides complete statistical behaviour of a device with higher accuracy [4, 8]. The literature revels that linear drift model and nonlinear drift model of memristor are available for mimicking the memristive like characteristics in simulation environment [4, 8, 15]. The present memristor model is constructed in MATLAB environment with considering of linear drift model of memristor. The simulation results are shown in fig. 3 and 4. For this modelling, the width of the TiO2 film (D) is considered as 10 nm and width of doped region (w) is considered as 1 nm. The other parameter such as resistance of doped region, RON = 100 Ω, and undoped region, ROFF = 5 KΩ and frequency of operation is 10 rad/sec considered.

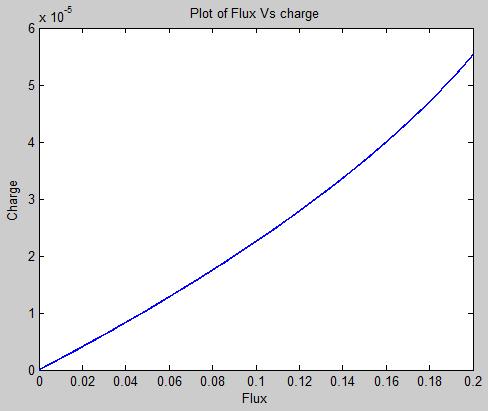


Fig. 3: Simulative Plot of Flux V/S Charge at ω = 10 rad/s. The magnetic flux is a Single-valued function of charge. The monotonically increasing functions of magnetic flux (φ) and charge (q) is related as following equation of memristor,

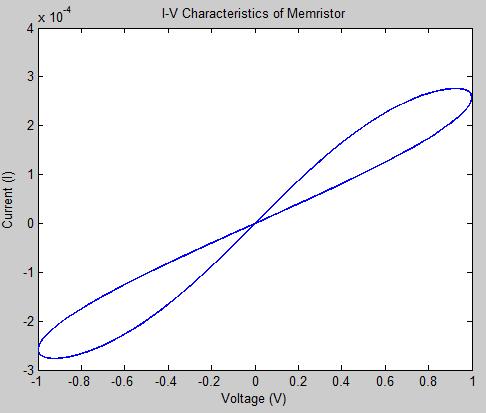


Fig. 4: Simulative Plot of Current V/S Voltage at ω = 10 rad/s. The M-efficiency factor (ROFF/RON) is considered as 160. The hysteresis loop represents the coupled equations of motion for current-controlled memristor (equation no. 1 and 2). The current is nonlinear with the applied voltage, resulting in hysteresis loops rather than straight lines. Theoretically, at high frequency the hysteresis loop vanishes and become a straight line.

**Recent Development Scenario of Memristor**

The first memristor is realized by HP laboratory on the basis of Tio2 thin film [3]. Along with such implication, there are many research groups who find out the natural memristive system in many domains. The scientist Liang Li and Edward Cox at Princeton University reported that cells have a *rudimentary memory*, which is similar to memristor [17]. As reported [18], our skin behaves as a memristor due to the dominance of the sweat ducts on the skin conductance at sufficiently low frequencies [18-20]. In 2011, the Indian research group S.P. Kosta et al reported the *Human blood liquid memristor* [21]. Before the memristor was realized by HP researcher, the Indian research team Upadhyaya et al also found out the memristor like characteristics but they don’t aware of their discovery related with the memristor, they called as their discovery as *‘polarity-dependent memory switching device’* [22].

The research on memristive systems has been mainly focused on materials such as, platinum/organic-films [3], TiO2 [23-26], Gd2O3 [27], VO2 [28], silicon and amorphous silicon [29], organic material [30], ZnO [31, 32], Nitride memristor [33], sol gel memristor [34], aniline-derivatized conductive-polymers [35] and grapheme embedded in insulating polymers [36] etc. There are many hysteresis structures which are reported in many sciences tributary but the researchers are unknown from their discoveries. If we have to identify the class of memristive characteristics then it is mandatory to check the nonlinear resistive characteristics, pinched hysteresis loop and nonlinear charge (q) - flux (φ) curve [18].

The memristor simultaneously act as logic (gates) and memory (latches), which is novel approach of material implication [37] and it is also hold the multivalued logical states which give many application domains. The combination of memory and nonlinear resistance with external low biasing property of memristor makes its promising solution for non-volatile memory. The memristor is main work horse in the field of modern Neuromorphic Systems [38-41]. Further the multivalued operation of memristor make new paradigm in the field of soft computing [13, 42], image processing [43]; memristor based chaotic circuit [44, 45], crossbar-based design [46-50], and many more. The memristor will be shows potential in the view of natural processing of computers. As we know that the Von-Neumann architecture is getting bottleneck due to large serial computation and memory latency. The Memory latency will be reduced in the conventional architecture if memristor implemented as a parallel manner. Similar way the power consumption will be reduced and it can bridge between future computations.

**Criticism about Memristor**

It was widely announced that the memristor was the god particle for science and engineering domains. The prediction of memristor is based on symmetrical relationship between charge and magnetic flux but in early realized memristor does not having magnetism and magnetic signals which neither applied nor measured [51]. As a point of view of resistance, the direction of charge flow will be increase or decrease the memristor resistance but this dependency in charge and resistance at the nanoscale is very well known to the world before it predicted [52-56]. The researchers also fail to explain Landauer’s principle of minimum energy costs for information processing and the coupling of diffusion currents at the boundary between two regions in the view of electrochemistry [57].

The hype of memristor further create problem regarding with the implementation viewpoint. The memristor promises faster, smaller and cheaper technology, but there is no scientific evidence of commercial device level memristor is realized and reported in the literature until now. The memristor does not having proven and matured technology that changes the mainstream silicon technology [58]. The implementation of memristor required conventional system redesign and it is not beneficial as cost point of view for semiconductor industry.

**Applications Perspective of Memristor**

The interesting and singular nanoscales properties of memristor will be become a main work horse for circuit designing, soft computing, memory technology and neuromorphic hardware solution in the coming future.

***Memristor for Memories:*** The fast switching performances at very low biasing with low power consumption promises the memristor will be next paradigm in the memory technology in general and DRAM in specific. Memristors are often promoted as an emerging bi-stable switch for resistive random-access memory (ReRAM) [59]. The Moore’s expected law does not fulfil with the conventional technologies hence the integration of technologies such as spintronics, carbon nano tube field effect transistors and Memristor will be a better solution for System on Chip domains (SoC) [60].

***Memristor for Neuromorphic Computation:*** The field of neuromorphic computing tries to overcome problem of sequential execution and memory latency of conventional computer architecture using memristor. The memristor is support in the view of massive parallelism and plasticity of the brain. The resistive memristor structure mimics the synaptic behaviour of human brain. The non-volatile property of memristor makes a better solution and addressed some of the challenges in front of Neuromorphic Computation [61, 62].

***Memristor for Soft Computing:*** The memristor is a promising solution in the Artificial Neural Network (ANN) for learning and anticipating [63-67]. Along with the ANN, the memristor will play key role in the fuzzy logic [13, 68-69], genetic algorithm [70] and Neuro-Fuzzy system [71]. The memristor based ANN system are not matured enough to fulfil the current state of art development. There is no evidence that theoretical and simulated results of memristor application are carrying over the actual circuit and computation [72].

**Conclusion:** Memristor are on the way to change the future of science and technology. It is having many application domains that emerged few years back but we have to look at hidden memristive property in many aspects of natural things and phenomena’s. The circuit designing, soft computing, memory technology and neuromorphic computation are some of the application area, but not limited where we have to work in future perspectives. In order to continue further future progress in many sector of science and engineering, the memristor is likely to be key player in many applications. Although the mature technology is not reported that solve real time problem using memristive expertise. In future, the memristor will open new door of applications for energy efficient, reliable and scalable products.

Researcher arecontinue to explore new aspects of memristive system and part of published in the reputed journal. But the question remains at same place, *can memristor breakthrough conventional science?*, as a researcher i am very much optimistic towards potential of memristor. There is required little bit of time to change something from conventional. As a world is dynamic and there is certain possibility and probability that memristor make a new roadmaps, but one thing is, changes does not come with over the night, it required endurance and hardwork of at least one scientific generation.

**References**

1. Chua, L. O. Memristor - the missing circuit element, IEEE Trans. Circuit Theory, 18, 1971, 507–519.
2. Ketaki Kerur, A Study of The Memristor- The Fourth Circuit Element, M.Sc, project report for Visvesvaraya Technological University, 2010
3. Strukov, D. B., Snider, G. S., Stewart, D. R. & Williams, R. S. Nature, 453, 2008, pp.80–83
4. O. Kavehei, A. Iqbal, Y.S.Kim, K.Eshraghian, S. F. Al-Sarawi, Andd. Abbott, The fourth element: characteristics, modeling and electromagnetic theory of the memristor, Proc. R. Soc. A, 2010.
5. L. Chua and S.M. Kang, “Memristive Device and Systems,” Proceedings of IEEE, Vol. 64, no. 2, 1976, pp. 209-223.
6. Z. Biolek, D. Biolek, V. Biolková, "Spice Model of Memristor with Nonlinear Dopant Drift", Radio engineering, vol. 18, no. 2, 2009, pp. 210-214.
7. Yogesh N Joglekar and Stephen J Wolf, "The elusive memristor: properties of basic electrical circuits", European Journal of Physics, vol. 30, 2009, pp. 661–675.
8. Robinson E. Pino, Kristy A. Campbell, Compact Method for Modeling and Simulation of Memristor Devices, Proceeding of international Symposium on Nanoscale Architecture, 2010, pp.1-4.
9. Rak and G. Cserey, “Macromodelling of the memristor in SPICE,” IEEE Trans. Computer.-Aided Design Integr. Circuits Syst., vol. 29, no.4, Apr. 2010, pp. 632–636.
10. Z. Biolek, D. Biolek and V. Biolková, “SPICE model of memristor with nonlinear dopant drift”, Radio Eng., vol. 18, no. 2, Jun. 2009, pp. 210–214.
11. D. Batas and H. Fiedler, “A memristor SPICE implementation and a new approach for magneticflux-controlled memristor modeling”, IEEE Trans. Nanotech., vol. 10, no. 2, Mar. 2011, pp. 250–255.
12. S. Benderli and T. A. Wey, “On SPICE macromodelling of TiO2 memristor”, Electron. Lett., vol. 45, no. 7, Mar. 2009, pp. 377–379.
13. Merrikh-Bayat, Farnood, and Saeed Bagheri Shouraki. "Memristor crossbar-based hardware implementation of fuzzy membership functions." Fuzzy Systems and Knowledge Discovery (FSKD), 2011 Eighth International Conference on. Vol. 1. IEEE, 2011.
14. Karel Zaplatilek, Memristor modeling in MATLAB and Simulink, Proceedings of the European Computing Conference, 2010, pp. 62-67
15. Yogesh N Joglekar and Stephen J Wolf, The elusive memristor: properties of basic electrical circuits, Eur. J. Phys.30(2009) 661–675
16. S.W.Keemink, Mimicking synaptic plasticity in memristive neuromorphic systems, Life Sciences Graduate School, University of Utrecht, Utrecht, Netherlands, 2012
17. Tiny organisms remember the way to food, Available at: <http://www.newscientist.com/article/dn11394-tiny-organisms-remember-the-way-to-food.html> , Retrieved: 28 December, 2012.
18. Gorm K. Johnsen, An introduction to the memristor – a valuable circuit element in bioelectricity and bioimpedance, J Electr Bioimp, vol. 3, 2012, pp. 20 –28.
19. Johnsen GK, Lütken CA, Martinsen ØG, Grimnes S. Memristive model of electro-osmosis in skin. Phys Rev E, 83, 031916 (2011).
20. Grimnes S. Skin impedance and electro-osmosis in the human epidermis. Med Biol Eng Comp. 1983;21;739-49
21. S.P. Kosta, Y.P. Kosta, Mukta Bhatele, Y.M. Dubey, Avinash Gaur, Shakti Kosta, Jyoti Gupta, Amit Patel and Bhavin Patel, Human blood liquid memristor, Int. J. Medical Engineering and Informatics, Vol. 3, No. 1, 2011
22. H. M. Upadhyaya, Suresh Chandra: “Polarity dependent memory switching behaviorin Ti/Cd Pb S/Ag system.” Semiconductor Science and Technology 10, 332-338(1995)
23. D.H. Kwon, K.M. Kim, J.H. Jang, J.M. Jeon, M.H. Lee, G.H. Kim, X.S. Li, G.S. Park, B. Lee, S. Han, M. Kim, C.S. Hwang, Atomicstructure of conducting nanofilaments in TiO2resistive switching memory. Nat. Nanotechnol.5(2), 148–153 (2010)
24. C. Nauenheim, C. Kuegeler, A. Ruediger, R. Waser, Investiga-tion of the electroforming process in resistively switching TiO2 nanocrosspoint junctions. Appl. Phys. Lett.96(12) (2010)
25. S.J. Song, K.M. Kim, G.H. Kim, M.H. Lee, J.Y. Seok, R. Jung, C.S. Hwang, Identification of the controlling parameter for the set-state resistance of a TiO2resistive switching cell. Appl. Phys. Lett. 96(11) (2010)
26. T.A. Wey, S. Benderli, Amplitude modulator circuit featuring TiO2 memristor with linear dopant drift. Electron. Lett.45(22), 1103-U8 (2009)
27. X. Cao, X.M. Li, X.D. Gao, W.D. Yu, X.J. Liu, Y.W. Zhang, L.D. Chen, X.H. Cheng, Forming-free colossal resistive switching effect in rare-earth-oxide Gd2O3films for memristor applications. J. Appl. Phys.106(7) (2009)
28. T. Driscoll, H.T. Kim, B.G. Chae, M. Di Ventra, D.N. Basov, Phase-transition driven memristive system. Appl. Phys. Lett.95(4) (2009)
29. S.H. Jo, T. Chang, I. Ebong, B.B. Bhadviya, P. Mazumder, W. Lu, Nanoscale memristor device as synapse in neuromorphic systems. Nano Lett.10(4), 1297–1301 (2010)
30. Francesca Pincella, Paolo Camorani, Victor Erokhin, Electrical properties of an organic memristive system, Appl Phys A (2011) 104:1039–1046
31. Kyung Hyun Choi, Maria Mustafa, Khalid Rahman, Bum Ko Jeong, Yang Hui Doh, Cost-effective fabrication of memristive devices with ZnO thin film using printed electronics technologies, Appl Phys A (2012) 106:165–170
32. Murali S et al. Resistive switching in zinc–tin-oxide. Solid State Electron (2012), <http://dx.doi.org/10.1016/j.sse.2012.06.016>
33. Byung Joon Choi et al, Nitride memristor, Appl Phys A (2012) 109:1–4
34. E. Gale, D. Pearson, S. Kitson, A. Adamatzky, B. de Lacy Costello, “Aluminium Electrodes Effect the Operation of Titanium Oxide Sol-gel Memristors,” arXiv:1106.6293v1
35. T. Berzina, A. Smerieri, M. Bernabo, A. Pucci, G. Ruggeri, V. Erokhin, M.P. Fontana, Optimization of an organic memristor as an adaptive memory element, Journal of Applied Physics 105 (12) (2009) 124515.
36. T.W.K. Dong Ick Son, J.H. Shim, J.H. Jung, D.U. Lee, J.M. Lee, W.I. Park, W.K. Choi, Flexible organic bistable devices based on graphene embedded in an insu-lating poly(methyl methacrylate) polymer layer, Nano Letters 10 (7) (2010)2441
37. Julien Borghetti, Gregory S. Snider, Philip J. Kuekes, J. Joshua Yang, Duncan R. Stewart and R. Stanley Williams, ‘Memristive’ switches enable ‘stateful’ logic operations via material implication, Nature, Vol 464|8 April 2010, http:// doi:10.1038/nature08940
38. S.H. Jo, T. Chang, I. Ebong, B.B. Bhadviya, P. Mazumder and W. Lu, Nanoscale Memristor Device as Synapse in Neuromorphic Systems, Nano letters, Am. Chem. Soc., vol. 10, no. 4 pp. 1297 -1301, 2010.
39. G. S. Snider, “Self-organized computation with unreliable, memristive nanodevices, Nanotechnology, vol. 18, p. 365202, 2007.
40. A. Afifi, A. Ayatollahi, and F. Raissi, “STDP implementation using memristive nanodevice in CMSO-nano neuromorphic networks,” IEICE Electron. Expr., vol. 6, no. 3, pp. 148–153, Feb. 2009.
41. Y. V. Pershin, S. L. Fontaine, and M. D. Ventra, “Memristive model of amoeba learning, Phys. Rev. E, vol. 80, p. 021926, 2009.
42. B. Linares-Barranco and T. Serrano-Gotarredona, Memristance can explain Spike-Time-Dependent-Plasticity in Neural Synapses, Nature Precedings: hdl:10101/npre.2009.3010.1, Mar 2009
43. T. Prodromakis and C. Toumazou, A Review on Memristive Devices and Applications, ICECS- 2010, pp-936-939
44. B. Muthuswamy and P. P. Kokate, “Memristor-based chaotic circuits,” IETE Tech. Rev., vol. 26, no. 6, pp. 417–429, Dec. 2009.
45. M. Itoh and L. O. Chua, “Memristor oscillators,” Int. J. Bifurcation Chaos, vol. 18, no. 11, pp. 3183–3206, Nov. 2008.
46. P. Vontobel, W. Robinett, P. Kuekes, D. Stewart, J. Straznicky, and R. Williams, “Writing to and reading from a nano-scale crossbar memory based on memristors, Nanotechnology, vol. 20, p. 425204, 2009.
47. M. B. Laurent, “Pattern recognition using memristor crossbar array,” U.S. Patent 7 459 933, Dec. 2, 2008.
48. A. Afifi and A. Ayatollahi, “Implementation of biologically plausible spiking neural network models on the memristor crossbar based CMOS/Nano circuits,” in Proc. Eur. Conf. Circuit Theory Des., 2009, pp. 563–566.
49. J. Borghetti, Z. Y. Li, J. Straznicky, X. M. Li, D. A. A. Ohlberg, W. Wu, D. R. Stewart, and R. S. Williams, “A hybrid nanomemristor/transistor logic circuit capable of self-programming,” in Proc. Nat. Acad. Sci., 2009, pp. 1699–1703.
50. M. B. Laurent, “Programmable Crossbar Signal Processor,” U.S. Patent 7 302 513, Nov. 27, 2007.
51. Neil D. Mathur, The fourth circuit element, Nature, Vol 455, 30, 2008, doi:10.1038/nature07437
52. Vongehr, S. (2012). The Missing Memristor: Novel Nanotechnology or rather new Case Study for the Philosophy and Sociology of Science?. arXiv preprint arXiv:1205.6129. p.10
53. Chun Ning Lau, Duncan R. Stewart, R. Stanley Williams, Marc Bockrath: “Direct Observation of Nanoscale Switching Centers in Metal/Molecule/Metal Structures.” Nano Letters 4(4), 569-572 (2004)
54. X. Wu, P. Zhou, J. Li, L. Y. Chen, H. B. Lu, Y. Y.Lin, T. A. Tang: “Reproducible unipolar resistance switching in stoichiometric ZrO2 films.”Applied Physics Letters 90, 183507 (2007)
55. R. Waser, M. Aono: “Nanoionics-based resistive switching memories.” Nature Materials 6, 833-840 (2007)
56. Y. V. Pershin, M. Di Ventra: “Spin memristive systems: Spin memory effects in semiconductor spintronics.” Phys. Rev. B 78, 113309 (2008)
57. Meuffels, P., & Soni, R. (2012). Fundamental Issues and Problems in the Realization of Memristors. arXiv preprint arXiv:1207.7319
58. Jagdish Kumar, Memristor- why do we have to know about it?, IETE technical review, vol-26, issue -1, 2009, pp.3-6
59. Prodromakis, T., and C. Toumazou. "A review on memristive devices and applications." Electronics, Circuits, and Systems (ICECS), 2010 17th IEEE International Conference on. IEEE, 2010, pp. 936-939.
60. Eshraghian, K.; Kyoung-Rok Cho; Kavehei, O.; Soon-Ku Kang; Abbott, D.; Sung-Mo Steve Kang; "Memristor MOS Content Addressable Memory (MCAM): Hybrid Architecture for Future High Performance Search Engines," IEEE Transactions on Very Large Scale Integration (VLSI) Systems, vol.19, no.8, Aug. 2011, pp.1407-1417.
61. Erokhin, T. Berzina, A. Smerieri, P. Camorani, S. Erokhina, and M. Fontana, “Bio-inspired adaptive networks based on organic memristors,” Nano Communication Networks, vol. 1, no. 2, 2010, pp. 108 – 117.
62. S. H. Jo, T. Chang, I. Ebong, B. B. Bhadviya, P. Mazumder, and W. Lu, “Nanoscale memristor device as synapse in neuromorphic systems”, Nano Lett., vol. 10, pp. 1297–1301, 2010
63. Hu, J., & Wang, J. Global uniform asymptotic stabil-ity of memristor-based recurrent neural networks with time delays. In: 2010 International Joint Conference on Neural Networks, IJCNN 2010, Barcelona, Spain, pp. 1-8, (2010).
64. Pershin, Y. V., & Di Ventra, M. Experimental demon-stration of associative memory with memristive neural net-works. Neural Networks, 23(7), 881-886, (2010a).
65. Wu, A. L., Wen, S. P., & Zeng, Z. G. Synchroniza-tion control of a class of memristor-based recurrent neural networks. Information Sciences, 183(1), 106-116, (2012).
66. Wu, A. L., Zeng, Z. G., Zhu, X. S., & Zhang, J. E. Exponential synchronization of memristor-based recur-rent neural networks with time delays. Neurocomputing, 74(17), 3043-3050, (2011).
67. Wu, A., & Zeng, Z. Dynamic behaviors of memristor-based recurrent neural networks with time-varying delays. Neural Networks (2012). doi:10.1016/j.neunet.2012.08.009
68. Klimo, Martin, and Ondrej Such. "Memristors can implement fuzzy logic." arXiv preprint arXiv:1110.2074 (2011).
69. Merrikh-Bayat, Farnood, Saeed Bagheri Shouraki, and Farshad Merrikh-Bayat. "Memristive fuzzy edge detector." Journal of Real-Time Image Processing (2011): 1-11.
70. Merrikh-Bayat, Farnood, and Saeed Bagheri Shouraki. "Programming of memristor crossbars by using genetic algorithm." Procedia Computer Science 3 (2011): 232-237.
71. Merrikh-Bayat, F., and Shouraki S. Bagheri. "Memristive Neuro-Fuzzy System." IEEE transactions on systems, man, and cybernetics. Part B, Cybernetics: a publication of the IEEE Systems, Man, and Cybernetics Society (2012).
72. Keemink, S. W. "Mimicking synaptic plasticity in memristive neuromorphic systems." (2012). Available at: <http://igitur-archive.library.uu.nl/student-theses/2012-0831-200644/UUindex.html>