Investigation of Memristor-Based Memory Cell in the Framework of Low Power Consumption and Improved Read/Write Time

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Abstract

Memristor is a non-linear passive circuit element. It was visualized by Leon Chua in 1971. Memristor can form a non-linear relationship with electric charge and magnetic flux. Memristor has the capability to hold data even if it is not connected to any power source. This property makes it non-volatile in nature. Memristor is a non-volatile memory which can be used for data storage. International Technology Roadmap for Semiconductors acknowledges that it is difficult to scale the transistor beyond its current size and to overcome the existing memory issues, emerging memristor technology is being developed. The objective of this research is to realize the memristor based non-volatile memory which can consume less power with better Read/Write time. In this research, properties and construction of memristor is analyzed. We use MATLAB to verify the operation of the memristor in a Simulink model built with parameter values given in recently published papers. In order to construct a memristor, various softwares like LTspice and MATLAB are used. More specifically, this paper describes the superiority of memristor memory in terms of low power consumption compared to transistor-based memory cells.

Keywords—Memristor, Non-volatile memory, Read/Write circuit, SRAM Cell, Average Power/Energy

I. INTRODUCTION

THE Memristor is a non-linear and fourth circuit element. It was introduced by Leon Chua in 1971 [1]. It actually regulates the flow of current in a circuit It also remembers the amount of charge that has previously flowed through it. It has the ability to store data in the form of resistance. Due to this property it is also known as non-volatile device. In 2008, researchers at HP LAB proved the existence of fourth fundamental circuit element known as memristor [2]. Memristor is the combination of memory and resistance and it is a passive element. Unlike transistor, it does not have an equivalent circuit.

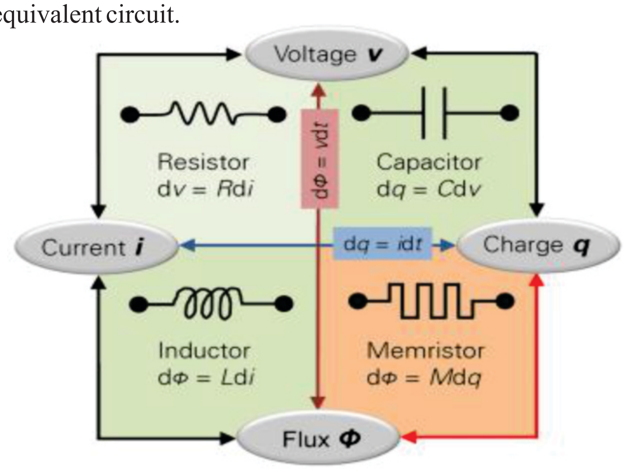

Fig. 1. Memristor as fourth circuit element [1]

Memristance is a charge dependent resistance [3] [4]. Unit of Memristance is Ohm. Memristor is a passive circuit element because it does not produce energy [5].

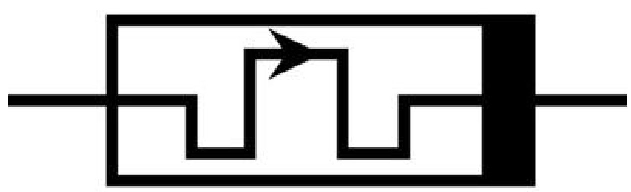

Fig. 2. Symbol of Memristor [1]

Memristors are categorized in many types on the basis of design and construction.

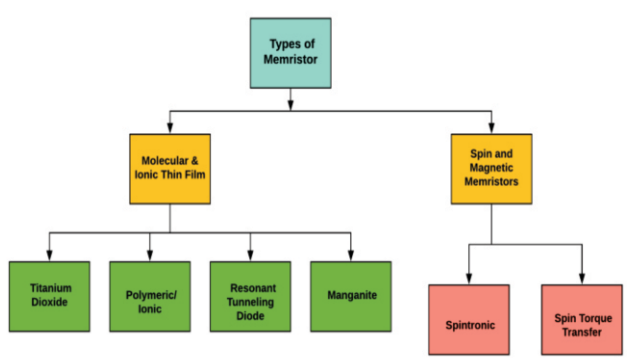

Fig. 3. Types of Memristor [1]

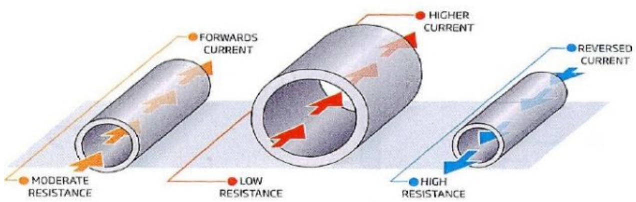

Fig. 4. Memristor Pipe Analogy [2]

For memory design, the power dissipation and area are the main factors and the SRAM block is an important part in SoC design. Memristor can form a non-linear relationship with electric charge and magnetic flux [6] [7]. Memristor has the capability to hold data even if it is not connected to any power source. This property makes it non-volatile in nature. The main objective of this research is to make memristor based non-volatile memory which can consume less power and energy. In this research, construction and properties of memristor is analyzed. Analogy of memristor is different from resistor and it is analogous to special kind of pipe. The diameter of this pipe is not fixed and it describes the physical analogy of memristor. When water flows through it in one direction, diameter of this pipe increases. When diameter of pipe increases, resistance decreases. In opposite direction, diameter of pipe decreases when water flows through it [8].

II. LITERATURE REVIEW

The memristor was first hypothesized in 1971 by Leon Chua [9] [10]. He was the professor of Electrical Engineering at University of California. The first functional memristor was introduced by HP Labs in 2008 [11]. Leon described this element as missing circuit element which is also known as memristor. It exhibits peculiar behavior which is different from resistor, capacitor and inductor. Memristor can save its electronic state. The first resistive switching was identified by Hickmott in 1962. I-V plot of resistive switching is similar to pinched hysteresis loop with zero crossing. Dielectric breakdown is not a resistive switching event because insulating state cannot be recovered. Hickmott utilized SiO, Al_2O_3, Ta_2O_5, ZrO_2 and TiO_2 as the materials of insulator. These all can exhibit reversible resistive switching. Hickmott argued about electric fields present across the thin-films of oxide material which were suitable to induce dielectric breakdown [12] [13]. Hickmott's interest in resistive switching led to observe the effects of non-volatile memory devices [14].

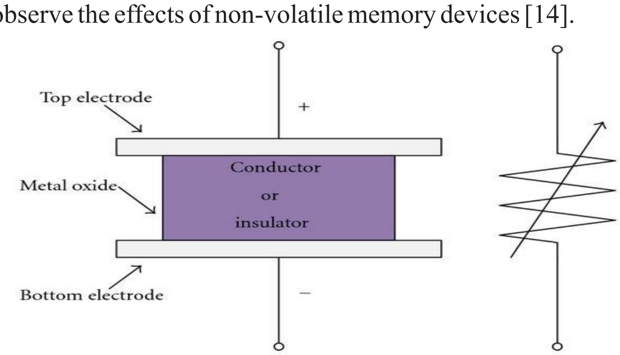

Fig. 5. Basic Structure of Resistive RAM [2]

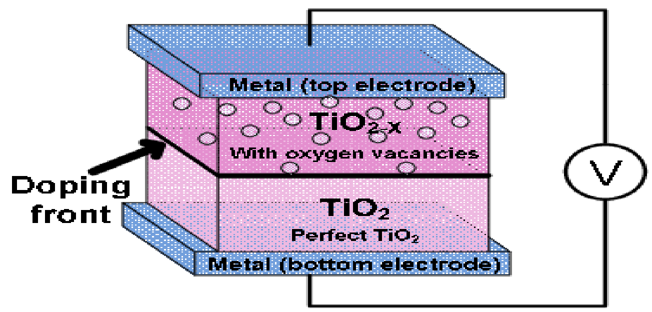

Fig. 6. TiO_2 thin-film memristor [2]

In 2008, Stanley Williams found a perfect memristor in titanium dioxide [15] [16]. Titanium dioxide is a semiconductor simply like silicon and it is extremely resistive in its unmodified state [17].

The two terminal memristor utilizes TiO_2 as resistive material and when a voltage is applied through cathodes, oxygen particles diffuse in relation to polarity of the voltage. Unlike resistors, memristors can be programmed [18].

Memristor has sandwiched metal/insulator/metal structure [19]. Active insulating layer is inserted between top and bottom electrode. Memristor can exhibit pinched hysteresis characteristic [20].

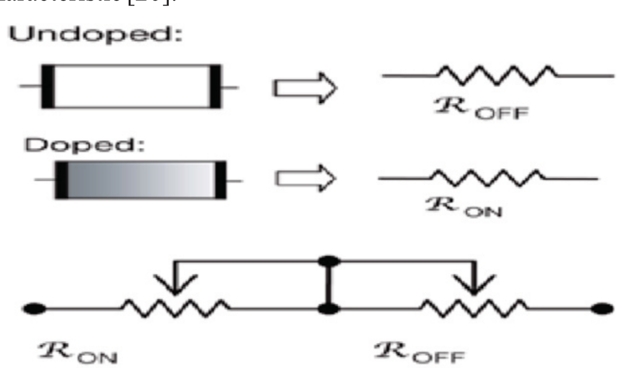

Fig. 7. Equivalent circuit representation [2]

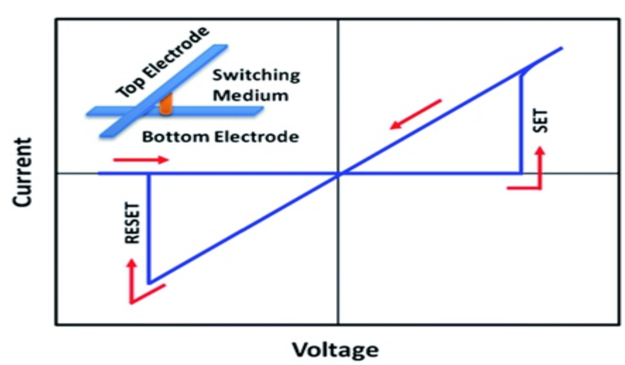

Fig. 8. Current-Voltage characteristics of memristor [3]

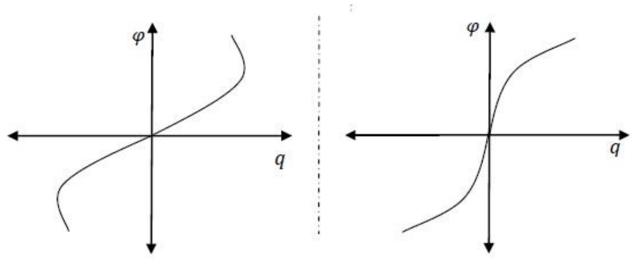

Fig.9. Memristor φ-q curves [4]

When the frequency of forcing signal increases, it shrinks the area of each lobe of pinched hysteresis loop. At high frequencies memristor will produce a straight line which will be the representation of a linear resistor [21] [22]. Chua used four circuit properties φ, q, V and I to predict the existence of memristor. Memristor has the essential characteristic of hysteresis loop. If the size of the pinched hysteresis curve increases, power dissipation increases as well [23]. The φ-qcurve of memristor is always monotonically increasing function [24] [25].

III. EXPERIMENTAL WORK

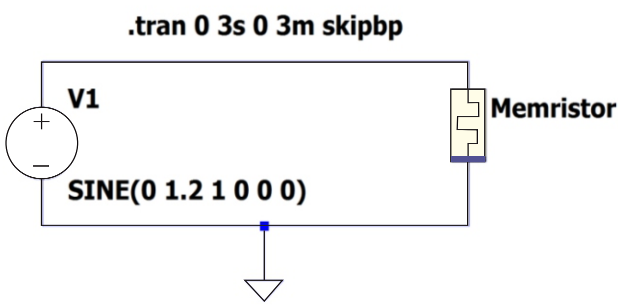

Fig. 10. Memristor Model in LTSpice

This is the most direct simulation of a circuit and it computes the behavior of the circuit. A model consists of subcircuit and symbol. In this LTSpice model, initial operating point solution is not selected and subcircuit model of memristor has been added which includes model definition.

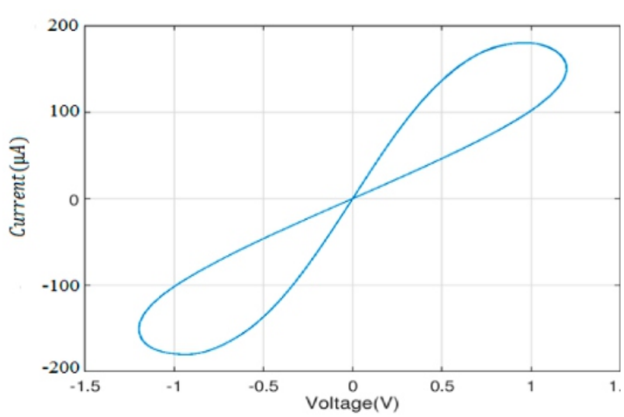

Fig. 11. V-I Plot of Memristor

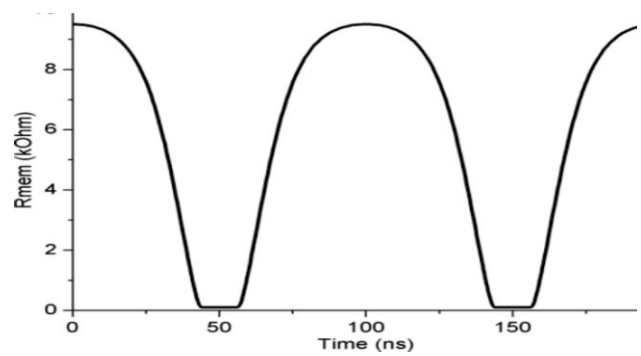

Fig. 12. Rmem VS Time

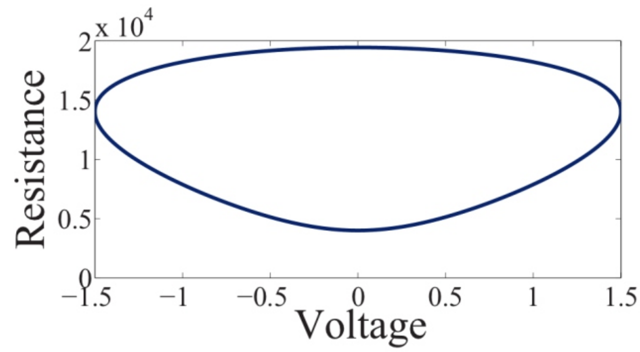

Fig. 13. Memristor resistance vs Voltage

For memory design, the power dissipation and area are the main factors and the SRAM block is an important part in SoC design. Memory cell can be designed by using memristor.

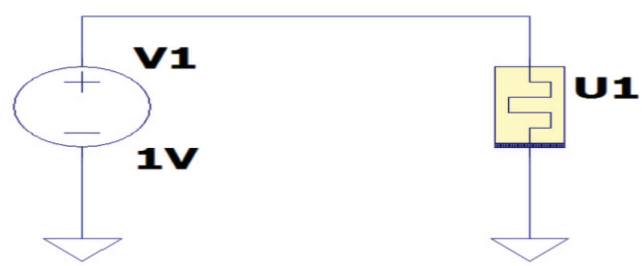

Fig. 14. Memristor Write operation structure

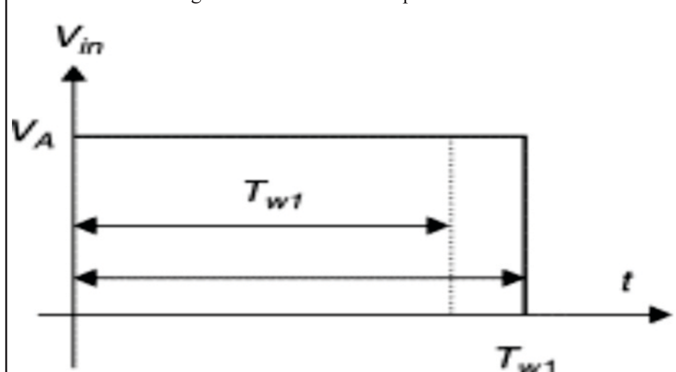

Fig. 15. Positive voltage pulse to Write One

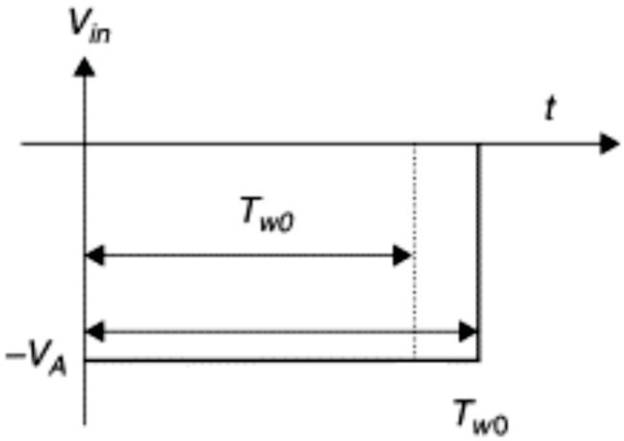

Fig. 16. Negative voltage pulse to Write Zero

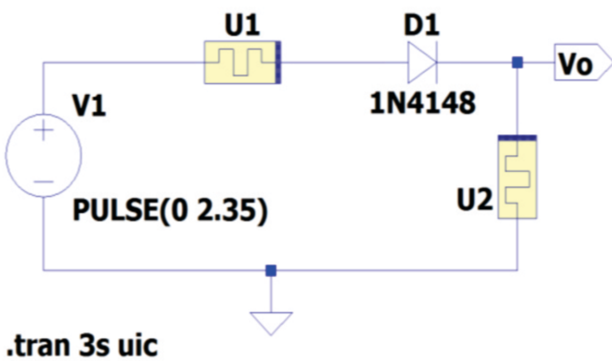

Fig. 17. Read circuit for memristor memory

Circuit is simply a voltage source with memristor in series and the positive pulse will change the memristance of memristor to its R_{off} value. When positive pulse is applied, it will write a logic one and when negative voltage pulse is applied, it will write logic zero.

While applying positive voltage to circuit, Memristor U1 is in the ON state and U2 is used as a load. The output voltage drop across the U2 indicates which data is stored on the memory cell and when the negative pulse is applied, stored data is logic 0 and U1 is in OFF state. Due to OFF state of U1, diode switches OFF and there is no current in U2.

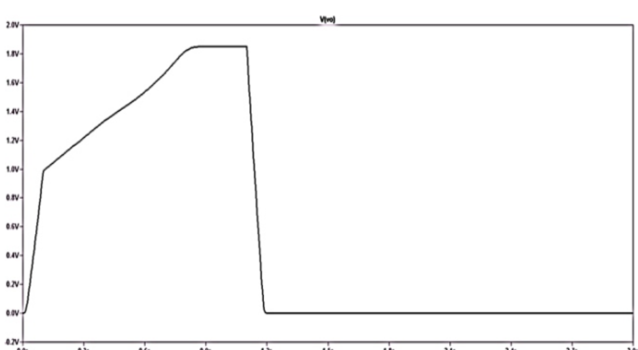

Fig.18. Output voltage waveform during positive voltage

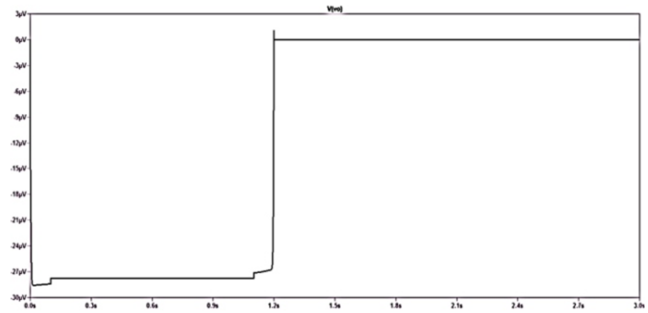

Fig. 19. Output voltage across U2 Memristor during nagative voltage

U2 Memristor acts as a load and it stores logic zero. When negative voltage is applied to read circuit, Memristor U2 gives low output. At first, there are negative micro-volts across load and then the output voltage reaches zero volts. Memristors have the benefit of being nonvolatile device and the memristor is relied upon to change to the ON state quicker than changing to the OFF state.

Proposed design describes the single bit memristor based memory. It can store only two logic levels. Proposed write circuit shows swift access time and furthermore low power utilization. Nonvolatile memory is essential for giving storage to nano-technology.

SRAM cell is mainly used for the cache memory in microprocessors and it is widely accepted as the standard memory cell. Memristor is compatible with conventional CMOS to construct non-volatile memristor based memory cell.

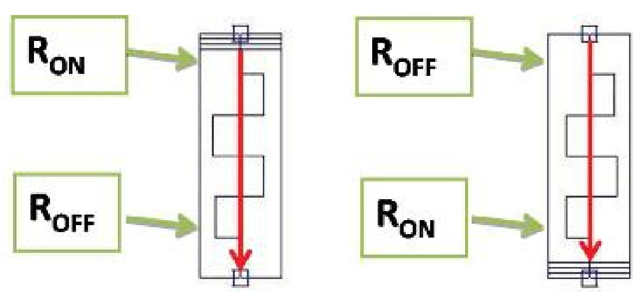

Fig. 20. Memristor's configuration from ON to OFF and OFF to ON

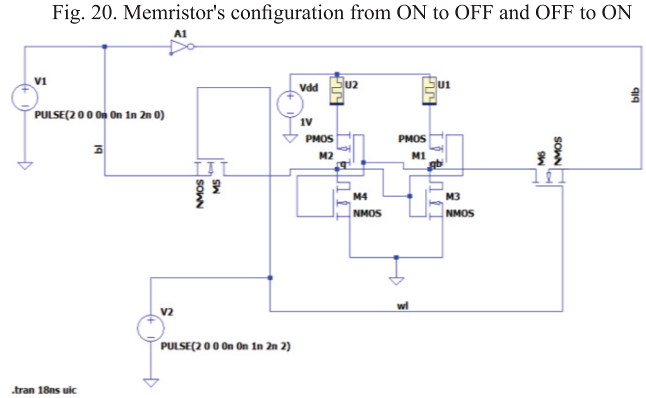

Fig. 21. Memristor based 6T SRAM Cell

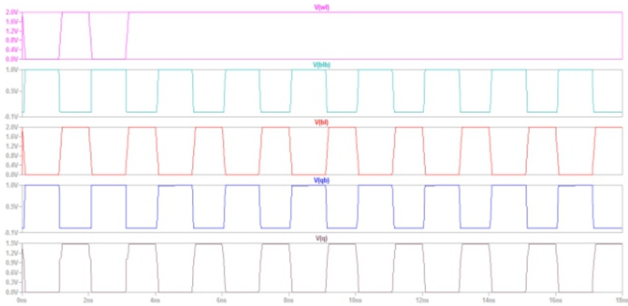

Fig. 22. Output waveforms of Memristor based SRAM Cell

Non-volatile memory cell can be designed using CMOS transistors and memristors. It shows the feasibility of integration of memristors with CMOS.

Table I. Average Power at each node of Memristor Memory Cell

Circuit Node	Average Power
At Memristor U1	74.26pW
At Memristor U2	412.01nW
At M1	4.9187nW
At M2	1.4595µW
At M3	6.8455nW
At M42	6.83nW
At M5	2.0889µW
At M6	891.14pW
At VDD	3.9753µW

IV. RESULTS AND DISCUSSION

It has been shown experimentally that memristor exhibits pinched hysteresis loop and a small voltage drop across non-volatile memristor will yield an enormous electric field. Memristor based non-volatile memory cell consumes less power.

Table II. Calculations for read circuit for high level logic

Average Power	Energy	Read Time
192.62µW	577.86µJ	3ps

For read circuit, average power consumption at output for reading logic 1 is 192.62µW and for reading logic zero or low output, average power at output is 1.063pW.

Table III. Calculations for read circuit for low level logic

Average Power	Energy	Read Time
1.063pW	3.189pJ	3ys

For write logic one, average power consumption of write voltage is -6.2492mW which is reasonable for writing logic one and for write logic zero, average power of write zero pulse is approximately 67.506µW.

Table IV. Calculations for write circuit for positive pulse

Average Power	Energy	Write Time
-6.2492mW	-6.2492mJ	1.000032µs

Table V. Calculations for write circuit for negative pulse

Average Power	Energy	Write Time
67.506µW	67.506µJ	1ps

Table VI. Average Power Comparison between SRAM and Memristor Memory

Circuit Node	Average Power Memristor based SARM)	Average Power (6T SRAM Cell)
At M1	4.9187nW	7.3531nW
At M2	1.4595µW	2.3366µW
At M3	6.8455nW	7.0488nW
At M4	26.83nW	28.881nW
At M5	2.0889µW	2.6963µW
At M6	891.14pW	1.3532nW
At VDD	3.9753µW	5.0481µW

LTSpice model of memristor is based on nonlinear transient analysis. Transient analysis calculates a circuit's response. A model consists of subcircuit and symbol. In this LTSpice model, initial operating point solution is not selected.

Table VII. Energy Comparison

Circuit Code	Energy (Memristor based Memory Cell)	Energy (6T SRAM Cell)
At M1	0.088537fJ	0.13235fJ
At M2	26.271fJ	42.059fJ
At M3	0.12322fJ	0.12688fJ
At M4	0.48293fJ	0.51986fJ
At M5	37.601fJ	48.534fJ
At M6	0.016041fJ	0.024358fJ
At VDD	71.555fJ	90.865fJ

It clearly shows that average power and energy in memristor based 6T memory cell is reduced compared to that of the conventional 6T SRAM memory cell and thus power consumption is also reduced by using memristor.

V. CONCLUSION

In this paper, fundamental properties of memristor have been discussed. Memristor is a non-volatile memory and it exhibits pinched hysteresis loop. Memristor memories are also non-volatile and it is better than conventional 6T SRAM Cell. Memristor based non-volatile SRAM Cell consumes less average power and energy as compared to conventional 6T SRAM. The switching power consumption for memristor can be smaller than flash memories. In terms of density, memristor based memory is better than NAND flash memory.

Table VIII. Density Comparison between Memristor and NAND Flash

	Memristor	NAND Flash
Non-Volatile	Yes	Yes
Density	4.5 TB/sqin	1700 GB/sqin (3D-NAND)

Density of single layer memristor crossbars is 4.5 Terabits per square inch. In memory application, memristor uses non-volatile resistance to characterize digital information.

Memristor can contribute in artificial neural networks. A new type of neural network can be made with memristors. Von Neumann computing system based implementations of neural networks are suffering from memory wall. Memristor can provide energy efficient neuromorphic computing.

When a memristor is used to act as a neuron, it is not vital that conductance of memristor accomplish continuous change. Pulses can change the conductance of memristor. Memristors with tunable resistance states are emerging building blocks of artificial neural networks. Hardware implementations of artificial neural networks can be feasible due to memristor. Synaptic memristor has attracted much attention for its potential in neuromorphic applications.

VI. ACKNOWLEDGMENT

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1. In science, there are no shortcuts to truth." - Carl Sagan
2. "The most exciting phrase to hear in science, the one that heralds new discoveries, is not 'Eureka!' but 'That's funny...'" - Isaac Asimov
3. "The saddest aspect of life right now is that science gathers knowledge faster than society gathers wisdom." - Isaac Asimov
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