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Design of Memristor, Memristive based Logic gates and its Application

Pooja N[1], J C Narayanaswamy[2]

[1]*PG Student, Dept. of Electronics and Communication Engineering, Bangalore Institute of Technology, Karnataka, India*
[2]*Assistant professor, Dept. of Electronics and Communication Engineering, Bangalore Institute of Technology, Karnataka, India*

Abstract - *During the early days, memristor technology has undergone an invasive growth, which has the capability to transform the information processing and storage in whole circuit theory. By using the memristors the information can be stored and processed on the same physical location. To inspect any advanced computing architectures, the Memristor based digital logic circuits has various ways, in which they may provide an optimistic alternative to conventional IC technology. This paper presents the design of memristor and memristive based logic gates. The V-I characteristics of the designed memristor is observed. The logic gates which have been designed using memristor can perform the computations and the value can be stored. Further, the designed memristor is applied to the application of memory like content addressable memory (CAM). And also, the comparison of the performance metrics like area and delay is done between the CAM without memristor and CAM with memristor.*

Key Words: **Memristor, logic gates, Content addressable memory (CAM)**

1. INTRODUCTION

In recent years, as there is a rapid growth in digital electronics, memory with less area occupation becomes an important factor in current integrated circuits and systems. In 1971, the scientist named Leon Ong Chuan who was working at a University of California, Berkeley, theorized a fourth element called as a memory resistor or memristor. A memristor is a two terminal device with a combination of both memory and a resistor. Memristor is a non-volatile electronic device i.e., data will be stored if the power supply is turned off. The memristor would provide a relationship between magnetic flux and charge to that of the relationship between the voltage and current of a resistor. Hence, the memristor will act similar to that of a resistor whose value could vary depending on the current passing through it.

Memristor is one of the best types to implement any type of memories and also for any state full logic operations, since there is a greater advantage of the memristor in terms of storage and nanometer dimensions. Due to this, the performance characteristics of the memristor are seen as a major factor in the field of electronics. The memristor mainly depends on resistance switching mechanism, where it determines state of the analog memory of the device. The relationship between the time integral of current and voltage of the memristor depends on the magnitude and polarity of the voltages across it. The uniqueness of the memristive devices is its non-volatile property and this is the main cause to differ from the other elements of the fundamental electronic/electrical circuit. Some of the other advantages of the memristor are in manufacturing high performance memory and logic applications, such as Nano scale size, non-volatility, high-density, low-power, good scalability, and so on. It is also possible to improve the circuit's performances and power dissipation by using these memristors.

In this work, a memristor is designed and by using this memristor the logic gates are designed. By using this designed memristor-based logic gates many typical logic operations and values can be performed and stored. This would be helpful for the design and implementation of any kind of computational architecture. By using the designed memristor, the different types of memories like BRAM, Re-RAM, CAM etc. can be designed.

2. METHODOLOGY

Almost 40 years after the invention of the memristor (1971), the scientist named Stanley Williams has fabricated a two-terminal titanium dioxide Nano scale device as Group in HP Labs, where the device mainly shows the features of memristor. Later on, a group of scientists and researchers started to make a research on memristor since it has many unique properties and make a lot of achievements based on this.

Memristors constitutes a group of resistive switching multi-state memory devices which are of two terminals device in which, the device can be well suited with already existing integrated circuit technologies. One of the main properties of this memristors is non-volatility property. The passive device named "memristor" gives the functional relationship between the electric charge (q) and flux (φ). The flux (φ) between the memristors two terminals is given as a function of amount of charge (q) flowing through this device. And also, the energy cannot be stored in the device. This two terminal device is also known as charge controlled device. The symbol of the memristor is shown in the below Fig -1.

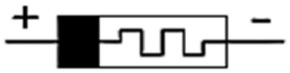

Fig -1: Memristor symbol

The memristor will have the higher resistance when the current flows outwards from the black thick line and the resistance decreases when the current flows into the black thick line. When the applied external voltage is removed then the memristor remains in its last state i.e. memristor have resistive memory. Hence the resistance of the memristor can be changed by changing the direction of applied voltage or current.

The fabricated memristor component consist of the two thin film coatings of Titanium di-oxide ($TiO2$) with the "doped" and "un-doped" regions which are covered in between the platinum chemical substance. The doped region consists of oxygen vacancies which indicate the resistance reduction in the material by providing the electrons which carries the current along with it. When the positive voltage is applied to the device, oxygen vacancies will be moved to the un-doped region which makes the device to act as a metal insulator which results in turning on the device. If the applied voltage polarity is reversed, then the device will be turned off. And also, the un-doped region of the device indicates the high resistive region. The doped and un-doped regions of the memristor are shown in below Fig -2.

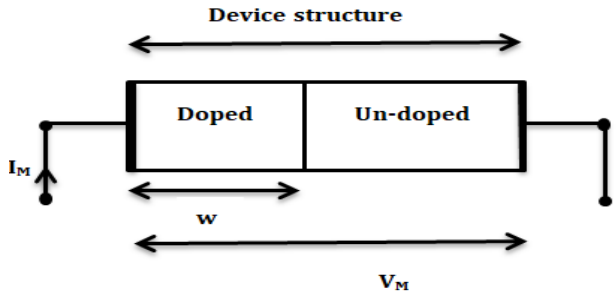

Fig -2: Doped and un-doped regions

Where, the term w indicates the doped section, I_M and V_M indicates the current and voltage of the memristor.
The overall resistance of the device is the total contribution from the two layers, since the electric current has to go through both doped and un-doped regions, which is being passed through the device.

3. PROPOSED SYSTEM

The memristor is an element which changes its resistance depending on how much charge that flows through it. The memristor inhibits the features of a linear resistor with memory and also shows the nonlinear characteristics. Memristor is a non-linear electrical component which provides the relation of charge and flux, where the function of flux indicates the amount of charge flowing into it and the equation (1) of this is shown below.

$$\varphi = f(q) \quad \text{.....(1)}$$

The relation between the charge and flux can also be defined by using the below equation (2)

$$M(q(t)) = d\,\varphi\,(q)/dq \quad \text{.....(2)}$$

The memristor also provides the linkage and relation between the quantities like voltage (v), current (i), charge (q) and flux (φ) and these are shown below

$$V(t) = M(q(t))i(t) \quad \text{.....(3)}$$

$$i(t) = w(\varphi(t))v(t) \quad \text{.....(4)}$$

$$w(\varphi) = dq(\varphi)/d\varphi \quad \text{.....(5)}$$

The scientist Chua has described that the memristor is a part of memristive systems and the following equation gives the relation between the fundamental elements.

$$V = M(w, i)\, i(t)$$

$$dw/dt = f(w, i) \quad \text{.....(6)}$$

Where,
w represents the unity of conductance
M(q) represents unity of resistance

Initially to know the characteristics of memristor, the two input signals i.e. sine and square signal with respect to time and amplitude are given to a non-linear device so that the voltage, current, flux and charge characteristics can be obtained. To design a memristor, the functions like mobility of electrons, on resistance, off resistance, initial resistance, device length, time and voltage are provided. Here, the default values provided to design a memristor are:

Mobility of electrons = 10^ -14
On resistance (minimum) = 0.1k
Off resistance (maximum) = 38k
Initial resistance = 1k
Device length = 10nm

By using the below given equation and by substituting the values and presenting this equation in the matlab code, leads to the design of the memristor.

$$V(t) = [((R_{ON}\, w(t))/D_L) + R_{OFF}(1 - (w(t)/D_L)]\, i(t) \quad \text{.....(7)}$$

$$dw(t)/dt = ((\mu v R_{ON})/D_L)\, i(t) \quad \text{.....(8)}$$

The above equation (6) represents the hysteresis loop and the equation (7) and (8) represents the mathematical model of the memristor. And also the saturation condition of the memristor is shown by setting the threshold value of on resistance and off resistance.

The below fig -3 shows the characteristics of the fundamental electrical quantities (v,I, φ,q) of the memristor.

3.1 output of designed memristor

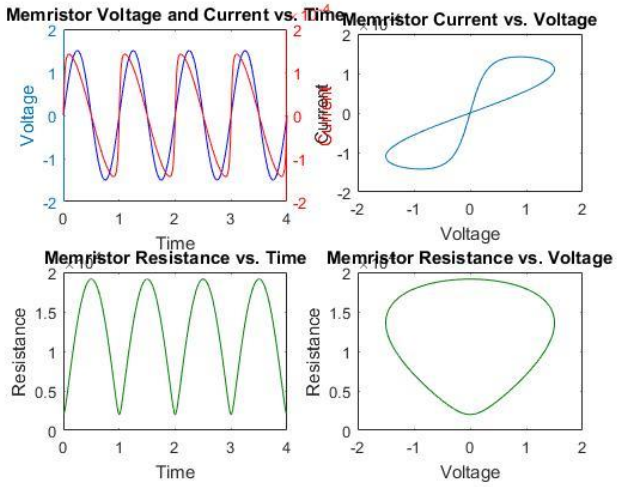

Fig -3: Characteristics of the memristor

In the above fig -3, the first graph shows the relationship between current–voltage versus time, here the current increases as the applied voltage increases with respect to time.

The second graph shows the relationship between current versus voltage, here the slope of the hysteresis curve indicates the electrical resistance. The modifications in the slope of the pinched hysteresis curves exhibit the switching between different resistances states which is the main factor in a two terminal resistance memories.

The third graph shows the relationship between resistances versus time, since the instantaneous resistance lies in the span [R_{ON}, R_{OFF}] the values of the resistance are determined based on the externally applied voltage. For an input sine wave, the memristance will have the values at the time instance t = (2n+1) T/2.

The fourth graph shows the relationship between resistance versus voltage, here initially the voltage and current across the memristor are 0 volt and 0 amperes and the resistance will be R_i and the memristance value depends up on the voltage v(t), such that resistance R_i increases for v(t) <0 and resistance R_i decreases for v(t) > 0.

3.2 Logic Gates

Here, the boolean logic gates have been designed using the above designed memristor. The memory of the designed memristor is used to store the data and performs the respective operations.

Initially to design the logic gates, a cell based on threshold logic is designed, and this cell will operate based on control voltage (V_C). By applying the initial threshold voltage the memristor will be turned on, in which they show the linear conductance. And also, the memristors resistance will decreases in the direction of the current flow. By using this cell, the entire family of logic gates can be designed by using the resistive switching property of the memristors.

OR gate

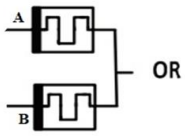

Fig -4: OR gate using memristors

The above fig -4 shows the structure of the OR gate using memristors, here the two memristors are connected in parallel to the polarities and when the current flows into the memristor, the resistance decreases and reaches R_{ON} state (minimum resistance) and when the current flows out of the memristor, the resistance increases and reaches R_{OFF} state (maximum resistance). The OR gates output voltage is given by the below equation.

$$V_{out} = (R_{off}/(R_{off} + R_{on}))\, V_{DD} \text{ ..... (9)}$$

AND gate:

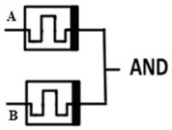

Fig -5: AND gate structure using memristors

The above fig -5 shows the structure of the AND gate using memristors, here the two memristors are connected in parallel at opposite polarities to that of the OR gate, when the current flows into the memristors, the resistance increases and reaches R_{OFF} state and when the current flows out of the memristor, the resistance decreases and reaches R_{ON} state. The AND gates output voltage is given by the below equation.

$$V_{out} = (R_{ON} / (R_{OFF} + R_{ON}))\, V_{DD} \text{ ..... (10)}$$

NOR gate:

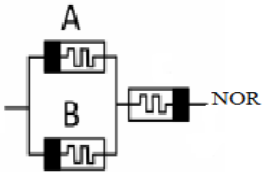

Fig -6: NOR gate structure using memristors

The above fig -6 shows the structure of the NOR gate using memristors, here the two input parallel memristors are

considered and these are in-turn connected with the output memristor in series. Initially, a low resistance value will be written to the output memristor and for the input memristor the input values will be given and then the input voltage will be applied. Since, low resistance value is given to the output memristor, the input memristor has to be given with high resistance and the voltage should be high and only when both memristors have high resistance, then to switch the configuration of the output memristor to logic 0 from logic 1, the voltage across the output memristor should be high enough.

NAND gate:

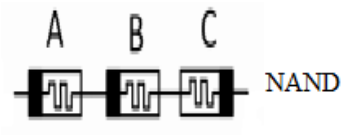

Fig -7: NAND gate structure using memristors

The above fig -7 represents the structure of a NAND gate using memristors, here the two input memristors are connected in series and also the output memristor is connected to these memristor in series with an output memristor. In this NAND gate, when the memristance of both the input memristor are low, then the voltage across the output memristor should be high to change the configuration of the output memristor from logic 1 to logic 0.

XOR gate:

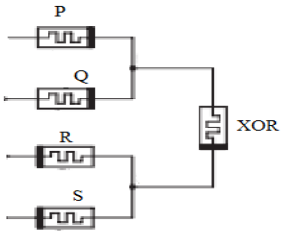

Fig -8: XOR gate structure using memristors

The above fig -8 shows the structure of the XOR gate using memristors, here the XOR gate consists of one AND and OR gate. Initially the voltages are given to the AND and OR gate and from this the output memristor is connected whose initial resistance is high. And the voltages of the AND gate depends on the voltages of the OR gate. In the XOR gate, when Vp=0, Vr=0 and then the voltage of Q and S=0. Then the voltage of the AND and OR gate will be equal to 0, due to this output memristor will have high resistance. If the voltage of P=1, then the voltage of R is also 1, and then if the voltage of Q=0, the voltage of S is also 0. Then the voltage of AND and OR will be 0 and 1, due to this the output memristor will have low resistance.

XNOR gate:

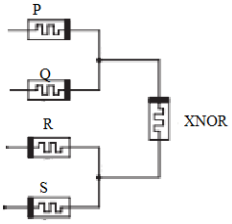

Fig -9: XNOR gate structure using memristors

The above fig -9 shows the structure of the XNOR gate using memristors, here the XNOR gate structure is similar to that of XOR gate structure, i.e. one AND and one OR gate with an output memristor connected to it. But the only difference is that the output memristor is connected in the reverse direction. The operation of the XNOR gate is just opposite to that of XOR operation because the output memristor is connected in reverse direction and also due to the reverse polarity, the output of XNOR is opposite to that of XOR.

3.3 Simulation Results of Logic Gates

The below fig -10 shows the simulation results of the designed logic gates using memristor.

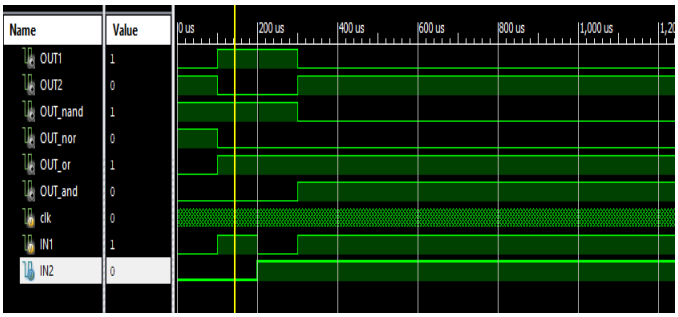

Fig -10: Output of logic gates using memristor

4. APPLICATION OF DESIGNED MEMRISTOR

Content addressable memory (CAM) design using memristor

Content addressable memory (CAM) is the computer memory that operates like a hardware search engine. This CAM is much faster to that of any other algorithmic methods for search-intensive applications. This CAM is familiar as an associative storage where the user will provide the data whose address location is not known, and the CAM helps the user to know the address location by searching its whole memory in a single clock cycle for the given input data and returns the address location of the data where it is located. CAM is paired up with the conventional memory (SRAM) along with an extra comparison circuit, which will be active at every clock cycle. CAM searches for the address location of the data in a

parallel manner and hence this can be a faster memory compared to the other memories.

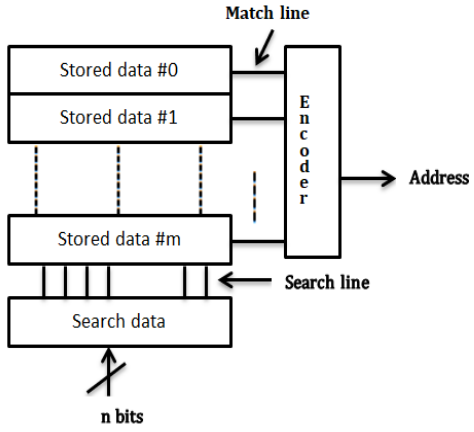

Fig -11: Basic CAM diagram.

The above fig -11 shows the concept of CAM. In the above figure the input data which has to be searched and n-bit input data is given to the search term. The CAM also contains m stored data. The n-bit search data is now transmitted to the search line which is further compared with the stored data which can be helpful in knowing the address of the data. Each stored data is associated with the match line, in which this match line indicates the matched data. It states whether the search data given through the search line is matched with the data which has been stored. And if the search data is not matched in the stored data then it is a not match situation, in this case the address cannot be known. The match line is then given to the encoder, where the address location can be known for the matching cases of the data.

The main application done in this work is, the design of CAM memory using the designed memristor. This CAM memory has been designed by using memristor instead of using conventional memory (SRAM). By this designed CAM application, the performance parameters are achieved i.e. the speed is increased, area and delay are decreased compared to that of the conventional CAM memory. This CAM plays a significant role in the packet classification and forwarding of the obtained packets in internet routers. And also this designed CAM can be used in many applications like data compression and encryption, IP addressing etc.

The below fig -12 shows the simulation results of CAM memory using memristor.

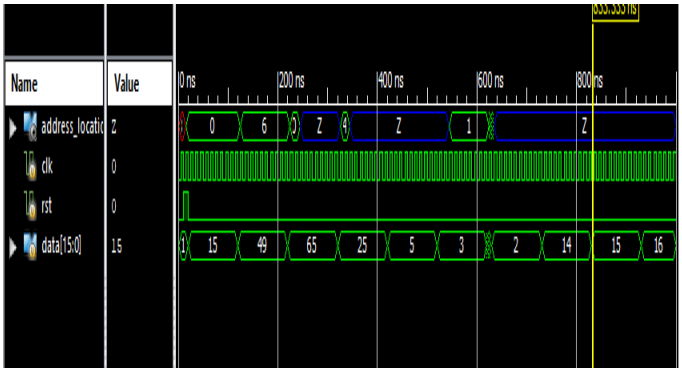

Fig -12: Output of the CAM memory using memristor

In this output figure, if the given input data is not present in the stored data then the address location is shown as high impedance, and if the input data is present then the particular address location of given data is obtained.

Table -1: Comparison of CAM with memristor and CAM without memristor

Performance parameters	CAM with memristor	CAM without memristor
Delay(ns)/ frequency(MHz)	3.426/291.860	3.788/263.964
LUTs	39	49
Slices	21	27

From the above Table -1, it is clear that the performance parameters for CAM with memristor are better and it is now best suitable for many of the applications.

5. CONCLUSION

The basic theory of memristor and its current-voltage characteristics have been shown. By using the designed memristor, the logic gates are designed. And also, the application of memristor like CAM memory is designed. The performance parameters like speed and area are achieved. The designed CAM memory with memristor is compared with the CAM memory without memristor.

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