International Journal of
INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING
ISSN:2147-6799 www.ijisae.org Original Research Paper

Design and Analysis of Passive Switching Crossbar Memristors Arrays using MATLAB

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Submitted: 05/05/2024 **Revised**: 17/06/2024 **Accepted**: 25/06/2024

Abstract: Passive switching crossbar Memristors arrays represent a fundamental architecture in modern electronics, offering versatile applications in signal routing, memory storage, and computational tasks. This study focuses on the design and analysis of such arrays using MATLAB simulation techniques. The crossbar arrays consist of rows and columns of passive switches, typically diodes or memristors, where signals are routed based on the states of these switches. Through detailed simulations and analyses, this study provides insights into the operational principles of passive switching crossbar arrays, highlighting their advantages and limitations in practical applications. Results are validated against theoretical expectationsand demonstrate the utility of MATLAB as an effective instrument in exploring and optimizing such intricate electronic system's performance. Summarize the key findings from the studyon passive switching crossbar arrays. Reinforce the significance of MATLAB as a tool for designing and analyzing complex electronic systems. Emphasize the potential impact of the study's results on advancing the field of passive switching technologies. Through detailed simulations and analyses, this study provides insights into the operational principles of passive switching crossbar arrays utilizing memristors. Results are validated against theoretical expectations and demonstrate the utility of MATLAB as an effective instrument in exploring and optimizing such intricate electronic system's performance

Keywords: *demonstrate, MATLAB, validated, significance, instrument*

1. Introduction:

During the process of developing integrated circuits, the semiconductor industry has, for a considerable amount of time, placed priorities on reducing size, conserving power, increasing reliability, and lowering costs. Each and every one of these achievements is a direct consequence of the industry's unrelenting pursuit of Gordon Moore's trend prediction from 1956, It predicted that every 18 months, the density of transistors on a single device will quadruple [15]. Over the years, the scaling growth of CMOS (complementary metal oxide semiconductor) devices has been consistent, which has been a huge boon to technologies that process and store information. The ITRS (International Roadmap for Semiconductors) declares the growing complexity of scaling transistors has caused scaling rates to decelerate. Data acquired from well-known semiconductor manufacturers is the basis for this information. Two of the many factors that contribute to the scaling difficulty are leakage currents that result from the device getting smaller insulation and conduction problems with materials of wire and dielectric. Both of these factors are involved in the scaling difficulty. Furthermore, parasitic capacitances, which are known to diminish the performance of CMOS devices, are frequently associated with them. It is anticipated that the parasitic capacitances will have an even more significant influence as the characteristics of the device become more similar to one another [16]. The CMOS scaling industry is confronted with an increasing number of economic constraints as the cost of fabrication facilities and the testing of new methods continues to rise. An accurate crossbar architectural representation is crucial for preventing read failures in crossbar memory. No matter the array's dimensions or the storage device's contents, this remains true.

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2. Crossbar Architecture

Within the crossbar architecture, every spot where a collection of parallel nanowires intersects is where a memristor cell is implanted that are arranged in a perpendicular manner on top of another set of parallel nanowires [18]. The crossbar design makes it possible to construct dense arrays of devices; its objective is to guarantee that every device in the array can be accessed independently, with no suffering of the interference by other array devices. Two nanowires are used to connect cells that are located in the same column, while a single nanowire is used to connect cells that are located in the same row. All that needs to be done is provide a balanced voltage and ground the row (column) that houses the cell of interest is required to read or program the contents of a cell that is contained within a crossbar array.

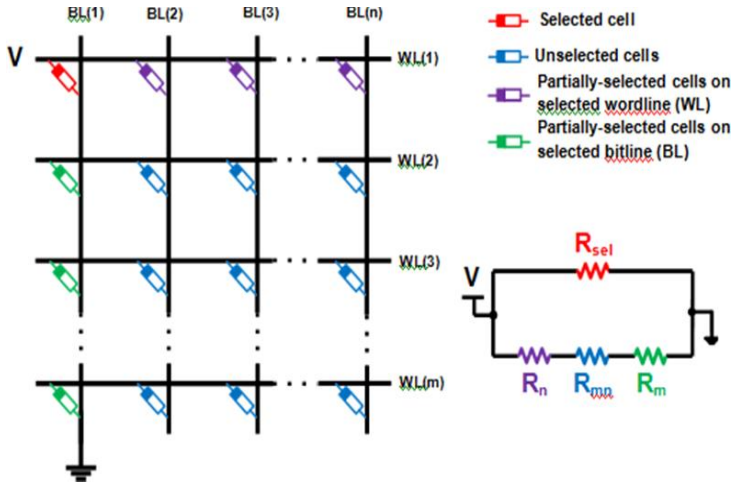

Fig 1: To facilitate writing operations, a crossbar memory structure based on memristors is set up. Furthermore, the effect of each array resistance during operation is shown using a similar circuit model. Cell R1,1 is the selected cell, and its symbol Rsel indicates this. The partially-selected cells are denoted by Rm and Rn, respectively, whereas the cells in the unselected lines are represented by Rmn [68].

A typical crossbar array of memristors is shown in Figure 1. This array is made up of n columns (bitlines) and m rows (wordlines). The symbol Ri, j is utilized to represent each individual memristor. In this symbol, i stands for the row index, and j has the meaning of the column index. Cells deemed partially selected are those situated on the same wordline (WL(1)) and bitline (BL(1)), while the cells that are not selected are considered to be unselected. This occurs when the memristor R1,1 in red is selected for read/write operation. Unless otherwise specified, all cells that are not chosen or are only partially chosen are grouped together and referred to as unselected cells in this thesis. This is the case without any other exceptions. When reading and writing to or from a single cell, the crossbar array is capable of being partitioned into four distinct groups of memristors [18]. The fact that all of the memristors that are contained within each group are connected in parallel makes the formation of the groupings much simpler or more straightforward. Assuming that line resistances are not taken into consideration, the total resistance of a crossbar array with dimensions of m × n may be reduced to the comparable circuit depicted in Figure 1. This circuit is comprised of four potential values of resistance.

- Group I (Rsel): Cell designated for writing (red).
- Group II (Rm): Some of the m − 1 cells on the specified bitline are chosen (green).
- Group III (Rn): Some of the n − 1 cells on the specified wordline (purple) have been chosen.
- Group IV (Rmn): cells that are not on the designated bitline or wordline (unselected cells), totaling (m − 1)(n − 1) cells (highlighted in blue).

Table 1: Conventional Memories vs. New Memories: A Comparison

	Traditional Memories				Other Emerging Memories			
	DRAM	**SRAM**	**NOR Flash**	**NAND Flash**	**FRAM**	**MRAM**	**PCRAM**	**ReRAM (Memrist**
Cell Element[a]	1T1C	6T	1T	1T	1T1C	1(2)T1R	1T(D)1R	1R
Feature Size (*nm*)	36-65	45	90	22	180	65	45	<5
Density ($Gbit/cm^2$)	0.8-13	0.4	1.2	52	0.14	1.2	12	154-309
Read Time (*ns*)	2-10	0.2	15	100	45	35	12	<10
Write Time (*ns*)	2-10	0.2	10^7	10^6	65	35	100	0.3
Retention Time	$4-64ms$	N/A	10 Yrs	10 Yrs	10 Yrs	>10 Yrs	>10 Yrs	>10 Yrs
Endurance (cycles)	$>10^{15}$	$>10^{15}$	$>10^5$	$>10^5$	$>10^{12}$	$>10^{15}$	$>10^9$	$>10^12$
Non-volatile	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Multilevel Capacity	No	No	Yes	Yes	Yes	Yes	No	Yes

Memory application is the particular element of the memristor that has been the subject of the most thorough study. The design of a universal memory that is based on memristors is made possible by the crossbar architecture [30]. This memory combines a number of qualities, including DRAM high density, SRAM speed, and non-volatility of Flash, among more characteristics. For the purpose of ensuring the development of computer memory, the semiconductor sector has been given the obligation of conducting research on revolutionary technologies. There has been some indication that resistive RAM based on memristors might possibly replace the transistor-based memory systems that are now in use. Table 1 provides a comparison of a number of different memory technologies, including those that are now in the process of developing and those that have already been developed.

Sneak-path Leakage in Crossbar Array

Although the design of crossbar is commendable in general, possess drawback when it comes to memristors. This is because sneak-paths, or current leakages, are common in this material. The selection of a certain cell for operation of read and write creates sneak-paths, which are unexpected electrical channels that connect nearby cells (Figure 2 [118]). When a certain cell in the crossbar is chosen, sneak-paths become apparent. Among the many consequences of the sneak-path problem are an increase in the allowable power consumption, a restriction on the largest array size, and a decrease in the effective read margin. The design of high density crossbars is a significant problem. This problem stems from the fact that sneak-path might happen if the top electrodes of the cells in one row and the bottom electrodes of the cells in another column are coupled. Reading data that's been kept within a memory cell is feasible to be disrupted by unwanted currents coming from nearby cells, particularly when sneak-path procedures are used. As can be seen in the comparable circuit shown in Figure 2, the resistance of the cells that were not picked creates a resistance channel that is parallel to the resistance of the cell that was selected. The amount of data that is being processed as well as the array size both have an effect on the Isneak current, which is the current that flows through the cells that have not been picked. It is possible to get a higher Isneak value by expanding the size of the array and include a greater cells that are not chosen and have a low resistance. It is possible that the existence of sneak-paths will cause the unintended overwriting of cells that have not been picked during a write operation's execution. It should come as no surprise that the sneak-path problem is directly responsible for all of the other challenges that are associated with this designing.. It has previously been stated that the practical application of memristors in daily electronics greatly depends on the reliability of the reading and writing processes in memristor-based cross-bar arrays. Several strategies have been developed to improve overall reliability related to the dependability of reading and writing operations in crossbar arrays. The sneak-path issue has a significant influence on the dependability of write and read operations, as stated in the explanation that was given in Section 2. Regarding the writing process, the voltage loss problem has a considerable impact. A drop in voltage that is brought about by the resistance in the lines of the crossbar array [11] is the root cause of the problem that we are now dealing with.

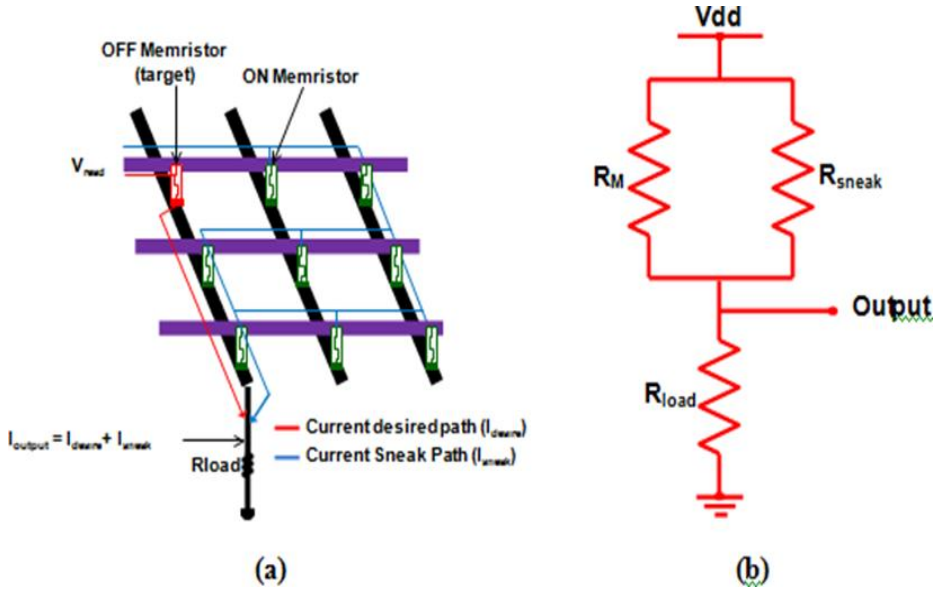

Fig 2: In a crossbar design, this is an example of the sneak-paths effect whenever a crossbar array is being read. The electric current goes by the term of Idesire that flows through the red cell, and The current name is known as Isneak that flows through cells that are not wanted. When these two currents come together, they make Ioutput, which is not what was meant to happen. b) An similar circuit model can be used to show the effect 'sneak-paths'.

To address the problem of voltage drop brought on by line resistance, it would seem that increasing the write voltage would be an effective approach. However, this method also results in an increase in the maximum voltage that is delivered to the cells that have not been chosen before. The installation of the double-sided ground biasing (DSGB) approach is an efficient solution that may be utilized to remedy this problem. In this method, the ground is connected to both sides of the wordline array that has been picked, while the bitline that has been chosen is connected to the voltage that is being written to [13]. A dual voltage source architecture is still another method that may be used. In this design, each of the sides of the wordlines is used to deliver voltage that have been selected [21]. In spite of this, both approaches lead to an increase in the amount of chip surface that is used, which in turn reduces the efficiency of the array. Furthermore, neither approach offers substantial advantages in terms of limiting voltage degradation.

3. Improved Techniques for Crossbar Array Write Operation

As a result of the reliability considerations associated with the process of write, it's been imperative to allocate heightened consideration" to the read operation in crossbar designs after the analysis of the read operation. The process of writing in passive crossbar memory structures has the potential to provide extra complexity to the crossbar structure, which may extend beyond the cells that were originally intended. There is a possibility that an error will occur in crossbar memory if the voltage that is delivered to the cell is inadequate to get them to the ideal condition, or if the cells status that have not been chosen is disrupted. During the process of conducting write operations on a crossbar array, two problems that might occur are voltage degradation and sneak-path. When it comes to the full commercialization of creating crossbar memory, the reliability of writing operations is very essential. This research is presented throughout Section 5.2 of this chapter. The purpose of this endeavor is to ascertain the best-case scenario and the worst-case scenario for these schemes, considering both the presence and absence of line resistance. In compared to the EDA tools that are now available, these mathematical models will make it possible to simulate the crossbar write process efficiently while also improving its accuracy.

Memory that is based on resistive technology experiences leakage current as a result of unexpected routes in the crossbar happening during write operations. Selectors are often made up of diodes and transistors in traditional memory systems. Their purpose is to prevent undesirable current from flowing through the circuit of the memory system. Nevertheless, this often leads in more space being required above. While biassing the other lines in the crossbar, the cells are used to perform the write operation that are part of the crossbar array. A write voltage is applied across the designated cell to do this. Both of the following conditions must be satisfied before an operation of write is considered effective: a) the chosen cell needs to transition to the state that was intended for it, and b) the states of the cells that were not selected in the process must stay unaltered. In order for the first criterion to be satisfied, It's been imperative that the applied write voltage magnitude exceeds the selected memristors' threshold voltages (RESET or SET). However, this is not always the case. Consequently, this will guarantee that the cell transitions to the new state that was intended for it to be transformed into. It is of the utmost importance that the maximum voltage that is delivered to cells that have not been chosen be much lower than the threshold voltages of these cells in order to guarantee that the remaining state of these cells is maintained. In the event that either one or all of the conditions are not satisfied, a write failure will come about. The status of the cells that were not picked might be thrown off if the lines that were not selected are not slanted in the suitable manner. Both process variation, which may result in variations in the threshold voltages of the device, and write failure may result from line resistances. Process variation is the most common cause of write failure. When line resistance is present, the write voltage intensity that reaches the chosen cell(s) is reduced. The magnitude of this reduction is dependent on the distance that separates the cell(s) and the voltage driver. Within smaller arrays, the influence of line resistance is trivial; however, as the array size enhances, the line resistance impact becomes more substantial. The high line resistance existence in extended crossbar arrays makes it difficult for adequate voltage to travel across the cell(s) that have been chosen. This is because the line resistance is elevated. The "write voltage window" is a crucial assessment that is used for the purpose of determining how well the write process is performing. The variation in voltage which was administered to the cell that was selected and the maximum voltage that was applied to any of the cells that were not selected is what this term refers to. The "write voltage window" is mostly affected by the line resistance as well as the biasing method that is used.

Floating Lines Write Scheme

Within the floating lines write framework, which is seen in Figure 3, the target cell's wordline receives a write voltage of Vw, but the bitline remains at zero. None of the other lines are slanted in any way. Out of the three different writing systems, this particular scheme is the most complicated, and frequently misunderstand its precise behavior. In this design, the chosen cell frequently flips on and off effectively. On the other hand, based on the crossbar array's topology, it is possible that the state of the cells that have been partly selected bitline (green) and wordline (purple) will not be retained.

In this setup, the wordlines and bitlines that are not now selected do not get any direct delivery of electrical potential. The m and n values depend on voltages that are present on the lines that are not chosen, which are denoted by Vword and Vbit. When arrays have a aspect ratio of non-square (m ≠ n), the floating approach is used to manipulate the arrays. During the partial selection process, cells belonging to Group III (purple) and Group II (green) encounter an undesirable voltage of around Vw. This voltage is caused by the n m and m n arrangements, respectively. Increasing the distance between m and n results in an increase in the intensity of the disturbance. However, regardless of the shape of the array, Group IV (blue) cells suffer a drop in voltage as the array size enhances.

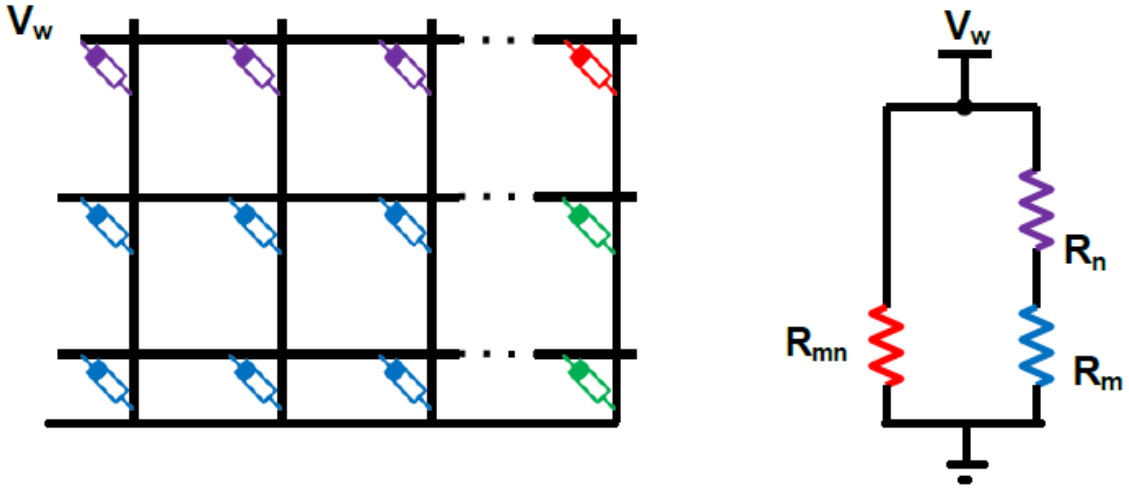

Fig 3: The floating lines structure may be described using a schematic diagram and the circuit model which is associated. The colors of Group II, III, and IV cells are green, purple, and blue, respectively.

This holds true for all types of arrays. For all intents and purposes, The dimensions and arrangement of the crossbar array have a significant impact on the floating system's performance. When referring to the voltages that are applied to bitline and wordline that have been defined, the phrases "Vsel word" and "Vsel bit" are used. Wordlines and bitlines that have not been chosen are subjected to voltages that are denoted by the symbols Vword and Vbit, respectively.

When using the floating lines approach, the maximum voltage that is supplied to the cells that have not been chosen is determined by the array's aspect ratio you are using. When the aspect ratio is 1:1 (m = n), the voltage disturbance in this approach stays below Vw/2. This is true regardless of the size of the array you are manipulating. The write operation will thus always be successful with this configuration; however, this is only the case if the crossbar array is in the shape of a square. It is also possible for a partly chosen cell to have a voltage that is somewhat close to Vw. An obvious write failure occurs whenever the array is traversed and the value of m is not equal to the value of n.

Table 2: The floating lines write approach can be used to calculate the voltage drop across various cell groups assuming that each cell has the same resistance, represented by the symbol R.

	Voltage DropFormula	Voltage drop	Current
Selected cell(s)	$V_{sel\ word} — V_{sel\ bit}$	$V_w — 0 = V_w$	V_w/R
Group II cell(s)	$V_{word} — V_{sel\ bit}$	$V_w/2 — 0 = V_w/2$	$V_w/2R$
Group III cell(s)	$V_{sel\ word} — V_{bit}$	$V_w — V_w/2 = V_w/2$	$V_w/2R$
Group IV cell(s)	$V_{word} — V_{bit}$	$V_w/2 — V_w/2 = 0$	≈ 0

4. Experimental Results and Discussions

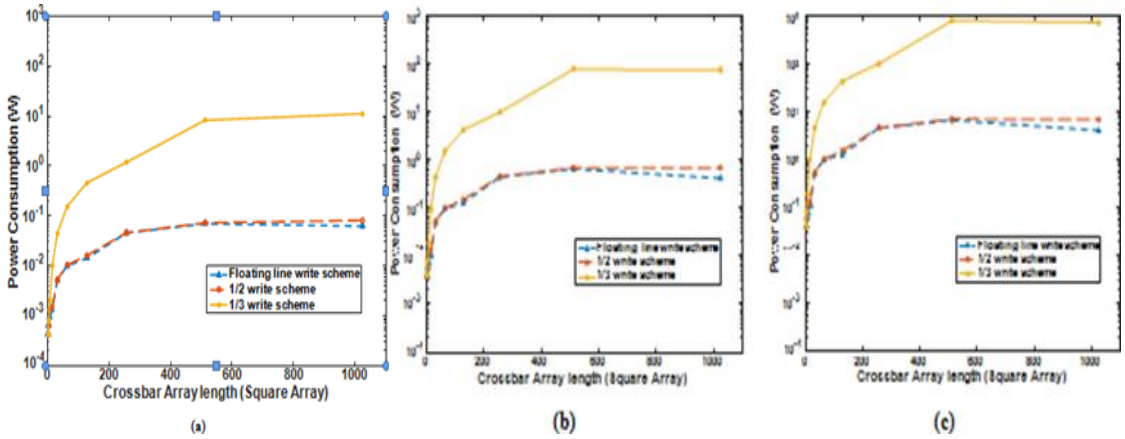

Fig 4: Power consumption comparison of the three write techniques with random array resistance pattern: (a) 101, (b) 102, and (c) 103. The power value is uniformly increased for all three designs to highlight the contrast between them.

In brief, independent of the influence of line resistance, each of the three writing styles that were discussed before has both positive and negative aspects to offer potential readers. Only when the array is shaped like a square is it deemed reliable to use the floating approach; in other cases, the status of cells that have not been picked is confused. When compared to other systems, the V/2 technique offers protection for a higher number of cells than the others. On the other hand, the condition of the m + n — 2 cells that are constantly subjected to a voltage of Vw/2 may be overwritten if the write voltage is provided for an extended period. On the other hand, the V/3 approach applies a low voltage of Vw/3 that is safe around all of the groups of cells that have not been chosen. For the purpose of obtaining a full evaluation, it is necessary to take into consideration the amount of power that is being used while examining these designs.

5. Conclusions

For denser arrays in particular, a rigorous analytical model was created to enhance the dependability of writing operations in crossbar memory. This chapter's crossbar analytical frameworks explain the crossbar by considering the real-world situation in which each cell group in the crossbar may simultaneously include both high-resistance as well as low-resistance state cells. In order to evaluate the effectiveness of three different crossbar write schemes that are currently in use with and without taking into account line resistance, this model was brought into play. All that is required for the floating approach to be considered reliable is for the array to have a square shape. In comparison to earlier systems, the V/2 plan offers protection for a higher number of cells than those earlier schemes. However, if a voltage of Vw/2 is applied across m + n — 2 cells for a lengthy period of time, it is possible that the state of these cells will be overwritten. This is because the cells are constantly exposed to the voltage. On the other hand, the V/3 method applies a lower voltage of Vw/3 to all of the cell groups that have not been chosen. This is a more equitable approach; nevertheless, it comes at the expense of foregoing power savings opportunities. The first experiments laid the groundwork for the creation of a compensated voltage method for the low-power V/2 system. To lessen the likelihood of a write failure, this tactic increases the maximum permitted array size by utilizing the dual voltage approach. Depending on the settings utilized, this compensatory method may raise the array maximum size by a factor of three. By utilizing V/3 write scheme with two distinct configurations, this chapter aims to provide a novel method for writing multiple cells. The amount of power utilized is significantly reduced by 55% when every cell in a standard 512 × 512 crossbar array's wordline is written simultaneously using the novel technique compared to the standard manner. Selectors are often made up of diodes and transistors in traditional memory systems. Their purpose is to prevent undesirable current from flowing through the circuit of the memory system. Nevertheless, this often leads in more space being required above. The write operation on the cells that comprise the crossbar array is accomplished by applying a write voltage to the chosen cell and concurrently biasing the other lines in the crossbar. Depending on whether or not the following conditions are satisfied, it could be considered successful to write an operation: In the first scenario, the selected cell undergoes a transition to the desired state, whereas in the second scenario, the states of cells that are not selected stay unaltered. In order to fulfill the first criteria, the applied write voltage, represented by the symbol Vw, has to be larger than the memristors' ideal threshold voltages as stated for the SET and RESET procedures.

This will therefore guarantee that the cell transitions into the new form that was intended for it. It is essential that the greatest voltage that is supplied to unselected cells be much lower than their threshold voltages to guarantee that these cells' condition is maintained. In the event that either one or all of the prerequisites are not satisfied, a write failure will occur. The status of the cells that were not picked might be thrown off if the lines that were not selected are not slanted in the suitable manner. The output voltage may be affected by line resistances and, in turn, by process variation, both of which can induce variations in the threshold voltages of the device and, thus, write failure. The line resistance presence weakens write voltage that reaches the chosen cell or cells since write voltage strength is proportional to the distance between the voltage driver and the cell or cells. In smaller arrays, line resistance has little to no impact; nevertheless, its influence grows substantially with increasing array size. A high line resistance makes it difficult for enough voltage to pass across the chosen cell(s) when large crossbar arrays are present. The write operation's performance may be assessed using the "write voltage window" assessment. The variation in voltage that was administered to cell had been selected and the maximum voltage that was applied to any of the cells that were not selected is what this term refers to. The "write voltage window" is mostly affected by the line resistance as well as the biasing method that is used.

Floating Lines Write Scheme

As shown in Figure 3, the floating lines write approach involves supplying the wordline of the target cell with a write voltage of Vw, while the bitline is left at zero. This technique is displayed in the figure. The other lines are not influenced in any way. The exact operation of this system is commonly misunderstood, despite the fact that it is the most complicated of the three writing systems. In this setup, the selected cell switches successfully the majority of the time. However, depending on how the crossbar array is constructed, it is possible that the status of the cells that have been partly chosen on bitline (green) and wordline (purple) which is selected and won't be preserved.

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