

Design Framework for Reliable, Energy Efficient Cross-Point based Resistive Memory

Abstract—Since the conventional memory technologies approaching their scaling limit, the non-volatile memory technologies, such as Phase Change RAM (PCRAM), Magnetoresistive RAM (STT-RAM) and Resistive Memory (ReRAM) have attracted much attention because their non-volatility, high speed, low power consumption and good scalability. Among these emerging memory technologies, the ReRAM has shown great potentials as one of the most promising candidates for future universal memory. The ReRAM, due to its simple structure, small cell size and potential for 3D stacking. Besides, the unique non-linearity of ReRAM provides the possibility to build a cross-point structure based ReRAM without CMOS access device, with the smallest cell size of $4F^2$. However, the cross-point structure also suffers from its inherent disadvantages and brings in extra design challenges. In this work, the design challenges of cross-point structure based ReRAM are comprehensively analyzed. In addition to the cell-level analysis, a precise mathematical model is built to perform a detailed design methodology is developed. With the proposed methodology, designers can explore the most energy/area efficient ReRAM design with different design constraints.

I. INTRODUCTION

The scaling of traditional memory technologies, such as SRAM and DRAM, is approaching a technological and physical limit. In order to effectively follow Moore's Law [1] in the near future, new memory technologies are desired. In the past few years, the non-volatile technologies, including Phase Change RAM (PCRAM), Magnetoresistive RAM (STT-RAM) and Resistive Memory (ReRAM) have been widely accepted as the candidates for next generation memory to meet the need of higher density, faster access time, and lower power consumption. Among all of these emerging memory technologies, ReRAM has many unique characteristics, including simple structure, non-linearity and high resistance ratio, making it be considered as the most promising technology. Researchers have shown that the state-of-art single-level-cell ReRAM can achieve sub-8ns random access time for both read and write operation with resistance ratio > 100 [2]. Also, HP labs and Hynix have already announced that they are going to commercialize the memristor-based ReRAM and predicted that ReRAM could eventually replace the traditional memory technologies [3].

Different from other non-volatile memory technologies, ReRAM can be implemented in a cross-point style structure. Generally speaking, in a nano cross-point array, the bistable ReRAM cell is sandwiched by two layers, orthogonal nanowires, without any access device. Therefore, the cell size of ReRAM can be further reduced to $4F^2$ per bit. However, the simplicity of cross-point structure without access cell also brings in additional challenges on the peripheral circuit design as well as memory organization. There are many literatures that analyzed the design challenges of the cross-point ReRAM array [4] [5] [6] [7]. Nevertheless, all of these researches focus on the cross-point memory array itself but do not take into account the peripheral circuitry and different programming methods. Besides, the analysis of area and energy consumption is also lacking. In this work, we carefully analyzed the design challenges of cross-

point structure based ReRAM. A precise mathematical model is built to evaluate the reliability, energy consumption and area of different design schemes and various cell parameters. Based on the study, a detailed design framework is developed. With the proposed methodology, designers can explore the most energy/area efficient ReRAM design with different design constraints and cell parameters at the very beginning of the design stage. On the other hand, the system designers can also leverage the proposed framework to provide valuable feedback to device researchers to adjust their experiments and offer more useful ReRAM cell. We believe that this kind of two-way communications will be very helpful to accelerate speed-to-market of ReRAM memory.

The rest of this paper is organized as follows. In Section II, the memristor based memory and the basic concept of ECC are introduced. Section III discusses the mathematical model used in this paper and evaluates various ECC designs for memristor-based ReRAM architecture. Section IV shows results of the experiment conducted in this study. Finally, the conclusion is presented in Section V.

II. PRELIMINARIES AND MOTIVATIONS

This section provides some preliminaries on ReRAM technology and cross-point architecture. Then the limitations of cross-point architecture are discussed, which motivates the work in this paper.

A. Background of ReRAM technology

Table I compares the state-of-art non-volatile memory technologies. Obviously, the ReRAM and STT-RAM are the most promising technologies because they have faster access time than PCM and FeRAM with reasonable endurance. However, although the STT-RAM shows the fastest read/write latency among all non-volatile memory technologies, the structure of the memory cell is complex and it has large cell size. On the other hand, the ReRAM has very simple cell structure and can be implemented as a cross point structure, which can work without access devices. The easy structure provides the possibility of high density integration and 3-D stackability to ReRAM based memory. Besides, the ReRAM also has much higher ON-OFF resistance ratio than STT-RAM. Therefore, with all of these advantages, ReRAM based memory is a highly competitive technology compared to all of the emerging non-volatile memory technologies.

As implied by the name, the ReRAM uses its resistance to represent the stored information. The resistance of a ReRAM cell can be

TABLE I
COMPARISON OF NON-VOLATILE MEMORY TECHNOLOGIES

Metric	STT-RAM	PCM	FeRAM	ReRAM
Cell Size(F^2)	6 – 20	4 – 8	15	4
Read Latency(ns)	1-10	20-50	20-80	5-50
Write Latency(ns)	2-20	150	100	5-50
Endurance	10^{15}	10^8	10^{12}	10^{8-10}

switched between high resistance state (HRS) and low resistance state (LRS) by applying an external voltage across the cell. The resistance switching behavior of the metal oxides have been noticed for several years and attracted great research interest recently for the potential application as next generation non-volatile memory technology. A ReRAM memory cell is usually built on a Metal-Insulator-Metal (MIM) structure. The resistance switching behaviors have been observed in many MIM nanodevice with different metal oxide materials. For example, a TiO_2 based MIM structure ReRAM was proposed by HP Labs in 2008 [8]. The proposed ReRAM is considered as the first experimental realization and a theoretical model of the fourth fundamental circuit elements, which is predicted by Chua [9] about 40 years ago. The memristor-based ReRAM has a very small cell size of $50 \times 50 nm^2$ with access time less than 50ns. Another HfO_2 -based bipolar ReRAM is implemented by ITRI this year with as small as 7.2ns access time [2].

Although there are several different ReRAM proposed by researchers, all of them can be divided into two classes: the unipolar ReRAM and the bipolar ReRAM. For a unipolar ReRAM cell, the resistance switching behaviors do not depend on the polarity of the voltage input across the cell and only relate to magnitude and latency of the voltage input. However, for a bipolar ReRAM, the voltage polarity for a ON-to-OFF switching (RESET operation) is different from a OFF-to-ON switching (SET operation). A unipolar ReRAM can be easily stacked on top of diodes to built a one diode one resistor (1D1R) ReRAM. However, as mentioned, the SET and the RESET operation have different latency and therefore the performance is mainly determined by the long voltage pulse. Besides, the control of SET, RESET and read operation without any disturbance is another crucial design challenge, especially in the high speed ReRAM design. Therefore, the reported state-of-art high performance ReRAM technologies are dominated by bipolar ReRAM [? Added reference here].

B. Cross-Point Architecture

There are two possible memory structures for ReRAM implementation: the traditional MOSFET-accessed structure and the cross-point structure. For the one cell one access device structure. In the MOS-accessed memory array, the conventional memory cell is substituted by the ReRAM cell where the access device remains to be the MOSFET. In this structure, each ReRAM cell has to be accompanied with a MOSFET access device, whose size is much larger than the ReRAM cell. In this case, the area of the memory array is mainly dominated by MOSFET access device rather than the actual ReRAM cell. Therefore, the ReRAM's advantage of ultra small cell size will be eliminated.

On the contrary, the cross-point structure is more area-efficient for the ReRAM based memory array [10]. A schematic view of typical cross-point memory array is shown in Figure. 1(a). It can be seen that in the cross-point array, the only item at each crossing point is the ReRAM cell. Therefore, the area of the array is significantly reduced since the large MOSFET access part is removed. Figure. 1(b) shows that the cell size of the cross point memory can achieve $4F^2$, the theoretical minimum size for a single layer single level memory cell. Besides, as aforementioned, the good stackability and the high resistance ratio provide the capability of building multi-layer multi-level cross-point ReRAM array, which can further increase the area efficiency of the ReRAM array [2] [11].

For the cross-point structure, a two-step writing methodology, ERASE-before-RESET, is used to prevent the unintended writing. In read operation two ways are exhibited for preventing a read failure:

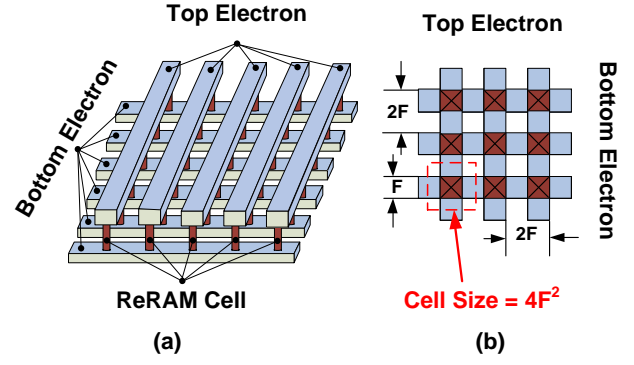


Fig. 1. A schematic view of typical cross point architecture.

the first is to supply the same voltage to the unselected row and selected column. In this way, only the data on the select row is read from the selected column. The disadvantage of this method is the voltage drop on the crossing points of the unselected row and the selected column may not be ideal zero because of variations, and this imposes a limitation on the array size. The second way is a two-step write operation. The disturbance current of the partial selected cell on the selected column will be read out beforehand as a background current. Later the total current, comprised of both partial selected cell and full selected cell, will be read out. The state of the selected cell can then be determined by computing the difference between the total current and background current.

III. MODELING OF THE CROSS-POINT MEMORY

In this section, a detailed mathematical model of cross-point memory array is built. By using the proposed model with specific parameters and boundary conditions, different read/write schemes can be easily evaluated at the very early stage of the design.

A. Basic model of Cross-Point Memory

Figure. 2 shows the circuit model of the M by N cross point ReRAM array. The horizontal lines are word line and vertical lines represent the bit line. The ReRAM cells are located at each cross point of one word line and one bit line. The resistance of the ReRAM cell at the cross point of the i^{th} word line and j^{th} bit line is indicated as $R_{i,j}$. We assume the resistance of the interconnect nanowires between two adjacent cross point has the same value of R_{line} . The input resistance of each word line and bit line is R_v and the resistance of sense amplifier is R_s . In order to set up the Kirchhoff's Current Law (KCL) equations, the voltage at each cross point is indicated as $V_{i,j}$ for word line and $V'_{i,j}$ for bit line. A detailed cross point is also shown in Figure. 2. Besides, the input voltage for the i^{th} word line is V_{Wi} and for the i^{th} bit line is V_{Bi} . In the case of two side voltage input of word line, the voltage at the other end of the i^{th} word line is denoted as V'_{W1} . Finally, the voltage at the sense amplifier is V'_{Bi} during the read operation.

B. Edge Conditions for Different Write/Read Schemes

Based on the circuit model, the current equation for each cross point can be built following the KCL:

$$\sum_{I=1}^k I_k = 0. \quad (1)$$

All of the cross points have similar structure and therefore it is easy to set up the KCL equation for each cross point. However, the cross point at the edge of the array may have different condition for different write/read schemes. For example, the unselected word line

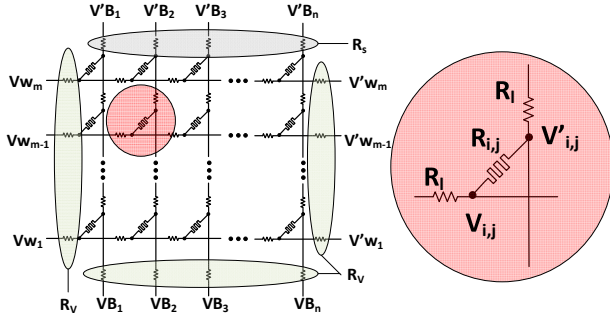


Fig. 2. The basic model of typical cross point array.

for write operation can be either half biased or left floating. Thus, the edge conditions should be carefully considered for each write/read schemes. However, generally speaking, all of the cross points can be classified into three major categories: Normal point, Activated point and Floating point.

The normal point located inside the memory array. In other words, for all of the nodes with $1 < i < m$ and $1 < j < n$, the KCL equations take the form of

$$R_l^{-1}V_{i,j-1} - (2R_l^{-1} + R_{i,j}^{-1})V_{i,j} + R_l^{-1}V_{i,j+1} + R_{i,j}^{-1}V'_{i,j} = 0, \quad (2)$$

for the node at word line layer and

$$R_l^{-1}V'_{i-1,j} - (2R_l^{-1} + R_{i,j}^{-1})V'_{i,j} + R_l^{-1}V'_{i,j+1} + R_{i,j}^{-1}V_{i,j} = 0, \quad (3)$$

for the node at bit line layer.

Besides, the activated point and floating point represent the node at the edge of cross point array with different conditions: a edge point, which have been directly connected to the voltage input or the ground, can be considered as a activated mode. Otherwise, it is floating node. Take the point located at the intersection of i_{th} word line and 1_{st} bit line for example. If the i_{th} word line is activated by a voltage input of V_{Wi} , then this cross point is activated point, and the KCL equation for this point is:

$$-(R_v^{-1} + R_l^{-1} + R_{i,1}^{-1})V_{i,1} + R_l^{-1}V_{i,2} + R_{i,1}^{-1}V'_{i,1} = -R_v^{-1}V_{Wi}, \quad (4)$$

otherwise, it is left floating and has the KCL equation take the form of

$$-(R_l^{-1} + R_{i,1}^{-1})V_{i,1} + R_l^{-1}V_{i,2} + R_{i,1}^{-1}V'_{i,1} = 0. \quad (5)$$

For the reasons of clarity, a vector $V_{2mn \times 1}$ is used to represent all of the variables in the KCL equations:

$$V = [V_1^T, V_2^T \dots V_m^T, V'_1{}^T, V'_2{}^T \dots V'_m{}^T]^T, \quad (6)$$

where,

$$V_i = [V_{i,1}, V_{i,2} \dots V_{i,n}]^T, \quad (7)$$

$$V'_i = [V'_{i,1}, V'_{i,2} \dots V'_{i,n}]^T. \quad (8)$$

Then the KCL equations can be considered as a system of linear equations and has the form of

$$A_{2mn \times 2mn} \cdot V_{2mn \times 1} = C_{2mn \times 1}, \quad (9)$$

where A is the coefficient matrix of and C contained the constant terms. As shown in Equation(2)-(5), the KCL equations for each node have very simple structure and are very similar to each other. Therefore, the system of linear equations has a relatively fixed format and simple structure, which will be very easy to establish the questions and to adjust the coefficient according to different

design schemes. As shown in Equation (referred to as blocked matrix), the coefficient matrix A can be partitioned into 4 smaller blocks.

$$A = \begin{bmatrix} A1 & A2 \\ A3 & A4 \end{bmatrix} \quad (10)$$

All of the submatrix has the same size of $m \times n$. $A2$ and $A3$ are diagonal matrices and have the form of: $A2_{i,j} = A3_{i,j} = R_{i,j}^{-1}$. $A1$ and $A4$ are a little bit more complex than $A2$ and $A3$. $A1$ can be further divided into

is a tridiagonal matrix and only has nonzero elements at the location in the main diagonal, and the first line below and above diagonal. Similarly, the $A4$ is a special tridiagonal matrix, which has nonzero elements in the main diagonal, and the n^{th} line below and above diagonal, where n is the number of bit line in the cross point model. The value of the elements in $A1$ and $A4$ can be easily derived from Equation (2) and (3). However, as mentioned, the edge condition varies with different program schemes. Therefore, the coefficients related to the edge condition should be update according to the program scheme as follow:

detailed discuss on the mathematic

C. Analysis of the Computing Complexity

IV. ANALYSIS OF DESIGN CONSTRAINTS

A. Overview

As shown in Figure. 2, in order to write or read the cross point array, the external voltages should be applied at the end of the word line and the bit line. Although there are several potential read/write schemes can be used to program the memory array, it is difficult to point out which schemes is the most proper choice under given design constraints of area/energy/reliability. Therefore, in this section, studies on different operation schemes and present are conducted. The results of this study can be very useful to guide the design of the cross point array. Since it is impossible to consider all of the data pattern stored in the array, in this work, the best and worst cases are studied.

Table II shows the circuit parameter of our baseline design. The data is consistent to the recently published studies on ReRAM [7] [10]. In this section, the reliability, energy consumption and area overhead for the four write schemes are detailed. Then the sensitivities of these schemes to the data pattern of HRS and LRS ReRAM cells, and interconnect wires are studied.

Considering that program schemes for write and read operation are different and the the requirement for write and read are also dissimilar, in the following section we carefully study the write and

TABLE II
PARAMETERS OF THE BASELINE CROSS POINT ARRAY

Metric	Description	Values
S_{cell}	Cell Size	$4F^2$
R_l	Interconnection Resistance	1.25Ω
R_s	Resistance of SA	100Ω
V_{RESET}	Threshold voltage for RESET	$2.0V$
V_{SET}	Threshold voltage for SET	$-2.0V$
V_{READ}	Read Voltage of Cell	$0.5V$
R_{off}	HRS Resistance	$500K\Omega$
R_{on}	LRS Resistance	$10K\Omega$
$V_W(R)$	Word Line Voltage during Read	$\pm 1V???$
$V_W(W)$	Word Line Voltage during Write	$0/2V$
$V_W(H)$	Half Selected Word Line Voltage	$1V$
$V_B(R)$	Bit Line Voltage during Read	$10K\Omega????$
$V_B(W)$	Bit Line Voltage during Write	$0/2V$
$V_B(H)$	Half Selected Bit Line Voltage	$1V$
M	Number of Word Line	64
N	Number of Bit Line	64

read operation separately. And then the results are combined together to provide a design methodology for the cross point array.

B. Write Operation

To write a ReRAM cell, a external voltage is required to applied across the cell for a certain duration. Intuitively, there are four possible schemes for the write operation:

- 1) According the location of the target cell, activate one word line and one bit line and leave all of the other lines floating (FWFB schemes).
- 2) Activate the targeted word line and bit line. Left all the other word line floating and half bias the other bit line (FWHB schemes).
- 3) In contrast with the scheme 2, activate the targeted word line and bit line. Left all the other bit line floating and half bias the other word line (HWFB schemes).
- 4) Activate the targeted word line and bit line. Half bias all of the other bit line (HWHB schemes).

Since the reliability, energy consumption and area overhead for these schemes are different from each other. We will address these problem separately and then combine all of the constraints to provide a design guideline for write operation.

Reliable Write Operation.

The most important issue for the write operation is the reliability concern. In the ideal condition, the resistances of interconnect wires and the sneak currents at unselected cells are negligible. Therefore, all of these four schemes can provide enough voltage drop across the specified cell. However, the realistic circuit is not perfect and the electronic behavior of the array will deviate from the ideal scenario with different data pattern stored. A reliable write operation can be defined as: switching the selected cells into required states without disturbing the states of unselected cells. Therefore, there exist two potential write errors: **write failure**, an unsuccessful write on selected cell, and **write disturbance**, an undesirable write on unselected cell. All of the write schemes should at least meet the reliability requirement at the worst case. On the other word, the designer should make sure there is not any write failure and write disturbance even in the worst case.

First of all, we will discuss the inherent problem of FWFB scheme, which may result in severs write disturbance. A worse case scenario for FWFB write disturbance can be defined as: all of unselected cells in the activated word line (or all of unselected cells in the activated bit line) are at HRS and other cells are in LRS. In this case, the voltage drop at unselected cells are mainly applied at the HRS cells at the word line (or bit line). Figure. 3 shows an example of this case for a 64×64 cross point array. It clearly that all of the unselected cells at the activated bit line will be disturbed. This inherent problem exists at all of the FWFB schemes and becomes very serious with the large On-OFF resistance ratio. Considering that the reported On-OFF resistance ratio of ReRAM cell is always > 50 [12]–[17], it is impossible to build a cross point structure ReRAM with the FWFB scheme. Therefore, in the following discussion, we only compare the results of FWHB, HWFB and HWHB schemes. For each of these three schemes, we can either write one word line at the same time or only write one bit per access and separate the write operation to several arrays. In the following discussion, we start from one bit per access write operation. And then the results of one word line per access method are compared.

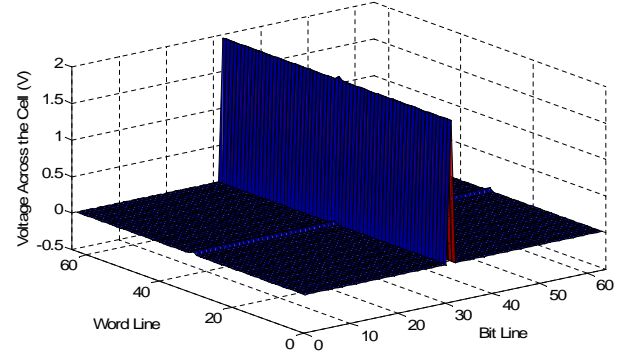


Fig. 3. Write Disturbance for FWFB Schemes. ($V_{W32} = 2V$, $V_{B32} = 0V$. $R_{x,32}$ at HRS, others at LRS.)

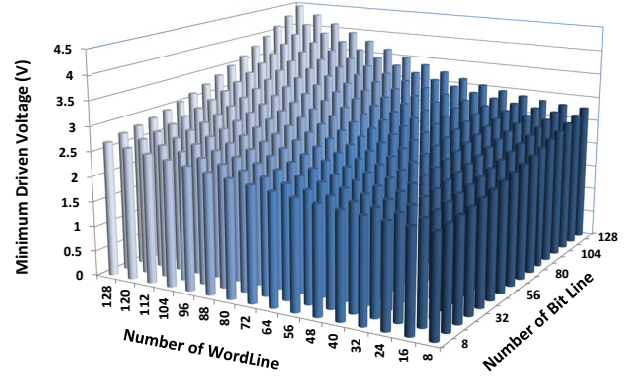


Fig. 4. Write Voltage Requirement (Threshold Voltage = 2V).

The write failure results from the voltage drop at the interconnect wires along the word line and bit line. It has been shown that, for one bit per access write operation, the worst case of voltage drop is:

$$\begin{cases} R_{i,j} = R_{on} \\ V_{WM} = V_W(W) \\ V_{BN} = V_B(W). \end{cases} \quad (11)$$

In order to avoid the **write failure** and successful program the selected ReRAM cell, the driven voltage should be increased to a higher level, making sure the voltage across the cell exceed the threshold voltage at the worst case. Figure. 4 shows the lower bound of the driven voltage for different size of cross point array. The minimum word/bit line voltage increases from 2.01 V for a 8×8 array to 4.47 V for a 128×128 cross point array. Besides, for a given memory capability, the cross point can be organized with different number of word line and bit line. For example, a 4K bits cross point array can be implemented either by a 64×64 array or by a 32×128 array. In the latter case, the voltage drops along the word line and bit line are different with each other. Therefore, Figure. 5 exams the voltage requirement for different array organization. The results show that from the reliability point of view, the cross point array with same numbers of word line and bit line is the best choice.

However, in the other hand, the increasing of the driven voltage also increases the voltage applied at the unselected cell. Therefore, a **write disturbance** will occur when the voltage applied at the unselected cell exceeds the threshold voltage for SET or RESET operation. Figure. 6 shows the worst case (maximum) voltage applied at unselected cells with the minimum driven voltage shown in

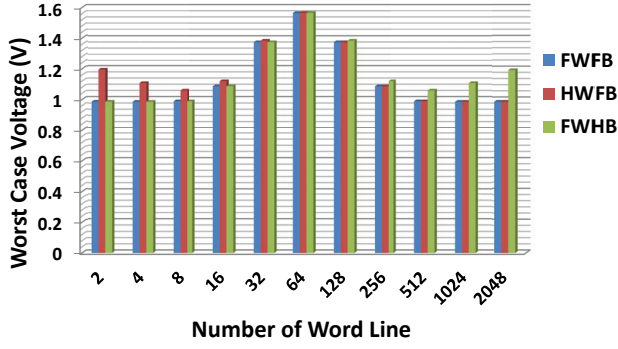


Fig. 5. Write Voltage Requirement with Different Memory Shape. (Array Capacity = 4Kbits, Activated Word Line Voltage = 2V, Activated Bit Line Voltage = 0V.)

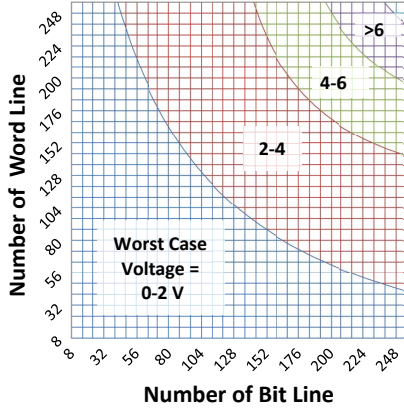


Fig. 6. The

Figure 4. Since the threshold voltage of the cell is 2V, all of the word/bit line combinations at the region with worst case voltage more than 2V are unreliable and can not avoid write failure and write disturbance at the same time. Thus, Figure. 6 provides the hard constraint of array size, and all of the following energy and area tradeoffs should be bounded by this constraint.

Energy Consumption of Write Operation.

The energy consumption of a write operation for a cross point array can be calculated as:

$$E_{write} = E_{select} + E_{unselect} + E_{line}, \quad (12)$$

where the P_{select} is the energy consumed to change the state of the selected cell, the $E_{unselect}$ and E_{line} are the undesired energy wasted at the unselected cell and the interconnect wires. The write operation can

First of all, Figure ?? shows the energy consumption for

Area cost of Write Operation.

The write operation requires $m+n$ access device for a $m \times n$ array. Therefore, the average number of ReRAM cells per access device can be calculated as $mn/(m+n)$. By given a array capacity C_{array} , it is easy to find that the optimal array organization can be achieved when $m = n = \sqrt{C_{array}}$ and the maximum number of cells per access device is: $\sqrt{C_{array}}/2$. However, the area overhead of the

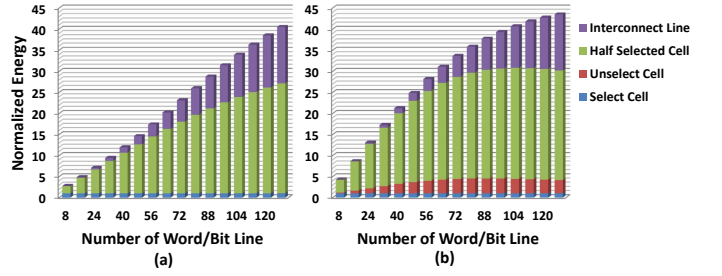


Fig. 7. The Normalized Energy Consumption. (a): FWFB scheme (b): FWHB and HFBW Schemes.

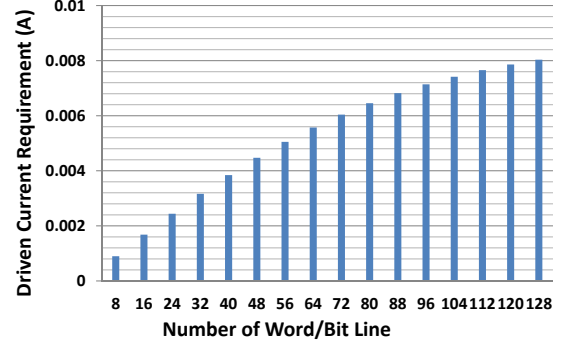


Fig. 8. The

access device also related to the driven current. Figure ?? shows the required driven current for different

Multi-Bits Write Operation.

Non-linearity of the ReRAM Cell.

C. Read Operation

D. Discussion on Non-linearity of the ReRAM

An

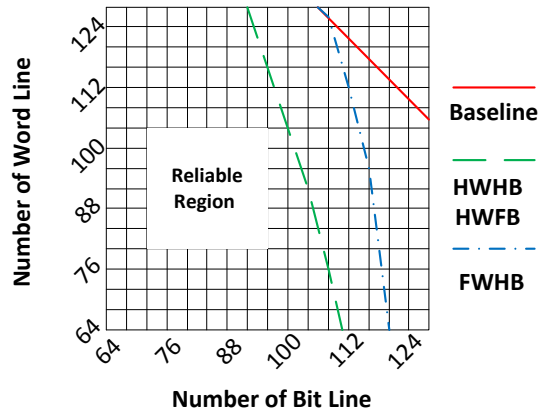


Fig. 9. The

E. Framework

F. Experimental Results

G. Conclusion

REFERENCES

- [1] G. E. Moore. Cramming more components onto integrated circuits. *Electronics*, 38(8), April 1965.
- [2] S. Sheu et al. A 4mb embedded slc resistive-ram macro with 7.2ns read-write random access time and 160ns mlc-access capability. In *Proceedings of IEEE International Solid-State Circuits Conference 2011, ISSCC '11*, 2011.
- [3] <http://www.hpl.hp.com/news/2010/jul-sep/memristorhynix.html>.
- [4] A. Flocke et al. A fundamental analysis of nano-crossbars with non-linear switching materials and its impact on tio2 as a resistive layer. In *Nanotechnology, 2008. NANO '08. 8th IEEE Conference on*, pages 319 –322, 2008.
- [5] M.M. Ziegler and M.R. Stan. Design and analysis of crossbar circuits for molecular nanoelectronics. In *Nanotechnology, 2002. IEEE-NANO 2002. Proceedings of the 2002 2nd IEEE Conference on*, pages 323 – 327, 2002.
- [6] M.M. Ziegler and M.R. Stan. Cmos/nano co-design for crossbar-based molecular electronic systems. *Nanotechnology, IEEE Transactions on*, 2(4):217 – 230, 2003.
- [7] J. Liang and H.-S.P. Wong. Cross-point memory array without cell selectors -device characteristics and data storage pattern dependencies. *Electron Devices, IEEE Transactions on*, 57(10):2531 –2538, 2010.
- [8] D. B. Strukov and et al. The missing memristor found. In *Nature*, 2008.
- [9] L. Chua. Memristor-the missing circuit element. *IEEE Transactions on Circuit Theory*, (5), Sep 1971.
- [10] C. Xu et al. Design implications of memristor-based rram cross-point structures. In *Proceedings of Design Automation Test in Europe Conference Exhibition 2011*, 2011.
- [11] M.-J. Lee et al. Stack friendly all-oxide 3d rram using gainno peripheral tft realized over glass substrates. In *Electron Devices Meeting, 2008. IEDM 2008. IEEE International*, pages 1 –4, 2008.
- [12] and others C. Ho. 9nm half-pitch functional resistive memory cell with jlua programming current using thermally oxidized sub-stoichiometric wox film. In *Electron Devices Meeting (IEDM), 2010 IEEE International*, pages 19.1.1 –19.1.4, 2010.
- [13] W.C. Chien et al. A forming-free wox resistive memory using a novel self-aligned field enhancement feature with excellent reliability and scalability. In *Electron Devices Meeting (IEDM), 2010 IEEE International*, pages 19.2.1 –19.2.4, 2010.
- [14] J. Lee et al. Diode-less nano-scale zrox/hfox rram device with excellent switching uniformity and reliability for high-density cross-point memory applications. In *Electron Devices Meeting (IEDM), 2010 IEEE International*, pages 19.5.1 –19.5.4, 2010.
- [15] H.Y. Lee et al. Evidence and solution of over-reset problem for hfox based resistive memory with sub-ns switching speed and high endurance. In *Electron Devices Meeting (IEDM), 2010 IEEE International*, pages 19.7.1 –19.7.4, 2010.
- [16] S. S. Sheu et al. A 4mb embedded slc resistive-ram macro with 7.2ns read-write random-access time and 160ns mlc-access capability. In *Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2011 IEEE International*, 2011.
- [17] W. Otsuka et al. A 4mb conductive-bridge resistive memory with 2.3gb/s read-throughput and 216mb/s program-throughput. In *Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2011 IEEE International*, 2011.