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A Review on Resistive Random Access Memory

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ABSTRACT – In this paper, current progresses in designing aspects of the Resistive Random Access Memory (RRAM) has been discussed. RRAM is one of the most promising and emerging memory technologies. With the increase in demand for better and efficient memories, the need for a technology in which advantage of both volatile and non volatile memories exists has evolved. RRAM has two major benefits that it can be accessed randomly as well as it is a non volatile memory technology. In this paper, a holistic review of RRAM has been presented in terms of various performance parameters, such as on/off ratio, endurance, retention and operating voltage.

Index Terms - Dielectric constant, non volatile memories, Resistive Random Access Memory, resistive switching, volatile memories.

I INTRODUCTION

Semiconductor memory is an electronic data storehouse device realized on semiconductor based integrated circuit. It has now become fundamental for electronics industry. With the agile growth in the necessity for semiconductors, new and improved semiconductor memory technologies are being explored. Older semiconductor memory technologies are still in extensive use and will remain for many more years to follow. The memories can be classified into two categories- volatile and non volatile. Volatile memory is the one that looses contents of the data if power is switched off and retains the data till the device power is on whereas non volatile memory, often known as the secondary memory technology does not lose its data even when the power is turned off [1]. The most explored and developed semiconductor memory technologies are Read only memory(ROM) in which data is written once and can be read as many times, Random access memory(RAM) in which reading and writing of data can be done in any order as desired and flash memory in which data is written and erased in blocks. Each one can be further classified and has its own benefit and use [2]. Classification of semiconductor memories has been discussed in table I. SRAM and DRAM are volatile memories which come under RAM. FRAM (Ferroelectric RAM), MRAM (Magnetoresistive RAM), PRAM (Phase change RAM), RRAM (Resistive RAM) are all Random Access Memories but non volatile. EPROM, UVEPROM, EEPROM, OTPROM and FLASH are non volatile memories which comes under ROM [3].

Table I Classification of Semiconductor Memories

Semiconductor Memories			
RAM		ROM	
SRAM	FRAM	EPROM	FLASH
DRAM	MRAM	UVEPROM	
	PRAM	EEPROM	
	RRAM	OTPROM	
VOLATILE	NON VOLATILE		

II. NON VOLATILE RAM

Non volatile random access memory, also known as NVRAM is a type of memory technology that accesses the data randomly and stores the information irrespective of power on or power off. Various types of NVRAM are Ferroelectric RAM (FRAM), Magnetoresistive RAM (MRAM), Phase change RAM (PCRAM) and Resistive RAM (RRAM) [4]. FRAM has ultra high endurance, low power consumption, faster write performance, gamma radiation tolerance and much large number of write and erase cycle. It is used for faster read operations as compared to MRAM. Drawbacks of using FRAM are low storage density and capacity limitation. Cost of FRAM is also comparatively higher than other NVRAMs [5].

MRAM is usually used for low power applications as it consumes less power as compared to DRAM for read operations, MRAM has high endurance as compared to RRAM and has high read write operations. Also, MRAM is highly dense [6]. But large cell size is required and large power is required for data write. PCRAM is bit alterable and is highly scalable with greater aerial density [7].

But cost of PCRAM is higher than RRAM and MRAM.

On the other hand, RRAM memory is highly dense. Cost of RRAM is comparatively lesser than all other NVRAMs. RRAM can exhibit multilevel resistance property by stacking the MIM stack further [8]. Although endurance of RRAM is not as high as FRAM or MRAM and it consumes higher write power but it can be the technology of the future because work is being carried for increasing endurance of RRAM [9].

RRAM is widely used as a storing device. Also, it is used as a reading device to read data from a cell where a small read voltage is applied that does not affect state of the memory cell to detect whether the cell is in HRS or LRS. RRAM structure is also used as a switch and as a data propagation device [10]. Various neuromorphic computing is also done by RRAM cell. Principle of operation of all NVRAM memory technologies with their advantages and disadvantages have been tabulated in table 2. Among all the Non volatile RAMs, RRAM is the memory technology of the future as it is highly dense and low cost with multilevel switching and stacking in materials.

Table II Detailed descriptions of NVRAM memory technologies

S.no	Type of RAM	Principle of operation	Advantages	Disadvantages
1.	FRAM	Fieroelectricity	• Ultra high endurance • Low power usage • Faster write performance • Gamma radiation tolerance. • Much larger no. of write erase cycle	• Low storage density • High cost • Capacity limitation
2.	MRAM	Magnetoresistivity	• High speed read write operation • High endurance • Low power as compared to DRAM • High Density	• Large cell size required. • Large power required for data write.

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3.	PCRAM	Space charge conduction	• Fast read operation • Bit alterable • High scalability • Greater aerial density	• Multiple bit storage per cell of flash. • High cost
4.	RRAM	Resistive switching	• Highly dense • Stacked and multilevel cells • Relatively low cost	• High write power • Less endurance as compared to FRAM and MRAM.

II. RRAM STRUCTURE

RRAM is a two terminal device, passive in nature, in which an insulating layer having switching characteristic is inserted between two electrically conducting electrodes whose resistance is altered by application of external voltage across the metal-insulator-metal stack [11]. The MIM stack can be multilevel switching with multilayer stack, depending on the type of application. RRAM is composed of MIM stack [11]. Top electrode is referred to as TE, Bottom electrode is referred to as BE. In between layer is referred to as Oxide layer. Various metals like Au, Ti, TiN, Pt, W, Ta, La etc can be used in the stack. Also, insulating materials like HfO_2[12], TiO_2[13], Al_2O_3, Ti_2O_5[14], Nb_2O_5, ZnO, ZrO_x, WO_x, Cu_xO, NbO_x , SiO_2[15] etc with high dielectric constant k can be used. The optimum value of dielectric constant,k should lie between 25<k<30 [21]. These materials will have good insulating properties and thermal stability. If the insulating material is a two level stack, it's called as binary RRAM. Similarly, if the insulating material is a three level stack, it' called as trinary RRAM [13]. Also, the RRAM architecture, if horizontally stacked 3D is known as HRRAM and if vertically stacked 3D is known as VRRAM.

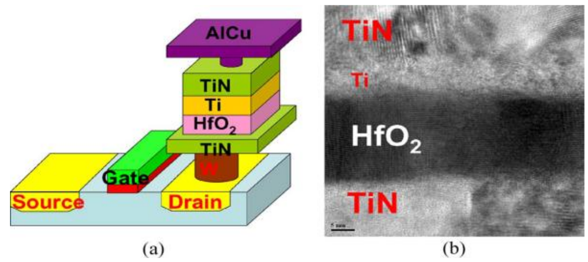

Fig.1 RRAM structure

A. RRAM WORKING

Resistive random access memory is based on resistive switching mechanism of memories, whose resistivity can be, electrically, switched between high and low resistance states. [8]. The RRAM switching can be either unipolar or bipolar. Fig.2 shows the RRAM switching characteristics.

I. UNIPOLAR SWITCHING: In unipolar switching, the switching direction depends on the amplitude of applied voltage, but not on the polarity of applied voltage. Therefore, Set/ Reset can occur at same polarity [16].

II. BIPOLAR SWITCHING: In bipolar switching, the switching direction depends on the polarity of applied voltage. Therefore, Set occurs at one polarity and reset occurs at other polarity [16].

Fig. 2(a) shows unipolar RRAM switching characteristics. In this, compliance current, I_{cc} cut off is same at both the polarities.

Fig. 2(b) shows bipolar RRAM switching characteristics. Here, the compliance current, I_{cc} does not have same value at both the polarities.

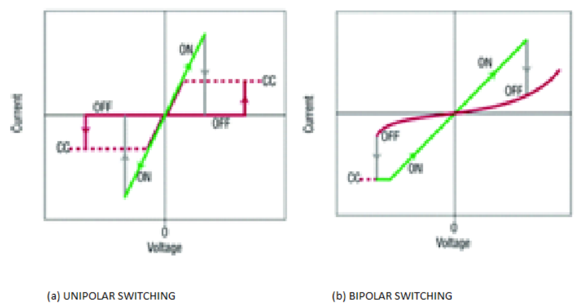

Fig.2 RRAM Switching characteristics

The switching behavior depends on the oxide material, choice of metal electrode and their interfacial properties [17]. When appropriate voltage is applied to the RRAM, the Metal insulator metal cell can be switched between High resistance state, known as HRS and Low resistance state, known as LRS. Digital logic level of HRS is 0 and that of LRS is 1. Its states are called forming, set and reset [18]. When the initial voltage is applied and RRAM goes from HRS to LRS, it's known as forming. Once the RRAM is formed, it is in on state. The on state is called as SET state. As polarity of voltage changes, the potential goes from LRS to HRS, then it is called as off state. Off state is called as reset state. Working of RRAM is shown in fig. 3. RRAM stores data using ions as changes in electrical resistance rather than electrons. Ions behave in nanometer scale [19]. Cells have two electrodes at which the ions dissolve and they precipitate [20]. This changes the electrical resistance which can be exploited for the data storage. RRAM generates defects in a thin oxide layer, known as oxygen vacancies which can charge and drift under the electric field. Motion of the oxygen ions and vacancies in the oxide is analogous to the motion of electrons and holes in semiconductor [21]. Compliance current is the current used to avoid permanent breakdown and control the resistance of LRS using voltage sweeps [16]

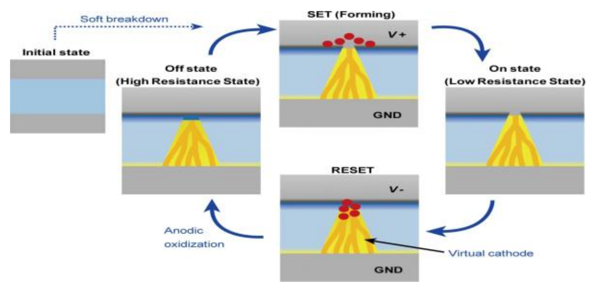

Fig.3 States in RRAM switching

III. PERFORMANCE PARAMETERS

In order to discuss advantages and disadvantages of RRAM, it is important to analyze its performance parameters. Various performance parameters of RRAM are operating speed, operating voltage, endurance, resistance ratio and retention time [22].

A. Operating speed: It is the minimum time for programming the RRAM cell. The switching speed reported so far is between 5ns to 100ns.

B. Operating voltage: Operating voltage is directly proportional to the power consumed in the circuit. In flash memory, the drawback is high operating voltage. This should not be the case with RRAM in order to be better than flash memory. Hence, the desirable operating voltage in case of RRAM is a few volts.

C. Endurance: Switching of an RRAM device between HRS and LRS can cause permanent damage to the RRAM cell. Hence, its endurance, often called as electric fatigue, which is the number of set and reset cycle, gets affected. The desirable range of endurance is 10^7 cycles to 10^{12} cycles.

D. Resistance Ratio: The ratio of resistances at HRS to that of LRS of RRAM is known as resistance ratio impacts the accuracy of the cell. If resistance ratio is less, i.e upto 6 or 7, cell cannot distinguish between HRS and LRS. Therefore the desirable resistance ratio for RRAM cell is greater than 10 [15].

E. Retention time: It tells about the intrinsic ability of the memory cell to retain its contents. The desirable retention time is 10 years with or without power on.

IV. RRAM DESIGN PARAMETERS

Designing an RRAM involves various performance parameters to be concerned like power consumption, speed, HRS/LRS ratio and multilevel storage [15]. For low power consumption requirement, Set power and reset power need to be optimized. This can be achieved by optimizing stop voltage, V_{stop}, Compliance current, I_{cc} and voltage sweeps between Set and Reset states [23]. For designing a high speed RRAM, materials with high dielectric constant values should be fabricated which influences the read, write and erase speed of RRAM. For good endurance of RRAM, HRS/LRS ratio should be chosen such that electric fatigue or RRAM exhibits greater endurance property. This is usually done by choosing bilayer [17] trilayer [13] doped oxides of suitable materials [24]. And for Multilevel storage design of RRAM, number of stable switching states should be increased. This is achieved by increasing number of stable states with binary, trinary, bilayer or trilayer so that greater number of switching may take place between high resistance state and low resistance state [11]. Table III shows detailed description of RRAM design based on performance parameters.

Table III. RRAM Design based on Performance parameter

S.no	Parameter Performance	Findings and techniques
1.	Power consumption	Set power and reset power contributes to the power consumption. These can be optimized by optimizing V_{stop} , Compliance current I_{cc} and voltage sweeps between set and reset states. [25]
2.	Speed	Operating/switching speed refers to reading, writing and erasing speed of RRAM. Materials with suitable response time can be opted to optimize speed of RRAM with high dielectric constant.[22]
3.	HRS/LRS Ratio	The ration of high resistance state to low resistance state affects the electric fatigue of RRAM, commonly known as its endurance and can be increased by choosing bilayer and trilayer doped oxides of suitable materials like HfO_2. [25]
4.	Multilevel storage	Multilevel storage can be increased by increasing number of stable switching states between HRS and LRS of an RRAM. This can be increased by taking materials like $Ti/Cu_xO/Pt$ or $Ti/HfO_2/Pt$.[23]

V. RRAM DESIGN

RRAM is designed on MOS by connecting layers of insulating and conducting materials on top of it in MIM format, i.e metal-insulator-metal [26]. RRAM can exhibit multilevel resistance switching property by either modifying amplitude of the voltage pulse or the compliance current and increasing the stack of RRAM cell from 3 level to 4 or 5 or 6 level and so on [27]. The stack can be of metal as well as the insulating material [28]. Comparison of performance parameters wrto. various material used is shown in table no. 4. $TiN/HfO_2/SiO_2/Ti$ is a binary bipolar RRAM has good endurance of 10^{5}, on/off ratio of 10^3 and retention of 1hour@125^{o}C [12]. A trinary RRAM $TiO_{2x}/HfO_{2y}/TiO_{2x}$ has better endurance and retention of 10^7 and 1hour@150^{o}C [32]. This shows that trinary RRAM shows better endurance than a binary RRAM [32]. Ag/ZnO/Ti/Au stack of bipolar RRAM shows excellent on/off ratio of 10^8 [34]. And $Ti/SiO_x/C$ shows excellent retention of 1hour@260^{o}C [33] because of one of the highest bandgap of 9ev among various insulating materials. Hence its evident that trinary RRAM shows better endurance, scaling and retention than a binary RRAM [24]. Researchers have experimented with various combinations of different materials to improve one or the other parameter. Some have three layer, four layer, five layer and six layer [13].

Table IV. Comparison of performance parameters wrto. Material used

S.No	Material Used	On/Off Ratio	Endurance	Retention	Operating voltage	Reference
1	$TiN/HfO_2/SiO_2/Ti$	10^3	10^5	1hour@125^{o}C	3/-2 V	E.Ray Hsieh et al., IEEE 2017
2	$TiO_{2x}/HfO_{2y}/TiO_{2x}$	N.A	10^7	1hour@150^{o}C	4/-3.5 V	Panagiotis Bousoulas et al., IEEE 2017
3	Ag/ZnO/Ti/Au	10^8	Not mentioned	Not mentioned	3/-3 V	G.Tallatida et al. IMW 2009
4	$Ti/SiO_x/C$	N.A	10^7	1hour@260^{o}C	4/-2.5V	Alessandro Bricalli et al. IEEE 2018

VI. CONCLUSION

A review of the resistive random access memory has been carried out with all the memory technologies available. Among all, RRAM is one of the most promising memory technologies in terms of storage density, non volatile behavior and its property of resistance switching makes it more versatile in the field of data storehouse devices. All the performance parameters have been discussed here showing reliability of RRAM.

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