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Optimizing of Resistive Random Access Memory to Increase Its Practicability

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Abstract:

The progress in Integrated Circuit Technology, has promoted the development of emerging technologies like AI and Iot. It also requires the memory technology a high standard. Resistive random-access memory (RRAM) has the advantages of lower power consumption, fast speed and owns a strong compressibility, and it is regarded as the most promising NVM in next generation. This review explains basic principle of RRAM, several switching mechanisms, and different materials of the dielectric layer, then compares performance of RRAM in different materials. The RRAM that is completed can replace Flash memory due to its function currently, and can be applied to different fields like Neural Network and IoT. However, the experimental data of RRAM is still not stable. Till now, feasible methods include Defect Engineering, Nanostructure or looking for better materials. Ion doping is one of Defect Engineering, it has been used for years and is proven to be useful on improving the stability and memory window of RRAM. As the fundamental in the development of electronics, the optimization of RRAM definitely has great influence on it. If RRAM can be widely used in the future, the development of new technologies will inevitably be astonishing.

Keywords:RRAM, Defect engineering, Neural network

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1. Introduction

As the development of high computing, the requirements for memory cell are also increasing. Memory cells can be mainly divided into two categories: volatile memory (VM) and non-volatile memory(NVM). VM can store data when the power is on while NVM can store data if the power is cut off. Currently, the dominant memory cells in electronic devices are DRAM (VM), SRAM (VM) and Flash Memory (NVM) [1]. SRAM has a very high read/write speed, but it takes more space for each unit; DRAM won't take much space for a single cell, but it doesn't have an enough capacity; though Flash has a very large capacity, its speed is very low. In addition, the development of Flash has encountered a bottleneck for several years. To make up for the disadvantages, the next generation of memory cell is required with characteristics like high speed, lower density and high capacity. Recently, there are a lot of emerging non-volatile memory, and RRAM is the most promising one among them: it has a simple structure, a higher write/read speed, a lower energy consumption and is compatible with CMOS technology. If RRAM can be widely applied in the industry, the development of electronic technologies like computer, IoT technology, man-made neural network and so on will be accelerated. This article suggests several possible improvement solutions for the shortcomings of RRAM which found in researches and experiments from the perspectives of defect engineering and material replacement.

2. The Working Principle of RRAM

RRAM is the memory cell that is a sandwich structure composed of two metal electrodes and a dielectric layer. Its storages data depends on the change of resistance in its dielectric layer. When a opening voltage is applied on the electrodes, based on different mechanisms, some conductive filaments will be formed in the dielectric layer. In high resistance state (HRS), it's “0”, and in low resistance state(LRS), it represents ”1”. The dielectric layer has several working modes, and this paper discusses the conductive filament mechanism type, which is the most promising one. The complexity requirements for materials and structures of RRAM devices are not significant, and it is compatible with COMS technology, so the miniaturization of chips will be simpler compared to others, and there is no need to invest a large amount of additional cost in the research and development of RRAM technology. Also, the operating current of RRAM is very small, and it indicates that RRAM saves a lot of energy and it meets the conditions for miniaturization.

2.1 Three different switching mechanisms in RRAM

In general, the switching mechanism of RRAM can be divided into three types because of the use of different materials: TCM (Thermochemical Mechanism), VCM (Valence Change Machanism) and ECM (Electrochemical Metallization). RRAM devices have two switching characteristics during the SET and RESET process in all: unipolar type and bipolar type. For bipolar RRAM device, the switching of high resistance state to low resistance state needs to reverse the voltage applied on the two electrodes, and voltage applied on unipolar devices is constant during the SET and RESET. Based on the property of the dielectric layer, TCM RRAM is unipolar and VCM and ECM are bipolar.

2.1.1 Thermochemical Mechanism type

The first type is called Thermochemical Mechanism. Usually, the dielectric layer of such RRAM is composed of transition metal dichalcogenides [2]. TCM RRAM is unipolar, when a high voltage is applied on the electrodes, some defects will be produced in the oxide film. Under the effect of electric field, these defects (oxygen or metal vacancy) will slowly form a conductive filament, and the dielectric layer transforms from HRS to LRS. In the forming process, the current goes through the filament must be limited in case the middle is permanently penetrated. This is the SET process. For RESET, the voltage should be applied in the same direction but no restriction to current. Since the current flows through the filament can be very large, lots of heat will be produced so that the filament is blown, and the dielectric layer returns to HRS.

2.1.2 Electrochemical Metallization

This type of RRAM usually composed of one active metal electrode and one inert metal electrode. The ingredient of the conductive filament is mostly metal atoms. When a positive voltage is applied on the active metal electrode, some metal cations will be produced, and goes toward another electrode under the effect of the inert metal. When these ions reach the negative electrode, they will be reduced to atoms. With more and more atoms reach here, the conductive filament will be formed. This is the SET process. VCM is bipolar types, so during the RESET, a reverse voltage should be applied on the electrodes, and the atoms composed of the filament will slowly become ions and the filament is dissolved. Figure1 shows the principle of the ECM type RRAM.

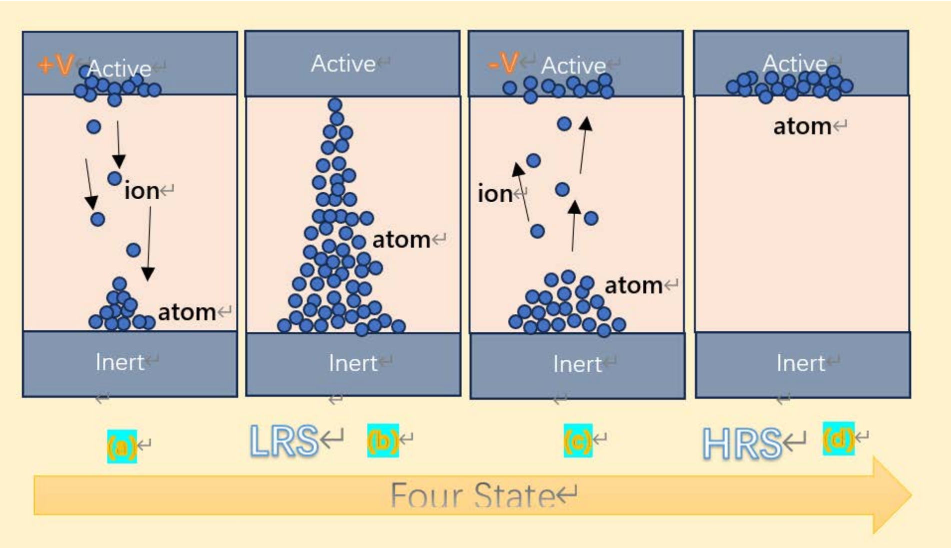

Figure 1. Principle of the ECM type RRAM

Where (a) Metal ions assemble the inert electrode. (b) The conductive filament is formed by metal atoms. (c) The atoms become ions and the filament starts to dissolve. (d) All atoms return to the top electrode.

2.1.3 Valence Change Mechanism type

Like the ECM type, VCM is also a bipolar type. Differ from ECM, VCM RRAM forms the conductive filament usually by oxygen vacancies in the TMDs film. When a positive voltage is applied on the electrodes, some oxygen vacancies will be produced under the effect of the strong electric field. Then they become cations and were attracted by the negative electrode. When oxygen vacancies accumulate to a certain extent, the conductive filament is formed, and the dielectric transforms from HRS to LRS, this is SET. When an opposite voltage is applied, the oxygen vacancies in the filament will also experience the same process in SET and the filament finally dissolve and disconnect. The mechanism for VCM is shown in Figure 2.

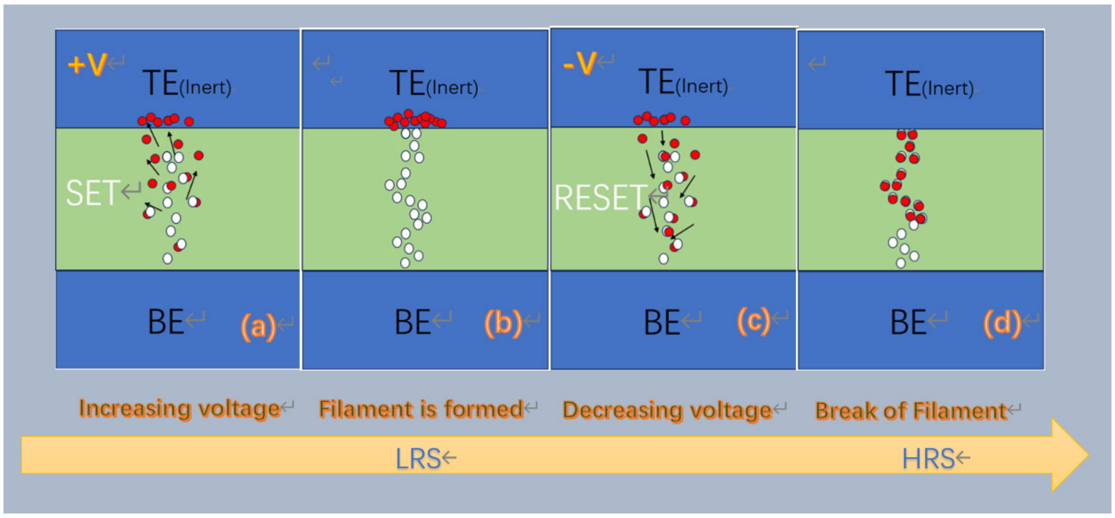

Figure 2. The mechanism for VCM

Where (a) Oxygen vacancies are forming. (b) The conductive filament is formed. (c) The filament is dissolving. (d) The filament breaks.

2.2 Different types of dielectric layers(based on materials)

Due to the composition of the dielectric layer, RRAM usually uses two types of materials: solid electrolyte and Metal oxide.

2.2.1 Solid Electrolyte Type

The solid electrolyte here refers to sulfide compounds and oxides containing silver and copper, like Cu2S, Ag2S, Ag: GeSe, Cu2Ge50Te50 and so on. Usually, this type of RRAM has advantages of a high retention (>10,8), high memory window (>10,6), high write and read speed(<5ns), low operating voltage (<1V), low working current (<1nA) and the feasibility of multi value storage.

2.2.2 Metal oxide type

Metal oxide type includes binary metal oxides and multicomponent metal oxides. Among the two, binary metal oxides have more types, and it gets more attention from the industry. Usually binary metal oxides include HfOx, LaOx, AlOx, ZrOx, TaOx and so on [3]. Compared with other materials, binary metal oxides have a simpler structure, so its preparation process is relatively complete; its composition ratio can be precisely controlled, and it is also compatible with CMOS technology [2]. The other type is multicomponent metal oxides, mainly there are PCMO, LCMO, LSMO, SrTiO3, SrZrO3, SrRuO3 and so on. Usually, this type of RRAM has a complex fabricating structure, and it is not compatible with CMOS technology. Although multi oxide materials also exhibit excellent resistive switching characteristics, their processing is complex, the composition ratio is difficult to control, and they are incompatible with current CMOS processes. These problems affect the uniformity and reliability of devices, so the application prospects of multi oxide materials are not optimistic by researchers [4].

2.2.3 Comparation of RRAM in different types

The comparation of some RRAM based on different materials in the past years is shown in the Table 1 [5].

Table 1. Performance of different types of RRAM

Type of dielectric layer	Material used	Memory Window	Retention	Endurance	Voltage Mode
Solid electrolyte	TiN/Cu2Ge50Te50	>10^2	NS	10^4	Bipolar
Solid electrolyte	Cu2GeTe3/Ta/GdAlO/TiN/TiN	10	3.6*10^6	10^7	Bipolar
MetalOxide	Ta/TaOx/Pt	~10	~10^7	10^9	Bipolar
MetalOxide	Pt/ZnO/Pt	10^3	10^6	10^6	Bipolar
MetalOxide	Ta/TaOx/TiO2/Ti	20	>10^4	>10^12	Bipolar
MetalOxide	Cu/HfO2/Pt	5	10^5	10^9	Bipolar
MetalOxide	Ag/a-ZnO/Pt	10^7	10^7	100	Bipolar
Metai Oxide	Cu/HfO2/TiN/Ru	30	10^6	10^8	Bipolar
Metal Oxide	Ti/HfO2/TiN	10	10^4	10^7	Bipolar
Metal Oxide	ITO/Zn2TiO4/Pt	10^2	10^4	100	Bipolar
Metal Oxide	Cu/Al2O3/Pt	NS	<10^3	10^5	Bipolar
Metal oxide	Pt/HfOx/Cu/Pt	10^4	NS	10^4	Bipolar
Metal oxide	Cu/ZnO/NiO/ITO	10^3	10^4	160	Bipolar
Metal oxide	Pt/Ta/TaOx/Pt	20	10^5	4.5x10^8	Bipolar
Metal oxide	W/TiO2/HfO2/TaN	20	10^4	10^7	Bipolar
MetalOxide	Pt/ZnO/Pt	10^4	NS	>10^2	Unipolar
Others	Au/h-BN/Au	10^7	10^6	50	Bipolar
Metal Oxide	Ti/MnO2/Pt	50	>10^4	>10^5	Bipolar
Metal oxide	Cu/WO3/Pt	10	3*10^4	150	Bipolar
Metal Oxide	Ag/CuxO/SiOx/n-Si	10^7	2*10^4	1.2*10^4	Bipolar
Metal Oxide	Ag/DmcT-cc/TiO2NP/FTO	10^4	2*10^4	NS	Bipolar
Metal Oxide	Au/ZnOxS1-x/Al	10^6	10^4	100	Unipolar
Metal Oxide	Pt/Ta/ZrO2/Pt	~10^2	NS	2*10^7	Bipolar

2.3 Possible fields RRAM can apply for in the future

As the improvement of RRAM , it can replace flash memory according to its high speed and highly integrated properties. Currently, there is a gap between storage and memory, and this gap limits the development of high-performance computer. So a concept called storage class

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memory (SCM) has been suggested: it has both high read/write speed and high retention, and can fill up the gap [1]. RRAM has the potential to meet the requirement. Another promising application area of RRAM currently is neural network. Due to the scalability of RRAM chips, their high-density integration can be achieved, and they have the potential to be used in the research of large-scale brain like computing chips. Artificial Neural Networks (ANNs), also known as Neural Networks (NNs), originated from the imitation of animal brain neural network behavior by humans. By adjusting the connection relationships between a large number of neuron nodes through certain algorithms, an algorithmic mathematical model capable of processing information is established in order to achieve learning behavior similar to that of the human brain [6]. Neural network requires a large number of neurons to construct, and RRAM can be used to simulate neurons or act as artificial synapses. In the application of resistive switching memory in artificial synapses, the abstract weights in neural network algorithms are mapped to the conductance values of the resistive switching memory. Therefore, developing resistive switching memory with strong voltage-controlled conductance capability is crucial for its application in artificial synapse devices Research has found that some RRAM devices can achieve continuous changes in conductivity at appropriate voltages, thus possessing the ability to simulate neural synapses. Continuous changes in conductivity can be achieved through two methods: direct current scanning and pulse current scanning.

Besides, the construction of Iot(Internet of Things) also requires NVM like RRAM. For example, the Power Gating is used to cut off the circuit while the system is in standby mode [7]. However, if SRAM or DRAM is applied, data can’t be stored if the power is cut off, and transporting them to additional Flash memory needs more space and power supply. That will limit the total performance of the system. As a result, advanced NVM like RRAM is needed as it has a fast speed which is the same as those of SRAM and DRAM, and NVM can stored information even if power is cut off.

2.4 Challenges RRAM is facing currently

Although RRAM is the most promising next-generation NVM device, its current development is not sufficient to support its practical applications. There are still many problems with RRAM: the lack of stability and uniformity, unclear exact switching principl. The parameters of RRAM chips are still unstable, and solving such problems requires proposing new and constructive methods, or modeling the working mechanism of the chip. At the atomic level, the formation of filaments has randomness, and the key to solving the problem is to make the process of filament formation stable. At present, some proposed theories suggest improving the conductive filament type RRAM to a non-filament type structure, or changing the composition of the filament by doping different impurities, or adding nanocrystalline structures to the resistive switching layer to enhance stability during the forming process.

3. Methods to improve the performance of RRAM.

Improving the performance of RRAM can be considered from two aspects: replacing materials and changing structures. Among them, material replacement includes replacing the material of the dielectric layer and the material of the electrode and changing the structure mainly relaters to defect engineering and so on. The general principle of improvement is to explore and understand the physical mechanism of resistance change process through experiments, in order to find ways to improve device performance.

3.1 Improvement by defect engineering

Generally speaking, creating defects into the resistive switching layer of RRAM can greatly improve the ability of conductive filaments to capture charges and enhance the switching ratio. And these defects including doping metal ions, creating vacancies, inserting layers (Interface Engineering) and some new materials and soon. Usually, these defects can help make forming process of the conducting filament to be more stable, and can help trap charges, elevate the memory window. Some even change the switching mechanism inside and enhance the internal electric field in the dielectric layer. Wang and his team members in Anhui University and Hefei Normal University, using first principle to analyze the process of oxygen vacancies forming conductive filaments in HfO2 quantitatively, and the influence of defects on the electronic structure of the material was analyzed [8]. Based on the model, the performance of hafnium oxide resistive switching memory was improved by doping metal atoms. They doped Ag, Mg, Ni, Cu, Al, Ta, Ti these seven metals inside the dielectric layer to study their influence systematically, and they find that: Metal Ni has the smallest formation energy in defect systems, which is most likely to exist within defect bodies, and has the highest equipotential value, resulting in a more uniform partial wave charge density in the system.

Moreover, Yang come from Anhui University also improve the performance of Single layer a-GeTe resistive random-access memory by creating vacancy structure in the dielectric layer [9]. The single layer a-GeTe RRAM is composed of two graphene electrode and single-layer a-GeTe resistive switching layer, and its memory window is about 10^4. After Yang had found the conductive filament is formed by the movement of Te vacancies, he successfully lowered down the working voltage in the SET process and increase the memory window from 10^4 to even 10^9, by creating one or two Te vacancies on the two-dimensional switching layer. Besides, he also tried to institute the electrodes of the RRAM by other two-dimensional materials like InP3 and Mo2C. He found that the improved RRAM with a InP3 electrodes can have a higher on state current and memory window, and the launching voltage is also decreased at the same time, which helps reduce the power demanded. But when he uses Mo2C to institute the electrodes, it brings a opposed effects: both on state current and memory window is lowered, and the launching voltage is also increased. However, the change of electrodes didn’t has a clear influence. After analysis he found: the reason InP3 has the most elevation is that the maximum mobility of electrons at their electrode interface leads to an increase in current density and a decrease in required voltage.

In addition to doping defects into the resistive switching layer, there are also some new theories proposed to improve the performance of RRAM: the concept of Hybrid RRAM (HRRAM) is one of them. Like its name, the conductive filament of HRRAM is composed of both metal ions and oxygen vacancies. The forming of this type of filament is energetically favorable: in the RESET process, the oxygen vacancies can be removed faster than the metal atoms, so the result is part of the filament will be broken, and that saves energy. For example, the filament can be Cu+Vo, Al2O3+Vo or GdOx+Vo, and oxygen vacancies need to be easily removed to enhance the endurance of the filament during RESET process. Moreover, the proper balance between the metal-interstitials and oxygen vacancies is essential.

3.2 Changing the material of dielectric layer and electrodes.

Creating a simulation model of RRAM can help the scholar analyse and have a clear understanding the mechanism of the resistance switching, and help find a better material to improve the performance of the cell. Sun and his team members in Chongqing Normal University they used the two-dimensional axisymmetric structure in COMSOL Multiphysics simulation software to analyze the electric thermal coupling model of metal oxide resistive random-access memory (RRAM) [10]. The RRAM structure is a Ti/HfO2/ZrO2/Pt bilayer structure, and the SET and RESET processes of Ti/HfO are validated and analyzed using 2/ZrO2/Pt. Research has found that CF1 (HfO2 layer), CF2 (ZrO conductive wire 2 layers), and resistive dielectric layer can affect the electrical performance of the device. Ti/HfO2/ZrO2/Pt exhibits stable high and low resistance states when the width ratio of the conductive wire to the transition layer (6:14) and the thickness ratio of HfO is 2 to ZrO2 (7.5:7.5). On this basis, a comparison of three commonly used RRAM metal top electrode materials (Ti, Pt, and Al) shows that the Ti electrode has the highest resistance switching ratio, about 11.67. Finally, by combining the optimal size of the conductive wire and the optimal top electrode material, the I-V hysteresis loop was obtained, and the switch ratio R closed/R was calculated as 10.46. Suns established a comprehensive RRAM model, explained and analyzed the resistance mechanism, and provided the optimal geometric dimensions for Ti/HfO hysteresis characteristics and electrode material 2/ZrO2/Pt structure.

4. Conclusion

RRAM is a very promising non-volatile memory, it has the potential to replace Flash memory in the future. This article introduces the basic principle of RRAM, its different types and the challenges scholars are facing currently when translating RRAM into practical applications: unstable and uneven experimental data is the biggest problem. Till now, in terms of memory window, retention, and endurance, the best-known RRAM data can reach 10^9, 10^7, and 10^12, separately, but these advantages can’t be combined so far. To improve the performance of RRAM, there are two basic ways of thinking: from structure or material. While Defect Engineering, nanostructure and interface Engineering are to change the structure, the electrode or the dielectric layer can be replaced due to material change. Defect engineering is currently almost the most mature improvement process, which has been used for more than a decade, like ion doping, which has long been proved useful to improve the property of the conducting bridge inside the cell. RRAM can be applied for many regions like Internet of Things, neural network and some other fields that requires a large amount of storage space. However, the flaw of this article is that the conclusions summarized in this article are all analyzed by other papers, rather than obtained through actual experiments or tests. In order to fundamentally address these defects in RRAM devices, future scholars must conduct more practical experiments.

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