Extended Abstracts of the 2014 International Conference on Solid State Devices and Materials, Tsukuba, 2014, pp426-427

Current Status of Cation-Based Resistive Memory

Michael N. Kozicki and Hugh J. Barnaby

School of Electrical, Computer, and Energy Engineering
Arizona State University
Tempe, Arizona, 85287-5706, USA
Phone: +1-480-965-2572 E-mail: michael.kozicki@asu.edu

Abstract

This paper provides an update on the status of cation-based resistive memory, which utilizes metal (Ag or Cu) ion conducting materials between oxidizable and inert electrodes. The memory elements exhibit resistance switching via bias dependent ion transport through the solid-state ion conductor and reduction/oxidation (redox) reactions at the electrodes. A wide range of applications has been demonstrated and non-volatile resistive random access memory (ReRAM) has already entered the marketplace. The paper briefly reviews device operation, particularly in the context of low energy applications, and presents recent research results on the radiation-hard aspects of the technology.

1. Introduction

Moore's Law has led us to expect that device elements will continue to shrink and thereby enable electronic systems to increase in functionality but with a decrease in cost. This has led to the introduction of smaller and lighter mobile devices, such as smartphones, tablet computers, and ultra-thin notebook computers, which do not use bulky, power-gulping hard disk drives but instead favor solid state data storage. In addition, we are seeing a new generation of wireless electronic devices which service the "Internet of Things" (IoT), the advanced connectivity of devices, systems and services. One class of "things" in the IoT concerns the human body, where more instrumentation is being implanted to improve quality of life for those with disease or failing organs. These applications demand both small form factor components and low energy operation, the latter being mandatory in battery-powered systems which typically have a total energy budget between recharges of much less than a few tens of kilojoules. Since memory and storage now and in the foreseeable future account for a significant part of an information processing and communications system, it is obvious that memory must not only be suitably compressed but also must function at extremely low energy, meaning that storage elements will have to work with circuit voltages of less than one volt and operating currents below a few tens of microamps. The mobile electronics and IoT markets are burdened with significant cost sensitivity and so the new memory technologies should be manufactured with as few critical processing steps as possible and with high array efficiencies to minimize chip area. In addition, since the IoT includes medical devices, radiation tolerance becomes a necessity as the components must remain 100% functional following pre-implant gamma sterilization or during therapeutic or diagnostic radiation exposure.

Programmable metallization cells (PMCs) are metal–electrolyte/insulator–metal structures that are switched from a high resistance state to one or more low resistance states by the application of a small bias. Their operation relies on the formation and dissolution of conductive filaments between oxidizable and inert electrodes via ion transport mechanisms and electrochemical reduction-oxidation (redox) reactions [1]. PMC characteristics have been shown to be highly suitable for next-generation non-volatile memory (NVM), particularly since current NVM technologies based on charge storage mechanisms are facing serious scaling challenges [2]. Although the leading incumbent, Flash memory, provides high density at low fabrication cost, it suffers from high operating voltage, low programming speed, and low endurance, and it is incompatible with ultra-low energy CMOS applications. It is also not radiation hard as it can only tolerate a few tens of krad (Si) and so is of limited use in the context of medical devices or space and nuclear applications [3]. Alternative non-volatile technologies have therefore been in development for some time with the promise of overcoming these limitations but it is resistive random access memories (ReRAM) that are currently the most promising candidates. Of these, PMC-based variants have led the race and are now in commercial use due to their excellent scalability, wide dynamic range, high operational speed at low voltage, low operating current, and compatibility with back-end-of-line CMOS fabrication [4,5].

2. Device Operation

A variety of chalcogenide, and oxide cation conductors and electrode materials have been used in PMC-like structures [1]. In most cases, one electrode is "oxidizable", i.e., it can supply ions into the ion conductor on the application of a small bias, and the other electrode is relatively inert, supplying electrons into the reaction environment to reduce the ions. Ag and Cu are most often used in the oxidizable electrode and materials such as W, Pt, and TiN have been used as the inert electrode. Ag- or Cu-doped chalcogenide glasses (ChG), such as Ag-Ge-S, or oxides, such as SiO_x or WO_x, have been shown to be suitable for PMC devices as they are stable solid electrolytes with good metal ion conductivity at room temperature. Applying a positive voltage to the oxidizable electrode allows the net dissolution of the metal and reduction of the ions at the inert electrode to form a metallic (Ag or Cu) filament, which then bridges the relatively insulating electrolyte and sets the low resistance ON state of the device. A resistance change of several orders of magnitude is achievable with a programming energy in the order of 1 pJ [6]. The ON-state resistance can be set by programming current and time; it is possible to program multiple discrete resistance levels to represent more than one binary digit per cell [6,7]. The asymmetry of the device (oxidizable and inert electrodes) allows the above process to be reversed by applying an opposite bias which oxidizes/dissolves the conducting bridge and places the cell in its high resistance OFF state. Symmetric program-erase cycling beyond 10^6 operations has been demonstrated for Ag/Ag-doped Ge-S/W devices at voltages below 0.6 V with unambiguous differentiation of ON and OFF states achieved for currents as low as 1.6 µA [8].

PMC is the technology platform for Conductive Bridging Random Access Memory (CBRAM®), a commercially available non-volatile memory product [9]. CBRAM has been identified as one of a small number of viable candidates for next-generation nonvolatile memory by the International Technology Roadmap for Semiconductors (ITRS) [10]. The stability of the on-state in CBRAM's 1T-1R cells is sufficient to allow more than 10 years data storage at 85ºC [11], indicating a level of non-volatility comparable to standard Flash memory.

3. Gamma Radiation Hardness

Fig. 1 illustrates the radiation hardness of chalcogenide glass-based PMC devices, showing cumulative distributions of ON- and OFF-state resistances for 5 µm diameter Ag-Ge-S ($Ge_{40}S_{60}$) cells programmed using a voltage sweep of 0 – 1V on an Agilent 4155 parameter analyzer and 100µA current limit, after exposure to gamma radiation from a ^{60}Co source with total-ionizing doses (TIDs) up to 10 Mrad($Ge_{40}S_{60}$) [12].

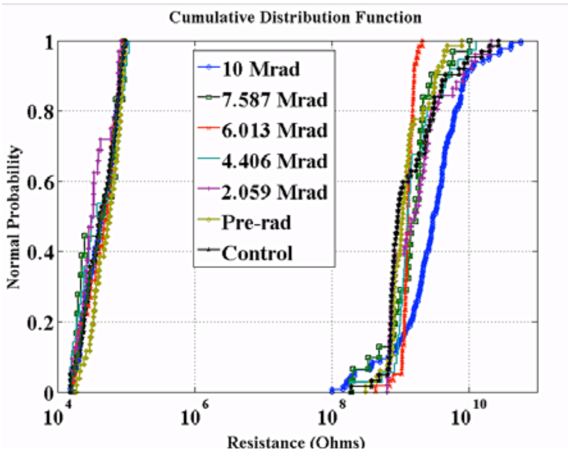

Fig. 1. Cumulative distributions of ON and OFF-state resistances of Ag-Ge-S based PMC device for gamma radiation total-ionizing doses from 2.059 to 10 Mrad($Ge_{40}S_{60}$).

The average ON-state resistance is in the order of 4kΩ and the OFF-state resistance average ranges from mid-10^8 Ω to mid-10^9 Ω. As is evident from the data in the figure, there is negligible difference between the irradiated devices and the non-irradiated controls which suggests a considerable tolerance to gamma radiation. Retention of CBRAM 1T-1R arrays has also been assessed. Checkerboard patterns were programmed into a 128 kBit EEPROM-type memory before exposure and read after. No errors were noted after 447 krad on CBRAM devices, whereas comparable Flash devices tested at the same time had unacceptable error counts [13].

4. Conclusions

Programmable metallization cells are capable of low voltage (<0.6V) and low energy (1 pJ) operation and are therefore ideal candidates for next generation non-volatile memories for mobile and IoT applications. Recent research shows that PMC devices have a high tolerance for gamma radiation and may also be suitable for medical device applications.

Acknowledgements

The authors wish to acknowledge the technological support of Adesto Technologies, the Center for Applied Nanoionics and the Center for Solid State Electronics Research at ASU, and the financial support of Defense Threat Reduction Agency (under grant no. HDTRA1-11-1-0055.

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