Abstract

Programmable Metallization Cell (PMC) memory is based on the electrochemical control of nanoscale quantities of metal in thin films of solid electrolyte. A silver layer and an inert electrode formed in contact with a Ag\(^+\)-containing electrolyte film creates a device in which information is stored via the electrodeposition of silver. This results in large non-volatile resistance changes. This paper highlights voltage, current, speed, endurance, and retention aspects of PMC as well as the process temperature stability of Ag-Ge-S electrolyte devices.

Keywords: Non-volatile memory, solid electrolytes, chalcogenide glass, electrodeposition, resistance change.

Introduction

The semiconductor industry has acknowledged, via the International Technology Roadmap for Semiconductors, that there will be severe problems with the scaling of solid state memory as we move toward the end of this decade. Physical size reduction of memory based on charge storage (e.g., DRAM, Flash) will result in unacceptable retention or state detection characteristics and the voltage, power, and cost requirements of future systems rule out most other approaches. Programmable Metallization Cell (PMC) memory, which is based on the electrochemical control of nanoscale quantities of metal in thin films of solid electrolyte, shows great promise as an ultra-scalable and manufacturable solid state memory [1]. Key attributes are low internal voltage, low power consumption, and the ability for the storage cells to be physically scaled to minimum lithographic dimensions. Electrolyte formation is a relatively simple process, involving the dissolution of silver in a chalcogenide (e.g., Ge-Se, Ge-S) glass. Standard processing equipment may be utilized and no high temperature steps are necessary. A silver-containing layer and an inert electrode formed in contact with the electrolyte film (see Fig. 1) creates a device in which information is stored via electrical changes caused by the oxidation of the anode silver and reduction of silver ions in the electrolyte. This occurs at an applied bias as low as a few hundred mV and can result in a resistance change of many orders of magnitude even for currents in the µA range. A reverse bias of the same magnitude will reverse the process until the excess silver has been removed, thereby erasing the device. Since information is retained via metal atom electrodeposition rather than charge storage, PMC memory is non-volatile with excellent retention characteristics.

Fig. 1. Field emission scanning electron microscope photograph of a cross section of a PMC memory device, showing the main layers. This device was formed in a 40 nm via in a PMMA dielectric.

This paper shows the basic attributes of PMC memory devices. Attention is given to current-voltage characteristics, which illustrate low voltage and low current operation, as well as speed, endurance, and elevated T retention capabilities. Recent results that show the process temperature stability of Ag-Ge-S electrolyte devices are also presented.

Device Fabrication and Results

Fig. 1 above illustrates the basic structure of a PMC memory test device. The bottom electrode is typically tungsten although it can be composed of various electrochemically indifferent materials (e.g., nickel). The dielectric can be a variety of materials although we have concentrated on two: SiO\(_2\) for devices with D > 100 nm and poly-methylmethacrylate (PMMA) for sub-100 nm devices (the device of Fig. 1 is 40 nm in diameter and was fabricated using electron-beam exposure of a PMMA dielectric film on Ni). The solid electrolyte is typically formed after via etch by depositing a 50 nm thick Ge-Se or Ge-S base glass layer followed by a 25 nm thick layer of Ag, both by PVD. The Ag
is then photodissolved into the base glass using uv light (405 nm, 1 J/cm

2) at room temperature. The photodissolved Ag will combine with Se- or S-rich base glasses to form a solid electrolyte with high Ag ion mobility and availability [2,3]. An additional 50 nm of Ag is added to create a source for the electrodeposition and this is capped with the top electrode layer (this can also be a variety of metals but we tend to use Au to prevent tarnishing of the silver during testing).

Fig. 2 above shows a 1 µA limit current-voltage curve for a 50 nm thick Ag-Ge-Se solid electrolyte on W device (D = 240 nm, SiO

2 dielectric). The device switches from an R

off of >10

10 Ω (limit of the measurement apparatus) to an R

on near 200 kΩ at 240 mV. This result is typical for tungsten electrode devices of 1 µm diameter and less [1] (Ni electrode devices, such as that in Fig. 1, write at 180 mV). R

on is independent of area as electrodeposition occurs in a region of only a few tens of nm in diameter. For a current-limited write, R

on is inversely proportional to the write current; if we use a 10 µA limit, the on state resistance is closer to 20 kΩ. The electrodeposit is essentially dissolved at -150 mV and the device returns to its high resistance state. One consideration for Se-based devices is that they do not tolerate processing temperatures above 230 °C without modification and so a low temperature back end of the process is necessary. The Ag-Ge-S electrolyte devices have much better process temperature stability with acceptable changes following high temperature processing; write voltage rises from 250 to 380 mV and erase from -100 to -170 mV for processing at 370 °C for 15 min (Fig. 3).

Fig. 4 shows the switching and cycling characteristics for a µm scale Ag-Ge-Se device; the y-axis is the voltage across a series resistor. The on state is around 1 MΩ (limited by test system parasitics). Write and erase transitions occur within the 35 nsec rise/fall time of the ±1 V input signal. Single pulse measurements confirm that the actual write and erase times are less than 25 nsec (system limit). The curve of Fig. 4 was obtained after 1.25 x 10

11 cycles and the smoothed (noise reduced) waveforms are essentially identical to those obtained for this device at 10

8 and 2.5 x 10

11 cycles, indicating no discernible device degradation with cycling. Fig. 5 uses extrapolated data (1 month actual test time) to illustrate R

on dependence on write current for 10 years at room temperature and at 70 °C. To maintain sub-100 kΩ R

on after 10 years at 70 °C, a write current in excess of 30 µA is required.

Fig. 5. On resistance after 10 years at room temperature (RT) and 70 °C for programming current limits from 15 to 40 µA.

References