



Static impedance behavior of programmable metallization cells



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ABSTRACT

Programmable metallization cell (PMC) devices work by growing and dissolving a conducting metallic bridge across a chalcogenide glass (ChG) solid electrolyte, which changes the resistance of the cell. PMC operation relies on the incorporation of metal ions in the ChG films via photo-doping to lower the off-state resistance and stabilize resistive switching, and subsequent transport of these ions by electric fields induced from an externally applied bias. In this paper, the static on- and off-state resistance of a PMC device composed of a layered (Ag-rich/Ag-poor) Ge₃₀Se₇₀ ChG film with active Ag and inert Ni electrodes is characterized and modeled using three dimensional simulation code. Calibrating the model to experimental data enables the extraction of device parameters such as material bandgaps, workfunctions, density of states, carrier mobilities, dielectric constants, and affinities.

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1. Introduction

The programmable metallization cell (PMC), which is based on the electrochemical control of nanoscale quantities of metal in thin films of solid electrolyte, shows great promise as a scalable and manufacturable solid-state memory technology [1–3]. The PMC technology, also known as Conductive Bridge Random Access Memory (CBRAM[®]), has matured to the point where memory devices are commercially available. The cells achieve resistive switching through the formation and dissolution of nano-sized conductive filaments within a solid-state electrolyte material [2]. The solid electrolyte, often comprising a chalcogen-rich germanium-selenide (or -sulfide) chalcogenide glass (ChG) or oxides (e.g., SiO₂, WO₃, Ta₂O₅), is sandwiched between two electrodes, an electrochemically active anode (Ag, Cu) and an inert cathode (Ni, W, Pt). Bias-dependent transport of Ag (or Cu) ions, via the application of a voltage or current across the electrodes, and electrochemical reduction–oxidation (redox) reactions allow Ag- or

Cu-rich filaments to be grown or dissolved in the active film where ions are conducted [4–10,15–18].

In order to reduce the energy needed for filament growth or dissolution, electrochemically active metal is typically introduced into the film during fabrication when a metal/glass bilayer is exposed to light in a process known as photo-doping. Exposure to photons of ultra-violet (UV) light causes metal to diffuse into the film and form ternary phases that extend into the film from the active metal side. Within this photo-doped, metal-rich region, the film resistivity is many orders of magnitude less than undoped glass [11]. However, even with metal concentrations as high as tens of atomic percent, these metal doped chalcogenide films have resistivities that are still many orders of magnitude higher than the metallic filaments [12]. After a typical photo-doping process involving Ag and a ChG, the resulting structure comprises an Ag-rich ternary layer extending from the active Ag anode and a region of relatively undoped (high resistivity) glass, as illustrated in Fig. 1. Photo-doping can be used in PMC processing to produce such a layered structure and thereby reduce the span of undoped material over which a filament must be grown. Reducing the thickness of material to be bridged decreases the switching voltage and filament formation time.

Material parameters associated with both the Ag-rich (photo-doped) and Ag-poor (unphoto-doped) layers in the ChG film are

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not well known. A precise physical model that captures the electrical behavior of the PMC in both its low-resistance on-state (LRS) and high resistance off-state (HRS) has therefore yet to be developed.

The primary objective of this paper is to model the PMC with a device simulator and extract material parameters associated with the ChG film when the device is in its HRS and LRS. Extraction is performed by adjusting these parameters, which include material bandgaps, affinities, dielectric constants, carrier mobilities and effective state densities, in order to fit simulation results to electrical data on actual PMC devices. These extracted values are compared to first principles calculations on GeSe films, as well as results reported in literature. Obtaining an accurate set of material parameters for both Ag-rich and Ag-poor ChG systems enables greater fidelity in PMC device simulation, which significantly enhances our ability to understand the underlying physics of ChG-based resistive switching memory.

2. Device details

The PMC device is a two-terminal structure, comprising a bottom inert electrode (cathode), the solid electrolyte, and an oxidizable metal layer, which can also be the top electrode (anode). The PMCs studied in this work consist of an Ag-doped chalcogenide film ($\text{Ag-Ge}_{30}\text{Se}_{70}$) sandwiched between an Ag anode and a Ni cathode [4–10]. Fig. 1 illustrates a cross section of the PMC device. Fig. 2 shows the top-view of a PMC test device with via dimension of $250\ \mu\text{m}$ by $250\ \mu\text{m}$. Such relatively large devices were used to reduce the effects of parasitic in the probe pads and metallization.

Under the application of positive bias above a specified threshold at the anode, the Ag layer will be oxidized allowing metal ions to enter the electrolyte and migrate towards the cathode. There they will be reduced to form a conductive filament that shunts the high resistance electrolyte, resulting in a low resistance state (LRS) [13,18]. Ion hopping has been proposed as the primary mechanism of cation transport during the formation of the filament [5–7]. The reset process is initiated when a negative voltage on the previous anode is applied. As a result of this bias, the filament metal is oxidized and mobile cations tend to dissolve laterally into ChG matrix [14]. At some point the diameter of the tip of the filament goes to zero, after which the device rapidly returns to its high resistance state (HRS) [16].

The PMC devices studied in this work are fabricated on a $100\ \text{mm}$ (diameter) $0.5\ \text{mm}$ (thick) p-type silicon wafer. The oxide and metal stack, comprising $100\ \text{nm}$ of SiO_2 , $100\ \text{nm}$ of Ni and $100\ \text{nm}$ of SiO_2 is deposited in an e-beam evaporator tool (Lesker PVD75 E-beam Evaporator). Device vias are then created to expose

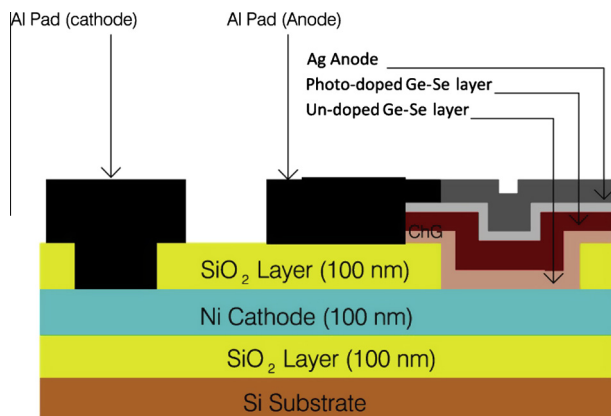


Fig. 1. Illustration of PMC device cross-section with Ag anode, Ni cathode and chalcogenide (ChG) layer showing the two layer photo- and unphoto-doped ChG structure.

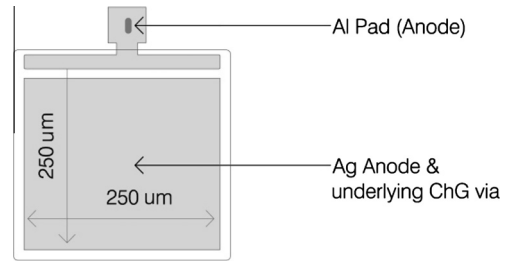


Fig. 2. Top (planar) view of a PMC device with via dimension $250\ \mu\text{m}$ by $250\ \mu\text{m}$.

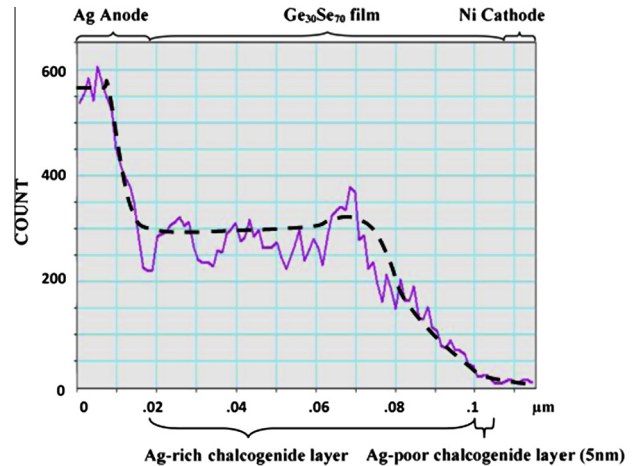


Fig. 3. Atomic profile of Ag along the PMC device obtained from EDS measurements, showing low Ag count near the cathode side.

the underlying Ni to define the active area of the device using a wet etch step. Deposition of $85\ \text{nm}$ $\text{Ge}_{30}\text{Se}_{70}$ and $30\ \text{nm}$ Ag films in via areas is performed using a thermal evaporator (Cressington 308). The wafer is then exposed to UV light ($\lambda = 324\ \text{nm}$, $E = 3.82\ \text{eV}$) for $1\ \text{h}$ at a power density of $10\ \text{mW}/\text{cm}^2$ in order to allow Ag photo-doping of the chalcogenide film. An additional $35\ \text{nm}$ of Ag is then deposited on top of the silver-doped $\text{Ge}_{30}\text{Se}_{70}$ layer to create the anode. Finally, the metal pads are deposited using an e-beam evaporator.

Photo-doping of silver into the ChG film dramatically changes the properties of the material [19,20]. Fig. 3 shows the Ag atomic profile along the cross section of the PMC device after the photo-doping process, where the solid line represents the actual data obtained from energy dispersive spectroscopy (EDS) measurements, and the dashed line represents the trend line. The inclusion of Ag into the ChG film changes its electrical properties from dielectric to solid-state electrolyte. This improves the material stability and repeatability of resistive switching [21–23]. Capturing the impact of Ag incorporated into the glass is critical to accurate parameterization of the PMC device.

3. Parameter extraction approach

After processing, the PMC structure may be described as a non-uniformly doped electrolyte with a significantly reduced Ag doping concentration close to the bottom Ni electrode. As can be seen from the Ag atomic profile shown in Fig. 3, the Ag concentration in the $\text{Ge}_{30}\text{Se}_{70}$ is relatively low up to $5\ \text{nm}$ from the cathode contact. This low Ag concentration will result in a high resistivity layer which will dominate the off-state resistance of the PMC. During the write process (HRS to LRS switching), Ag^+ ions from the anode and from the Ag-rich photo-doped layer contribute to the formation of the

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