This paper proposes using hourglass-shaped metal filaments to improve the ON/OFF resistance ratio and retention characteristics of switching devices for use in reconfigurable field programmable gate arrays (FPGAs), because of their scaling potential, low power consumption, high ON/OFF resistance ratio, etc.\textsuperscript{1–4}

The switching mechanism of PMCs can be explained by the formation and rupture of active metal (Ag or Cu) filaments in insulating solid electrolytes.\textsuperscript{3} Conductive filament formation (dissolution) occurs under positive (negative) electric potentials at the active electrode, and is referred to as the SET (RESET) process. With the SET and RESET processes, devices enter the low resistance state (LRS) and high resistance state (HRS), respectively.

Even though PMC devices with chalcogenide materials show high ON/OFF resistance ratios adequate for FPGA applications, they exhibit poor retention properties and low glass transition temperatures.\textsuperscript{5–10}

In this paper, we propose a PMC device with multi-layer oxide electrolytes for FPGA applications. We use a 3-nm-thick Al\textsubscript{2}O\textsubscript{3} layer, because of the large band-gap and low ionic mobility of Cu.\textsuperscript{11} Furthermore, an additional TiO\textsubscript{2} layer serves to introduce an element with high ionic mobility of Cu, thus allowing the optimum control of Cu diffusion and the formation of hourglass-shaped (HG) filaments. As a result, both high ON/OFF resistance ratios and good data retention capabilities are achieved.

**Experimental**

The PMC devices were fabricated on 300-nm-diameter W bottom electrodes. The 300-nm-diameter spacer was patterned by E-beam lithography through 90-nm-thick SiO\textsubscript{2}. After spacer patterning, W-deposition was performed using physical vapor deposition, and the electrodes were made by chemical mechanical polishing. Next, 3-nm-thick Al\textsubscript{2}O\textsubscript{3} and 1-nm-thick TiO\textsubscript{2} layers were deposited by atomic layer deposition (ALD) using trimethylaluminum, tetraisopropoxide, and H\textsubscript{2}O precursors. Having completed that, 50-nm-thick Cu electrodes were deposited by DC sputtering from a Cu target. Finally, oxygen-deficient AlOX was formed by a controlled H\textsubscript{2}O pulse during ALD. The fabricated PMC devices were electrically tested using an Agilent B1500A semiconductor device analyzer.

**Results and Discussion**

Fig. 1a compares the Cu-ion mobility in the different oxide electrolytes from the physical tunneling gap reduction induced by Cu thermal diffusion.\textsuperscript{3} The fast Cu-ion mobility in TiO\textsubscript{2} was confirmed by the steep decrease in resistance observed after thermal annealing. In addition, the lower forming voltage (the first SET) of the TiO\textsubscript{2} electrolyte (see Fig. 1b) supports the notion of a higher Cu-ion mobility in the TiO\textsubscript{2}.\textsuperscript{12} Fig. 1c shows the Cu/Al\textsubscript{2}O\textsubscript{3}/TiO\textsubscript{2}/W PMC device structure. The HG filament formation was expected, because of the adoption of a multi-layer oxide structure consisting of both high and low Cu-ion mobility materials.\textsuperscript{13,14} Although the HG-filament PMC was expected to show high uniformity, fast switching, and excellent memory disturb characteristics, insufficient ON/OFF resistance ratios were observed, which might be attributed to the persistence of partial Cu-filaments after the RESET process.\textsuperscript{15,16}

Consequently, we adopted oxygen-deficient Al\textsubscript{2}O\textsubscript{3} as an upper oxide, to suppress the formation of bulky upper HG filaments and accelerate filament rupture during the RESET process. We also obtained switching behaviors with high ON/OFF resistance ratios in the multi-layer and defect-engineered oxide-electrolyte-based PMC devices (AlOX/TiO2), as shown in Fig. 2a. The AlOX/TiO\textsubscript{2}-based PMC...
Figure 2. (a) Typical DC I-V curves for the Al2O3, AlOx, and AlOx/TiO2 electrolyte-based PMC devices. High forming voltages and two-step forming can be seen for the Al2O3- and AlOx/TiO2-based PMC devices, respectively. (b) Forming voltage and resistance after the first RESET process, for various PMC structures. (c) Pristine resistance for various AlOx thicknesses. (d) Schematic diagram of the RESET process of the fabricated AlOx/TiO2-based PMC device.

Figure 3. (a), (b) High forming voltage and RESET current were observed for the stoichiometric Al2O3-based, Al2O3/TiO2, and thick TiO2-based AlOx/TiO2 PMCs. (c) Bulky conductive filament formation phenomena resulting from the suppressed Cu migration through the upper oxide region, and the increased forming voltage.
values, a value that is suitable for reconfigurable FPGA applications. Furthermore, we confirmed the retention characteristics of \( \sim 10 \) years at 80°C through mean time to failure (MTTF) measurements based on the temperature-accelerated retention test; this is shown in Fig. 4b.

**Summary**

In this work, we explored the effects of the oxide electrolyte Cu-ion mobility on the Cu filament shape. In particular, we successfully created HG filaments by using a multi-oxide structure consisting of layers with different Cu-ion mobilities. In addition, engineering defects in the upper oxide electrolyte resulted in the creation of optimum conditions for the formation of HG Cu filaments. As a result, Cu/AlO\(_x\)/TiO\(_2\)/W devices exhibited the high ON/OFF resistance ratios and strong data retention properties necessary to produce PMCs for reconfigurable FPGA applications.

**Acknowledgments**

This work was supported by the Future Semiconductor Device Technology Development Program (10045085) funded By MOTIE (Ministry of Trade, Industry & Energy) and KSRC (Korea Semiconductor Research Consortium).

**References**

17. J. Guy, G. Molas, P. Blaise et al., IEDM Tech. Dig. 6.5.1-6.5.4 (2014).