A theoretical study of scaling behaviour of mushroom PCRAM devices using the Gillespie Cellular Automata Approach

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ABSTRACT

We investigate the scaling characteristics of vertical "mushroom" phase change random access memory (PCRAM) cells down to sub-10nm dimensions using an electro-thermal model combined with the Gillespie cellular automata (GCA) phase-transition approach. The size of the amorphous dome formed during the Reset process decreases linearly with simultaneous reduction of the bottom TiN heater width and $Ge_2Sb_2Te_5$ (GST) phase change layer volume with re-design of the cell geometry required for sub-15nm dimensions. Re-crystallisation of the amorphous dome is primarily nucleation-dominated, however a transition to growth-dominated crystallisation is observed for dimensions below 20nm. The scaling trend features a resistive window of a factor of 10 even for very small dimensions predicting the scalability and operability of mushroom PCRAM cells in the sub-10nm region.

Key words: phase change random access memory, electro-thermal simulations, Gillespie cellular automata, amorphous domes, crystallisation behaviour, resistive window

Phase change random access memory (PCRAM) with its fast programming speeds, high endurance, low power consumption and scalability features is one of the primary candidates for next-generation non-volatile solid-state memory [1]. Scaling of PCRAM cell size has a direct effect on various material and device properties [2-3]. Phase change devices as small as a few nm in dimensions have been shown to switch reversibly with low currents and fast switching speeds [4].

In this manuscript we study the scaling behaviour of mushroom type PCRAM. In particular we investigate the variation in amorphous dome radius, crystallisation characteristics and the Reset/Set resistive window as the cell size is reduced. We combine electro-thermal simulations with the Gillespie cellular automata (GCA) approach to simulate the phase change switching process. The GCA approach is a stochastic simulator capable of spatio-temporal modelling in phase change devices, and has been previously described in detail in Ref. [5]. This approach is potentially capable of spanning the length scales between atomistic modelling and bulk scale methods such as the Johnson-Mehl-Avrami-Kolmogorov (JMAK) or the classical nucleation and growth methods.

Scaling of the PCRAM cell shown in Fig. 1(a) was performed by simultaneously reducing the heater width (HW) of the TiN layer, and the thickness (TH) and width (W) of the phase-change GST layer from 60nm down to 6nm while keeping the scaling factors of TH/HW=1.2 and W/TH=1.25 constant. The test bench consists of an electrical pulse source, a series load resistance of 10 kΩ and the PCRAM itself. We apply Reset and Set pulses of 2.5V, 50ns and 1.5V, 100ns respectively.

The amorphous dome formed during the Reset process decreases linearly in size as the cell dimensions are reduced. Figure 1(b) shows the variation in the height of the amorphous region as dimensions are scaled down. For sub-15nm heater widths the applied Reset pulse of 2.5V is insufficient to amorphise the GST layer. This is due to the switching layer being too thin and heat being lost to the electrodes and consequently re-design of the cell is required. We use a stacked TiN/W top electrode [6] which enhances the heat confinement in the cell. This ensures that the temperature exceeds the melting temperature to generate the amorphous dome. Alternatively, larger

amplitude pulses can also be used for the same purpose although this is not desired in real devices as it leads to increased power consumption.

Crystallisation (Set) of the amorphous dome occurs by forming crystal nuclei which nucleate and then grow until the dome is fully crystallised. The number of crystals formed is higher for larger dimensions and decreases for smaller dimensions indicating a transition in crystallisation from nucleation-dominated to growth-dominated behaviour as the cell size is scaled down as shown in Fig. 1(c). Figure 1(d) illustrates that the resistive window between the Set and Reset states decreases as dimensions are reduced but still maintains a one order of magnitude difference even for sub-10nm cell dimensions predicting that mushroom PCRAM cells are scalable and operable in this region.

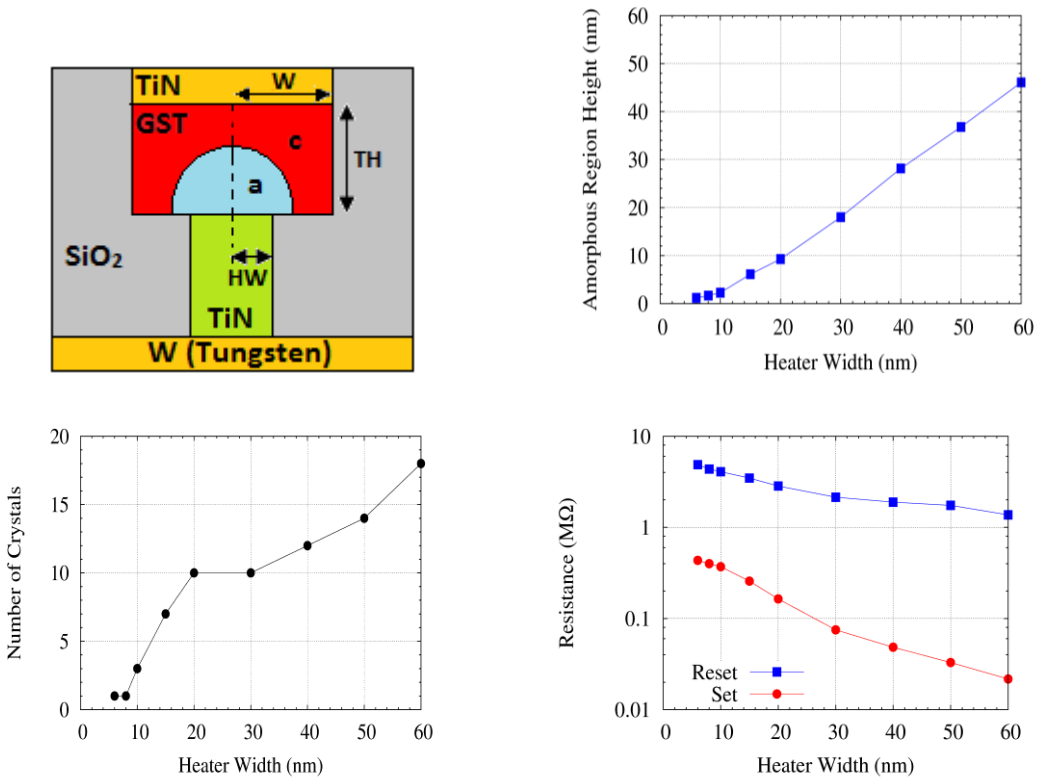

Fig. 1 (a–top left) PCRAM mushroom cell (side view) with cylindrical symmetry along central dashed line. Essential to PCRAM operation is GST amorphous dome, denoted by 'a' which is embedded in the crystalline 'c' matrix. Reset and Set pulses of 2.5V, 50ns and 1.5V, 100ns respectively are applied, (b–top right) Scaling of amorphous region height for various heater widths, (c–bottom left) Variation in number of crystals versus heater widths (scaled from HW/TH/W (nm) = 60/72/90 down to 6/7.2/9), (d–bottom right) Variation in the Reset and Set resistive window versus heater widths.

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