Set Programming Method and Performance Improvement of Phase Change Random Access Memory Arrays

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A novel slow-down set waveform is proposed to improve the set performance and a 1 kb phase change random access memory chip fabricated with a 130 nm CMOS technology is implemented to investigate the set performance by different set programming strategies based on this new set pulse. The amplitude difference ($I_1 - I_2$) of the set pulse is proved to be a crucial parameter for set programming. We observe and analyze the cell characteristics with different $I_1 - I_2$ by means of thermal simulations and high-resolution transmission electron microscopy, which reveal that an incomplete set programming will occur when the proposed slow-down pulse is set with an improperly high $I_1 - I_2$. This will lead to an amorphous residue in the active region. We also discuss the programming method to avoid the performance degradations.

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Recently, tremendous efforts have been made towards enhancing the set properties of the phase change random access memory (PCRAM) chip, especially focusing on improving the uniformity of set resistances and avoiding set failures in memory arrays.\cite{1-3} Considering that the conventional rectangular set pulse will generate a large resistance fluctuation and thus limit the write reliability, some non-conventional optimized shapes of set pulses such as a set-sweep programming pulse,\cite{4} stair-case pulse,\cite{5} and multiple step-down pulse,\cite{6} have been proposed to achieve a better resistance uniformity. However, to the best of our knowledge, these previous works only lie in evaluating the performance improvement on the PCRAM chip from the point of view of the chip characterization. The impact on the cell’s physical characteristics and the causes of set performance degradations under different pulse conditions, which are crucial to give a deeper insight on the PCRAM programming technology, are still unexplored.

In this Letter, we propose a new waveform of set pulse to improve the set performance of the PCRAM arrays. A 1 kb mushroom-shaped PCRAM array of cells based on a 130 nm CMOS technology is used to present a systematic investigation on the set properties with different set strategies numerically and experimentally by measuring set resistance distributions and observing cell characteristics through thermal simulations as well as high-resolution transmission electron microscopy (HRTEM). A 70-nm-diameter tungsten (W) bottom-electrode contact (BEC) with doped TiN fabricated above a 200 nm W plug is utilized as a heater. An 100-nm-thick Ge_{x}Sb_{y}Te_{z} chalcogenide film is deposited above the W heater. A TiN adhesive layer is stacked upon the chalcogenide film, followed by the deposition of a W top-electrode contact (TEC) with a 200 nm diameter.

The new slow-down set waveform is composed of two single pulses with different amplitudes and durations. As shown in the insets of Fig. 1(a), the first set pulse with high amplitude ($I_1$) and short duration ($T_1$) is used to quickly heat the phase change material (PCM) above the melting temperature ($T_m$ $\approx$893 K). Then the second current pulse with low amplitude ($I_2$) and long duration ($T_2$) will cool down the PCM from $T_m$ and finally realize a crystallization process. Compared with a typical rectangular set pulse, the slow-down set pulse has a larger falling edge in the time domain, which means a more efficient sweeping around the optimal current points of all the memory cells. Figure 1(a) shows a comparison of the resistance distributions based on the typical set pulse and our proposed set pulse. The typical set current of the traditional rectangular set pulse is $\sim$0.8 mA,\cite{7} and the current amplitude $I_2$ of the slow-down set pulse is set to be the same as that of the traditional set pulse for an accurate comparison. It can be noted that the proposed set pulse makes the set resistances more uni-
form in the lower resistance region with a lower programming power. Moreover, as shown in Fig. 1(b), the set performance is increased at the cost of set time. However, it is worth noting that the minimum set time for the correct write operation is only 120 ns. Compared with other non-conventional optimized shapes of set pulses, this novel slow-down pulse achieves less set time than the set-sweep programming pulse (150 ns set time) and stair-case pulse (150 ns set time), which could be attributed to a fast heating of the first set pulse and an efficient sweeping of the second set pulse. The multiple step-down pulse (180 ns set time) characterized by writing pauses needs more set time due to these pauses. All the above test results prove that the slow-down pulse exhibits better performances than other set technologies, which is contributing to a properly optimized pulse shape.

Figures 2(a) and 2(b) characterize the set resistance distributions of the PCRAM array programmed by the slow-down current pulses with different pulse amplitudes ($I_1$, $I_2$). As viewed from the chip circuit design, the first and second set amplitude can be adjusted from 0.96 mA to 2.88 mA and from 0.48 mA to 0.96 mA, respectively. As a result, we choose two relatively intermediate values (1.6 mA, 0.6 mA) and make one of these two parameters fixed while change another one in a certain range. All the cells are initialized to reset state by a rectangular pulse of 2 mA, 100 ns. Insets: the pulse schematics used to program the PCRAM array.

To explore PCRAM cell characteristics based on different programming strategies, a two-dimensional thermal analysis of the PCRAM device is performed for simulating the temperature distribution during a set operation. The cell is programmed by three different pulses with shape-A, shape-B and shape-C, respectively. The amplitudes of the shape-B pulse and shape-C pulse satisfy the conditions as ($I_{1b} > I_{1a}$, $I_{2b} = I_{2a}$) and ($I_{1c} = I_{1a}$, $I_{2c} < I_{2a}$), respectively, where $I_{ij}$ denotes the amplitude of the $i$th pulse with shape $j$. It should be noted that the set power offered from the chip for crystallization is much lower than that for the transition to the closed-packed hexagonal phase. Therefore, Ge$_2$Sb$_2$Te$_5$ is only converted into the face-centered cubic (fcc) phase in the actual chip programming situation, and only the phase transition between the amorphous phase and the fcc phase is discussed here. First, as shown in Fig. 3(a), after being programmed by the first set pulse with shape-A, the core area above the BEC quickly reaches the melting point and then changes into the molten state, while the surrounding area with less heat efficiency is heated above the crystallization temperature ($T_c$, ~423 K). Then, as shown in Fig. 3(b), the whole active region of the PCRAM cell cools down and maintains at the crystallization point for a period of time during the second set pulse. As a result, the crystalline area covers the top of the BEC, indicating a complete crystallization process. Secondly, when the PCM cell is programmed by a shape-B pulse with a higher $I_1$, as shown in Fig. 3(c), a higher temperature can be reached and results in a larger molten volume.
Moreover, during the second set pulse, the area above BEC gathers more heat while still being maintained at a temperature above \(T_m\) and thus a residual amorphous state appears at the end of the pulse, as shown in Fig. 3(d). Finally, for the case of a shape-C pulse, as shown in Fig. 3(e), the temperature distribution and the melted area are identical to those for the shape-A pulse after the first set pulse melts the PCM cell due to the same current amplitude \((I_{2c} = I_{1a})\). During the first set pulse, the surrounding area of the active region is heated to a temperature between \(T_m\) and \(T_c\) for a period of time and changed into the crystalline state. However, as shown in Fig. 3(f), the temperature under \(I_{2c}\) is much lower than that desired to transfer the molten state to the crystalline state, thus this melted area ends at the amorphous state.

To further investigate the effect on the cell characteristics caused by programming pulses with high \(I_1 - I_2\), we examined the cross-sections of two samples programmed respectively by the set pulses with high \(I_1\) (1.92 mA) and low \(I_2\) (0.48 mA) through HRTEM scanning. The distributions of the set resistance are investigated in a 1 kb PCRAM array pro-

As discussed above, the pulse amplitudes \((I_1, I_2)\) are crucial for the set performance, which are decreased with increasing \(I_1 - I_2\). Through the thermal simulations, one can note that the set pulse with high \(I_1 - I_2\) will result in insufficient set energy and thus an amorphous residue will be achieved at the end of the set operation. In addition, based on the result of HRTEM, the area with the highest temperature will show an obvious boundary between the crystalline state and the amorphous state. Furthermore, the majority of the active area is in the crystalline state, which is characterized by the selected-area electron diffraction (SAED) image, as shown in Fig. 4(d). These images prove that the dome-shaped area caused by set pulses with high \(I_1 - I_2\) is the amorphous residue located at the center above BEC, which exhibits a high resistance and thus results in a relatively higher resistance than the complete crystalline state as shown in the above resistance distribution tests.

![Fig. 4. HRTEM images (a,b) of the cross-section of the PCRAM cells. (c) HRTEM image of the boundary between two states (the d-spacing value of (200) in fcc phase was measured with \(d(200) = 3.04\,\text{Å}\), which agrees well with that in Ref. [13]). (d) SAED pattern of the crystalline phase.](image_url)
grammed by the new slow-down set pulse with different programming strategies. The amplitude difference \((I_1 - I_2)\) of the set pulse is proved to be a significant parameter for high-performance set programming and a high \(I_1 - I_2\) will lead to a set performance degradation. This can be explained such that the crystallization power with high \(I_1 - I_2\) is not sufficient to maintain the whole active region (especially for the high-temperature area) at the crystallization point for plenty of time, thus an amorphous residue in the hottest area will be obtained at the end of the set operation. Therefore, to improve the set performance of the PCRAM array, the current amplitudes \((I_1, I_2)\) of the set pulse should be properly chosen to ensure a relatively low \(I_1 - I_2\) and simultaneously satisfy the demands on low-power operations.

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References


