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Statistical Analysis of the Correlations between Cell Performance and its Initial States in CRRAM Cells

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ABSTRACT

Variability has been one of the critical challenges in the implementation of large resistive random access memory (RRAM) arrays. Wide variations in the set/reset, read and cycling characteristics can significantly reduce the design margins and feasibility of a memory array. Predicting the characteristics of RRAM cells is constructive to provide insights and to adjust the memory operations accordingly. In this study, a strong correlation between the cell performance and its initial state is found in CRRAM cells by 28nm CMOS logic technologies. Furthermore, a verify-reset operation is proposed for identifying the type of conductive filament in a cell. Distinctive CRRAM characteristics are found to be linked directly to the initial CFs, enabling preliminary screening and adaptive resets to address the large variability problems in sizable CRRAM arrays.

Introduction

RRAM has been regarded as a highly competitive candidate to become one of the next generation nonvolatile memory solutions. It has many advantages, such as fast P/E speed, low-power consumption and superior scalability [1-3]. However, to implement RRAM technologies in sizable memory arrays, there are still many critical challenges to be overcome [4]. The number and density as well as distribution of oxide vacancies (V_{O-}) in the RRAM films vary greatly from cell to cell, which control the formation and rupture of conductive filaments (CFs) by generating or recombining V_{O-} [5]. Large variability occurs as RRAM cells scaled in size and film thickness, which can be attributed to the increased sensitivity toward slight process variations. The number and density of V_{O-} initially presented in RRAM dielectric film not only affect its initial resistance states before forming, but also greatly influence its resistive switching characteristics. In this study, we propose a new method for categorizing RRAM cells by the type of conductive filaments initially presented and analyzing the differences amongst these cells in the subsequent resistive switching characteristics.

Categorizing Cells by Initial States

The samples characterized in this study consist of 1T1R contact RRAM(CRRAM) cells which are prepared by 28nm CMOS logic process [6]. The cross-sectional TEM of a CRRAM cell is shown in Figure 1(a), where the resistive switching film is composed of $TiN/TiON/SiO_2$ sandwiched between the top tungsten and bottom Si electrodes. As outlined in the cell layout shown in Figure 1(b), the RRAM node is serially connected to a select transistor for controlling the forming, set and reset current during operations. It is believed that the oxygen vacancies (V_{O-}) reside across SiO_2 and TiON layers in the CRRAM cells [7-8]. The presence of V_{O-} plays a key role in forming/disrupting of connective filaments, which results in resistance switching between high low resistive states.

Measurement data on the CRRAM arrays suggests that a significant portion of the cells contains V_{O-} even before forming. The densities and distribution of the pre-forming V_{O-} vary widely from cells to cells and can lead to different type of CFs, which are believed to cause distinctively different resistive switching characteristics as illustrated in Figure 2. The distribution of the initial read current of CRRAM cells at low V_{SL}, shown in Figure 3, reveals a large variation in its read current level ranging from pA to μA. After initial read operation, a reset operation, called verify-reset, is applied before the forming operation. As shown in Figure 4, only the cells with medium initial read current level exhibit change in its current level, while resistance levels of the rest of the cells remain the same. These unique behaviors can be explained by the correlation of the size of the pre-forming CFs and its switching mechanisms, illustrated in Figure 2. Cells with low initial read current contain Weak CFs(WCF) before forming, as shown in Figure 2(a). In reset operations, large current induced localized heating disrupts the CFs, leading to the increase in resistance [9]. However, as a result of the low reset current and the scarce of V_{O-}, there is virtually no change in the CF after a reset operation. On the other hand, cells with high initial read current contain Strong CFs(SCF) initially, with densely packed V_{O-}. In a verify-reset operation, the reset current is not high enough to rupture the SCFs. As a result, the read current in SCF cells remain the same. Cells with Medium CFs(MCF) are the only type that exhibits resistance change by a verify-reset. Through verified reset operations, these cells can be categorized into 3 types, WCF, MCF and SCF. Based on its initial conditions, the set/reset of the three types of cells will be different, as illustrated in Figure 2(c) and (d) [10].

The pre-forming SCFs is also expected to cause low reset efficiency. To reset SCF cells successfully, a much higher reset current is needed, as shown in the DC switching characteristics in Figure 5. The operation conditions for different cells are summarized in Table 1. The presence of pre-forming SCFs (cannot be ruptured by a normal reset) will also limit the read current window in SCF cells. Consequently, the maximum read current ratio of SCF cells is less than 2X, see Figure 6.

Reliability Comparisons

Retention characteristics under 150°C bake tests for 200 hours reveal that there is no significant difference amongst the three different types of cells, as shown in Figure 7. By incremental step pulse programming (ISPP) method, cycling characteristics on the three types of cells are compared. Detailed flow chart in ISPP operation is illustrated in Figure 8. All three types of cells can endure 10k cycles without significant change in their read window, as shown in Figure 9. Aside from the small read window, it is also harder to switch states in SCF cells. The number of pulses required to complete a set/reset operations in SCF cells is much higher than that in WCF and MCF cells, especially after 1k cycles, as shown in Figure 10. The high reset current in SCF cells may cause oxidation at electrode interface, blocking oxygen ion and electron transport, which eventually leads to the low set/reset efficiencies [11]. Over-set and over-reset results are compared in Figure 11. MCF and WCF cells are found to exhibit better reliabilities over SCF cells, as expected.

Conclusions

A scheme of categorizing CRRAM cells based on its pre-forming CF is firstly proposed. Strong correlation between the pre-forming states and the RRAM switching characteristics is established. To address the variability challenges in RRAM arrays, a verify-reset has been demonstrated for fast screening of cells with poor read window and degraded reliability.

Acknowledgement

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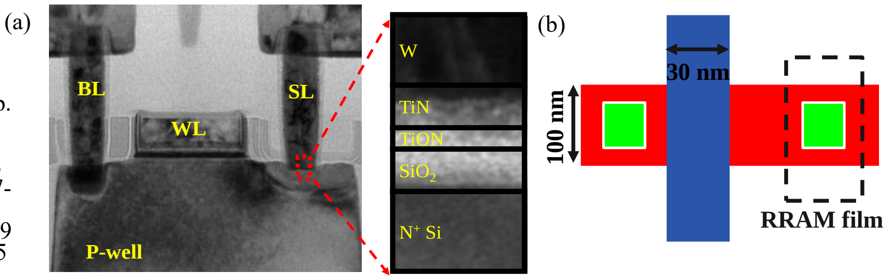

Figure 1 (a) TEM picture of the 1T1R CRRAM cells and the composition of its RRAM film. (b) Layout illustration of the cell fabricated by 28nm CMOS logic process.

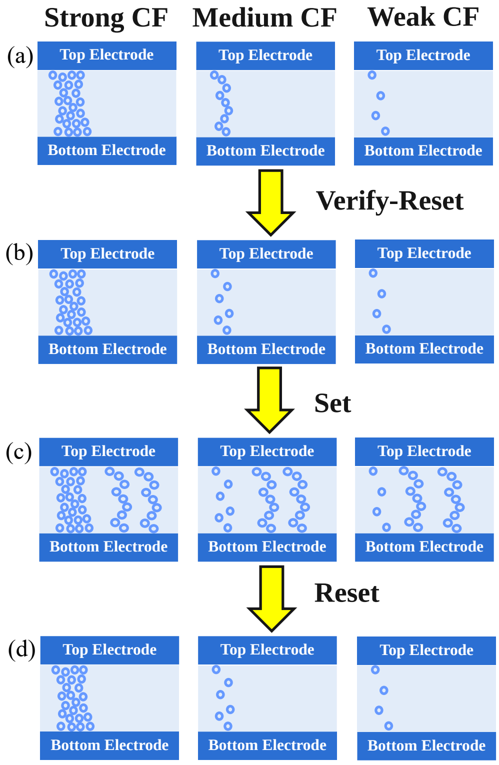

Figure 2 Schematic diagram of the different type of CFs of cells in (a) initial state, (b) that after verify-reset and that in (c)LRS (d) HRS.

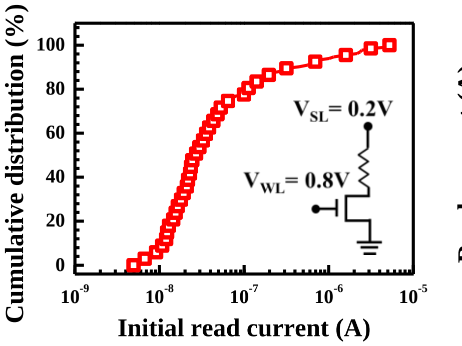

Figure 3 Initial read current distribution of 1T1R CRRAM read under low SL bias of 0.2V.

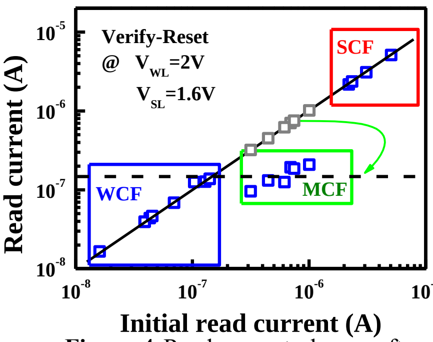

Figure 4 Read current change after a verify-reset operation before forming.

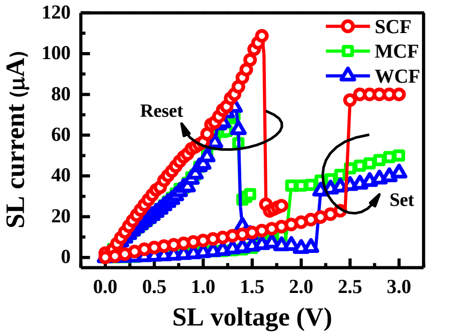

Figure 5 DC switching characteristics of cells of 3 different initial states, WCF, MCF and SCF.

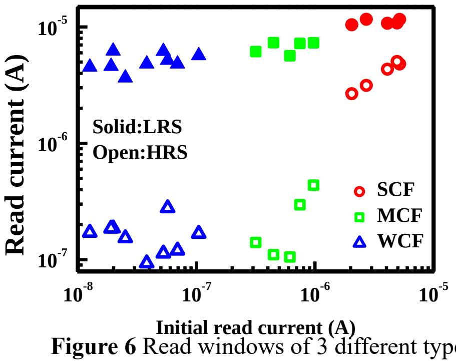

Figure 6 Read windows of 3 different types of cells obtained by DC switching sweeps.

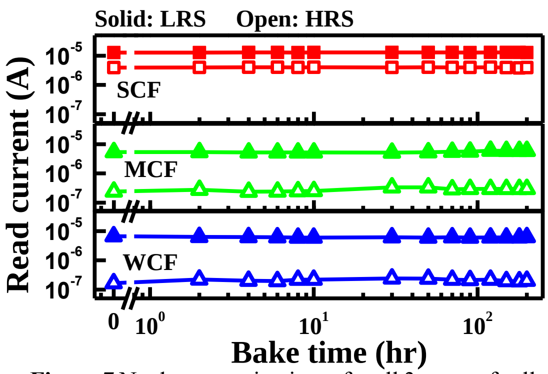

Figure 7 No data retention issue for all 3 types of cells under 150°C bake for 200 hours.

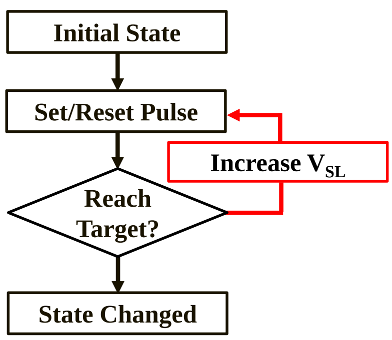

Figure 8 Operation flow of the Incremental step pulse programming (ISPP) algorithm.

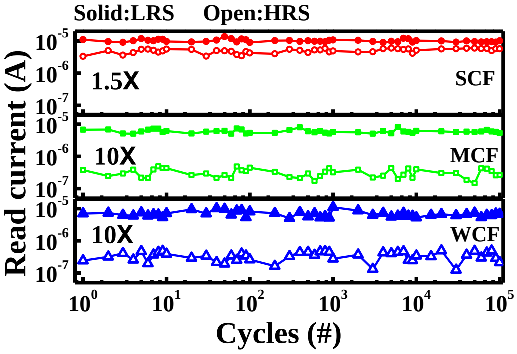

Figure 9 WCF, MCF and SCF cells can all endure over 10k set/reset cycles with minimal change in its states by the ISPP scheme illustrated in figure 8.

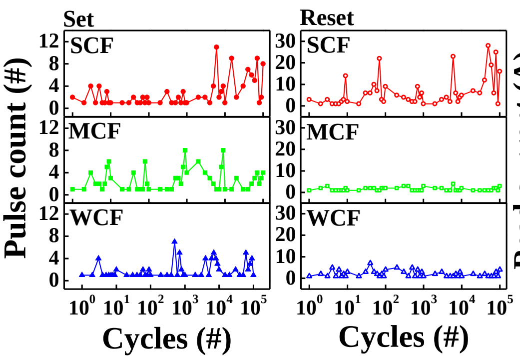

Figure 10 Summary of pulse counts in ISPP operations indicate that SCF cells required more pulses to complete resistive switching.

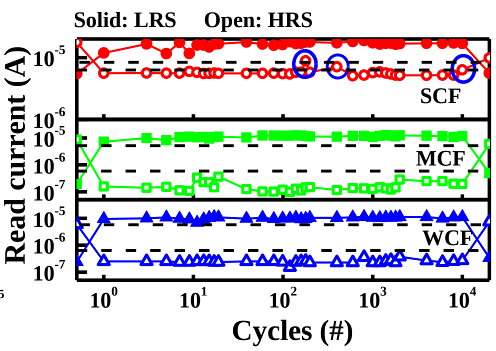

Figure 11 All cells can pass over-set tests, but MCF and WCF cells exhibit better immunity toward over-reset tests.

Operation	MCF/WCF			SCF		
	WL	SL	BL/PW	WL	SL	BL/PW
Set	0.8V	3V	0V	0.8V	3V	0V
Reset	1.5V	1.5V	0V	1.8V	1.8V	0V
Read	0.8V	0.2V	0V	0.8V	0.2V	0V

Table 1 Summary of optimized operation conditions for the 1T1R CRRAM cells. For SCF with large initial read current, reset conditions have been changed to allow larger reset current to enable the rupturing of CFs.