Low-Voltage and High Thermal Stability Single-Element Te Selector with Failed Bit Pruning Operation Enabling Robust Cross-Point Memory

Yaxin Ding, Junjie An, Jiabin Shen, Shujing Jia, Jingrui Guo, Lingfei Wang, Tiancheng Gong, Pengfei Jiang, Yuan Wang, Yuting Chen, Min Zhu, Chunmeng Dou,* and Qing Luo*
stable high resistive state. The FBP operation can have a similar effect to removing BD cells. Moreover, the criteria and the key parameters for selector FBP are proposed. Furthermore, the requirements of FBP are studied by circuit simulation. Read or write (R/W) error rates and power consumption caused by failed bits can obviously be decreased by the FBP operation. In addition, reduced error rates caused by FBP can further improve inference accuracy of the stored AI model, which is critical for weight storage-based neural networks. After that, we systematically study the key parameters for FBP of typical selector devices. These five common selectors can all achieve a suitable high resistance level after pruning. Except from competent selector performance, Te-selector well suits the requirements of FBP. This work presents a new feature of the selector for robust high dense cross point memory.

2. Results and Discussions
2.1. Definition of Selector Pruning

The breakdown of selector cells not only induces increasing power consumption but also incurs crosstalk effects in reading and writing the cells on the same column or row with the broken-down cells in the crossbar memory array (Figure 1a). Two methods are proposed to eliminate the side effects. As shown in Figure 1b, disabling method refers to removing all devices in the same row and column with the broken-down cells. The number of defunct cells caused by this method substantially increases with the increase of failed bits and array sizes. The effect is clearly shown in the plan schematic of the disabling method (Figure S1, Supporting Information). In practical applications, it not only reduces the memory capacity but also speeds up the wear-out of the whole array as increased accessing frequency of the remaining cells. As a comparison, removing the BD cells from the array can be a better solution. However, it is unpractical to physically remove the BD cells from the crossbar array. As shown in Figure 1c, the FBP operation (pruning method) can deal with the side effects caused by the broken-down cell by pruning the selector to a high resistive state, which can achieve the same effect as removing the BD cell from the array. To show the benefits of the pruning method compared with the disabling method obviously, we study the variation of defunct cells caused by two methods under different failed bits and array sizes. The comparison of the defunct cells under the two methods when the array size is 1GB is shown in Figure S2a (Supporting Information). The difference in the number of defunct cells between the two methods is gradually increasing with the increase in failed cells. The pruning method can reduce about $7 \times 10^9$ defunct cells compared with the disabling method when the number of failed cells is $5 \times 10^4$. The reduced number of defunct cells by FBP is defined as the difference between defunct cells caused by the two methods. When the number of failed cells is 1000, the reduced number of defunct cells by FBP substantially increases with increasing array size (Figure S2b, Supporting Information). The pruning method can effectively improve the storage capacity of a memory array.

Ideal selector devices should have fast switching speed, high selectivity, sufficient on-state current, and ultralow off-state current under working mode (Figure S3, Supporting Information), which is critical for constructing a high-density crossbar memory array. Although the key features of a working selector device are well-known, the characteristics of the selectors after BD have been rarely discussed. Here, we propose the FBP operation for failed selector devices (Figure 1d). After the BD of the cells, if the failed selector can be manipulated to a stable high resistance state by applying voltages, the failed

![Figure 1](https://example.com/figure1.png)

**Figure 1.** a) The Breakdown (BD) of 1S1R cell induces increasing crosstalk and power consumption in the cross-point memory array. Suppressing the side-effects due to the BD cells by b) disabling the rows and columns with BD cells and c) pruning the BD points from the array. d) Ideal characteristics of a selector device in crossbar array after breakdown (BD).
bit can be pruned from the array. The applied voltage can be defined as the prune voltage. It should be smaller than 2 times the threshold switching voltage ($V_{th}$) of the selector to avoid activating the half-selected cells in the 1/2 voltage biasing scheme. The cell resistance after prune operation should be as high as possible to suppress the leakage current, which can support cross-point memory with increasing size and number of increasing fail bits. Finally, a threshold voltage should be applied to the cell to check the stability of the cell resistance after pruning, because the pruned device will continue to be stressed under half-selected voltages. The FBP operation is considered to have completed successfully, if the pruned selector cannot switch to a low resistance state under a threshold voltage.

2.2. Device Requirements for FBP

The proposed FBP can be implemented in the controller of the cross-point memory and performed by a few steps (Figure 2a). After detecting the failed bit, FBP operation is first carried out, which increases the cell resistance and suppresses the leakage due to the BD cells. Then, the address of the failed bit is redirect to a new one in the redundancy rows. Consequently, the cross-point memory can still perform normal read and write (R/W) with minimized defunct cells caused by the failed bits. Previous study[25] has shown the reliability of SPICE simulation. Thus, SPICE simulation is carried out to analyze the device requirements for FBP in large cell arrays. The detailed parameters are shown in Figure S4 (Supporting Information). The line resistance of WL and BL is 10 Ω. And the resistance of LRS (low-resistive-state) and HRS (high-resistive-state) is 10 and 100 kΩ, respectively. Under the normal operation of the 1S1R cell, if the voltage across the cell exceeds the threshold switching voltage, the selector is turned on. The cell resistance is approximately equal to the resistance of the RRAM due to the low on-state resistance of the selector. And the cell resistance is approximately equal to the off-state resistance of the selector if the applied voltage is less than the threshold switching voltage. When the cell breaks down, the resistance before FBP is approximately equal to the resistance of LRS of RRAM, and the resistance after FBP needs to be high. We investigate the optimization effect of FBP by simulating the effect of different cell resistances after pruning on the array performance. Figure 2b,c shows the contour map of the cell leakages in a 1 Kb cell array having 10% fail bits with and without pruning the BD cells, in which the leakage can be effectively suppressed by pruning the cell to high resistance. Negligible leakage current can be observed after pruning the failed bit to a stable high resistance (10 MΩ). The black squares mark the positions of fail bits. The influence of the cell resistance after pruning ($R_{PR}$) is evaluated by considering the voltage (Figure 2d) and power consumption (Figure 2e) to read or write the far cell in the arrays having different sizes ranging from 1 Kb to 1 Mb when the fail bit rate is

Figure 2. a) Proposed failed bit prune operation flow in the cross-point memory. The detection, pruning, and replacement by redundancy cells of the failed bits are performed in sequence. Simulated leakage currents in a 1 Kb cross-point memory array having 10% failed bits b) with and c) without pruning the BD cells. Negligible leakage current can be observed after pruning the failed bit to a stable high resistance (10 MΩ). The black squares mark the positions of fail bits. Simulated d) voltage and e) power consumption versus the cell resistance after pruning for read/write the far cell in the arrays having 10% failed bits. Negligible degradation on voltage and power can be observed in the 1 Mb array when $R_{PR}$ exceeds 7 MΩ. f) The maximum array size as a function of cell resistance after pruning considering 10% and 30% failed bits. With a $R_{PR}$ of 10 MΩ, the 1 Mb cross-point memory can tolerate 30% error rates.
10%. When \( R_{\text{PR}} \) exceeds 7 \( \Omega \), negligible degradation on write voltage (voltage loss <1%) and power consumption (power consumption increase < 0.58%) can be observed in the 1 Mb array. The required value of \( R_{\text{PR}} \) increases as the fail bit rate increases to 30% (Figure S5, Supporting Information). Increasing \( R_{\text{PR}} \) is expected to support the cell arrays with larger array sizes or more error rates. As shown in Figure 2f, an \( R_{\text{PR}} \) of 10 \( \Omega \) also chose the other four typical selector devices (Ag filament-based selector, NbO\(_x\) filament-based selector, Ag filament-based selector, NbO\(_x\) filament-based selector, and TaO\(_x\) capacitor) to study the FBP operation (Figure S7a–d, Supporting Information). Therefore, we take the Te device as an example to investigate the FBP operation of selectors. As shown in Figure 3a, the cross-section transmission electron microscopy (TEM) image and corresponding energy-dispersive spectroscopy (EDS) elemental mapping of Te device before programming show uniform elemental distribution. Typical First Fire (FF) and switching characteristics of Te under triangular voltage pulses with rising/falling edge of 1 \( \mu \)s are shown in Figure 3b. It should be note that the Te device shows low \( V_{\text{th}} \) (1.3 V) under voltage pulse, which is critical for low power consumption operation. The schematic of the measurement circuit and the current response of the Te device are shown in Figure S8a (Supporting Information). A typical endurance test of a Te-based selector shows that it fails in the low-resistance-state (HRS, or weight-0) than those in the low-resistance-state (LRS, or weight-1). Consequently, the error rates caused by the failed bits are likely to be suppressed by pruning all failed bits to HRS (Figure S6a, Supporting Information). A case study on storing the weight values of a binary LeNET model is also carried out (Figure S6b, Supporting Information). The inference errors of the model caused by 10% failed bits can be reduced by 60% after pruning.

### 2.3. Prune Operation Study of Typical Selector Devices

Ovonic threshold switches (OTS) have successfully been used in the 3D new nonvolatile memory products such as PCM. Among them, the pure single-element Te selector has attracted attention due to its simple composition and excellent switching reliability. Therefore, we take the Te device as an example to investigate the FBP operation of selectors. As shown in Figure 3a, the cross-section transmission electron microscopy (TEM) image and corresponding energy-dispersive spectroscopy (EDS) elemental mapping of Te device before programming show uniform elemental distribution. Typical First Fire (FF) and switching characteristics of Te under triangular voltage pulses with rising/falling edge of 1 \( \mu \)s are shown in Figure 3b. It should be note that the Te device shows low \( V_{\text{th}} \) (1.3 V) under voltage pulse, which is critical for low power consumption operation. The schematic of the measurement circuit and the current response of the Te device are shown in Figure S8a (Supporting Information). A typical endurance test of a Te-based selector shows that it fails in the low-resistance-state (HRS, or weight-0) than those in the low-resistance-state (LRS, or weight-1). Consequently, the error rates caused by the failed bits are likely to be suppressed by pruning all failed bits to HRS (Figure S6a, Supporting Information). A case study on storing the weight values of a binary LeNET model is also carried out (Figure S6b, Supporting Information). The inference errors of the model caused by 10% failed bits can be reduced by 60% after pruning.

### 2.4. Prune Operation Study of 1S (Te) 1R

The Te selector not only shows excellent performance for FBP but also shows outstanding selector performance under its working mode, such as low threshold switching voltage. Low voltage operation requires a high uniformity in the switching characteristics of the device. Statistical distribution of \( V_{\text{fire}} \), \( V_{\text{th}} \), and \( V_{\text{hold}} \) in 80 Te devices shows stable switching behavior of devices (Figure S8b, Supporting Information). In addition, thermal stability is critical for OTS selectors. To study the thermal stability of the Te selector, we annealed Te devices at the temperature from 200 to 430 °C for 30 min under the N\(_2\) atmosphere. And it shows stable switching behavior even after annealing at 430 °C for 30 min (Figure S8c, Supporting Information), indicating it can withstand the thermal shock from the back-end-of-line (BEOL) fabrication process. The difference in \( V_{\text{th}} \) is due to the increase of the TiN resistance. Therefore, the single element Te device shows promising performance for FBP operation of the 1S1R crossbar array application. Furthermore, we investigate the FBP operation of the 1S1R device with Te selectors and TaO\(_x\) RRAM cells. The IV curves of 1S1R devices are shown in Figure 4a. Inset shows the schematic of the equivalent circuit. Whether the RRAM cell is in the low- (LRS) or high-resistance states (HRS), the pruning operation can be performed using a low voltage (≈2 V) after the selector is broken down (Figure 4b,c). When the selector is broken down and the RRAM is operating normally, the 1S1R cell has the highest resistance value when R is in an HRS if FBP operation is not performed.
on the selector. Compared to the HRS of RRAM, the pruned selector shows a much higher resistance, which results in 400X and 258X in maximum array size (Figure 4d). The resistance is read at the voltage of 0.4 V.

3. Conclusions

Selector devices are essential for implementing high-density memory arrays as they suppress sneak path leakage. The breakdown of one-selector-one-resistor memory cells can induce crosstalk effects when reading and writing the cells on the same column or row with the BD cells. In addition, it can lead to substantial power consumption of the memory arrays. In this work, we propose the selector FBP to eliminate the side effects caused by failed bits and analyze its device requirement, and finally demonstrate its universality. The target requirement of the FBP was given by spice simulation. After systematically studying the FBP of five typical selectors, we find that the pruning method can universally be applied to all the materials systems of selectors. Among them, Te-selector not only achieves a suitable high resistance level after FBP.
under a low voltage (2 V) but also shows excellent working performances, such as low threshold voltage (1.3 V) and high thermal stability (430 °C) (Table 1). This work demonstrates a new expected selector feature enabling robust high-density cross-point memory.

4. Experimental Section

Te-based T-shaped structure OTS devices with 60 nm/120 nm/150 nm/200 nm-diameter TiN plug bottom electrode were prepared. GeSe-based and GeS-based devices of the same size were also fabricated. In these devices, 20 nm thick Te/GeSe/GeS films were deposited by RF-magnetron sputtering, followed by a deposition of TiN top electrode. In addition, a Pt/NbO x/TiN device and a Pt/Ti/Ag:SiO x/Pt/Ti device are also fabricated. First, a 40 nm thick TiN bottom electrode was deposited by ion beam sputtering on a SiO 2/Si substrate, followed by a dry etching to pattern after the first lithography process. Then, a 50 nm thick NbO x film was deposited by RF-magnetron sputtering after the second lithography process, followed by a lift-off process. Finally, a 40 nm thick Pt top electrode was deposited by magnetron sputtering after the third lithography process, followed by a last lift-off process.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

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