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A Novel Ternary Content Addressable Memory Design Based on RRAM with High Intensity and Low Search Energy

Runze Han, Wensheng Shen, Peng Huang[#], Zheng Zhou, Lifeng Liu, Xiaoyan Liu and Jinfeng Kang[*]
Institute of Microelectronics, Peking University, 100871, China
E-mail: [#]hp19981031@126.com, [*]kangjf@pku.edu.cn

Abstract

A novel ternary content addressable memory (TCAM) design based on RRAM is presented. Each TCAM cell consists of two parallel RRAM to store and search for ternary data. The cell size of the proposed design is 8F^2, enable a ~60x reduction compared with conventional SRAM based implementations. Simulation results also show that the search delay and search energy of proposed design at the 64-bit word search are 2ps and 0.18fJ/bit/search respectively, where the significant improvements are achieved compared to previous publications. The desired characteristics of RRAM device for implementation of high performance TCAM search chip are also discussed.

1. Introduction

Content addressable memory (CAM) is a storage system, which is widely used in very-high-speed searching applications such as network routers, database engines and intrusion prevention systems. A typical CAM system structure is shown in **Fig. 1**. TCAM is a class of CAM which stores an additional value *X* indicating the value is *not in concern*. As the scaling down of technology, large area, high leakage current and high latency [1,2] hinders the further development of the high-intensive CMOS-based TCAM. Recently, several studies propose hybrid memristor-CMOS based TCAM with two-terminal memristor used as nonvolatile storage elements [1-4]. These designs have higher capacity and lower search energy. However, these designs still need transistors in the TCAM cell, so the potential of the memristor is not fulfilled.

In this work, a pure RRAM based TCAM is proposed to further improve the storage capacity. Basic functionality of the TCAM is experimentally verified. Other functional parameters such as delay, search energy are calculated by using the HSPICE tool. Desired RRAM device characteristics to fabricate high performance TCAM chip are also discussed.

2. Proposed TCAM Cell and Structure

The proposed TCAM cell include two adjacent RRAM devices. The resistance states of the TCAM cell represent different logic values are shown in **Fig. 2**. To search a logic “0”, a read voltage V_{read} is applied through SL while SL’ is grounded. If a TCAM cell is in logic “0”, i.e., R1 is in high resistance state (HRS), R2 is in low resistance state (LRS), then the current flows to the match line is low, marked as matched. Otherwise, the mismatch current flows to the match line is high. Based on the proposed TCAM cell, a RRAM crossbar array for searching is shown in **Fig. 3**. Data in the form of voltage pulse is applied to search lines. The results of match/mismatch are represented by low/high current flows through match lines. A RRAM cell only consumes 4F^2 cell area, therefore, the proposed TCAM cell area is 8F^2, enable a ~60x cell reduction compared with SRAM-based cells, as is shown in **Fig. 4**.

3. Results and Discussion

The proof-of-concept demonstration utilizes the RRAM crossbar array of $Pt/(HfO_x/AlO_y)_m/TiN$ cell structure [5]. With limitation of test equipment, basic functionality of TCAM with only 2-bit stored word is experimentally verified. The current in the match situation is much lower than mismatch situations, which denotes the search data and the stored data are matched, as is shown in **Fig. 5**.

The abbreviations used in this work are summarized in **Table I**. The simulation is based on 22nm technology node. A simulation on the responding current flows in match lines in the RRAM crossbar array contains sixteen 16-bit stored words is shown in **Fig. 6**. The simulation results are in consistence with the experimental results.

With search word width increases, the search delay in full match situation is increasing, which is shown in **Fig. 7**. With R_{on} increases, the search delay is increasing while the power consumption is decreasing, as is shown in **Fig. 8**. Sensing margin is defined as the ratio of the lowest current flows through the match line in mismatch situation to the highest current in the match situation. **Fig. 9** indicates that a larger R_{on} helps to enlarge the sensing margin. Therefore, a trade-off among power consumption, delay and sensing margin should be concerned when making RRAM devices. The sensing margin decreases with increase of word width and the decrease of resistance ratio window (R_{off}/R_{on}), as is shown in **Fig. 10**. Therefore, a large resistance window is helpful to distinguish the match current in longer word width search. Comparison of the proposed TCAM structure to prior works is shown in **Table II**. The search delay and search energy are improved by using the proposed design.

4. Conclusions

A RRAM-based TCAM design with high integration density and low search energy is proposed. The optimized R_{on} with sufficient resistance ratio window of R_{off}/R_{on} larger than 1000 are presented to achieve a low search energy and high match/mismatch sensing accuracy TCAM chip.

Acknowledgements

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References

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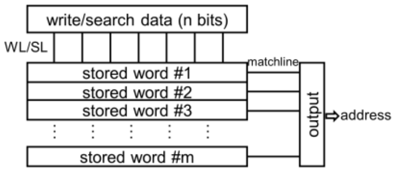

Fig. 1 General CAM system structure

Table I Parameter used in the simulation

Symbol	Meaning
R_{on}	Low resistance of RRAM
R_{off}	High resistance of RRAM
C_{RRAM}	Capacitance of RRAM
C_{wire}	Capacitance of wiring
R_{wire}	Resistance of wiring

* R_{wire}=12.75Ω, C_{wire}=0.046fF [6]
C_{RRAM}=(25*ε_0*4F^2/5nm)≈10^{-20}F(HfO_2-based)

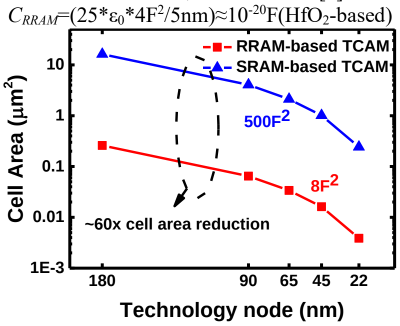

Fig. 4 The proposed TCAM cell design based on pure RRAM shows ~60x cell area reduction compared with traditional SRAM design.

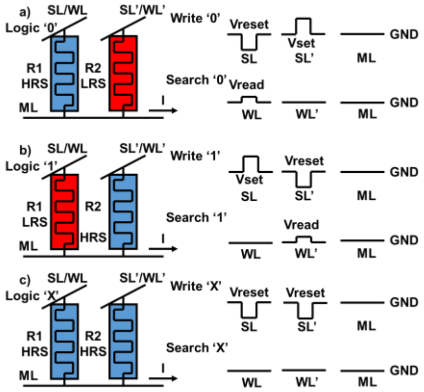

Fig. 2 A TCAM memory cell design based on pure RRAM devices with cell area ~ 8F^2. a), b) and c) represent the RRAM cell resistance states and diagrams of writing and searching '0', '1','X' in a TCAM cell respectively.

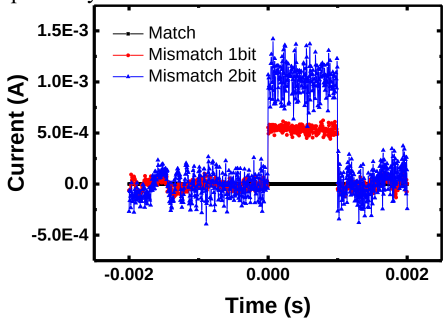

Fig. 5 Measured responding current waveforms with 2-bit word width in the match line. The mismatch current are much higher than the match one.

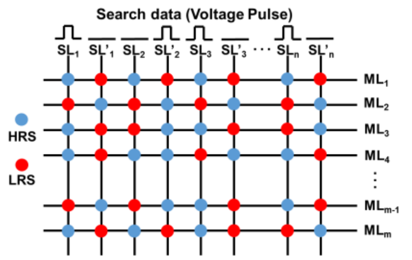

Fig. 3 Proposed RRAM crossbar array with m n-bit words for searching process in the TCAM system. Data is converted to voltage pulse waveform applied through search lines, at each cross-point of search line and match line is the RRAM device. Two adjacent RRAM in the same match line represent a single bit. The low/high current flows through match line represent match/mismatch of search and stored word.

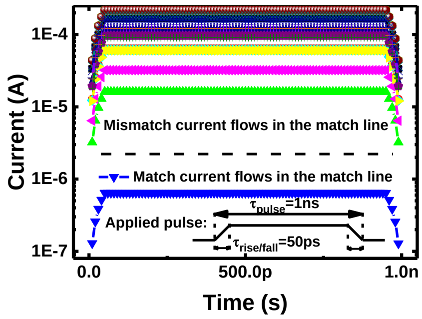

Fig. 6 Simulation of responding current waveforms with sixteen 16-bit words in match lines. The down triangle blue line represent match current while others represent mismatch ones. R_{on}=10kΩ,R_{off}=10MΩ.

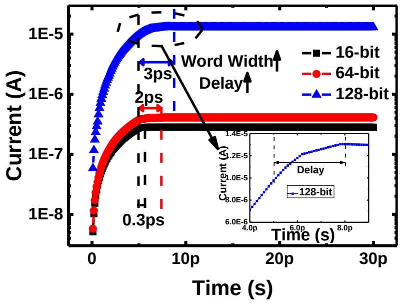

Fig. 7 The responding full match current waveforms at different word width. When word width increases, under the impact of interconnect wire capacitance and resistance, search delay is increasing.

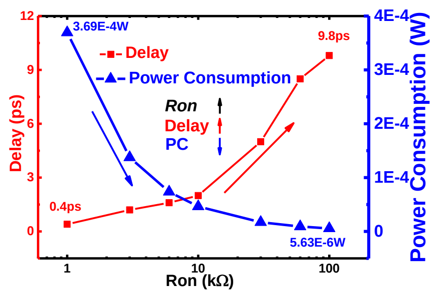

Fig. 8 The full match search delay and power consumption vs. R_{on} in four 64-bit stored words TCAM. Resistance window is set to 1000. As R_{on} increases the search delay increases, the power consumption decreases.

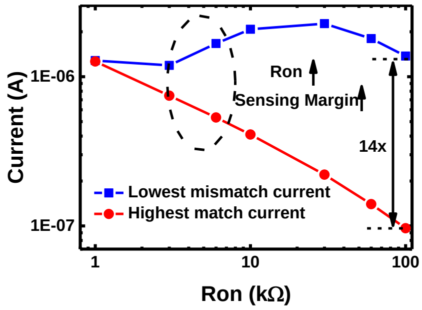

Fig. 9 Sensing margin vs. R_{on} in a 64-bit word TCAM. Resistance window is 1000. To get a considerable sensing margin, a larger R_{on} is preferred.

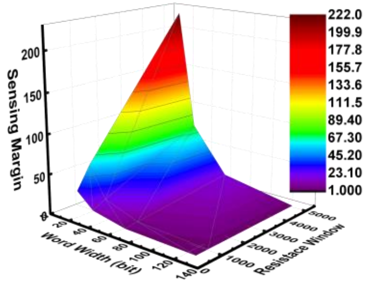

Fig. 10 Sensing margin vs. word width and resistance window. As the resistance window increases, the sensing margin increases in the same word width. While the sensing margin decreases with increase of the word width.

Table II Comparison to prior works

	[7]	[8]	[9]	[2]	**This work**
Technology	65 nm	90 nm	μm	μm	22nm
CAM/TCAM	TCAM	TCAM	TCAM	TCAM	TCAM
Word Width (bit)	72	32	144	128	64
Cell Structure	16T	6T2MTJ	11T3MTJ	5T2M	2RRAM
Supply Voltage (V)	1	1.2	1.8	1.8	0.2
Search Delay	1.9 ns	0.29 ns	8 ns	2 ns	**2ps**
Search Energy (fJ/bit/search)	1.98	1.04	7.4	0.99	**0.18**

* The search pulse width is set to 1ns width.