Enhanced read performance for phase change memory using a reference column

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Abstract: A reference column is employed to improve the read performance of phase change memory (PCM). In this way, a changeable reference current replaces the constant one; both the reference cell and the selected cell have the same bit line (BL) parasitic parameters and read transmission gate parasitic parameters in the read operation. Simulated in a 40 nm CMOS process, read access time of 4-Mb PCM is 30.65 ns with 190.9 ns improvement. Monte Carlo simulations show a 80.5 ns worst read access time compared to the conventional 1.58 μ s.

Keywords: phase change memory, read access time, reference current, PCRAM, sense amplifier

Classification: Integrated circuits

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1 Introduction

Phase change memory (PCM) has been attracting great interest as one of the most promising candidates for the next-generation nonvolatile memory devices [1]. The storage mechanism of PCM is based on reversible phase change transitions between a high resistance amorphous state (reset state for data “1”) and a low resistance crystalline state (set state for data “0”) of a chalcogenide alloy ($\text{Ge}_2\text{Sb}_2\text{Te}_5$ or GST) [2, 3]. As a continuous growth in scalability, parasitic parameters in the array have been a major obstacle in reducing the read access time [4]. This limit of parasitic parameters has been discussed a lot in various kinds of memories [5], while that is not specific in PCM. In this paper, we will discuss a method for improving the read performance, which has been applied to the development of 4-Mb standalone PCM with 40 nm CMOS technology.

2 Conventional read circuit analysis

Fig. 1(a) shows schematic of the read circuit of PCM which is a fully differential sense amplifier (SA). The red zone is the selected 1T1R cell, which comprises a GST element R_{GST} and a selection transistor NM0. The 1T1R cell is selected by a word line (WL) and a bit line (BL) from numbers of cells in the array. The read current I_{read} and the reference current I_{ref} are generated by V_{clamp} and a reference circuit, respectively. A ~ 100 mV V_{RBL} is low enough to avoid the additional set operation. In the SA, PM2 and NM4 copy I_{read} , PM3 and NM3 copy I_{ref} . When reading a set cell, $I_{\text{read}} > I_{\text{ref}}$. So PM2 copies a larger current than NM3 does, V_1 will rise to near VDD; also NM4 copies a larger current than PM3 does, V_2 will drop to near 0 V; DO of the SR latch will output VDD or “1”.

When we consider the read operation, the effect of parasitic parameters in the array can't be ignored. Parasitic parameters can be divided into two categories: bit line parasitic parameters and read transmission gate parasitic parameters. As shown

in Fig. 1(b), bit line parasitic parameters include parasitic capacitors of the selection transistors. Read transmission gate parasitic parameters include parasitic capacitors and resistors of read transmission gates. There are n 1T1R cells in one Local Bit Line (LBL) and m LBLs share one SA. Bit line parasitic parameters are related to n ; read transmission gate parasitic parameters are related to m . In the read operation, SA has to charge parasitic capacitors in the array at first.

Fig. 1. (a) Schematic of the conventional read circuit. (b) Parasitic elements in the read operation: parasitic capacitors and resistors of wires (in orange); parasitic capacitors and resistors of selection transistors (in red); parasitic capacitors and resistors of read transmission gates (in ruby).

Fig. 2. (a) Simulation results of the conventional read access time.
(b) I_{read} and I_{ref} versus time.

In this work, the GST resistance is modeled base on the conventional GST element used in a 40 nm PCM device [6]. The set resistance distribution is from a few $\text{K}\Omega$ to $100\text{ K}\Omega$ and the reset resistance distribution is from $1\text{ M}\Omega$ to dozens of $\text{M}\Omega$.

The 64-Kb unit block of 4-Mb PCM contains 1024 X-selectors, 64 Y-selectors and one SA. Large numbers of X-selectors and Y-selectors result in considerable parasitic capacitors and resistors on BL. More parasitic elements result in a higher

Fig. 3. Proposed read method.

read current. If a constant reference current is still being used, the read access time will be longer. Fig. 2(a) is the simulation results of conventional read access time. R_{GST} are 30 K Ω (set) and 2 M Ω (reset), respectively. The read access time is 221.6 ns, which is determined by reset speed. Fig. 2(b) shows the relationship between I_{read} and I_{ref} versus time. At first, set state I_{read} and reset state I_{read} rise to their maximum currents. Then they begin to drop as the natural exponential curves, just like the charging process of a capacitor. Due to their resistances difference, set state I_{read} is higher than reset state I_{read} when they reach a stable value. In the conventional method, I_{ref} is independent of time. When reading a reset selected cell, DO will not output a correct result until reset state I_{read} is lower than I_{ref} . A pseudo reading zone is therefore created.

3 Proposed read method

In the read operation, the extra charging process of parasitic capacitors causes a long readout time. If I_{ref} is designed to be changeable like I_{read} , the read access time may be reduced. Proposed read method is shown in Fig. 3. A new reference column which comprises one reference cell and $n - 1$ dummy cells is introduced. The reference cell comprises a reference poly-resistance R_{ref} and a NMOS transistor NM1. R_{ref} is set between the highest resistance in set distributions and the lowest resistance in reset distributions. Gate of NM1 is controlled by EN signal. Dummy cell is composed of a GST element and a NMOS transistor. The gates of NMOS are connected to the ground, so these NMOS are always switched off. The reference cell and the selected cell have the same bit line parasitic parameters. Read transmission gate RTG_0 controls the read operation. Besides, an extra RTG is connected between RBL1 (Read Bit Line) and the ground. This RTG has the same topology and size as RTGs in the array. Multiplier of the extra RTG is $m - 1$. Control terminal of the extra RTG is connected to ground, so this RTG is always switched off. In this way, the reference cell and the selected cell have the same RTG parasitic

parameters. LBL_0 is connected to RBL1 through RTG_0 . RBL0 and RBL1 are connected to SAs. During the read operation, with the help of the selected EN, WL and RTGs, two cells are connected to the SA: a reference cell through RBL1 , a cell to be measured through RBL0 . In the reference side, there are one selected cell, $n - 1$ unselected cells, one selected RTG and $m - 1$ unselected RTGs; in the array, there are also one selected cell, $n - 1$ unselected cells, one selected RTG and $m - 1$ unselected RTGs. Different from the conventional methods which use a constant reference current [6, 7], the reference cell and the selected cell have the same parasitic elements in the proposed method.

Fig. 4(a) shows schematic of the proposed SA. Compared to the aforementioned method, NM6 and a new reference current I_{refnew} are introduced. NM6 helps V_{clamp} generate I_{refnew} from the reference cell. Then I_{refnew} is compared with I_{read} . Fig. 4(b) shows schematic of the V_{clamp} generator. V_{bg} is the bandgap voltage. The proposed method uses one voltage (V_{clamp}) to generate I_{refnew} and I_{read} , which is different from previous methods which use two different voltages/circuits to generate I_{read} and I_{ref} [6, 7, 8]. In the proposed method, I_{refnew} and I_{read} are more likely to have a similar variation trend. The design is symmetric in terms of parasitic parameters and SA topology. A short current signal instead of a long current signal routing from the SA to reference cells is used [8].

Fig. 4. (a) The schematic of the proposed SA. (b) Generator of the clamp voltage V_{clamp} .

In many non-volatile memories, the reference current is generated by averaging the read-out current of paired high resistance state (HRS) and low resistance state (LRS) written reference cells [8, 9]. But large deviations of HRS and LRS will cause reference-currents deviation. Therefore, the single-reference scheme has wider sense margin if properly designed. Compared to the previous method [8, 9, 10], no reference cells need to be programmed in the initialization phase.

4 Performance evaluation

Simulated in SMIC 40 nm CMOS process, the proposed method is utilized in 4-Mb PCM to verify performance. The 4-Mb PCM is used to replace SRAM and EEPROM in applications like printer and Bluetooth speaker. In the array and the reference column, we have $n = 1024$, $m = 64$. Fig. 5(a) and Fig. 5(b) are the

simulation results of readout time when WL_1 and WL_{1024} are selected, respectively. R_{ref} is $300\text{ K}\Omega$. R_{GST} are $30\text{ K}\Omega$ (set) and $2\text{ M}\Omega$ (reset), respectively. In the simulation, parasitic resistances and capacitances of the bit line metal are also taken into account. Parasitic resistance of the whole LBL is about 68.6Ω and parasitic capacitance of the whole LBL is about 14 fF . Parasitic capacitance of the GST element is considered and it is approximately 18.86 aF . The read access time is 30.65 ns , which is determined by set speed of Fig. 5(b).

Fig. 5. (a) The simulation result of readout time when WL_1 is selected. (b) The simulation result of readout time when WL_{1024} is selected.

Fig. 6. Currents comparison in the proposed method: Conv.: conventional method; Prop.: proposed method.

Fig. 6 shows the relationship between I_{read} and I_{refnew} versus time. In this new scheme, I_{refnew} first rise to its maximum current, then begin to drop as the natural exponential curve, finally reach a stable value. I_{refnew} curve has been in the middle of set state I_{read} and reset state I_{read} early, since the reference cell and the selected cell have the same parasitic parameters. When reading a set selected cell: as I_{refnew} is lower than I_{read} , DO will output a correct result. When reading a reset selected cell: as I_{refnew} is higher than I_{read} , DO will output a correct result. When I_{refnew} and I_{read} are the same, V_1 and V_2 are the same, and SR latch output “0”. This is why in most cases DO can always output the correct reset result. The read current is as

small as $1.8 \mu\text{A}$, which is the smallest read current of PCM in the world, to our best knowledge.

According to the simulation results below, the disable of EN is set above $5.11 \mu\text{s}$ to ensure all the bits are correctly read. On the contrary, conventional disable of EN is set at $6.6 \mu\text{s}$.

Fig. 7. (a) Monte Carlo simulation result of the conventional method.
(b) Monte Carlo simulation results of the proposed method.

Fig. 8. Comparisons of the read access time under different process corners and the worst R_{GST} .

Monte Carlo simulation results of the read access time are shown in Fig. 7. It can be used to compare the worst case of the conventional and proposed method. Monte Carlo simulations are performed using the industry compatible SMIC 40-nm model parameters. Accomplished in process & mismatch analysis, three times standard deviation (3σ) is used as the variances of parameters and mismatch of MOS and resistor. The GST device is modeled as the resistance distribution in order to reflect the effect of process variation [6]. In each simulation, 4000 trials were run. Variations of V_{clamp} , parasitic capacitance of the GST element and parasitic elements of the bit line metal are also considered. Circuits in Fig. 3, Fig. 4(a) and Fig. 4(b) are all included in Monte Carlo simulation. The worst read access time of the proposed method (determined by set speed) is 80.5 ns. On the contrary, the worst read access time of the conventional method (determined by reset speed) is $1.58 \mu\text{s}$. It is clearly that the worst read access time is largely reduced. Timing

margin between the regular case and the worst case is reduced from 1.51 μs to 80 ns.

Fig. 8 shows the comparisons of the read access time with the above two methods under different process corners and the worst R_{GST} , respectively. The worst R_{GST} is 100 $\text{K}\Omega$ (set) and 1 $\text{M}\Omega$ (reset), respectively.

Fig. 9. The read operation under both the process corner SS and the worst R_{GST} : (a) reading a set cell; (b) reading a reset cell.

Fig. 9 is the simulation results of the read operation under both the process corner SS and the worst R_{GST} . When SA begins to work, V_1 and V_2 are charged and begin to rise; the read current and the reference current begin to charge parasitic elements. As I_{read} and I_{refnew} are almost the same in this moment, V_1 and V_2 are the same. When V_1 and V_2 are the same, SR latch outputs “0”. When reading a set cell, after distinguishing point of the proposed method, V_1 is nearly 2.5 V; V_2 is nearly 0 V. SR latch outputs “1”. When reading a reset cell, after charging process, V_1 is nearly 0 V; V_2 is nearly 2.5 V. SR latch outputs “0”. The worst variation of process corner and R_{GST} won’t influence a correct readout result.

Fig. 10 and Fig. 11 are the simulation results of the read operation under both the worst variation of V_{TH} and R_{GST} . Increase or decrease of V_{TH} of the transistors in the SA are marked by arrows in Fig. 10(a) and Fig. 11(a). Variation of V_{TH} is about 70 mV, which is the worst variation of V_{TH} in SMIC 40 nm CMOS process. In Fig. 10, the selected cell is a set cell. R_{GST} is 100 $\text{K}\Omega$. The variations of V_{TH} make I_{read} decreases and I_{refnew} increases. This results in a long pseudo reading zone in Fig. 10(b). In Fig. 11, the selected cell is a reset cell. R_{GST} is 1 $\text{M}\Omega$. The

Fig. 10. When the selected cell is a set cell: (a) variations of V_{TH} ; (b) the simulation result.

variations of V_{TH} make I_{read} increases and I_{refnew} decreases. The worst variation of V_{TH} and R_{GST} won't influence a correct readout result.

Fig. 11. When the selected cell is a reset cell: (a) variations of V_{TH} ; (b) the simulation result.

The comparison between the proposed read method and the prior read methods is shown in Table I. In the read circuit of memory, the read access time will decrease as bits per SA (the number of cells sharing a SA) decrease or the read current increases. In Table I, we try to compare their performance in a same standard.

Table I. Performance summary and comparison

	This paper	Ref. [7]	Ref. [11]	Ref. [12]	Ref. [13]
Technology	40 nm PCM	130 nm PCM	90 nm PCM	90 nm PCM	130 nm PCM
Power supply (V)	2.5	1.5	1.8	1.2	3.3
Read access time T (ns)	30.65	9.9	37.5	12	98
Bits per SA F (Kbit)	64	8	4	32	0.125
Cell read current (set) I_s (μA)	1.8	20	N/A	55	18
T/F (ns/Kb)	0.48	1.24	9.375	0.38	784
$T \cdot I_s$ (ns $\cdot\mu A$)	55.26	198	N/A	660	1764
$T \cdot I_s/F$ (ns $\cdot\mu A/Kb$)	0.86	24.75	N/A	20.63	14112

5 Conclusions

Parasitic elements on BL have always been a big limit for the read performance in various kinds of memories. This paper presents a novel read method for 4-Mb PCM in 40 nm CMOS process. The proposed method uses a reference column to generate a reference current. The reference column is composed of one reference cell and a certain number of 1T1R cells. The reference cell and the selected array cell have the same parasitic parameters in the read operation. Simulation results show a 30.65 ns read access time compared to the previous 221.6 ns. Monte Carlo simulation shows a 80.5 ns worst read access time compared to the conventional 1.58 μs . This method can be easily applied in the practical products and it is also useful in MRAM, RRAM and Flash.

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