Bit-error rate improvement of TLC NAND Flash using state re-ordering

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Abstract: In scaled technologies, large cell-to-cell interference and F-N tunneling disturbance degrade threshold voltage (V_t) window which we can place program states. Moreover, in *Triple Layer Cell* (TLC) NAND Flash we should place seven program states ($P_1 \sim P_7$) in the narrow V_t window, incurring large *bit-error rate* (BER). In this paper, we propose a state re-ordering technique to increase the efficiency of V_t window utilization in TLC NAND Flash memories. Our simulation results show that under equivalent V_t window sizes, the proposed technique provides 12.5~18.4% smaller BER compared to conventional Gray-code mapping.

Keywords: TLC NAND Flash Design, code-mapping

Classification: Storage technology

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1 Introduction

During programming operations of NAND Flash memories, cell-to-cell interference and F-N tunneling disturbance vary threshold voltages of the

E-state cells [1, 2]. This narrows the window where *threshold voltages* (V_t 's) of program-state cells can be placed. The cell-to-cell interference and the F-N tunneling disturbance become larger as the NAND Flash technology is scaled down, making worse such a phenomenon. Moreover, the cell-to-cell interference also degrades V_t distributions of program-state cells. Consequently, in sub-30 nm *Triple-Level Cell* (TLC) NAND Flash it is challenging to place seven program states in the narrow V_t window.

2 State re-ordering

Due to the narrow V_t window, we cannot avoid overlapped regions between adjacent states in TLC NAND Flash memories, as shown in Fig. 1. At these regions, we have bit-errors during read operations and they are recovered using an *error correcting code* (ECC) technique in the off-chip controller [2]. In scaled NAND Flash memories, BCH code is widely used for the ECC technique [3]. Typically, 1 KB word is the basic processing unit of the BCH code and extra parity bits are added to this unit for error correction. A group of 1 KB word and corresponding parity bits is called as one code-word. The maximum number of bit-errors which the BCH code can correct in single code-word, namely maximum correction number (MCN), is decided by the number of parity bits (i.e. MCN: 40-bit for '1 KB word + 560-bit parity') [4].

Fig. 1. The mapping between states and page information under Gray-code

To read the information of three pages stored in TLC NAND Flash, we need seven read levels (RL's) as shown in Fig. 1. Here, we should note that in TLC NAND Flash, Gray-code has been used for the mapping between each state and page information [5]. For example, '110' (the 1st page: 0, the 2nd and the 3rd pages: 1) is mapped to P₇-state while P₆-state represents '010' (the 1st and the 3rd pages: 0, the 2nd page: 1). Under such an environment, one, two and four RL's should be assigned for the 1st, the 2nd, and the 3rd page readings respectively, as shown in Fig. 2. As addressed above, some bit-errors occur during read operation of each *read level* (RL), which are corrected by using BCH code. For successful error corrections, the inequality conditions of Fig. 2 should be satisfied.

To deliver these requirement, we need to control the number of bit-errors occurring at the overlapped region of adjacent states by varying the distances between VL_i 's (VL_i : the verify level of P_i state). Fig. 3 shows the relation between ΔVL_2 (ΔVL_i : when $i > 1$, $VL_i - VL_{i-1}$. When $i=1$, $VL_1 -$

reading method	Gray-code	
	1 st page read
	2 nd page read
	3 rd page read
1 st page read	# of bit-errors(@RL ₄) ≤ MCN	
2 nd page read	# of bit-errors(@RL ₂) + # of bit-errors(@RL ₆) ≤ MCN	
3 rd page read	# of bit-errors (@RL ₁) + # of bit-errors(@RL ₃) + # of bit-errors(@RL ₅) + # of bit-errors(@RL ₇) ≤ MCN	

Fig. 2. Reading methods and inequality conditions for successful error correction under Gray-code (MCN: Maximum Correction Number)

Fig. 3. The relation between the verify level distance and the corresponding bit-error number (simulation results)

minimum V_t of E-state cells) and the corresponding number of error-bits in P_1 and P_2 states. For simplicity, we assume that V_t 's of P_1 and P_2 states have a Gaussian distribution with 150 mV standard deviation. As shown in Fig. 2, four RL's (RL₁, RL₃, RL₅, and RL₇) are necessary for the 3rd pages reading due to Gray-code mapping. Under the assumption that the MCN is 40-bits, the average number of bit-errors per each RL in the 3rd page reading is 10-bits. In Fig. 3, we can observe that as ΔVL_2 increases, the corresponding reduction of bit-errors becomes exponentially reduced. This implies that large ΔVL_1 , ΔVL_3 , ΔVL_5 and ΔVL_7 are required to regulate the number of the corresponding bit-errors below 10-bits, degrading the efficiency of V_t window utilization. This makes it difficult to satisfy the 40-bit MCN requirement under the narrow V_t window in sub-30 nm technologies.

We alleviate this problem by proposing a state re-ordering technique. Fig. 4 shows the proposed technique. Here, '110' is mapped to E-state while P_7 -state represents '110' under Gray-code mapping. Then, the information of E and $P_1 \sim P_6$ states under the Gray-code mapping is mapped to $P_1 \sim P_7$ states. In the proposed scheme, two, two and three RL's are assigned for the 1st, the 2nd, and the 3rd page, as shown in Fig. 5. Since the number of RL's for each page varies, the inequality conditions for error correction also change. Compared to Gray-code mapping, the number of RL's for the 1st page reading increases in the proposed method. This degrades the efficiency of V_t window utilization to a certain degree. However, in the 3rd page reading,

Fig. 4. The mapping method of the state re-ordering technique

Fig. 5. Reading methods and inequality conditions for successful error correction under the state re-ordering technique

the number of RL's decreases, improving the utilization efficiency more significantly.

In order to validate the proposed technique, we simulate and compare an occupied V_t window size between Gray-code mapping and the proposed technique. For simplicity, we assume the following conditions in these simulations: all erase or program states ($E, P_1 \sim P_7$) have a Gaussian distribution and all program states have the same standard deviation value as $\sigma V_{t,P\text{-states}}$ while they have different average values. For two mapping scenarios, the average and standard deviation of E-state cells are assumed to be equivalent: 0 V and 350 mV, respectively. We also assume that the MCN is 40-bits and each state has equivalent cell numbers for every code-word. We consider that the minimum grid of verify level variation is 50 mV due to a circuit limitation. Based on the above assumptions, we can achieve proper ΔV_{L_i} 's to satisfy the inequality conditions of Fig. 2 and Fig. 5 for 1536 code-words, which is one-block size ($=64\text{WL}$ per one block $\times$ 24 code-words per one WL) in TLC NAND Flash. Using these ΔV_{L_i} 's, we are able to generate V_t distributions for two mapping scenarios, as shown in Fig. 6. When $\sigma V_{t,P\text{-states}} = 150$ mV, our proposed technique shows 150 mV smaller V_t window size compared to Gray-code mapping.

We made the same comparisons for ' $\sigma V_{t,P\text{-states}} = 140$ mV' and ' $\sigma V_{t,P\text{-states}} = 130$ mV', whose results are shown in Fig. 7 (a). Here, the proposed state ordering shows at least 150 mV smaller window size than the Gray-code mapping. This implies that under the same V_t window, the proposed technique will show better *bit-error rate* (BER) compared to the Gray-code mapping. In order to prove this, we compared maximum number of bit-errors for 1536 code-words under the equivalent V_t window condition. For each $\sigma V_{t,P\text{-states}}$, we used the V_t window size of Gray-code mapping obtained from Fig. 7 (a). The results are shown in Fig. 7 (b), where the

Fig. 6. V_t window comparison of two mapping techniques ($\sigma V_{t,P\text{-states}} = 150 \text{ mV}$, μ of $V_{t,E\text{-state}} = 0 \text{ V}$, $\sigma V_{t,E\text{-state}} = 350 \text{ mV}$)

Fig. 7. Gray-code mapping vs. state re-ordering
(a) V_t window size comparison satisfying the MCN = 40-bits for 1536 code-words
(b) Maximum number of bit-errors for 1536 code-words under the equivalent V_t window size

proposed technique shows 12.5~18.4% smaller number of bit-errors. This proves the aforementioned conjecture well.

3 Conclusions

We propose the state-reordering technique to ameliorate the efficiency of V_t window utilization. Our simulations prove that the proposed technique occupies smaller V_t window in TLC NAND Flash, compared to Gray-code mapping. Hence, this implies that we can improve BER of TLC NAND Flash memories by using the proposed technique.