

Flash Type Comparison for SLC/MLC/TLC and Ultra MLC Technology

Author: Ethan Chen/ Precyan Lee

E-mail: ethan.chen@advantech.com.tw; precyan.lee@advantech.com.tw

Table of Contents

1. Introduction	1
2. Flash Memory	1
Physical Structure.....	1
Types of NAND Flash	3
3. Ultra-MLC	4
Introduction.....	4
Advantage(s).....	5
4. Performance	5
Observations	5
5. Endurance	6
Testing Methodology.....	6
Observations	6
6. Data Retention	7
7. Conclusion(s).....	7
Appendix A	8

1. Introduction

Flash memory is a non-volatile storage element that can be electrically programmed/re-programmed and erased. As technology continuously advances, the demands for greater density and better performance with flash memory become large as well. Most importantly, flash memory is no longer a component that resides only in your computer – It could act as a photo album or a file cabinet that stores all your personal treasures or business portfolios.

The purpose of this paper is to provide an overview on flash technology, specifically on NAND flash, a memory technology that has been deeply connected to our day-to-day life. In addition, we would like to introduce another MLC flash member, Ultra MLC, which delivers better performance and endurance – just like the legendary SLC flash.

The paper is organized as follows: Section 2 explains the differences between NAND and NOR flash, and provides information on NAND flash including SLC and MLC. Section 3 introduces Ultra MLC – the mechanism and its advantages. Section 4 and 5 provide performance and endurance information with Ultra MLC, respectively. Finally, a conclusion is provided.

2. Flash Memory

Physical Structure

NAND and NOR are the types of flash memory, commonly taken side-by-side for comparison due to their nature in data storing. To distinguish their differences, one could think that NOR flash is used for code storage whereas NAND flash is used for file storage.

The reason for such a differentiation comes from the fact that NOR flash is capable of achieving fast random access and performing fast read operations, but is restricted by slower write and erase operations. Therefore, NOR flash is more suitable for infrequent data modification, and it is common to see that boot code, firmware or operating system to be stored in NOR flash.

On the other hand, NAND flash is capable of performing fast write and erase operations. It also consumes less layout area, which could be translated to greater density and lower cost-per-bit. Almost as good as it sounds, NAND flash has one thing that is unable to outperform NOR flash: That is, slower random access, as the trade off to space saving. Nevertheless, NAND flash is still widely used in various types of file storage elements such as USB flash drives and memory cards, where data constantly needs to be loaded and updated.

Figure 1 represents the physical differences between NOR and NAND flash. The NOR structure (Left) is designed to connect each memory cell (highlighted in yellow) vertically, whereas the NAND structure (Right) is designed to connect each memory cell (highlighted in yellow) horizontally. $10F^2$ and $4F^2$ represent the layout area per cell for NOR and NAND, respectively. As we mentioned before, NAND flash requires less layout-area consumption and therefore delivers a wider range of capacities and lower bit-cost.

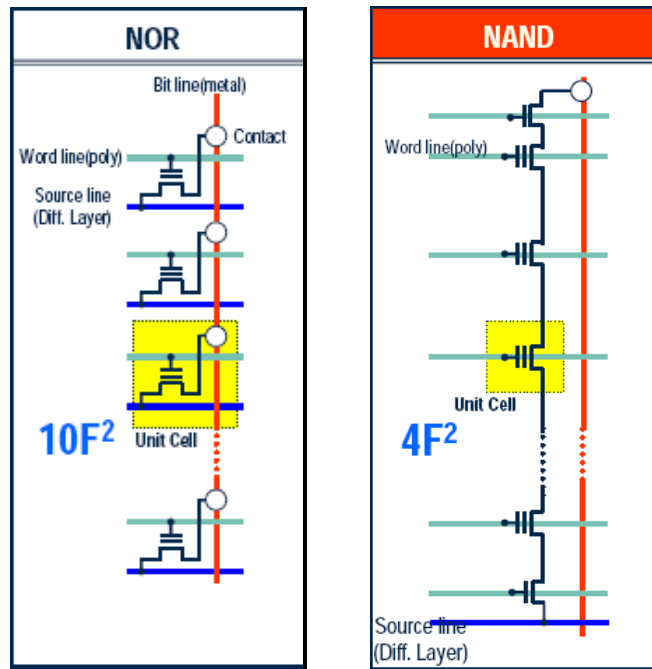


Figure 1: (Left) Cell Array for NOR and (Right) Cell Array for NAND

In the rest of the paper, we will focus on NAND flash and introduce Phison's unique design of Ultra MLC including its mechanism, performance and endurance.

Types of NAND Flash

Generally, NAND flash is categorized in two types – SLC (single-level cell) and MLC (multi-level cell). NAND-makers have recently announced the latest flash technology - TLC (ternary-level cell), also known as three-bit per cell, which is the new addition to the NAND family. However, it is beyond the scope of our topic, and will not be covered in the paper.

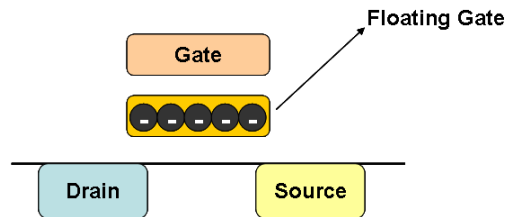


Figure 2: Basic Structure of a Memory Cell

Each cell is consisted of a single transistor and a floating gate, which is located between Gate and Source/Drain and allows electrons to be stored inside, as shown in Figure 2. For SLC flash, only one bit could be stored to each cell at a time, and there will be two possible states for each cell – 0 or 1. As for MLC flash, two bits could be stored to each cell at a time and there will be four possible states for each cell – 00, 01, 10 or 11. Cell state is determined by the threshold voltage (V_t) of each cell, and the voltage is an interpretation of the amount of charges stored inside the floating gate, as shown in Figure 3.

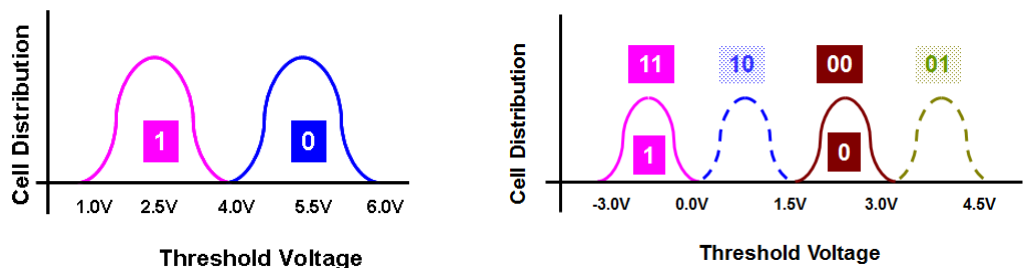


Figure 3: Cell Distribution vs. Threshold Voltage for SLC Flash (Left) and MLC Flash (Right), Respectively

Because MLC flash stores 1 more bit at each cell than SLC flash does, MLC provides higher density and lower bit-cost. Unfortunately, nothing comes for free – the trade off for cost-saving is greater power consumption and poorer endurance, due to more voltage levels required and technology limitation. It is common to see that SLC flash is used in industrial applications, whereas MLC flash is used in commercial applications.

3. Ultra-MLC

Introduction

Although SLC flash is more enduring and provides better performance than MLC flash does, cost is still an issue to users. What if we could have the best of the both worlds – a new gene that delivers greater performance and endurance, but yet at the same time, is an economical solution?

The answer is yes – Ultra MLC.

The very idea with Ultra MLC is that MLC flash consists of a number of fast and slow pages, and only fast pages will be used for programming when using Ultra MLC. One can think of Ultra MLC as an extended version of MLC flash. Table 1 and Figure 4 explain the concept of Ultra MLC: The first and second bit of a memory cell corresponds to a fast and slow page, respectively, as shown in Table 1 (Left). Since we program fast pages with Ultra MLC, only the bits highlighted in red in Table 2 (Middle) will be used.

MLC Flash		→	Ultra MLC Flash		↔	SLC Flash
1st Bit (Fast)	2nd Bit (Slow)		1st Bit (Fast)	2nd Bit (Slow)		Bit
1	1		1	1		1
1	0		1	0		
0	1		0	1		
0	0		0	0		0

Table 1: Cell Content for MLC (Left), Ultra MLC (Middle) and SLC (Right), Respectively

When the two bit-sets (10 and 00) from MLC flash are discarded, the bit data from Ultra MLC is almost identical to that with SLC flash. In Figure 4, the threshold voltage ranges that correspond to 10 and 00 will be discarded, leaving the ones for 11 and 01. Differentiating the amount of charges inside the floating gate becomes easier, since a more separate cell distribution reduces the chance to misjudge the threshold voltage for each cell.

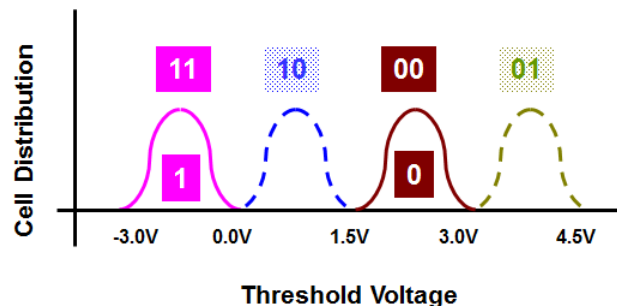


Figure 4: Cell Distribution vs. Threshold Voltage for Ultra MLC

Advantage(s)

Ultra MLC	
Advantage(s)	Description(s)
Performance enhancement	<ul style="list-style-type: none"> ● Only fast pages are programmed with Ultra MLC flash and therefore the write performance is improved. ● Please refer to "Section 4: Performance" for details.
Lifespan extension	<ul style="list-style-type: none"> ● Ultra MLC's endurance is better than that of MLC by at least 10X. ● Please refer to "Section 5: Endurance" for details.
Cost-effective solution	<ul style="list-style-type: none"> ● The characteristics of Ultra MLC are similar to that of SLC flash, but Ultra MLC is a much more economical solution cost-wise.

Table 2: Major Advantages of Ultra MLC

4. Performance

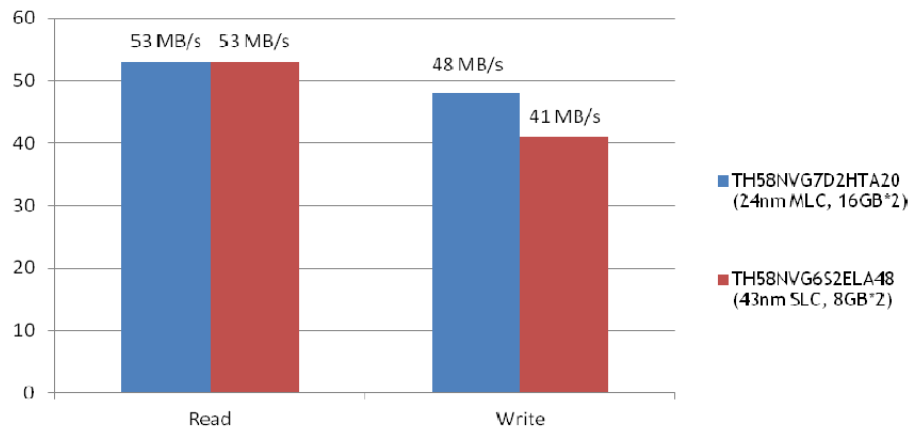


Figure 5: Read/Write Performance for CF with PS3016-P8

Observations

With the same usable capacity of the SSD, the sustained write performance has been obviously improved, and the read performance with ultra MLC is also comparable to that with SLC one.

5. Endurance

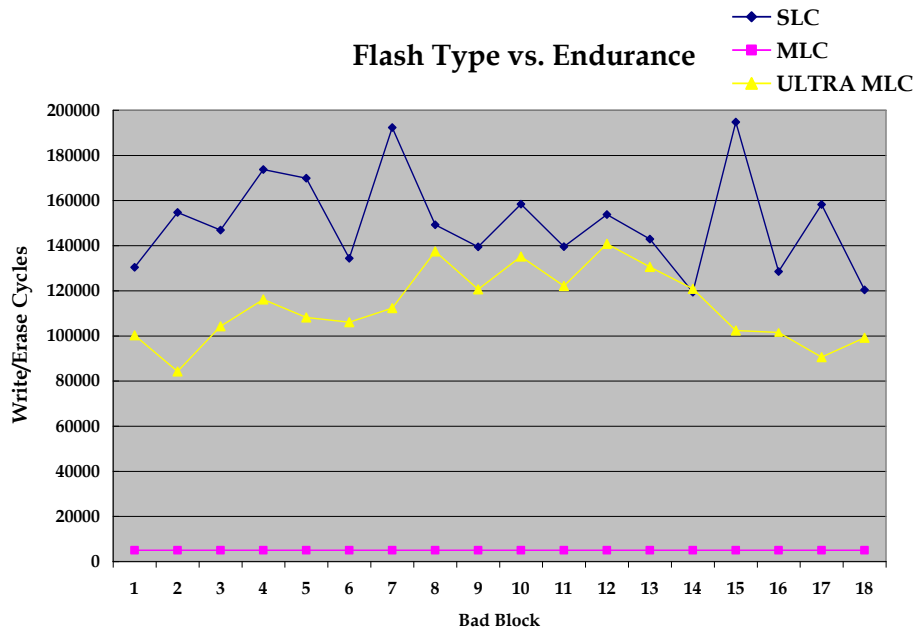


Figure 6: Endurance Comparison among SLC, MLC and Ultra MLC

Testing Methodology

We program and erase only one block at a time until it becomes unusable (later bad block) and then move on to the second block so on and so for.

Observations

In Figure 6, it is obvious to see that Ultra MLC outperforms MLC in terms of withstanding a greater amount of usage. In general, MLC endurance is considered to be about 3K times, and our previous experiments have allowed us to conclude that endurance of Ultra MLC is at least 10 times greater than that of MLC.

	Program / Erase Cycle	Cumulative Block Failure Rate (%)
MLC Flash	3,000	Less than 0.04
Ultra MLC Flash	30,000	

Appendix A displays the ECC values based on the three types of flash. Since MLC consists of four voltage levels, the chance of one bit interfering the other becomes greater, which could be translated into a higher ECC value. Therefore with MLC flash, a controller's ECC-ability needs to be more robust.

On the contrary, SLC and Ultra MLC have only two voltage levels and the possibility of bit-interference becomes less, which could be observed from a lower ECC value in Appendix A.

6. Data Retention

The data in memory may change after a certain amount of storage time. After block erase and reprogramming, the block may become usable again.

Program / Erase Cycle	Estimated Data Retention Time (Years)	
	MLC Flash	Ultra MLC Flash
Initial (<100)	10	10
300	10	10
1,000	3	10
3,000	1	10
5,000		10
30,000		1

Conditions:

Vcc= 3.3V, Ta=40 Celsius degree, 40 bit ECC for 1Kbyte

Cumulative failure rate: Max 1,000ppm

The 1,000ppm above is the device failure rate when one or more 1Kbyte areas become uncorrectable.

7. Conclusion(s)

Ultra MLC, a part of the MLC family has been proved to provide better performance and greater endurance by programming only fast pages. Our experiment has shown that the read/write performance is improved. Additionally, endurance of Ultra MLC is at least ten times greater than that of MLC, which is used by programming both fast and slow pages. We believe that Ultra MLC is the most economical alternative for Industrial NAND flash applications when it comes to stable and cost-efficiency requirements.

Advantech Co., Ltd. –Founded in 1983, Advantech delivers visionary and trustworthy industrial computing solutions that empower businesses. We cooperate closely with solution partners to provide complete solutions for a wide array of applications in diverse industries, offering products and solutions in three business categories: Embedded ePlatform, eServices & Applied Computing, and Industrial Automation groups. With more than 3,400 dedicated employees, Advantech operates an extensive support, sales and marketing network in 18 countries and 39 major cities to deliver fast time-to-market services to our worldwide customers. Advantech is a Premier Member of the Intel® Embedded and Communications Alliance, a community of embedded and communications developers and solution providers. (Corporate Website: www.advantech.com).
Copyright© 2013 Advantech Co., Ltd. All rights reserved.

Appendix A

SLC		
Endurance	Max ECC	Failure Type
130420	0	Erase Fail
154682	0	Erase Fail
146872	0	Erase Fail
173730	0	Erase Fail
169906	0	Erase Fail
134393	0	Erase Fail
192340	0	Erase Fail
149203	0	Erase Fail
139485	0	Erase Fail
158384	0	Erase Fail
139575	0	Erase Fail
153753	0	Erase Fail
142934	0	Erase Fail
119374	1	Erase Fail
194743	0	Erase Fail
128475	0	Erase Fail
158222	0	Erase Fail
120384	0	Erase Fail

MLC		
Endurance	Max ECC	Failure Type
31132	10	Erase Fail
61588	18	Erase Fail
52286	9	Erase Fail
63206	19	Erase Fail
56847	15	Erase Fail
54888	14	Erase Fail
52543	10	Erase Fail
60782	17	Erase Fail
58269	12	Erase Fail
60128	9	Erase Fail
50923	8	Erase Fail
39572	19	Erase Fail
51206	14	Erase Fail
62755	13	Erase Fail
39284	11	Erase Fail
42756	9	Erase Fail
52931	14	Erase Fail
30845	21	Erase Fail

Ultra MLC		
Endurance	Max ECC	Failure Type
100261	0	Erase Fail
84238	0	Erase Fail
104283	0	Erase Fail
116143	0	Erase Fail
108135	0	Erase Fail
106080	0	Erase Fail
112328	0	Erase Fail
137423	0	Erase Fail
120583	0	Erase Fail
135190	0	Erase Fail
122059	0	Erase Fail
140787	0	Erase Fail
130579	0	Erase Fail
120857	0	Erase Fail
102394	1	Erase Fail
101495	0	Erase Fail
90572	0	Erase Fail
99184	0	Erase Fail