msystems' x4 Technology:
4-Bit/Cell NAND Usage Impossible? Possible!

White Paper

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May 2006

01-WP-0406-00, Rev 1.0

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SCOPE

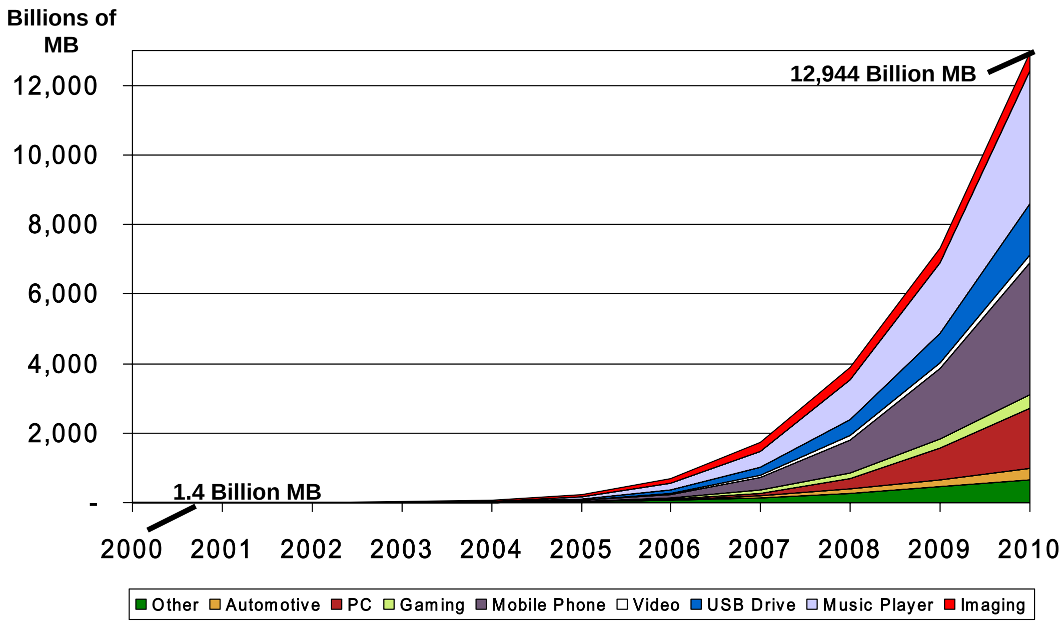
This white paper discusses how the escalating demand for personal storage media in the consumer electronics space has fuelled growth in the NAND flash memory market and is now driving the development of a new generation of breakthrough technologies. As evidence, this paper introduces msystems' x4 NAND technology, enabling a new generation of 4-bit/cell NAND flash media that, until now, was considered impossible to utilize. Rooted in current 2-bit/cell MLC NAND production processes, x4 NAND components enable optimal flash manufacturing cost savings.

To help set the scene, this paper also briefly discusses how companies have overcome some initial skepticism to drive the widespread adoption of 2-bit/cell MLC NAND flash technology which, for the majority of consumer electronics market segments and applications, is now positioned as the flash media of choice.

A discussion then follows on the feasibility of using 4-bit/cell NAND to further condense the amount of data bits per wafer, which will ultimately help to significantly drive down costs. We also look at the major obstacles that need to be overcome, including data reliability, performance and flash lifespan, and how msystems' x4 NAND technology can effectively address these. Finally, the paper provides a more thorough overview of msystems' x4 NAND, outlining how msystems developed the technology, the benefits that x4 NAND components will bring to a new generation of consumer electronics devices, and why msystems is best positioned to take this next major step.

PHENOMENAL FLASH MEMORY GROWTH

From automotive equipment to mobile phones, USB flash drives (UFDs), music players and imaging equipment, the demand for NAND flash memory has spiraled upward, as shown in Figure 1.

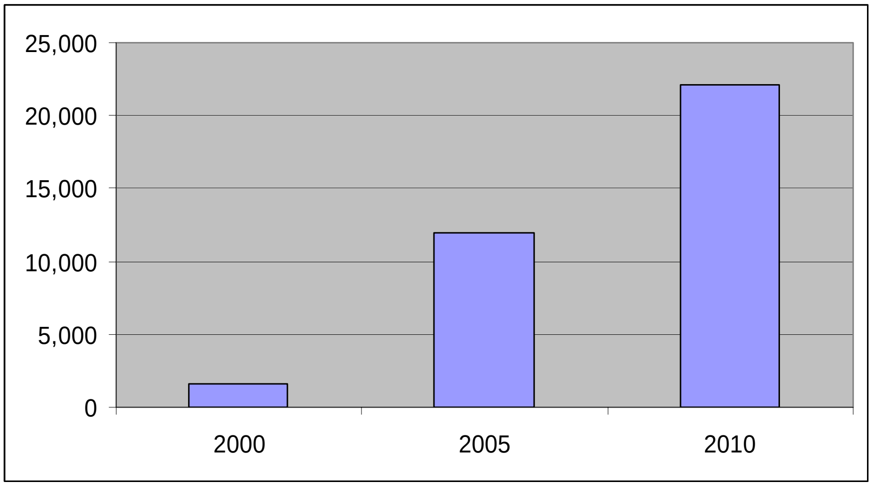


Gartner, May 2006

Figure 1: NAND Flash Consumption, Current and Forecast

This demand has been fuelled by a number of key factors including the age of mobility, which can be defined as consumers wanting to easily store, access and control their data and content anywhere, anytime. Lower flash prices and increased availability of digital content, both premium and self-generated (including movies, music, games and photographs) have also acted as catalysts to drive adoption. In turn, this has acted as an education process for many consumers who, through MP3 players, USB flash drives and memory cards in particular, have become familiar with the value of having more memory to store more of their personal content.

In this memory-hungry environment, the NAND flash memory market has seen phenomenal growth, as shown in Figure 2.



Data source: Gartner, May 2006

Figure 2: Worldwide NAND Flash Growth, Current and Forecast (Millions of Dollars)

Perhaps the best illustration of the rapid rise of NAND flash has been the success of the Apple® iPod® nano, which has witnessed sales of millions of units since its introduction in mid 2005. As the first mass market consumer electronics device to feature high-density embedded NAND flash, this success served as a watershed event to demonstrate that large densities of NAND flash could be cost effective enough to be deployed in inexpensive, high volume devices.

msystems has defined this increased awareness and demand as the emergence of the personal storage age. Predicated on the fact that all of us want access to content whenever and wherever we go, the personal storage age has sent consumer electronics device manufacturers in search of smarter storage solutions – a central component in helping them gain traction and market share.

To cost-effectively support the demand for more memory, the flash memory market took a number of decisive steps: the increase in NAND production capacity, the conversion to larger 12” silicon wafers, the introduction of finer processes, and most recently, the shift from single-level cell (SLC, binary, or 1-bit/cell) NAND flash technology to 2-bit/cell MLC NAND flash technology. 2-bit/cell MLC NAND flash enables significant cost savings by storing twice the data in essentially the same silicon die per given manufacturing process. This has the potential to reduce costs for higher density memory production with gigabyte offerings - all with little additional capital expenditure. As memory requirements continue to grow, both flash suppliers and consumer electronics device vendors seek new ways to produce higher density flash at reduced costs.

However, this approach also creates added complexity for managing the use of flash memory in new devices, prompting manufacturers to look for ways to easily and quickly integrate 2-bit/cell MLC NAND-based personal storage into new devices.

NAND Flash Media Trends

When looking at the history of flash data storage in consumer electronics devices, two related trends become instantly apparent: falling cost of NAND flash media and the degradation in media quality and specifications.

The falling cost of NAND flash media is a result of new manufacturing technologies that continually increase the number of bits that can be stored in every cell, such as 4-bit/cell NAND flash. But this results in the degradation of the media quality and specifications. In fact, with every new generation of silicon, the usability of the raw NAND flash material as storage media diminishes. This degradation is caused not only by new advanced technologies but also by continually decreasing lithography (also known as manufacturing process, or geometry). The decrease in the manufacturing process, from 400nm in 2000 to down to 60nm today, causes severe problems in manufacturing, making it difficult to create and align all the small structures in the silicon wafer. These manufacturing problems lead to phenomena, such as current leakage and increased parasitic capacitance, that are hard to model and simulate and therefore hard to mitigate without adding considerable circuitry. Reducing the feature size also reduces the area in which electrons are stored: on a wafer 1000th the thickness of a sheet of paper or the diameter of the human hair. Add to this the need to ensure that the flash must be capable of enduring an ample number of write/erase cycles for the required end-user application, and must perform at adequate levels. Every new generation of raw material increases the complexity of all of these tasks.

4-Bit/Cell NAND Flash

Given the need to provide users with more and more memory and the now undisputed success of 2-bit/cell MLC NAND, the effort to store 4 bits/cell would seem to be **the** next logical step. The benefits are clear and huge, but so are the challenges. So much so, in fact, that the notion of workable, usable 4-bit/cell NAND flash was considered by many as a holy grail of NAND flash, which was thought to be impossible to utilize during this decade. But msystems' x4 NAND technology is expected to prove that it can be done.

The Benefits

Due to its increased density as compared with both its predecessors, SLC and 2-bit/cell MLC NAND, 4-bit/cell NAND flash technology results in major benefits:

- Significant increase in fab bits/wafer output, revenues and profitability – over 30% cost savings in comparison with 2-bit/cell MLC NAND flash production given the same density and manufacturing process, achieved with no changes to manufacturing processes.
- Significant cost savings achieved through storing twice the data in essentially the same silicon die compared with 2-bit/cell MLC NAND flash.
- Production of higher density flash dies to fulfill consumers' hunger for higher storage densities for new applications.
- Availability of a wider range of consumer electronics devices with higher memory densities at more affordable prices.

The Challenges

In general, it can be said that 4-bit/cell NAND flash technology is by a few orders of magnitude more complex to manage than its predecessor, 2-bit/cell MLC NAND flash. This is because each cell in the 4-bit/cell NAND flash media stores an electrical charge capable of creating 16 different voltage levels, as shown in Figure 3.

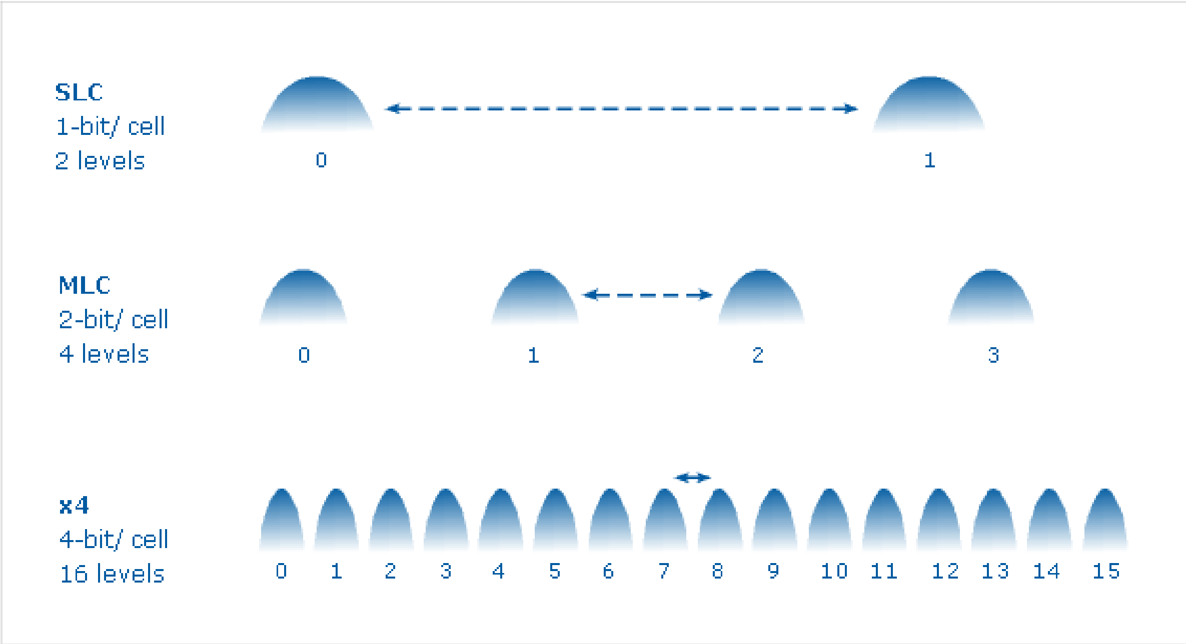


Figure 3: Voltage Levels in 1-Bit, 2-Bit and 4-Bit/Cell Technologies

With such a large number of levels in a single voltage window, adjacent levels are very close to one another, resulting in several challenges:

- Electrons stored in adjacent levels tend to shift easily from one level to another, causing bit errors. The number of errors when using 4-bit/cell NAND flash technology is several orders of magnitude higher than in 2-bit/cell and 1-bit/cell NAND flash technologies.
- Write and read performance are lowered, since many more delicate iterations are required to place and sense the charge correctly.
- Power consumption levels might be higher, due to the extended read and write efforts.
- Flash endurance and data retention are compromised, due to the additional stress mainly a result of the extended read and write efforts.

Naturally, without a system-solution approach to the challenges listed above, 4-bit/cell NAND flash in pure media form is impossible to use as anything but mechanical samples. It cannot be integrated into any device or otherwise used as a personal storage medium for any purpose. Thus, 4-bit/cell NAND flash production has been deemed futile, and deployment in consumer electronics devices has been, until today, considered a physical and practical impossibility.

MSYSTEMS' X4™ NAND COMPONENTS

Realizing the Benefits of 4-Bit/Cell NAND Flash

To enable 4-bit/cell NAND flash to be used at all in consumer electronics devices or elsewhere, these challenges must be met with a comprehensive, systems-solution approach.

Drawing on its vast patent portfolio and years of experience in meeting flash management challenges with TrueFFS® flash management technology, now a de-facto standard in the flash market, msystems has recently developed and patented x4 technology to enable production, utilization and integration of 4-bit/cell NAND flash in x4 NAND components. Each x4 NAND component consists of an x4 controller with specially customized TrueFFS, and 4-bit/cell NAND media.

msystems' x4 technology features:

- **Unparalleled error detection and correction code (EDC/ECC)**: New methodologies and algorithms not only detect errors and correct them in order to bring the flash within application-optimal reliability specifications, but do so while optimizing performance, and minimizing silicon redundancy and power consumption.
- **Extended flash lifespan**: In order to maximize flash lifespan, specially customized wear-leveling algorithms ensure that data is distributed evenly over the entire flash media.
- **Data encoding algorithms, silicon-level architectural changes, and unique flash media features**: A range of technological advances optimize reliability and performance.
- **Specifications tailored to requirements**: Distinct application portions are handled differently according to their specific performance and reliability requirements.

Eliminating Host Integration Efforts

As a direct result of the above features included with msystems' x4 technology, x4 NAND components are expected to require little to no integration efforts on the host platform. This should quicken market penetration of 4-bit/cell NAND flash. A large number of existing NAND flash designs can support msystems' x4 NAND components with no redesign efforts to enable consumer electronics device vendors to quickly achieve better and more competitive price points and thus, higher adoption rates. This, of course, also enables NAND flash vendors who opt for msystems' x4 NAND components to push more silicon dies out the fab doors more quickly and at higher profit margins.

Balancing Application Requirements and Bill of Materials Cost

When 2-bit/cell MLC NAND media was introduced some four years ago, its specifications were considered by industry experts as unusable. The staggering success of the Apple iPod nano, based in part on this very flash technology, proved that it is certainly good enough. But despite the degradation in media quality and specifications, even today's 2-bit/cell MLC NAND flash provides the most memory-hungry applications with higher specifications than they actually require. Such design overkill is an unnecessary expense.

As an analogy, consider the different qualities of gas available at gas pumps: regular, plus and premium. Although some high-end vehicles require plus or premium, the vast majority of vehicles operate efficiently on regular gas. With the introduction of x4 NAND components, it is conservatively estimated that over 50% of NAND-consuming consumer electronics devices will be able to match effectively with x4 NAND components. This rate will likely grow as the media matures to include an even wider range of devices.

Table 1 shows some examples of the margins between current 2-bit MLC flash specifications and application requirements. These margins indicate that the consumer electronics device market can be moved to x4 NAND without affecting typical usage scenarios.

In fact, with x4 NAND components, with its capability to analyze requirements and treat various types of data differently, the effect of the user experience can be virtually zero. For example, operating system code can be stored to guarantee its reliability, whereas multimedia files can be stored according to the required write performance for a particular operation.

Table 1: Memory-Hungry Application Requirements vs. 2-Bit/Cell MLC Flash Specifications

Application	Parameter	Application Requirements	Flash Specifications
DSC	Sustained write performance	DSC requires flash capability of burst write performance high enough to write a burst of shots quickly. High **sustained** write performance is not required.	Current MLC flash provides ~2-4 MB/sec sustained write performance. Only a small portion of the flash must run at this high write rate to meet DSC requirements (only burst capability is required).
	Endurance	With commercial DSCs, the mechanical shutter is designed to last for ~20,000 exposures. Assuming that each photo is 3MBytes, only 60GBytes of usable storage density is required.	Current MLC flash endurance is ~10,000 Write/Erase cycles. When a 2GB memory card is used, the usable density is ~10,000 times 2GB, or ~20,000 GBytes - much more than required.
MP3 player	Sustained read performance	MP3 players read the compressed data residing inside the flash memory at ~1MB/min rate	Current MLC flash provides more than 10MB/sec sustained read performance – far more than required.

SUMMARY

Due to its increased density as compared with both its predecessors, SLC and MLC 2-bit/cell NAND, 4-bit/cell NAND flash results in major benefits:

- Significant increase in fab bits/wafer output, revenues and profitability – over 30% cost savings in comparison with 2-bit/cell MLC NAND flash production given the same density and manufacturing process, achieved with no changes to manufacturing processes.
- Significant cost savings achieved through storing twice the data in essentially the same silicon die compared with 2-bit/cell MLC NAND flash.
- Production of higher density flash dies to fulfill consumers' hunger for higher storage densities.
- Availability of a wider range of consumer electronics devices with higher memory densities at more affordable prices.

But flash technologies such as 4-bit/cell NAND become ever more difficult to work with as flash designers reduce the amount of silicon used. The specifications of raw flash material plummet to unusable performance and reliability levels, while flash endurance and data retention are compromised. The major challenge, then, is to bring these levels up to standards acceptable within the consumer electronics space through a comprehensive, system-solution approach.

2-bit/cell MLC NAND flash has met this challenge and is currently being used by the mainstream consumer electronics market – despite the fact that it was initially viewed with skepticism as not good enough. In fact, based on typical usage scenarios, there is a margin to enable the further reduction of 2-bit/cell MLC NAND specifications, while continuing to meet application requirements.

This margin opens the way for 4-bit/cell NAND flash in the consumer electronics space, where cost has become a "make or break" consideration. In a fiercely competitive market, increasing the bill of materials with flash specifications that are better than applications require can cripple their success. But the considerable obstacles presented by this technology must first be mitigated in order to derive the associated cost benefits.

With unparalleled EDC and ECC, specially customized wear-leveling algorithms to extend the flash lifespan, data encoding algorithms, flash architecture changes, unique flash features and specifications tailored to meet actual application requirements, msystems' x4 technology is expected to make 4-bit/cell NAND flash usable in x4 NAND components, and welcomed by a majority of consumer electronics applications.

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