M-Systems
Flash Disk Pioneers

White Paper

Two Flash Technologies Compared: NOR vs NAND

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Introduction

Two main technologies dominate the non-volatile flash memory market today: NOR and NAND. NOR flash was first introduced by Intel in 1988, revolutionizing a market that was then dominated by EPROM and EEPROM devices. NAND flash architecture was introduced by Toshiba in 1989. Most hardware engineers are not familiar with the differences between these two technologies. In fact, they usually refer to NOR architecture as “flash”, unaware of NAND flash technology and its many benefits over NOR. This is mainly due to the fact that most flash devices are used to store and run code (usually small), for which NOR flash is the default choice.

The Major Differences

Table 1 highlights the major differences between NOR and NAND. It shows why NAND and NAND-based solutions are ideal for high capacity data storage, while NOR is best used for code storage and execution, usually in small capacities.

This table can also be used as a quick reference guide to compare NAND, NOR and DiskOnChip, since it addresses the main issues that need to be considered when choosing a flash-based storage solution.

Table 1: Major Differences between NOR and NAND

	DiskOnChip **(NAND-Based)**	**NOR**	**NAND**
Capacity	8MB-1024MB	1MB-16MB	8MB-128MB
XIP capabilities (code execution)	XIP boot block	Yes	None
Performance	Fast erase (3msec) Fast write Fast read	VERY SLOW erase (5 sec) Slow write Fast read	Fast erase (3msec) Fast write Fast read
Reliability	<u>Extremely high:</u> Built-in EDC/ECC solves bit-flipping. Bad block management supplied by TrueFFS.	<u>Standard:</u> Bit-flipping issues reported Less than 10% the life span of NAND.	<u>Low:</u> Requires at least one bit for error management (bit-flipping issue). Bad block management required.
Erase Cycles	100,000 – 1,000,000	10,000 – 100,000	100,000 – 1,000,000
Life Span	At least as high as NAND. Usually much better thanks to TrueFFS.	Less than 10% the life span of NAND.	Over 10 times more than NOR
Interface	SRAM-like	Full memory interface	I/O only, Requires toggling both CLE and ALE signals.
Access	Random on code area,	Random	Sequential

	DiskOnChip **(NAND-Based)**	**NOR**	**NAND**
method	sequential on data area.		
Ease of use (hardware)	Easy	Easy	Complicated
Full system integration (H/W & S/W)	Easy. TrueFFS Drivers available for: Windows CE VxWorks Linux SymbianOS (EPOC) Windows XP/NT/XPE/NTE QNX/Neutrino Many others	Hard. Drivers available for Windows CE only or through third party companies. Interrupts are disabled till suspend operation is performed.	Very hard. A simplistic SSFDC driver may be ported.
Ideal usage	Both Data and Code storage in any application that requires a file system. Examples: High-end Set Top Boxes High-end mobile handsets PDAs Embedded designs Thin clients	Code storage – limited capacity due to price in high capacity. May save limited data as well. Examples: Simple home appliances Embedded designs Low-end set top boxes Low-end mobile handsets Code storage of digital cameras	Data storage only – due to complicated flash management. Code will usually not be stored in raw NAND flash. Examples: PC Cards Compact Flash Secure Digital media MP3 players (Data only)
Price	Low	High	Low

*TrueFFS is M-Systems patented flash management and Disk emulation software. TrueFFS was chosen by most major OS vendors as the standard solution for flash management.

The Right Flash for Your Application

While NOR offers eXecute In Place (XIP) capabilities and high read performance, it is mostly cost effective in low capacities (1MB-4MB) and suffers from extremely low write and erase performance. On the other hand, NAND architecture offers extremely high cell densities and high capacity, combined with fast write and erase rates.

There are many other differences between these two technologies which will be further discussed below. However, those listed in the table are enough to strongly differentiate the types of applications using them: NOR is typically used for code storage and execution, mainly in capacities up to 4MBcommon in applications such as simple consumer appliances, low end cell phones, and embedded applications; raw NAND is used for data storage in applications such as MP3 players, digital cameras and memory cards. The code for raw NAND-based applications is stored in NOR devices.

Solving the complicated issue of NAND flash management and providing full disk emulation, DiskOnChip can be used for both code and data storage, and is usually used in applications that require an operating system and a file system such as: high-end Set Top Boxes (STBs), high-end cell phones, thin clients, connected devices such as webPADs, embedded applications and many more.

NAND Flash – Performance First

Flash devices are divided into erase units, also called blocks. (This division is necessary to reduce prices and overcome physical limitations). Writing information to a specific block, in any flash device, can only be performed if that block is empty/erased. In most cases, this means that an erase operation must precede a write operation. While in NAND devices an erase operation is straightforward, NOR technology requires all bytes in the block to be written with "zeros" before they can be erased. Since the size of erase blocks in NOR devices ranges from 64Kbyte to 128Kbytes (in NAND: 8Kbytes to 32Kbytes), such a write/erase operation can take up to 5 seconds(!)In stark contrast, NAND performs the identical operation in 4 msec maximum. The erase block size difference further increases the performance gap between NOR and NAND, as statistically more erase operations must be performed in NOR-based units per any given set of write operations (especially when updating small files).

At a glance:

NOR reads slightly faster than NAND

NAND writes MUCH faster than NOR

NAND erases much faster than NOR (4msec vs. 5 sec)

Most writes must be preceded by an erase operation

NAND has smaller erase units for fewer erases in less time

Interface Differences

NOR flash is basically a random access memory device. Is has enough address pins to map its entire media, allowing for easy access to each and every one of its bytes. NAND devices are interfaced serially via a rather complicated I/O interface, which may vary from one device to another or from vendor to vendor. The same eight pins convey control, address and data information. NAND is typically accessed in bursts of 512 bytes; i.e., 512 bytes can be read and written at a time (similar to hard drives). This makes NOR ideal for running code, while NAND is best used as a data storage device (hard drive/block device replacement).

At a glance:

NOR is memory mapped

NAND is I/O mapped

NOR is an XIP device

NAND is accessed in bursts of 512 bytes

Capacity/Cost per MB

Due to the efficient architecture of NAND flash (see Figure 1), its cell size is almost half the size of a NOR cell. This, in combination with a simpler production process, enable NAND architecture to offer higher densities, with more capacity on a given die size, as shown in Table 2. As a result, NOR capacities dominate the market range from 1MB to 4MB (although 16MB is also available), while NAND capacity range is from 8MB to 128MB. This again stresses the role of NOR devices as a code storage media, while NAND devices are ideal for data storage, and are found mostly in data-rich applications. NAND is also dominating the memory card market (CompactFlash, secure digital, PC Cards, MMC).

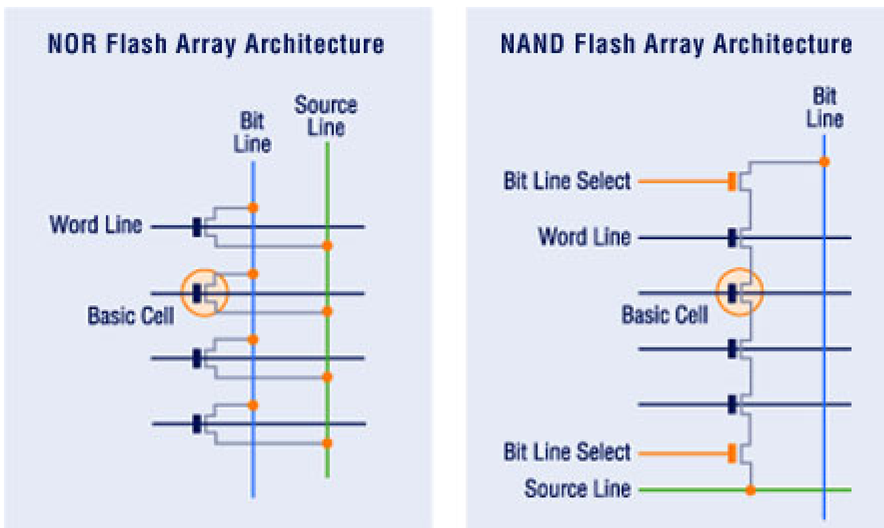
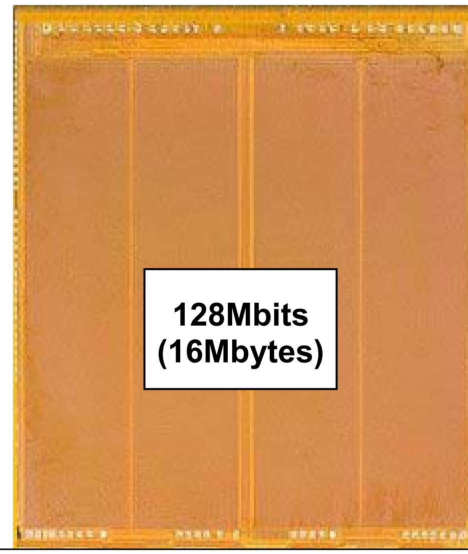


Figure 1: Comparison of NOR vs NAND Architectures

Table 2: Size and Density: DiskOnChip Millennium Plus vs NOR

	32MBytes (256Mbits) DiskOnChip Millennium Plus (NAND-based)	**16MBytes (126Mbits) NOR Flash**
Die photograph		
Density %	244% better than NOR	

<u>At a glance:</u>

NAND is available from 8MB to 128MB

NOR is available from 1MB to 16MB

32MB NAND is about half the size of 16MB NOR

NAND is better priced

NOR provides a good solution in low capacities 1MB to 4MB

Reliability and Life Span (Endurance)

One of the main considerations of working with a flash media is its reliability. Flash is the preferred storage solution for systems in need of a very long life span, and huge MTBF rates (Military applications, consumer appliances, mobile devices, communications and many more). When comparing the reliability of NOR to NAND, three main factors must be taken into account:

- Bit-flipping
- Bad block handling
- Life span (number of erase cycles allowed).

Bit-Flipping

All flash architectures today suffer from a phenomenon known as “bit-flipping”. On some occasions (usually rare, yet more common in NAND than in NOR), a bit is either reversed, or is reported reversed. One such reversal may seem insignificant; however, this “minor” glitch may hang your system completely if it corrupts a critical file. When the problem is just of reporting, repeating the read operation may solve it; however, if the bit was actually reversed, an error detection/correction algorithm must be applied (as offered in the DiskOnChip). Since this phenomena is more common in NAND devices than in NOR, all NAND vendors recommend using an EDC/ECC algorithm. When using NAND for multimedia information, this problem is not critical, but when using it as a local storage device to store the system OS, configuration files and other sensitive information, an EDC/ECC system MUST be implemented.

Bad Block Handling

Due to yield considerations, NAND devices (only) are shipped with bad blocks randomly scattered throughout them. Shipping NAND devices free of bad blocks comes with a very high price tag caused by the low production yield rate, and is therefore not a cost-effective option.

Working with NAND devices, especially for local storage, requires initially scanning the media for bad blocks, and then mapping them all out so they are never used. Failing to do so in a reliable manner may result in a high failure rate of the final device, and even a total recall.

Life Span/Endurance

As mentioned above, a flash block must be erased before writing to it. But the number of times that it can be erased is limited, as shown in Table 3.

Table 3: Erase Cycle Limits

	Min Erase Cycles Allowed (per erase block)	Max Erase Cycles Allowed (per erase block)
NAND	100,000	1,000,000
NOR	10,000	100,000

NAND devices offer up to 10 times the life span of NOR devices. In fact, since the block size of a NAND device is usually about 8 times smaller than that of a NOR device, each NOR block will be erased relatively more times over a given period of time (especially significant when working with small files) than each NAND block, which further extends the gap in favor of NAND.

At a glance:

NAND has more than 10 times the life span of NOR

All flash suffers from bit-flipping issues

NAND suffers more from bit-flipping and requires EDC/ECC

NAND usually has some bad blocks randomly scattered throughout

Ease of Use

Using a NOR-based flash is a straightforward process. Just connect it as you would connect other memory devices, and run your code directly from it (if you don't mind the slow performance). Using NAND, on the other hand, is a tricky issue. NAND has an I/O interface and requires toggling two signals (OLE and CLE). Accessing one NAND from vendor A is not necessarily the same as accessing another NAND from vendor B. A driver MUST be written and used for performing any operation on a NAND device. Writing information to NAND is also tricky since you have to make sure you are not writing the information to a bad block. This means that virtual mapping MUST be implemented on NAND device at all times.

At a glance:

NOR has a standard memory interface

NAND is an I/O device and requires a relatively complicated driver for any operation

Using NAND requires bad block handling

Using NAND requires implementing Error Detection/Correction Code (EDC/ECC)

Software Support

A distinction must be made between two levels of software support: basic read/write/erase operations, and high level software for disk emulation and flash management algorithms (including wear leveling, performance optimizations, etc.).

Running code from NOR devices requires no special software support. Running code from NAND requires a driver – usually referred to as an MTD (memory technology driver). Both NAND and NOR require MTDs for write and erase operations. While MTDs are basically all that is required for NOR write/erase, a NAND driver must also have bit error and bad block management code.

Higher level software is available for NOR devices from many vendors, yet the standard is M-Systems' NOR version of its TrueFFS drivers, used by Wind River, Microsoft, QNX, Symbian, and even licensed by Intel. Other software packages are available by other third party software houses. NAND devices, on the other hand, lack noticeable software support. However, its high capacity, low cost and fast performance make NAND an ideal candidate for data storage, in general, and hard drive emulation (block management), specifically. Based on NAND technology, M-Systems DiskOnChip is supported by TrueFFS for both disk emulation and for NAND flash management, including bit error correction, bad block handling, and wear leveling, thus conveying all of NAND advantages without any of the disadvantages of difficult system integration. TrueFFS is provided both as source code and in binary format for all major operating systems such as VxWorks, Windows CE, Linux, QNX/Neutrino, Windows XP/XPE, Windows NT/NTE, DOS and many more.

At a glance:

Reading from NOR requires no driver

Raw NAND has limited software support

TrueFFS is the flash management software chosen by all major vendors

TrueFFS supports NAND-based DiskOnChip, providing disk emulation and NAND flash management.

Conclusion

Use of NOR devices is widespread in the industry. They offer an easy memory interface and are suitable for code execution, making them ideal for devices that do not need data storage. Their architecture makes them a good alternative in the range of 1MB to 4MB. NOR offers good read performance but poor write and erase times, disqualifying it from being used as a data storage device. However, as today's devices become more and more sophisticated, they are expected to offer more features, richer programs and store more information locally. This requires larger capacities, both for code and data storage, and considerably faster erase/write times. NAND offers all of this, plus better prices in capacities ranging from 8MB to128MB. However, most engineers are reluctant to use it due to its non-standard interface and complicated management.

Based on NAND architecture and combined with TrueFFS software, DiskOnChip offers all of NAND advantages without the hassle that goes with it. DiskOnChip includes a built-in EDC/ECC mechanism (based on the Reed-Solomon algorithm), and a standard, memory-mapped SRAM interface. M-Systems' TrueFFS software handles all of NAND's negative qualities, such as bad block handling, wear leveling, error correction, block device emulation and more. In addition, DiskOnChip offers an XIP boot block enabling it to function both as a boot device replacement (traditionally an EEPROM or a small NOR flash device), and as your system's local storage device. This block can also be used to replace small serial EEPROMs or ROM.

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