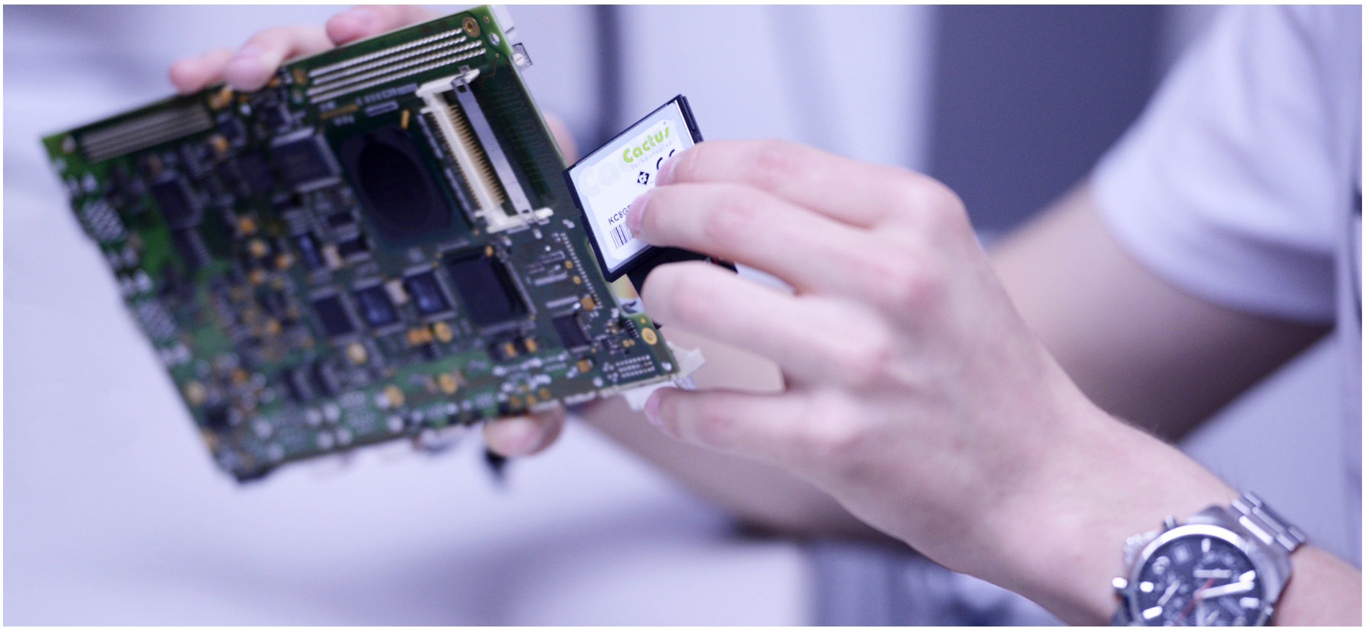
syslogic



Syslogic White Paper

Evaluation of flash-based storage media for industrial and OEM applications

1 Introduction

More and more devices are being interconnected in the industry. The Industrial Internet of Things (IIoT) is becoming reality. According to recent studies, the IIoT market will double over the course of the next five years. This will increase the demand for all components necessary to realize the IIoT – including storage media. Especially compact, NAND-based units are gaining popularity.

NAND flash-based storage media, commonly referred to as flash drives, have considerable advantages over hard disk drives. They are more compact and less sensitive to shock and vibration. Unlike hard disk drives, they can have a positive impact on system speed. NAND flash-based storage media with a fixed BOM (Bill of Material) offer industrial enterprises a high degree of security in terms of system compatibility.

But NAND-based units also have a considerable drawback: they age and only achieve a limited amount of write/erase cycles. What does this mean for the industry? Are flash drives suitable for industrial application? What about their reliability and service life? How do I choose the right product from all available flash drives?

This white paper discusses the most important aspects of NAND flash-based storage media. It constitutes a guide for evaluating storage devices.

1.1 Which factors play a role in evaluating storage media?

Every application has specific requirements regarding the storage capacity, temperature range and vibration resistance of suitable storage media. Other factors necessitate a precise analysis in consideration of the total cost of ownership of a product. This is particularly apparent when comparing the service life of a production machine with that of IT equipment. In the industry, it pays off to invest in storage devices that have a long service life and long-term availability. Unanticipated field failure and the qualification of new storage media, which becomes necessary if the originally used devices are no longer available, can be costly.

There are other aspects to be taken into consideration when evaluating industrial flash drives. This white paper explains what happens when NAND cells age and elaborates on the measurements used by manufacturers of flash drives for specifying the service life of the storage medium (endurance) or the life span of stored data (data retention). To evaluate a storage medium appropriately, an understanding of the internal mechanisms of a NAND flash drive is required.

1.2 Requirements to be specified

A wide range of flash drive technologies are on the market today. They include TLC (Triple-Level Cell), MLC (Multi-Level Cell), SLC (Single-Level Cell), pSLC (Pseudo-Single Level Cell) and 3D NAND. Finding the right technology for a specific application relies on the following factors:

- Assumed read/write speed
- Required endurance (service life of storage media)
- Required retention (life span of stored data)
- Data security in case of a power cut
- Temperature and vibration resistance
- Long-term availability of the selected product

2. How NAND-based storage media work

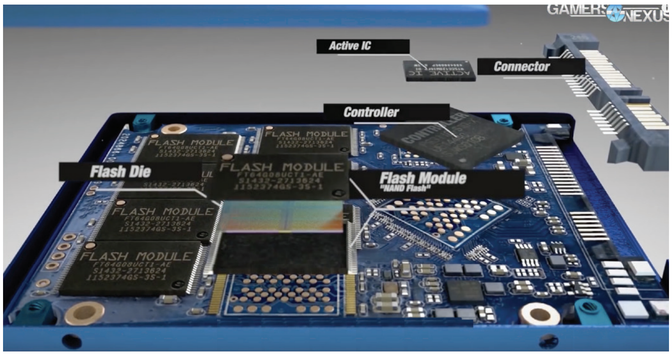
2.1 Introduction

NAND stands for NOT-AND, which refers to the logic of the NAND gate. NAND-based storage media are not volatile: data stored on them remain in place even when the storage medium is not connected to a power supply.

2.2 The structure of NAND-based storage media

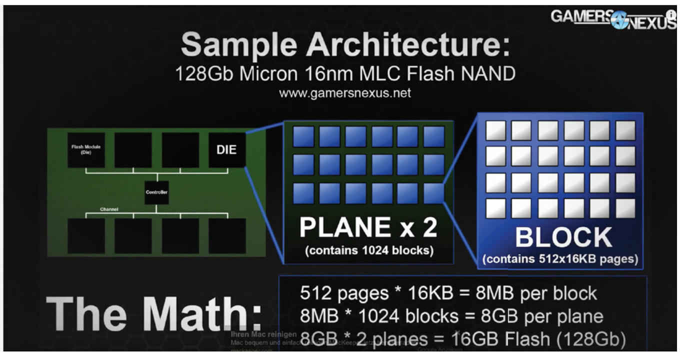
Regardless of their format (e.g. 2.5", Compact Flash, SD Card, micro SD Card or M.2), NAND-based storage media consist of the following components:

- Flash module – the actual storage module
- Flash controller – the brain of the storage medium
- Active IC circuits
- Interface – to control the storage medium



2.3 The structure of flash modules

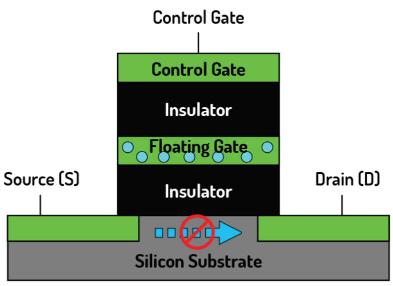
The flash module is structured as follows: the NAND cell is the smallest component of every storage medium. These cells form pages, the pages form blocks, the blocks form planes, and the planes form dies. A die is the actual storage module as listed in point 2.2. It is controlled by the flash controller.



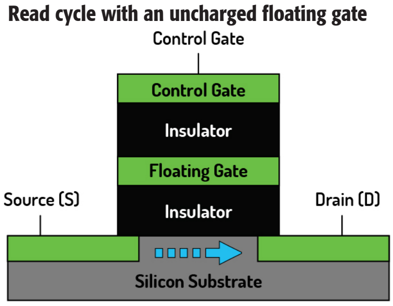
2.4 The function of 2D NAND cells

Flash drives store information in NAND cells. A NAND cell uses a transistor channel (source-drain) and two gates, one control gate and one floating gate. The floating gate is insulated by an oxide layer separating it from the control gate and transistor channel. When the programming voltage pushes electrons through the oxide layer into the floating gate (tunnel effect), they permanently remain there, even when the voltage disappears. The oxide layer effectively traps the electrons.

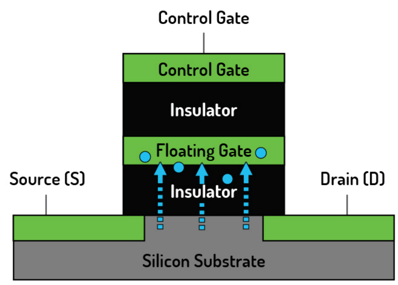
Read cycle with a charged floating gate



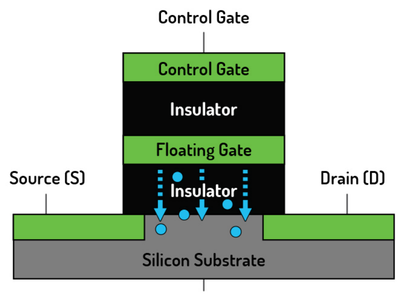
Read cycle with an uncharged floating gate



Writing on a NAND



Erasing a NAND



To read a value from the storage cell, a reading voltage is applied to the transistor. The electricity flowing between the source and drain is measured. If the floating gate is charged, i.e. there are many electrons inside the floating gate, a logical "0" is read. This is because no electricity is flowing between the source and drain (see diagram above).

To release the electrons, an erasing voltage is applied to the transistor. If only few electrons are inside the floating gate, a logical "1" is read because electricity is flowing between the source and the drain (see diagram below).

To write on the storage, a high voltage is applied to the control gate. This pushes electrons from the oxide layer into the floating gate (see diagram above). This is called the tunnel effect: the electrons cross the oxide layer to reach the floating gate.

To erase the storage cell, a high voltage is applied to the oxide layer. This pushes the electrons from the floating gate into the oxide layer. Just as in the write process, the tunnel effect comes into play.

2.5 Measuring the service life of storage media

Manufacturers use two ratings to specify the endurance (service life) of flash drives.

TBW (Terabytes Written)

Specifies the total volume of data (in TB) that can be written during the service life of an SSD storage unit before the average unit breaks down for wear.

DWPD (Drive Writes Per Day)

Specifies the volume of data that can be written to the storage medium every day during the warranty period and within specified conditions.

TBW tells the user how much data can be written throughout the total service life of the device. DWPD tells the user the maximum volume of data that can be written per day within the warranty period. This system has a drawback: the user is dependent on the manufacturer's information. This makes it difficult to compare devices. It is not always clear whether the specified values are relevant to the intended application. The values strongly depend on the load applied during the test. The JEDEC (Joint Electron Device Engineering Council) provides guidelines for the various load types. But many manufacturers do not specify which guidelines they are using to test their flash drives. As a result, the specifications of different manufacturers are often difficult to compare.

3. The different NAND flash technologies

3.1 Differences between SLC, MLC, TLC and 3D-NAND

The development from SLC to MLC and TLC storage media – and, ultimately, 3D units – is strongly driven by the consumer market. There is a demand for greater storage capacity on smaller and smaller units, which effectively decreases the price per megabyte of storage capacity. Due to this increase in storage density, NAND flash technology is becoming more competitive on the HDD-dominated market. Unfortunately, high storage density has a negative impact on the endurance and reliability of NAND-based storage media. A distinction is made between the following technologies:

SLC-NAND (Single-Level Cell) stores one bit per NAND cell. Depending on the flow or absence of electricity between source and drain (see 2.3), a logical "0" or "1" is read.

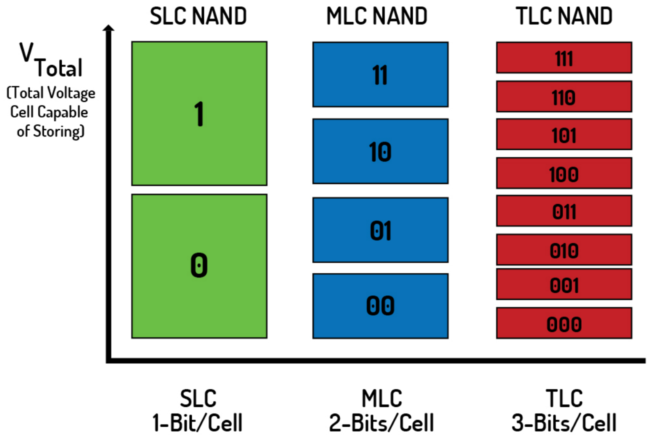
MLC-NAND (Multi-Level Cell) and eMLC (Enterprise) store two bits per NAND cell, yielding four different charge states per NAND. The term eMLC (Enterprise) is relevant in this context. The main difference of eMLC storage media is their programming. Using the controller, their manufacturers increase the number of write/erase cycles the devices can achieve. Experts disagree on the effectiveness of this process and whether eMLC is really any different from MLC.

TLC-NAND (Triple-Level Cell) store three bits per NAND cell, yielding eight different charge states per NAND.

In 3D-NAND devices, planar NAND cells (just as those in SLC, MLC and TLC) are stacked vertically for even greater storage density. Modern 3D-NAND storage media are based on MLC or TLC-NAND. They are also referred to as V-NAND or 3D-V-NAND (vertical). Shorter connections between the storage cells (stacked architecture) can increase storage capacity and speed while reducing power consumption.

The consumer market primarily uses TLC media. They can store three bit per NAND and are produced at high volumes, resulting in a high amount of storage capacity at a low cost. But TLC storage devices have a limited data retention rate. They must distinguish between eight different charge states to read three bits – even the first signs of wear make this impossible. SLC achieve the most read/write cycles per NAND, as they only need to distinguish between two charge states. They have the best data retention rates.

3D-NAND are becoming increasingly popular in the consumer segment. They are not yet relevant for industrial application.

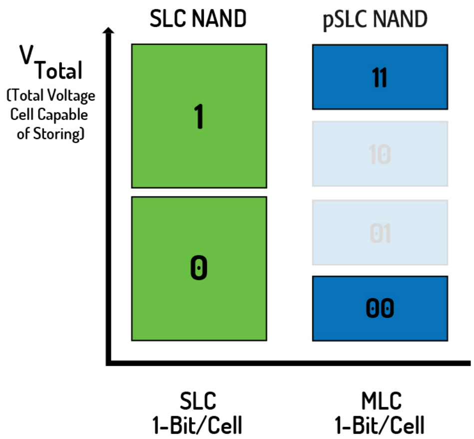


SLC, MLC or TLC-NAND – one, two or three bits per NAND.

3.2 Pseudo Single-Level Cell – the best of MLC

The fewer charge states a storage medium has, the more stable its stored information. This principle makes pSLC storage media (Pseudo Single-Level Cell) an interesting compromise both technically and economically. The pSLC technology uses the low-cost MLC-NAND units with only two different charge states. They are considerably faster than regular MLC-NAND devices and achieve a higher number of possible P/E (program/erase) cycles – 20,000 rather than 3,000. The endurance of these storage media is six times higher than that of MLC drives while the price per stored bit only doubles.

This high amount of P/E cycles is possible thanks to the easier identification of charge states: the device only has to distinguish between two states (unlike the four of MLC), and the difference between the charge states is considerably larger than it is in MLC. To increase the differences in voltage between the charge states, the manufacturer needs to adapt the firmware. The pSLC technology also requires special MLC-NAND.



pSLC uses MLC-NAND but only stores one bit per cell.

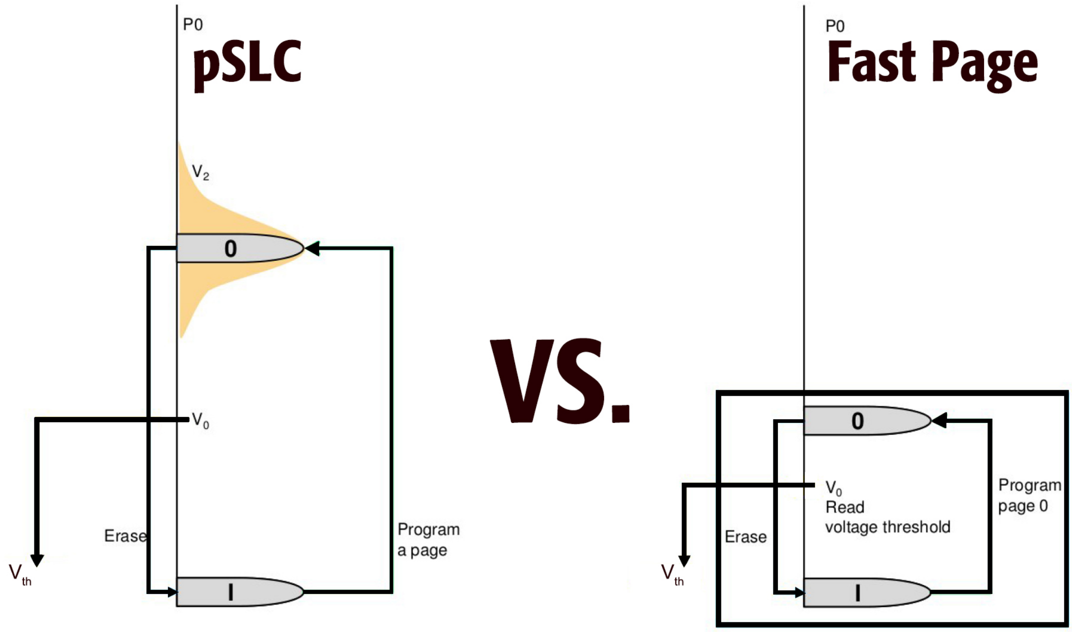
3.3 Fast Page Mode is not the same as pSLC

Besides Pseudo-SLC, there is also the Fast Page Mode (also referred to as MLC+ or Turbo Mode). The two technologies are not identical, although the Fast Page Mode also writes only one bit to a MLC-NAND.

As suggested by the name, the main advantage of the Fast Page Mode is its speed. It increases the read and write speed at the expense of storage capacity. Any MLC-NAND storage medium can be operated in Fast Page Mode without modifying the firmware. The disadvantage: the endurance of the individual flash cell (NAND) is only minimally better than that of regularly used MLC storage media. While the Fast Page Mode only stores two charge states, the difference in voltage between them is as small as that between four charge states. The previously outlined drawbacks of MLC-NAND also apply: they are prone to error as the charge state is hard to identify and they have limited write/read cycles, which reduces their endurance.

Each manufacturer names their products differently, so it can be hard to distinguish between the individual technologies. It is important to exercise diligence when evaluating different storage media. Terms such as iSLC, turbo mode, MLC+, eMLC and SuperMLC are frequently thrown around on the market. Many of them are simply MLC units operated in Fast Page Mode.

Only a small number of specialized companies, including Cactus Technologies, actually use the pSLC technology (greater voltage differences and higher endurance).



pSLC distinguishes between considerably larger voltage differences than the Fast Page Mode.

4. Wear in NAND storage media

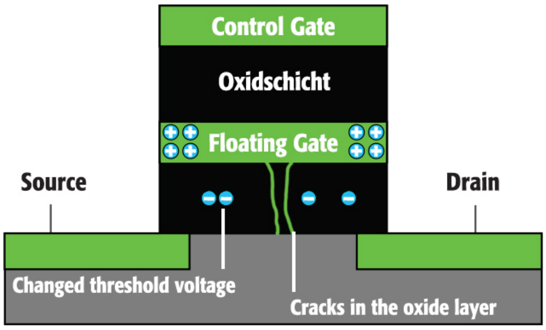
4.1 Changes in the threshold voltage

There are two main manifestations of wear. The first is a changed threshold voltage. Whenever the programming voltage is applied to generate the tunnel effect, a strong electric field accelerates electrons towards the oxide layer. Some of these electrons remain trapped in the oxide layer instead of passing through it. This can change the threshold voltage over time and, ultimately, make the cell unreadable.

4.2 Cracks in the oxide layer

The second manifestation of wear are cracks developing in the oxide layer over time. Electric charge runs off through these cracks, and the NAND cell slowly loses the stored bit. High temperatures accelerate this effect. Especially towards the end of the service life of a NAND cell, its data retention capacity decreases enormously. Both Single-Level Cell NAND (SLC) and Multi-Level Cell NAND (MLC) have a retention rate of 10 years. Towards the end of the product life cycle, this drops to a single year. MLC units reach this point after 3000 P/E cycles, SLC units after 100,000.

Extreme temperatures have an additional negative impact on retention rates. Again, MLC NAND are considerably more sensitive to this than SLC NAND. While there are MLC-NAND storage media for the extended temperature range, they are only screened. The SLC technology, on the other hand, is available in flash drives with storage modules that are specifically designed for the extended temperature range.



Changes in threshold voltage and cracks in the oxide layer wear out storage cells, which has a negative impact on their endurance and retention.

4.3 Influence of disturb and read disturb on data durability

The conclusion that data retention is highest when erasing and rewriting are kept to a minimum is not entirely accurate. While this does slow down the effects of wear, even storage media that are primarily used in read mode will eventually wear out.

Each write process puts the cells around the active cell under stress: they have a slightly higher voltage (program disturb). Read processes have the same effect (read disturb). In this case, the adjacent pages accumulate charge. Over time, the stored potential in these cells increases. This causes read errors that disappear after the affected block is deleted.

On account of the lower voltage involved, read processes have a weaker effect than write cycles. But they also cause bit errors that must be corrected by the error correcting code (ECC) and solved by deletion of the affected block (see 5.1). Keep in mind: this effect is particularly pronounced with applications that read the same data again and again. Even if a storage medium is only read, it is necessary to erase blocks and write pages on a regular basis to correct errors.

4.4 Influence on NAND shrinks on wear

The larger the area of a chip, the more space there is for the NAND flash cells. This allows for a thick oxide layer, which guarantees unambiguous charge states (either conductive or non-conductive). As mentioned in 4.1 and 4.2, all NAND cells wear down, and the oxide layer disintegrates. This process affects thicker oxide layers more slowly. Accordingly, large NAND shrinks have higher endurance than small ones.

The production of NAND flash cells is a very complex process. Only a small number of companies worldwide (Samsung, Toshiba, Sandisk, Micron, Intel, SK Hynix) produce NAND flash cells. Depending on the manufacturer, they are available with different shrinks.

Due to increasing cost pressure, the storage density of flash drives is increasing steadily. At the same time, the size of the NAND cells – and, in turn, their quality – is decreasing. The largest currently available Toshiba A-grade NAND cells measure only 43 nm. They are the most durable NAND cells on the market – and the most expensive. Besides these 43nm SLC NAND, the various manufacturers offer SLC-NAND in sizes of 32, 24, 21 and 14nm. There is a vast difference in endurance between the largest 43nm NAND and the smallest 14nm NAND. The 14nm NAND are even smaller than the 15nm NAND currently used for MLC (Multi-Level Cell) storage media in the consumer segment.

5 Preparing NAND flash storage for industrial application

Manufacturers of flash drives use sophisticated controllers and firmware to improve the reliability and endurance of their products. Clever controller functions can alleviate technological disadvantages, such as limited P/E cycles and fading data, considerably. This makes NAND-based storage media suitable for many industrial applications. The following section explains the most important functions.

5.1 Error Correction Code

Corrects bit errors and then copies and erases the block affected by the error.

5.2 Garbage Collection

The garbage collection generates empty blocks. To do this, it checks blocks on the flash drive that have not been completely emptied yet. If necessary, it frees them up by redistributing the data, so the blocks can be erased and rewritten. This process is important for the performance of the flash drive. Deleting files in the file system only declares them invalid but does not physically delete them. The actual data remain in the storage cell. The garbage collection, then, does what its name suggests: it tidies up. This process is usually kept in the background to minimize its impact on the storage speed of the drive.

5.3 Wear Leveling

Wear leveling ensures that flash cells are worn down evenly. It achieves this by distributing write accesses evenly across the flash cells. Even single worn-out flash cells can cause data errors. This makes wear leveling very important for the endurance of a flash drive. Manufacturers of industrial flash drives integrate a combination of static and dynamic wear leveling into their flash controllers. This has two effects: firstly, write accesses are distributed across the least-worn cells. Secondly, static data that are never or rarely modified are occasionally moved. This ensures that all flash cells participate in the wear leveling process, which considerably improves retention rates.

5.4 Write Abort Handling

Write abort is a disruption of the power supply during a write process, e.g. due to a power cut. If there is no battery or supercapacitor to bridge the gap, the data being written will be lost. Such incidents must not damage the firmware and metadata of the flash drive. Industrial flash drives are normally equipped with a safety switch that protects the firmware and metadata in case of a power disruption.

6 Summary

Anyone attempting to evaluate flash drives for industrial application should be aware of the parameters influencing endurance and retention (see point 1.2). Syslogic only sells flash drives produced by established industry experts. Storage units by Cactus Technologies are particularly popular for demanding applications. Their Taiwanese manufactured storage media products are built for industrial and OEM system use. Its product portfolio includes SLC, pSLC and MLC units (Single-Level Cell, Pseudo Single-Level Cell and Multi-Level Cell).

High-quality A-grade NAND and clever firmware

Not only does the product portfolio of Cactus Technologies offer the different flash technologies mentioned above, it also has a range of different formats, such as Compact Flash, CFast, SD and microSD Card, 2.5“ disk and M.2. The company offers the right storage solution for nearly any industrial application.

All Cactus devices are equipped with high-quality A-grade NAND and sophisticated, well-established flash controllers and firmware. The storage media by Cactus Technologies are some of the most durable flash drives on the market. They are used worldwide by renowned companies in industries such as automation, railway, automotive and healthcare. Cactus is one of few companies offering storage devices that have been qualified for the extended temperature range of -45 to +90 °C. The company also takes care of the various industry-specific certifications for its customers, such as ISO/TS16949 for automotive and EN50155 for railway applications.

Long-term availability

Besides their sturdiness and endurance, Cactus products have another decisive advantage: they remain available unchanged for a long time. The company guarantees availability over multiple years. This is possible by virtue of its careful selection of components. Cactus further operates its own warehouse, allowing it to access components even beyond the production period. The best example for the long availability of Cactus storage products is the 203 series, which has been on the market with only minimal changes since 2005.

All Cactus storage media further have a fixed BOM (bill of material). This ensures that all items within a product series are completely identical, using the same firmware and the same flash modules. The system successfully prevents compatibility issues within product series.

If any modifications become necessary, Cactus will change the item number and notify its customers early on via a product change notification (PCN). This gives them an opportunity to test the changed SSD units before installing them in their devices.

Careful evaluation prevents trouble, expenses and damage to your company's reputation
Flash-based storage media have become an established component of the industry. Studies have predicted that developments such as the IIoT (Industrial Internet of Things) and Industry 4.0 will increase the share of flash drives further.

The key figures laid out in this white paper constitute a solid basis for your storage evaluation process. They can save you a lot of trouble and follow-up expenses. Considering the large amount of providers on the market, it pays off to choose a company with significant experience in industrial environments.

The concrete choice of technology strongly depends on your specific application. The following overview summarizes the most important differences.

Product Grade Selector

Product Grade	Industrial	OEM	Commercial
NAND Types	SLC Single Level Cell	pSLC Pseudo SLC	MLC Multi Level Cell
Bit/Cell	1	1	2
Endurance Cycles	100K / 80K / 50K	20K	3K
Reliability	●●●●●	●◖	●
Data Retention	●●●●●	●◖	●
Life Cycle	●●●●●	●●	●●
Locked-BOM	✔	✔	✔
Cost	$$$$	$$$	$$