NAND Flash 101

EBOOK

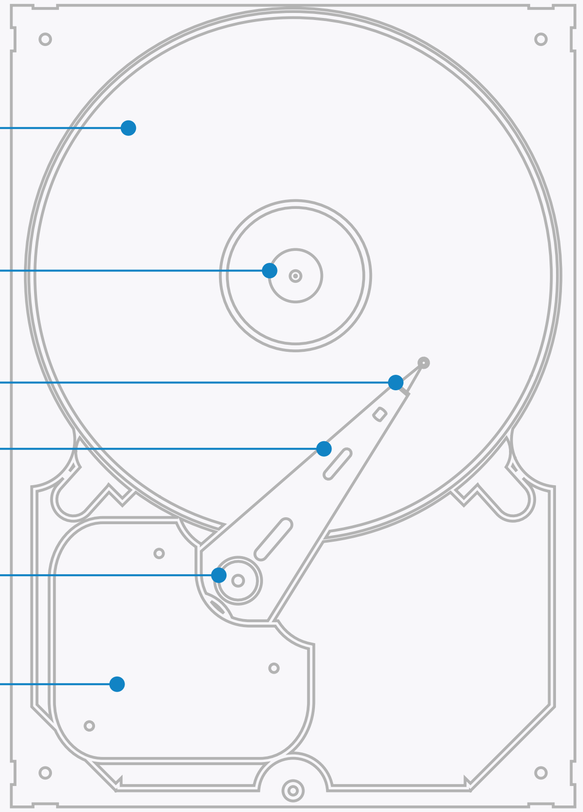
Overview

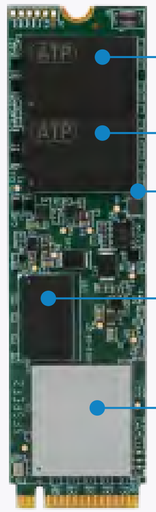
Introduction: What is NAND Flash Memory?

NAND flash memory is a type of non-volatile solid-state storage that persistently stores and retrieves data. It is non-volatile memory since it retains data when power is not applied.

Unlike hard disk drives, storage devices with flash memory have no mechanical moving parts — they don't have spinning platters or read/write heads. Instead, they store data in stationary NAND flash chips.

HDD vs SSD





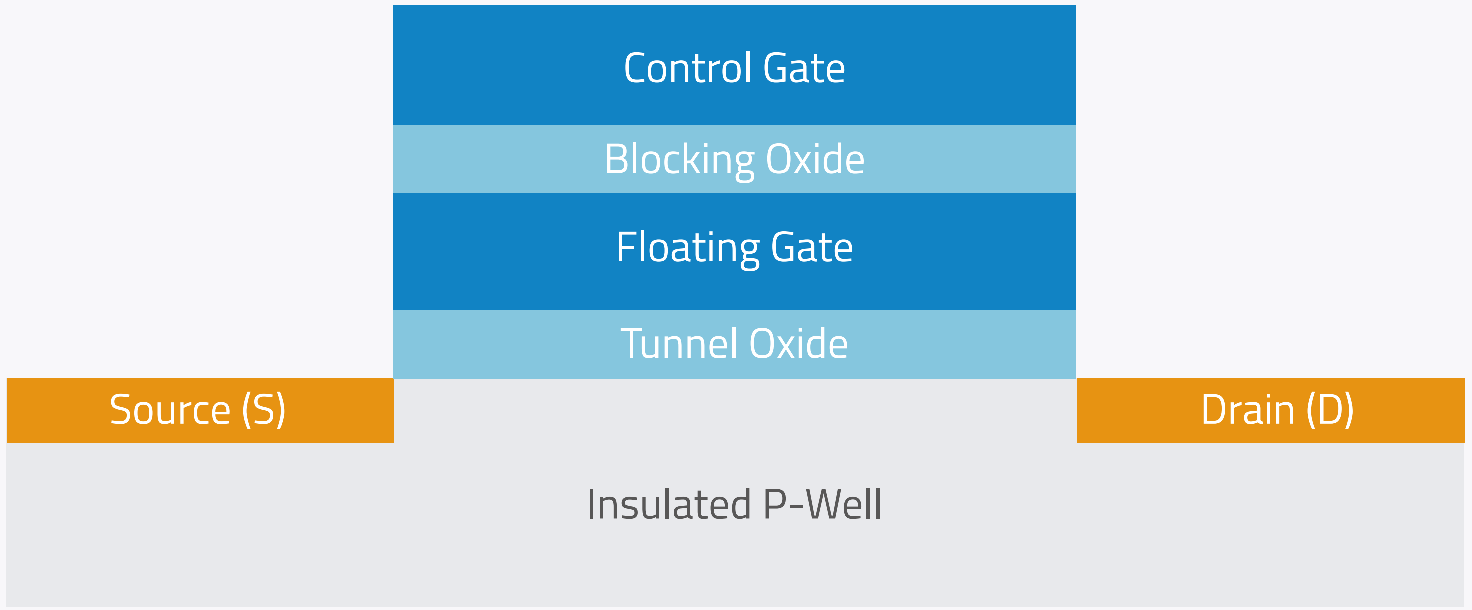
NAND Flash Cell Structure

The basic building block of flash memory is the NAND flash cell. The following diagram shows the main elements of a single NAND flash cell. Each cell contains a floating gate transistor, where the data are stored, through program/erase operations.

Oxide layers insulate the Floating Gate (storage layer), preventing the electrons to leak out of it.

Any electron stored in the FG is trapped, which means the cell is programmed (charged) and has a binary value of 0.

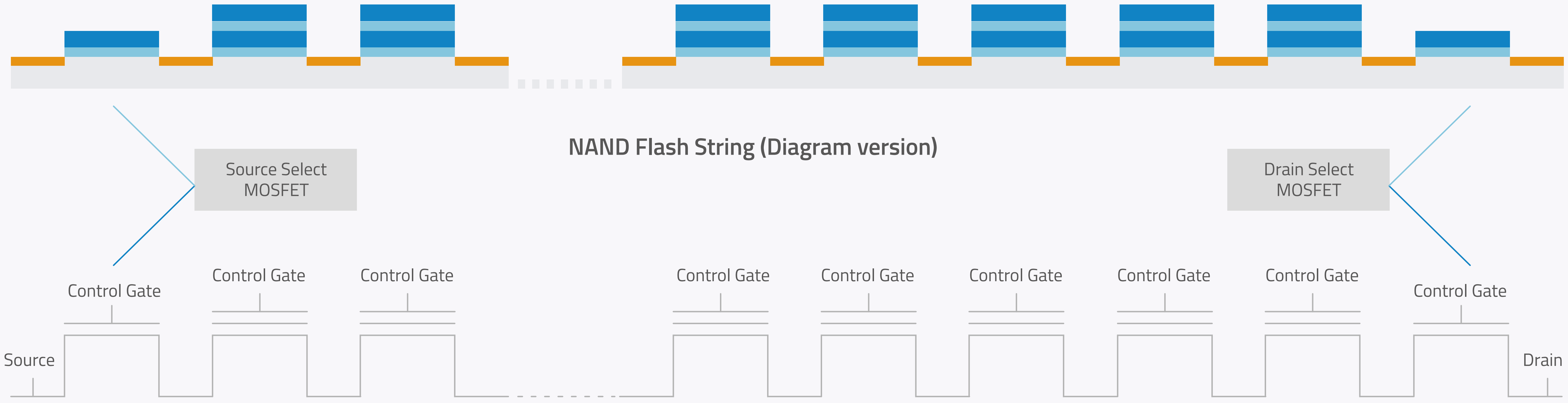
When the FG holds no charge, it has a binary value of 1.



NAND Flash Cell Structure

NAND Flash String

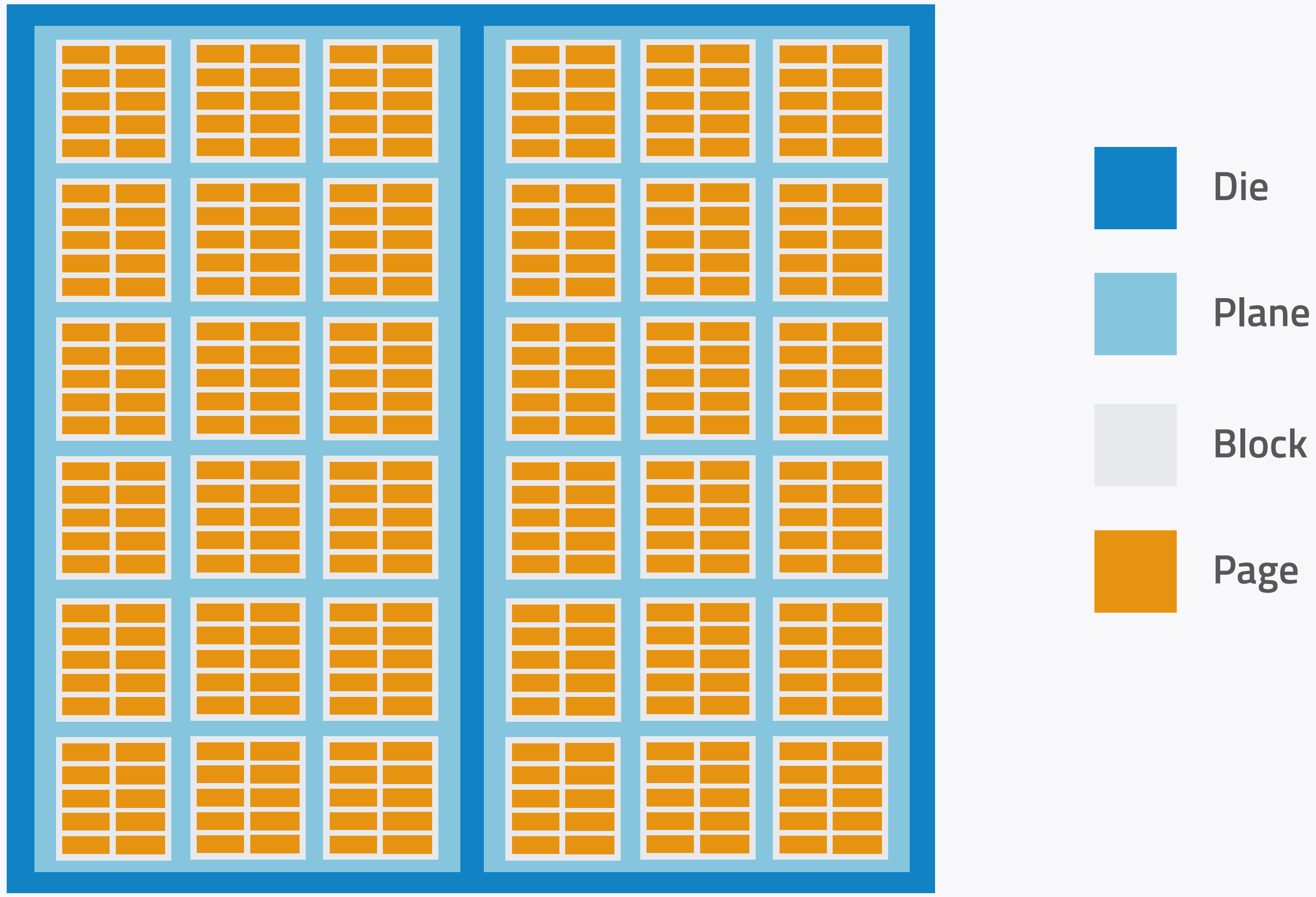
Several (32 to 128) NAND flash cells connected in series form a String, which is a quite compact structure. Several strings vertically arranged form a block.



NAND Flash String (Schematic version)

NAND Flash Layout

A physical NAND **Page** is the group of NAND flash cells belonging to the same block, which share, horizontally, the same Control Gate (called Word Line). A NAND **Block** is composed of several pages. Several NAND blocks form a **Plane**. Finally, planes form a **Die**. Each memory chip contains one or more dies.



Basic Operations

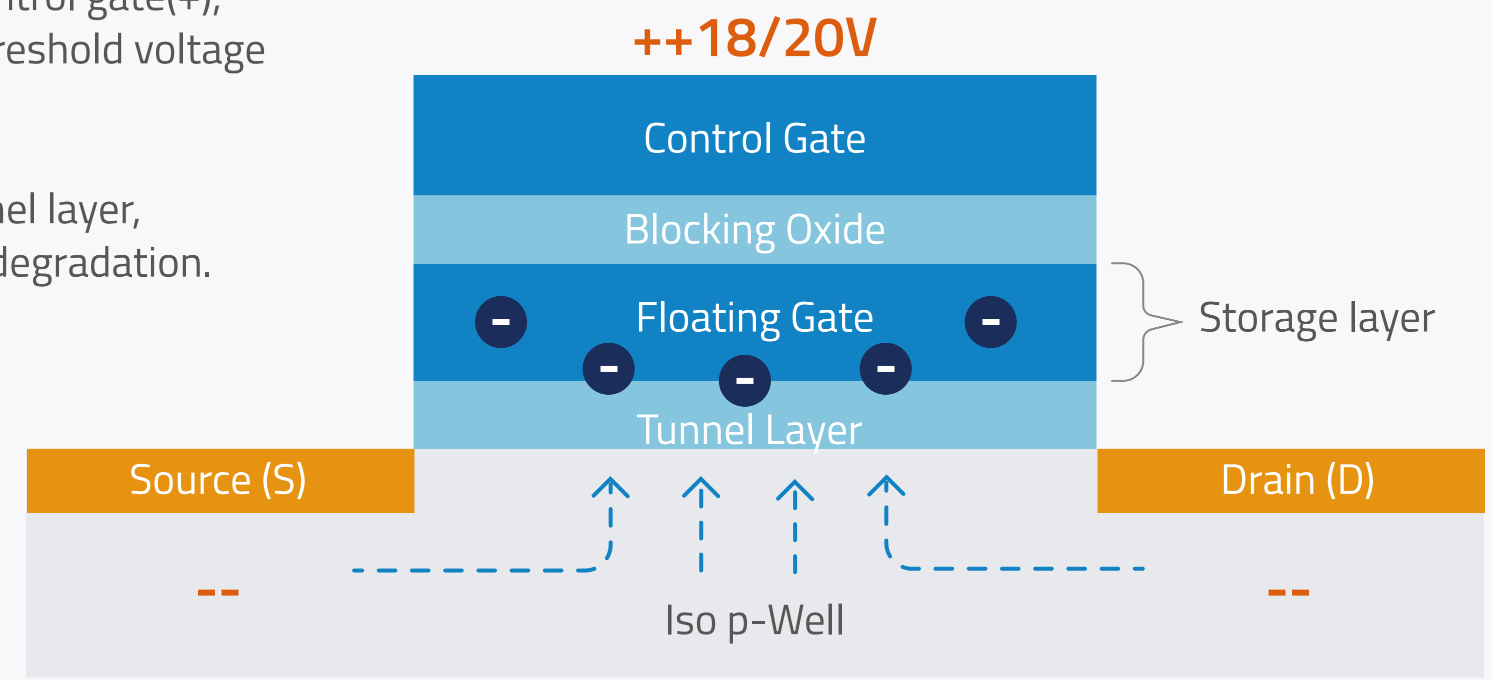
Program (Write) Operation

A page is the smallest unit that can be programmed or written to, which is typically 8 to 16 KB in size. To write data, several positive high voltage (15V / 22V) pulses are applied to the control gate. After every pulse, a read-verify is performed. The program sequence will be completed once the verify will pass on all cells in the selected page. During each pulse, electrons move from the iso-p-well to the floating gate.

- Electrons are injected into the floating gate mainly through Fowler-Nordheim (FN) tunneling effect.

- FN tunneling requires a high electric field between the Source (-) and the control gate(+), which enable electrons to flow into the floating gate, thus increasing the threshold voltage of the NAND cell (V_t).

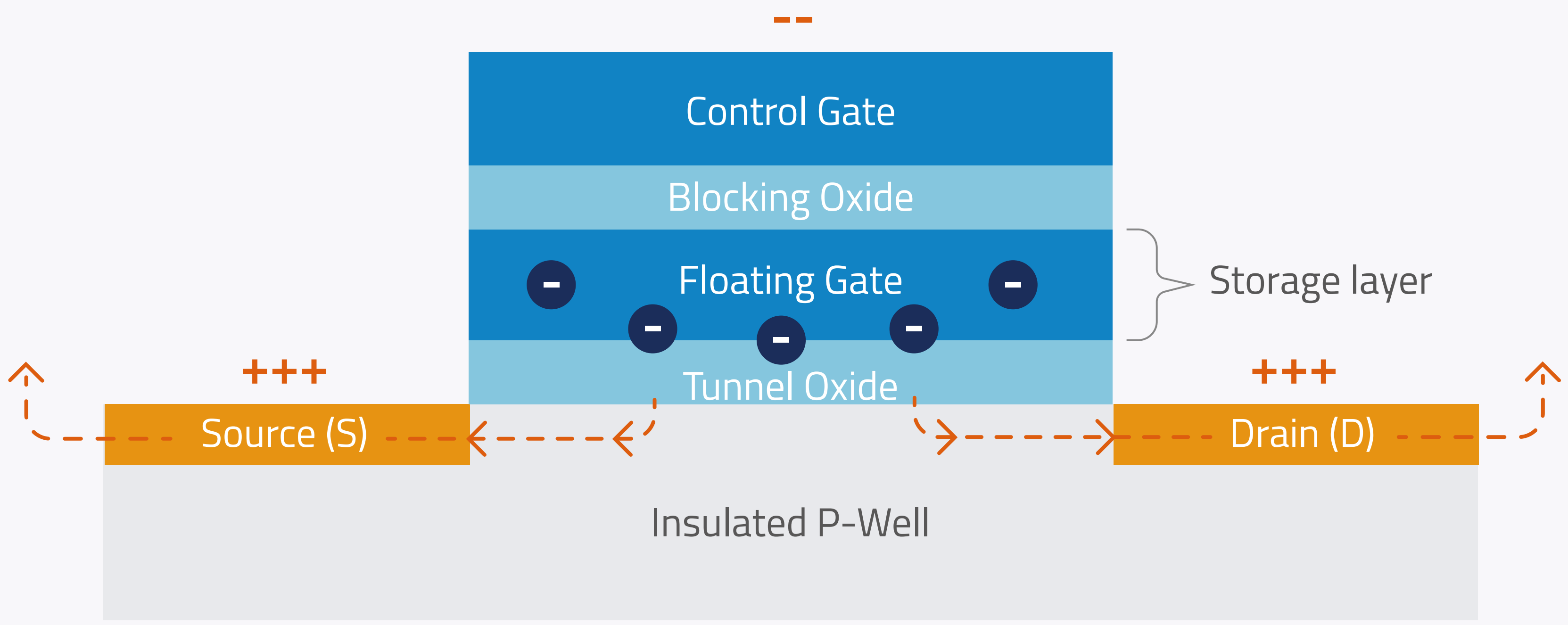
- The flow of high energy (Hot) carriers (electrons and holes) through the tunnel layer, during Program Operation, leads to oxide lattice damages and tunnel layer degradation.

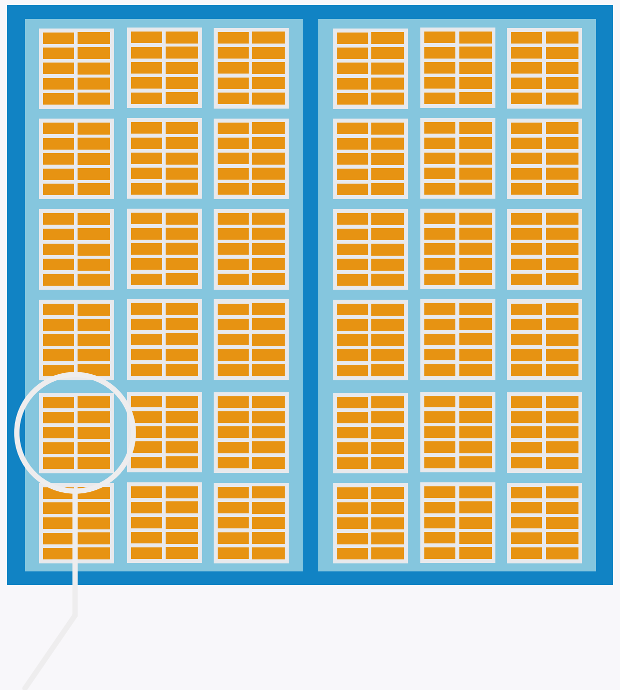


Basic Operations

Erase Operation

A block is the smallest NAND die portion that can be erased. To erase data, several negative high voltage (-15V / -22V) pulses are applied to the control gate. After every pulse, a read-verify is performed. The erase sequence will be completed once the verify will pass on all cells in the block.





- An erase operation clears the data from all pages in the block.
- If some pages contain active data, these are first copied to a spare block. The old block is then erased and ready to be written with new data.

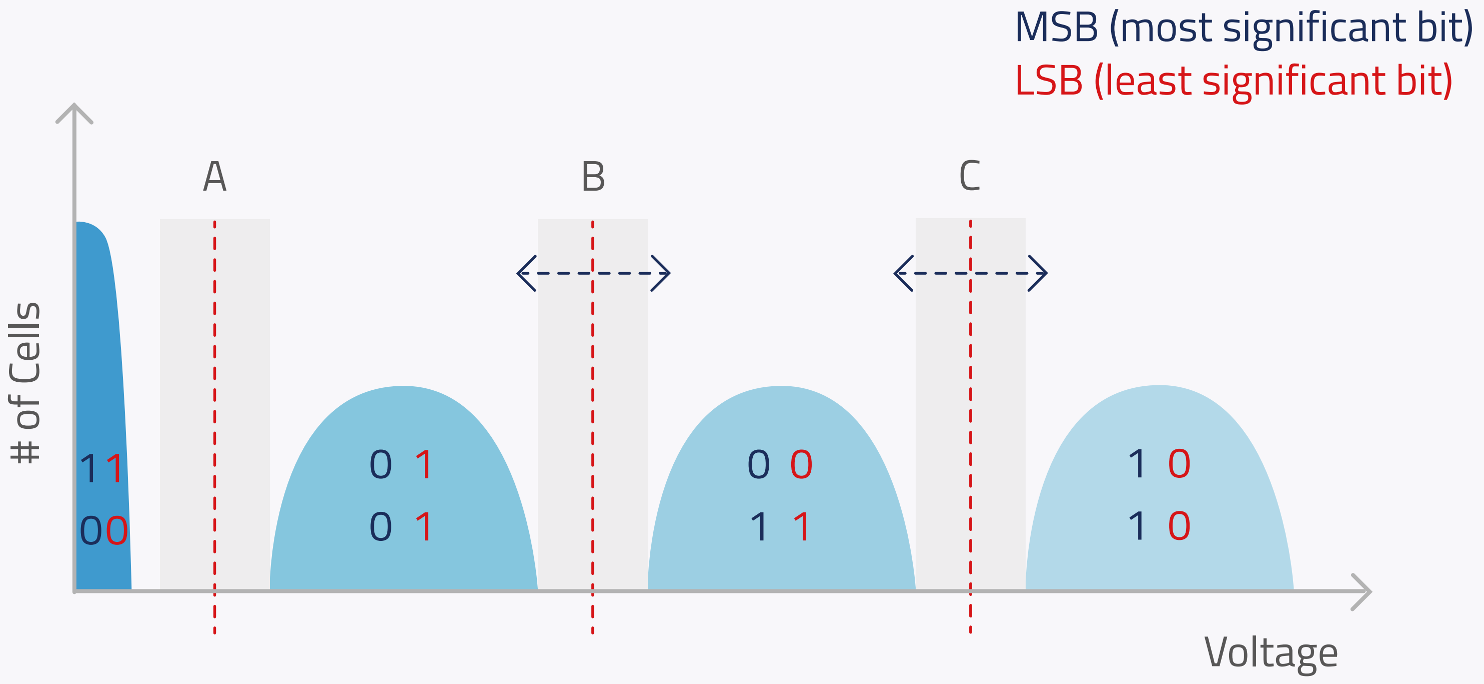
Basic Operations

Read Operation

A read operation is performed by comparing stored voltages with a threshold voltage (V_{th}). The maximum amount of data which can be read with a single read command from a NAND is a page. A page is the minimum read unit.

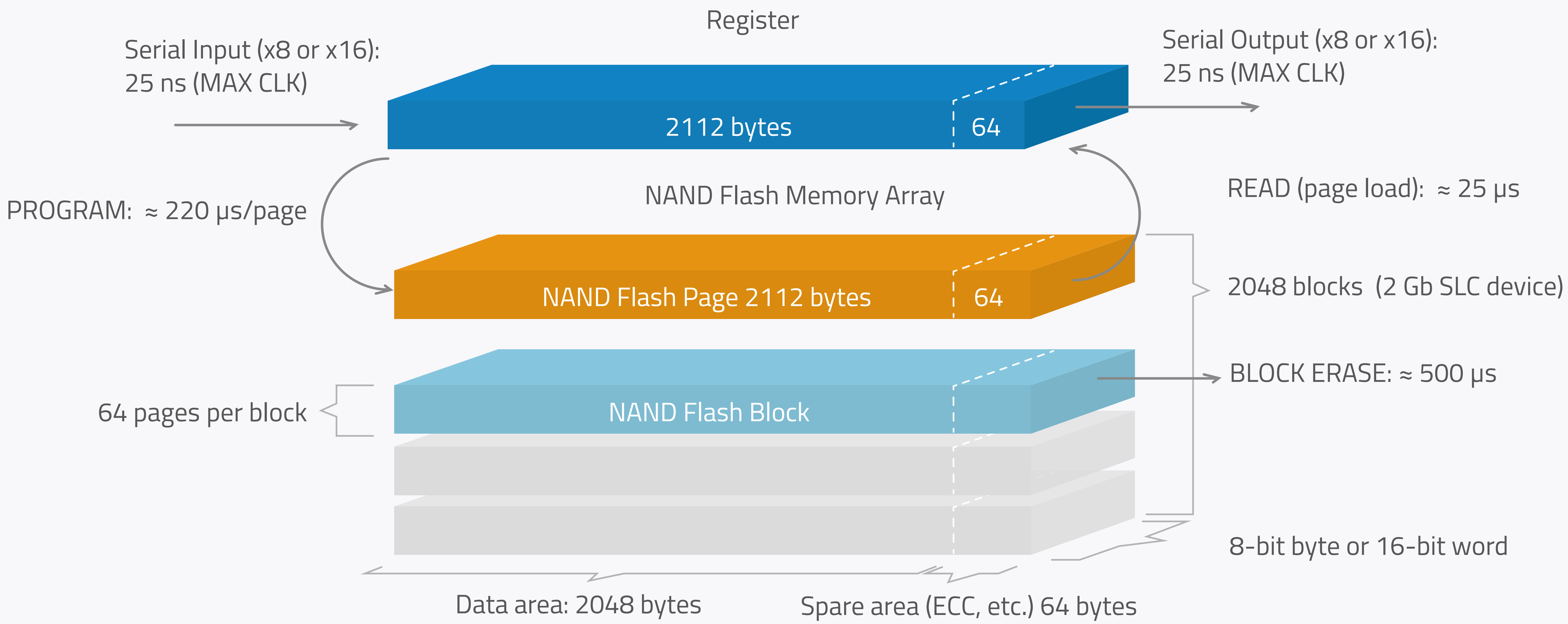
MLC (multi-level cell) flash can take four different voltage levels to store two bits and employs three different thresholds to separate the levels.

Example: MLC Read Thresholds



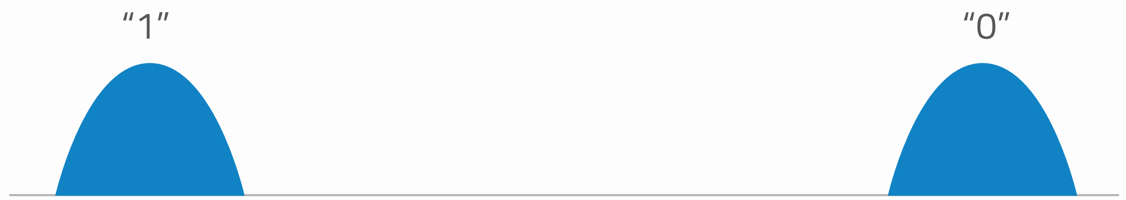
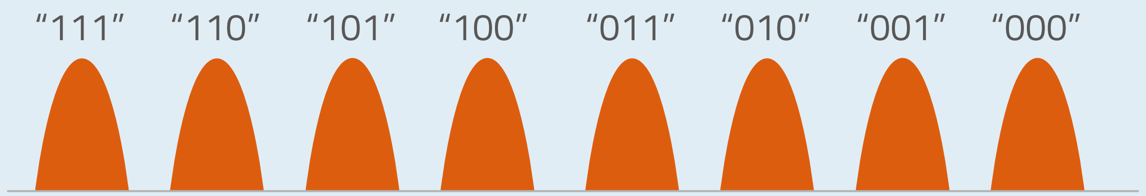
NAND Flash Layout

Here is an example of a 2 Gb flash device organized as 2048 blocks. The figure below shows how long erasing, programming and reading approximately takes.

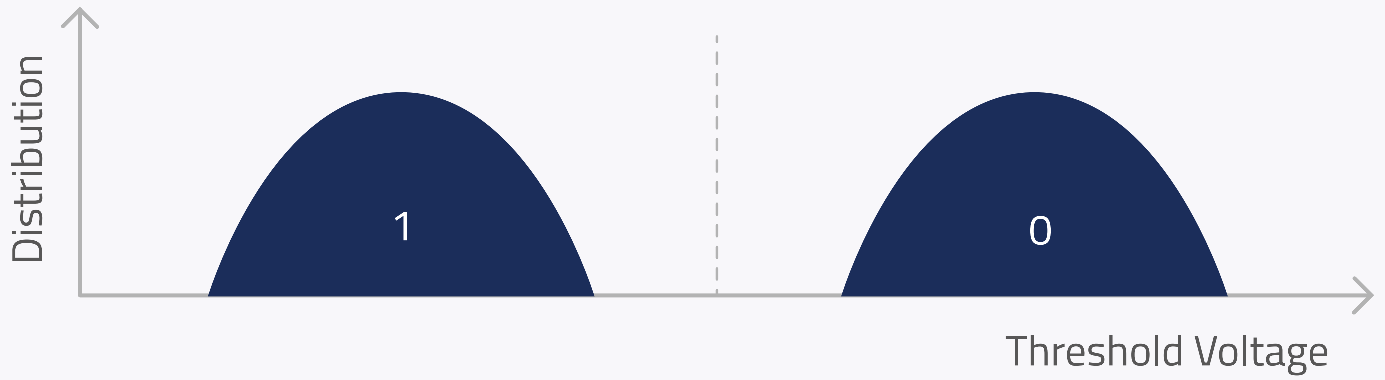


NAND Flash Types

Comparison Table

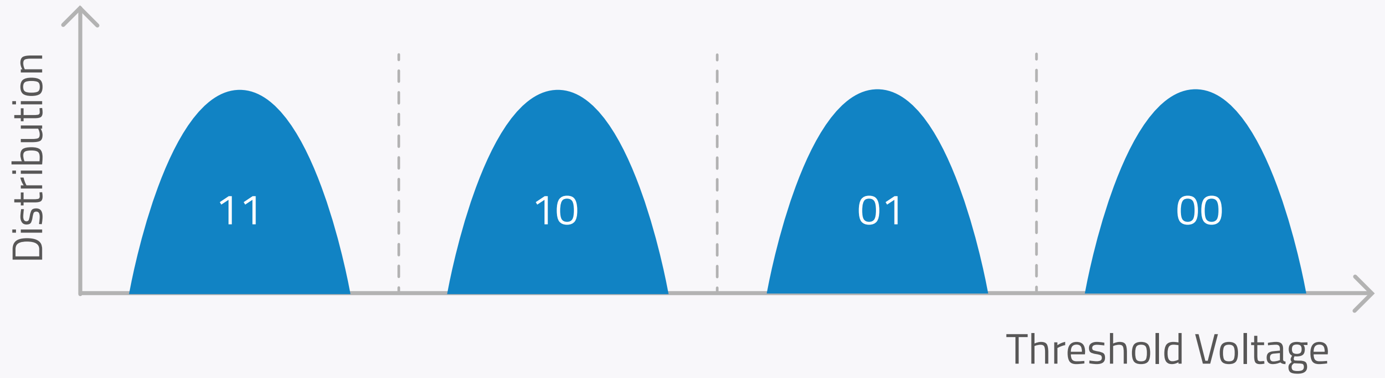
Technology Type	Definition	Endurance	Programming
SLC (Single-Level Cell)	Stores 1 bit per cell	50 to 100K P/E Cycles	 "1" "0"
SLC Mode (Pseudo SLC / Advanced MLC)	▪ MLC flash that functions like SLC ▪ Stores 1 bit per cell instead of 2	20 to 50K P/E Cycles	 "11" "10" "00" "01"
MLC (Multi-Level Cell)	Stores 2 bits per cell	3 to 5K P/E Cycles	 "11" "10" "00" "01"
TLC (Triple-Level Cell)	Stores 3 bits per cell	~ 1K P/E Cycles	 "111" "110" "101" "100" "011" "010" "001" "000"

NAND Flash Types and Threshold Voltage (V_{th}) Distribution



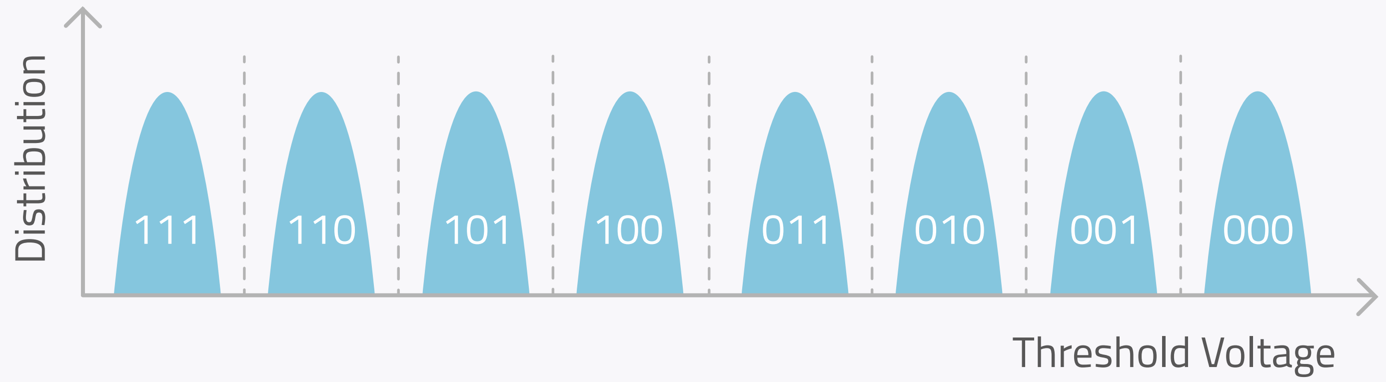
SLC

- High voltage margin makes cell reading easier and quicker.
- Small impact of leakage and cell interference
- Wider distribution of logic levels means programming or erasing at lower voltage for increased durability and longer product lifetime



MLC

- Lower cost per bit compared with SLC
- Closer distribution means voltage leakages can generate more impact and reduce product lifetime

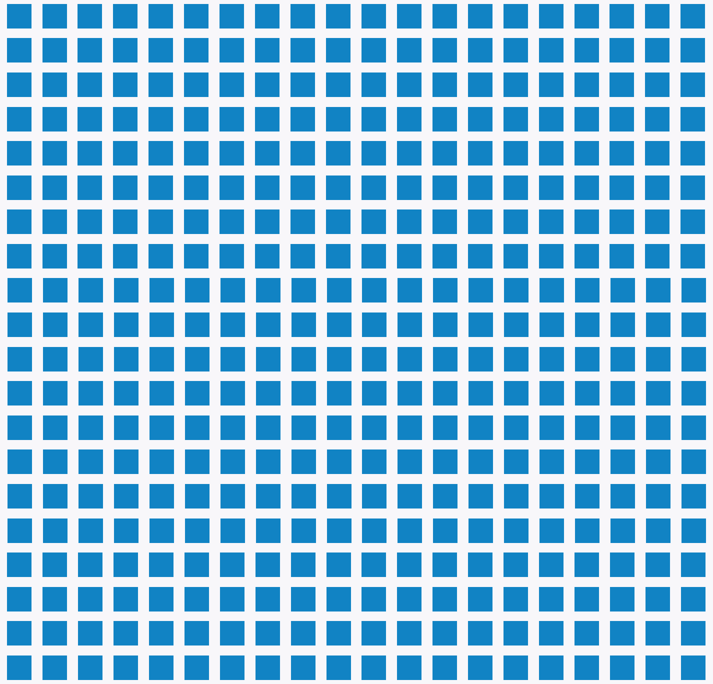


TLC

- Lower cost per bit compared with MLC
- Very narrow voltage margin makes programming and reading speed very slow
- Much closer distribution magnifies wear and significantly reduces product lifetime

NAND Flash Architectures

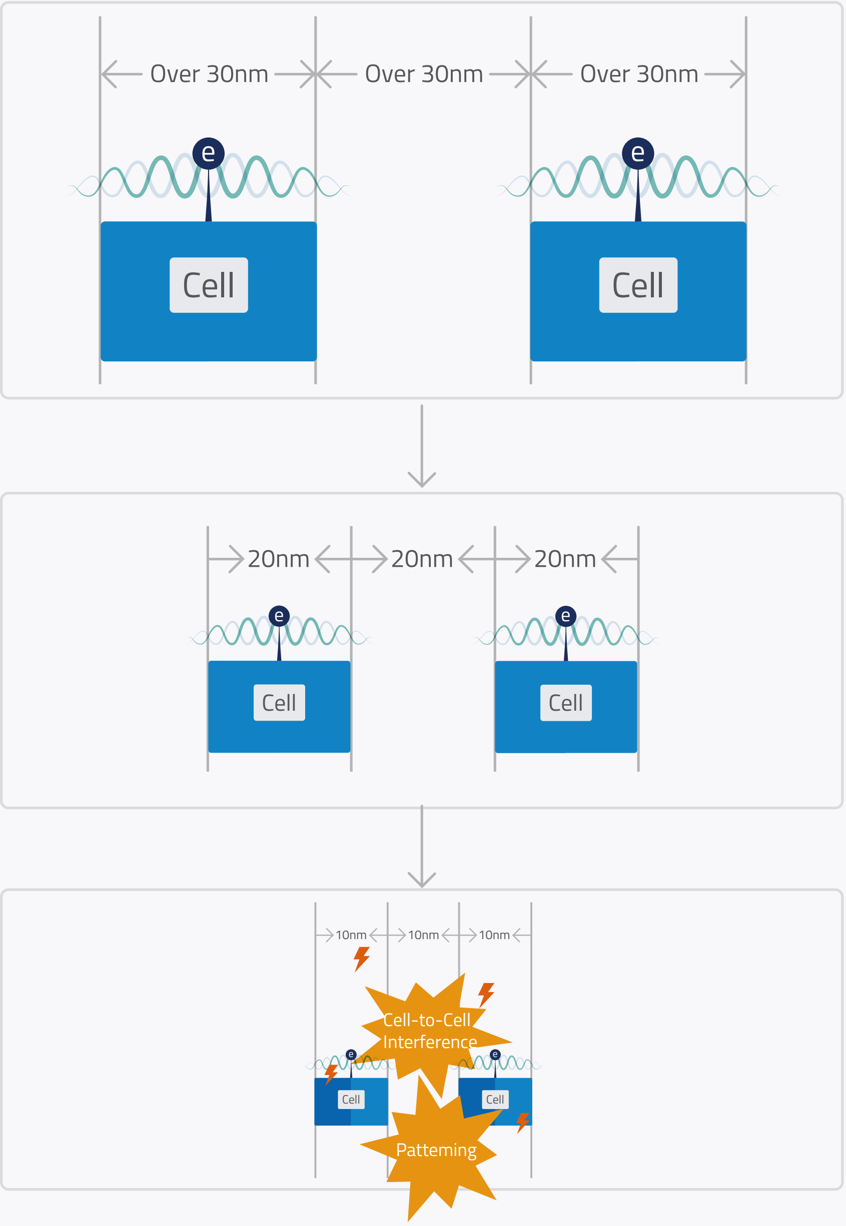
Planar (2D) NAND



Limitations:

- **Scaling limitations**
  Reduction of memory cell sizes to fit more in a die. However, there will be a time when shrinking the photolithography will not be possible.

- **Cell-to-cell interference and leakage phenomena**
  As memory cells continue to shrink, leakage or migration of electrical charge from one cell into an adjacent cell increases. This drastically reduces the reliability of the flash memory which eventually leads to data corruption.



- Traditional NAND flash architecture.
- Memory cells are arranged side by side on a single die layer.
- Drive capacity is determined by how many cells will fit on the die – more cells mean higher capacity.

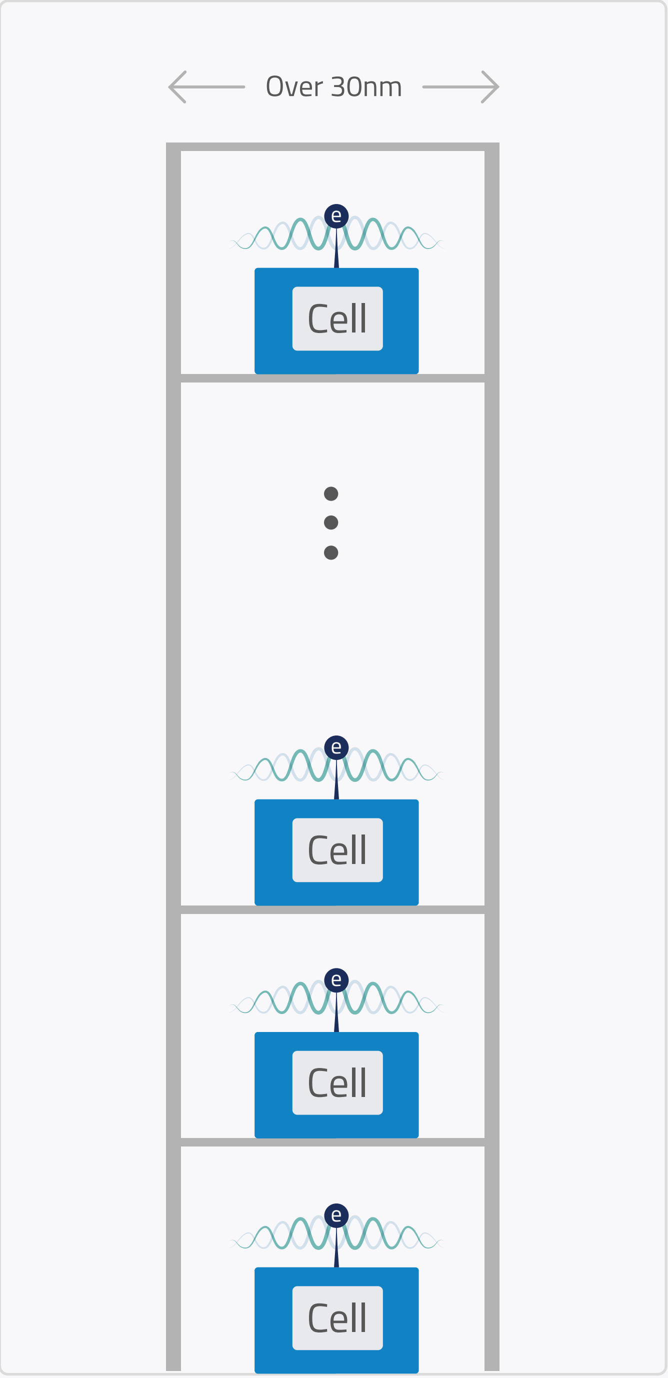
NAND Flash Architectures

3D NAND

- 3D NAND is the vertical stacking of memory cells.
- This method of stacking increases the capacity in each footprint without having to shrink the cell size.

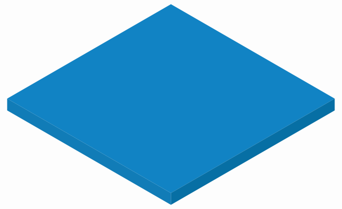
Benefits:

- **Higher densities per die** without increasing footprint, resulting in generally lower cost per bit.
- **Reduced cell-to-cell interference** due to the relaxation of NAND lithography, thus increasing drive reliability and endurance.
- **Enhanced data write performance.** Accelerates processing of larger data structures at newer NAND input/output (I/O) industry standards, providing the potential for up to 2X faster performance compared with 2D NAND.



NAND Flash Architectures

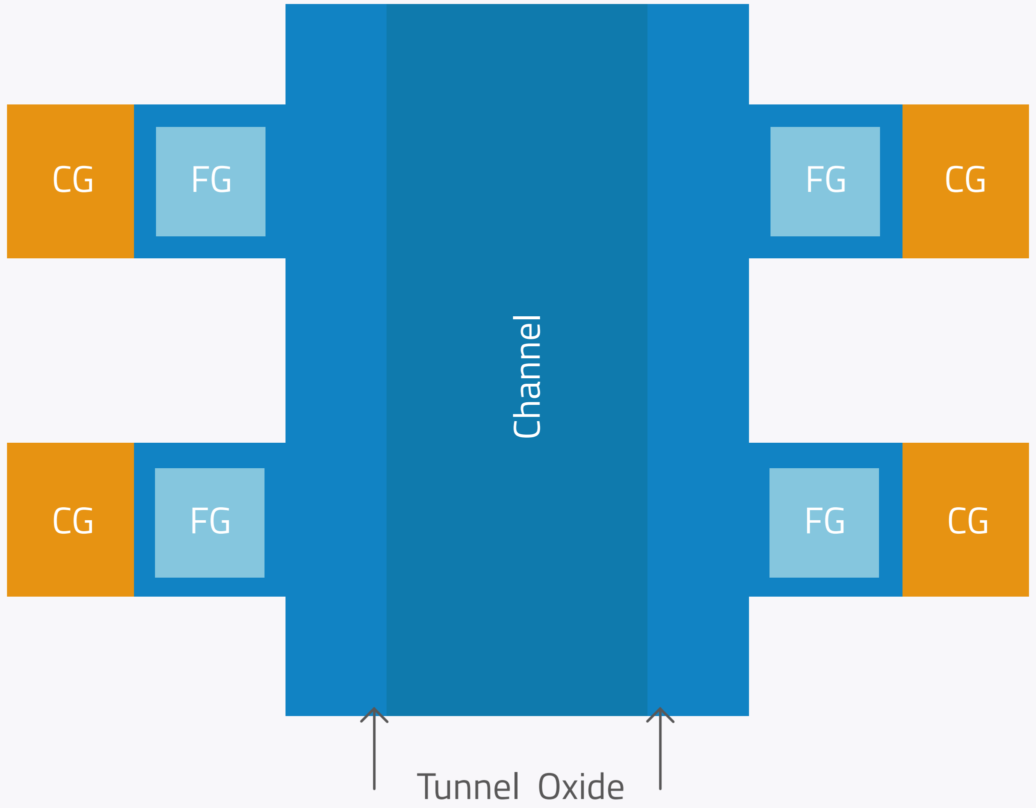
Summary of Features

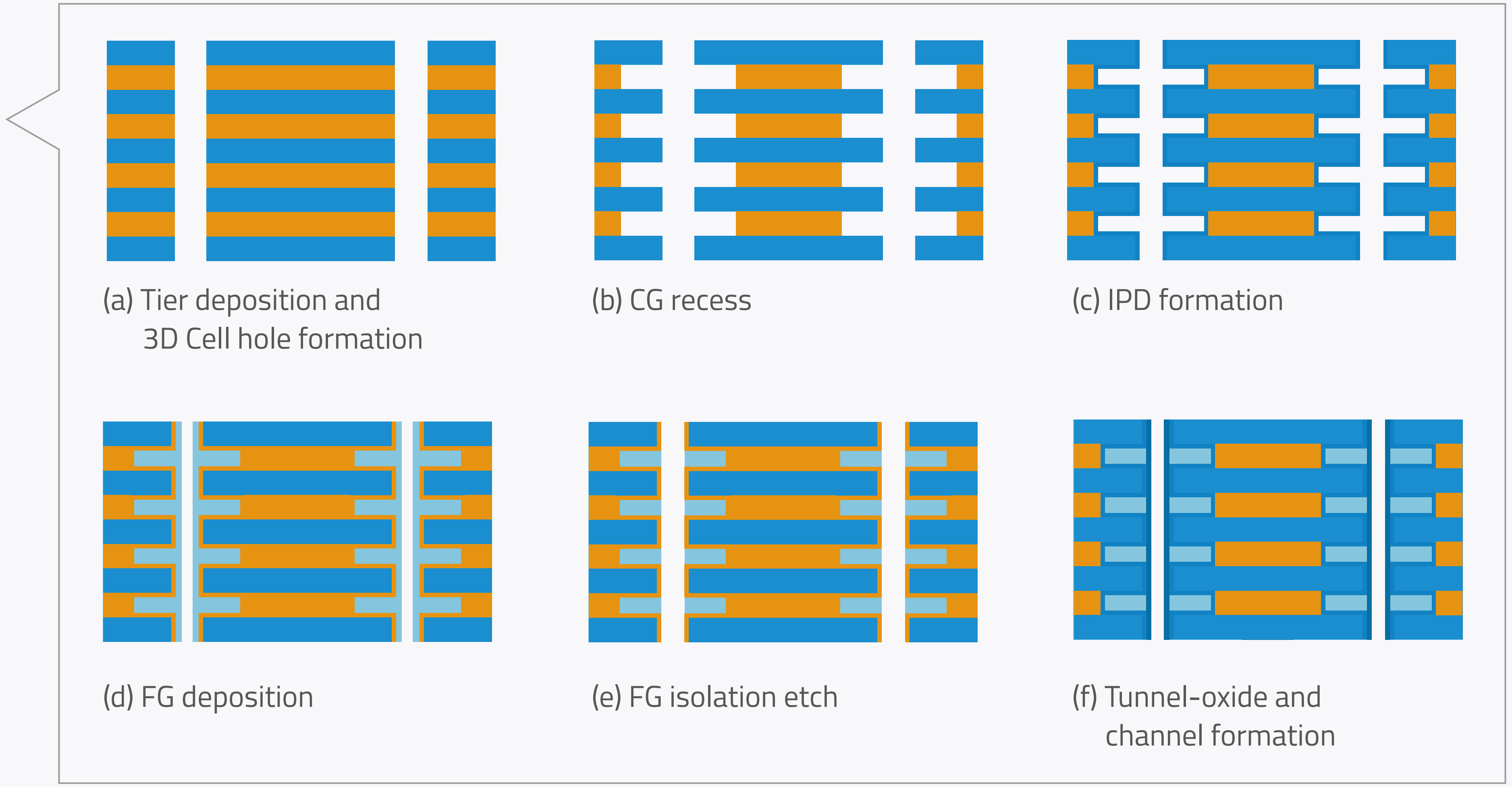
Technology	2D NAND	3D NAND
Image		
Capacity*	Max. 128 GB	Currently up to 1920 GB (Space for future increase)
Design	Floating Gate	Floating Gate or Charge Trap
Industrial Temperature Support	Available	Available
Performance	Slower	Faster

*Current maximum capacity of ATP SSDs. To stay updated on specification changes and new offerings, please visit the ATP website (https://www.atpinc.com) regularly.

3D NAND Flash Architectures

Floating Gate

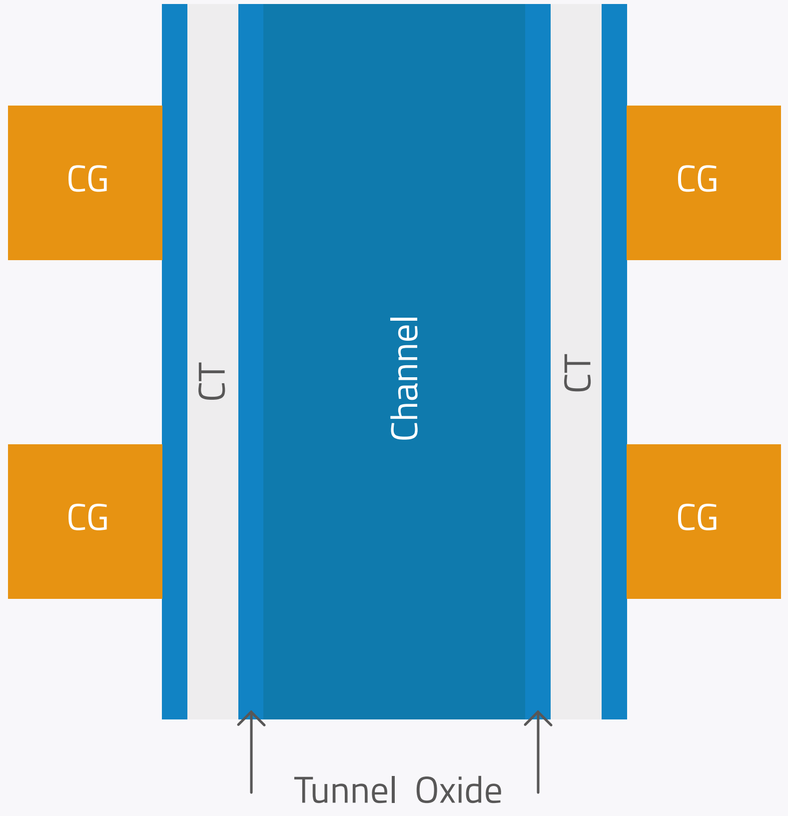




Source: Intel/Micron/IEDM

3D NAND Flash Architectures

Charge Trap



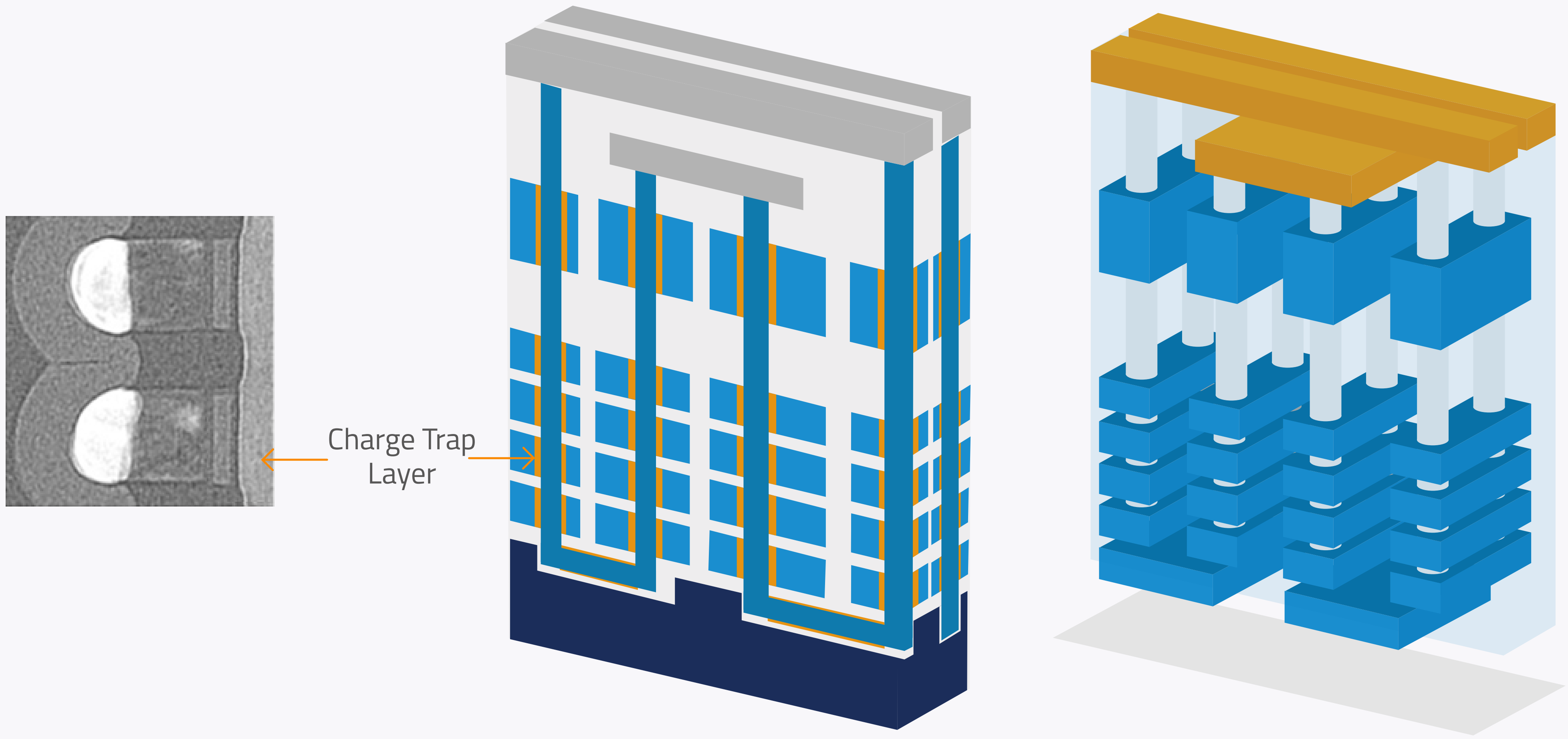
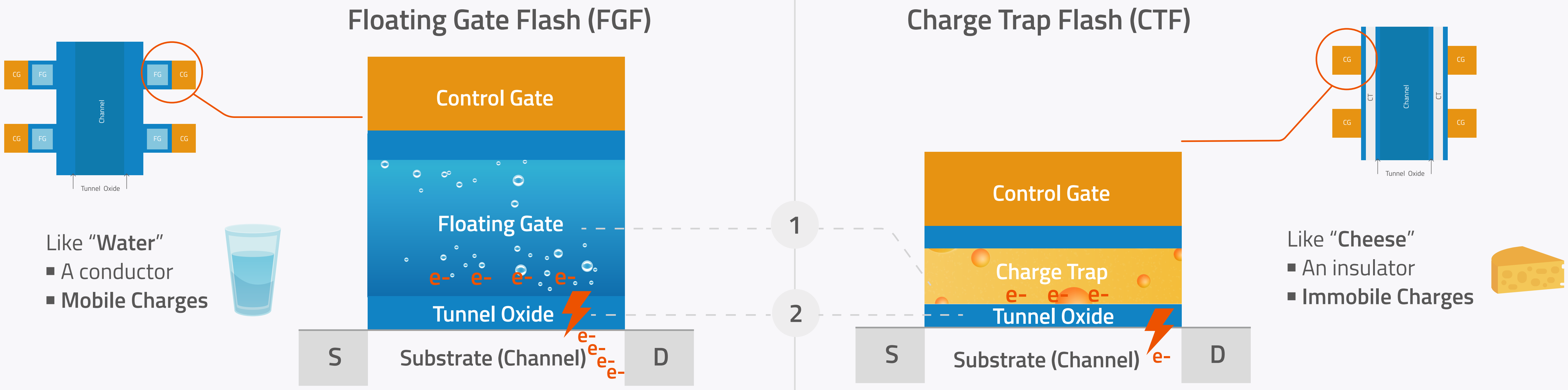


Image source: spansion.com / Flash Memory Summit 8-13-13

3D NAND Flash Architectures

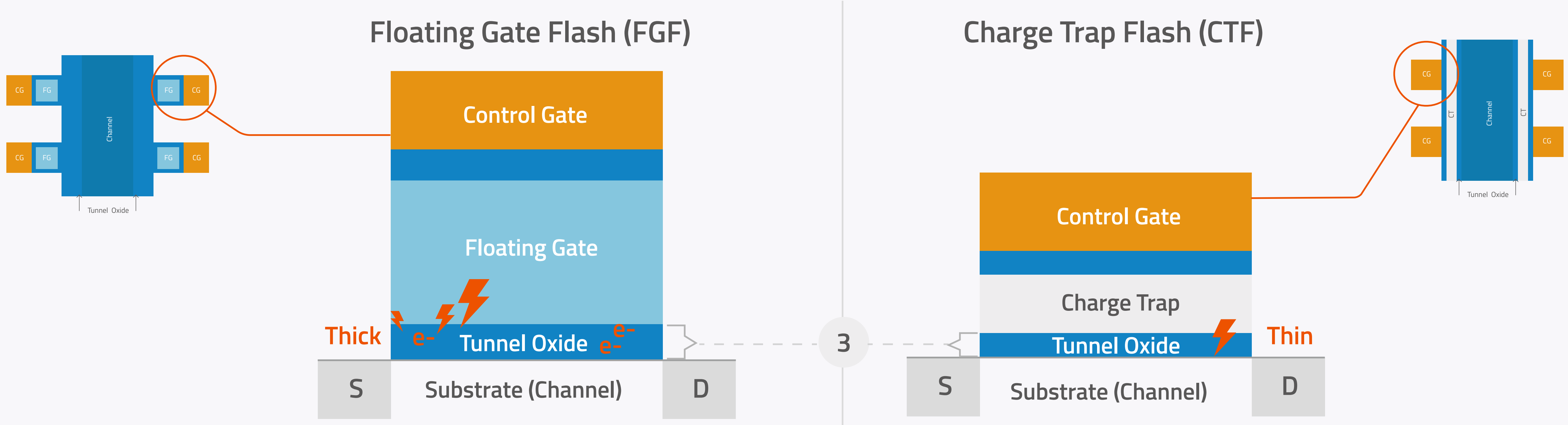
Comparison: Bit Reliability



	Floating Gate	Charge Trap
1. Material	"Water" Polysilicon: Electrons can freely move	"Cheese" Silicon Nitride: Electrons are trapped at CT layer. They are not free carriers anymore and barely move.
2. Tunnel Oxide Degradation (When leakage occurs at the tunnel oxide layer…)	All electric charge drains out to substrate	Only the charge close to the leakage point drains out. Most of the electric charge is maintained.

3D NAND Flash Architectures

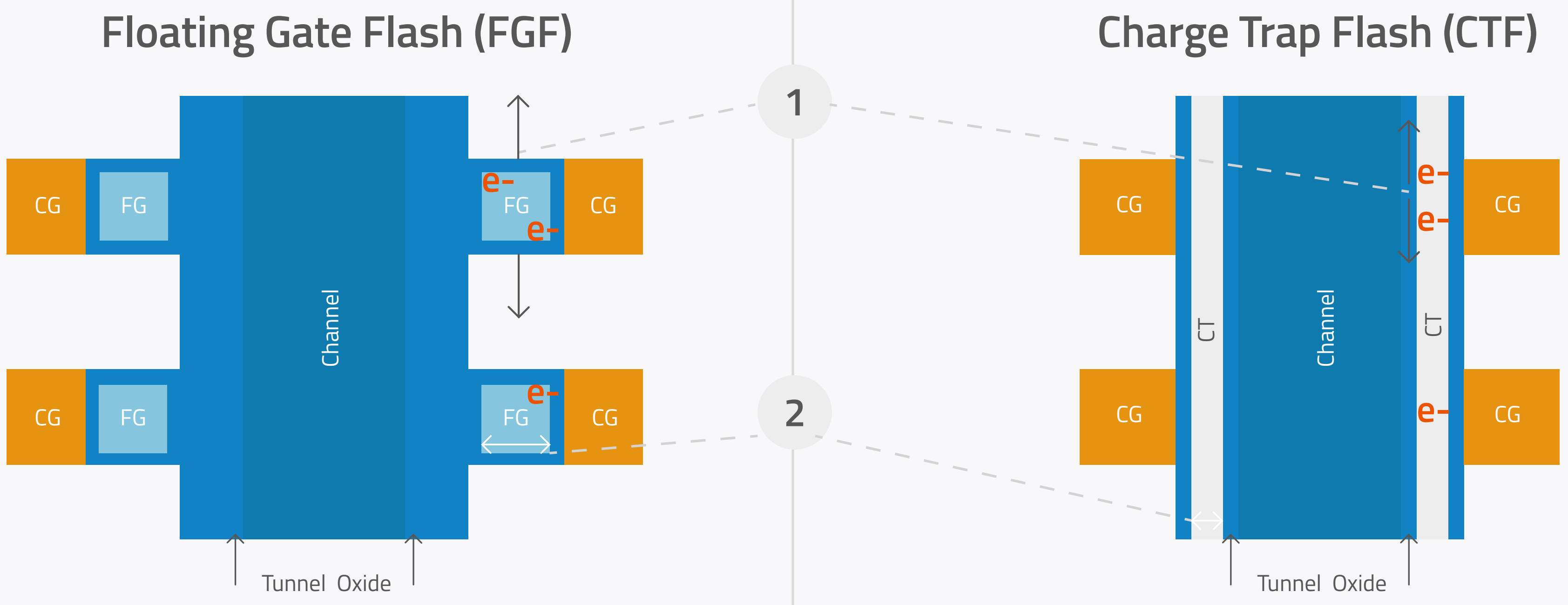
Comparison: Endurance (Theoretical)



	Floating Gate	Charge Trap
3. Flash Wear (Endurance)	**Thicker tunnel oxide** ▪ Requires higher programming voltage ▪ Causes high tunnel oxide stress ▪ Increasing oxide defects cause short circuits (oxide defect can trap electrons that pass through) ▪ FG no longer holds charges ▪ Leads to faster flash wearout ▪ Reduces endurance	**Thinner tunnel oxide** ▪ Requires lower tunneling voltage ▪ Causes less stress on tunnel oxide ▪ Improves overall endurance

3D NAND Flash Architectures

Comparison: Data Retention (Theoretical)



	Floating Gate	Charge Trap
4. Data Retention and the Impact of Disturbances (Read/Program)	1. Isolated charge storage node for good cell-to-cell charge isolation (reduces capacity coupling between neighboring cells) ⟶ Not susceptible to charge spreading	1. Continuous charge storage node prone to charge dispersion between cells 2. Fast initial charge loss due to shallow trapped electrons

3D NAND Flash Architectures

Floating Gate or Charge Trap?

Before jumping into a quick purchase decision, here are some important considerations that could help:

- **Reliability over Industrial Temperature**
  Do you need a storage device that can handle application-specific workloads for extended periods of time where temperatures swing from extremely cold (-40°C) to extremely hot (85°C)?

- **Device Density: Bigger is Not Always Better**
  How much storage does your application actually need? Some applications require higher capacities made possible by 3D NAND technology but many industrial and embedded applications still use lower storage densities.

- **Data Structure Size**
  The usage case or workload, including factors such as data type/size, read/write-intensity, sequential/random access, command queueing, etc. should generally be carefully considered when choosing the right NAND technology for industrial applications.

Floating Gate or Charge Trap?

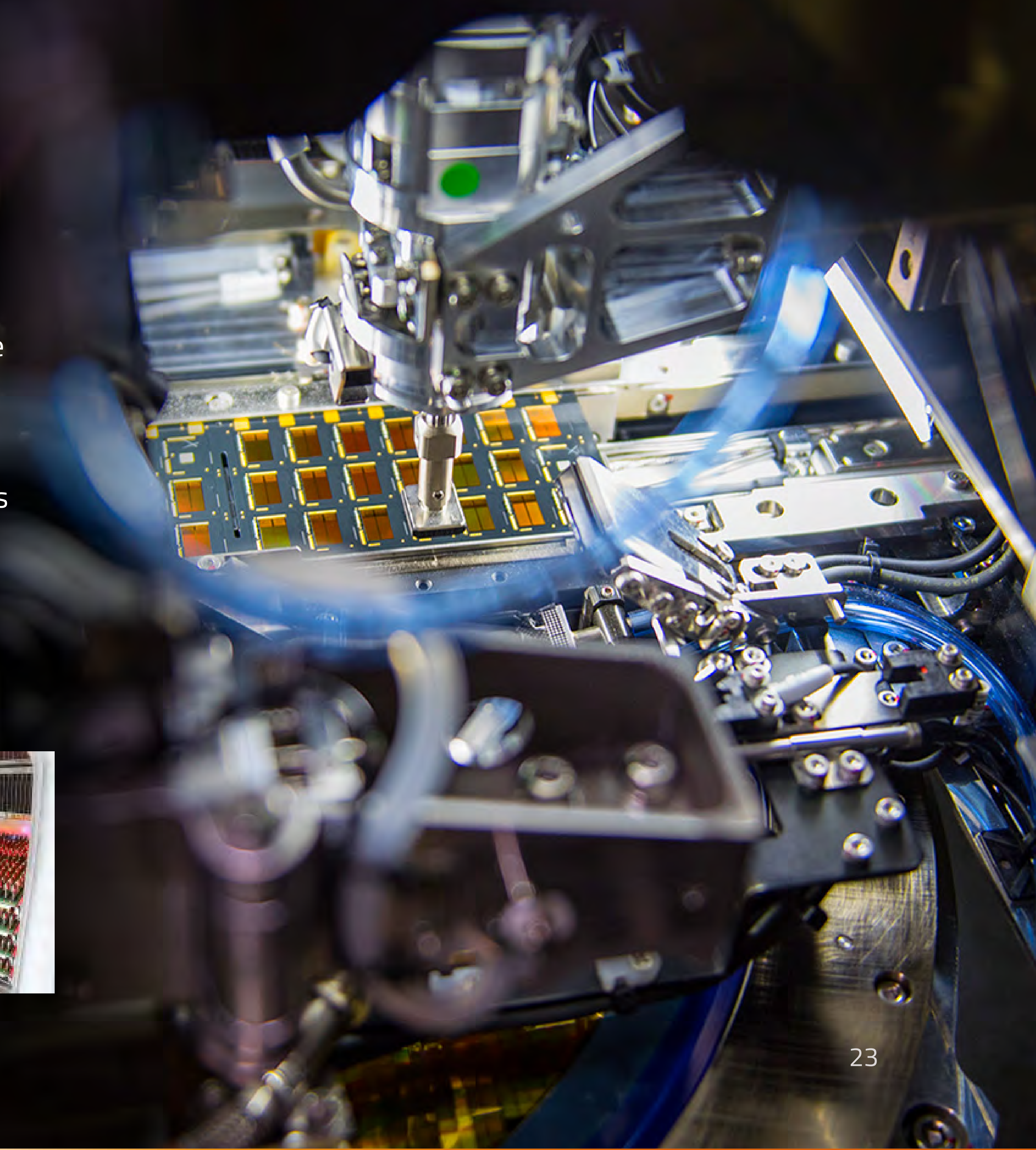
It all depends on application-specific needs.

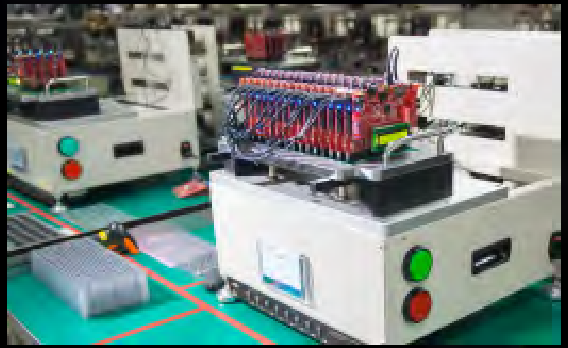
Go with storage that is extremely reliable and characterized for **the intended usage** case to deliver long years of dependable operation in the toughest conditions.

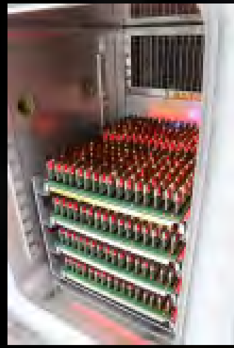
- Networking / Telecommunications
- Industrial/ Embedded PC
- The Internet of Things
- Automotive Computing
- Aerospace and Defense
- Health Care
- Enterprise Mobility

ATP’s 3D NAND Solutions: “Industrial Only”

- ATP has **nearly 30 years of extensive experience** as a leading industrial storage manufacturer.
- **Comprehensive portfolio** of 2D/3D NAND flash solutions using both floating gate and charge trap technologies, in a wide array of capacities, temperature ranges, performance and endurance ratings, security features and even customizable options for your needs.
- ATP manufactures its 3D NAND flash products in its own purpose-built factory with **advanced self-packing capabilities** and expert handling of handle critical and challenging processes such as deposition and etching.
- **Stringent testing** from IC to product level ensures longer product service life, improved reliability and extended endurance.







WHY INDUSTRIAL ONLY?
Because TCO Matters

Organizations trying to reduce cost may be tempted to purchase goods based on cheap price. However, purchase price is just the tip of the iceberg. A better metric for cost savings is total cost of ownership (TCO), which is the sum of all related costs incurred within the entire service life of the product.

With ATP's quality guarantee, customers can rest assured that they get the best value out of their TCO. ATP's high-performance, high-endurance memory and storage solutions go through rigorous design validation, qualification, and outstanding production processes. Customers can rest assured that competent ATP support is available before, during and after sales.

"Industrial Only" Commitment

Designed and manufactured with extensive screening & testing

High-quality components are the building blocks of high-quality products; thus, ATP makes sure that screening begins at the integrated circuits (IC) level, where NAND flash is screened for temperature tolerance, data retention, disturbance, and other attributes. Meticulous NAND characterization and extensive product reliability tests under extreme temperatures and operating conditions ensure that every product is highly reliable.

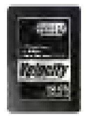
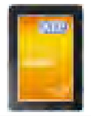
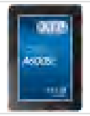
Best TCO value with longevity & higher endurance for industrial applications

ATP memory and storage solutions perform dependably over long periods of time. High P/E cycles and long product service life, maximum availability and minimal downtime all translate to better return on investment (ROI) and best total cost of ownership (TCO) value. Additionally, ATP offers longevity support for legacy DRAM modules through a partnership agreement with Micron Technology, Inc.

Full in-house process ownership for uncompromising quality guarantee

From the time wafers are received, to NAND flash screening, design and validation, pilot run and mass production, ATP maintains complete control of all stages of the manufacturing process. By taking charge and ownership of the processes, ATP delivers uncompromising quality guarantee. ATP also maintains control of its supply and value chains, implements controlled bill of materials (BOM) with longevity planning and maintains buffer inventory to ensure steady supply. This flexibility and manufacturing competence are clear differentiators compared with turnkey solutions in the market.

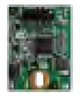
Complete Flash Portfolio

Product			Dimensions (L x W x H mm)	Flash Type	Densities	Operating Temp.	Data Transfer Rate (max.)	TBW* (max.)	Power Failure Protection / PowerProtector	Secure Erase (S/W)**	Life Monitor (S/W)**
SATA											
2.5" SSD			100.0 x 69.9 x7 / 9.2	SLC	8 GB~256 GB	-40°C~ 85°C	Read: 520 MB/s Write: 420 MB/s	21,333 TB	✓	✓	✓
				iTemp pseudo SLC	60 GB~480 GB		Read: 540 MB/s Write: 500 MB/s	18,000 TB	✓	✓	✓
				iTemp MLC	64 GB		Read: 440 MB/s Write: 80 MB/s	145.5 TB	✓	✓	✓
				MLC		0°C~ 70°C		174.6 TB	✓	✓	✓
				iTemp 3D TLC	120 GB~1920 GB	-40°C~85°C	Read: 560 MB/s Write: 480 MB/s	5,585 TB	✓	✓	✓
				3D TLC		0°C~ 70°C					
M.2	2280 D2-B-M		80.0 x 22.0 x 3.5	iTemp pseudo SLC	60 GB~240 GB	-40°C~ 85°C	Read: 560 MB/s Write: 500 MB/s	9,000 TB	✓	✓	✓
				iTemp 3D TLC	120 GB~960 GB		Read: 560 MB/s Write: 440 MB/s	2,792 TB			
				3D TLC		0°C~ 70°C					
	2242 D2-B-M		42.0 x 22.0 x 3.5	SLC	8 GB~64 GB	-40°C~ 85°C	Read: 530 MB/s Write: 400 MB/s	5,333 TB	✓	✓	✓
				iTemp pseudo SLC	60 GB~120 GB		Read: 560 MB/s Write: 500 MB/s	4,500 TB			
				iTemp MLC	16 GB~64 GB		Read: 440 MB/s Write: 80 MB/s	145.5 TB			
				MLC		0°C~ 70°C		174.6 TB			
				iTemp 3D TLC	120 GB~480 GB	-40°C~ 85°C	Read: 560 MB/s Write: 440 MB/s	1,396 TB			
				3D TLC		0°C~ 70°C					

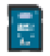
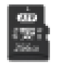
Product		Dimensions (L x W x H mm)	Flash Type	Densities	Operating Temp.	Data Transfer Rate (max.)	TBW* (max.)	Power Failure Protection / PowerProtector	Secure Erase (S/W)**	Life Monitor (S/W)**
SATA										
mSATA		50.8 x 29.85 x 3.5	SLC	8 GB~128 GB	-40°C~ 85°C	Read: 530 MB/s Write: 430 MB/s	10,667 TB	✓	✓	✓
			iTemp pseudo SLC	60 GB~120 GB		Read: 560 MB/s Write: 500 MB/s	4,500 TB			
			iTemp MLC	16 GB~64 GB		Read: 440 MB/s Write: 80 MB/s	145.5 TB			
			MLC		0°C~ 70°C		174.6 TB			
			iTemp 3D TLC	120 GB~480 GB	-40°C~ 85°C	Read: 560 MB/s Write: 440 MB/s	1,396 TB			
			3D TLC		0°C~ 70°C					
SlimSATA		54.0 x 39.0 x 4.0	SLC	8 GB~128 GB	-40°C~ 85°C	Read: 530MB/s Write: 430 MB/s	10,667 TB	✓	✓	✓
			iTemp pseudo SLC	64 GB~256 GB		Read: 550 MB/s Write: 440 MB/s	8,533 TB			
			iTemp MLC	16 GB~512 GB		Read: 550 MB/s Write: 450 MB/s	1,067 TB			
			MLC		0°C~ 70°C		1,280 TB			
CFast		36.4 x 42.8 x 3.6	SLC	8 GB~32 GB	-40°C~ 85°C	Read: 500 MB/s Write: 300 MB/s	2,667 TB	✓	✓	✓
			iTemp MLC	16 GB~128 GB		Read: 510 MB/s Write: 175 MB/s	267 TB			
			MLC		0°C~ 70°C		320 TB			

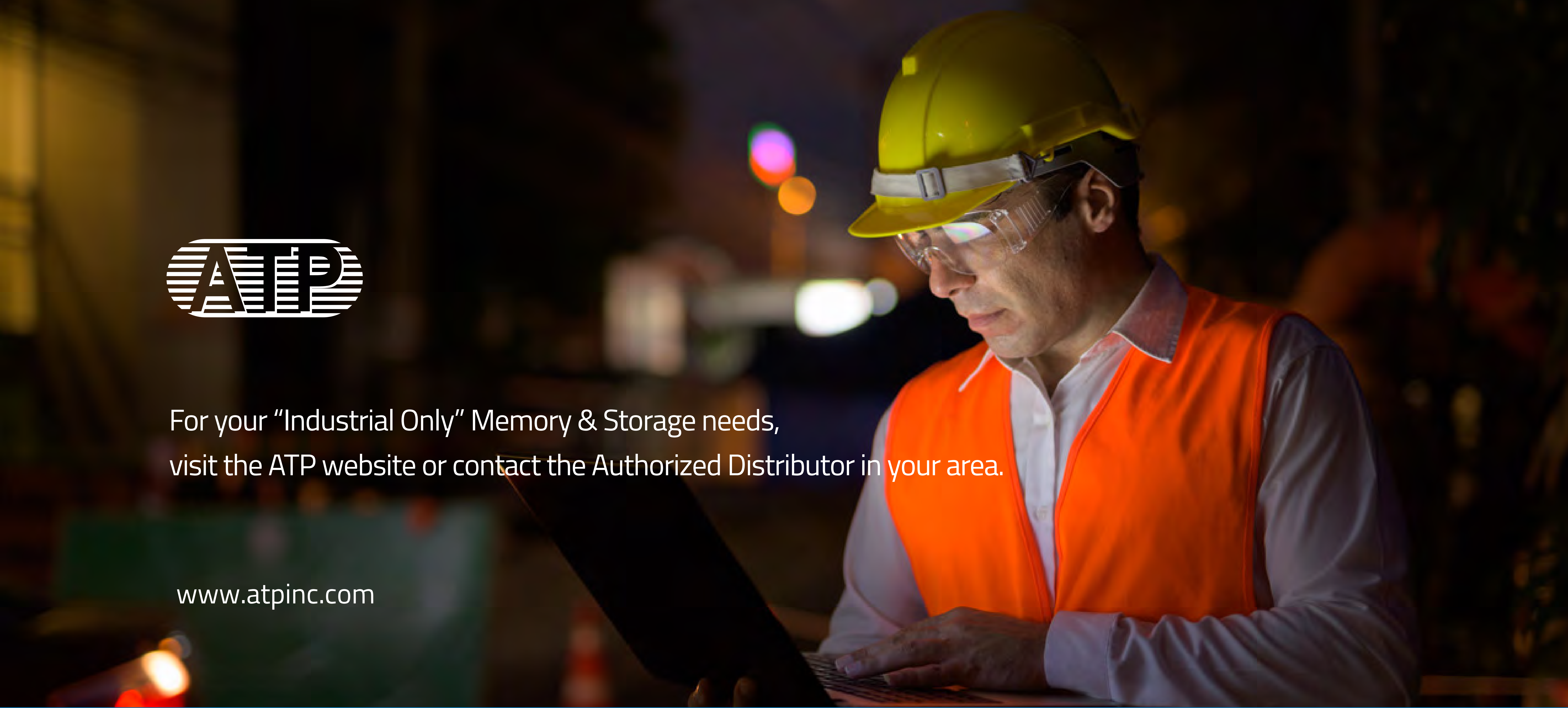
* Under highest Sequential write value. May vary by density, configuration and applications.
** ATP software support for demo use only.
*** By project support

Complete Flash Portfolio

Product		Dimensions (L x W x H mm)	Flash Type	Densities	Operating Temp.	Data Transfer Rate (max.)	TBW* (max.)	Power Failure Protection / PowerProtector	Secure Erase (S/W)**	Life Monitor (S/W)**
NVMe										
M.2		80.0 x 22.0 x 3.5	iTemp 3D TLC	120 GB~1920 GB	-40°C~ 85°C	Read: 3,280 MB/s Write: 3,050 MB/s	5,120 TB	✓	✓***	✓
			3D TLC		0°C~ 70°C		5,120 TB			
PATA/IDE										
CompactFlash		36.4 x 42.8 x 3.3	SLC	512 MB~32 GB	-40°C~ 85°C	Read: 61 MB/s Write: 55 MB/s	1,280 TB	✓	-	✓
			pseudo SLC	8 GB~16 GB	0°C~ 70°C	Read: 110 MB/s Write: 80 MB/s	128 TB	-	-	✓
			MLC	16 GB~32 GB		Read: 108 MB/s Write: 46 MB/s	38 TB	-	-	✓
USB Drive										
eUSB		36. 9 x 26.6 x 9.5	SLC	1 GB~32 GB	-40°C~ 85°C	Read: 30 MB/s Write: 25 MB/s	1,280 TB	✓	-	✓
			MLC	8 GB~32 GB	0°C~ 70°C	Read: 25 MB/s Write: 19 MB/s	38.4 TB	✓	-	✓
			MLC	16 GB~64 GB	0°C~ 70°C	Read: 44 MB/s Write: 17 MB/s	76.8 TB	✓	-	✓
NANODURA		34 x 12.2 x 4.5	SLC	512 MB~8 GB	-40°C~ 85°C	Read: 21 MB/s Write: 16 MB/s	192 TB	-	-	✓
			MLC	8 GB~16 GB	0°C~ 70°C	Read: 25 MB/s Write: 18 MB/s	19.2 TB	-	-	✓

* Under highest Sequential write value. May vary by density, configuration and applications.
** ATP software support for demo use only.
*** By project support

Product		Dimensions (L x W x H mm)	Flash Type	Densities	Operating Temp.	Data Transfer Rate (max.)	TBW* (max.)	Power Failure Protection / PowerProtector	Secure Erase (S/W)**	Life Monitor (S/W)**
SD										
SD/SDHC/SDXC		32.0 x 24.0 x 2.1	SLC	512 MB~8 GB	-40°C~ 85°C	Read: 70 MB/s Write: 39 MB/s	192 TB	✓	✓	✓***
			iTemp pseudo SLC	4 GB~8 GB	-40°C~ 85°C	Read: 76 MB/s Write: 50 MB/s	128 TB			
			pseudo SLC	4 GB~8 GB	-25°C~ 85°C	Read: 76 MB/s Write: 50 MB/s	128 TB			
			iTemp 3D pseudo SLC	8 GB~64 GB	-40°C~ 85°C	Read: 98 MB/s Write: 60 MB/s	320 TB			
			3D pseudo SLC	8 GB~64 GB	-25°C~ 85°C	Read: 98 MB/s Write: 60 MB/s	320 TB			
			iTemp MLC / 3D TLC	8 GB~256 GB***	-40°C~ 85°C	Read: 98 MB/s Write: 64 MB/s	154 TB			
			MLC	8 GB~128 GB***	-25°C~ 85°C	Read: 96 MB/s Write: 61 MB/s	154 TB			
			iTemp 3D TLC	32 GB~256 GB	-40°C~ 85°C	Read: 98 MB/s Write: 64 MB/s	154 TB			
			3D TLC	32 GB~256 GB	-25°C~ 85°C	Read: 98 MB/s Write: 64 MB/s	154 TB			
microSD/ microSDHC/ microSDXC		15.0 x 11.0 x 1.0	SLC	512 MB~8 GB	-40°C~ 85°C	Read: 80 MB/s Write: 39 MB/s	192 TB	✓	✓	✓***
			iTemp pseudo SLC	4 GB~16 GB	-40°C~ 85°C	Read: 76 MB/s Write: 54 MB/s	256 TB			
			pseudo SLC	4 GB~16 GB	-25°C~ 85°C	Read: 76 MB/s Write: 54 MB/s	256 TB			
			iTemp 3D pseudo SLC	8 GB~64 GB	-40°C~ 85°C	Read: 98 MB/s Write: 62 MB/s	640 TB			
			3D pseudo SLC	8 GB~64 GB	-25°C~ 85°C	Read: 98 MB/s Write: 62 MB/s	640 TB			
			iTemp MLC / 3D TLC	8 GB~256 GB	-40°C~ 85°C	Read: 98 MB/s Write: 61 MB/s	154 TB			
			MLC	8 GB~32 GB	-25°C~ 85°C	Read: 68 MB/s Write: 24 MB/s	39 TB			
			iTemp 3D TLC	32 GB~256 GB	-40°C~ 85°C	Read: 98 MB/s Write: 61 MB/s	154 TB			
			3D TLC	32 GB~256 GB	-25°C~ 85°C	Read: 98 MB/s Write: 61 MB/s	154 TB			
Managed NAND										
e.MMC		11.5 x 13.0 x 1.3 (max.)	3D pseudo SLC	8 GB~64 GB	-40°C~ 85°C /105°C	Read: 300 MB/s Write: 240 MB/s	1,320 / 1,213 TB	✓	✓	✓***
			3D MLC	16 GB~128 GB		Read: 300 MB/s Write: 170 MB/s	824 / 309 TB			



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