3D NAND Technology Scaling helps accelerate AI growth

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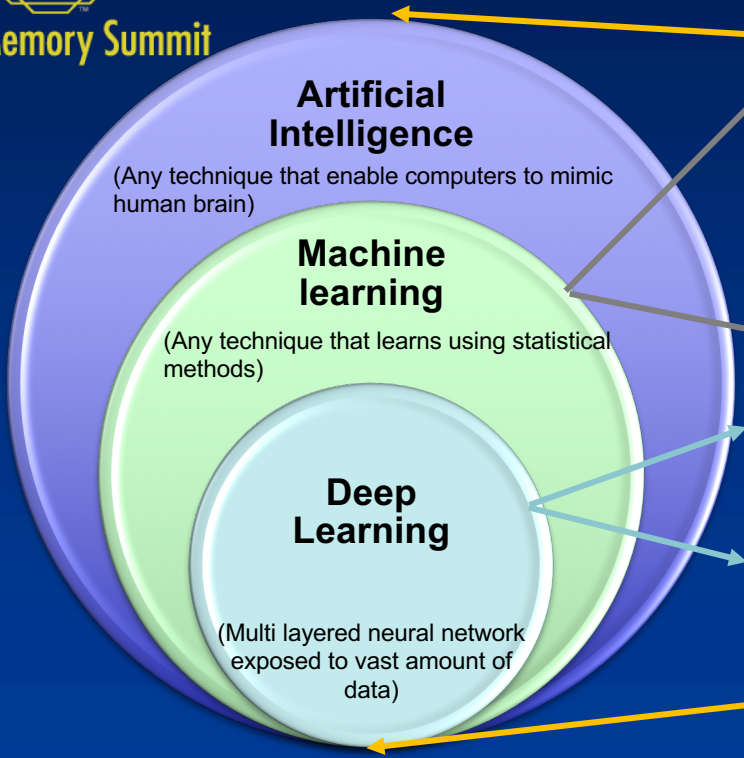
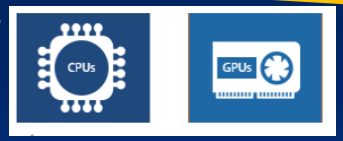
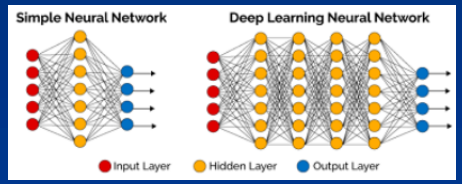
Agenda

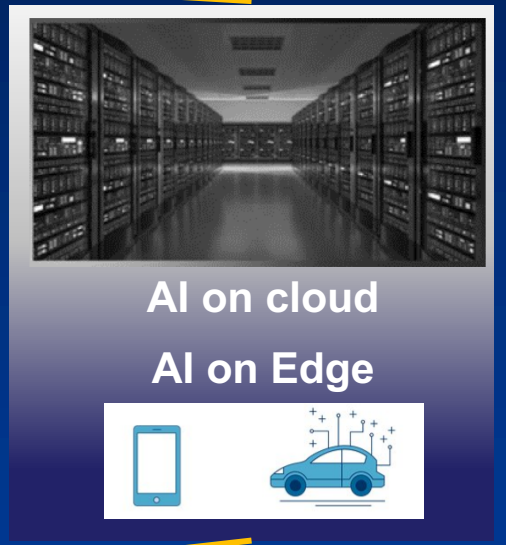
- 3D-NAND Scaling & AI
- Flash density trend
- NAND Layer Count scaling trend
- $/GB trend
- NAND technology Bandwidth comparison
- Flash Energy/Power trends
- Summary

Where do AI algorithms run?









- Deep learning multilayered neural network require high throughput data ingestion, lower power consumption, small system footprints , and lower system cost
  - **AI acceleration to be realized by 3D-NAND scaling**

Characteristics of AI

- Deep Learning, Machine Learning and all forms of Analytics on Data requires ingestion of large amount of data at very high throughput – Real time AI require data pattern & relationship learning
- Workloads tend to be In-Memory database centric – need to ingest data at high rate & throughput
  - To have a large dataset it requires lots of memory and lots of servers.
  - DRAM is extremely expensive, challenges with bit cost reduction via scaling
- As data sets used for training ML/DL are growing over time – Flash with its low latency & high throughput is most optimal solution for AI storage

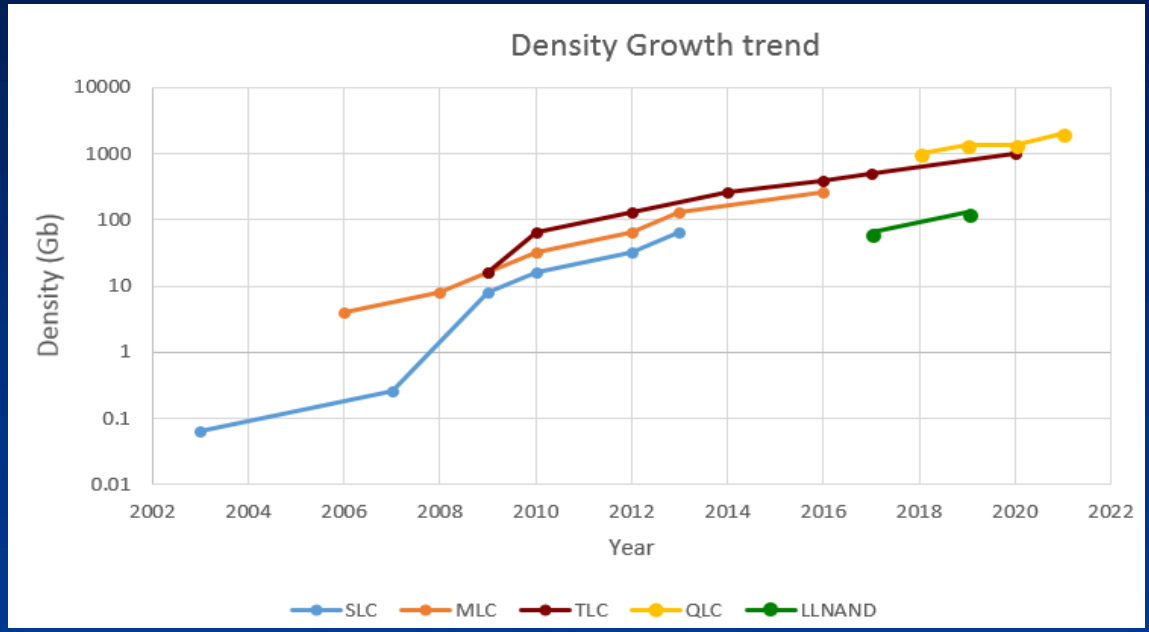
Attributes of AI

- Flash has very high read throughput density to assist workloads like deep learning
- Real Time analytics require low latency access to lots of data.
  - e.g., credit card fraud detection, image recognition
- Flash with increasing density can allow for lots of data to be accessed at fairly low latency
- Flash enables High IOPs with low read latency, smaller footprint and lower power compared to HDD
- Low Latency NAND and SCMs - fill performance and cost gap between Memory and Storage

3D-NAND Scaling & AI

- 3D-NAND technology scaling provides high throughput density, lower power consumption, and smaller system footprints – critical to accelerating AI growth
- 3D-NAND enables multi-terabit TLC and QLC densities through cell layer count increases, innovations in circuit design, process technology, and stacked packaging
- The resulting cost reductions, throughput increases, and lower power consumption enable flash driven AI growth.
- Density, performance, and reliability tradeoffs must be considered for TLC, QLC, MLC, and low latency NAND. High throughput data ingestion and system reliability requirements for AI optimized workloads critical

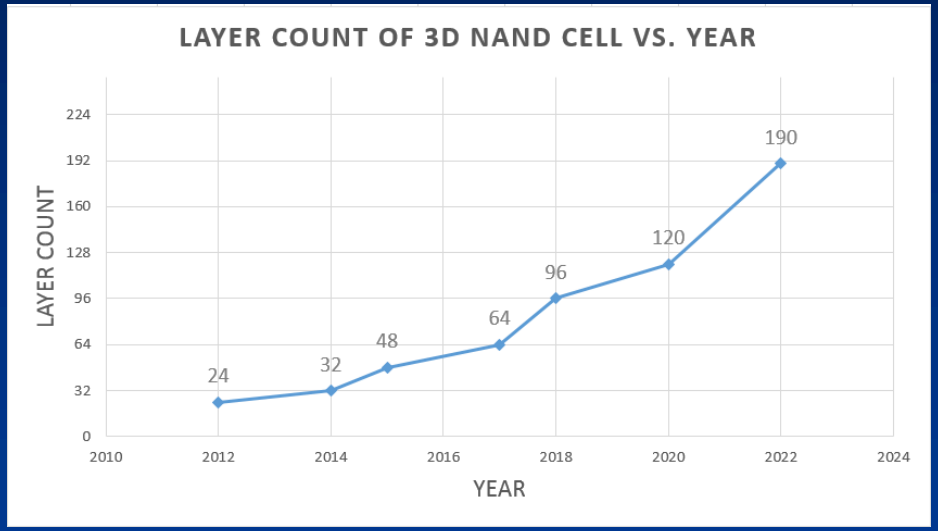
Memory density trend

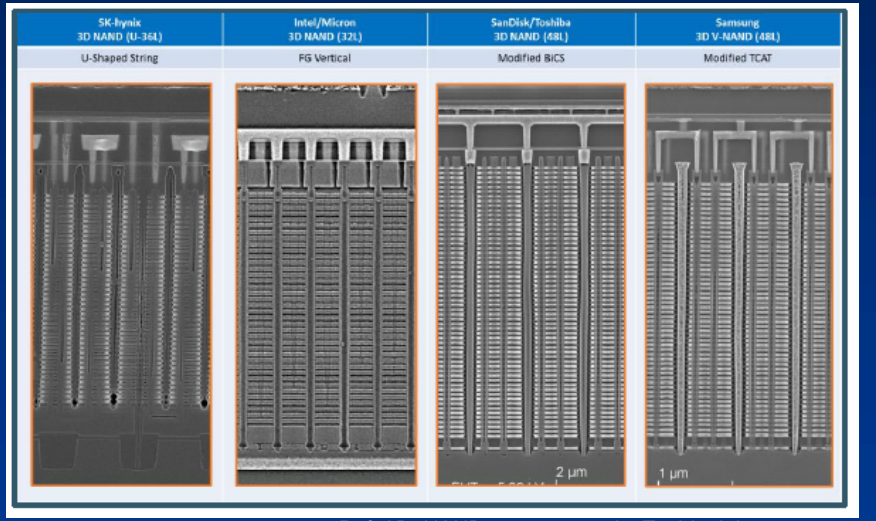


- Flash density growth will continue via 3D NAND layer count scaling 2018-2022+ - TLC, QLC, LL-NAND
- 3D NAND scaling on a 18-24 month cadence thru 2020 – 64L > 96L >120L >190L
- Flash with increasing density can allow for lots of data – accelerating AI growth

Layer count trend for 3D NAND

Flash Memory Summit



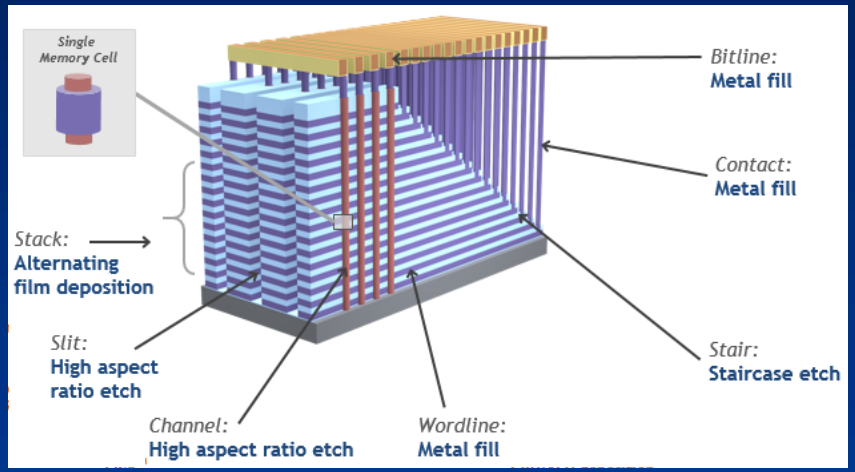


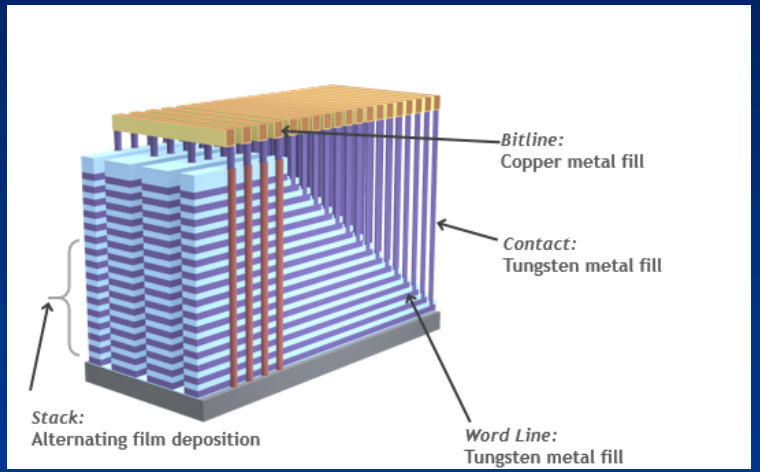
Ref: 3D NAND process trends. TechInsights

- 3D-NAND scaling expected to continue via 3D Layer count increase >200 layers & lithography shrink in 2022+ & beyond – no need for EUV for 8+ years in flash
- Significant 3D-NAND Process, Architecture & Cell materials innovations needed for continued >200Layer scaling

3D NAND Scaling Process challenges

Flash Memory Summit

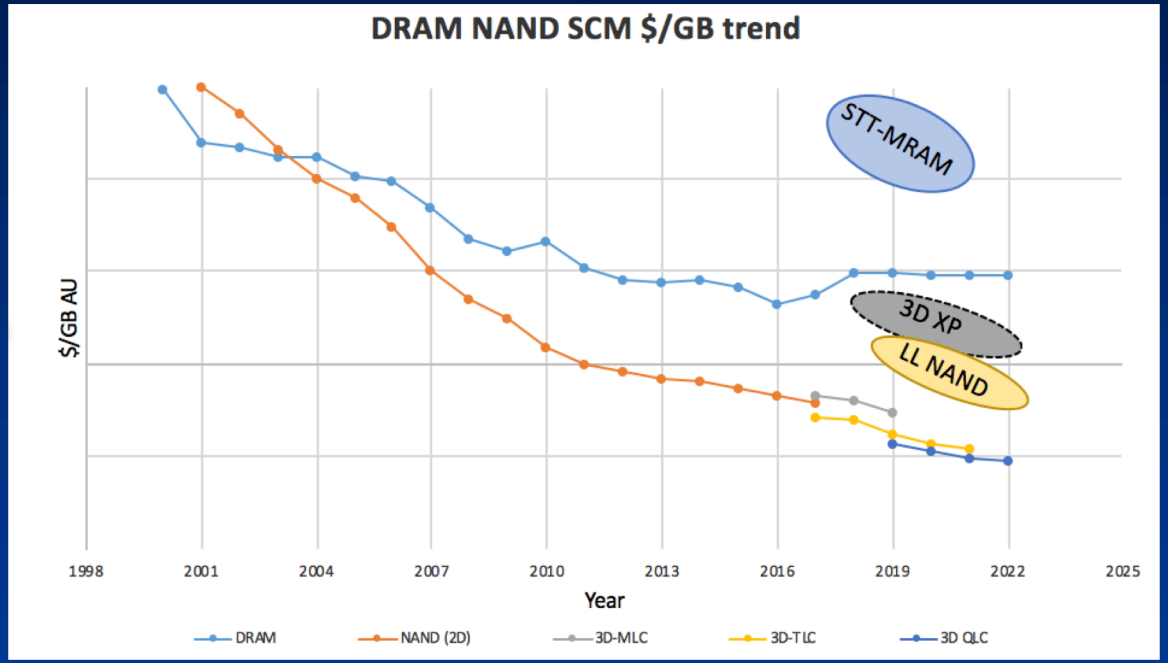




Ref: T. Lill LAM Research, FMS2017

- Increase in number of layers make the high aspect ratio etch challenging-z-directional 3D-NAND cell process controls become critical with multiple etch processes
- Process innovations required in High AR Channel Etch, Stair case contacts, defect control, wafer yield

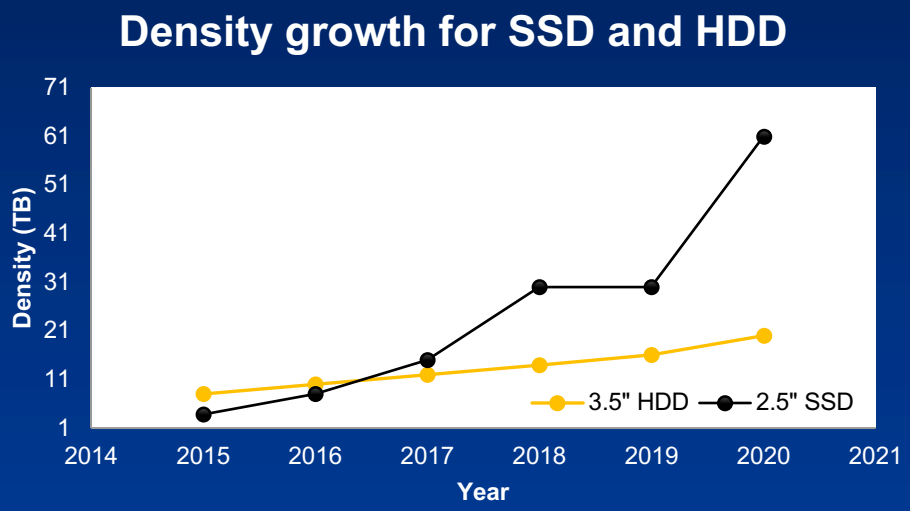
$/GB trend for DRAM, NAND, SCM

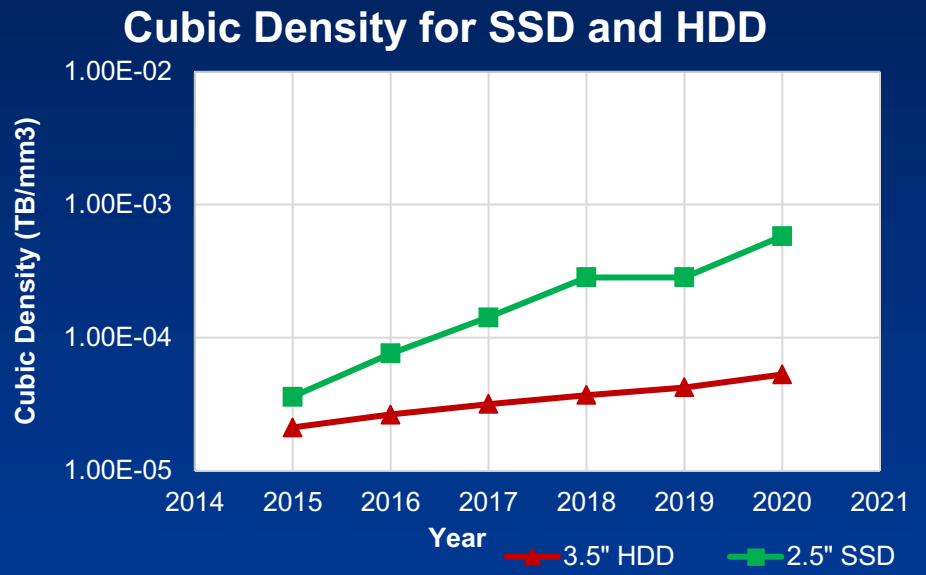


- Flash Market Demand growth – driven by high density 3D NAND bit cost scaling with increased layer count
- Strong penetration of 3D TLC & QLC in Cloud Datacenter & Enterprise Storage in 2018-20
- 3D-NAND scaling enabled bit cost reduction combined with low latency, high throughput accelerating flash driven AI growth

Density Growth for SSD and HDD

Flash Memory Summit

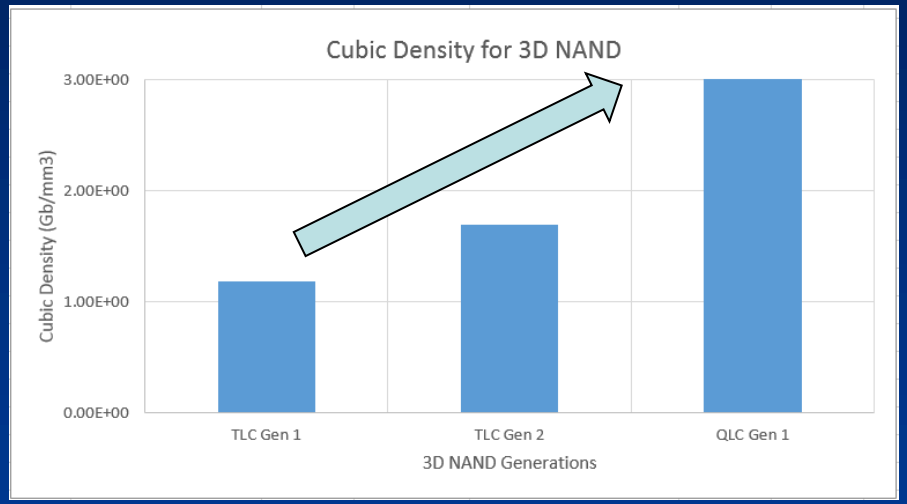




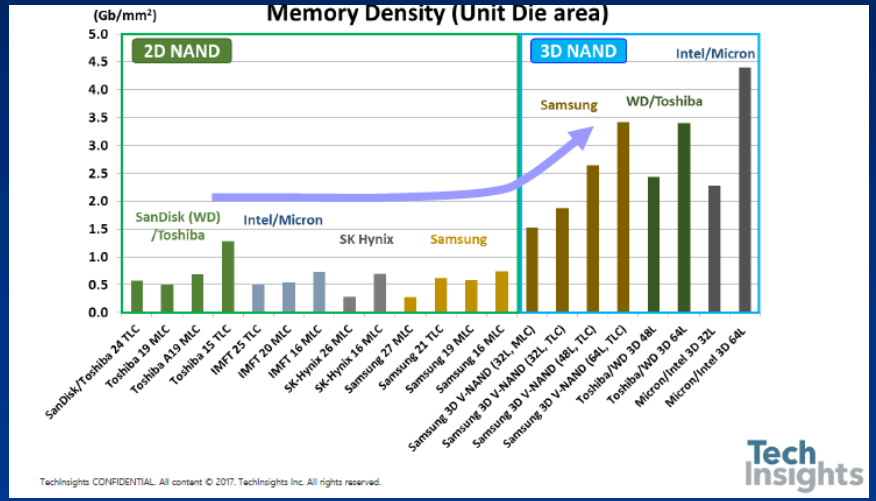
- Drastic increase in Flash-SSD vs HDD in the past 5 years.
- SSD density growth driven by increase in number of layers and capacity for 3D TLC and QLC NAND
- Flash-SSD enables smaller system footprint over HDD– flash driven AI system acceleration (Petabytes of storage can be put in single rack-mount enclosure)

Density growth for 3D NAND

Flash Memory Summit



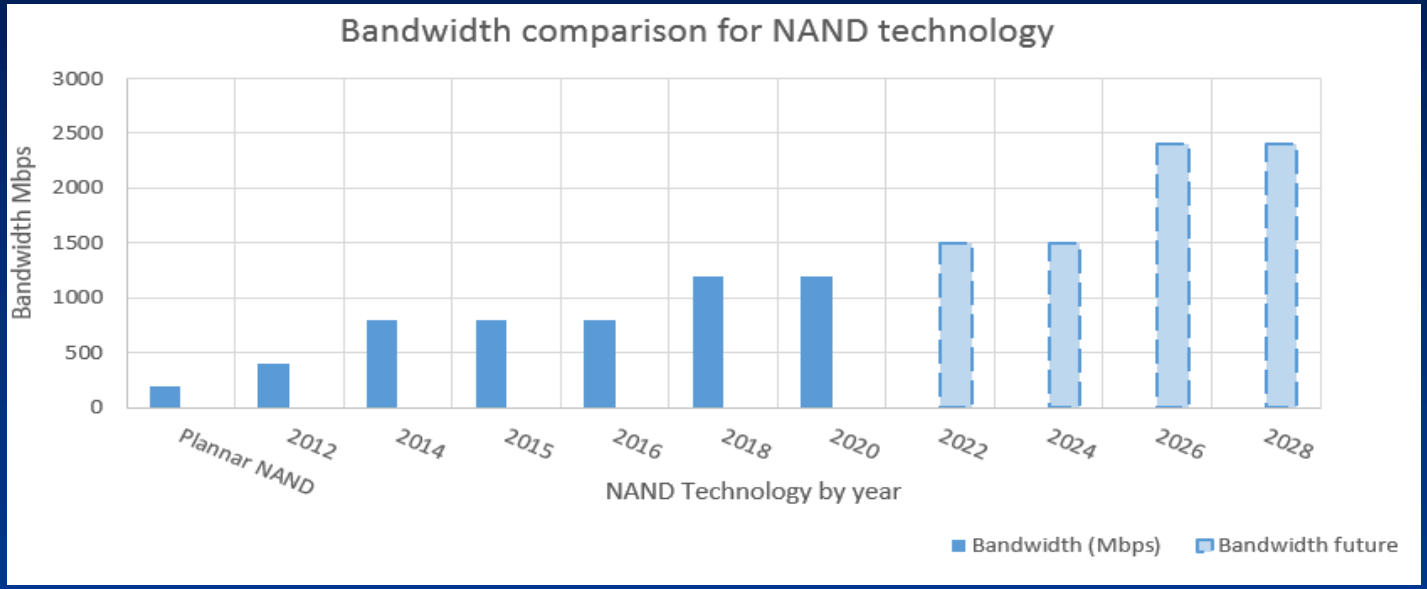
Max Flash memory density/mm3 in 16DP stacked Package



Max Flash memory density/mm2 in 2D Si area

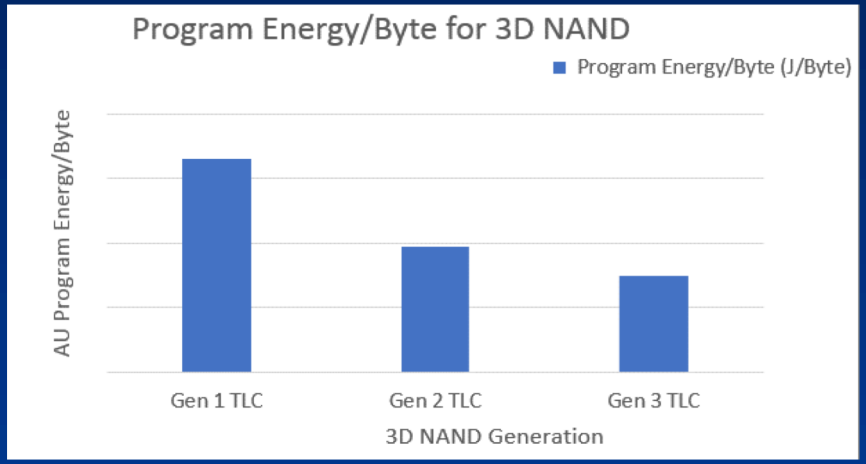
- Increase in 3D-NAND layer count drives significant increase in Si density/mm2 & Package density/mm3
- 3D-NAND scaling density/mm3 increases driving significant storage system footprint efficiencies – optimal for AI Storage solutions

NAND technology vs. Bandwidth

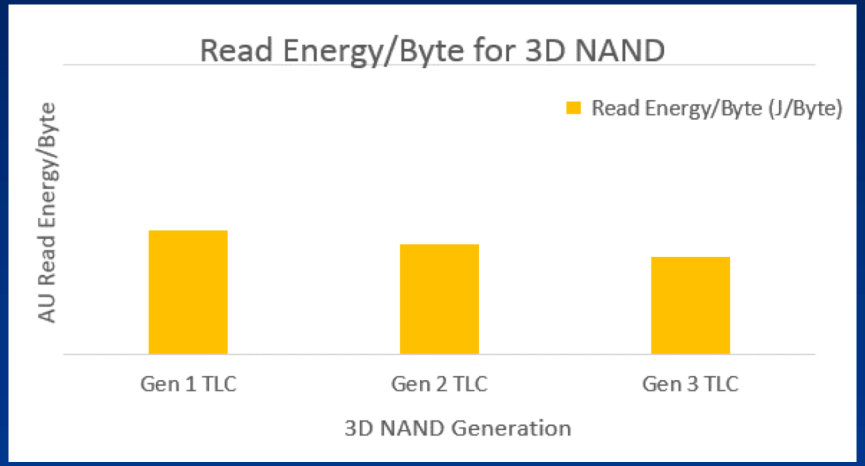


- Bandwidth is the maximum amount of data that can travel through the channel.
- Complex workloads and volume of data is feed to Deep learning set.
- Thousands of threads processing this massive data have to reply on high data delivery rate from storage
- Flash has a very high read throughput density (over HDD) - optimal for deep learning workloads

NAND technology Energy trend



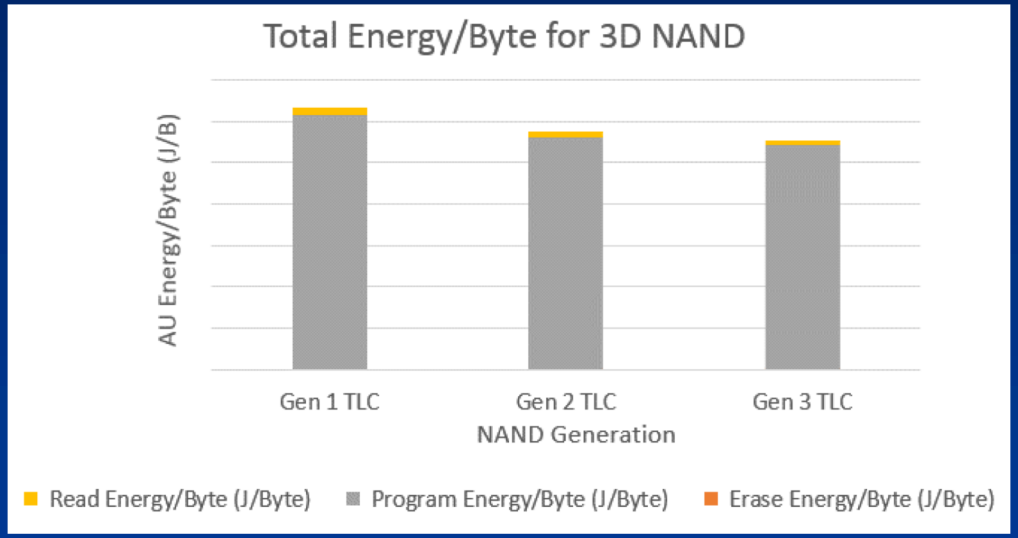
$$(Energy/Byte)_{program} = \frac{Vcc * Icc1 * tprog}{Page\ Size}$$



$$(Energy/Byte)read = \frac{Vcc * Icc2 * tread}{Page\ Size}$$

- With 3D-NAND generations, program and read Energy decreasing trend
- Flash consumes less power vs HDD – significant difference in cost at large scale AI storage systems

NAND technology Energy trend



- Assuming 8% Read, 23% Program and 14% Erase workload

Summary

- AI growth will be accelerate by 3D-NAND technology scaling via high throughput density, lower power consumption, and smaller system footprints
- 3D-NAND enables multi-terabit TLC and QLC densities through cell layer count increases, innovations in circuit design, process technology, and stacked packaging.
- The resulting cost reductions, throughput density increases, and lower power consumption expects to enable significant flash driven AI growth.