

# FMS Timeline

## 1952

MIT's Dudley Buck creates first semiconductor NVM from ferroelectric crystals.

## 1955

Bell Labs' Merz and Anderson create monolithic 256-bit FRAM ferroelectric NVM, the first monolithic memory chip.

## 1961

C.T. "Tom" Sah of Fairchild envisions floating gate NVM using charge storage on the gate electrode of a MOS tetrode transistor.

## 1965

Dov Frohman-Bentchkowsky writes Berkeley PhD thesis "Charge Transport and Trapping in MNOS Structures and its Memory Applications" and builds a 9-bit prototype.

## 1966

Edgar A. Sack, Ting L. Chu and others of Westinghouse use a Metal-Nitride-Oxide-Silicon (MNOS) structure as a charge-trapping element.

## 1967

Dawon Kahng and Simon Sze (2014 FMS Lifetime Achievement Awardee) invent the Non-Volatile Memory Floating Gate at Bell Labs; this is published as "A Floating Gate and Its Application to Memory Devices" (Bell System Technical Journal).

John R. Szedon (2020 FMS Lifetime Achievement Awardee) and Ting L. Chu of Westinghouse propose using a charge trap as a nonvolatile memory bit at the IEEE Solid State Device Research Conference.

## 1968

Stanford R. Ovshinsky announces the Ovonic Memory Switch, the basis for 3D XPoint memory as announced by Intel and Micron in 2015, and as later productized by Intel as Optane.

## 1970

Dov Frohman-Bentchkowsky invents the Erasable Programmable Read-Only Memory (EPROM) at Intel.

After work with Stanford R. Ovshinsky, Intel's Gordon Moore co-authors article for Electronics Magazine on the first demonstration of Phase Change Memory (PCM), the NVM technique used by 3D XPoint as announced by Intel and Micron in 2015, and as later productized by Intel as Optane.



# 1971

Dov Frohman-Bentchkowsky presents "A fully-decoded 2048-bit electrically-programmable MOS ROM" paper describing the EPROM at the IEEE International Solid-State Circuits Conference (ISSCC) in Philadelphia, PA. His "Memory Behavior in a Floating-Gate Avalanche-Injection MOS (FAMOS) Structure" paper as published in Applied Physics Letters cites the 1967 Kahng/Sze Bell Labs Floating Gate publication.

# 1972

Toshiba's Iizuka, Masuoka and others introduce the first double-layered polysilicon memory cell with Floating Gate electrical erase as Stacked-Gate Avalanche-Injection Type MOS (SAMOS) Memory at the Conference on Solid State Devices and Materials in Tokyo. Fujio Masuoka goes on to receive the 2013 FMS Lifetime Achievement Award.

# 1974

General Instrument ships EAROM, the first commercial EEPROM.

# 1975

Hitachi files for patent on NAND-type MROM.

Portable digital camera invented at Eastman Kodak Company with digital image storage on a cassette tape.

# 1976

Eli Harari (2012 and 2022 FMS Lifetime Achievement Awardee), then of Hughes Microelectronics, files for patent on first practical floating gate EEPROM using thin SiO<sub>2</sub> and Fowler-Nordheim tunneling for program and erase.

# 1977

Eli Harari (2012 and 2022 FMS Lifetime Achievement Awardee), then of Hughes Microelectronics, publishes "Conduction and Trapping of Electrons in Highly Stressed Thin Films of Thermal SiO<sub>2</sub>" (Applied Physics Letters).

P.C.Y. Chen of Fairchild introduces SONOS charge trap NVM cell in IEEE Transactions on Electron Devices paper.

Patent granted to TI's Gerald Rogers for mask ROM configured as a NAND array to reduce chip area and cost.

# 1978

Eli Harari (2012 and 2022 FMS Lifetime Achievement Awardee), then of Hughes Microelectronics, publishes "Dielectric Breakdown in Electrically Stressed Thin Films of Thermal SiO<sub>2</sub>" (Journal of Applied Physics).

Micron Technology is founded in Boise, Idaho by Ward and Joe Parkinson, Dennis Wilson, and Doug Pitman.

Hughes Microelectronics introduces first CMOS NOVRAM 256-bit chip (non-volatile SRAM) employing Fowler-Nordheim floating gate EEPROM at IEEE ISSCC in San Francisco.

George Perlegos (2017 FMS Lifetime Achievement Awardee) designs the Intel 2816, which was introduced in 1980 and became the first commercially successful EEPROM.

# 1979

IEEE Solid State Circuits publishes paper titled "An Electrically Alterable Non-Volatile Memory Cell Using Floating Gate Structure" by Guterman, Rinawi, Chieu, Holvorson, and McElroy of Texas Instruments.

Hitachi presents paper describing 16K EEPROM using Silicon-Nitride-Oxide-Silicon (SNOS) charge trap technology at IEEE ISSCC in Philadelphia, PA.

# 1980

Hughes Microelectronics introduces the 3108, first CMOS EEPROM 8Kb chip employing Fowler-Nordheim tunneling.

Intel introduces the 2816, a 16Kb HMOS EEPROM with a FLOTOX (floating gate tunnel oxide) structure employing Fowler-Nordheim tunneling, at IEEE ISSCC in San Francisco.

Fujitsu files for patent on improvements to Hitachi's 1975 MROM.

# 1981

British scientist and inventor Kane Kramer designs first digital audio player (IXI) based on magnetic bubble memory chips.

# 1982

SEEQ Technology presents paper at ISSCC in San Francisco introducing its 5213, the first EEPROM with an on-chip charge pump for in-system write and erase, an invention used in all flash memory devices.

Ramtron introduces first commercial FRAM NVM.

# 1983

Intel introduces 2817A 16Kb EEPROM.

# 1984

First paper describing flash EEPROM (later known as NOR flash) presented by Toshiba's Fujio Masuoka (2013 FMS Lifetime Achievement Awardee) at IEEE International Electron Devices Meeting (IEDM) in San Francisco.

Intel begins flash process development.

George Perlegos (2017 FMS Lifetime Achievement Awardee) founds ATMEL (which stands for "Advanced Technology for Memory and Logic").

# 1985

Exel files for patent on first NOR Flash cell.

NEC's Kitamura files for first MLC (Multi-Level Cell) EPROM patent (in Japan).

# 1986

Flash card concept introduced with ECC and on-card controller by Intel.

Intel forms unit focusing on solid state drives.

R. Stewart *et. al.* of RCA publish first paper on a NAND-configured UV-EPROM at IEEE VLSI Symposium.

# 1987

Toshiba's Fujio Masuoka (2013 FMS Lifetime Achievement Awardee) presents paper on NAND flash memory at IEEE IEDM in Washington, DC; the 35th anniversary of this inventive paper was celebrated at the 2022 FMS.

Intel introduces NOR flash chips.

# 1988

SunDisk founded by Eli Harari (2012 and 2022 FMS Lifetime Achievement Awardee) to develop new "System Flash" architecture combining embedded controller, firmware and flash to emulate disk storage, and files for first MLC (Multi-Level Cell) flash patent.

First flash memory sampled by Intel as 1Mb NOR chips. Intel's Design Team of Richard Pashley, Stefan Lai, Bruce McCormick and Niles Kynett go on to receive 2011 FMS Lifetime Achievement Awards.

Intel and Psion design flash-based mobile PC.

First flash-based digital camera, Fuji DS-1P, demonstrated.

150mm wafers used.



\$25,600,000

\$100,000,000

\$170,000,000

\$295,000,000

# 1989

SunDisk files for patent on "System Flash" which describes on-chip cell management.

M-Systems founded and introduces Flash Disk concept (precursor to flash SSDs); M-Systems co-founders Dov Moran and Aryeh Mergi went on to receive 2018 FMS Lifetime Achievement Awards.

Intel ships 512Kb and 1Mb NOR flash.

Psion flash-based PC introduced.

Microsoft introduces Flash File System in joint effort with Intel.

DigiPro introduces 8MB NOR Flashdisk at Comdex.

Western Digital and SunDisk pioneer NOR-based SSD fully emulating an ATA HDD.

Personal Computer Memory Card International Association (PCMCIA) founded.

Silicon Storage Technology (SST) founded to produce NOR SuperFlash, compatible with a CMOS logic process.

# 1990

Sony introduces EReader using flash memory.

Kodak flash-based camera prototypes shown.

PCMCIA sets standard on ATA PC Card form factor and pinout, using SunDisk "System Flash" specification for full HDD compatibility.

Intel 1MB and 4MB linear flash PCMCIA cards introduced.

Intel introduces 2Mb NOR chip.

SunDisk introduces first NOR flash SSD: 20MB 2.5", fully compatible with Conner peripherals 2.5" ATA HDD.

Toshiba verifies NAND flash chip operation, and begins 4Mb and 16Mb NAND flash chip development.

# 1991

Kodak ships DCS-100, its first DCS at \$13,000.

Zenith, Poqet and HP palm-sized notebook computers using flash memory cards shown at Spring Comdex.

# 1992

Toshiba ships first mass-produced NAND flash chips (4Mb).

Information Storage Devices introduces flash-based voice recorder chip.

AMD introduces its first NOR product.

Fujitsu introduces its first NOR product.

M-Systems introduces TrueFSS, the first flash memory card FTL; this was later adopted by the PCMCIA as its FTL.

Intel launches second-generation FFS2.

Intel introduces 8Mb NOR flash chips and 4MB-20MB linear flash memory cards.

Intel introduces 1Mb "boot block" NOR flash with sectors for BIOS applications—first use of internal write state machine to manage flash write algorithm.

SunDisk introduces first serial 9Mb NOR Flash chip for SSD applications.

PCs begin using flash for BIOS storage.

The Joint Photographic Experts Group published the JPEG standard, enabling digital cameras to store compressed photos using media such as flash memory.

\$505,000,000

\$864,805,000

\$1,860,089,000

\$2,610,603,000

## 1993

Toshiba ships 16Mb NAND flash chips, which enable portable storage with the first PCMCIA cards.

Datalight introduces "Card Trick" flash management software.

Apple introduces NOR flash-based Newton PDA.

Intel introduces 16Mb and 32Mb NOR flash.

Intel and Conner Peripherals introduce jointly-developed 5MB/10MB ATA flash disk drive.

AMD introduces 5-volt-only NOR using negative gate erase.

## 1994

SunDisk introduces CompactFlash card.

Norris Communications introduces Flashback, the first portable digital voice recorder with flash memory.

0.5 micron process announced.

SunDisk introduces 18Mb Serial NOR flash chip for SSD applications.

M-Systems introduces NOR-based DiskOnChip.

## 1995

Flash (NOR and NAND) revenues exceed \$1B.

Casio introduces the QV-11 digital camera with flash rather than film or floppy.

Mitsubishi introduces Divided Bit-Line NOR (DiNOR) flash memory.

SunDisk changes its company name to SanDisk, and has its IPO on the same day.

CompactFlash Association (CFA) founded.

## 1996

\$2.6B in flash memory revenues, 163,063% growth in 10 years.

Toshiba introduces SmartMedia Memory Card (also called Solid State Floppy Disk Card).

Samsung starts shipping NAND flash.

Kodak DC-25 is first DSC with CompactFlash card.

Datalight introduces "FlashFX" flash management software supporting NOR and NAND in a single driver.

SanDisk introduces world's first MLC (2 bits/cell) flash chip (80 Mb) in a CompactFlash (CF) card.

Palm introduces flash memory-based PDA.

0.35 micron process announced.

Lexar Media spins off from Cirrus Logic.

USB Association (USBA) founded.



\$2,701,678,000

\$2,492,552,000

\$4,560,493,000

\$10,637,231,000

# 1997

500 million flash chips ship.

SaeHan Information Systems introduces flash-based MPMAN MP3 player.

SanDisk and Siemens introduce MultiMedia Card (MMC and MMCplus).

Sony introduces the Memory Stick.

First cell phones ship with flash memory.

M-Systems introduces NAND-based DiskOnChip.

200mm wafers begin production.

SanDisk begins using 256 Mb MLC flash chips in its CompactFlash (CF) cards.

Intel introduces 2-bit/cell 64Mb MLC StrataFlash chip.

MultiMediaCard (MMC) unveiled by SanDisk and Siemens.

SanDisk begins transition from NOR to NAND flash.

Atmel introduces DataFlash based on SPI NOR and 8-pin interface, leading to widespread consumer product usage.

# 1998

NOR revenues exceed \$2B.

250nm process announced.

SaeHan Information Systems and licensee Eiger ship first mass-produced MP3 player (MPMAN) with 32MB.

Diamond Rio introduces PMP300 MP3 player.

MultiMediaCard Association (MMCA) founded by 14 companies.

Apple iMac introduced without floppy but with USB, encouraging USB-based external storage.

USB Implementers Forum first publishes USB Mass Storage Class spec (finalized in 1999) to standardize USB-based storage.

# 1999

NOR revenues exceed \$4B.

Over one billion flash chips ship.

Toshiba and SanDisk create flash memory manufacturing joint venture.

Micron announces NOR products.

Hagiwara Sys-Com begins shipping FlashGate, a USB SmartMedia flash memory card drive.

Dov Moran (2018 FMS Lifetime Achievement Co-Awardee) is co-inventor on M-Systems patent filing for USB flash drive.

Lexar Media introduces CompactFlash-to-USB JumpSHOT.

Panasonic (Matsushita), SanDisk and Toshiba introduce SD memory card.

# 2000

Flash (NOR and NAND) revenues exceed \$10B.

M-Systems (working with IBM) and Trek Technology introduce USB flash drives.

Intel ships its one-billionth flash unit.

160nm process announced.

Panasonic (Matsushita), SanDisk and Toshiba establish SD Association to standardize and promote the Secure Digital memory card.

SLC NAND-based SD cards introduced in 8MB to 64MB capacities.

\$7,594,502,000

\$7,766,797,000

\$11,739,282,000

\$15,610,575,000

## 2001

NAND revenues exceed \$1B.

Toshiba and SanDisk announce 1Gb MLC NAND.

SanDisk introduces first NAND "System Flash" product.

Hitachi introduces AG-AND.

Samsung begins mass production of 512Mb flash memory device.

Saifun develops NROM with charge trap flash structure, the basis for Spansion's MirrorBit.

## 2002

Olympus and FujiFilm introduce xD-Picture Card.

MMCmobile card introduced by MMCA (MultiMediaCard Association).

Sony and SanDisk jointly introduce the Memory Stick PRO and half-size Memory Stick PRO Duo cards.

M-Systems introduces Mobile DiskOnChip, the first SSD in a chip; this was used in handsets by Nokia, Motorola and Ericsson.

AMD introduces MirrorBit using hot electron injection-based charge trap flash.

Cypress introduces Programmable System on Chip (PSoC) with first embedded SONOS using quantum mechanical tunneling-based charge trap flash.

130nm process announced.

## 2003

NAND revenues exceed \$5B.

SanDisk introduces miniSD card.

Sony and SanDisk jointly introduce Memory Stick PRO Micro.

Spansion spins out of AMD and Fujitsu.

Samsung introduces TaNOS structure, a technology later used in 3D NAND, at IEEE IEDM in Washington, DC.

## 2004

NAND prices drop below DRAM prices.

U3 software system for USB flash drives introduced by SanDisk and M-Systems.

SanDisk and Motorola introduce TransFlash card, now the microSD card.

Datalight introduces multi-threaded "FlashFX Pro." management software to support multimedia NAND devices.

Spansion announces MirrorBit Quad 4-bit NOR.

90nm process announced.

Hynix and ST Micro form flash joint venture.

Hynix NAND product introduced.

Infineon NAND product introduced based on Saifun Charge Trap Flash.

Panasonic and Sanyo introduce first flash-based camcorders.

SanDisk introduces Flash Sansa MP3 players.

Freescale (later Everspin) ships first commercial MRAM NVM.

Pankaj Mehra and Sam Fineberg of Hewlett-Packard present Persistent Memory paper at IEEE Computer Society's 18th IPDPS.



\$18,568,940,000

\$20,076,313,000

\$22,182,405,000

\$18,435,970,000

## 2005

NAND revenues exceed \$10B.

Over three billion flash chips ship.

NAND GB shipments overtake those of DRAM.

Apple introduces first two flash-based iPods: iPod shuffle and iPod nano.

Microsoft introduces Hybrid Hard Disk Drive concept.

MMCmicro card introduced by MMCA.

70nm process announced.

Micron introduces NAND product.

## 2006

Flash revenues exceed \$20B.

First Flash Memory Summit held in San Jose.

Intel introduces Robson Cache Memory (now called Turbo Memory).

Microsoft introduces ReadyBoost.

SanDisk announces 3-bit MLC (aka TLC) NAND technology.

M-Systems announces 4-bit MLC technology.

SanDisk announces microSDHC card.

SanDisk acquires Matrix Semiconductor.

SanDisk acquires M-Systems.

Samsung and Seagate demonstrate first Hybrid Hard Disk Drives.

IMFT formed by Intel and Micron to manufacture NAND flash.

STEC acquires Gnutech.

Spansion introduces ORNAND flash.

56nm process announced.

300mm wafers begin production.

Micron acquires Lexar Media.

Open NAND Flash Interface (ONFi) V1.0 spec published.

Numonyx and Samsung introduce phase change NVM.

## 2007

Flash revenues exceed \$22B, almost 9 times 1997 revenues.

NAND revenues exceed \$14.5B.

Non-Volatile Memory Host Controller Interface (NVMHCI) Working Group formed, with Intel's Amber Huffman as Chair.

Toshiba introduces eMMC NAND.

IMFT begins shipping 50nm NAND flash.

Toshiba introduces first SATA-based MLC SSD.

Apple introduces the iPhone.

Fusion-io announces 640GB ioDrive MLC NAND-based PCIe X4 board.

BitMICRO launches 3.5" SSD with capacity of 1.6TB (for military applications).

Spansion acquires Saifun.

Several laptop MLC SSDs introduced with up to 128GB storage.

Dell introduces SSD option for laptop models.

Sub-\$200 netbook computers introduced with flash memory storage.

Microsoft introduces flash-based Zune Player.

Seagate announces Hybrid Storage Alliance.

Seagate introduces first hybrid HDD, the Momentus PSD.

MMCA/JEDEC e.MMC spec published.

Toshiba presents 3D flash BiCS memory at IEEE VLSI Symposium.

## 2008

NVMHCI 1.0 Spec released by Intel.

SanDisk introduces ABL to enable high speed MLC, TLC and X4 QLC NAND.

34nm process announced by Intel and Micron.

Toshiba introduces first 512GB MLC SATA-based SSD.

Intel and STMicro spin off Numonyx.

IBM demos first "Million IOPS" array.

EMC announces use of flash-based SSDs for enterprise SAN applications.

Apple introduces SSD-based MacBook Air with no HDD option.

Micron, Samsung and Sun Microsystems announce high-endurance flash memory.

Violin Memory introduces first fully flash-based storage appliance.

Samsung announces 150GB 2.5" MLC SSD with SATA II Interface.

Several companies announce MLC flash SSDs with up to 256GB for notebook apps.

Micron introduces first serial NAND flash.

Apple sells one million flash-based iPhones in 3 days.

MMCA merges into JEDEC.

SNIA Solid State Storage Initiative (SSSI) formed.

HGST releases first SSD with a SAS interface.

\$19,302,693,000

\$26,734,247,000

\$28,123,615,000

\$28,213,759,000

## 2009

SanDisk and Toshiba present 4-bit/cell flash at IEEE ISSCC in San Francisco.

Intel and Micron introduce 34nm TLC NAND.

Samsung introduces first full HD camcorder with 64GB SSD.

Seagate enters SSD market.

SandForce introduces first compression-based SSD controller.

Virident and Schooner introduce first flash-based application appliances for the data center.

Pillar Data converts Axiom SANs to SSD.

WD acquires SiliconSystems and gets into SSD business.

NVELO introduces first PC flash caching software "Dataplex."

SanDisk introduces 100-year flash storage vault.

AgigA ships NAND-backed DIMM.

National Inventors Hall of Fame inductees include Dov Frohman-Bentchkowsky (1971 EPROM inventor at Intel) and Dawon Kahng (1967 Floating Gate co-inventor at Bell Labs with 2014 FMS Lifetime Achievement Awardee Simon Sze).

## 2010

Toshiba introduces 128GB SD card based on 16-chip stack.

Intel, Micron introduce 25nm TLC and MLC NAND.

Numonyx acquired by Micron.

Microchip acquires SST.

Samsung Electronics begins producing 64Gb 3-bit NAND.

Samsung Electronics introduces high-speed 512GB SSD utilizing toggle-mode DDR NAND memory.

Seagate announces first self-managed hybrid HDD, Momentus XT, with 4GB NAND flash and 500GB HDD storage.

Universal Flash Storage Association (UFSA) founded.

JEDEC publishes two specs for Solid-State Drives: "SSD Requirements and Endurance Test Method" and "SSD Endurance Workloads."

## 2011

LSI acquires SandForce.

SanDisk acquires Pliant.

IMFT introduces 20nm NAND flash.

Intel announces Smart Response Technology (SRT) SSD caching for PCs.

Seagate announces second generation Momentus XT hybrid HDD with 8GB NAND flash and 750GB HDD storage.

Apple acquires signal-processing controller IP firm Anobit.

Fusion-io acquires virtualization-aware flash caching software company IO Turbine.

NVMHCI renamed "NVM Express" (aka NVMe) and NVM Express Work Group established; NVMe Rev. 1.0 published.

JEDEC publishes first Universal Flash Storage (UFS) spec.

SNIA publishes two Solid State Storage Performance specs: Enterprise and Client.

JEDEC publishes Serial Flash Discoverable Parameters (SFDP) spec.

Facebook launches the Open Compute Project (OCP) to enable broad industry collaboration of open source software and scalable energy-efficient data center hardware.

Intel's 1988 NOR Flash Memory Design Team of Richard Pashley, Stefan Lai, Bruce McCormick and Niles Kynett receive first FMS Lifetime Achievement Awards.

## 2012

SanDisk and Toshiba announce 19nm process in 128Gb chips at IEEE ISSCC in San Francisco.

Ultrabooks ship with Smart Response Technology (SRT) SSD cache.

Macronix and Winbond enter NAND business.

Seagate introduces SSHD, a Hybrid Hard Drive (HDD) pairing flash with an HDD.

Elpida introduces ReRAM.

Micron and Intel introduce 20nm 128Gb NAND chip using hi-k planar cell.

SK hynix formed upon SK Telecom's acquisition of controlling interest in Hynix Semiconductor.

MOSAID samples 333GB/s HL-NAND.

Adesto acquires ATMEL's Serial NOR business.

DensBits Technologies introduces Memory Modem.

Proximal Data introduces AutoCache.

SanDisk acquires FlashSoft.

EMC acquires XtremIO.

OCZ acquires Sanrad.

Samsung acquires NVELO.

Intel acquires Nevex and introduces CacheWorks.

LSI introduces Nytro flash with MegaRAID Cache-Cade caching software.

Integrated Device Technology (IDT) introduces first NVMe SSD controller chip.

Micron introduces 2.5" PCIe enterprise SSD.

IBM acquires Texas Memory Systems.

Cypress Semiconductor acquires Ramtron.

Western Digital acquires HGST.

JEDEC and ONFi introduce toggle mode.

SNIA forms NVM Programming TWG.

SanDisk founder Eli Harari receives FMS Lifetime Achievement Award.



\$29,797,262,000

\$30,236,484,000

\$30,385,906,000

\$33,732,901,000

## 2013

Samsung announces 24-layer 3D V-NAND at FMS and demos it in a 1TB SSD.

11 companies participate in first NVMe Plugfest.

Diablo Technologies announces Memory Channel Storage tech.

SMART Storage Systems incorporates Diablo Tech designs into ULLtraDIMM.

SNIA NVDIMM SIG formed; many NVDIMM products introduced.

Western Digital and SanDisk introduce SSHD using iSSD combined with a Hard Disk Drive.

Toshiba introduces line of SSHDs.

Everspin Technologies announces shipments of STT MRAM.

Micron and others sample 16nm flash memory.

SanDisk releases CFast 2.0 professional video memory card.

M.2 PCIe interface formalized.

Western Digital acquires sTec, Virident, Velobit.

SanDisk acquires SMART Storage Systems.

NVMdurance introduces software to extend flash endurance.

Micron acquires Elpida.

Intel introduces Intel Cache Acceleration Software.

First UFS devices sampled by Toshiba at 8GB.

Panasonic ships first commercial embedded ReRAM in an MCU.

Adesto ships Mavriq CBRAM: first commercial stand-alone ReRAM.

SNIA publishes NVM Programming Model V1.0.

JEDEC publishes JESD235: first HBM DRAM standard

Fujio Masuoka, formerly of Toshiba, receives FMS Lifetime Achievement Award.

## 2014

Samsung, SanDisk and Toshiba announce 3D NAND production facilities.

Samsung starts mass-producing the first 3D flash SSDs based on its second generation 32-layer Vertical NAND (V-NAND) using TLC.

SanDisk introduces 4TB Enterprise SSD.

Intel ships first NVMe SSD.

SanDisk announces 128GB microSD card, a 1000x increase in capacity on device's 10th anniversary.

IBM announces eXFlash DIMMs using SanDisk ULLtraDIMM's implementation of Diablo Memory-Channel Storage technology.

Spansion introduces HyperFlash NOR with 333 MB/s HyperBus.

Toshiba acquires OCZ.

Everspin introduces and ramps production of ST-MRAM.

Adesto ships one-millionth CBRAM.

SK hynix acquires Violin Memory's PCIe SSD business.

Seagate acquires LSI/Avago storage business.

SanDisk acquires Fusion-io.

HGST acquires Skyera.

Samsung acquires Proximal Data.

Simon Sze, formerly of Bell Labs, receives FMS Lifetime Achievement Award.

## 2015

Flash Memory Summit's 10th conference.

SanDisk introduces InfiniFlash storage system.

Cypress Semiconductor acquires Spansion.

Toshiba, Samsung, and SanDisk announce 48-layer 3D NAND.

Intel and Micron announce 256Gb 3D NAND.

Samsung introduces first NVMe m.2 SSDs.

SanDisk introduces 200GB microSDXC UHS-1 card.

Cypress introduces 4MB serial FRAM.

Intel and Micron announce 3D XPoint Memory.

Intel announces 3D XPoint-based "Optane" DIMMs and SSDs.

Micron introduces device with CMOS Under 3D NAND Array (CUA).

SanDisk introduces 200GB microSD card.

Mellanox and partners demonstrate pre-standard NVMe over Fabrics (NVMe-oF).

Pure Storage has IPO.

JEDEC publishes first DDR4 NVDIMM-N Persistent Memory Module spec.

LightNVM and Open-Channel SSD support added to Linux kernel.

Bob Norman, formerly of SanDisk and Micron, receives FMS Lifetime Achievement Award.

## 2016

All major vendors ship 3D NAND products.

XMC breaks ground on first China-owned NAND flash fab.

Micron introduces 768Gb 3D NAND.

Western Digital acquires SanDisk for \$19 billion.

Everspin announces 256Mb MRAM chips.

IBM adapts TLC to PCM.

Samsung ships 48-layer 3D NAND.

NVMe-oF (NVM Express over Fabrics) Rev. 1.0 published.

NVMe-oF products demonstrated by at least 12 vendors.

Toshiba introduces Through-Silicon Via (TSV) in 16-die stack NAND.

Spin Transfer Technologies delivers fully functional ST-MRAM samples.

Micron launches Xccela Consortium.

Toshiba ships industry's first NVMe BGA "SSD on a chip."

Western Digital demonstrates prototype of the first 1TB SDXC card.

Adesto launches CBRAM-based Moneta family of ReRAM.

SFF Committee becomes SNIA SFF Technology Affiliate.

SNIA publishes Swordfish Scalable Storage Management API spec V1.0.0.

Microsemi acquires PMC-Sierra.

JEDEC publishes JESD235a: HBM2 DRAM standard.

Kinam Kim, President of System LSI / Semiconductor Business at Samsung, receives FMS Lifetime Achievement Award.

\$49,176,520,000

\$56,396,437,000

\$41,940,494,000

\$51,152,080,000

## 2017

Flash Memory market exceeds size of entire 1990 semiconductor market.

Microchip ships its 75-billionth SST SuperFlash-based device.

SK hynix announces 72-layer 3D NAND.

Toshiba migrates all new SSDs to 64-layer BiCS FLASH TLC.

Intel ships Optane (3D XPoint) SSD.

Intel's "Ruler standard" donated to Enterprise & Data Center SSD Form Factor (EDSFF) WG.

HPE acquires Nimble Storage and Simplivity.

Micron ships first string-stacked 3D NAND.

Samsung and Toshiba/WD announce 96-layer 3D NAND.

NGD Systems ships NVMe 24TB Computational Storage Device (CSD).

Everspin samples 1Gb STT MRAM chip.

Global Foundries introduces embedded eMRAM.

WD develops TLC on 64-layer 3D NAND.

JEDEC and SNIA win FMS Award for NVDIMM-N Standard.

ScaleFlux first to deploy production-qualified Computational Storage.

Eli Harari (2012 and 2022 FMS Lifetime Achievement Awardee) inducted into National Inventors Hall of Fame.

George Perlegos, formerly of Intel, SEEQ and ATMEL, receives FMS Lifetime Achievement Award.

## 2018

Cypress introduces 16Mb FRAMs.

Toshiba completes \$18B memory business sale.

Samsung launches high-speed Z-SSD.

Micron ships Enterprise SSD using QLC and 1Tb 3D NAND die.

Hyperstone introduces flash controllers with AI and Machine Learning.

Intel samples Optane (3D XPoint) DC Persistent Memory DIMM.

China's "Big Fund" Phase 2 targets over \$30B for semiconductor investments.

NVMe/TCP Transport Binding spec ratified by NVMe WG.

SNIA forms Computational Storage Technical Work Group (TWG).

Gyr Falcon Technology ships AI accelerator incorporating first use of TSMC's eMRAM.

SNIA publishes Performance specs for Solid State Storage and for Real World Storage Workloads.

Amber Huffman of Intel receives first FMS SuperWomen in Flash Leadership Award.

Microchip acquires Microsemi.

Dov Moran and Aryeh Mergi, M-Systems co-founders, receive FMS Lifetime Achievement Awards.

## 2019

All major vendors ship or sample 96-Layer NAND; SK hynix, Samsung and Micron sample 128-layer NAND.

All leading foundries produce embedded MRAM (eMRAM).

Lightbits Labs ships first commercial NVMe/TCP software-defined disaggregated storage.

YMTC samples 32-layer "Xtacking" NAND.

Intel ships Optane (3D XPoint) DIMMs.

Micron ships first QLC enterprise SSDs.

Intel ships SSDs with both Optane (3D XPoint) and QLC NAND.

Open-Channel SSDs begin transition to NVMe Zoned Namespaces (ZNS).

Computer Express Link (CXL) introduced, CXL Consortium incorporates, and V1.0 and V1.1 specs published.

NGD Systems ships first scalable ASIC-based Computational Storage NVMe SSD.

Eideticom ships first NVMe-based Computational Storage Processor.

SNIA publishes Key Value Store API V1.0, and wins FMS Award.

Toshiba Memory becomes KIOXIA.

Phison and AMD ship first PCIe 4.0 x4 NVMe SSD and motherboard solution.

Calline Sanchez of IBM receives FMS SuperWomen in Flash Leadership Award.

Sanjay Mehrotra of Micron, and formerly of Intel, SEEQ, IDT, ATMEL, SanDisk and WD, receives FMS Lifetime Achievement Award.

## 2020

Flash Memory Summit's 15th conference (held as a virtual online-only event).

WDC ships 112-layer BiCS 3D NAND as 512 Gbit TLC part.

KIOXIA ships first Automotive UFS at 512GB density.

Lightbits Labs ships first clustered, redundant, scale-out NVMe/TCP software solution.

Infineon acquires Cypress Semiconductor.

KIOXIA acquires LITE-ON Technology.

NVMe ZNS Command Set Spec V1.0 published.

NVMe Computational Storage Task Group formed.

Open Compute Project (OCP) publishes V1.0 specs: NVMe Cloud SSD and NVMe Datacenter SSD.

JEDEC publishes first DDR4 NVDIMM-P Persistent Memory Module spec.

JEDEC publishes DDR5 SDRAM standard and Universal Flash Storage (UFS) Card Extension 3.0 standard.

SNIA publishes specs for Native NVMe-oF and Cloud Data Mgmt. Interface (CDMI).

KIOXIA ships first PCIe 4.0 x4 Enterprise NVMe SSD.

Dialog Semiconductor acquires Adesto Technologies.

DNA Data Storage Alliance launched.

Micron ships Crucial SSD with 176-layer TLC 3D NAND.

IBM is first to base enterprise storage on only QLC flash.

Barbara Murphy of WekaIO receives FMS SuperWomen in Flash Leadership Award.

John R. Szedon, formerly of Westinghouse, receives FMS Lifetime Achievement Award.



\$58,817,659,000

\$51,485,810,000

\$39,057,000,000

Flash \$69,026,000,000  
DRAM+SRAM \$95,285,000,000

# 2021

NOR revenues exceed \$3.6B, primarily for SPI NOR.

KIOXIA and WDC announce 162-layer 3D NAND.

SK hynix starts mass production of 176-layer "4D" NAND.

Samsung announces the first DRAM-based memory running on CXL, based on DDR5.

JEDEC publishes XFM (Crossover Flash Memory) Embedded and Removable Memory Device standard.

SK hynix completes first phase of Intel NAND and SSD business acquisition, branded as Solidigm, and Intel exits the flash business.

NVIDIA launches GPUDirect Storage (GDS), providing a direct NVMe-to-GPU data path.

KIOXIA and Samsung announce PCIe 5.0 x4 Enterprise NVMe SSDs.

Renesas acquires Dialog Semiconductor.

NVMe 2.0 standard released as a set of 9 specs: base, 3 cmd. sets, 4 transports, and Management I/F.

Winbond dual-buffer NAND with SPI interface gets wide adoption for automotive code storage, including for Advanced Driver Assistance Systems (ADAS) and Over-the-Air (OTA) updates.

SNIA publishes Transport Layer Security (TLS) spec V2.0.

Samsung introduces SmartSSD computational storage drive (CSD).

Toshiba demonstrates MAS-MAMR (Microwave Assisted Switching – Microwave-Assisted Magnetic Recording) HDDs.

# 2022

35th anniversary of NAND Flash celebrated at FMS.

PCI-SIG releases PCIe 6.0 spec.

Universal Chiplet Interconnect Express (UCIe) V1.0 spec published to standardize die-to-die interconnects.

JEDEC publishes JESD238: HBM3 DRAM standard.

Micron 2400 SSD shipped with 176-layer QLC 3D NAND.

Lightbits Labs ships first clustered NVMe/TCP software-defined public cloud storage solution.

Solidigm demonstrates prototype Penta-Level Cell (PLC) SSD.

CXL Consortium and JEDEC sign MOU to advance DRAM and Persistent Memory.

NVMe Boot Specification published.

JEDEC publishes UFS 4.0 standard and Automotive SSD standard.

DNA Data Storage Alliance joins SNIA as a Technology Affiliate.

SNIA publishes Computational Storage Architecture and Programming Model V1.0.

Micron ships Crucial SSD with 232-layer TLC 3D NAND with 6-plane architecture.

Yan Li of Western Digital receives FMS SuperWomen in Flash Leadership Award.

Yoshishige Kitamura (formerly of NEC), SanDisk founder Eli Harari (2012 FMS Lifetime Achievement Awardee), and Greg Atwood (formerly of Intel, Numonyx, and Micron) receive FMS Lifetime Achievement Awards.

# 2023

SK hynix ships 238-layer TLC "4D" NAND using peripheral under cells (PUC) layout.

KIOXIA and WDC announce 218-layer TLC and QLC 3D NAND using 4-plane CMOS directly Bonded to Array (CBA) technology.

Solidigm ships P5430 enterprise SSD with 192-layer QLC NAND.

SK hynix showcases samples of world's first 321-layer NAND at FMS.

JEDEC publishes JESD317: CXL-attached Memory Module (CMM) spec.

SCSI Trade Association (STA) becomes SNIA SCSI Trade Association Forum (STA Forum).

SNIA Swordfish V1.2.4a becomes an ISO Standard.

NEO Semiconductor launches 3D X-DRAM, the first 3D NAND-like DRAM.

SNIA publishes Computational Storage API V1.0.

Micron samples industry's first 8-high 24GB HBM3E memory.

Samsung introduces 32Gb/s GDDR7 DRAM.

WDC announces its split into independent HDD and flash businesses.

Samsung, SK hynix, and Micron introduce Low-Power Double Data Rate 5X (LPDDR5X) DRAM.

Micron presents 3D Stacked NVDRAM with ferroelectric capacitors at IEDM.

IBM ships 3592 JF 50TB tape cartridge with compressed capacity up to 150TB.

Amy Fowler of Pure Storage receives FMS SuperWomen in Flash Leadership Award.

Amber Huffman of Google Cloud, and formerly of Intel, receives FMS Lifetime Achievement Award.

# 2024

Samsung, SK hynix, and Micron begin HBM3E volume production.

SNIA's DNA Data Storage Alliance publishes DNA Stability Evaluation Method for DNA Data Storage Containment Systems V1.0.

NEO Semiconductor launches 3D X-AI, the first 3D Memory with AI Processing.

Computational Storage specs published: NVMe Computational Programs V1.0 and NVMe Subsystem Local Memory V1.0.

SK hynix ships 321-layer TLC flash using "Three Plugs" process and 1Tb capacity.

JEDEC publishes GDDR7, using Pulse Amplitude Modulation (PAM) for high frequency DRAM operations.

SK hynix releases Zoned UFS (ZUFS 4.0) mobile NAND capable of on-device AI apps.

Ultra Accelerator Link (UALink) Consortium formed to define AI accelerator intercommunication industry standard.

Micron ships first automotive-grade quad-port SSDs for autonomous and AI-enabled workloads.

First notebook PCs with Compression-Attached Memory Modules (CAMMs).

WDC/Kioxia switch to 2 wafers (logic+core) for BiCS8 3D NAND.

Micron 2500 SSD with 232-layer QLC 3D NAND ships.

Harriet Coverston of Versity Software, and formerly of Sun Microsystems, receives SuperWomen of FMS Leadership Award.

Hideaki Aochi, Ryota Katsumata, Masaru Kito, Masaru Kido, and Hiroyasu Tanaka of Toshiba, now KIOXIA, receive FMS Lifetime Achievement Award for creation of the first 3D NAND.

# 2025

Micron, Samsung and SK hynix introduce LPDDR5X memory with 128GB small outline compression attached memory module (SOCAMM), co-developed with NVIDIA.

Micron samples 1γ (1-gamma) node-based LPDDR5X memory, improving bit density per wafer by more than 30% over 1β (1-beta).

Phison demonstrates E28 SSD controller with NAND-based AI cache to accelerate GPU inference speed.

JEDEC publishes JESD270-4: HBM4 standard with 8 Gb/sec xfer speed and 2 TB/sec bandwidth.

SK hynix samples 16-layer HBM3E and 12-layer 2TB/s HBM4.

NEO Semiconductor introduces 3D X-HBM high-bandwidth memory.

The UALink Consortium, with over 85 member companies, releases Ultra Accelerator Link™ 200G 1.0 spec with scale-up interconnect for AI clusters.

Seagate's Exos M HAMR (heat-assisted magnetic recording) 32TB HDD enters production.

Western Digital completes spin-out of Sandisk, which it had acquired in 2016.

Samsung samples hybrid CXL memory module (CMM-H) combining DRAM and NAND for persistent and tiered memory.

PCIe 7.0 available with 128 GT/s raw bit rate and 512 GB/s bi-directionally.

Flash memory named #1 storage innovation of last 25 years in Coldago Research survey.

# 2025

(continued)

HBM 2025 sales expected to double to over \$30 billion.

Micron samples 36GB 12-Hi 1β (1-beta) HBM4 modules.

KIOXIA ships 8th gen. 218-layer BiCS 3D flash SSDs with CBA wafer bonding, and previews 10th gen. 332-layer flash.

NVIDIA launches Spectrum-X networking platform, which accelerates AI network performance over traditional Ethernet.

Atomic Ethernet Industry Association (AEIA) formed to support an architecture ranging from chiplets to global connectivity, in collaboration with OCP, SNIA, and the IEEE.

LTO Consortium's Linear Tape-Open 10 (LTO-10) drives and media (30TB native / 75TB compressed) start shipping.

Solidigm unveils a cold-plate liquid-cooled hot-swappable E1.S form factor SSD.

Twist Bioscience spins out DNA-based Atlas Data Storage.

Western Digital supports disaggregated storage with mix of HDDs and SSDs, and invests in ceramic data storage pioneer Cerabyte.

SD Association celebrates 25 years of establishing SD memory card standards.

Intel completes final phase of its \$9 billion sale of NAND and SSD business to SK hynix.

Rita Gupta of AMD, and formerly of Intel, receives SuperWomen of FMS Leadership Award.

Jim Pappas, formerly of Intel and DEC, receives FMS Lifetime Achievement Award.



***This Timeline is viewable online, and available as a PDF, in the "About/Timeline" page on the [FutureMemoryStorage.com](https://www.FutureMemoryStorage.com) website, where you can also suggest additions and changes.***

