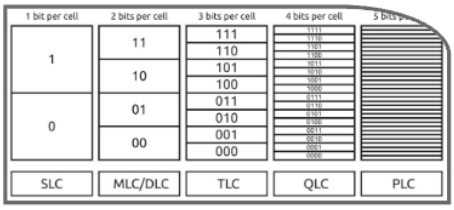
LIFETIME ACHIEVEMENT AWARD - 2022

Yoshishige Kitamura, Eli Harari, and Greg Atwood

Yoshishige Kitamura, Eli Harari, and Greg Atwood are the co-recipients of the 2022 Flash Memory Summit Lifetime Achievement Award for each playing an important role in bringing Multi-Level Cell, or MLC, to the flash memory industry.

The Importance of MLC

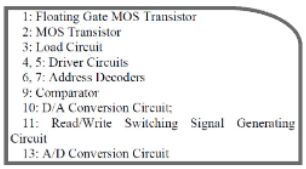


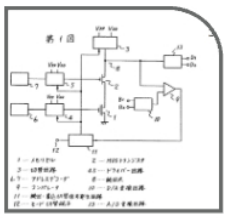
Storing more than one bit in a data cell is a critical aspect of virtually all Flash memory shipped today. When Flash chips supporting 2 bits per data cell were first marketed in 1996, the feature became known as Multi-Level Cell, or MLC. In MLC Flash memory, each transistor is programmed into one of several intermediate threshold-voltages, or current-conduction levels, and these fall somewhere between the on and off states of a single-bit-per-cell transistor (called Single-Level Cell, or SLC). The original MLC devices were based on NOR Flash, and these transitioned to the now-dominant NAND Flash. Chips able to support 3 or 4 bits per data cell have come on the market, with 5 bits per cell being imminent, and these are generally called Triple-Level Cell (TLC), Quad-Level Cell (QLC), and Penta-Level Cell (PLC), respectively.

Because of the dramatic importance of these ever-greater data densities, Flash Memory Summit awarded the 2022 Lifetime Achievement Award to three individuals who were instrumental in enabling the original MLC functionality in floating gate-based storage.

Yoshishige Kitamura

Yoshishige Kitamura invented the concept of storing multiple bits in a single memory cell to reduce the memory's overall cost. As an example, he chose EPROM, which uses a floating gate. (Shown here is an NEC EPROM with its transparent window to allow UV light to erase data after being written.) Kitamura's invention was created in 1985 while he was employed at Nippon Electric Co. (later NEC), the Japanese corporation that at that time was the world's largest semiconductor manufacturer, and the world's leading supplier of DRAM and EPROM devices.


1: Floating Gate MOS Transistor
2: MOS Transistor
3: Load Circuit
4, 5: Driver Circuits
6, 7: Address Decoders
9: Comparator
10: D/A Conversion Circuit;
11: Read/Write Switching Signal Generating Circuit
13: A/D Conversion Circuit



Kitamura's invention is set forth in his 1985 Japanese patent application S62-34398, filed on 8 August 1985. Shown here is Figure 1 from this document, with a translated description of its numbered items. Portions of the invention description read "FIG. 1 illustrated a non-volatile memory with two bits in one element" and "the two bits to be written are converted into an analog signal by the D/A conversion circuit 10." NEC did not obtain a patent based on Kitamura's application, and the invention was never actually used in an NEC product. In the 1980s Japanese companies did not believe in the value of patents, so companies filed patent applications that were termed 'laid open patent applications' with the sole purpose of keeping someone else from patenting what their company had invented.

Kitamura worked at NEC throughout his career, first in bipolar IC evaluation and software development, then in metal gate and silicon gate MOS memory chips, microprocessors, and other ICs, and finally in development of computer-automated design (CAD) and device models

for MOS ICs. His work was selected three times for presentation at the IEEE International Solid State Circuits Conference (ISSCC). After retiring from NEC in 2006, Kitamura joined Japan's SSIS (*Society of Semiconductor Industry Specialists*) where he currently leads a course in memory and power devices titled "Introduction of Major Devices."

Eli Harari

Dr. Eli Harari's work at SunDisk (renamed SanDisk in 1995) led to the first Flash memory chips and products that incorporated MLC technology. From SunDisk's founding in 1988, it was clear to Harari that the biggest market for Flash memory was in data storage, as opposed to the code storage applications typical for EPROMs. Since data is generally more voluminous than code, Flash affordability was thus of paramount importance. As a result, most companies that began to compete in the Flash memory arena in the 1990s were focused on reducing costs by shrinking transistors through Moore's Law scaling.

When Harari founded SunDisk, a key goal was creating a Flash memory cell able to store more than one bit of information. He filed SunDisk's first patent disclosing the MLC Flash memory concept on June 8, 1988, a few days after the company's founding. Issued in 1992 as US Patent 5,095,344, and titled "Highly Compact EPROM and FLASH EEPROM Devices," it disclosed "multistate storage."

Filing the patent was the easy part, but producing an MLC chip turned out to be far more complicated. A critical component that made for a more reliable MLC Flash chip was a family of inventions by Bob Norman, Sanjay Mehrotra, and Eli Harari called System-Flash, and each of these co-inventors became FMS Lifetime Achievement Award winners in 2015, 2019, and 2012, respectively. In System-Flash, a dedicated intelligent controller works in tandem with metadata maintained onboard each Flash chip in order to reliably manage the data correction and cell retirement aspects of wear-leveling that is essential to ensure Flash memory's long life and reliability.

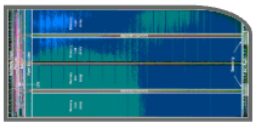
SunDisk's first working MLC chip was a 12 million cell test chip in 1989 which stored 18 million bits, or 1.5 bits per cell. It took seven more years before SanDisk's 1996 introduction of a 10MB CompactFlash (CF) memory card whose Flash chips stored 2 bits per cell. Shown here are the front and back of facsimiles of this 10MB CF card, and the back includes citations to two SanDisk MLC patents. One year later in 1997, SanDisk produced 32MB MLC Flash chips for use in its CF cards. Nine years later in 2006, SanDisk introduced the world's first commercial Flash memory with three bits per cell (TLC), and in 2008 the world's first 4 bits-per-cell "X4" (QLC) Flash for use in Secure Digital High Capacity (SDHC) cards and Memory Stick PRO Duo cards. The X4 technology was invented by M-Systems, whose founders received the 2018 Lifetime Achievement Award, and whose company was acquired by SanDisk in 2006.

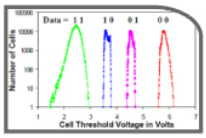
Eli Harari is an inventor of over 180 patents. He received his BsC with Honors in Physics from the Univ. of Manchester in 1969, and his PhD in Solid State Physics from Princeton Univ. in 1973. His recognitions include the IEEE Robert N. Noyce Medal in 2009, the National Medal of Technology and Innovation presented by President Obama at the White House in 2014, and induction into the National Inventors Hall of Fame in 2017. He was the 2012 Flash Memory Summit Lifetime Achievement Award winner for founding SanDisk, the company that created the market for data storage in flash.

Greg Atwood

Greg Atwood was the key person at Intel responsible for putting MLC Flash into volume production. While working on EEPROM device development, Atwood learned of telephone answering machines that used EEPROM-based storage to capture linear values for voice recordings. He thought that the same concept could be used to store multiple bits per Flash cell. Although he was at that time unaware of Kitamura's patent application, he knew that the concept of storing multiple bits on a floating gate was feasible. He convinced FMS 2011 Lifetime Achievement Award co-honoree Dr. Richard Pashley to free up some of his Flash memory team members to form a group to work on this effort as its success would lower production costs by half.

At first this technology, dubbed by Intel as "StrataFlash," was expected to require significant management and error correction, and so it was initially designed to be paired with a controller in a PCMCIA card. An early prototype was demonstrated at the 1995 IEEE ISSCC. When further characterization proved that it could meet nearly all of the specifications of Intel's standard NOR Flash without a controller, Intel changed its strategy and developed a StrataFlash chip that could be sold into all of its Flash applications.





Shown here is a photomicrograph of the 8MB Intel StrataFlash memory as first sold in 1997, along with a histogram showing the threshold voltage distributions for data stored in this device. The success of this product eventually allowed Intel to phase out its SLC technology altogether. Atwood was recognized as the 13th Intel Fellow, and the first Intel Fellow from the Memory Group.

Greg started his career in 1979 at Intel after receiving a Master's Degree in Physics from Purdue University. His first job was the design of the high-performance transistors used on the 80186 through 80386 microprocessors. Despite the fact that Atwood never changed employers, he worked for three companies: Intel, Numonyx (spun off from Intel in 2008), and Micron Technology (which acquired Numonyx in 2010). In the late 1990s, he initiated the Intel effort to investigate emerging memories as potential successors to Flash. Atwood started the Phase Change Memory Program, which led to a short-lived product at Micron and set the foundation for what eventually became 3D XPoint memory. As a Senior Fellow at Micron in 2010, he led the pathfinding efforts in the technology and product development group focused on future memory technologies, components, and systems. Greg holds over 40 patents covering a wide range of technical topics. He retired from full time work in 2021, although he remains active as a part-time consultant.

Lifetime Achievement Award Committee member Brian Berg, 2022 Award Co-Recipient Dr. Eli Harari, and Lifetime Achievement Award Committee member Chuck Sobey

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Note: Co-Recipient Yoshishige Kitamura received his award *in absentia*.