Honda Foundation Report No. 174
Commemorative lecture at the 39th Honda Prize
Award Ceremony on the 19th November 2018

Great Encounters That Led Me to the Invention of Flash Memory

Dr. Fujio Masuoka

Professor Emeritus, Tohoku University

Representative's Address:

Dr. Koji Sakui

Principal Scientist, Honda Research Institute Japan Co., Ltd.

HONDA FOUNDATION

Dr. Fujio Masuoka

Professor Emeritus, Tohoku University

■Date of Birth

May 8th, 1943

■Biography

1966: Graduated from Department of Electronic Engineering, School of Engineering, Tohoku University
1971: Obtained a doctorate in engineering from Department of Electronic Engineering, Graduate School of Engineering, Tohoku University
1971: Joined Tokyo Shibaura Electric Co., Ltd. (currently Toshiba Corporation)
1994: Resigned Toshiba Corporation and appointed as a professor of Graduate School of Information Sciences, Tohoku University
1996: Transitioned to a professor of Research Institute of Electrical Communication, Tohoku University
2005: Appointed as the director and chief technology officer of Unisantis Electronics (Japan) Ltd.
2007: Retired Tohoku University and appointed as a professor emeritus of the Tohoku University
2012: Changed the corporate name from Unisantis Electronics (Japan) Ltd. to Semicon Consulting Ltd., continuing up to today

■Major Patents, Papers, and Publications (out of 189 patents, 79 papers, and 114 Int'l conference publications)

- F. Masuoka, U.S. Patent, 4, 437, 174, Mar.13, 1984(national patent application, 1981)
- F. Masuoka, U.S. Patent, 5, 245, 566, Sept. 14, 1993 (national patent application, 1987)
- F. Masuoka, et al., IEEE Tech. Digest, IEDM, 1984, p.464-467.
- F. Masuoka, et al., IEEE Tech. Digest, IEDM, 1987, p.552-555.
- B. Fulford: "Unsung Hero in Japan", Forbes Global, June 24, p.24-26 (2002)
- 2010 Computer History Museum (CHM) (elected to the Hall of Fame)
- 2011 Consumer Electronics of America (CEA) (elected to the Hall of Fame)
- Special Issue for Dr. Masuoka, IEEE Solid-state Circuits Vol.5, No.4 (2013).
- "Transition of Semiconductor Memories and Their Future Prospects," Journal of the Institute of Electrical Engineers of Japan, Vol. 136, Issue 1, p.34-37 (2016)

■Major Awards Received (out of 16 awards)

1980: Invention Award, National Commendation for Invention, Japan Institute for Promoting Invention and Innovation
1997: IEEE, The Morris N. Liebmann Memorial Award
2000: The Main Prize of Ichimura Industrial Award, the New Technology Development Foundation
2002: International Conference on Solid State Devices and Materials, SSDM Award
2005: The Economist Innovation Awards
2007: Medal of Honor with the Purple Ribbon
2012: The Photographic Society of America (PSA), Progress Medal
2013: USA Flash Memory Summit, Lifetime Achievement Award
2013: Person of Cultural Merit
2017: Orders of the Sacred Treasure, Gold and Silver Star

<u>Substitute Lecturer: Dr. Koji Sakui</u>

Principal Scientist

Honda Research Institute Japan Co., Ltd.

■Biography

1981: Joined IC Lab, Toshiba Research and Development Center, Toshiba Corporation (served as a visiting scholar in electrical engineering at Stanford University from Aug. 1991 to Feb. 1993 during his years at the company)
1998: Led NAND development (design, device, and applied technology) as a manager of the Flash Memory Design Department, Toshiba Corporation
2004: Served as a general manager of Memory System Department, Sony Corporation, managing the development of a high-speed flash system
2007: Served as a research scientist in the NAND Products Group, Intel Corporation (US), and engaged in the development of SSDs for multi-bit NAND products
2009: Served as a visiting professor at Tohoku University, conducting a study of vertical transistors
2010: Served as a senior architect and technologist, Micron Japan Ltd., and registered 54 US patents for 3D NAND
2017: Became a principal scientist at Honda Research Institute Japan Co., Ltd. (continues up to today)
2018: Became a principal scientist at Tokyo Institute of Technology (continues up to today)
2009: Became a part-time professor at the School of Advanced Science and Engineering, Waseda University, responsible for the "Integrated Circuits" lectures (continues up to today)

He holds an engineering doctorate, the IEEE Fellow membership, 67 Japanese patents, and 144 US patents; and published 25 papers.

This report is the gist of the commemorative lecture at the 39th Honda Prize Award Ceremony at the Imperial Hotel, Tokyo on 19th November 2018.

Dr. Masuoka, thank you for that kind introduction. As you've just heard, my name is Koji Sakui and I am Principal Scientist at Honda Research Institute Japan. Allow me to offer my most heartfelt congratulations. It is a great honor for me to offer the representative's address on behalf of Dr. Masuoka—in fact, it feels presumptuous—so thank you for bearing with me.

When we were both at Toshiba, for 13 years, Dr. Masuoka was a great source of guidance to me. In a surprising twist of destiny, I am presently doing research work on artificial intelligence, or AI, at the Honda Group's basic research facility, Honda Research Institute Japan.

I would now like to speak on the subject of flash memory.

Fig. 1

〈Fig. 1〉 Ladies and gentlemen, no doubt most or all of you have smartphones. How many gigabytes of storage does your phone have? This is the kind of conversation we have routinely nowadays. When we talk about "how many gigabytes," we're talking about flash memory. That flash memory is where we put our music data, videos and photos.

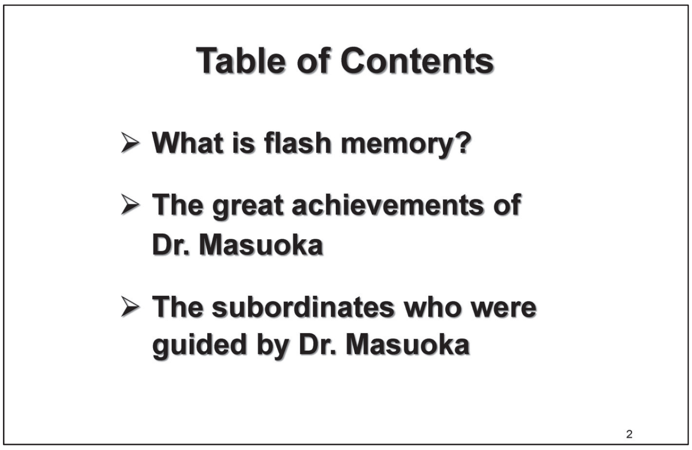


Fig. 2

〈Fig. 2〉 We just watched the Honda Foundation's video on what flash memory is, but I'd like to reprise the basics briefly if I may. I will then speak about Dr. Masuoka's great work. Finally, I will conclude by sharing a few episodes that showcase what we, the disciples and subordinates of Dr. Masuoka, have learned from this great man.

■ What Is Flash Memory?

On November 23, 2017, a TV program on Dr. Masuoka was presented as a special feature. It was produced by Kenichi Sasaki, NHK's Chief Educational Producer, who is in attendance today. NHK followed that program with a three-minute digest entitled "Human." I'd like to play that digest for you now.

(Video plays)

Fig. 3

Reference URL: https://www.facebook.com/NHKhuman/posts/195188218052637/

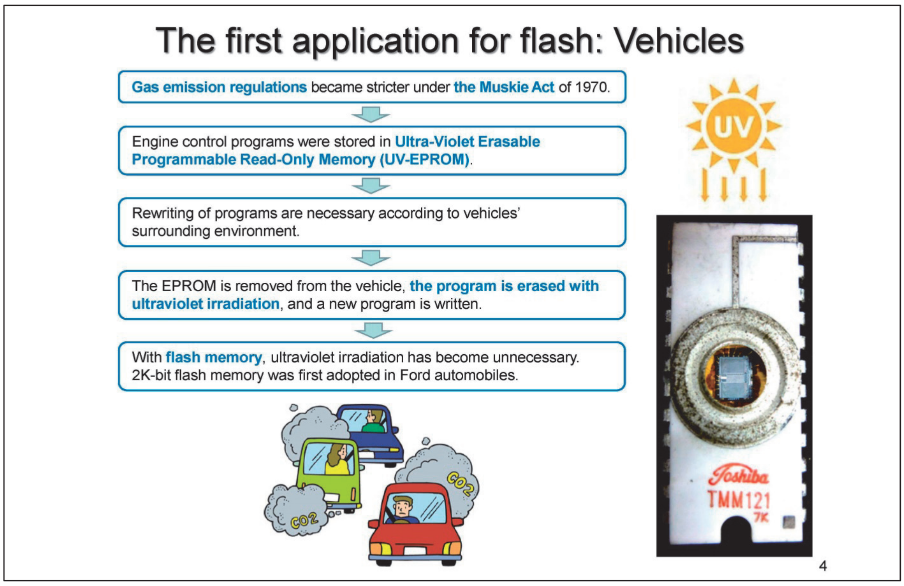


Fig. 4

〈Fig. 4〉 Today, flash memory is used in USB memory, smartphones, and many other applications, but what do you suppose was its original application and purpose? President Hachigo just concluded a discussion of ECU, and many of you assembled here today are affiliated with Honda. However, most of you would never have thought that the first application of flash memory was in on-board systems. That realization may be surprising, so let's unravel some of that history.

In 1970, about half a century ago, regulations on car exhaust were tightened with the passage of the Clean Air Act in the United States (also known as the Muskie Act). Automakers had to find ways to control their engines. The first type of memory used to control car engines was EPROM. Dr. Masuoka contributed hugely to EPROM, too, before he invented flash memory. In the center of this photo of processor memory, you can see a glass window. This window was used for irradiating the memory with UV light. The UV light erased any programs on the memory in one batch. This was EPROM. Now, testing had to be done in a wide variety of environments in which cars might operate, from the deserts of Arizona to the cold of Alaska. In each case tuning was required, which meant engine control was required. This was a grueling process.

With EPROM, reprogramming was an unwieldy and cumbersome business. You had to physically remove the circuit board from the engine, irradiate it with UV, write the new program to the circuit board, then reinstall the circuit board in the engine. The arrival of flash memory did away with this UV irradiation; the program could be overwritten electronically. I've heard that the first automaker to do this was Ford.

Today, of course, flash memory is used not only in automobiles but in computers and consumer electronics. Refrigerators, rice cookers, you name it—they all incorporate flash memory.

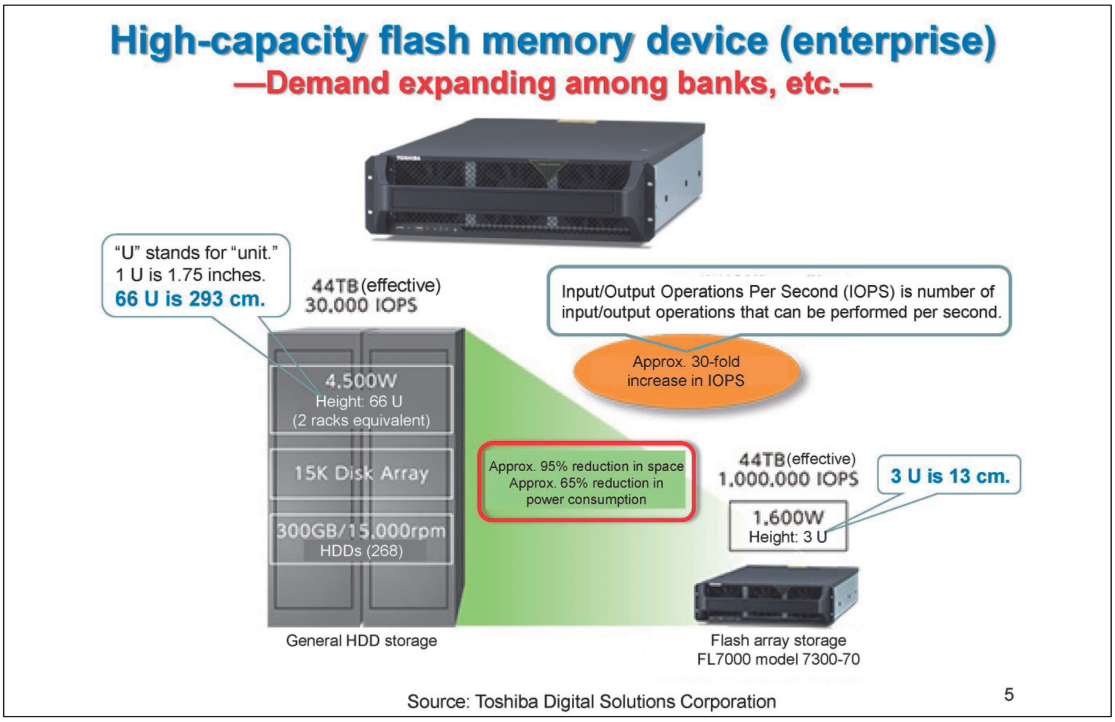


Fig. 5

〈Fig. 5〉 Recently demand for large-capacity storage devices, such as enterprise servers, has been growing, at banks and so on. At left you can see the capacity of conventional hard-disk storage. At right, you can see the capacity of an all-flash enterprise server. Let's start with speed. "IOPS" means "input/output per second," that is, the number of input and output operations that can be performed per second. The improvement is a factor of 30. A quantum leap.

Now let's look at size. This "U" stands for "unit," one unit being 1.75 inches, so 66 U is 293 centimeters, so about 3 meters. With SSD, a kind of flash memory, the size is only 3 U, or 13 centimeters. That's just one-twentieth the size, incredibly small. And flash memory saves power, too. Power consumption falls from 4,500 watts to 1,600 watts. That's the difference between current hard-disk storage and flash storage. Such dramatic downsizing means you save money on the housing, too, with a huge cost reduction in terms of heat value. The blessings we receive from flash memory are nothing short of extraordinary. These are the kinds of enterprise servers being used at major banks today.

The Google website shows a photo of a data station on the Gulf of Finland. It uses the icy waters of the Gulf of Finland for cooling purposes. Hard disks are constantly being turned by motors, like record turntables, and those spinning motors generate a lot of heat. So the data station needs the Gulf of Finland's frigid waters to keep it cool.

What I want to focus on here is that SSDs and flash memory are faster and use less power than hard disks. And that's not all: As we've just seen, they use less space. The running costs for this data station using hard disks are enormous. Because running costs typically equate to about three times initial investment, Google and other major data-station users are evincing keen interest in flash memory and have started replacing their hard disks with it.

How big a business is flash memory? Worldwide, it's on the scale of about 6 trillion yen.

There are basically two types of flash memory: the kind used in your smartphones, and the kind used in SSDs. There are two kinds of SSDs. One of them is used in PCs and tablets.

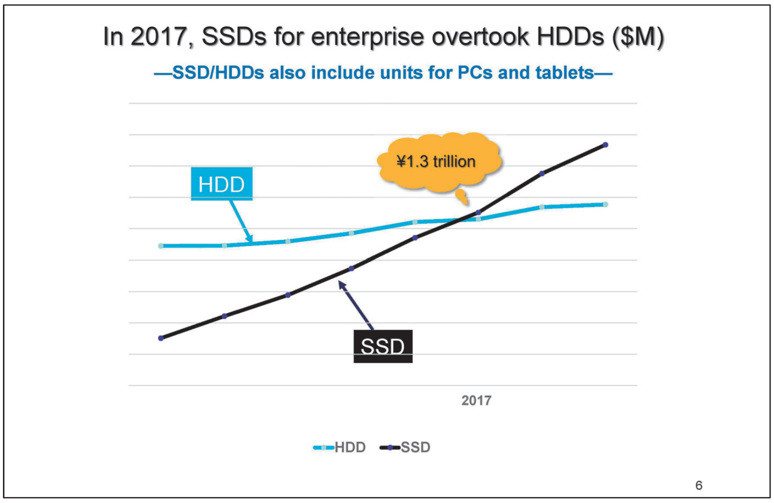


Fig. 6

〈Fig. 6〉 If we compare on the basis of the enterprise servers used by major banks and the like, we see that SSDs overtook hard-disk drives, HDDs in 2017. This is a revolutionary development. When SSDs surpassed HDDs, their market size was about 1.3 trillion yen. SSDs have become a major contributor to electronics firms' global sales.

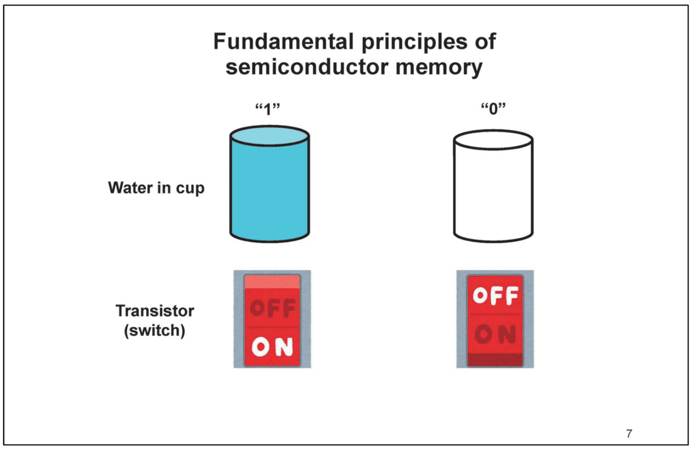


Fig. 7

〈Fig. 7〉 But what about semiconductor memory? Talking about semiconductors can get a bit abstruse, as technical concepts such as electrons and holes are used, but let's forget that for now and consider the analogy of a cup of water.

The cup on the left is filled with water, while the cup on the right is empty. We can define these states as 1 and 0. The world of computers is binary, also consisting of ones and zeroes. The only question is, does the cup hold water, or does it not? The ON and OFF states of a transistor work on the same principle. Turning a 1 into a 0 or vice versa is called *switching*. Logically, allocating 1 to ON and 0 to OFF or the contrary works either way as well. This is a basic principle of semiconductor memory.

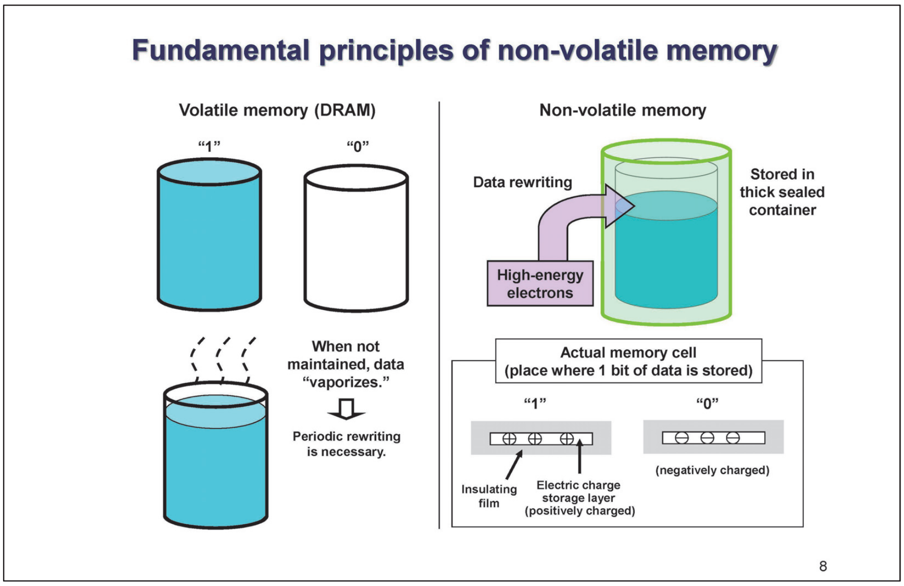


Fig. 7

〈Fig. 7〉 There are two types of semiconductor memory. One is volatile memory, such as the DRAM inside a PC. Volatile memory is memory whose data disappears when the power source is shut off. The opposite is non-volatile memory, which holds its data even when power is interrupted. Examples include USB and smartphone memory.

Volatile memory is like the example we've just seen, of a cup that is either full of water or empty. How does non-volatile memory differ? Non-volatile memory is like a cup in a thick, covered container. Why does that make a difference? Volatile memory is analogous to an uncovered cup: the water we put in evaporates over time unless it is topped up, or in computer terminology, refreshed. The data in volatile memory is written over and over cyclically. The reason why batteries for smartphones run down is that they contain DRAM, which runs down the batteries by continually refreshing the data.

Non-volatile memory is like the cup encased in thick glass. Placing water in the glass requires a great deal of energy. In non-volatile memory, that energy comes in the form of high-energy electrons. Pardon me for abruptly talking about electrons. These high-energy electrons are analogous to the water in our cup metaphor. Once they are in the memory, they stick around. This is the principle of non-volatile memory. If I may get a bit more scientific about it, the "glass" that encases the "water" corresponds to an insulating film of silicon dioxide, or silica.

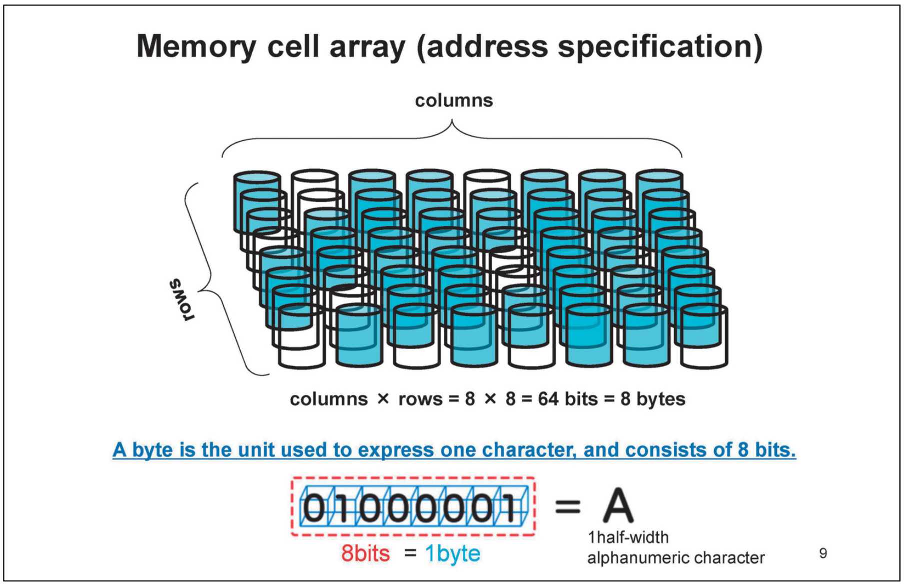


Fig. 9

〈Fig. 9〉 Memory has addresses. Specified by rows and columns, addresses allow a system to issue an instruction to fetch the data at such-and-such an address, or to write data to a certain address. Here we see an array of cups, eight rows long and eight columns deep, making up 64 cups. Numerous patterns can be made by specifying which cups hold water and which do not. If we have 64 cups, we have 64 bits of data, or 8 bytes.

A byte is a unit of data sufficient to express one character of text, where 8 bits equals 1 byte. One half-width alphanumeric character requires 8 bits to express it, so a unit of 8 bits is commonly accepted as a byte.

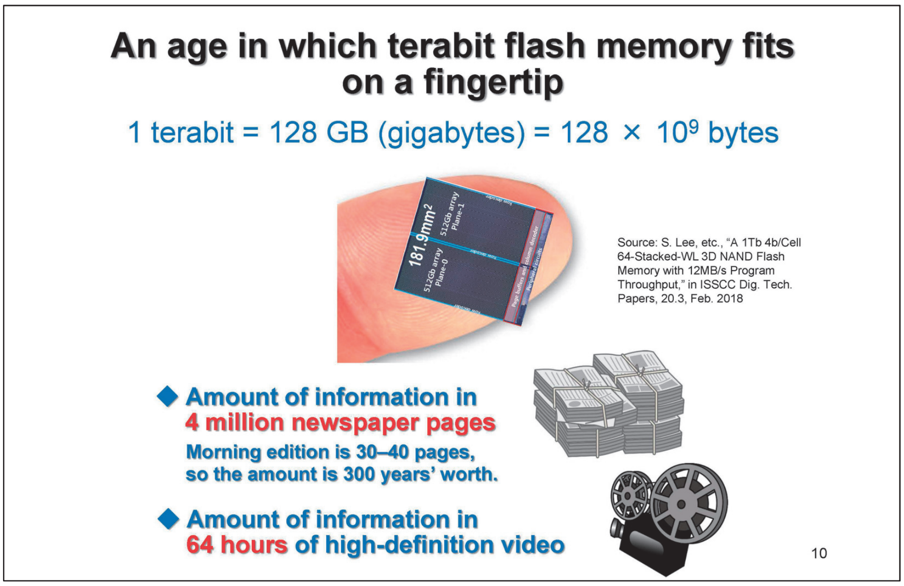


Fig. 10

〈Fig. 10〉 At this point you may be thinking that semiconductor memory is pretty simple. But how much capacity does a given system have? The capacity of flash memory is rising constantly, and today we have entered the realm of terabits of data. The prefix *tera-* means “10 to the 12th power,” which is an awkward sum to use, so instead of saying “terabit” we say 128 gigabytes. I think this is a more familiar term, for some smartphones are said to use 64 gigabytes. In exponent terms, 128 gigabytes is 128×10^9 bytes. But how much information does 128 gigabytes hold?

When my colleagues and I joined Toshiba, I, too, was involved in the development of DRAM. We developed a 1-megabit DRAM chip, which is said to hold the equivalent of four pages of newspaper. A terabit is on another order altogether: It is the equivalent of 4 million pages of broadsheet. Imagine, if you will, 300 years’ worth of morning newspapers. Amounts this big are impossible to conceptualize. In digital terms, it’s enough to store 64 hours of high-definition video. Quite amazing, really. Sixty-four hours’ worth of video, stored on a chip you can hold on the tip of your finger. So I hope I have given you some indication of the prodigious amount of data flash memory can hold, without getting bogged down in technical details.

■ The Great Work of Dr. Masuoka

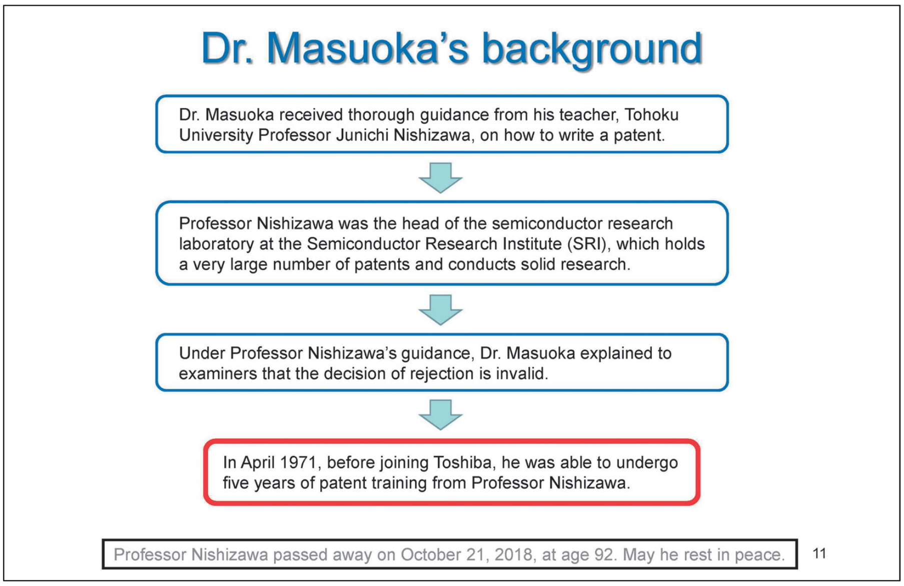


Fig. 11

〈Fig. 11〉 Now I’d like to proceed to describing to you the monumental work of Dr. Masuoka. As you’ve seen from the Honda Foundation video on Dr. Masuoka’s background, Dr. Masuoka gained thorough instruction on how to write a patent application from his former professor Dr. Junichi Nishizawa. As a professor at Tohoku University, Dr. Nishizawa owns an impressive list of patents, testament to his sterling research work. He also served as the head of the semiconductor research laboratory at the Semiconductor Research Institute (SRI). So Dr. Nishizawa not only mentored Dr. Masuoka on research matters, he also taught him how to write patent applications.

I was told that, under Dr. Nishizawa's tutelage, Dr. Masuoka explained to patent examiners from patent offices in Tokyo, and sometimes from the Japan Patent Office, that the final rejections issued by them were without legal force. Dr. Masuoka worked at Dr. Nishizawa's lab for five years, earning his Master's degree and Doctorate degree there. When he joined Toshiba in April of 1971, Dr. Masuoka was already a seasoned hand at writing patent applications. With five years of rigorous instruction from Dr. Nishizawa under his belt, Dr. Masuoka had completed his patent training before his career at Toshiba began. He understood the patent process better than engineers serving at Toshiba at the time.

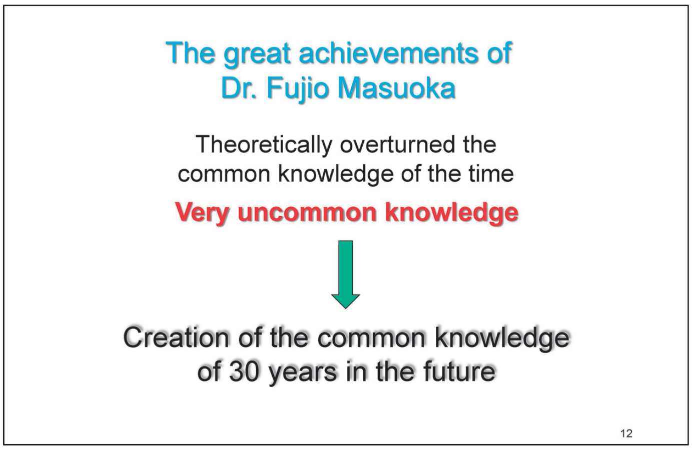


Fig. 12

〈Fig. 12〉 Covering all of Dr. Masuoka's extensive roster of accomplishments in one presentation would be an impossible task. But with the time available to me I would like to describe them to you as best I can. Dr. Masuoka overturned the conventional thinking of his day. This is an incredible feat in itself—and Dr. Masuoka's ideas *really* turned the received wisdom on its head. He tabled proposals that we lesser mortals could not even understand. That is to say, he imagined the commonplace of 30 years in the future. People who can see 25 years into the future are regarded as visionaries. Steve Jobs is one example. Visionaries are truly rare in this world, but without a doubt Dr. Masuoka is one.

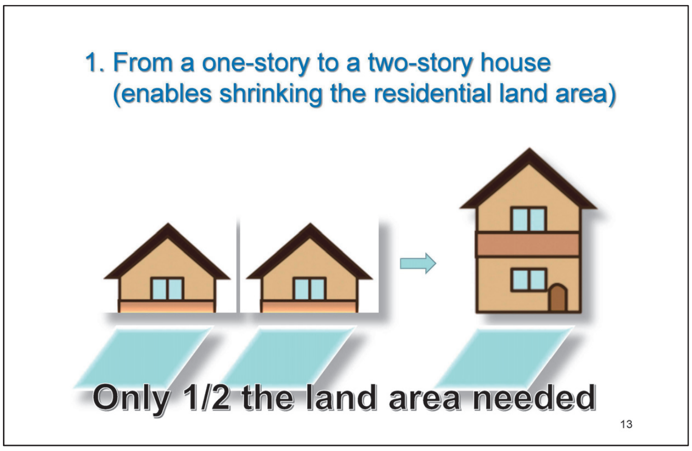


Fig. 13

〈Fig. 13〉 His first idea was to change the layout of the semiconductor from one level to two.

As with house construction, a two-level layout maintains the same available area with half the footprint. Memory developers are under constant pressure to increase chip capacity. If a chip of one square centimeter today has a capacity of 1 megabyte, next year it must have twice as much. The next year, capacity must double again. This year's 1-megabyte chip must give way to 2 megabytes next year, and the 2-megabyte chip to 4 megabytes again next year. Relentlessly shrinking the size of the chip is of paramount importance.

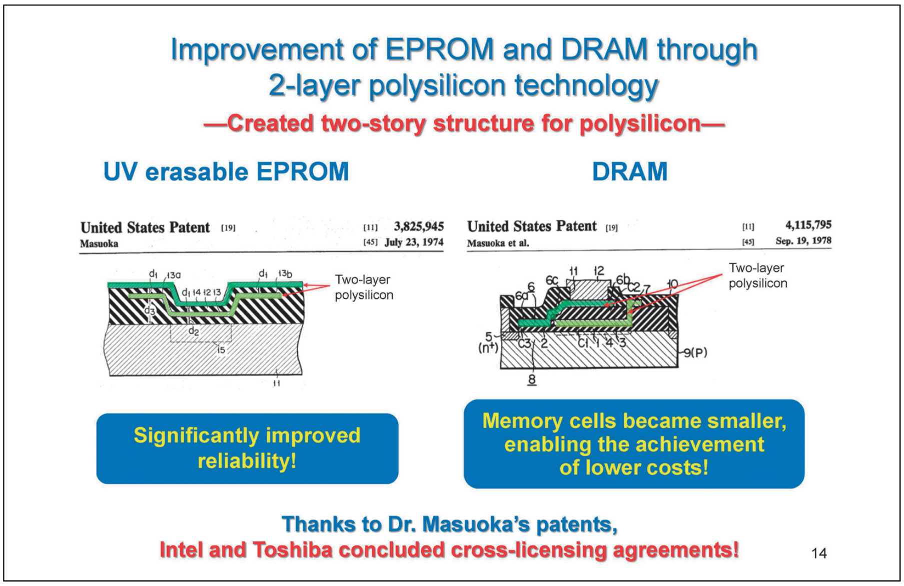


Fig. 14

〈Fig. 14〉 Dr. Masuoka first introduced his two-level polysilicon design on EPROM, the memory with the glass window we encountered earlier. He then moved on to improve DRAM. If I may go into a little detail here, polysilicon is a material commonly used in semiconductor fabrication; Dr. Masuoka's innovation was to introduce the two-level layout, or the gate stack structure. EPROM's reliability improved dramatically. This was the work Dr. Masuoka was achieving before he began his work in flash memory.

Next, Dr. Masuoka shrank the memory cell size in DRAM, achieving significant cost reductions. Thanks to Dr. Masuoka's patent, Intel and Toshiba concluded a free cross license for this technology. This was the first of Dr. Masuoka's great works.

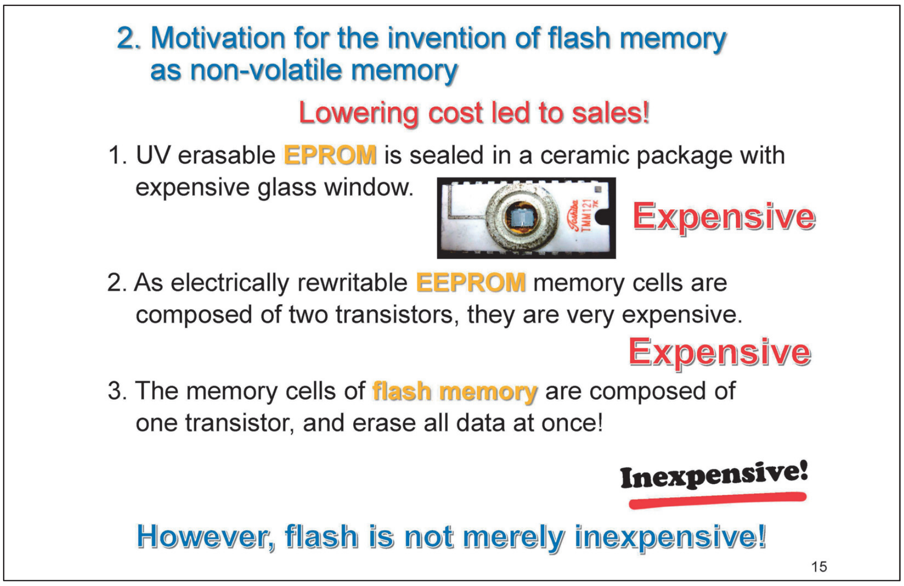


Fig. 15

〈Fig. 15〉 How did Dr. Masuoka come to set his sights on flash memory? Dr. Masuoka's motivation in pursuing flash memory was his desire to create less expensive non-volatile memory. He believed this innovation would yield improved sales. That relates to my earlier discussion of flash memory being used to help lower costs.

For example, EPROM, the memory whose photo I showed you earlier, which used UV light to clear data, incorporated a prohibitively expensive glass window embedded in a ceramic package. Another type of memory cell, EEPROM, which I haven't covered, could be overwritten electrically. This version, however, included two transistors, making the memory cells inordinately large and expensive.

Dr. Masuoka thought carefully about this feature, wondering if a single transistor could be made to erase all data as a batch. This is the inquiry that led to flash memory. That is to say: EPROM, with its glass windows, is expensive. EEPROM, with its two-transistor configuration, is expensive. Flash memory would use only a single transistor. This would be cheap. But low cost was only the beginning of the benefits.

Fig. 16

〈Fig. 16〉 Dr. Masuoka’s first paper on flash memory, which he presented to the IEEE International Electron Devices Meeting, or IEDM, in 1984, has the word “Flash” written on it.

At that time I was in my fourth year at Toshiba. One day Dr. Masuoka was seated behind me, talking with several other people. IEDM was coming up in December in San Francisco, so it was about the right time to submit a paper. They were discussing what the new memory type should be called. It was June 1984, if I recall correctly. When it came time to submit the paper, Dr. Masuoka was still racking his brains as to what to name his new memory.

The head of SRAM at the time, a fellow named Ariizumi, suggested: “Dr. Masuoka, how does ‘Flash’ sound to you?” “I like it!” replied Dr. Masuoka, and the name stuck. Dr. Masuoka explained the name as follows: “The data disappears in a flash, like a strobe on a camera, so ‘Flash’ is a good name.” In the title of his paper, Dr. Masuoka used the word “Flash.” All of this transpired in a conversation behind me. I remember it well.

Toshiba didn’t think to register the name as a trademark. The company approved the title without any other preparations. As the term “Flash” was a familiar name, several years later Intel established an internal group named “Flash Memory Division.” Intel worked intensely to develop flash memory.

On the campus of Intel headquarters in Santa Clara, California, next to the Robert N. Noyce Building, stands the Intel Museum. One of the exhibits inside is a flash memory booth. When I saw that flash memory booth, it sent a shiver down my spine. A placard on the exhibit explained that a Japanese company, Toshiba, had invented flash memory, and that Intel was developing it. I thought, “What an amazing company Intel is!” The United States is a country that looks at people who have accomplished great things and judges them on their legitimate merits, no matter where they're from. Of course, Intel wrote that note with pride and confidence. That placard is displayed in a museum that is open to the public, visited by groups of schoolchildren and general museum-goers. The impact of seeing that placard has never left me.

Fig. 17

〈Fig. 17〉 In 2012 Dr. Masuoka received an award from the Photographic Society of America (PSA). I don't know if Dr. Masuoka envisioned receiving such an award when he chose the name "Flash" for his invention, but it's an interesting coincidence. Dr. Masuoka received the PSA Progress Award just as the newspapers were announcing, "Canon stops selling film cameras, ending more than 80 years of history." It was flash memory that caused silver-halide photographic film to all but disappear. But flash memory was not merely the replacement for silver halide.

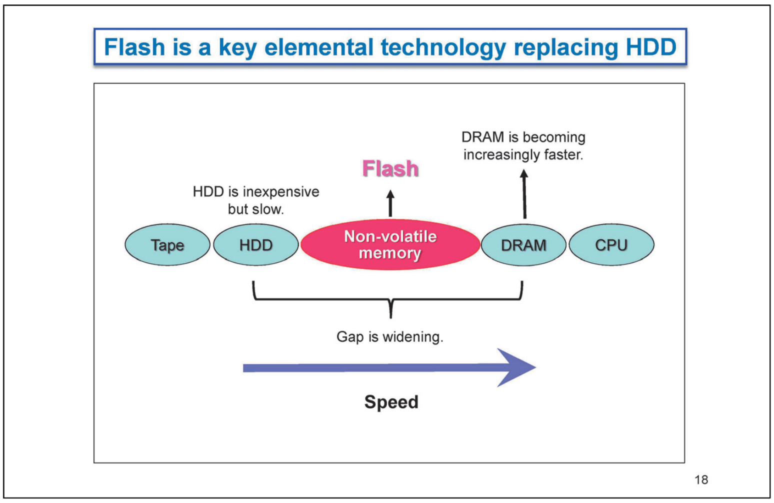


Fig. 18

〈Fig. 18〉 Flash memory is an important elemental technology in place of HDDs. It completely changed the architecture of computers. This is DRAM, which is volatile memory.

On the left we see an HDD. With CPUs and DRAM becoming faster and faster, the gap between these technologies and HDDs was growing ever wider. The technology that bridged this gap was flash memory. But it was no mere replacement for film photography. It gave rise to a completely new architecture.

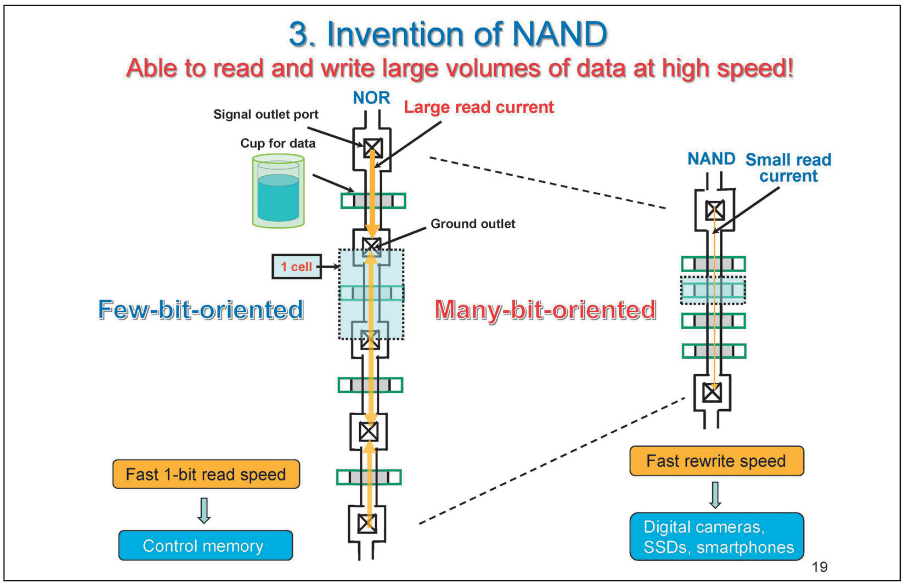


Fig. 19

〈Fig. 19〉 This schematic illustrates the invention of the NAND flash. On this side is a NOR flash. The decision on whether current flows is determined by whether there is water in the cup or not. In the NOR flash, the current flows through a single transistor, so the current is extremely high.

After inventing the NOR flash, Dr. Masuoka invented the NAND flash. This is a very long serial connection or cascade connection. Today the longest NAND cascade connections extend to 128 memory cells in a series. Of course, reading data using this arrangement requires much less current than a NOR flash does. On the circuit or device level, NAND flash was designed many-bit-oriented, in contrast with NOR flash, called few-bit-oriented, allowing it to read and write large volumes of data at high speed. That’s the advantage that a NAND flash brings.

Fig. 20

〈Fig. 20〉 So NAND flash memory enables access to large volumes of data. What have been the benefits? At the top of the list is the digital camera. You used to see those *Purikura* photo booths that printed stickers to trade with friends. They are still around, but high-school students all carry digital cameras with them everywhere, most recently in the form of smartphones. And then there's USB memory. To make sure that my presentation went smoothly, I brought all my data in a USB memory stick. And, of course, there is the smartphone. A whole popular culture has been spawned, all thanks to the NAND flash memory. NAND has transformed the culture.

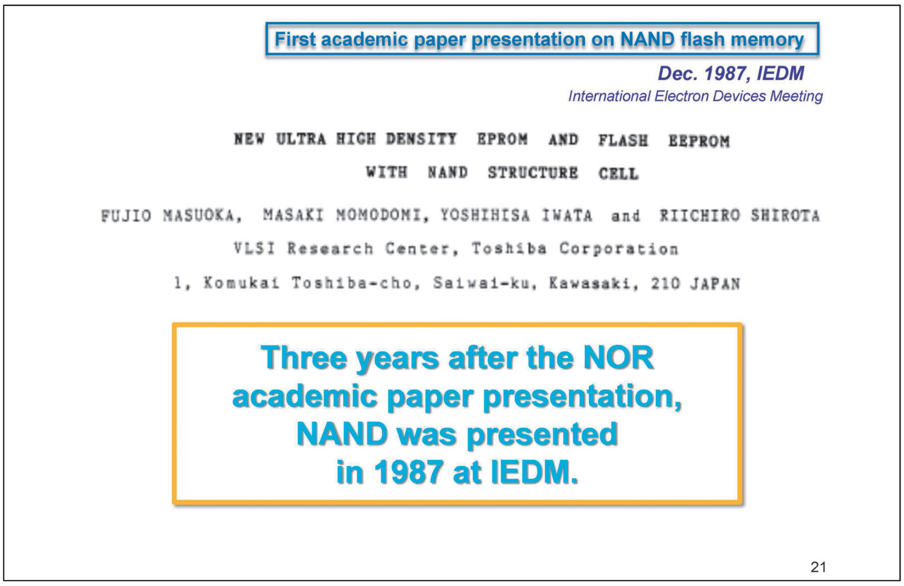


Fig. 21

〈Fig. 21〉 This is Dr. Masuoka's first thesis on the NAND flash, published in 1987. He presented the paper at IEDM, as he had his NOR paper three years earlier.

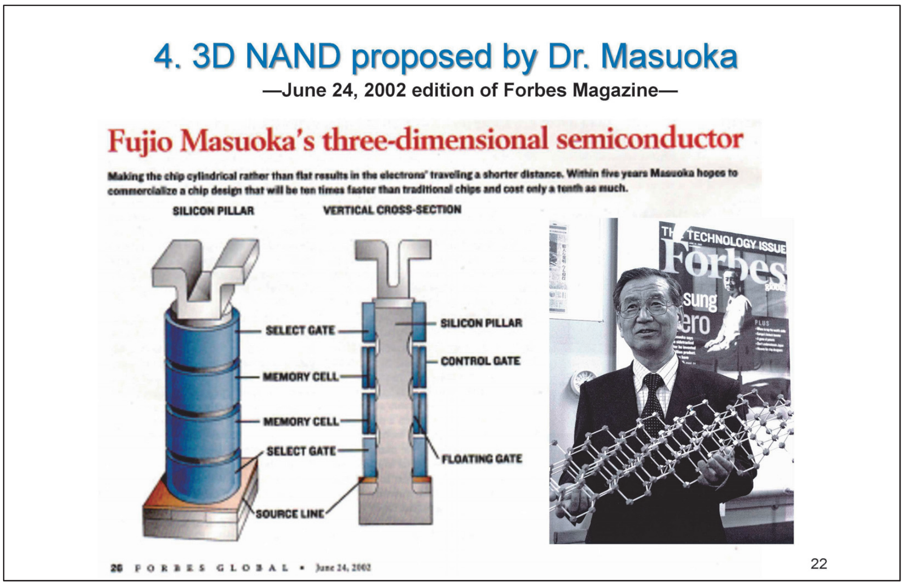


Fig. 22

〈Fig. 22〉 The fourth achievement of Dr. Masuoka, concerning NAND, is illustrated by this 2002 feature on him in Forbes Magazine. It highlights the future shape of NAND: The three-dimensional NAND flash.

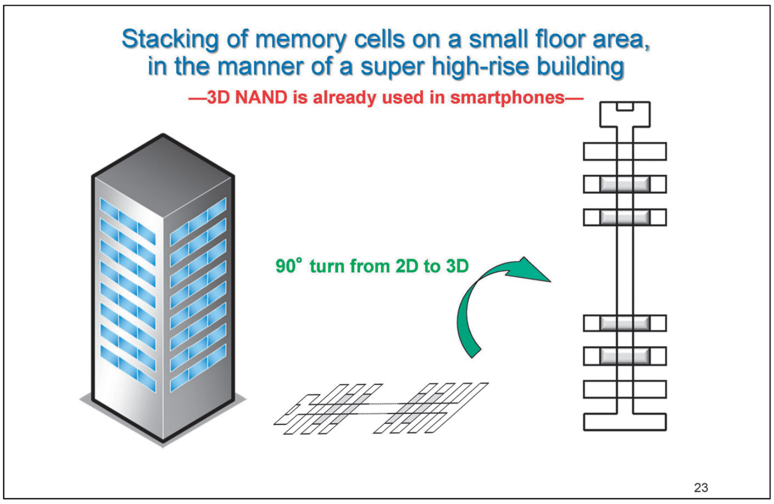


Fig. 23

〈Fig. 23〉 What is 3D NAND? To explain this innovation, I need to go back to my analogy of the bungalow and the two-story building. A 3D NAND flash is a multistory building made of memory cells—a skyscraper. An ordinary NAND flash can be thought of as a bungalow, or perhaps a rowhouse. That's the old type of NAND. Now suppose we rotate the rowhouse 90° and set it on its side. That's a 3D NAND flash.

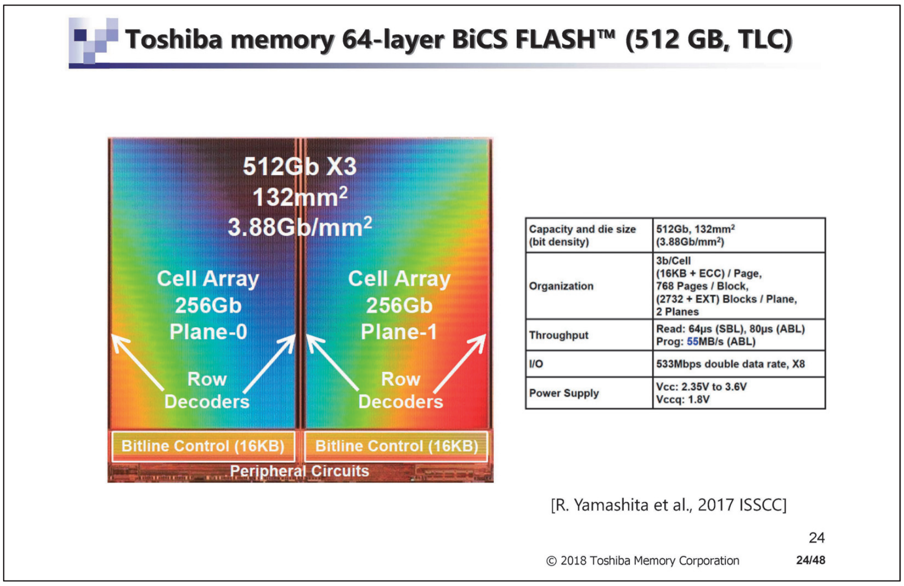


Fig. 24

〈Fig. 24〉 Among the esteemed guests in attendance here is Mr. Momodomi, a director of Toshiba Memory. I've borrowed two slides from Mr. Momodomi to illustrate the 64-story 3D NAND architecture Toshiba announced two years ago. This 3D NAND is in your smartphones right now. At the International Solid-state Circuit Conference, or ISSCC, which is held every February in San Francisco, Toshiba Memory announced a 96-story 3D NAND. This design is also in commercial use. A real skyscraper, quite remarkable.

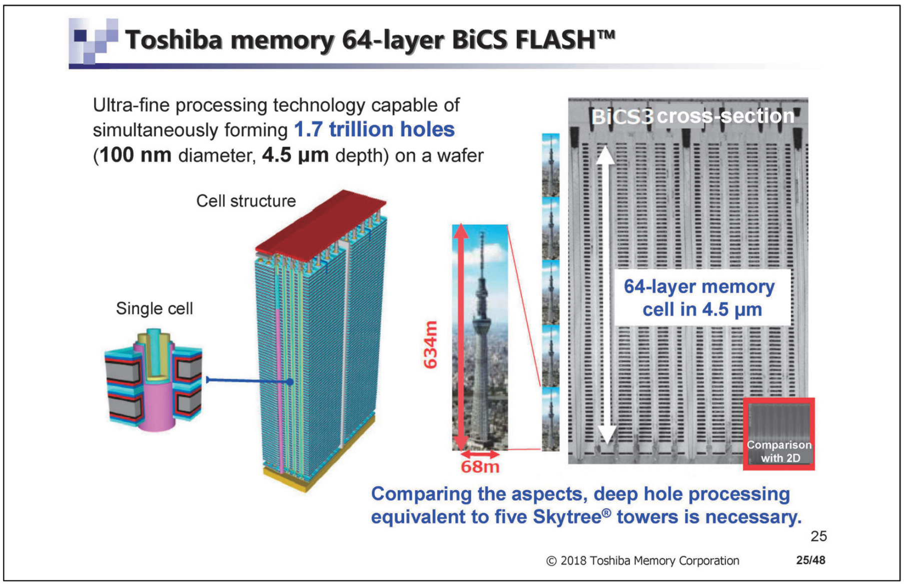


Fig. 25

〈Fig. 25〉 How impressive a skyscraper is it? Using the 64-layer example, we see that each of these vertical structures, called pillars, has a diameter of 100 nanometers, which is a tenth of a micron. A nanometer is a thousandth of a micron, a micron being a millionth of a meter. The depth of each pillar is 4.5 microns.

Mr. Momodomi expressed it eloquently when he compared this 3D NAND to Tokyo Skytree®. Skytree® has a diameter of 68 m at its base and is 634 m tall. Toshiba Memory's design requires digging enough high-aspect holes to fit five Skytrees. And this is exactly what Toshiba Memory has done. This idea is working in your smartphones. That's the state of the art at this moment.

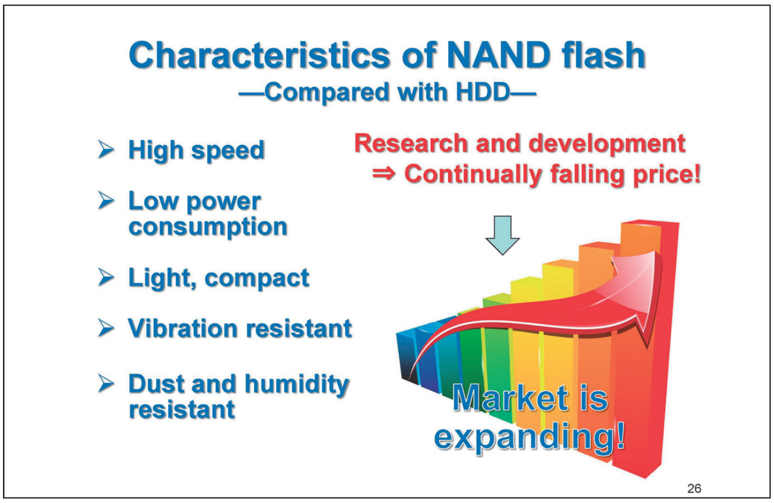


Fig. 26

〈Fig. 26〉 To summarize, NAND flash memory has numerous advantages over HDDs. It is much faster. Power consumption is low. It's lighter and smaller. Resistance to vibration is excellent, because it isn't built like a record player with a needle that can skip when jogged, as in the case of HDDs. It's resistant to dirt, dust and humidity. And today, people like Mr. Momodomi at Toshiba Memory and other companies are working diligently in R&D to lower costs still further, relentlessly expanding the market. I mentioned earlier that the market for these semiconductors is worth 6 trillion yen worldwide. That amount is expected to rise to 10 trillion yen in short order.

■ Dr. Masuoka in the Eyes of His Subordinates

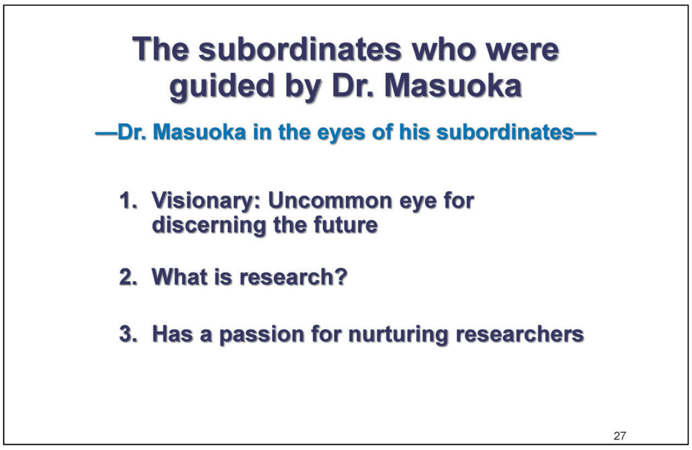


Fig. 27

〈Fig. 27〉 Now I hope you won't mind if I talk a little bit about my colleagues and myself—Dr. Masuoka's subordinates, who benefit from his guidance. Several of those assembled here are my friends and colleagues who, like me, have been privileged to receive guidance from Dr. Masuoka. I would now like to present to you Dr. Fujio Masuoka as seen through the eyes of his subordinates. First, as I mentioned earlier, Dr. Masuoka is a man who can see 30 years into the future. I have no such gift, but Dr. Masuoka has it in abundance. He has the extraordinary power of being able to probe the future.

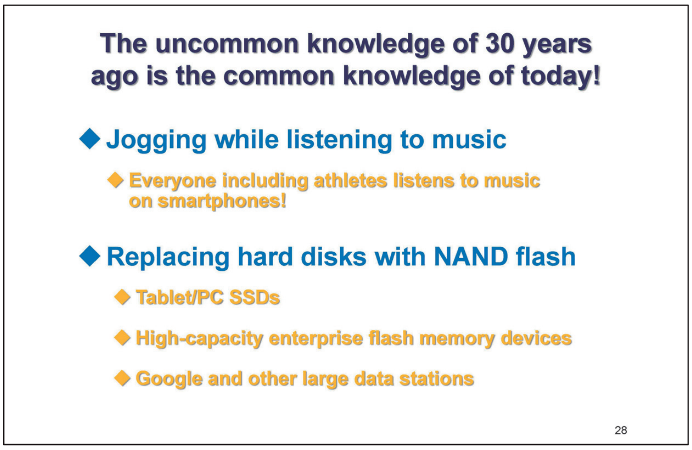


Fig. 28

〈Fig. 28〉 One such episode happened around 1990, I think. A student who wanted to join Toshiba was seated at the wing of Dr. Masuoka's desk for an interview. Dr. Masuoka asked him, "Young man, would you like to be able to listen to music while you jog?" "Yes, sir!" replied the student.

At the time there was the Sony Walkman. It was heavy and bulky. That was followed by the CD Walkman, which was impractical for jogging because the needle would skip. Nowadays you see even professional athletes like tennis player Kei Nishikori, ear buds in their ears, listening to music just before they play. That's the era we live in today.

Displayed behind Dr. Masuoka's desk was the test chip for our 4-megabit NAND. Many times I heard him say, "If we use this, we can replace the hard disk." Every time he interviewed a student, he made this remark, and every time I heard it I thought, "Oh, there he goes again."

Why was I skeptical? The four megabits of memory we had at the time was barely adequate to store one short song. Not only that, but the cost per bit of NAND was tens of thousands of times that of HDD. So when Dr. Masuoka told students that NAND would replace HDD, they couldn't believe their ears. I won't say none of us believed him, but his confidence was certainly hard to understand.

And now here we are. Google's HDD data station is switching over to flash memory, as I pointed out at the beginning of my talk. Banks are using flash memory in their enterprise servers, and we all use it in our smartphones. It's a whole new world now—a world Dr. Masuoka foresaw decades ago.

Another of Dr. Masuoka's great traits is his understanding of research. Dr. Masuoka opened our eyes to the true nature and meaning of research. He fostered young researchers with a fiery passion. I am one of those who was blessed to learn from Dr. Masuoka and I am truly grateful. The accomplishments I've just outlined testify to the validity of his insight.

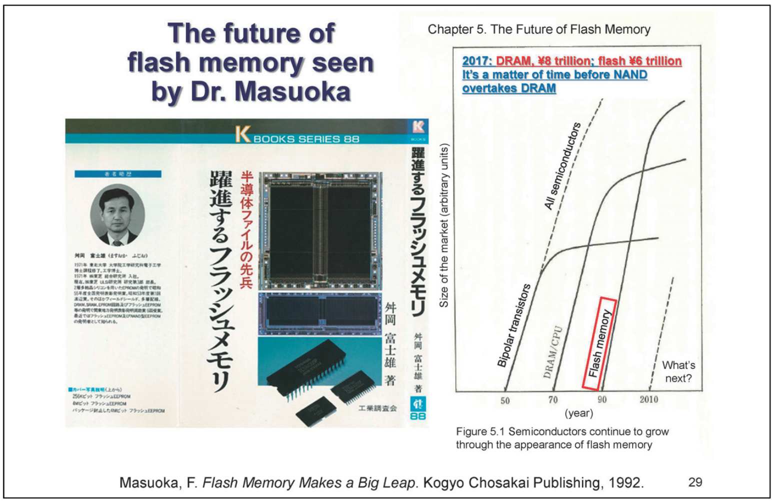
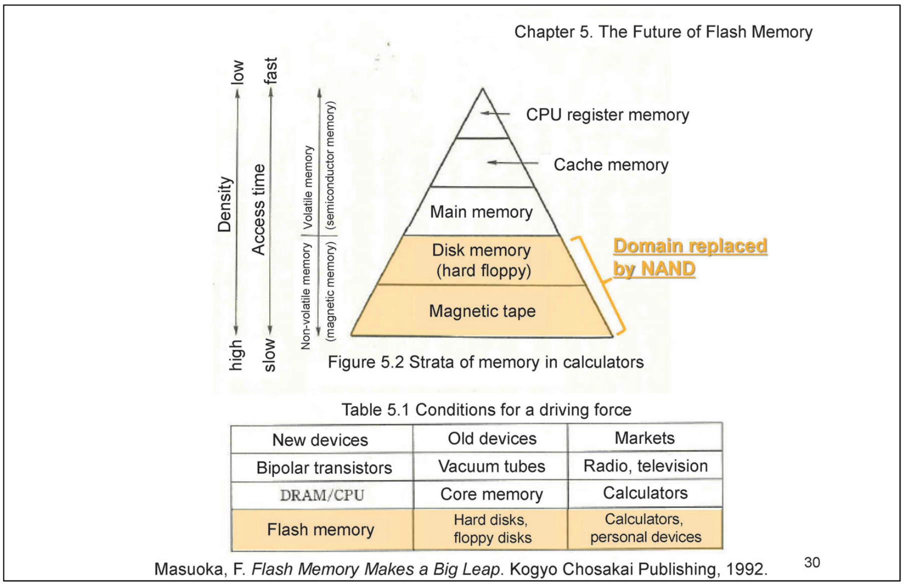


Fig. 29

〈Fig. 29〉 Dr. Masuoka really told us those things, and he was right. The evidence is all around us. I don't mean to plug Dr. Masuoka's books, but his book, *Flash Memory Makes a Big Leap*, published in 1992, is still in bookstores today. Chapter 5 is entitled, "The Future of Flash Memory."

In that chapter, we can see this graph whose axes are named "size of the market" and "year." Within it, each curve is labeled "bipolar transistors," "DRAM," "flash memory," and, finally, "What's next?" Well, we know what came next. Flash memory has become 3D with the advent of the vertical transistor, driven by new logic architectures. Dr. Masuoka predicted all of this.



New devices	Old devices	Markets
Bipolar transistors	Vacuum tubes	Radio, television
DRAM/CPU	Core memory	Calculators
Flash memory	Hard disks, floppy disks	Calculators, personal devices

Fig. 30

〈Fig. 30〉 I'd like to show you another diagram. This is from the same chapter, "The Future of Flash Memory." The colored squares indicate fields Dr. Masuoka believed would be taken over by NAND. This has indeed come to pass. A 30-year-old prediction has come true just as Dr. Masuoka said it would, attesting to this man's extraordinary prescience and vision.

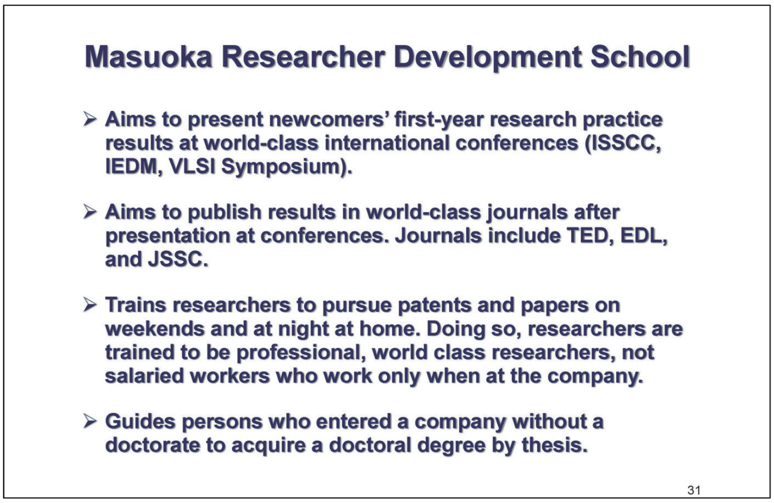


Fig. 31

〈Fig. 31〉 Dr. Masuoka's passion shone as he trained us young researchers. At one time Dr. Masuoka's department had 10 to 12 freshly graduated and inducted employees. Dr. Masuoka tasked them with a goal: to make a presentation to a world-class international conference.

These were freshmen, in their first year at Toshiba. The challenge was a daunting one, for the freshmen as well as their mentors. Examples of top-flight conferences included ISSCC, IEDM and the VLSI Symposium. And that's not all: Separately from the conference challenge, the 12 new recruits were required to complete reading assignments and discuss them regularly. The freshmen were assigned a 600-page textbook to read, in English, and to read about 50 pages a week in preparation for weekly discussions.

In a conventional reading assignment, each member of the group is assigned a different chapter: Person A reads Chapter 1, person B reads Chapter 2 and so on. If a weekly discussion covered 50 pages, each member would read only a few pages assigned to him or her. This, Dr. Masuoka decided, would not do. Instead, the entire group worked through the textbook 50 pages at a time. Any member could be called on at random to explain the chapter in their own words. Word-for-word translations into Japanese were not acceptable. "Ms. C, explain Chapter X. Mr. D, tell us what Chapter Y says." Dr. Masuoka is a stern schoolmaster.

In the academic-conference assignment, simply presenting did not suffice. The objective was not merely to publish a paper, but to publish in a top journal. As soon as we had presented our dissertations, there was no time to rest but we must get to work on releasing the paper. We were told to get them published in one of the top-flight journals, such as *Transactions on Electron Devices* or *Electron Device Letters*.

Moreover, the new hires were instructed to work on their patent applications and papers at home, on weekends or at night. I hope you won't take from this that Dr. Masuoka was some kind of a demon. On the contrary, his purpose was to impress on his charges that they were not mere salaried employees, who worked at the office and then went home. They were elite researchers in a professional world. I believe that this rigorous training was a blessing, a key reason why I am where I am today, and I believe my fellow disciples of Dr. Masuoka, gathered here, feel the same way.

I joined Toshiba with a Master's degree. Those who did not possess a Doctorate degree could acquire one by publishing a thesis. What made Dr. Masuoka such a wonderful instructor was that he understood the motivating power of having a thesis or patent with your name on it. Whenever an employee got published, the first page of the paper would be photocopied, framed and hung on the office wall. In time the walls became covered with thesis covers; we ran out of places to hang them. The aim was not to puff up the pride of that particular researcher. It was to stimulate and boost the motivation of all of us as a group.

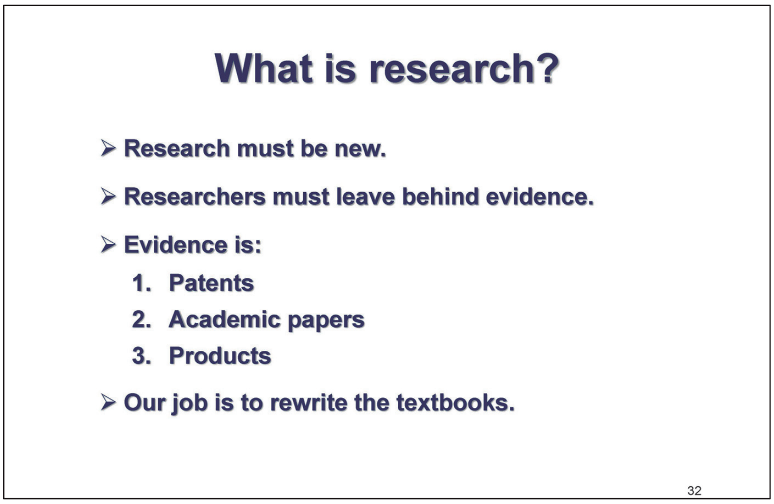


Fig. 32

〈Fig. 32〉 “What is research?” Dr. Masuoka would say. We heard it every day, like a mantra. “Research findings have to be new!” Also, “A researcher always provides evidence!” What constitutes evidence? For a researcher, there are three kinds of evidence: Patents, theses and products. Another of Dr. Masuoka’s sayings was, “Our job is to rewrite the textbooks.” I must have heard him say that ten thousand times. No, I don’t want to exaggerate. Probably about a thousand times.

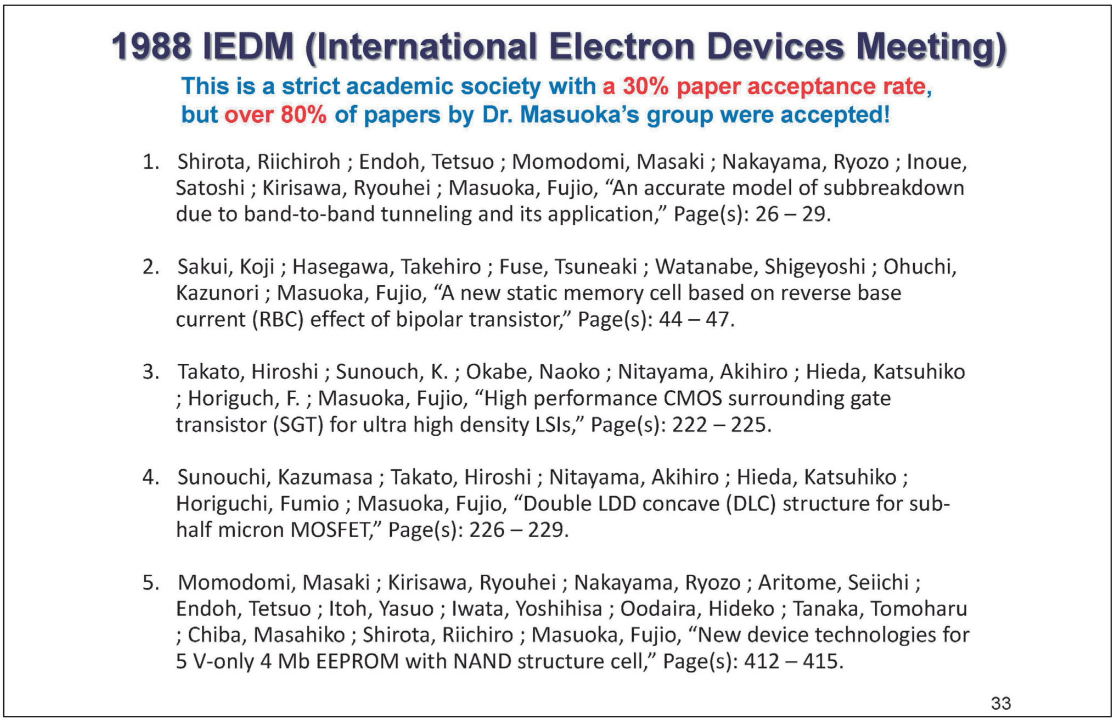


Fig. 33

〈Fig. 33〉 Let me give you an example. IEDM is an academic society with high standards. Its acceptance rate is about 30%, meaning that for every 10 papers submitted, only about three are likely to be accepted. At Dr. Masuoka’s lab, out of six papers submitted, IEDM published five.

When one of us had a submission to make, we were allowed to work through the night, writing our papers at the office. At about midnight Dr. Masuoka would leave his office, while the rest of us working on our theses would stay. He would then call us around 2 in the morning or so and say, “Okay, read me the first half.” After we’d read about five lines, he’d say something like, “That’s a bit better but it still won’t pass muster. Keep trying.” The deadline was that day. And that was how Dr. Masuoka made sure our papers got accepted.

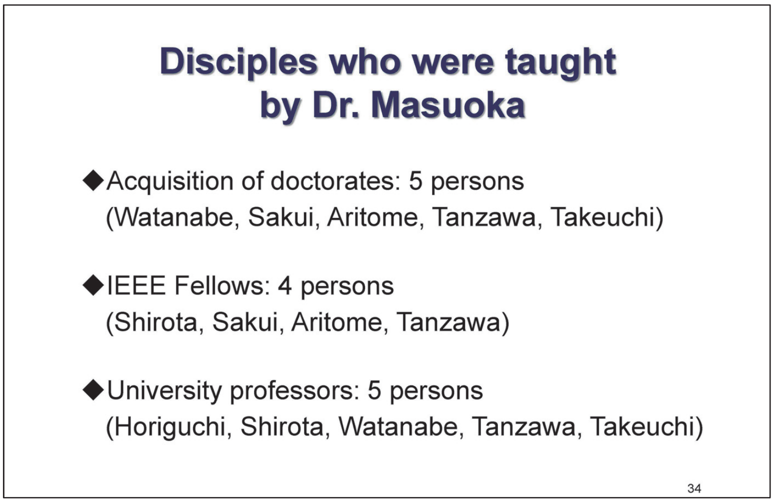


Fig. 34

〈Fig. 34〉 And that is how five of us, all assembled here, earned our Doctorate degrees. Four of our members were elected IEEE Fellows. Also, five of us have become university professors.

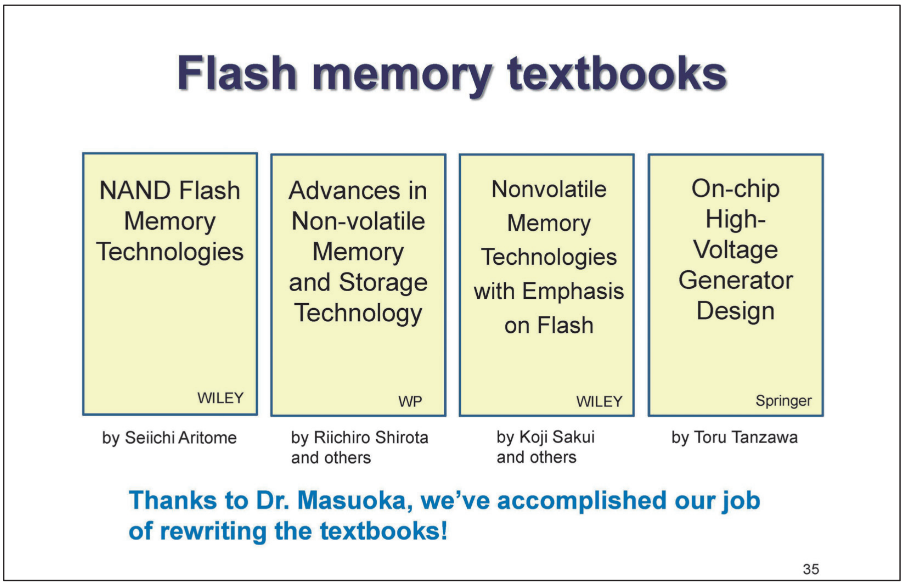


Fig. 35

〈Fig. 35〉 Dr. Masuoka said that we would rewrite the textbooks on flash memory and he was right. Dr. Aritome published a textbook through IEEE—entirely in English. Dr. Shirota wrote a book in English. I wrote a 100-page chapter on NAND flash. And Dr. Tanzawa wrote a textbook on circuits.

Fig. 35

〈Fig. 35〉 Thanks to Dr. Masuoka's tutelage, we wrote the textbooks on our field. These photos were taken over 30 years ago. As you can see, even amid our heavy workloads of research and development, we could get together for drinks and have fun. In this snapshot you can see Dr. Shirota. I look even worse—that's me in the center. When I look back on the research development over 30 years ago, I realize that every day was filled with meaning. We studied hard but we had fun as well.

Dr. Masuoka, congratulations on receiving the Honda Prize!

The age of flash, which Dr. Masuoka told us about over 30 years ago, has come. The flash memory that Dr. Masuoka and a few engineers developed is now a ¥6 trillion business. Through the development of flash, they generated a great number of patents and academic papers, and succeeded in rewriting the textbooks.

We disciples feel tremendous gratitude toward Dr. Masuoka!

36

Fig. 36

〈Fig. 36〉 Dr. Masuoka, congratulations to you on winning the Honda Prize. Nobody deserves it more. The era of flash has arrived, just as you told us it would more than 30 years ago. I got involved with NAND a little late, but when you developed the 4-megabit NAND flash, only about 10 engineers, including you, were working on this technology. Today flash memory is a 6-trillion-yen business whose development processes have generated numerous patents. Thanks to everything you've taught us about patents, Dr. Masuoka, we, your disciples, have registered an impressive number of patents in the United States. We've written academic papers and textbooks. We, your followers, truly owe you a deep debt of gratitude.

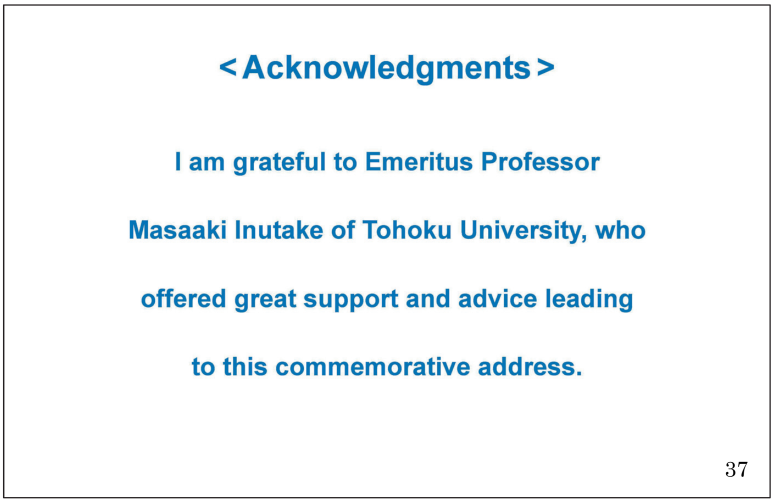


Fig. 37

〈Fig. 37〉 In closing, I also note that this address was made possible by Dr. Masuoka and by his friend Dr. Masaaki Inutake, Professor Emeritus of Tohoku University, who offered tremendous support and guidance. I would like to take this opportunity to express my deep appreciation.

This concludes my address on behalf of Dr. Masuoka. Thank you very much for listening.

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