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The Age of the Digital Nomad
—Impact of CMOS Innovation—

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Changing Life Style

A *Digital Nomad* is the symbol of a new lifestyle in which people are freed from constraints of time and location, thanks to the progress of mobile intelligent devices and high speed communication networks. The book titled *"Digital Nomad"* was published in 1997 by the author and David Manners of *Electronics Weekly* (UK) [1]. The first version was written in English followed by Japanese and Chinese versions in the following year. Figure 1 shows photographs of the books and the authors.

Fig. 1 "Digital Nomad" published in 1997 and picture of co-authors

We have observed gradual changes in lifestyle from the traditional way to the nomadic way, notably in the past decade. It was quite common, by the turn of the 21st century, that a large number of people commuted to their workplaces, for example offices in the central part of big cities, at 9am or 10am either by cars or by trains every morning, and left the places in the evening at 5pm or 6pm. The regular movement of people, back and forth, creates the phenomena of heavy traffic for cars and the "rush hour" of trains.

In the timeframe of the mid-1990's when the book was published, cell-phones were just about to take off, but their capabilities were limited only to talking. The situation is quite different today with the emergence of personal and intelligent mobile devices such as mobile PCs, tablet PCs, and smart-phones, and most of us are enjoying the nomadic lifestyle in one way or another. Figure 2 shows a conceptual image of the *Digital Nomad* [2]. If you have an intelligent mobile terminal, you can access any kind of information through the network. You don't have to be at your office at 9am sharp every morning anymore. Thereby you have more freedom from the constraints of time and location. There are three essentials to support the comfortable nomadic lifestyle, namely, an intelligent mobile terminal, a high speed communication network, and cloud computing. Without these essentials of modern infrastructures, the change in our lifestyle would have been quite difficult. As shown in the Figure, Steve Jobs of Apple made a great contribution for opening the age of the "*Digital Nomad* ".

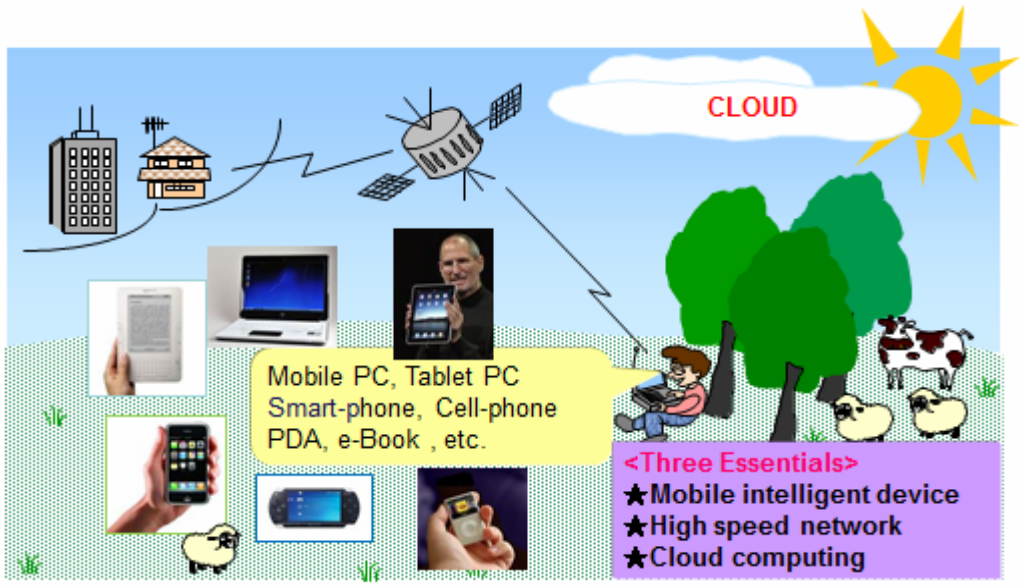

Fig. 2 Conceptual image of "Digital Nomad"

Figure 3 shows the general trend of electronic equipment in which everything is getting smaller and smarter, showing the way to the "nomadic tool." Computer, consumer, and communication products are converging to intelligent mobile devices, which are collectively called "digital consumer products." In the past, there were clear boundaries between consumer, computer, and communication markets, but these boundaries are now disappearing, resulting in "market convergence". There are two major driving forces behind the trend of market convergence; firstly, the digitalization of information and secondly, CMOS innovation. In this paper, a brief history of CMOS innovation and its impact to our society from macroscopic viewpoint, instead of technical details, will be described.

Fig. 3 Market convergence driven by digitalization of information and CMOS innovation

If we look back on the historical evolution of electronic equipment, it is seen that progress has been made in such a way that the four requirements shown below are satisfied;

1) More intelligence (or higher information processing capability)
2) Smaller size (for better portability)
3) Lower power (for longer battery life)
4) Lower cost (for more affordability as a personal device)

The basic requirements, listed above, leads to the formulation of a *"Figure of Merit"* for electronic equipment as shown below [3]:

$$\text{Figure of Merit} = \frac{(\text{Intelligence})}{(Size)\times(Cost)\times(Power)},$$

where (Intelligence) needs to be defined for each type of equipment; for example, "MIPS" can be used for a general purpose computer, "MOPS" for a signal processing system, and "FLOPS" for a numerical calculation system. The rest of the parameters, (Size), (Cost), and (Power) are self explanatory. It should be noted, however, that the (Size) cannot be too small beyond the human interface, such as for the case of calculator which has already reached its minimum size.

Generally speaking, the higher the *Figure of Merit*, the higher is the value of the nomadic tool. Semiconductor technology has made progress in a direction to maximize the *Figure of Merit*. And "CMOS Innovation" has played the most important role in this regards, and it was the fundamental force for changing our society towards a nomadic lifestyle.

History of CMOS Innovation

CMOS has come a long way since F. M. Wanlass made a presentation of the idea of CMOS at ISSCC in 1963 [4], followed by the first commercial products introduced by RCA in 1968. Since its introduction to the market, CMOS devices were far superior in terms of power dissipation, but they were slower and more expensive, and integration density was lower compared to other devices. This situation did not change by the late 1970's, and the common understanding of the industry or "industry consensus" in those days can be summarized as below;

1) NMOS will remain as the main-stream device
2) Bipolar will be utilized for analog and high speed application
3) PMOS will gradually phase out, and
4) CMOS will remain as special device for niche market where the low power is an absolute necessity.

A big change in this situation occurred in 1978 when Hitachi pioneered the re-engineering of the CMOS based on the invention, called "Twin-well CMOS", by Y. Sakai and T. Masuhara, then at Central Research Lab. of Hitachi [5]. The joint engineering team of Central Research Lab. and Semiconductor Division made a bold challenge to develop high speed 4K Static RAM compatible to Intel's 2147, the highest-speed device at the time, based on the new technology. The team overcame various difficulties, and the initial target was achieved. The result was presented at ISSCC 1978 by T. Masuhara who led the project [6].

Table 1 compares the features of NMOS and CMOS 4K SRAM. Intel's 2147 chip was based on NMOS technology and had an access time of 55-70 ns. Hitachi's 6147 was pin-compatible with Intel's 2147, but was based on re-engineered CMOS technology. The 6147 achieved the same speed as the 2147, but the power dissipation was only 1/8 in active mode and 1/15,000 in standby mode compared to 2147. The 6147 from Hitachi was an epoch-making device and got a great deal of attention among the technical society.

	2147 / Intel (1977)	6147 / Hitachi (1978)
Product	HMOS 4K Static RAM	HiCMOS 4K Static RAM
Technology	NMOS	Twin-Well CMOS
Speed	55 / 70 ns	55 / 70 ns
$I_{Active}/I_{Standby}$	110 mA / 15 mA	15 mA / 0.001 mA
Chip Size	16.2 mm^2	11.5 mm^2

Table 1 Comparison of parameters for NMOS and CMOS 4K SRAM

I was in charge of the memory business operation of Hitachi's Semiconductor Division in this timeframe, and my responsibility was to make the new CMOS device a commercial success. There are three critical steps for any new technology to become a commercial success; firstly, development of competitive devices, secondly, cost effective mass manufacturing, and thirdly, marketing and sales for revenue. These three steps are quite different in nature, and different kinds of people are engaged in each step. They have to be carefully organized in order for all project members to work towards the same direction sharing the same mission and same philosophy; that was my major role.

The first CMOS device from Hitachi, 6147, was intended to show the technical superiority of the new CMOS compared to NMOS device, and it was a great success from an engineering view point. Hitachi was awarded IR-100 for this development, as shown in Fig. 4. The 4K SRAM 6147 clearly marked a mile stone in the semiconductor history; changing technology direction from NMOS to CMOS.

Fig.4 1979 IR-100 awarded to CMOS 4K SRAM (left), and chip photo of HM6147(right)

Because of the limited market size of the 4K device, we had to introduce a product with a much larger market size in order to get the commercial success; that was the 16K SRAM. In those days, 16K SRAM was the most advanced product in terms of density, and its market size was estimated to be much larger than that of 4K SRAM. A big project was organized with the objective to develop, manufacture, and commercialize the device, and to establish the No. 1 position in the world. Members in each section did their best for the common goal. The project of 16K SRAM was successfully completed, and commercial samples were prepared and delivered to potential customers.

In a sense, the project was a challenge to the "industry consensus" in late 1970's, when NMOS was believed to be the mainstream of the semiconductor industry. A typical comment we heard, from our competitors, in those days was like this: "Hitachi's new CMOS chip would be great if it were producible in volume". As was previously mentioned, development and manufacturing are quite different. It is true that even though an excellent device is developed, its value will be diminished if it were not producible in volume. Therefore, we had to demonstrate that the new CMOS devices were producible en masse in a cost effective way as commercial items.

Our potential customers also had some concerns about our CMOS device since no other chip companies were following our way, which means that there is no "second source" of the device. Therefore, I had to visit customers by myself, especially the strategic ones, in order to explain the basic philosophy of our CMOS direction, including our supply capability and future prospect. Through direct contact with customers, I got a confidence that if we have a big inventory, their concerns will mostly disappear. The big inventory tells, indirectly, that the device is mass producible. So, I took a strategy to build an inventory of 16K SRAM under the name of "strategic inventory," since the inventory level of commodity memories was under strict control.

Production went very smoothly, and "strategic inventory" was built more rapidly than I expected. We were ready to ship any amount of the new 16K SRAM. However, orders from customers did not arrive. The inventory level reached the critical point where the top management paid strong attention, and a big question was raised about our CMOS strategy instead of following the industry standard NMOS approach. A very drastic action from the top was about to be taken to change the direction of the technology; from CMOS back to NMOS. Almost in that same instance, a Goddess of business smiled to us with big orders from the customers. Our 16K SRAM grew nicely, and Hitachi took the No. 1 position in the world in 1981.

With the commercial success of 16K SRAM, confidence in CMOS was established inside Hitachi, and our next strategy was to expand the adoption of CMOS technology to other devices including MPUs, MCUs, logic circuits and DRAMs. The 8-bit microprocessor was the first to follow in this direction; the first CMOS MPU, HD6301, was introduced to the market in 1981. Table 2 summarizes the comparison of 8-bit MPUs based on CMOS and NMOS which had been developed previously. As is seen from the table, the CMOS version was twice as fast, and its power dissipation was 1/30 in active mode and 1/7,000 in standby mode. The success of CMOS 8-bit MPU contributed to setting a new direction of technology for microprocessors and logic devices.

		6801 / Hitachi (1979)	6301 / Hitachi (1981)
Product		8bit MPU	8bit MPU
Technology		4 Micron NMOS	3 Micron CMOS
Speed		1 MHz	1 MHz, 1.5MHz, 2MHz
Power	Active	900 mW	30 mW (f = 1MHz)
	Standby	70 mW	0.01 mW
Pin Count		40 Pins	40 Pins

Table 2 Comparison of parameters for NMOS and CMOS 8bit MPU

Soon after the introduction of our CMOS 8-bit MPU, Epson (then Shinshu-Seiki) started the project to develop the "all CMOS computer", using two CPU chips from Hitachi. The project was a great success, and the new product called HX-20 was introduced to the market in 1982[7]. It was explained, by the company, as "the world's first hand-held computer" and named as one of the mile-stone products of the company. It may be appropriate to call it the ancestor of the nomadic tool.

In the time frame from the early to mid80's, there were a lot of arguments in the semiconductor industry about whether the future mainstream is either NMOS or CMOS. The discussion was initiated in digital ICs first as seen in the ISSCC Panel in 1981, "CMOS vs. NMOS for VLSI". Similar shifts from bipolar to BiCMOS and then to CMOS was also seen in analog and communication IC's in mid1980's and beyond. DRAMs and Flash Memories followed this direction in the similar timeframe due to the necessity to implement functions such as high sensitivity sense amplifiers, redundancy, and voltage conversion on the same chip. Meanwhile in the 1990's and later, a gradual shift of opinion in favor of CMOS was also observed in high-end processors for servers. In the final stage, RF devices also shifted to CMOS as seen in the 2001 ISSCC Panel, "Years of RF-CMOS".

Figure 5 summarizes the evolution of semiconductor device structures converging to CMOS. Simply stated, it is obvious that the past several decades could be described as the period of "CMOS convergence". The original CMOS devices developed by RCA were applied primarily to ultra-low-power equipment, such as for military applications, in which speed was not an issue. The next big markets for CMOS were watches and calculators, both of which also did not require high speed.

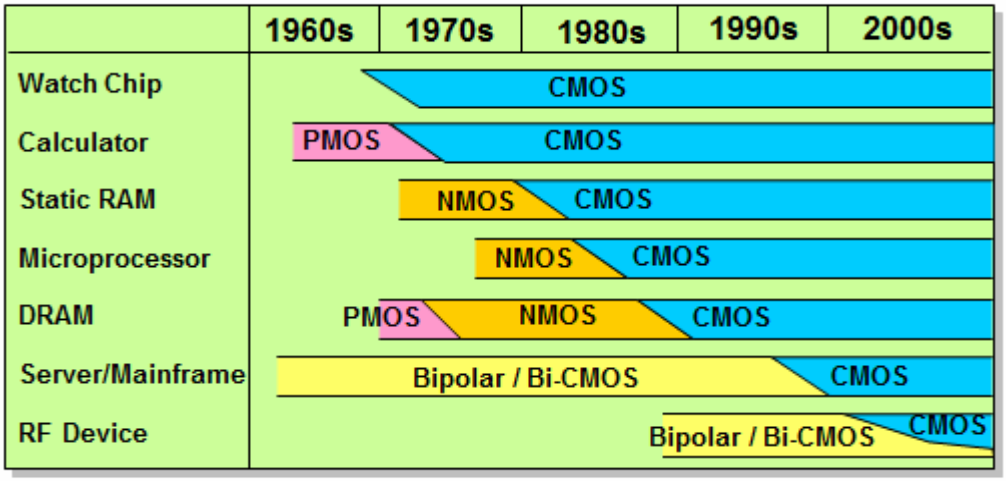

Fig. 5 Evolution of device technology converging to CMOS

Hitachi's introduction of high-speed CMOS SRAM, 6147(4K) and 6116(16K), in the late 1970's demonstrated, for the first time in the industry, that CMOS can match NMOS in terms of performance while maintaining its low power feature. The rest of the devices such as MPU, DRAM, Flash memory followed the same course as SRAM as shown in the Figure. Then the technology shift was seen for mainframes which had been based on bipolar or BiCMOS technology. Here is an interesting testimony from the top of a giant computer company, Louis V. Gerstner, ex-IBM Chairman and CEO, in his biographical book titled *"Who Says Elephants Can't Dance?"* [8], how the CMOS impacted their main frame business;

- IBM's sales of mainframe was declining because of a precipitous drop in market share.

-The technical team made a bold move to a totally different architecture: from bipolar to CMOS.

- Had we not made the decision to go with CMOS, we'd have been out of the mainframe business by 1997.

With the shift of technology for servers and mainframes towards CMOS, almost all kinds of electronic equipment today, from small to big or from mobile to stationary, are based on CMOS. It can be said that CMOS innovation laid the foundation of today's civilization.

Future Prospects

<Technology Aspects>

One of the major changes expected in the future of semiconductors is the diversification of technology direction. One direction is to keep enhancing device performance and integration density through the extension of Moore's Law [9] which is called the "More Moore" direction. On the other hand, there are newly emerging devices in the semiconductor industry, such as sensors, MEMS devices, display devices, power devices, and bio chips, which depend on utilizing the basic properties of materials, rather than depending on simple shrinking of devices. These are called "More Than Moore" devices (MTM) and are expected to make a great deal of contributions to newly opening markets such as robotics, medical/health care, smart grid, and sensor networks.

It is quite likely that CMOS will remain as the mainstream of device structures of "More Moore" direction in the foreseeable future, since there is no sign of the emergence of a new device which can replace CMOS. One strength of CMOS in IC technology is that it realizes many functions such as digital logic, memories, buffers, clock trees, analog, RF, voltage generation and power supply, temperature compensation and ESD protection. However, the future is not a simple extrapolation of the past trends, and CMOS will experience different ways of innovation toward the future as is discussed below.

CMOS chips will keep increasing in integration density on a monolithic chip by shrinking the device geometry, introducing new materials, and adopting new device structures such as the FinFET. However, increasing the density on a chip will become increasingly difficult because, firstly, the feature size of the device is approaching the theoretical limit determined by not only physical constraints but also practically by increasing leakage currents and parameter variations, and secondly, the investment for device development and for manufacturing is becoming prohibitively expensive. Because of these difficulties, extending Moore's Law will become harder than before.

A countermeasure for this issue is the 3D integration of chips. Various new technologies, such as TSV (Through Silicon Via), are being developed and they will contribute to the realization of 3D integration. TSV is the technology which can connect chip to chip by opening holes through the Si chips. Figure 6 shows the historical evolution of device structures to extend the Moore's Law. It is seen from the figure that CMOS played the major role in the past several decades for extending the trend. Towards the future, the 3D integration of CMOS chips will extend Moore's Law for more decades, and it will contribute to increasing the *Figure of Merit* of electronic equipment.

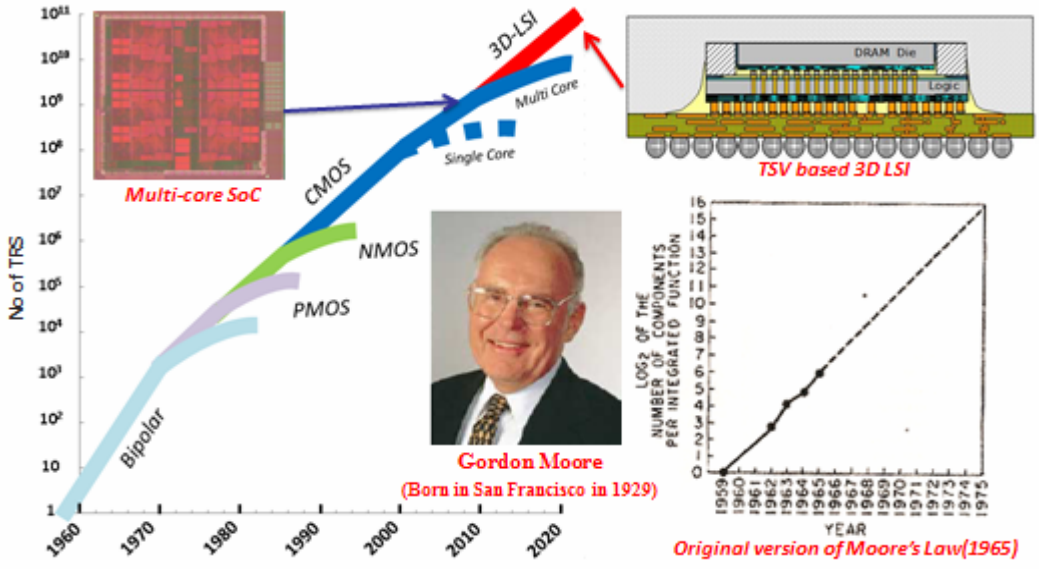

Fig. 6 Device evolution to extend Moore's Law

< Application Aspects>

We will see the emergence of new markets in the coming decades owing to the further innovation of semiconductor technologies. Currently, the digital consumer market is driving the semiconductor industry, where smart-phone and tablet PC are the hottest items. What will come next? There was held an interesting discussion at the ISSCC Panel of 2000 regarding the ultimate nomadic tool, "When Can I Buy a Dick Tracy Watch for Christmas?" With the further increase of *Figure of Merit* value, it may not be too long before we get a Dick Tracy Watch as a Christmas item, at least from the technological view point.

Figure 7 shows the evolution of major semiconductor markets in the past several decades, and forecast beyond the digital consumer market. The emerging market will include the new automotive market, such as EV and HEV, robotics, medical and health care, and sensor network market.

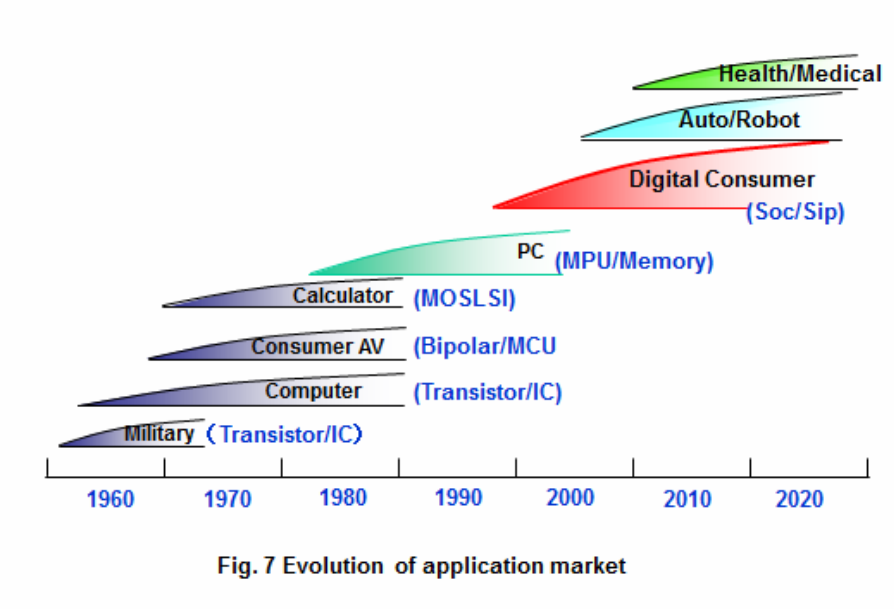

Fig. 7 Evolution of application market

Among those emerging markets, robotics will be the most challenging for chip technology and will become the next technology driver of the semiconductor industry. Figure 8 shows a prediction of robot intelligence cited from Hans Moravec of Carnegie Mellon University [10][11]. Generally speaking, the intelligence of today's robot is far inferior to human intelligence, especially in the field of pattern recognition and language understanding.

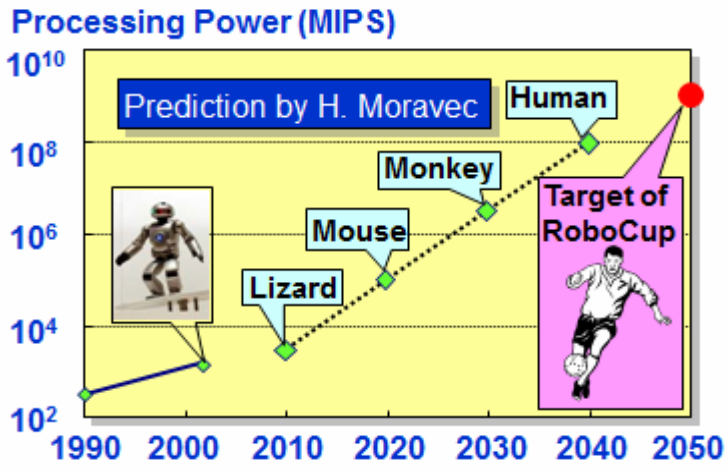

Fig. 8 Rise of robot intelligence towards RoboCup in 2050

However, robot intelligence will dramatically increase in the coming decades, owing primarily to the progress of high performance and low power CMOS innovation combined with 3D integration technology. Although it is not a simple issue to compare intelligence between a robot and a human, one way of looking at the evolution of a robot's intelligence to the level of human intelligence in the timeframe of 2040 is shown in Fig. 8. It is interesting to note that the goal of "RoboCup" is set to be achieved in 2050 [12]. The RoboCup is a very ambitious project with a goal of having a team of robots playing with a human team in 2050 and winning. Will it really be achieved? It is clear that an enormous amount of pattern processing, matching and recognition needs to be done in the robots or by accessing the big data stored in the data center. In either case, much higher integration and higher power efficiency is needed for processing and storage than is available now. No one knows for sure if it can be achieved, except one thing; the answer will depend very heavily on the progress of semiconductor technology, where the challenge is to achieve the human level intelligence within the limit of allowable power consumption.

We should be facing a very interesting and challenging future ahead of us.

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