

Implications of Makimoto's Wave

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<Abstract>

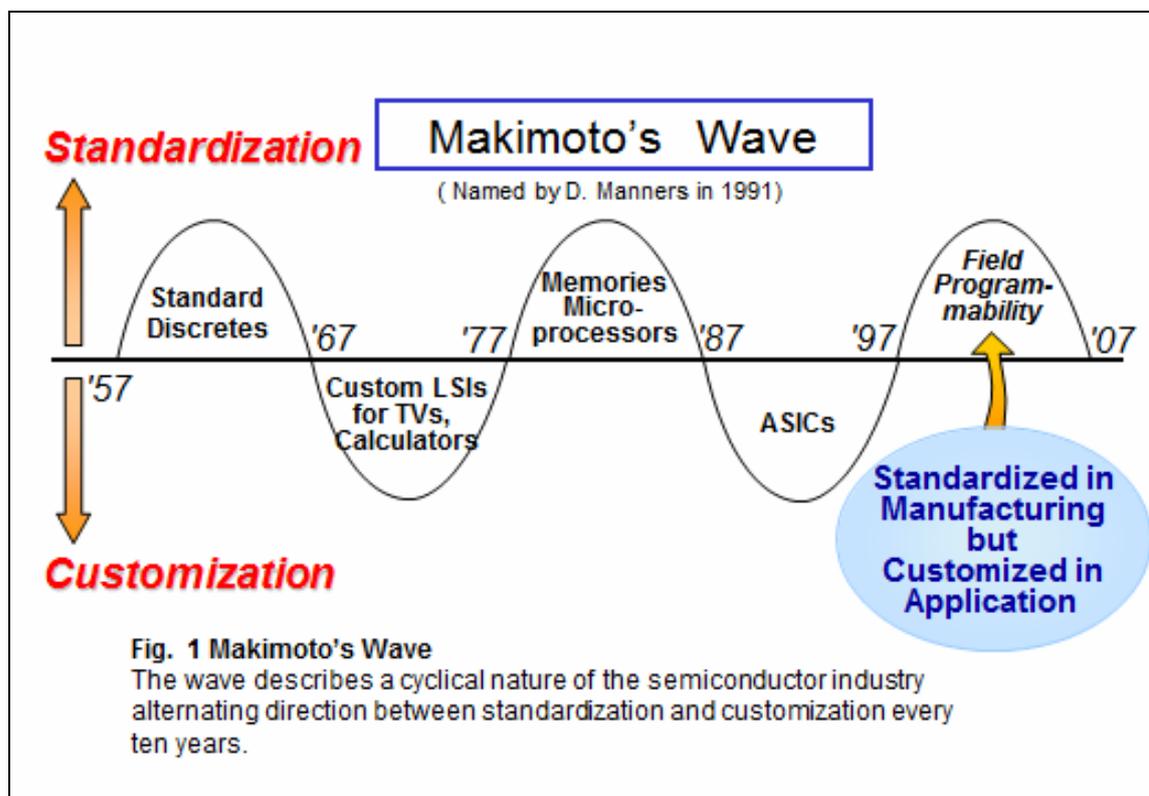
This paper will discuss some subjects related to Makimoto's Wave since it was published in 1991, including the mutual relationship between chip innovations and the computer revolution from a macroscopic viewpoint. The basic implication of the Wave is that the semiconductor industry alternates direction between standardization and customization every ten years. The Wave concept has provided and will provide a way to predict future trends of semiconductor technology development. An extended version of the Wave, covering up to the year 2027, will be provided.

Key Words: history, semiconductor, MPU, MCU, ASIC, FPGA, SoC, SiP, NV-RAM

Introduction

The computer and semiconductor technologies have made synergistic progress since the timeframe of 1950's when the transistorized computer was developed. The semiconductor innovations contributed to the revolutionary progress of the computer, and there is no question that the semiconductor has been and will be the most powerful engine of the computer or of the IT in general. On the other hand, the computer industry has continuously served as the market and technology driver of the chip industry by providing market opportunities and technological challenges. This paper will discuss the mutual relationship between chip innovations and the computer revolution from a macroscopic viewpoint rather than from technical details.

I have been engaged in the chip industry for more than half a century since 1959 when I joined Hitachi's semiconductor division. My first assignment was the yield improvement of Ge transistor. Since then, I have been assigned various types of products, up to today's SoC (System on Chip) and SiP (System in Package). Through the wide range of experiences, I discovered, in 1987, a cyclical nature of the industry which alternates direction between Standardization and Customization every ten years. It was expressed in a sinusoidal wave form as shown in Fig. 1. Sometime later from my discovery, I got an interview from David Manners of UK, and he was very much interested in and impressed by my wave concept. He wrote an article on the subject on the Electronics Weekly in 1991[1]. To my surprise the wave was named as "Makimoto's Wave". About a year later, the Wave concept was introduced in the ANNUAL REVIEW issue of the IEEE Spectrum in 1992[2], and gradually caught attention from the semiconductor society as a guidepost of future development of technology and market.



With the turn of the 21st century, the computer society started to show interest in the concept, and I received invitations to talk at various conferences in the computer field. The first talk was delivered at FPL (Field Programmable Logic) 2000 in Villach, Austria with the title of “The Rising Wave of Field-Programmability”. In this timeframe, field programmable devices became available, as had been predicted in the Wave, which contributed to enhancing performance of the computer for various applications. Invited talks were also delivered at SC06 in Tampa, US and ISC07 in Dresden, Germany.

The Wave concept is still alive, and it provides with us a great deal of insight for the direction of technology development in the future.

Digital Technologies Innovations

Digital technologies have undergone various innovations since the invention of transistor in 1947 at Bell Laboratories in the US, which was the most significant milestone in the history of the semiconductor industry. However the invented transistor was point contact-type which was unstable and uncontrollable because of its mechanical structure. Therefore, this type of transistor was not very useful for the practical applications, and we had to wait for various innovations to follow.

Although the process of technology innovations is quite complex, it can be classified into three basic patterns. The first category is “Disruptive Innovation” meaning the development of products or technologies which cause obsolescence of those in the previous generation. There are various examples in this category, but the most important ones, beside the invention of transistor, include the invention of Integrated Circuit by Jack Kilby in 1958 and by Robert Noyce in 1959, and the development of 4bit microprocessor at Intel in 1971. The second category is “Exponential Innovation” which means that the

rate of the progress is exponential. This is known as Moore's Law which can be summarized as "the number of transistors on a chip doubles every 18 to 24 months". Gordon Moore first discovered the exponential trend of the density increase and contributed a paper on the Electronics magazine in 1965[3]. The third category is "Cyclical Innovation" which is called Makimoto's Wave, the main subject of this paper.

Cyclicity of the Industry

Following is the brief history of semiconductor industry, from the viewpoint of the trend between "Standardization" and "Customization", for every ten years after the invention of the transistor [4]. The 1st decade (1947-1957) can be regarded as the incubation period of the semiconductor industry. Many innovations were made in this period especially in the field of discrete devices; the invention of junction transistor being the most important one.

In the 2nd decade (1957-1967), the production of transistor started in the US followed by Japan and other countries, and the semiconductor industry took off in this period. Large US corporations, such as WE, RCA, and GE, led the industry. One of the important aspects of the industry was that transistors were standardized and they were interchangeable each other. The lesson was learned from the case of vacuum tubes, since the transistor manufacturers were also engaged in vacuum tube business. This period can be characterized as the decade of "Standardization".

The production of IC/LSI started in the 3rd decade (1967-1977). The IC/LSI found the new market opportunities such as calculators and electronic watches. In the design of LSI, the most important criterion was to minimize the chip size, since the yield of LSI depended very heavily on the chip size. In order to achieve this goal, the custom design was the natural choice in this period which can be characterized by "Customization".

In the middle of the 3rd decade (1967-1977), the MPU or microprocessor was developed in 1971, and its production started to rise in the 4th decade (1977-1987). There was a drastic change in the way of designing electronic systems from the custom design to the MPU based design. The reason was that the design cost of the custom chip was too high, and the time to market was too long; effectively prohibiting the custom approach to low volume items or short life cycle items. Although, the MPU based approach had some redundancy and hence higher unit cost, the overall cost was justifiable for many cases because of its lower initial cost. This period can be characterized by "Standardization".

At the end of the 4th decade, in 1987, I noticed that the semiconductor industry has a cyclical nature to alternate direction between "Standardization" and "Customization" every ten years, as is described above. Then I naturally thought that the trend can be extended toward the foreseeable future for another 20 years up to 2007.

As was predicted in the Wave, production of ASIC (Application Specific IC) started in the 5th decade (1987-1997), which directed to the "Customization" side, the opposite direction from the 4th decade in which the general purpose standard product, such as MPU, played the major role. There were

two noticeable factors which drove this trend; firstly the emergence of new design methodology such as Gate Array and Cell Based IC which made custom design much easier, and secondly the inherent capability of the ASIC to provide higher performance and lower power compared to the standard MPU based approach. This period can be characterized by “Customization” in which the pioneers were LSI Logic for Gate Array, and VLSI Technology for Cell Based IC.

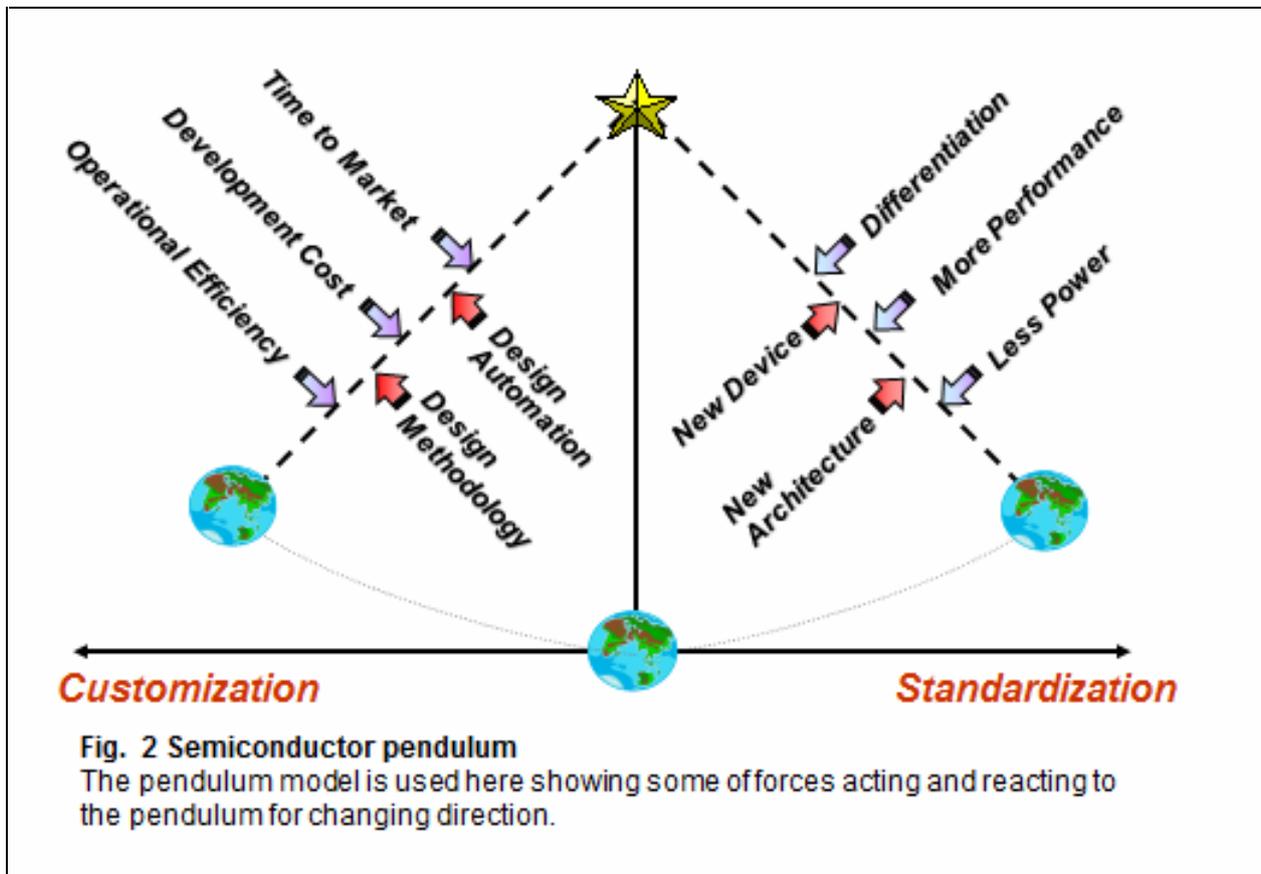
Although the ASIC was utilized for wide range of applications, there were still some drawbacks to be improved; slower time to market, higher development cost, and less flexibility to adapt to the market change. In order to address these issues, various types of field programmable devices were introduced to the market in the 6th decade (1997-2007). One of the earliest examples was field programmable MCU introduced by Hitachi under the trade name of ZTAT. The ZTAT stood for “zero turn-around time”, meaning the device was programmable at user’s site. The product was a great hit since it provided a benefit of faster time to market and more flexibility to market changes. Most of today’s MCUs are made in the ZTAT way, in a sense that they are field programmable rather than mask programmable. FPGA or Field Programmable Gate Array was another example which got momentum in the 6th decade, led by such companies as Xilinx and Altera. The beauty of field programmability is that the product is “standardized in manufacturing but customized in applications” as shown in Fig. 1. In the meantime, the field programmable devices gave a strong impact to the computer industry toward reconfigurable computing which provided higher performance and more flexibility to cover wide range of applications, such as medical imaging, high speed computing, and data analytics.

Semiconductor Pendulum

The semiconductor industry has made a progress in such a way to provide the best customer satisfaction, as is the case with other industries. It is generally said that “the customer is the king”, and customers ask difficult tasks to suppliers which are often contradictory each other. Their requests are classified in two groups as follows;

- (a) Higher performance, lower power, lower unit cost, and more differentiation
- (b) Lower initial cost, faster time to market, and more flexibility

For addressing requests in (a), “custom approach” will be better suited, while addressing requests in (b), “standard approach” will be the choice. It is clear that neither custom nor standard approach is almighty for the customer satisfaction. The Makimoto’s Wave implies that the choice of custom or standard is the time dependent issue, influenced by technology and market development. There are some forces to push the industry toward custom direction one time and toward standard direction another time. This point is illustrated in Fig. 2 as the “semiconductor pendulum”.



The pendulum model is used here to interpret the basic mechanism of the cyclical nature of the chip industry. Imagine a long pendulum swinging between standard and custom direction. There are various forces acting on and reacting to the pendulum, as shown in the figure. For example, the emergence of new device structure such as FPGA and new architecture such as MPU/DSP are some of forces to push the pendulum toward standardization direction. However, if the pendulum goes too far to that direction, there will be reacting forces such as “need for differentiation”, “need for higher performance”, and “need for lower power”. And the pendulum will be pulled back to the opposite direction.

On the other hand, progress of design automation and emergence of new design methodology are some of forces to push the pendulum toward custom direction. However, again, if it goes too far to that direction, there will be reacting forces such as “need for shorter time to market”, “need for less initial cost”. And the pendulum will be pulled back to the opposite direction. In this way, the pendulum has been and will be swinging between “Customization” and “Standardization” with the period of about ten years at each side.

Democratization of Computing

A macroscopic review on the computer revolution will be described in relation to chip innovations. J. V. Atanosoff of Iowa State University invented the core principles of electronic digital computing in 1939 and then completed the ABC or Atanosoff-Berry Computer together with C. E. Berry in 1942. [5]. ABC was the first electronic digital computer in the world which was followed by Colossus developed as the

code-breaking machine in the UK in 1942, and ENIAC developed at University of Pennsylvania for the U.S. Army in 1946.

Since those days, the computer made a revolutionary progress toward various directions; toward high performance computing such as supercomputer, toward reconfigurable computing for covering wide range of applications, and toward more democratization of computing. The democratization of computing was the most influential to our society and impacted our life style in a big way.

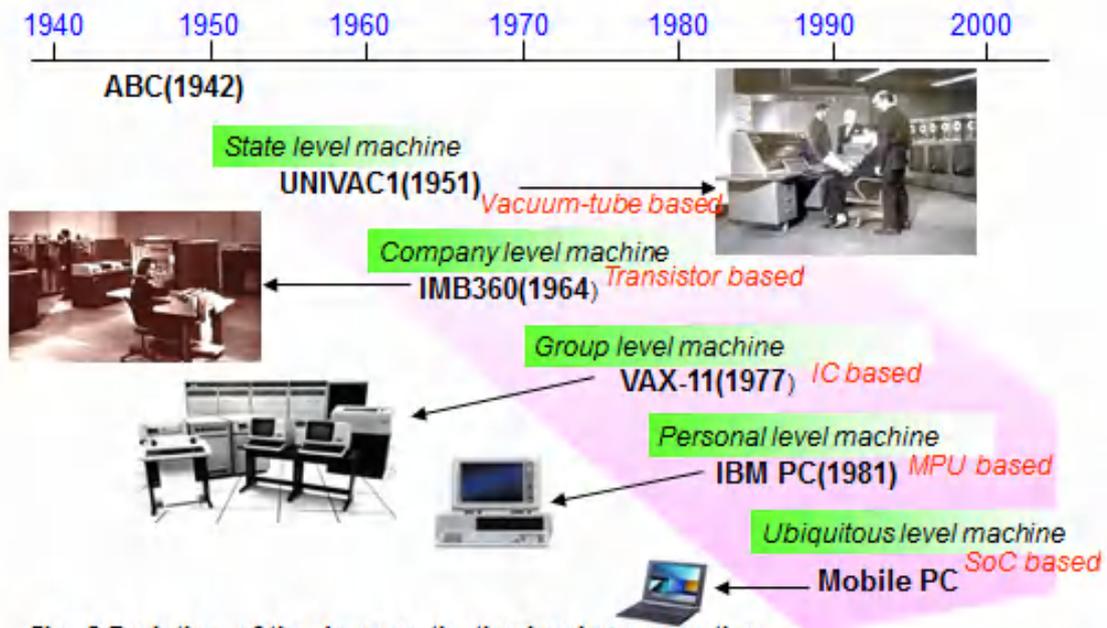


Fig. 3 Evolution of the democratization level of computing
 The democratization started from State level and reached to Personal level, and finally to ubiquitous level driven primarily by chip innovations.

A historical evolution of the democratization of the computer is shown in Fig.3. At the dawn of the computer age, one of the popular machines was ENIAC which was developed for the U. S. Army for about 500,000\$. It was a huge system which contained about 18,000 vacuum tubes, weighed about 30 tons. Only the wealthy state could afford to purchase such a huge machine in those days. In a sense, the computer was the “state level machine”. The first commercial computer called Univac 1 was introduced in 1951 by Univac based on vacuum tubes, and again, its first customers were U.S. Government agencies such as Census Bureau, the U.S. Air Force, and the U.S. Army Map Services.

In 1964, IBM introduced their IBM System 360 which was based on transistors in the hybrid structure called Solid Logic Technology, or SLT. The system was scalable and covered a wide range of performance from low end to high end. The 360 family became very popular and created a big wave of computerization for companies through the range of industries. Now the computer became the “company level machine”. In the late 1960’s to 70’s, when the IC became readily available, the computer was more democratized by the development of minicomputers by Digital Equipment and Nova. One of the most popular machines was VAX-11 from DEC introduced in 1977 using TTL IC. A university research group could afford to have a minicomputer, and it became the “group level machine”.

The next step of the democratization came with the introduction of PC by Apple (1977) and IBM (1981) based on the microprocessor. The PC became the “personal level machine” as its name implies. The further progress of the chip technology made it possible for the computer to become portable and mobile like mobile PC or tablet PC, resulting in the “ubiquitous computing”. The key enabler for the “ubiquitous level machine” was SoC or System on Chip.

The level of democratization started from the “state level” with vacuum tube, and then shifted to the “company level” with transistor, to the “group level” with IC, to the “personal level” with MPU, and to the “ubiquitous level” with SoC.

Of course, there were many factors which contributed to the computer revolution towards democratization, but it is quite clear from the above discussion, that the chip innovation was the most important key enabler for this revolution.

Figure of Merit

If we trace the historical evolution of the computer toward the democratization, it is seen that the progress has been made in such a way to satisfy the four requirements shown below;

- 1) More intelligence (or higher MIPS value), 2) Smaller size, 3) Lower power, and 4) Lower cost.

The four requirements, listed above, lead to the formulation of a “Figure of Merit” for the computer as shown below [6]:

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

Where (Intelligence) means the information processing capability, and MIPS value can be used in the case of general purpose computer. The rest of parameters, i.e., (Size), (Cost), and (Power), is self-explanatory.

An assumption is made here that the computer has made a progress in such a way to maximize the Figure of Merit value, and the semiconductor technology has also made a progress to boost the value. A comparison of Figure of Merit for Univac1 (1951) and a mobile computer (2006) was made as shown in Fig. 4. It was found that the Figure of Merit increased 1.5×10^{17} times during the period of 55 years which translates into CAGR (Compound Annual Growth Rate) of 105% or “doubling every year”.

	 UNIVAC-1 (1951)	 Mobile PC (2006)	Ratio
Performance (MIPS)	0.1	2,300	2.3×10^4
Size (cc)	7.4×10^8	1.7×10^3	2.3×10^{-6}
Power (W)	1.3×10^6	52	4.2×10^{-5}
Price (\$)	9×10^5	1,500	1.6×10^{-3}
Figure of Merit (relative)	1	1.5×10^{17}	1.5×10^{17}

Fig. 4 Comparison of Figure of Merit of Univac 1 and Mobile PC
 The comparison shows that the Figure of Merit increased 1.5×10^{17} times during the period of 55 years.

The evolution of Figure of Merit and four parameters, MIPS, Size, Cost, and Power, are shown in Fig. 5. Although some deviations of plots are observed, the general trend of the Figure of Merit, shown by the red bold line, supports the above assumption. The gradient of the red line, or the rate of progress, is estimated as “1000times in 10 years”, which corresponds to “doubling every year” as is the case of Fig. 3. The Figure of Merit is a “rule of thumb” which provides a macroscopic guideline for both the computer and semiconductor technology development. This is one of ways to correlate the world of computer and semiconductor technologies. Therefore, researchers in the both fields are advised to work closely together sharing the common goal of the Figure of Merit in the development project.

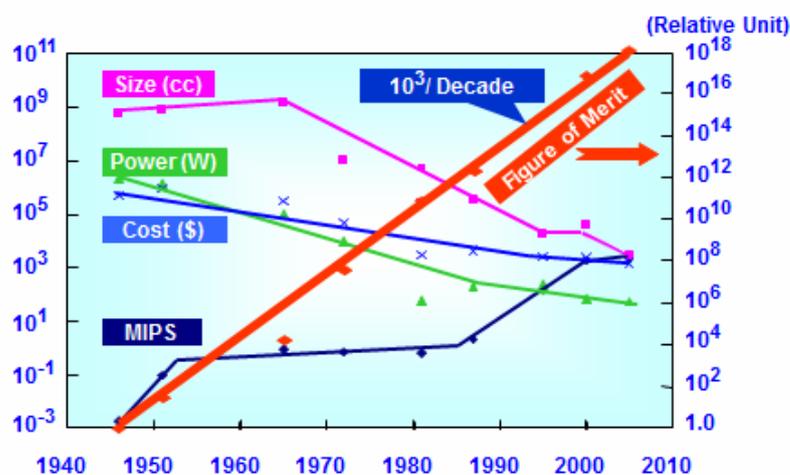
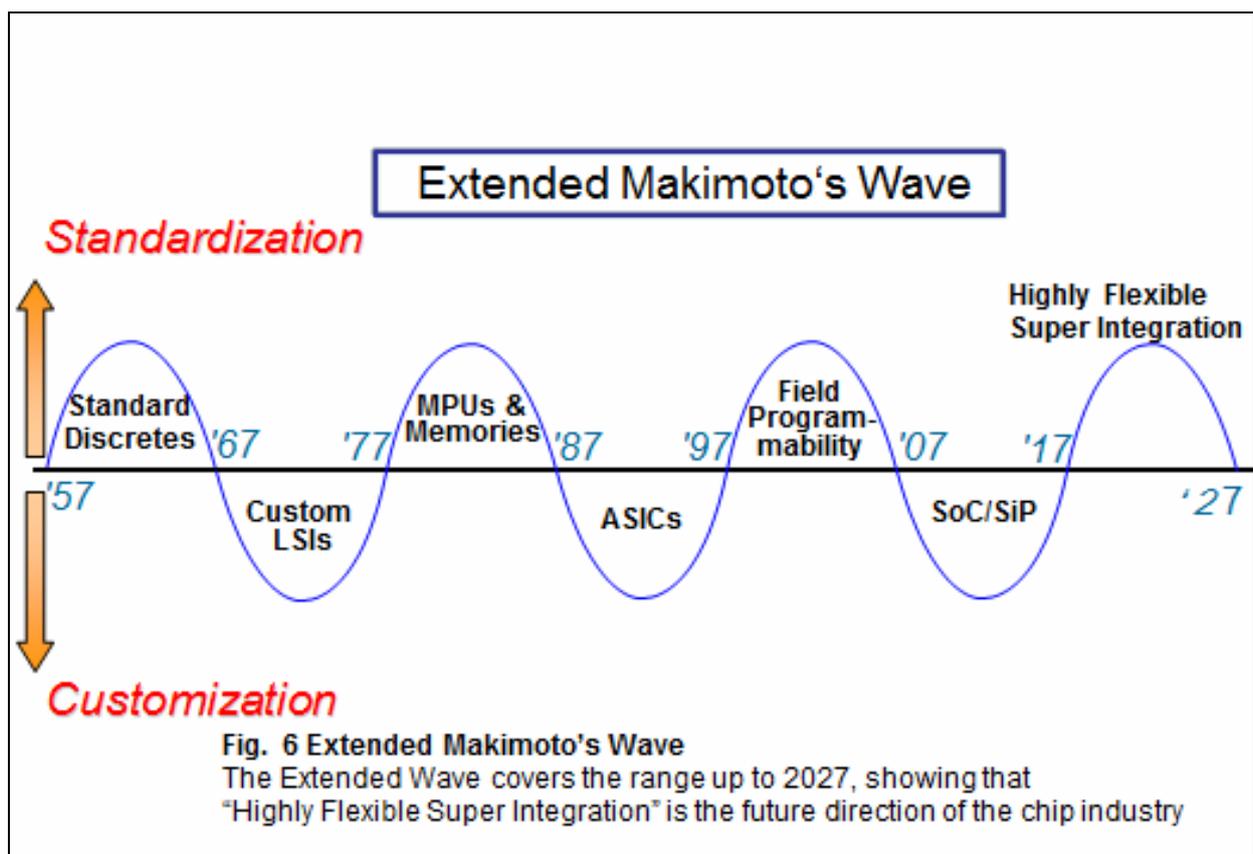


Fig. 5 Evolution of Figure of Merit of computer
 The gradient of the red bold line shows that the rate of progress is estimated as “1000 times per decade”.

Future Challenges

As is shown in Fig. 1, the original Makimoto's Wave covers the range of 50 years from 1957 to 2007, but the year 2007 has already gone. Fig. 6 is the extension of the original wave which shows that the cyclical nature of the industry is still alive for another couple of decades. Today's semiconductor industry trend is represented by SoC and SiP which points to the Customization direction. SoC and SiP are not just simple components, but they are the heart of the system, and therefore, they have to be customer specific or application specific products rather than general purpose standard products. The best example is the case of Apple's application processors, A5 and A6, which were custom designed for their iPad and iPhone. By choosing the custom approach, Apple succeeded in developing high performance and low power system which became the major source of strength for their mobile terminals; thus making a great contribution for launching the age of "Digital Nomad".[7][8] Samsung seems to be taking a similar approach as Apple; making their tablets and smartphones with their in-house processors. On the other hand, Qualcomm's processors target larger number of customers in the single market. Their product is called ASSP or Application Specific Standard Product which is getting momentum these days, boosting Qualcomm to No. 3 ranking in the chip industry in 2012, from No.6 position in 2011.



The next decade of 2017-2027 will be different from the current decade because the integration density on a chip will become too high for the custom approach for many applications. An industry wide effort will be made to develop product with high level of flexibility with high performance, low power, and low cost in order to cover wide range of system applications. This trend can be named as "Highly

Flexible Super Integration” or “HFSI”. One of approaches to this direction is the case of Altera’s “Programmable Silicon Convergence”, in which a chip contains multiple functional units such as MPU, DSP, FPGA, and other elements, capitalizing on the increase in the integration density in the next decade. [9] This is certainly an interesting challenge since some level of redundancy will be justifiable compared to the high cost of custom design.

There will be another new element of technology which will contribute to the realization of “HFSI”; that is the newly emerging non-volatile RAM. Simply stated, the NV-RAM has combined features of random access memory and non-volatile memory. If available, there will be significant changes in the way of designing chips and electronic systems; firstly, the memory hierarchy will be quite different from today’s system since NV-RAM can replace SRAM, DRAM, and Flash memory, resulting in performance improvement and power consumption reduction, and secondly, logic functions will be constructed by the array of NV-RAM providing the high level of flexibility. Although several types of NV-RAM have been pursued so far, promising NV-RAMs currently under development include ReRAM (Resistive RAM), STT-MRAM (Spin Transfer Torque Magnetic RAM), and CNT-RAM (Carbon nanotube based RAM). Although each technology has its own pros and cons, CNT-RAM, the newest entrant, seems to have the unique inherent characteristics of high reliability such as 1000 years of data retention at 85°C and unlimited endurance cycles, thanks to its robust switching mechanism. The NV-RAM will be the powerful enabler of the “HFSI” which will greatly contribute to the progress of computer or IT in general.

In accordance with chip innovations, the computer technology will undergo drastic innovations toward various directions including; to a tiny computer embedded in things as a part of Internet of Things, or IoT, to a high performance computing such as a supercomputer in the range of Exa FLOPS or more, and to a high level of AI machine such as a robot. At a first glance, a robot may look different from a computer, but actually it is a very sophisticated moving computer with high performance/low power processing capability. According to Hans Moravec of Carnegie Mellon University, the robot intelligence will dramatically increase in the coming decades, owing primarily to the progress of chip technology. It is predicted that the robot intelligence will reach the level of a mouse by 2020, the level of a monkey by 2030, and the level of a human by 2040. [10]

With the purpose of accelerating global research activities in robotics, the RoboCup was started in 1997 in Nagoya, Japan. The RoboCup is an international annual event of robotics competition with a target to create a robot soccer team which can beat human champion of world cup soccer by 2050. The technology developed for the RoboCup on the way to its goal will greatly affect many aspects of our society and our daily life.

Will the target of RoboCup be achieved by 2050? No one knows for sure, but it is clear that the success will depend very heavily on the chip innovations together with the computer revolution. A very exciting and challenging future should be ahead of us!

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Biography of T. Makimoto

Dr. Makimoto is President of SSIS (Society of Semiconductor Industry Specialists). He received Ph. D degree from the University of Tokyo in 1971 for the research of high frequency transistor. His interests include wide range of fields in the semiconductor electronics and its related subjects. He is IEEE Fellow since 1997. E-mail address: makimoto@tsugio.jp

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