International Technological Competitiveness of the Japanese Semiconductor Industry

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Abstract:

One result of my current analysis on the wafer process technology of the Japanese semiconductor manufacturers leads to a hypothesis that they produce semiconductor devices with surplus quality by using excessive wafer process technology and are thus unable to make the devices as cheaply as the competitors in the US, Korea and Taiwan.

From the history of Research and Development (R&D) and the mass-production of Dynamic Random Access Memory (DRAM), a certain technological culture was born in the Japanese semiconductor manufacturers in the 1970s. It was the culture to pursue a technological extreme, and to produce DRAM with extremely high quality. They produced DRAM with high quality for mainframes (all-purpose computers) by this technological culture and Japan became the world leader in the DRAM market in the 1980s. However, the demand for DRAM changed from mainframes to personal computers (PCs) in the 1990s. The Japanese semiconductor manufacturers could not change this technological culture, and continued making DRAM with surplus quality with the use of excessive technology. As the result, they were defeated by foreign competitors in the area of manufacturing cost reduction, and lost international competitiveness.

Keywords:

Japanese Semiconductor Industry, International Technological Competitiveness, Wafer Process Technology, Cost Competitiveness, DRAM

JEL codes: O3, L6

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1. Introduction

1.1 Structure of this paper

The first purpose of this paper is to explain the causes of the decline in international competitiveness of the Japanese semiconductor industry from a viewpoint of wafer process technology from 1990 to 2000. The second purpose is to clearly evaluate the international competitiveness in wafer process technology of the current Japanese semiconductor industry.

Engineers and managers at the Japanese semiconductor manufacturers think that the cause of the decline of Japanese competitiveness was due to the management, poor strategy and high cost but that the wafer process technology was not related to the decline. The result of research interviews and literature led to the tendency noted above. However, Fujimura (2000) insisted that there were problems in the technological development at the Japanese semiconductor manufacturers [1].

However, I consider the true cause of the decline to be that the Japanese semiconductor manufacturers missed the mark in the technology. This hypothesis is supported by the following items.

The wafer process technology consists of three phases: elementary process technology, integration process technology and mass-production technology [2]. The international competitiveness of the three phase technology in the Japanese semiconductor manufacturers is evaluated by an analysis of the research interviews, and this supports the following hypothesis. The semiconductor manufacturers produce surplus quality devices by using excessive elementary process technology, high integration process technology and high mass-production technology. With respect to the reduction in manufacturing costs, the level of Japanese technologies in all three phases is low. In other words, Japanese semiconductor manufacturers missed the mark in technology.

This reason is borne out by analyzing the history of R&D and mass-production of DRAM from the viewpoint of the three phase technology. A certain technological culture was born in Japan at the semiconductor manufacturers from 1970s to 1980s; it is the culture that pursued technological extremes and produced DRAM with extremely high quality. They produced DRAM with high quality for mainframes in this technological culture and Japan became the world champion in the DRAM market in the 1980s. According to Yoshioka (2004), the demand for DRAM changed from mainframes to PCs in the 1990s [3]. The semiconductor manufacturers were unable to change this technological culture, and continued making DRAM with surplus quality by using excessively high levels of technology. As a result, they were defeated by foreign competitors in the area of manufacturing cost reduction and thus lost international competitiveness.

1.2 Background

The international competitiveness of the Japanese semiconductor manufacturers declined dramatically from 1990 to 2000. What was the true cause of the decline? The engineers and managers think that the cause of the decline in competitiveness was due to the management, strategy and high cost but felt that the wafer process technology itself had no influence on the decline. The result of research interviews and literature led the tendency noted above. Below please find two examples that are in line with the opinions above.

The first example is the result of interviews conducted on 21 engineers from *Semiconductor Leading Edge Technologies* (*SELETE*) [4], (Interview A). As to the true cause of the decline of international competitiveness, 14 out of 21 pointed out a problem of cost competitiveness (high cost). In addition, the problem of management and strategic weaknesses were also thought to be major sources of the decline. However, only two noted that the decline in the wafer process technology might be a critical issue. When asked how the Japanese technological level compared with those of foreign competitors, 20 out of 21 assess the Japanese level as equal to or superior to others. Many engineers replied as follows: "Regarding the technological level, Japan was not defeated", "Japanese technology is equal to or superior to those of the US, Korea and Taiwan" or "Japanese technology is still not behind" (Interview B). Moreover, from these interviews, I understand engineers feeling that the cause of the decline of competitiveness is due to issues of management, strategy and high cost but not the wafer process technology.

The second example is shown in the following. To decide guidelines for the Japanese semiconductor industry, *Semiconductor Industry Research Institute Japan (SIRIJ)* was established in 1995 through the joint investment of ten Japanese semiconductor manufacturers [5]. The management board and research department consists of employees from these ten Japanese semiconductor manufacturers.

Semiconductor Industry Strategy Promotion Committee was formed within *SIRIJ* and the committee consisted of the top managers from the semiconductor manufacturers and university professors [6]. The committee wrote a report, "Problems and countermeasures for Japanese semiconductor industry", which was used as the guideline in 2003 [7].

According to the report, problems in the Japanese semiconductor industry were "cost competitiveness" and the "department store approach with variety products." With respect to technology, it was stated that Japanese design technology is superior to that of competitors in Korea and Taiwan but is inferior to that of competitors in the US. Japan's wafer process technology ranks with the US as being at the forefront, however, Korea is closing the gap. Further, the report went on to state that Japanese semiconductor industry should: 1. Restructure business practice and the system, 2. Reduce manufacturing costs, 3. Strengthen the design and system technologies, 4. Develop leading edge wafer process technology, 5. Open application markets and 6. Protect intellectual property rights along with applying trading regulations. According to the report, though a problem was found in design technology, no concerns were aired with respect to the wafer process technology.

To sum up, engineers and managers at the Japanese semiconductor manufacturers feel that problems are largely based on management, strategy and cost competitiveness led to the decline in international competitiveness, but do not feel that there is any problem in technology, particularly in the area of wafer process technology.

Many previous studies shown the same tendency. Oyane (2002) attributes the cause of decline to politics [8]. The very success of the industry and the decline of the industry in the US provoked a sharp reaction from the latter, which tried to impose various constraints on the Japanese semiconductor manufacturers under the guise of leveling the playing field. These constraints were so successful that they eventually took the wind out of the Japanese sails and ultimately left it vulnerable to attack both from a resurgent US, and emerging Asian competitors.

Itami (1995) notes that US semiconductor manufacturers, such as *Intel*, focused on micro-processing units (MPU) in response to the Japanese onslaught and this enabled their survival [9]. Korean semiconductor manufacturers focused on DRAM, and they have made the huge investments necessary to become and remain competitive in the industry. Japanese semiconductor manufacturers, by contrast, failed to focus on any one product, and they have spread their investments too thinly, and have taken on foreign competitors without a clear strategy.

Kawanishi (1997), a former top semiconductor manager noted that the delay in decisions on investment and a larger overhead led to the decline in the cost competitiveness of the Japanese semiconductor manufacturers [10].

These authors note that semiconductor manufacturers were part of large, sprawling business concerns with high overheads, and large companies like Hitachi or Toshiba were steeped in heavy electronic cultures averse to risk and slow in decision making. Semiconductor manufacturers required heavy investments in the silicon cycle. By the time Japanese semiconductor manufacturers got around to making their investments, they were too late to capture the bulk of profits on the upswing.

However, Fujimura (2000) pointed out the problem of development in the wafer process technology as a factor for the decline of Japanese international competitiveness [11]. Fujimura's two points are as follows.

1. Lack of capacity of "physical limit" improvement, in other words, technology development based in science.
2. Lack of capacity of optimum restructures of "physical limit", or the systematic ability to apply technology to industry.

Based on the three phase technology that the author has defined, the two factors above were also expressed in these words; in the Japanese semiconductor industry, the development capacity of the element process technology is weak and the ability of integration process technology is also low. In short, Fujimura insisted that the fall in the development capacity in the wafer process technology is the cause of the decline in Japanese international competitiveness.

On the other hand, Fujimura analyzed the reason for the rise of Korea, Taiwan and the US semiconductor manufacturer, *Micron technology, Inc* in the following way. As semiconductor equipment manufacturers grew, any company that could buy the right manufacturing equipment could produce DRAM. Korea easily obtained the elementary process technology by purchasing advanced equipment developed by the Japanese semiconductor manufacturers and this made Korea very successful in the production of DRAM. In Taiwan, foundry manufacturers were set up which only produced semiconductor devices. These foundry manufacturers do not have to develop new semiconductor devices and advanced processes. Thus, they were able to reduce production costs. *Micron technology* aimed at winning by cost competitiveness from its inception. They produce DRAM by use of a process flow shorter than that of the Japanese competitors and they also produced DRAM with small chip size. As a result, the number of DRAM made on one wafer was increased and the manufacturing cost of DRAM was reduced. Fujimura insists that these countries and the semiconductor manufacturers gained marketing power by the cost competitiveness in spite of the technological strength of Japan.

Did the fall in the technological development capacity that Fujimura pointed out really occur? If the technological development capacity falls, the real technological level will also decrease. However, engineers and managers in the Japanese semiconductor manufacturers think that a sign of the fall of technological level was not evidenced. Which assertion is right?

Fujimura and employees in the Japanese semiconductor manufacturers insist that the lack of cost competitiveness is the cause of the decline of international competitiveness. However, it is also felt that the technology has nothing to do with the cost competitiveness. Is this right? Is not the wafer process technology really related to the cost competitiveness?

1.3 Motivation for this study

Although Fujimura points out that there was a problem in the technological development capacity of the wafer process technology, engineers and managers in the Japanese semiconductor manufacturers do not agree. They still think that the U.S., Korea and Taiwan did not defeat Japan in the area of technology in the past, or even in the present. Is their thinking true? What led them to this belief? When the wafer process technology is divided into the three phases, elementary process technology, integration process technology and mass-production technology, which Japanese technology is strong or weak? Is there really no relation between cost competitiveness and the wafer process technology? What will increase the international technological competitiveness of the Japanese semiconductor manufacturers?

Considering the future direction of the Japanese semiconductor manufacturers, it is extremely important to clearly assess their international technological competitiveness. As noted previously, most people felt that there were no problems with the wafer process technology. Based on this premise, the future direction of Japanese semiconductor manufacturers is clear. However, if this thinking were to be incorrect, it would be necessary to radically modify the policies, directions, and strategies of Japanese semiconductor manufacturers.

However, there has not been any research that has focused on the international technological competitiveness in Japanese semiconductor manufacturers because their technology is secret and it is difficult to compare the technology directly by benchmarking. Moreover, the definition of the technology itself is ambiguous since the wafer process technology is so complex.

1.4 Purpose of this study

The first purpose of this study is to clarify the cause of international competitiveness decline of Japanese semiconductor industry from a viewpoint of the wafer process technology from 1990 to 2000. The second purpose is to evaluate the current international competitiveness in the wafer process technology of the Japanese semiconductor industry.

In this study, the wafer process technology will be divided into the three phases; elementary process technology, integration process technology and mass-production technology, which will be defined in the next section.

2. Wafer process technology

Before explaining the declining competitiveness linked to the technology, we must know something about the wafer process technology used in the production process of semiconductors. There are three phases of wafer process technology involved; elementary process technology, integration process technology and mass-production technology as shown in Fig.1.

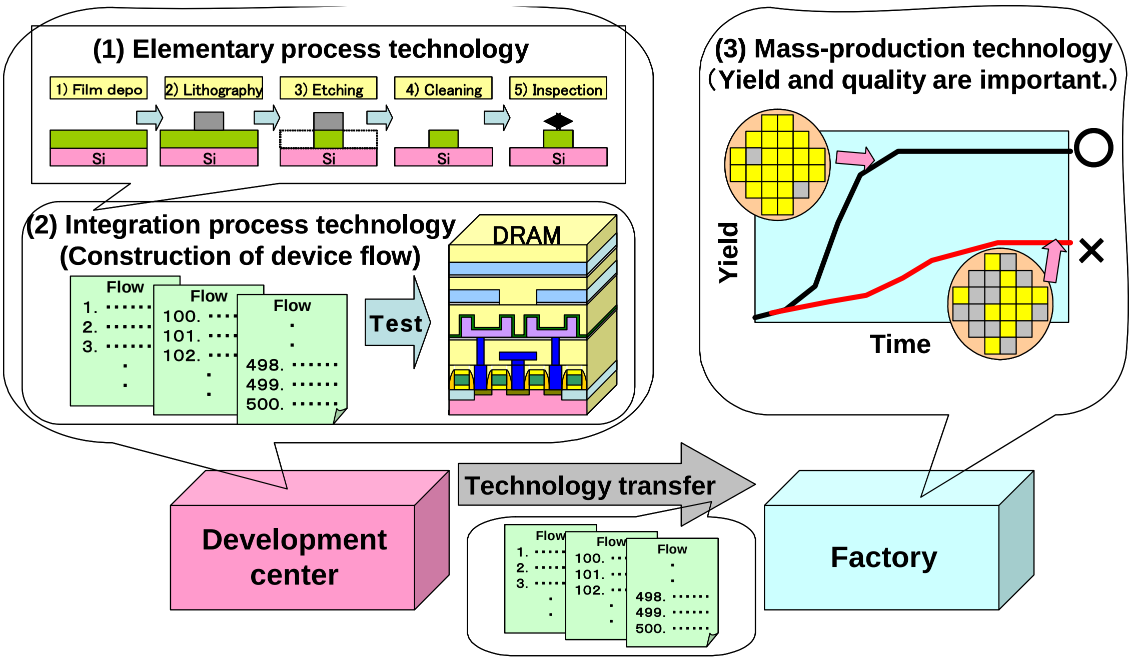

Fig.1 Three phases of wafer process technology.

(1) Elementary process technology

Semiconductor devices are produced through many steps, and the minimum basic unit technologies for these steps are called elementary process technology. The following technologies are included in the elementary process technology; 1) a thin film deposition on the silicon wafer by chemical vapor deposition (CVD) or sputtering, 2) lithography by which the resist mask is made on the film, 3) etching which removes non-masked film using the chemical reaction of plasma, 4) cleaning technology by which the resist mask and other residue are cleaned off and 5) inspection technology. Fine processing technology is a combination of lithography and etching.

Gate electrode etching, in which the finest processing is demanded, demonstrates the difference between 'high' and 'low' elementary process technology as shown in Fig.2.

The characteristic of anisotropy is needed for the etching of the gate electrode. Anisotropy is the condition in which the etch advances only in one direction. Superior etching produces a perpendicular sidewall as shown in Fig. 2(a)-B rather than a taper (A) or an overhang sidewall (C). Precision here has a major impact on transistor performance. As to fine processing, minimum pattern size, as well as the aspect ratio, are critical as shown in Fig. 2(b). B is superior to A because the pattern size of B is smaller than that of A. C is superior to B because the aspect ratio of C is higher than that of B. As to uniformity, A is superior to B in Fig. 2(c).

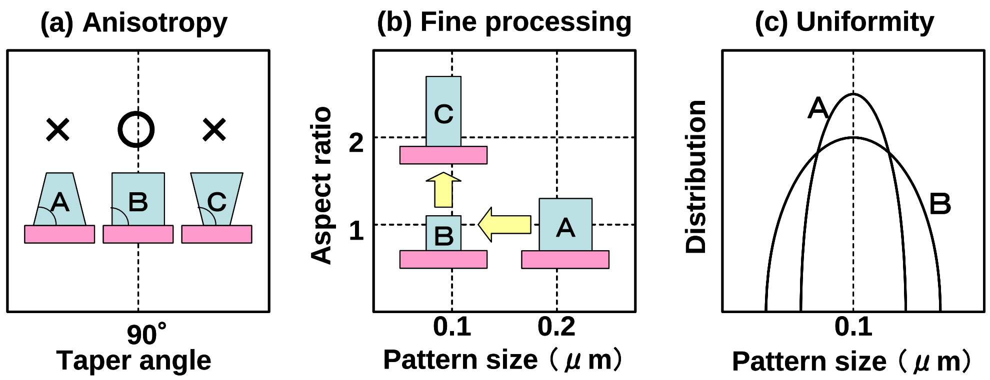

Fig.2 What is high level etching technology?

A technological difference appears at points such as etching rate, throughput, selectivity to under-layer or resist mask and charging damage. The technological level of gate electrode etching is judged by considering all characteristics listed above as well as fine pattern processing. The high capacity of technological development enables them to improve the physical limit in gate etching and to develop new gate etching technology.

(2) Integration process technology

Integration process technology builds a process flow in which the semiconductor device is formed on the silicon wafer by the combination of the elementary process technologies. There are over 500 steps involved in the manufacturing process flow of DRAM. It is important that specifications of semiconductor device performance are realized, for example, I-V (electric current and voltage) characteristics, access speed and electrical consumption power.

What is high-level integration process technology? In constructing the process flow, the technology realizing high performance indicates higher level. Performance alone, however, is not sufficient to ensure competitiveness. From the point of cost competitiveness, maintaining the current level of performance with minimum steps, minimum mask number, and minimum period of time shows high-level technology.

Regarding the integration process technology, there are two evaluation indices, performance and cost.

(3) Mass-production technology

Mass-production technology makes semiconductor devices on silicon wafers based on the process flow built by the integration process technology. Quality and yield are crucial in the mass-production technology. The quality involves three elements: performance, reliability and uniformity.

Most performances are determined at the time when the process flow is built according to the integration process technology. Reliability is based on the defect rate at the time of shipment and long-term guarantee. The long-term guarantee is related to the integration process technology as well as mass-production technology. However, mass-production technology has a large impact on reliability. Uniformity is the capacity to produce semiconductor devices with a small discrepancy in performance and reliability. Elementary process technology and mass-production technology have a large impact on uniformity.

The yield indicates the rate of products with semiconductor devices satisfactorily built on the silicon wafer. Several hundred semiconductor devices are produced on each circular silicon wafer with diameters between 20 to 30 centimeters. However, small particles from equipment and steps with small process margins lead to defective products during the several hundred steps in the process flow [11]. As a result, all of the semiconductor devices built on the silicon wafer will not necessarily perform properly. The yield rate must be factored in.

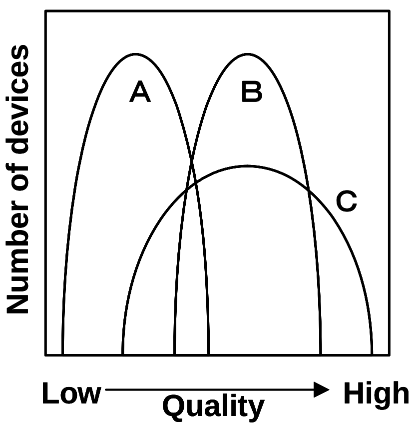

Fig.3 Technology and quality

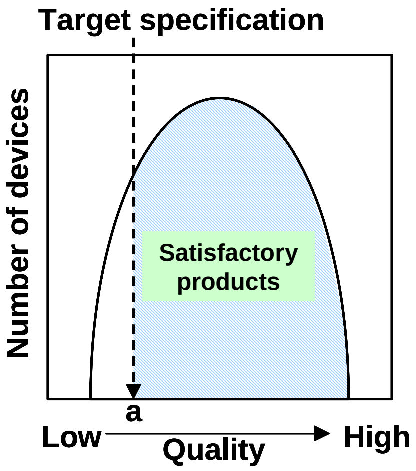

Fig.4 Quality and yield

What is high-level mass-production technology? A factory having the technology to mass-produce semiconductor devices with high performance, high reliability and uniform quality, is a high-level factory. A good factory is the one that can produce high quality semiconductor devices. As shown in Fig. 3, the technology that mass produces with distribution of B is higher than that of both A and C in quality.

Normally, the yield is low during the first stage of mass-production in the factory because there are a lot of steps with small process margins and small particle generation in initial process flow just after development in the integration process technology. Therefore, it is necessary for the problems in the process flow to be identified and corrected early in order to quickly raise the yield.

As shown in Fig. 1-(3), achieving a high yield in a short span of time and maintaining a high yield indicates a high level of mass-production technology. A high yield acts to reduce the cost of semiconductor devices. Technology and cost competitiveness cannot be ruled out as being unrelated. Higher yield results in lower cost for the semiconductor devices with higher cost competitiveness.

Along with integration process technology, mass-production technology is another factor used for the evaluation of quality and cost.

(4) Quality and yield

Please refer to Fig. 4 to help clarify the relationship between quality and yield. There is a discrepancy in performance or quality of the semiconductor devices built on one silicon wafer. If the target specification for quality is set at point A, then all devices with quality exceeding that of point A are judged to be satisfactory. The yield is the percentage the number of devices that exceed the specifications divided by the total number of devices built on the silicon wafer. Therefore, if the target specification of A is raised, the yield will decrease. In other words, even with the same quality distribution, the setting of the target specification will alter the yield rate.

A high yield is not necessarily equivalent with higher quality semiconductor devices. It is important to realize that quality and yield are two completely difference indices.

3. Current technological status of Japanese semiconductor industry

3.1 Survey method on three phase technologies

Now let’s take a look at the international technological competitiveness of Japanese semiconductor manufacturers based on the three phase technologies. The simplest method would be to compare the above three phase technologies across a range of

Japanese and non-Japanese semiconductor manufacturers, either relative to each other or to benchmarks. Semiconductor manufacturers are, however, extremely reluctant to allow outsiders to observe their operations - for obvious reasons - which makes this method impossible.

The following methods have been used in this study, based on interviews of three groups of engineers.

(1) Interviews with engineers of equipment manufacturers

Equipment manufacturers deliver equipment to semiconductor manufacturers throughout the world. Engineers of equipment manufacturers install the equipment, and they have a chance to talk with the engineers at the semiconductor manufacturers during the start-up process. They also have an opportunity to compare the levels of elementary process technologies at Japanese and non-Japanese semiconductor manufacturers. Three engineers were interviewed, taking care not to compromise their non-disclosure requirements (Interview C).

(2) Interviews with Japanese engineers at contracted manufacturers at overseas foundries

Foundries are businesses which mass-produce semiconductor devices on contract but are not involved with design. Most of them are frequently located in Taiwan or China. Their customers include Japanese semiconductor manufacturers whose engineers can compare wafer process technology at their home base and the foundry during technology transfer of the process flow. A total of three engineers were interviewed (Interview D and E).

(3) Interviews with engineers who have moved from Japanese to non-Japanese semiconductor manufacturers

In spite of ‘lifetime employment,’ some engineers – sometimes key engineers – have left Japanese semiconductor manufacturers and joined overseas semiconductor manufacturers as a result of restructuring in the 1990s. Such engineers can also compare the elementary process, integration process and mass-production technologies of their current and former employers. One engineer was interviewed (Interview F).

The comparisons of these three groups of engineers provide revealing insights into the three types of technology we discussed above.

3.2 Survey results

(1) Competitiveness of elementary process technology

The consensus of the engineers from the three groups was that Japanese elementary process technology was very advanced. According to the comments of three engineers of dry etching equipment manufacturers, the Japanese fine processing technology and the development capacity are higher than those of foreign competitors (Interview C).

Three Japanese engineers in semiconductor manufacturers at contract manufacturers of overseas foundry manufacturers, and a retired engineer from another Japanese semiconductor manufacturer who joined a manufacturer in another Asian country, also said that the level of Japanese elementary process technology and the development capacity are high (Interview D, E and F). They emphasize that the fine processing technology of Japanese semiconductor manufacturers is far superior to foreign competitors (Interview D).

One engineer argued that semiconductor manufacturers elsewhere in Asia could not create new elementary process technology (Interview F). The Taiwanese foundries are, at least, dependent on the equipment manufacturers for the elementary process technology (Interview D). Japanese semiconductor manufacturers were not content with the performance of standard equipment, and placed orders for customized equipment which provide higher levels of performance (Interview C).

In contrast, the comment of engineers of the equipment manufacturers is that the elementary process technology and the development capacity in Japan are excessive (Interview C). The reason for this assertion is that the other semiconductor manufacturers in Asia do not place special orders for equipment and that they can produce the same sort of semiconductor devices with the same pattern size and the same degree of integration using standard equipment (Interview D and E).

(2) Competitiveness of integration process technology

According to a comment from an engineer of a semiconductor manufacturer, the integration technology to produce the high-performance semiconductor devices in Japan is high. However, there is a Japanese tendency to create transistors that exceed specification (Interview E). It is very likely that excessive performance is also set as a goal along with excessive elementary process technology.

It is a form of technological snobbery to say that the highest specifications necessitate the highest level of technology and lower specifications necessitate lower-level technology. Producing cost-competitive devices requires a sophisticated deployment of technological resources, particularly in the phase of integration process technology. Two Japanese engineers were told by engineers at a Taiwanese foundry that it was cut by one third because the process flow brought over from Japan was too long (Interview D). The Japanese engineers had concerns as to whether the devices would perform reliably. Taiwanese products perform reliably, the yield rate rose and profitability increased (Interview D). Japanese semiconductor manufacturers appear to use more mask layers than elsewhere in Asia (Interview E) and this matter has a direct impact on cost competitiveness.

(3) Competitiveness of Mass-production technology

High quality semiconductor devices are often equal to a high level of mass-production technology as shown in the following examples. A Japanese engineer proudly commented on his company's mass-production factory overseas saying, "Only our factory can guarantee the quality of DRAM for over ten years." (Interview G). It should be noted that it is a sign of a high level of mass-production technology to produce DRAM at a mass-production factory overseas with a 10-year warranty. However, if the main user for DRAM is PCs, it is a sign of excessive quality. There is no need to produce DRAM with such a quality that it merits a 10-year warranty for personal computers.

The much vaunted mass-production technology of Japan is weak in cost competitiveness. One reason is that the slow pace at the start up for the yield of Japan compared to that of Taiwan (Interview E). In addition, since there is a larger number of equipment (Interview E), the throughput of the Japanese semiconductor manufacturers is poor. Moreover, the Japanese semiconductor manufacturers feel a need to increase not only the yield but also the quality level of the devices while the some semiconductor manufacturers in Asia are mainly concerned with raising the yield rate at start up (Interview F).

During R&D activity, the Japanese semiconductor manufacturers want to incorporate new technology, but Asian semiconductor manufacturers will not add new technology unless it leads to a rise in the yield. Equipment and processes or process flows are not changed unless absolutely necessary (Interview F).

Indeed, they sometimes extend the life of mass-production technology deliberately to maintain KrF lithography [12] for semiconductor devices under 100 nm when competitors had switched to more advanced ArF lithography [12] from the 130 nm generation of semiconductor devices. This shows the high level of technological expertise of the Asian semiconductor manufacturer for being able to extend of the lifetime of their existing equipment (Interview F).

Even if this is making a virtue out of necessity, and if the result of extending the life of equipment is improved cost competitiveness while achieving the required performance and reliability, it can be considered as astute technology management.

3.3 Hypothesis

Though the survey may be a bit fragmented, it does serve as an analysis of the three phase technology in the Japanese semiconductor industry. Based on these results, I would like to make propose the following theory.

There is little doubt that the elementary process technology of Japanese semiconductor manufactures is high. Their development abilities in this phase also appear to be high. Moreover, the integration process and mass-production technologies necessary to produce high quality semiconductor devices are also high. However, it is very likely that the elementary process technologies are excessive and the high levels of integration process and mass-production technology lead to the manufacture of DRAM of excessive quality for the purposes for which they are required.

From the viewpoint of cost competitiveness, the three phase technologies of elementary process, integration process and mass-production technology are problematic. Special orders for equipment and poor throughput result in a larger number in pieces of equipment. Moreover, Japan has not been able to pursue a rise in the yield similar to that seen in other Asian countries since there are more masks and a greater number of steps in the process flow. As the result, the pace of the increase of yield at the start up is slow.

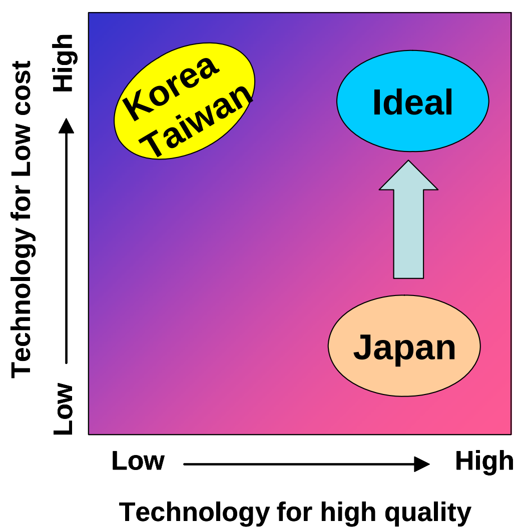

Fig.5 Two evaluation axes about technology.

Based on this theory, the decline in the international competitiveness of the Japanese semiconductor manufactures cannot be attributed to drops in the technological development capacity as Fujimura insisted. Rather, it would seem to be a more accurate assessment of the situation to say that the other Asian countries think that Japanese technological level is excessive.

In conclusion, from the aspect of the three phase technologies, problems at the Japanese semiconductor manufactures are as follows (Fig.5). In all three phases, Japanese technologies to make semiconductor devices with high quality are superior, but excessive. To the contrary, in all phases, Japanese semiconductor manufacturers either lacked or did not utilize the technology necessary to be cost competitive. To put it bluntly, Japanese semiconductor manufacturers missed the mark with the technology.

4. History of DRAM from aspect of technology

The current status of the Japanese semiconductor industry with respect to three phase technologies has been discussed. It has been suggested that excessive elementary process technology, high integration process and mass-production technology create semiconductor devices with excessive quality. When and how was this technological culture formed?

In this section, the history of the DRAM will be discussed from the point of technology. This shows that the technological culture currently seen in Japan was formed more than 25 years ago. It also shows that this technological culture, which enabled Japan to claim the top share in the DRAM market in the 1980s, is also responsible for the drop in its international competitiveness in the 1990s.

4.1 History of DRAM from 1970s to 1980s

(1) Competitive source in the DRAM market in the 1980s

The history of the DRAM started with the invention of the 1K bit DRAM by Intel in 1971. As shown in Fig. 6, the US held the top share in the DRAM market in the 1970s and the DRAM was created in this environment. The major Japanese electronics companies invested huge amounts of money and human resources into the R&D of DRAM, and they had overtaken the US to gain a dominant share of the global market by the early 1980s.

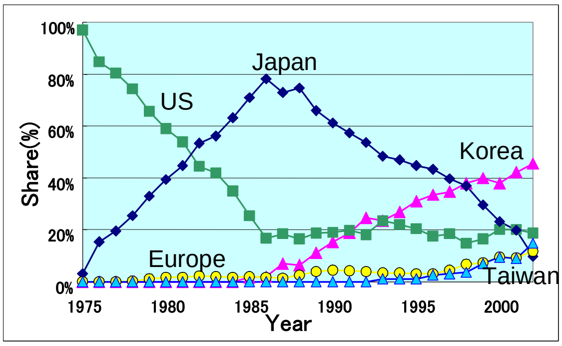

Fig.6 DRAM share by country

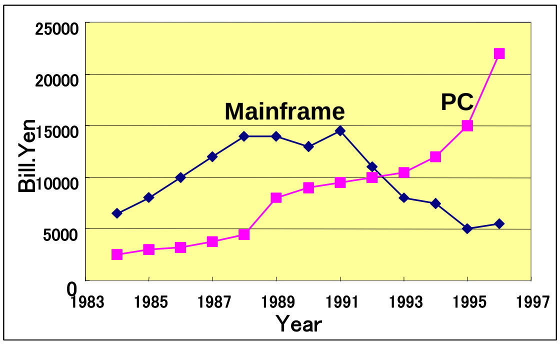

Fig.7 Japanese computer shipment

At that time, the source of competitiveness in the DRAM market was high quality. Yoshioka's analysis of the process describes how Japan surpassed the US [19]. As shown in Fig. 7, the shipment of mainframes in Japan increased from the 1970s to the 1980s. Japan's share in the DRAM market also increased and eventually surpassed the US in 1982. In the mid-1980s, Japan held an 80% share of that same market. Japan was the world leader in the mass-production of DRAM for mainframes.

The main demand by the mainframe manufacturers on the DRAM manufacturers was high quality [13]. The demand for reliability was particularly stringent and a 25-year guarantee was sought (Interview H). It is said that the demands were influenced by the company now known as Nippon Telegram and Telephone Corp. (NTT) because of their need for a long-term guarantee for phone operator systems. The Japanese semiconductor manufacturers exhibited a great number of strengths to mass-produce a high quality DRAM that could meet NTT's strict reliability demands and this resulted in surpassing the US in market share.

(2) Technology that produces high quality DRAM

What kind of technology led to the creation of high quality DRAM with a 25-year warranty? It was fine processing technology expanding the frontiers of extreme performance and integration process and mass-production technology in pursuit of high quality. This technological culture of the Japanese semiconductor manufacturers remains and is connected to the excessive technology and quality.

Innovations of fine processing technology

Known as Moore's law, the degree of integration level of semiconductors has increased by four times every three years. Along with increasing degree of integration, minimum future sizes have decreased by 0.7 times every three years. The future size reduction increases complexity and speed, and reduces the consumption of electric power by the scaling rule. In other words, size reduction alone results in higher performance, and has continuously been a target for engineers of DRAM and other semiconductor devices.

With the advent of size reduction, the semiconductor manufacturers were faced with two problems, improving the fine processing and maintaining uniformity. Finer pattern delineation leads to higher performance DRAM. The better uniformity in the fine processing enabled them to mass-produce high performance and uniform DRAM repeatedly. However, the contact aligner [14] and the isotropic wet edging technology

[15] could not improve fine processing and uniformity in the early 1970s.

To solve this problem, new projection aligners, which were named as Stepper or Scanner [14], were developed by *Nikon* and *Canon* at the end of the 1970s. This method made it possible to create extremely small resist mask reliably that were reproducible and uniform [16]. From the end of the 1970s to the beginning of the 1980s, dry etching equipment known as reactive ion etching (RIE) [15] was developed by a number of companies including Nichiden Anelva Corp., Toshiba and Tokuda Seisakusyo Co. Ltd. and Hitachi [16]. It is possible to use anisotropic fine processing with the use of RIE.

Japanese semiconductor manufacturers simultaneously attained fine processing and uniformity with these innovations. Their engineers usually continued to push the envelope with respect to the performance of equipment. When they were no longer satisfied with the performance, they would develop new processes and equipment. It was not unusual for semiconductor manufacturers to work hand in hand with the equipment makers to develop this technology.

Integration process and mass-production technology in pursuit of high quality

Many devices must be incorporated into the process flow to produce a high performance and highly reliable DRAM. New structures to realize high performance transistors and new processes, such as annealing processes to reduce damage and defect caused by charged particles in a thin film, are needed. In addition, a sufficient number of inspection processes must be included to detect defects and to confirm the measurements of fine pattern. This led to an increase in the number of mask layers and process flows. However, these were all indispensable parts of the process flow for the high quality DRAM in the late 1970s and early 1980s.

Extremely high performance equipment was used in factories. According to the process flow, which included a large number of steps, mass-production of high quality DRAM was now possible. Engineers and technicians quickly mastered the use of the new equipment brought on by the technological innovation in factories. Improvements at each step of the process flow were vigorously pursued to enable extreme performance along with the reduction in particles and the expanded process margin.

These efforts set the standards for the succeeding generations. Production of high quality DRAM became the norm while engineers continued to strive for more. The idea of producing a DRAM inferior in quality to the preceding generation was inconceivable. This made perfect sense in the 1970s and early 1980s.

Formation and establishment of the technological culture

As stated above, pursuit of the utmost in elementary process technology and high quality DRAM led to the formation of the technological culture during the late 1970s and through the 1980s at the Japanese semiconductor manufacturers. This technological culture was also the driving force behind the competitive strength of the Japanese semiconductor manufacturers. It made perfect business sense and it was now common that the users requested high quality DRAM. As the result, the constant drive to extend the limits in elementary process technology producing higher quality DRAM was not questioned and eventually became the norm.

The technological culture still remains today and the evidence of the excessive technology and quality in the production of semiconductor devices formed more than 25 years ago. With this deeply rooted technological culture, how did the Japanese semiconductor manufacturers respond in the 1990s to the emergence of Korea and Taiwan in the area of the mass-production of low cost DRAM?

4.2 History of DRAM in the 1990s

(1) ***Competitive source in the DRAM market in the 1990s***

Figure 6 shows the rise of the Japanese DRAM industry and its precipitous decline. Figure 7 gives a clue for this rise and fall. There was a major shift in the computer world from the late 1980s, and consequently in the DRAM market. The proportion of DRAM going into PCs rose dramatically, at the expense of mainframes.

Along with this shift, there was a change in the share of DRAM market by country. With the decreased number of shipments of mainframes, Japan, the top shareholder in the mid-1980s saw its share decline in the DRAM market. On the other hand, the increase in the shipments of PCs helped propel Korea past Japan to claim the highest share in the DRAM market.

Yoshioka explains the rise of Korea in the following way [3]. With the change in the product components in the world computer market, so changed the demand for DRAM. In other words, the main destination for DRAM shifted from mainframes to PCs. Through the mass-production of DRAM for PCs, Korea was able to overtake Japan and become the world leader in DRAM market. *Micron technology*, the top DRAM manufacturer in the US, surpassed Japan in the year 2000.

At that time, the demands of DRAM for PCs were low price and mass volume. There was no need for high quality DRAM with 25-year guarantees. Low cost was the force behind the competition for the DRAM for PCs. As such, Korea, Taiwan and the *Micron technology* were able to overtake Japan by mass-producing low cost DRAM.

(2) Technology that produces low cost DRAM

What kind of technology allows for wafer process technology of DRAM with low cost? The answer is to find the most cost effective technology in the areas of elementary process, integration process and mass-production technology.

As to elementary process technology, semiconductor manufacturers can reduce development costs, the number of processes and time by using the standard equipment. Semiconductor manufacturers must make the best effort to prolong the useful life of the technology to the extent possible.

In the area of integration technology, it is necessary to build the process flow that will realize semiconductor devices of appropriate quality in a short period of time. This also means that we must drastically reduce the number of masks and work steps. The device structure had to be kept as simple as possible. Semiconductor manufacturers must reduce damage and strictly limit the inspection processes. For example, Kanazawa (2000) notes that *Micron technology* uses only two-thirds of the number of masks as Japanese semiconductor manufacturers in the DRAM process flow and this has led to a large reduction in overall costs [17].

It is important in mass-production factories to meet the minimum standards for the specific product, quickly raise the yield and maintain that high yield level. The throughput of the equipment must be improved to raise the yield and the process margin must be increased while the occurrence of particles must be prevented as much as possible.

The pursuit of low cost and mass volume is hardly glamorous compared to the quest for ever greater quality and performance. However, this is also an important aspect of high-level technology. When we heard that *Micron technology* could produce DRAM with only two-thirds of the number of the masks, Japanese semiconductor manufacturers tried to produce the DRAM in a similar manner but were unsuccessful (Interview H). It was not so easy to imitate the technology that produced DRAM with only two-thirds of the number of masks. This, in itself, had now become a sign of high level technology.

One can say that the Korean DRAM manufacturers, *Micron technology* and the Taiwanese foundry manufacturers operated on the principle of pursuing the abovementioned technology that led to an increase in their cost competitiveness.

4.3 The cause of Japanese international competitiveness decline

As the driving force behind competitiveness in the DRAM market became low cost, what kind of countermeasure did the Japanese semiconductor manufacturers have? They must have seen the shift in the demand of DRAM from mainframes to PCs. Japan could not change the technological culture that had been in place for the past 25 years. Simply put, they continued to produce DRAM with the same excessive quality using the excessive wafer process technology as they did in the 1980s. As a result of literature severance in section 3.2(3) (Interview G), this technological culture permeates through the Japanese semiconductor manufactures. As the result, the Japanese semiconductor manufactures lost the battle of cost competitiveness and withdrew from the DRAM market.

4.4 Mistake of Japanese semiconductor manufactures

The comments of Japanese semiconductor industry on their lost in the cost competition of DRAM development to Korea was because Japan "lost in management, strategy and cost competitiveness" but "did not lose in technology" as noted in the first section.

It is correct in a sense that Japan did not lose in technology. Indeed, Japan did not lose to Korea, Taiwan and the US semiconductor manufacture with respect to wafer process technology that enabled Japan to make such high quality DRAM. This can also be said about technological and development strength of Japan shown by the fine processing technology in the elementary process technology. Therefore, it can be surmised that the assertion of the Japanese semiconductor industry that it did not lose in technology, can be tied to the fact that they succeeded in the production of high quality DRAM and in the elementary process technology that still remains superior.

However, Japan's insistence that it did not lose the technological battle is one reason that the Japanese semiconductor manufacturers drove themselves into a corner. This is because the high-level elementary process technology and the technology that produced the high quality DRAM were no longer the key to competitiveness since 1990s once the demand for DRAM shifted to PCs. Rather, the excessive elementary process technology and the excessive quality became a handicap to competitiveness in the PC's DRAM market where cost competitiveness is so important. In other words, Japanese semiconductor manufacturers have been missing the technological target since the 1990s. This was the first mistake by the Japanese semiconductor manufactures.

The second mistake is found in the opinion that "Japan lost the management, strategy and cost competitiveness" battle. The people of Japanese semiconductor manufacturers think that cost competitiveness is based on the scale of the economy and the investments. They think that cost competitiveness has no relation with the technology in semiconductor production. However, cost competitiveness also has a great effect on the technology in semiconductor production. A unique technology for the production of low cost DRAM really exists. It is the elementary process technology to prolong the life of equipment, the integration process technology to construct the process flow using fewer masks to reduce step and to enable production in a shorter amount of time, and the mass-production technology to realize a high yield in a timely manner. Above-mentioned technologies are completely different from the technologies in which Japan excelled to produce high quality DRAM. As a result, the Japanese semiconductor manufactures lost in the technology area of low cost to Korea, Taiwan and *Micron technology.*

5. Summary

In this paper, the wafer process technology was divided into the three phase technologies, such as elementary process, integration process and mass-production technology. The decline of international competitiveness in the Japanese semiconductor manufactures was discussed from viewpoint of these technologies. In addition, the past and current status of the technological competitiveness in the Japanese semiconductor manufactures has been examined. The results of the analysis are as follows.

The hypothesis below is proposed for the current status of the Japanese semiconductor manufactures. Excessive elementary process technology has been used along with high integration process and mass-production technology to produce semiconductor devices with excessive quality in Japan. In addition, the elementary process, integration process and mass-production technologies have all played a role in Japan's inability to cheaply produce semiconductor devices.

From the 1970s through the 1980s, the technological culture necessary to produce high quality DRAM was formed through the pursuit of extreme performance of elementary process technology and extreme quality of semiconductor devices. This is linked with the current excessive elementary process technology and excessive quality semiconductor devices found in Japan. This technological culture enabled Japan to claim the top share in the market through its production of high quality DRAM in the 1980s. However, when the demand shifted from the mainframes to PCs in the 1990s, the Japanese semiconductor manufacturers could not change their technological culture in pace with the aforementioned shift. As a result, Japan lost out to Korea and others who were able to mass-produce DRAM with low cost. This in one of the major reasons why the Japanese semiconductor manufactures suffered a decline in its level of international competitiveness.

Notes and References:

[1] Fujimura, S. (2000), *Handotai rikkoku futatabi (Revitalization of the Japanese semiconductor industry),* Tokyo: Nikkan-kogyo-shimbunsya.

[2] Definitions and explanations of the three phase technologies discussed in the second section.

[3] Yoshioka, H. (2004), 'Consideration of Catching-up of Samsung Electronics in the DRAM Market: From the Aspect of Change in the Demand for DRAM', *The journal of Korean Economics Studies,* Vol.4, August, pp.21-44.

[4] Official name is *Semiconductor Leading Edge Technologies* (*SELETE*). *SELETE* is a consortium established by more than 10 of the Japanese semiconductor manufacturers. It has been developing the elementary process and module process technology in transistor, wiring and lithography for the next generation. The engineers at *SELETE* are those who were sent from the development centers and mass-production factories from the various semiconductor manufacturers.

[5] *The Semiconductor Research Institute Japan* (*SIRIJ*) was established in 1995. Member companies are *Fujitsu, Matsushita, NEC, Oki, Renesas, Rohm, Sanyo, Sharp, Sony and Toshiba*. *SIRIJ* plans and implements programs to revitalize the Japanese semiconductor industry, increase its international competitiveness and explore the many possibilities of the semiconductor devices. It is composed of researchers sent from the member companies and when necessary research groups are formed with those from the semiconductor and related industries to collect and analyze information.

[6] The members are Hiroyuki Yoshikawa (*AIST*) chairman, Naoyuki Akigusa (*Fujitsu*), Tadahiro Ohmi (*Tohoku University*), Masanobu Oyama (*Toshiba*), Kiyonori Sakakibara (*Keio University*), Hajime Sasaki (*Japan Electric*), Ichiro Nakajima (*AIST*), Koichi Nagasawa (*Mitsubishi*), Kunio Hasegawa (*Hitachi*) and Masataka Hirose (*MIRAI*).

[7] A report from the committee in *SIRIJ* (2003), *"Problems and countermeasures for the Japanese semiconductor industry"*.

[8] Oyane, S. (2002), *Nichi-bei-kan handotaimasatsu (Friction in the R&D of Semiconductors between the US and Japan),* Tokyo: Yushindo.

[9] Itami, H. (1995), *Nihon no handotaisangyo: Naze mitsuno gyakuten ha okottaka? (Japanese Semiconductor Industry: why they lost in 3 kinds of technology development?),* Tokyo: NTT Syuppan-kabushikikaisya.

[10] Kawanishi, T. (1997), *Waga handotai keiei tetsugaku (My Management Philosophy on Semiconductor Development),* Tokyo: Kabushikikaisya Kogyo-chosakai.

[11] Process margin refers to the surplus in the process. If the semiconductor devices are not produced with enough surpluses in the process, a slight change in the characteristics in the process will lead to many defective products. With the initial process flow after

built by integration process technology, many small margin processes are included in the process flow. These processes are found and measures are taken, such as altering the process conditions or improving the device structure. So a slight change in the characteristics in the processes will not result in defects at the mass-production factories.

[12] In photo-lithography, the minimum line width possible formed to the resist mask is proportionate with the optical wavelength. Therefore, the shorter the wavelength, the finer the resist mask can be made. The optical wavelengths have progressed from extra high-pressure mercury g-line (436 nm) and I-line (365 nm), KrF (248 nm), ArF (193 nm). Roughly speaking, the KrF was used up until the 130 nm generation and the ArF was used in most places from the 100 nm generation.

[13] Nonaka, I. and K.Nagata (1995), *Nihongata Innovation system: Seicyo no kiseki to henkaku heno cyosen, (Japanese Style Innovation System: Challenge in Growth and Reform)* Tokyo: Hakuto-shobo.

[14] Contact aligner refers to attaching wafers on a pre-burned pattern of a photo mask, applying light to transfer a pattern in a manner like taking a picture. With this method, the mask and wafer come in contact with light so the mask may be consumed, leading to defects and decreasing the yield. Also, in principle, the resist mask cannot be smaller than the size of the opened photo mask. To resolve these issues, there must be space between the photo mask and the wafer for projection aligner. For further details, refer to *"Hajimete no Handotai Lithography Gijyutu" (Beginning Lithography Technology)* by Shinji Okazaki, Shogi Suzuki and Takumi Ueno (2003), Kogyo-chosakai.

[15] In the beginning, wet etching was used for the semiconductor processing. For example, wet etching for silicon used KOH solution and a FOH solution was used for silicon dioxide. But, the processes in wet etching proceeded in all directions. This is called isotropy. As a result, the wet etching overhang form is generated under the resist mask. So, the sidewalls of the pattern have a taper angle. There was no problem with the 1K to 4K bit DRAM when the minimum pattern size was over 10 μm. However, after the 16K bit DRAM, fine processing below 5 μm was needed so the anisotropic etching process became necessary. The solution was dry etching technology known as reactive ion etching (RIE). For further details, refer to *"Handotai Dry Etching Gijyutu" (Semiconductor Dry Etching Technology),* by Tokuyama, T (1992), Sangyo-tosho.

[16] Tarui, Y (1991), *Handotai rikkoku Nippon: Dokusoteki na sochi ga kizukiageta kiroku (Semiconductor oriented nation, Japan: The records of R&D of creative devices),* Tokyo: Nikkan-kogyo-shimbunsya.

[17] Kanazawa, Y (2000), *Wagakuni handoutaisangyo no mezasubeki tokoro (Goals of the Japanese Semiconductor Industry),* Tokyo: Kikaishinko-kyokai.

Interview list:

(A) Results of survey conducted with 21 engineers by the author and Tsunetoshi Arikado, former CEO and 1st Research Department Head of *Semiconductor Leading Edge Technologies,* Inc in September 2004.
(B) Interviews conducted with five engineers from the Japan Semiconductor Consortium in September 2004.
(C) Interview conducted by the author with three engineers at a dry etching equipment maker. (5/4/2004)
(D) Interview conducted by the author with two engineers from a Japanese semiconductor maker. This maker consigned work to a foundry. (4/27/2004)
(E) Interview conducted by the author with an engineer from a Japanese semiconductor maker. This maker consigned work to a foundry. (4/19/2004)
(F) Interviews conducted by the author and Hidemi Yoshikawa with an engineer that left a Japanese semiconductor maker to work at another semiconductor maker in Asia. (7/10/2004)
(G) Interview conducted by the author with an engineer at a Japanese semiconductor maker's DRAM factory in Southeast Asia. (1/28/2004)
(H) Interviews by the author and Hidemi Yoshioka conducted with a former department head of the semiconductor department at *Hitachi Ltd*. (8/19/2004)