RIETI Discussion Paper Series 03-E-003

Determinants of Microlithography Industry Leadership: The Possibility of Collaboration and Outsourcing

CHUMA Hiroyuki
RIETI

AOSHIMA Yaichi
Hitotsubashi University

Research Institute of Economy, Trade & Industry, IAA
The Research Institute of Economy, Trade and Industry
http://www.rieti.go.jp/en/

RIETI Discussion Paper Series 03-E-003

Determinants of Microlithography Industry Leadership: The Possibility of Collaboration and Outsourcing

Hiroyuki Chuma,
Institute of Innovation Research, Hitotsubashi University & RIETI
Yaichi Aoshima
Institute of Innovation Research, Hitotsubashi University

Abstract

The main purpose of this paper is to examine the reasons why Japanese microlithography manufacturers lost their competitiveness in the latter half of the 90's mainly based on the field interviews and publicly available data. Especially, we shall focus on the following four possible determinants of competitiveness in this industry: 1) Characteristics of the major units (including software) that compose micro-lithography, and the methods of their production and procurement. 2) Inter-firm R&D collaboration for new product development; 3) Product architecture and the other ways of incorporating product quality; 4) Changes in demand for microlithography and the marketing strategies of each company to adapt to such demand changes. Many people mention that the rapid growth of ASML can be ascribed to their extensive strategies of outsourcing and R&D collaboration, and that the modular product architecture enabled them to carry out such strategies . However, we will discuss how such an explanation is not necessarily appropriate. ASML's current position has been established but not because of their extensive use of outsourcing; the modular product architecture was not a major source of their competitiveness either. We are not saying that the competitiveness of Nikon and Canon have weakened just as a result of the transitory process of the ordinary business cycle. Rather, we found deeper structural factors that caused problems for the two Japanese companies. While the manufacturing industry is being transformed from an engineering-based to a science-based one, vertically integrated Japanese R&D systems, like Nikon's or Canon's, have begun to exhibit serious drawbacks to innovation.

Keywords: Microlithography, Competitiveness, R&D collaboration, Outsourcing
JEL Classification: L1, L2, L6

1. Introduction

The made-in-Japan reduction projection-type microlithography called a stepper was invented in the semi-governmental VLSI research consortium that was initiated in 1976. As a result of that research in this consortium, Nikon succeeded in introducing the first Japanese stepper in 1980.[1]

At that time, GCA in the US accounted for a 90% share in the worldwide stepper market. However, after 1980, Nikon's steppers had rapidly penetrated the market, and Nikon took away GCA's share. Their growth was supported by the strong fair wind that the Japanese semiconductor chipmakers, including Fujitsu, Hitachi, NEC, and Toshiba, grasped, which was 90% or more of the 256K-DRAM market in the 80s.[2] Nikon soon overtook GCA, became No.1 producer in the Japanese market in 1983 and No.1 in the world by 1990.[3] Canon also surpassed GCA with their superior optical and precision machine technologies although they were late arrivals in this market. As a result, Nikon and Canon had continued to dominate this market, with 70-75% of the share together, up to about 1995.

However, the microlithography market experienced a dramatic change since the late 90s, along with the losing competitiveness of the Japanese semiconductor industry that had seemed stable. The change was triggered by the leap of ASML in The Netherlands. The market share of ASML that did not reach even 10% in 1990 and behind Hitachi's rose to 14% in 1995, and kept increasing with 16% in 1996, 20% in 1997, 23% in 1998, 29% 1999, and 30% in 2000. In the same period, the shares of Nikon and Canon were 45%/29% (Nikon/Canon) in 1995, 45%/27% in 1996, 43%/25% in 1997, 44%/23% in 1998, 35%/23% in 1999, and 36%/21% in 2000.[4] The decreasing trend is remarkable especially for Nikon. Considering the recently announced merger of SVGL, ASML's share accounted for 37% in 2000, and attained the top share of the world IC stepper market in the first half of 2002; ASML 45%, Nikon 31%, Canon 20%.

The main purpose of this paper is to examine, from an economic perspective, the reasons why Japanese microlithography manufacturers lost their competitiveness in the latter half of the 90's based on our field interviews and publicly available data. Especially, we shall focus on the following four possible determinants of competitiveness in this industry.

1. Characteristics of the major units (including software) that compose microlithography, and the methods of their production and procurement;
2. Inter-firm R&D collaboration for new product development;

3. Product architecture and the other ways of incorporating product quality;
4. Changes in demand for microlithography and the marketing strategies of each company to adapt to such demand changes.

Many people, including those related to the industry, mention that the rapid growth of ASML can be ascribed to their extensive strategies of outsourcing and R&D collaboration, and that the modular product architecture[5] enabled them to carry out such strategies (see, for example, Roest and Schuurmans; 1997).

However, we will discuss how such an explanation is not necessarily appropriate. ASML's current position has been established but not because of their extensive use of outsourcing; the modular product architecture was not a major source of their competitiveness either. We are not saying that the competitiveness of Nikon and Canon have weakened just as a result of the transitory process of the ordinary business cycle. Rather, we found deeper structural factors that caused problems for the two Japanese companies. While the manufacturing industry is being transformed from an engineering-based to a science-based one, vertically integrated Japanese R&D systems, like Nikon's or Canon's, have begun to exhibit serious drawbacks to innovation.

In the next section, we shall begin by explaining the outline of our research methods. We will then examine the competitiveness of microlithography companies from various aspects. After briefly introducing ASML's business, we describe make-or-buy strategies adopted by the three companies for the major units composing microlithography, and discuss the importance of such strategies as determinants of competitiveness in this industry in Section 3.2. Section 3.3 examines the pros and cons of each company's R&D system by considering situations of the semiconductor device market. There we refer to the difference among three companies in terms of R&D collaboration with outside companies or institutions. Section 3.4 examines the product architecture characterizing the microlithography of each company, and different ways of incorporating product quality based upon it. We also discuss its impact on competitiveness. Finally, we summarize our discussions in section 4.

2. Methods and subjects of interview research

This research is based on our field interviews at the three companies, Nikon, Canon, and ASML. We also conducted interviews at Nissei Sangyo (currently Hitachi High-Technology), ASML's sales agency in Japan, and IMEC in Belgium, ASML's or Philips' R&D collaborator for silicon process technology.

For Nikon and Canon, we interviewed the following people, each of whom we met twice for one and a half to two hours.

- A manager and a leader in the production departments, who are in charge of final assembly, testing, and adjustment;
- a manager and a leader in the product (or fabrication) engineering departments;
- a director and a manager in the development and design departments, who are responsible for system design;
- a manager and a leader in the personnel and the general affairs departments.

Before conducting interviews, we visited the assembly plants of each company. We also had discussions with people from the managerial planning section in Nikon and Canon for about two hours as preliminary research. In addition to these visits, we visited Ohara Optics Inc., Canon's subsidiary and the Nikon Sagamihara and Tochigi factories for glass and lens production and to understand the source of subtle differences in each projection lens.

We visited ASML twice. The first time, we participated in the ASML factory tour offered as an IFST2001[6] accompanying program sponsored by IMEC. IFST2001 was held in Antwerp, Belgium.[7] On this tour we conducted several interviews with ASML's engineers. Another day we met ASML's senior technologist and spent about two hours interviewing him. We also visited IMEC for interviewing four executive scientists each of whom we met for two to three hours. The clean room tour was also conducted there for about two hours. As for Nissei Sangyo, we interviewed two directors in charge of ASML business, each for two hours. An overall study was executed mainly for the period from the end of May 2000 to the middle of May 2001, including preliminary studies.

3. Outsourcing, collaboration, and modular architecture

To develop the various elemental technologies required for microlithography, a large amount of company-specific investment is inevitable. This considerably increases the businesses risk of vertically integrating development and manufacturing of the major units composing the product. On the other hand, decreasing this risk by having exclusive and long-term relationships with a small number of unit makers or R&D institutions tends to actualize a potential problem of conflicting interests. Thus, existing economic theories have suggested that Nikon and Canon types of vertical integration are more efficient when a transaction involves a large firm-specific investment with serious potential problems of conflicting interests between assembly makers and suppliers (for example, Klein; 1988).

However, it is doubtful if this kind of conflict can be solved only by vertical integration as shown in Coase (2000). As Segal and Whinston (2000) indicate, depending on how company specific investment influences the competitiveness of a seller or a buyer in the market, an exclusive relationship between independent companies could be more efficient than vertical integration. That is, economic theories cannot tell *a priori* which is better; and only a detailed investigation of individual cases leads to the right answer.

Therefore, in the subsequent sections, we begin with confirming facts to answer the following questions:

1. How do ASML, Nikon, and Canon make use of outsourcing and collaboration in their new product development and manufacturing processes? Is there any difference?
2. Is such a difference related to a difference of product design architecture?
3. Is this difference a major determinant of competitiveness in the three companies?

3.1 ASML and Philips

ASML has a very close connection to Philips. In fact, people who left Philips established ASML in 1984.[8] At first, ASML was jointly owned by Philips and ASM International, which is a semiconductor equipment maker of CVD, RTP, etc. However, since ASML continued to lose money, ASM International transferred 50% of their share to Philips and the remainder to two banks in The Netherlands in 1988. Even after this, ASML's business was sagging, especially during a recession period in 1991 to 1992. Then Philips succeeded in listing the share of ASML, after various tries, on the Amsterdam security market and NASDAQ in 1995 in order to reduce its business risk. Before then, ASML was a wholly-owned subsidiary of Philips. At that time, the semiconductor market was beginning to boom. Philips sold its ASML share in the NASDAQ after March 2000 when the stock prices were the highest. Currently, Philips possesses only 5.8% of ASML stock, although it is still the top shareholder except for the US mutual fund, Capital Group International (10.8%).

The relationship between ASML and Philips is much more intimate than can be imagined from this level of ownership. Our interviews revealed that many of ASML employees used to work for Philips. That also applies to management. In fact, the current president & CEO had experience at Philips as a director in the consumer electronics division and the semiconductor division. He also served as a supervisory board member of ASML from 1995 to 1997. Before Philips, he worked for the semiconductor divisions of Motorola Inc. and the General Electric Company. The ex-president of ASML is also a Philips man. He was engaged in Philips's IC department for many years as an engineer, and had work experience at overseas production facilities such as those in South Korea and Mexico for several years. He continued his position as a president from 1990 to 1999, and currently is a member of the supervisory board.

In addition, among three board of management members except for the above CEO and CFO, one comes from Philips, one from AMD, and one from (born and bred) ASML. Two of six supervisory board members also come from Philips and one of them is appointed as Chairman. The other four members are from IBM Microelectronics, Carl Zeiss, TNO (Netherlands Organisation for Applied Scientific Research), or University of Amsterdam. A senior technologist whom we interviewed also had played an important role for many years in the leading US chipmaker. It is impressive to have appointed engineers or scientists in the top management position who know chipmakers thoroughly.

Both companies are geographically located within easy driving distance. The main body of Philips is located at Eindhoven in The Netherlands; ASML is located on a central street of the city of Veldhoven only 20 minutes by car from Eindhoven. Both Philips Centre for Industrial Technology (CFT) and Philips Research Eindhoven are also located just several kilometers from ASML. Moreover, the semiconductor department of Carl Zeiss, which supplies the projection lens unit, is only about four hours away by car.

As described above, there are close human relationships between Philips and ASML, facilitated by physical proximity.

3.2 Outsourcing of major units

Major units of microlithography can be broadly classified into the following eight units:

A) A light source or a light generating unit;
B) an illumination unit that controls a bunch of light and brings it to the reticle (or photomask);
C) a reticle stage on which the reticle is placed;

D) a projection lens unit that projects light passing through the reticle and makes an image upon the silicon wafer on which resist or photosensitizer is applied;
E) a wafer stage upon which a silicon wafer is placed;
F) a loading unit that conveys reticles and wafers to the stages and installs them;
G) an alignment (scope) unit that adjusts the stages and other units, which are auto-focused along the optic axis when exposed;
H) a body unit that holds all the above units.

In this section we will first examine differences among the three companies in terms of outsourcing these major units, and relationships between such differences and competitiveness in the market place.

A. Projection lens and illumination units

Carl Zeiss supplies all the ASML's projection lenses, which is the central unit in microlithography. It used to supply lens units to GCA and Hitachi.[9] However, after the market withdrawal of both companies, Carl Zeiss has been supplying exclusively to ASML. The (refractive) projection lens unit consists of various kinds of 30 to 40 individual lenses (Levinson (2001)). Carl Zeiss group takes charge of the entire development and manufacturing activities, ranging from research and development of the projection lens unit, processing of individual lenses, assembly of the lens unit, and testing and adjustment of them. On the other hand, Nikon and Canon internalize all these tasks. They also develop and manufacture illumination units by themselves.[10]

If we consider the potential problem of conflicting interests brought by exclusive transactions between ASML and Carl Zeiss, it seems that Nikon and Canon with vertically integrated systems could be more competitive, other conditions being constant. However, if there is any mechanism built into the exclusive relationship to avoid conflicting interests, relative competitiveness may be determined by the pure technological competences of the three companies. In this respect, AMSL and Carl Zeiss seem to exchange R&D scientists and engineers on a regular basis. The aforementioned member of the supervisory board from Carl Zeiss also used to be the former president and CEO. Moreover, in the past, there were also both short- and long-term exchanges of scientists or engineers between both companies. Through these mechanisms, ASML seems to successfully avoid most conflicting interests.

Lastly, according to several industry experts, Nikon and Canon had been going ahead in terms of projection lens performance until the mid of the 90's. Since then, however, such an evident difference virtually disappeared especially after KrF laser became a dominant technology. It is said that such a situation has been brought about through the extensive use of “PMI (phase measuring interferometer)” and the Zernike sensitivity method (ZSM) based on the data acquired by PMI (e.g., Nakashima, Higashi, and Hirukawa (2002) or Ware (2002)). Actually such an analysis could allow any of these three companies to adopt a precise cause-and-effect approach to both lens design and manufacturing and to minimize wavefront aberrations in the finished lens assembly. Hence, it is probable that such an improvement of the projection lens performance tended to strengthen the competitiveness of ASML relative to Nikon or Canon in the late 1990s.

B. Stage

The performance of the wafer stage and the reticle stage, as well as that of the projection lens unit, has a significant impact on the final performance of microlithography. The faster the stage could move, the higher throughput could be achieved. In addition, the more accurately one can control stage positions, the more one can improve resolution and overlay accuracy (Levinson (2001)).

ASML entrusts all the stages to Philips CFT, Philips Research or Philips’ subsidiary manufacturers, including stage development, vision systems, linear electro-motor technology, metallurgy, tribology, thermal control, motion control and assembly & test. It also conducts joint works with Philips CFT and/or Philips Research from the early stages of new product development. Reflecting these facts, the R&D expenses which ASML paid to Philips occupied 34% of the total purchases from Philips in 1999. On the other hand, Nikon and Canon are doing all the development and manufacturing of both hardware and software within their own companies including subsidiaries. However, if we consider the very close relationship between ASML and Philips, and the roles of subsidiaries in Nikon and Canon, there may be no substantial differences among the three companies in development, manufacturing, and procurement of stage units.

Therefore, the extent by which the stage provides for the competitiveness of three companies depends on the difference of the pure technological capabilities of R&D and manufacturing. Although Philips’ stage acquired a favorable reputation even in the beginning of the 1990s, there seems to be no obvious difference in this respect according to our interviews of major chipmakers in Japan and the assessment shown in the industry journals and articles.

C. Light sources

After the emergence of the stepper in the 1980's, the light source of microlithography advanced toward shorter wavelengths, from g-line and i-line that are the mercury light source, to KrF and ArF that are the excimer laser sources.[11] All three companies have been outsourcing these light sources. The g-line and i-line were provided by Usio Electric Co. in Japan; KrF and ArF are supplied mainly by Cimer in the US. For the excimer, Cimer held 90% of the world share in 2000.

Therefore, we cannot conclude that the difference of outsourcing strategies for light sources brought about competitive differences among the three companies.

D. Body

The body plays an extremely important role in guaranteeing the structural strength of microlithography. Since the body, made of cast metal, uses special materials, Japanese companies have in-house R&D for it. However, manufacturing was subcontracted to some independent suppliers with long-term relationships. ASML also subcontracts the body. However, we could not confirm how body development and manufacturing are divided among ASML and outside suppliers.

It has become easier to manufacture high performance cast metal by optimal control technology using an advanced annealing furnace, compared to 20 years ago when this manufacturing depended on a molder's craftsmanship. Therefore, the make-or-buy decision for body units is not supposed to affect the competitiveness of microlithography makers.

E Alignment unit

Alignment adjusts and corrects the relative positions of projection lenses, wafer or reticle stages and other units by using a laser beam, so that light passed through the reticle and the projection lens makes the best image at a specific area on the wafer stage. The relative position is automatically adjusted from the center of the projection lens as a basic coordinate (optical axis) by the order of 40 to 60 nanometer with an alignment scope, reflectors, interferometers and optical and heat sensors (Levinson (2001)). The three companies do not make all the components for the alignment unit. Especially, an interferometer and other sensors tend to be bought from other specialty makers.

However, as Canon’s and Nikon’s R&D scientists say, important technologies accumulated by microlithography makers do not reside in producing interferometers and sensors themselves, but in the ability to measure, adjust, and correct through using these tools to make high performing alignment units. For example, the way to measure the relative position between the reticle and the wafer, which are adjusted by examining projected images, forms part of the know-how. Disclosure of this type of know-how to competitors weakens a company's competitiveness.[12] Thus, Nikon and Canon have all these technologies to themselves. On the other hand, in the case of AMSL, a lot of this type of know-how seems to come from Carl Zeiss and Philips though we do not have enough evidence to clearly prove this. This may lead to an advantage for Nikon and Canon.

However, alignment technologies themselves, applied to microlithography, are fairly stable ones and are not facing a fast innovation cycle. In this sense, compared to a stage and a projection lens unit, an alignment unit does not cause a serious problem in developing new products. Therefore, the handicap of ASML, in this respect, may be considerably small.

F. Software

Software is indispensable for controlling the various major units discussed above. Such software is broadly classified into the following three types:

A) The unit software that controls the computer installed in each major unit. This reflects technologies accumulated in each department or company specialized in a particular unit.
B) The software that controls integration across major units. This reflects the core technologies required for developing and designing the entire system of microlithography.
C) The software that is used to deal with various troubles occurring at the design and manufacturing stages, by collecting measurement data. Some companies call this "tool software." Product (or fabrication) technologies for volume production are directly reflected in this tool software.

Nikon and Canon are basically developing all the above-mentioned (A), (B), and (C) software inside except OS. On the other hand, ASML develops (B) and (C) inside, but (A) is developed by a supplier that takes charge of each major unit. Therefore, if the unit software and the software for system integration have to be simultaneously developed in an integrated way, the competition advantage probably exists at Nikon and Canon.

These two types of software, however, have been developed independently of each other, even at Nikon and Canon, with predetermined interfaces. Also, there seemed to be almost no need for software engineers for the three types to have mutual exchanges of information. Therefore, it is implausible that a difference in the way of developing software determines relative competitiveness.

However, throughput of microlithography is affected by various kinds of functions and characteristics put into software. Especially, it is critical whether software has enough flexibility to adapt to the distinctive process technologies of each chipmaker. In this respect, Japanese chipmakers, who have purchased many machines from Nikon and Cannon, have not disclosed their process technologies to equipment suppliers. The following remarks by a R&D executive engineer at Canon and a senior technologist at ASML indicate this point:[13]

> "Only recently, have Japanese chipmakers started to disclose their own process technologies to microlithography makers. Five years or more ago, microlithography makers knew almost nothing about what was happening inside the clean room. The chipmakers disclosed process information only when they had serious problems. Otherwise, they did not. However, the tendency to open processes has risen recently. … European and American chipmakers began to open their processes very early. And then, a similar tendency to open processes has started to emerge among Japanese chipmakers, only recently."(Canon)

> "In that particular field, almost every customer or chipmaker has some sort of method (software to improve exposure processes) themselves. So, at a technology conference like the SPIE conference, for example, you might see 10 or 15 papers from Toshiba, Infinion, IBM, and others whose engineers internally develop some methods. Most of these are not very effective though because they do not work with tool suppliers. Then, they are very difficult to implement. They may have a great idea, but unless they are working with us, they are not able to implement it. Likewise, we cannot think of everything here. When customers have a good idea, it's good for us to interact with them to get those ideas to be able to improve the performance of our tools." (ASML)

According to these remarks, it is fairly possible that ASML's software is designed to achieve higher throughput. In this respect, a director of a design engineering department at a Japanese company was describing his frank impression of "Certainly, we are likely to be defeated in software" and "The necessity of knowing chipmakers' processes has become very high." Since Nikon and Canon have not been able to directly obtain process information from Japanese chipmakers, they may face many obstacles in improving software performance.

3.3 R&D systems: the role of interfirm R&D collaboration

In the previous section, we examined how much the three companies depend on outsourcing by each major unit, and how outsourcing strategies lead to competitiveness in the market. This section deals with the differences in the R&D system, another important source of competitive advantages.

A. Characteristics of R&D systems

ASML does not have a R&D department in the style of Nikon and Canon. The senior technologist at ASML made the following remark:

> "…(we have a close relationship) especially to the Philips Research Lab because they have a wide range of expertise and many different products. It would be impossible for a small company like us to have such a wide range of research. They make electronics, microscopes, light bulbs, and digital electronics... They have a lot of basic technologies that would be useful for us."
>
> "For our side, we are mostly a manufacturing company, and without a very good research environment. I think that research scientists are, in general, not going to have a real happy home here because the focus here is on customer applications and manufacturing tools, not so much on the research side."
>
> "We have a few very good engineers. Their background is systems. I would say that the basic concept of steppers was originated at ASML for the scanner and so forth.[14] But they worked closely with the Philips guys to develop the basic capabilities. "

As indicated above, R&D activities at ASML are almost integrated with those at Philips. R&D engineers from the Philips Semiconductor Division, one of the star divisions at Philips, seem to support ASML, specializing in the manufacturing function, especially in the development of a stage that is one of the core units of microlithography. In addition, Carl Zeiss exclusively takes charge of technology development for the projection lens and the illumination system, another core unit of microlithography.

This arrangement is quite reasonable under the condition that the ASML brand is not enough to collect numerous competent R&D researchers from a wide variety of specialized fields. Systems engineers at ASML decide overall machine specifications and integrate individual units, responding to chipmakers' demands. Most element technology developments are exclusively entrusted to outside companies, like Carl Zeiss and Philips, and independent research institutes, such as IMEC, described later.

On the other hand, differing from ASML, Canon has its own R&D departments, both for optical technology and precision machine technology, directly controlled by headquarters. Canon has the Fabrication Technology Lab., the Optics Lab. and the Production Technology Lab. Advanced technologies developed at these research labs. are transferred to the Development Center for Semiconductor Equipment and the Center for Advanced Optical Technology, and then integrated into commercial products. [15]

Although Nikon does not have these independent R&D institutions, the "Company (Research) Support Center" is responsible for production technologies and basic technologies cutting across various business units, within which research divisions, such as the Division of Optical Technology and the Division of Precision Machining Technology, exists. In addition, Nikon has Nikon Research Corporation of America in the US. Therefore, there are not substantial differences in the development organizations of Canon and Nikon.

Since AMSL depends more on outside suppliers exclusively, especially Philips and Carl Zeiss, one may say that ASML has a handicap against Nikon and Canon, since exclusive contractual relations tend to be accompanied by conflict-of-interest problems. However, as was mentioned before, Coase (2000) and Segal and Whinton (2000) have said that these problems of conflicting interests can be overcome in various ways, including a personnel exchange across contractual parties, without adopting vertical integration. Therefore, the impact of the above differences in R&D systems between ASML and Japanese makers on total R&D competence should be discounted.

Additionally, the advantages of vertical integration based on element technology development, may decrease as the performance required for microlithography approaches the current physico-chemical limit. To achieve the required product performance, the microlithography makers increasingly need to collaborate with companies beyond the field of optical and precision machinery technology. More concretely, they have to collaborate, for example, with photomask, resist, coater-developers, and chipmakers having highly advanced process technologies. Furthermore, as the center of the semiconductor market shifts from DRAM to logic IC and system LSI[16], semiconductor devices have become highly differentiated. This increasingly requires the microlithography makers to quickly grasp chipmakers' differentiated demands with a deep understanding of their processes.

In the next section, we shall examine how the above types of R&D collaboration adopted by ASML become a source of competitiveness by illustrating the impact of differentiation of semiconductor devices and the resolution enhancement technologies (RET) that began to be used frequently in the latter half of the 90's (Wong (2001)).

B. The significance of inter-firm R&D collaboration: The impact of RET

It is known that the resolution (or critical dimension (CD)) of microlithography is in inverse proportion to the numerical aperture (NA) of the lens, and directly proportional to the wave length (λ) of the light source, according to the Rayleigh law. That is, the formula, $CD = k1(\lambda/NA)$, and the coefficient k1 is assumed to be a constant. However, this expression is only an approximation. In reality, k1 could be still variable. More concretely, CD is influenced by resist materials, film thickness and uniformity after coating and deposition of resist, development processes after exposure, and so on. In fact, if the contrast of the resist improves, clearer images can be obtained obviously with other conditions being constant.

The resolution can be improved further by resolution enhancement technologies (RET) even if NA and λ are constant, which raises the contrast ratio by using the diffraction phenomenon of light. RET is broadly divided into illumination-related technology and photomask-related technology. The modified illumination technology is as famous as it was formerly, raising resolution by letting the light go diagonally into the projection lens. As a latter example, there are technologies such as a phase shift mask method and the optical proximity correction method, which raise the resolution by generating a slight gap of the circuit image on the photomask to consider the diffraction phenomenon in advance. Advancing RET, it became easier to obtain a high resolution after the mid 90's, which is almost equal to half of the source light wavelength. Various methods for RET have been introduced, not only by microlithography makers but also by chipmakers (for details see Wong (2001)).

However, the heavy use of RET has required highly advanced manufacturing technology for making more refined and complex photomasks. In addition, as photomasks became increasingly specific to particular devices, the collaboration between microlithography makers and photomask makers has become important.[17] For instance, a design engineer at Dai Nippon Printing (DNP) Co. mentioned that it takes 24 hours to make one piece of a photomask even when using advanced EB lithography systems. It took only one hour several years ago.[18] In addition, because of the low yield of photomask production and the delay of developing inexpensive resist materials, volume production using the most advanced ArF microlithography still faces difficulties. In the case of F2 microlithography, called the next generation machine, the development of resist materials available for volume production is still the most serious bottleneck. Some concerns for photomasks also remain.[19]

All these trends have dramatically increased the need for intimate R&D collaboration between microlithography makers and outside companies that produce products having direct interactions with an exposure process, such as resist materials, coater-developers, and photomasks. Until recently, microlithography had kept a fairly independent position within the semiconductor production process. However, as the required performance approached the current physico-chemical limits, it has become indispensable for it to be synchronized with other processes or element technologies to achieve further performance improvement.

To adapt to such a situation, ASML adopted its distinctive and effective collaboration strategies more than ten years ago. For example, ASML has a long-term and intimate relationship with IMEC[20] in Belgium, the semi-governmental non-profit organization that is said to be the most advanced research institute for the semiconductor technology in Europe.

To know what is going on inside IMEC, let's look at the "193 nm Optical Lithography" project executed in 1999 as an example among the various collaborative projects of IMEC. The objective of this project was to explore an appropriate way of using resist materials and photomasks for producing devices by the 0.18 μm design rule, by using ASML's ArF lithography and Tokyo Electron's resist coater-developers. Participants could bring the results achieved by this project back to their companies as long as they shared the cost of it. The names of companies that participated in this project and the number of people from each company are as follows:[21]

- R esist makers: Arch Chemicals (7 people), Brewer Science (8 people), Clariant (1 person), JSR (2 people), Shipley (1 person)
- R esist coater-developer maker: Tokyo Electron (1 person)
- C hipmakers: IDT (5), Infineon Technology (1 person), Intel (5 people),

Micron Technology (1 person), Texas Instruments (1 person)

- P hotomask testing, adjusting makers and solution providers: KLA-Tencor (2 people)

As indicated above, many people from the fields of microlithography, resist, and device makers were involved in this project. For resist makers, it was very useful to exchange information with specialists in device-making and vice versa. The microlithography makers could ask many outside specialists to brush up their machines for the further improvement, and also effectively obtain knowledge related to resists and photomasks. For ASML, IMEC should be a very important partner for R&D collaboration. The following comments made by ASML's senior technologist indicate how ASML regards IMEC as an important partner.

> "IMEC is one of our strongest partners. We have a long and very useful relationship with them. One of our difficulties here is that we don't have any way of doing processes other than lithography. A lot of time would be needed to obtain (knowledge) for other processes…. So, we keep a long and good relationship with IMEC."

> "… we tend to put (out) new tools. We do that for a couple of reasons. One is to put the tools into the environment like a fab. to see how it is integrated. Also, it gives many of our customers opportunities to see how our tool performs when they buy it. …Some companies that cannot afford to buy their own to just do process development ask IMEC to do those kinds of jobs."

> "Several very good engineers are working there (IMEC). Also, there are a few engineers working in this building who used to work at IMEC. And, vice versa, there are a few engineers at IMEC who used to work here. …There are just a lot of personal interactions. They go on back and forth. A good situation for both of us is, I think, that IMEC improves their standing over time through a relationship with us. It's also true for us."

On the other hand, Nikon and Canon do not have a "meeting place" that corresponds to IMECs. This is because there is no institutional arrangement to secure such a "meeting place" in Japan (Goto; 2000). There are some cases of serious collaboration, but they are mostly bilateral relationships in the form of a joint venture.

Nikon and Canon have been able to exchange various pieces of precious information with many established chipmakers, such as NEC, Toshiba, Fujitsu, Hitachi, Intel, and TI under long-term relationships. However, information obtained through such bilateral relationships seems limited and qualitatively different from information that cuts across the many companies that IMEC provides. As Fujimura (2000) says, performance optimization at the cluster level that aggregates several pieces of individual equipment has become indispensable. In this situation, the lack of an IMEC type of collaboration mechanism in Japan could be a factor that decreases the competitiveness of Nikon and Canon.

3.4 Modular architecture and competitiveness

In the preceding two sections, we examined some sources of competitiveness of Nikon and Canon by focusing on two aspects: outsourcing of the major units and R&D collaboration. This section deals with determinants of competitiveness in more detail at the manufacturing stages through which product quality is incorporated. In general, it is assumed that ASML also has an advantage against Nikon and Canon at this production stage. Especially, its shorter production leadtime tends to be emphasized, which is said to be supported by the modular structure of its product. Is this really true?

A. Microlithography and the degree of modularization

As already discussed, microlithography can be decomposed into major units such as the wafer stage, the reticle stage, the illumination system, the projection lens, the alignment system, the loading system, and bodies. Designing a product with a modular structure means to make a clear decomposition of these units so that they do not interfere with each other. If this decomposition is successful, it becomes possible to reduce tasks to subtly tune the units so that scarcely any human skills are required in the final assembly. As long as performance at each unit satisfies predetermined specifications, the performance of a final product can be guaranteed almost automatically. In addition, if a product is completely modularized, a company can outsource the development and manufacturing of major units, which leads to a reduction of development and manufacturing leadtime.

There is some evidence to indicate the uniqueness of ASML's microlithography in terms of the independence of each major unit or modularity. For instance, users of ASML machines can easily draw out the wafer stage for maintenance and clean it by themselves; the same thing is true for the illumination system.

Microlithography makers, in principle, do not have users touch the optical axis (the center section in the projection lens running in a vertical direction) that becomes the origin for alignment because it is a critical part for obtaining exposure accuracy. This principle reveals that ASML machines have unusual structures. In addition, the ASML machines have an autocalibration function that returns them to their originally stipulated position by automatically adjusting them for 30 minutes after the user draws out and puts back the waferstages.[22]

Looking back at a series of ASML machines introduced in the 90s, it is remarkable that ASML tends to carry over the same major units as long as possible, even with a change of the light sources, and that it tends to limit the number of newly added functions to as few as possible, normally only one or two. For example, the PAS5500 body that was introduced in 1991 has been used throughout the 90s regardless of the type of light sources, whether i-line or excimer. When introducing the KrF stepper, ASML had already changed the reduction magnification of the projection lens to 4:1; it was maintained for the KrF scanner that was introduced later.[23] Since Nikon and Canon changed the reduction magnification to 4:1 only when they introduced scanners, they had to change stages and projection lenses at the same time, which made design tasks very complex.

However, it is quite difficult for a product requiring extreme performance, like microlithography, to have a complete modular structure that achieves independence of units. Actually, in state-of-the-art KrF and ArF scanning machines, exposure accuracy is affected even by subtle differences in wiring and piping, the stopping position of the wafer-loading robots, and in the slight impact on the projection lens. Therefore, the accuracy of the final product cannot be attained simply by combining major units even if each unit satisfies the prescribed accuracy. This is because the final performance required for microlithography exceeds the limits of the machining and assembly accuracy applied in each unit production.

Even the most skilled workers can only control the machining and assembling precision for the major units, at most, at the sub-micron level. Thus, the final performance is pursued automatically, first by acquiring the positional information between major units through alignment scopes (= microscope) with a measurement capability of 1-5nm, and by controlling those units based on feedback information obtained from various sensors. For stable optimization, it is necessary to set the initial parameter values that appropriately reflect individual unit differences, and static and dynamic differences among the final machines caused by unit combinations. However, since the machine requires extremely high accuracy, what regularity should be applied to set the initial parameter has not been theoretically established. Therefore, engineers have to obtain data to understand the characteristics of the major units and the final microlithography, and then statistically find a certain kind of regularity from them to set the optimal values for parameters.

According to a chief engineer of the product engineering department at Canon, who is in charge of wafer and reticle stages, 90% of the know-how required for problem solving comes from vague experimental laws obtained though such empirical data, and only the remaining 10% is theoretically understood. If continuity between old and new products is high, part of this 90% will be gradually theorized, which will be reflected in the design of the future products. However, when a project faces a discontinuous change, like one from a stepper to a scanner, most of the experimental laws obtained through the development of a stepper cannot be applied to that of a scanner. In fact, the complications of the machine and the rapid scale-down of the device cause a lot of unprecedented events. Therefore, the above-mentioned engineer mentions that he has to rely on experimental laws much more than before.

ASML's microlithography is probably not an exception on this point, although it may be more modularized than its competitors. For example, in the case of a standard machine, it takes (a) 4 to 10 days in one work-shift to assemble the major units sent from Carl Zeiss or Philips, (b) 20 to 30 days to set the optimum parameter values based on obtained data after the final assembly, and (c) a further 20 to 30 days to re-assemble major units at the user site, which are decomposed for delivery, and adjust the machine so it will be available. From the time of receiving the formal order from the chipmaker to completion of the product takes approximately 9 months. Both Nikon and Canon have timelines similar to that of ASML. According to our interviews at Canon, it takes 6 to 21 days in the two work-shifts for the above (a) and 28 to 29 days for (b); at Nikon, it takes 6 to 10 days in the one work-shift for (a), 40 to 60 days for (b), and 30 to 50 days for (c).

This comparison indicates that, even for ASML machines that are more modularized in design, it is inevitable that it will take one to three months at the final assembly and adjustment stages for solving complicated interference problems. In this sense, the most advanced microlithography cannot be completely modularized making it extremely difficult to achieve mutual independence of the composing units. It requires a very sophisticated integration processes. We may say that it is the "ultimate integral machine."

B. Modularity and Competitiveness

How to shorten the time between the formal order and delivery is critical for competitiveness in the marketplace. It becomes increasingly important with the rapidly shortened product life cycles of DRAM and logic ICs. To adapt to this market trend, each company makes a maximum effort to minimize leadtime by improving product design and assembly and adjustment processes. Below, we examine such an effort made by each company.

First of all, let's refer to Canon's example to understand the flow of the final assembly process. Canon has two separate groups for the final assembly, called Final Assembly Groups 1 and 2. Final Assembly Group 1 takes charge of assembly of major units, such as a body, a stage, an illumination system, and a projection lens. 20 to 25 peaces of units, in total, arrive at the place of Final Assembly Group 1, each of which is electrified to confirm whether it satisfies a specification (= unit performance guarantee). According to our interview, the interference problems between units are not examined at this point in time.

People in Final Assembly 1 first assemble a body and put a stage on it. Then they assemble a projection lens, an alignment system, and an illumination system in that order. People in Final Assembly 2 enclose these units with a chamber for the best thermal control, connect the units with wires and pipes, and then electrify them again. At this stage of re-electrification, many mechanical troubles emerge, partially because of incorrect assembly. Therefore, there is a process to solve such problems at this stage. Then, the assembled machine enters the test and adjustment stage. This test and adjustment stage is broadly divided into optical and mechanical stages. The former is for testing and adjusting the optical performance, such as the auto-focus accuracy of the projection lens; the latter is for testing and adjusting the precision machine parts, including stages and alignment systems. Most of these adjustments are done by modifying off-set values.

ASML has a similar assembly and adjustment flow. All major units, including the projection lens for ASML's machines, are tested by being electrified by suppliers before delivery. However, the number of the major units delivered to ASML is 10 to 11, less than those delivered to Canon, which means that ASML's machines are decomposed to bigger chunks compared to Canon's machines. This implies that test and adjustment processes for the major units are more frontloaded. Reflecting this fact, ASML's factory itself is assembling and testing its products only by less than 10% of the total added value (George (2002)). As for specific test items, the same test is conducted immediately after arrival at ASML, to confirm that there is no error in the units before and after delivery.

In addition to such unit-by-unit tests, ASML conducts another test by combining several units, called a functionality test. For this test, engineers or workers use a specific machine, called a test module, prepared for functional testing, to which the unit in question is installed. A test module itself is a large-scale machine that can be called “bare” microlithography. Engineers utilize the test module to obtain data for testing interference problems occurring between the major units. All major units except the projection lens are tested on this test module, and only units that pass this test are sent to the final assembly. Since major suppliers have the same test modules, they do the same kinds of tests before delivery to ASML. Only the projection lens is tested after the final assembly by doing actual exposures.

The final assembly process of Nikon has been close to that of Canon. However, they have recently transformed their original process to a new one, called “block production.” In block production, the major units are integrated into five to six modules defined as blocks, which are electrified for testing and adjustment before the timing when Final Assembly Group 2 at Canon electrified their machines. Its organizational structure also reflects block production, in that each organizational unit corresponds to each block, including design, product engineering, and manufacturing as a set. In this respect, Nikon’s recent process is close to ASML’s that frontloads test and adjustment processes as early as possible. However, unlike ASML, Nikon does not seem to conduct a functionality test with the test modules.

Judging from the above comparison, ASML’s machine has the highest modularity among the three. The functionality test using the test module seems to contribute to a reduction of production leadtime. It is highly probable that the modular strategy adopted by ASML improved its relative competitiveness in the latter half of the 90’s. However, Canon and Nikon have also been introducing similar modular strategies for reducing leadtime. According to our interviews with Japanese chipmakers, currently ASML has no advantage, at least in terms of production leadtime. Therefore, we cannot conclude as strongly as common opinion insists, that modular strategy is the critical source of ASML’s competitiveness.

Lastly, we should note that when ASML had tried to modularize their tools to the extent of its ability, the original intention was to greatly enhance chipmakers’ TCO (total cost of ownership) by trying to provide secularly upgradable ones (van den Brink et.al. (1991)•j). Actually around 1990, ASML’s existence was in imminent danger and chipmakers were facing the phase when the generation of microlithography was expected to change from the era of mercury lamp to excimer laser. Eventually, however, such ASML’s intension itself was not accomplished to its satisfaction. In this sense, the advanced modularization around this time was a kind of ASML’s catch-up strategy to cope with vertically integrated Japanese giants: Nikon and Canon.

C. Modular Architecture as an Endogenous Variable

In the previous section, we explained that the companies have been trying to increase the modularity of their machines to adapt to rapidly shortened product lifecycles of DRAMs and logic ICs. ASML was especially remarkable in this respect. However, we cannot affirm that an ASML-type of modular strategy is always the best method for every company to improve competitiveness. This is because product architecture is also affected by several factors, such as the abilities of skilled workers, product engineers, and design engineers to find and solve both known and unknown problems, and the specific preferences of familiar chipmakers to microlithography.

If it is difficult to obtain enough skilled workers and product engineers who can effectively solve both known and unknown problems, adopting a modular strategy may be preferable for reducing dependence on experienced skills on the shop floor. On the other hand, if there are enough skilled workers and product engineers who have high problem solving abilities, relying on less modularized methods may result in producing higher performance machines in a shorter time and with less cost.

Preferences of chipmakers also affect the degree of modularity of microlithography. In this respect, a technical sales director at Nissei Sangyo, and a sales agent at ASML in Japan, made the following points:

> "For machines of a certain company, it is possible to manually adjust the projection lens unit itself, for example, by inserting spacers or changing some individual lenses. However, in the case of ASML's projection lens units, it is not possible to manually rotate lenses because all the lenses are fixed by screws, although they are equipped with an automated adjustment function. Therefore, each unit has a high independence and a rigid structure under which its (exposure) accuracy is robust even when it is transported or moved. In the case of a certain Japanese company's projection lens unit, it is not unusual for the property to slightly change when the unit is transported or moved. This is the flip side of the projection lens unit's having flexibility."

> "ASML's machine is different from the Japanese ones in that whoever starts it up can get the same level of accuracy. Since Japanese machines are designed so that they keep a certain margin or room for later adjustment, it can happen that pre-determined accuracy cannot be attained when the errors

> of each unit accumulate in the same direction. This difference enables ASML to realize faster final assembly."

In fact, Intel still keeps internal production of CPUs as its primary device, and has used only Japanese (especially Nikon's) microlithography on which it can easily reflect its own advanced process technologies.

Leaving a margin or room for adjustment between the major units means intentionally raising, at the design phase, the probabilities of having interference problems. Therefore, to do this, design engineers have to assume that there are enough skilled workers and product engineers who can pursue the ultimate exposure accuracy at the assembly stage. That is, whether to design machines that reflect chipmakers' preferences depends on the level of abilities that skilled workers, product engineers, and design engineers have for promptly solving known and unknown problems.

However, as the performance level required for the machine approaches the current physico-chemical limit, microlithography itself has become rapidly advanced, complicated, and huge. As a result, even skilled workers and competent product engineers cannot fully solve problems occurring in the production process. This considerably increases the cost of leaving an adjustment margin, which means not pursuing modularity intentionally, as Fujimura (2001) pointed out. Moreover, demand-side factors, such as rapidly shortened product lifecycles, increase the importance of both R&D and production leadtime and thus raise the cost of leaving an adjustment margin furthermore.

In addition, as optimum control technology has been further developed, software-based adjustments have become more effective than hardware-based ones to adapt to the needs of chipmakers. About this point, ASML's President & CEO advocates, associated with "Moore's law," "Dunn's law": Every 4 years, a software development team will double in size (Dunn (2002)).

Under such circumstances, the ASML-type design architecture that attempts thorough modularization might be more advantageous than the Nikon and Canon types of architecture that intentionally leave an adjustment margin for the later fabrication or assembly stage. However, it is not certain whether this conjecture is applicable for the next generation of F2 laser microlithography. The merit of modularization is not always realized equally at any generation in the product evolution.

Interestingly, whereas ASML and Canon basically do not manually adjust the projection lens at the final assembly and adjustment phase, Nikon does. At Nikon, the projection lenses are designed and manufactured with the assumption of having a manual adjustment at the final assembly stage. Actually, some skilled engineers directly adjust the projection lenses by relying on their five senses. Besides, the strategy that intentionally leaves an adjustment margin seems to be strengthened as chip size shrinks. Certainly, such a strategy involves the risk of lengthening the testing and adjustment processes. However, as the required performance of microlithography is about to reach the current physico-chemical limits, especially the limits of optics, mutual interference problems centered on the projection lens unit become more and more serious. Our interview research also revealed that many serious production problems are derived from the projection lenses or from subtle differences among individual lenses.

Probably because of such a tendency, even Canon and ASML seemed to realize the need for adjusting projection lenses at the final assembly and adjustment stages. In this regard, a senior technologist at ASML and a director of the production technology department at Canon made following comments:

> "We don't have the ability here to do any lens adjustment, although we do them to a minimum extent. However, there might be a general tendency toward having more flexibility of projection lenses as a result of rapid miniaturization. …248 nm is the main technology now. People want to print a 130 nm feature that is about the half the (current) wavelength. If you are looking into optics that does that, you will find extremely limited depth of focus. This means very tight requirements on operating projection lenses (as a logical consequence, the demand for more flexible lenses will be increased). " (ASML)

> "Currently, we do not re-adjust the accuracy of the (projection) lens itself after it has been installed into the body. I heard that a certain company began to do such an adjustment with a kind of adjustment mechanism. But this is not necessarily good since, from the long-term perspective, it creates additional factors that reduce the lens accuracy. On the other hand, too much time will be spent if we have to dismantle the machines and the units and re-assemble them when some troubles are found after the lens has been installed into the body. It is difficult to balance these."(Canon)

Therefore, the strategy that does not adjust the lens unit after it has been installed may possibly lengthen the time for final assembly and adjustment, resulting in delayed delivery time in the case of the next generation of F2 machines. In this sense, such a strategy that minimizes an adjustment margin, or one that intentionally increases modularity, may not be always best. Microlithography might be de-modularized as it approaches its physical and chemical limits.

4. Summary and Implication

In this paper, we examined the reasons why Japanese microlithography makers have lost their competitiveness in the late 90's, based on our field interviews and publicly available data. The general opinion says that the source of ASML's competitiveness resides in its extensive use of outsourcing, interfirm R&D collaboration, and the modular architecture adopted for its products. However, our analyses revealed that there is not much virtual difference among ASML, Nikon, and Canon in terms of the use of outsourcing if one considers the particular exclusive relationship between ASML and Philips. ASML seems to more effectively put a potential demand on the chipmakers, and it is reflected in software that enables improvement of throughput. This may be one of the critical sources that confer a competitive advantage on ASML.

As for R&D systems, it was shown that various kinds of scientists at Philips and Carl Zeiss support ASML, specialized to system design and assembly. System designers at ASML, who played crucial roles in the 90's, also came from Philips where the pioneering stepper was invented independently of GCA's, indicating that ASML and Philips are closely integrated in R&D activities. Based on such observations, we concluded that the difference between ASML and Nikon or Canon resides in the following two facts: (a) ASML has an exclusive R&D collaboration contract with Carl Zeiss. (b) ASML successfully meets with resist makers, photomask makers, coater-developer makers, and chipmakers via IMEC, the famous semiconductor-related non-profit research institute in Europe.

Then, we conjectured that, although the above (A) does not seem to affect the relative competitiveness of the three companies, (B) seems to enlarge ASML's advantage considerably. This is because, as the performance of microlithography becomes crucially and directly limited by current physico-chemical limits, in addition to the conventional optical and precision machinery technologies, highly advanced and broader element technologies obtained through collaboration with various makers and research institutes become inevitable.

Regarding this point, ASML is advantageous to Nikon and Canon since it has an opportunity to enjoy a unique place provided through IMEC, where many related companies with advanced technologies collaborate together as well as experienced engineers or board members who come from many prestigious chipmakers. In other words, a vertically integrated organization like Nikon or Canon, which has internally incorporated advanced element technologies only related to optics and precision machinery, is no longer able to effectively create innovation in this industry, compared to one that is specialized to system design and final assembly and dependent on interfirm R&D collaboration.

In addition, we discussed that, as the semiconductor business shifts from DRAM to logic or system ICs, it has become critical for the microlithography makers to promptly and properly catch up with the speed of change in semiconductor markets in developing new products.

As for the relationship between modular architecture and competitiveness, we discussed first that even a relatively modularized ASML machine cannot avoid interference problems among major units since ultimate performance is required for current microlithography. However, some differences were observed between ASML and Canon or Nikon in attempts for modularization. ASML uses distinctive testing modules to functionally test interference problems, cutting across major units as well as ordinary ones, to test each of them separately, which should be effective in reducing production leadtime. Nikon and Canon attempted to introduce similar but rather conventional testing procedures. In this sense, ASML is still ahead of them. We speculated that this difference gave rise to ASML's competitive advantage in the late 90's. However, both Nikon and Canon have spent their resources to change design, assembly, and adjustment processes so as to keep mutual independence of the major units as much as possible. As a result, the differences in production leadtime among the three companies have almost disappeared.

We also critically indicated that modular architecture characterizing ASML machines could be endogenously induced as a result of various institutional constraints. Specifically we exemplified that the form of product architecture in microlithography is apt to depend on the capabilities of skilled production workers, product engineers, and design engineers to promptly find and solve known/unknown problems, and sometimes on the preferences of powerful chipmakers that have a long-term relationship with the lithography maker in question.

In addition, we discussed that, when the primary task of microlithography makers is to flexibly adapt to the requirements of knowledgeable and demanding chipmakers, the product might be well designed with de-modularized architecture that leaves more adjustment margins among the major units. In this sense, product architecture could be endogenously selected so that it might not be a real source of competitiveness.

The future direction of product architecture as an endogenous variable will be affected by not only the demand of chipmakers but also other various factors. Among them, as Baldwin and Clark (2000) insists, (a) rapid sophistication and complication of microlithography, and (b) the increased importance of a short leadtime due to the shortened lifecycles of DRAM and logic ICs may favor the ASML-type production system that minimizes later adjustments. However, further improvement of microlithography performance toward the limits of optics may drive it in the opposite direction. In reality, further scaling down of semiconductor chips is creating more serious interference problems among the major units than before and most of serious ones are related to projection lenses. To solve such problems, Nikon has been increasing *ex post* manual adjustment margins. Such a non-ASML type of design strategy might be effective as a way to effectively challenge the limit of optical microlithography.

Finally, we want to refer to the role of integrated (problem-solving) skills at the production sites that support a non-ASML type of design philosophy. Several studies about Japanese manufacturers have pointed out that the integrated skills of production workers to promptly and properly solve known/unknown problems, as well as those of product engineers and design engineers, are the main sources of competitiveness among Japanese manufacturing firms (for example, Koike, Chuma, and Ohta; 2000). To form such problem-solving skills at the production sites, the following three abilities are crucial: adequate knowledge about products and production processes, long-term experience, and logical-thinking abilities that narrow down the possible causes of problems by observing actual phenomena.

However, the importance of such skills seems to be declining in the microlithography industry that “uses quantum mechanics as indispensable knowledge for the first time in our industrial history (Fujimura, 2000, p.164),” under the never-ending process of pursuing micro-fabrication. This is a first because “adequate knowledge of products and production processes” that production workers should have has become too subtle and sophisticated. Accordingly, it became difficult to find even a simple error since an observed problem tended to be the result of complex interactions among such simple errors. In the companies that we visited, product engineers or design engineers identified assembly orders and ways of wiring or piping by considering subtle conditions like air flow, which used to be done by workers at the production site. As a result, the number of workers that have “abilities to narrow down the possible causes of problems by observing actual phenomena," especially for unknown problems, has dramatically decreased. Then, required skills for production workers have shifted from those for solving unknown problems to those for solving known problems mainly due to human errors, or to those for "how to quickly assemble and adjust machines." Most of the unknown-problem solving activities were left to specialized product engineers in each major unit. As a manager of the product engineering department at Canon put it, "a product is being manufactured with abilities that go beyond those which human-beings can have just with the maximum use of their five senses." It is highly possible that such a trend will be broadly observed at the production sites of Japanese companies while industry structures are being shifted from one that is engineering-based to one that is science-based. This will become another factor that weakens the competitiveness of Japanese manufacturing firms in addition to their already mentioned R&D system.

Bibliography

- Baldwin, C. T. and K. B. Clark (2000). The Design Rules: The Power of Modularity Vol. 1, Cambridge MA: MIT Press.
- Chuma, H. (2001). "Sources of Machine-tool Industry Leadership in the 1990s: Overlooked Intrafirm Factors," Economic Growth Center Discussion Paper, Yale University, 2001, No.837.
- Coase, R. H. (2000). "The Acquisition of Fisher Body by General Motors," Journal of Law and Economics, Vol. XLIII, April, pp. 15-31.
- DeJule, R. (2001). "Mix-and-Match: A Necessary Choice," Semiconductor International, February 2000.
- Dunn, J. D., (2002), Presidential Address at the ASML Bits & Chips Conference held on April 16th in Velthoven, The Netherlands.
- Fujimura, S. (2000). Handotai Rikkoku Hurarabi (in Japanese), Nikkan Kogyo Shinbun-sha.
- Gomei, Y. and M. Suzuki (1998). "A Cost-of-Ownership Study on Lithography Systems," Semiconductor International, July.
- Goto, A. (2000). Inobeishon to Nihon Keizai (Innovation and Japanese Economy) (in Japanese), Iwanami Shoten.
- Hand, A. J. (2001). "KrF Lithography: Not Finished Yet," Semiconductor International, February 2001.
- George, R., (2002), "Marketing and Development of High Tech Product Families: Based on ASML Semiconductor Business Experience," (from http://sepc.twi.tudelft.nl /~toet/onderwijs/in4073/slides/ASML/)
- Koike, K., H. Chuma, and S. Ota (2001). Monozukuri no Gino: Jidousha Sangyo no Shokuba de (in Japanese). Toyo Keizai Shimposha.
- Henderson, R. M. and K. B. Clark (1990). "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms," Administrative Science Quarterly, Vol.35, No1, pp.9-30.
- Klein, B. (1988). "Vertical Integration as Organized Ownership: The Fisher-Body General Motors Relationship," Journal of Law, Economics, and Organization, vol.4, pp.199-213.
- Langlois, R. N. and W. E. Steinmuller (1999). "The Evolution of Competitive Advantage in the Worldwide Semiconductor Industry, 1947-1996," in Mowery, D. C. and R. R. Nelson (eds.), Sources of Industry Leadership: Studies of Seven Industries, Cambridge University Press.

- Levinson, H. J. (2001), *Principles of Lithography*, SPIE Press, Bellingham, Washington, USA.
- Roest, P. and P. Schuurmans (1997). "Strategic sourcing als basis voor innovatie: ASMLithography," Nijenrode Management Review, Vol.2, pp.14-23.
- Segal, I. R. and M. D. Whinston (2000). "Exclusive Contrasts and Protection of Investments," Rand Journal of Economics, Vol.30, no.4, pp. 603-33.
- van den Brink, M., B. A. Katz, and S. Wittekoek (1991). "New 0.54 Aperture i-line Wafer Stepper with Field by Field Leveling Combined with Global Alignment," SPIE Conference Paper, March 1991, San Jose, CA, USA.
- Wong, A. K.K. (2001), *Resolution Enhancement Technologies in Optical Lithography*, SPIE Press, Bellingham, Washington, USA.

1 Canon entered the stepper market in 1983. Canon had accounted for 80% of the share for the previous aligner market. See Henderson and Clark (1990) about the competitive environment for the aligner market.

2 Refer to Langlois and Steinmuller (1999).

3 According to the report by the U.S. Department of Commerce, the Japanese makers' world share in the stepper market in 1989 was 75%.

4 The same trend is observed for the dollar based sales share.

5 The modular design philosophy is to design an entire system product so that it consists of structurally and functionally independent units (called modules). A product designed under this philosophy is known as having modular architecture.

6 International Forum on Semiconductor Technology

7 During the three days when IFST was being held, we also had a chance to talk to many engineers or scientists from Nikon and Canon both during the day and at night.

8 According to our interview with a senior technologist at ASML, the original model of ASML steppers was developed in the late 70's by people in the electronics department at Philips.

9 Hitachi was manufacturing i-line steppers until 1993, and then withdrew from the market.

10 Only Nikon internalizes production of the lens materials for various microlithography devices as described later.

11 The early steppers used a visible light called g-line with 436nm of wavelength. Then, the ultra violet light called g-line with 365nm of wavelength became dominant. The light sources of g-lines and i-lines are mercury lamps. On the other hand, the currently popular light source is a KrF excimer laser with 248nm of wavelength. In addition, microlithography using the ArF laser with 193nm of wavelength began to be produced around 2000. The F2 laser with 157nm of wavelength is supposed to be used for the next generation of optical microlithography, whose production is expected to start around 2004-2005. These three light sources are called DUV (Deep Ultra Violet) light sources, which are far below visibility.

12 ASML has entrusted part of such instrumentation technology or metrology to Agilest Technology.

13 According to our interview with a technical director at Nissei Sangyo, for Taiwanese, Korean, and US chipmakers, particular sales engineers called "application engineers" make suggestions for process changes, together with engineers at the chipmakers, for improving throughput. ASML hires several people from chipmakers, not only as managers and R&D engineers, but also as application engineers.

14 According to our interview, all three engineers that led the system design of the previous three generations of products were physics majors; among them, two came from Philips and the remaining engineer is a trueborn ASML person. We can confirm that Philips has played an important role in this respect.

15 According to the latest annual reports, the sales share of the microlithography department within Canon is 10% or less, and the share for Nikon has reached about 60%.

16 System LSI is often called SOC (System On Chip). It is LSI that integrates multi-functions, such as the input/output function, the interface function, and the arithmetic processing function, etc. in the same chip.

17 The person in charge of the photomask department at Dupont made the following interesting comments: “The mask industry has gone through a huge transformation recently, with masks again becoming a vital component of the lithography process. Masks used to be relegated to a commodity item, with little attention paid to them outside the purchasing department."(a quotation from Hand;2001)

18 A presentation by Mr. Naoya Hayashi of Dainippon Printing Co. at the SEAJ Forum 2001.

19 A presentation by Mr. Kazuaki Suzuki at the SEAJ Forum 2001.

20 IMEC was founded as a spinout institute from The Institute, that was involved in a spinout from the Catholic University Leuven in Belgium.

21 IMEC Annual Report in 1999.

22 It is necessary to readjust the relative positions among the illumination unit, the reticle stage, the projection lens unit, the wafer stage, and so on by using various sensors to execute such a calibration function.

23 Scanners use only the center section of the projection lens, called a slit, which has little aberration. The circuit pattern on the reticle is exposed and transcribed on the wafer little by little through this slit. Therefore, to expose all circuit patterns on the reticle, both a wafer stage and a reticle stage have to move, and these two movements need to be carefully synchronized. Since this synchronization has to be achieved at the nanometer order, it requires extremely sophisticated measurement and control technologies. This scanner is mainstream in the current microlithography market. On the other hand, since a stepper exposes the entire circuit pattern on the reticle at the same time, the reticle is fixed. Since the stepper uses not only the center section of the lens but also a peripheral part, it tends to be influenced by the lens aberration compared with the scanner.

25 Business Week, August 28, 2000.