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Architectural innovation in science-based industry:
How a manufacturer can manage suppliers by outsourcing all components

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Abstract

In the semiconductor industry, photolithography equipment is used to expose patterns on wafers to be manufactured into semiconductor chips. This equipment consists of extremely complex, large-scale industrial machines containing many high-technology components. The Dutch company, ASML, entered the market later than other such companies, but managed to take over Nikon's dominant position by outsourcing all components. ASML achieved an architectural innovation by prioritizing system design and fine-tuning components. We confirmed that the Mirroring Hypothesis was partially supported, because mirroring was observed between the technical architecture of the system and the division of labor, but not between the divisions of labor and knowledge.

Keywords

Architectural innovation, Mirroring Hypothesis, system integrator, virtual organization, supplier management

1. Introduction

Reconstructing an entire product design involves changing the relationships among the product's components while leaving the core design concept untouched. Because this core design remains unchanged, one might assume that the reconstruction should not be difficult. In actuality, however, changing a linkage among components is extremely difficult. Henderson and Clark (1990) proposed the notion of "architectural innovation". To explain this notion, they chose a semiconductor exposure tool from a science-based industry in the 1970's. This tool has a complex architecture which integrates elemental technologies from various fields. Chesbrough and Teece (1996) called this type of change "systemic innovation". Several subsequent studies have noted that in many cases, manufacturers of final products take the initiative to carry out systemic innovation (e.g., Brusoni et al., 2001; Brusoni and Principe, 2011; Heide, 2003; Kapoor, 2013;

Parmigiani, 2007).

A series of previous studies (Brusoni et al., 2001; Brusoni and Principe, 2001, 2011; Principe, 1997) examined architectural innovation in science-based industries, using aircraft engine manufacturers as a representative example. The researchers examined the period between 1980 and 1990. In the 1980's, when control systems changed from hydromechanical to digital electronic, engine makers successfully performed architectural innovation by creating loosely coupled organizations with control system suppliers. The engine makers fulfilled the basic design and system integration, and delegated the design details and manufacturing to the suppliers (Brusoni et al. (2001). In the 1990's, engine makers needed new gearboxes in order to develop new large commercial turbofan engines. One manufacturer achieved this objective by integrating their organization with a gearbox supplier. Other manufacturers outsourced to gearbox suppliers and failed in development (Brusoni and Principe, 2011).

The loosely coupled organization reported by Brusoni et al. (2001) is described in other studies using the concept of the "virtual organization". Virtual organizations solve problems while functioning autonomously and continuously to coordinate a modular architecture (Daft and Lewin, 1993; Sanchez and Mahoney, 1996). When product architecture is changed from integral to modular, or modular to another modular, the linkages among components must be adjusted. To resolve this problem, virtual organizations optimize both expertise and the combination of components by utilizing external markets (Chesbrough and Kusunoki, 2001).

Chuma (2006) claimed that the successful growth of an R&D organization (virtual organization) depended on including not only suppliers but also other outsiders. His study examined how ASML, a semiconductor industry exposure tool manufacturer, succeeded in building a new architecture and beating its competitors in the late 1990's and early 2000's. ASML collaborated with consortiums and universities, learning technical expertise and component knowledge. ASML also outsourced all components to external suppliers. Eventually, ASML was able to fine-tune many components for integration into the product. Our study examined ASML's next architectural phase in the mid-2000's. How did the manufacturer adjust the linkage among components? We focused on the function of the system integrator.

2. Theory and Research Objectives

2.1 Architectural innovation in complicated system products

For this research, we focused on two studies of aircraft engine development by Brusoni and colleagues (Brusoni et al., 2001; Brusoni and Principe, 2011). We chose these studies because aircraft engines are complicated system products composed of multi-technology and many components. A huge number of suppliers and parts makers is needed to support the manufacture of a large product. There are complex interdependencies among components. A change to a core component can generate imbalances at the level of the whole product. The target product for this study, a semiconductor exposure tool, has the same characteristics.

These two studies (Brusoni et al., 2001; Brusoni and Principe, 2011) indicated that it would be extremely difficult for manufacturers to outsource a core component to an external supplier in order to deploy architectural innovation. In the study by Brusoni et al. (2001), three aircraft engine makers achieved architectural innovation of a new key component, the digital control system. Company A outsourced the manufacturing to its former internal supplier, which had spun off from Company A. Company B ordered its development and manufacturing from an internal supplier. Company C ordered the development and manufacturing from a wholly external supplier by creating a loosely coupled organization among an in-house department, the supplier, and universities. This approach required the most effort, but allowed Company C to absorb new technical knowledge. Finally, Company C accomplished the architectural innovation by maintaining concept design and system integration while outsourcing the detailed design and manufacturing to the supplier.

In the second study, Brusoni and Principe (2011) examined an architectural innovation for developing a digital gearbox. Of the three engine makers, Firm A outsourced the design and manufacturing to an external foreign supplier, and focused on gearbox architecture. However, Firm A failed in adjusting the interface among components. Firm C delegated the detailed design and manufacturing to an external supplier and focused on gearbox architecture. However, Firm C's product resulted in an integration failure between the gearbox and the whole engine. Firm B cooperated with an internal supplier belonging to its industrial conglomerate and succeeded in building a new architecture. Firm B and the supplier communicated closely with each other and split the R&D cost. To put it briefly, with the new gearbox, it was very difficult to accommodate the radical change with external suppliers.

Brusoni and Principe (2011) proposed that, to achieve architectural innovation in the development of a high-technology product, manufacturers should build close relationships with their suppliers and maintain frequent communication. Brusoni and Principe also emphasized the importance of system integration capabilities. One practical implication was that a manufacturer in a science-based industry would require a fully worked-out plan for supplier management.

Previous studies (e.g., Brusoni et al., 2001; Brusoni and Principe, 2011; Chesbrough and

Kusunoki, 2001; Chuma, 2006) examined the role of the system integrator but did not clarify the internal organization structure, the specific content of the knowledge acquired, or the procedures and knowhow of supplier management. Therefore, for this study, we obtained an organization chart and component specification sheets, and unveiled the details.

2.2 The Mirroring Hypothesis

Regarding organization structure, we considered whether the data from our study would support the "Mirroring Hypothesis" (Colfer and Baldwin, 2016). This hypothesis states that "in the design of a complex system, the technical architecture, division of labor, and division of knowledge will 'mirror' one another in the sense that the network structure of one will correspond to the structure of the other" (Colfer and Baldwin, 2016, p. 712). Technical architecture refers to the product architecture, which describes how components with individual functions are linked together. The division of labor describes how people or teams are assigned to particular tasks, and how they are linked via organizational relations. The division of knowledge describes how people or teams possess and exchange design-relevant information.

According to Colfer and Baldwin (2016), the Mirroring Hypothesis was partially supported in the across-firm subset, that is, in the virtual organization. They stated that mirroring was observed between the technical architecture of the system and the division of labor, but not between divisions of labor and knowledge. As Brusoni et al. (2001) observed, some firms "know more than they make" (Brusoni et al. ,2001, p. 597). In other words, a manufacturer can possess technical knowledge related to a component provided by a supplier because the manufacturer collaborates with the supplier to develop the component.

Similarly, air conditioner manufacturers possess component knowledge (Cabigiosu and Camuffo, 2012). Manufacturers design or produce some of these components internally, but also strengthen their relationships with suppliers in order to access and acquire component knowledge. Furthermore, Furlan, Cabigiosu and Camuffo (2014) demonstrated that if the architecture of an air conditioner is not changed but the component knowledge is changed to a large extent, the manufacturer collaborates with suppliers on development and acquires new knowledge. That is to say, because mirroring was not observed between the divisions of labor and knowledge, the Mirroring Hypothesis was not fully supported. The same result was seen in the auto industry (Cabigiosu, et al., 2013; Macduffie, 2013; Zirpoli and Becker, 2011). We intend to discuss this further by analyzing two cases of architecture change in exposure tools for semiconductor chips.

2.3 Research Objectives

Our research objectives are as follows: Previous studies (Brusoni et al., 2001; Colfer and Baldwin, 2016) have asserted that manufacturers must acquire component knowledge in order to perform as system integrators when facing major changes such as architectural innovation. This assertion denies the congruence between the divisions of labor and knowledge. However, the researchers do not clarify the process of acquiring and gaining knowledge from suppliers. Although they point out that manufacturers conduct collaborative development and information exchange with suppliers, they do not provide details or specifications. We intend to reveal these procedures and tactics. We will also examine the types of actors, in addition to suppliers, that manufacturers have incorporated into their virtual organization.

The object of our study was complex equipment in a science-based industry similar to aircraft engine manufacturing as studied by Brusoni et al. (2001) and Brusoni and Principe (2011). We chose an exposure tool used for manufacturing semiconductor chips. This large-scale industrial equipment has an extremely complex architecture consisting of many high-technology components. The Dutch company ASML entered the market after several others, yet still managed to unseat Nikon from its dominant position by integrating all outsourced components. ASML demonstrated excellence in both system design and the fine-tuning of these components.

Furthermore, ASML's suppliers were not subsidiaries or spinoffs. They were wholly external companies. Compared to the aircraft engine examples in the studies by Brusoni et al. (2001) and Brusoni and Principe (2011), it was even more difficult for ASML to build this strong relationship with its suppliers. We assume that this architectural innovation hurdle will continue to increase.

How could ASML integrate all outsourced components into the final complex system product? What was the internal organization structure that enabled ASML to design a whole product, direct detailed specifications, and fine-tune components to prevent conflicts? Furthermore, how did ASML intensify supplier management?

Chuma (2006) attributed ASML's remarkable success to the building of very strong relationships with suppliers, industry consortiums, and universities. As one example of supplier management, ASML made contracts with each of its individual suppliers for an exclusive strategic alliance in R&D, design, manufacturing, pricing, and customer support. ASML sometimes provided non-interest loans to its suppliers.

In this study we sought to clarify the structure and operation of internal organization, the methods for increasing suppliers' commitment, and the pathway to legitimacy for next-generation products. We investigated ASML's architectural innovation, which was the equivalent of systemic innovation, after the period covered by Chuma's study (2006).

3. Data and Methods

The present study is a case study comparing a Dutch company, ASML, and a Japanese company, Nikon. These companies compete aggressively within the semiconductor oligopoly. We collected data from various documents including public and informal academic papers, articles, and internal documents. We also interviewed staff from ASML, Nikon, suppliers, and an external partner. Thus, this study used multiple data sources, which allowed us to obtain construct validity by triangulating evidence within the case (Yin, 1994). We categorized these data as either quantitative or qualitative.

Quantitative data are obtained from empirical documents as follows:

- The product design shows the technical architecture (obtained from company brochures and internal technical documents)
- The market share transition shows company performance (obtained from a database created by a supplier)
- The number of academic papers categorized as either "solo" or "joint" shows the level of company collaboration with suppliers and external partners (obtained from the research papers of the SPIE Advanced Lithography Conference)

Qualitative data are obtained mainly from interviews and supplementarily from internal documents and public documents including industry magazines, annual reports and company histories.

- The component suppliers' list shows the divisions of labor.
- The organizational chart shows how to organize an effective team.

Furthermore, qualitative data relating to supplier management and the virtual organization can explain the following:

- How the manufacturer acquires the same level of knowledge as its suppliers
- How the manufacturer uses the complete product architecture and expertise to obtain market penetration

Interviews were conducted between 2014 and 2017, as follows: six with ASML, three with Nikon, five with suppliers and two with consortiums. The average length of each interview was 2-3 hours. The resulting data allowed us to understand the relationships among the technical architecture, as well as the patterns in the divisions of labor and knowledge. We then compared our data with the study by Chuma (2006) in order to obtain external validity (Yin, 1994).

The following is a partial list of interviewees:

- ASML: Executive Vice-President, Logistics Manager in Supplier Management, Director of System Engineering, and VP of Source Technology
- Nikon: Executive engineer, Quality Assurance engineer, Sales and Marketing manager
- Gigaphoton (Laser Supplier): Marketing manager, Development manager, CTO
- Consortium: CEO of IMEC, fellow of IMEC Japan

4. Overview of Technology and Companies

4.1 Overview of exposure tools for semiconductor chips

The most important step in semiconductor device manufacturing is optical lithography, and the semiconductor exposure machine plays an important role. Figure 1 shows the basic design of the reduction projection-type semiconductor exposure tool.

An ultraviolet light source emits light which is collected by the illumination lens and then passed through a reticle. The reticle contains the image of the circuit to be printed on the wafer. The projection lens is used to expose this reticle pattern on the wafer. The reticle is placed on the reticle stage. The wafer is placed on the expose/measurement stage on the laser interference control stage, and exposure is performed in a step-and-repeat process, moving in synchronization with the reticle stage while maintaining high positioning accuracy. With this technique, the reduced reticle pattern can be reproduced on the wafer with good uniformity and in high volume. The main performance requirements of the exposure tool are (1) the resolution with which fine, complex patterns can be transferred, and (2) wafer throughput per unit time.

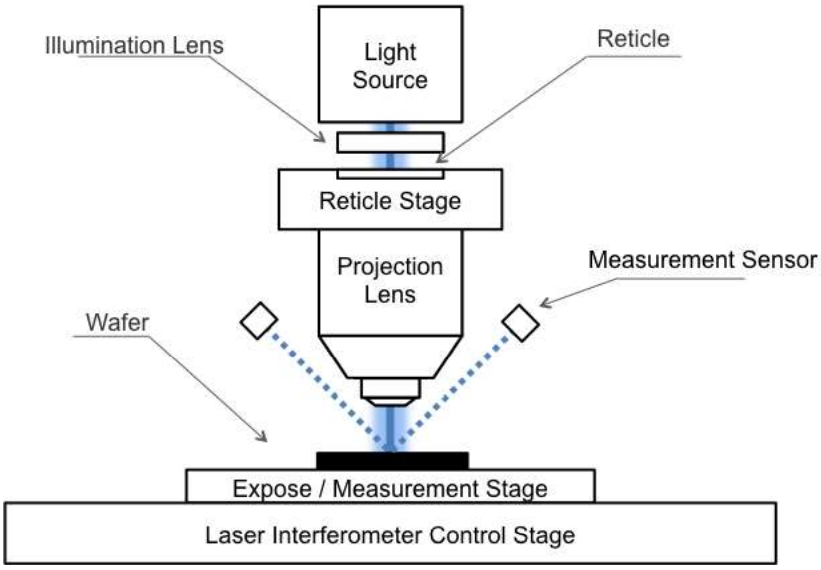


Fig. 1. Reduction projection-type exposure device

4.2 History of semiconductor exposure equipment development at Nikon and ASML

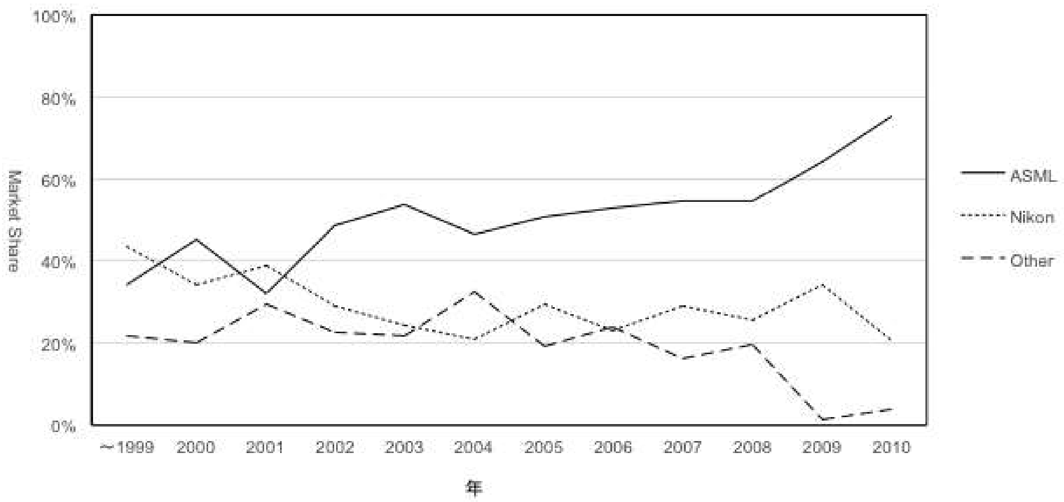
The development of Nikon's semiconductor exposure equipment began in 1976 (Takahashi, 2006), when the Ultra-LSI Technology Research Association (ULSI Labs) was established at the initiative of the Ministry of International Trade and Industry (now the Ministry of Economy, Trade and Industry). A researcher at ULSI Labs asked Nikon to develop a reduction projection-type exposure system. Two years later, in 1978, Nikon delivered Japan's first reduction projection exposure system to ULSI Labs. Nikon's exposure system achieved high resolution and positioning accuracy, providing the foundation for Japan's leap into the global semiconductor industry. In the 1990's, the excimer laser replaced the mercury lamp as the light source for exposure systems[i]. In 1995, Nikon became the world's first manufacturer to sell scanners that transferred images while scanning patterns on masks with thin slits. In terms of global market share, Nikon became No. 1 in 1990. In 1990-1995, Nikon gained a 50-55% market share and an apparently unassailable position as an exposure tool manufacturer.

ASML's development team originated in Philips's Semiconductor Division. In 1971 a group of engineers at the Philips Natuurkundig Laboratorium developed a prototype exposure tool called the Silicon Repeater Mark 1, and produced an improved version in 1978. The group continuously improved the product until around 1983. During this period, however, they were plagued by ongoing performance issues in their exposure lens and wafer stages. Considering external sales, Philips decided to spin off this group in partnership with a local semiconductor equipment distributor called Advanced Semiconductor Materials International (ASMI), forming a joint-venture company called ASML.

From the beginning, ASML has used the approach of procuring parts from external companies and assembling them into a system. According to the ASML company history[ii], "If modular design was not possible, neither development nor production could be done."

A key contributor to ASML's growth was a European semiconductor consortium, the Interuniversity Microelectronics Center (IMEC). IMEC was established in 1984 by the Belgian government to bolster the region's microelectronics industry. Luc Van den Hove, the current CEO of IMEC, identifies ASML as their strategic partner. He recalls that "in the early days when IMEC was first established, we were not very successful in partnering with the industry's leading semiconductor manufacturers. However, thanks to strategic support from ASML, IMEC's importance was eventually recognized and we were able to greatly expand our industry partnerships over time." Today, ASML supplies all IMEC's exposure tools, and their presence has grown as more and more semiconductor manufacturers began leveraging IMEC's services.

Figure 2 shows the trend in market share of excimer lithography equipment since 2000. Although both companies held a competitive market share until around 2000, ASML has maintained a clear lead over Nikon since 2002. This is due to the fact that the entire product design has changed significantly, as described in the next section.



Sources: Shipment volume collected by Gigaphoton

Fig. 2. Market share of excimer lithography equipment[iii]

4.3 Architectural Innovation

In 2000 ASML introduced dual-stage technology, an architectural innovation that dramatically increased wafer processing speeds by running the exposure and measurement processes simultaneously (Figure 3). In 2004, ASML successfully introduced another major innovation: the industry's first immersion lithography technology (Figure 4), in which more complex chip designs could be manufactured by immersing the space between the exposure lens and the wafer in water. However, evaporation caused problems with temperature change and defects, which ASML had to resolve. Nikon, on the other hand, introduced their dual-stage and immersion technologies simultaneously in 2005, a year after ASML[iv].

Chesbrough and Teece (1996) characterized this shift to whole-product design as "systemic innovation". It was previously conceptualized as "architectural innovation" (Henderson and Clark, 1990) and later, as "Dynamic Shifts in Product Architecture" (Chesbrough and Kusunoki, 2001).

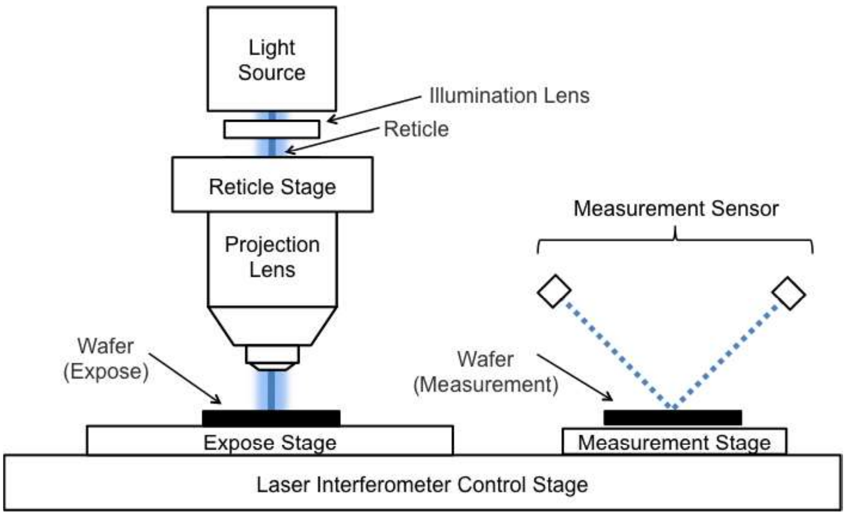


Fig. 3. Design of dual-stage technology

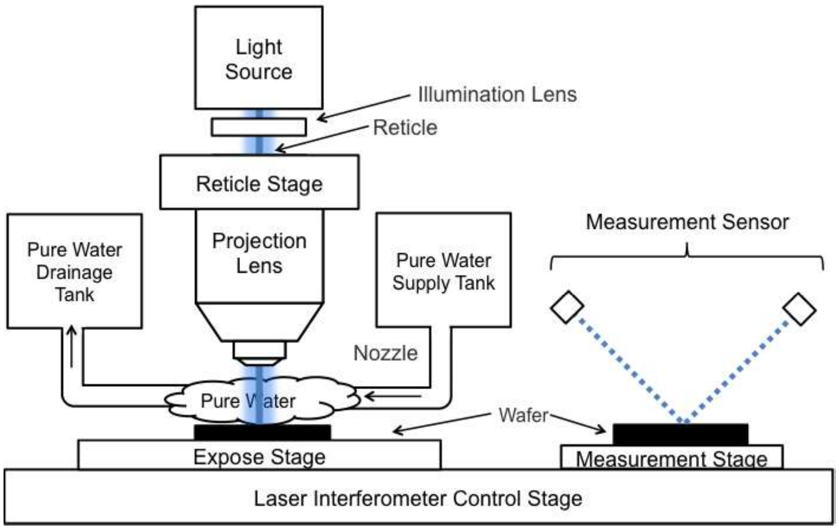


Fig.4. Design of immersion lithograph technology

5. Mirroring structure on product and organization

As stated above, Nikon was late in launching its new architecture and failed to regain market share. This was because architectural innovation was not successful: Nikon could not provide the level of performance required by its customers. This in turn was due to the major difference in its internal organizational structure from that of ASML.

5.1 Component suppliers

In this section we compare the management structure of the suppliers who provide each component. As shown in Table 1, ASML only produces software internally, outsourcing all other components. In contrast, Nikon outsources only the laser light source. Thus there is a big difference between the two companies in terms of the component knowledge for performing functions and the architectural knowledge for linking components. As Chuma (2006) shows, the exposure tool is not a completely modular device that can be completed by integrating the procured components with software, such as a PC or mobile phone. Rather, ASML must exchange precise information with its suppliers in order to learn about these components.

Table 1. Component Suppliers

Component	ASML	Nikon
Light Source	Cymer (US), Gigaphoton (Japan)	Cymer (US), Gigaphoton (Japan)
Illumination	Zeiss (Germany)	In-house
Reticle Stage	Philips (Netherlands)	In-house
Projection Lens	Zeiss	In-house
Wafer Stage	Philips	In-house
Alignment	Zeiss, Philips, Agilent (US), TNO (Netherlands)	In-house
Body	Philips	In-house
Software	In-house	In-house

Sources: Based on authors' fieldwork and Chuma (2006)

5.2 Organizational Structure

This section describes ASML's organizational structure.

As Table 2 indicates, the organizational pattern corresponds to the product architecture. That is, ASML has adopted mirroring theory (Colfer and Baldwin, 2016).

For new product development at ASML, the CTO appoints a product manager, and a systems engineer and marketing manager are responsible for launching the product. Below this level, there are up to 17 component-based units (from the main component to sub-components such as the laser, lens, etc.), and each has a unit leader. The system engineer works closely with all units to manage costs and schedules, meeting weekly with the product manager and

Table 2. ASML Organizational Chart

Product Mgr. (each model) + SE and Marketing Mgr.			
	Unit Leader (Component 1)	Unit Leader (Component 2)	Unit Leader (Component 3)
Project Mgr. (Task Force 1)			
Project Mgr. (Task Force 2)			
Project Mgr. (Task Force 3)			

Sources: Based on authors' fieldwork[v] marketing manager to discuss issues requiring approval. In the table, components are shown in the rows, and projects are shown in columns. “Project” refers to a specific task. For example, in the development of immersion lithography technology as shown in Figure 4, one project involved resolving the problem of keeping pure water in a stage that was moved and stopped repeatedly at high speed.

Decisions made at ASML are conveyed to every component supplier. Suppliers rarely coordinate amongst themselves. Rather, ASML is the central communicator among its suppliers, acting as the ultimate system integrator. Under the system engineer, a software engineer performs the programming to construct an interface among components[vi].

On the other hand, since Nikon has a high proportion of in-house production, they have established a system for consistent transition from R&D to in-house production. Nikon’s functional organization is divided into R&D, design, production, technical service, customer service, and market information analysis. This organization is not clearly divided into units as is ASML, and the manager in charge of R&D is also responsible for managing costs and schedules. Because all components other than the laser unit were developed internally, coordination among these components was not emphasized. However, in practice, interface construction was difficult.

6. Supplier Management

How does ASML integrate complex components from external suppliers into a single system? We will now describe this management in detail.

6.1 Basic policy

ASML has hundreds of suppliers. Each company supplies one part; it is rare for two companies to supply the same part. Single-company supply is preferred because it makes costs transparent and dramatically cuts costs for customers[vii]. The three key components of the exposure system are the lenses, supplied by Carl Zeiss, the stage, supplied by Philips (now VDL-LTG), and the excimer laser light sources, supplied by two companies, Cymer and Gigaphoton.

The basic principle of ASML’s product design is to match performance and cost, and if reliability drops, ASML chooses to reduce performance instead. This attitude is not seen in performance-oriented Nikon[viii]. ASML prioritizes the user’s return on investment (ROI) and the reduction of product defects. Thus the Systems Engineer plays a critical role. As the Executive VP states, “The Systems Engineer looks at the whole and breaks the required performance down into individual units (components). If a unit does not meet the required level, the other units are adjusted to maintain the level of the overall system. If this still does not resolve the issue, we have to drop the entire performance.[ix]"

6.2 Complete knowledge sharing

Design specification sheets are divided into two types: the EPS (elementary performance specification) and TPS (test performance specification)[x]. The EPS and TPS for the laser are each 50-80 pages in length, and are updated each time the product version changes. For example, for a spectrum-related item, the EPS specifies the definition and target values, and the TPS specifies the measuring instrument to be used and the measurement frequency. Lead time is important because the specifications are prepared over a year in advance of delivery. Suppliers must report the lead time to ASML, drilled down to the second-tier supplier level. In other words, ASML has the same level of component knowledge as the supplier, and converts it to explicit knowledge while updating it. They then build the architectural knowledge to connect the components.

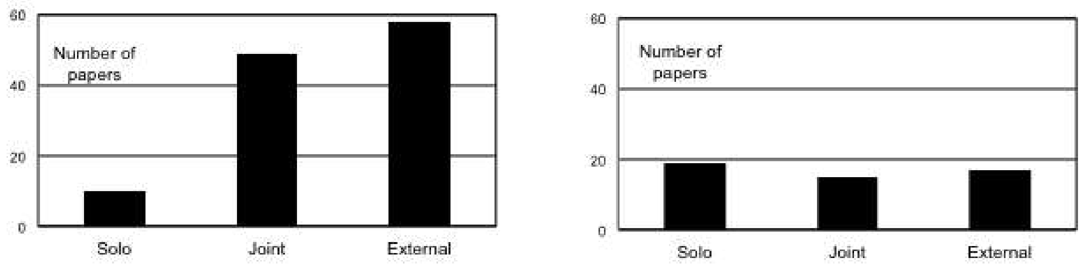
In contrast, of the three key components, Nikon outsources the laser only. Parts needed to produce in-house components are also outsourced, but unlike ASML, there is no single-company supply rule or transparent-cost rule. In addition, the specification sheet provides only the main performance target value. Other target values are determined in discussions with the laser manufacturer and parts manufacturers[xi]. In-house production is highly prioritized, and in the 1980s, Nikon had a team to research excimer lasers[xii]. If this research were implemented, all three key components could be made in-house.

7. Standardization via neutral organizations

7.1 Academic appeal

To describe the levels of external collaboration for ASML and Nikon, we have categorized the research papers submitted to the SPIE of academic societies as being authored by one of the following: consortium, chip manufacturer (customer), equipment manufacturer, or supplier.

A search was conducted for research papers published by the SPIE[xiii] Advanced Lithography Conference between 1995 and 2010 pertaining to ASML and Nikon exposure tools. The search returned 117 papers on ASML and 51 papers on Nikon. Research papers can be categorized as follows: solo papers written entirely by employees of ASML or Nikon, joint papers written by ASML or Nikon and a collaborating company, or external papers written entirely by an external entity. Figure 5 compares the number of papers for the two companies in each of these categories. Interestingly, this figure indicates that ASML has published very few solo papers (only 10), accounting for a mere 8.5% percent of the total. However, 49 joint papers have been published, almost 5 times the number of solo papers. In contrast, Nikon has published more solo papers than joint papers (19 solo papers), accounting for approximately 37% of the total list.



ASML **Nikon**

Sources: Authors' search for SPIE papers

Fig. 5. Number of papers published, by category

The difference in the number of solo versus joint papers can be directly attributed to the difference in the R&D structures at ASML and Nikon. ASML has demonstrated their ability to flexibly delegate tasks both internally and externally, and even to design entire products in cooperation with external parties. Nikon, on the other hand, pursues closed research and development by continuously leveraging cross-sectional knowledge.

It is worth noting that external entities such as research institutes and suppliers have published three times as many papers about ASML as about Nikon. This suggests that these external entities have conducted R&D activity autonomously and generated knowledge. This makes sense given that ASML outsourced all components to external suppliers.

7.2 Collaboration partners

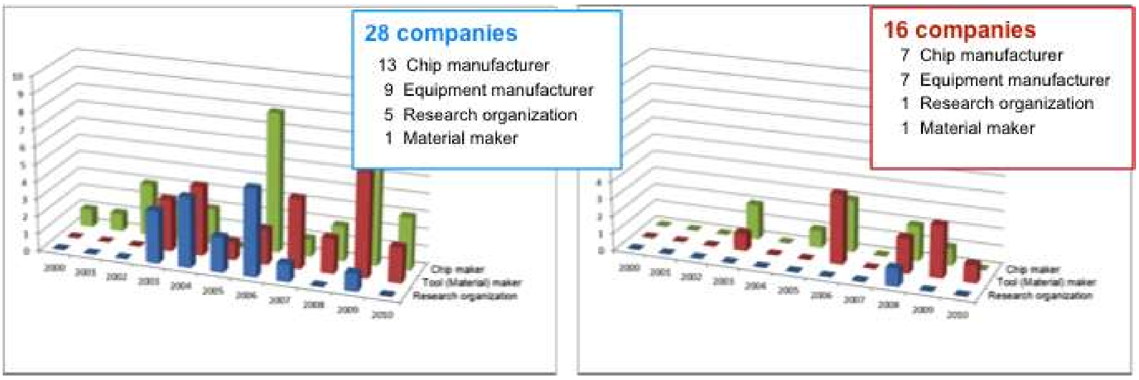
As indicated in the previous section, ASML is willing to share the industry roadmap by jointly presenting advanced research to academic societies.

Given the above, what kinds of external organizations did these two companies work with? Fig. 6 summarizes the transition in the number of coauthored papers with consortiums, equipment manufacturers/suppliers, and chip manufacturers based on the above data sources. ASML has more co-authors with external organizations than Nikon. The ASML co-authors include 28 institutions, five of which are research organizations: two consortiums and three research institutes. The most frequent co-author is the consortium IMEC (10 papers), which has published co-authored papers annually since 2002. Of the suppliers, projection lens maker Carl Zeiss has published several (8) co-authored papers with ASML.

On the other hand, Nikon has published coauthored papers with 16 external organizations, most of which are chip and equipment manufacturers, and only one research organization. Characteristically, there are no co-authorships with consortiums.

Several consortiums have been established in Japan, including Semiconductor Leading Edge Technologies (Selete), Advanced SoC Fundamental Technology Development (ASPLA), and Ultra-Advanced Electronics Development Organization (ASET), but there has not been sufficient collaboration with Nikon. ASML's cooperation with consortiums can be understood as an important strategic matter. By deepening its cooperation with IMEC over many years, ASML has strengthened the relationship with chip and equipment manufacturers who are also IMEC members.

Chuma (2006) states that ASML delivered prototypes to IMEC, giving chip and equipment manufacturers a chance to try them out. We analyzed exposure tool purchase data[xiv] for chip manufacturers who were also IMEC members from 1999 to 2010. The proportion of chip manufacturers who purchased ASML tools increased from 43% (1999-2003) to 59% (2004-2007) and to 71% (2008-2010). This indicates that the leading company has established its position, in part, by cooperating with consortiums.



ASML **Nikon**

Sources: Authors' search on SPIE papers

Fig. 6. Collaborators of co-authored papers

8. Result

As we described above, ASML accomplished its architectural innovation and built a secure market position by procuring all components from external suppliers. This approach forced ASML to take on innovation challenges even more difficult than those faced by aircraft engine makers as reported by Brusoni et al. (2001) and Brusoni and Principe (2011). Among the six cases introduced in these two studies, most of the suppliers are either current or former internal suppliers.

Only one case involved a loosely coupled organization between the engine manufacturer and an external supplier, which enabled the manufacturer to achieve architectural innovation. The engine maker controlled the concept design and system integration, and outsourced the detailed design and manufacturing to the supplier. Similarly, ASML completed its new architecture by creating loosely coupled organizations with external suppliers and members of consortiums, sometime including customers. Because the internal organization structure was a component-based unit, we further confirmed that the technical architecture and division of labor mirrored one another as described by Colfer and Baldwin (2016). In contrast, Nikon was unable to perform well because it did not create an organization that mirrored the technical architecture.

In the next sections, we categorize the management methods seen in our study into two phases of the product development process.

Concept design

When ASML develops a new product, it architects a whole-product perspective at the system level but not at the component level. First, ASML assesses the number of linkages among components. This task is performed by a product manager, systems engineer, and marketing manager. Each unit of organization is uniquely allocated to one component, as proposed in the Mirroring Hypothesis. Finally, to reinforce the whole-product perspective as the de facto standard, ASML encourages consortiums, mainly IMEC (neutral organization), to pursue some particular area of expertise or component-related technology, resulting in the development of a future roadmap. Because the consortiums include some potential customers, ASML gets the chance to introduce its next-generation product.

Detailed design

Because ASML and its suppliers share a common destiny, they have mutual transparency regarding costs. The key point is an appropriate balance between quality and cost.

Suppliers must create enormous specification documents which include second-tier suppliers' lead times, and update these documents regularly. These specifications allow ASML to have the same level of component knowledge as the suppliers. That is, because ASML has component knowledge beyond its organizational boundaries, the divisions of labor and knowledge do not mirror each other.

The systems engineer at ASML is responsible for adjusting interfaces among all components. In order to match the entire performance and total cost, the systems engineer directs the level of output provided by each component. He/she is also responsible for speeding up development and for identifying any parts that are causing problems.

Thus, the systems engineer regulates ASML's capability of a system integrator.

9. Conclusions and Discussion

ASML's internal organization structure was divided into several units corresponding to components in order to build the new architecture. We confirmed that the technical architecture and division of labor mirrored each other. However, because ASML acquired the same level of component knowledge as the suppliers, the divisions of labor and knowledge did not mirror each other. As a result, the Mirroring Hypothesis was not fully supported.

Although ASML did not produce any components, it allocated considerable engineering resources to each component in order to share information with suppliers and evaluate performance. ASML and its suppliers exchanged testing performance knowhow and updated information including second-tier supplier's levels of lead time and cost structures. When a conflict occurred among components, systems engineers were able to resolve it completely.

ASML built a virtual organization that included suppliers, chip manufacturers, consortiums, and research institutes. This virtual organization pursued basic research for an extended period, eventually developing the new architecture of an expensive, science-based piece of industrial equipment.

By contrast, although Nikon produced almost all components internally except for laser light sources, it still encountered problems in completing the new architecture. Nikon fell behind ASML in deploying a new organizational structure in its attempt to develop the new architecture. This result might seem surprising. One of the major reasons was that Nikon prioritized an internally-developed lens component rather than a laser component provided by external suppliers. This was because Nikon had developed many lens-related products such as microscopes, telescopes, and analog and digital cameras. Thus, it was inevitable that Nikon would give priority to the lens component.

Regarding organizational structure, Nikon did not institutionalize the systems engineer position as did ASML. This lack of a systems engineer resulted in inefficiency in overcoming development obstacles. Furthermore, the development department was not divided into several units corresponding to components, which was in opposition to the Mirroring Theory. Therefore, we confirmed the basic rule that it is essential that "the technical architecture and division of labor mirror each other".

We admit that our analysis of the Nikon case has some limitations. Nikon might have attempted to arrange a paired organizational structure to be symmetrical with the technical architecture. However, even if Nikon had done so, it still would have failed in establishing the new organization structure. Therefore, we confirmed that Nikon kept the functional organization which was not mirrored to technical architecture when achieving its architectural innovation. Unfortunately, we were unable to obtain details about the ways in which Nikon's engineers shared information in pursuit of this innovation. How did Nikon control the linkage among components without symmetrical organization and a systems engineer? Had we been able to clarify these points, we could have contributed further evidence to the Mirroring Hypothesis.

Lastly, we address the contribution to practice.

For consumer goods like the smartphone, PC, and TV, it is generally thought that multiple suppliers should be standard tactics in preparation for unexpected contingencies. In this case, manufacturers cannot ask suppliers to disclose their costs. For industrial goods like exposure tools, however, it is rational for manufacturers to assign a single supplier for each component and to request a strong commitment. Moreover, even in the global economy era, ASML has a basic policy of dealing with nearby suppliers as much as possible. This would suggest that an ongoing close relationship is necessary to achieve systemic innovation.

In fact, in 2012, ASML acquired Cymer, a U.S. company, one of the two suppliers of the excimer laser that is one of ASML's core components. The development unit of the next generation laser (EUV) was transferred to the Dutch headquarters.

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Further reading

Reflect & Imagine: 20 Years of ASML, ASML, Chapter 1, pp.6-19, 2004.

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[i] A device that generates ultraviolet laser light using a mixed gas such as a rare gas or halogen. Representative mixed gases include XeF (wavelength 351 nm), XeCl (wavelength 308 nm), KrF (wavelength 248 nm), ArF (wavelength 193 nm).

[ii] Reflect & Imagine: 20 Years of ASML (2004)

[iii] The number of excimer exposure machines installed at the chip maker reached about 4,000. Based on the database accumulated by Gigaphoton, we conducted a in-person interviews on tracking and built our own database.

[iv] Nikon (executive engineer)

[v] ASML (Logistics Manager in Supplier Management)

[vi] This resembles the software engineering for the aircraft engine described by Brusoni and Principe (2001).

[vii] ASML (Manager, Logistics Supplier Management)

[viii] Gigaphoton (Marketing Manager)

[ix] ASML (VP of Source Technology)

[x] Lammers et al. (2008) first described these documents.

[xi] Gigaphoton (Marketing Manager)

[xii] Nikon (Quality Assurance Engineer)

[xiii] SPIE (International Society for Optical Engineering)

[xiv] Gigaphoton's database

本ワーキングペーパーの掲載内容については、著編者が責任を負うものとします。

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