Benchmarking Semiconductor Lithography Equipment Development & Sourcing Practices Among Leading-Edge U.S. Manufacturers

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ABSTRACT

The semiconductor lithography equipment industry has evolved to where knowledge of technology alone is insufficient to survive in the market. An interdisciplinary set of skills has become necessary to fully comprehend the dynamics of the lithography industry. Understanding the fundamental technology, the management issues in a manufacturing equipment market, and the role of industry-sponsored consortia are all critically important to the lithography industry.

A dramatic shift in the semiconductor lithography equipment market occurred in the mid-1980s which sparked a furry among political circles in the United States. Between the late 1970s and late 1980s the market share of U.S. companies dropped from nearly 90% to less than 20%. The rapid expansion of the semiconductor market, particularly in Japan, coupled with the perceived unresponsiveness of U.S. lithography suppliers to customer requests provided a window of opportunity for Nikon and Canon. In addition, the technological expertise necessary to manufacture lithography equipment increasingly forced semiconductor manufacturers world-wide to purchase the equipment from suppliers rather than to develop internally.

In the 1990s, U.S. semiconductor manufacturers have adapted to the new market conditions for lithography equipment sourcing. Lithography technology remains critical to the semiconductor manufacturing process. Constrained to buy lithography equipment from suppliers, manufacturers are forced to develop strategies for effective technology supply chain management. Driven by technology development cycles, semiconductor companies have a four year time constant for learning and continuously improving their sourcing strategy. As a result of their dependency upon suppliers, semiconductor corporate equipment sourcing strategies have been geared to maximize supplier switching flexibility while simultaneously minimizing capital expenditures. This approach has lead many manufacturers to create preferred supplier relationships and tools for ensuring competitive behavior among suppliers. The industry's objective: to ensure continuous development of leading-edge lithography technology. This report benchmarks how individual companies have organized their equipment development and sourcing practices and their respective merits.

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Thesis Advisor: Professor Joel Clark, Dept. Materials Science and Engineering

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Chapter 1

The Art Of Managing Manufacturing Equipment Development & Sourcing

1.1. Thesis Research Objectives

The MIT Technology Supply Chains Research Group

This research is part of a larger MIT project on technology supply chains direct by Professor Charles H. Fine. The MIT project seeks to characterize the equipment development and sourcing practices across multiple industries. The underlying hypotheses driving this research program have been the foundation of this project on semiconductor lithography equipment technology supply chains.

The S.M. Lithography Thesis Objectives

The vision is to expand the academic knowledge-base and provide the framework for semiconductor manufacture's and their equipment suppliers to seek optimal strategies in the management of lithography technology development and sourcing. This vision is built upon seven specific objectives:

1. To integrate an international database on semiconductor lithography equipment development and sourcing proactices, compile an interpretation of lithography industry trends, and recommen metrics for benchmarking manufacturing equipment development and sourcing activities.

2. To map-out a dynamic model of users, suppliers, end-product customers, and government involvement in the lithography industry.

3. To develop an understanding of the critical links along the lithography technology supply chain.

4. To identify benchmark technology development and sourcing processes which are to the mutual advantage of both users and suppliers of lithography equipment.

5. To explore the true end-product customer-driven technology pull for advancing lithography to progressively smaller linewidths.

6. To develop case studies of lithography equipment development and sourcing processes within and between equipment users and their suppliers.

7. To clarify the details concerning current and future government policies in support of lithography equipment technology.

A key source of data in fulfilling these objectives was to directly ask lithography technology managers working in semiconductor manufacturing companies. Literature research only reveals the technical aspects of lithography. To learn how the industry functions and its daily management challenges required fieldwork. Eventually, through this thesis project the "Lithography Technology & Policy Story" which others can locate via literature research can become available.

1.2. Lithography Thesis Research Design Tools

Three core research tools were developed to collect data from six semiconductor manufacturing companies and the Sematech research consortia:

1. The 7 Step Corporate Management Survey Approach,
2. The 7 Lithography ED&S Questionnaires, and
3. Three Tools for Encouraging Corporate Participation.

Nineteen of 21 interviews with lithography managers were recorded on audio tape to supplement written notes. On average, each of the six companies required a minimum of three interviews to capture sufficient information from each company. An early sampling of five independent interviews with Texas Instruments indicated the first three interviewees answered 80%+ of all desired questions (Consult 80/20 Rule).

The 7 Step Corporate Management Survey Process

From the thesis' inception it was realized the need for a methodological process to survey the semiconductor industry's lithography equipment development and sourcing practices. In the end six U.S. Semiconductor manufacturers (Advanced Micro Devices, Digital Equipment Corp., IBM, Intel, Motorola, and Texas Instruments) were the subjects of a seven step process.

I. IDENTIFY TARGET

- Key target companies identified with background literature search complete.
- Specific company location, background research, and key people contacts identified.

II.. ORGANIZE PLAN OF ACTION

- Input thesis vision and project enrollment brochures.
- Lithography project introduction materials prepared with proposal tailored to the specific company.

III. ENROLLMENT IN PROJECT VISION

- Initiate contact, research project introduction, and assure positive feedback on mutual benefits.
- Conduct initial telephone interview of essential data.

IV. CLOSING THE SALE: COMMITTMENT

- Draft on-site visit scheduling plan to fit with company schedules
- Meeting dates established, objectives clearly stated, and schedule confirmed for each interviewee available.

V. PRELIMINARY DETAILS

- Travel, housing, etc. Logistics settled for term of expected visit.
- Incorporate survey questionnaire tools to attain pre-visit basic informations and maintain interviewee contacts.
- Develop tailored question sets for each interviewee opportunity given at each company based on survey tool.

VI. INTERACTIVE COMPANY INTERVIEWS

- Conduct on-site interviews at company
- Ensure full data collection, interview notes and recordings.

VII. POST-INTERVIEW REPORTS AND FEEDBACK

- Short-term response: thank you notes and initial overview of research data collected.
- Author final case-study report for each company to confirm data.

Three Tools For Encouraging Corporate Participation

The critical success factor to the "Corporate Management Survey Process" was step III. Enrollment in Project Vision. Fundamentally, it was quickly learned that managers wanted to know what were the benefits to them, how much time would it take, and what specific information we wanted to learn from them. Hence, three tools were developed to help in this process of enrolling each semiconductor company's interest in participating:

1. The 7 Benefits to Corporate Participation
2. Details in the Research Process
3. Introductory Questionnaire

Introducing the research project and expectations also had to be straight-forward to the participant. A key diagram used to introduce "The 7 Benefits to Corporate Participation" as in Figure 1.1.

The 7 Benefits to Corporate Participation

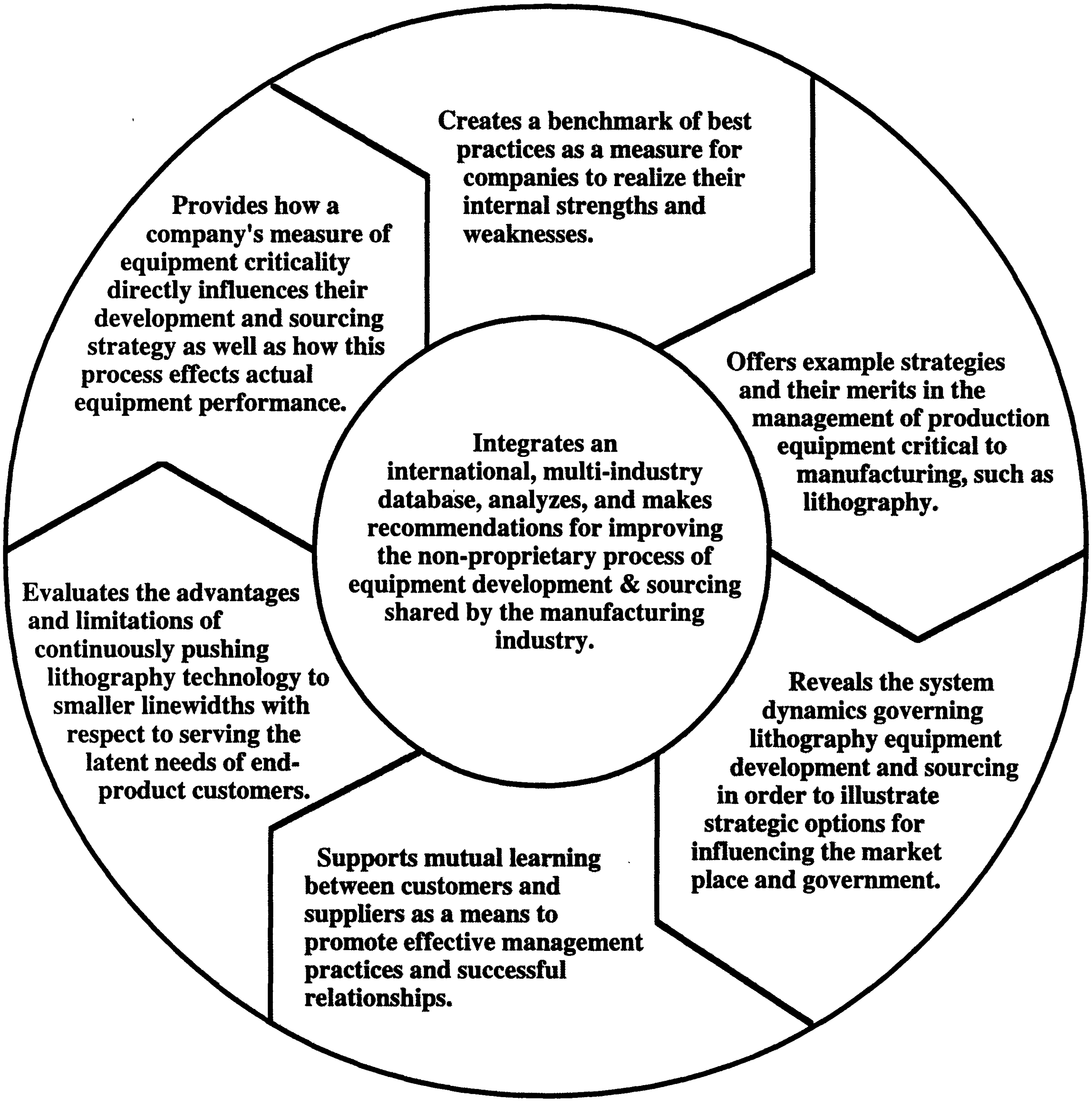

FIGURE 1.1

The 7 Lithography Questionnaires

A wide variety of questions needed to be asked of managers in leading-edge semiconductor companies to learn of their lithography equipment development and sourcing process. Seven questionnaires were developed to be appropriate for interviewees at different level within the corporation:

1. Semiconductor Products Marketing Department
2. Semiconductor Technology General Manager
3. Lithography Equipment Sourcing Manager
4. Lithography Technology Development Manager
5. Lithography Supplier Liaison
6. Process Engineering
7. Fab Manager

Typically, only 3-4 of the questionnaires were completed at any one given company. However, the overlap of questions among the seven ensured nearly 80-90% coverage of all desired questioning from only 3-4 interviews. Overall, the questions categorized into seven levels of analysis:

1. Metrics and Values of Lithography Equipment Criticality
2. Drivers of Progressively Smaller Linewidth CD Lithography
3. Internal Lithography Equipment Development Process
4. External Customer-Supplier Relations
5. Metrics of Lithography Equipment Performance, Costs, etc.
6. Interactions with Industry Associations, Government, etc.
7. Miscellaneous Queries

The specific questions were kept consistent throughout the entire process. Some adaptations and evolvement of specific questions occurred for clarity and to the intent of the question is understood. A comment from one the early interviewee indicated the necessity for continuous improvement of the questioning process:

> "There is always interesting challenges here as to what the answers ought to be. Because, we tend not to think exactly parallel to what people who write surveys think." -- Interviewee

Chapter 2

A Political Economist's Perspective on Japan's Entrance into the Semiconductor Equipment Market

Nippon Kogaku K.K. and Canon Inc.'s Entrance and Subsequent Dominance in the Lithography Equipment Market, 1975-1995.

ABSTRACT

A dramatic shift in the semiconductor lithography equipment market occurred in the mid-1980s which sparked a furry among political circles in the United States. What was once a lithography equipment market which was 90% U.S.-based in the late-1970s became less than 20% by the late 1980s. In the early 1990s, roughly 86% of lithography equipment is produced by three Japanese manufacturers: Nikon, Canon, and Hitachi.

These Japanese suppliers happened to be manufacturing a product in which incremental process improvements, refined technology, and impeccable customer service, the hallmarks of Japanese corporate culture, were key elements to success. Accelerated by timely, indirect participation in the MITI orchestrated VLSI Technology Research Association, Nikon and Canon had core technical competencies which positioned them very competitively to enter the lithography equipment market. Despite some politically-charged views in the West, Nikon and Canon's success in the marketplace is not about 'Japan Inc.' targeting lithography technology or any concerted Japanese effort to keep-out foreign competition.

The rapid expansion of the semiconductor market, particularly in Japan, coupled with perceived unresponsiveness of U.S. lithography suppliers to customer requests provided a window of opportunity for Nikon and Canon. In addition, the technical expertise necessary to manufacture lithography equipment increasingly forced semiconductor manufacturers worldwide to out-source the equipment and further opened the market to suppliers during the 1980s.

Lessons from the VLSI Project and the ever-present trade friction with the U.S. has significantly influenced the nature of MITI's modern engineering research associations in Japan, as exemplified by the Super Silicon Crystal Project. Korea is attempting to emulate Japan's approach. However, whether Japan is an appropriate role model to emulate is questionable.

2.1. THE HYPE AND MYSTIQUE OF JAPAN'S EMERGENCE

The Market Power Shift of the Lithography Equipment Industry

If semiconductors are the "crude oil" of the second industrial revolution, then the fantastically precise machines that make microchips are the drilling rigs of the information age.[1] As the machines which essentially pattern the circuit designs of 100+ chips per minute with accuracy's to dimensions on the submicron (≤10-6 m) scale, lithography equipment can be characterized as the workhorse of the industry. Ever since the marketing of 64 kilobit (Kb) dynamic random access memory (DRAM) chips in the early 1980s successive, incremental advances in lithography technology has paced each generation of semiconductor technology (from 64 Kb, 256 Kb, 1 Mb, 4 Mb, to the 64 Mb DRAMs in production today).

In the mid-1970s the dominant players in the lithography equipment business were the U.S. suppliers Perkin-Elmer Corporation and GCA.[2] For most the decade these two firms led their competitors with their respective lithography technologies. Canon entered the lithography (wafer exposure) business in 1979 with an automated version of the proximity aligner, a technology that Perkin-Elmer had made obsolete with a more advanced projection aligner technology introduced back in 1973. However, Canon's machine represented such a great improvement over previous products of its type that it enabled many semiconductor manufacturers to use it instead of the more expensive projection aligner (of Perkin-Elmer's) or stepper aligner technology of GCA.[3]

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1 *Business Week* "The New Japanese challenge in chipmaking," April 18, 1983 p.114B.

2 Geophysics Corporation of America (GCA).

3 Global Competitiveness of U.S. Advanced Technology Manufacturing Industries: Semiconductor Manufacturing and Testing Equipment, Report to the Committee on Finance, United States Senate, Investigation No. 332-303 Under Section 332(g) of the Tariff Act of 1930, USITC Publication 2434, Washington D.C. September 1991 p.4-9.

Later in 1981, Nippon Kogaku K.K.[4] entered the market with its first product extremely competitive with GCA's stepping aligner lithography technology. It was quite clear by the early 1980s that stepping aligners was to be a superior and preferred technology for the most advanced, smallest circuit design patterns, however it came at a significant cost in manufacturing throughput compared to the proximity/projection aligners. During this period either of the lithography technologies were competitive in the market, depending upon the type of application for the equipment used by semiconductor manufacturers.

However, over the course of the 1980s there was a clear shift in the market share powers in lithographic equipment. From 1982 to 1989 world sales of lithography (and associated) equipment nearly tripled, from $415 million to $1.2 billion, but the sales by U.S. companies declined from $240 million to $215 million, and their market share dropped from 62% to 21%. Over the same time period, the market share of Japanese companies nearly doubled from 38% to 70% and their sales rose by a factor of nearly six, Figure 2.1. GCA and Perkin-Elmer Corp., the U.S. suppliers that dominated the market at the beginning of the 1980s, lost their leadership position to Nikon and Canon of Japan.[5] See Table 2.1. The turning point occurred, coincidentally, in 1985 when Nikon and GCA virtually split the world market share as suppliers for the then dominant stepping lithography equipment.[6]

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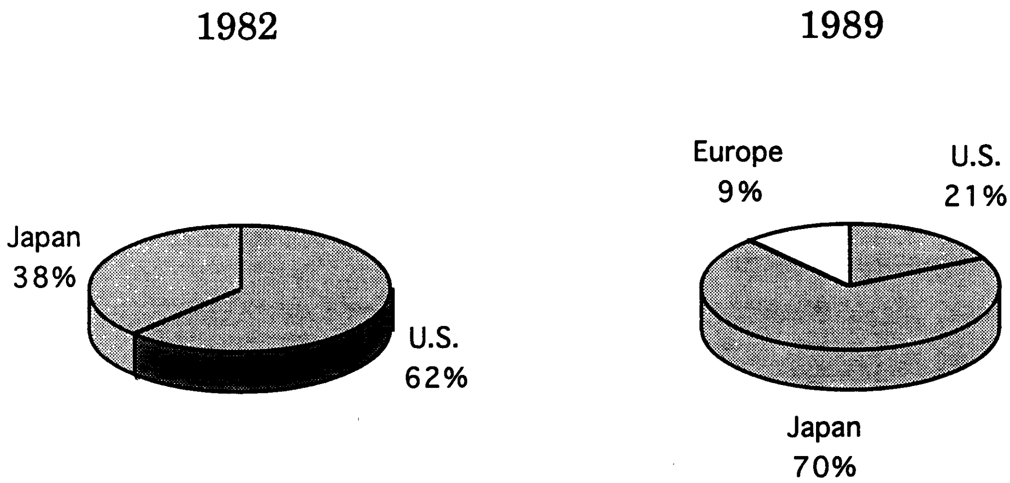
4 Nikon is formally named Nippon Kogaku K.K.. It's common nameplate is Nikon and its U.S. Subsidiary is named Nikon Precision, Ltd.
5 Global Competitiveness . . .,Prev.cited.
6 *The Japan Economic Journal*, July 2, 1985 p.17.

Global Lithography Equipment Market Share Percentages by Supplier Origin



Source: VLSI Research, Inc.[7]

FIGURE 2.1

Top 5 Ranking Lithography Equipment Suppliers World-Wide Market Share

	1982	Market Share
#1	Perkin-Elmer (U.S.)	32.6%
#2	Canon (Japan)	15.8%
#3	Nikon (Japan)	13.5%
#4	GCA (U.S.)	10.4%
#5	Eaton (U.S.)	5.6%

	1989	Market Share
#1	Nikon (Japan)	37.9%
#2	Canon (Japan)	24.1%
#3	GCA (U.S.)	9.3%
#4	ASML (Neth.)	8.8%
#5	SVGL *(U.S.)	5.8%

* SVGL was formerly Perkin-Elmer

TABLE 2.1

7 Global Competitiveness . . ., Prev.cited.

Hype, Fear, & Rage within U.S. Political Circles

The clear shift in market leadership of lithography technology was quickly identified as another story in the legacy of losing a vital sectors of U.S.-born technology to the Japanese. Then it became an issue of U.S. national security. During the heights of the cold war, semiconductor technology provided the technological basis for America's qualitative lead in nuclear missiles, precision guided munitions, cruise missiles, surveillance and early warning systems, communications, aircraft, and an assortment of conventional weaponry.[8] The concerns were both of military and economic security. What if, for example, Japanese corporations develop state-of-the-art equipment, would they sell it within the Soviet-bloc? Will they sell such equipment to their competitors in the U.S.? Or will they withhold them? Will the experience gained in equipment manufacturing give them any extra edge in production know-how?

Of course, it wasn't only in the lithography equipment industry were U.S. semiconductor equipment suppliers were being confronted by the competitive Japanese. The hype played up within U.S. political circles lend to supporting government investments into GCA to help them survive in the lithography market and, ultimately, the formation of the U.S. semiconductor customer supplier consortia Sematech in 1988.

However, many fear that money alone will not revive the U.S. semiconductor equipment industry. Robert Graham, CEO of Novellus Systems Inc. believes, "There is enough money in the industry. What it lacks is good management."[9] The truths to Mr. Graham's message becomes quite evident when one delves deeper into the woes of America's lithography equipment industry.

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8 Okimoto, Daniel I., et.al., Competitive Edge: The Semiconductor Industry in the U.S. and Japan (Stanford University Press: Stanford, CA) 1984 p.3.

9 *Electronic Business* "Semi equipment makers: partner or perish," vol.17, no.10, May 20, 1991 p.34.

Hype, Fear, & Economic Planning within Japanese Political Circles

Not without coincidence, it was by equally prevalent hype and realistic fear which drove the Ministry of International Trade and Industry (MITI) to have major headaches about the economic viability of Japan's semiconductor industry. By its wide range of product applications, semiconductor technology is absolutely essential to a spectrum of industries: telecommunications, computers, machine tools, avionics, consumer electronics, and robotics, to name a few. In addition, the rumor that IBM was on its way to launching a one-chip-computer became a rallying force within political circles in Japan and the reference was often made to Commodore Perry's black ships which in 1853 forced Japan to completely change its relations with the outside world.[10] Significant figures within Japan's ruling Liberal Democratic Party (LDP) and MITI made it very clear that to leave the potentially huge Japanese computer industry to the vagaries of the free market would be unwise in the long run. Japan would ultimately be a nation hostage to IBM's technological whims and would hinder Japanese companies' abilities to compete in related technology products, as mentioned.[11]

"We have too many computer makers in Japan to cope with the monster, IBM," said Tomisaburo Hashimoto, a leader of the LDP in 1975, "the reorganization of the computer industry and the establishment of a more unified and more integrated development organization for VLSI technology are urgently needed."[12]

Henceforth, MITI was pressured by the LDP to build support among

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10 Sigurdson, Jon Industry and State Partnership in Japan: The Very Large Scale Integrated Circuits (VLSI) Project (Tryckericentralen AVC: Lund, Sweden) Research Policy Institute, Univeristy of Lund, Sweden 1986 p.61.

11 Anchodoguy, Marie Computer Inc.: Japan's Challenge to IBM (Harvard University Press: Cambridge, MA) 1989 p.3.

12 *Nikkan Kogyo Shinbun*, Tokyo, May 7, 1975 (translation from original).

industry to form a Very Large Scale Integrated (VLSI) Technology Research Association out of the necessity to match IBM's next-generation computer technology. In Japan, IBM was expected then to introduce the "one-chip computer" at the latest by 1980. Therefore, the target technology and time limit was clear from the beginning for MITI and the LDP.[13] As credence to this view, U.S. Federal Bureau of Investigations (FBI) undercover operations disclosed the IBM Spy Incident (IBM *supai jiken*) indicting Hitachi for secret missions in search of IBM computer technology.[14]

Hype and fear of IBM led MITI down a path of an attempt at economic planning and resulted in the now famous VLSI Project.

2.2. THE TIMELY RESEARCH ASSOCIATION: JAPAN'S VLSI PROJECT

The Birth of Engineering Research Associations in Japan

The British research associations of the 1960s and 70s served as an inspiration and role model in certain aspects of Japan's similar policy instrument - the engineering research association (*kogaku kogyo gijitsu kenkyu kumiai*). The father of Japan's evolving engineering research associations (ERA) was a Dr. Masao Sugimoto, director of the Mechanical Engineering Laboratory (MEL, 1953). Dr. Sugimoto had the opportunity to tour facilities in the U.K. during his tenure at MEL and was instrumental in the formation the first ERA to improve automotive radiator technology in 1955.[15]

However, Japan's engineering research associations evolved to be much

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13 Sakakibara, Kiyonori From Imitation to Innovation: The Very Large Scale Integrated (VLSI) Semiconductor Project in JapanAlfred P. Sloan School of Management Working Paper 1490-83 (M.I.T.: Cambridge, MA) October 1983 p.16.

14 Anchordoguy, prev.cited.

15 Sigurdson, p.12.

different that the U.K. role model. Law providing the means for government involvement and setting limits to engineering research associations in Japan were formulated in 1961. Most notable early example was the camera association created soon thereafter in 1962. At the time many of the organizational ideas were borrowed from the Scientific Instrument Research Association (SIRA) in the U.K. The differences in the structure of the Japanese ERA system was two-fold:

1. Company membership was generally on average 12-17 companies during the 1960s and 70s.
2. None of the ERAs in Japan were permanent organization and rarely lasted more than six years.[16]

Initially the camera association did not have its own research laboratory and the research was done at universities and in member companies. A Japan's camera technology had in 1955 already reached the level of manufacturers in West Germany and it was necessary to move into new technological fields. There was a realized need for the camera makers to introduce the use of electronics and plastics in order to compete more efficiently in the world market. Overall, the camera association provided the technological basis for continuous improvement for the manufacture of cameras and is seen as an outstanding success. Member companies naturally included Nippon Kogaku K.K. (Nikon), Canon, Olympus, Konishiroku (Konica), Fuji Films and others.[17]

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16 Sigurdson, p.23.

17 Sigurdson, p.20-22.

MITI clarified that engineering research associations had four main benefits to Japan:

1. Risk-sharing and cost-sharing between participating units
2. Pooling of resources to speed-up the research process and eliminate overlap
3. A comprehensive research approach which means that resources are pooled both horizontally and vertically through to marketable products
4. Exchange of information which raises the technological level through the relevant system of an industrial sector.

Since the enactment of the engineering research association law in Japan some thirty ERAs had been established up until 1976. These ERAs included everything from automotive components, cameras, to electric power systems. Then came the Very Large Scale Integrated (VLSI) Technology Research Association (code named the VLSI Project).

Struggles in the Formation & Organization of the VLSI Project

At the onset Japanese companies were unhappy with the assertions that they couldn't be competitive in the world market. The rivals Hitachi, Fujitsu, Toshiba, Mitsubishi and NEC were clearly from different roots and competitive groups within Japan. MITI was also skeptical of the results of a massive joint effort aimed at developing VLSI technology and anticipated strong resistance from the semiconductor companies. However the political powers within the LDP persisted.[18] Although with much grumbling, all five companies agreed they could not help but to follow the "bureaucrat's blueprint" if they were to get

[18] Sakakibara, p.4.

any government subsidies.[19] Cases of such allegiance to cooperate with government authority by the Japanese dates back to an era of Workmen's Guilds during the Tokugawa Period.[20]

Thus, during the four year project, an average of ¥17.5 billion ($72 million)[21] was invested annually, roughly 50% of which came from MITI. Ironically, nearly a quarter to a third of the projects money was spent in the U.S. to purchase the most advanced semiconductor manufacturing and test equipment from U.S. suppliers.[22] It is important to keep in mind, however, that annual research expenditures on the order of $72 million is not an overwhelmingly large amount. Leading U.S. semiconductor manufacturer's R&D spending independently in 1977 was $96 million by Texas Instruments, $110 million by Motorola, and $44 million by Fairchild Camera & Instrument, for example.[23]

Once the VLSI Project was established, the unrest between companies in the association still prevailed. The first year was a tough time for the companies to negotiate where the cooperative research laboratory would be located and agreeing upon what research the consortia would do jointly. It is important to note that the Japanese social imagery of working harmoniously together and avoiding confrontation does not apply in this case. The strict social hierarchy was lost once researchers stepped out of their home companies and had to negotiate with competitors in the market.

The VLSI project's first chairman of the board was Hitachi's president,

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19 *Asahi Shinbun*, Tokyo, July 16, 1975 (translation from original).

20 Takekoshi, Yosoburo The Economic Aspects of the History of the Civilization of Japan (MacMillan Co.: New York) vol.3, 1980 p.242.

21 At the 1975 exchange rate of ¥243 = $1.

22 Sakakibara, p.14.

23 *Business Week* July 3, 1978 p.76.

Hirokichi Yoshiyama and the managing director was a retired MITI bureaucrat, Masato Nebashi, who had much experience in managing national projects as an executive official.[24] Nebashi's appointment is exemplary of the Japanese system of *amakudari*, "decent from heaven." Some 300 bureaucrats annually join the ranks of the business world as directors or senior advisors of corporations they monitored during their government career, most typically from within the Japanese ministries.[25]

Eventually the 100 researchers brought together under one roof developed a sense of cohesion and began to make significant research advances. The leadership of Mr. Nebashi has been frequently cited as playing a critical role in helping the researchers to communicate and function as a group

"What I did was the typical Japanese way: All I did for this four years was to drink with them as frequently as I could. I wanted to understand their complaints on those occasions and tried to eliminate problems," says Nebashi.[26] Researchers characterized Nebashi's leadership as traditional "management by whisky."

The Intangible, Unexpected Results of the VLSI Project

If the objective of the VLSI Project was to be capable of building a one-chip computer like IBM by 1980 then the project failed miserably. Although, it is important to keep in mind that, even to this very day in 1994, neither IBM nor any other company has built a one-chip computer. However, if the objective was for these Japanese companies to understand and develop state-of-the-art semiconductor process technology to manufacture the ultimate one-chip

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24 Sakakibara, p.22.

25 Van Wolferen, K. The Enigma of Japanese Power (Knopf: New York) 1989 p.45.

26 Nebashi, Masato *"VLSI kaihatsu - kyogo gosha ni yoru kyodo project no yonen kan* (Developing VLSI - A four year project of competitive firms)" *Management*, Tokyo, November 1980, p.60. Reprinted in Sakakibara.

computer, should it ever be designed, then the VLSI Project was an extraordinary success.

It was clearly decided during the first year of the VLSI Project that circuit design development would not be included in the joint effort and each company eventually established independent pilot production lines. As a result much of the effort taken by the consortia concerned improving manufacturing processes.[27] The expertise of Japan's *zaibatsu* groups in absorbing new technology and refining manufacturing techniques has been Japan's forte ever since the ship engine yards of Pre-World War II.[28]

Six research teams eventually evolved within the VLSI Project and included MITI's Electro-Technical Laboratory (team leaders in parenthesis):[29]

1. Lithography Technology	- electron beam	(Hitachi)
2. Lithography Technology	- x-ray source	(Fujitsu)
3. Lithography Technology	- optical beam	(Toshiba)
4. Crystal Technology		(ETL)
5. Processing Technology		(Mitsubishi)
6. Testing & Devices Technology		(NEC)

The associations three groups in lithography technology are cited as the most important and had the most profound effect upon Japanese equipment suppliers outside of the joint research project, namely Nikon and Canon.[30]

27 Okimoto Competitive Edge: . . ., Prev.cited.

28 Johnson, Chalmers MITI and the Japanese Miracle: The Growth of Industrial Policy, 1925-1975(Stanford University Press: Stanford, CA) 1982.

29 Sakakibara, p.18.

30 Sigurdson, p.119.

The Impetus for Japan's R&D Interests in Lithography

Before the VLSI project started in 1976 Japanese semiconductor manufacturers were exclusively dependent on U.S. equipment suppliers. Thus in the past, Japan could only develop its industry in step with the U.S. industry and was perpetually trailing the development of their U.S. competitors. Apparently, the Japanese semiconductor industry sector realized that in order to innovate and be competitive is was also necessary to develop and manufacture its production equipment domestically.

Proximity/projection aligner lithography equipment was already under development within Canon before the conception of the VLSI Project in 1976. As previously noted, stepping aligner lithography was seen as the up-and coming technology whose market was exclusively owned by GCA in the 1970s. This could have been acceptable, however Japanese semiconductor companies were dissatisfied with the performance of GCA's equipment and the unresponsiveness of GCA to their needs. A former executive of GCA recounts the story most vividly:[31]

> By 1980, from the Japanese perspective, the GCA 4800 Stepper was becoming unreliable in its performance, had low throughput, was difficult to operate, and suffered large amounts of downtime. By 1980,...Japanese [customers] departed from the concept of purchasing systems based on acceptance criteria established by U.S. semiconductor manufacturers. [They] began to demand systems based on performance criteria established by Japanese manufacturers. This was a very important change in attitude. GCA was aware of this change but was not responsive to these demands. It believed systems acceptable to U.S. manufacturers should continue to be acceptable to Japanese manufacturers... Further, it was noted by [Japanese] users that GCA was expending too much of its resources to treating reliability problems rather than solving them.

31 Global Competitiveness... USITC Publication 2434, p.4-10.

Desiring to be self-sufficient and with an initial sense of GCA's woes, MITI tapped the shoulder of Nippon Kogaku K.K. to get into the stepper business in the late 1970s. The camera business was maturing and the company quickly agreed.[32]

Japan's Trademark: Incremental Process Improvements

Choosing to concentrate on semiconductor process development may have been the smartest move the VLSI Project members made. While innovative changes in semiconductor technology was bound to continue, although possibly at a reduced rate, the basic integrated circuit manufacturing process was not apt to change radically in the foreseeable future. As statistics of Japanese semiconductor manufacturer performance through the 1980s clearly indicate, mastery of process technology was the most essential requirement for competitive semiconductor production. Advances in manufacturing processes have been largely dictated by the requirements of further circuit miniaturization, improved reliability, operating speed and performance, and lower energy consumption in successive generations of semiconductor devices.[33]

Historically it is proven that "continuous process improvement" is Japan's trademark in international business circle. Case studies have endlessly documented quality circles (QC) and related management methods creating unparalleled successes in the Japanese automotive industry. Although less dramatic than new product design but no less commercially, process improvements tend to be incremental in nature, but the cumulative value is often great. With the right circumstances it can spell the difference between success and failure in the marketplace.

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32 *Forbes* "Ruined for one, Ruined for all?" vol.137, no.7, April 7, 1986 p.88.

33 Sigurdson, p.69.

As for semiconductor lithography equipment, the situation is no different. Given their apparent technology prowess but weakness in optimizing the equipment for manufacturing applications, GCA's weakness were Japan's characteristic strength. By this basic formula Nikon and Canon reaped significant gains in the worldwide lithography equipment market.

The Amazing Match of Nikon's Core Competencies to the Market Opportunity

For both Nikon and Canon it was possible to identify three technologies necessary for success in developing lithography equipment: optical technology, precision mechanical technology and electronics. A critical factor which led the consortia companies to seek Nikon and Canon's involvement in the VLSI Project was the need for state-of-the-art optics in lithography. Optical engineers in Japan in fact were only found in optical companies. Consequently, integrated circuit (IC) makers do not have an easy access to optical engineers and have been and still are dependent on optical companies.

Nikon, in particular, was invited to develop stepper lithography equipment because it already had two vital technologies internally: high-resolution lenses, which it has been grinding for medical microscopes since 1925, and exquisitely precise controls for observatory telescopes.[34] In contrast, when it came to advanced electron beam and x-ray lithography techniques the semiconductor makers, had the technical skills within their divisions. This was especially true in the case of Toshiba and Hitachi.

Canon's Innovative Corporate Culture Provides an Early Lead in Development

Originally, Canon was in a less favorable position to enter the lithography equipment market compared to Nikon. Canon did not have the required in house competence in high-precision mechanical technology but was clearly driven harder by the entrepreneurial spirit than was the case at Nikon. Canon

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34 *Business Week* "Nikon Doesn't Mean Just Cameras Anymore" June 15, 1990 p.106.

had dabbled in the lithography business as far back as 1968. Jon Sigurdson provides the most succinct story of Canon's history:[35]

> The early origin of Canon's entry into the new field was the desire of printing companies to have high precision lenses for making photomasks which were ordered by the IC-makers. At Canon it was realized that the demand for lenses would considerable expand if the company could capture the lens market not only for photomasks (*shashin seihan*) but also for aligners. Thus it was decided to make 1:1 projection aligners as well. In 1970 the Micron Project, inside Canon, was established in order to handle the development of aligners. The main purpose of this project was to develop micro-precision technology. The company engineers initially had great difficulty with the mechanical technology as the camera technology was not sufficiently precise.

Nikon & Canon's Limited, yet Significant Involvement in the VLSI Project

In contrast to Canon, Nikon began an entirely new development in lithography steppers in 1977 to cooperation with the VLSI Project. Although Canon also worked in association with the VLSI Project but was assigned the task of further developing the older lithography method called projection alignment that it had been manufacturing since the early 1970s. Canon had hoped to simultaneously develop the projection aligner and start new development in steppers. Manpower was lacking and the company decided to move ahead in optimizing the projection alignment lithography system.

However, it is important to stress that neither was Nikon or Canon formally participating in the VLSI Project nor were there any informal associations with any of the big five participating electronics companies.[36]

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35 Sigurdson, p.86.

36 Sigurdson, p.85.

These "participating" units such as Canon and Nikon were only paid for delivering equipment and services and did not share in the research results nor did they participate in discussions organized within the VLSI Project. These contracts provided a means to start a completely new development within Nikon and stimulated Canon's development process. The benefits of the linkages with the VLSI Project were two-fold:

1. They received very good information about the technology trends and future needs of the IC maker through the demanding equipment specifications requested in the contract.
2. Both companies were essentially guaranteed payment to deliver a prototype lithography machine to the VLSI Project group.

The specifications for the equipment were far more important than the R&D subsidy as the former provided a certification, or verification, that it would pay off to move ahead to develop the new machine. This specifications were clearly the "voice of the customer" and more importantly the voice of five very large customers. Within Canon, for example, 30 engineers had to be allocated to the new project. From a business point of view such an intense development effort would be risky. It would have been difficult to achieve consensus among 30 engineers on the direction of the research inside the company had it not been for clear target specifications provided by the VLSI consortia. In the end, the payment received by Canon for its delivery of the prototype projection aligner covered roughly 1/4 to 1/5 of the total development costs.[37]

Goodwill and Relational Contracting with Lithography Suppliers in Japan

"Some characterize big business as the brain and the central nervous system of Japan's economy. If that is the case, then small enterprise is the

[37] Sigurdson, p.87.

economic, political, and social heart and backbone of Japan."[38] In the case of Nikon and Canon's relationship with the VLSI Project companies this couldn't be more true. How these equipment suppliers became strong market powers in lithography is a clear case example of what has been called "relational contracting."

Evidence of relational contracting with suppliers dates as far back as the Japan's textile industrial development. We could imagine a parallel story occurred with Nikon and Canon as it did with textile suppliers:[39]

> "Look how X got his price down. We hope you can do the same because we really would have to reconsider our position if the price difference goes on for months. If you need bank financing to get the new type of vat[40] we can probably help by guaranteeing the loan."

A similar conversation with Canon could have been:

> Look how Perkin-Elmer improved the alignment accuracy and throughput speed with its new projection aligners. We hope you can do the same because we really would have to reconsider our position if the performance difference continues for the next generation of equipment purchases. Through the VLSI Project, if you need a buyer of your first prototype machine we can probably help by guaranteeing the purchase.

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38 Patrick, H.T. And Rohlen, T.P. "Small Scale Family Enterprises," in The Political Economy of Japan: The Domestic TransformationK. Yamamura and Y. Yasuba eds. (Stanford University Press: Stanford) vol.1, 1987 p.333.

39 Dore, Ronald "Goodwill and the Spirit of Market Capitalism" *The British Journal of Sociology* vol.34, no.4, 1983. Reprinted in D. I. Okimoto and T. P. Rohlen, eds. Inside the Japanese System: Readings on Contemporary Society and Political Economy (Stanford Univ. Press: Stanford) 1988.

40 vat = a machine commonly used in the textile industry

It is plausible to make such assertions based on a multitude of further case studies in the automotive industry, for example relations between Toyota's purchasing manager and the managers or owner-managers of sub-contracting firms.[41] Accounts of Nikon's development of lithography steppers also gives credence that such type of relational contracting existed:[42]

> "What [Nikon] did is . . . looked at what GCA was doing and took the machine, tore it apart, learned it . . . Then they put their first prototype together and it was a very lousy machine. But the semiconductor manufacturers in Japan didn't say it was a lousy machine. They said 'let's see what we can do to help you make it better.' So they put it in a semiconductor factory . . . right next to GCA and they started figuring out which one is good and which one is bad and what are the advantages and disadvantages. And they ... [used] it over a three to four year period. . . The machine in Japan became better than GCA."

Subsequently, Nikon entered the lithography stepper market in 1981 and captured 20% of the market in Japan the first year. With unexpected success Nippon Kogaku K.K. invested ¥4 billion to set up a dedicated stepper manufacturing line in February of 1982.[43] By 1984, Nikon had captured 60% of the Japanese market for lithography steppers, compared to 30% of GCA. The image of technological supremacy of Nikon's product in Japan over that of GCA can thus be appreciated. The stepper relied ultimately on the craftsman's skill in the final polishing of the lenses which form the heart of the

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41 Dore, Ronald, prev.cited.

42 Global Competitiveness... USITC Publication 2434, p.4-10.

43 Kishimoto and Kitahara "Perspectives on the Semiconductor Manufacturing Manufacturing Equipment Industry - Case Studies" *Japan Semiconductor Technology Reports* vol.1, no.2, Autumn 1985.

device. Nikon carries out everything from lens production to manufacturing of the focusing control equipment in-house, whereas, at the time, GCA had to purchase lenses from outside.

Relational Contracting on the Supplier-Subcontractor Level: Ushio Denki

Often when one thinks of customer supplier relations within Japan the image of a monolithic, interwoven vertical groups known by the code word, *keiretsu*. However the pyramidal structure of sub-contracting networks within keiretsu groups is a somewhat caricatured description, which is becoming increasingly inappropriate as more subcontractors cross group boundaries, often with their patron companies encouragement, to serve more than a single customer company. This is definitely the case for the lithography equipment suppliers Nikon and Canon.[44]

Even one level deeper is an example case study of ultra-violent lamps, the light source for lithography equipment, supplied by Ushio Denki, a supplier under Canon since the 1960s. A further effect of the contract with the VLSI project was that Canon and Nikon, in turn, give a substantial development contract to Ushio Denki to develop the highly specialized ultra-violet lamps needed in advanced lithography equipment. Canon together with Nikon encouraged Ushio Denki to develop the light source. However, there was no formal contract - only a gentlemen's agreement.[45] This was a large market opportunity for Ushio Denki to manufacture aligner lamps, largely because it was anticipated that the ultra-violent lamps would need to be replaced every month for every machine which used them.

By 1986, Canon, Nikon, Hitachi, and even GCA were using the Ushio Denki

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44 Sako, Mari "Partnership between Small and Large Firms: The Case of Japan," paper prepared for the Commission of the European Communities Conference on Partnership Between Small and Large Firms, Congress Centre, Brussels, June 1988.

45 Sigurdson, p.96.

lamps in their lithography equipment. Due to design differences, Perkin-Elmer was using lamps from an alternate supplier in the U.S. Although an important component of the lithography machine, their was nothing precluding Ushio Denki from serving market opportunities in Japan, U.S. or Europe for its lamp technology. This case parallels the similar experiences of Nippon Denso in the automotive industry. Having developed expertise in electronic, computer controlled engine distributors, Nippon Denso leveraged itself outside of it's original partner, Toyota, to serve the world market.

Technology Targeting and Market Control: The Myth of "Japan, Inc."

The original hype and fear in American political circles as Nikon and Canon captured more and more of the world lithography equipment market was simple: Here comes Japan, Inc. out to conquer yet other market segment. The elementary flow in the Japan, Inc. metaphor has always been that it evoke images of a "smoke-filled boardroom where deals are made and conspiracies are hatched for economic conquest."[46] Certainly in the case of lithography the metaphor is further misleading. The loose connections between semiconductor manufacturers and lithography suppliers demonstrate that no single body had a master plan. Although it can't be denied that the VLSI Project accelerated the capabilities of Canon and Nikon, it wasn't clearly the objective of the VLSI members to create and subsequently dominate the world lithography equipment market.

Being fierce competitors since the camera wars, Canon wasn't going to allow Nikon to enjoy the full benefits of their new market either. Independently, Canon development and brought to market a competitive lithography stepper in June 1983. The rivalry within Japan made competition with GCA and Perkin-Elmer a side interest.

Keeping in mind that: "Companies, not societies, compete for markets; companies, not governments, trade; and in the end it is companies that

46 Van Wolfren, K. The Enigma of Japanese Power (Knopf: New York) 1989 p.48.

prosper or stagnate - in Japan, as well as in the United States or Europe."[47] MITI, the LDP, nor the VLSI Project member companies anticipated such a successful development in optical lithography. In addition, it's unlikely that they could have orchestrated such an effort if they truly wanted. When one analyzes Japan's political structure it becomes apparent that their really isn't a leader of the system. van Wolfren best characterizes and traces this state of Japanese decentralized politics back to the Meiji-era of feudal lords: "If the source of real power is unclear, it will also be unclear how to attack it."[48] Had Japan's Prime Minister the similar political power as a U.S. President or French Prime Minister it is believed that deal with political and trade issues in Japan would be so much easier than they are, even today.

As well, on the corporate level, Japan's legacy of cross-share holding interests doesn't apply to Canon or Nikon. Both suppliers have stocks which are owned by multiple big business groups on the order of 3-6%. However, all of their major stocks are held by financial institutions from Japan and Europe (Chase Manhattan - London - owns 1.9% of Nikon). None of these share holding relationships are with their semiconductor customers.[49]

2.3. DECADE OF CHANGING TIDES IN THE LITHOGRAPHY MARKET

Japan as an Inappropriate Role Model for Korea

When Korea's semiconductor industry came on-line in the 1980s Nikon dominated the lithography equipment market shares in Korea. Korea had followed Japan's lead to enter the dynamic random access memory (DRAM) market. A market which Nikon's equipment had by that time been optimized

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47 Anchordoguy, Marie Computers Inc.: Japan's Challenge to IBM (Harvard Univ. Press: Cambridge) 1989 p.12.

48 Van Wolfren, p.28.

49 *Kaisha Shiki Ho* (Company Quarterly Report) "Company Profiles" Tokyo 3Q1993.

to manufacture high-volume memory chips.[50]

After years in the semiconductor business, Korean companies had growing pains. Sponsoring a symposium in Silicon Valley, CA (U.S.A.), representatives of about 50 Korean companies highlighted the growing disparity between Korea's emergence as a major player in chip production and its over dependence on foreign equipment technology.[51] Significant differences in political economic structure and history precludes Korea from following Japan as a role model for developing their own basic semiconductor equipment industry.

Opportunities for the Next Market Power Shift in Lithography Equipment

Today, industry standard manufacturing has come down to the 0.35 micron circuit pattern line level. It is believed optical techniques in lithography have reached their technological limits. As circuit linewidths become smaller and smaller the opportunity for revolutionary changes in lithography for semiconductor manufacturing exists. For 0.18 micron and below optics may give way to x-rays and/or electron beam technology. Canon and Nikon will have to acquire new core competencies and knowledge of eventually have their market prowess replaced by keen U.S. companies looking to recoup historic pride or possibly by the Koreans, in a long-shot. Innovation and competitive pricing will be the mold for next-generation lithography equipment.

New Age of ERAs within Japan: The Super Silicon Crystal Project

Lessons from the VLSI Project, among a multitude of others, and the ever present trade friction with the U.S. has significantly influenced the nature of MITI's modern engineering research associations in Japan, as exemplified by

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50 *Electronic Business* "Canon challenges Nikon's lead in Korea," May 20, 1991 p.68.

51 *Electronic News* "Korean Firms Woo U.S. Fab Gear Makers," September 19, 1994 p.64.

the Super Silicon Crystal (SSi) Project. Japan confronts a very different challenge in the SSi Project. It's no longer a story of catching-up with competitor technology, it is about sharing R&D costs among small suppliers, incrementally improving bulk-silicon process technology, establishing a world wide industry standards for silicon wafers, and opening the door for participation by foreign companies, for example in the U.S. and Europe.

Eleven SSi companies will establish a large diameter (400 mm, compared to today's industry standard 200 mm) wafer development company in Tokyo, spending ¥18 billion over 7 years, beginning in the Spring of 1995.[52] MITI has learned that coordinating supplier companies in pre-competitive technologies is viewed with less trade conflict internationally, especially if U.S. firms are involved. In addition, by sponsoring the research effort on Japan soil, MITI assures the technical capability will remain, and most likely flourish, among Japanese supplier companies. The advancement of supplier companies has been the success story of Engineering Research Associations ever since their inception by the Mechanical Engineering Laboratory's director, Dr. Masao Sugimoto, when he visited the U.K. in 1953.

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52 *Solid State Technology*, vol.37, no.10, October 1994 p.16.

Chapter 3

Corporate Equipment Sourcing Strategies to Minimize Capital Expenditures while Maximizing Supplier Switching Flexibility

Note

Imbedded with the text are five digit codes which references information attained in the process of interviewing managers in the semiconductor industry. See appendix 4.2. for a sample set of interview questions.

3.1. Equipment Criticality: Lithography as the Competitive Technological Driver of the Semiconductor Industry

Consumer demand for faster, cheaper electronics and computer systems is the key driver for the semiconductor industry. This phenomena is most clearly illustrated in the microprocessor (MPU) market. Driven by continued strong PC shipments, worldwide sales of 16- and 32-bit microprocessors have doubled in just two years and topped $10 billion in 1994, according to the Semiconductor Industry Association (SIA).[53] The underlying, enabling technology feeding consumer demand is the incremental improvements in lithography manufacturing equipment capabilities.

Indirectly, when the consumer desires to purchase a 100 MHz over a 66 MHz Pentium™ Processor they are telling Intel: "I want to buy 0.5 µm generation lithography technology, not 0.7 µm generation lithography technology!" In a similar fashion, when you take your car to the gas station to buy 92 Octane instead of 86 Octane gasoline you're telling Shell Oil Co.: "I want to buy the latest fuel formulation technology, not a two generation old fuel technology." In both cases your computer still performs the same functions and your car will get you to your destination. Increasingly consumers are always seeking to buy better, smaller, faster, cheaper electronics.

Sampling the industry's leading microprocessor manufacturer's, the performance metrics most important to the customer are: faster processor speeds (Megahertz, MHz), system software compatibility, lower price, and minimum power consumption. (11004) With the exception of system software compatibility being dictated by microprocessor design, being competitive in the customer's eyes means pushing lithography technology to the smallest linewidths with minimum mask overlay tolerances. Likewise in commodity memory product markets, for example dynamic random access memories (DRAM), the overriding customer pleasing metric is low price.

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53 "SIA Cites '94 MPU Sales Explosion," *Electronic News*, April 10, 1995, p.48.

Microprocessor Clock Speed & Power Requirements Driven by Lithography

Linewidth is the *primary* driver of progressively faster microprocessors. The speed of a microprocessor is determined by the speed of the six million transistors incorporated, which is ultimately determined by each transistor's gate width. Consider the Intel Pentium™ microprocessor as an example. The first generation 60 MHz Pentium processor was manufactured using 0.8 μm level lithographic technology. Process refinements on the same lithography equipment technology allowed Intel to bring actual linewidth critical dimensions (CD) closer to 0.7 μm.[54] By tightening lithographic processes Intel was able to introduce the 66 MHz Pentium. Speeding up the transistor is a necessary and sufficient condition for small, 5-10%, changes in the microprocessor's frequency response (MHz). (21007)

However, in creating the 90 MHz Pentium, merely shrinking the transistors by using next generation 0.5 μm lithography equipment is a necessary but *not* sufficient condition. Signal timing, keeping all the components in-phase with each other, requires a complete redesign of the Pentium processor. The benefits are a 50% speed improvement over the original 60 MHz and 36% faster than the 66 MHz.[55] Once again, Intel realized roughly an additional 10% clock speed improvement through refining the 0.5 μm lithography process to create the 100 MHz Pentium.[56] This cyclic clock speed improvement of Pentium processors will continue for the 0.35 μm generation products introduced in 1996, as in Figure 3.1.[57]

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54 0.7 μm is a rough estimate of the linewidth CD, exact dimensions are rarely released publicly.

55 Disclaimer: The real-time speed of the computer the end-user realizes is not equivalent to the increased microprocessor clock speed (MHz).

56 Intel typically identifies this as 0.6 micron technology. What CD a manufacturer uses is not necessarily equivalent to the technology generation identifiers used in the industry.

57 "Intel Offers Some Peeks in Products, Production," *Electronic News*, April 3, 1995, p.2.

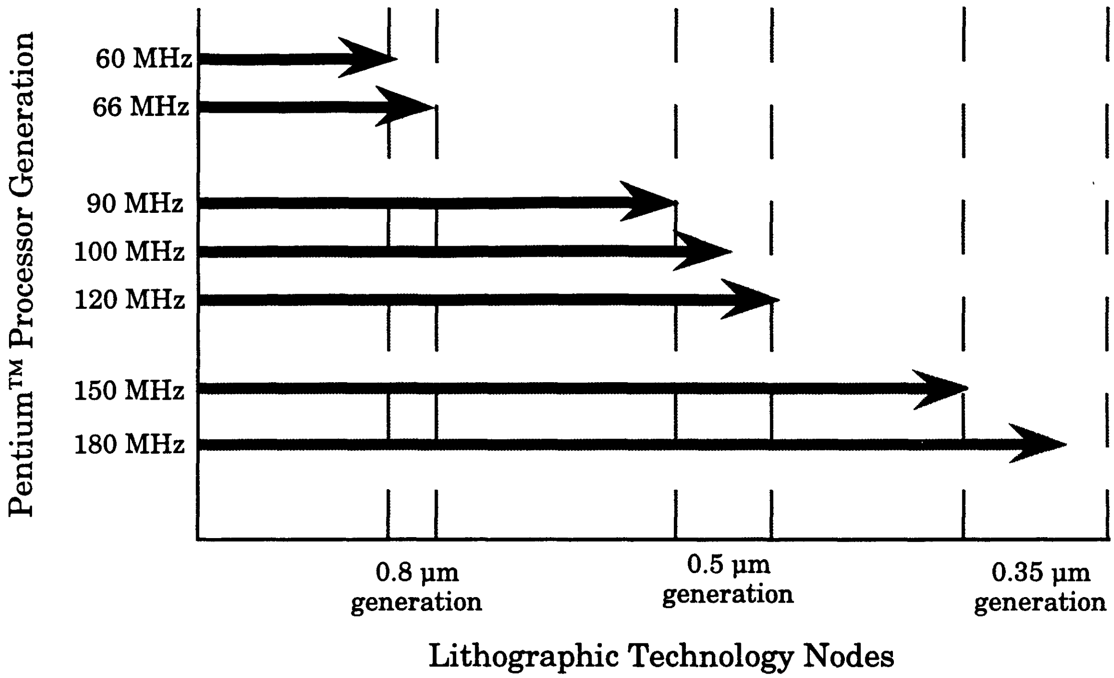

FIGURE 3.1

Charting the progression of Motorola-IBM PowerPC, Digital Alpha, TI SPARC® and AMD's K5 would reveal similar correlations between microprocessor clock speed and lithographic technology improvements. In fact, microprocessor manufacturers are increasingly competing based on their ability to shrink lithographic dimensions. It is this competitive atmosphere motivating companies like IBM to invest in 0.25 µm and 0.18 µm lithography technology research and development. IBM's objective: *To attain competitive leverage in their products, something that IBM would have that the rest of the world wouldn't have for some period of time.* For example, when the PowerPC first came into the market its process technology was a generation more advanced than what Intel started on the Pentium. Motorola and IBM began marketing advertisements in the Wall Street Journal and press nationwide emphasizing technological superiority of the smaller, faster PowerPC.

In addition to increased processor clock speeds, the transistor shrinkage provides for lower operation power, thereby shrinking the size of the heat sink, computer cooling systems, and energy requirements. Factors customers such as Compaq and Dell like to see in competitor microprocessor products. From a technology standpoint during the 486 generation, Advanced Micro Devices (AMD) originally offered smaller, cheaper, and less power-hungry microprocessors than Intel. Essentially all the market players are using Complementary Metal-on-Silicon (CMOS) design rules and confronting the same technological barriers to advancement. AMD had been able to leverage the unique capabilities of its lithography equipment supplier, ASM Lithography, to manufacture microprocessors with tighter mask overlay alignment tolerances. Although the linewidth CD may have been similar, with better overlay accuracy AMD could pack transistors more closely together providing for a smaller chip.

One prominent, high-speed microprocessor manufacturer's experience best illustrates the importance of alignment accuracy in lithography equipment:

> "With the general trend that you shrink your linewidth, you shrink the overlay by the same amount -- we spent an extra $120,000 for a stepper to make sure and get overlay from 125 nm to 105 nm. It's very critical." (22044)

Leveraging Lower Manufacturing Costs through Lithography

Pushing the limits of lithography stepper equipment is the norm among leading-edge semiconductor manufacturers. The way to make the lowest cost product is to push your lithography as hard as you possibly can. Shrinking the chip die size ten percent is ten percent of silicon real-estate saved. No other process step can provide this direct savings. If you make your film layers one percent thicker or thinner it doesn't mean anything. (11028) Essentially, using smaller linewidth CD and tighter overlay tolerances provides for smaller die sizes, hence more chips per silicon wafer, hence lower manufacturing costs per chip, and often incrementally improves process yields. In Figure 3.2 a model $1\frac{1}{2}$" silicon wafer illustrates how a smaller die size increases the number of chips per silicon wafer.

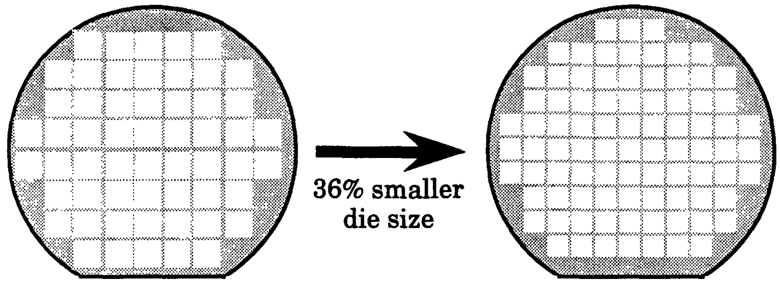

Illustration of die size shrinkage relationship
to number of chips per silicon wafer

FIGURE 3.2

DRAM devices have been the drivers of the most advanced lithography technology for years because of this basic premise: the smaller the chip, the more chips per wafer. The wafer process unit cost doesn't change based on the number of chips on it. If IBM could produce a 10% smaller DRAM chip than Samsung then IBM's cost is potentially 10% less than Samsung's. Overall, costs per bit for new DRAM generations have remained competitive because of the shrinkage associated with each lithographic technology jump. DRAMs have seen a 4X bit-count increase per generation (4X/gen), from 1 Mb → 4 Mb → 16 Mb. In each generational jump 2X/gen has come from lithographic scaling down and 1.5X/gen from chip size increases. The remaining 1.3X/gen has been gained from cell size reductions and architectural advances.[58]

[58] *The National Technology Roadmap for Semiconductors* (Semiconductor Industry Association (SIA); San Jose, CA) December 1994, p.16.

Lithography Capital Equipment & Manufacturing Costs

Semiconductor manufacturing is a high technology business and being on the cutting-edge is an expensive venture. During the 0.5 µm lithographic generation semiconductor manufacturers paid between $2.3 - $3.0 million for each i-line stepper in their factory. An i-line stepper for the 0.35 µm generation technology is comparably around $3 million. Those semiconductor manufacturers which venture into the newer deep-ultraviolet (DUV) lithography equipment expect to pay roughly $3.6 - $4.2 million per machine. (51132) This typifies the escalation of capital equipment costs prevalent in the semiconductor industry at this time.

Overall, a flourishing semiconductor company's capital equipment expenditures average 25% of annual revenues, unprecedented by any other industry.[59] Comparing the capital expenditures with the revenues of semiconductor manufacturers clearly illustrates the extent of the industry's investments, Table 3.1 and 3.2. Lithography equipment represents nearly a third of any given semiconductor company's capital purchases.

SIA's 35% figure is frequently cited as the proportion of the industry's capital costs dedicated to lithography technology.[60] Functionally, lithography in the semiconductor manufacturing world includes metrology, scanning electron microscopy (SEM), tracking systems, as well as stepper equipment. A 0.5 µm generation, 5000 wafer starts-per-week (WSPW) volume fab has grown to become a $1 billion investment. Capital equipment is about $500 million, with the lithography function costing ~$165 million with 30 sub-systems. Henceforth, roughly 33% of capital equipment costs are for the lithography function. Independently, lithography stepper equipment is estimated to be more on the order of 15-20% of capital equipment costs for a new fab. (12040)

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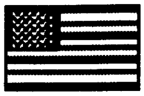
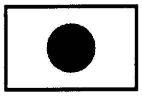
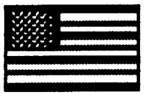
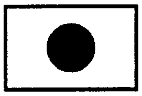
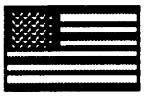
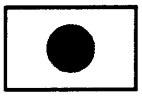
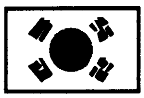
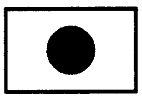
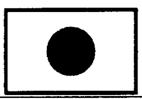
59 "Intel Tops VLSI Research Rankings; Korean Vendors Growing Fast" *Electronic News*, November 14, 1994, p.80.

60 *The National Technology Roadmap for Semiconductors*, (SIA; San Jose, CA) December 1994, p.81.

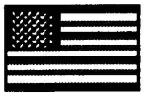
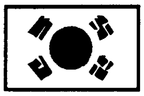
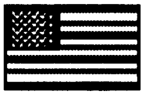
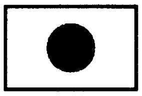
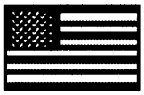
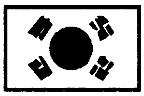
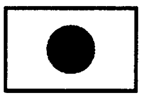
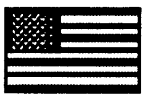
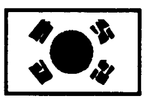
Top-Ten Merchant Semiconductor Manufacturers
(worldwide sales in $M)

1994 Rank	Flag	Company	1994E Revenues
1		Intel	11682
2		NEC	7731
3		Motorola	7113
4		Toshiba	7025
5		IBM	6075
6		Hitachi	5852
7		Samsung	5743
8		Texas Instruments	5337
9		Fujitsu	3685
10		Mitsubishi	3528

Source: VLSI Research Inc.

TABLE 3.1

Top-Ten Merchant Capital Spenders
(worldwide purchases in $M)

1994 Rank	Flag	Company	1994E Capital Expense
1		Intel	2839
2		Samsung	1544
3		Motorola	1309
4		Fujitsu	981
5		Texas Instruments	902
6		Hyundai	695
7		NEC	694
8		IBM	678
9		Toshiba	639
10		Goldstar	595

Source: VLSI Research Inc.

TABLE 3.2

Of course, not everyone is building $1 billion scale fabs. Nonetheless, in terms of cost criticality, manufacturers concur that photolithography is the single largest manufacturing investment, above and beyond chemical vapor deposition (CVD), etch, or thermal processes. (11011) Fab lines are almost always centered around lithography equipment. Manufacturing throughput is largely determined by lithography throughput, often intentionally.

Extent of Lithography Equipment Criticality to Semiconductor Products

Given the consumer market drivers for faster, cheaper semiconductor devices and the magnitude of capital investments associated, leading-edge manufacturers are pushing the limits of new lithographic equipment capabilities. Particularly in linewidth CD and alignment accuracy, manufacturers of memory and microprocessor devices are operating at 90-100% of the limits of their lithography machine's specified capabilities. A select number of manufacturers track process capability index, Cpk, performance metrics for linewidth CD. (12042)

However, not all semiconductor products, and only a 25% of a given leading-edge product, utilizes the most advanced lithographic capabilities available. Rising equipment costs, and common sense, has semiconductor manufacturer's mixing lithographic equipment from previous generations with the most advanced equipment. For example, among the microprocessor manufacturing companies surveyed, currently about 25% of the lithography equipment on the manufacturing floor is going to be leading-edge, 0.35 μm capable. This implies that roughly 25% of the mask layers for a Pentium, PowerPC, Alpha, or SPARC chip is critical level. (11036)

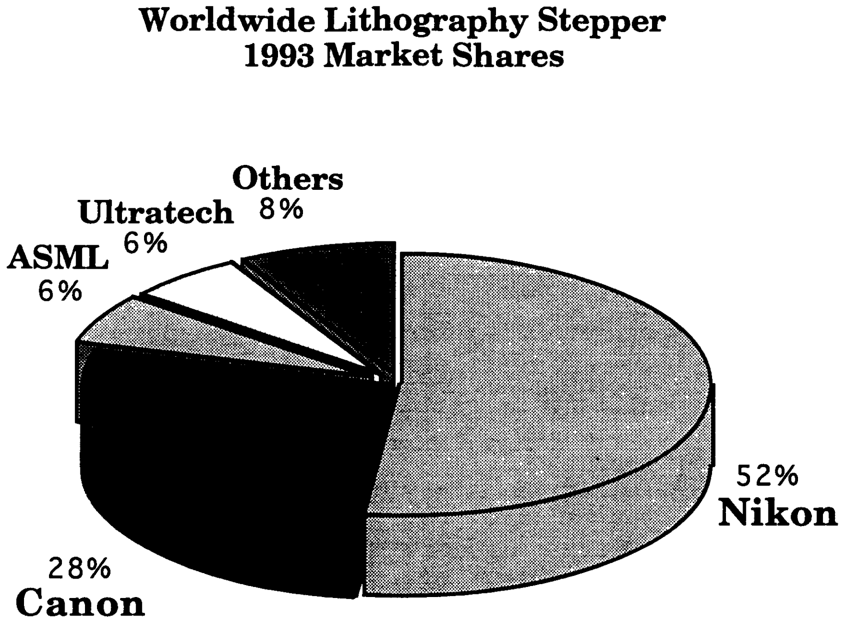


FIGURE 3.3

Limited Supply Base for Leading-edge Lithography Tools

Worldwide there are only four leading-edge suppliers of leading-edge lithography equipment technology: Nikon, Canon, ASM Lithography, and Silicon Valley Group Lithography (SVGL). By leading-edge it is implied that these suppliers are capable of supplying lithography solutions for 0.5 µm, 0.35 µm, and 0.25 µm generations in a timely manner. Figure 3.3 outlines the 1993 worldwide market shares of all optical lithography equipment manufacturers.[61] Nikon has been the market share leader of the industry since the late 1980s. SVGL has been in existence for many years but has only recently become in a competitive position offering lithography equipment to the open market.

61 "VLSI Report -- Special Survey XVII: '93-'94 Semiconductor Manufacturing Equipment and Materials Industry," U.S. Joint Publications Research Service, JPRS-JST-94-035-L, Foreign Broadcast Information Service, 14 July 1994.

Ultratech Stepper, Inc. specializes in ≥ 0.8 μm high-throughput lithography equipment. Ultratech pioneered the concept of mix-and-matching leading-edge lithography equipment with high-throughput equipment for noncritical layers. Since then nearly every lithography equipment supply has followed suit in providing manufacturers a selection of critical-level and non-critical level steppers. Leading-edge suppliers are limited in number by the unique technical capabilities required, driving a high cost barrier for market entry by competitors, as outlined further in section 3.2.

Lithography Criticality in Summary

Lithography is the driving technology for the semiconductor industry. No other manufacturing function provides the leverage to feed customer demands for faster, smaller, cheaper products. No other process step requires nearly as significant a portion of capital equipment and manufacturing costs. CVD, etch, and thermal processes are undoubtedly all essential for fabricating a functional integrated circuit. However, it is having the most advanced lithographic equipment which determines if you are a leading-edge semiconductor manufacturer or not.

3.2. The Make-Buy Spectrum: Industry Focus on Supply Chain Management

Ironically, despite the fact that lithography plays such a central role in semiconductor manufacturing, internal development of lithography equipment technology is practically unheard of today among U.S. semiconductor companies. The locus of lithography knowledge and sources of innovation rests in the external matrix of equipment supplier companies. As a result, the industry relies upon the supplier base for lithographic capabilities.

Semiconductor companies have gradually divested from equipment manufacturing over the last two decades. Surprisingly, lithography equipment was one of the earliest technologies to be out-sourced by manufacturers. The last company in the world vertically integrated to be a lithography equipment developer and a major semiconductor producer was Hitachi. Since the late 1980s, Hitachi has been unable to keep pace with the technological improvements of market leaders Nikon and Canon. In 1993 Hitachi announced that it was freezing development of next-generation equipment and withdrawing from the business. Hitachi's equipment was intended mostly for its own use, and the company has struggled with outside sales. The cost of development has increased with each successive generation and it appears this has driven Hitachi's decision to withdraw from the optical stepper equipment manufacturing. However, Hitachi continues to have significant manufacturing capabilities in electron-beam lithography equipment, plasma and metal etching equipment, and scanning electron microscopes (SEM), just to name a few.[62]

Most U.S. semiconductor companies never even attempted to develop internal capabilities because they never had an impetus to build up an expertise in optical stepper equipment. Lithography suppliers had been always been able to supply industry needs. In the U.S. only AT&T Bell Labs and IBM have retained a degree of lithography technology development knowledge, but have long ago given up the concept of building their own optical lithography equipment. (31021) During the 1970s and prior, semiconductor manufacturers internally made optical exposure equipment called 'aligners' at a time when the industry was young and the supporting technology infrastructure largely undeveloped. By the time the industry transitioned to optical stepper equipment technology no U.S. semiconductor companies had the desire to internally *make* optical lithography equipment.

The two key issues creating a reliance on suppliers: (1) The unique technical expertise necessary for the design and manufacture of lithography equipment resulting in (2) The costs of maintaining lithography equipment technology knowledge and manufacturing capability in-house became prohibitively high for any one semiconductor company to afford. The degree of

62 "VLSI Report --" JPRS-JST-94-035-L, 14 July 1994, prev. cited.

optics design, polishing, and mounting expertise necessary is at a level inapplicable to any other aspect of the semiconductor business. To provide a feeling of the manufacturing capabilities required, from the time the original glass melts it takes three months just to cool the lens with the purity and precision necessary. The weight of the optics in a typical Nikon stepper is nearly 2,000 lbs., including glass plus mounting. The optics for a 22 mm field size requires multiple lenses that are on the order of four feet in diameter, six inches thick mounted in a tube more than three feet high. The stages stepping to each exposure area on a silicon wafer requires nanometer (10^{-9} m) scale tolerances. This extreme precision mechanics capability requirements are found nowhere else in the semiconductor business except lithography.

Nowadays, the costs for development of a new lithographic tool is in the \$50 - \$100 million range.[63] For a company, such as SVGL, with a new tool the market entry fee is more on the order of \$200-\$300 million. Together with the need for engineering support of existing products in the field , it has been suggested that a 20%+ market share is necessary to remain in the business for the long-term.

The Make-Buy Spectrum

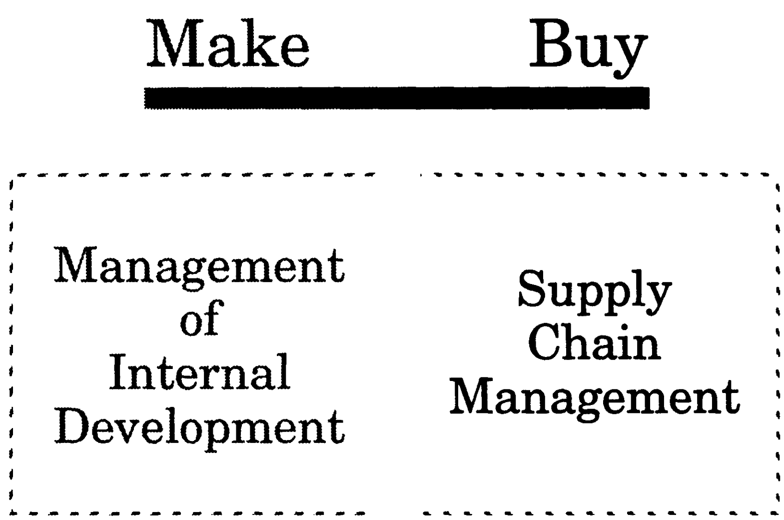


FIGURE 3.4

[63] Spencer, William J., "Meeting the Competitive Challenge: National Interests in a Global Market -- The Example of Optical Exposure Tools," SEMATECH, International Symposium on Semiconductor Manufacturing (ISSM) Proceedings, September 1993.

Years ago, when incorporating lithography technology into their manufacturing process, semiconductor companies essentially had a choice to make along the "Make-Buy" Spectrum, Figure 3.4. The choice was either to "Make" and manage the internal development of lithography technology or "Buy" the equipment thereby requiring technology supply chain management. The fact is semiconductor manufacturers have chosen to buy and have been buying lithography equipment from suppliers since the late 1970s.

Semiconductor manufacturers realized their core competencies are in manufacturing process integration and chip design. The internal capabilities along the Make-Buy spectrum are on the order of being able to create specifications, evaluate equipment options, and make software adjustments necessary for operation as part of the manufacturing process. Nearly all U.S. semiconductor manufacturers contract the maintenance of lithography equipment with their suppliers. As far as equipment maintenance is concerned, it is believed the opposite is true among Japanese semiconductor producers. With the exception of IBM, internal lithographic capabilities are kept at a minimum level to maintain the knowledge for equipment evaluation, full operational abilities, and possibly a selection of lithography process support technologies, i.e. resists and masks.

3.3. Cyclicality: The Industry-wide Equipment Sourcing Cycle

Supply-Side Lithography Equipment Market Cyclicality

One of the challenges confronted by the semiconductor equipment suppliers is surviving the peaks and troughs of manufacturer's buying patterns. This cycle is largely driven by the technology advances of lithography equipment. Since the mid 1980s the historic pattern has been to advance technological capabilities for DRAM bit count by a factor of four (4X) every four years. This has pressured suppliers to provide the appropriate lithography equipment to meet the needs of DRAM manufacturers on the leading-edge.

Worldwide Lithography Equipment Sales

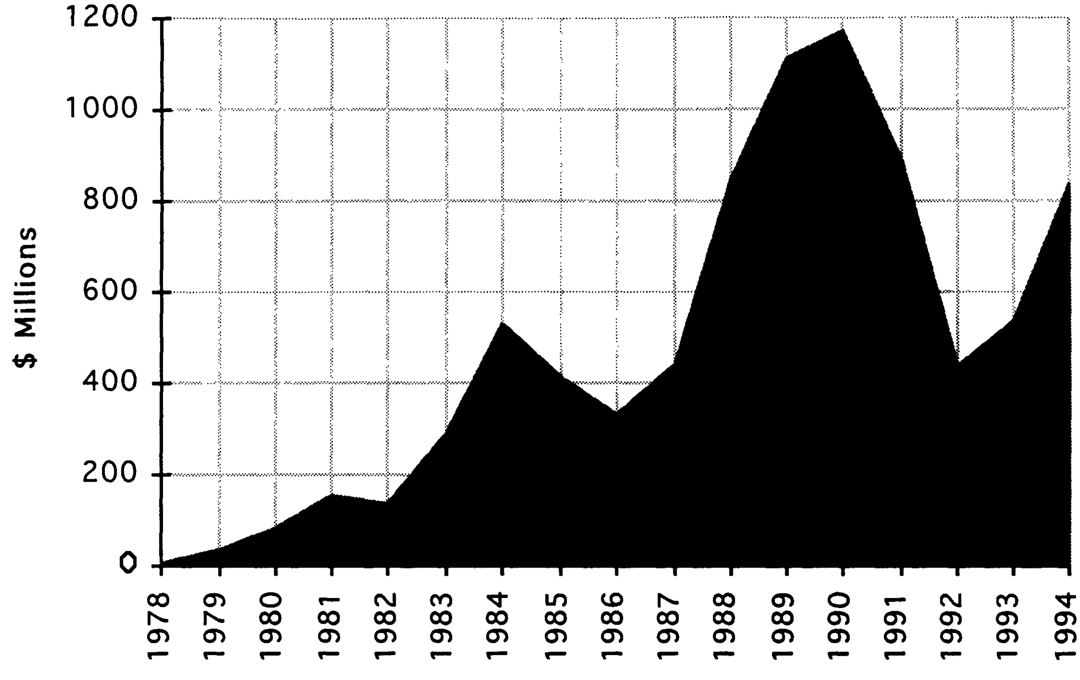


FIGURE 3.5

The cyclic nature of the semiconductor industry is clearly apparent in the worldwide lithography equipment sales figures over the last 16 years, Figure 3.5.[64] Among the different types of semiconductor equipment, lithography steppers are introduced at the earliest stages of building a production line because they are central to the manufacturing process. For that reason, lithography shows the earliest trends in the semiconductor manufacturing equipment market as a whole. Although lithography equipment suppliers seemingly struggle through the troughs in the cycle, overall they have experienced a 36% compounded annual growth rate over the last 16 years. Paralleled with the expansion of the semiconductor industry, the dominant lithography equipment suppliers have survived quite well overall. The

[64] Compiled from various sources: Dataquest, VLSI Research Inc., and JPRS Reports.

downturn in 1992 sales figures was exacerbated by a worldwide recession striking the Japanese economy most severely during this time.

Texas Instrument's forecasts for semiconductor manufacturing equipment expenditures illustrates the industry cyclicality from the manufacturer's viewpoint. TI estimates indicate overall capital expenditures for 1994 and 1995 will grow to roughly $650 million annually and will balloon in 1996 to over $1 billion, the height of the next anticipated silicon cycle. One particular lithography equipment supplier has indicated selling 50-60 lithography steppers in the U.S. market during 1994, but in the previous two years had orders for only 10-12 annually. This pattern is very typical for the equipment industry over the last decade.

Internal Sourcing Cycles among Semiconductor Manufacturers

A typical cyclic pattern consistent with this concept has evolved within semiconductor manufacturer's organizations managing their technology supply. Figure 3.6 outlines four aspects of integrating a new lithographic generation into a manufacturers fab line: (1) basic technology development, (2) equipment evaluation and sourcing, (3) process development, and (4) volume manufacturing. Basic technology development is on the order of a 2 1/2 years effort, process development 2 years, equipment evaluation 12 months, with equipment delivery times averaging 9 months. (51023)

For a semiconductor manufacturer *basic technology development* encompasses concept modeling, deciding design rules, circuit design testing, and setting desired manufacturing equipment specifications. *Equipment evaluation and sourcing* involves the entire process of interacting with the supplier from evaluating prototype equipment specifications to the final delivery of production-worthy equipment to the fab floor. (A comprehensive overview of the lithography equipment evaluation and sourcing process is provided in section 3.7). And, finally, *Process Development* is simply using the circuit design to create manufacturing process specifications and producing prototype products in preparation for volume manufacturing.

Stages of Internal Technology Development for Volume Manufacturing

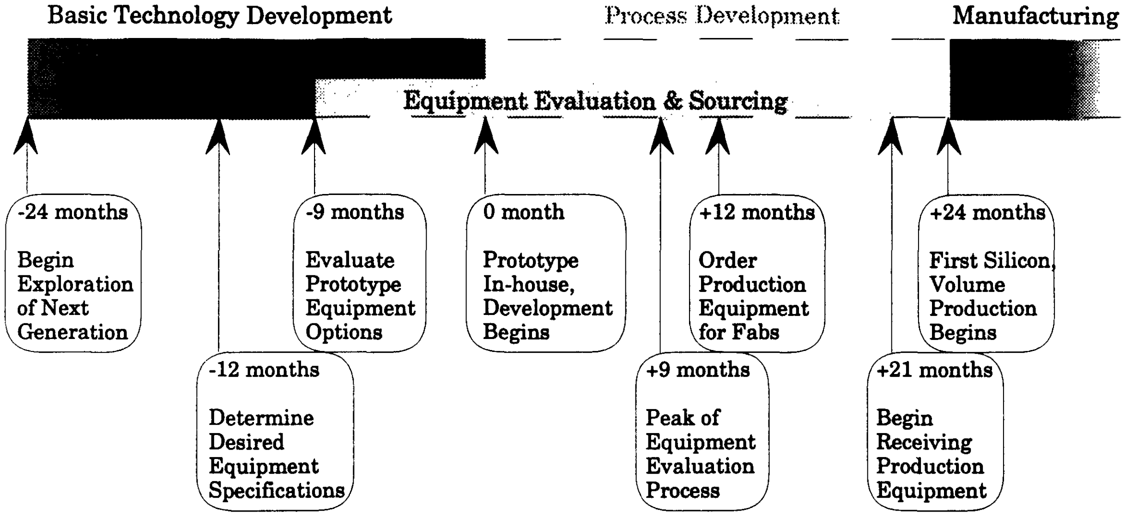


FIGURE 3.6

For a given lithographic generation this process is on average a 4 year venture. For example, take Intel's introduction of 0.35 µm generation technology into their Pentium™ microprocessor product line. Let's assume Intel began volume production of Pentium microprocessors using 0.35 µm generation equipment in January 1995. Roughly around January 1993, 24 months earlier, Intel began process development for the 100 MHz Pentium design. And probably as far back as January 1992 Intel began to determine the critical dimension (CD) and overlay accuracy metrics needed in the specifications for 0.35 µm generation equipment. This is the typical cycle every semiconductor manufacturer in the industry follows. Of course, the exact time duration and starting time varies within each company.

Although everyone within the semiconductor industry understands the basic framework for internal technology development, many companies had difficult identifying further detailed steps. The 3-4 year time constant for technology and process development seems to make standardizing the steps difficult as organizations evolve. (31014) More importantly, the semiconductor industry is noteworthy for a high degree of employee migration and turn-over rates. Standardizing the process and learning from the shortfalls of previous generation's technology development cycles becomes difficult under these conditions.

In addition, it is important to note that the entire league of leading-edge manufacturers step through this 3-4 year cycle at nearly the same time. (22047) One experience of AMD's lithography manager provides an anecdotical illustration:

> "We didn't know if we were going to buy i-line or deep-UV [lithography equipment for 0.35 µm generation]. And we tested both types and ended up buying the i-line. It was interesting, too, because we were in Japan precisely the same time Intel was doing their same evaluations and we were either behind them a week or ahead of them a week, I don't remember exactly. . . And we'd run into each other at the airport and one supplier would be getting ready for the next guy's demo. But we came to completely different conclusions about what to do at the end of that which I always found interesting." (42064)

3.4. Interdependence & Dependency Among Semiconductor Manufacturers

Capability Learning Dependency Loop Model

Envision a basic model for learning within an organization. Company "X" does "N" amount of lithography technology development in-house. The amount of work done in-house increases the amount of learning about lithography technology the "X" organization acquires doing this work. After time, this increased learning thereby enhances the internal capability to perform more lithography development. If more lithography work is done in-house then learning continues and the cycle builds upon itself. This is the capability learning dependency loop diagram of Figure 3.7.

Capability Learning Dependency Loop

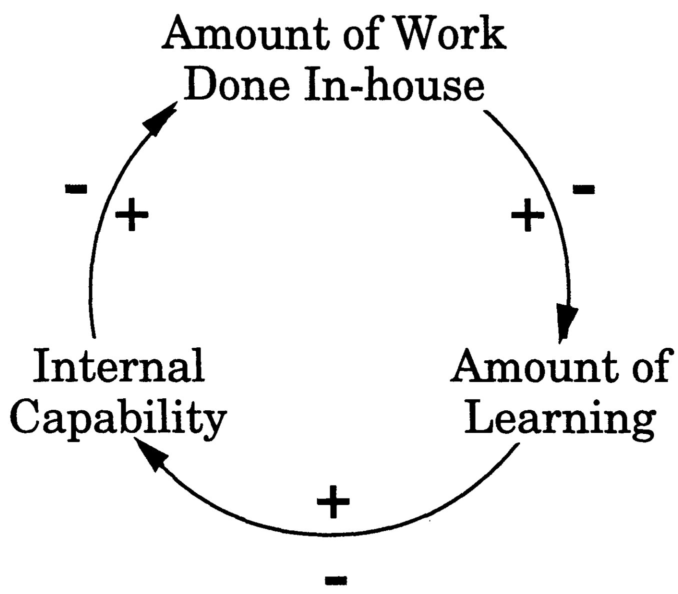


FIGURE 3.7

However, the loop can work to positively re-inforce internal capability or negatively. This is the state-of-affairs in the U.S. semiconductor industry. The limited amount of lithography development done in-house has steadily reduced learning of the most advanced lithography technologies, hence internal capability has fallen in parallel. Dependency on the lithography equipment supplier has come to the level were manufacturers are purchasing off-the-shelf equipment ready for volume manufacturing of their products without modifications. (51023) Likewise, equipment maintenance is largely contracted out from supplier. The costs associated with maintaining an internal knowledge based is assumed to be far greater than having contracted services. (51025)

The Metrics and Investment in Internal Lithographic Capabilities

Measuring a semiconductor companies internal capabilities can be characterized by their activities in three areas: (1) lithography equipment development activities, in terms of optical steppers or advanced equipment technologies, (2) internal mask fabrication and development activities, and (3) internal resist fabrication and development activities. Masks and resists are the core supporting lithographic technologies essential for the practical operation of a lithograph tool. SVGL could create the world's greatest 0.25 μm deep-ultraviolet step-and-scan lithography equipment, but without equally capable and production worthy resist and mask technologies the tool would be useless to semiconductor manufacturers.

Each leading-edge American semiconductor manufacturer has, on average, 35 personnel focused on lithography basic technology research, process engineering, and equipment engineering. It appears that having a minimum of 25-30 people is the critical mass necessary for performing lithography technology development and sourcing within a leading-edge company. This implies that in order to effectively convert raw manufacturing technology into a viable lithography process, companies typical investment in human capital knowledge is on the order of $1.5 million annually (based on $42,000 average gross annual salary). (11116) These numbers don't include the number of lithography engineers, maintenance, or operators of each individual fab, but merely the countable centralized personnel focused on lithography technology within each given manufacturer.

Internal Optical Stepper Equipment Technical Capabilities

The degree of internal lithography *equipment* capabilities among U.S. semiconductor manufacturers has been alluded to frequently in the prior sections of this text. With the possible exception of IBM, the typical limits of a semiconductor company's equipment capabilities is making specifications, testing the equipment functionality, and using the equipment to its fullest.

Everything short of being able to make modifications to the equipment's components.

Process development and manufacturing system integration is really the core competence of semiconductor companies. One manufacturer's viewpoint illustrates the general state-of-affairs among the leading-edge companies:

> "We treat the equipment in development just like it was production equipment . . . We want to use it, we don't want to play with it, we want to use it. We do certain things with steppers for example, we definitely explore modified illumination schemes and phase-shift masks . . . But, our primary interest is using it to help develop silicon products. Not to develop steppers. Now, we talk with the stepper suppliers, particularly Nikon and Canon, and we certainly feedback what changes we would like to see . . . But, we don't actually do any mechanical engineering, software, or any development per se, no optics, etc. And, that's basically always been the case." (31021)

Internal Mask Houses & Technology Development

The typical independent U.S. mask suppliers in the industry include Photronics, Toppan and DuPont. There is seemingly a bi-modal distribution of internal mask capabilities among leading-edge semiconductor companies. Fundamentally, (1) either companies have minimum internal capability and out-source the mask manufacturing completely, or (2) companies have internal mask manufacturing capabilities, as well as out-source to manage capacity or out-source higher/lower technically challenging mask manufacturing jobs. An example of the companies with each strategy is outlined in Table 3.3.

Internal Mask Strategies Among Six Leading-Edge Companies

Use Internal Masks?	Yes, internal manufacturing capability	No, out-sourced completely	Mixed in-and-out sourcing
AMD		✔	
Digital		✔	
IBM	✔		✔
Intel	✔		✔
Motorola	✔		✔
Texas Inst.		✔	

TABLE 3.3

IBM, Intel, and Motorola have retained full internal mask manufacturing capabilities. AMD, Digital, and Texas Instruments has chosen external sourcing from either Photronics, Toppan, or DuPont. Only within the last 5 years have Digital and TI shifted their mask manufacturing outside. In both cases the motivating factors to outsourcing were two-fold: (1) maintaining an internal capability does not provide a competitive advantage, and (2) maintaining an internal mask house was not cost effective. (12038)

The estimate is that to fully maintain and update mask writing equipment for internal purposes would require investments of ~$56 million over a 3-5 year period. (31021) On the other hand, if purchased from a supplier, a mask set is on the order of a $100,000 venture. A typical microprocessor or DRAM mask set includes anywhere from 20-25 mask levels. Individual masks have been quoted in the range of $3,500 - $9,000 each depending upon the stringency of specifications. (52170) The simple math indicates one would need 560 mask sets, or maybe 300 new products, over these 3-5 years to justify the return-on-investment.[65] For the wide diversification of products within Motorola and IBM it is reasonable to believe they can cost effectively maintain an internal capability by cost measures.[66] Intel, alternatively, may be maintaining an internal mask facility as an investment in intellectual property protection of their microprocessor circuit designs imprinted on lithography masks.

Mask making is clearly viewed among the industry as a pre-competitive technology. The intercommunication among Motorola, IBM, and Intel's masks houses are seemingly frequent. As well, it has not been uncommon for Digital, for example, to assist DuPont on mask manufacturing reliability issues. (31021)

Internal Resist Technology Development

Leading-edge resist suppliers include Shipley, JSR, Sumitomo, TOK, OCG, AZ, AT&T and IBM. IBM is the only U.S. merchant semiconductor manufacture with an internal resist facility. IBM's Resist Facility has consistently been on the leading-edge and is the only viable deep-ultraviolet resist available on the market, as of early 1995. However, IBM's resist facility hasn't historically been a competitive supplier on the open market. (31021)

As with optical stepper equipment, the industry relies upon suppliers and invests internally in maintaining an expertise in characterizing the performance of the various resists on the market. Each semiconductor company may have a half dozen or fewer resist specialists assisting their process development and characterization efforts.

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65 Often there will be multiple exact copies of a mask set for a single product. Generally this is to have duplicate copies at a single fab site for more flexible process flows or when manufacturing the same product at multiple fab sites. These calculations are best estimates based on available numbers.

66 It is understood that Motorola treats its Mask House as a profit center. IBM hasn't clearly indicated whether its Burlington Mask Facility is subject to cost scrutiny or not.

Dependency Molds Semiconductor Equipment Technology Management Style

The lack in in-house lithography capability has forced interdependency among U.S. semiconductor manufacturers. Learning is achieved via industry-wide consortia such as Sematech, Semiconductor Industry Association (SIA), and the Semiconductor Research Center (SRC). Long-term research and development of lithography technology has been exported to the academic and supplier community. Semiconductor manufacturers provide financial support of long-term research activities coordinated by the SRC. The SRC's primary function is to decide upon appropriate 5-10 years advanced research projects at U.S. colleges and universities. Individually, some manufacturers support various academic research projects on a case-by-case basis, but this is rare. One case example would be between TI and the Interuniversity Microelectronics Center (IMEC), University at Louven, Belgium, researching optical lithography options for 0.18 μm technology 1-Gigabit DRAMs.[67] (61022)

Dependency on lithography equipment suppliers also means the opportunity to gain competitive advantage through technology has diminished. Open-access to leading-edge lithography technology makes the capability available to all who can afford the capital investment. What has become critically important, however, is the ability to keep up-to-date with your competitors who are purchasing the most advanced technology. To some degree, manufacturers compete on their ability to leverage suppliers to provide them with the newest generation equipment in a timely manner. Having a preferential relationship with the supplier could give a company better access to the newest technical capabilities. This was the case for AMD when it was initially able to attain better alignment accuracy specifications from its supplier that Intel. This originally provided AMD with the ability to produce smaller 486-class MPUs than Intel. Since this time Intel has been able to

[67] "TI, IMEC Join in Lithography R&D" *Electronic News*, Feb. 27, 1995, p.56.

leverage its supplier such that the differences in 486-class chip dimensions is no longer an issue.

Leading-edge semiconductor manufacturers generally receive their first production worthy next-generation lithography equipment usually within 6-9 months of each other. For example, 0.5 µm equipment was acquired by all of these manufacturers by 2Q1992 ±6 months. (11110) Likewise, for 0.35 µm lithography, manufacturers began receiving prototype equipment as early as 1Q1994 with the latest reported start of 0.35 µm level technology by 2Q1995. (11026)

According to manufacturer's, the 6-9 month variation in availability of next-generation technology provides minimal competitive advantage. Market conditions for microprocessors in the semiconductor industry provide little advantage to having a six month technology lead. In DRAMs, in contrast, being first to market with the next-generation 64 Mb chips means you can set the market price high, given the limited supply. Market dominance for the 'first to market' manufacturer is limited to those first 6-9 months. Typically, one can purchase four 16 Mb sets at extremely competitive prices compared to one 64 Mb set. The true return-on-investment analysis of these market leaders requires further study.

Nonetheless, the bottom line concept: *suppliers determine the progression of lithography technology advancement.* Motivating continuous improvement in the free-market atmosphere implies ensuring multiple suppliers attain competitive capability and drive to move the technology forward. To achieve this end manufacturers have chosen, unknowingly, a simple philosophy: *"Minimize capital expenditures while maximizing supplier switching flexibility."*

Maximizing supplier switching flexibility has evolved to mean: (1) have the ability to easily switch to the most technically competent supplier, or (2) maintain the threat of being able to switch suppliers if your strategic partner fails. Minimizing capital expenditures is may be an obvious concept, but in this context it further implies: (1) seek the opportunity for volume purchasing from a single supplier to attain the economies-of-scale in equipment pricing, and (2) avoid the hidden costs of switching suppliers.

The expertise of semiconductor companies has become to characterize the performance of equipment and supporting lithography technologies as it suites their manufacturing process needs. As a strategy to ensure some independence for the supplier, a subset of manufacturers avoid designing their process around any one specific equipment set. (12043) Ideally, the semiconductor manufacturing process would be totally independent of the lithography equipment supplier, purchased off-the-shelf, with the same specifications. In reality, this doesn't occur. The details of mask design is dependent upon which lithographic tool is being used for circuit patterning. For example, a mask designed for a Canon stepper would not function correctly on a Nikon, and vice versa.

Assessing Supplier Switching Costs

Semiconductor manufacturers have a difficulty giving a numeric cost associated with switching suppliers. However, four core concepts surfaced repeatedly: (1) the learning curve of process engineers to optimize performance on unfamiliar equipment, (2) mask alignment systems between manufacturer's tools are totally different and requires experiential knowledge to correctly model, (3) the support infrastructure, in terms of maintenance personnel and parts, changes with the name-brand of the equipment, and (4) relationships with established suppliers is easier to maintain than to go through the mutual learning curves of creating a new relationship with an alternative supplier. (11028)

The potential switching costs incurred by a given company is largely determined by their internal corporate equipment sourcing strategy. A semiconductor manufacture with a more centralized approach to lithography sourcing will incur greater switching costs than a diversified, decentralized manufacturer. Before evaluating relative switching costs it first becomes necessary to understand how companies have organized their semiconductor lithography equipment sourcing approach.

3.5 Internal Corporate Equipment Sourcing Strategies

Semiconductor manufacturers have a spectrum of organizational infrastructures to cope with the cyclic process of incorporating new lithographic technologies. The fundamental organization of a semiconductor company at the manufacturing level is composed of three spheres of influence: process\equipment development, manufacturing equipment technology organizations, and the fabrication lines. In some companies these three spheres are clearly delineated, others combine these functions together into one group. Typically there is always a clear distinction between those responsible for sourcing of equipment and those personnel working on process development. The fab is inevitably the site of integration, as in Figure 3.6.

Three Spheres in the Semiconductor Realm

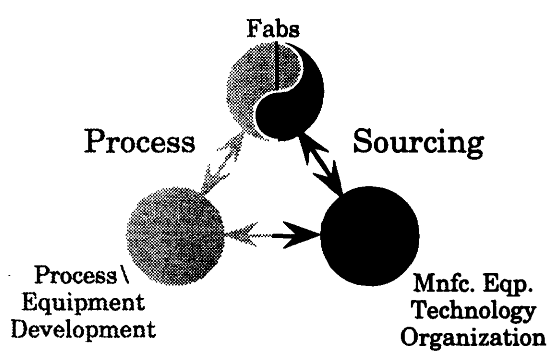


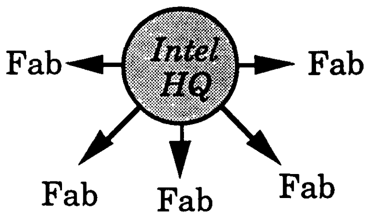
FIGURE 3.8

Different organizations tend to have their own names for these three spheres, as noted in Table 3.4. What truly differentiates a given semiconductor company is the relative degree of centralization versus decentralization inherent in its equipment sourcing approach. Figure 3.9 lists six leading-edge U.S. semiconductor manufacturers by their degree of centralization (from top to bottom), images of their sourcing structure, and brief notes characterizing each company's market conditions and methods.

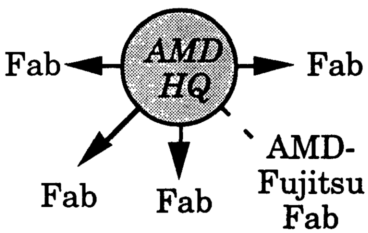
	Fabs (example)	Process\Equipment Development	Manufacturing Equipment Technology Organization
Intel	Fab 12	Product Development Group	Process Equipment Development (PED)
Advanced Micro Devices (AMD)	Fab 25	Submicron Development Center (SDC)	Strategic Technology Council (STC), Core Equipment Teams (CET)
IBM	CMOS	Equipment Engineers, Process Development Group	Semiconductor Equipment Council (SEC) Focus Teams
Digital (DEC)	CMOS 5, Fab 6	Equipment Engineers, Process Development Group	Equipment Selection Teams (EST)
Texas Inst.	DMOS 5	Semiconductor Product Development Center (SPDC), Productization	Manufacturing Technology Center (MTC)
Motorola	MOS 12	Advanced Products Research and Development Laboratory (APRDL)	Manufacturing Technology Group (MTG)

Six Perspectives on the Three Spheres
TABLE 3.4

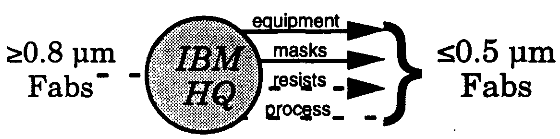
Centralization - Decentralized Equipment Sourcing Practices



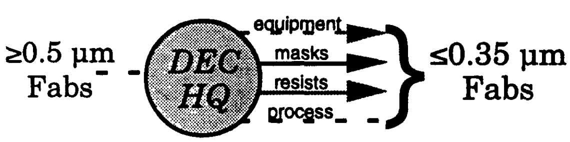
Intel
- Total centralization
- Limited product line
- "Copy Exactly" processes
- Internal dedicated mask fabrication
- Industry role model strategy



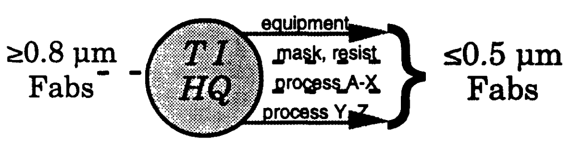
Advanced Micro Devices
- Centralized with limited variance
- Limited product line
- Product fabs with similar process
- Resist, Masks single supplier source
- Deviation in Joint Venture Fab



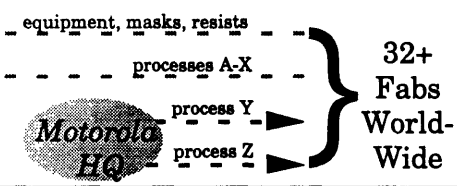
IBM Microelectronics
- Newly centralized equipment selection
- Single-sourced internal mask house
- Resist recommendations to fabs
- Processes independently developed



Digital Equipment Corp.
- Independent equipment selection
- Few fabs with dedicated product lines
- Single sourced mask supplier tied
- Geographic proximity with Shipley



Texas Instruments
- Newly implemented central sourcing
- Restricted choice equipment selection
- Independent masks, resists, processes
- Key product processes centralized



Motorola SPS
- Highly decentralized, independent fabs
- ~3,000 semiconductor products
- Key products with centralized process
- Matrix organization between fabs

FIGURE 3.9

There is a strong positive correlation between a company's degree of decentralization and product diversity. Intel has one mainline product microprocessors and thus has evolved a totally centralized equipment sourcing process. On the opposite end of the spectrum is Motorola with over 3,000 differentiated products spread over 30 fabs, highly decentralized. Each company's strategy has either a deleterious or positive effect on its potential supplier switching costs and associated volume equipment purchasing prices.

#1	Switching Costs	Equipment Costs
Intel "Copy Exactly" Centralization	HIGH	MEDIUM

100%, every single fab is running a technology the same way. The decisions are all made before the factory is even built. All new technologies come into production identically at all sites. All equipment purchases are made the same at all factories. Contracts with suppliers are all the same. As far as masks, Intel has a fully-capable mask facility to make their own masks. All of Intel's advanced masks are made in-house. Decisions are made centrally by a committee of the product development group, process equipment development (PED), and fabs to negotiate technical specifications and pricing with at least two supplier candidates.

Having chosen the same supplier over the last 10 years, the internal inertia necessary to switch suppliers is high. Intel typically buys equipment in large lots, filling high-capacity fabs potentially providing significant cost reductions. However, Intel is seemingly willing to pay a little extra to maintain internal consistency and minimize ramp-up cycle times.

#2	Switching Costs	Equipment Costs
AMD Variance Limited Centralization	HIGH	MEDIUM

Similar to Intel, AMD's limited product line promotes consistency to use a single supplier. AMD also only has five fabs and the desire to develop the operational expertise and support infrastructure for multiple suppliers doesn't exist. Although for a given technology the same supplier and model is used, each fab may be upgrading at different times. The variance may be differences in minor improvements the supplier has made to the product since the last purchase, for example. AMD's purchase volumes are respectably large enough too attain a degree of discounting, yet still has an allegiance to the original supplier. Similar to Intel's situation, internal inertia for switching suppliers is high.

#3 *IBM Momentum To Centralize with Internal Lithographic Capabilities*	Switching Costs	Equipment Costs
	MEDIUM	MEDIUM

It is truly a toss-up between Digital and IBM on who deserves the #3 title. IBM looks-up to the Intel model and has made significant strides in the last generation to centralize equipment selection. For a given product type, every manufacturing organization for that product at each plant must have identical equipment, no matter if the fab is in Fishkill, NY or Sones, France.[68] IBM's Strategic Equipment Council tries to make it very difficult for fabs to deviate in new lithographic generation equipment selection.

The driving forces for IBM's restructuring are largely cost motivated. Each fab independently created customized engineering specifications driving up the costs of equipment. Through centralization, common specifications can be decided for each generation so that the purchase orders and contracts will look the same to the supplier, providing pricing leverage. Consensus is built around a single preferred supplier through the Strategic Equipment Council's Focus Teams in each technology, e.g. lithography. All masks are sourced internally, with few exceptions. Fabs seemingly have more flexibility in choosing the best available resist on the open market.

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68 Key exception: IBM Japan. Proximity and business climate in Japan with suppliers Nikon and Canon gives IBM Japan in Yasu some autonomy.

IBM's extensive internal lithography research and development repitore provides greater ability to quickly learn the nuances of various suppliers equipment. IBM hasn't added any significant new capacity in the last several years. Older fabs upgrading equipment to the next generation have little desire to choose an equipment supplier different then their current install base. Unquestionably, IBM's greater degree of centralization does provide leveraging with the supplier to lower its overall equipment costs.

#4	Switching Costs	Equipment Costs
Digital's Limited Independence	MEDIUM	HIGH

> "The philosophical mentality around here is the fact that engineers need to have the freedom to do what's best technically. It's always been an engineering driven company and always will be, I think. Although we're changing that to some degree as we go into different markets." (31108)

Digital has two fabs on the leading-edge and each fab choose different equipment suppliers. The engineering atmosphere does provide Digital with the technical capability to switch suppliers on-the-fly. However, Digital's close-knit group has historically had a strong bias toward a single style of lithographic equipment, making the impetus to change more a factor of personal tastes. Digital's lower volumes split between two fabs provides minimal pricing leverage with suppliers. However, Digital has been successful in attaining more stringent, tighter equipment specifications from its supplier than most of its competitors. Digital has an early leading capability to manufacture using deep-ultraviolet lithographic equipment with a tight linewidth CD and excellent alignment accuracy tolerances. This is strongly facilitated by Digital's lower volume demands and engineering culture. Close geographic proximity with its resist manufacturer also facilitates early access and collaborative efforts. Digital's stringent specifications has similarly been pushing the limits of their mask supplier's capabilities, forcing a degree of collaborative development with the supplier. Digital's Alpha MPU's design and technology is clearly on the leading-edge, if only the market share data would follow suite. . .

#5 *Texas Instruments' Diversified Preference*	Switching Costs	Equipment Costs
	LOW	LOW

Like IBM, TI began an effort to centralize equipment sourcing during the early 1990s. In the process Texas Instruments has structured its organization in the optimal position of maintaining low supplier switching costs as well as an ability to leverage lower equipment costs. TI's Manufacturing Technology Center (MTC) provides fabs with a *suggestive* choice between two suppliers, and only two suppliers. TI's Productization group tends to lead the development of next-generation technology and does process development on both suppliers equipment, usually side-by-side. When the time comes to made volume equipment purchasing decisions, fabs have a choice among the two suppliers the Productization group has thoroughly tested in prototype manufacturing processes. Equipment performance data is readily available from Productization and prices are negotiated henceforth.

An important note: MTC provides fabs with a *suggestive* choice between the two suppliers. In lithography, as in other areas, MTC developed a preferential business relationship with one of the two suppliers. Given competitive technical capabilities, MTC will strongly suggest choosing the *preferred* supplier, giving the preferred supplier possibly 75%+ of TI's lithography purchases. 75%+ of TI's extensive global semiconductor operations is an appreciable volume to garner TI pricing leverage with a chosen supplier. As for masks and resists, each fab is free to choose as desired among the supplier base. TI continues to diversify its product base into application-specific-integrated circuit (ASIC) markets and will enjoy the mutual benefits of a preferential supplier strategy.

#6 *Motorola's Product-driven Decentralization*	Switching Costs	Equipment Costs
	LOW	MEDIUM

Within Motorola the fab manager is king. Every fab chooses their own equipment, resist, and mask supplier without specified guidance from the hierarchy above. And, that hierarchy is quite lean. With on average ~3,000 products manufactured among 32+ fabs globally, the necessity for product mobility across fabs is minimal. Each fab handles its own process development and product designs are created by Motorola's Product groups. Motorola has product-driven organization were the Product groups choose the fab they wish to manufacture a given product depending upon the technical capability, capacity, and costs of each fab. Hence, within Motorola, the fabs compete for a Product Groups' business.

Typically 2-3 leading-edge fabs will develop processes around next-generation lithographic equipment capabilities. The centralized Advanced Products Research and Development Laboratory (APRDL) often does design and process development for key microprocessor or memory products on its multiple pilot lines. However, the fab that manufactures the APRDL product has complete autonomy to choose a different equipment supplier. This can often occur because the fab manager must keep the fab floor flexible to manufacture an assortment of products in the long-run.

This decentralization doesn't necessarily imply chaos. On the contrary, Motorola has an organizational matrix which provides a steady flow of communication among lithography managers across all fabs. Often the Motorola's leading-edge fabs form "user's groups" to meet with Canon or Nikon as a single voice, for example. Likewise, when a new fab is starting-up and making choices among equipment suppliers, this internal network within Motorola provides a wealth of knowledge and resources to draw upon. This organizational matrix eases supplier switching based on best technical and cost. Suppliers are constantly competing for every increment of Motorola's business. This competitive atmosphere applies pressure among suppliers to lower pricing, yet pricing-by-volume is limited by the size of the fab.

Internal Metrics of the Success of Equipment Sourcing Strategies

> "Just the fact that we're making money. We've been pretty successful. It's kind of a given. It's like, I'm a human being and I am living on Earth, that's the way things happen at Motorola, that's the way it's going to be, and no one is going to change it. And it seems to be working." (51012)

The above comment encapsulates the feeling of the semiconductor industry. Fundamentally, the lithography equipment they have chosen has functioned appropriately, through their given sourcing methods they feel like they're reducing capital costs, and have successfully reduced *time-to-money*. (51012) Few companies have *hard* metrics for measuring the success of their equipment sourcing strategy. In addition, the 3-4 year cycle time for introducing new lithographic generations makes the effort of comparative study difficult.

3.6. Supplier Relations & Equipment Evaluation: The 7 Steps to Lithography Equipment Sourcing

Arms-length	Preferred Supplier	Strategic Partner

There is a spectrum of customer-supplier relations in the semiconductor lithography realm along three points: (1) An arms-length relationship were contact occurs on an as needed basis between customer and supplier, (2) The supplier is among a core network of preferred suppliers with periodic communications established, and (3) A supplier as a long-term, strategic partner with frequent interactions. (42065) One could pick any customer-supplier pair and place them on this continuum. Most semiconductor companies would rather not have it publicly known the degree of closeness they have with their supplier. Given that manufacturers often compete for the attention and leverage on their suppliers, the details of their relationship becomes an issue of confidentiality. In any case, each supplier management strategy brings its own rewards and drawbacks.

There is a strong tendency towards the center of the spectrum among manufacturers. Having a *preferred supplier* is seemingly far more favorable than the extremes of *arms-length* or *strategic partner*. In an arms-length relationship there is little response from the supplier to meet your needs. On the other extreme, there is a feeling of being locked into one supplier and at their mercy, i.e. high supplier switching costs. Preferred suppliers provides the favoritism of economies-of-scale with a given supplier, get their attention for your specific concerns, and often provides an avenue for feedback of possible improvements. In essence, a business relationship while maintaining a residual supplier switching capability as needed. Consider for example onoe perspective from a very profitable semiconductor manufacturer:

> "We operate with all suppliers of key products exactly the same, sharing information, working very closely with them. But the choice isn't there. We don't have any long-term strategic partners. We have long-term companies, companies we do business with. This thing of strategic parnters, I find it a hateful concept. It says, "You can screw me, but you're my partner, so I forgive you." It's a business relationship based upon neutral profitability. That describes our relationship will all our suppliers, whether its steppers, tracks, ashers, resist suppliers, etc." (42065)

The tool consistently used to designate a preferred supplier is through an *approved equipment supplier list*. With the exception of Motorola, everyone has some form of listing their suppliers of choice. Intel may call it the *Plan of Record* or Texas Instruments may call it a supplier alliance, but the concept is the same: selecting a given suppliers equipment as the production tool of choice for a technology generation.

Getting on the approved list, or more simply, to be the chosen requires a lengthy evaluation process. Figure 3.10 is the semiconductor industry's plain, vanilla seven step equipment sourcing process. Manufacturers tend to go through these seven stages in evaluating, choosing, and installing lithography equipment.

Vanilla 7 Step Equipment Sourcing

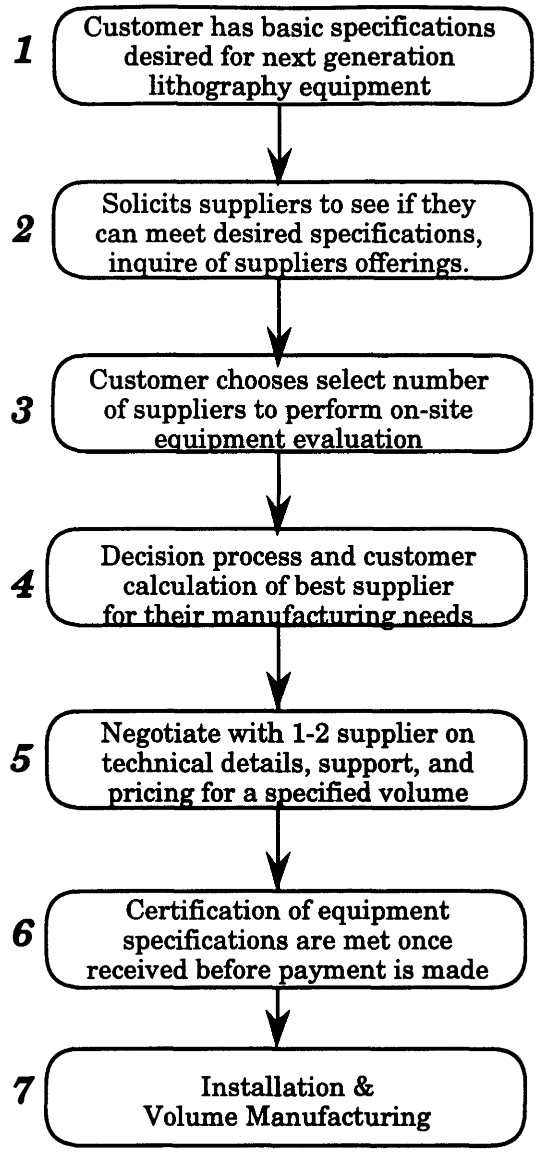


FIGURE 3.10

Top 5 Semiconductor Equipment Selection Criteria

#1	Equipment meets or exceeds technical CD and overlay specifications
#2	Positive past experience and/or management capability of supplier
#3	Cost-of-Ownership competitiveness of equipment in question
#4	Superior service contract, low maintenance, and high MTBF
#5	Guaranteed on-time delivery of equipment to fab site

TABLE 3.5

In the equipment selection criteria most often used by semiconductor are ranked as in Table 3.5. The most important factor is that the tool meet technical specifications, if it can't do that then it is useless to the manufacturer. (41024) If technical specifications are comparable among two or three suppliers then positive past experience with the supplier plays a significant role, often more than Cost-of-Ownership.

3.7. Opportunities for Further Learning in Creating and Managing Semiconductor Lithography Technology Supply Chains

U.S. semiconductor manufacturers have a fundamental premise to minimize capital expenditures while maximizing supplier switching flexibility. This conceptual approach is not unique to the semiconductor business nor to American soil. However, it is the means by which customers and suppliers interact, the market conditions, and technology which makes this story unique. The automotive, electronics, or aerospace industries may not have similar sourcing strategies for their critical equipment. If not, why? If it is similar to the semiconductor industry, in what ways? It is through comparitive study that real learning can occur.

Likewise, the U.S. semiconductor industry does not exist in isolation. Learning how Japanese, Korean, and European semiconductor companies cope with the industry cyclicality and managing their lithography supply chains is of equal interest. Does the differences of cultural or geographic proximity provide NEC a completely different sourcing strategy than IBM. Are they equally effective? Are the objectives truly the same?

Chapter 4

APPENDIX

TSC Symposium Breakfast Presentation

Learning from Lithography Equipment Technology Supply Chain Management in the Semiconductor Industry

Corporate Equipment Sourcing Strategies
to Maximize Supplier Switching Flexibility
while Minimizing Capital Expenditures

Thursday, May 11
Twenty Chimneys Room
Stratton Student Center
MIT Bldg. W20-306

Charles Pieczulewski
Master's Thesis Seminar
Presentation 7:45 a.m.
Breakfast 7:30 a.m.

What is Lithography Equipment?

Imagine a tool that . . .

- Limits the performance measures your customers use in choosing your products
- If improved, single-handedly lowers your manufacturing cost per unit
- Most expensive set of tools in your factory
- Limited number of suppliers in the world capable of providing this tool

Criticality of Lithography to the Semiconductor Industry

★ Providing consumer demand for faster, cheaper, and lower power electronics is enabled by lithography technology

★ 10% Reduction in chip size = 10% reduction in cost per chip

★ 33% of Capital Equipment Costs for new $1 billion manufacturing fabs

★ Only 4 Leading-Edge Suppliers WW: Nikon, Canon, ASML, & SVGL

Lithography Knowledge in the Hands of Equipment Suppliers

Make	Buy
Management of Internal Development	Supply Chain Management

Issues:

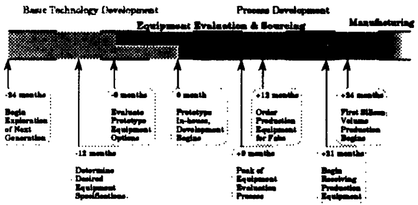
Cost Effectiveness

Sources of Innovation

Locus of Technology Know-How

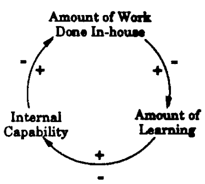
Manufacturer's CHOICE: Focus on Supply Chain Management

Long Time Constant for Learning Supply Chain Management



Semiconductor Industry 3-4 Year Sourcing Cycle

Lithography Technology Interdependency & Dependency



Lack of In-House Capability has forced interdependency:

- Learning via Consortium
- Industry Steps In-concert
- SIA, SEMATECH, SRC

Dependency on Supplier has diminished In-house Work:

- Industry-wide out-sourcing of lithography support technologies
- Purchase Off-the-Shelf solutions
- Free Access to Leading-Edge Lithography Technology

Restrictions to Dependency on Lithography Equipment Suppliers

#1 Lithography Technology does <u>not</u> provide a source of competitive advantage

- Lithography knowledge public domain
- Must keep up-to-date with technology leaders
  - >> Compete on ability to leverage suppliers <<
- 3-6 month technology lead insufficient
- Competition: DRAM v. Microprocessors

#2 Suppliers determine progression of technology advancement

- Motivate continuous technology improvement
- Create competitive supplier environment
- Ensure multiple capable suppliers

Creating Competitive Suppliers: Semiconductor Industry Choice

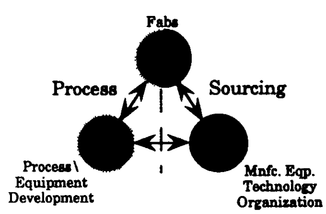
"Maximize Supplier Switching Flexibility

- Have the ability to easily switch to the most technically competent supplier.
- Or, maintain the threat of being able to switch suppliers if your strategic partner fails.

while Minimizing Capital Expenditures"

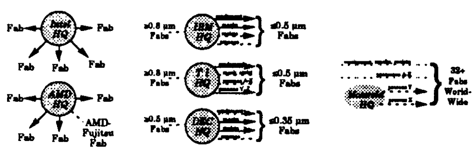
- Volume Purchasing from Single Supplier
- Avoid hidden supplier Switching Costs

Blue-Print for Process Development & Equipment Sourcing Interface



3 Spheres in the Semiconductor Equipment Realm

Centralized - Decentralized Internal Equipment Sourcing



Centralized | Decentralized

"Time to Money"

Measurement of Supplier Closeness

Arms-length | Preferred Supplier | Strategic Partner

Semiconductor Industry Tendency for Center
"Preferred Supplier"

Examples ?

Supplier Preference via Approved Equipment List

PROS
- Reduces redundant activities at multiple fabs
- Volume discount purchasing from supplier
- Reduces equipment evaluation costs
- Product manufacturing mobility across all fabs

CONS
- Promotes Single Supplier Allegiance
- 2-3 Generations with same supplier weakens switching ability

Motorola: Optimal Supplier Switching Condition, Volume Pricing via Multiple Large Fabs, Diversified Product Base.

"Getting on the Approved List"

Equipment Selection Criteria

#1 Equipment meets or exceeds technical specs

#2 Positive past experience, management of supplier

#3 Cost-of-Ownership

#4 Superior service contract, high MTBF

#5 Guaranteed on-time delivery to fab site

Learning from Semiconductor TSC

Corporate Equipment Sourcing Strategies
to Maximize Supplier Switching Flexibility
while Minimizing Capital Expenditures

Alternative Sourcing Strategies Abroad:
Europe, Japan, Korea

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  MIT-Japan Program
- Moral Support: MIT Colleagues

- Final Thesis Release: June 1995

4.2. Sample Questions from Corporate Survey

32152 How is the semiconductor equipment sourcing group organized? What people are involved in the sourcing process? Is the sourcing group organized to negotiate both technical and financial terms of the contract?

32150 Does AMD have an approved equipment or vendors list?

❑ YES ❑ NO

If yes, how does the equipment and/or vendor get on the approved list? If yes, What function does the "approved equipment" list serve for AMD?

31108 Is the lithography equipment purchasing decisions for AMD's new fab lines centralized at one location or does each fab choose its own equipment independently?

42057 If your current lithography equipment supplier, Canon for example, somehow loses their technological and/or cost competitive edge over competition, what is the likely steps AMD would take?

Switch suppliers at next opportunity
Give supplier a deadline by which to resolve problem themselves
Offer technical assistance to supplier in any way reasonably possible
Other, please specify:

42055 Does AMD form formal relationships with strategic equipment suppliers of lithography technology?

YES NO

If NO, is this a conscious decision or a particular reason not to do so?
If YES, what was the motivations for forming an alliance?

11028 If in your current 0.5 µm fab you have Nikon steppers in use, what would be the costs incurred if you switched to Canon or SVGL steppers for the 0.35 µm generation fab?