DARDEN
Graduate School of Business Administration
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NEXT-GENERATION LITHOGRAPHY (A): BETTING ON A NEW PRODUCTION TECHNOLOGY IN THE SEMICONDUCTOR INDUSTRY

Silence descended on the gathering of Industrial Advisory Board members when the Lawrence Livermore Laboratory scientist stepped forward and estimated how much it would cost to develop a working prototype for an extreme ultraviolet (EUV) system: $200 million. The year was 1995, and the gathering included the leading lithography technologists from U.S. National Laboratories, SEMATECH, and top semiconductor device companies—including Intel and Lucent. EUV was one of the handful of possible next-generation lithography (NGL) technologies discussed in industry circles. The industry representatives knew that the future of their industry—and of the electronics sector more broadly—hinged on their ability to bridge the technological discontinuity between optical lithography and next-generation systems. Even though bridging this gap was considered an industry imperative, the players were hesitant to commit over $200 million in seed funding to a high-risk technology a decade before the industry would require it.

To maintain the pace of technological change and their leadership positions in the industry, the companies represented at the conference had to decide how to place their bets in the evolution of lithography. Of all the modules in semiconductor manufacturing, lithography constituted the most critical module in enabling the industry to pack increasing levels of functionality into smaller and smaller chips. To ensure lithography did not limit the industry's ability to grow, the chip companies and their equipment suppliers faced a two-stage decision. First, they had to decide how to allocate R&D expenditures between advancing optical lithography and developing post-optical systems—the so-called next-generation lithography. The industry consensus projected that NGL systems would be required within a decade. Second, given this industry outlook, they had to choose on which NGL system to place their bet and how to design development programs to make NGL a reality.

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R&D Dynamics in the Semiconductor Industry

Since the early days of the industry in the 1950s, a confluence of private and public sector monies and initiatives fueled R&D in the semiconductor industry. Companies like IBM, Intel, Lucent (AT&T), Motorola, and Texas Instruments in the United States; Fujitsu, Hitachi, NEC, and Toshiba in Japan; and Infineon (Siemens Semiconductor Group), Philips, and ST Microelectronics (SGS-Thomson) in Europe had shouldered the responsibility for much of the industry's cutting-edge R&D. Government bodies such as the Department of Defense in the United States, the Ministry of International Trade and Industry (MITI) in Japan, and the European Union had augmented the private sector's efforts through grants to the private sector and the administration of research projects at national laboratories.

In the 1990s, the maturation of the industry evidenced by the emergence of new industry leaders, e.g., in Korea and Taiwan (see **Figure 1** for market share trends in the chip industry), downturns in the "Silicon Cycle" (the undercapacity-overcapacity cycle that occurred about every two to three years in the industry), and a reduction in funding from government sources brought new realities to the R&D funding model. No longer could the traditional sources of funding be taken for granted. At the same time, suppliers of semiconductor manufacturing equipment such as Applied Materials in the United States, ASML in the Netherlands, and Canon and Nikon in Japan furthered their technical expertise while expanding their products' capabilities from a narrow focus on hardware to a broader focus that included process technology.

These two forces—the erosion of traditional R&D funding sources and the advancing technical leadership of the equipment suppliers—forever altered the way new generations of equipment were developed. The new model relied on an unprecedented level of cooperation both across chip producers and between chip producers and their equipment suppliers. In the past, chip producers took the leading role in bridging technological discontinuities in the industry, while involving equipment suppliers late in the development process. Although in the development of NGL technologies, the chip producers would again guide much of the transition, it was likely that equipment suppliers would play a larger role early in the process well before commercialization.

Beyond Optical Lithography

For years, companies in the semiconductor industry anticipated that their rapid pace of technological change would hit a limit imposed by the physics of light.[1] One of the crucial steps in the manufacture of semiconductor devices, lithography, relies on light to project patterns on a thin wafer of silicon to trace what will become a device's circuitry. <See syllabus for directions on linking to the optical lithography movie> Improvements in the lithographic processes have permitted the dimensions of the circuitry to shrink to microscopic levels. Dramatic enhancements in

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[1] For an examination of the extensions to optical lithography, see: Rebecca Henderson, "Of Life Cycles Real and Imaginary: The Unexpectedly Long Old Age of Optical Lithography," *Research Policy*, 24 (1995): 631-643.

patterning resolution have enabled the industry to adhere to "Moore's Law," adapted from Gordon Moore's prophetic observation in 1965, that the number of transistors per chip seemed to double every 18-24 months.[2] Improvements in lithography have accounted for approximately one-half of the increase in circuit density.[3] As of June 1994, optical lithography was expected to satisfy manufacturing requirements down to the 0.18 micron (μm) technology node starting in 2001.[4,5] It was predicted that the outer boundaries of optical lithography would be reached by 2004, necessitating the transition to next-generation solutions.[6]

Exhibit 1 captures these predictions. **Exhibit 1** shows the expected move to NGL in 2004, when the smallest features on the chips would require a lithography tool to achieve a resolution of 0.13 μm. At this resolution, it was anticipated, for example, that a 4 Gigabit DRAM of size 18 x 36 mm could be manufactured using approximately 22 masks to transfer the circuitry onto the silicon wafer. The smaller resolutions permitted a tremendous gain in functionality without giving up much in terms of chip size.

If a company could beat this timeline, it would enjoy an insatiable demand for its chips. This prompted keen interest in NGL development efforts.

The Obstacles

In constructing development projects to bridge the optical/post-optical technological discontinuity, the parties confronted three major challenges. First, given the changing economics of the industry, which companies would take leadership roles and to what degree would companies collaborate? Second, were the candidate technologies technically feasible? Third, would the life of optical lithography continue to be extended?

In order to overcome these challenges, the leading chip firms had to decide the optimal combination of horizontal and vertical cooperation. On one hand the leading chip firms wished to cooperate with each other (horizontal cooperation) to pool funds, expertise, and guarantee a critical mass of purchase orders for the equipment suppliers. On the other hand, they not only wanted to be first to market with the more densely packed chips benefiting from the increased miniaturization afforded by NGL, but they also wanted to own the intellectual property generated while developing the new systems.

In terms of cooperation with equipment suppliers (vertical cooperation), the chip companies wanted to cultivate interest and commitments from the leading lithography suppliers. However, two obstacles stood in the way. First, although all the equipment suppliers wanted to work on what would become the dominant technology in the post-optical world, they would

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[2] http://www.intel.com/intel/museum/25anniv/hof/moore.htm.

[3] Lloyd R. Harriott, "Limits of Lithography," Working Paper, Bell Labs-Lucent Technologies (2000), 1.

[4] William H. Arnold, "The SIA Lithography Roadmap," *Microlithography World* (Winter 1995): 7-11.

[5] One micron = one-millionth of a meter where a red blood cell is approximately 8 microns in diameter.

[6] Arnold, op. cit.

prefer to be the sole source (or at least second source) of the new technology rather than being one supplier among many.

Second, chip producers aware of potential government funding for NGL had to consider seriously which equipment suppliers they would court. The leading suppliers of lithography equipment were from Japan—Nikon and Canon, and Europe—ASML. Tensions between the governments of the United States and Japan shrouded the semiconductor industry due to past trade disputes. This meant that if U.S. chip companies were to apply for government funding for NGL development, they would have to walk a tightrope between wanting to partner with the leading equipment suppliers (all non-U.S.) and furthering the technical expertise of non-U.S. suppliers with the help of funds from U.S. taxpayers.

The gathering assembled in 1995 attempted to lessen the uncertainties surrounding NGL through the construction of a technology roadmap and discussions of possible cross-company cooperation. In 1995, all of the NGL alternatives faced primary technical challenges— "show stoppers"—as well as secondary technical challenges requiring "proof-of-concept," both of which contributed to their performance uncertainty (see **Exhibit 2**). **Figure 2** presents a rendition of the technology roadmap that the industry constructed in the mid-1990s to guide the development of post-optical systems. The NGL options shared the characteristic that their illumination sources achieved wavelengths shorter than those in the optical spectrum. These shorter wavelengths allowed for an increase in circuit density, which would contribute to increased miniaturization and integration, with lower power consumption—enabling, for example, the proliferation of hand-held devices.

Research teams around the world pursued the NGL alternatives. Teams in Europe, Japan, and the United States conducted early studies of x-ray, electron projection lithography (EPL), extreme ultraviolet (EUV), and ion projection lithography (IPL or ion-beam). Governments and private companies committed sizable levels of resources to NGL research, most notably to x-ray lithography through the early 1990s.[7] Because of defect problems with x-ray systems, attention turned to the other options. Direct-write electron beam systems had also received early funding in the 1970s and 1980s, but their low throughput presented an almost insurmountable hurdle by the 1990s, when high throughput fabrication facilities (fabs) dominated semiconductor manufacturing.

Extreme ultraviolet and ion projection systems presented possible alternatives. The industry shied away from EUV systems, because initially it was assumed that the only way to generate the EUV radiation was by installing a synchrotron in the fab, a huge capital expenditure that fabs were reluctant to undertake either for x-ray systems or EUV systems. The final

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[7] By the mid-1990s, it was estimated that IBM's expenditures on x-ray lithography totaled over $1 billion (Henderson, op. cit., p.635).

alternative, ion projection, generated a fair bit of support in Europe, with a consortium under the aegis of Infineon at a research facility in Vienna, Austria.[8]

Narrowing the Field in the United States

Among the NGL projects proceeding around the globe, a number of projects were underway in the United States. Three of the leading U.S. semiconductor manufacturers—IBM, Intel, and Lucent—took a particular interest in NGL development. Although the U.S. lithography equipment suppliers were examining NGL alternatives, the chip companies spearheaded the NGL efforts in the United States. In addition to investing heavily in extensions to optical lithography, IBM and Lucent concentrated their research in x-ray, EPL, and EUV. Intel began pursuing EUV in earnest.

By 1995, it appeared that EPL and EUV were quickly becoming the favored technologies in the United States, but before the companies narrowed their bets, they had to carefully weigh the technologies' characteristics.

Technological considerations: EPL vs. EUV

The departure from the optical portion of the electromagnetic spectrum required the development of radiation sources, optics, and processing technologies new to the manufacturing environment. The industry anticipated that extensions to optical lithography would be based on deep-ultraviolet (DUV) light of 0.193 μm and ultimately down to 0.157 μm in wavelength. The NGL technologies would permit the industry to move further down the spectrum or even depart from the spectrum by using electrons or ions in the place of photons to pattern the wafers. Electron projection lithography (EPL) was considered a lower risk option relative to extreme ultraviolet (EUV) systems, but EUV systems appeared more extendible to pattern even finer features.

In contrast to light-based lithography, the resolution of EPL systems is not limited by the "wavelength" of accelerated electrons, rather by imperfections of the equipment or by interaction effects. Systems based on electron-optics, such as electron microscopes, have achieved resolutions roughly the size of a single atom. Instead of resolution, the limiting factors for electron-projection lithography include tool imperfections that cause blurring and interactions either between the electrons due to the electric forces associated with the particles' charges or between the particles and the wafer's surface. <See syllabus for directions on linking to the EPL movie>

An EPL system uses a beam of electrons generated in a "gun" to illuminate, segment-by-segment, the chip's pattern that resides on the "mask," or blueprint for the chip.[9] Then a set of

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[8] Funding from European governments through the Micro-Electronics Development for European Applications (MEDEA) program included a $36 million contribution towards the ion-beam project in Vienna (Peter Clarke, "Europe's Medea Backs Ion-Projection Lithography," *EE Times*, September 29, 1997).

lenses projects these segments, or "subfields," onto the wafer. The lenses employ magnetic fields to focus the beam of electrons, analogous to glass lenses in optical lithography systems.

EUV systems use electromagnetic radiation in the wavelength range of 0.010 to 0.014 μm (10 to 14 nanometers), for which no transparent material exists that can be used for lenses. The EUV systems channel the radiation from the illumination source and bounce the contained beams of radiation off of a series of focusing mirrors. <See syllabus for directions on linking to the EUV movie>

Both the early EPL systems and the EUV system required development in four primary areas: the illumination source, the optics, the mask, and the chemical process involving "resist" through which the image would be imprinted on the wafer. Along each dimension, EPL appeared to have a slight edge over EUV by the mid-1990s (see **Appendix** for a comparison of these performance dimensions).

Additional considerations: EPL vs. EUV

Although the EPL systems seem more straightforward along the primary technical dimensions relative to EUV, their biggest shortcomings are throughput and extendibility. The EPL systems have to overcome difficulties "stitching" the "subfields" together that make up the circuitry. Conceptually similar to a patchwork quilt, the interfaces between the fields of circuitry have to be delicately crafted so as to not detract from the integrity of the whole circuit. The stitching challenges contribute to the low throughput of the EPL systems.

In addition to questioning EPL's throughput potential, those who favored EUV over EPL also question how far EPL can be extended in terms of resolution. They believe that EUV will enter one technology after EPL and could outlast EPL by one, if not two, generations.

The key challenges facing EUV lithography include questions about the radiation source and its influence on the longevity of the optical elements, the mirrors, and the masks. These concerns translate into uncertainty regarding defect control and the attainable resolution.

EUV's unusual history, however, in addition to the technical concerns, had many questioning *its* viability. In contrast to the EPL technologies, the EUV technology grew only partially out of internal research at a chip company. Some of the early research for the EUV technology was conducted at the U.S. Department of Energy's national laboratories, completely outside of the semiconductor industry, for weapon systems. Given this very different history, companies wanting to pursue EUV faced additional obstacles to industry acceptance. First, questions arose as to whether the technology could be adapted to a use dramatically different from the original focus of the developers. Second, the industry infrastructure required to support

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[9] The entire chip pattern was projected by sequentially illuminating—scanning with the electron-beam—all segments (called "subfields") and stitching together the images of the subfields on the wafer by simultaneous motion of the "stages" holding the mask and the wafer.

the technology ranging from specialized chemicals to metrology techniques had to be developed from ground zero, whereas the other projects benefited from concurrent engineering efforts at IBM and Lucent in ancillary technologies like specialized masks.

Lawrence Livermore National Laboratories in the United States, Bell Labs, and Hitachi conducted the early research in EUV from 1988–1990.[10] As for equipment suppliers, Canon funded EUV efforts early on. Bell Labs and Canon, among others, filed patents covering some of the basic technologies upon which EUV systems would be built. Another U.S. national laboratory, Sandia joined the research efforts in the early 1990s, and collaborated with Bell Labs to build a machine with EUV capabilities in 1996.[11] However, in 1996, the U.S. government curtailed its funding of EUV research at the national labs, so either the private sector had to assume funding responsibilities or the semiconductor industry would never realize the development of a production-worthy EUV system.

Making Next-Generation Lithography a Reality

By 1996, IBM, Intel, and Lucent had to do some soul searching to determine their level of commitment to NGL. In general, their degree of leadership in R&D varied dramatically, as reflected in their patenting behavior (see **Figure 3**). Their net income positions also varied widely (see **Figure 4**). Their ability to add value and capture value influenced their willingness to assume the risks associated with NGL. They shared the opinion that they would only go ahead with their NGL development efforts if they could build strong partnerships with other firms. One of the primary decisions they faced was with which equipment supplier or suppliers should they partner in order to commercialize the technology? (See below for a list of potential equipment partners, **Figure 5** for their revenue performance, **Figure 6** for their unit sales, and **Figure 7** for the value per unit sold.) Furthermore they had to determine the terms governing those vertical partnerships, e.g., when to bring the supplier on board, how to divide up intellectual property, etc. Finally they had to decide whether they wanted to forge horizontal partnerships with other chip producers. All the while, the industry continued to extend the life of optical lithography well beyond limits deemed insurmountable only a few years prior.

Potential Equipment Partners

ASM Lithography

Based in the Netherlands, ASM Lithography (ASML) grew dramatically from the late 1980s to the 1990s, to join Nikon and Canon as the world leaders in lithography. Following its divestiture from Advanced Semiconductor Materials International in 1990, ASML received its financial backing from Philips and two Dutch banks.[12] ASML successfully expanded outside of

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[10] Charles Gwyn, et al., "Extreme Ultraviolet Lithography," Extreme Ultraviolet Limited Liability Company white paper, November 1999, .2.

[11] Ibid.

[12] Jeff Dorsch, "ASML Challenges Canon for No. 2 Spot," *Electronic News,* February 16, 1998.

Europe, penetrating the American, Korean, and Taiwanese markets, and it planned to make a play for the Japanese market, long dominated by Nikon and Canon.[13]

Canon

Through the 1980s, Canon surged onto the scene, capturing and retaining a second-place position in the lithography market. Canon approached the need for next-generation systems from two fronts. In addition to being actively involved in extending the life of optical lithography, for example, through its Innovative Double Exposure by Advanced Lithography (IDEAL) project, Canon also conducted research targeting next-generation systems. By 1993, Canon had secured a number of fundamental patents in the United States related to EUV, and roughly 300 U.S. patents related to x-ray lithography.[14]

Integrated Solutions Inc. (GCA)

The roots of Integrated Solutions Inc. (ISI) could be traced to one of the former leading photolithography suppliers in the United States—the GCA Corporation. GCA folded in 1993, and ISI arose from its "ashes."[15] Due to SEMATECH's selection of GCA as a preferred lithography supplier prior to its demise, ISI inherited technologies developed with U.S. government funding and a legacy of working with leading U.S. chip companies through SEMATECH. ISI migrated from a "mainstream" supplier of lithography tools to one focused on custom systems.[16]

Nikon

Like Canon, Nikon capitalized on its optics expertise from its camera business to become a leader in the lithography. By the mid-1990s, semiconductor equipment sales constituted approximately 60 percent of Nikon's sales, camera sales accounted for 30 percent, and the remaining 10 percent was made up of surveying instruments and microscopes.[17] With their systems in such high demand, Nikon estimated a lead-time of 12–18 months by 1995.[18] Nikon's presence in Asia, particularly in Japan and Korea, was very strong, but it faced more competition in Europe and especially in the United States. The president of Nikon's U.S. subsidiary, Nikon Precision, noted that one of the biggest changes the company confronted over time was the globalization of the industry and the increasing interconnections across companies: "'Customers are either global or have global alliances, and we cannot deal with any customer as an isolated case.'"[19]

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[13] Ibid.

[14] Phil Ware, "Patents that Push All the Limits," SubMicron Focus (Canon), Spring 1998, Volume 3, Issue 1.

[15] Dorsch, op. cit.

[16] Ibid.

[17] Judy Erkanat, "Breakfast in the Valley: Nikon Sees Market Action in Deep UV," *Electronic News*, July 14, 1997.

[18] These tremendous lead-times prompted the following bumper sticker: "'Honk if You've Got a Stepper'" (Erkanat, op. cit.).

[19] Erkanat, op. cit.

SVG (Perkin-Elmer)

Another primary U.S. lithography supplier of the past, the Optical Lithography business of the Perkin-Elmer Corporation, also fell on hard times in the early 1990s. With outside financial assistance, including from IBM, the Silicon Valley Group, Inc. (SVG) was founded, which salvaged the lithography operations of Perkin-Elmer. Eventually an even broader coalition of organizations came through to help shore up the company's financial position. Intel, Motorola, and Texas Instruments contributed $30 million, and, in an unprecedented move, SEMATECH made a $30 million equity investment.[20]

Ultratech Stepper

Although it faced severe financial problems a few times during its history, Ultratech endured as a leading U.S. lithography supplier. Ultratech engaged in an initial public offering in 1994, following a management buyout from General Signal the prior year.[21,22] In addition to pursuing a foothold in the disk drive industry, Ultratech catered to chip companies that were pursuing a "mix-and-match" strategy, whereby critical layers of circuitry would be patterned by the most advanced lithography tools, but for non-critical layers, lithography systems based on older technologies would be used.[23]

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[20] Dorsch, op. cit.

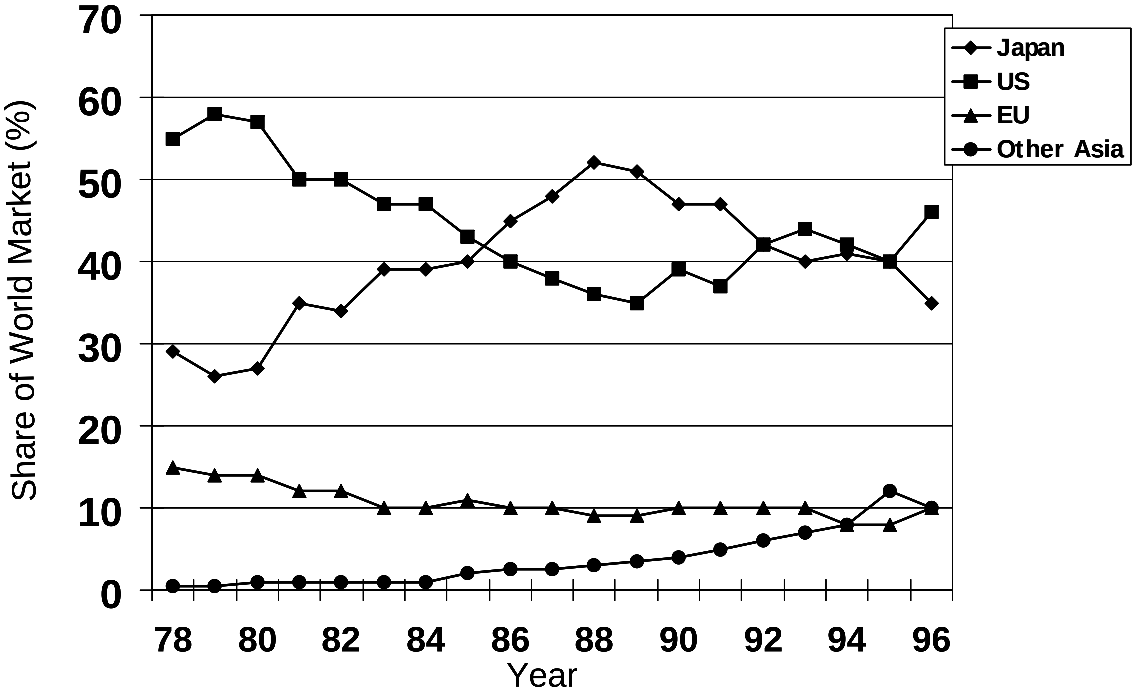
[21] Ibid.

[22] Ronald Dornseif, Clark Fuhs, Takashi Ogawa, Klaus Rinnen, and Amy Worley, "1999 Wafer Fab Equipment Market Share Estimates: Lithography, RTP/Diffusion and Implant," Dataquest Report, June 26, 2000.

[23] Dorsch, op. cit.

Figure 1

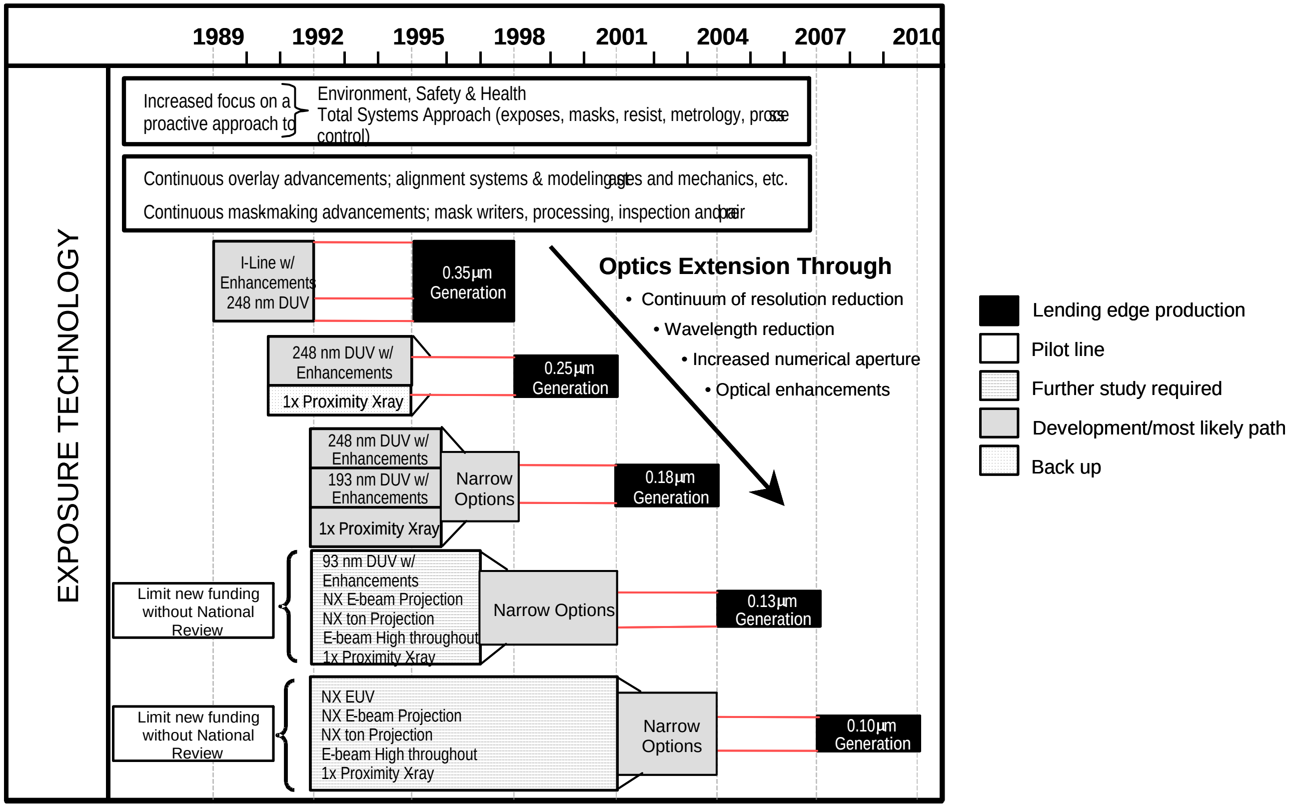
Leadership in the Semiconductor Industry



Source: Dataquest

Figure 2

The 1994 Lithography Roadmap



Source: Arnold, William H. *Microlithography World*, Winter 1995, p. 9.
Note: The "NX" represents a yet-to-be-determined level of reduction from the image on the mask to what is projected onto the wafer.

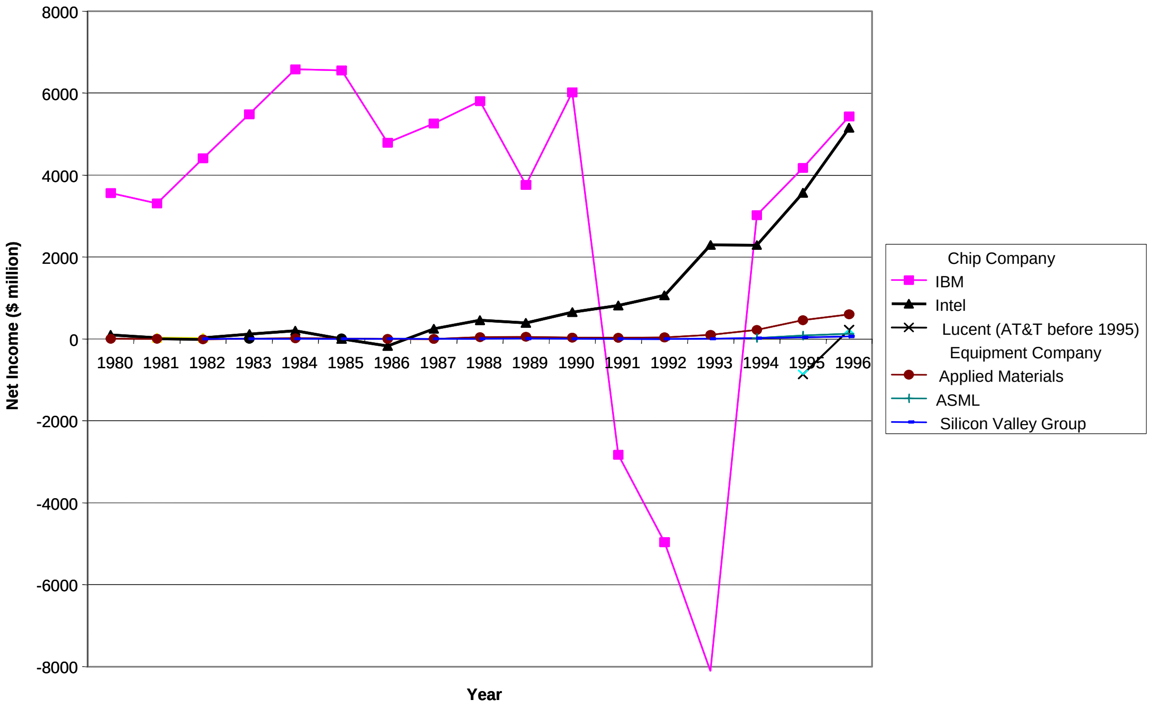
Figure 3

Patenting Behavior

Note: The patent classifications covered in these data series focus primarily on semiconductor devices and related process technology, not necessarily including lithography research. The data cover patents granted through December 31, 1998. The Lucent (AT&T) series includes patents for AT&T Corporation, Lucent Technologies, Inc., AT&T Global Information Solutions Company through 1996, and NCR Corporation for 1991-1996.(Source: Technology Assessment and Forecast Program (1999). "Technology Profile Report: Semiconductor Devices and Manufacture 1/1969 – 12/1998." U.S. Patent and Trademark Office, Office for Patent and Trademark Information, July.)

Figure 4

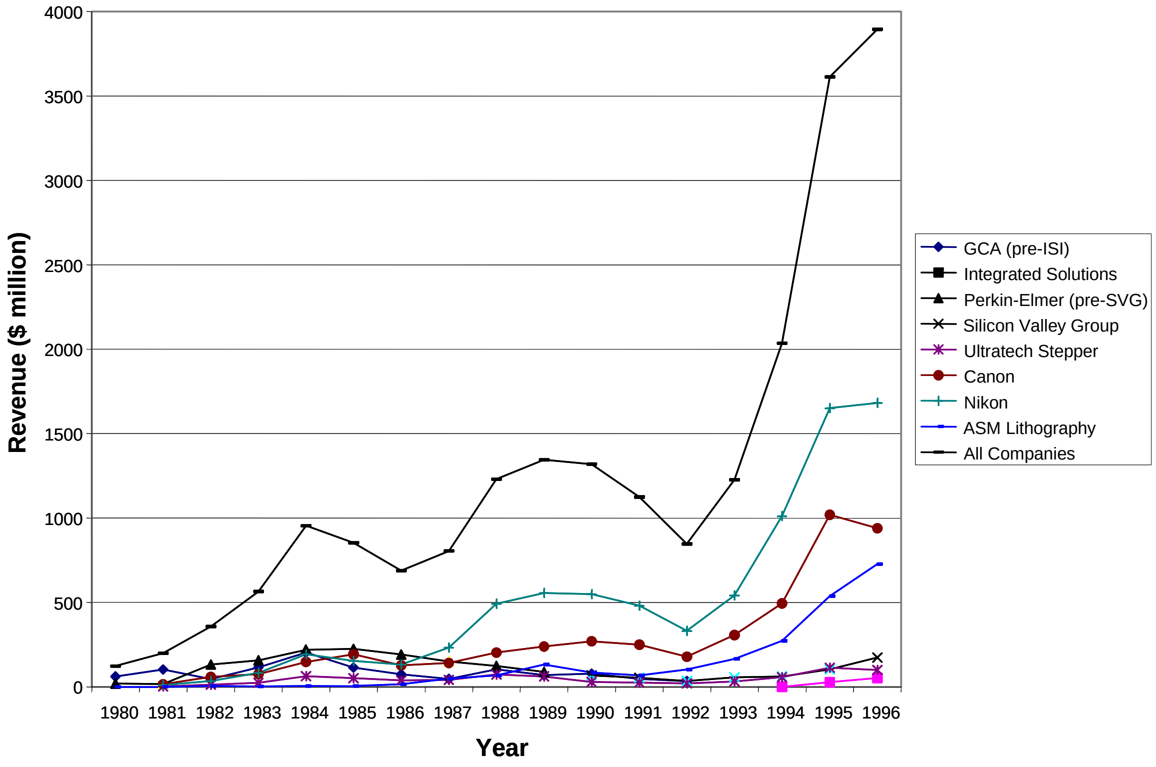
Income Growth Over Time



Note: These net income figure are for the whole company, not just the company's semiconductor operations.
(Source: Compustat.)

Figure 5

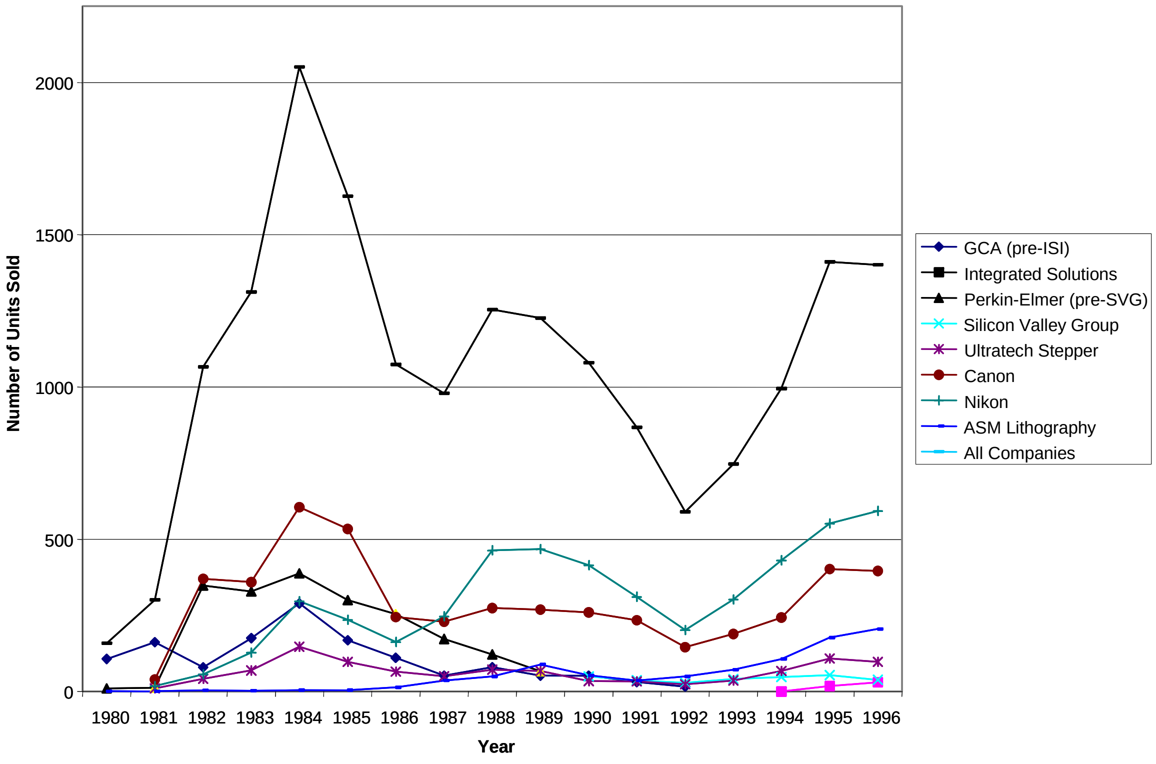
The Lithography Market



(Source: Dataquest)

Figure 6

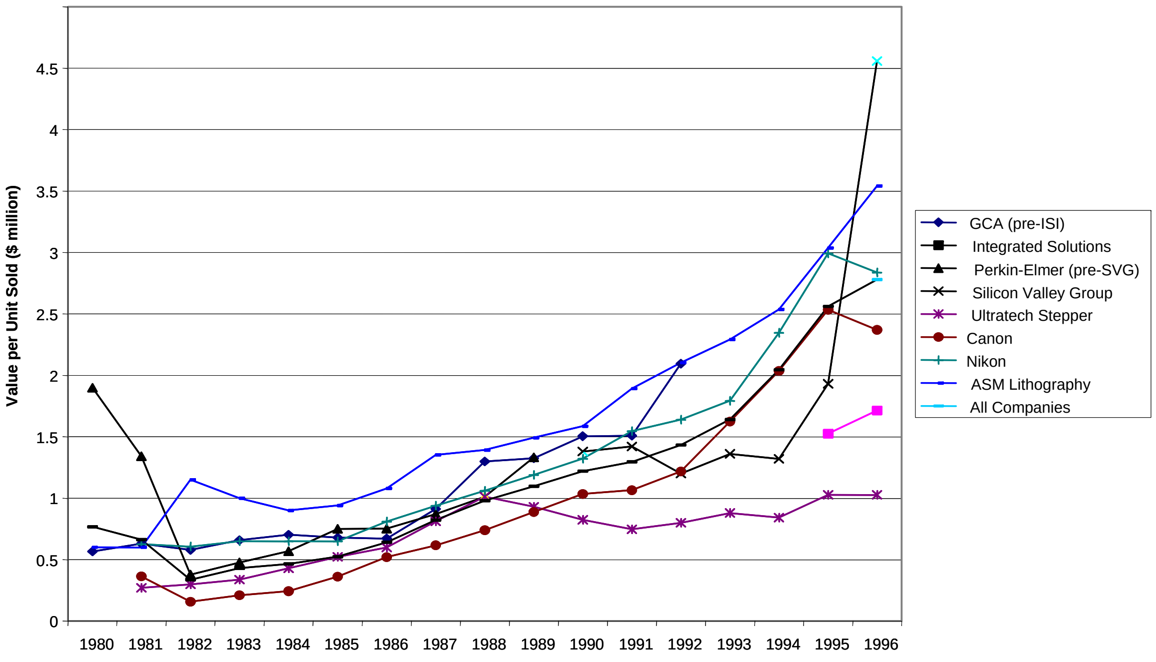
The Lithography Market in Terms of Volume



(Source: Dataquest)

Figure 7

Unit Values of Lithography Systems Sold



Note: In 1996, Silicon Valley Group sold no projection aligners, only higher-end steppers.
(Source: Dataquest)

Exhibit 1

NEXT-GENERATION LITHOGRAPHY (A): BETTING ON A NEW PRODUCTION TECHNOLOGY IN THE SEMICONDUCTOR INDUSTRY

Projected Processing Requirements

	Year of First Shipment (on production tooling)					
	1995	1998	2001	2004	2007	2010
Lithography Technology	Optical	Optical (Deep UV)	Optical (Deep UV)	NGL	NGL	NGL
Resolution (µm)	0.35	0.25	0.18	0.13	0.10	0.07
Function						
• DRAM (bits)	64M	256M	IG	4G	16G*	64G
• Microprocessor (logic transistors/cm^2)	4M	7M	13M	25M	50M	90M
• ASIC (transistors/cm^2 auto layout)	2M	4M	7M	12M	25M	40M
Device Size						
• DRAM (mm)	10 x 20	12 x 24	15 x 30	18 x 36	22 x 44	28 x 50
• Microprocessor (mm)	16 x 16	18 x 18	19 x 19	21 x 21	23 x 23	25 x 25
Minimum Mask Count	18	20	20	22	22	24

(Adapted from: William H. Arnold, "The SIA Lithography Roadmap," *Microlithography World* (Winter 1995): p. 8.)

*A 16-gigabit DRAM would have the capacity to hold four years of the contents of a typical daily newspaper ("Nikon's Reduction-Projection Electron Beam Exposure System." *Business Wire*, January 26, 1999).

Exhibit 2

NEXT-GENERATION LITHOGRAPHY (A): BETTING ON A NEW PRODUCTION TECHNOLOGY IN THE SEMICONDUCTOR INDUSTRY

Technological Obstacles

NGL Technology	Show Stoppers	Proof-of-Concept Required
E-Beam Projection	• Column designs to minimize Coulomb interaction impact on Critical Dimension (CD) control • Development of NX strutted membrane mask technology	• Thermal management • Robust single level resists with high sensitivity
E-Beam High Throughput (Direct-Write)	• Viability of array cathodes (stability, lifetime) • Efficient proximity effect correction techniques	• Pattern generation complexity • Robust high sensitivity resist systems
EUV	• Development of optics fabrication technology (1Å RMS) • Development of reflective multilayer mask technology	• Low cost surface imaging resist systems • Development of point source illumination
Ion Projection	• Development of NX stencil membrane mask technology • Column designs to minimize space charge impact on resolution	• Low distortion optics • Cost-of-ownership
1X X-Ray*	• Improved mask capability (overlay, CD, defects) • Point source system/collimator for granularity	• Aligner capability and availability • Extendibility to 0.13 µm

(Adapted from: William H. Arnold, "The SIA Lithography Roadmap," *Microlithography World* (Winter 1995): 10.)

*Note: "1X" means that the image that is projected onto the wafer is the same size as the image on the mask. Optical lithography tools are frequently "5X" where the image on the mask is reduced in size by 5 before it reaches the wafer. Such reduction helps to eliminate transferring defects found at the mask level to the wafer.

Appendix

Comparing the EPL and EUV Technologies

When it came time to place their bets on NGL systems, the chip companies looked particularly closely at EPL and EUV systems. Some of the dimensions along which they compared the systems are found below.

1) *The source*: the EPL systems used a non-controversial electron source, whereas EUV's source was not straightforward but surely would entail a more complicated energy source to generate the "plasma" producing the photons needed to pattern the resist on the wafer. The EUV system also required a condenser to funnel the resultant radiation to illuminate the mask properly;

2) *The optics*: the EPL systems drew on 50-year-old technology at the foundation of electron microscopes and 35 years of experience with e-beam lithography systems, while EUV required a projection system of carefully polished mirrors coated with multilayer reflective material. Because many materials readily absorbed EUV radiation, EUV required a radical transformation in the optics systems from *refractive* systems common in optical lithography to a *reflective* system;[24]

3) *The mask*: Mask development was a daunting proposition across all of the NGL projects, as articulated in the following quote: "In fact, many have suggested that the next-generation lithography challenge is actually a mask-making challenge for all of the leading NGL candidates."[25] For the EPL systems, this dimension required the most fundamental development. The construction of a mask based on a membrane concept was totally new. The concept for the EUV mask was also novel and entailed the reflection of the radiation from the nonpatterned portions of the mask into the camera section of the tool. The radiation that hit the patterned portion of the mask was absorbed. The camera in the EUV system then reduced the image by ¼ before the image was projected onto the thin layer of resist spread on the wafer.[26] Even with these new requirements for the operation of their masks, the EUV developers felt their requirements were less of a departure from know-how developed for optical mask-making than the new membrane-based or stencil masks used in the EPL systems;

4) *The resist*: In order to pattern the wafer with the circuit's image from the mask, a photo-sensitive material had to be spread across the wafer that was illuminated and then developed like in any basic photographic process. The pattern that remained after the developing step allowed for the circuitry to be built up either by etching selectively or by imparting impurities to influence how electrical currents would flow through the chip. The resists developed for these next-generation lithography applications were much more advanced than

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[24] The industry did have some history with reflective optics. Older optical systems, scanning projection aligners, used through the early 1980s, utilized reflective lenses (Henderson, op. cit., 639).

[25] David Lammers, "Scalpel is Set to Go Commercial," *EE Times*, December 11, 1998.

[26] Gwyn, et al., op. cit., 3, 97.

what is found on a typical photographic plate. The EPL researchers planned on coating the wafers with resists used in deep-ultraviolet (DUV) systems, thus leveraging the emerging infrastructure for advanced optical systems. EUV, however, had particular requirements for its resists because the very short wavelengths of its radiation made it highly absorbent. Wafers had to be coated with very thin layers of a new breed of resist to mitigate this absorption problem and successfully transfer the image from the mask onto the wafer. EUV developers also planned to leverage resist development efforts for 0.248 μm DUV optical lithography.