Of Life Cycles Real and Imaginary:
The Unexpectedly Long Old Age of Optical Lithography.

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Abstract

The history of many industries can be characterized as a series of technological "life cycles." This has led some to argue that the limits to a technology are a predictable function of its underlying physics and the structure of the dominant design. This paper uses the unexpectedly long old age of optical photolithographic alignment technology to suggest that this belief is probably incorrect. Unexpected changes in user needs and in the capabilities of component and complementary technologies permitted optical photolithography to dramatically exceed its "natural" limits. However belief in the existence of a predictable life cycle had important implications for the evolution of the technology since it provided a framework within which industry participants embedded tacitly held, largely unexamined knowledge about the ways in which user needs and component and complementary technologies were likely to evolve. These results lend support to those that have argued that it is important to explore both the social context of a technology and the dynamics of the technology itself if one is to fully understand patterns of technological evolution.

"Proponents of all the new lithographic technologies face a common obstacle: the stubborn refusal of conventional ultraviolet lithography to die..." (High Technology, 1983)

Introduction

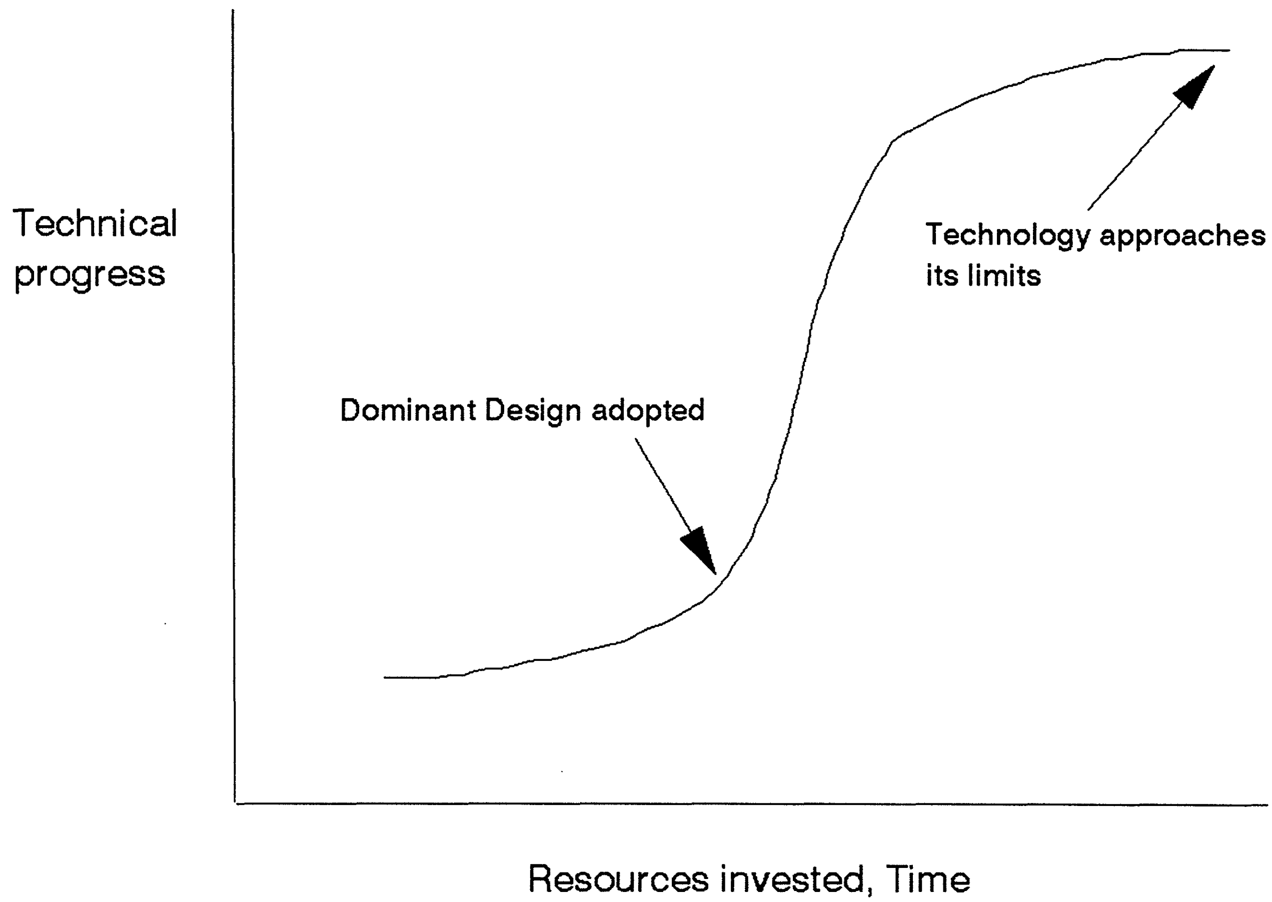
Many technologies move from a period of "infancy" through the adoption of a dominant design to a period of maturity and eventual "exhaustion" of the dominant design (Abernathy and Utterback, 1978; Anderson and Tushman, 1990; Tushman and Rosenkopf, 1992). In the case of technologies whose evolution follows this pattern, the adoption of a dominant design facilitates a transition to a focus on incremental product development and aggressive investment in process technology, but it simultaneously limits the technology's ultimate performance. Returns to investment in the technology eventually fall dramatically, setting the stage for a move to another generation of technology and a repetition of the cycle (Dosi, 1982; Foster, 1986; Gardiner, 1984, Sahal, 1985) (Figure (1)). Although not all technologies follow this pattern, the life cycle has been shown to be a useful ex post descriptive device in industries as diverse as automobiles, cement, sailing ships, heart implants, disk drives, turbo jets and computers (Abernathy and Utterback, 1978; Constant, 1980; Foster, 1986; Anderson and Tushman, 1990; Christensen, 1993a,b).

Insert Figure 1 about here.

Several authors have suggested that the regularity of the life cycle implies that one can predict the limits of a technology from a knowledge of the laws of physics. In his 1986 book Innovation, The Attackers Advantage, for example, Foster suggested that no matter how much the design of sailing ships is refined, fundamental limits in the efficiency with which sales can translate the power of the wind to motion constrains the speed at which sailing ships will ever be able to sail. This idea echoes the much more detailed work of Constant (1980), who described the "presumptive anomalies" that led aerospace engineers to predict the limits of the piston engine from a knowledge of fundamental physics.

Sahal (1985) also suggested that the limits of a dominant design are technologically determined. He hypothesized that the elaboration of a dominant design usually takes place

Figure (1): Schematic of the life cycle



through changes in scale or increases in complexity, and suggested that beyond a certain point this process causes the design to collapse "under its own weight." A technology ultimately becomes impossibly complex, too small, or too large. A similar idea is advanced in the work of Gardiner (1984) who drew a distinction between "robust" and "lean" designs. He suggested that when a dominant design is first adopted it is usually "robust" in that it can be extended or "stretched" in a variety of ways. Over time, as the possibilities inherent in the technology are exhausted, designs become increasingly "lean" and must ultimately be replaced. These ideas have been widely adopted as aids to technological forecasting (Van Wyk, 1985).

However the usefulness of the life cycle as a tool that can be used to predict the limits of a technology has been challenged by evidence suggesting that technologies sometimes substantially exceed their "natural" limits.[1] For example Utterback and Kim (1985) describe the dramatic improvements in the performance of home iceboxes that occurred when the industry was confronted with competition from home electric refrigerators, major innovations in stream locomotive technology upon the introduction of diesel electric technology, and improvements in the quality and efficiency of gas illumination that "nearly bankrupted the fledgling Edison Electric Company." Similarly Christensen (1993a) suggested that the life cycle provided little guidance to firms seeking to understand the limits of disk drive component technology, and demonstrates that individual components often showed dramatic and unexpected improvements in performance. He suggested that the technology was simply "too complex" to forecast accurately, and that predictions of limits within particular firms became self fulfilling since they led to resources being allocated to competing technologies.

This paper breaks open the history of the limits to optical photolithographic alignment technology to show that any prediction of the limits to the performance of a particular technology predicated on the "technological logic" of the product itself is likely to be fundamentally misleading. The imminent obsolescence of optical lithography has been

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[1] DeBresson and Lampel (1985) outline a comprehensive critique of the assumption that Abernathy and Utterback's product/process life cycle model describes a deterministic relationship between industry evolution and firm strategy or structure.

confidently predicated since 1977, yet the technology still dominates its industry. Through a detailed study of the evolving limits to optical photolithographic performance I show that a technology's limits are determined not only by the structure of the dominant design and the laws of physics, but also by the capabilities of its components, by the needs and preferences of its users, and by the evolution of key complementary technologies.

I suggest that this complexity was effectively invisible to industry participants since aggressive incremental exploitation of the prevailing design led knowledge about component performance, user capabilities and complementary technologies to develop an embedded, tacit, "taken for granted" quality that led to levels of current performance being mistaken for absolute limits. Thus the case of optical photolithography illustrates why arguments framed in terms of inherent technical limits may be common in mature industries, and why *ex post* arguments framed in terms of underlying technological dynamics have such a seductive clarity. However from an *ex ante* perspective, it suggests that the life cycle may be more useful as a description of the embedded knowledge of industry participants and hence as a tool for predicting patterns of investment than as a means of predicting absolute physical limits.

The paper begins with a brief description of the history of optical photolithographic aligners. I show that the "life cycle" provides a plausible ex post description of the technology's history but that predictions of the limits to the technology's performance derived from so called "inherent technological limits" have been consistently proven wrong. The following section explores the evolution of the limits to optical lithographic limits in detail to show that they are a function of the performance of component technologies, of user needs and capabilities and of the evolution of complementary technologies, and explores the tacit assumptions that led industry experts to predict the limits of the technology with such spurious accuracy.

The paper closes with a discussion of the implications of these results for our understanding of technological limits as a conceptual and predictive tool. An extensive body of research in both the organizational and economic traditions suggest that competition between technologies and the selection of a dominant design is shaped as much by organizational, institutional and strategic factors as it is by any intrinsic technological superiority (Hughes, 1983; David, 1985; Farrell and Saloner, 1985; Tushman and Rosenkopf, 1990; Anderson and Tushman, 1990; Bijker et. al. 1987; Powell and DiMaggio, 1991; Van de Ven and Garud, 1991; Garud and Rappa, 1993). The history of optical lithography suggests that these factors may be equally important in shaping the evolution of "incremental" technological development.

The Unexpectedly Long Old Age of Optical Lithography.

Optical photolithographic aligners are complex pieces of capital equipment used in the manufacture of solid state semiconductor devices. They are designed to transfer small, intricate patterns to the surface of a wafer of semiconductor material such as silicon.[2] During the photolithographic process the surface of a wafer is coated with a light-sensitive chemical, or "resist," while the pattern that is to be transferred to the wafer is drawn onto a template, or "mask." The image of the mask is then projected down onto the surface of the resist, so that only those portions of the resist defined by the mask are exposed to light. The exposed resist is stripped away, and the pattern that remains is used as the basis for further processing. This process may be repeated as many as twenty times during the manufacture of a semiconductor device, and each layer must be located precisely with respect to the previous layer (Watts and Einspruch, 1987). Photolithographic aligners are used to position the mask accurately with respect to the wafer and to project the image of the mask onto the wafer surface. (Figure 2 gives a simplified representation of this complex process.) Optical photolithographic aligners use visible light to expose the resist, while electron beam ("e-beam") aligners use electrons and X-ray aligners use x-rays.

Insert Figure 2 about here.

An aligner's performance is defined principally by its minimum feature size

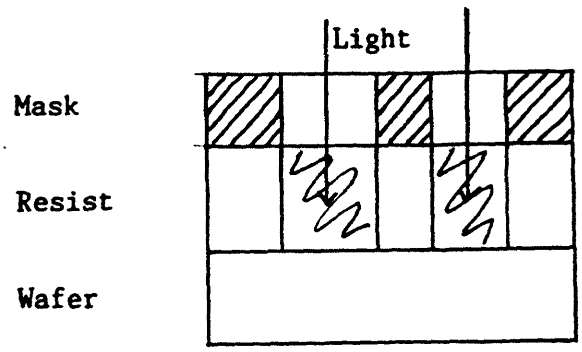
[2] Here and in the discussion that follows I draw upon a detailed qualitative and quantitative data base collected over the course of eighteen months field work in the photolithographic industry. A description of the data and of the study's methodology is given in Appendix A.

Figure (1)

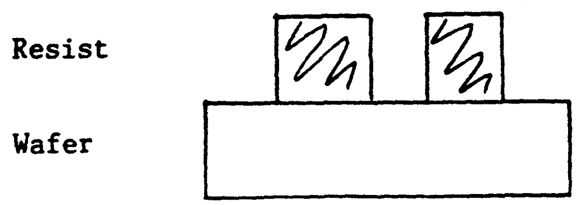
The Lithographic Process

(This is a highly schematized version of a very complex process)

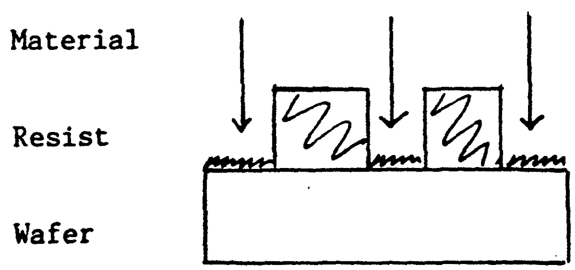
1. Expose Resist



2. Develop Resist



3. Deposit Material



4. Remove Remaining Resist

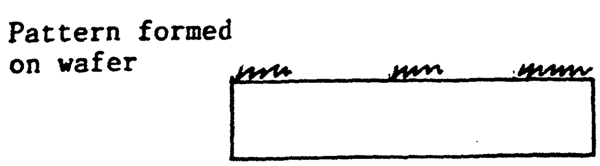
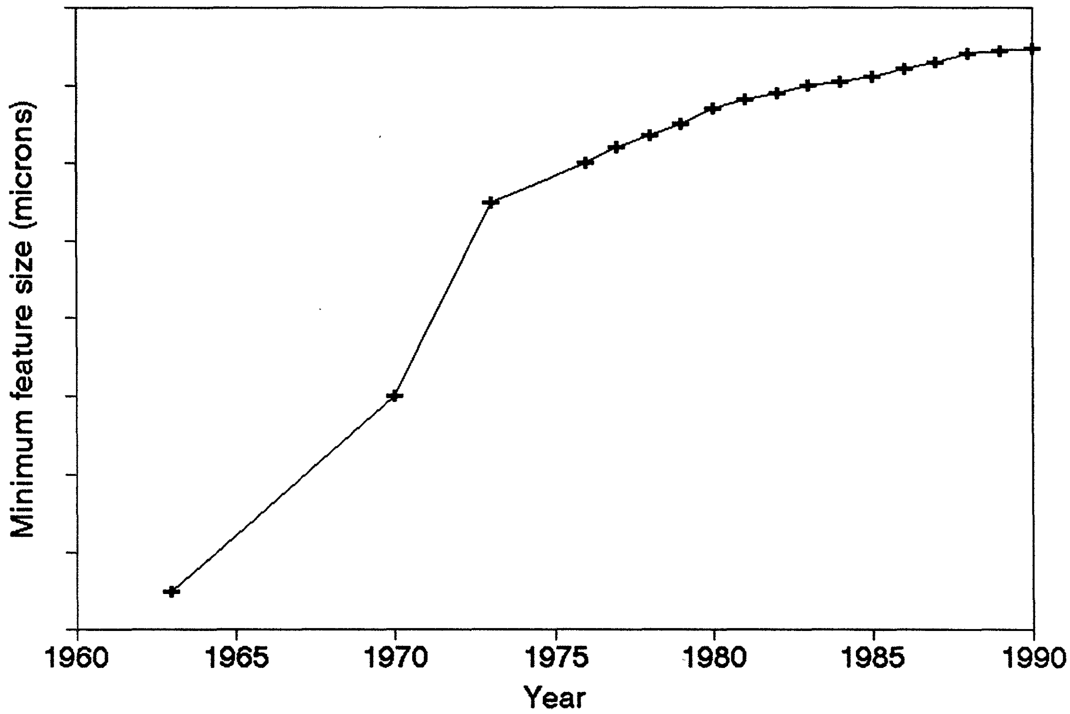
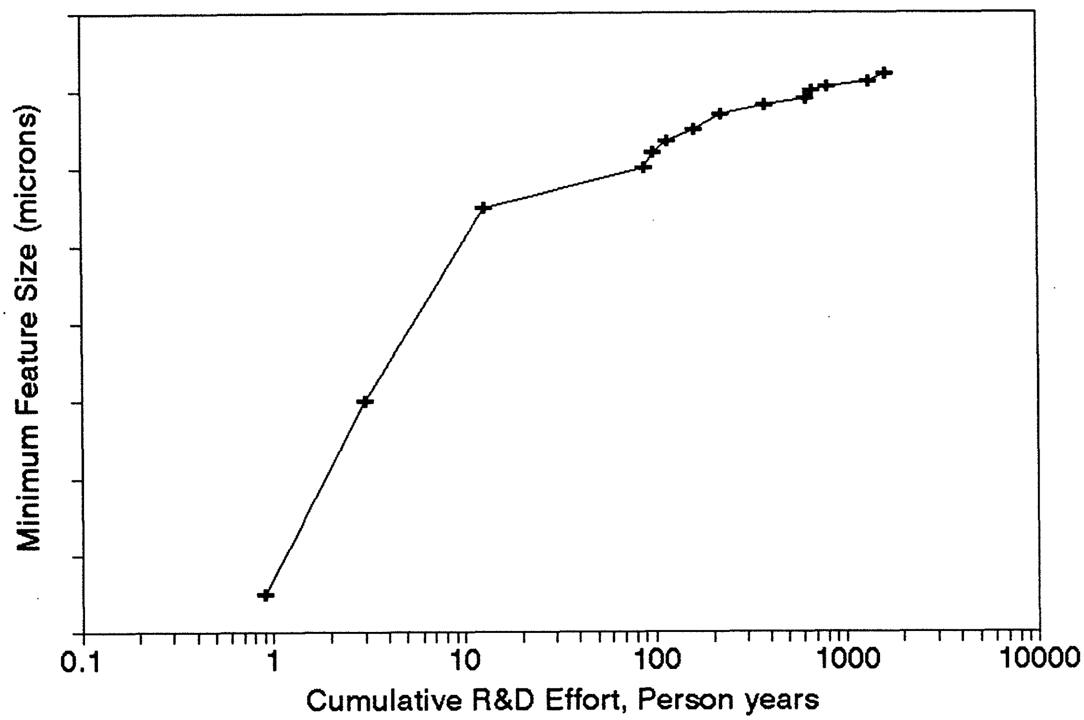


Fig (3a) Minimum Feature Size over Time



Fig(3b) Minimum Feature Size vs. Effort



capability, or by the size of the smallest pattern element that it can successfully transfer to the surface of the wafer.[3] Since smaller circuits run both faster and cooler than larger ones, progress in the manufacture of solid state semiconductor devices has come largely through continued reductions in circuit size, and progress in photolithography has taken the form of continuous, dramatic, reductions in minimum feature size. The aligners of the late sixties cost a few thousand dollars and produced images that were about 10 to 15 microns (μm) in size, while a modern production aligner sells for two to three million dollars and can produce lines considerably less than a micron in width.[4]

Figures (3a) and (3b) show the evolution of minimum feature size capability as a function of time and of the cumulative resources invested in product development respectively. At first glance these curves appear to be strikingly consistent with the classical theory of the technology life cycle. As Abernathy (1978) and Anderson and Tushman (1990) have suggested, the transition to a regime of rapidly increasing technological capability occurred simultaneously with the introduction of a product embodying a "dominant design," in this case Kulicke and Soffa's 686 model in 1966. And as Sahal (1985) and Foster (1986) suggest, progress in optical technology has become increasingly expensive as its "limits" have been approached. Early rapid advances in performance have been succeeded by much slower progress more recently, and industry experts now suggest that the wavelength of visible light constrains the performance of optical lithographic aligners to a minimum feature size of around .20μm. At current rates of progress in semiconductor processing, this implies optical lithography will be replaced in leading edge applications within the next three to four years.

Insert Figure 3 about here.

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[3] Other important dimensions of aligner performance include throughput and yield. During the period covered by this paper, however, both x-ray or e-beam aligners were notably slower than optical aligners, and were not characterized by significantly higher yields.

[4] One micron (1μ) = 1000 millimeters

A more detailed exploration of the industry's history, however, highlights the dangers inherent in using the life cycle as a predictive device. Figure (4) graphs predictions of the "limits" to optical lithographic performance over time. Industry experts have been confidently predicting the obsolescence of optical lithography for the last fifteen years. The first investments in e-beam and x-ray lithographic technology were made before 1970, and e-beam aligners were in (limited) use as a production tool in at least one company by 1977. IBM alone has invested over a billion dollars in x ray lithography.

Insert Figure 4 about here.

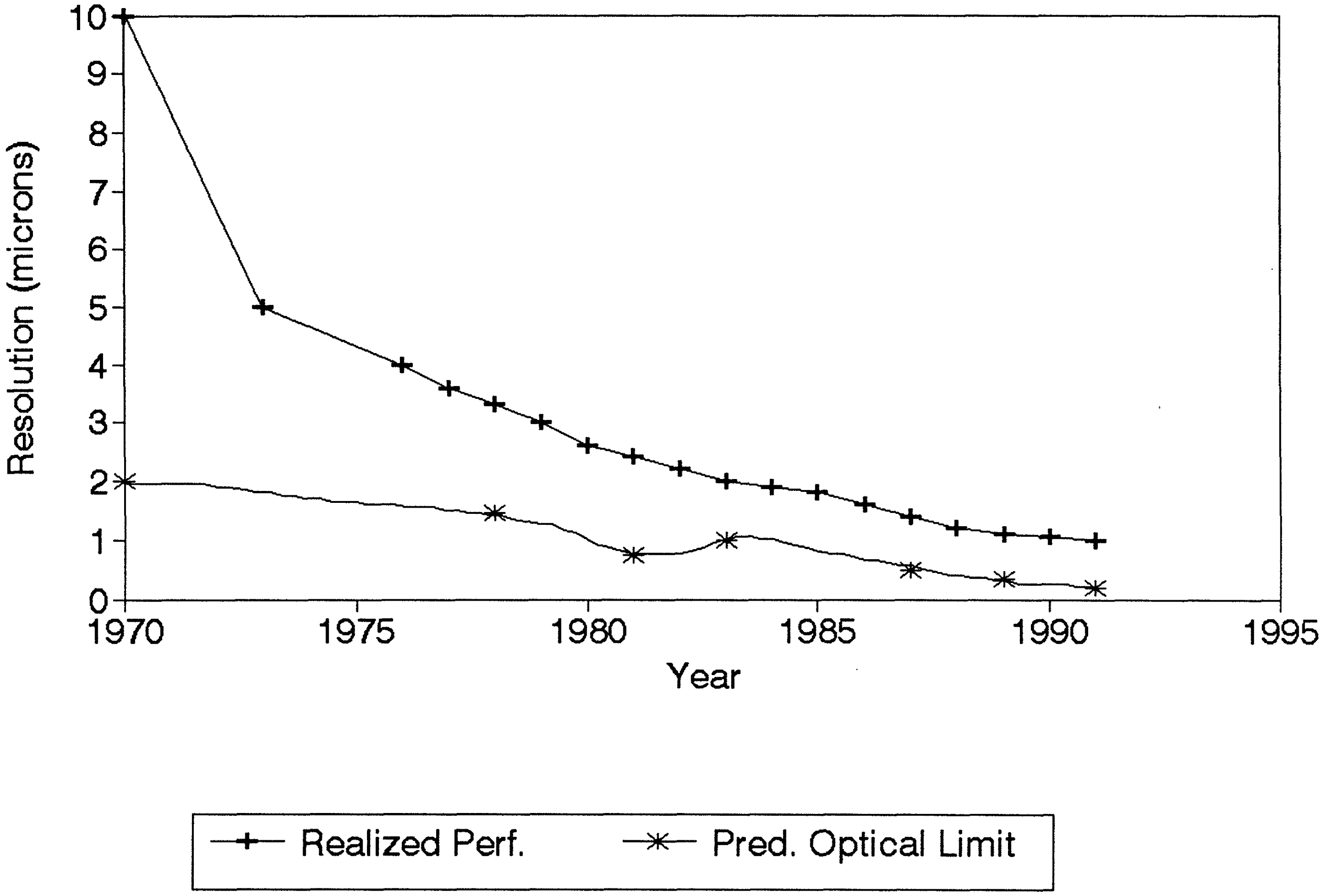
But despite the continued publication of articles with titles like "Electron Beam - Now a Practical LSI Production Tool," (Solid State Technology, 1977), "X-Ray Lithography: Optical's Heir" (Semiconductor International, 1982), and "X-Ray Lithography, Wave of the Future?" (Electronic Business, 1989), optical photolithography continues to dominate industrial production. Understanding the unexpectedly long old age of optical lithography - and hence of the difficulties inherent in predicting technological limits - requires an understanding of two interdependent factors. On the one hand it requires a knowledge of the ways in which the limits to optical lithography performance were shaped by the evolution of individual components, changes in user needs and capabilities, and by the potential of complementary technologies. On the other it requires an appreciation of the ways in which deeply embedded tacit knowledge, developed during extended periods of incremental development, obscured the importance of this context in shaping the performance of the technology so that industry debate could be plausibly framed in terms of inherent physical constraints.

Defining the Limits of Optical Lithographic Performance

Wavelength: An Insuperable Barrier?

The experts who first forecast the death of optical lithography based their predictions on the fact that X-rays and e-beams have much smaller wavelengths than optical light. The

Fig (4): Predicted Limits of Optical Lithography vs. Realized Performance



most important determinant of the minimum feature size capability of an aligner is its "resolution," or the size of the smallest image that it can focus successfully at the wafer surface.

Aligner resolution is given by the Rayleigh criterion, or by the expression:

$$\textit{Resolution} = k_1 \times \frac{\textit{Wavelength}}{\textit{Numerical Aperture}}$$

where *Wavelength* is the wavelength of the exposing source, *Numerical Aperture* is a measure of the size of the aligner's lens, and k_1 is a constant determined by a variety of factors including the optical characteristics of the aligner lens and the chemical composition of the resist.

From the Rayleigh criterion it is immediately clear that there are three routes to improving the minimum feature size of an aligner, or reducing its resolution: reducing the wavelength of the exposing source, increasing the size of the aligner lens or changing the value of k_1.[5] In 1977, when the inherent limits of optical lithography were first confidently predicted, aligner lenses were believed to be limited to a numerical aperture of about .167 and k_1 was believed to have a value of around 1.0. Given these values, it was straightforward to use the Rayleigh criterion to predict the limits of optical lithography.

The optical aligners of the late seventies used "g line" sources - optical sources with a wavelength of about 436 nanometers, or .436μm[6], and thus were limited to the production of devices whose smallest feature size was around 2.6μm. Stretching the dominant design by moving to smaller and smaller wavelengths would improve aligner resolution, but industry experts believed that it would be difficult to use optical wavelengths shorter than the "i-line," around 240nm, or .240μm. This implied that the limits to optical photolithography were

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[5] Notice that improving the performance of an aligner means *reducing* resolution. Smaller resolution implies finer lines on the wafer.

[6] Before the introduction of excimer laser sources into production settings around 1989, optical aligners used in production settings used ultraviolet sources. These sources emit light at a range of frequencies. A "g-line" source emits most of its energy at around 436nm, but also emits some energy at adjacent frequencies.

around 1.44μm.

Dramatic increases in Numerical Aperture, or lens size, were considered unlikely since industry experts believed that optics was a relatively mature, well understood science. Moreover increases in Numerical Aperture were rejected as a route to improved resolution because of their effect on the aligner's *depth of focus*. Depth of focus is a measure of the margin of error available to an aligner's user, since it is the distance above and below the wafer plane in which the image is accurately projected (See figure 5). Too small a depth of focus makes it impossible to focus the aligner on the wafer, so that improved resolution buys the user no benefit in terms of smaller feature size.

Insert Figure 5 about here.

Depth of focus is given by the expression:

$$DepthofFocus = k_2 * \frac{Wavelength}{NumericalAperture^2}$$

Where k_2 is a constant with a value of 0.5. Thus increasing numerical aperture as a road to smaller resolution carries a much greater penalty in the form of reduced depth of focus than does simply reducing wavelength, since while resolution falls as the inverse of numerical aperture, depth of focus falls as the *square* of numerical aperture. Figure (6) shows depth of focus as a function of resolution for the two strategies of reducing wavelength and increasing numerical aperture. Increasing numerical aperture greatly reduces the ratio between depth of focus and resolution, and hence the "margin of error" available to the semiconductor manufacturer.

Insert Figure 6 about here.

In the early eighties semiconductor manufacturers required a depth of focus that was about three times that of an aligner's resolution. Superimposing this constraint on figure (6) leads to the prediction that aligners whose numerical aperture is greater than 0.170 will have

Figure (5): Depth of Focus and Resolution

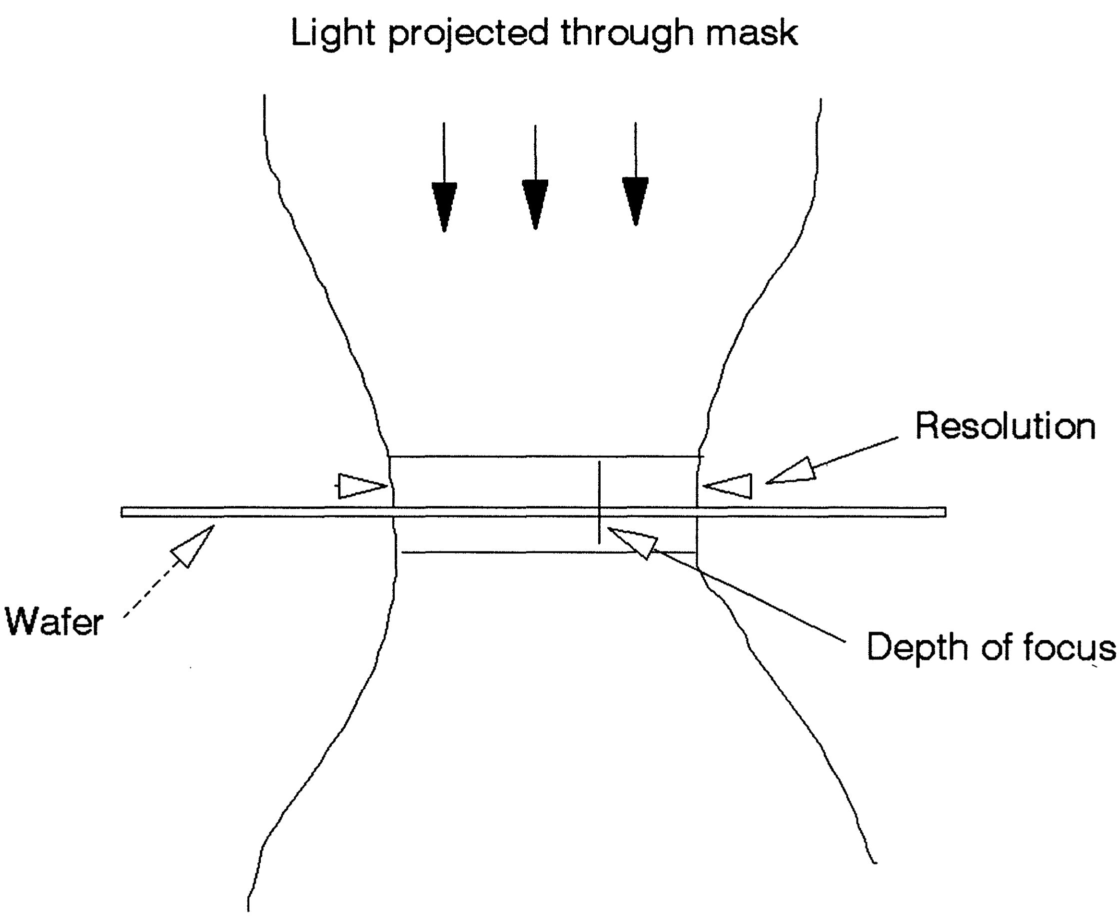
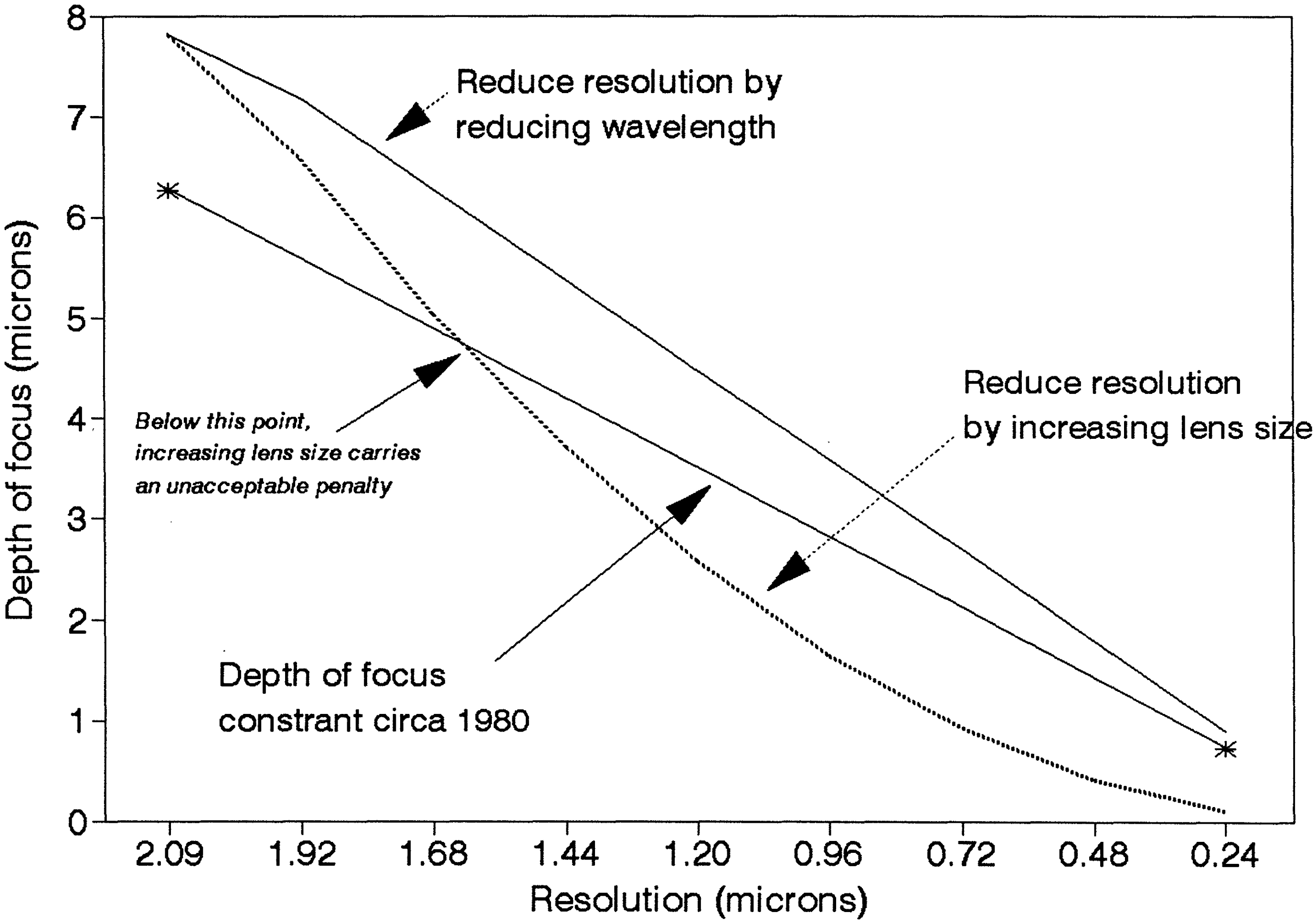


Figure (6): The depth of focus to
resolution constraint circa 1980.



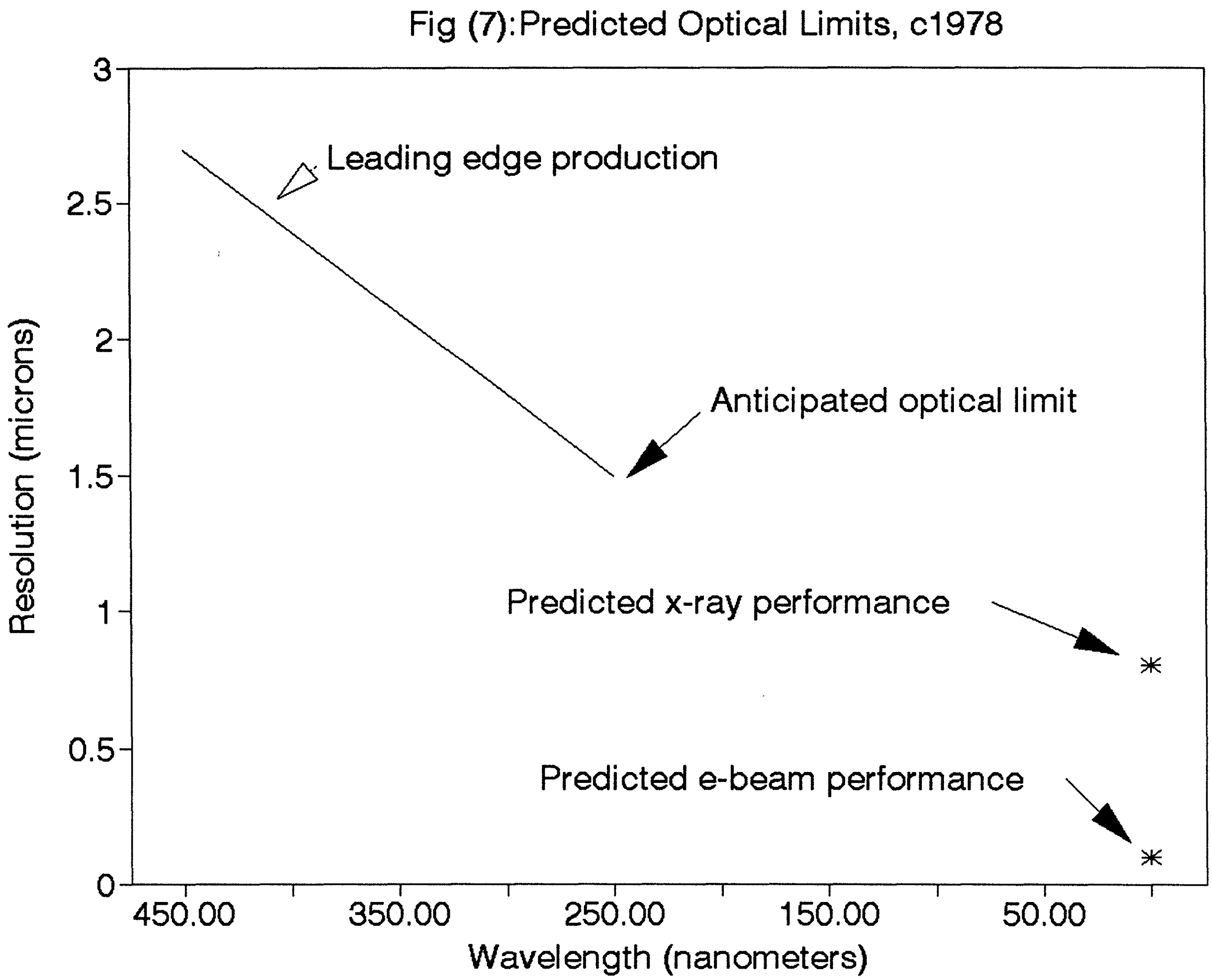


Fig (7):Predicted Optical Limits, c1978
Leading edge production
Anticipated optical limit
Predicted x-ray performance
Predicted e-beam performance
Resolution (microns)
3
2.5
2
1.5
1
0.5
0
450.00
350.00
250.00
150.00
50.00
Wavelength (nanometers)

an unacceptably small depth of focus to resolution ratio.[7] Thus as long as semiconductor manufacturers continued to require a depth of focus three times that of their target resolution, reductions in the wavelength of the exposing sources seemed to be the only practical means of improving minimum feature size, and industry expects could confidently predict that the limit to optical lithographic performance was around 1.4μm. Either X-ray or e-beam aligners were expected to replace optical lithography before the end of the decade (Figure 7).

Insert Figure 7 about here.

Notice that if X-ray or e-beam aligners *had* replaced optical lithography "on schedule" ex post analysis could frame the technological trajectory of optical lithography in terms of ever decreasing wavelength with the exhaustion of the dominant design predictable from a knowledge of the Rayleigh criterion. Understanding why this prediction, and the series of predictions made over the course of the next ten years proved to be incorrect highlights the role of unexpected changes in component technologies, customer needs and capabilities and complementary technologies in defining the limits to a technology. Between 1980 and 1990 advances in lens design and production techniques pushed numerical apertures to previously inconceivable sizes, rapid advances in semiconductor processing technology and a concomittment increase in photolithographic user sophistication relaxed the constraint that depth of focus had to be three times aligner resolution, and a combination of increasing user sophistication and the development of new resists pushed the value of k_1 from 1.0 to 0.8 in production and less than 0.5 in research settings. Together these changes have pushed the "limits" of optical lithography to within 0.2μm.

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[7] Formally, if Depth of Focus = 3 * Resolution, or if

$$\frac{k_2 \lambda}{NA^2} = 3 * \frac{k_1 \lambda}{NA}$$

, then if k_1 = 1 and k_2 = 0.5, by simple algebra, NA = 0.170.

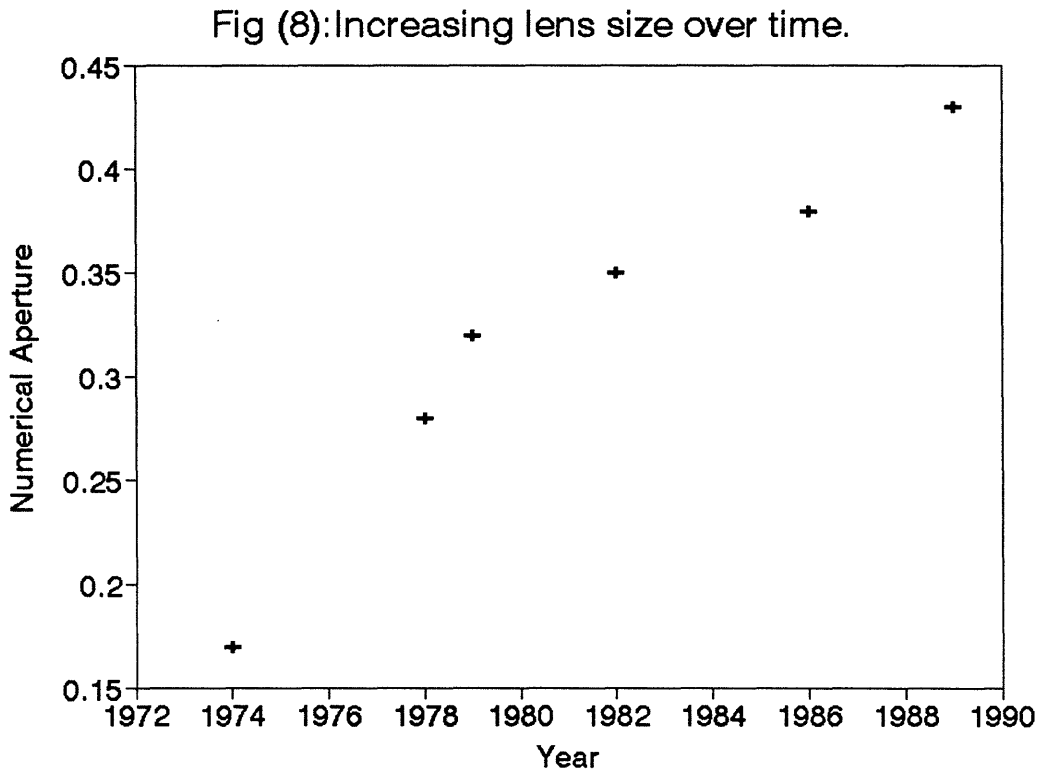


Fig (8):Increasing lens size over time.
Numerical Aperture
0.45
0.4
0.35
0.3
0.25
0.2
0.15
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
Year

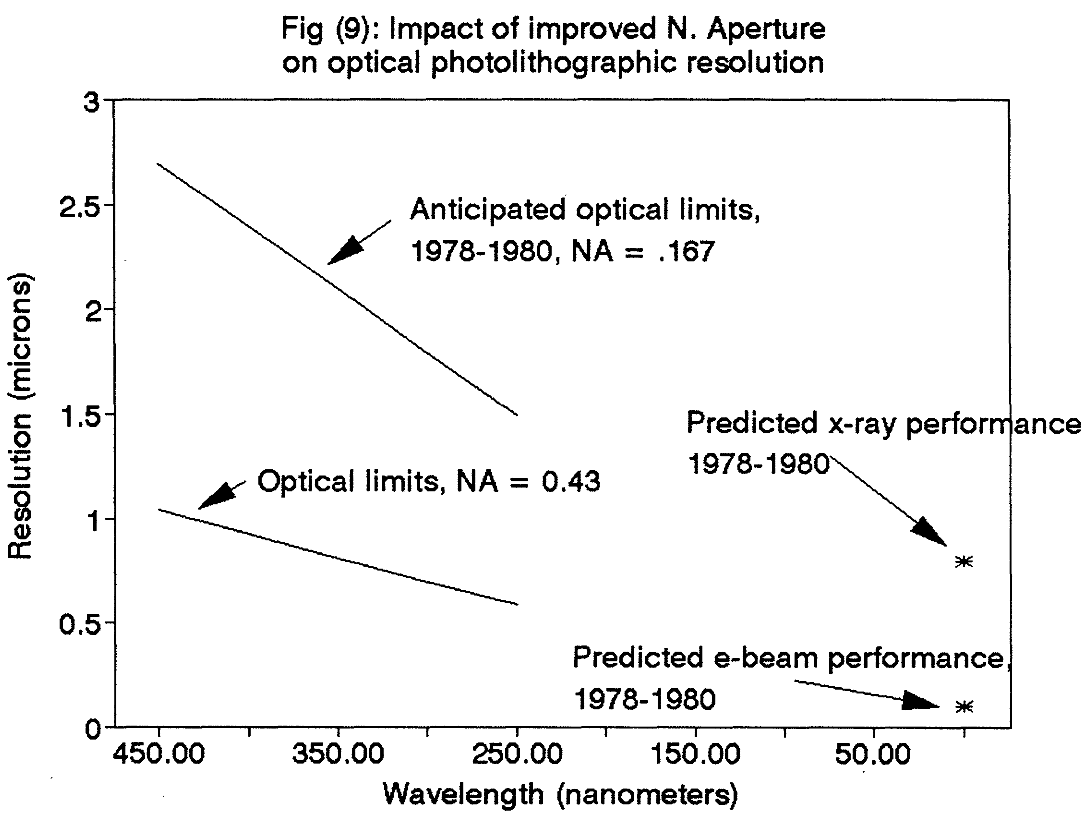


Fig (9): Impact of improved N. Aperture
on optical photolithographic resolution
Resolution (microns)
3
2.5
2
1.5
1
0.5
0
Anticipated optical limits,
1978-1980, NA = .167
Optical limits, NA = 0.43
Predicted x-ray performance
1978-1980
Predicted e-beam performance,
1978-1980
450.00
350.00
250.00
150.00
50.00
Wavelength (nanometers)

Taking Component Performance for Granted.

The first challenge to the wavelength of light as an insuperable barrier to smaller feature sizes came from the successful introduction of ever larger lenses (Figure 8). Breakthroughs in optical design and in manufacturing techniques coupled with the use of new materials enabled the construction of lenses with numerical apertures that were unthinkable by the standards of five years before, and pushed the "limits" of optical lithography - even with the use of the old "g-line" sources - to around 0.9μm.

Insert Figure 8 about here.

To the degree that these larger lenses could be optimized to work with the shorter wavelength "i-line" sources, - as, by the end of the decade they increasingly were - they extended the limits of the technology to around 0.5μm, all other things equal (Figure 9).

Insert Figure 9 about here.

An exploration of why it was that 0.167 came to be accepted as a limit for Numerical Aperture hints at the complexity of the construction of technical "limits." The belief that 0.167 was a realistic limit rested on three core assumptions: on the extrapolation of the then current product architecture, on the belief that refractive lens technology was essentially mature and unlikely to improve significantly, and on the belief that the need to maintain a ratio of 3:1 between depth of focus and resolution was a binding constraint. In the event the first assumption fell foul of architectural changes in product architecture (Henderson and Clark, 1990), the second to unanticipated advances in the design and manufacture of large scale refractive lenses, and the third to unforeseen improvements in the capabilities of semiconductor manufacturers, the users of optical lithographic equipment.

Between 1974 and 1980 optical photolithography was dominated by scanning projection alignment technology. Scanning projection aligners use reflective lenses to scan the image of the mask across the wafer surface. While reflective lenses can be easily modified to take advantage of lower wavelengths, it is very difficult to increase their numerical aperture beyond 0.167. Photolithographic aligners that use the refractive lenses that can be built with larger numerical apertures were not introduced until 1978, and it was not until 1980 that it became clear that they would be widely accepted.[8] Pre 1980 projections of the limits to optical lithography were thus contingent on a particular product architecture - that of the scanning projection aligner - rather than projections of absolute physical limits.

Projections of the difficulties implicit in improving numerical aperture were also confounded by unexpected developments in refractive lens technology. Two large Japanese conglomerates with extensive experience in optics, Nikon and Canon, entered the industry in the early eighties and between them made a series of breakthroughs in lens design that took some years to diffuse to their Western rivals.

The third factor that led industry experts to underestimate the power of increasing Numerical Aperture as a route to improvements in minimum feature size was the significant change in user needs and capabilities that triggered a relaxation in the depth of focus to resolution constraint that had characterized the early years of photolithographic technology.

User needs and capabilities.

As the discussion above suggested, given adequate resolution, the performance of an optical aligner is limited by its depth of focus. As long as semiconductor manufacturers required a depth of focus to resolution ratio of 3:1, a strategy of improving Numerical Aperture in order to improve resolution was indeed inherently limited. Unexpected changes in semiconductor manufacturer requirements broke this constraint. As optical aligners nudged their "limits" semiconductor manufacturers devoted increasing amounts of time to managing the depth of focus constraint. *Current* leading edge manufacturing practice requires a resolution to depth of focus ration of only around 1:1, permitting the use of lenses with Numerical Apertures as large as 0.50 (Figure 10). At wavelengths of 240 nanometers, and with a value for k_1 of 1.00, this opened the possibility of optical lithography reaching $0.48\mu m$.

[8] Reflective lenses focus light by reflection: refractive lenses focus light by refracting it through the body of the lens.

Figure (10): Changes in the depth of
focus to resolution constraint.

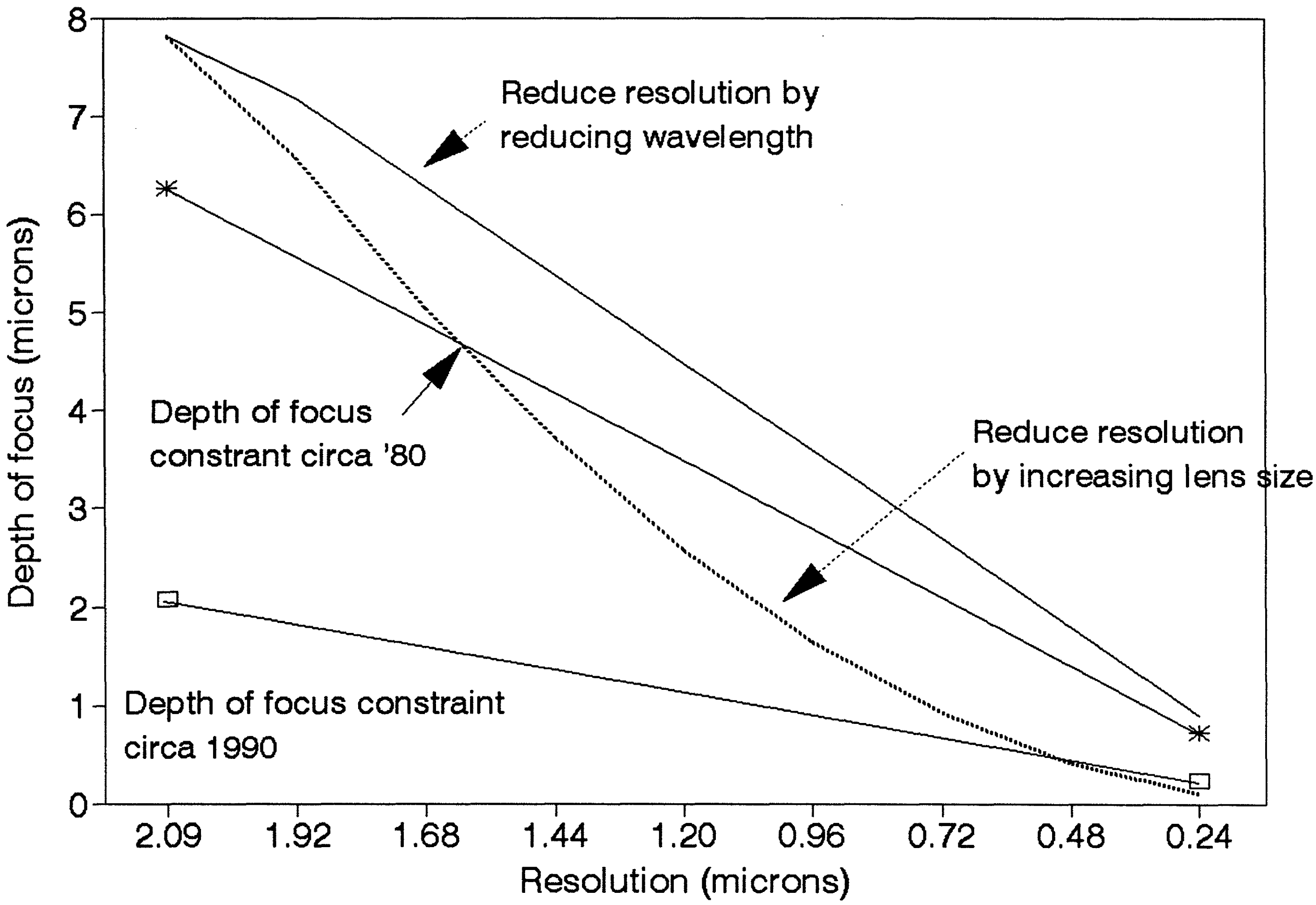
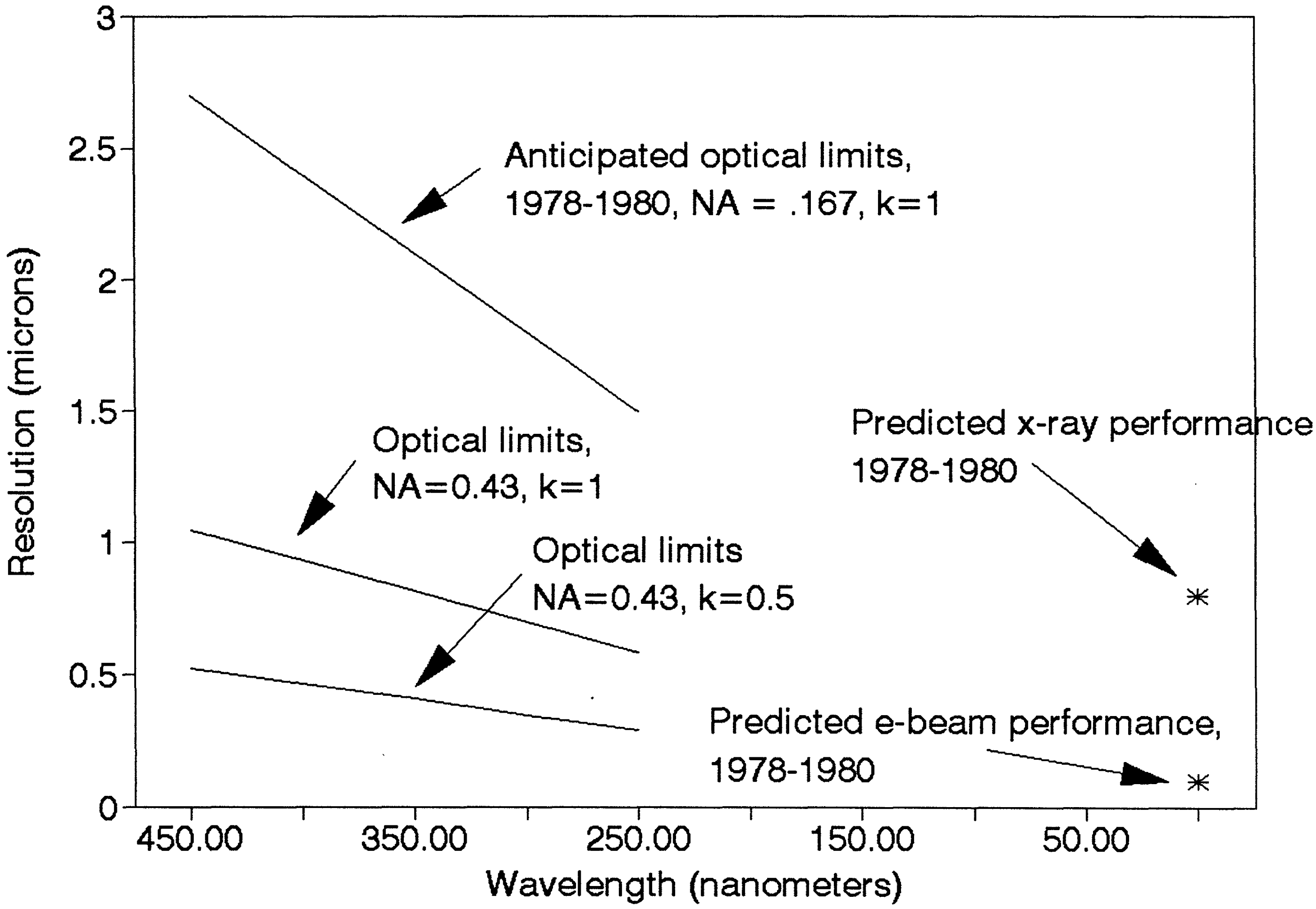


Fig (11): Impact of improved values of
k1 on optical photolith, resolution



Insert Figure 10 about here.

Complementary Technologies

The limits of optical lithography were also relaxed by unanticipated developments in component technologies, notably in masks and resists. Early discussion of the limits to optical lithography assumed that in a production setting k_1 was approximately 1.0. Subsequent developments showed that any assumption about the value of k_1 summarized an enormous amount of tacit and only poorly understood information about the performance of a particular semiconductor manufacturing process. Progress in production control techniques, better resist systems and finer control of alignment technology have since reduced the commonly accepted value of k_1 to around 0.8 in production settings and to as low as 0.5 in more controlled conditions. This advance has further shifted the limits of optical lithographic performance (Figure 11).

Insert Figure 11 about here.

Unanticipated developments in the evolution of complementary technologies have also been important in determining the performance of X-ray and e-beam aligners. Improvements in the performance of optical lithography have put increasing pressure on alternative lithographic techniques. For example the first X-ray aligners were designed to have minimum feature size capability in the 1-1.5μm range. To replace optical aligners now they must demonstrate performance in to within 0.1μm. Without accurate masks and reliable resists an aligner's ability to resolve the smallest imaginable image onto a wafer surface is quite useless, and it has proved to be surprisingly difficult to develop robust X-ray masks that can deliver this level of performance.[9] Sufficiently powerful X-ray sources have also proved to

[9] Masks designed for use with X-ray aligners are more difficult to develop than masks suitable for use with optical photolithographic aligners for two reasons. In the first place they require the development of alternate materials, since optical masks are transparent to x-rays. In the second place they are inherently more fragile. Since optical photolithographic aligners use

be almost prohibitively expensive.

Conclusions

The unexpectedly long old age of optical lithography suggests that the belief that the limits of a technology are determined by the internal structure of the technology may be fundamentally misleading. In the case of optical photolithography, the "natural" or "physical" limits of the technology were relaxed by unanticipated progress on three fronts: by advances in the performance of component technologies, particularly lenses, by significant changes in the needs and capabilities of users, and by unexpected developments in the performance of complementary technologies.

These conclusions have intriguing implications for both managerial practice and further research. With respect to managerial practice, they suggest that the use of the life cycle as a tool to predict the limits of a technology must be tempered by the recognition that a statement of the problem in terms of inherent technical limits rests on a series of assumptions about the probable evolution of user needs and capabilities and the potential of component and complementary technologies that may or may not be accurate. To the degree that investment behavior is shaped by these assumptions they may be self fulfilling, but they may also be upset by unexpected changes in the scientific or strategic context of the industry. A thorough analysis should thus combine careful analysis of the technology's scientific or physical potential with a willingness to question the common wisdom that provides the stable context for incremental development.

These conclusions have equally far reaching implications for future research since they reinforce the suspicions of those who have suggested that so called "normal" technical evolution may be quite as "socially constructed" as moments of discontinuity (Bikjer et al., 1987; Wynne, 1988; Pickering, 1992). Previous research in the analysis of technological changes has persuasively argued that the process of convergence to a "dominant design" is

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reduction lenses optical masks are typically five times the size of the pattern that is ultimately projected on the wafer, while X-ray aligners require the use of masks that are the same size as the final design.

underdetermined by technical or scientific factors alone. Several economists have stressed the role of externalities, uncertainties and strategic interactions in explaining the fact that apparently "inferior" technologies are sometimes much more successful than their scientifically superior rivals (David 1985; Farrell and Saloner, 1985). Similarly scholars working within the organizational and institutional traditions have shown that competition between alternate technologies and the emergence of a dominant design is shaped by the organizational and institutional context in which the technology is embedded (Hughes, 1978; Bikjer et. al. 1987; Tushman and Rosenkopf, 1990; Powell and DiMaggio, 1991; Van de Ven and Garud, 1991; Garud and Rappa, 1993).

The results presented here suggest that technical limits are determined by advances in component and complementary technologies and the capabilities of users. A thorough investigation of the forces that shaped *their* evolution is the subject of ongoing research, but preliminary work suggests that all three reflect a complex interplay between the strategic incentives of firms in the industry, exogenous scientific developments and socially constructed beliefs about the future of the technology. It is in this context that the "life cycle" may prove to be of most interest. For while this research suggests that the limits to optical photolithographic technology were not exogenously determined, industry beliefs that they were appears to have played an important role in shaping both investment and user behavior. The life cycle acted as a cognitive structure that served to organize embedded knowledge about the technology, and as such played an important role in the social construction of knowledge within the industry. The case of optical photolithography thus reinforces the results of those who have suggested that technical structure and social context are simultaneously determined, and lends further support to the belief that progress in understanding the determinants of technological change is most likely to come from detailed studies of the process of technical choice (Thomas, 1994).

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Appendix One.

Data and Methodology.

The data were collected during a two-year, field-based study of the photolithographic alignment equipment industry. (Full details can be found in Henderson, 1988.) The core of the data is a panel data set consisting of research and development costs and sales revenue by product for every product development project conducted between 1962, when work on the first commercial product began, and 1986. This data is supplemented by a detailed managerial and technical history of each project. The data were collected through research in both primary and secondary sources. The secondary sources, including trade journals, scientific journals, and consulting reports, were used to identify the companies that had been active in the industry and the products that they had introduced and to build up a preliminary picture of the industry's technical history.

Data was then collected about each product development project by contacting directly at least one of the members of the product-development team and requesting an interview. Interviews were conducted over a fourteen month period, from March 1987 to May 1988. During the course of the research, over a hundred people were interviewed. As far as possible, the interviewees included the senior design engineer for each project and a senior marketing executive from each firm. Other industry observers and participants, including chief executives, university scientists, skilled design engineers and service managers were also interviewed. Interview data was supplemented whenever possible through the use of internal firm records. The majority of the interviews were semistructured and lasted about two hours. Respondents were asked to describe the technical, commercial and managerial history of the product development projects with which they were familiar, and to discuss the technical and commercial success of the products that grew out of them.

In order to validate the data that was collected during this process, a brief history of product development for each equipment vendor was circulated to all the individuals that had been interviewed and to others who knew a firm's history well, and the accuracy of this account was discussed over the telephone in supplementary interviews. The same validation procedure was followed in the construction of the technical history of the industry. A technical history was constructed using interview data, published product literature, and the scientific press. This history was circulated to key individuals who had a detailed knowledge of the technical history of the industry who corrected it as appropriate.