I-LINE, DUV, VUV, OR X-RAY?

Donald W. Johnson and Chris A. Mack*

Microlithography Consulting Co., Inc., P.O. Box 718, Brookline Village, MA 02147
*FINLE Technologies, P.O. Box 261034, Plano, TX 75026

ABSTRACT

It is no longer possible to have just the best technology in the semiconductor equipment and materials market and remain successful. Each product tends to last for only one generation of IC devices. This high rate of imaging technology change means that the material or equipment manufacturer must have a large base of expertise to keep up with the rapidly changing needs and requirements of the technology. Also necessary is a large source of capital to finance development, manufacturing, and testing equipment. Unfortunately, the sequence of short business cycles, with limited lifetimes for each lithographic technology, is expected to continue for at least another ten years, until some technology or technologies, with long lifetimes through a large number of device generations, is firmly in place.

The intent of this paper is to compare the potential IC manufacturing requirements, product timing, and the technological capabilities of i-line, DUV (248 nm), VUV (193 nm), and x-ray. From this we intend to project the technological potential of each. To do this we intend to determine the limiting resolution and DOF of each technology, evaluate the resist and processing capabilities, examine the engineering requirements. We will evaluate the impact of phase shift mask technology, surface imaging, and planarization and their impact on lithographic potential. From this information we will provide a comparison of these four technologies. This data will then be compared to IC device requirements and timetables from which a lithographic product need and lifetime relationship can be determined for each technology.

INTRODUCTION

In today's competitive environment it is not sufficient to have just the best technology on the market and be successful. The market is highly dynamic, and the competition will catch up within six months or so. This is before most final decisions are made on the lithography process of choice for each emerging device generation. However, if one does not have one's product developed during this window of opportunity it could spell disaster. The high rate of imaging technology change has made it necessary to have the newest state-of-the-art product available on time and be looking at the next couple of generations. This rapid change also means that the material and equipment vendors must have a large base of research experience to keep up with the needs and experiences of new product development. Recently each new product has tended to last for only one generation of device types, Figure 1. Unfortunately, this high rate of short technology cycles is generally expected to continue for the next ten years, until some new technology or mixture of differing technologies, with long lifetimes through a large number of product generations, is firmly in-place in IC manufacturing. Until that time it will be necessary to provide the capital and manpower necessary to stay competitive with optical technology.

The window of opportunity for each new technology is only during the device R&D and pilot development stage, as indicated in Figure 2. Manufacturer R&D groups are generally quite receptive to working with the newest, highest technology product available. However, the closer to actual production, the more likely the manufacturer is to use a well characterized, familiar technology. Once the manufacturing process has been set, it is almost impossible to change the equipment, materials, or process. If one has not developed a technological success with leading edge IC manufacturers, it will be very difficult to get follow-on business. In reality, however, most material and equipment sales and profits are realized long after the glamour of the technology has worn off. Each new technology will

 0-8194-0829-8/92/$4.00

not reach its peak utilization for five to seven years after introduction. The major challenge is then to have the technology and products developed by the time they are needed by the industry. It is our intent in this paper to postulate the capability of each of the optical technologies in order to help project what will be used and when it will be needed.

DEVICE TECHNOLOGY REQUIREMENTS

Kopp [1] and Larrabee [2] have recently reported in great detail on leading edge device technology requirements. We will summarize the major points of their data as it pertains to lithographic projections. They have shown that the major events in the development and introduction of new process generations follow a long-term industry calendar, which is an indication of the rate at which the semiconductor industry has gotten things done in the past. This industry history supports the use of a carefully defined calendar of process generations to make predictions on future technology needs. The developments in successive device generations will increasingly follow a rigid calendar, which encourages major developments in the process, equipment, or materials. We can therefore use this calendar for at least the next ten years as there appears to be no decrease in the increase in the number of components per chip or decrease in the minimum linewidth for each device generation.

DRAM has been the technology indicator for advanced manufacturing development, and will remain the worldwide "technology driver" in the future. DRAM manufacturing will continue to establish the global norms in pattering technology (excluding maximum exposure field size). Therefore, estimates of minimum circuit geometries and the related timing of industry events should begin with future DRAM generations. Product introductions occur in about 2.5 year intervals and peak production occurs in roughly 3 year intervals, indicating a slow worldwide stretch of manufacturing time to recover ever increasing development costs.

Historically, the baseline process used in initial manufacturing must be in place two to three years before device qualification by the customer or product introduction. The manufacturing tools are generally in place one year earlier. Table 1 shows the process generation overlap and lifetime and the need for device manufacturers to have four or five generations somewhere in the works. Lithographic tools and materials must be in full production prior to volume device production, and must be developed one generation before. The "process development and improvement" interval is where new and newly developed equipment, materials, processes, and procedures are made production worthy.

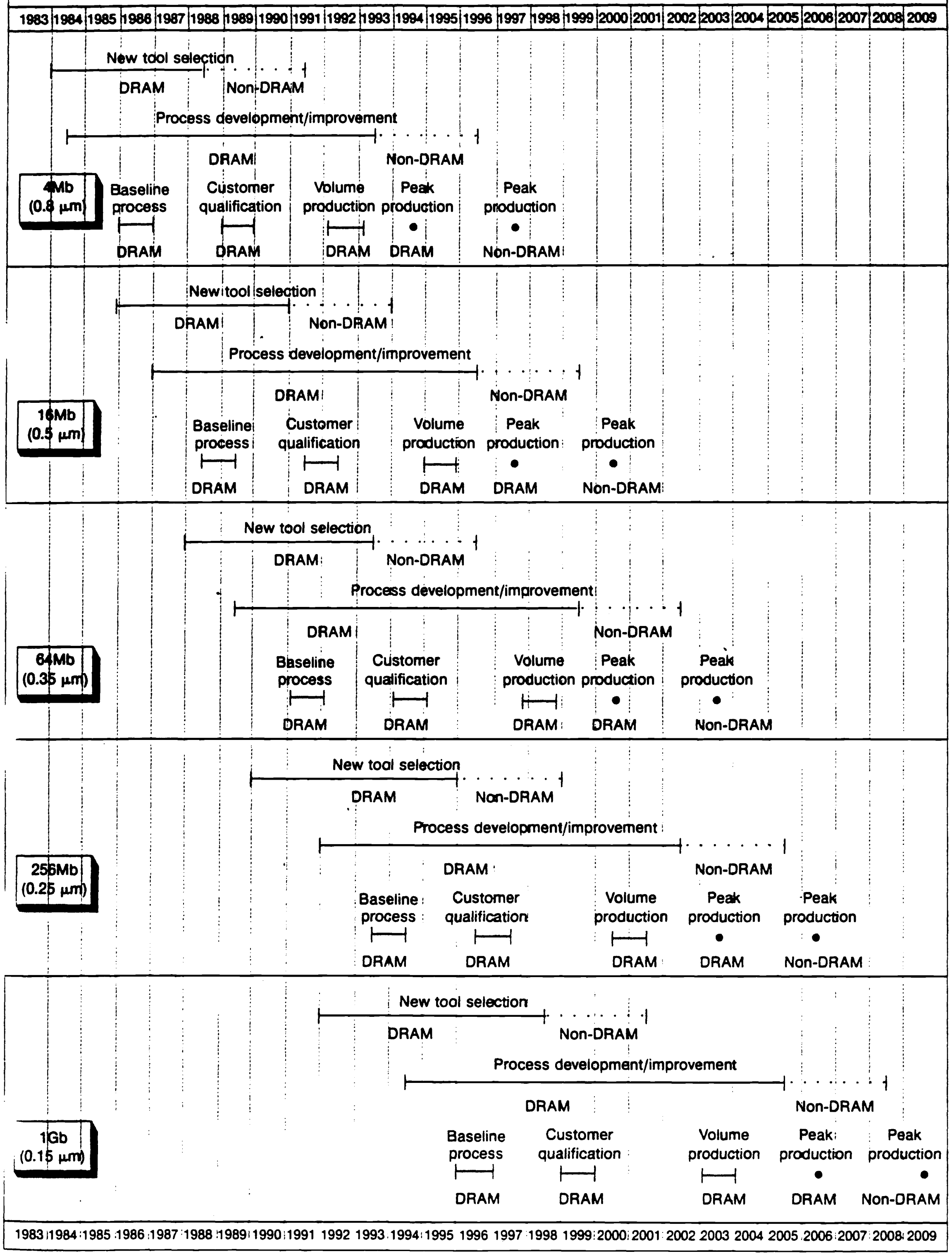
Due to the rapid technology change, extensive R&D in new lithography development is also required. We see this rapid change in lithographic technology continuing for another ten to fifteen years. By that time the industry should be moving away from processes using optical lithography, which would be at its capability limits, into a technology, or a mixture of technologies, which would not be near its capability limits. Then an IC manufacturer would be able to use the same imaging technology for many future generations of devices.

LITHOGRAPHIC CAPABILITIES

For at least the past decade the capabilities of optical lithography, x-ray lithography, and e-beam direct writing have been seriously miscalculated. In particular, the capabilities of optical lithography have been greatly underestimated. The question still remains, just how much better can we make each technology? I-line, Deep-UV (DUV), Vacuum-UV, and X-ray all have fairly well characterized capabilities based upon historical analysis. Some will be able to do better than their projections and some will be waiting in the wings for longer than anticipated.

A dozen years ago, e-beam was on the verge of displacing scanning projection systems. Ten years ago x-ray was just around the corner from becoming the major imaging technology. And a few years ago we were saying that i-line would not be adequate for even 0.5 μm production. Now we see that i-line is being used for half micron production, and will also be used for 0.35 μm and possibly even 0.30 μm

Table 1. Projected Worldwide Milestones for Five Process Generations



JANUARY 1992 SEMICONDUCTOR INTERNATIONAL 35 device production. New optical lithography techniques have already shown 0.2 μm capability [3], and may even be capable of 0.1 μm (100 nm) production. With the advent of phase shift masking technology, the capabilities of all optical technologies have been extended, but just how much? What are the capabilities of some of the other emerging technological improvements, such as surface imaging and planarization? We are now well aware of what device requirements will be needed when for each device generation. The difficult task is to determine what lithographic technology will be capable of meeting these demands, and when.

Let us study the currently available technologies, I-line, DUV, VUV, and X-ray, and see just what each is capable of and what it is not. Is i-line really capable of 0.3 μm in a production environment? Can DUV meet the needs of today? Will VUV be ready, and how far can it go? When will we really need x-ray? To answer some of these questions we will look at each technology in a classical sense in this section, in order to see the capability of each in meeting our future device requirements. In the following section we will look at the potential extended capabilities of each technology and present a model to predict what each may ultimately be capable of performing.

I-line technology is based upon well understood chemistry [4] and extensive manufacturing experience of positive photoresist and mercury arc step-and-repeat technology. DUV is undergoing extensive development and requires new resists, new source technology, and possibly new imaging technology. VUV probably requires a switch to surface imaging technology. X-ray requires almost everything new, and astronomical expenses. In addition, all optical processes can be enhanced by the use of phase-shift masking technology, which appears to be rapidly headed for full acceptance in device manufacturing. DUV has had considerable resist difficulties, VUV is only in its early stages of development and appears to be primarily an engineering program, and X-ray is still mired in multiple problems, primarily mask development and equipment costs.

<u>I-LINE</u>: Positive i-line lithographic technology uses the classical single layer resist and step-and-repeat imaging. The resist requires a high degree of transparency, bleaching upon exposure, and exposure through the depth of the resist. This high transparency leads to a high sensitivity to thickness and reflectance differences and puts a significant strain on process latitude. Positive i-line resist exposure and development, as well as its photochemistry are identical to the standard positive photoresists which are very well understood. It is capable of producing sub 0.3 μm images on planar wafers, but it is at the limit of currently available 366 nm imaging technology using binary masking techniques. It is reaching its limits in the classical Rayleigh resolution and depth of focus (DOF) analyses, where

$$w = k_1 \lambda/\mathrm{NA} \text{ and} \qquad (1)$$

$$\mathrm{DOF} = k_2 \lambda/(\mathrm{NA})^2, \qquad (2)$$

where w is the feature width, NA is the numerical aperture of the objective lens of the projection system and l is the wavelength. The term k_1 is called a "process dependent constant" which is an engineering euphemism for an unknown variable. In practice k_1 is 0.5 - 0.6 in R&D and 0.7 - 0.8 in production and k_2 is approximately 0.6 in R&D and 0.5 in production. Under these conditions, with the currently available exposure equipment with a nominal NA of 0.55 we find that classical analysis gives us an R&D resolution of 0.33 μm with a DOF of ±0.8 μm and an production resolution of 0.47 μm and DOF of ±0.6 μm. One of the major reasons for the decreased performance in production is the device topography and multiple reflective surfaces in the imaging process noted above. To improve the performance in 0.5 μm production or below, very tight thickness control is required as well as the use of anti-reflective coatings. To be capable of reaching 0.3 μm in production, i-line lithography requires additional processing aids and this, fortuitously, has been made possible with the development of phase-shift masking technology. The resists themselves are still capable of undergoing an additional generation of development, and should be capable of giving all of the available performance which can be squeezed from i-line technology.

DUV: This technology has required the development of new sub-technologies for most of its component steps: new light sources, new resists, new chemistry, and new processing have to be developed and understood. The only thing not new is that the exposure equipment and masking technology are still primarily step-and repeat, 5X reduction with binary chrome masks, although step-and scan is also being introduced. The development of the KrF excimer laser source **I-LINE, DUV,** at 248 nm appears to have adequately met the need for today's exposure equipment and we can expect to see additional improvements in its power, stability, and lifetimes. Also the 250 - 260 nm output of the high pressure mercury arc appears to have enough power for the step-and-scan system. The same success can not be said for the resist, however. No longer can we use the standard diazoquinone/novolak chemistry. The sensitivity and transparency requirements have ruled these out; although most engineers still desire to use single layer, through-the-resist imaging. What has been developed is the so-called "chemically amplified" resists, where a photo-acid generator is decomposed by exposure and a thermal, acid catalyzed reaction, gives the desired chemical transformations. However, these resists still do not have the desired transparency levels, as there has not yet been demonstrated a resin system which is transparent at 248 - 250 nm, yet thermally stable enough to withstand the subsequent manufacturing process. Until very recently only negative tone resists have been commercially available, and many have excessive sensitivity to storage and bake conditions as well as delay time after coating. Recently a positive acting, silicone containing resist has been announced, but its performance has yet to be fully investigated. In addition, several groups are studying surface imaging using the DESIRE Plasmask resist. When compared to ARC processing, single layer dry processing approaches are on the same order of complexity and cost. It cannot be said at this time that a production viable DUV lithographic system has been developed.

Using the classical k_1 and k_2 ranges we get a theoretical R&D resolution of 0.25 µm with a DOF of ±0.7 µm at .50 NA. Only with considerable process aids could we expect to come close to this in the production environment. In addition, on all but the least critical layers it will now become absolutely necessary to use ARC materials, and, furthermore, phase-shift masks will be required for 0.25 µm dimensions. Each new increase in requirements will also require an improved resist system. Still there is not any guarantee that a resist system will be sufficiently developed within the next 1 - 2 years when i-line technology will no longer be capable of meeting future device needs.

VUV: The vacuum UV region refers to wavelengths less than 200 nm; although at wavelengths above 190 nm it is not necessary to operate in a vacuum. The primary light source in this region is the ArF excimer laser at 193 nm, and the F_2 laser at 157 nm is also available. At 193 nm it is necessary that oxygen be excluded from the light path, as it absorbs at this wavelength. As with DUV, vacuum UV requires the development of new sub-technologies. Again it is not necessary to make exposure system or masking changes, but it is beneficial that reflective optics be incorporated. The excimer laser system is very closely related to the system developed for DUV; thus much of its early development has already been completed. The resist system will be different from i-line or DUV resists, and it will no longer be possible to use through-the-resist imaging schemes, although transparent aliphatic systems may be applicable for equipment development and set-up situations. It now becomes almost mandatory that surface imaging processes be used, as aromatic resins required for thermal processing are highly absorbing at 193. Several different resist systems have been reported [3]. ARC's will not be needed and single layer resist processing will be acceptable for all imaging layers. Based on the reported data, it can be anticipated that robust VUV resists and processes should be available within the next 1 - 2 years. However, it will still take some time to develop the exposure equipment. Based on available information, we see no material or equipment barriers to the development of 193 nm imaging systems. The real question is the benefits and availability of VUV vs. DUV. If 193 exposure equipment develops more rapidly than positive DUV resists, then DUV technology may be passed by.

Using classical resolution and DOF, process latitude analysis, we would reach the conclusion that this technology is not capable of production utilization. However, as we will discuss later, the continuing evolution of better processing, along with processing aids, will allow this technology to meet sub-0.25 µm processing needs in the near future. Surface imaging will give a tremendous boost to process capability, as will phase shift masks, which should be well understood by the time this technology is into process implementation. In addition, the use of resist planarization techniques now become practical and lead to even further process latitude improvements.

X-RAY: When we mention x-ray lithography we primarily need to understand that virtually every aspect of this technology will be new: new sources, new exposing equipment, new masks, new resists, new processes, etc. All of which indicate a very long development cycle. X-ray technology has been under considerable development for over 15 years, and still does not yet have a strong focus or direction. There are major problems in masking technology and in focusing requirements, sources, and cost. There are still several approaches under evaluation in a number of these areas. Even if it were required today, it does not appear that x-ray technology would be ready for use for at least a couple of device generations. We will not cover the potential of x-ray technology in this analysis, as projection x-ray lithography is theoretically capable of meeting device requirements for many years to come; although it will likely suffer from DOF constraints. From a practical point of view, the IC manufacturer will resist the implementation of this technology until it is absolutely required to meet device manufacturing requirements. Thus we can expect that optical lithography will be used until it can no longer perform. We will answer the question of when x-ray technology might be introduced by determining when optical technology will not be capable of meeting manufacturing requirements.

LIMITS OF OPTICAL LITHOGRAPHY

It has always been difficult to predict the ultimate limit of optical lithography. The Rayleigh resolution equation (Eq. 1) has often been used for first order predictions. The term k_1 is the "process dependent constant" as defined in Equation 3, where some guess is made as to the value of k_1.

$$k_1 = w(\mathrm{NA})/\lambda \quad (3)$$

In fact, k_1 is simply a scaled linewidth and to predict a resolution limit by arbitrarily picking a value for k_1 is equivalent to arbitrarily picking the resolution limit. It is the goal of this analysis to *determine* a reasonable minimum value for k_1.

Historically, k_1 has decreased dramatically since the introduction of projection lithography. Figure 3 shows a plot of the decrease of k_1 over the past twelve years [5]. The trend for decreasing k_1 will certainly continue, but how far? There are many factors which must be considered when answering this question, but first a methodology must be developed which adequately correlates the evolving needs of manufacturing with the trends in lithography.

The basic need of manufacturing, at any feature width, is sufficient process latitude. Although process latitude takes many forms, the two most important are exposure latitude and depth-of-focus. Figure 4a shows a typical focus-exposure process window. The two curves represent contours of constant linewidth at values of ±10% deviation from the nominal critical dimension (CD). Any values of exposure and focus which fall inside this "window" give an acceptable process with respect to CD. Similarly, resist sidewall angle and resist thickness loss contours can also be included as shown in Figure 4b. The area of overlap of all of the spec curves gives the final process window that is delivered by the process. For manufacturing, an analysis of the built-in focus errors of a process (e.g., wafer topography and non-flatness, autofocus errors, field curvature and astigmatism, wafer and reticle tilt, etc.) can determine the needed depth-of-focus. A similar analysis of exposure errors (e.g., substrate reflectivity variations, resist thickness and sensitivity changes, illumination non-uniformity and control, reflective notching situations, etc.) will give a minimum acceptable exposure latitude required to achieve reasonable yield. The needs of manufacturing can be represented by insetting a rectangle in the process window, the dimensions of which are equal to the minimum acceptable exposure and focus latitude (Figure 4c). Good results are obtained when the manufacturing needs are completely within the process window.

(Note: one could reasonably argue that the rectangle in Figure 4c over-estimates the needs of manufacturing. In the parlance of statistical process control, the length and width of the rectangle represent the control limits (say, 3σ values) of exposure and focus. However, the proper representation of a 3σ surface in two dimensions is not a rectangle, but an ellipse of major and minor axes equal to the 3σ values of exposure and focus. A corner of the rectangle represents a 6σ error (3σ in exposure *and* 3σ in focus) and thus it is an overly stringent requirement that this corner must fit inside the process window. Although an ellipse is preferred, a rectangle will be used in this analysis solely for simplicity.)

Determining the resolution limit is a two step process. First, the required manufacturing focus and exposure latitude (i.e., the size of the rectangle) must be determined by an analysis of production needs. Second, the smallest feature (for various feature types) which gives a process window containing the required rectangle is determined. This feature size is then the resolution limit. Obviously, manufacturing needs will vary from product to product and manufacturer to manufacturer. As process control has improved over the years through improved processing equipment, monitoring techniques, and better materials, the required focus and exposure latitude rectangle has shrunk. This could be plotted vs. time as in Figure 3, if desired. The advent of real-time adaptive process control will further reduce the required rectangle. For the purposes of this analysis, the following manufacturing needs will be assumed as function of the wavelength used:

	Exposure Latitude	DOF (total range)
At i-line	30%	1.5 µm
At 248 nm	25%	1.0 µm
At 193 nm	20%	0.8 µm

The reduction of manufacturing requirements with wavelength is not meant to imply that lower wavelengths need less process latitude, but rather that the manufacturing needs have, and will continue to decrease with time, as will the wavelength used. We feel that these numbers are reasonable, but they are arbitrary. The reader can certainly replace these numbers with his/her own estimates and perform the analysis given below. The main purpose in this paper is to present the methodology for determining resolution limits - the conclusions drawn are subject to the validity of the assumptions used.

Determining the process window is a much more difficult task. This window can be determined experimentally, but only for a given process. To predict a process window for the future, lithography modeling is an essential tool. The windows given in Figure 4 were generated with PROLITH/2 (FINLE Technologies). Using this model, the effects of numerical aperture, partial coherence, wavelength, feature size and type, resist and process parameters, etc., can be examined in detail. However, this analysis will require the generation of thousands of such process windows. Although the time required to simulate one reasonably dense focus-exposure matrix is not excessive (10 - 20 minutes on a 486 PC), it is far too long to generate the number required for this study. Consequently, this study requires a simpler (and, by default, less exact) method of predicting the future process window.

The Lumped Parameter Model (LPM) [6,7] is ideally suited for this type of task. In the LPM approach, an aerial image is simulated using a conventional image model. A very simple model for the exposure and development of the resist is then used to quickly predict the resulting resist feature width as a function of exposure. By repeating this through focus, a focus-exposure matrix and resulting process window can be generated. Version 2.2 of PROLITH/2 has the LPM built-in, allowing the generation of an approximate process window within a few seconds. The LPM resist model uses only two parameters, the resist thickness and a lumped contrast (base e). Higher contrast and thinner resists result in improved process latitude. The size and shape of the process window can be matched very closely with either experimental data or the primary parameter model of PROLITH/2 by adjusting the contrast.

With a tool and method in place, we are ready to begin. But first, one must determine the appropriate input parameters for the LPM. Today's high contrast resists give performances which match the LPM with a lumped contrast of about 3. A few years ago, a value of 1.6 was found to match experimental results [7]. Our assumption is that resists will continue to improve in the coming years. Further, by the time 193 nm lithography arrives, surface imaging will dramatically reduce the effective resist thickness. For the purposes of this analysis, the following LPM resist parameters will be used:

	Lumped Contrast	Resist Thickness
At i-line	4	1.0 μm
At 248 nm	5	0.7 μm
At 193 nm	7	0.2 μm

Again, the reader who disagrees with these numbers can easily repeat this analysis using different estimates.

Since the LPM uses the standard PROLITH/2 aerial image model, all of the imaging parameters must be specified. First, diffraction-limited lens performance will be assumed. Although this ideal performance can never be achieved, it is certainly the trend and the goal of lens designers and manufacturers to approach this ideal as closely as possible. It is the authors' belief that the next generation of steppers will be equipped with variable *NA* and partial coherence (σ). The advantage of such a system is that the optimum *NA* and σ can be chosen to maximize image quality [8,9]. Further, we shall assume that the mask can be arbitrarily biased any amount for any feature, within limits. In this way, the optimum bias can be chosen to maximize performance [10]. If phase-shifting masks (PSM) are used, one should assume that the optimum PSM configuration is used. For now binary (i.e., conventional) masks will be assumed and issues with PSM will be discussed in the following section. With these assumptions in place, one cannot determine the resolution of a particular process without first determining the *NA*, σ and mask bias which maximizes the size of the processes window.

Again, the LPM is the ideal tool to efficiently determine the optimum *NA*, σ, and mask bias. PROLITH/2 allows the user to specify a range for *NA*, σ, and mask bias and then determines the values which give the maximum exposure latitude over a specified focus range using the LPM. The LPM predicts the linewidth and resist loss process windows, but sidewall angle is currently not calculated. For this study, a ±10% CD specification and a maximum resist loss of 10% are used to determine the process window. For example, Table 2 shows the resulting optimum stepper and mask bias settings for various 0.5 μm feature types at i-line. The ranges used were *NA* from 0.3 to 0.7, σ from 0.1 to 0.9, and mask bias up to 2 μm.

One should note that many practical issues are being ignored in order to arrive at these results. No attempt is made to determine whether more than one of the four critical dimension feature types can be printed at the same time (for example, both dense and isolated lines on the same mask). Also, a positive resist is assumed so that dark-field contacts can be used. If resist tone were a variable, it could also be optimized to give the best performance (for example, using a negative tone resist to print the isolated line) [11].

Table 2 - Optimum printing of 0.5 μm features at i-line exposure.

Feature	NA	σ	Mask Bias (μm)	Exposure Latitude
lines and spaces	0.58	0.26	0.08	63.3
isolated line	0.56	0.10	0.07	62.8
contact array	0.56	0.14	0.19	63.6
isolated contact	0.63	0.14	0.20	57.1

Using the parameters and manufacturing requirements discussed above, the LPM was used to estimate the resolution limits of i-line, 248 nm and 193 nm lithography. The results showed that 0.42 - 0.45 μm features can be printed with an i-line with NA's between 0.49 and 0.68, partial coherence between 0.15 and 0.28, and various mask biases. Deep-UV (248 nm) lithography was capable of resolving features in the range of 0.27 - 0.29 μm using a stepper with NA's between 0.52 and 0.69, partial coherence between 0.10 and 0.33, and various mask biases. Finally, an advanced 193 nm process could achieve 0.20 - 0.22 μm resolution when the NA was between 0.56 and 0.69, partial coherence between 0.24 and 0.54, and various mask biases.

It became clear in the course of this study that k_1, the scaled linewidth, has little relationship to resolution for a variable NA stepper. The above results, however, show that resolution does scale with wavelength, and printing features about 10% bigger than the wavelength is possible. An ultimate resolution of 0.2 μm with binary masks is quite challenging, but still not sufficient to meet the needs for the 1GB DRAM device generation. Some improvement could be obtained with annular sources [8], but the biggest payoff may come from phase-shifting masks, with additional gains from surface imaging, planarization.

PHASE-SHIFTING MASKS - THE PARADIGM SHIFT: Lithography can be thought of as an information transfer process. A conventional mask is a binary representation of the features to be printed (1 for glass, 0 for chrome). The information is transferred to the wafer by diffracting light through the mask, collecting as much as possible of the diffracted light by the objective lens, projecting an image onto the wafer, exposing and developing the photoresist, and finally transferring the pattern to the substrate. Each step in the process results in the loss of some amount of information. The goal of lithographic improvement has always been to minimize the information lost at each step and thus to maximize the information transferred to the wafer. For example, increasing the numerical aperture or lowering the wavelength of the projection system reduces the information lost as a result of diffraction.

Phase-shifting masks represent a fundamental shift from this approach. Rather than minimizing the loss of information, the goal of a PSM is to increase the amount of information contained on the mask. Thus, for a lithography process with a given information loss, the use of a PSM can increase the amount of information transferred to the wafer. Of course, there are many problems with this approach. Aside from the practical issues of making the mask, a new set of CAD/optimization tools will be required to manage and optimize the new data being placed on the mask.

A full analysis of the capabilities of various PSM schemes is beyond the scope of this paper. However, one PSM feature will be examined in detail using the LPM approach outlined above. To arrive at the ultimate potential of PSM, an isolated 0-180° phase-edge mask pattern will be examined. As was discussed in reference [12], this pattern prints as a line in positive photoresist with a width of about $0.25\lambda/NA$. Using the LPM approach to discover the potential of this pattern at each wavelength, it was found that the resists defined above for each wavelength could easily resolve isolated lines with widths of one-half of the wavelength with more than enough exposure latitude over the given focus ranges. Granted, the behavior of an isolated phase-edge is the best that PSM can offer. However, it does give some indication as to the potential of PSM.

SURFACE IMAGING/PLANARIZATION: These additional process improvement techniques should also be explored to determine their impacts. Surface imaging technology appears to be a necessity at 193 nm, and is being evaluated at i-line and DUV. In many ways the impact of surface imaging is more dependent on the etching characteristics of the process rather than the lithographic limitations. Surface imaging in a thin layer will potentially lead to higher resolution since less information is lost in passing through the imaged film. This will lead to improved contrast, a lower k_1 value, and better resolution. However, since additional processing (silylation and etching) must be of equal or better selectivity than wet development, it must remain a potential increase in contrast until proven, which it undoubtedly will.

Planarization of the imaging layer has been discussed in relation to 193 nm surface imaging techniques. In fact, the benefits of planarization can only be realized in surface imaging techniques where uniform resist thicknesses can be obtained. Planarization by itself does not change the focus exposure window. It does, however, significantly reduce the required manufacturing process requirements; thus, significantly improving overall process latitude. With an advanced 193 nm tool, an advanced surface imaging, planarized resist, and a circuit layout optimized to take advantage of phase-shifting masks, 0.1 μm device production may well be possible.

PROCESS NEEDS: We have made some ambitious claims about the future of optical lithography. In order for these predictions to come true a number of very important problems must be overcome.

Advanced Stepper - The next generations of optical steppers must continue their push for diffraction-limited performance with numerical apertures up to at least 0.6, possibly as high as 0.7. Computer controlled variable NA and partial coherence is essential, with annular sources as a possibility. At the same time, field size needs to increase to about 16 cm^2 or adequate field stitching must be developed. Of course, the progression to 248 nm and 193 nm wavelengths must continue.

Advanced Resist - One of the major reasons for the decline in k_1 as seen in Figure 3 has been the improvement in resist technology as shown in Figure 1. The improvement must continue if we are to meet the ambitious goals outlined here. Resists are being asked to do more and more with less and less quality in the aerial image. A choice of resist tones would be beneficial towards optimizing the aerial image, but a positive resist is essential.

Process Improvements - Along with improvements in resist technology it is also necessary that improved processes be introduced over time. These new process techniques will include phase shift masks, surface imaging, and resist planarization techniques.

Process Control - In order to achieve high yields with reduced process latitude, process control must become an integral part of the design and execution of a lithography process. Real-time adaptive process control will change from oddity to necessity as process models become process controllers.

CONCLUSIONS

We have shown that using binary masks and properly optimizing *NA* and partial coherence along with improving processing techniques we could obtain resolution limits increasingly approaching the linewidth of the exposing light as we progress to shorter wavelength exposures. The results are summarized in Table 3. When we add the improvements of phase shift masks we now show resolution limits approaching one half of the exposing wavelengths, or better, as also noted in Table 3. With the development of surface imaging and planarized resist surfaces, it appears possible that 100 nm (0.1 μm) processing using optical lithography will likely become reality. If further wavelength reduction using 157 nm F_2 excimer lasers is developed, optical lithography could potentially produce 75 nm dimensions, still with adequate manufacturing windows.

Table 3 - Calculated resolution limits using LPM model for advanced optical lithographic technologies with current and advanced processing, μm.

	Binary Chrome Masks	Phase Shift Masks
i-line	0.42	0.21
248 nm	0.27	0.14
193 nm	0.20	0.09

Depending on the desired process requirements and the capability of new technology development it is possible to determine a timetable for each new technology within a few years of its required need. A lack of development of a certain technology will not delay the introduction of a device generation, but will extend the capabilities of existing technology or promote the development of newer alternatives. Such is the case for 0.35 μm 16 MB DRAM production, where i-line processes are being installed in place of the projected DUV processes.

We will leave it to the reader to correlate the optical lithographic potentials with the device requirements and timetables in Table 1. We present one such comparison in Figure 2. Undoubtedly, there will be disagreements with the timing of events, and the reader can modify this comparison to fit his/her own models. Leave it to be said that 4 GB DRAM, 0.10 - 0.12 μm, requirements appear to be entirely within the capability of optical lithography and 16 GB optical technology is potentially available, assuming the continued improvement in processing technology. Optical lithography will be in peak production at the end of the next decade, 2010. Non-optical techniques will not be needed, even in process development, until the next century, assuming there is still a desire for smaller linewidths below 100 nm.

References

1. R.J. Kopp, *Semicond. Internat.*, 34, January 1992; ibid., *Semicond. Internat.*, 34, January 1991.
2. G. Larrabee, P. Chatterjee, *Semicond. Internat.*, 84, May 1991.
3. M.A. Hartney, D.W. Johnson, A.C. Spencer, *Proc. SPIE*, **1466**, 238 (1991).
4. D. W. Johnson, *Proc SPIE*, **469**, 72 (1984).
5. G. E. Fuller, *Solid State Technology*, **30**, 113, September, 1987.
6. R. Hershel and C. A. Mack, Lithography for VLSI, VLSI Electronics - Microstructure Science, Chapter 2, R. K. Watts and N. G. Einspruch, eds., Academic Press (New York), 19-55 (1987).
7. C. A. Mack, A. Stephanakis, R. Hershel, *Proc. Kodak Microelectronics Seminar*, 228 (1986).
8. C. A. Mack, *Proc. KTI Microelectronics Seminar*, 209 (1989).
9. C. A. Mack, *Proc. SPIE, Optical/Laser Microlithography III*, **1264**, 71 (1990).
10. C. A. Mack and P. M. Kaufman, *J. Vac. Sci. Tech., B*, **6**, 2213 (1988).
11. C. A. Mack and J. E. Connors, *Proc. SPIE, Optical/Laser Microlithography V*, **1674**, to be published in these proceedings, (1992).
12. C. A. Mack, *Proc. KTI Microlithography Seminar*, 23 (1991).

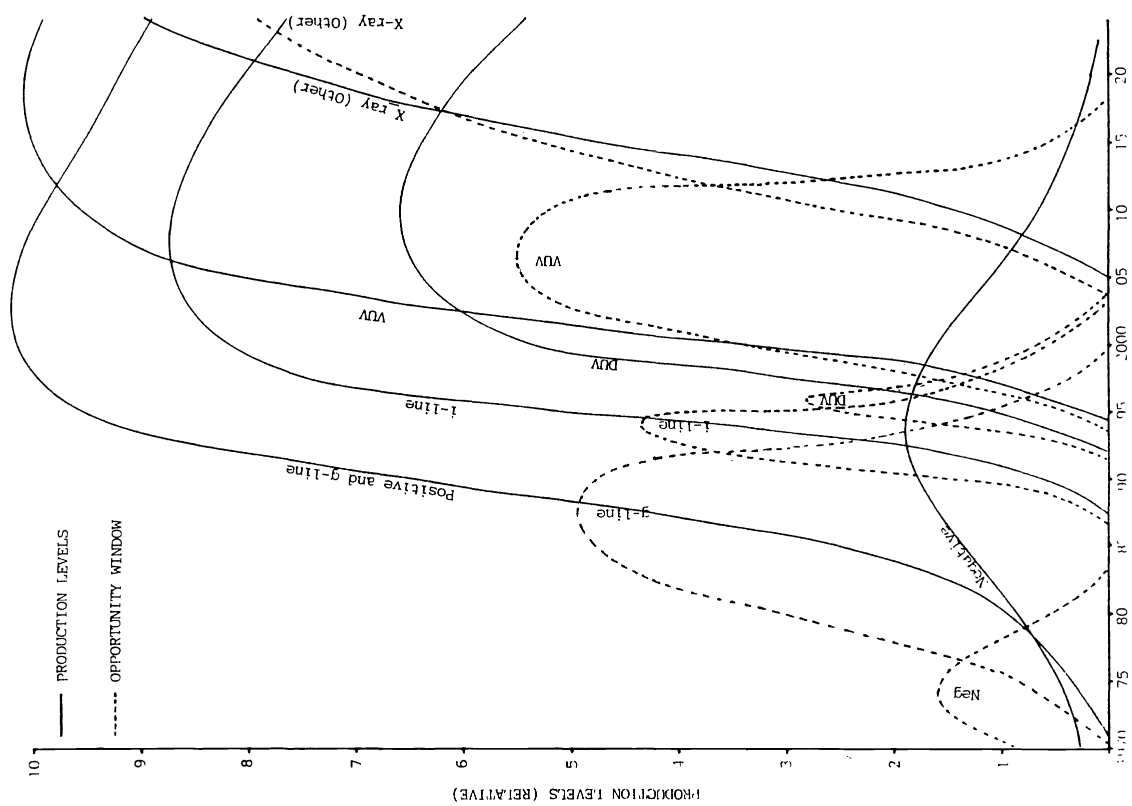


Figure 2. Technological window of opportunity and production volume for imaging technologies.

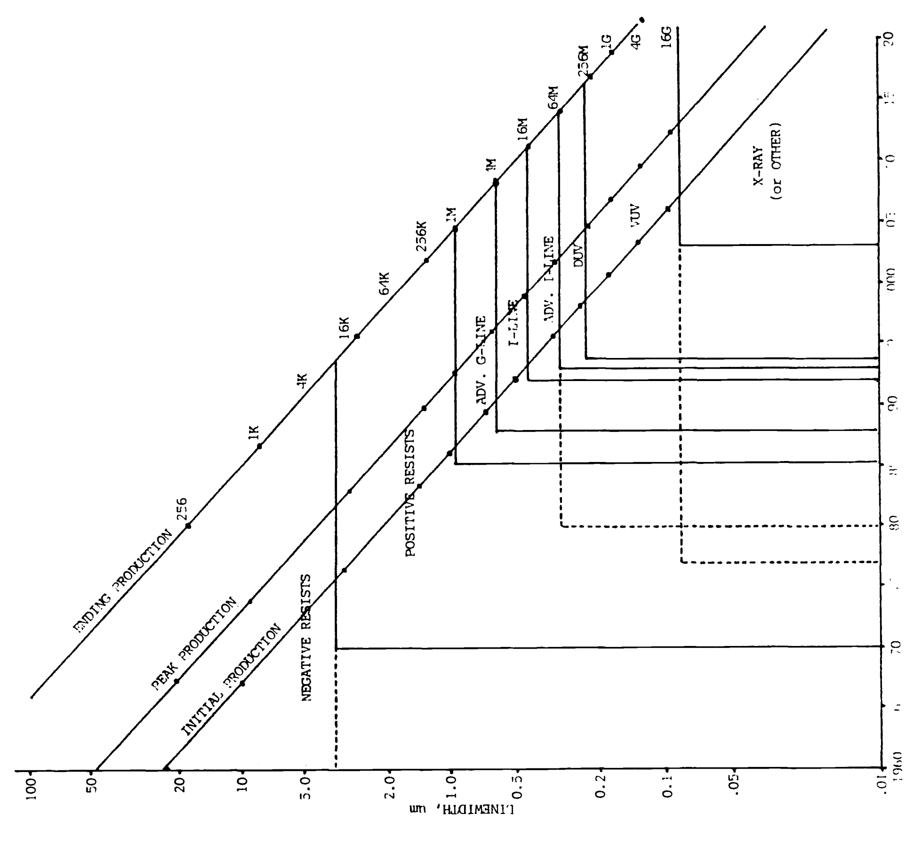


Figure 1. Evolution of Lithographic Technologies.

Figure 3. Historical decline in the process dependent constant, k_1.

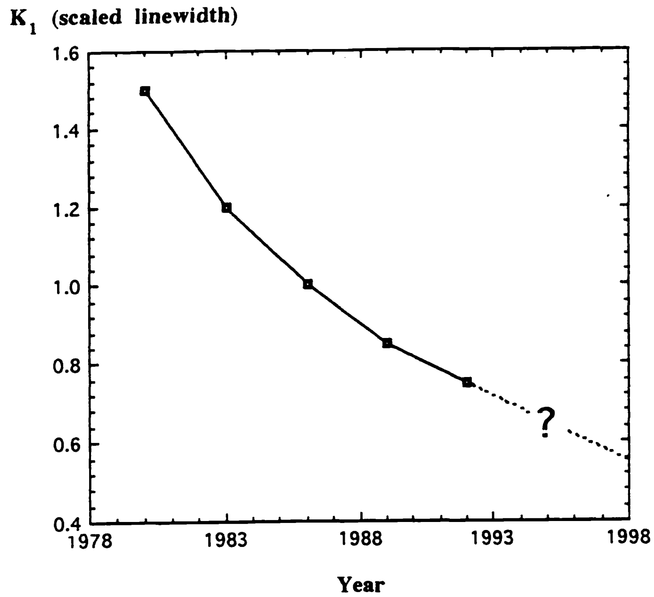
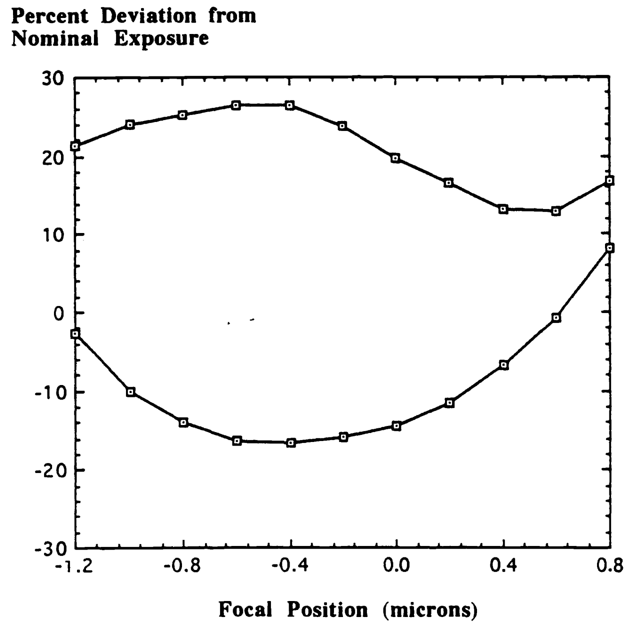


Figure 4a. Typical focus exposure process window for ±10% CD deviation from the nominal.



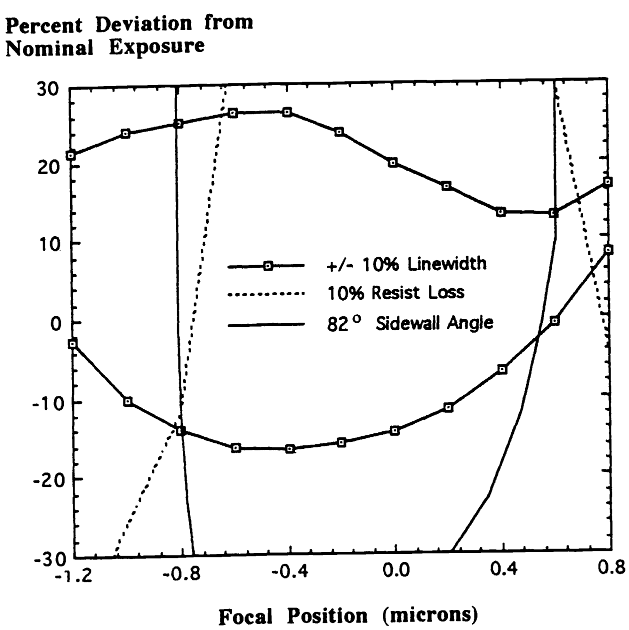


Figure 4b. Focus exposure process window for ±10% CD deviation with additional constraints of resist loss and sidewall angle.

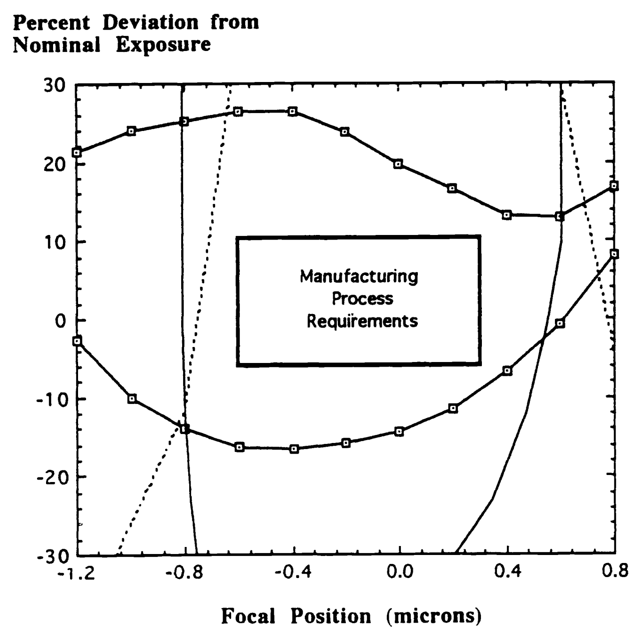


Figure 4c. Manufacturing exposure and focus process requirements superimposed on the focus exposure process window.