Cost of Ownership for X-Ray Proximity Lithography

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ABSTRACT

The cost of running a lithographic system is one of several factors considered by an integrated circuit manufacturer in deciding on a tool set for the fabrication of a new device generation. In this paper, we present an analysis of the cost of ownership for a synchrotron-based x-ray proximity printing system. We consider the total number of lithography tools that would be needed for a 0.25-micron manufacturing plant with 5000 200-mm wafer starts per week. We compare the cost of x-ray with that of deep ultra-violet lithography for patterning critical levels. For reference, we calculate costs for the noncritical levels as well. We examine x-ray costs as functions of synchrotron under-utilization, of reticle cost and usage, and of throughput. Our analysis indicates that, under the assumptions of identical process yield and throughput, x-ray system costs with a fully utilized synchrotron are competitive with deep ultraviolet costs if the manufacturing product has high volume. For low or moderate volume products deep ultra-violet lithography is cheaper, predominantly because of lower reticle costs. The lack of a strong economic driver for x-ray suggests that it is unlikely to be introduced into manufacturing until it is clear that no optical technology can adequately meet production needs.

1. INTRODUCTION

In the two decades since the invention of x-ray proximity lithography,[1] significant advances have been made toward making the technology production worthy.[2-4] Defect-free reticle capability[2] and synchrotron reliability[3,4] have been demonstrated, and numerous devices and test circuits have been built.[2,5-7] E-beam 1× reticle-writing capability is now sufficient to obtain 100-nm x-ray-to-x-ray overlay, 3σ,[8] and 36-nm or better critical dimension (CD) control, mean + 3σ.[2,9-11] The requirements that x-ray lithography has yet to meet are: (1) availability of a high-throughput stepper; (2) availability and rapid turn-around of reticles; (3) reticle overlay and CD control adequate for 0.25-µm and smaller CDs; (4) an insertion plan; and (5) an adequate infrastructure. With these shortcomings, x-ray lithography remains the most serious candidate for successor to optical lithography in production.

The issue of cost for x-ray lithography has been addressed by Wilson[12] in 1986 and by Hill[13] in 1989. Since these papers were written, x-ray lithography has evolved considerably, as have a number of factors affecting cost-of-ownership. The projected costs of equipment and reticles have gone up, and the estimated use of reticles has gone down. In this paper, we revisit x-ray cost-of-ownership and compare the economics of x-ray and deep ultra-violet (DUV) lithographies for use at 0.25-µm critical dimension (CD). In doing this, we make the large assumption that, when industry begins 0.25-µm production, adequate infrastructure will be in place, and that reticles, steppers, and resists will be available for either technology. We consider building a new fab that is to have 5000 200-mm wafer starts per week (wspw). The fab will run both high and low volume products using a process that requires 25 lithography levels, out of which 10 are critical levels. We calculate the number of steppers that will be needed of each type, and we compute the cost per wafer level exposure (pwle) for both the critical and noncritical levels. By analyzing the problem in terms of building a fab, we are forced to confront the issue of synchrotron under-utilization head-on. Our analysis focuses on the cost of operating the lithography system and does not include development or installation costs.

2. LITHOGRAPHY TOOL SET

2.1 Tool Set Description

For most, but not all, non-critical levels, the minimum linewidth is 2 × CD or smaller. Wherever possible, IC manufacturer like to use equipment that is well characterized and that has a proven track record. Thus, a typical choice for the non-critical level stepper is the tool that was used for the critical level on the proceeding IC generation, in this case, a 5× i-line stepper with a 25 × 25 mm^2 field. It is quite possible that some large geometry noncritical levels, such as well implant and pad masks, will be done with either

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a 1×, 2×, or 2.5× scanning system, which might have a field of ~ 50 × 50 mm^2.[14] If the light source is sufficiently bright, the scanning tool throughput can be quite high, making it attractive for controlling lithography costs. However, the benefit of increased throughput must be weighed against the overlay problems associated with using three tools in a mix-and-match mode. For the sake of simplicity, in this study we assume that all noncritical levels are exposed with a static-field i-line stepper.

We assume that the critical-level tool, whether x-ray or DUV, is to be a scanning stepper with a 25 × 50 mm^2 field. A synchrotron based x-ray system could have a field size as large as 50 × 50 mm^2, however, reticles of that size with adequate overlay may be difficult to fabricate. If a point source is used for x-ray, then the field will be static rather than scanning. But, a point source is unlikely to be bright enough to provide adequate throughput for production. We analyze throughput for both the synchrotron and point source in Sec. 6. In the case of DUV, a static-field tool may be advantageous from the standpoint of reticle costs and possibly throughput. However, these advantages might be offset by the cost and difficulty of building a fused-silica lens of size sufficient to cover a 25 × 25 mm^2 field.[14]

2.2 Throughput Calculations, Wafer Size, and Stepper Quantity

The number of steppers that the fab will require is obtained from the total number of exposures required per hour, divided by the net stepper throughput, which is calculated from

$$T_{NET} = U_{TOOL} \times 3600/(t_{OH} + N\times(t_{STEP} + t_{EXPO}) + t_{TRACK}). \qquad (1)$$

In Equation 1, U_{TOOL} is the fraction of the total fab operating time during which the stepper is processing production wafers, N is the number of steps taken on each wafer, and t_{OH}, t_{STEP}, and t_{EXPO} are the wafer overhead time, the time to step from field to field, and the time to expose a single field, respectively. The quantity t_{TRACK} is that fraction of the coat/develop track cycle time that is attributable to one wafer out of the total number that were run in sequence through the track and stepper without interruption. A typical one-wafer cycle time is ~ 800 sec. Thus, if a single lot of 24 wafers is run, the track adds an additional 33 seconds of overhead per wafer. We will assume in our analysis that eight 24-wafer lots are to be cascaded, reducing t_{TRACK} to 4 sec. The number of steps is calculated from

$$N = A_{WAFER}/(A_{FIELD} \times U_{FIELD}) \qquad (2)$$

where A_{WAFER} and A_{FIELD} are the areas of the wafer and field respectively, and U_{FIELD} is the stepper field utilization.

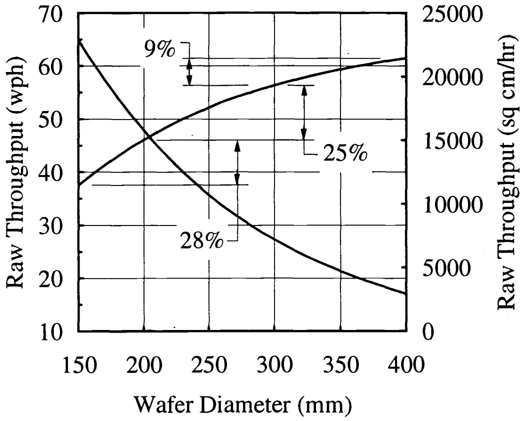

Figure 1. Impact of wafer size on throughput for an i-line stepper with 25 × 25 mm^2 field and 30, 0.4, and 0.5 sec. overhead, step, and exposure times.

The impact of wafer size on raw throughput for the i-line steppers is plotted in Fig. 1 both in terms of wph and cm^2/hr. In raw throughput calculations, U_{TOOL} and U_{FIELD} are set to unity, and t_{TRACK} is set to zero. The i-line stepper overhead, exposure, and step times are taken to be 30, 0.4 and 0.5 seconds, respectively. From Fig. 1, it is evident that while the throughput in wafers per hour (wph) goes down with increasing wafer diameter, the throughput in cm^2/hr goes up. The increase in Si area processed per unit time increases 25% in going from 200-mm to 300-mm dia. substrates, but the increase in going from 300-mm to 400-mm is only 9%.

Table 1 Lists the assumptions made in our preliminary calculation of the number of critical and noncritical-level steppers that will be needed by the fab. For this preliminary calculation we assume that the x-ray and DUV steppers have identical net throughputs. In Table 1, spatial, temporal, and throughput dimensions are mm or mm^2, sec, and wph. We assume that field and tool utiliziations are each 80%. For the noncritical-level i-line steppers, it is reasonable to assume that the listed times, utilizations, and net throughputs will be met. For the critical-level DUV or x-ray scanning tool, a 1-sec. exposure time is possible for either tool but is guaranteed for neither. The step and overhead times for the scanning steppers are tool manufacturer's goals, but are faster than the times of scanning steppers available today. The limitations on throughput for each technology will be reviewed in Sec. 6.

Table 1. Inputs for and Outcomes of Preliminary Stepper Quantities Calculations.

Level	Fld. Size	W. Dia.	wspw	N_{STEP}	t_{OH}	t_{STEP}	t_{EXPO}	T_{RAW}	T_{NET}	Qty
Noncritical	25 × 25	200	5000	62	30	0.4	0.5	48	32	14
Noncritical	25 × 25	300	2222	141	30	0.4	0.5	27	18	11
Noncritical	25 × 25	400	1250	251	30	0.4	0.5	17	11	10
Critical	25 × 50	200	5000	31	30	0.5	1.0	53	36	8
Critical	25 × 50	300	2222	70	30	0.5	1.0	32	21	6
Critical	25 × 50	400	1250	126	30	0.5	1.0	20	13	6

We note that, even though the net throughputs given in Table 1 are considerably lower that the raw throughputs, they are high compared with real fab throughputs today, which are closer to 20 wph using 150-mm wafers.[15] From Table 1, it is evident that the capital investment required to process a given area of Si goes down with increasing wafer diameter. Despite the potential economic advantage of using larger wafers, in our analysis we use 200-mm diameter substrates because it is difficult to project equipment costs for larger sizes. For the case explored in Table 1, a synchrotron with 16 beamline capability will be under utilized for any of the three wafer sizes. This issue of synchrotron under-utilization and its impact on lithography costs will be discussed further in Sec. 5.

3. HOURLY COST OF RUNNING THE LITHOGRAPHY SYSTEM

In determining the hourly cost of running each lithographic systems, we utilize a straight-line five-year depreciation cycle and we neglect salvage value of equipment. For uniformity of treatment, we assumed that per-year service contracts are 5% of the capital equipment cost. This adds 25% overhead to each tool. Additional overhead is accounted for by the tool footprint and labor. Input parameters that apply to all three lithography systems are listed in Table 2.

Table 2. Cost of Ownership Common Inputs.

Parameter	Value
Amortization Schedule	5 years
Work Days per Year	350 days
Work Hours per Day	24 hours
Yearly Service Contract Cost as Fraction of Capital Cost	0.05
Cleanroom Footprint Cost	\$360/ft^2/yr
Wafer Diameter	200 mm

Lithography costs per hour are computed from

$$C_{LPH} = C_{ED} + C_L + C_{FP} + C_M \tag{3}$$

where C_{ED} is the hourly capital equipment depreciation cost, C_L is the labor cost per hour, C_{FP} is the cleanroom footprint cost, and C_M is the tool maintenance, or service contract, cost. Inputs and hourly running costs for i-line, DUV, and x-ray are given in Tables 3, 4, and 5. For the case of x-ray, the hourly rate assumes that all 16 synchrotron ports are utilized. For the inputs used here, DUV is 44% more expensive to run on an hourly basis than i-line, and x-ray is 16% more expensive than DUV.

Table 3. Hourly noncritical-level Stepper and Track Cost.

Parameter	Value
i-Line Stepper Capital Cost	$2.7M
Coat/Develop Track Capital Cost	$2.0M
Stepper & Track Cleanroom Footprint	150 ft^2
Operators/System	1/2
Labor Cost	$15/hr
System Hourly Cost	$161/hr

Table 4. Hourly DUV Stepper and Track Cost.

Parameter	Value
Stepper Capital Cost	$5.0M
Coat/Develop Track Capital Cost	$2.0M
Stepper & Track Cleanroom Footprint	200 ft^2
Operators/System	1/2
Labor Cost	$15/hr
System Hourly Cost	$232/hr

Table 5. Hourly X-Ray Stepper and Track Cost.

Parameter	Value
Stepper Capital Cost	$4.0M
Synchrotron Capital Cost	$ 25M
Ports per Synchrotron	16
Beamline Capital Cost	$0.5M
Coat/Develop Track Capital Cost	$2.0M
1/16 Synchro. & Stepper & Track Footprint	300 ft^2
Synchrotron Labor Cost	$30/hr
Operators/System	1/2
Labor Cost	$15/hr
System Hourly Cost	$270/hr

4. TIME INDEPENDENT LITHOGRAPHY COSTS

4.1 Photoresist and related costs

Inputs for resist costs are given in Table 6. Since DUV resists are sensitive to x-ray wavelengths, and vice versa, the costs for the two resists are assumed to be identical. The $2K/gal. price, which is more than twice that of i-line resists, is a factor of 3 or 4 below market. It anticipates a drop in price based on volume and manufacturing methods improvements. We assume that the i-line levels will require a top level antireflection coating (TARC). For DUV levels, the BARC chosen consists of a sputter-deposited film of α-C.[16,17] Costs for deposition and etch of the BARC are given in Tables 7 and 8. If a spin-on BARC had been chosen instead of α-C, the BARC cost would drop by a dollar. However, the effectiveness of a BARC depends on its thickness as well as

Table 6. Resist and ARC Costs.

Parameter	Value
i-Line Resist Cost	$800/gallon
X-Ray and DUV Resist Cost	$2K/gallon
Resist Usage	4.5 ml/wafer
TARC Cost	$675/gallon
TARC Usage	4.5 ml/wafer
BARC Deposition Cost	$1.83 pwle
BARC Etch Cost	$0.48 pwle
i-Line Resist & TARC Cost	$1.75 pwle
DUV Resist & BARC Cost	$4.69 pwle
X-Ray Resist Cost	$2.38 pwle

Table 7. α-C BARC Deposition Cost.

Parameter	Value
Sputter System Capital Cost	$2.0M
Sputter System Footprint	50 ft^2
Operators/System	1/2
Labor Cost	$15/hr
Number of Chambers	2
Raw Throughput/Chamber	30 wph
Net Thruput/Chamber (70% Utilization)	21 wph
α-C BARC Deposition Cost pwle	$1.83 pwle

Table 8. α-C BARC Etch Cost.

Parameter	Value
Etch System Capital Cost	$0.5M
Etch System Footprint	50 ft^2
Operators/System	1/2
Labor Cost	$10/hr
Raw Throughput	80 wph
Net Throughput (70% Utilization)	56 wph
α-C BARC Etch Cost pwle	$0.48 pwle

its complex refractive index. A conformal BARC will deliver better CD control than a spin-on film, which tends to have variable thickness at topographic steps.[16,17]

The BARC process costs, like all other costs within the model, assume a fully yielding process. The issue of defects and yield will be discussed in Sec. 7. For x-ray, which can use a single-layer resist process, the per-wafer-level-exposure (pwle) cost is 36% higher than for the two-layer i-line process because the resist material cost is higher for x-ray. The DUV coating cost with BARC is twice that of the single-layer x-ray resist.

4.2 Reticle usage

It is sometimes assumed that in IC production, on average, each reticle set is used to pattern tens of thousands of wafers. That this is not necessarily so can be seen from Figure 2, which is a histogram of the average number of wafers processed per device in the year 1992 for three of our company's fabs. This histogram, from which information about reticle usage can be inferred, builds on the two-fab histogram we published in reference 18. In Figure 2, the term device denotes a particular IC chip or chip revision. For some devices multiple reticle sets were used to increase production. Others devices might have been either in the process of ramp up or ramp down. In Fig. 3, the distribution of the 253 devices from Fig. 2 are plotted as a function of the number of wafers processed for each. The average is 1800 wafers processed per device and the mean is 226. For only 8% were more than 10,000 wafers produced, and for 26% less than 100 wafers were processed. In Sec. 5.1, we will see that reticle usage has a significant effect on CoO.

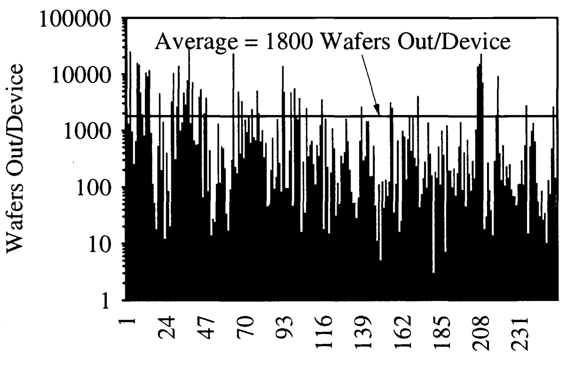

Figure 2. A histogram of the average number of wafers processed per device, or chip, type can be taken as an indication of reticle usage. The histogram is a composite from three fabs.

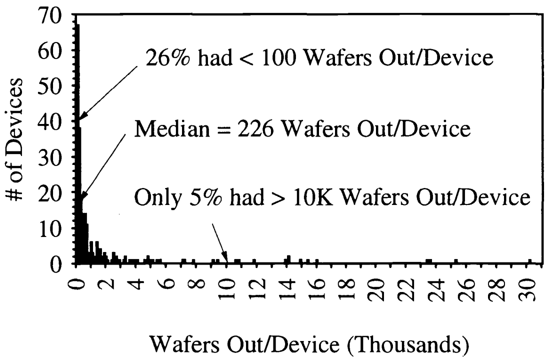

Figure 3. The distribution of devices as a function of wafers out per device shows that the majority of devices - and by inference, reticles - are associated with a relatively small number of wafers.

5. COST OF OWNERSHIP COMPARISON

The total cost of lithography pwle is given by:

$$C_{TOT} = C_{LPH}/T_{NET} + C_{RESIST} + C_{RET} \qquad (4)$$

where C_{RESIST} is the pwle cost of the resist materials, as given in Table 6, and C_{RET} is the pwle cost for the reticle, which is obtained by dividing the reticle cost by the number of wafers processed with that reticle.

5.1 Impact of Reticle Cost and Usage

The cost of a noncritical level i-line reticles is assumed to be \$3.4K. The DUV scanning system will require a 6×9 in^2 reticle, which is likely to cost in the range of \$6K to \$15K. We make the assumption that a DUV process for 0.25-µm CD will not require phase-shift masks (PSMs). Defect free x-ray reticle prices are difficult to predict. However, since the mask blanks are considerably more complicated than a chromium-on-quartz optical reticle, and since the CD and overlay specifications will have to be tighter than for optical, it seems likely that the minimum price will be ~ \$20K per mask. With 5000 wspw using a process with 10 critical levels and with an average usage of 2,000 wafer-level-exposures-per-reticle (wlepr), the yearly critical-level reticle expenditure for a single fab is \$25M, roughly an order of magnitude more than is spent for all the reticles for a fab today. For a company such as ours that owns several fabs and generates \$1.6B in revenues with a 19% profit margin, \$25M represents more than 10% of its profits.

In Fig. 4 lithography costs pwle are plotted for both x-ray and DUV as a function of wafer level exposures per reticle. The net throughput used in Fig. 4 is 36 wph, which is the value given in Table 1. At high volumes of wlepr, x-ray appears to be slightly cheaper than DUV. However, this difference in cost is more than off-set by uncertainties in the input parameters to the model. For an average reticle usage of 2,000 wlepr, costs for both technologies are close to being dominated by the reticle cost. For the 50% of devices for which < 226 wafers were processed, the cost of running the lithography system is synonymous with the reticle cost. That is, the reticle cost is the cost of doing lithography. In this low volume regime, if an x-ray mask costs is n× the cost of a DUV reticle, x-ray lithography is n× as expensive as DUV. This impact of the reticle cost on pwle costs applies in the case of PSMs as well.

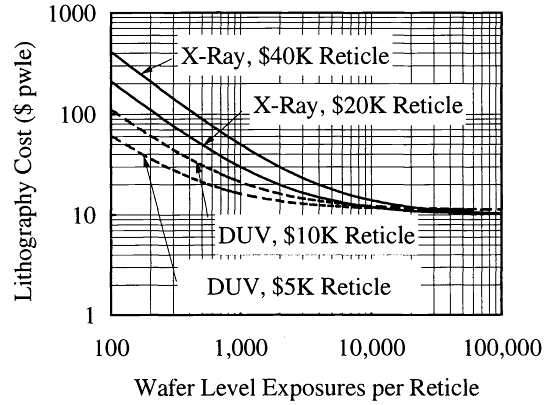

Figure 4. Lithography cost in \$ pwle are plotted as a function of reticle usage for both DUV and x-ray.

A factor besides usage that will affect total expenditure for x-ray masks is membrane breakage. X-ray mask membranes are typically 2.5-μm thick and are made of materials such as Si, Si_xN_y, SiC, or diamond. These membranes have been shown to be extraordinarily strong in that, if properly designed, they can hold off a full atmosphere of pressure over a 25-mm dia. area.[19,20] Nevertheless, as packaged, handled, and used today, they are far more prone to breakage than are quartz reticles, even though the latter are typically equipped with nitro-cellulose pellicles that are only ~ 1-μm thick. On average, 3% of optical reticles might arrive at an IC fab with damaged pellicles. The turn-around time for replacement of the pellicles is 24 hours or less. An additional 5 to 10 pellicles a year might be replaced because of damage caused by either operator or equipment malfunction. And the pellicle replacement cost is only a few hundred dollars. Breakage of the reticle itself is extraordinarily rare, occurring perhaps once a year. If x-ray technology is to be used for IC manufacturing, the problem of membrane breakage will have to be eliminated.

5.2 Impact of Synchrotron Under Utilization

Fig. 5 contains three plots, each for a different throughput, of lithography costs pwle as a function of the number of wafer level exposures required per hour for the entire fab. In these plots, the stepper, in-line track, and synchrotron are all treated as discrete quantities. The small teeth in the curves correspond to incremental increases in the number of exposure stations needed. Each large tooth corresponds to the addition of another synchrotron. In calculating a given curve, the throughput is held constant, and the per hour cost for a lithography station is calculated from

$$C_{LPH} = (C_{STEP} + C_{TRACK} + C_{BL} + C_L + C_{FP} + C_M)\times n_{STA}\times T_{NET}/n_W + n_{SYN}\times C_{SYN}/n_{STA} \quad (5)$$

where C_{STEP}, C_{TRACK}, C_{BL}, and C_{SYN} are the per hour capital depreciation costs for a stepper, wafer track, beamline, and synchrotron. C_L, C_{FP}, and C_M are the per hour labor, tool cleanroom footprint, and tool maintenance costs. The quantities n_{STA} and

n_{SYN} are the number of lithography stations and synchrotrons required, and n_W is the total number of wafer-level-exposures-per-hour (wleph) needed by the fab. The term $n_{STA} \times T_{NET}/n_W$ distributes the per hour cost of running n_{STA} lithography stations over the total number of wleph for the fab. Similarly, $n_{SYN} \times C_{SYN}/n_{STA}$ effectively distributes the cost of the synchrotron(s) over the number of lithography stations that are actually used.

The difference in pwle costs for a synchrotron with a half component of steppers as compared with a fully utilized synchrotron is 7 to 10% depending on stepper throughput. Similarly, if 17 steppers are needed rather than 16, and a second synchrotron is purchased to accommodate that one additional stepper, the increase in costs is 8 to 11% pwle. The synchrotron has a relatively minor effect in part because the high fixed costs of $10 pwle for the reticle and $3 for the resist. A half utilized synchrotron represents 1/3 of the capital investment per exposure station as compared with 19% for a synchrotron with 16 steppers. The per hour cost of running a half utilized synchrotron is ~ 17% higher than that of a fully utilized one.

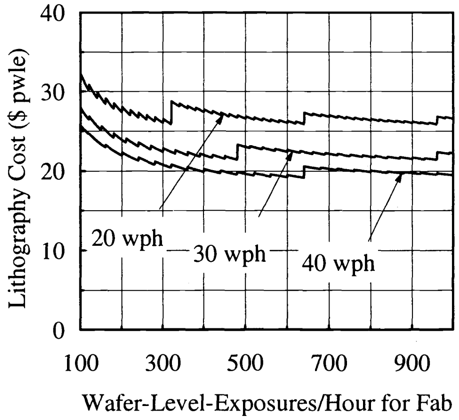

Figure 5. Comparison of lithography costs in $ pwle, as a function of total fab wafer-level exposures per hour, for net throughputs of 20, 30, and 40 wph.

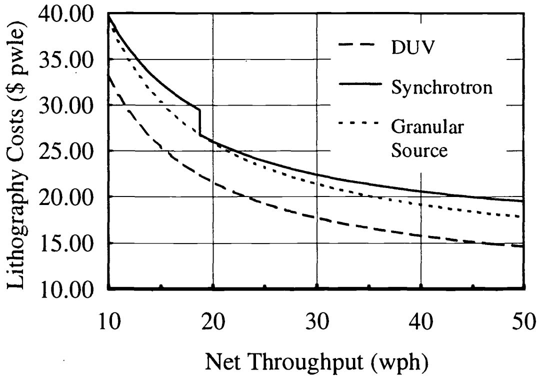

Figure 6. Comparison of lithography costs in $ pwle for an x-ray stepper with synchrotron light source, an x-ray stepper with a hypothetical granular source of the same brightness, and a DUV stepper.

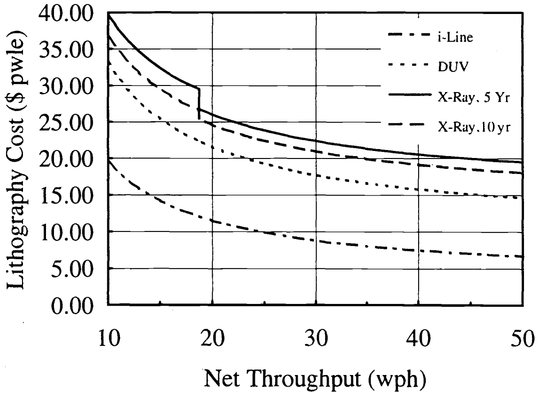

Figure 7. Comparison of exposure costs for x-ray stepper where the synchrotron source is depreciated 5 and 10 years, DUV, and noncritical-level i-line costs.

In the development phase where only one or two steppers are needed, the synchrotron will have a large effect on pwle costs, but, it is not likely to be large enough to make it a show-stopper. An under-utilized synchrotron is analogous to a new facility where unused floor space is held until additional tools are needed to increase the fab capacity. If the additional overhead is considered insupportable, the cost can be ameliorated, through the formation of partnerships between IC manufacturing companies for sharing of synchrotrons. The issue of synchrotron reliability and system downtime will have to be looked at carefully though since all critical-level lithography will be depending upon a single light source.

In Fig. 6, pwle costs for x-ray and DUV are plotted as a function of net throughput for the case of 300 wph total fab throughput. For x-ray, costs are plotted both as if each stepper had a discrete source of brightness comparable with a synchrotron and for the case of a synchrotron. In this plot, steppers have been treated as a continuous rather than discrete quantity. In Fig. 7, noncritical level i-line costs are shown as well. For x-ray, the two curves correspond to 5 and 10 year depreciation cycles. A comparison of critical and non-critical level costs makes evident the economic drive to use mix-and-match. At net throughputs of 20 to 40 wph, the i-line levels are roughly half the cost of the DUV levels, and x-ray is 20 to 30% more expensive than DUV. The reason that the noncritical levels are so much cheaper is the lower i-line stepper, reticle, and resist costs. The difference in cost between x-ray and DUV is driven by the reticle cost. If the pwle cost of the reticle is deducted from each, then the DUV and x-ray curves in Fig. 7 are coincident, accept at low throughput where the addition of a second synchrotron raises x-ray costs slightly above those of DUV.

6. THROUGHPUT LIMITATIONS

The inputs used in throughput calculations for DUV and x-ray are given in Table 9. For completeness, we have included a throughput calculation for an x-ray laser point source. Synchrotrons and laser point sources typically have different spectrums. The assumption here is that the synchrotron is centered at 1.0 nm and the point source at 1.4 nm. The x-ray mask membrane is assumed to be 2.5-μm-thick Si. The mask membrane transmission and the resist absorption are different for the two wavelengths. But, the mask-resist efficiency, i.e. the product of the mask transmission times the resist absorption only differs by ~30% for the two cases studied here.[21] The resist absorbs ~ 13% of the 1.4-nm point-source radiation that is incident on the mask. For the case of the synchrotron, the resist absorption is ~ 10% of the mask-incident 1.0-nm radiation. Since the point source is radiating into 2π steradians, it is assumed that the point-source stepper has a square field, 25 × 25 mm^2, rather than a scanning field.

Table 9. Inputs Raw Throughput Calculations.

Parameter	DUV, Laser Source	X-Ray, Synchrotron	X-Ray, Laser Point Source
Wafer Diameter (mm)	200	200	200
Field Size (cm^2)	12.5	12.5	6.25
Number of Steps	25	25	50
Step Time	0.5	0.5	0.5
Overhead Time	30	30	30
Field Scan Length (mm)	50	50	N/A
Overscan Length (mm)	5	17	N/A
Total Scan Length (mm)	55	67	N/A
Si Mask Membrane Thkness (μm)	N/A	2.5	2.5
Mask Transmission	1	0.59	0.35
Resist Absorption (μm^{-1})	N/A	0.17	0.37
Resist Dose (mJ/cm^2)	N/A	68	31
Mask-Resist Efficiency	N/A	0.10	0.13
X-Ray Conversion Efficiency (%)	N/A	N/A	10
Source-to-Substrate Distance (cm)	N/A	N/A	40
Conversion. Factor, Φ (mW/mA/cm)	N/A	1.5	N/A

For a scanning DUV stepper with a pulsed laser source, system throughput is likely to be limited primarily by the repetition rate of the laser and the number of pulses that are required to achieve good field uniformity rather than by photon flux. The number of pulses required will depend upon the variation in pulse-to-pulse energy. DUV throughput, as a function of the number of required pulses, is shown in Fig. 8. for 500 and 1000 Hz sources. The DUV scan speed is given by

$$S_{DUV} = N_{PPS} \times W_{SLIT} \times f_{LASER} \tag{6}$$

where N_{PPS} is the number of pulses per slit width, W_{SLIT} is the slit width, in this case 5 mm, and f_{LASER} is the laser frequency. The exposure time per field is given by

$$t_{EXPO} = L_{TOTAL} / S_{DUV} \tag{7}$$

where L_{TOTAL} is the total length that is scanned, including overscan. For example, a raw throughput of ~ 64 wph for 250 pulses per field was calculated using the exposure time required to deliver 275 pulses. The time required to reverse the direction of scanning beam is incorporated in the 0.5 sec step time. At 500 Hz and 250 pulses per field., the scan speed is 100 mm/sec and the exposure time is 0.55 sec. However, this corresponds to only 25 pulses per slit width. If the number of pulses required per slit is 50 or 100 then the exposure time per field will go to 1.1 or 2.2 seconds respectively. With a 2.2 sec exposure time, raw throughput would be 37 wph. If the laser frequency were doubled to 1K Hz, then the exposure time would drop to 1.1 sec and the throughput would be in excess of 50 wph. With careful design, a DUV scanning stepper has a good chance of meeting the 1 sec exposure time used in our initial calculations for Table 1.

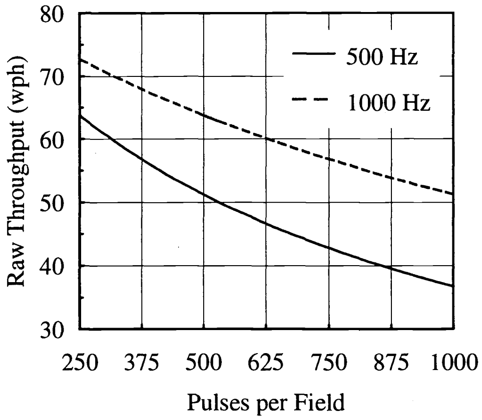

Figure 8. Calculated DUV scanning stepper throughput as a function of required number of pulses per field for a system with 30 sec overhead time, 0.5 sec step time, and 25 steps per 200-mm wafer.

For the x-ray synchrotron, the scanning speed for the stepper is determined from[2]

$$S_{SYN} = \Phi \times I \times T/D \tag{8}$$

where Φ is a conversion factor in mW/mA/cm, I is the ring current in mA, T is the mask membrane transmission, and D is the dose to the resist in mJ/cm^2. The exposure time per field is then obtained from Eq. 7. In Fig. 9 are plots of raw throughput as a function of synchrotron current for four different doses. Synchrotrons typically operate with average currents of 150 to 500 mA.[3,4,22] We can see that in that range, throughputs in excess of 60 wph can be obtained for a 25 mJ/cm^2 resist. Reported doses for resists that offer adequate CD control for 0.35-µm CDs are between 50 and 75 mJ/cm^2.[2,3] Provided that these doses can be maintained or lowered for 0.25-µm and smaller CDs, and that targeted stepper overhead and step times are met, at a current of 300 mA, a raw throughput of 50 wph or greater can be obtained. At 500 mA, the throughput can exceed 60 wph.

For a laser-plasma x-ray point source, exposure time per field can be calculated from

$$t_{EXPO} = D \times 2\pi r^2 / (\eta \times T \times P_{LASER}) \tag{9}$$

where r is the source-to-substrate distance in cm, η is the fractional x-ray conversion efficiency, and P_{LASER} is the laser power expressed in mW.

The source-to-substrate distance should be chosen to obtain the maximum flux to the wafer plane that is consistent with obtaining good overlay. A potential contributor to the overlay budget that is caused by beam divergence is the so-called run out error.[23] For our calculations, we assume a 30-cm source-to-substrate distance, which is believed to allow for adequate overlay, including run out, for the 0.25-µm device generation.[24] In Fig. 10, we compare the throughput for a point source with that of a synchrotron. The inputs used in plotting Fig. 10 are listed in Table 9. The dose used for the synchrotron is 68 mJ/cm^2. The dose for the point source was chosen such that the energy absorbed in the resist would be the same as in the synchrotron case, 115 J/cm^3. Note that the point source requires a 2 kW laser to obtain 20 wph raw throughput. At 20 wph, the point source x-ray system would have throughput competitive with cell-projection e-beam.[25] Such a point source tool might also be useful for IC development work. However, for high-throughput, such as is required in IC production, a synchrotron is necessary.

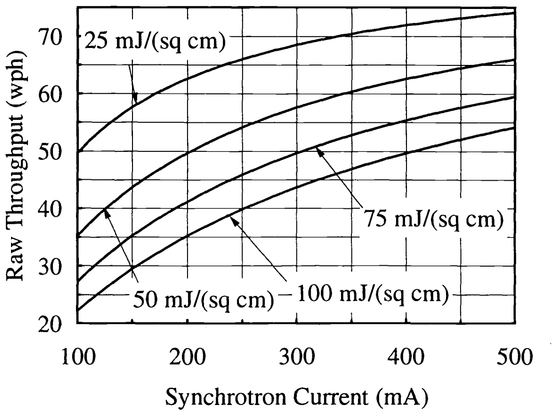

Figure 9. Calculated x-ray scanning stepper throughput as a function of synchrotron current.

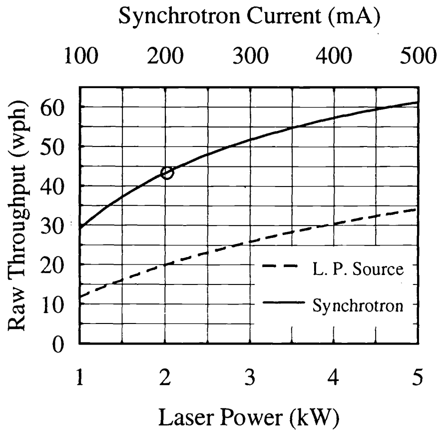

Figure 10. A comparison of synchrotron-based stepper throughput, as a function of ring current, with laser-point-source stepper throughput, as a function of laser power.

We have made the assumption that the step and overhead times for DUV and x-ray will be the same. But, the issues that are likely to limit these times are not the same for the two technologies. For DUV, the reticle and wafer are well separated within the stepper. Although the wafer must be leveled globally, and perhaps field by field as well, the DUV reticle-plane leveling is usually done only during stepper installation and is rarely change thereafter. For x-ray, the mask membrane and wafer planes must be brought into parallel at gaps in the range of 20 to 40 µm. Thus the two planes must each be aligned parallel to some third reference surface. X-ray has the added task of scanning each wafer for particles that might collide with the mask membrane. And helium must be introduced between the mask and wafer to eliminate the attenuation loses that would occur for an exposure through air. Incorporated in the overhead time is the gap-settling time associated with bringing a thin membrane into close proximity with a wafer.[26] The subsystems for wafer and mask handling and for gapping and helium fill must be designed for speed as well as precision if targeted throughput goals are to be met.

7. SYSTEM AVAILABILITY, RELIABILITY, AND UPTIME

Achieving high net throughput requires high tool utilization. Stepper manufacturers help make this possible by optimizing the tool/operator interface so that job set-up and change-over times are minimized and by maximizing system uptime. A frequently quoted tool uptime goal is 97% of fab operating time, but actual percentages in typical IC fabs are 85 to 95%. Tool uptime is maximized by minimizing the required service, preventative maintenance, and engineering test times, and by maximizing the mean time between failures. A bulb change, which is one standard preventative maintenance task for an i-line system, takes two hours and is performed every 600 hours. This consumes 0.3% of the fab operating time. For a synchrotron based lithography system, 3% of the possible system uptime is consumed by the 15-minute ring fill that is required for every eight hour shift. Other factors that influence tool utilization are: no work; no operator, job start-up; and reticle changes. In our analyses, we assumed 80% utilizations for the lithography system. This utilization figure can be met only if stepper and synchrotron vendors work together to coordinate preventative maintenance schedules and to maximize system ease-of-use.

8. YIELD LIMITATIONS

In our analysis, we have neglected yield, even though its impact on costs is tremendous. For the case of DUV, the use of a BARC will introduce statistical defects, although it is difficult to predict the magnitude a priori. Errors in CD caused by lack of adequate DOF and by any uncompensated thin-film interference effects will also contribute to yield losses. For 1× x-ray, CD and overlay control at the mask will not be as good as in the case of DUV at 4× demagnification. Optical stepper magnification can by altered as needed to compensate for process-induced expansion or contraction of the wafer. In the case of x-ray, it is possible that the compensation can be made in mask writing, but this is likely to add to mask cost. The overlay errors may translate into either a yield loss or into a limitation on field size, which will reduce throughput somewhat. Further, there are no pellicles available for x-ray. Thus, there is a potential for a killer defect that could reduce yield to zero. This problem can and should be addressed by scanning the mask for particles while it is in use in the stepper, although this may add to wafer overhead time. X-ray's real strength is its process latitude, which is much greater than in the case of DUV. The greater process latitude comes from the shorter wavelength, which allows for a greater DOF or gap range, and from the lack of thin-film interference effects. These are strong arguments in x-ray's favor, but to make an argument for lower x-ray costs as compared with DUV based on yield will require a convincing experimental demonstration. A demonstration that would be encouraging for x-ray would be a multiple-level x-ray experiment on a 256 Mb memory, or comparable device, that yielded a fully functional part. If obtaining fully functional part is unlikely because of non-x-ray-related fabrication issues, the next best demonstration might be the production of a large number of defect-free masks, in combination with more device and CD control comparisons in the manner of references 2 and 11. Electrical measurements of defect densities using serpentine and comb test structures could also be used.

9. CONCLUSIONS

We have presented a CoO analysis using a fairly simple model which requires a relatively small number of inputs: capital equipment, cleanroom, tool maintenance, and labor costs; resist and reticle materials and usage costs; and net tool throughput. We have used the model to analyze both critical and noncritical level lithography costs for the 0.25-μm device generation. Our analysis indicates that the processing costs for critical levels are likely to be twice those of i-line noncritical levels, or more. This difference in pwle costs is driven by the higher cost for steppers, reticles, and resists for the critical level processes.

Our comparison of x-ray and DUV suggests that, under the assumption of identical throughputs and yields, the two technologies are comparable in pwle costs for products where the number of wafer-level-exposures-per-reticle exceeds 10,000. For low to moderate volume products, DUV is substantially cheaper because its reticle cost is likely to be no more than one half that of x-ray's. A lower reticle cost becomes particularly advantageous for the situation where only a few hundred wafers are processed with a given reticle set. For that situation, the reticle cost is synonymous with the lithographic processing cost. Thus, a technology with a reticle that is n× as expensive as that of a competing technology is n× as expensive to use. We present data that indicates that for our company this category of low reticle usage applies to more than half of all reticles used in production.

In the case of low reticle usage, a DUV lithography system can be tailored to meet demands for reduced CoO by using a smaller reticle. A six-inch square reticle might be 30 to 50% cheaper than a 6×9 in^2 reticle that is needed to cover the full-field of the scanning tool. To the extent that the cost of the reticle is pixel driven, the same argument can be made for x-ray, although the savings for x-ray may not be as great because of the higher mask blank cost. But, a smaller membrane for x-ray would also be advantageous from the standpoint of maximizing mask robustness, and it would facilitate meeting overlay specifications. The cost advantage of a smaller reticle suggests that for either technology stepper designers would be wise to minimize step and overhead times as much as possible so that high throughput can be obtained without minimizing the number of steps per wafer.

From the lack of a substantial difference in cost for a high-volume product processed with either x-ray or DUV it follows that there is no economic driver for bringing x-ray to production until it is certain that optical lithography can no longer meet production needs. We must then ask: Is there still a window for x-ray at 0.25-μm? Many within the optical community are confident that 0.25-μm generation will be done optically, and many in the x-ray field doubt that the infrastructure for x-ray will be in place in time for 0.25-μm. Because of the high cost and risk associated with changing from one technology to another, IC manufacturers require that a new technology be extendible to at least a second generation. If x-ray is to be used at 0.18-μm, then IC manufacturers will need to be convinced that x-ray can do 0.12-μm in production as well. It is quite possible that we will see an end to reduction in CD in manufacturing for reasons of economics rather than because of fundamental device-physics limitations. To avoid this possibility, every effort should be made in system design to reduce x-ray lithographic costs. The way to do this is to drive x-ray mask costs down and to maximize system throughput.

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11. REFERENCES

1. D. L. Spears and H. I. Smith, "High-resolution pattern replication using soft x rays," Electron Letters, Vol. 8, 102-104 (1972).
2. R. Viswanathan et al., "Fabrication of high performance 512K static-random access memories in 0.25 μm complementary metal-oxide semiconductor technology using x-ray lithography," J. Vac. Sci. Technol. B **11**, 2910-2919 (1994).
3. J. P. Silverman, C. N. Archie, J. M. Oberschmidt, and R. P. Rippstein, "Performance of a wide-field flux delivery system for synchrotron x-ray lithography," J. Vac. Sci. Technol. B **11**, 2976-2980 (1993).
4. D. E. Andrews and C. N. Archie, "Helios compact synchrotron x-ray source: one year of operation at ALF," SPIE vol. 1924, 348-352 (1993).
5. A. Yoshikawa et al., "Synchrotron radiation lithography applied to fabrication of deep-submicrometer nMOS devices at all exposure levels," Microelectronic Engineering 11, 233-236 (1990).
6. D. Friedrich, H. Bernt, L. Schmidt, and W. Windbracke, "Degradation behavior of 0.5-mm p-channel metal-oxide-semiconductor transistors fabricated by means of x-ray and optical lithography," J. Vac. Sci. Technol. B 8, 1638-1642 (1990).
7. K. Deguchi, K. Komatsu, H. Namatsu, M. Sekimoto, M. Miyake, and K. Hirata, "Step-and-repeat x-ray/photo hybrid lithography for 0.3-μm MOS devices," IEEE Trans. Electron Devices, Vol ED-34, 759-764 (1987).
8. J. F. Conway, C. N. Alcorn, D. D. Patel, J. A. Ricker R. C. Yandow, L. Hsia, and A. L. Flamholz, "Fabrication of high-density SRAM chips using mix-and-match lithography," SPIE Vol. 1924 300-308 (1993).
9. M. A. McCord, A. Wagner, and D. Seeger, "Effect of mask absorber thickness on x-ray exposure latitude and resolution," J. Vac. Sci. Technol. B 11, 2881-2887 (1993).
10. M. A. McCord, A. Wagner, and T. Donohue, "Resolution limits and process latitude of x-ray mask fabrication," J. Vac. Sci. Technol. B 11, 2958-2963 (1993).
11. W. G. Waldo, A. D. Katnani, and H. Sachdev, "Resist optimization for SOR x-ray lithography using an orthogonal experimental design," SPIE Vol. 1671, 2-23 (1992).
12. A. D. Wilson, "X-ray lithography: can it be justified?" Solid State Technology, Vol. 29, 249-255 (1986).
13. R. W. Hill, "The future costs of semiconductor lithography," J. Vac. Sci. Technol. B 7, 1387-1390 (1989).
14. W. H. Arnold and G. C. Escher, "Wafer steppers for the 64M and 256M memory generations," presented as paper 4 in Session 1 of Photomask '93, to be published in SPIE publication CR-51, 64 to 256 Mbit Reticle Generation: Technology Requirements and Approaches, ed. Gregory Hern.
15. "The competitive semiconductor manufacturing survey: First report on results of the main phase," Report CSM-02, ed. R. C. Leachman, Berkeley Rountable on the International Economy, 2234 Piedmont Ave., U. of California at Berkeley (1993).
16. M. W. Horn, "Antireflection layers and planarization for microlithography," Solid State Technol. 34, 57-62 (1991).
17. Y. Suda, T. Motoyama, H. Harada, and M. Kanazawa, "A new anti-reflective layer for deep UV lithography," SPIE Vol. 1674, 350-360 (1992).
18. K. Early and W. H. Arnold, " Cost of ownership for soft-x-ray projection lithography," in Soft-X-Ray Projection Lithography, Vol. 18 of OSA Technical Digest Series (Optical Society of America, Washington, DC, 1993) 14-22. Also published in SPIE vol. 2087, ed. E. C. Grady and J. P. Moneta, 340-349 (1994).
19. A. Moel, M. L. Schattenburg, J. M. Carter, and H. I. Smith, "A compact, low-cost system for sub-100 nm x-ray lithography," J. Vac. Sci. Technol. B 8, 1648-1651 (1990).
20. L. E. Trimble et al., "Membrane fragility: Fact or illusion?" J. Vac. Sci. Technol. B 10, 3200-3203 (1992).
21. S. D. Hector, PhD Dissertation, MIT, to be published June 1994.
22. Private communications from Shiro Hamada of Sumitomo Heavy Industries, Ltd. regarding Aurora 2, and from Yoshio Yamashita, SORTEC Corporation, Japan.
23. A. N. Broers, "Practical and fundamental aspects of lithography," Materials for Microlithography, ACS Symposium Series 266, ed. L. F. Thompson, C. G. Willson, and J. M. J. Frechet, 18 (American Chemical Society, Washington, DC, 1984).
24. J. Maldanodo, presented at the ARPA Advanced Lithography Program Review, Fort Myers, Florida, 24-27 Jan. 1994.
25. Y. Nakayama et al., "Electron-beam cell projection lithography: A new high-throughput electron-beam direct-writing technology using a specially tailored Si aperature,"J. Vac. Sci. Technol. B 8, 1836-1840 (1990).
26. A. W. Yanof, G. L. Zipfel, and E. E. Moon, "X-ray mask membrane motion in narrow gap lithography: hydrodynamic model and experiment," J. Vac. Sci. Technol. B 11, 2920-2925 (1993).