Litho/mask strategies for 32-nm half-pitch and beyond: Using established and adventurous tools/technologies to improve cost and imaging performance

Burn J. Lin[*a]
[a] Taiwan Semiconductor Manufacturing company, Ltd.
8 Li-Hsin Rd 6, Hsinchu Science Park, Hsinchu, Taiwan 300-77 R.O.C.

ABSTRACT

Cost and imaging are becoming big concerns in lithographic patterning of 32-nm half pitch and beyond, affecting the choice of lithographic patterning tools and the corresponding mask technology. In this paper, the cost and imaging aspects of ArF immersion double patterning, multiple e-beam maskless lithography, and extreme-uv lithography are discussed with proposals to make the cost acceptable. The impacts of these technologies to the masking industry are quite different. They are also given here. Some comments are made on nano-imprint lithography.

Keywords: Optical lithography, EUV lithography, e-beam lithography, maskless lithography, multiple e-beams, double patterning, double patterning cost reduction, lithography cost reduction, dual lens, dual illuminator, non-linear resist, low residue-threshold resist, nano-imprint lithography.

1. INTRODUCTION

Litho/mask strategies for technologies using 32-nm half-pitch(HP) and beyond is a popular topics because of the difficult tradeoffs between the candidates of choice. The concerns are not limited to just imaging performance but costs as well. This constrain in cost is severe. Except for special situations, the die cost of the next generation should be lower than that of the current generation. Otherwise, there is no economic reason to advance to the next node. The issue with mask is that the ever-tightening spec makes it increasingly expensive. Hence, less number of companies can afford mask and less number of masks is needed. Masks become even more expensive.

Four types of lithography system are being developed to succeed ArF water-immersion lithography. The first one is a continuation of immersion lithography and uses two exposures to split the unresolvable pitches into resolvable ones in combination with two pattern transfer processes such as etching, to eliminate the interaction between the two exposures. This is the double patterning technique (DPT). In principle, this technique can double the resolution of a given imaging system, provided some design restrictions are implemented to prevent having to split the patterns into more than two masks. The main problem of the DPT approach is cost. The exposure and pattern transfer costs of each DPT layer is doubled making it very difficult to contain the cost of the next node to below that of the present one. In addition to restricted design rules, the overlay accuracy of the exposure tool and on the mask has to be tightened.

A second technique that holds promise for high resolution, large depth of focus(DOF), low cost, and elimination of design restriction is multiple-e-beam maskless lithography (MEBML2). E-beam lithography has a long history for wafer and mask writing. The direct writing capability eliminates the entire mask infrastructure along with the cost and cycle time associated with mask making. However, e-beam direct writing is a serial process. Its throughput is no comparison to the massively parallel replication process with optical lithography. With the advent of nanometer CMOS technology, MEMS, and data processing speed and capacity, massive parallelism can be applied to e-beam direct writing as well, making a significantly improved throughput feasible. However, MEBML2 is new and still requires heavy development.

A third technique to succeed ArF water-immersion is extreme-uv lithography (EUVL). A major advantage of EUVL lies in the leap-frog reduction of wavelength from that of ArF. In fact, the 13.5-nm wavelength adopted by EUVL is an order of magnitude smaller than the ArF wavelength in water, namely 134 nm. With such magnitude of wavelength reduction,

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[*] burnlin@tsmc.com; phone +886-3-505-5858; fax +886-3-563-7386

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the normalized pitch k_1 for 32-nm HP at 0.25 NA is 0.59 comparing with 0.22 using the 193-nm ArF wavelength at NA=1.35. Such a large k_1 not only eliminates the need of DPT and design rule restrictions, proximity correction and mask patterning also become simpler. The problems of EUVL is many fold, with cost leading the pack even if all obstacles to manufacture in EUV is solved.

A fourth often-considered technique is nano-imprint lithography(NIL). The resist image is formed by molding a template placed on top of the wafer with a molding fluid in between. After the fluid is solidified, the template is lifted to leave the exact complimentary replica on the wafer. Since imaging is performed without forming an aerial image but with direct contact, the replica can emulate the template to atomic precision. However, due to direct contact, many old problems that made contact printing obsolete have resurfaced.

In this paper, the first three technologies are discussed with an emphasis to make their cost acceptable and the challenges they face to make high volume manufacturing feasible. The impacts to the mask making technology are also discussed. Some remarks on NIL are given.

2. DOUBLE PATTERNING USING 193-NM WATER-IMMERSION LITHOGRAPHY

The semiconductor industry is using single patterning of ArF immersion lithography for products with half pitches 40 nm or slightly below. With double patterning, i.e. pitch splitting into two masks and patterning the two mask images independently, the half pitch can be reduced to 20 nm or slightly below in two generations. In order to confine pitch splitting to only two masks, additional restrictions in the design rules have to be implemented, more so for the second pitch reduction than the first. DPT is costly because two exposures with separate resist coating/developing/stripping and two pattern-transfer processes are required.

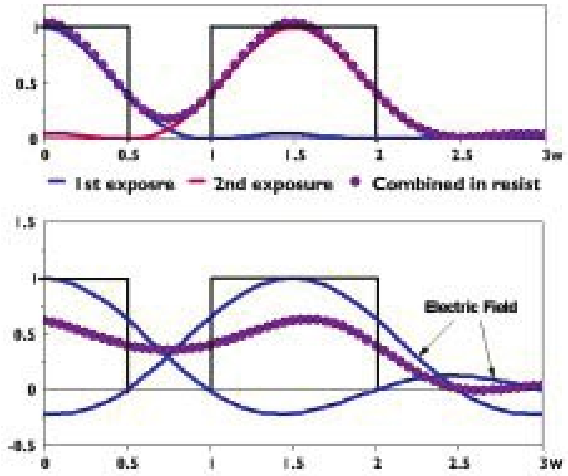


Fig. 1 Principle of double exposure: (a) Incoherent imaging removes the correlation of two patterns in (b) Coherent imaging.

The reason of double patterning instead of double exposure is that residual exposures in the resist tend to interact. The working principle of double exposure is shown in Fig. 1. Exposing the two line openings separately as shown in Fig. 1(a) removes the interaction of the two openings in one exposure under coherent or partially coherent illumination as depicted by coherent illumination in Fig. 1(b). The combined electric field is a direct summation of the fields in the former illumination and a statistical summation in the latter illumination. In either case, the combined light intensity in the dark space between the two openings is raised to an unacceptable level. Double exposure helps by making the two exposures completely incoherent to each other, taking advantage of the final latent image in the resist being a superposition of the two consecutive latent images. It helps but the interaction of the latent images is not removed completely. The residual exposures still build up. One needs to render the resist insensitive to further exposure. Hence the litho-etch-litho-etch process(LELE) that transfers the first resist image by etching, then strips the resist image to follow with a completely independent second resist coating, imaging, and etching. The litho-freeze-litho-etch process(LFLE) is used to replace LELE to reduce cost. The freezing step in LFLE is typically resist hardening by heat, radiation, or chemical treatment. These steps all require moving the wafer from the exposure tool to a processing tool, reducing throughput and alignment accuracy. The cost of the freezing step is not negligible either.

It is desirable to have a resist that double exposes without interference of the two subsequent images and does not need to remove the wafer from its chuck. There are proposals to make the resist forget the first exposure before getting the second exposure[1,2,3]. Instead of a self-erasing resist, a non-linear resist[4] whose latent image is nonlinear to the aerial image in the form of

$$I_{latent} = I_{aerial}^{\gamma} \qquad [1]$$

For two exposures,

$$I_{total} = I_{latent1} + I_{latent2} = I^{\gamma}_{aerial1} + I^{\gamma}_{aerial2} \qquad [2]$$

Assume that only the 1st diffraction order is imaged, the electric field $E(x) = \sin kx$ where $k = \frac{2\pi}{\lambda} NA$, and the intensity of the aerial image is $E^2(x)$

$$I_{aerial1}(x) = 1 + \cos 2kx \qquad [3]$$

$$I_{aerial2}(x) = 1 - \cos 2kx \qquad [4]$$

The general binomial series can be expressed by

$$(1+x)^{\gamma} = \sum_{i=0}^{\infty} \binom{\gamma}{i} x^i \qquad [5]$$

where $\binom{\gamma}{i} = \frac{\gamma(\gamma-1)(\gamma-2)\cdots(\gamma-i+1)}{i!} = \frac{\prod_{a=0}^{i-1}(\gamma-a)}{i!}$ [6]

Combining equations 2 to 5,

$$I(x) = \sum_{k=0}^{\infty} \binom{\gamma}{i} [\cos 2kx]^i + \sum_{i=0}^{\infty} \binom{\gamma}{i} (-1)^i [\cos 2kx]^i = 2 \cdot \sum_{i=0}^{\infty} \binom{\gamma}{2i} [\cos(2kx)]^{2i} \qquad [7]$$

When $\gamma = 1,\ I_{total} = 0$ [8]

When $\gamma = 2,\ I_{total} = \frac{1}{4}(3 + \cos 4kx)$ [9]

When $\gamma = 3,\ I_{total} = \frac{1}{8}(5 + 3\cos 4kx)$ [10]

The image contrast is,

$$Contrast = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \qquad [11]$$

For double exposure, I_{max} occurs at $x = \frac{n}{2k}$; and I_{min} at $x = \frac{2n+1}{4k}$

$$I_{\max} = 2 \cdot \sum_{i=0}^{\infty} \binom{\gamma}{2i} \qquad [12]$$

$$I_{\min} = 2 \cdot \sum_{k=0}^{\infty} \binom{\gamma}{2k} (0)^{2k} = 2 \qquad [13]$$

and

$$Contrast = \frac{\sum_{i=0}^{\infty}\binom{\gamma}{2i} - 1}{\sum_{i=0}^{\infty}\binom{\gamma}{2i} + 1} \qquad [14]$$

$$Contast = 0, \frac{1}{3}, \frac{3}{5}, \frac{7}{9} \quad \text{at } \gamma = 1, 2, 3, 4, \text{ respectively.}$$

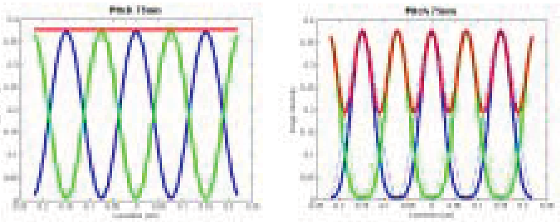


Fig. 2 I_{total} from double exposure, (a) γ=1, (b) γ=2.

The contrast increases from 0 towards unity as γ increases.
The situation of I_{total} at γ=1 and 2 is depicted in Fig. 2. When the resist is linear, the image is structureless, at γ=1, there is appreciable contrast.

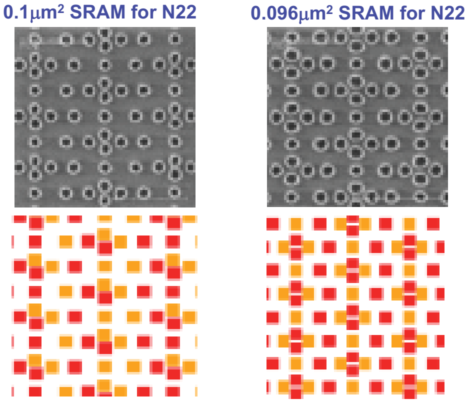


Fig. 3 Two DPT masks double exposed.

A nonlinear resist may not be as difficult as it seems to be. One of our baseline contact-hole resists exhibits good differentiation between exposures. We used it to double expose two masks fabricated for double patterning. The result is shown in Fig. 3 where the two masks are shown superimposed but of different colors. The superimposed images are the designed patterns not the proximity-corrected actual mask patterns. The resist images are encouragingly clean despite the close proximity of the patterns. What is shown serves as an existence proof. This particular resist needs further development to have sufficient process window for HVM.

After such a resist is developed, double exposure can achieve double patterning performance at the cost of double exposure. It is desirable to made double exposure cost close to that of single exposure. Here, we propose a dual-optical-train immersion scanner, to reduce the cost of double exposures. In the most straightforward scenario, a scanner with two sets of illuminator and imaging optics, a dual-reticle stage, and two wafer stages can be used to expose two reticles and two wafers simultaneously with a higher-power laser whose beam is split at the appropriate location to share most of the illumination path. The concept is depicted in Fig. 4. Only one track is needed for this scanner.

The cost of such system is estimated to be lower than that of two scanners using two tracks. An even less expensive version is to just use two illuminators and share the imaging lens as depicted in Fig. 5. A polarized beam splitter is used as an example. Other beam combining means can be used. To avoid cancellation of the aerial images from the two masks

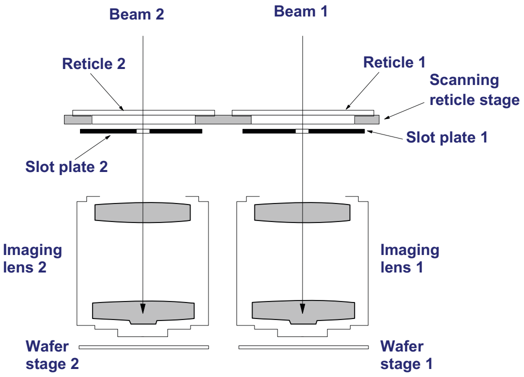


Fig. 4 Double-exposure scanner with dual optical trains.

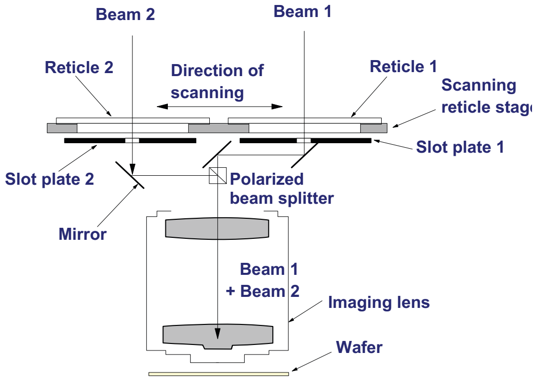


Fig. 5 Double-exposure scanner with dual illuminators.

in a simultaneous double exposure, the image of the two slots should be spaced apart to allow the first nonlinear latent image to form before the second exposure begins.

A comparison of the cost and footprint of the two systems with respect to those of two scanners and two tracks are shown in Table 1. Without intimate knowledge of the cost of scanner components, the figures used in the table are based on our estimate as an educated user. For the dual-lens and dual-illuminator version, the costs of optics, stages, and lasers are in addition to the components already exist in a conventional scanner. The track for the conventional system is configured for double patterning. The tracks for the dual systems are identical to each track on the conventional system. Hence, the dual-lens system costs 78.7% and has a footprint 57.5% of a conventional system. The dual-illuminator system costs 61.3% and occupies a footprint 49.9% of a conventional system. Using the dual-lens system saves more than 20% in cost and 42% in footprint. Going into a dual-illuminator system saves close to 40% in cost and 50% in space. These are not negligible if DPT is going to be with us for 32-nm and 22-nm HP.

Table 1 Cost and footprint comparison of the two dual-optics scanners with respect to two conventional scanners and tracks.

	Cost (with respect to conventional scanner)			Footprint (with respect to conventional scanner)		
	Dual lens	Dual illum	Two scanners	Dual lens	Dual illum	Two scanners
Scanner	100%	100%	200%	130%	100%	200%
Optics	50%	20%				
Wafer stage	10%					
Laser	2%	2%				
Reticle stage	4%	4%				
Track	15%	15%	30%	97%	97%	195%
Normalized to 2 systems	78.7%	61.3%	100%	57.5%	49.9%	100%
Total	181%	141%	230%	227%	197%	395%

Dual optics and nonlinear resists bring cost of DPT performance close to that of single exposure but mask cost, mask complexity, and design rule restriction are not relieved.

3. MULTIPLE E-BEAM MASKLESS LITHOGRAPHY

MEBML2 has the potential to eliminate mask cost, mask cycle time, and the mask infrastructure. E-beam sources and resist are well established. From the high-resolution potential and mild proximity effects, design rule restrictions can be waived. However, it is necessary to use 2 to 6 orders of parallelism to achieve just 10 wph. Developing such massively parallel system for high-volume manufacturing(HVM) is challenging. Also, it is necessary to keep each unit compact and inexpensive for clustering to produce throughputs exceeding 100 wph. Clustering also facilitates sharing a track with many exposure units. Large volume users can cluster ten or more units. When one unit goes down, the productivity hit is only a fraction of that from a malfunctioning scanner. Small volume users such as resist developers can purchase just a single unit to save development cost.

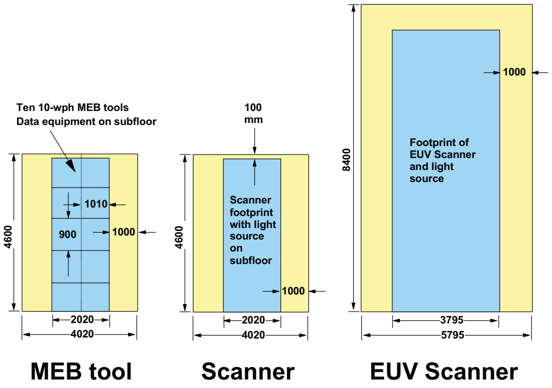


Fig. 6 Projected footprint of MEBML2 and EUVL tools comparing with a conventional scanner.

The MEBML2 units are inherently compact because of lower acceleration and deceleration requirement from low throughput[5]. Excluding the data processing unit placed in the factory sub-floor just as the laser source of conventional scanners, each exposure unit can be made to occupy a space between 1 and 1.5 m^2. Ten 1-m^2 units can be clustered together to make it occupy the space of a conventional scanner and much smaller than that of a EUV scanner as shown in Fig. 6

Table 2 Projected exposure and processing costs of MEBML2 and EUVL normalized to SP exposure cost/per layer.

All costs normalized to SP exposure cost / layer	Immersion SP	Immersion DP	EUV goal	EUV possibility	MEB goal	MEB possibility
Normalized exposure tool cost	3,628,751	3,628,751	4,535,939	4,535,939	4,535,939	2,721,563
Normalized track cost	558,209	558,209	488,486	209,351	488,486	488,486
Raw thruput (WPH)	100	100	100	20	100	100
Normalized exposure cost / layer	1.00	1.80	2.17	10.37	2.17	1.37
Normalized consumable cost / layer	0.91	2.27	1.43	1.43	1.05	1.05
Normalized expo+consum cost / layer	1.91	4.07	3.61	11.80	3.22	2.42

Massively parallel e-beam optics can be made inexpensive with MEMS technology. The dominating data processing cost decreases as rapidly as electronics. One major component, the DRAM, has dropped price by 3X in less than a year. It is conceivable that the price of a 5-wph standalong unit can be kept below $5M Euro. With clustering, more sharing of components is possible. Table 2 compares the projected exposure and processing cost of MEBML2 and EUVL normalized to single-patterning exposure cost per layer. So, the immersion tool for single patterning at 180 wph is 3,628,751 the cost of exposing one layer. The double-patterning immersion tool is assumed to be similar in price to that of SP but its throughput is only half of 200 wph. Processing cost more than doubles, because the extra pattern transfer step is counted as photo cost. The EUV tool price goal is set at 4,555,939 at 100 wph, similar with the MEBML2 tool price goal. There is a possibility of EUV losing is projected throughput by a factor of 5 because of optimism in resist sensitivity and source power. In this case, the exposure cost suffers though the processing cost is not affected. There is also a MEBML2 possibility of more cost sharing between components and more price drop in electronic components. Hence the drop in exposure cost even though there is no change in throughput.

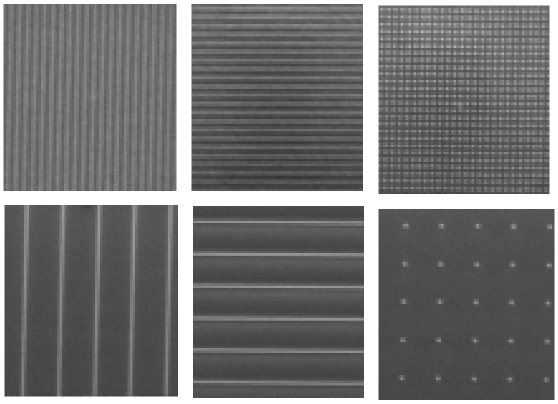
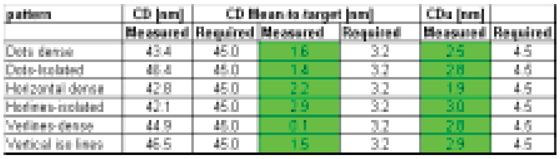


Fig. 7 Resist image from 110 beams of the MAPPER MEB ML2 system.

Hence, MEBML2 has the potential of exposure cost closest to that of SP immersion. The savings in mask cost and mask cycle time cannot be ignored even for memory manufacturers exposing more wafers per mask. One can neither ignore the ever increasingly difficult mask technology nor its losing business case. With the severe mask cost overhead removed, semiconductor design will have more varieties and opportunities. Small companies will again be able to innovate with new products and flourish.

Much development work is still needed to make MEBML2 a viable HVM technology. Controlling tens of thousands of e-beams or pixels for CDU and overlay accuracy, as well as ensuring low data error, have to be demonstrated. High-volume nanometer-precision exposure tool manufacturers have to pick up the technology to satisfy the market need.

Table 3 CD, mean to target, and CDU of 6 representative patterns from 11 randomly selected beams. Data from 110 beams are substantially identical.



pattern	CD [nm]		CD Mean to target [nm]		CDu [nm]	
	Measured	Required	Measured	Required	Measured	Required
Dots dense	43.4	45.0	1.6	3.2	2.5	4.5
Dots-Isolated	46.4	45.0	1.4	3.2	2.8	4.5
Horizontal dense	42.8	45.0	2.2	3.2	1.9	4.5
Horlines-isolated	42.1	45.0	2.9	3.2	3.0	4.5
Vertines-dense	44.9	45.0	0.1	3.2	2.0	4.5
Vertical iso lines	46.5	45.0	1.5	3.2	2.9	4.5

There is one 5-keV low-voltage MEBML2 system[6] and quite a few 50-keV high-voltage MEBML2 systems[7, 8, 9, 10]. There are pros and cons in these systems. In general, the system using low voltage and raster scanning has throughput relatively unaffected by pattern density. Many high-voltage systems can write contact holes and via much faster than high-density line/space patterns. If the latter are used, mixing MEBML2 for hole layers and cost-reduced DPT(CR-DPT), which is double exposure coupled with scanners using parallelism for line/space layers, is a possibility. It helps to remove the most stringent design rule restriction on hole layers and extends the smallest processing window of these layers. The savings from these layers are not negligible. Take a product that requires 6 critical metal layers. There are 16 front-end and back-end layers. Six out of 16 can enjoy the savings in exposure and mask costs.

Some encouraging results have been obtained recently from MAPPER. A variety of representative HSQ negative resist images have been delineated as shown in Fig. 7. They consist of dense lines of 45 nm HP in X and Y and dense islands as well as isolated line and islands. All 110 beam in the system produced good images. Each beam covers a 2x2 μm^2 area. The measured CD and CDU of 11 randomly selected beams are listed in Table 3. They all fall within 7%.

4. EUV LITHOGRAPHY

EUV lithography at λ=13.5 nm and NA=0.25, brings $k_1 \equiv \frac{W}{\lambda} NA$ from below 0.3 for an immersion scanner at λ=193 nm and NA=1.35 to almost 0.6 for 32-nm HP. It restores single patterning and removes design rule restrictions. It also makes sophisticated optical proximity corrections unnecessary, even though shadowing and non-uniform stray light require field-position-dependent corrections. There are close to 20 years of EUV development[11] resulting in impressive advances from the tremendous amount of research and funding. The physics associated with EUV is elegant.

EUV resist images of contact holes are shown in Fig. 8. The CD control within 80 nm of defocus is good. The contact hole layer was chosen because it is less affected by stray light. On the Advanced EUV Development Tool, the stray light level is still too high.

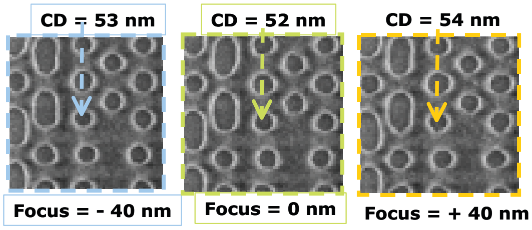


Fig. 8 Resist image of EUV delineated contact holes from the Advanced EUV Development Tool at IMEC.

The more EUV is advanced, the more of its limitations are known. Cost is definitely a major concern as discussed with Table 2. Developing the resist and mask infrastructure requiring expensive exposure tools and development of mask inspection and verification tools is another concern. Operating in a HVM environment with acceptable consumable cost such as EUV power, mirror lifetime, defect prevention without pellicle are not simple matters either.

Still, EUVL has a potential to bring lithography cost back to the level of ArF immersion single exposure. In order to realize that, the most important aspect is to achieve a throughput close to 200 wph for a tool estimated to cost much more than an immersion tool with a similar throughput. Much work is needed to increase the source power and resist sensitivity to improve throughput. The power conversion efficiency has to be improved and light loss in the optical train has to be decreased, to reduce the wall plug-in power and internal heating. If not reduced, a EUV scanner needs between 700 kW and 13 MW of raw power[5], making EUV power supply between 25% and 5X of a fully EUV-equipped factory.

In addition to conquering the EUV wafer exposure cost, the EUV mask infrastructure also needs cost reduction. The EUV mask blank requiring defect-free 40 layer-pair reflection coatings and a flatness at least an order of magnitude more stringent than ArF blanks[12], costing also more than an order of magnitude. For cost reason, actinic mask inspection has to be replaced with less expensive substitutes. Actinic verification and blank defect inspection are necessary. They cost much to develop and to manufacture. The projected small market size makes potential suppliers hesitate. The great mass of potential EUVL users and deep-pocketed EUV tool developers should substantiate their conviction by supporting these development activities.

5. NANO-IMPRINT LITHOGRAPHY

The most impressive aspect of nano-imprint lithography is the seeming absence of a resolution limit. Single-digit nanometer features have been printed[13]. Resist image formation does not require a sophisticated and expensive imaging lens or enormous number of beams. Line width roughness is not dependent on imaging but only on the template. For image formation, one only has to press a patterned template into a liquid molding material, solidify it then, lift the template. All are done in situ. There is no need to coat and develop the wafer on the track. Except for nanometer-precision alignment and dispensing of the molding fluid, the tool is basically similar to a contact printer in the seventies. Therefore, it cannot cost much more. With on-tool formation of the molded image, there are possibilities of process simplification such as combination of the via and metal layers[14]. No optical proximity correction is needed for NIL, only for etching and other non-photo processes. Design rule restriction is not an issue.

Some of the concerns in NIL are inherited from contact printing, namely particle defects. Some defect sources are similar to those in immersion lithography. Using a liquid in the critical-dimension areas requires extreme care, especially when the liquid is viscous. There is the concern on the time required to dispense the fluid evenly and without bubble, time required for the bubble to be dissolved, time needed for hardening of the molding liquid, and time required to lift the template without creating any damage. Therefore, throughput can be an issue. Proposals have been made to increase the throughput with multiple templates, another form of parallelism as with MEBML2.

No technology can escape the difficulties in mask making. NIL is no exception. First, the template is 1X. There is no leverage in CD control. Any CD variation on the template will be replicated faithfully. Not only that there is no pellicle to protect the template, intimate contact to the template is made at every molding, typically about a hundred times on each wafer. A template usually lasts several hundred moldings, obviously too few for HVM. As a result, many child templates are made to extend the utility of the expensive original template. One only needs to patiently fabricate the original. Child templates can be effortlessly made from the original. However, the template polarity is changed from mother to children, ditto for grandchildren. The preferred stud polarity is inevitably reversed to the less preferred pit polarity in just two generations. The logistics of handling and storing these templates has to be worked out.

Unlike the developed resist image, there is a layer of residual film in the squeezed areas. It is removed during the etching process. For etch depth and CD control, the uniformity of this film is very important. Controlling its thickness from field to field, especially near field boundaries is required.

Currently the molding fluid is dispensed by inkjets from a cartridge. The cartridge is discarded when the fluid is depleted. Depending on the eventual cost of the cartridge, it may make sense to make refilling feasible.

6. IMPACT TO THE MASK INDUSTRY

ArF immersion DPT has small impact to the mask infrastructure, except for evolutional tightening of specs and higher volume due to double masks. However, the total number of masks may not increase because of less affordable products to produce. The combination of tighter specs and smaller volume makes mask-making tools even more expensive, especially mask inspection tools. The economical pressure pushes users to team up to purchase tools thus further driving the volume down. This negative spiral endangers the survival of the mask industry.

EUVL requires a new mask infrastructure. For example, actinic wavelength may be required for the inspection tool. Because the EUV mask is not transparent, the present capability of combining reflective and transmissive inspections is lost regardless of the wavelength used. Verification tools such as AIMS tools for embedded defects in mask blanks are also EUV specific that need additional development. The market size is extremely small, because only the blank manufacturers need it. The EUV mask infrastructure development cost makes an additional twist to the already negative spiral of the mask industry. The industry has to be ready to adopt it.

MEBML2 may surprise the mask industry by bringing more mask business to demand more existing equipment than developing new equipment, due to higher affordability of new semiconductor products. Let the number of layers in a product be N_l and the number of critical layer requiring MEBML2 be N_c. If a company makes S sets of mask with N_l layers, then the total number of masks made is SN_i. When the critical layers are switched to MEBML2, then the company only makes $S(N_l\text{-}N_c)$ masks. However, αS additional masksets are ordered because of lower cost of the mask set, which enables existing customers to order more and incubates new customers due to the lower entry barrier. Another βS additional masksets are ordered due to the growth of the customer from the success due to their extra mask sets. So, the total number of less critical mask sets made, normalized to SN_i is

$$\gamma \equiv \frac{S(N_i - N_c) + (\alpha + \beta)S(N_i - N_c)}{SN_i} = (1 + \alpha + \beta)(1 - N_c / N_i)$$

When $\gamma > 1$, MEBML2 actually helps to create more demand for masks. These masks are non-critical masks. They are fabricated with existing technology and do not have a problem of a business case. The non-critical layers of future nodes will eventually tax the mask technology to its very limit. γ is plotted as shown in Fig. 9 as a function of N_c, using two sets of α and β values, representing a pessimistic case and an optimistic case. In each case, α and β are assumed to be linear functions of N_c such that when the number of critical layers is small the cost reduction effect is small. In the optimistic case, α is assumed to be 0.1 at N_c=1 and 0.8 at N_c=20 varying linearly in between. Similarly, β varies linearly between 0.3 and 1. From Fig. 9 γ is easily in the positive zone most of the time. The total optimistic volume of additional masks made can exceed 50%.

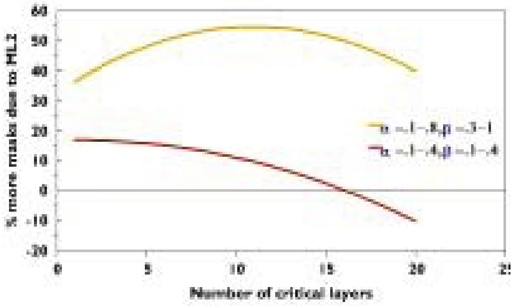


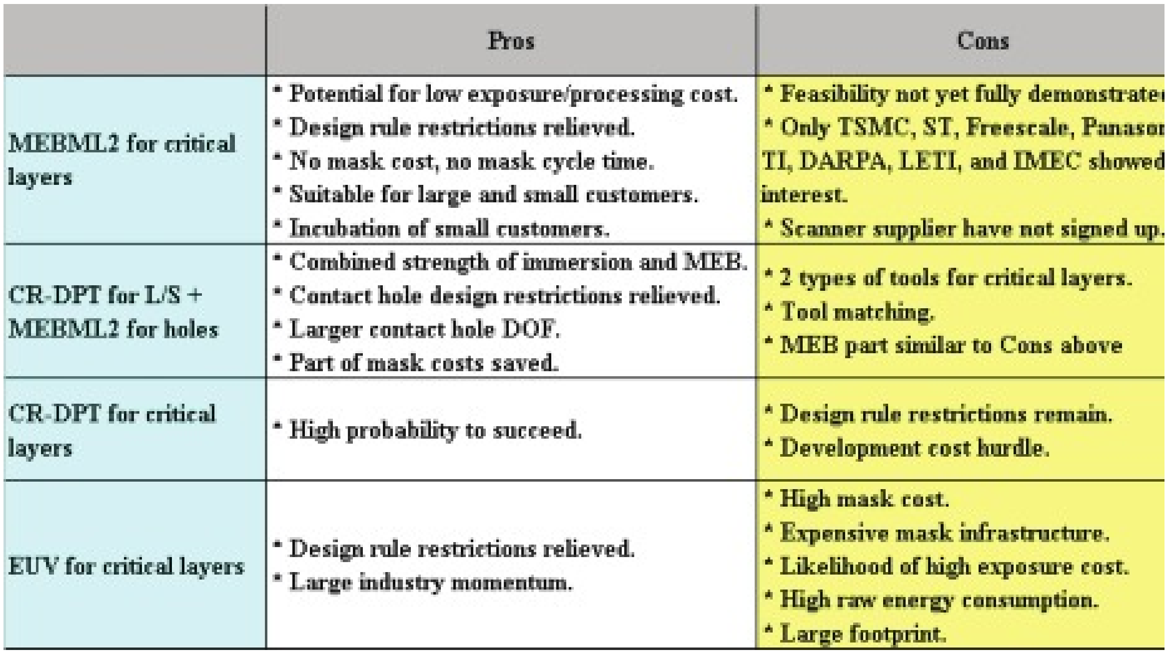
Fig. 9 γ–1 as a function of N_c at α = 0.1 to 0.8, β = 0.3 to 1 and α = 0.1 to 0.4, β = 0.1 to 0.4.

7. CONCLUSION

From what have been presented, a high-volume semiconductor manufacturer should prefer the NGL in this order. (1) MEBML2, (2) MEBML2 for hole layers and CR-DPT for line/space layers if MEBML2 is economical only for hole layers, (3) CR-DPT, (4) EUV. Their pros and cons are listed in Table 4.

In terms of risks, CR-DPT has more risks than straightforward DPT. MEBML2 has even higher risk. Among all the MEBML2 schemes, there are more choices for hole imaging. The risk of producing a EUV imaging tool is low but the financial burden to do so is high and the possibility of an economical EUVL imaging tool as well as an inexpensive infrastructure is quite low.

Table 4 Pros and cons of the four desirable scenarios.



	Pros	Cons
MEBML2 for critical layers	* Potential for low exposure/processing cost. * Design rule restrictions relieved. * No mask cost, no mask cycle time. * Suitable for large and small customers. * Incubation of small customers.	* Feasibility not yet fully demonstrate * Only TSMC, ST, Freescale, Panaso TI, DARPA, LETI, and IMEC showed interest. * Scanner supplier have not signed up.
CR-DPT for L/S + MEBML2 for holes	* Combined strength of immersion and MEB. * Contact hole design restrictions relieved. * Larger contact hole DOF. * Part of mask costs saved.	* 2 types of tools for critical layers. * Tool matching. * MEB part similar to Cons above
CR-DPT for critical layers	* High probability to succeed.	* Design rule restrictions remain. * Development cost hurdle.
EUV for critical layers	* Design rule restrictions relieved. * Large industry momentum.	* High mask cost. * Expensive mask infrastructure. * Likelihood of high exposure cost. * High raw energy consumption. * Large footprint.

Based on the foregoing considerations, the lithography strategy for a HVM semiconductor company should follow the decision tree shown in Fig. 10. If MEBML2 is demonstrated feasible it will be compared with the other candidates for cost. Otherwise, MEBML2 for holes and CR-DPT for lines/spaces is judged with the same feasibility and cost criteria. CR-DPT for all layers is feasible in terms of tools, processes, and masks but it has to be subjected to the cost criterion. EUVL needs to meet the feasibility criterion, then to be compared in cost with the other candidates. Cost should be based on dies, i.e. die cost. Even though design rule restrictions are reflected in the die cost, when the difference in die cost is insignificant the technology that requires less design restrictions wins. The technology with the lowest cost is now considered for the absolute cost so that 32HP HVM makes economic sense compared with products of the previous node. Similarly, when the die cost difference is insignificant and the technology is chosen for the least design rule restrictions, it still has to make economic sense for HVM.

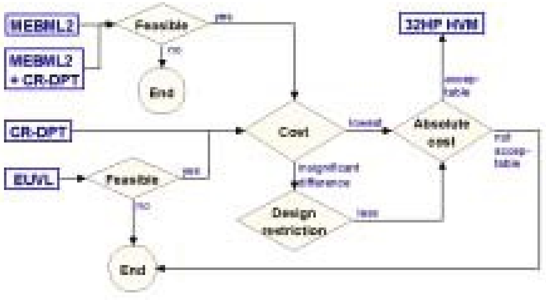


Fig. 10 Decision tree for 32nm-HP lithography.

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FIGURE CAPTIONS

Fig. 1 Principle of double exposure: (a) Incoherent imaging removes the correlation of two patterns in (b) Coherent imaging.

Fig. 2 I_{total} from double exposure, (a) γ=1, (b) γ=2.

Fig. 3 Two DPT masks double exposed.

Fig. 4 Double-exposure scanner with dual optical trains.

Fig. 5 Double-exposure scanner with dual illuminators.

Fig. 6 Projected footprint of MEBML2 and EUVL tools comparing with a conventional scanner.

Fig. 7 Resist image from 110 beams of the MAPPER MEB ML2 system.

Fig. 8 Resist image of EUV delineated contact holes from the Advanced EUV Development Tool at IMEC.

Fig. 9 $\gamma-1$ as a function of N_c at α = 0.1 to 0.8, β = 0.3 to 1 and α = 0.1 to 0.4, β = 0.1 to 0.4.

Fig. 10 Decision tree for 32nm-HP lithography.

TABLE CAPTIONS

Table 1 Cost and footprint comparison of the two dual-optics scanners with respect to two conventional scanners and tracks.

Table 2 Projected exposure and processing costs of MEBML2 and EUVL normalized to SP exposure cost/per layer.

Table 3 CD, mean to target, and CDU of 6 representative patterns from 11 randomly selected beams. Data from 110 beams are substantially identical.

Table 4 Pros and cons of the four desirable scenarios.