A high throughput NGL electron beam direct-write lithography system

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ABSTRACT

Electron beam lithography systems have historically had low throughput. The only practical solution to this limitation is an approach using many beams writing simultaneously. For single-column multi-beam systems, including projection optics (SCALPEL® and PREVAIL) and blanked aperture arrays, throughput and resolution are limited by space-charge effects. Multibeam micro-column (one beam per column) systems are limited by the need for low voltage operation, electrical connection density and fabrication complexities. In this paper, we discuss a new multi-beam concept employing multiple columns each with multiple beams to generate a very large total number of parallel writing beams. This overcomes the limitations of space-charge interactions and low voltage operation. We also discuss a rationale leading to the optimum number of columns and beams per column. Using this approach we show how production throughputs ≥60 wafers per hour can be achieved at CDs ≤100 nm, independent of both wafer diameter and die size. The Cost-of-Ownership (CoO) advantages of direct-write (maskless) lithography are significant especially for small-volume semiconductor fabrication, for example ASICs, SOCs and MPUs.

Keywords: Electron beams, field emission cathodes, electron beam lithography, multi-beam, multi-column, direct-write.

1. INTRODUCTION

At present, there is no practical solution for Next Generation Lithography (NGL) at the ITRS 100nm node for production in 2005. The leading contenders – EUVL, EPL, XRL, and IPL – all take an approach which use masks. Electron Beam Direct Write (EBDW) systems are maskless, thus eliminating mask amortization costs and expediting chip development cycles. EBDW systems have resolution capabilities of meeting all future ITRS nodes. Traditional single column, probe-forming or shaped-beam systems, are not production-worthy due to low throughput. Throughput is limited by the total current, for a given resolution, due to space-charge effects. Furthermore, systems that write with single pixel beams have the added difficulty of the high data rate, which is serial. Space-charge can be reduced by placing the current in beams that are separated from each other, such as the single-beam micro-columns of Chang *et al.*[1] and the distributed beams of Grove *et al.*[2]. The data rate problem can be solved by exposing many pixels in parallel such as shaped beams[3] and cell projection[4]. Advantest/Fujitsu[5], Winograd *et al.* [6], and Schneider, *et al.* [7] place 10 to 1000 beams in one column for parallel exposure but suffer from the space charge problem. Our solution is to combine these two approaches in a Multi-column × Multi-beam electron beam lithography system (M×M). The advantage of combining multi-columns and multi-beams is that a maskless system can be optimized for physical space requirements and throughput, while maintaining a small spot size on the wafer. Hence, EBDW in an M×M system can be attractive in terms of both resolution and lowered CoO in manufacturing.

2. M ´M SYSTEM OVERVIEW

The M×M approach was chosen as a way to minimize space-charge effects by distributing the current over the entire wafer. A simple calculation for the total current needed to expose a wafer is given in equation (1)

$$I = (\text{area of the wafer}) \times (\text{resist sensitivity}) / (\text{wafer writing time}) \qquad (1)$$

Assuming a resist sensitivity of $10\mu C/cm^2$ the current required to write a 300mm wafer in 90 seconds is ~80 μA. If we allow for 30 seconds of overhead a writing time of 2 minutes can be achieved. A current of 80μA is almost an order of magnitude greater than present state-of-the-art EPL (SCALPEL® and PREVAIL) systems, i.e. writing times of 20 minutes per wafer with 10 μC/cm^2 resist sensitivity or 2 minutes per wafer with state-of-the-art R&D resists with sensitivities of 1 μC/cm^2 (with an inherent shot noise problem).

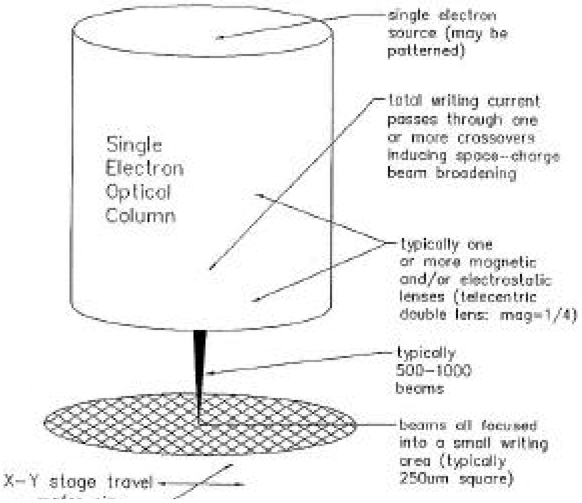

Fig. 1a. Single column – multiple beam

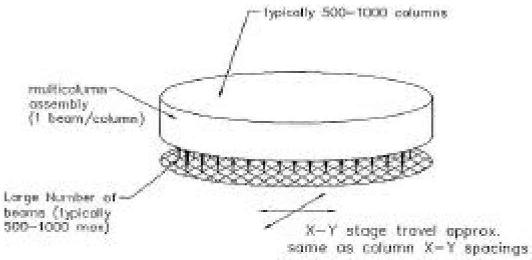

Fig. 1b. Multiple columns – single beam per column.

Figures 1a & b show a comparison of a single column approach versus a multicolumn approach. In the single column multi-beam approach, the total writing current passes through a single cross-over and space-charge effects limit performance[8]. Also from a practical perspective, magnetic lenses become large and difficult to manage, the stage travel must span the entire wafer, and throughput decreases with wafer size. The single beam multi-column approach minimizes the space-charge effects, but from a practical perspective needs a large number of columns and a high blanking rate; the high blanking rate is required because of constraints on the number of columns. As the number of columns required becomes large (>1000) the footprint of each column becomes so small that it precludes the use of high energy beams (>50keV), i.e. high energy beams require high voltages for focussing and deflection. Therefore, such systems need to operate with low energy beams ~1keV, requiring a surface-imaging resist. Our approach is to combine elements of both methods by using multiple columns with multiple beams in each column (M×M), as shown in figure 2.

To achieve a practical number of columns per system, a mini-column approach is used, as shown in figure 3. Each mini-column is comprised of a microfabricated source combined with conventionally machined electron-optical elements. The source is a complex microfabricated structure using an array of individual cold field emitters, beam-defining apertures, alignment deflectors and blanking electrodes. The source sits on top of a macroscopic column that consists of a rotation element to correct for source misalignments, an accelerating region, main and subfield deflectors and an electrostatic immersion lens. Alignment mark detection is accomplished with backscattered electron detectors on the wafer side of the immersion lens. The column is designed to produce a beam with a minimum spot size of 25nm.

The M×M system comprises 201 columns with 32 beams per column, for a total of 6432 beams. The number of beams per column and the number of columns is a compromise between various system parameters and is discussed below. Based on our simple calculation in eq. (1), production throughputs of 60 to 90 wafers per hour can be achieved using a design that can accommodate multiple writing stations, such as a cluster tool arrangement often used in other semiconductor manufacturing processes such as etch and deposition. Figure 4 (cluster tool configuration) shows a system footprint using this concept. In this configuration multiple writing stations can be attached to a cluster tool with pipeline wafer loading to achieve production throughputs.

The writing strategy for an M×M system is shown in figure 5. Each of the 32 beams is scanned in parallel in one axis by electrostatic deflectors. The stage scans a series of stripes in a serpentine fashion over the footprint of one column. Using parallel writing of all columns, the time to write the wafer is therefore the time to write an area equal to one column

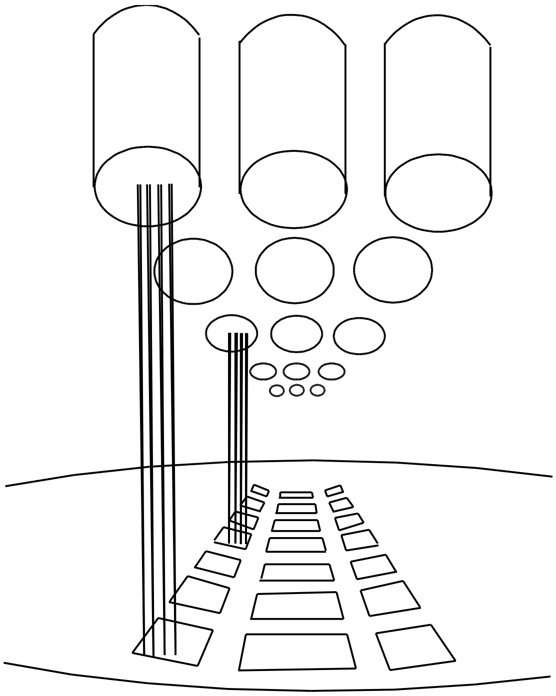

Fig. 2. M×M concept. Multiple columns, each generating Multiple beams. In this method, more beams can be generated than in either the single column (multiple beams) or multi-column (single beam/column) approaches.

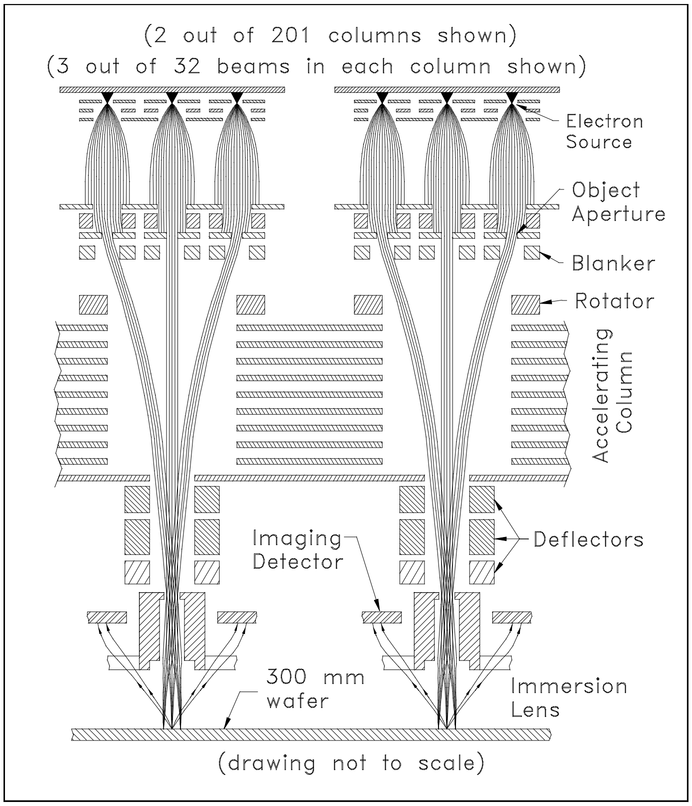

Fig. 3. Schematic view of two columns for the M×M system. The source-to-blanker region is a microfabricated structure providing differential pumping capability for the field emission sources. The column is approximately 160mm long, with a 20mm x 20mm footprint.

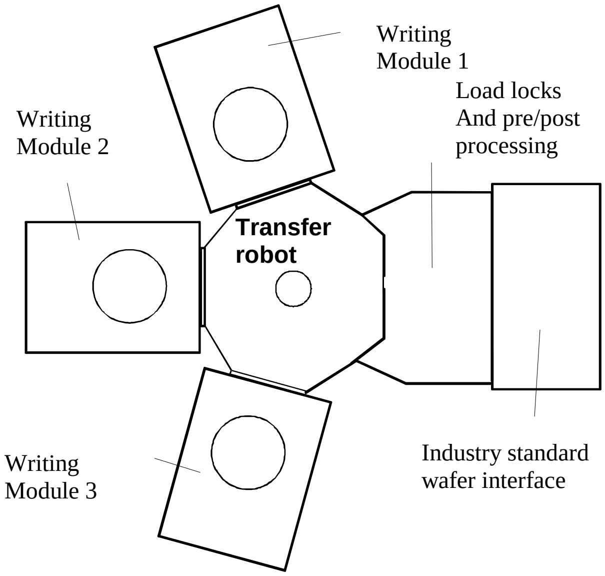

Fig. 4. Cluster tool configuration (plan view). Up to three writing modules can be clustered around the central transfer robot chamber. Pre-exposure and post-exposure processing is also possible.

footprint; hence, writing time is independent of wafer size. Several approaches are being considered in order to write a minimum CD level feature. The first approach uses a shaped spot that is ¼ the size of the CD level. The second approach, which is consistent with four-pass scanning, is to use a larger spot with a multi-pass technique.

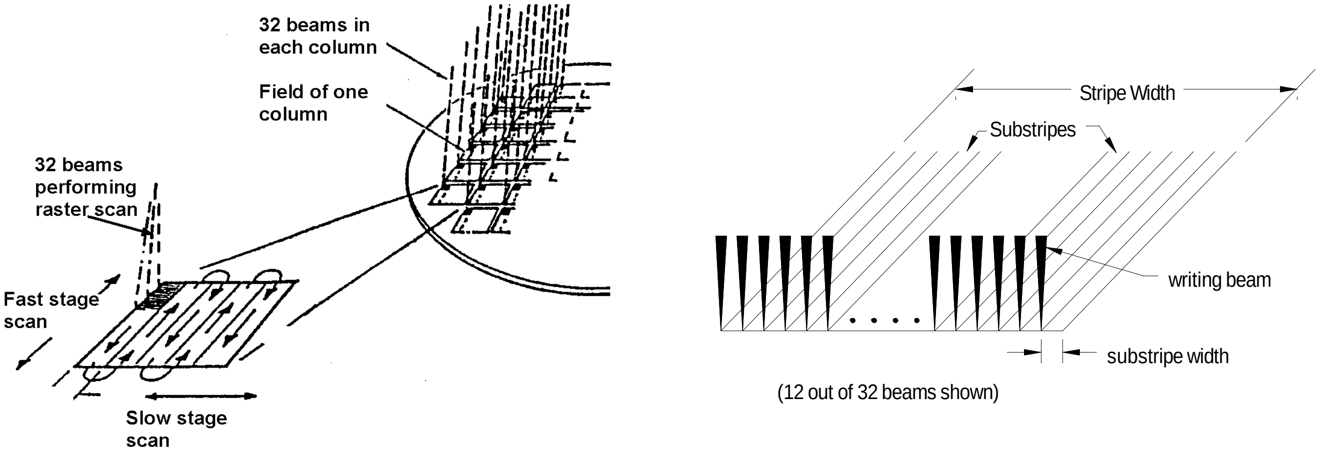

Fig. 5. Writing strategy. The entire wafer is written simultaneously, with each column covering an area ~ 20mm x 20mm equal to the column footprint. The stage moves continuously during writing.

3. OPTIMUM NUMBER OF COLUMNS AND BEAMS

An optimal design for a multi-column multi-beam system requires trade-offs between the critical parameters that comprise the system. These parameters include space-charge, blanking rate, resist sensitivity, stage speed and number of electrical connections.

Presently space-charge or Coulomb effects have limited most high throughput electron optical columns. Recently Han *et al.* [9] have calculated Coulomb effects in extended area sources used in EPL and BAA systems. They show, considering only stochastic beam blur, that maximum currents of between 1 to 10 μA can be achieved for a practical electron beam system with 0.1μm of resolution at practical column lengths (20-70cm) at a beam energy of (50 keV). The blur increases when space charge induced aberrations are considered (Winograd *et al.* [10]).

In EBDW the maximum blanking speed determines the data rate for each beam. The blanking rate is therefore inversely proportional to the number of beams. We believe that blanking rates in excess of 300MHz become problematic due to complex design requirements on the transmission lines at high frequencies.

Resist sensitivity determines the current necessary to expose a wafer. Resists are limited by some of the following factors: shot noise, etch resistance, resolution, etc. A resist sensitivity of 10 μC/cm^2 was chosen because it is consistent with available DUV resists[11] and gives a 5% shot noise (statistical dose variation) in the resist per 25nm pixel. A resist sensitivity of 1 μC/cm^2 gives a 16% shot noise for a 25 nm square pixel, which will give too many writing errors due to statistical dose variation.

To be consistent with low vibration and low power dissipation the stage is specified with a maximum velocity of 100 mm/s and a maximum acceleration of 0.1 g.

A practical limitation on the number of electrical connections to the source results in a lower number of beams per column. Let us consider the number of electrical connections per source: each source requires its own extraction electrode (1), focussing lens (1-2), alignment deflectors (2-8) and blanker (1-2). Therefore, the number of electrical connections per beam can vary from 6 to 14 connections. Advanced packing densities using ball grid arrays (BGA), that have a pitch of 0.05”, can support approximately 62 connections per square centimeter. Hence the number of beams per square centimeter is between 4 and 10.

Table I lists the critical system parameters for an M×M system obtained assuming an exposure time of 90 seconds and 30 seconds of overhead (30 wafers/hour), 10 µC/cm² resist and 25nm pixels.

Table I. Comparisons of Critical System Parameters for Various Numbers of Columns

Number of columns		Current per column	Data Rate	Stripe Width	Stage Speed	Stage stroke	Apertures per column	Number of electrical connections	
Cols	Area (cm^2)	(µA)	(MHz)	(µm)	(mm/s)	(mm)		Min	Max
201	4	0.4	195	51	76	20	32	192	448
77	10	1	250	102	97	33.3	64	384	896
45	16	1.7	216	102	169	42.9	128	768	1792
32	22	2.2	270	102	211	50	128	768	1792

From Table I it can be seen that by increasing the number of columns, all parameters become more favorable except the area required for each column. As the area for each column is reduced it becomes more difficult to make. A footprint of 2cm x 2cm is in the range that is practical to make without micro-fabricating the entire column as in the approach described in Chang *et al* [1]. The key to optimizing the parameters of this system is to use an array of object apertures illuminated by an array of very high brightness sources. The current system uses 32 micro-fabricated cold cathodes that illuminate 32 apertures using micro-fabricated optics. Each beam can be independently blanked. In order to cluster an array of 201 columns over a 300 mm wafer, a very compact electrostatic column has been developed. The columns are on 20 mm centers. Thus there are 6432 separate beams. At the wafer a current of only 12 nA is required in each beam to achieve the required throughput of 60 to 90 wafers per hour. The total current in each column is 0.4 µA, well below the electron-electron interaction limit. A field emitter is required to achieve the brightness B calculated from equation (2) assuming a 25 nm square pixel and an electron optical system with 1 mR semiangle.

$$B = 12\ \text{nA} / [(25\ \text{nm})^2 * \pi * (0.001\ \text{radians})^2] = 6 \times 10^8\ \text{A/cm}^2\text{sr}\ \ (\text{at } 75\ \text{kV}) \qquad (2)$$

Both cold and thermal field emitters can achieve this brightness, but only over a small illuminated area; thus, we need a cathode for each aperture. Cold field emission is preferred because the total heat associated with 6432 thermal field emitters would be prohibitive. The microfabricated cathode is easy to fabricate into micro-arrays. The challenge is to make a high yielding microfabricated cathode which has long lifetime and quiescent emission characteristics.

4. COST OF OWNERSHIP (COO)

Due to the lack of mask amortization costs, EBDW has a substantial Cost-of-Ownership advantage over systems requiring masks. The intent of CoO calculations is to make a fair comparison of competing technologies and to find the best configurations for a particular fab. International SEMATECH (IST) has worked very hard to make CoO a method for comparing the competing lithographies (both optical and NGL). The basic formula is the following:

$$\text{CoO (\$ per wafer level)} = \frac{\text{(Fixed + Recurring Costs)/hr}}{\text{Throughput}} + \frac{\text{Mask Cost}}{\text{Number of Exposures per Mask}} \qquad (3)$$

This equation explicitly shows the major factors:

> **Fixed Costs:** include the basic price for the tool (either optical or NGL). Additional fixed costs include installation, qualification and initial facilities (including floor space). “Standard” accounting techniques amortize this cost, which results in a per hour cost.
>
> **Recurring Costs:** include maintenance and consumables. The maintenance and gas costs of the excimer laser have been established. Similar costs for EPL, EUVL, IPL, and M×M are estimates. This category includes resist costs.

Throughput: Most optical lithographies have been achieving over 60 wafers per hour, with some systems approaching 90 wph. Most NGL lithographies struggle with this parameter.

Mask Cost is very important for optical lithography as it pushes to 180 nm and beyond. Advanced masks have been predicted to be as high as $80,000. The M×M tool uses no masks, but there is a small initial cost to process the data into the M×M format. This cost (shown here as $300) is substituted for the mask cost in these calculations.

Number of Exposures per Mask is very important in amortizing the high costs. The number of exposures depends upon the nature of the IC business. Lot sizes for ASICs are typically 500 or less, while MPUs are typically 1500. DRAMs can use the mask set for as many as 8000 wafer exposures, although the average is closer to 4000. Thus, IST has chosen the two levels of 500 and 8000 for comparison, with technologies requiring lot sizes under 500 wafers being impractical due to the excessive CoO. Maskless M×M can change this situation and is easily extendable to single chip personalization.

The data for this comparison are shown in Table II. Optical lithography and EPL data are from Sheldon *et al.*[12], and the updated EUVL data comes from Gwyn[13].

The M×M system is designed to have multiple writing modules in a cluster-tool configuration (Fig. 4). A single writing module is rated at 30 wafers/hour. CoO estimates are shown for single, dual and triple modules. Initial costs are assumed to scale as shown. Costs such as pattern data preparation do not scale.

Table II shows that M×M has a clear advantage in terms of CoO for all 500 mask exposure cases. A single M×M unit would be equivalent to the other lithographies for 8000 exposures, with the exception of the optimistic EUVL number. **In a dual or triple module configuration, M ´M has a significant CoO advantage over all other NGL and optical technologies.**

In figure 6, the Table II data has been expanded to show the advantage of M×M at low mask usage. CoO curves for single, dual and triple module M×M are also shown. The dual and triple writing module configurations for the M×M tool are more cost effective since they take full advantage of the efficiencies of the cluster tool configuration.

4.1. Risks of the M ´M CoO Model

The M×M estimates are made without access to the detailed IST CoO models, and certainly without having finished the detailed design of M×M. The throughput values are based upon careful system calculations and have little risk. The tool cost is a more risky estimate. The M×M CoO is essentially proportional to tool cost, but the charts and the data show room for cost expansion without loss of CoO advantage over the other NGL technologies.

5. DISCUSSION

We believe that the M×M system is superior because it uses multiple columns to avoid space-charge/stochastic effects and multi-beams to keep the data rate reasonable. The space-charge issue will keep competing NGL technologies – SCALPEL® and IPL – from extending beyond the 70 nm node to the 50 nm node without extensive R & D. The extendibility of M×M for two or more generations is a strong selling point. Among the leading NGL competitors, only EUVL promises such extendibility, but with high expected mask and tool costs.

The M×M system has significant CoO advantages over the competing NGL technologies, particularly when used with the cluster tool configuration that allows for multiple writing stations. Also, due to our maskless approach, chip development cycles will be significantly decreased, which indirectly affects the cost of ownership for fabrication of complicated IC chips. The M×M system allows for low volume chip production as well as single chip personalization. Finally, the M×M system allows for high throughput writing on standard DUV resists.

Table II - Cost-of-Ownership Calculations

Node	Technology	Tool Cost	Fixed + Recurring Costs	Throughput	Mask or Data Conversion Cost	Exposures / mask or data set	CoO/Level
		$M	$/hr	W/hr	$		$
130	193 optical binary mask	9.5	1432	35.8	25000	500	90
			1320			8000	40
100	157 optical binary mask	11	1597	36.3	31000	500	106
			1457			8000	44
70	157 optical alt ph mask	11	1597	36.3	53000	500	150
			1466			8000	47
70	EPL (SCALPEL®)	8.9	1035	23	33000	500	111
			940			8000	45
70	EUVL - SEMATECH	17.5	2006	34	66000	500	191
			1760			8000	60
70	EUVL - LLC revised	15	1268	50	41000	500	107
			1268	50		8000	30
70	**MxM - single module**	**12**	**1333**	**30**	**300**	**500**	**45**
			1333	**30**		**8000**	**44**
70	**MxM -dual module**	**15**	**1667**	**60**	**300**	**500**	**28**
			1667	**60**		**8000**	**28**
70	**MxM - triple module**	**18**	**2000**	**90**	**300**	**500**	**23**
			2000	**90**		**8000**	**22**

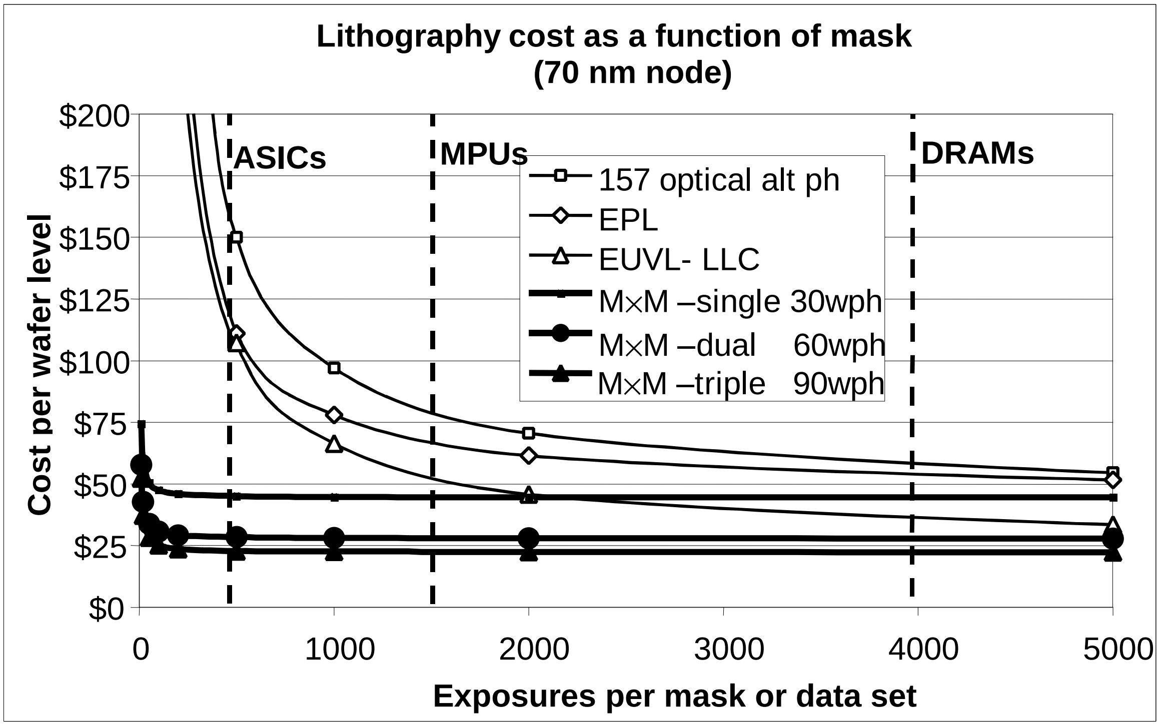

Fig. 6. Lithography cost as a function of mask usage (data from Table II).

ACKNOWLEDGMENTS

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