Modeling the Cost of EUVL Masks

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Overview

- The International SEMATECH model[1] of mask cost was used to analyze the factors that drive EUVL mask cost.
  - EUVL mask patterning cost is similar to that of advanced optical lithography masks.
  - EUVL mask price is most affected by defect free yield of the mask blank.
- Yield models were used to determine that reduction of mask blank defect density to <0.01 cm^{-2} will be required to lower EUVL mask price to where further defect density reductions have little effect on cost.

[1] Private communication with Phil Seidel, Ed Muzio and Walt Trybula of International SEMATECH. Also see http://www.sematech.org/public/resources/coo/index.htm.

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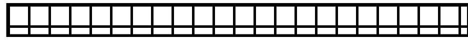
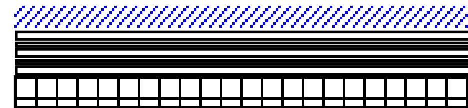
Basic EUVL Mask Fabrication Sequence

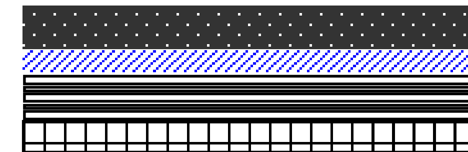


1. Substrate qualification

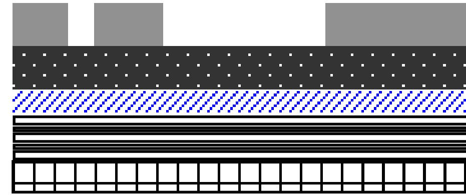
2. Multilayer deposition and defect inspection



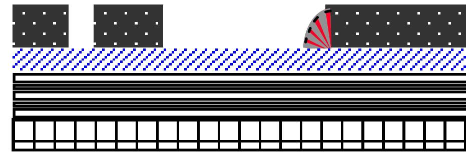
3. Buffer layer deposition



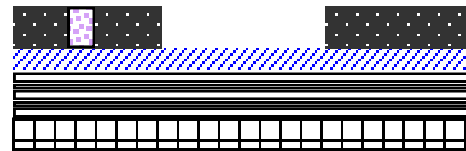
4. Absorber deposition



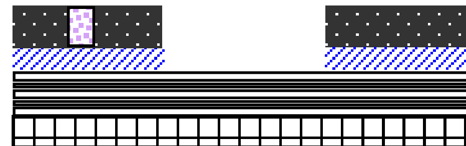
5. Pattern generation lithography



6. Pattern transfer into absorber



7. Defect inspection and repair



8. Buffer layer etch and final inspection

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Mask blank processing flow

	Step	Equipment	Number of tools	Estimated tool price	Tput (hours per mask)	Step Yield	Step cost
1	Clean	wet cleaning tool	1	$290,000	0.25	100%	$6
2	Multilayer coating	ion beam deposition	4	$4,000,000	1.5	100%	$308
3	Actinic Inspection	actinic inspection tool	5	$5,000,000	2	60%	$481
4	Reflectivity measurement	EUV reflectometer	2	$1,250,000	1	95%	$48
5	Buffer layer deposition	PECVD	1	$1,000,000	0.2	100%	$19
6	Absorber layer deposition	magnetron sputtering	1	$2,000,000	0.2	100%	$38
7	Absorber stack inspection	dark field inspection	1	$800,000	0.05	98%	$15
8	Ship	computer	1	$25,000	0.1	100%	$0

Substrate Price	$3,000	Total Yield	56%
Blanks required / week	200	Price	**$6,300**

Total defect density = 0.005 cm^{-2}

Assumes non-yielding substrates are reworked at cost of 2/3 of the substrate price and that mask blank price = mask blank cost.

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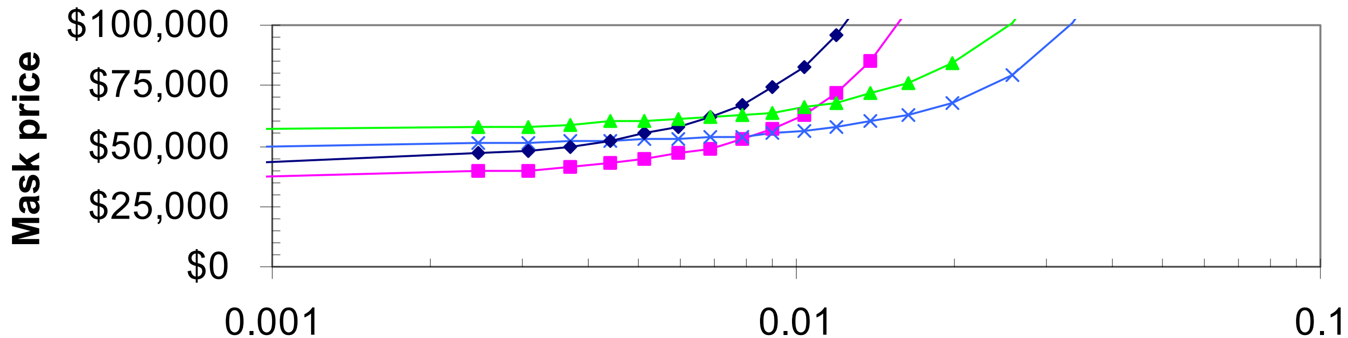
With multilayer defect repair, total mask blank defect density can be 0.01-0.02 cm^{-2}

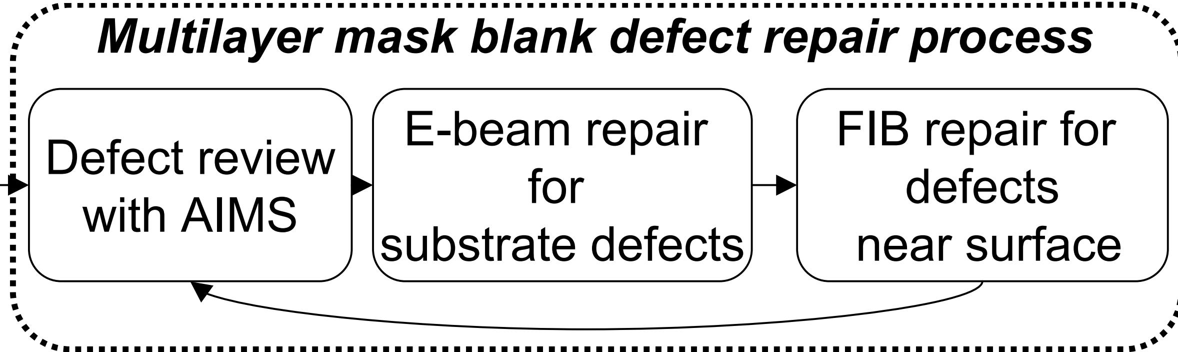


Poisson Yield Model

$$Y_D = \exp\left(-lh\, m^2 D'_0\right)$$

lh=critical area=100 cm^2

m=4X demagnification



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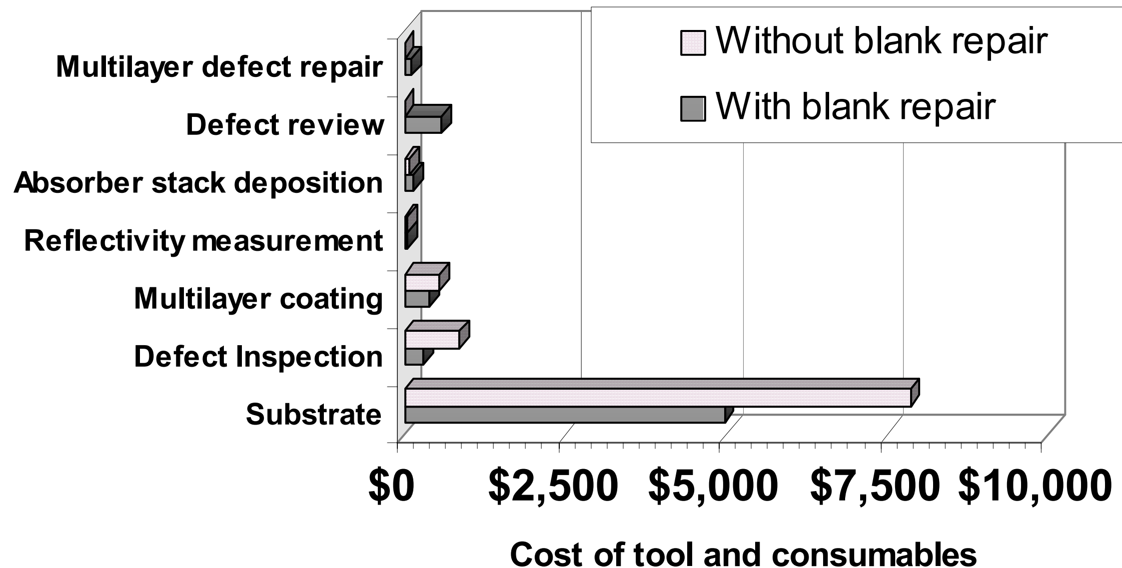
Mask blank fabrication flow with defect repair

	Step	Equipment	Number of tools	Estimated tool price	Throughput (hours per mask)	Step Yield	Step cost
1	Substrate acquisition	LTEM susbtrate					$4,882
2	Multilayer coating	Ion beam sputtering	5	$ 4,000,000	1.5	100%	$385
3	Defect inspection	Defect inspection tool	3	$ 5,000,000	1	62%	$288
4	Reflectivity measurement	Reflectometer	2	$ 1,250,000	1	98%	$48
5	Defect review	EUV AIM tool	1	$ 10,000,000	0.4	100%	$192
6	Phase defect repair	E-beam repair tool	1	$ 3,000,000	0.4	93%	$58
7	Absorbing defect repair	FIB tool	1	$ 3,000,000	0.4	93%	$58
8	Defect review	EUV AIM tool	1	$ 10,000,000	0.4	100%	$192
9	Defect inspection	Defect inspection tool	2	$ 5,000,000	1	95%	$192
10	Buffer layer deposition	PVD	1	$ 1,000,000	0.2	100%	$19
11	Absorber layer deposition	PVD	1	$ 1,000,000	0.2	100%	$19
12	Absorber stack inspection	Defect inspection tool	1	$ 5,000,000	1	98%	$96
13	Cleaning	Wet cleaning tool	1	$ 500,000	0.25	100%	$10
14	Ship	Bench and computer	1	$ 25,000	0.1	100%	$0

Defect density before repair (cm-2)	0.010		
Substrate Price	$3,000	Total Yield	49%
Blanks required / week	200	**Blank price**	**$7,700**

Assumes non-yielding substrates are reworked at cost of 2/3 of price and that mask blank price = mask blank cost.

Pareto chart of mask blank fabrication cost at a defect density of 0.01 defects cm^{-2}



- Increasing defect free yield and decreasing substrate price have the largest impact on mask blank cost.
- Multilayer repair steps have a relatively small cost compared to yield loss.

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Mask patterning process flow

	Step	Equipment	No. of tools	Estimated tool price	Tput (hours/mask)	Step Yield	Step cost
1	e-beam data prep	workstation	7	$50,000	9	99%	$13
2	e-beam data prep	software	2	$100,000	2	100%	$8
3	inspection data prep	software	5	$110,000	7	100%	$21
4	Coat/Bake	track element	1	$290,000	0.17	100%	$11
5	Write	e-beam writer	5	$22,000,000	5.5	100%	$4,231
6	Develop	track element	1	$290,000	0.17	100%	$11
7	Bake	bake station	1	$290,000	0.1	100%	$11
8	Etch	RIE tool	1	$700,000	0.5	100%	$27
9	Strip	track element	1	$800,000	0.1	100%	$31
10	Measure CD	CD SEM	1	$1,600,000	0.5	90%	$62
11	Measure Placement	metrology tool	1	$1,800,000	0.5	93%	$69
12	Clean	wet cleaning tool	1	$600,000	0.5	100%	$23
13	Pattern Inspect	bright field microscopy	5	$15,600,000	6	100%	$3,000
14	Repair -FIB	focused ion beam	2	$5,000,000	2	93%	$385
15	Post Repair Inspection	bright field microscopy	1	$15,600,000	1	100%	$600
16	Buffer Layer Strip	reactive ion etch	1	$600,000	0.25	100%	$23
17	Final clean	wet cleaning tool	0	$600,000	0.5	100%	$0
18	Final inspection	bright field microscopy	4	$15,600,000	6	100%	$2,400
19	Repair -FIB	focused ion beam	0	$5,000,000	0.5	96%	$0
20	Inspection	bright field microscopy	0	$15,600,000	0.25	100%	$0
21	Pellicle mount	removable pellicle	1	$25,000	0.25	100%	$301
22	Ship	computer for data log	1	$25,000	0.1	100%	$1

Blank Price	$7,700	Cumulative yield	73%
Masks Required / Week	100	Mask cost	$28,047
		Mask Price	**$56,000** (= 2× cost)

Equipment description refers to the generic functionality and not necessarily the specific supplier.
Equipment cost are current costs except for writer and inspection, which are extrapolated to 2006.

Updates to model since August

	Aug-01	Feb-02
Substrate price****	$1,500	$3,000
Mask blank repair tool set **	$0	$16M
Blank defect density before repair (cm^{-2})	0.005	0.01
E-beam tool price***	$18.2M	$22M
Inspection tool price*	$6.5M	$15.6M
Inspection tool Tput* (hrs/mask)	5.5	6
Repair tool price*	$3M	$5M

* Used ISMT values from 8-01

** Estimated price

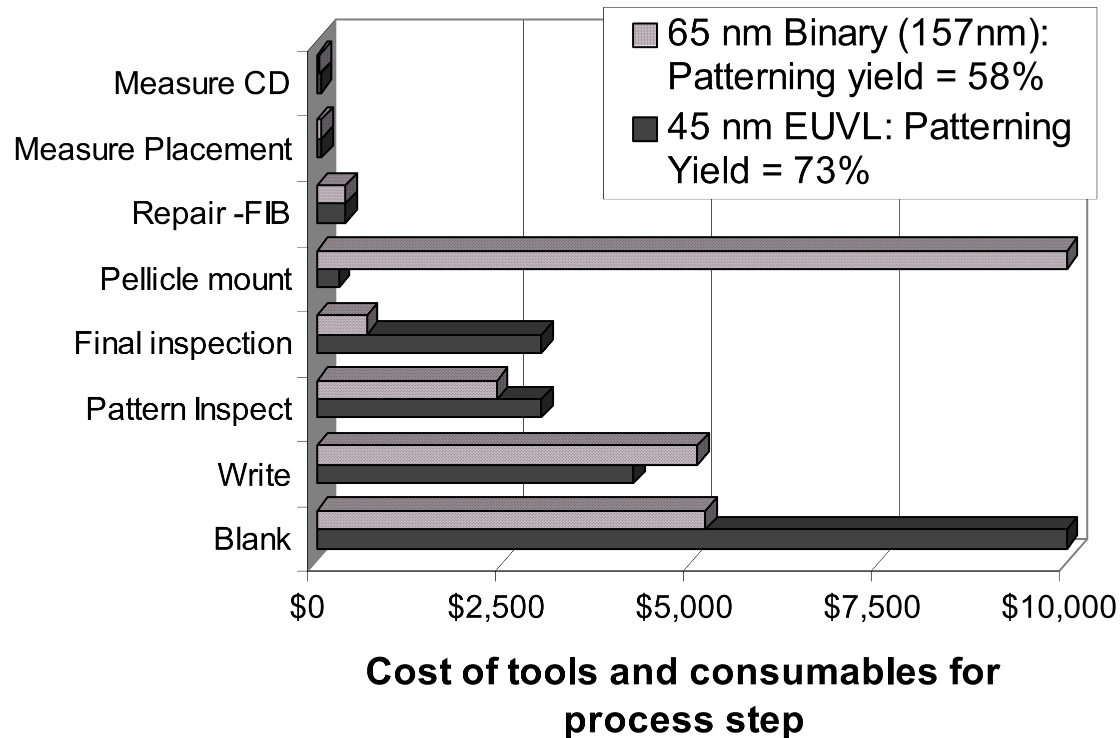
*** Used ISMT 70-nm node value because no OPC

**** Extrapolated supplier quotes to expected volume price

⇒ These changes resulted in a mask price increase from $33K to $56K.

- The tool prices are in future dollars, the present value at 3% discount rate of $56K is ~$48K.

Pareto chart of mask patterning costs



(assumes hard pellicle costing $10K; 157nm blank $3K)

- Reducing mask blank price would have the greatest impact on mask price.
- The cost of writing and inspection are about the same as for optical masks, except EUV requires more final inspection.
- Potential cost of not using a pellicle with EUV not included.

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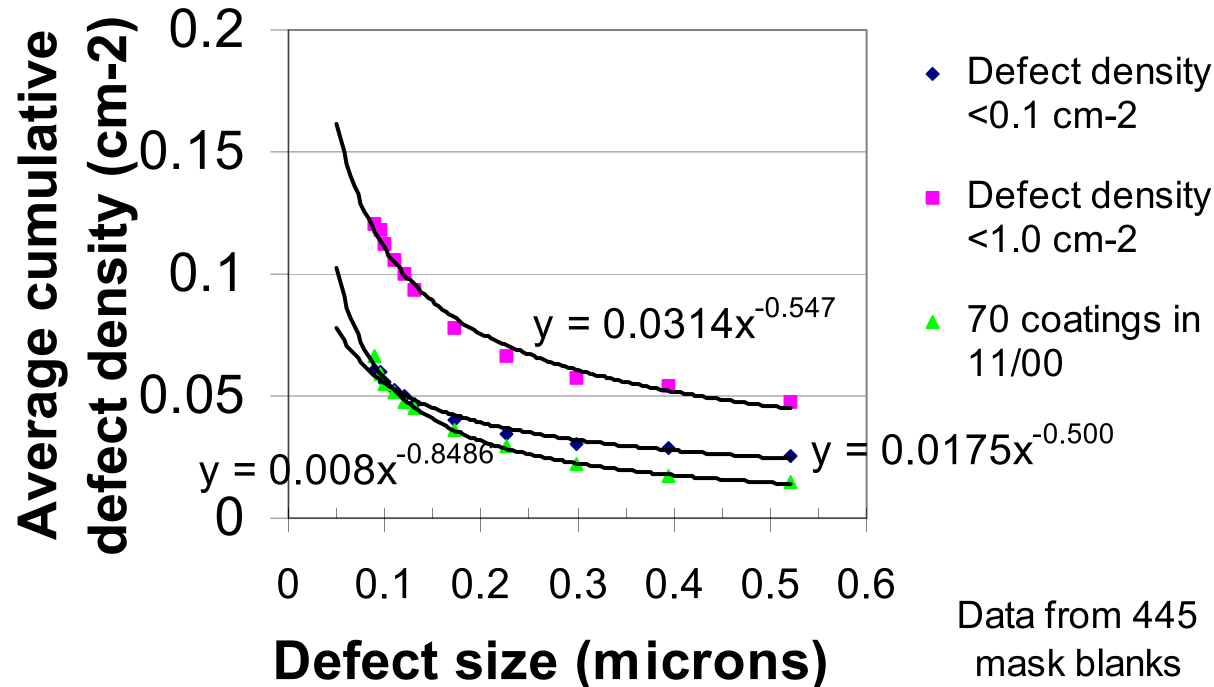
Defect density added in multilayer coating process does not significantly increase with decreasing defect size



Data from 445 mask blanks

For mask blanks with added defect density <0.1 cm^{-2}, defect density scales as (minimum defect size)$^{-n}$, where n=0.5 to 0.85. Typical IC processes have n=0.2 to 3.0.

A significant increase in defect density is not expected as minimum detected size is reduced.

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Learning curve used to determine required learning rate to achieve target yield

- Learning curve model[2]

  $D_0 = D_0^{\text{initial}} \, N_{\text{cycle}}^{\;\log(b)/\log(2)}$

  N_{cycle} is the number of learning cycles

  b is the learning factor (smaller is better)

- Historical learning rate at LLNL:
  - Median defect density has been reduced by a factor of 54% every time the number of learning cycles has doubled (b=0.54).
  - Learning cycles have been carried out at a rate of one per month.

[2] David R. LaTourette, "A yield learning model for integrated circuit manufacturing," *Semiconductor International*, July 1995, 163-70.

Conservative learning curve model indicates that yield targets can be met with repair and continued defect reduction

Learning at commercial suppliers

2nd generation ML coating tool

2005: 60% yield with repair

2007: 60% yield without repair

ML Coating Process-Added defect Density (cm-2)

1000.000
100.000
10.000
1.000
0.100
0.010
0.001

Sep-97 Sep-98 Sep-99 Sep-00 Sep-01 Sep-02 Sep-03 Sep-04 Sep-05 Sep-06 Sep-07 Sep-08

- Historical data from LLNL (>90nm)
- Median defect density learning curve (>50-nm)
- Median defect density for 20-40 consecutive coatings (>90 nm)
- Yield for 22 by 33 mm field
- Yield with repair

Poisson yield model assuming substrate defect density is equal to ML coating defects

Modest future learning curve with *one cycle per month* and 70% learning rate assumed (vs. 54% historical rate)

Possible EUV mask price values from CoO model

Substrate price	Defect density with repair (cm^{-2})	Blank price	Patterning yield	Mask price
$1,500	0.005	$4,500	73%	$47,000
$3,000	0.005	$6,500	73%	$53,000
$3,000	0.01	$7,700	73%	$56,000
$5,000	0.005	$9,100	73%	$60,000
$5,000	0.01	$11,000	73%	$66,000
$3,000	0.02	$11,800	73%	$68,000
$5,000	0.02	$17,400	73%	$84,000
$5,000	0.01	$11,000	50%	$88,000

- Mask price could range from $47K to $88K compared to a binary optical mask for 157nm at $50K. (A complementary PSM set might cost ~$100K.)

Conclusion

- Mask blank defect free yield drives EUVL mask price.
- To meet or exceed mask price goals:
  - ⇒ Continue to reduce defect density on mask blanks
    - If a supplier can achieve a learning curve with nearly the historical learning rate at LLNL, and
    - if second generation deposition tools become available in 2004
    - and multilayer defect repair techniques are successful,
    - the target yield can be achieved by 2005
  - ⇒ Continue to reduce defect printability with smoothing and defect avoidance
  - ⇒ Take advantage of evolutionary improvements in mask processing and equipment

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