Predictive Model of the Cost of EUVL Masks

Scott D. Hector
scott.hector@motorola.com
Motorola DigitalDNA^{TM} Laboratories, Austin, Texas 78721

Patrick Kearney, Claude Montcalm, James Folta, Chris Walton, William Tong, and John Taylor
Lawrence Livermore National Laboratory, Livermore, CA 94550

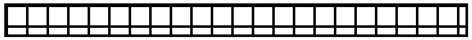
Pei-Yang Yan and Charles Gwyn
Intel Corporation Components Research, Santa Clara, CA 95052

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.

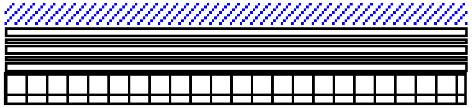
[1] Private communication with Phil Seidel, Ed Muzio and Walt Trybula of International SEMATECH. Also see http://www.sematech.org/publice/resources/coo/index.htm.

Basic EUVL Mask Fabrication Sequence

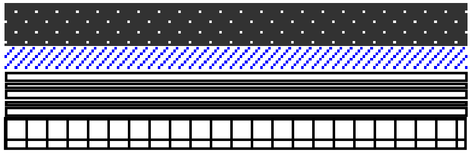


1. Substrate qualification

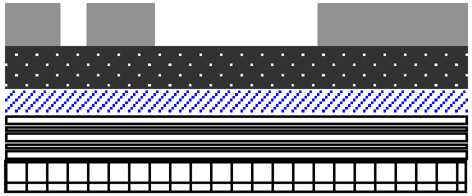
2. Multilayer deposition and defect inspection



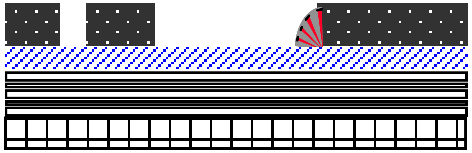
3. Buffer layer deposition



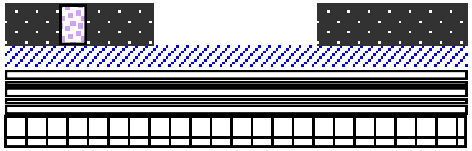
4. Absorber deposition



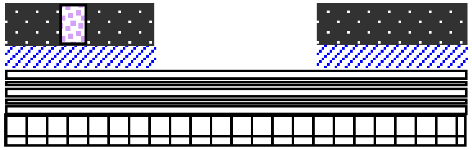
5. Pattern generation lithography



6. Pattern transfer into absorber



7. Defect inspection and repair



8. Buffer layer etch and final inspection

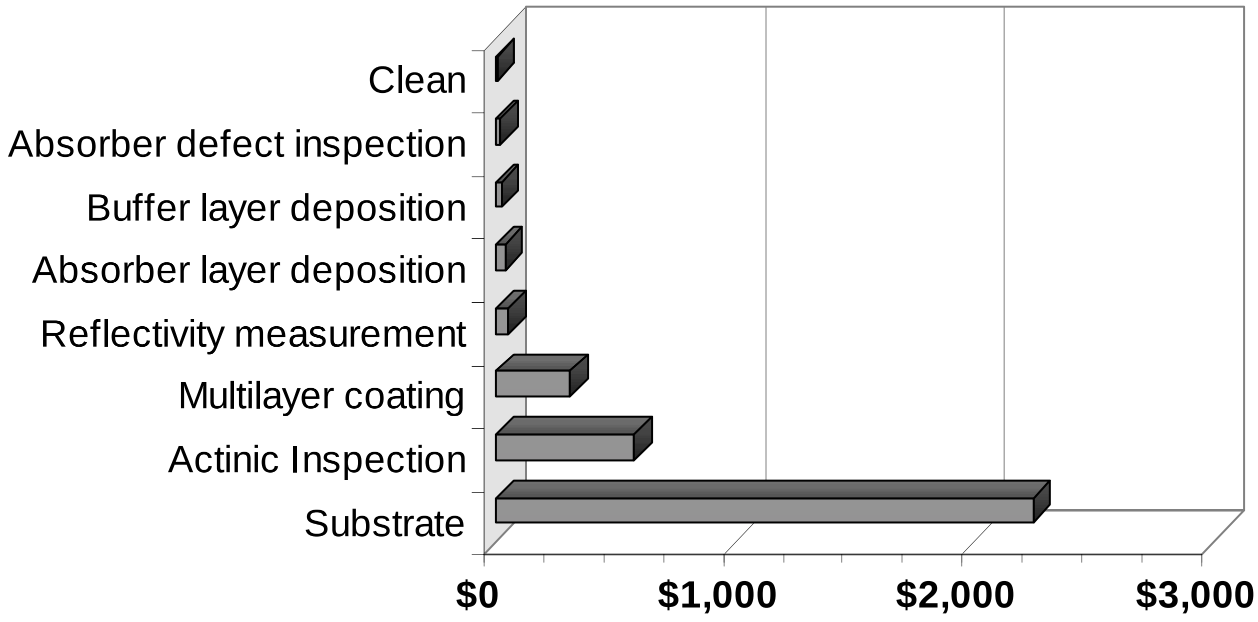
Mask blank processing flow

	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	$6,000,000	2	60%	$577
4	Reflectivity measurement	EUV reflectometer	2	$1,250,000	1	95%	$48
5	Buffer layer deposition	magnetron sputtering	1	$1,000,000	0.2	100%	$19
6	Absorber layer deposition	dark field inspection	1	$2,000,000	0.2	100%	$38
7	Absorber stack inspection	wet cleaning tool	1	$800,000	0.05	98%	$15
8	Ship	computer	1	$25,000	0.1	100%	$0

Substrate Price	$1,500	Total Yield	56%
Blanks required / week	200	Price	**$4,000**

Assumes non-yielding substrates are reworked at cost of $500
and that mask blank price = mask blank cost.

Pareto chart of mask blank fabrication cost



- Increasing defect free yield and decreasing substrate price have the largest impact on mask blank cost.
- The use of optical rather than actinic inspection would also reduce mask price by 6-12%, depending on defect free yield.

Mask patterning process flow

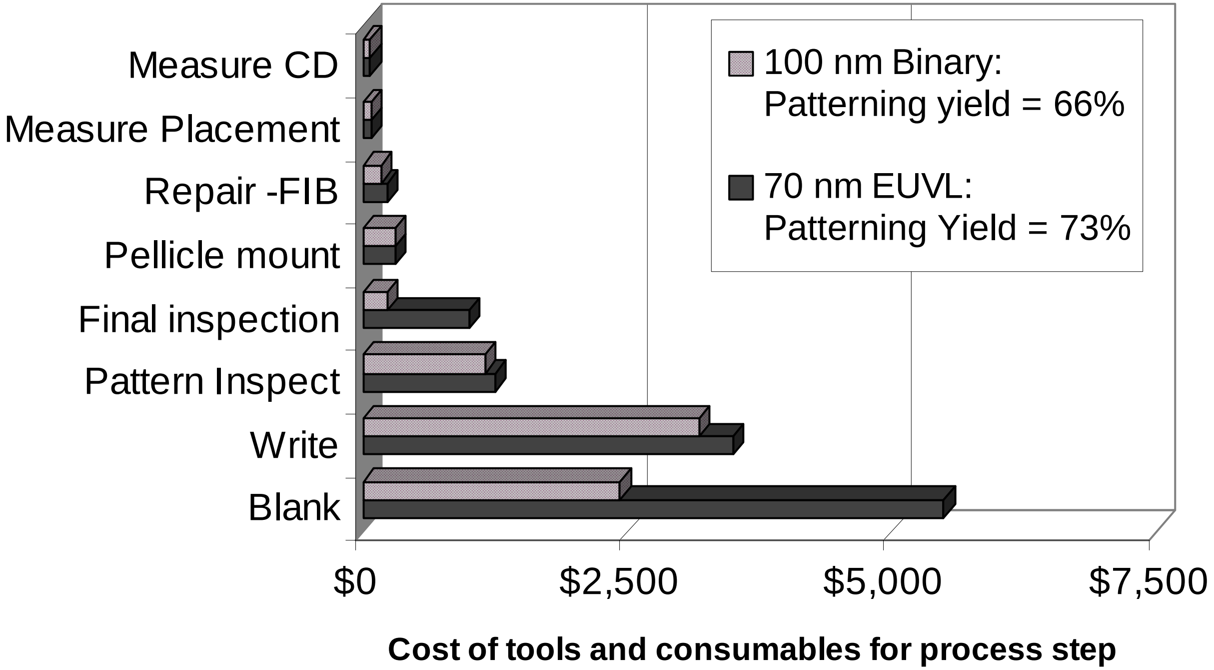
	Step	Equipment	Number of tools	Estimated tool price	Throughput (hours per mask)	Step Yield	Step cost
1	e-beam data prep	workstation	7	$50,000	9	99%	$13
2	e-beam data prep	software	2	$100,000	2	100%	$8
3	inspection data prep	software	5	$110,000	7	100%	$21
4	Coat/Bake	track element	1	$290,000	0.17	100%	$11
5	Write	e-beam writer	5	$18,200,000	5.5	100%	$3,500
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	$600,000	0.5	100%	$23
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	$6,500,000	5.5	100%	$1,250
14	Repair -FIB	focused ion beam	2	$3,000,000	2	93%	$231
15	Post Repair Inspecti	bright field microscopy	0	$6,500,000	1.1	100%	$0
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	$6,500,000	5.5	100%	$1,000
19	Repair -FIB	focused ion beam	0	$3,000,000	0.5	96%	$0
20	Inspection	bright field microscopy	0	$6,500,000	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	$4,000	Cumulative yield	73%
Masks Required / W	100	Mask cost	$16,748
		Mask Price	**$33,000** (= 2× cost)

Equipment description refers to the generic functionality and not necessarily the specific supplier.

Equipment cost are current costs except for the writer and pattern inspection, which have been extrapolated to 2006.

Pareto chart of mask patterning costs



- 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.

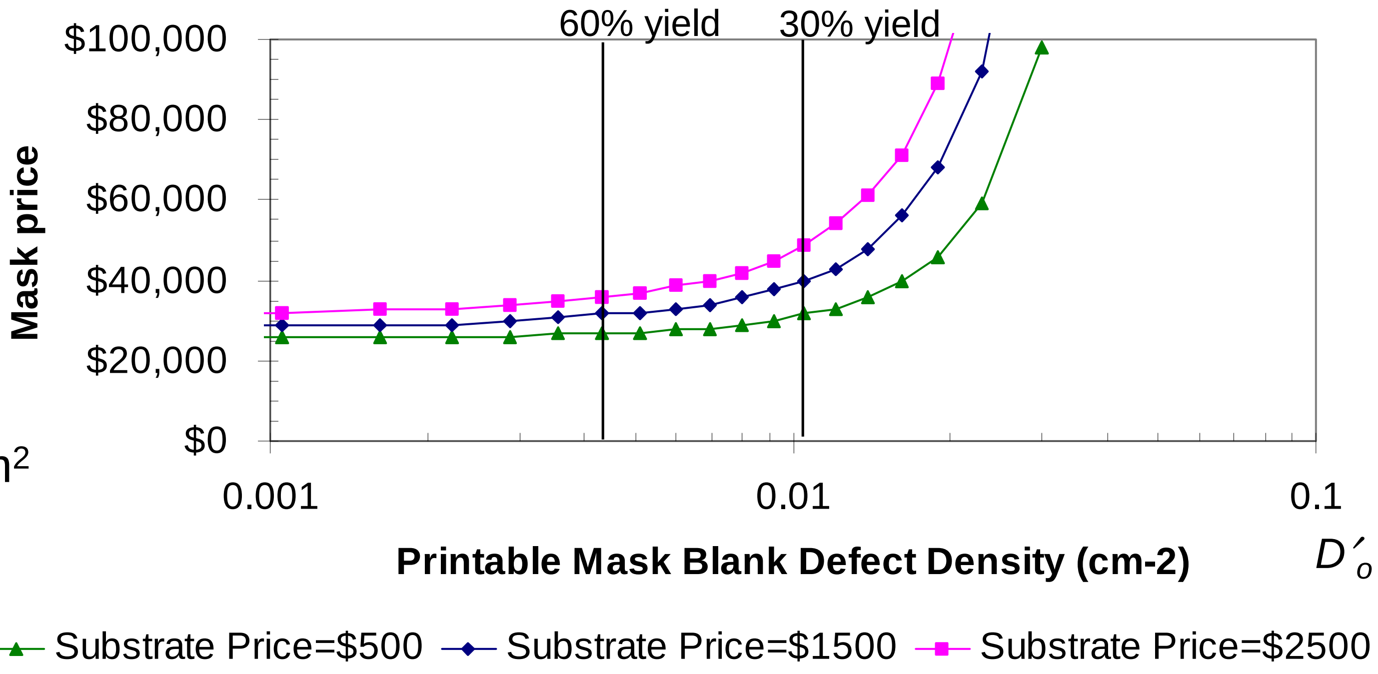
Printable mask blank defect density should be <0.01 defects/cm^2

Poisson Yield Model

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

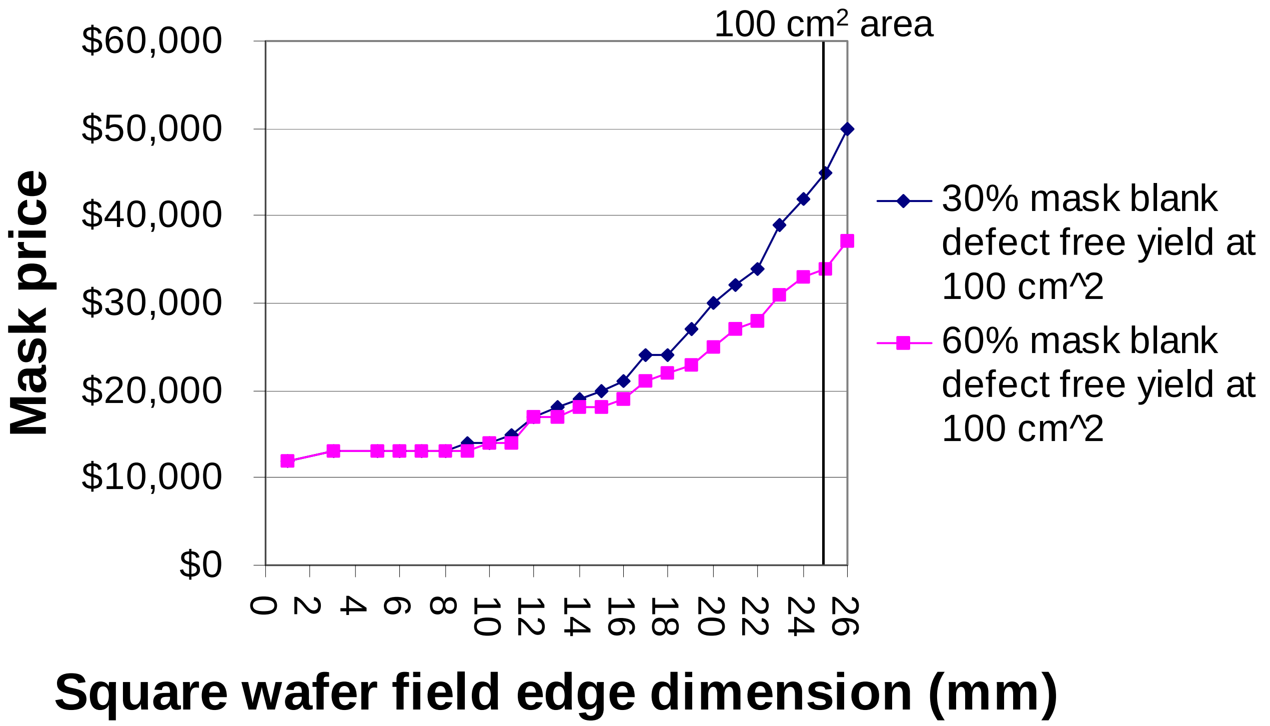
lh=critical area=100 cm^2

m=4X demagnification



- For printable mask blank defect density <0.01 cm^{-2}:
  - Mask substrate price and defect density have a diminishing effect on mask price.
  - $\Rightarrow$ *Reduce defect density and defect printability*

EUVL mask price decreases roughly as the square of field edge dimension

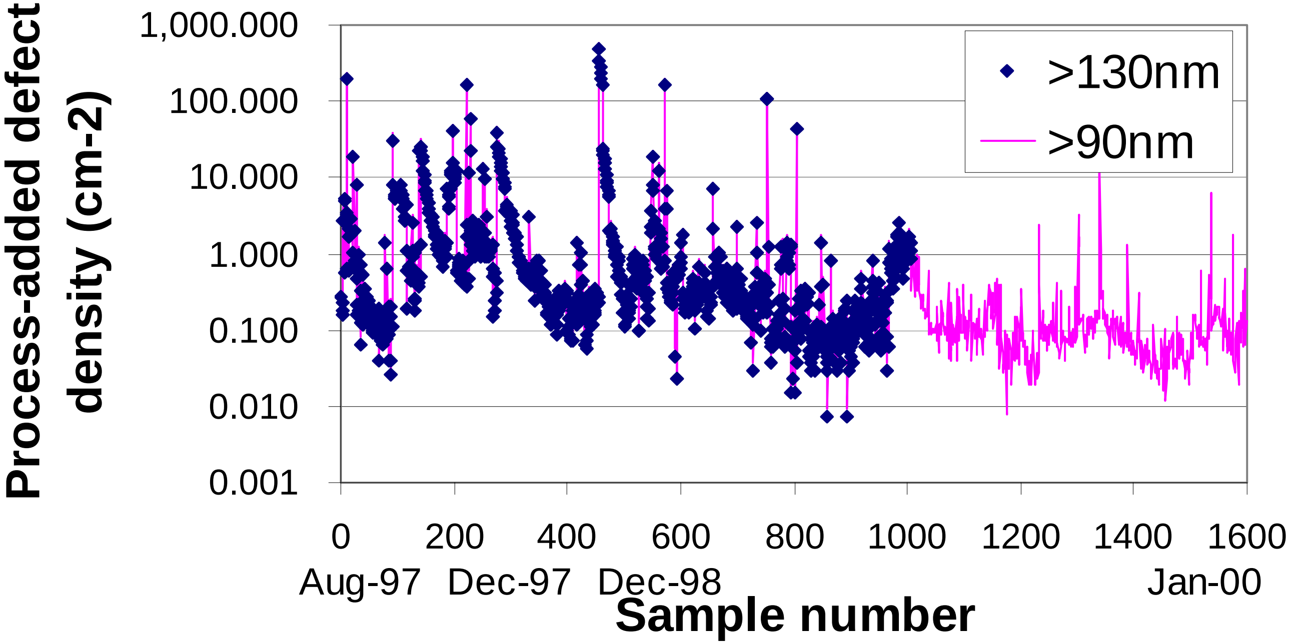


- Increased yield for CD and pattern placement
- Higher throughput on write and inspection tools
- Smaller critical area for defects

} At smaller field size

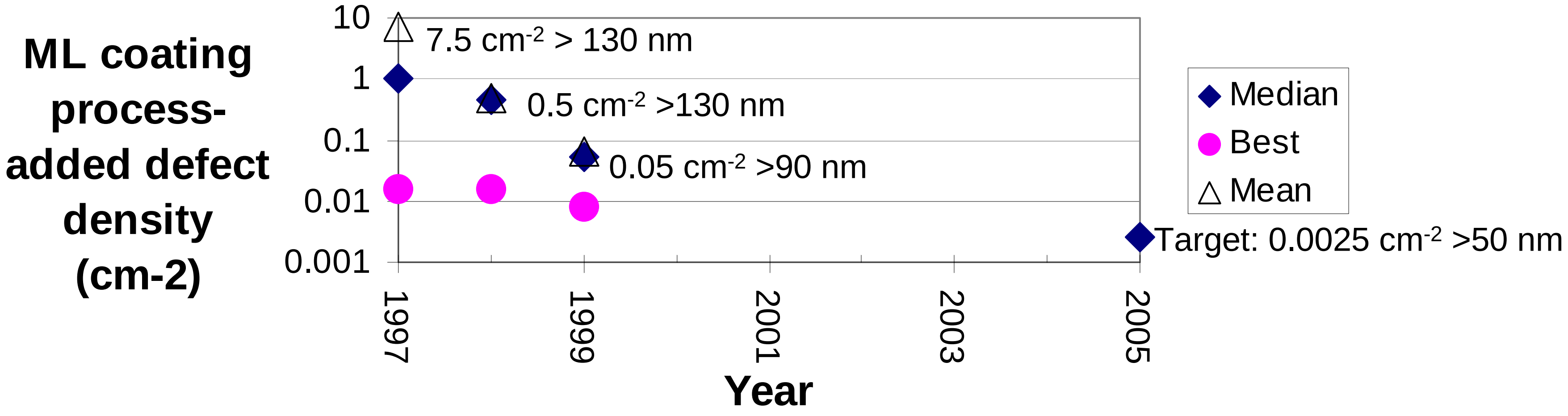
⇒ Mask price decreases as roughly the square of field edge length

Defect density reduced significantly over 30 month period



- During the 30 month period shown, 1600 mask blanks were coated with Mo/Si multilayers.
- The mean defect density added in multilayer coating process steadily decreased, even as minimum defect sensitivity of inspection was reduced from 130 to 90 nm.

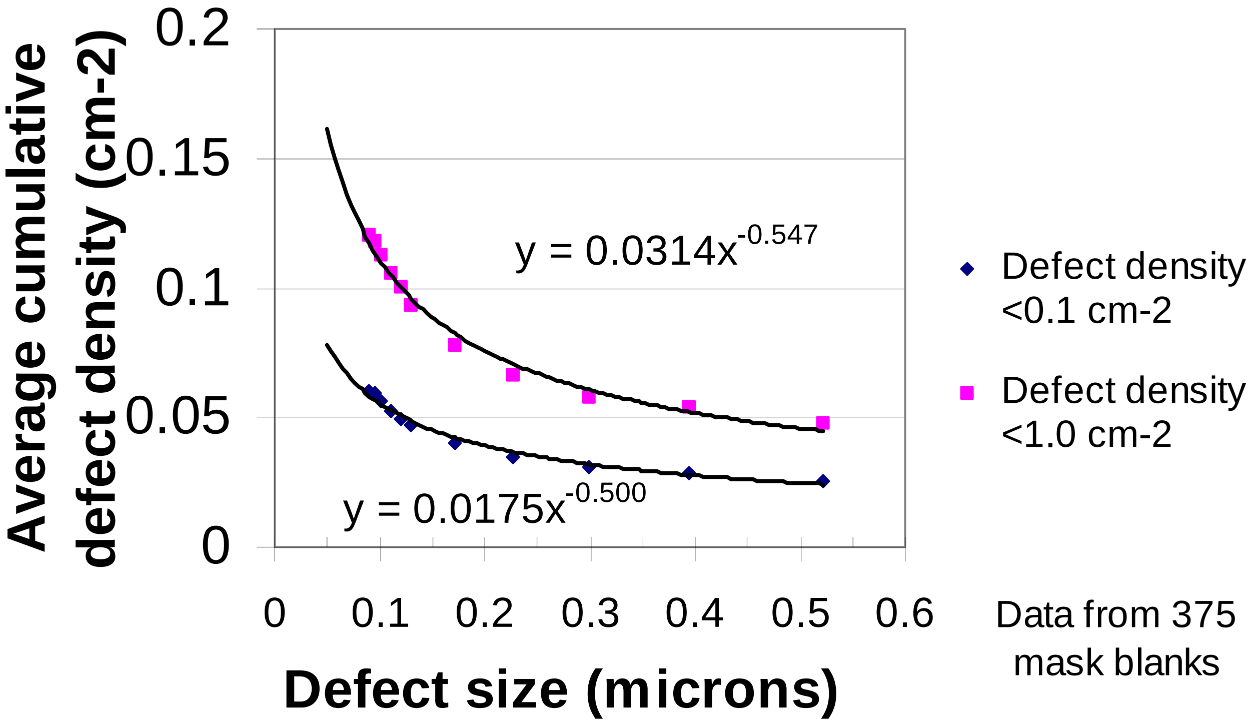
EUVL mask blank yield of 60% by 2005 supported by historical rate of progress



median and mean are for 40 consecutive mask blank coatings at year end

- Mean multilayer coating defect density lowered by 10× per year.
- Defect printability being reduced with defect smoothing
  - Smoothing of substrate defect by ion beam deposited multilayers has been demonstrated.
  - Buffer layers are being developed to further reduce substrate defect printability.

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



Data from 375 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. 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.

Required defect density reduction determined with Poisson yield model

	ML coating process	LTEM substrates
n (defect scaling power in model)	0.55	2* (1)
Minimum detectable defect size	90 nm	90 nm**
Defect density today	0.047 cm^{-2}	0.05 cm^{-2}
Calculated defect density for 50 nm minimum detectable defect size	0.065 cm^{-2}	0.16 cm^{-2}
Target defect density for defects >50 nm for 60% yield	0.0025 cm^{-2}	0.0025 cm^{-2}
Improvement factor required	*26*	*65 (36)*
Target yield for mask blank coating	=======>	*60%*

* Typical yield modeling literature value. Not yet measured on LTEM substrates.

** Estimated from measured inspection tool sensitivity on a silicon surface

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

- Learning curve model[2]

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

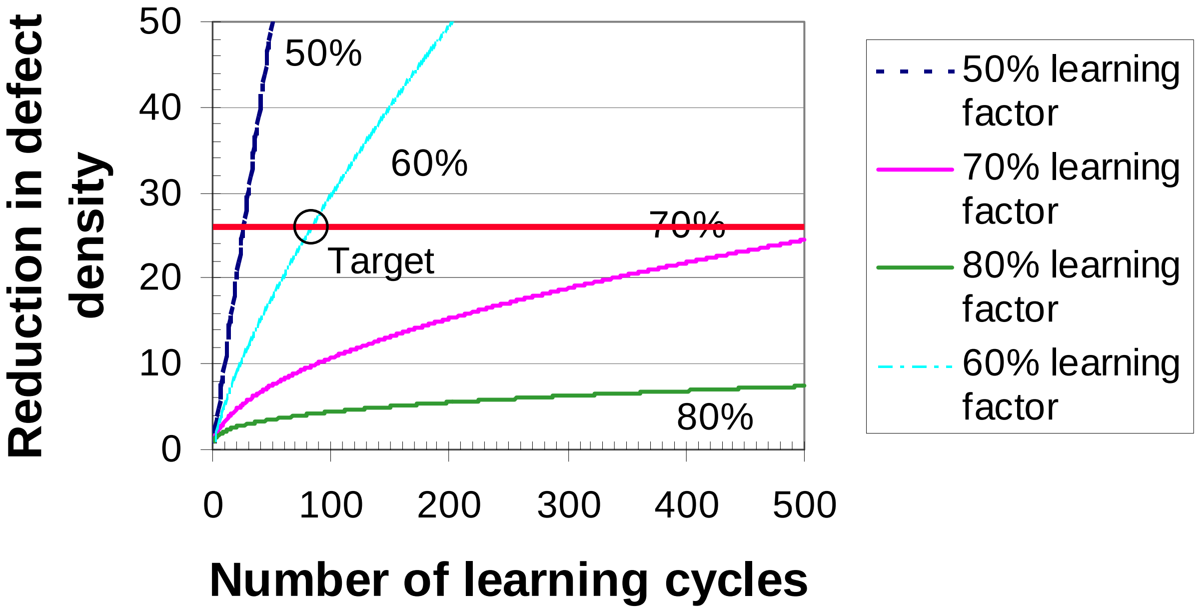
  N_{cycle} is the number of learning cycles

  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.

Learning curve required for target defect free yield is similar to historical trend



- To achieve the required factor of 26 reduction in defect density, a learning rate of 60% combined with a learning cycle time of two weeks would be sufficient to achieve 60% yield after 4 years.
  - After transferring the mask blank fabrication process to a commercial supplier, a focused defect reduction effort at the supplier would result in achievement of the target yield by 2005.

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 decreased cycle time, the target yield can be achieved in less than four years.
  - ⇒ Continue to reduce defect printability
  - ⇒ Take advantage of evolutionary improvements in mask processing and equipment