EUV Lithography in Perspective

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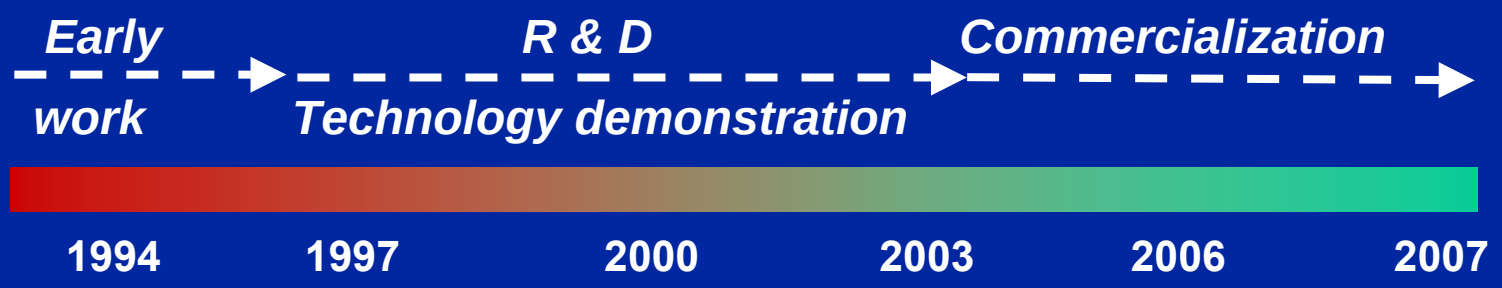
Objectives:

- ***Summarize the status of EUVL development in key areas***
- ***Note mask costs compare favorably with 193 nm***
- ***Emphasize system learning has minimized risks by uncovering all EUVL Surprises***
- ***Advocate a total system solution for remaining challenges***

EUV Lithography in perspective

Outline:

- Background
  - Reasons for EUVL
  - Special challenges and delays
- R&D and system demonstration
  - Optics
  - Sources
  - Tools
  - Multilayers
  - Masks
  - Resists
- Challenges/critical issues



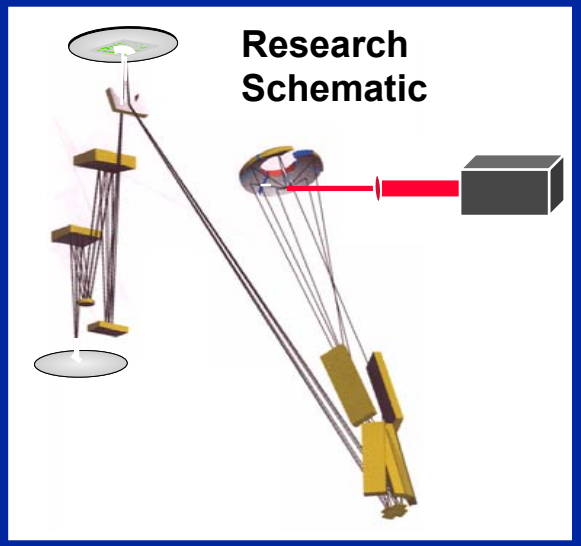
Background – Why EUV?

- *Similar to conventional optical lithography*
  - Resolution and depth of focus scale with NA and wavelength
  - Uses reduction optics (4x)
  - Builds on optical lithography design experience base
  - Uses extended optics manufacturing methods
  - Large k_1 supports multiple technology nodes – off axis illumination, phase shift masks, OPC can be used

$$\text{Feature size} = k_1 \frac{\lambda}{NA}$$

- *Technology exploits what we know*

Special challenges for EUVL

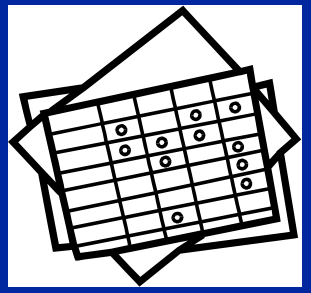


- *Differences from optical lithography*
  - Very short 13 to 14 nm nm light is absorbed by all materials/gases
  - Requires reflective optics coated with quarter-wave Bragg reflectors
  - Reflectivity constraints limit practical number of optical elements and requires aspheric surfaces
  - Uses reflective reticles with patterned absorbers
  - Requires vacuum operation with precision environmental control
  - Uses plasma source for EUV light

EUVL has encountered delays

1. DUV technologies have been extended beyond initial projections
2. Alternative technologies caused diversions of resources (e-beam, ion-beam, 157 nm, imprint, immersion, etc.)
3. Economic fluctuations caused program delays and increased costs
4. Projected technology costs discouraged industrial commitments
5. Lack of customer commitments discouraged industry investment

Where are we in the development process?



Optics

Optics fabrication

Status

- *Variety of aspheric optics produced by ASML Optics, Zeiss, Nikon and others*
- *Parent and clear aperture optic fabrication demonstrated – Up to 209 mm with 9 µm aspheric departure in clear aperture*
- *Continuous improvement demonstrated for Figure, Mid spatial frequency and High spatial frequency roughness (MSFR, HSFR)*
- *Visible metrology developed*

Off axis asphere with 9 µm aspheric departure

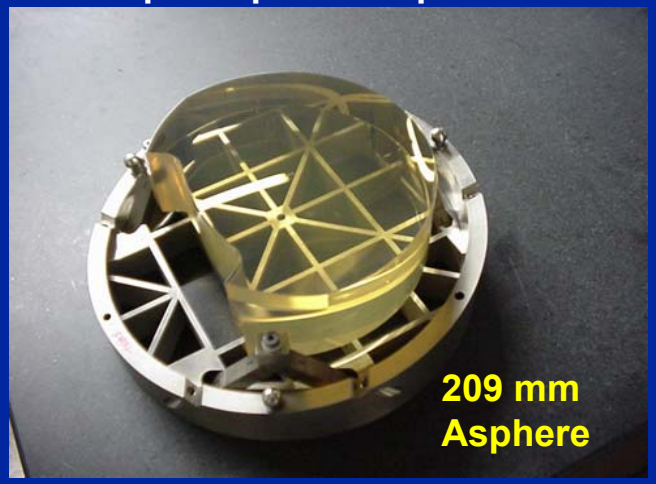
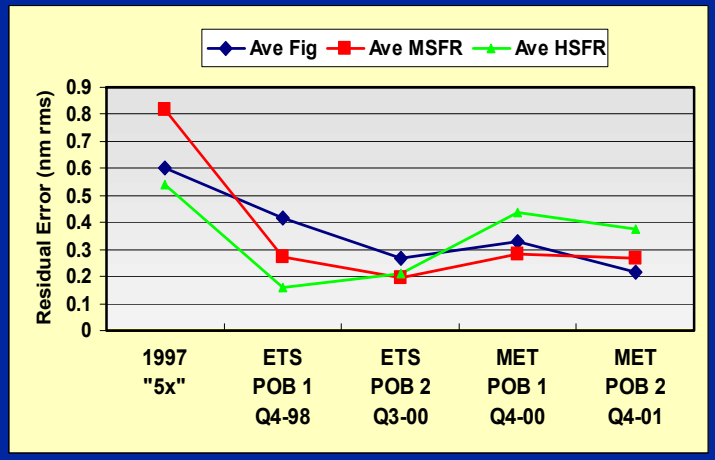


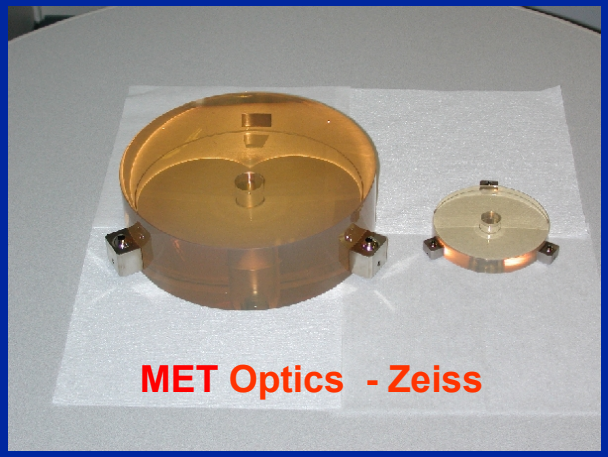
Figure and finish progress



Issues

- *Difficult to meet MSFR and HSFR specifications simultaneously*
- *Metrology accuracy impacted by errors introduced by optics, dust, alignment, etc.*

Optics fabrication

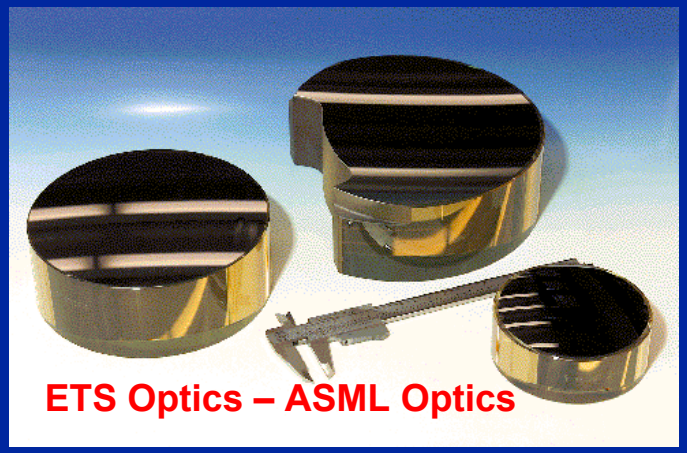


Conclusions

- Fabricate/polish only mirror clear aperture
- Use multilayer coating smoothing to relax HSFR finishing requirements
- Adapt novel kinematic mirror mounting
- Implement Lensless PSDI system to remove metrology error sources
- Apply validated design and thermal models

Challenges

Parameter	Present (best)	07 Requirement
Figure	0.22 nm rms	0.12 nm rms
MSFR	0.28 nm rms	0.10 nm rms
HSFR	0.37 nm rms	0.10nm rms
Lifetime	months	5 years

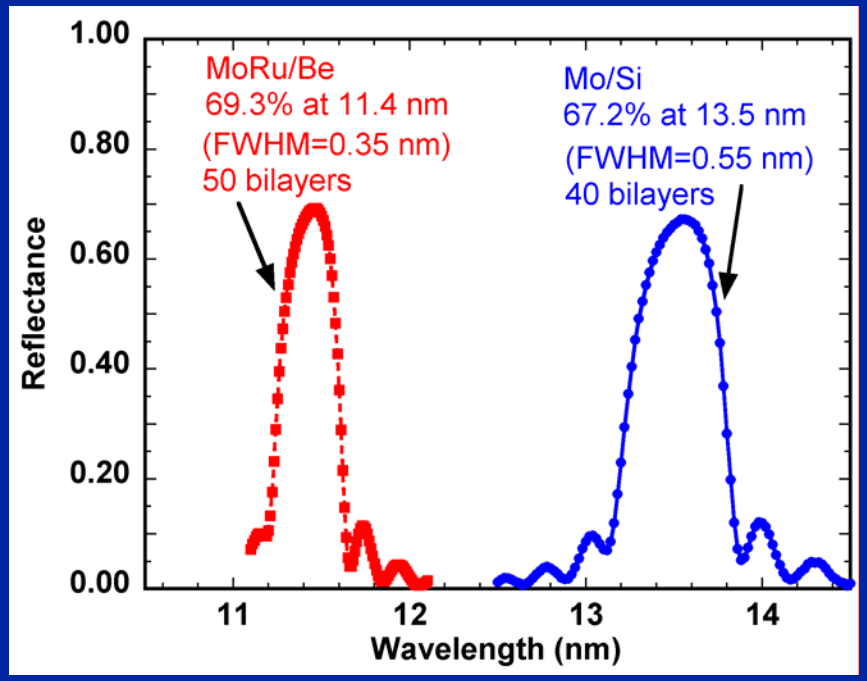


Multilayers

Multilayer coating development

Status

- Mo/Be and Mo/Si multilayer processes developed
- Processes include uniform and graded coatings
- Variety of capping layers characterized
- Smoothing process developed for Mo/Si for HSFR and covering of defects
- Interface engineering used to improve multilayer characteristics



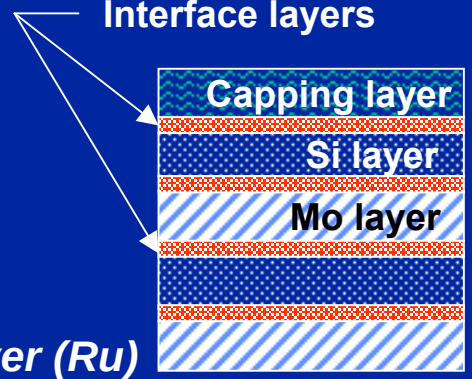
Issues

- Environmental issues in Japan and Europe using Beryllium
- Multilayer defect levels too high for masks
- Peak reflectivity lower than desired

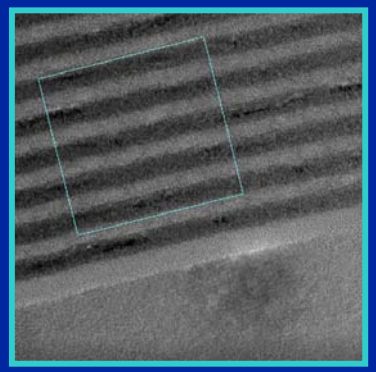
Multilayer Coatings

Conclusions

- *Discontinue Mo/Be research*
- *Focus on Mo/Si multilayers - improved bandwidth, reduced flare, good grading and smoothing characteristics*
- *Apply interface engineering to improve lifetime and reflectivity*
- *Cap ML stack with oxidation resistant layer (Ru)*
- *Use ML smoothing to relax HSFR requirements for optics*



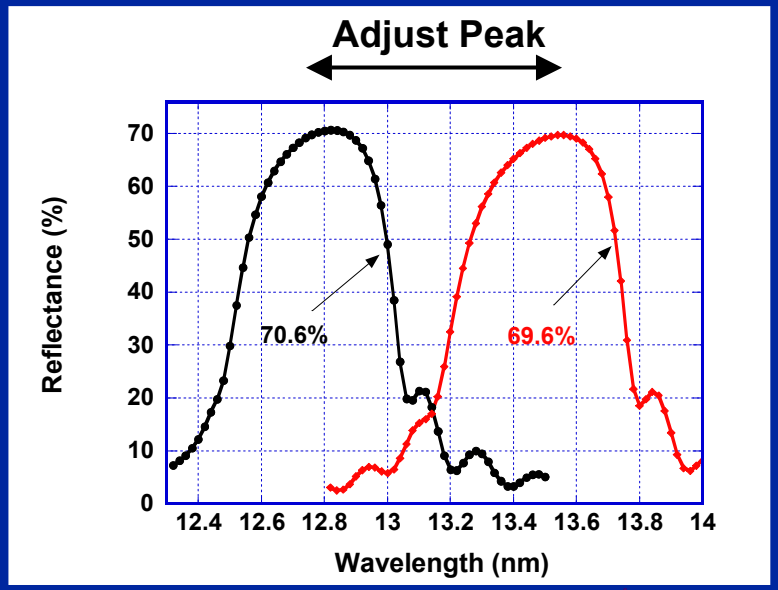
$Mo/B_4C/Si/B_4C$ ML



Challenges

Parameter	Best	07 Requirement
ML & capping layer Lifetime	Months	5 Yr
Residual stress	-410 MPa to +340 MPa	TBD
Peak reflectance	70 %	71 % **

**Theoretical reflectivity for Ru capped Mo/Si ML is 75.4 %



EUV Source

Source development

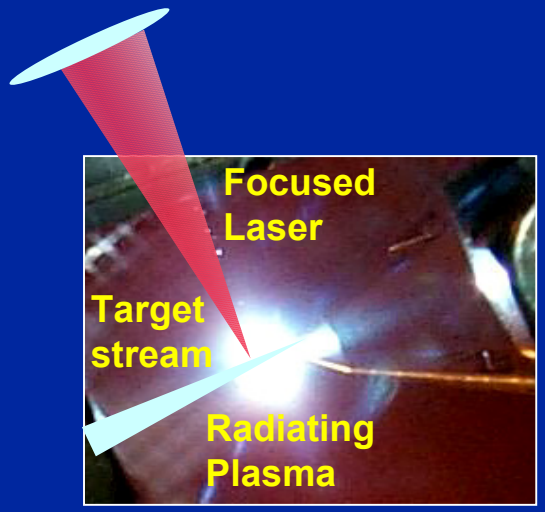
Status - Two types of sources in development

Laser-Produced Plasma sources

- Optical energy initiates and heats plasma
- No direct current flux on active source components
- Small (~0.25 mm dia.) radiation volume
- Scalable output with laser power
- Good plasma-nozzle separation supports scalability
- Electrical-to-optical conversion efficiency is low
- High perceived complexity/cost

Electric Discharge sources

- HV discharge currents initiate and heat plasma
- Better overall efficiency (~0.5%) than LPP
- Low perceived complexity/cost
- May require multiplexed sources
- High current flux on electrodes and other components leads to debris and lifetime issues
- Large (~0.35 x 2 mm) radiation volume



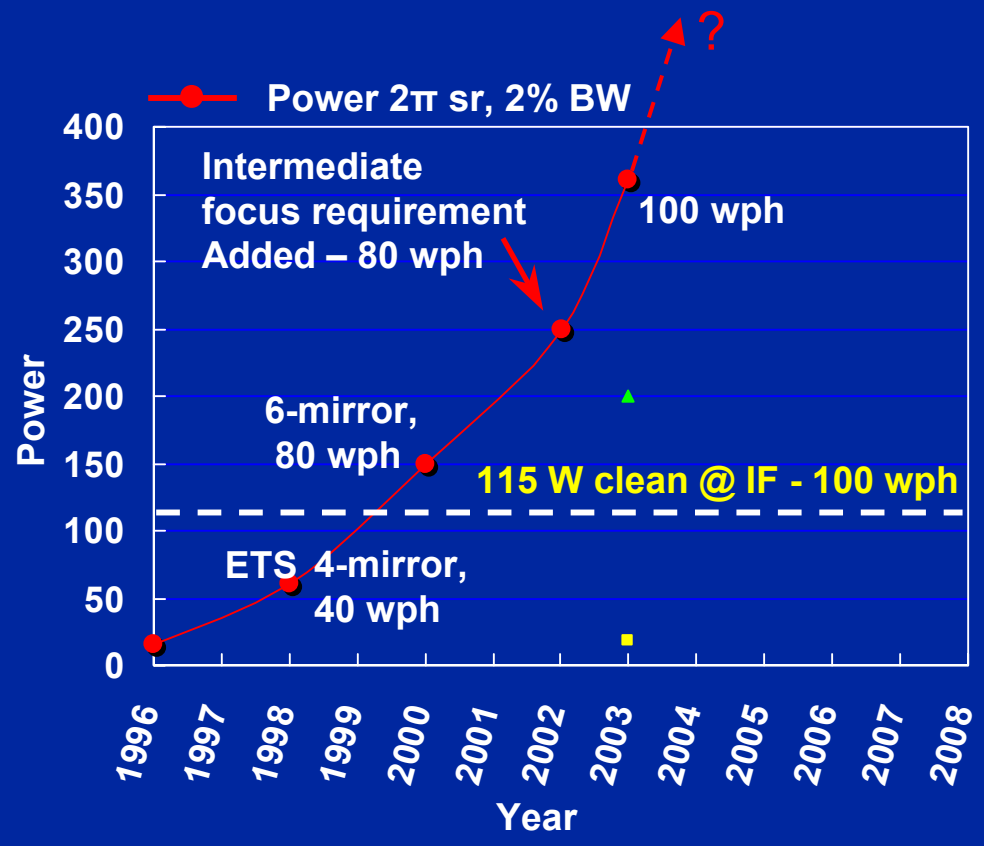
Laser Produced Plasma

Capillary Discharge

Source power requirements

Issues

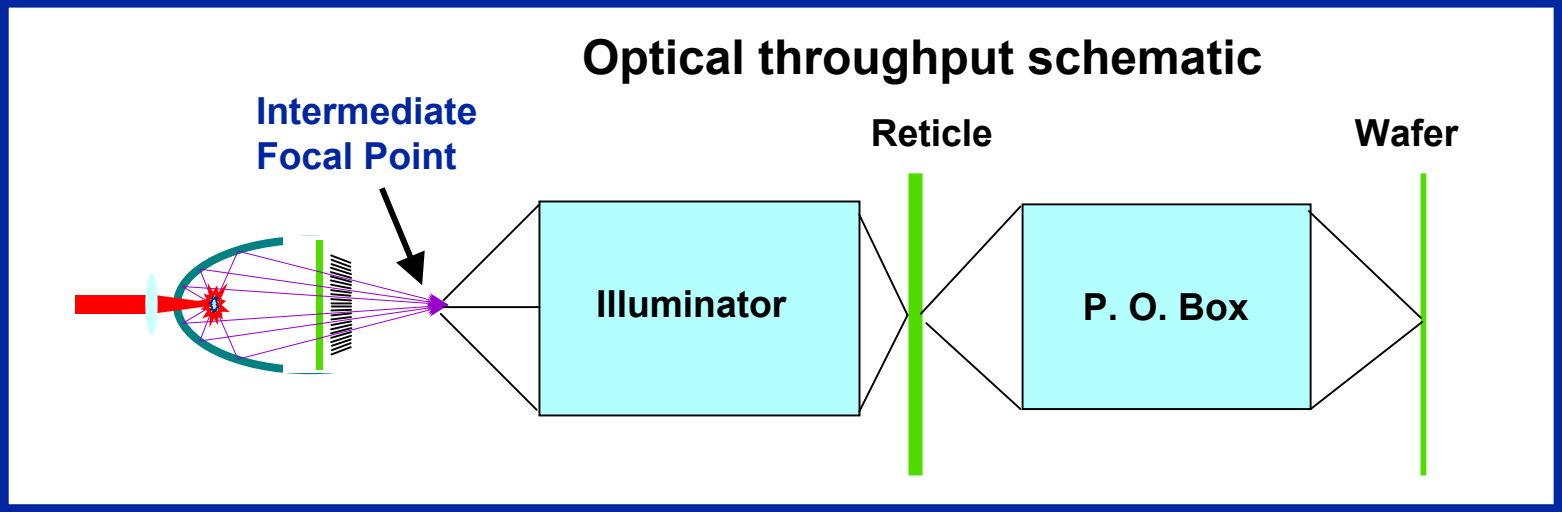
- Required source power increased dramatically with time
- Debris/erosion limits optics lifetime
- Thermal control difficult
- Projected high Cost of Ownership
- Source solution treated independently from total system



Conclusions

- Standardize clean power requirements to "Intermediate Focus" – 115 W
- Specifications set for spectrally pure, debris free power
- Standardize measurements using Flying Circus diagnostics

Challenge - Balance system/source requirements



Improvement opportunities

Source
- Conversion efficiency
- Collect ≥ 2π sr
- Efficient spectral filter
- Improve reflectivity
- Minimize loss for debris mitigation

Illuminator
- Minimize reflections
- Improve reflectivity
- Match multilayers
- Minimize loss for contamination protection

Reticle
- Improve reflectivity
- No attenuation for contamination protection

Projection Optics
- Improve reflectivity
- Reduce spatial roughness ≤ 0.10 nm
- Match multilayers
- Reduce polarization loss
- Zero attenuation resist outgassing window

Wafer
- Improve resist sensitivity
- Minimize non-scanning overhead

Source/system tradeoffs

System Characteristics (100 wph)	Present
Source to IF Efficiency	16%
Collection (% of 2 π sr)	80 %
Reflectivity of Coll. mirror	50 %
Spectral Filter transmission	50 %
Transmission of debris system	80 %
Illuminator Efficiency	8.4%
Reflectivity (4 ML, 3 GI @ 85%)	65 % (0.11)
Contingency loss	23 %
Reticle Reflectivity	65 %
Projection Optics Efficiency	7.9 %
Reflectivity (6 ML)	68 % (0.1)
Contingency loss	20 %
System aging degradation	37%
Wafer (power - 90 die per wafer)	300 mW
Resist sensitivity	5 mJ/cm^2
Total Source Power @ IF	115 W
LPP (No filter)	360 W
Discharge	720 W

Source/system tradeoffs and improvements

System Characteristics (100 wph)	Present	Improved
Source to IF Efficiency	16%	20.6 %
Collection (% of 2 π sr)	80 %	85 %
Reflectivity of Coll. mirror	50 %	55%
Spectral Filter transmission	50 %	55%
Transmission of debris system	80 %	80 %
Illuminator Efficiency	8.4%	10 %
Reflectivity (4 ML, 3 GI @ 85%)	65 % (0.11)	67 % (0.12)
Contingency loss	23 %	20 %
Reticle Reflectivity	65 %	67 %
Projection Optics Efficiency	7.9 %	9.2 %
Reflectivity (6 ML)	68 % (0.1)	69 % (0.11)
Contingency loss	20 %	15%
System aging degradation	37%	30 %
Wafer (power - 90 die per wafer)	300 mW	220 mW
Resist sensitivity	5 mJ/cm^2	3.5 mJ/cm^2
Total Source Power @ IF	115 W	53 W
LPP (No filter)	360 W	140 W
Discharge	720 W	255 W

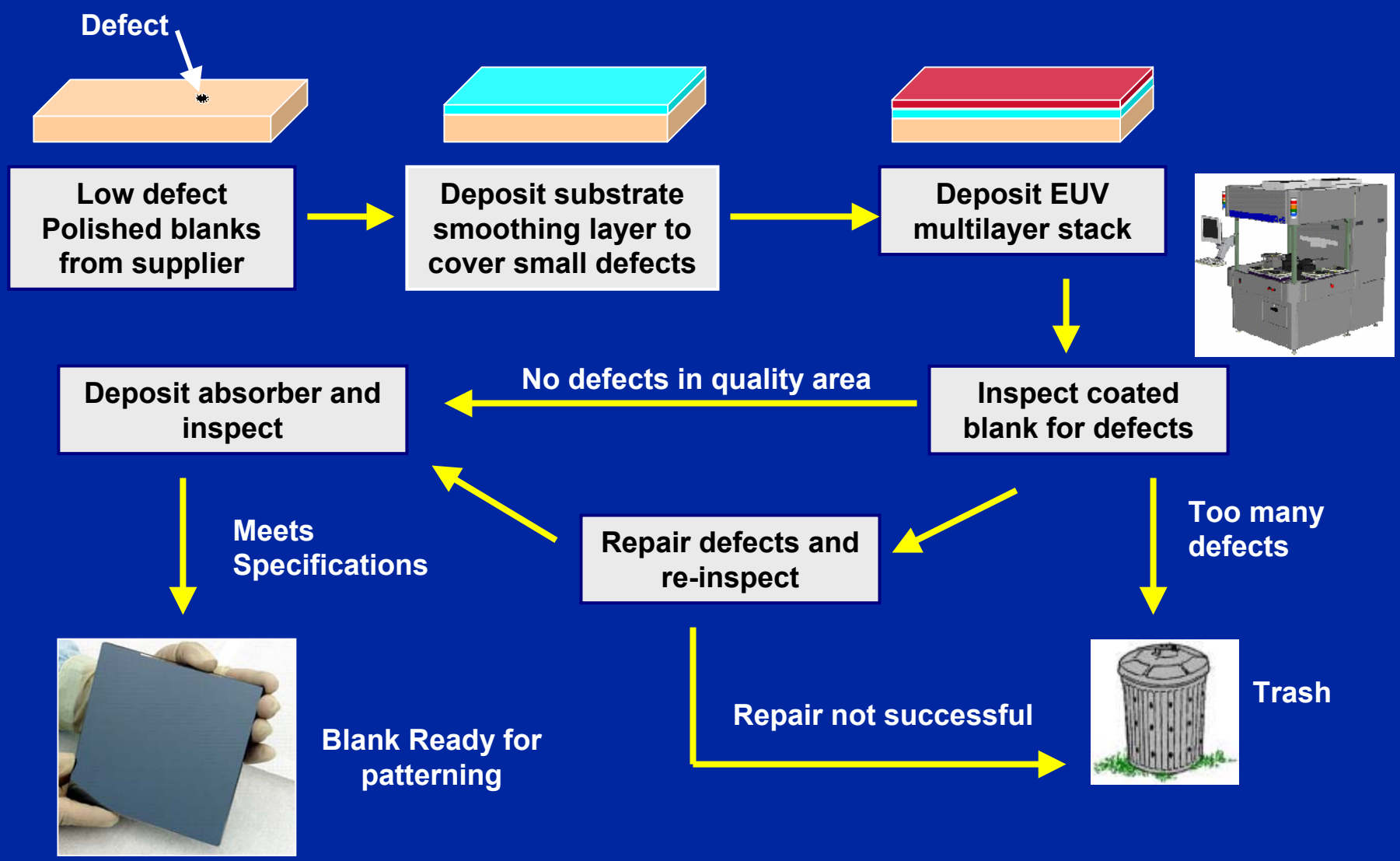
Source/system tradeoffs and improvements

System Characteristics (100 wph)	Present	Improved
Source to IF Efficiency	16%	18.7 %
Collection (% of 2 π sr)	80 %	85 %
Reflectivity of Coll. mirror	50 %	55%
Spectral Filter transmission	50 %	55%
Transmission of debris system	80 %	80 %
Illuminator Efficiency	8.4%	10 %
Reflectivity (4 ML, 3 GI @ 85%)	65 % (0.11)	67 % (0.12)
Contingency loss	23 %	20 %
Reticle Reflectivity	65 %	67 %
Projection Optics Efficiency	8 %	9.2 %
Reflectivity (6 ML)	68 % (0.1)	69 % (0.11)
Contingency loss	20 %	15%
System aging degradation	37%	30 %
Wafer (power - 90 die per wafer)	300 mW	137 mW
Resist sensitivity	5 mJ/cm^2	3.5 mJ/cm^2
Total Source Power @ IF	115 W	33 W
LPP (No filter)	360 W	87 W
Discharge	720 W	160 W

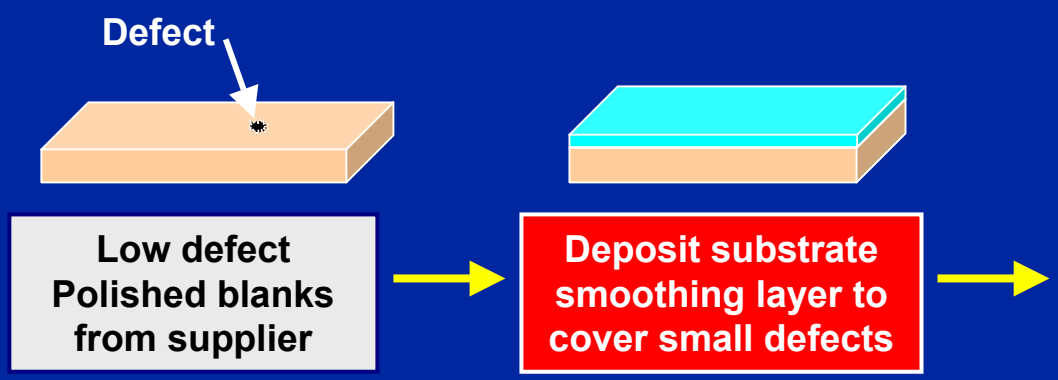
Reduce stage Overhead by 20%

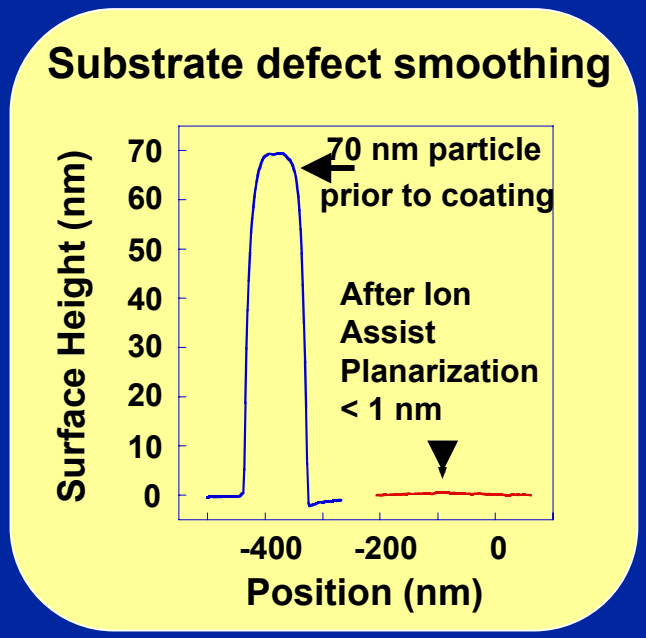
Masks

Mask blank manufacturing process review



Mask blanks – Smooth, flat, defect free substrates





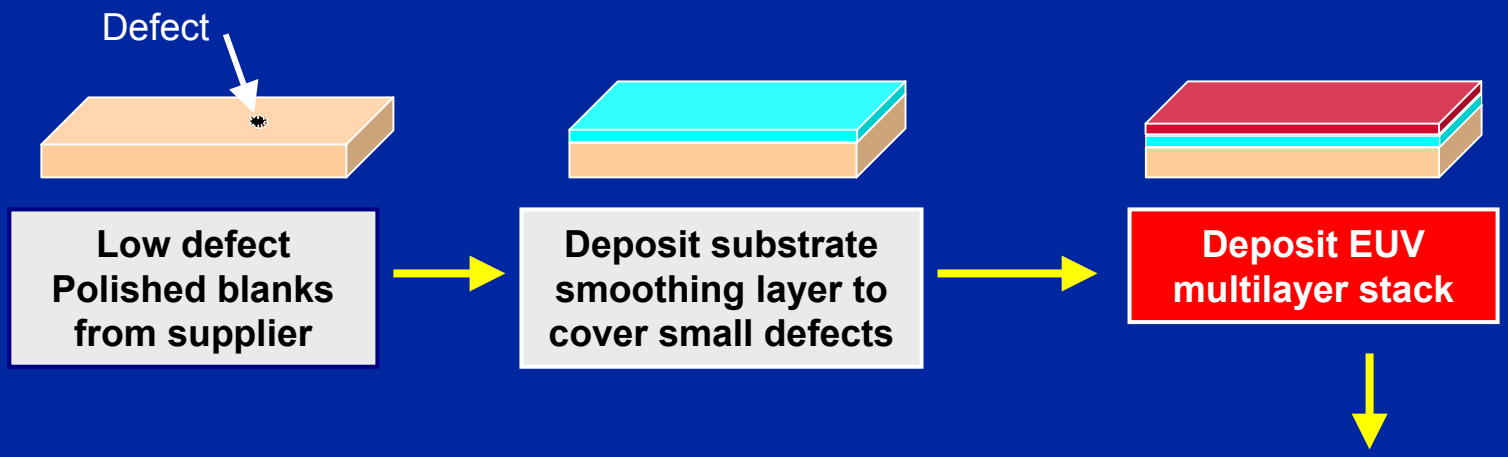
Status:

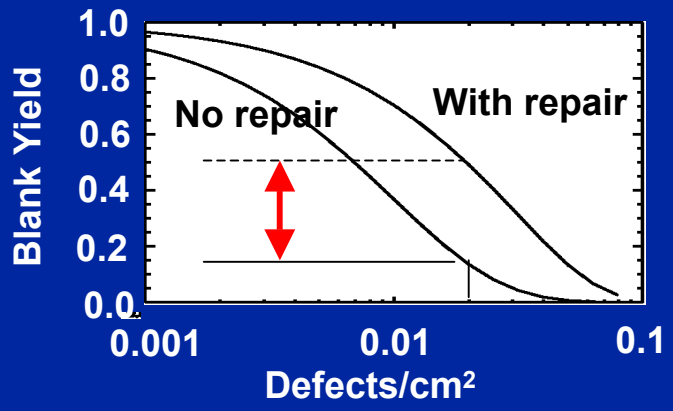
- LTEM used for thermal control
- Square mask format selected
- Multilayer smoothing covers < 70 nm defects
- SEMI Standard P37 approved

Issues and Challenges

Parameter	Best	Requirement in 07
Flatness	150 nm	50 nm
Smooth - HSFR	0.15 nm rms	0.15 nm rms
Defects	Smooth < 70 nm	Smooth/Remove

Mask blank multilayer stack – Defect free





Conclusions

- Improve multilayer deposition process
- Accept small number of repairable defects
- SEMI Standard P38 proposed

Challenge

Parameter	Present - Best	Requirement in 07
Defects	0.05/ cm^2 > 70 nm	0.005 cm^2 > 25 nm

Inspect and repair stack defects

Conclusions

- *Use demonstrated repair methods*
- *Develop combined inspection/repair tools*
- *Cr and TaN absorber processes developed*

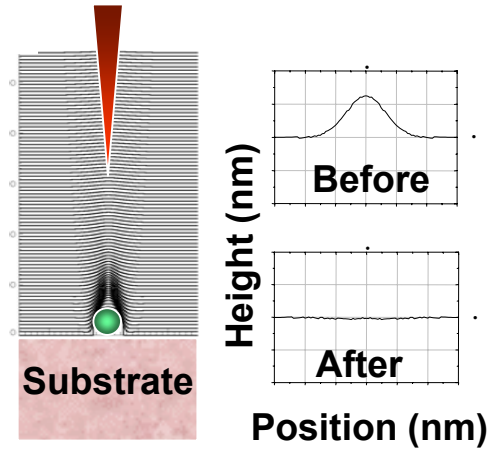
Deposit EUV multilayer stack

Inspect coated blank for defects

No defects in quality area

Repair defects and re-inspect

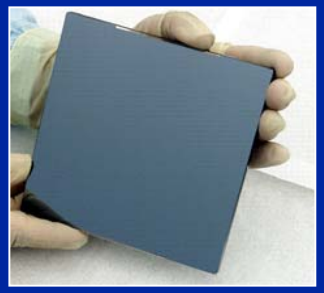
Phase defect repair



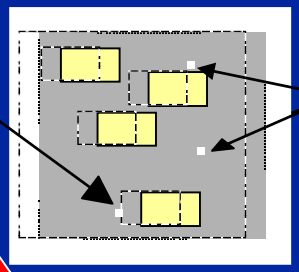
Challenge

- **New AIM inspection/repair tools required**

Mask patterning review

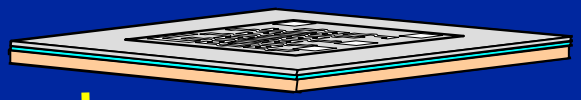


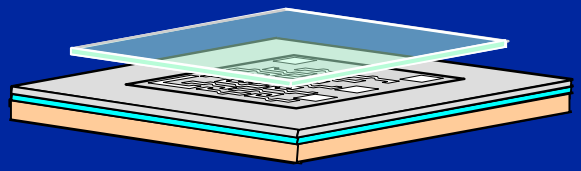
Shift Mask Pattern to Cover one or more defects



Mask Blank defects

Mask blanks from supplier → Deposit resist and prebake → E-beam write, Etch & Clean → Inspect patterned masks → Repair masks using FIB or ebeam → Final inspect & clean → Mount in frame with removable protective cover



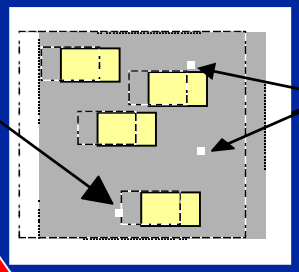


Mask patterning needs

Conclusions

- *Use standard ebeam patterning processes*
- *Shift pattern to cover selected defects*
- *Apply extended DUV inspection*
- *Use focused ion or ebeam repair*
- *Use AIM tool to verify repair*

Shift Mask Pattern to Cover one or more defects



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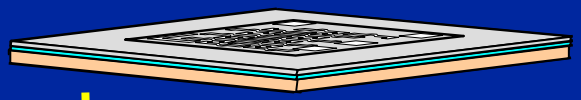
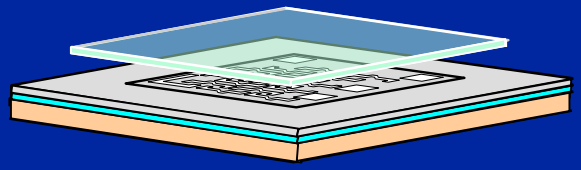


Mount in frame with removable protective cover



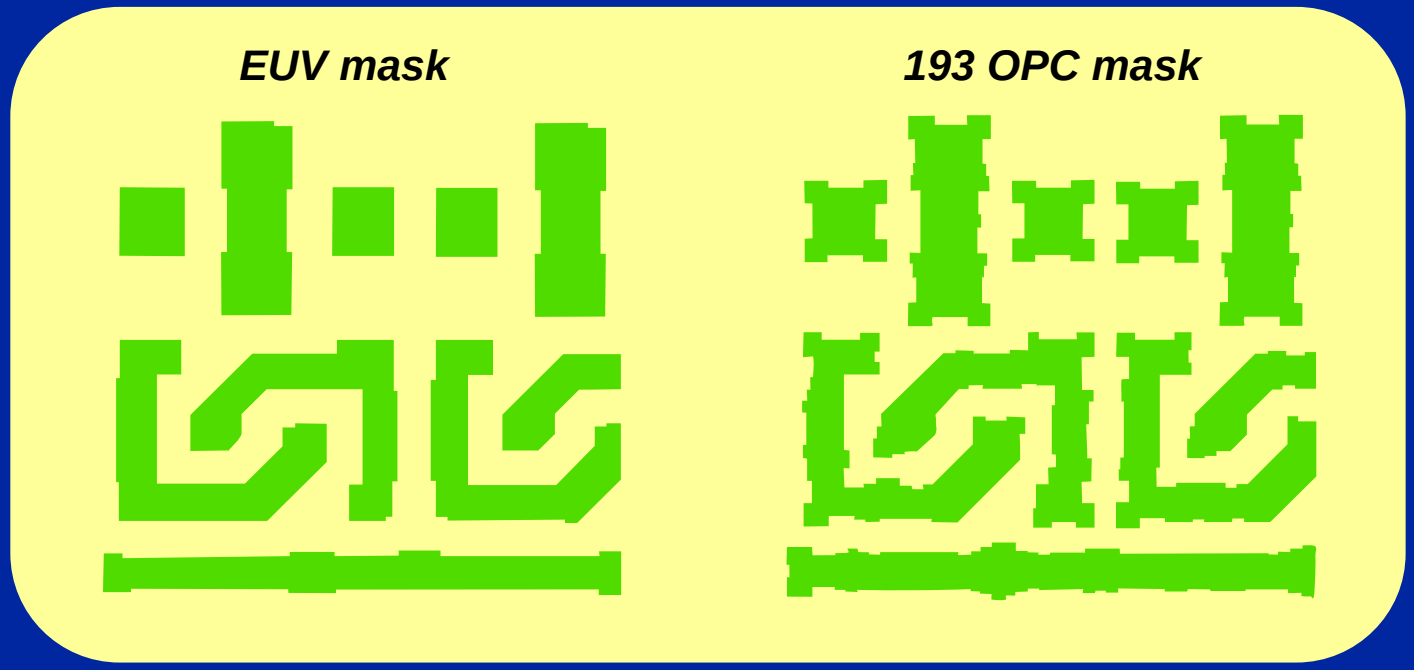
Challenges

- New AIM tool required for blank inspection and repair verification
- Protection solution required – SEMI Standard 3553

EUV and 193 mask comparison for 45 nm

Assumptions

- Both technologies will use essentially the same ebeam pattern tools
- 193 will require complex OPC, strong PSM, and other RET
- Similar DUV mask inspection and FIB repair equipment can be used
- EUV mask patterning much simpler than 193 OPC masks
- Inspection costs are proportional to mask complexity

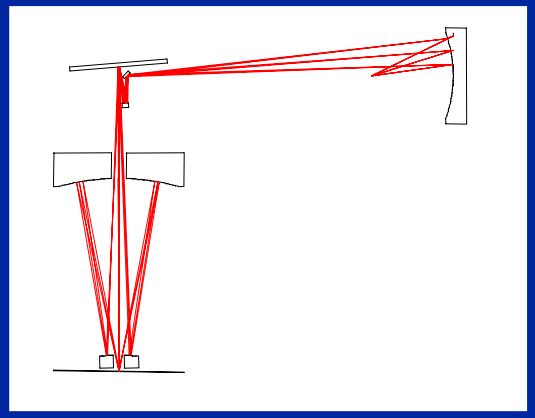


EUV Mask Costs for 45 nm – Equivalent maturity

	EUV vs. 193 Assumptions	*EUV Cost relative to 193*
Mask Blanks From supplier	Flat, defect free, similar complexity and specifications	2
Inspect, locate defects for pattern alignment	DUV inspection, similar resolution (PSM for 193)	1
Align and Pattern using ebeam	Standard process, Less complex patterning, write time - if complementary PSM are needed for 193 – fraction is smaller	0.5 – 0.8
Inspect and repair using FIB or ebeam	DUV inspection, simpler patterns, (defects above ML)	0.5 – 0.8
Mount in container	Similar to requirements for 193 pellicle mounting	1
	Total	0.5 – 1.3

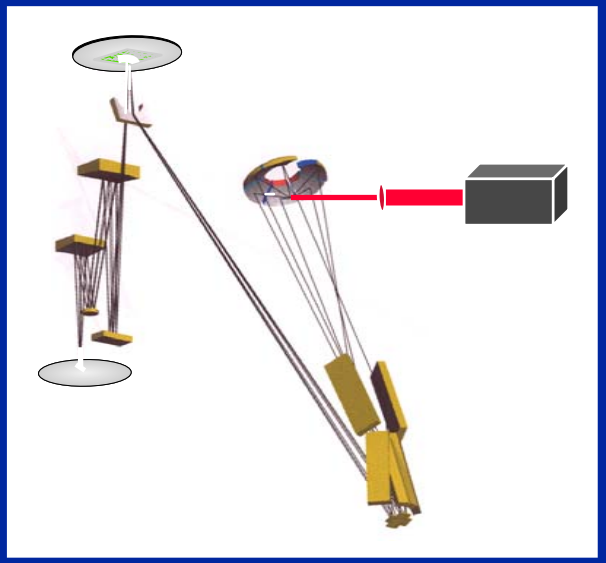
Exposure Tools

Exposure system status



Microsteppers

- Two mirror 5 to 10x
- Static printing
- 0.1 to 0.3 NA
- Low power source
- Used for resist evaluation



Full field system

- Scanning stages
- Standard mask
- High power source
- Used to evaluate resist, flare, resolution

Static Microexposure Systems

System (type)	Location	NA/ Magnification	Field size Min. Res.	Lens quality	Reticle Size
10x Microsteppers	Livermore, CA	0.1/10 x	0.5 x 0.5 mm	$\lambda/20$	1 in square wafer section
BESSY MET	Berlin, Germany	0.3/5x	200x600 microns^2	$\lambda/10$	8 inch wafer
BEL	Grenoble, France	0.3/10x	100x200 microns	$>\lambda/10$	8 inch wafer 6 inch reticle
ASET	Atsugi, Japan	0.3/5x	300 x 500	$\lambda/7$	8 inch wafer
MET	Berkeley, CA	0.3/5x	200 x 600	$\lambda/20$	6 inch reticle
Exitech MET	Intel, I-SEMATECH	0.3/5x	200 x 600	$<\lambda/20$	6 inch reticle

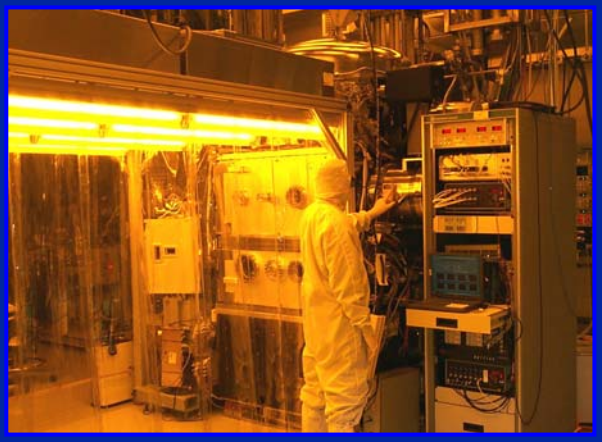
Other capabilities include a 10x interferometric exposure capability at Berkeley and at the U. of Wisconsin

Good selection of tools for resist and mask development

Full field exposure system

Engineering Test Stand Capabilities

- Synchronized scanning (24 x 32.5mm field)
- Excellent scanned imaging @ 80 nm
- Adjustable source power
- Flexible control system for operation and data logging
- Environmental control
- Fully instrumented with > 100 sensors



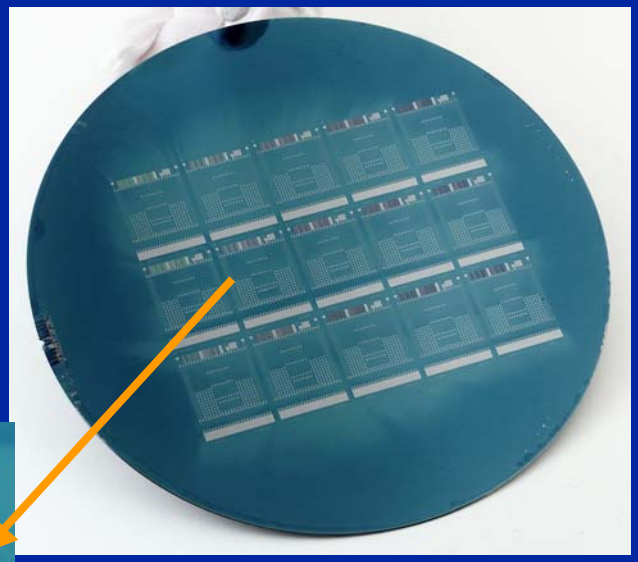
Front View

Right View

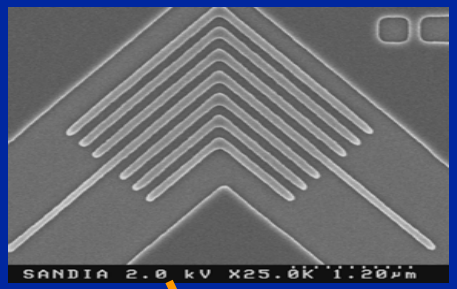
Control Consol

Full field Images produced by 0.1 NA ETS

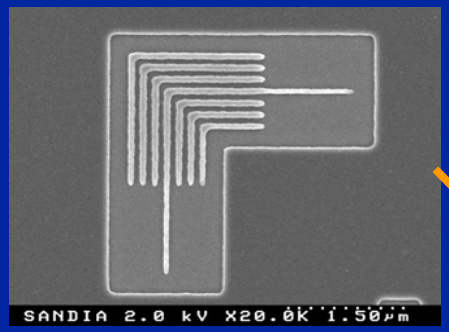
200 mm Wafer

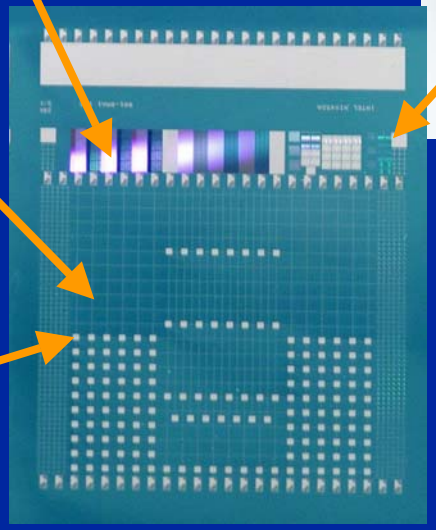


100 nm Elbows 1:1

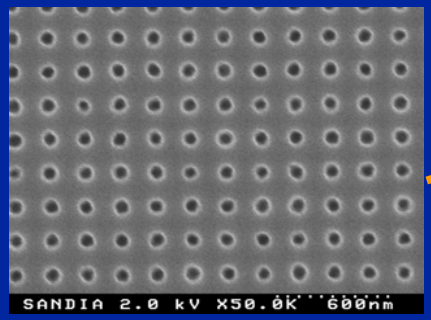


80 nm Elbows 1:1





100 nm contacts 1:1

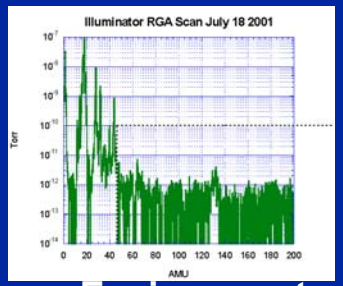


24 x 32.5 mm^2 field

ETS has provided extensive system experience

- ***System integration successfully demonstrated all unique aspects of EUV lithography***
  - ***Components***
  - ***Metrology***
  - ***Masks***
  - ***Environmental control***
  - ***Imaging***
- ***Practical learning obtained with over two years operation of tool***
  - **Continuous system upgrades**
  - **Optics replacement**
  - **Reticle changes & chucking**
  - **Many vacuum pump-down cycles**
  - **Software failures/improvements**
  - **Unplanned/planned maintenance**
  - **Operational mistakes**
  - **Recovery from accidental contamination**
  - **Component failures**
  - **Thermal excursions**

System Upgrades and maintenance

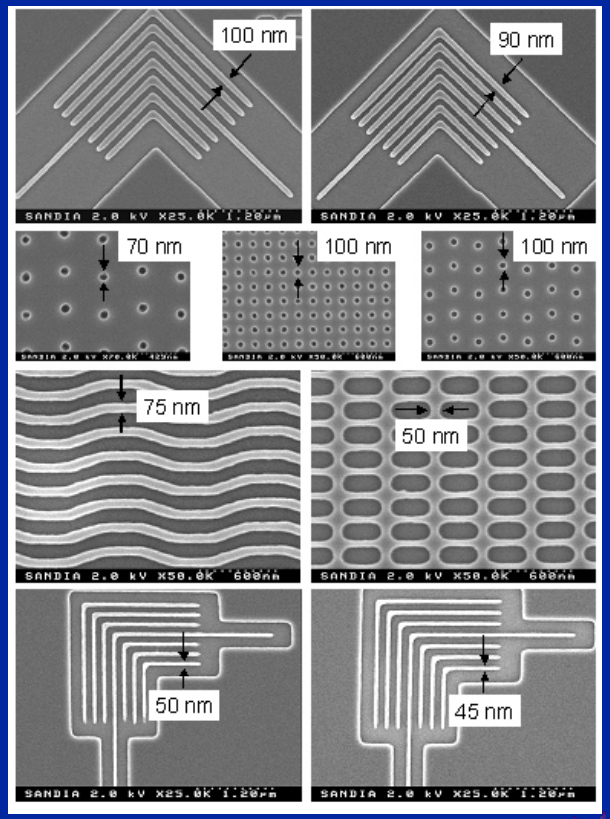


Environment Control

Optics contamination/erosion

ETS experience has minimized system risks

- *System and lithography modeling/simulation validated*
  - Excellent theoretical/experimental agreement
  - Expanded process understanding
  - Increased modeling confidence for system design
- *Imaging studies demonstrate optical lithography similarities*
  - Accurate flare characterization
  - Process window measurements
  - Mask parameter evaluation
  - Resist characterization (sensitivity, LER, resolution)



Two years of ETS operations have demonstrated that EUVL has no remaining technical surprises

System implementation

Conclusions

- Thermal, dynamic, and process modeling validated for tool design
- System integration validated subsystem interface choices, sensor placement, instrumentation, and environmental control
- Flare characterization has resulted in mitigation methods
- ETS learning has uncovered all EUVL surprises (no lurking issues)

System challenges

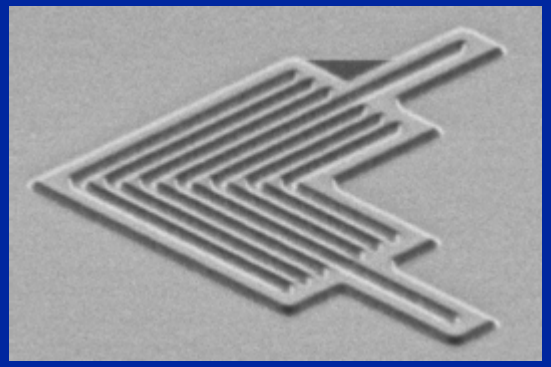
- Migrate ETS learning to commercial suppliers
- Implement system/source trade-offs to obtain a realizable source power
- Implement reticle protection (thermophoresis, electrostatic, other)
- Use environmental engineering to mitigate contamination/erosion
- Solidify beta and production tool development schedules

Resists

Resist Development

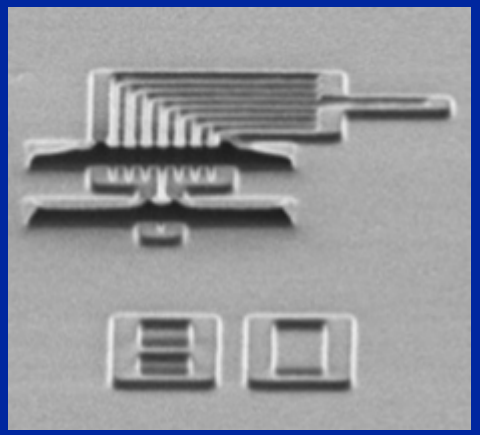
Status

- Both single layer and bilayer resists demonstrated
- DUV ultra thin resists viable > 85 nm
- Resist sensitivities demonstrated
  down to ~ 2.0 mJ/cm^2 , LER 5 – 7 nm @ 100 nm
- Pattern transfer into hard masks demonstrated



Issues

- Simultaneously achieve sensitivity,
  resolution, and low LER
- Availability of positive and negative resists



Conclusion

- Extend promising DUV resists

Challenges

Parameter	Present (best)	Required 07 – 32 nm
LER	~ 3 nm @ 10 mJ/cm^2	2 – 3 nm
Sensitivity	5 mJ/cm^2	2 – 3 mJ/cm^2
Resolution	~ 40 nm @ 5 mJ/cm^2	< 20 nm

Challenges/Critical Issues

Challenges/Critical Issues

Priority	Issue	Requirement	Challenges	Difficulty
1.	Source Power *	≤ 115 W @ IF	System tradeoffs	High
	Source and condenser Reliability *	~ 1 year lifetime	Debris, erosion & thermal control	Moderate to High
2.	CoO		System cost vs. throughput	
	Low cost mask blanks	50 nm flatness, low defects	Manufacturing, volume scale up	Moderate
	Contamination *	Mitigation, cleaning	Environmental control	Moderate
	High NA Optics	Figure, Finish, Lifetime	Continuous improvement	Low to Moderate
	Commercial masks	Costs < 193 nm	Implementation	Low
3.	Reticle Protection *	Protection in lieu of pellicle	Container design, in-situ cleaning	Moderate
4.	Resists *	3 mJ/cm^2, 2-3 nm LER, 20 nm Res.	New formulation	Moderate to High
5.	Thermal Management *	Support 100 wph	System design	Low

* *Requires system tradeoffs*

Challenges being met with world wide focus

Europe

> 50 Companies

Consortia:

- IMEC
- LETI
- MEDEA+
- PREUVE

Japan

36 Companies

Consortia:

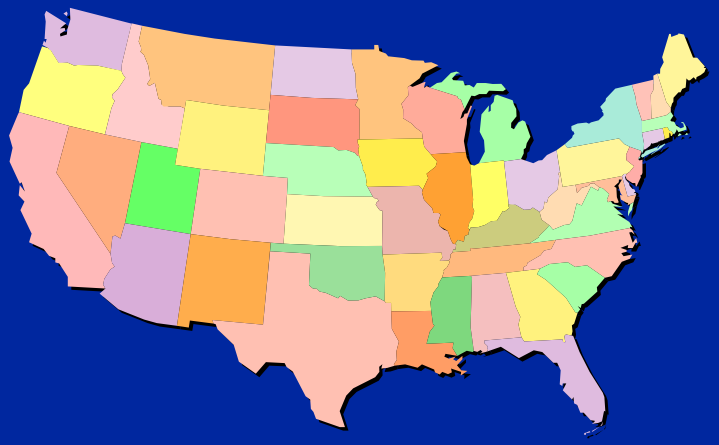
- ASET
- EUVA
- AIST

US

> 40 Companies

Consortia:

- EUV LLC
- I-SEMATECH**
- SRC
- VNL RDC



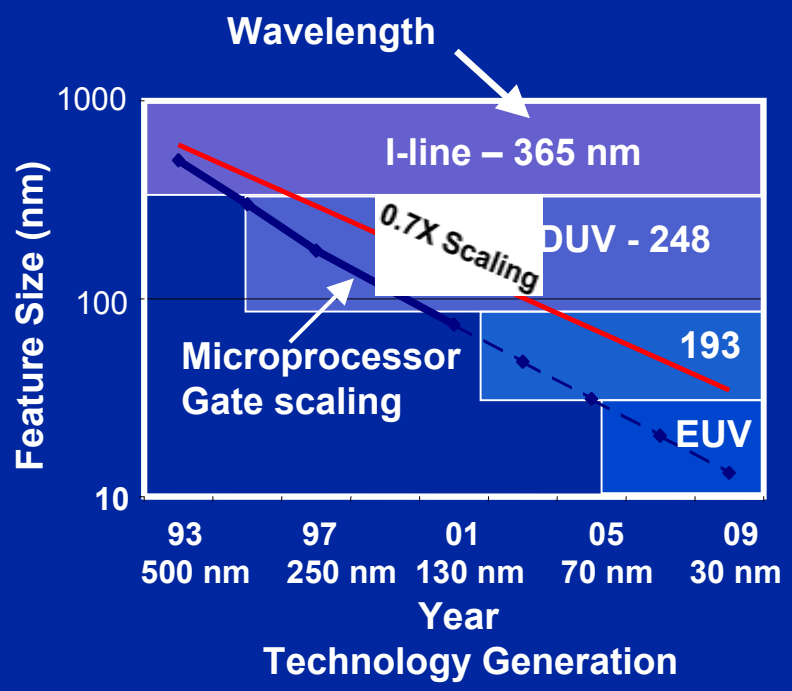
Publications & presentations

- > 40 Conferences and publications
- ~ 800 papers

*** I-SEMATECH preparing company directory*

Conclusions

- > Six years R & D and two years experience with full field ETS demonstrated EUVL technology feasibility and minimized risks
- Source/system tradeoffs can provide achievable, realistic source power goals
- Mask costs are affordable – costs and complexity potentially less than 193 nm masks
- Suppliers are engaged to commercialize the technology



EUVL can provide the only viable solution for 32 nm – Need user commitments!