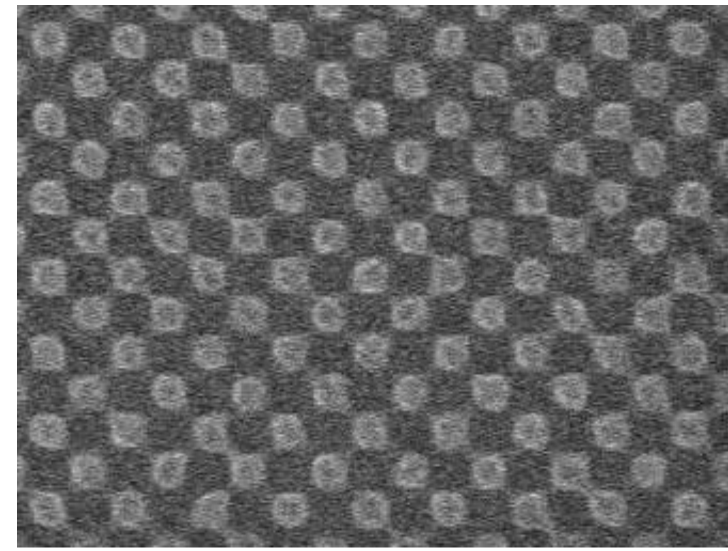
United States
EUV Regional Update

EUVL Workshop
June 2014
Maui

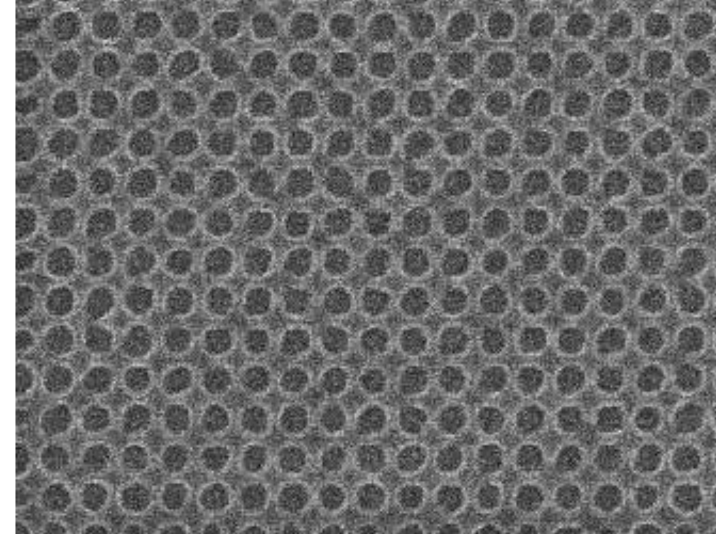
Greg Denbeaux

New contact pseudo-PSM developed

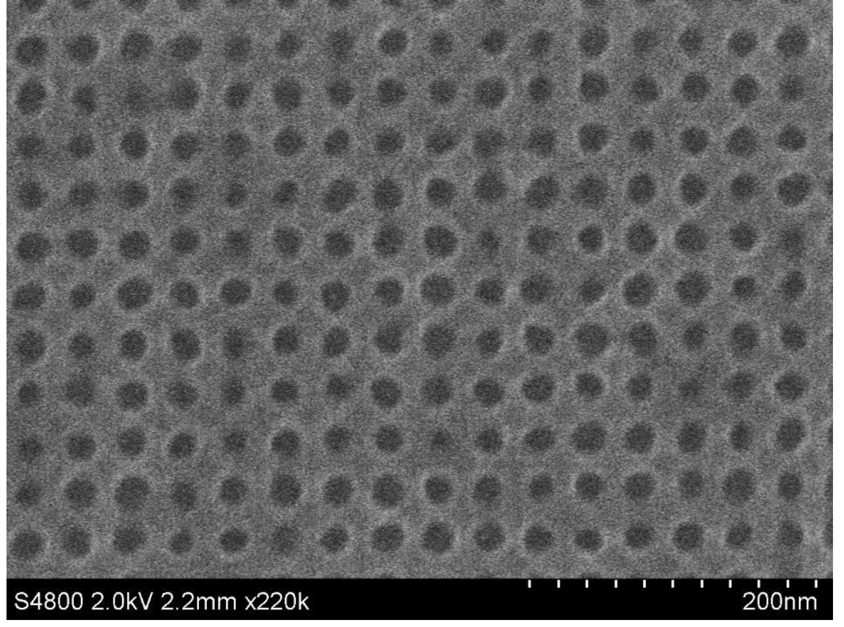
Conventional print of pseudo-PSM mask



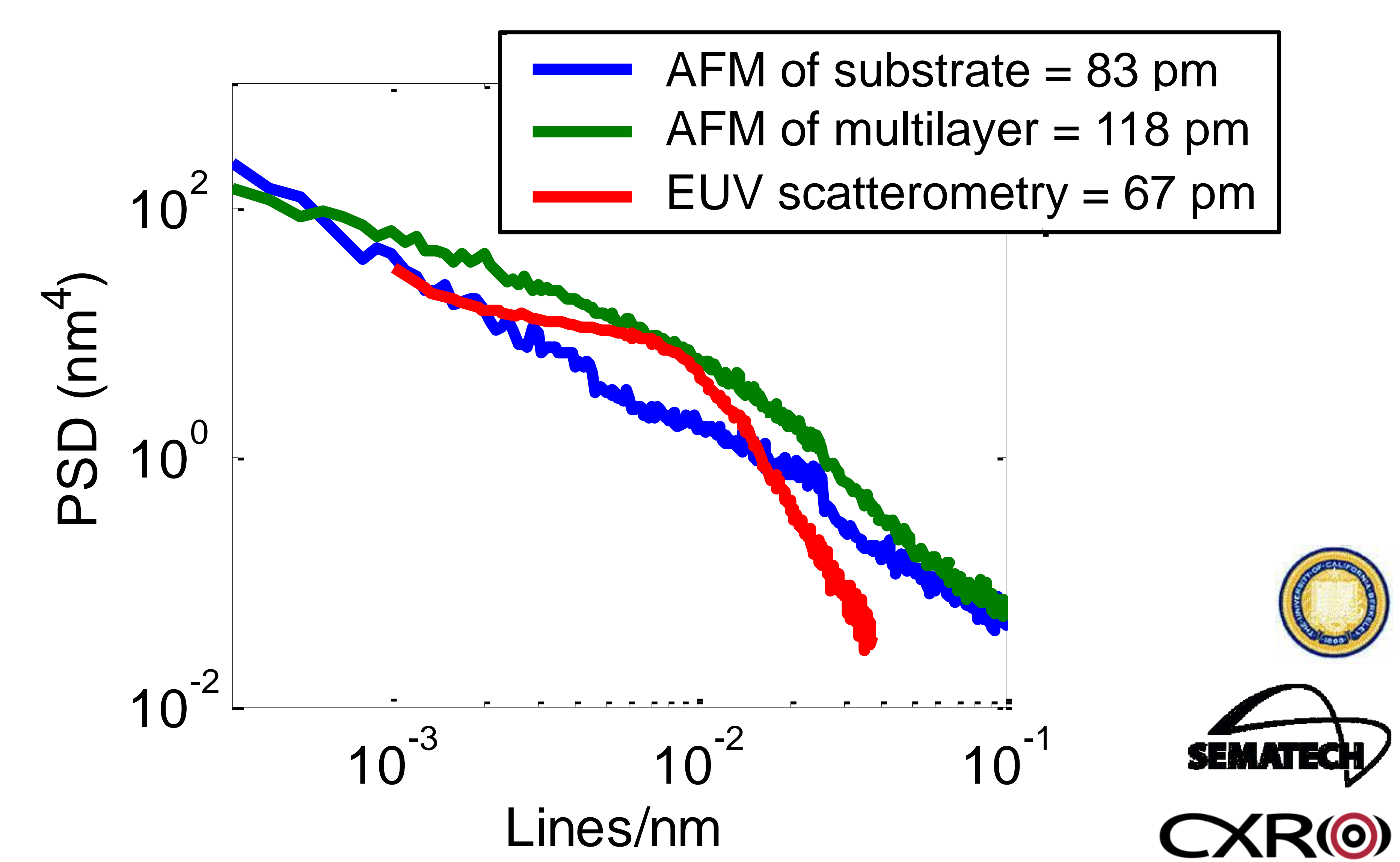
Pseudo-PSM mode



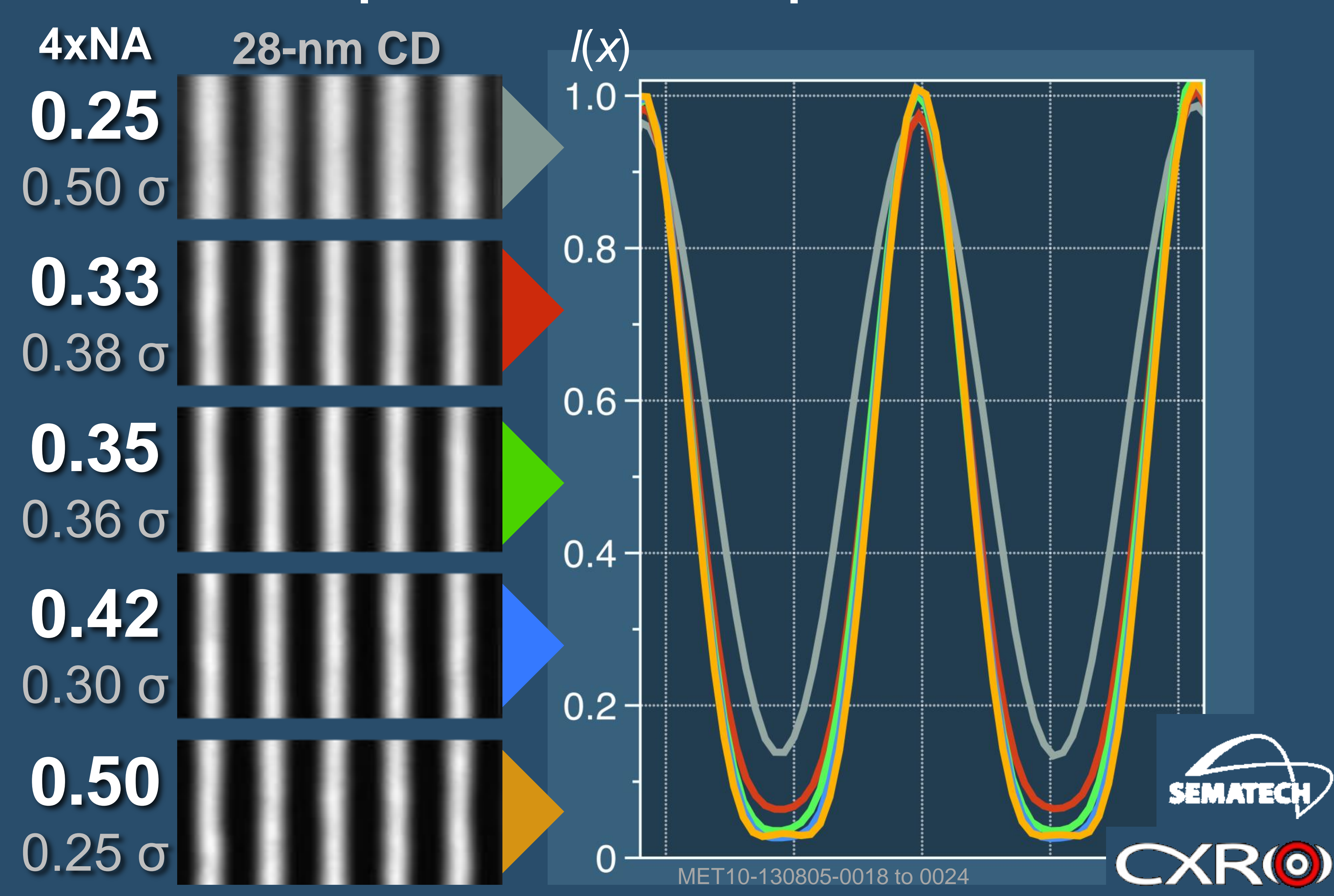
18-nm Pseudo-PSM contacts
(MET Tool limit)



EUV scatterometry: "true" measurement of 3D EUV mask roughness



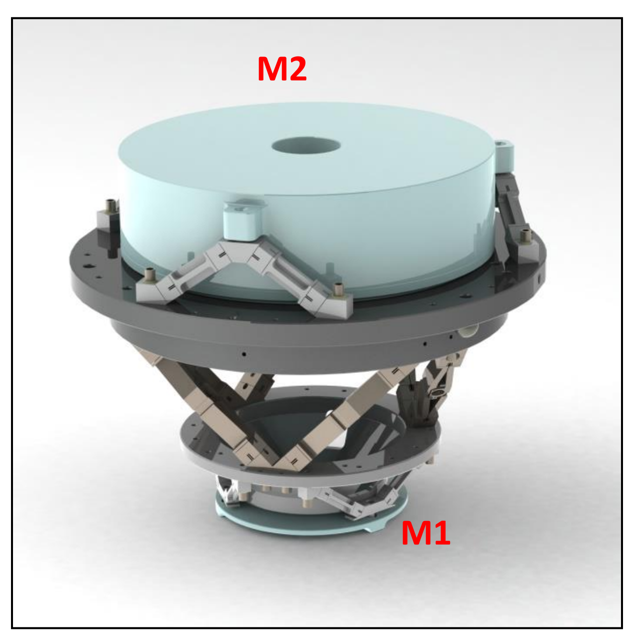
SHARP operational up to 0.625 NA



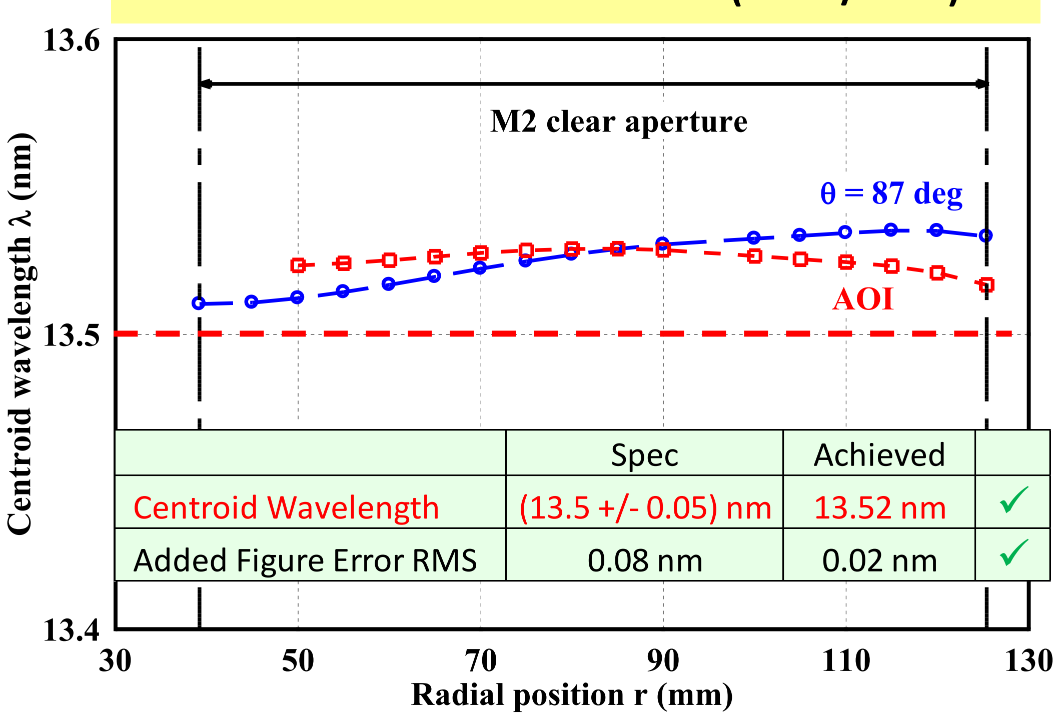
Pathfinder aspheres have been fabricated and multilayer-coated for the first EUVL Micro-Exposure Tool with NA = 0.5

Regina Soufli, regina.soufli@llnl.gov

Opto-mechanical design of Projection Optics Box



M2 pathfinder asphere, coated at LLNL and measured at ALS beamline 6.3.2. (CXRO/LBNL)



	Spec	Achieved	
Centroid Wavelength	(13.5 +/- 0.05) nm	13.52 nm	✓
Added Figure Error RMS	0.08 nm	0.02 nm	✓

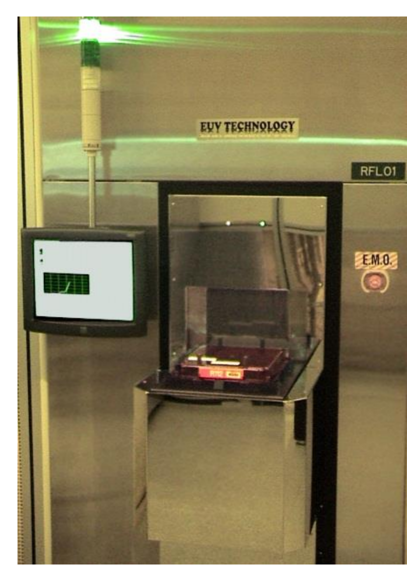
- H. Glatzel, *et al*, Proc. SPIE 9048, 90481K (2014).
- K. Kummings, *et al*, Proc. SPIE 9048, 90481M (2014).

euvtech

MARTINEZ, CA

EUV REFLECTOMETER

- Recipient of 2005 R&D 100 award
- Installed for over 14 years worldwide
- Fully automated user friendly operation
- Continuously improving performance - Improved software, laser, and speed.



MEASUREMENT SPECIFICATIONS HAVE EVOLVED OVER TIME

Item	1st Gen SEMATECH (2004)	2nd Gen EIDEC (2009)	3rd Gen (2013/14)	4th Gen (2014/15)
EUV Peak Reflectivity Precision (Rp ~60% abs)	3σ <= 1.5%	3σ <= 0.7%	3σ <= 0.35%	3σ <= 0.30%
EUV Peak Reflectivity Accuracy (Rp ~60% abs)	<= 1.5%	<= 1.0%	<= 0.5%	<= 0.5%
EUV Peak Reflectivity Precision (Rp ~0.3% abs)	N/A	3σ <= 0.05%	3σ <= 0.02%	3σ <= 0.01%
EUV Peak Reflectivity Accuracy (Rp ~0.3% abs)	N/A	<= 0.1%	<= 0.08%	<= 0.07%
EUV Median Wavelength Precision	3σ <= 0.015nm	3σ <= 0.01nm	3σ <= 0.003nm	3σ <= 0.003nm
Average EUV Median Wavelength Accuracy	<= 0.015nm	<= 0.01nm	<= 0.008nm	<= 0.006nm
Spot Size (mm x mm)	5 x 5	3 x 3	2 x 2	1.8 x 1.8

4TH GENERATION EUV REFLECTOMETER

EUV Tech now delivers the 4th generation EUV Reflectometers

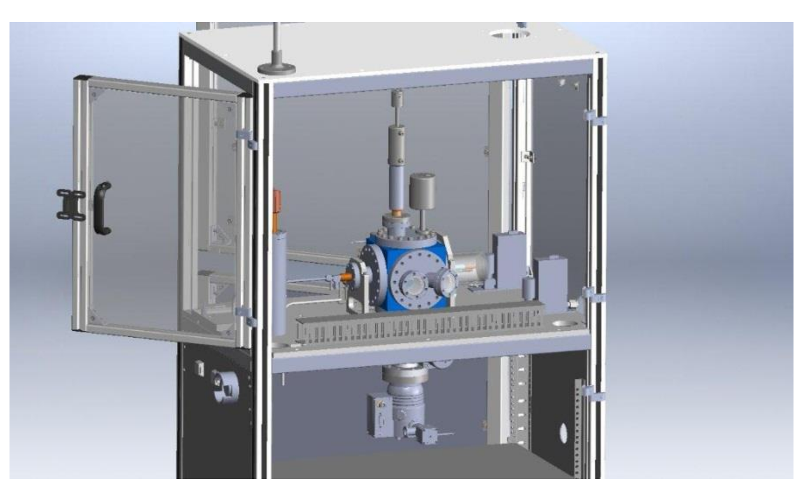
- Additional features of the 4th generation tools:
  - Improved measurement capabilities
  - Updated RSP200 opener
    - Optional Integrated Dual Pod/RSP2000 reticle handling system
  - Continued reduction in spot size
  - Field upgradable features
    - Ability to change the angle of incidence from the current 6 degree measurement angle to any fixed angle between 5 and 10 degrees (Not tunable)
    - To the HVM design
    - To 6.x nm region

EUV RESIST OUTGASSING TOOL

- Measures the contamination of optics from resist outgassing by using EUV (Extreme Ultraviolet) photon exposure, or alternatively by using electron beam (e-gun) exposure
- EUV Tech has successfully delivered 3 resist out-gassing tools.
- Two of them have been ASML certified
  - Third one in the certification process

EUV HYDROGEN RADICAL CLEANER

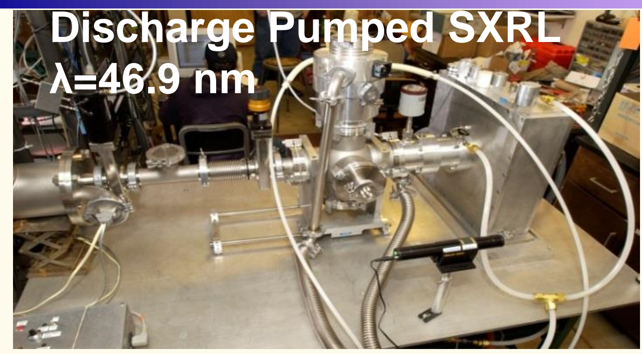
- Streamlined witness sample transfer process between resist outgassing tool and hydrogen cleaner
- Cleaning rate ~ 3 nm/hour
- Small footprint 36” x 24”
- Controlled and interlocked N2 and H2 flow

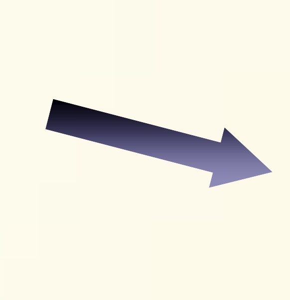


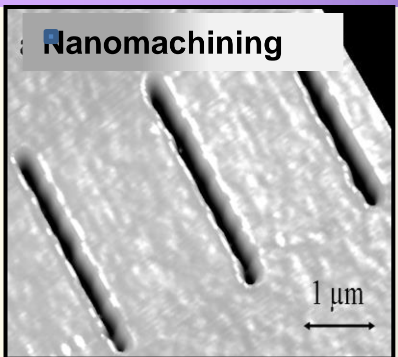
EUV TECH ROAD MAP

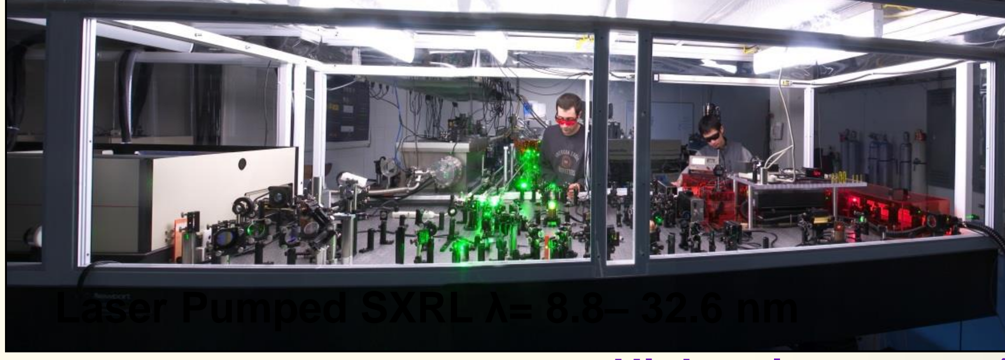
- EUV Resist Exposure Tool (Q1 2015)
  - generate contrast curves: ~ 1mm spot size
  - For transmission FTIR measurements: ~5mm x 5mm
  - For other analytic techniques: ~10mm x 10mm
- Stand-alone EUV Scatterometer (Q3 2015)
  - for high accuracy characterization of mask roughness
- HVM Reflectometer (Q4 2015)
  - High precision.
  - Absolute (internal) reflectivity and wavelength calibration.
  - Capability to find pattern location to be measured using fiducials.

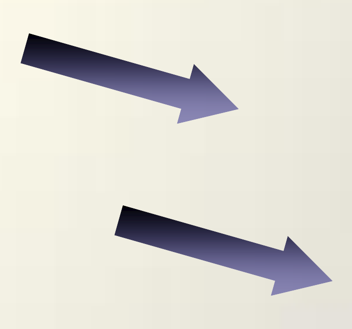
Compact extreme ultraviolet lasers enable nanoscale material applications on a table-top

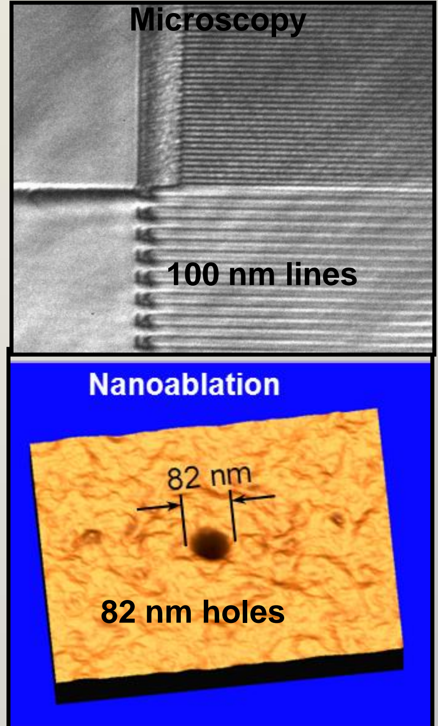


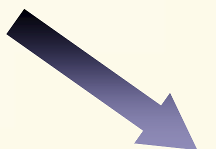




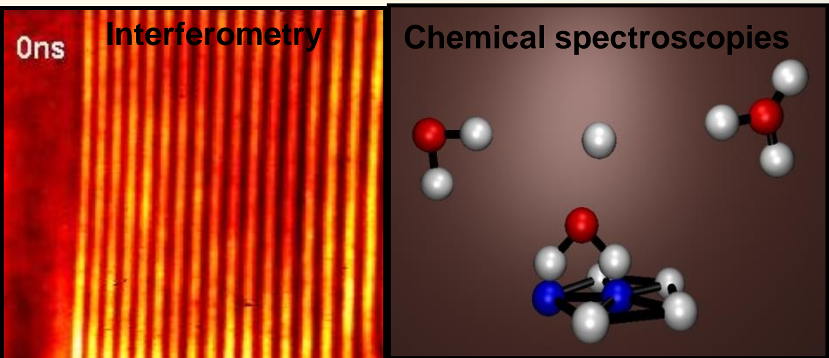


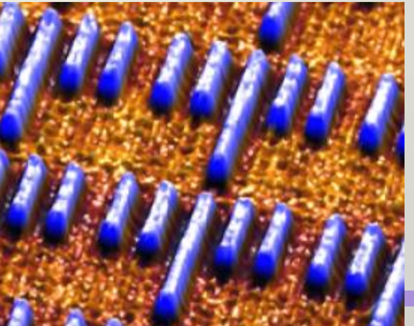






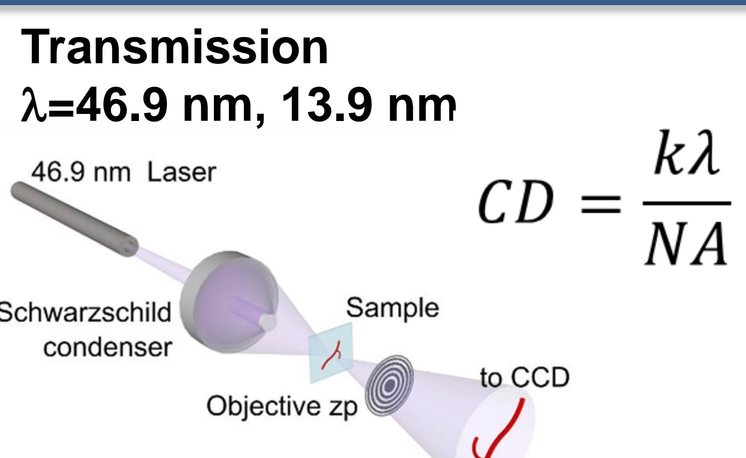
- High pulse energy (µJ-mJ)
- High monochromaticity ($\lambda/\Delta\lambda < 10^{-4}$)
- High peak spectral brightness





EUVL microscopes are critical photonic technologies for imaging nanostructures and surfaces

Transmission
λ=46.9 nm, 13.9 nm

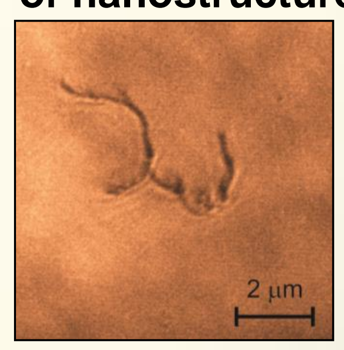


$$CD = \frac{k\lambda}{NA}$$

38 nm spatial resolution @ 13.9 nm

G. Vaschenko et al, Opt.Lett 2006

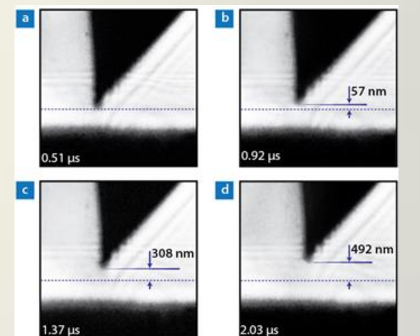
Single shot Imaging of nanostructures



50 nm Carbon Nanotubes
Spatial resolution: 50 nm

C. Brewer et al, Opt.Lett 2008

Time resolved Imaging of magnetic interactions

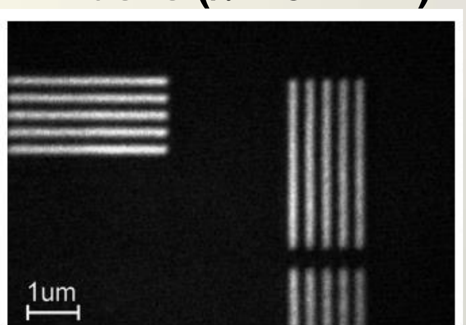


Frames from a SXR motion picture

S. Carbajo et al, Opt. Lett . 2012

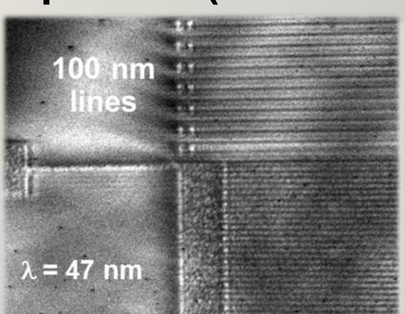
Reflection
λ=46.9 nm, 13.2 nm

Aerial inspection of EUVL masks (λ=13.2 nm)



F. Brizuela et al, Op.Lett. 2009, Opt. Exp. 2010

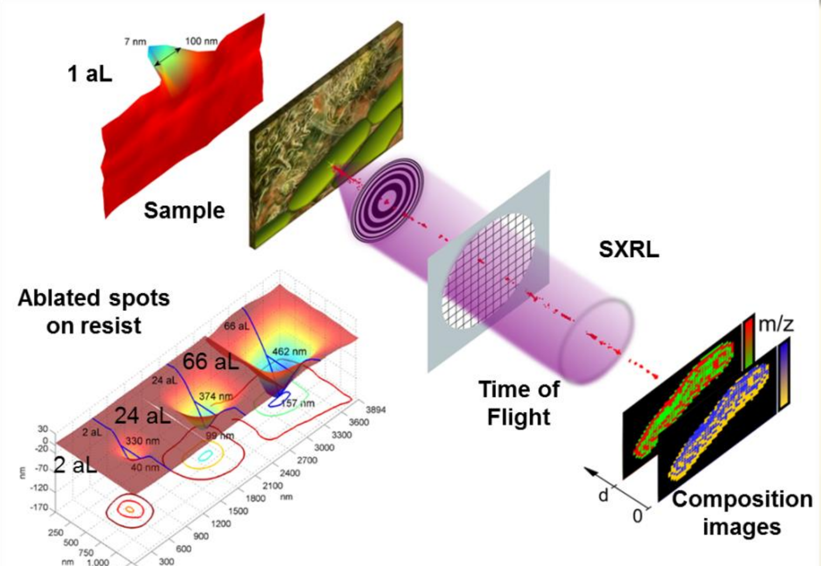
Semiconductor chip inspection (λ=46.9 nm)



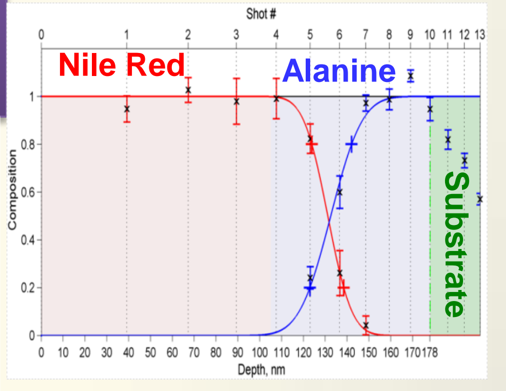
F. Brizuela et al, Opt. Exp. 2005

EUVL ablation mass spectrometry Imaging for composition mapping of organic and inorganic materials at the nanoscale

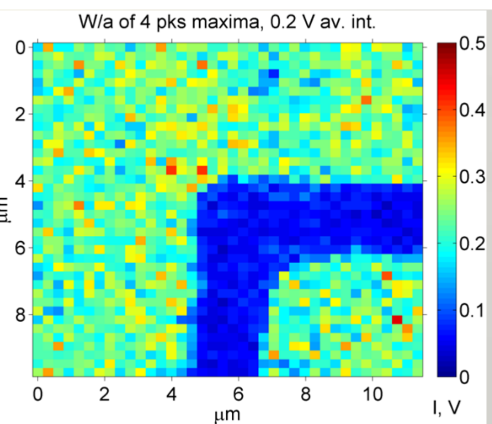
Concept exploits the high 3D localization of absorbed SXRL energy in materials and distinct ablation and ionization mechanisms, which are significantly different to visible and UV light



Depth profiling:
Resolution: 20 nm



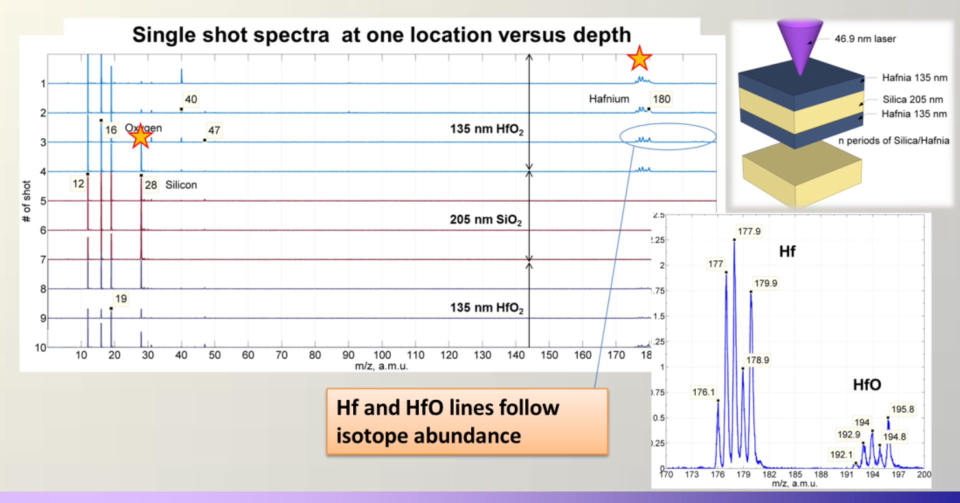
2D ion image showing distribution of resist on a sample. Resolution: 140 nm



Each single-shot ablation event removes 35 nm in HfO_2 and 70 nm in SiO_2 due to the difference in absorption of the materials

APPLICATIONS to organics and inorganics

- Interface chemistry
- Catalysis on surfaces
- Interdiffusion in materials
- Resist chemistry



Talbot defect free EUV printing of arbitrary motifs

Talbot Distance

Print at the Talbot plane

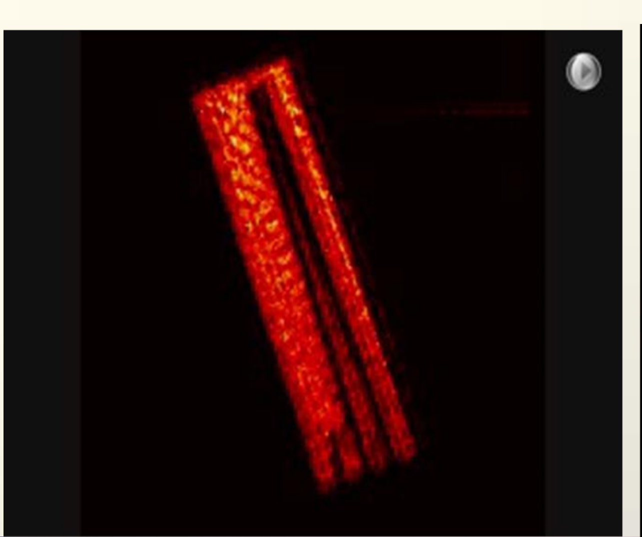
46.9nm capillary discharge laser

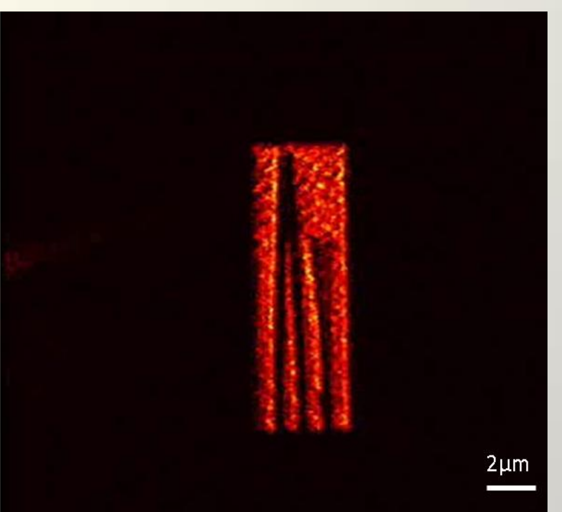
Periodic mask

Print without defects

Mask with defects

Time resolved EUVL Fourier holography: a diagnostic tool for MEMS and NEMS





Snapshot images of 10 µm long, 200 nm diameter pillars

CONTACT INFORMATION

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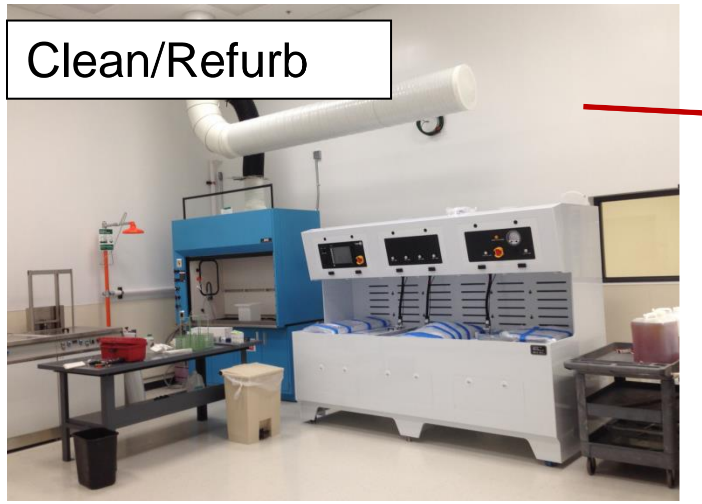
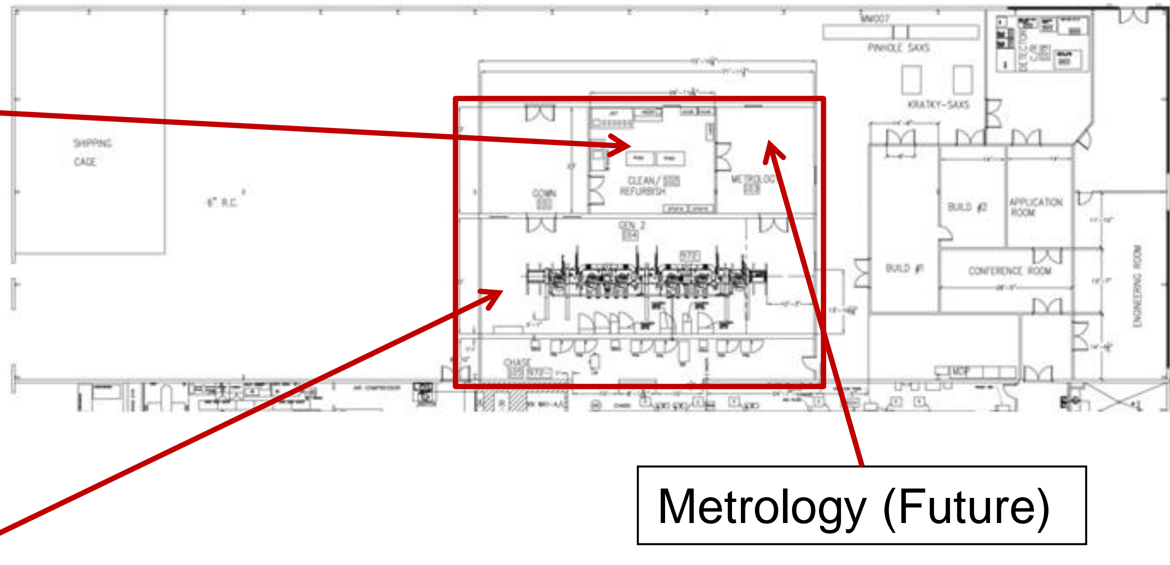
Carmen S. Menoni – carmen.menoni@colostate.edu – 970.491.8659

In 2014 - Commissioned Advanced EUVL Coatings Facility



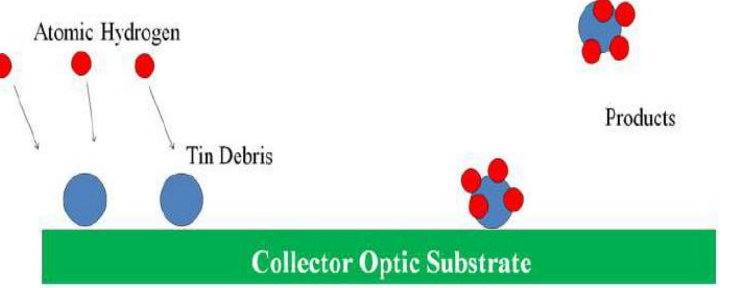


<u>For Collector, Illumination, Imaging Optics</u>

Details presented in P57

In-Situ Collector Cleaning by Hydrogen Plasma

Plasma produces H radicals, which bond to Sn and form SnH_4 (gas).



Sn Removal Rates:

• At 260 mTorr and 500sccm H_2 flow, Sn Removal Rates vary from 0.75 nm/min to 1.33 nm/min, based on radial position.

•Removal Rates are affected by pressure and flow. SnH_4 is weakly bound and can break apart on collision, re-depositing Sn. For a given pressure, there is an optimal flow rate that will maximize removal by blowing away SnH_4 without blowing away too many radicals. As pressure increases, optimal flow rises due to decreasing mean free path.

Surface Experiments and Effects on Multilayer Mirrors:

•Multilayer Mirror Samples were etched under same conditions.

•SRIM simulations showed small or insignificant sputtering yields for a variety of capping layer materials. They also showed no sputtering yield for Mo and a very small sputtering yield for Si.

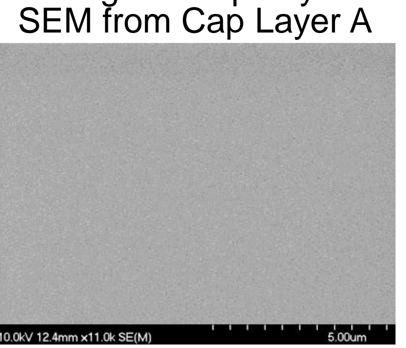
•MLM samples with two different capping layers were exposed to etching plasma for 45 minutes. Some were coated with Sn, others were not.

•SIMS measurements did not indicate any sputtering for MLM samples with either capping layer.

•EUV Reflectivity Results were performed at LBNL. After deposition and etching, Cap Layer A experienced reflectivity restoration from 5.6% to 46.1% (compared to 50.5% initial reflectivity). Cap Layer B experienced reflectivity restoration to about 46% (compared to 56% initial reflectivity). Also, bare Cap Layer A exposed to etching lost very little reflectivity, but bare Cap Layer B exposed to etching was reduced to 46% reflectivity.

•Damage to Cap Layer B due to hydrogen implantation and blistering (seen below). No blistering seen on Cap Layer A.

SEM from Cap Layer A

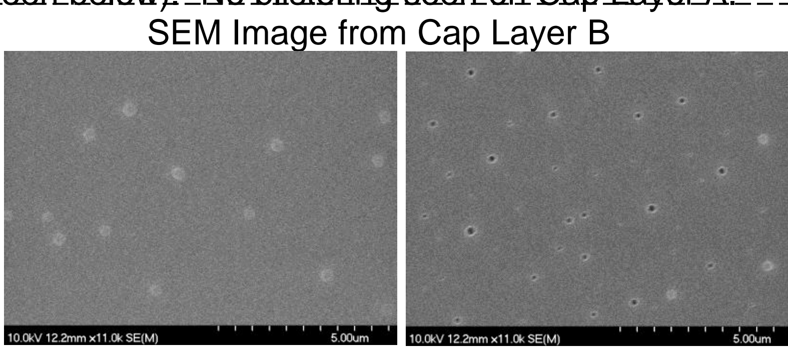


Left: Cap Layer A shows no damage after exposure to etching plasma.

Right: Cap Layer B shows blisters after deposition and 45 min. of etching.

Far Right: A bare Cap Layer B sample exposed to 45 min. of etching shows blistering with some popped blisters.

SEM Image from Cap Layer B

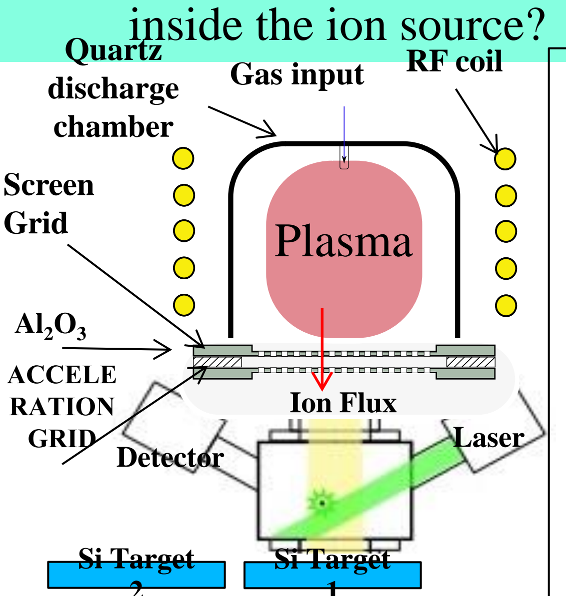


Sources of Particles in Mask Blank Manufacturing

Can a particles be produced inside the ion source?

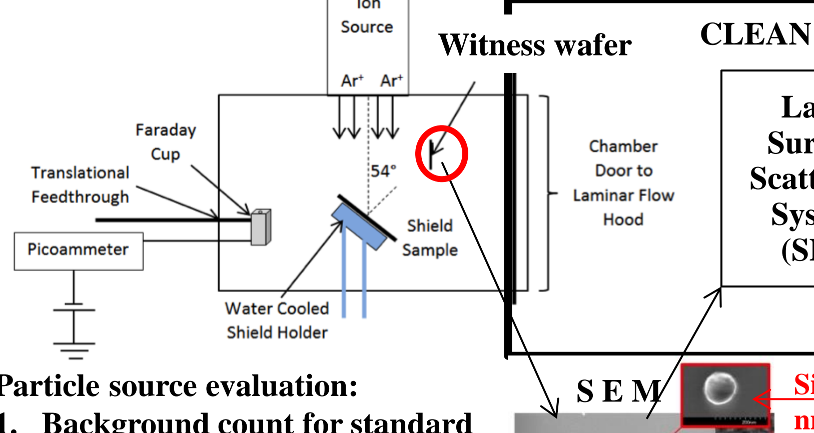
Object of study: Particles, size >100nm

Can particles be knocked out from the shield surfaces by ion/neutral flux?

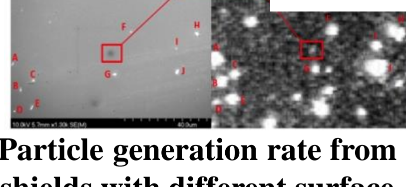


Experiment procedure:

1. A mark placed on grids on each side.
2. Ion beam on.
3. Particles counted with Stiletto
4. Ion beam off.
5. Particles counted on targets with SEM and SLS.
6. Ion source on.
7. Steps 2-6 repeated
8. Data acquired for different time steps.



SEM



Particle source evaluation:

1. Background count for standard loading procedure, gas flow open, pump, vent.
2. Background particle generation with ion source on/off.
3. Ion beam integration with the shield sample.

Particle generation rate from shields with different surface treatment procedure.

Adders Above Backg... (particles/mm2): 0.0, 0.5, 1.0, 1.5, 2.0

Sand blasted | Chem. Etch | Sand blast + post 1 pros. | Sand blast + post 2 pros.

Processes to generate particles:

- Gas flow on/off; Turbo on/off; Ion source discharge on/off

Ion source operation particle generation rate:

- No particles per first 3-5 hours of operation
- Up to 1 particle per 1 min per 1 sm^2 after 6 hours of operation

Effects on grids surface

Screen grid: - Embedded Ar and Si after 20 hours of operation.
- Globular structures on the surface; - redeposition between grids

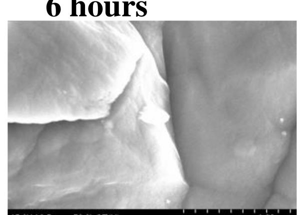
Acceleration grid: - etched hole edges; thermal defects cause flaking from hole walls

Answer to both questions: Yes !

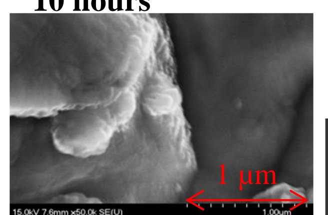
SEM Example: Acceleration grid, Away from target direction.

5 hours

6 hours



10 hours



On-going work:

Multilayer (Si/Mo) dep. films on shields with different surface particle generation rate measurement.

Resist outgas contamination testing at NIST

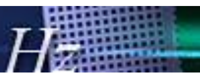
R. Berg, S. Hill, J. Curry, C. Tarrio and T. Lucatorto

Since 23 Feb 2014

- 66 measurements of E_0 or carbon growth
- 15 customer resists
- All passed requirements for carbon growth and XPS noncleanables

Ongoing work

- Studies of scaling with wafer area, exposure time, dose
- Participation in second SEMATECH round-robin and other intercomparisons.
- Additional measurements of temperature dependence of carbon growth
- Temperature control of outgas testing system



Molecular Organometallic Resists For EUV (MORE)

Contributions from Dan Freedman and Robert Brainard at CNSE and SUNY New Paltz
Funded by Intel and Sematech

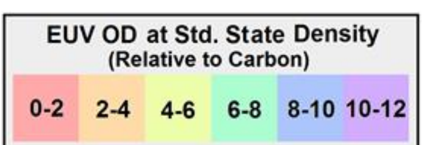
As EUV resolution improves, resists will be thinner. Traditional elements will no longer be able to stop enough EUV light for good photon statistics. Therefore, we are investigating elements in the periodic table with high EUV OD.

We hope to Share Advantages of the Inpria/Cornell HfO_2 Nanoparticle Resists:

- High EUV OD (better photon statistics).
- High stopping power of secondary electrons (less electron blur).
- Excellent etch resistance.
- But have better control of performance by using a broader range of materials.

To date, we have synthesized and screened ~500 organometallic compounds.

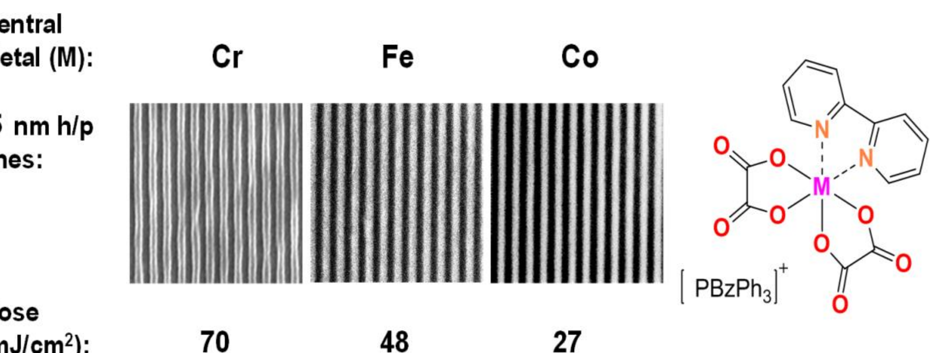
2.1 1 H																	2 He
1.0 3 Li	1.5 4 Be											2.0 5 B	2.5 6 C	3.0 7 N	3.5 8 O	4.0 9 F	10 Ne
0.9 11 Na	1.2 12 Mg											1.5 13 Al	1.8 14 Si	2.1 15 P	2.5 16 S	3.0 17 Cl	18 Ar
0.8 19 K	1.0 20 Ca	1.3 21 Sc	1.5 22 Ti	1.6 23 V	1.6 24 Cr	1.5 25 Mn	1.8 26 Fe	1.8 27 Co	1.8 28 Ni	1.9 29 Cu	1.6 30 Zn	1.6 31 Ga	1.8 32 Ge	2.0 33 As	2.4 34 Se	2.8 35 Br	36 Kr
0.8 37 Rb	1.0 38 Sr	1.3 39 Y	1.4 40 Zr	1.6 41 Nb	1.8 42 Mo	43 Tc	2.2 44 Ru	2.2 45 Rh $	2.2 46 Pd $	1.9 47 Ag	1.7 48 Cd T	1.7 49 In	1.8 50 Sn	1.9 51 Sb	2.1 52 Te	2.5 53 I	54 Xe
0.7 55 Cs	0.9 56 Ba	1.1 57 La	1.3 72 Hf	1.5 73 Ta	1.7 74 W	1.9 75 Re $	2.2 76 Os $	2.2 77 Ir $	2.2 78 Pt $	2.4 79 Au $	1.9 80 Hg T	1.8 81 Tl T	1.8 82 Pb T	1.9 83 Bi	2.0 84 Po γ	2.2 85 At γ	86 Rn γ



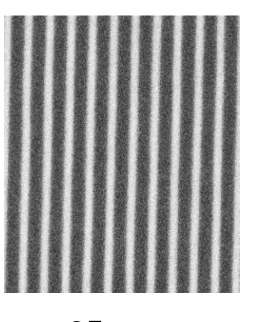
Address questions to:
rbrainard@albany.edu

Molecular Organometallic Resists For EUV (MORE)

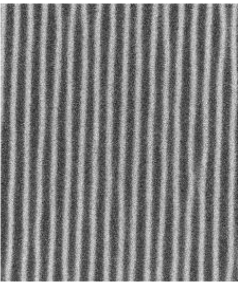
(A) First-Row Transition Metals with Oxalate Ligands.



(B) High-Resolution Platform (but slow).



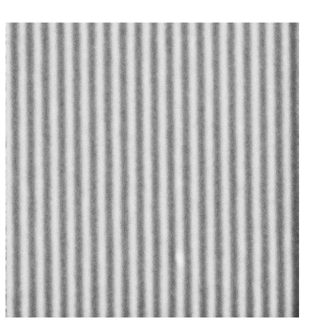
25 nm
300 mJ/cm²



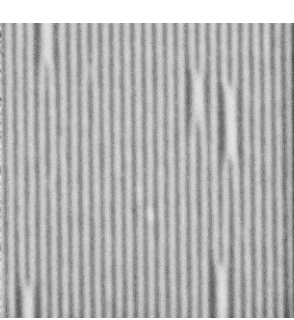
16 nm
600 mJ/cm²

(C) Newly Discovered Super-Fast Resist:

- Excellent Shelf-Life
- Passes Outgassing for AMET and BMET
- Development in Hexane or Water
- Straight-Forward Synthesis
- Multiple Variations being Explored



50 nm



35 nm

Dose = 5.6 mJ/cm²

Address questions to:
rbrainard@albany.edu

Studying the role of secondary electrons in EUV exposure of resists

Robert Brainard and Greg Denbeaux

EUV

hν

Vary Dose & Voltage

e- e- e-

Resist

Mass spectrometer

Number of reactions

Thickness Loss (Ellipsometry) Depth of reactions

Bake and Develop

Resist

SUNY College of Nanoscale Science and Engineering

EUV Lithography

June 2014

Dr. Michael Lercel (Chief Technologist)

Dr. Kevin Cummings (Director, Lithography)

SEMATECH

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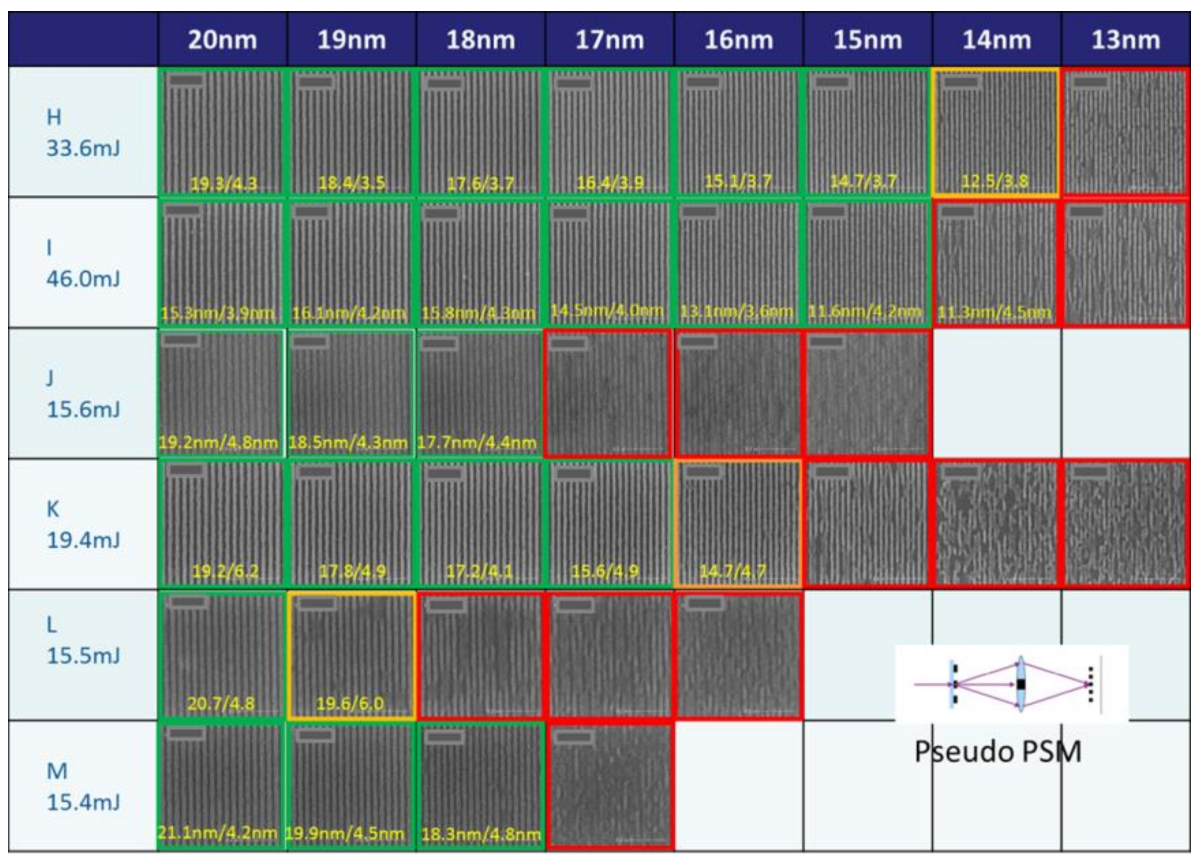
EUV Lithography

- Standard (PAG-based) resist material screening shows progress on resolution but dose remains high

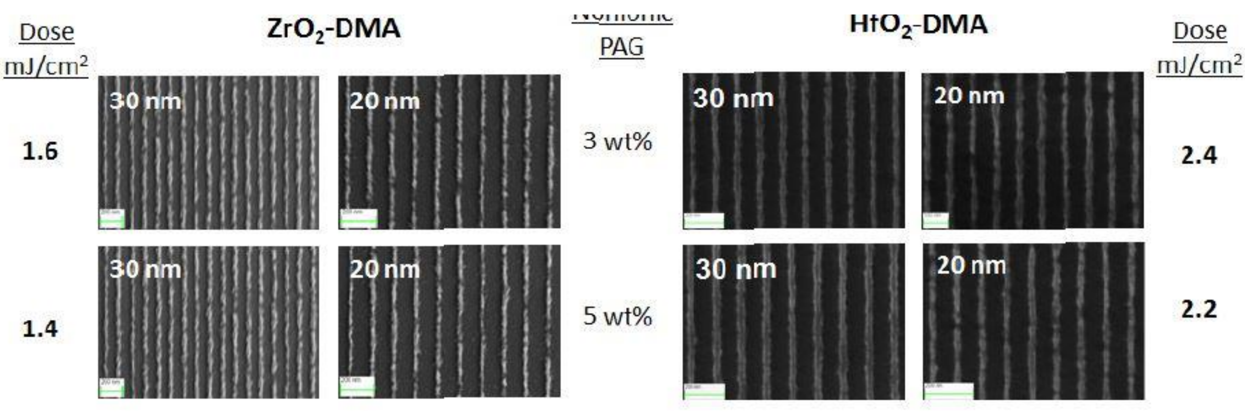


	20nm	19nm	18nm	17nm	16nm	15nm	14nm	13nm
H 33.6mJ	19.3/4.3	18.4/3.5	17.6/3.7	16.4/3.9	15.1/3.7	14.7/3.7	12.5/3.8	
I 46.0mJ	15.3nm/3.9nm	16.1nm/4.2nm	15.8nm/4.3nm	14.5nm/4.0nm	13.1nm/3.6nm	11.6nm/4.2nm	11.3nm/4.5nm	
J 15.6mJ	19.2nm/4.8nm	18.5nm/4.3nm	17.7nm/4.4nm					
K 19.4mJ	19.2/6.2	17.8/4.9	17.2/4.1	15.6/4.9	14.7/4.7			
L 15.5mJ	20.7/4.8	19.6/6.0						
M 15.4mJ	21.1nm/4.2nm	19.9nm/4.5nm	18.3nm/4.8nm					

Source: SEMATECH results (0.3NA MET)

EUV: Productivity

- Possible breakthroughs in resist technology could relieve source power burden
  - Throughput calculations assume 15mJ/cm^2
  - <5mJ/cm^2 demonstrated with nanoparticle resists



Cornell University work supported by SEMATECH
SPIE 2014

EUV: Yield

- Good progress on defect free EUV mask blank yields
  - Mask blanks with zero killer defects have been fabricated

SEMATECH April 2014

SEMATECH Resist and Materials Development Center (RMDC)

$10M

SEMATECH Albany MET

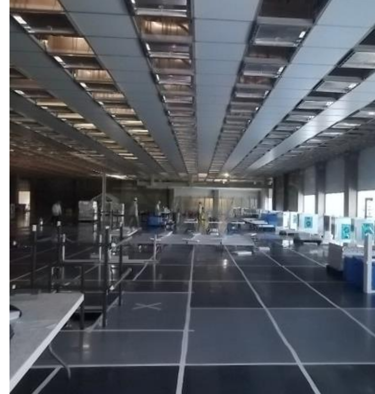
$15M

SEMATECH Berkeley MET

$65M

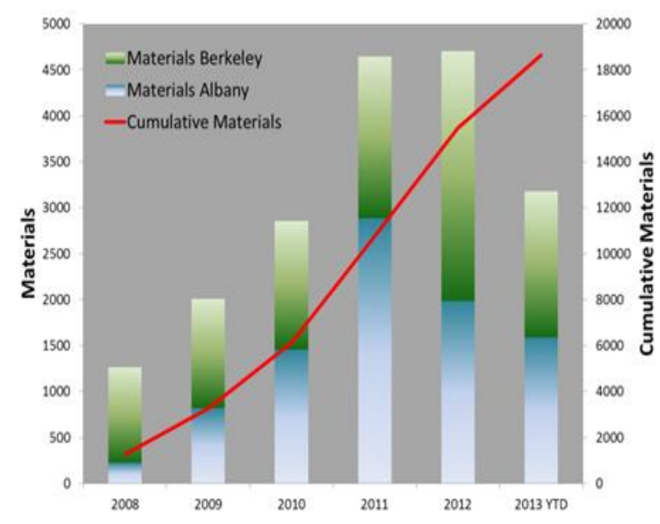
Albany ADT 2007-2012

$100+ M

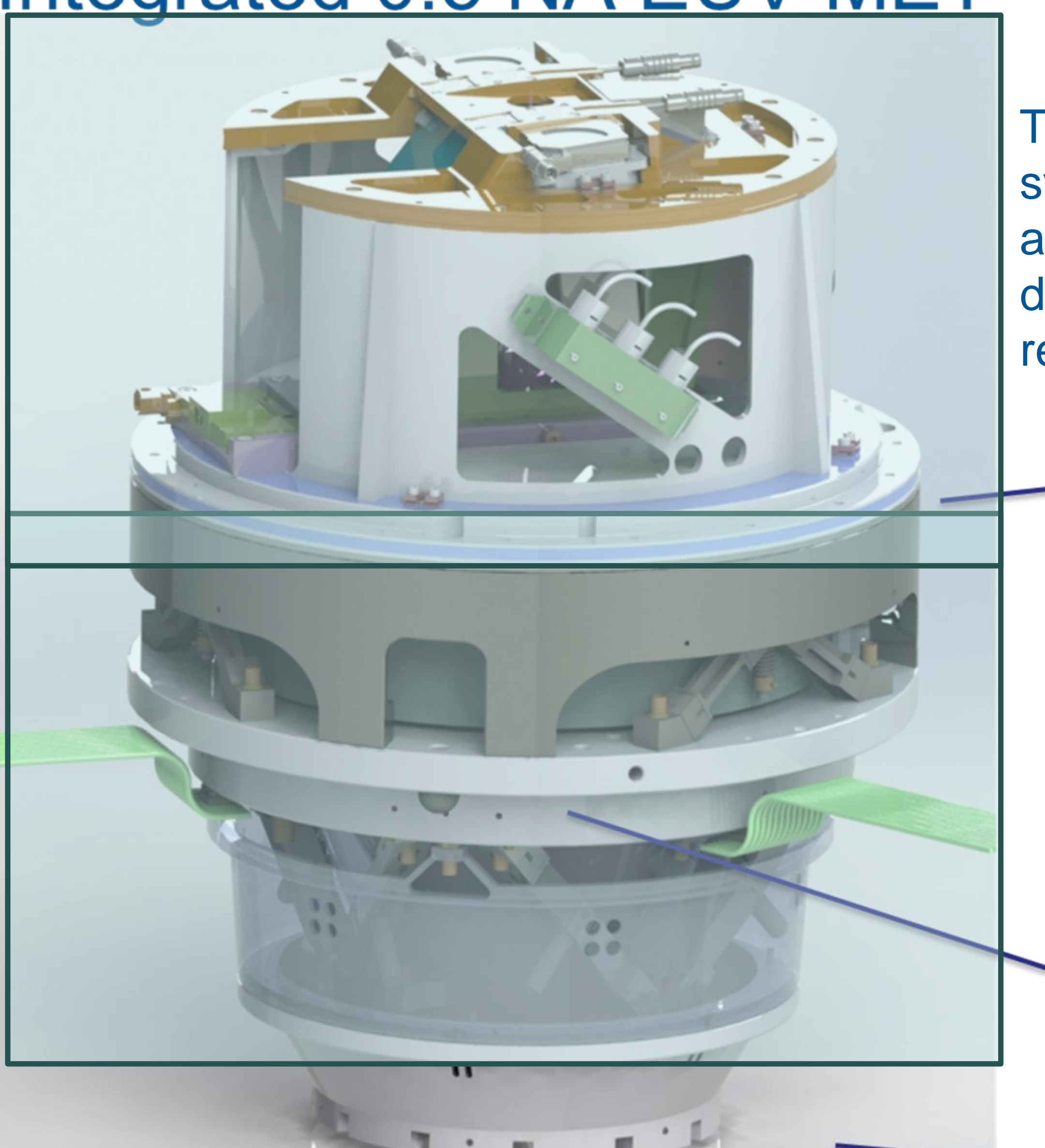


Albany EUV NXE:3300

- A model for shared infrastructure
- Leading-edge imaging capabilities
- EUV resist outgas testing
- Next-generation resist technologies
- More than 20,000 materials processed since 2008



Integrated 0.5 NA EUV MET



The resolution of the height sensor system is improved by 2x to accommodate smaller step and depth of focus at the ultimate resolution of the tool.

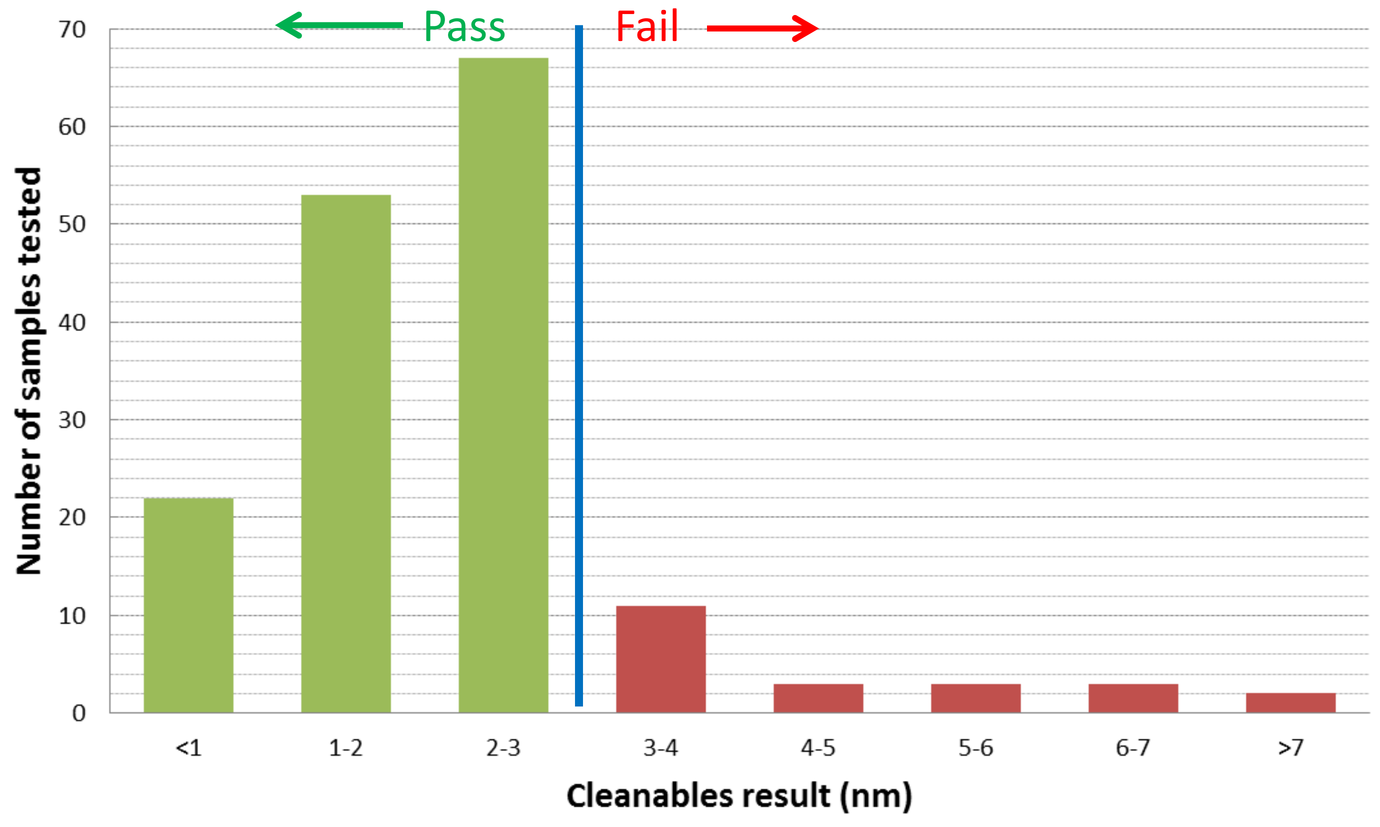
Zygo-Zeiss interface

On track for delivery in 2H2014

Three ball kinematic mount

height sensor channels

EUV Resist Outgassing: Cleanables Data Results as reported Feb 2014

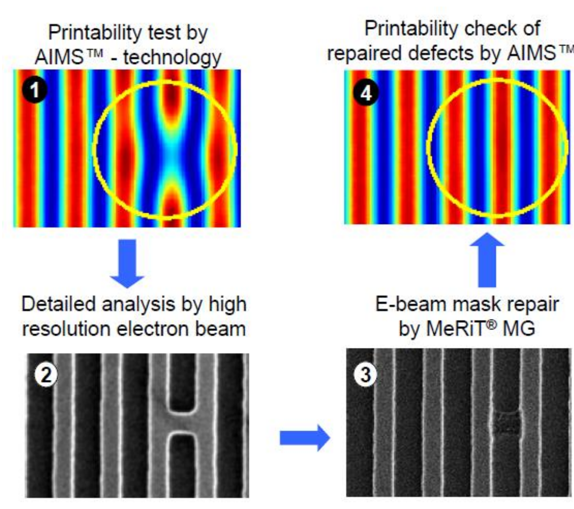


- 164 customer samples measured
- 87% pass cleanables

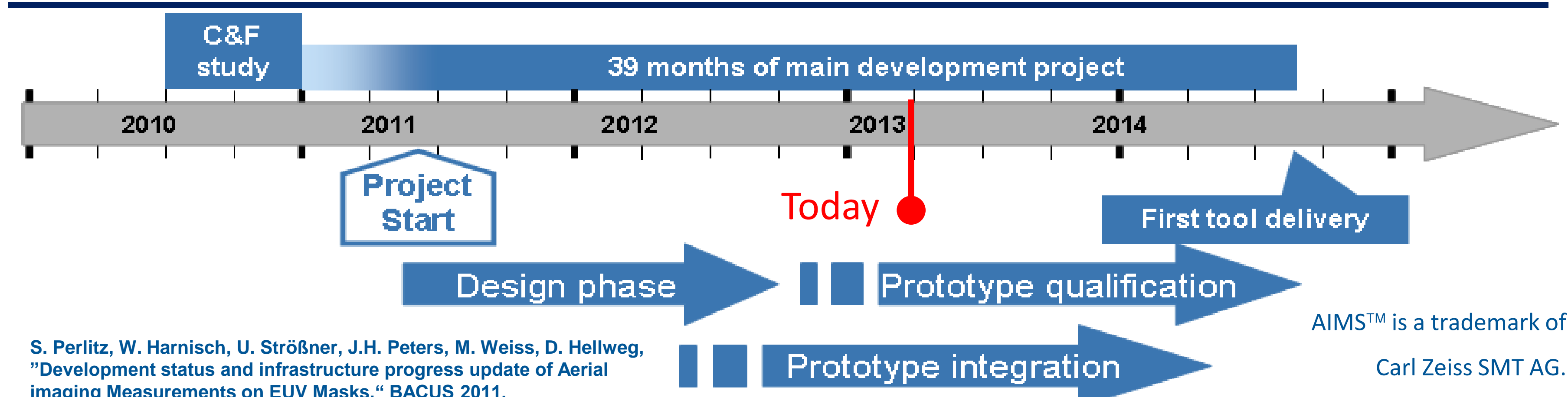
SEMATECH – Zeiss AIMS^{TM} collaboration
Enabling EUV Mask Tool Infrastructure

SEMATECH

- Zeiss AIMS^{TM} EUV project started 05/2011
- Five EMI members are participating



D.Hellweg, J.Ruoff, A.Herkommer, H.Feldmann, M.Ringel, U.Strößner, S.Perlitz, W.Harnisch, "Actinic aerial image review of EUV masks," Proc of SPIE 7969-15 (2011).



S. Perlitz, W. Harnisch, U. Strößner, J.H. Peters, M. Weiss, D. Hellweg, "Development status and infrastructure progress update of Aerial imaging Measurements on EUV Masks," BACUS 2011.

AIMS^{TM} is a trademark of Carl Zeiss SMT AG.

ENERGETIQ

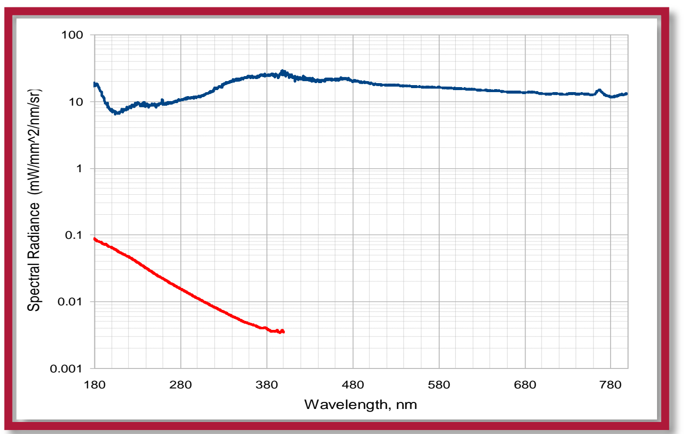
Energetiq Technology EUV Source Manufacturer

- Based in Woburn, MA
- Founded in 2004
  - Backed by Venture Capital including Intel Capital, Ushio and Shea Ventures
- Shipped more than 25 EUV sources
- Installations in Japan, Europe and USA
- Systems integrated
  - Actinic Mask Inspection
  - Resist Outgassing
  - Mask Contamination
  - Optics Testing

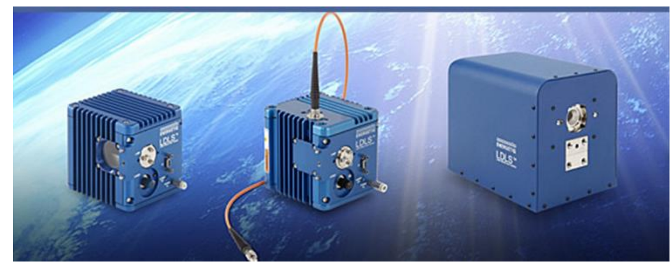
Energetiq's Products

ENERGETIQ

- High-brightness, long-life light source products
  - 1nm to 2000nm wavelength
- Product Applications
  - EUV Lithography and Metrology
    - Semiconductor Manufacturing
  - Soft X-Ray
    - Biological Imaging and Microprobe
  - UV/Vis/IR Imaging and Analysis
    - Spectroscopy
    - Inspection and Metrology



EQ-99 Broadband light source



ENERGETIQ

EQ-10 EUV Product Line

Typical Performance*	EQ-10	EQ-10HR	EQ-10HP
Power 2π (13.5nm±1%)	10W	2W	20W
Plasma Size (FWHM)	400um	1.6mm	400um
Maximum Brightness	5W/mm^2-sr	NA	8W/mm^2-sr
Repetition Rate	2kHz	10kHz	2kHz
Plasma Size Stability (σ)	<4μm		<4μm
Spatial Stability Position(σ)	<6μm		<6μm
Pulse-Pulse Stability	~2%		~2%

***Performance values are typical. Actual values depend on customer's particular operating conditions which vary by application.**