Overview of EUV Lithography

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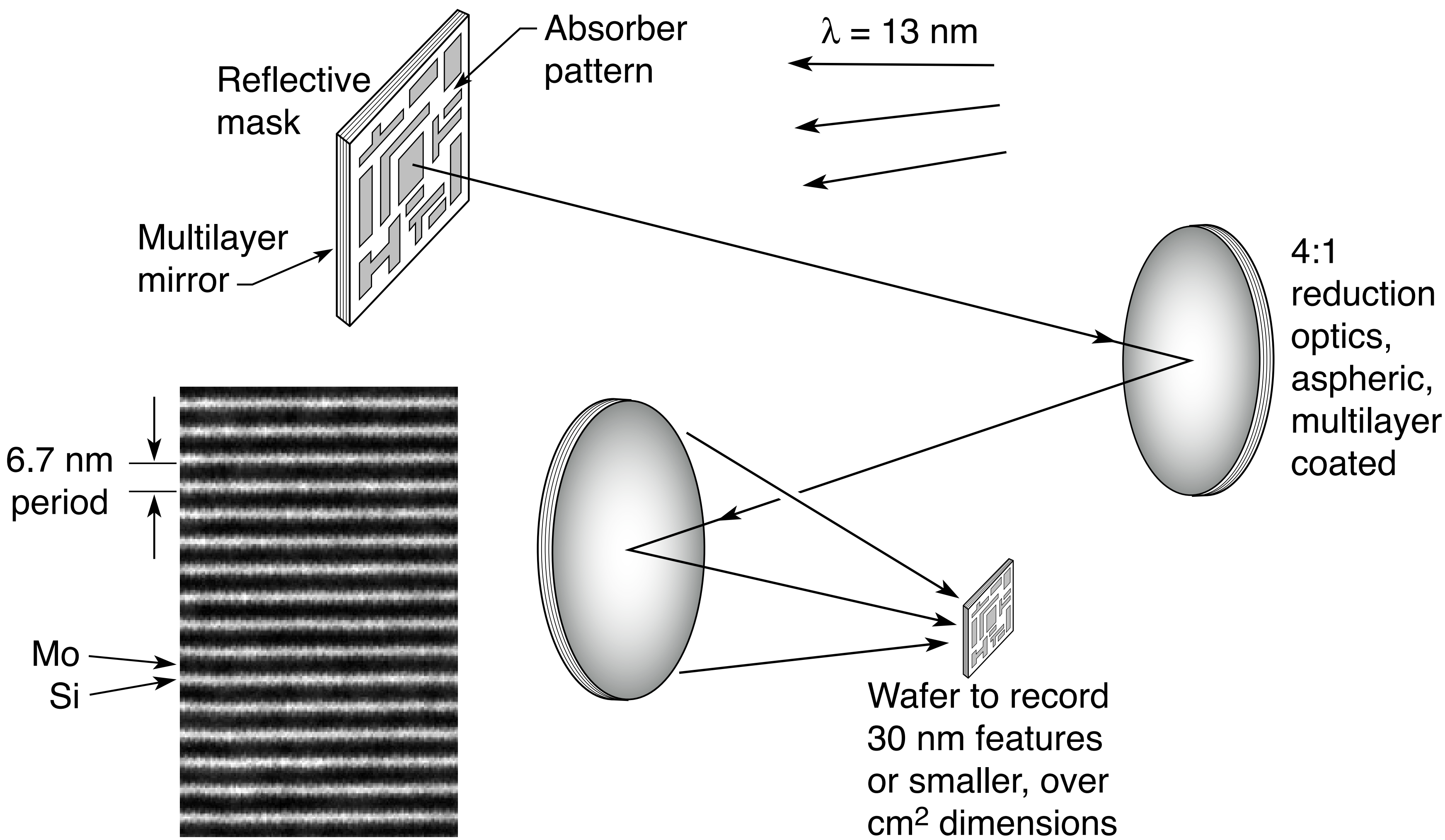
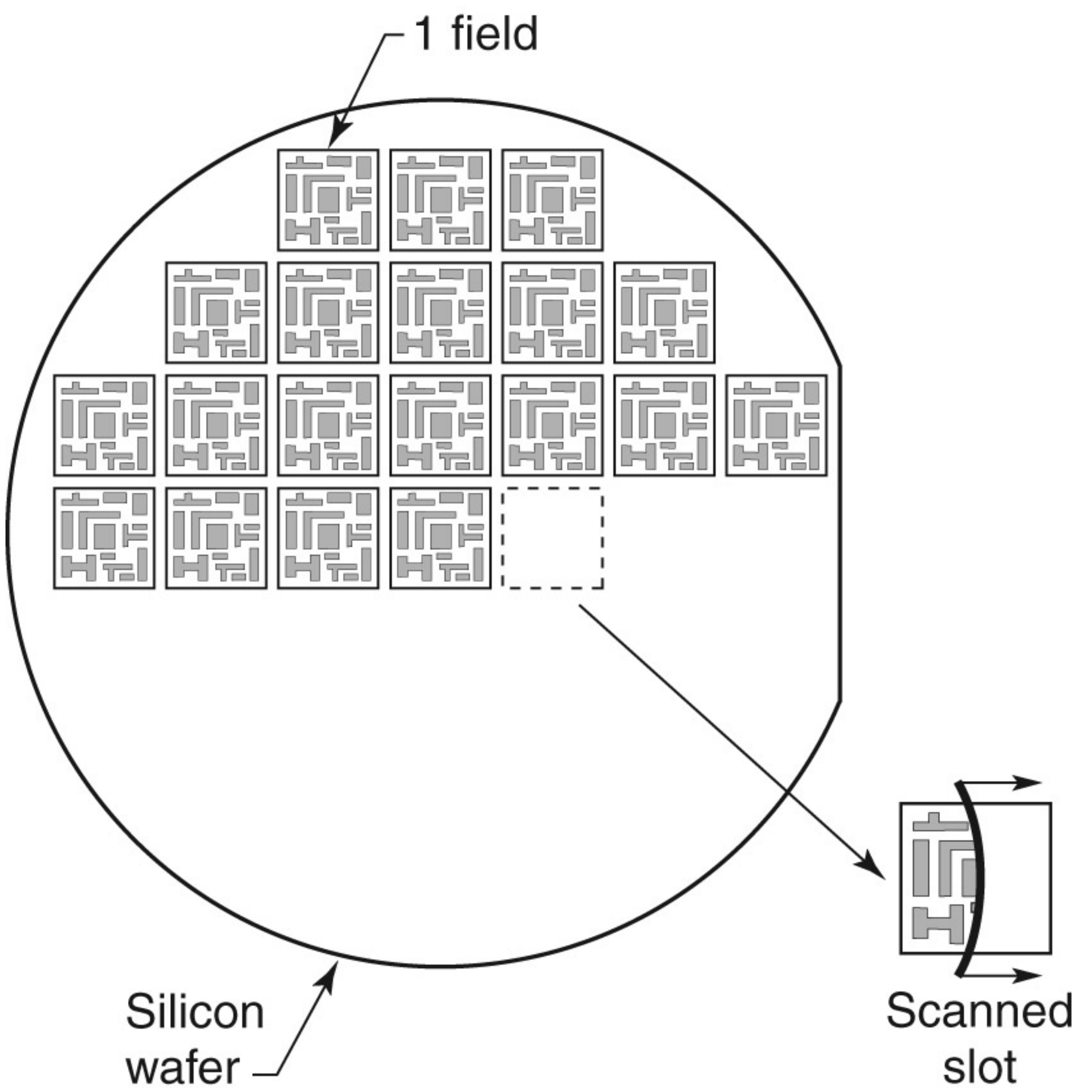
University of California, Berkeley

(http://www.coe.berkeley.edu/AST/sxr2009)

Extreme Ultraviolet (EUV) Lithography Based on Multilayer Coated Optics



EUV Lithography Will Use a Step and Scan Ring Field System



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International Technology Roadmap for Semiconductors†

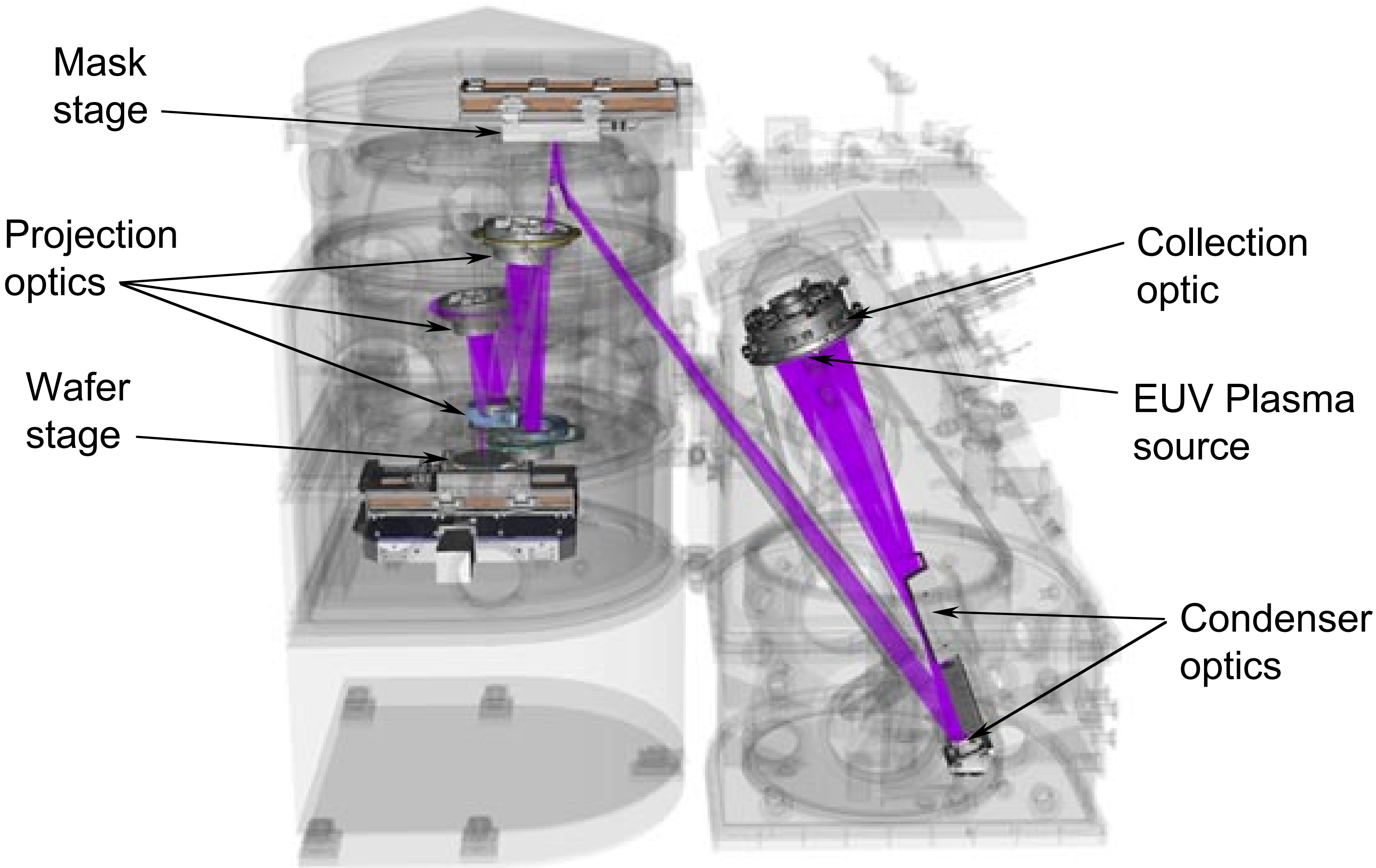
First year of volume production	2003* ~~2004~~	2005* ~~2007~~	2007* ~~2010~~	2009* ~~2013~~	2011* ~~2016~~
Technology Generation (half pitch, 1:1, printed in resist)	90 nm	65 nm	45 nm	32 nm	22 nm
Isolated Lines (in resist) [Physical gate, metalized]	53 nm [37 nm]	35 nm [25 nm]	25 nm [18 nm]	18 nm [13 nm]	13 nm [9 nm]
Chip Frequency	2.5 GHz	4.9 GHz	9.5 GHz	19 GHz	36 GHz
Transistors per chip (HV) (3 × for HP ; 5 × for ASICs)	190 M	390 M	770 M	1.5 B	3.1 B
DRAM Memory (bits per chip)	1.1 G	2.2 G	4.3 G	8.6 G	34 G
Field Size (mm × mm)	22 × 32	22 × 32	22 × 32	22 × 32	22 × 32
Wafer Size (diameter)	300 mm	300 mm	300 mm	450 mm	450 mm

†Semiconductor Industry Association (SIA), December 2004 update.

***Possible 2-year cycle for leading edge companies.**

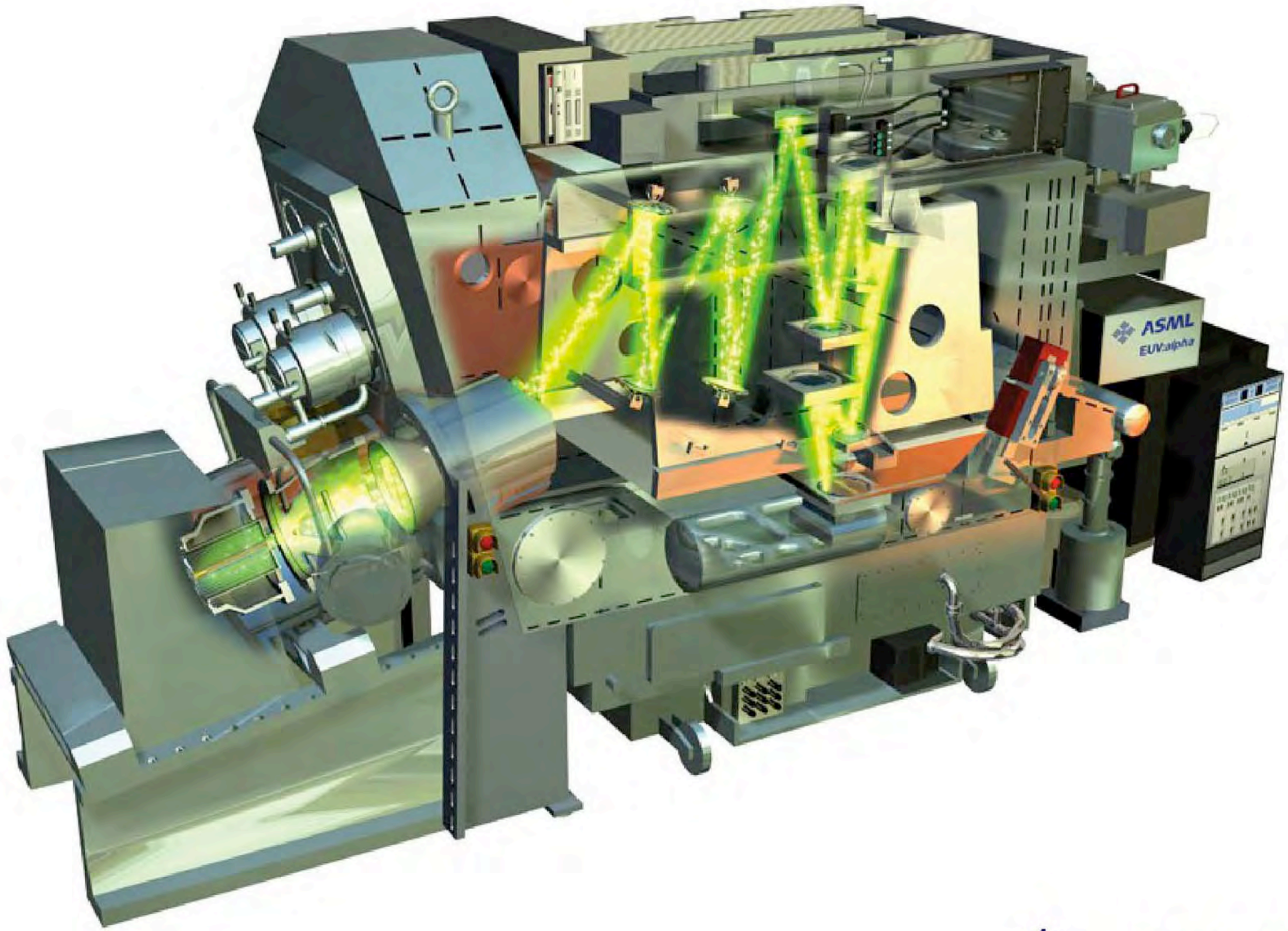
SIA_RdmpTbl_Sept2008.ai

The Engineering Test Stand (ETS): A Pre-manufacturing EUV Stepper



Courtesy of R. Stulen / Sandia

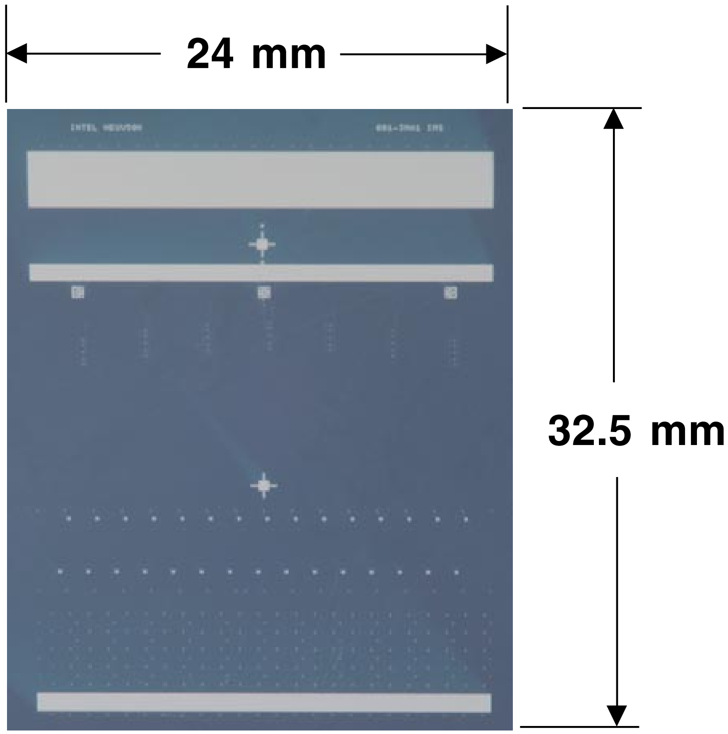
The ASML EUV alpha demo tool



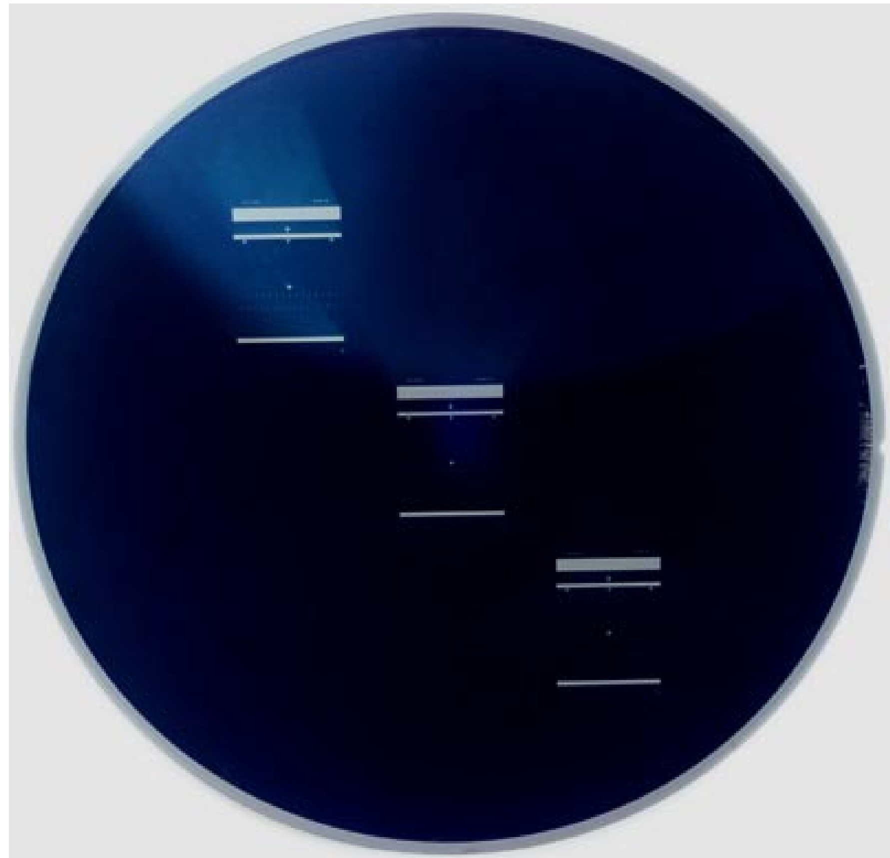
Courtesy of Dr. Hans Meiling, ASML

ASML

Full-field Images Printed on ETS



Using Shipley EUV-11A resist, scan time is ~15 minutes.



200 mm wafer

Courtesy of G. Kubiak, D. Tichenor, and B. Replogle, Sandia National Laboratories.

Diffraction Limited Aspherical Optics Are Critical to the Success of EUV Lithography

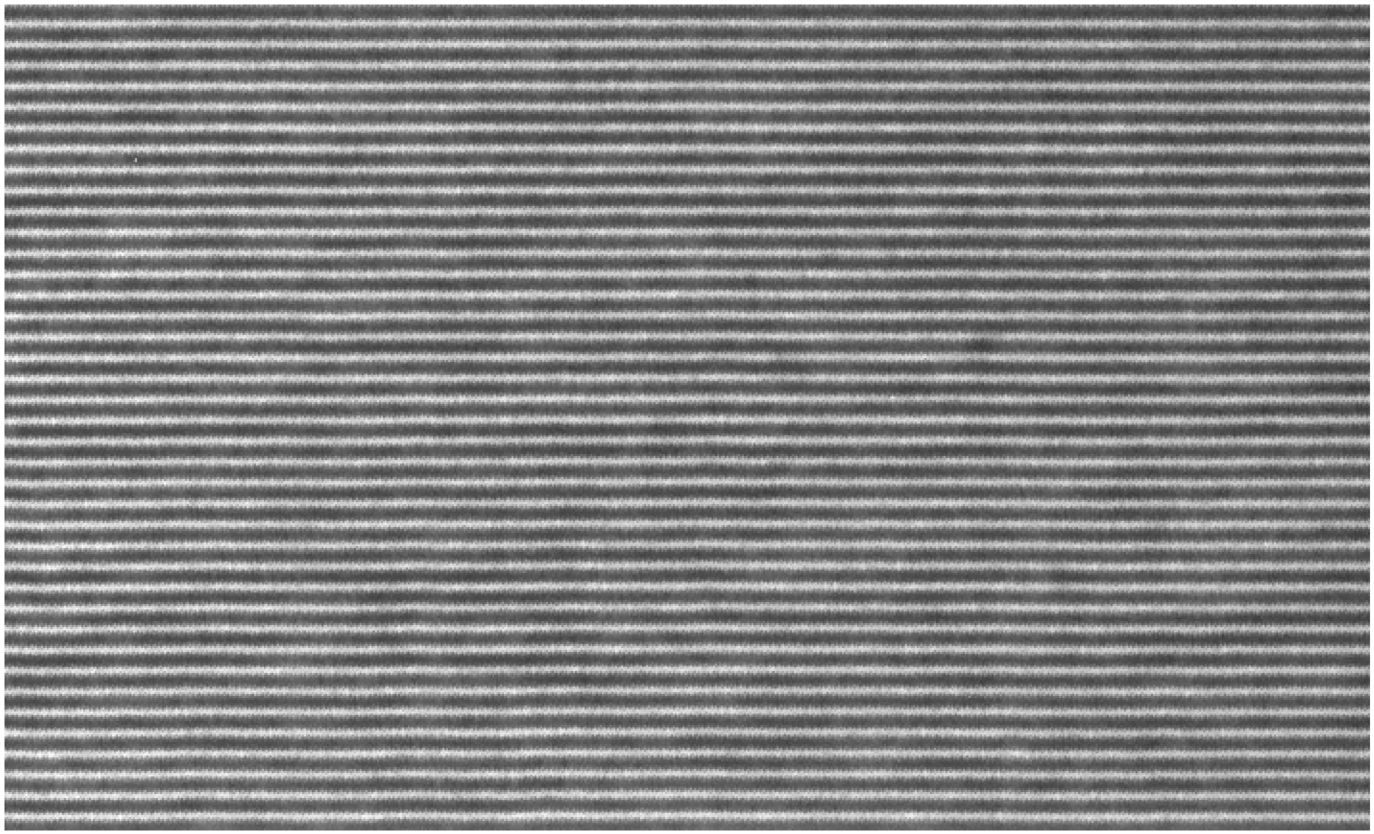
- λ_{euv} /50 figure
- Low flare
- Ultrasmooth finish
- 10 µm departure from a sphere

Tinsley Sample C
Zerodur-M
150 mm diameter

Courtesy of John Taylor, LLNL.

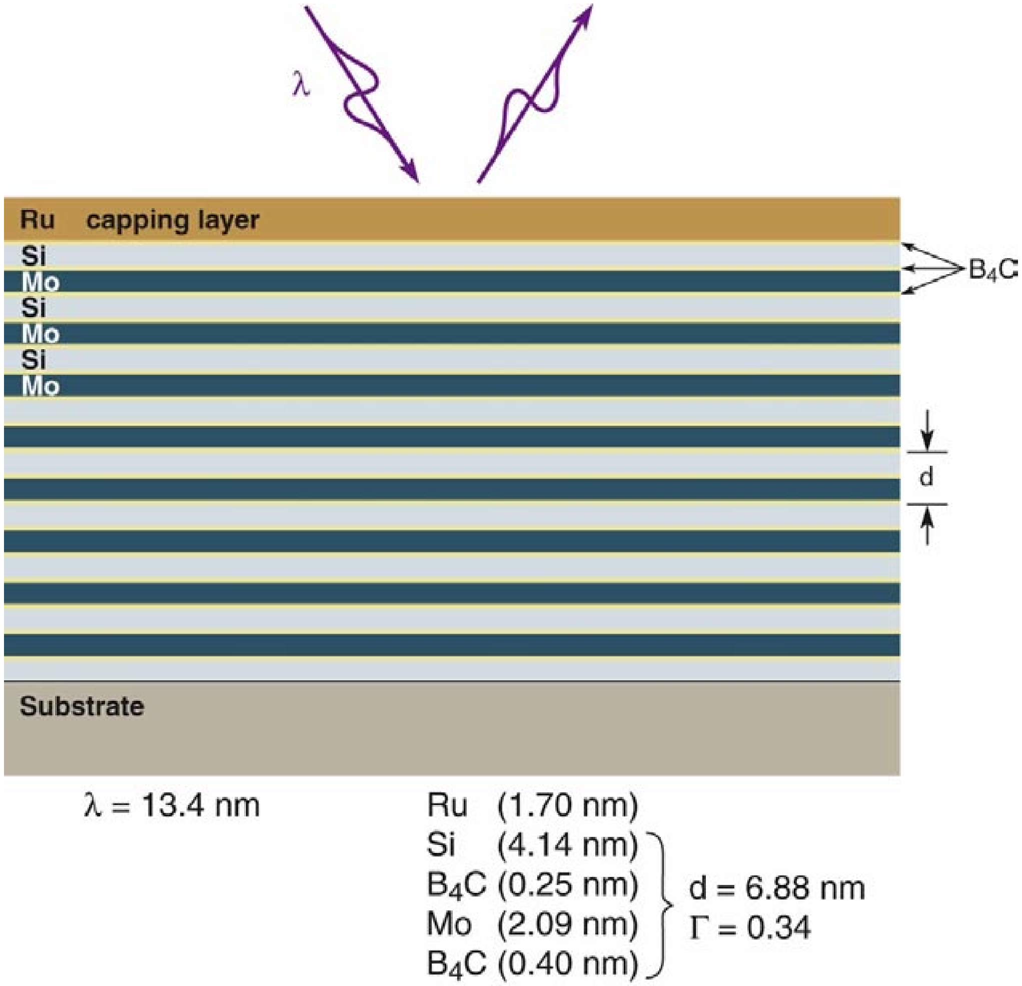
A High Quality Mo/Si Multilayer Mirror

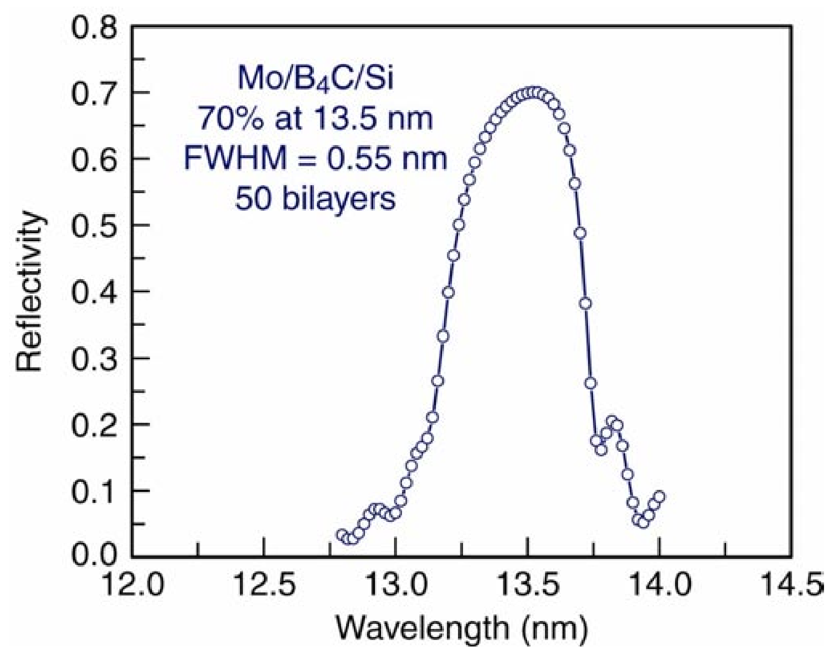
N = 40
D = 6.7 nm



(Courtesy of Săsa Bajt, LLNL)

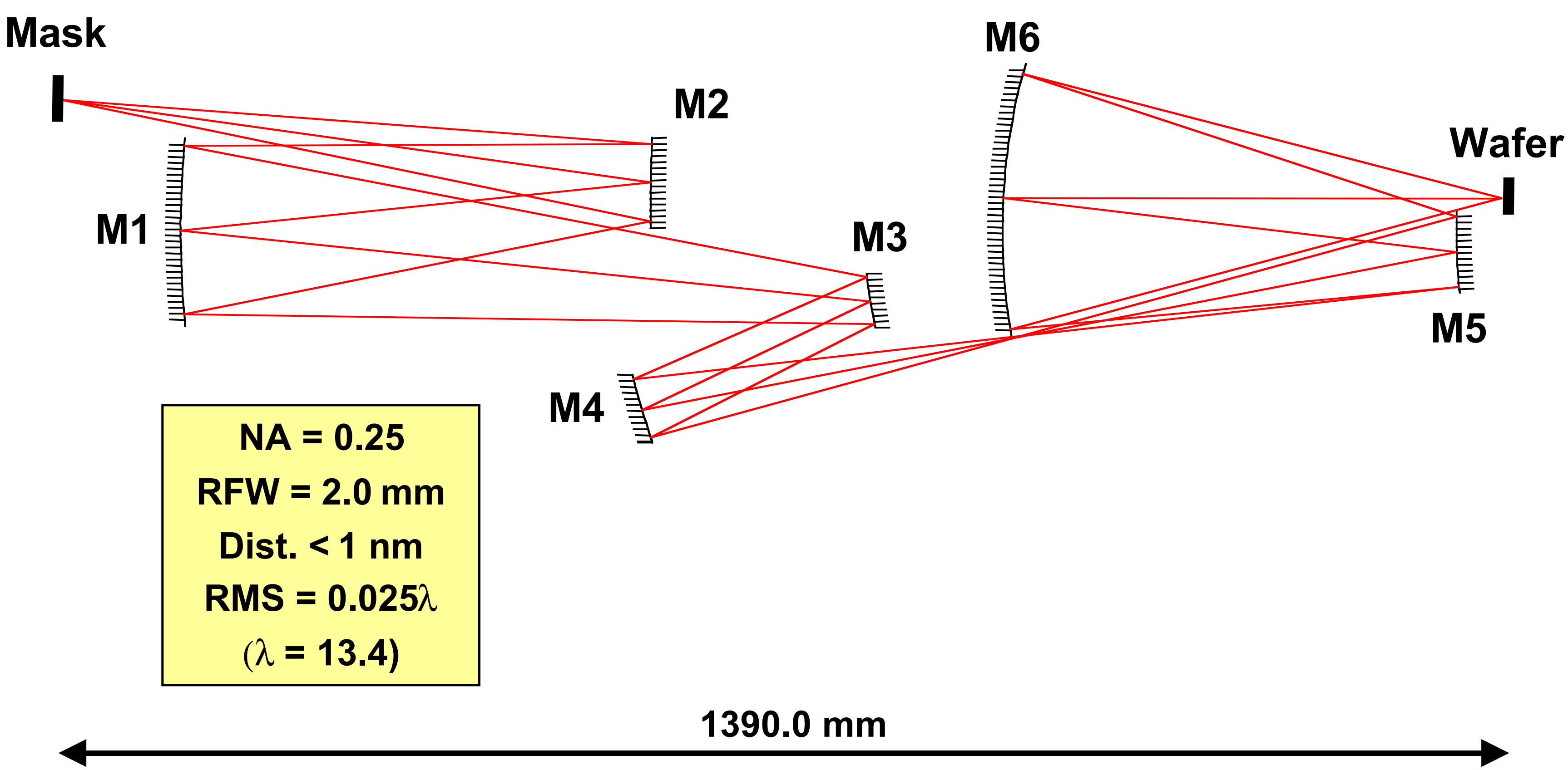
High Reflectivity, Thermally and Environmentally Robust Multilayers Coatings for High Throughput EUV Lithography





Courtesy of Saša Bajt / LLNL

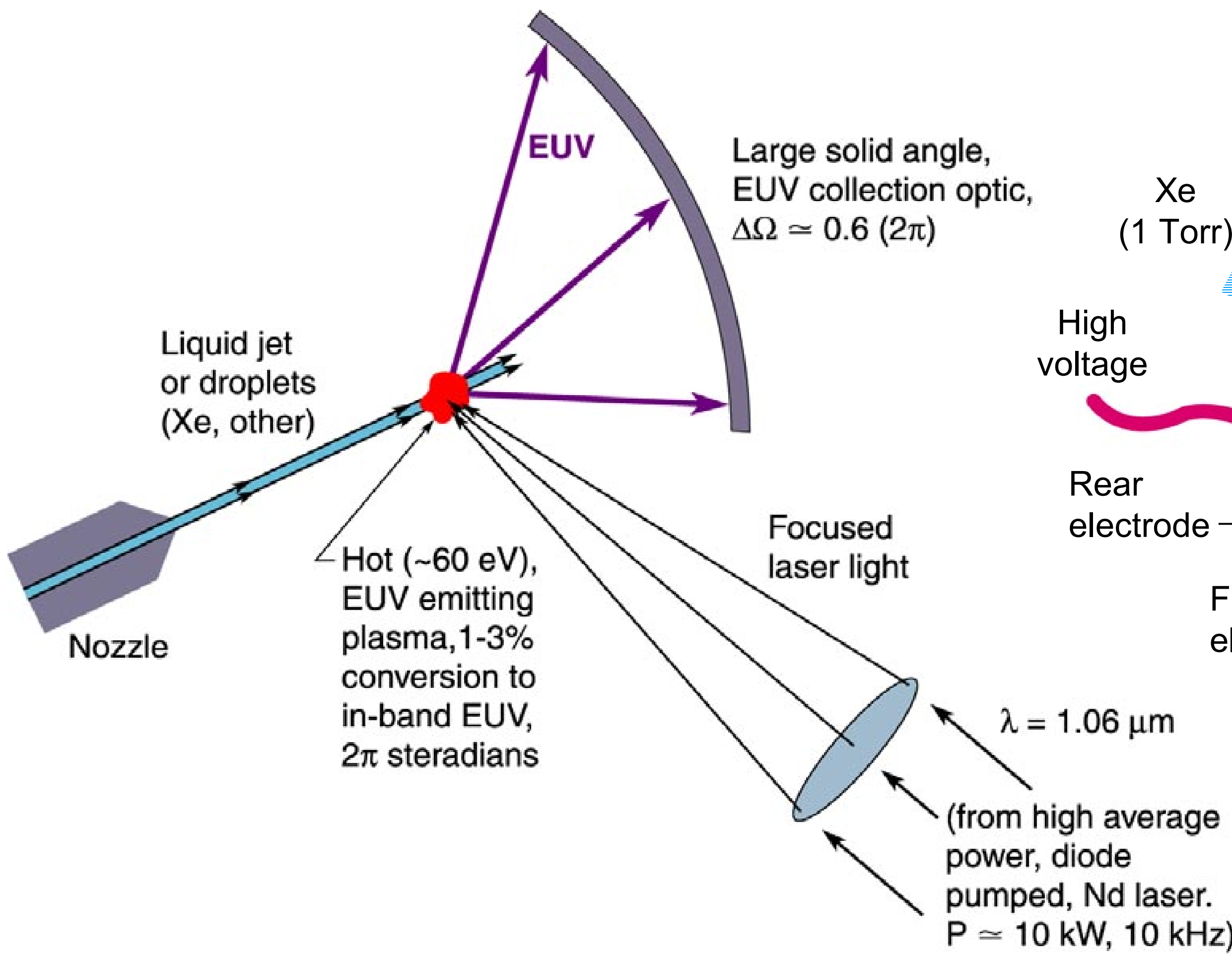
An Example of a 0.25 N.A. 6-Mirror EUV System



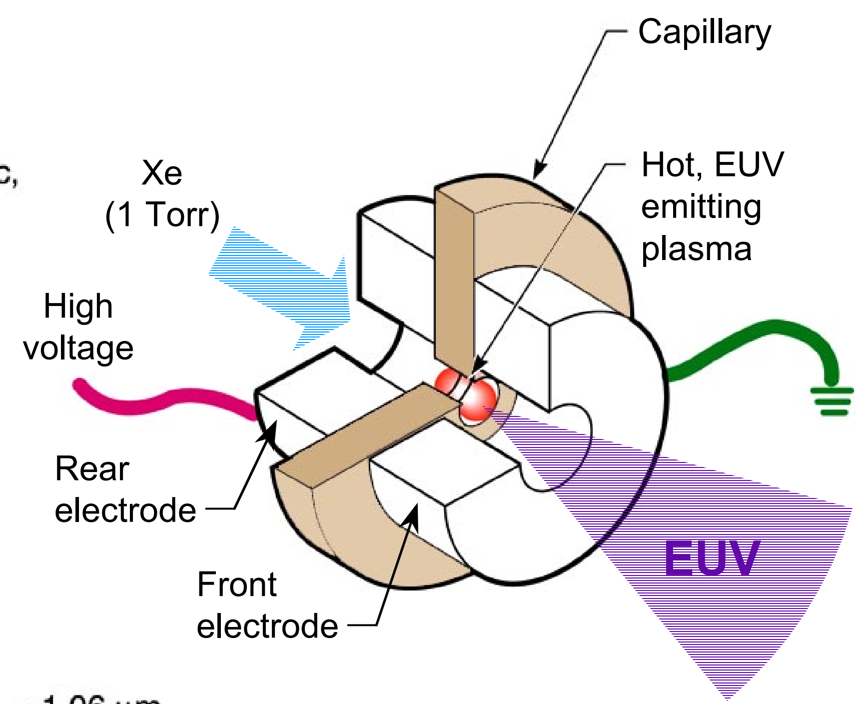
Courtesy of R. Hudyma and D. Sweeney, LLNL.

EUV Source Candidates for Clean, Collectable 13-14 nm Wavelength Radiation

Laser Produced Plasma Source

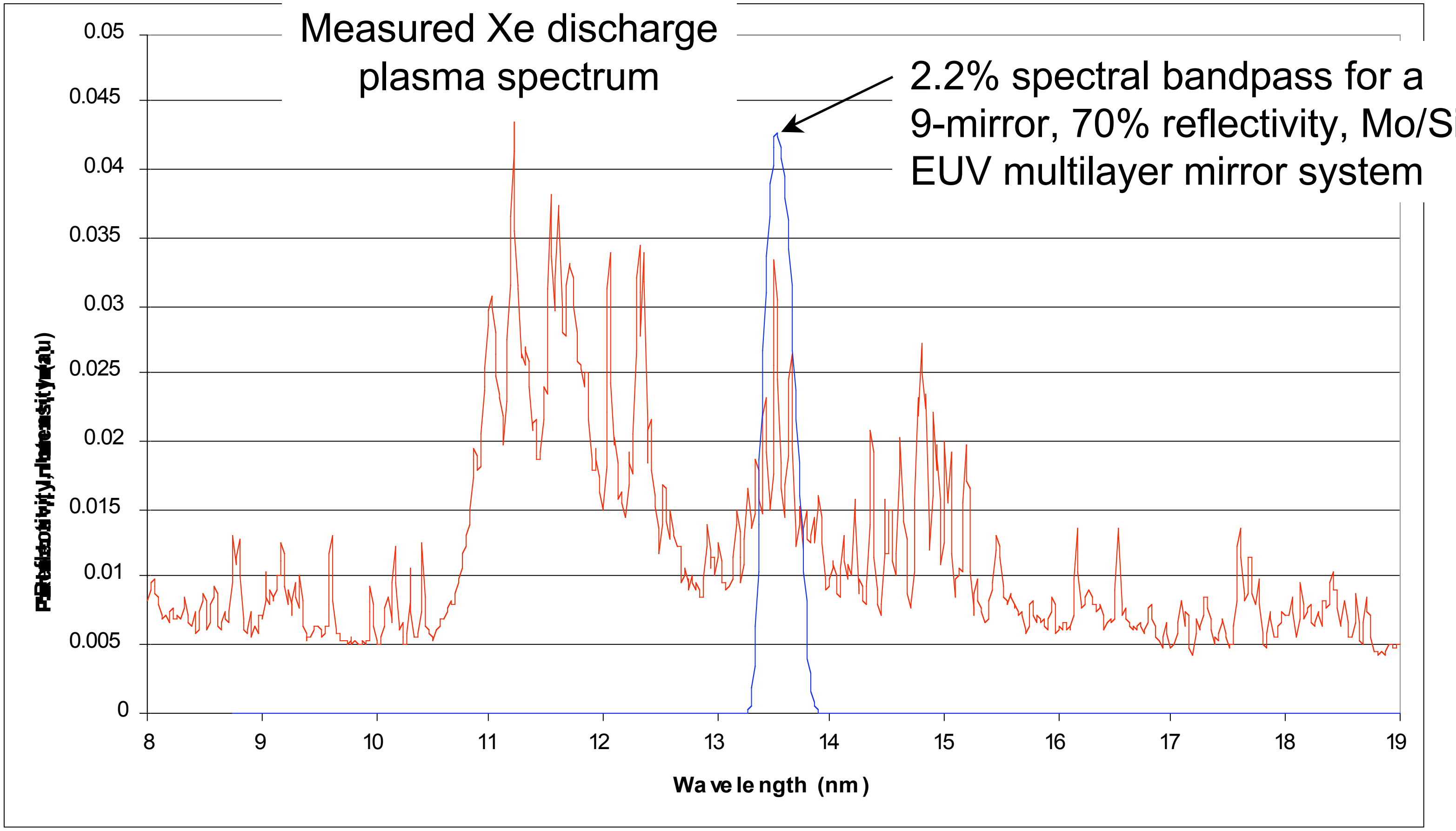


Electrical Discharge Plasma Source



Courtesy of Neil Fornaciari and Glenn Kubiak, Sandia.

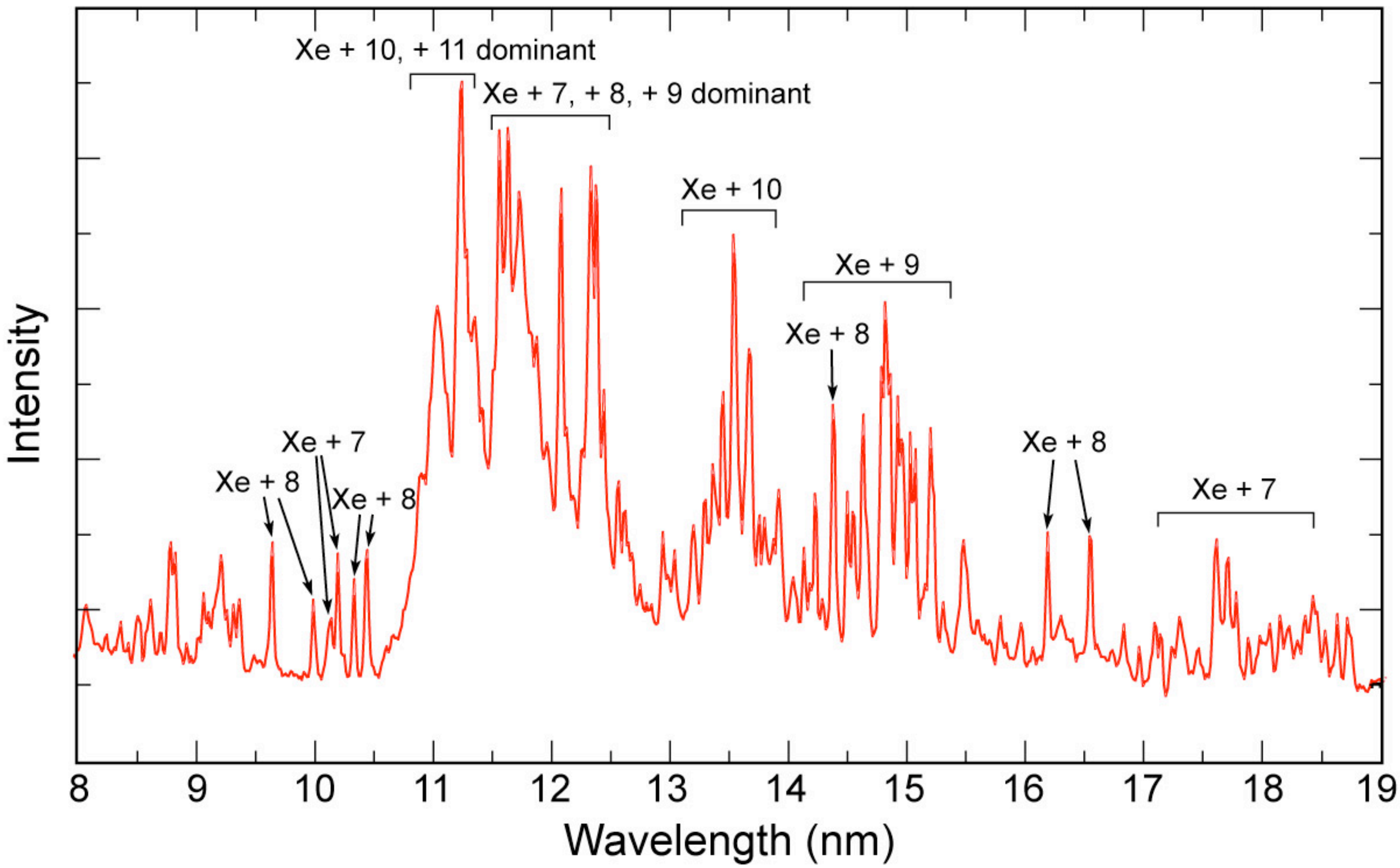
EUV Spectrum of Capillary Discharge Plasma with Nine Mirror Optical System



Multilayer Mirror Parameters:
40 bilayers, σ = 0.5 nm rms, Γ = 0.44, FWHM of curve centered at 13.5nm

(Courtesy of Jason Dimkoff, Sandia)

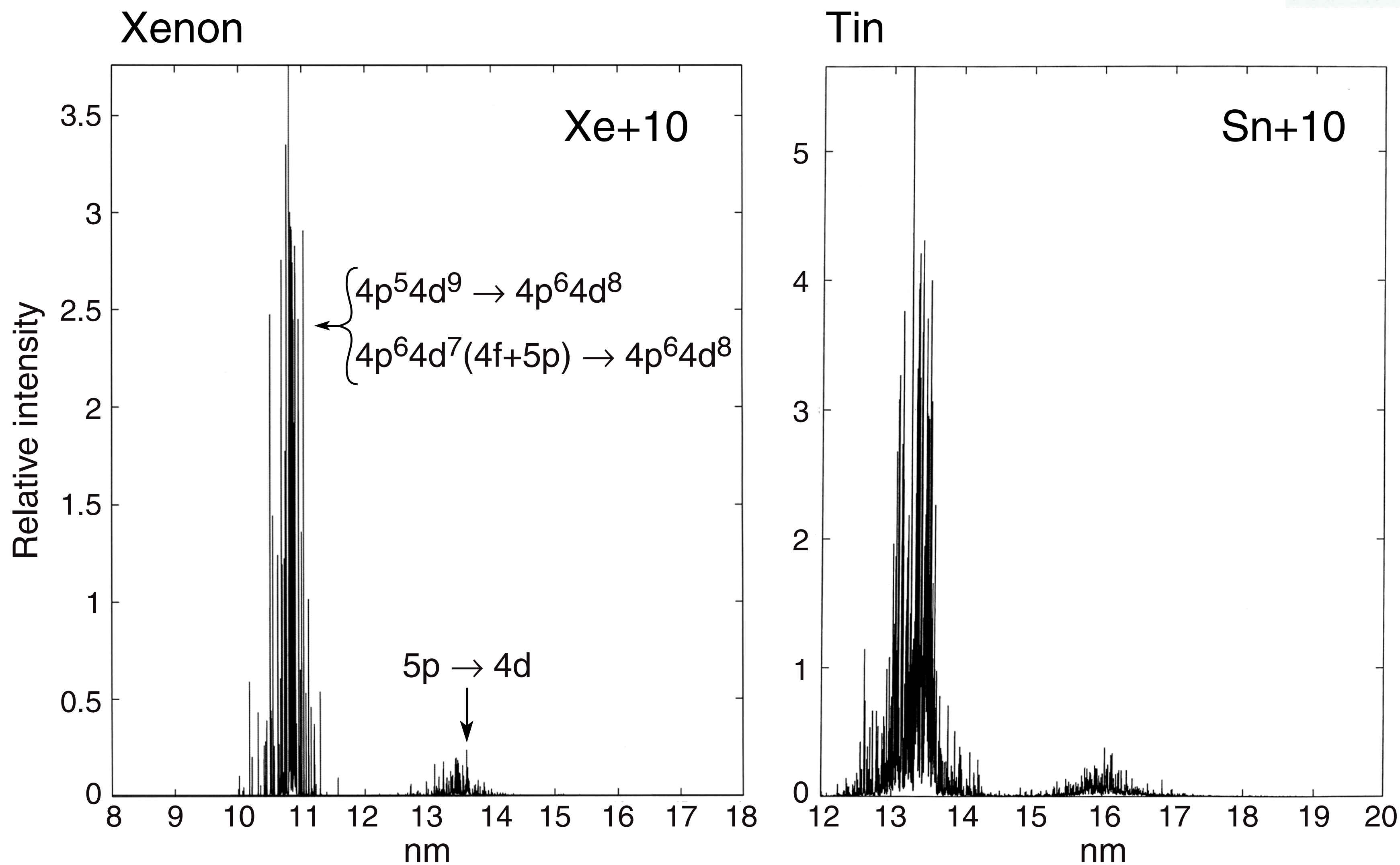
Typical EUV spectrum from a Xenon plasma in a capillary electrical discharge



References:

Blackburn J, Carroll P, Costello J and O'Sullivan G 1983 *J. Opt. Soc. Am.* **73** 1325
Gayasov R and Joshi Y 1998 *J. Phys. B* **31** L705
Kaufman V and Sugar J 1984 *J. Opt. Soc. Am.* B **1** 38
Kaufman V, Sugar J, and Tech J 1983 *J. Opt. Soc. Am.* **73** 691
Sugar J and Kaufman V 1982 *Physica Scripta* **26** 419
O'Sullivan G 1982 *J. Phys. B* **15** L765

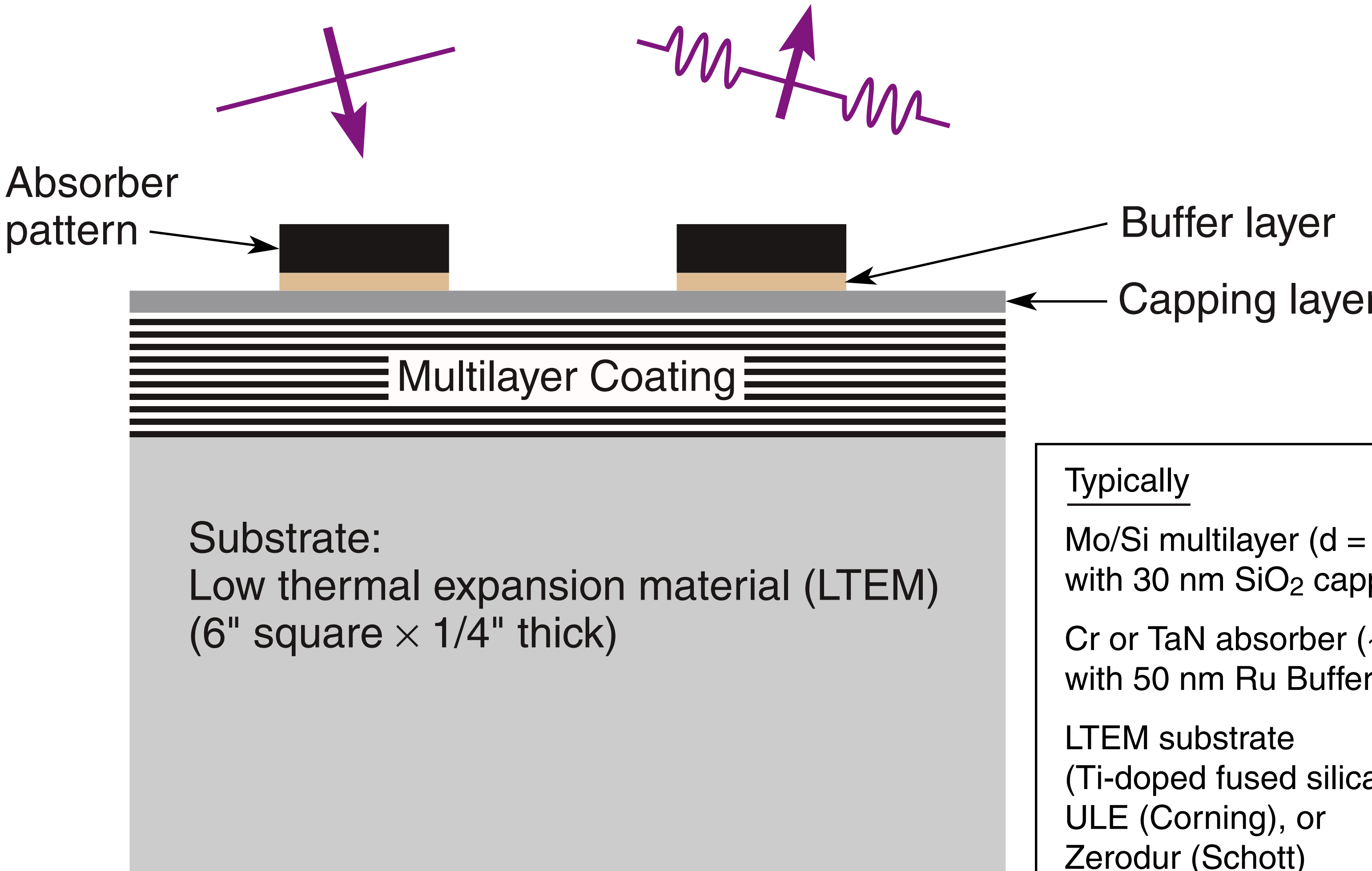
Comparative Spectra: Xe and Sn



- Debris is the issue

Courtesy of G. O'Sullivan (Univ. College Dublin)
R. Faulkner (UCD Ph.D, 1999)
A. Cummings (Nahond Univ. Ireland)

Reflective Mask for EUV Lithography



Typically

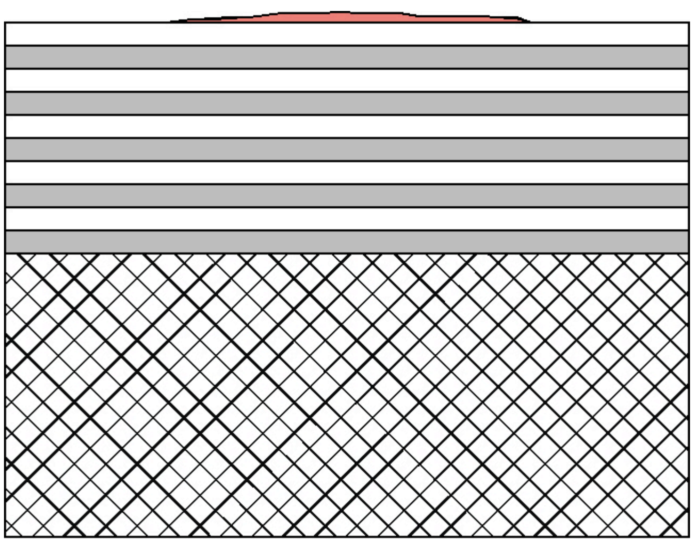
Mo/Si multilayer (d = 6.7 nm) with 30 nm SiO_2 capping layer

Cr or TaN absorber (~70 nm) with 50 nm Ru Buffer layer

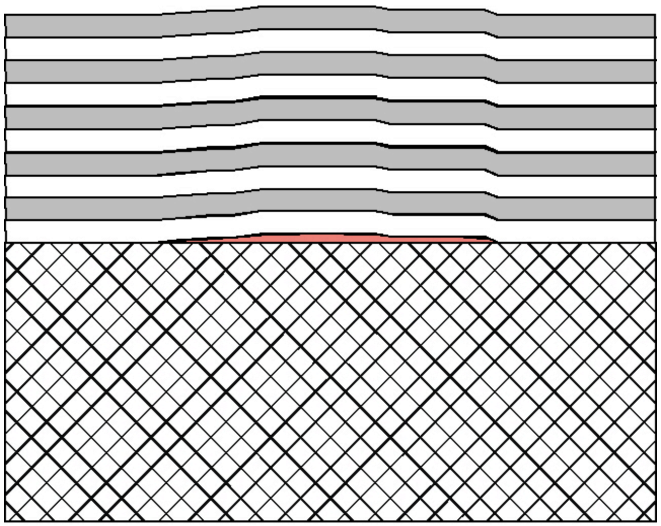
LTEM substrate
(Ti-doped fused silica)
ULE (Corning), or
Zerodur (Schott)

Mask Blank Defects Can Be On the Substrate Or Within the Stack

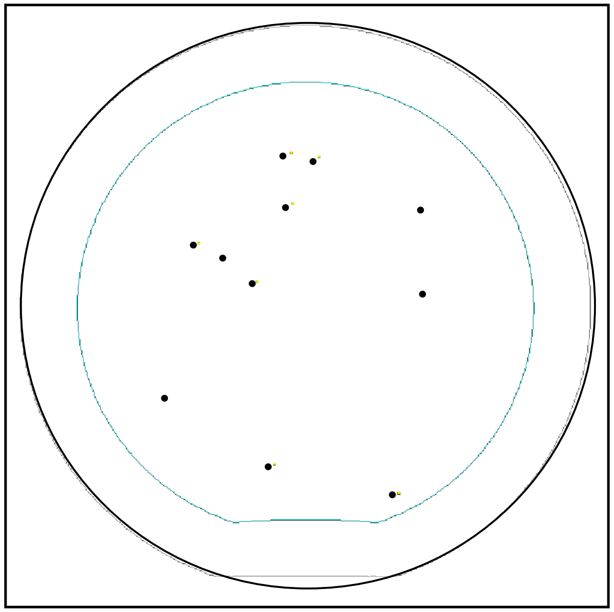
Amplitude Defect



Phase Defect

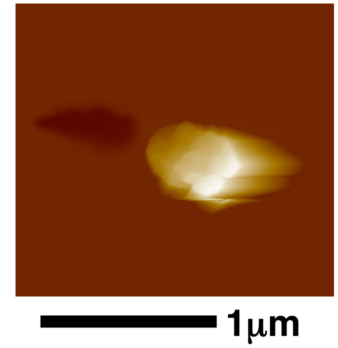


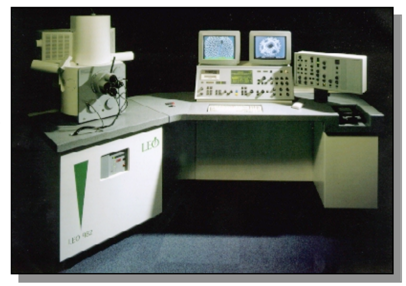
Defect Map Allows Correlation of Defects to Other Tools



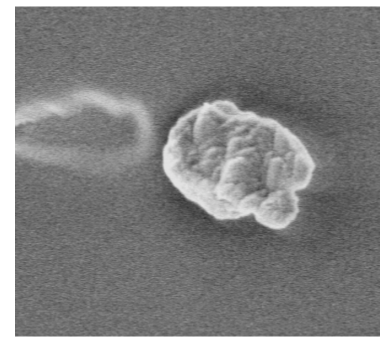
Defect map
of mask blank

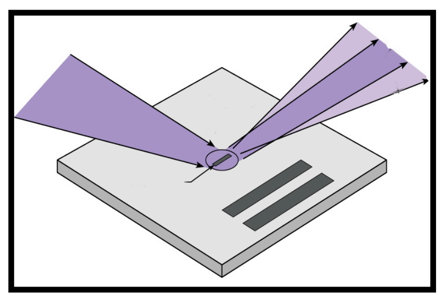
AFM



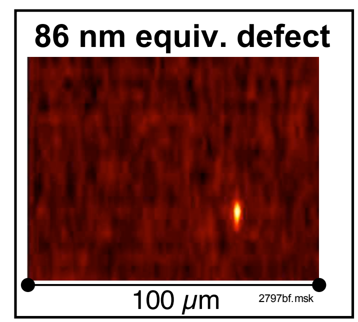


SEM



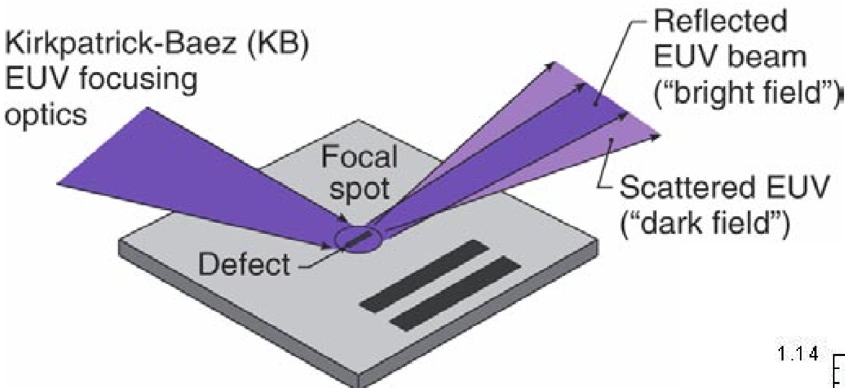


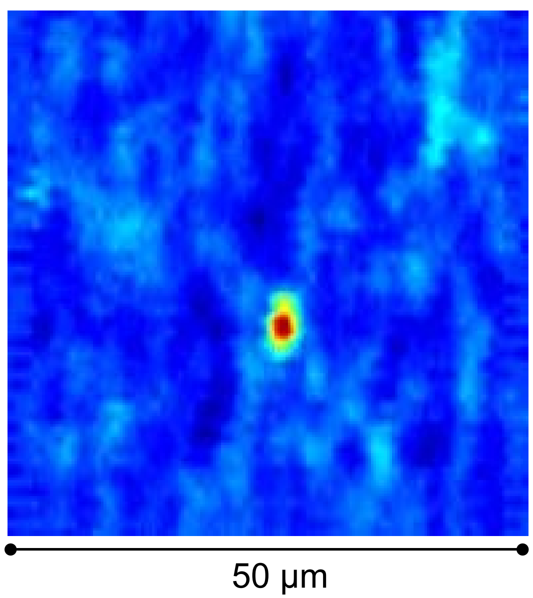
EUV Scatter

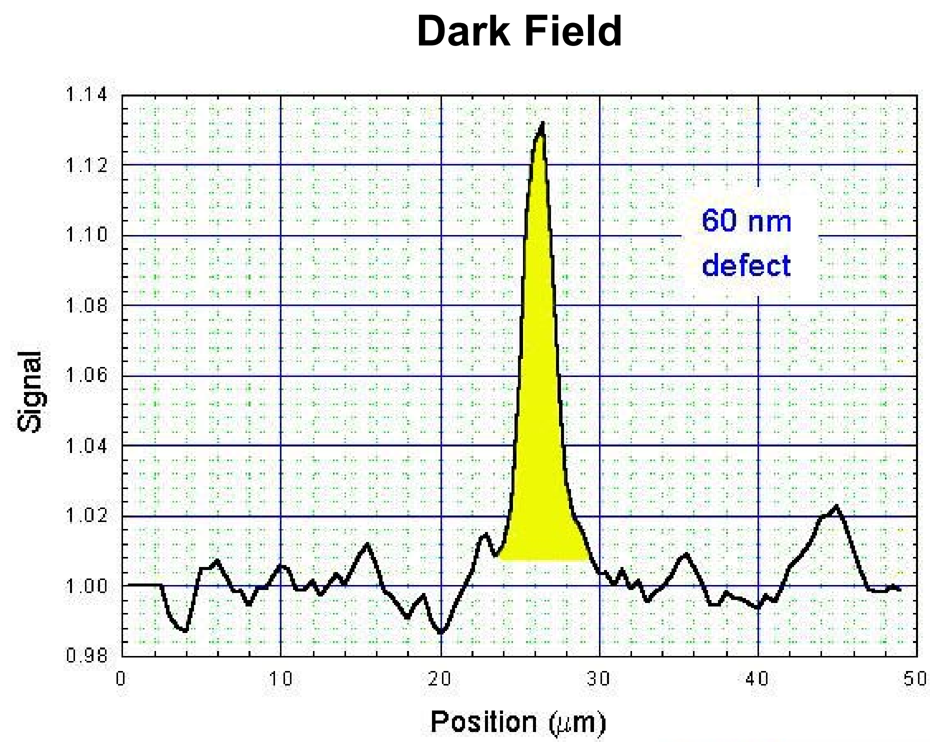


At-Wavelength Mask Blank Defect Inspection

- At-wavelength response to phase and opaque defects
- Correlation with conventional inspection tools



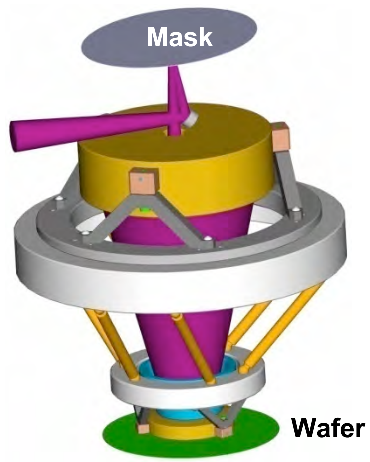




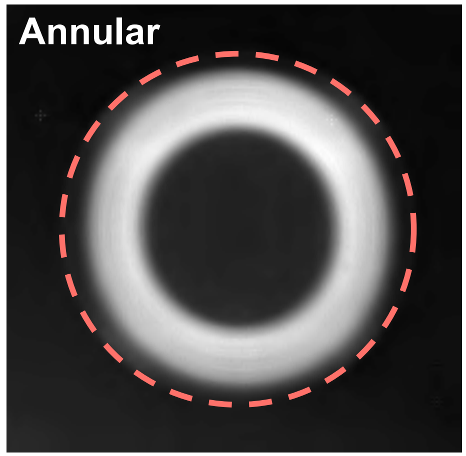
Courtesy of Moonsuk Yi (LBL) and J. Bokor (UCB/LBL).

Addressing critical EUV lithography issues for Sematech at the ALS: testing state-of-the-art EUV resists

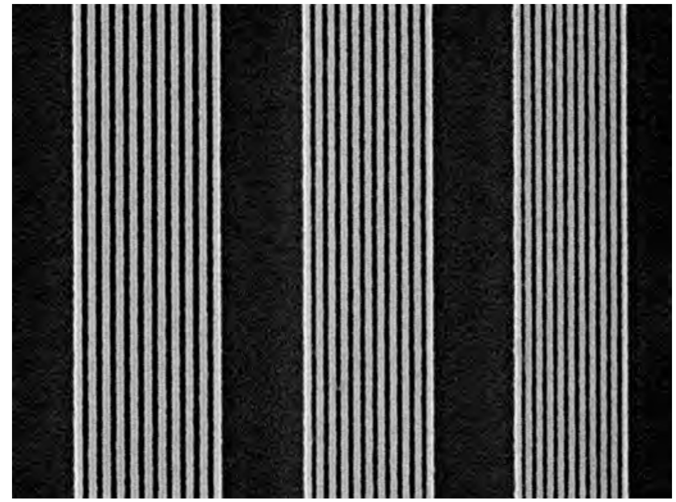
Two-bounce, 0.3 NA, MET at ALS Beamline 12.0



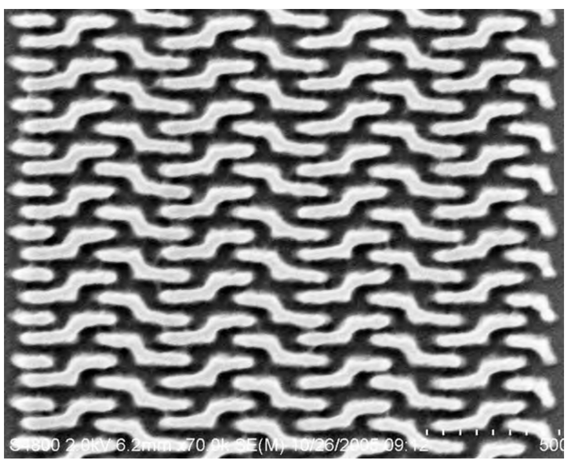
Programmable illumination



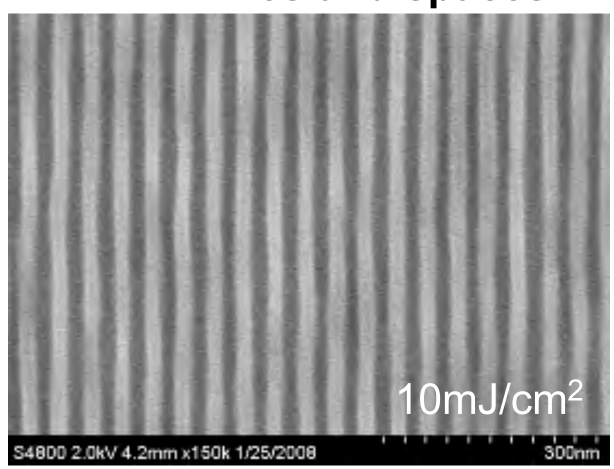
45 nm 40 nm 35 nm



35 nm



22 nm lines and spaces



Significant issue for EUV lithography

When will EUV resists be available with combined high spatial resolution (20 nm), high sensitivity (10 mj/cm^2), and low line edge roughness (LER, 1.2 nm)?

Major support and collaborators include Sematech, Intel, AMD, IBM, Samsung and others.
Courtesy of Patrick Naulleau, CXRO/LBNL.

Intel EUV MET Installation

Courtesy of Jeanette Roberts, Intel

J. Phys. D: Appl. Phys. (London) **37**, 3207(2004)

Plasma sources for EUV lithography exposure tools

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Abstract
The source is an integral part of an extreme ultraviolet lithography (EUVL) tool. Such a source, as well as the EUVL tool, has to fulfil extremely high demands both technical and cost oriented. The EUVL tool operates at a wavelength in the range 13–14 nm, which requires a major re-thinking of state-of-the-art lithography systems operating in the DUV range. The light production mechanism changes from conventional lamps and lasers to relatively high temperature emitting plasmas. The light transport, mainly refractive for DUV, should become reflective for EUV. The source specifications are derived from the customer requirements for the complete tool, which are: throughput, cost of ownership (CoO) and imaging quality. The EUVL system is considered as a follow up of the existing DUV based lithography technology and, while improving the feature resolution, it has to maintain high wafer throughput performance, which is driven by the overall CoO picture. This in turn puts quite high requirements on the collectable in-band power produced by an EUV source. Increased, due to improved feature resolution, critical dimension (CD) control requirements, together with reflective optics restrictions, necessitate pulse-to-pulse repeatability, spatial stability control and repetition rates, which are substantially better than those of current optical systems. All together the following aspects of the source specification will be addressed: the operating wavelength, the EUV power, the hot spot size, the collectable angle, the repetition rate, the pulse-to-pulse repeatability and the debris induced lifetime of components.

Table 2. Throughput case study.

EUV power (in-band, 2π)	1.0 kW
Transmission and collection efficiency	0.02%
Resist sensitivity	5 mJ cm^{-2}
Exposure time per wafer	23 s
Scan speed	170 mm s^{-1}
Throughput	100 wph

EUV Source Power Requirements are Set by Wafer Throughput Models

Updated EUV power and wafer throughput: **250 W** ~~120~~ **W**

Collectable EUV power ~~60~~ **W**

Collectable, in-band, "clean" (no debris, no out-of-band)

EUV Power @ reticle 3.5 W

Power @ wafer 140 mW

Illum. time per field 0.26 s

Illum. time per wafer 23 s

Raw wafer throughput ~~80~~ **wafers/hr**

120 wafers/hr

10 ~~5~~ **mj/cm^2 resist**
300 mm wafers
89 fields/wafer

Original courtesy of Jos Benschop and Vadim Banine, ASML.

J. Benschop et al., SPIE *3997*, 34 (2000),
V. Banine and R. Moors, SPIE *4343*, 203 (2002).

Ionization Energies for Xenon

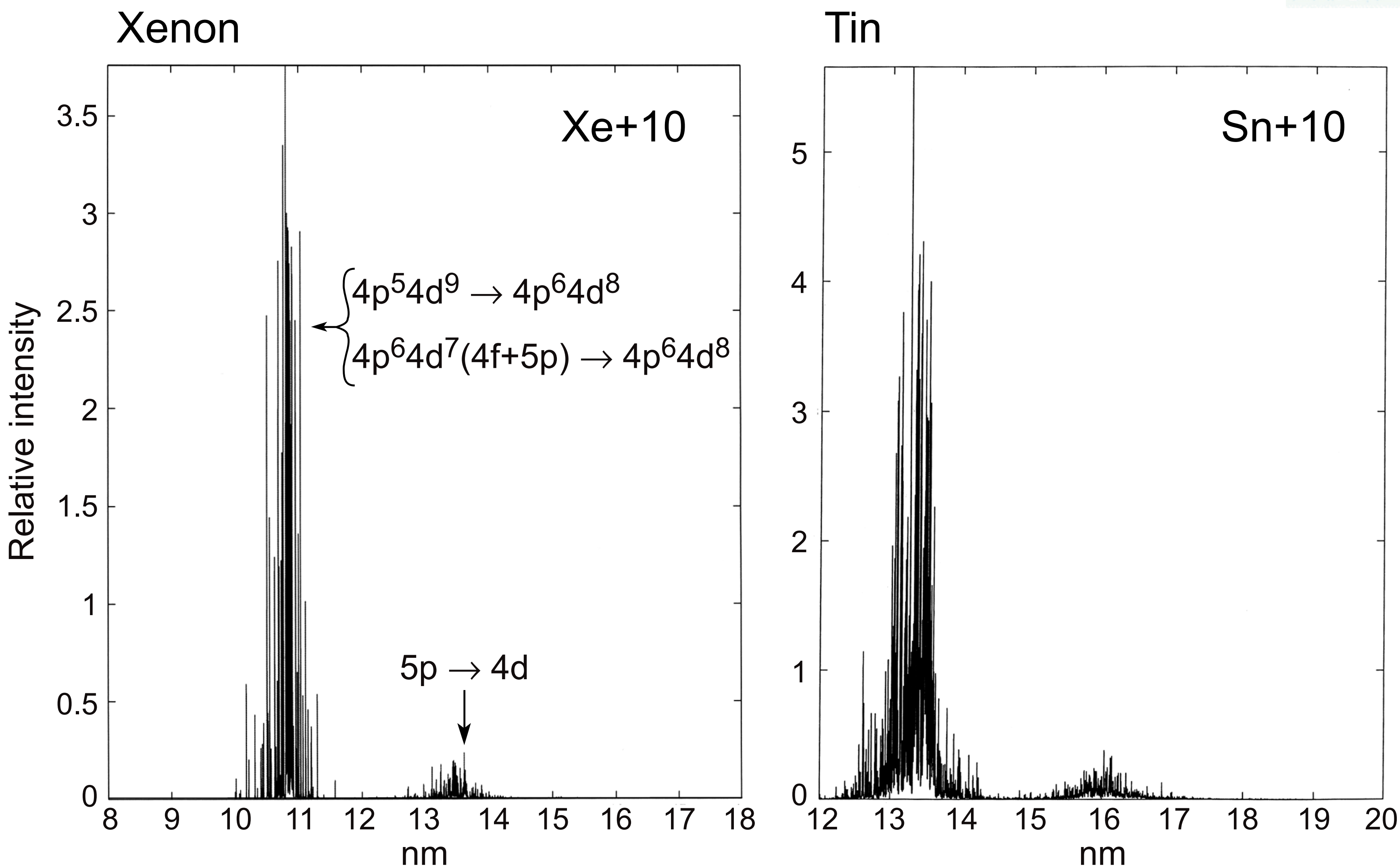
	Ionization energy (eV)									
Element	1 (H)	2 (He)	3 (Li)	4 (Be)	10 (Ne)	11 (Na)	12 (Mg)	27 (Co)	28 (Ni)	29 (Cu)
6 C	490.0	392.1	64.49	47.89						
7 N	667.1	552.1	97.89	77.48						
8 O	871.4	739.3	138.11	113.90						
9 F	1103.1	953.9	185.18	157.15						
10 Ne	1362.2	1195.8	239.09	207.26	21.564					
11 Na	1648.7	1465.1	299.86	264.21	47.286	5.139				
12 Mg	1962.7	1761.8	367.5	328.0	80.143	15.035	7.646			
13 Al	2304.2	2086.0	442.0	398.7	119.99	28.447	18.828			
14 Si	2673.2	2437.7	523.4	476.3	166.42	45.12	33.64			
15 P	3070	2816.9	611.7	560.8	220.31	65.02	51.80			
16 S	3494	3224	707.0	652.1	281.00	88.05	72.59			
17 Cl	3946	3658	809.2	750.5	348.5	114.20	96.84			
18 Ar	4426	4121	918.4	855.8	422.8	143.46	124.24			
19 K	4934	4611	1034.6	968.0	503.9	175.82	145.75			
20 Ca	5470	5129	1157.7	1087.3	591.9	211.28	188.38			
21 Sc	6034	5675	1288.0	1213.6	686.6	249.84	225.13			
22 Ti	6626	6249	1425.3	1346.9	788.2	291.50	264.98			
23 V	7246	6851	1569.7	1487.3	896.6	336.3	307.9			
24 Cr	7895	7482	1721.1	1634.8	1011.8	384.2	354.0			
25 Mn	8572	8141	1879.9	1789.5	1133.8	435.2	403.2			
⋮										
51 Sb	36668	35710	8670	8465	6717	2899.8	2819.2	1285	1215.3	693.2
52 Te	38177	37196	9041	8832	7025	3041	2958.1	1377	1306.3	746.1
53 I	39721	38716	9421	9207	7340	3185	3101	1472	1399.3	800.8
54 Xe	41300	40271	9810	9591	7663	3334	3247	1571	1495.4	857.4 . . .

Xenon (J. Gillaspy, NIST)

+11	+10	+9	+8	+7	+6	
43	44	45	46	47	48	e^-s
259	232	206	180	107	93	eV

Xe + 10 4f → 4d lines
are strong near 13.5 nm

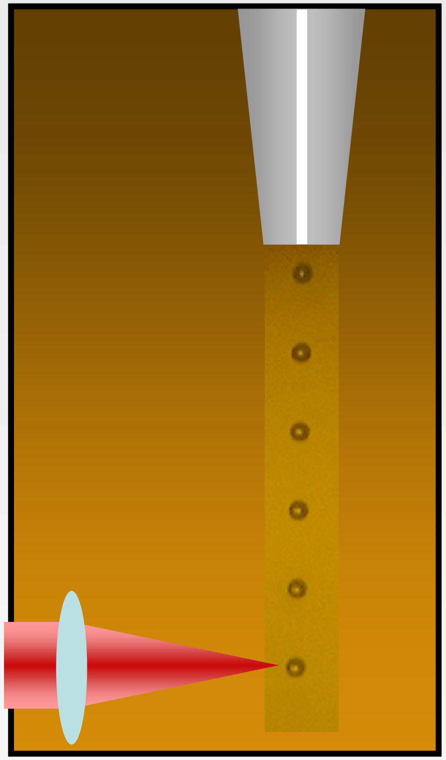
Comparative Spectra: Xe and Sn



- Debris is the issue

Courtesy of G. O'Sullivan (Univ. College Dublin)
R. Faulkner (UCD Ph.D, 1999)
A. Cummings (Nahond Univ. Ireland)

The UCF tin-doped droplet source



Martin Richardson

K. Takenoshita, C-S Koay, S. George, T. Schmid, S. Teerawattansook R. Bernath, C. Brown

Laser Plasma Laboratory
College of Optics and Photonics & CREOL, UCF

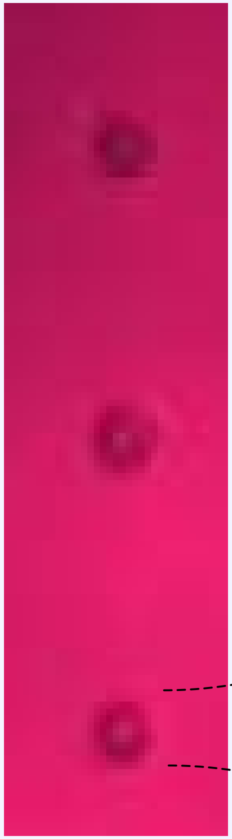
Moza Al-Rabban
Qatar University

Howard Scott
Lawrence Livermore National Laboratory

Vivek Bakshi
SEMATECH

Funded by SEMATECH, SRC Intel and the State of Florida

The tin-doped droplet laser plasma EUV source



Multi-component 30 -35 um diameter target at 30 kHz -- Location precision 3 um

Modest laser intensities I ~ 10^{11} W/cm^2

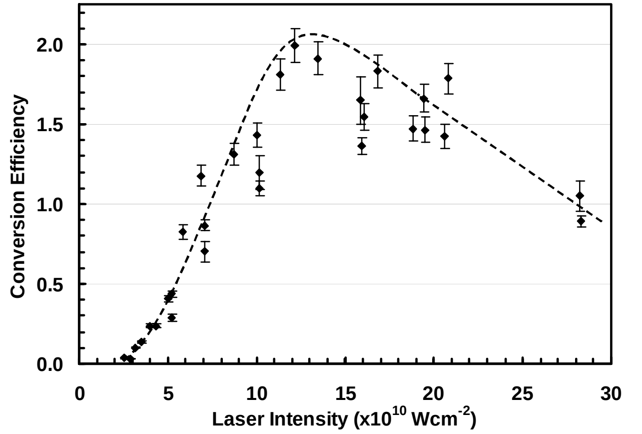
Mass-limited targets

Target contains only 10^{13} tin atoms

Recently demonstrated 30 kHz laser droplet irradiation with intelligent feedback beam and target control – continuous operation for 8 hours

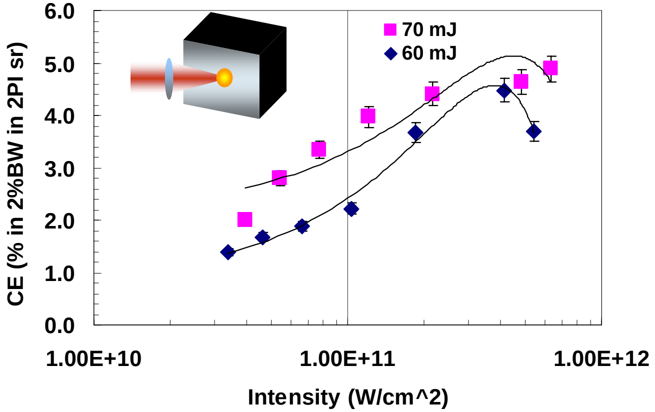
High CE demonstrated with Droplet Target

CE = 2% at 13.5 nm for tin-doped droplet target source

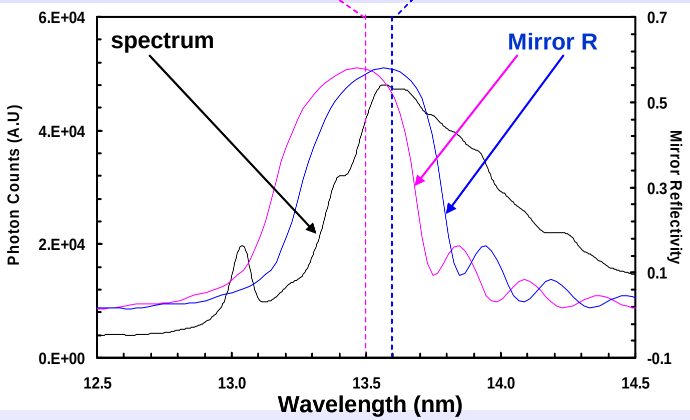


FOM FC2 team
F. Bijkerk S.A. vd Westen C. Bruineman

CE = 5.5 % with solid tin!



at 13.5nm, CE = 2% at 13.6nm, CE = 2.25%

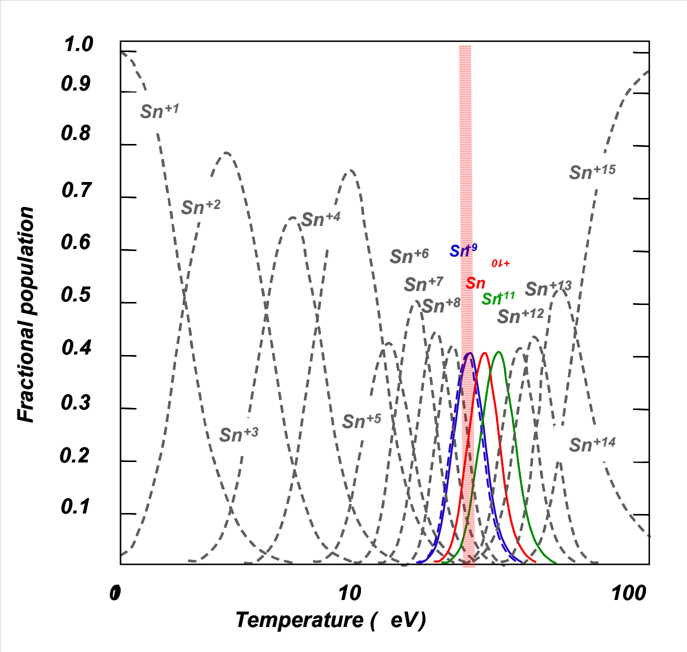


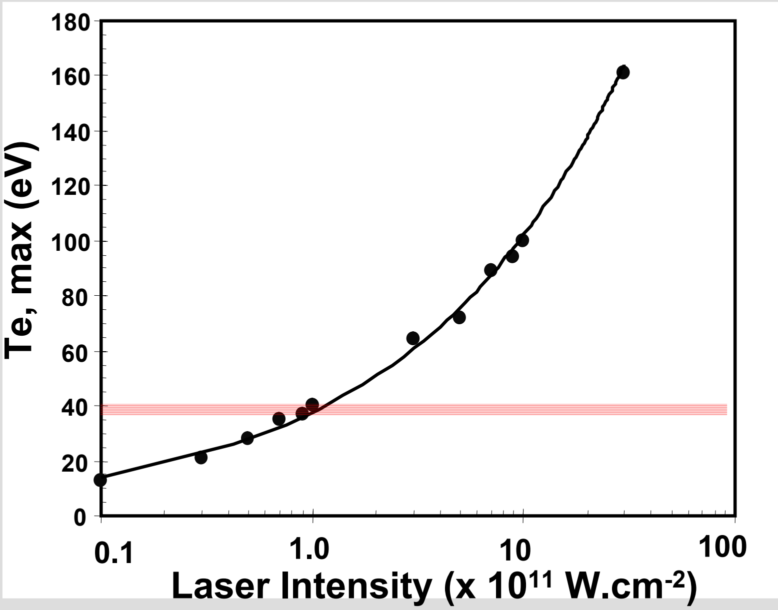
CE = 3% achievable with droplet source

--- for 30 kHz, 140 mJ laser

→ 120 W / 2π

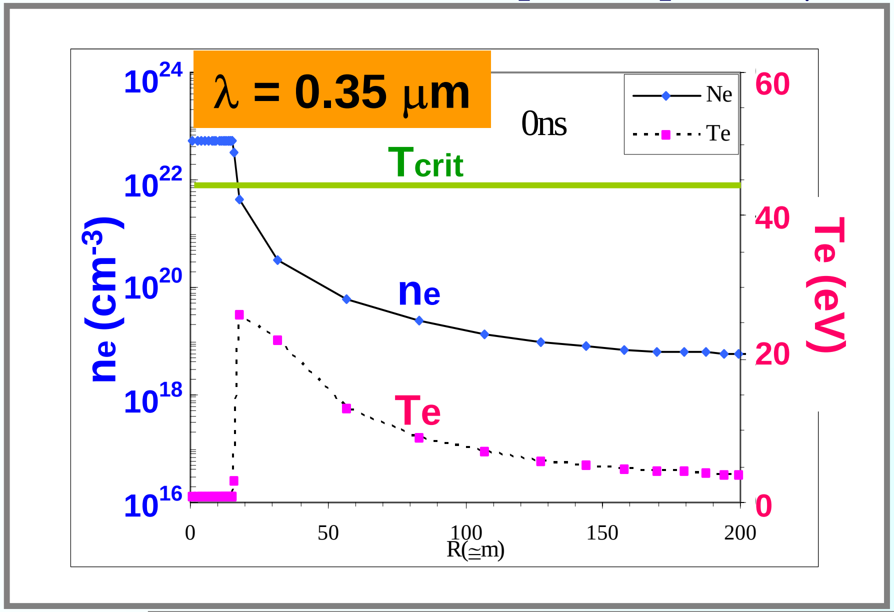
We can now manipulate the UTA emission spectrum

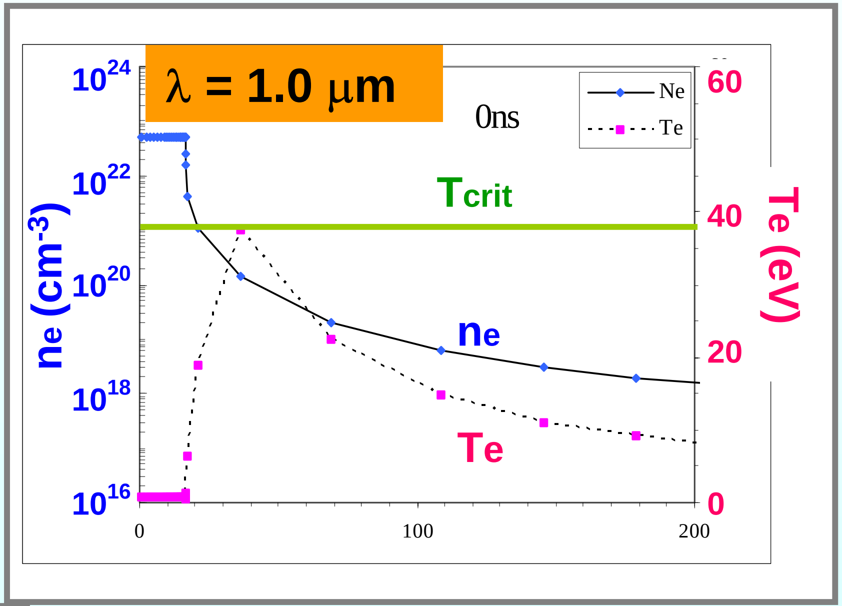


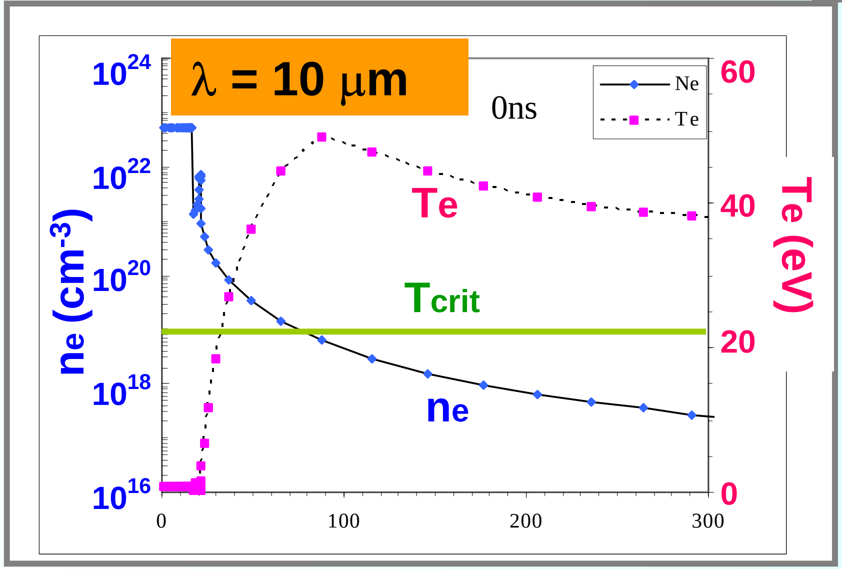


Conversion efficiency - Tin with other laser wavelengths

Condition: Tin-doped droplet, 35 μm dia, 10ns pulse, I = 1.0 x 10^{11} W/cm^2



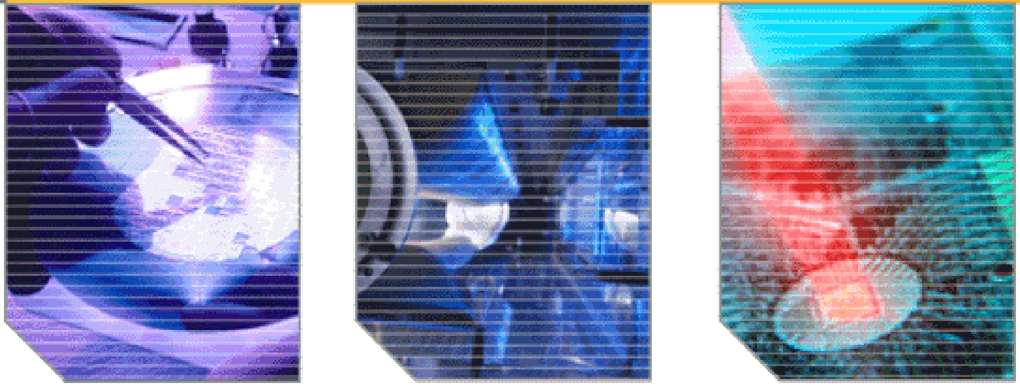




0.35μm: Te - Higher laser intensities required

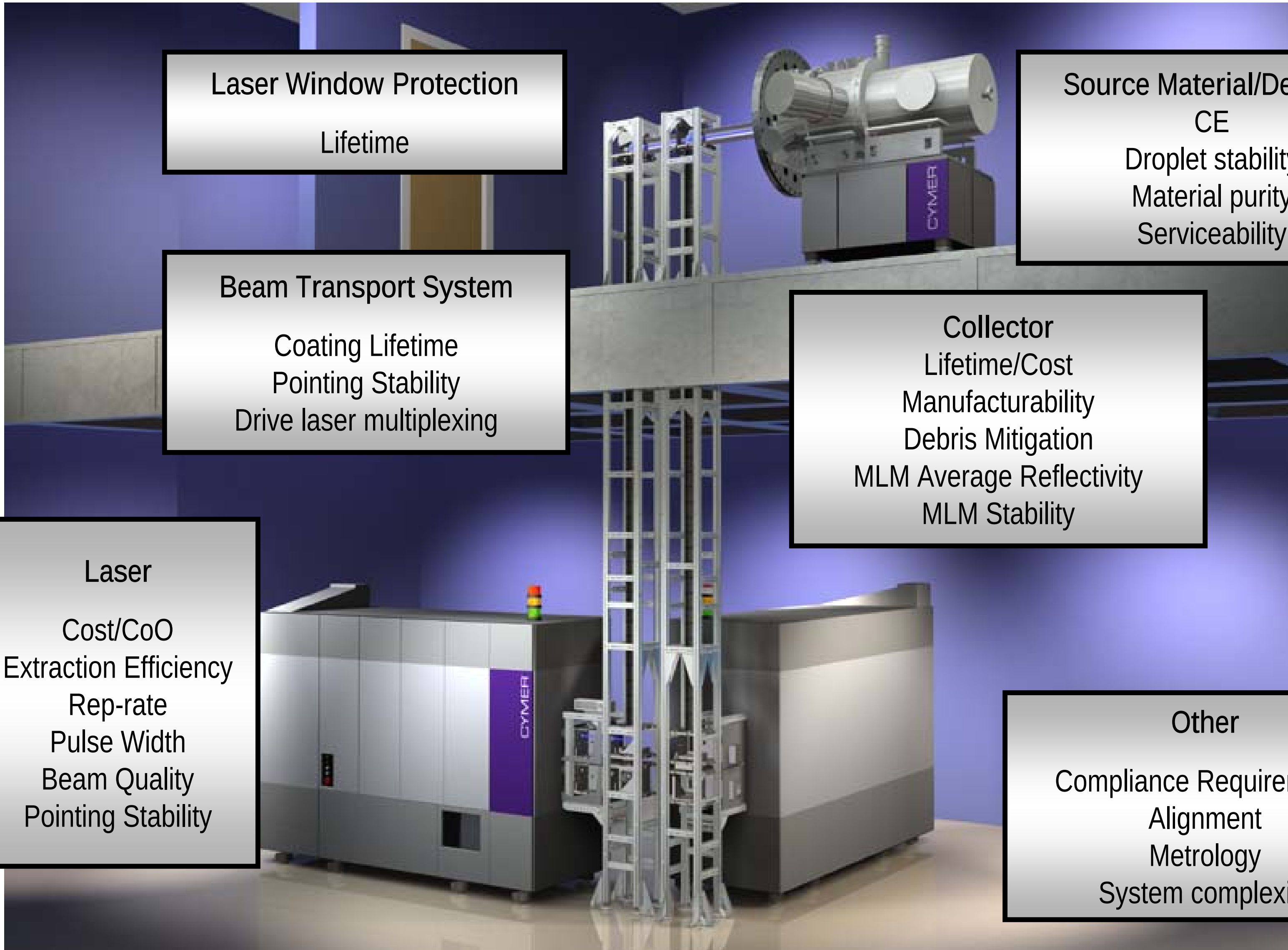
10μm: -Emission comes from lower n_e region

EUV Source System Development Update: Advancing Along the Path to HVM



I.V. Fomenkov, D.W. Myers, B.A. Hansson, D.C. Brandt, A. Ershov, B. Klene

Development of a Laser Produce Plasma EUV Source has Significant Challenges



Laser Window Protection

Lifetime

Beam Transport System

Coating Lifetime
Pointing Stability
Drive laser multiplexing

Laser

Cost/CoO
Extraction Efficiency
Rep-rate
Pulse Width
Beam Quality
Pointing Stability

Source Material/Delivery

CE
Droplet stability
Material purity
Serviceability

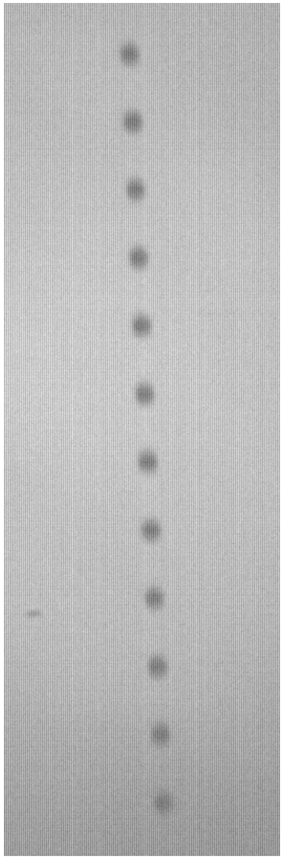
Collector

Lifetime/Cost
Manufacturability
Debris Mitigation
MLM Average Reflectivity
MLM Stability

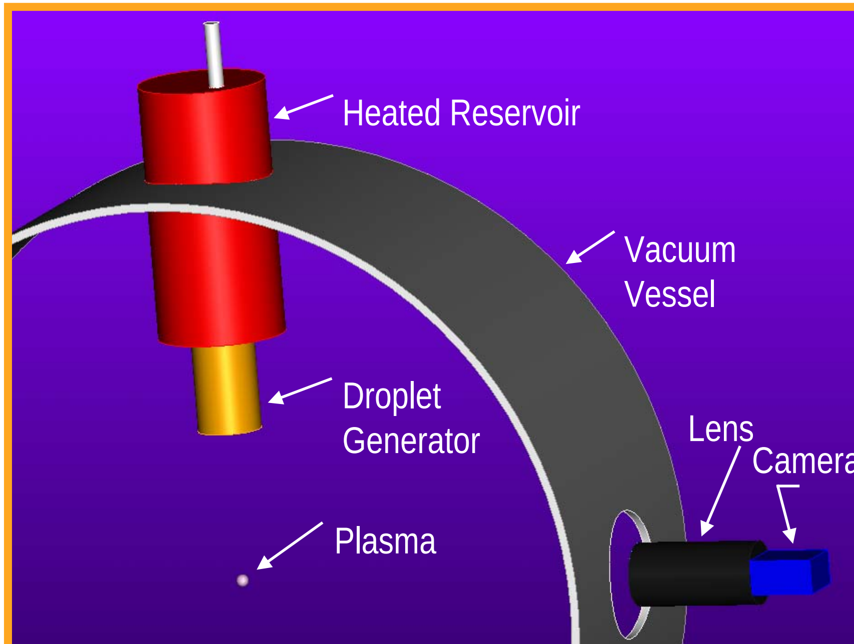
Other

Compliance Requirements
Alignment
Metrology
System complexity

Liquid Metal Droplet Generator Developed



100 μm Sn droplets at 36 kHz, captured using strobe lighting



- Continuous stimulated droplet generation of liquid metals (Li and Sn) at temperatures up to 250°C
- Droplets diameter $\leq$100 μm
- Droplet rates up to 48 kHz
- Working distance of 50mm

Ref: Poster #5751-108, Algots, Cymer

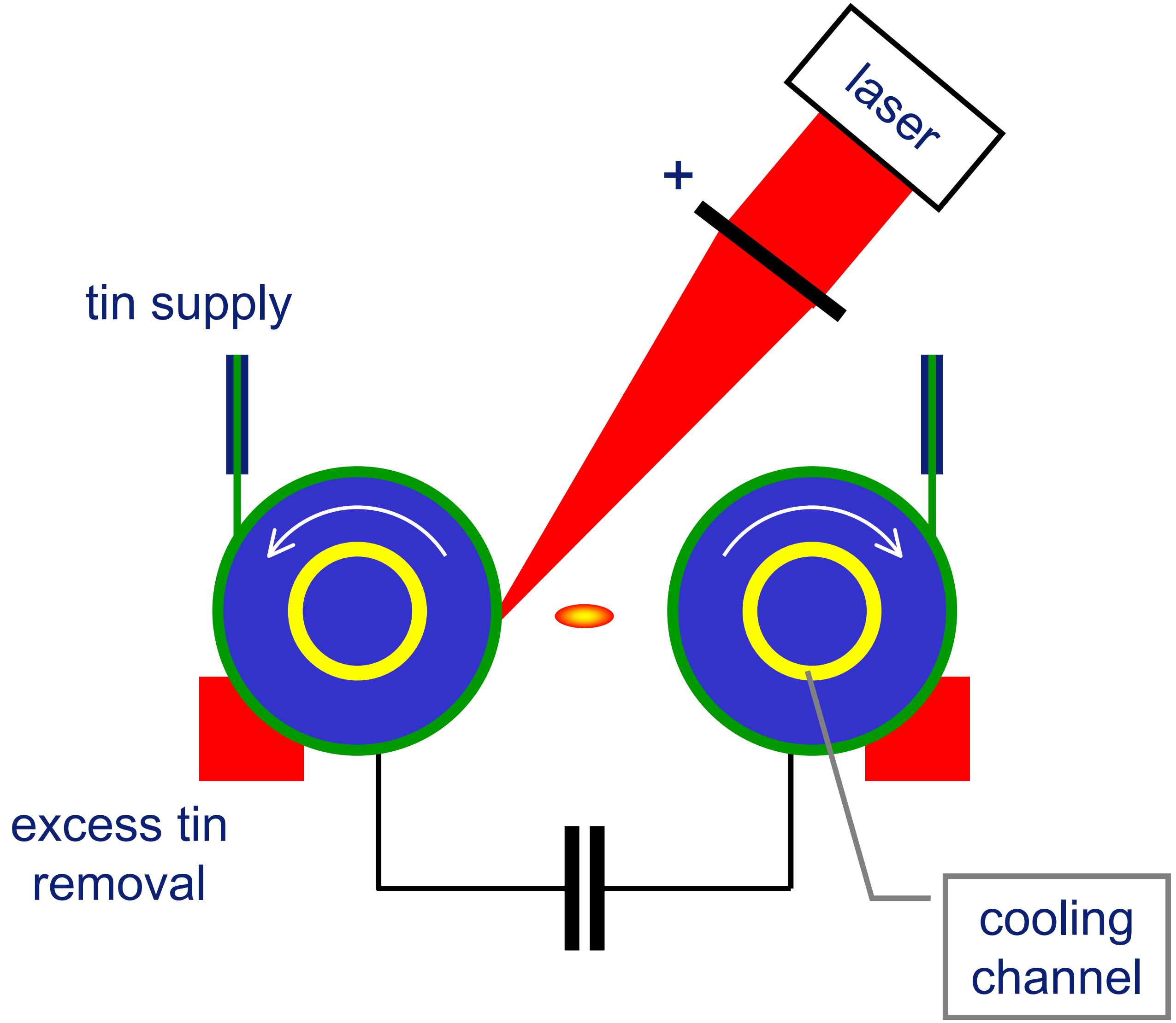
PHILIPS

Philips's EUV Source:

Update and Issues

J. Pankert,
EUV Source Workshop
San Jose 2005

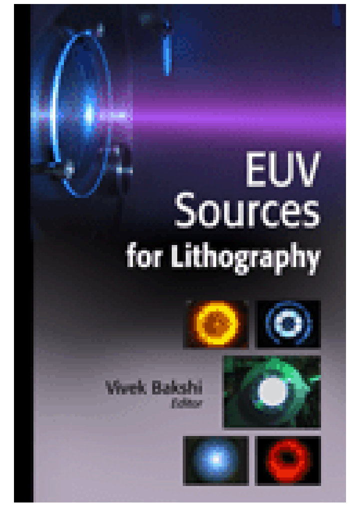
Schematics of the source



Summary of the properties

- Electrodes
  - Rotating: scalability to very high powers
  - Regenerative electrodes:
    - Liquid tin surface
    - Erosion problem fundamentally solved
- General properties
  - CE 2%
  - Pinch size < 1mm
  - 5 kHz demonstrated
  - 120 W continuous operation
  - 260 W short term (limited by vacuum vessel)

EUV Sources for Lithography (SPIE, November 2005)
Vivek Bakshi, Editor



This comprehensive volume, edited by a senior technical staff member at SEMATECH, is the authoritative reference book on EUV source technology. The volume contains 38 chapters contributed by leading researchers and suppliers in the EUV source field. Topics range from a state-of-the-art overview and in-depth explanation of EUV source requirements, to fundamental atomic data and theoretical models of EUV sources based on discharge-produced plasmas (DPPs) and laser-produced plasmas (LPPs), to a description of prominent DPP and LPP designs and other technologies for producing EUV radiation. Additional topics include EUV source metrology and components (collectors, electrodes), debris mitigation, and mechanisms of component erosion in EUV sources. The volume is intended to meet the needs of both practitioners of the technology and readers seeking an introduction to the subject.

Prices: $127 / $150 (SPIE Member/List)
(Available November 2005)