High brightness EUV & soft-X-ray MPP discharge source system development

Peter Choi, Sergey V. Zakharov, Raul Aliaga-Rossel,
Aldrice Bakouboula, Otman Benali, Philippe Bove, Michèle Cau,
Grainne Duffy, Blair Lebert, Keith Powell, Ouassima Sarroukh,
Clement Zaepffel, Vasily S. Zakharov,

NANO-UV sas
EPPRA sas

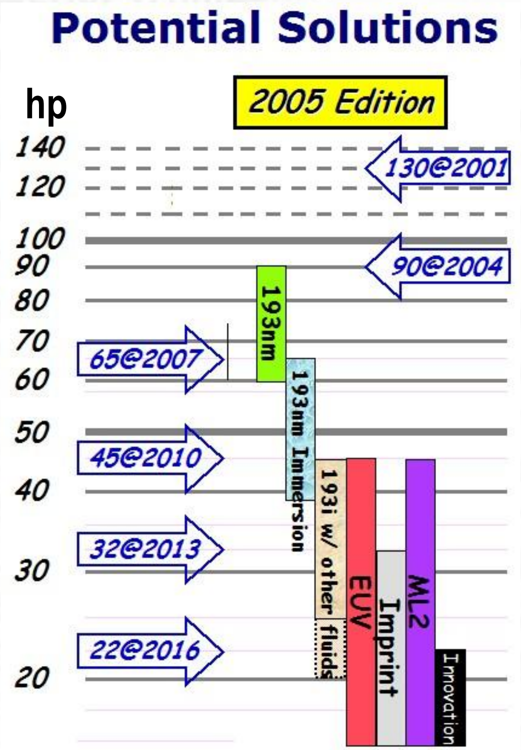
EUV Sources for EUV Lithography

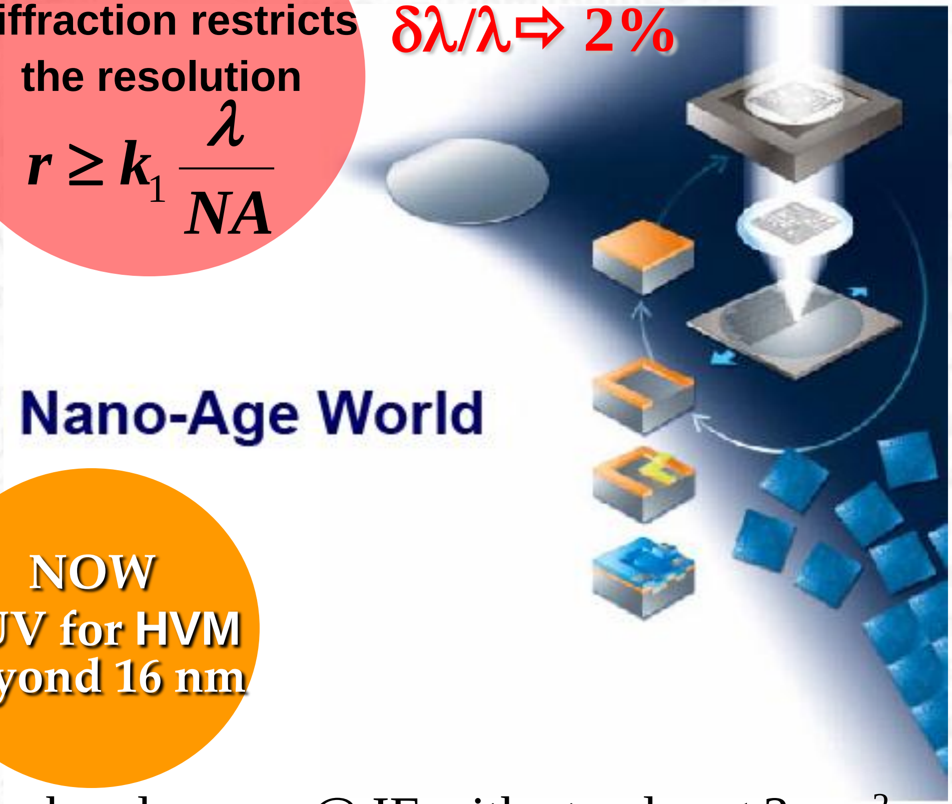
λ⇨ 13.5nm ($h\nu$=92eV)

$\delta\lambda/\lambda$⇨ 2%

Diffraction restricts the resolution

$$r \geq k_1 \frac{\lambda}{NA}$$





NOW
EUV for HVM
beyond 16 nm

- For HVM - 200-500 W of in-band power @ IF with etendue < 3mm^{2}sr
- For mask inspections ABI→AIMS→APMI – 10 →100 →1000 W/mm^2·sr

EUV source for HVM & actinic mask inspection
- a key challenge facing the industry

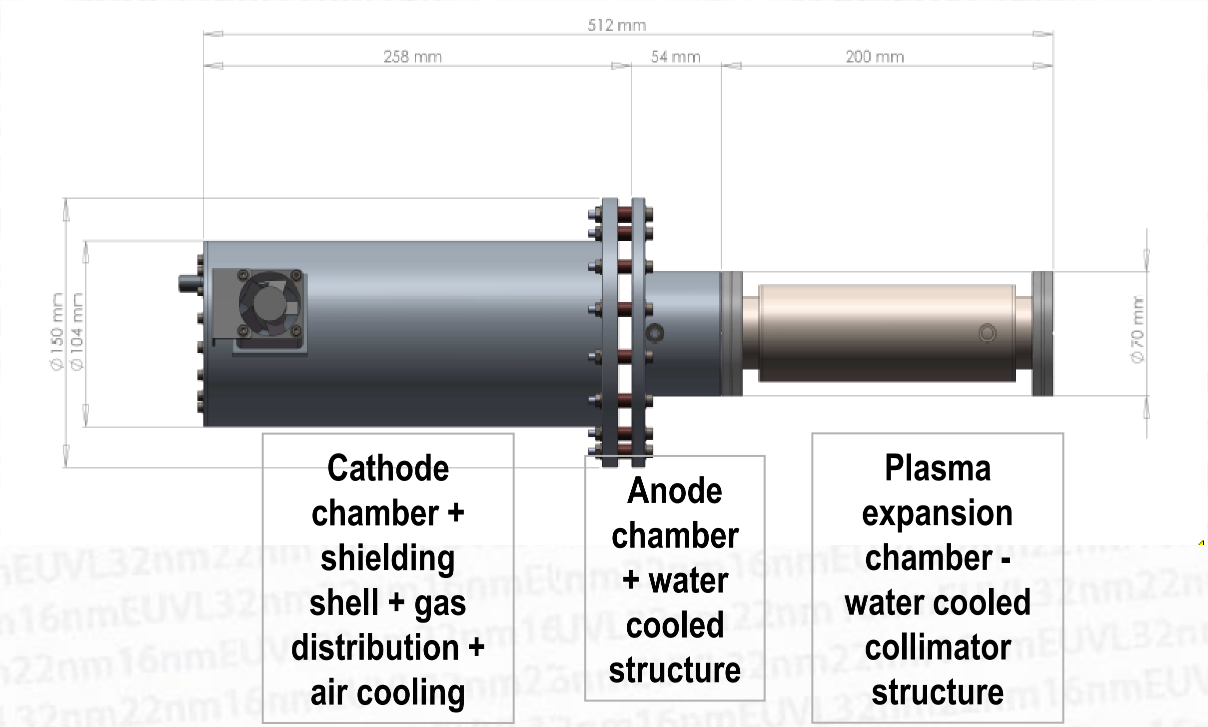
Nano-UV: Current Product Development

- Generic Source Products
  - high brightness unit source - CYCLOPS™ -B
  - high brightness multiplexed source - HYDRA™ -B
  - high power multiplexed source - HYDRA™ -P

- Research Metrology Products
  - Nano-patterning Resists Exposure Tool - GeNI™
  - Soft X-ray In Vitro Microscope - McXI™
  - EUV Mask Inspection Microscope - McEUVI™

2011
International
Workshop
on EUV
Lithography
June 13-17
Maui, Hawaii,
USA

i-SoCoMo™ - cell



Cathode chamber + shielding shell + gas distribution + air cooling

Anode chamber + water cooled structure

Plasma expansion chamber - water cooled collimator structure

Physical Dimensions:

- Source : 150 mm diameter, 520 mm length, 7 kg
- Instrument rack : 1300 x 600 x 800 mm, 200 kg

Utility requirements:

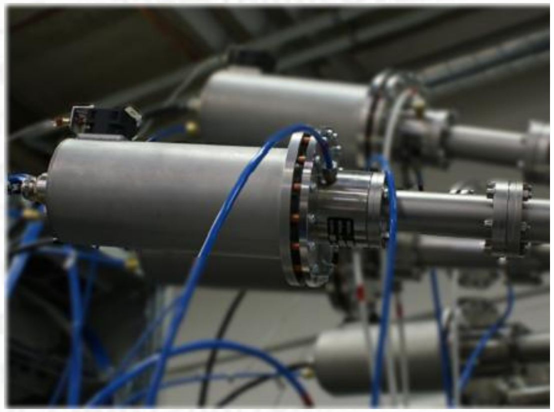
- Electrical : 200-240V, 2Ø, 50/60 Hz, 16A
- Cooling : Water cooled (2 litres per minute, 15°C - 25°C inlet)
- He, N_2 and Xe : 3 bar inlet

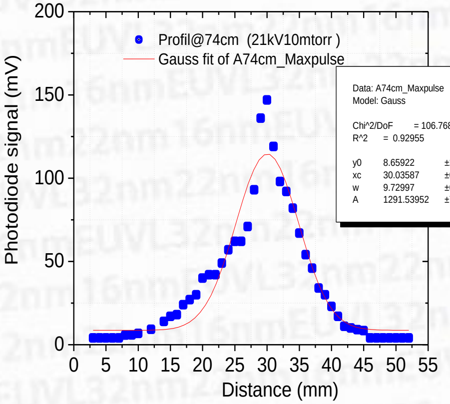
Nano-UV: EUV Source

micro - pulsed plasma

MPP Performance @ 21kV

- with SXUV20 A Mo/Si (350/500 nm) filtered diode from IRD
- 3 nm EUV band (12.4 nm -15.4 nm)
- Al coated (110 nm) on Si_3N_4 (250 nm) to reject OoB
- 200µm pinhole aperture in front of the diode
- typical etendue 1.7 10^{-2} mm^2.sr
- Discharge in He/N_2/Xe admixture, total Flow 3.2 sccm/min
- Cell capacity 1.7nF



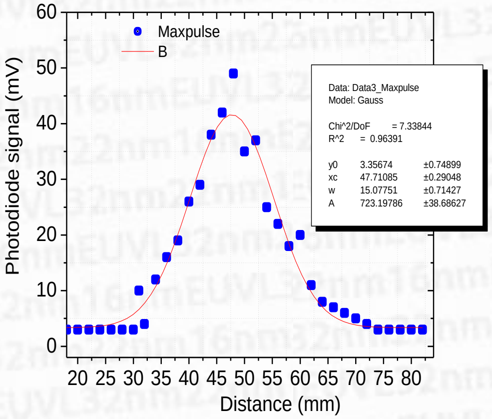


Data: A74cm_Maxpulse
Model: Gauss

Chi^2/DoF = 106.76808
R^2 = 0.92955

y0	8.65922	±2.19153
xc	30.03587	±0.22859
w	9.72997	±0.53783
A	1291.53952	±77.22706

Scanned signal profile @ 74cm



Data: Data3_Maxpulse
Model: Gauss

Chi^2/DoF = 7.33844
R^2 = 0.96391

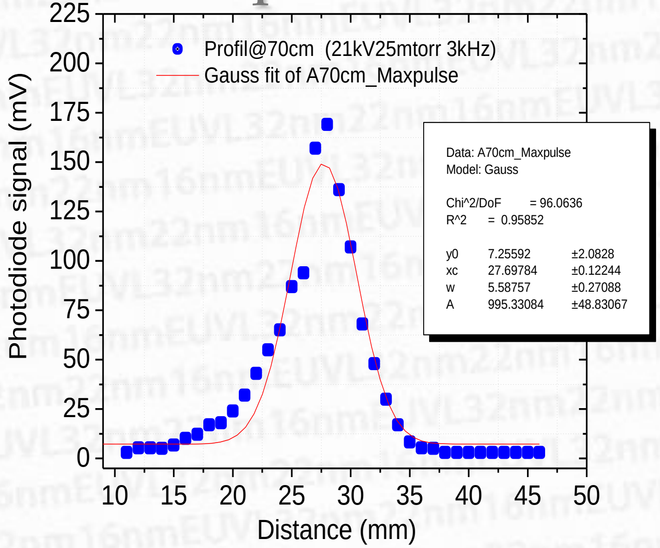
y0	3.35674	±0.74899
xc	47.71085	±0.29048
w	15.07751	±0.71427
A	723.19786	±38.68627

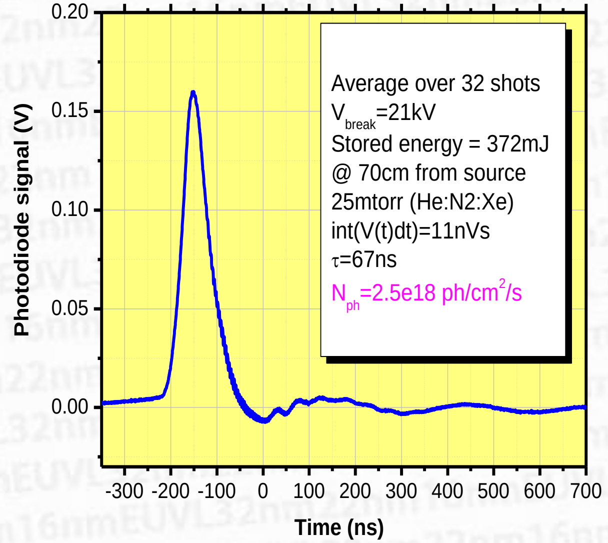
Scanned signal profile @ 98cm

Distance source to diode (cm)	Irrandiance @ 1kHz Ph/cm²/s	Beam HWHM (mm)	Radiation half angle divergence θ (deg)
74	8.2e17	6.13	0.8
98	1.8e17	9.65	
Radiation solid angle = 2*π (1-cosθ)= 6e-4 sr			

Source Characteristics I-a

- 3kHz repetition rate





Consider:

- Gaussian distribution of the beam (s = 2.8mm, W=5.6mm)
- Radial symmetry
- Discretize profile into rings with size = s /20

Use measured parameters:

- filter Si_3N_4 (100nm) + Al (110nm)
- 2000 TEM grid of 36% transmission
- given diode quantum efficiency 1.1 e^-/ph
- limiting aperture: 150µm pinhole diameter
- diode signal = 11 nV.s

At 70cm, 21kV, **3kHz**, EUV band 3nm (12.4nm -15.4nm) radiation:

- Peak irradiance ⇒ **2.5 E18 ph/cm^2/s** ⇒ **37W/cm^2**
- power in beam spot (1/e^2) ⇒ **16W**

Data presented at Kobe October 2010

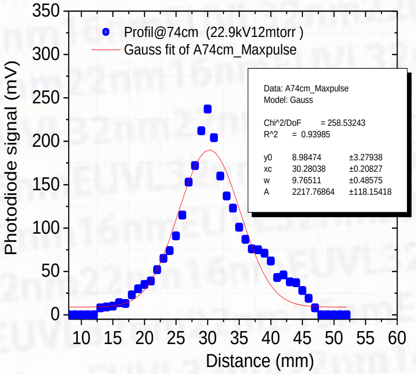
2011
International
Workshop
on EUV
Lithography
June 13-17
Maui, Hawaii,
USA

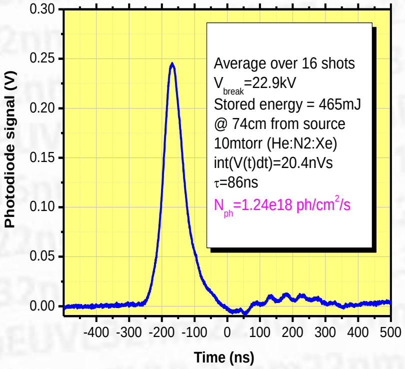
Source Characteristics I-b

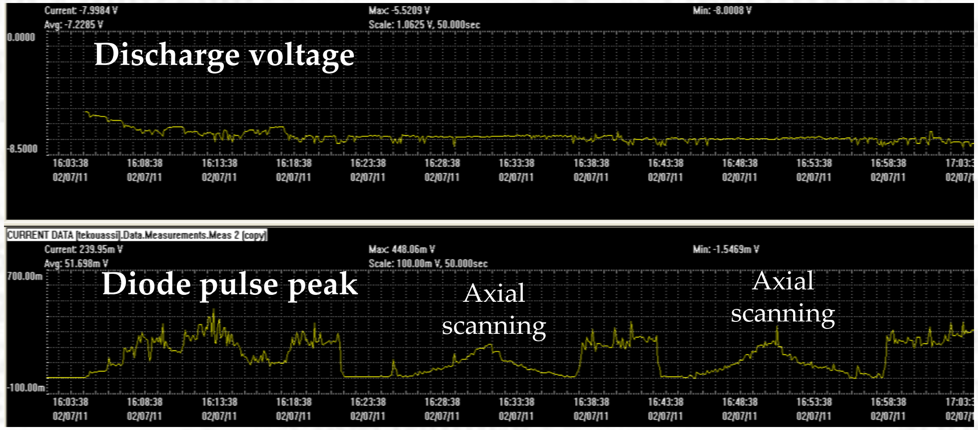
- 1kHz repetition rate

Measurement parameters

- Average mode over 16 shots:
- Source capacity =1.7nF
- Working pressure= 10mtorr (He:N_2:Xe mixture) with Flow=3.2sccm/min
- Distance between diode and the capillary=74cm
- Diode quantum efficiency @ 13.5nm=1.1e/ph
- Diode filter transmission band= 3nm (12.4-15.4nm)
- Al coated (110 nm) on Si_3N_4 (250 nm) to reject OoB
- Tin alloy cathode







StripChart
during the profile scan acquisition

At 74cm, 22.9kV, **1kHz**, EUV band

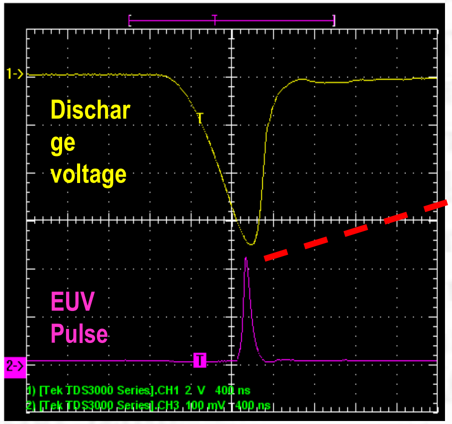
3nm (12.4nm -15.4nm) radiation:

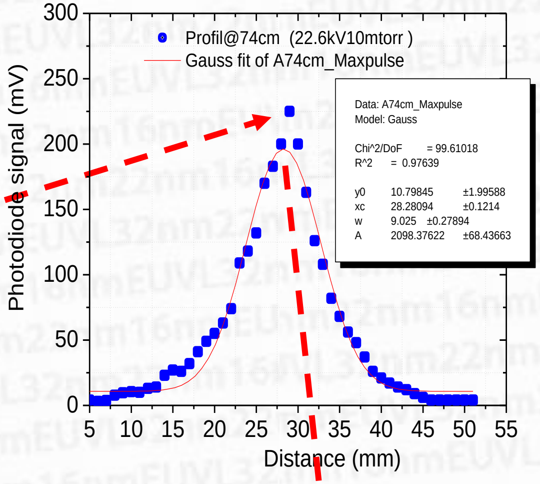
- Peak irradiance ⇒ **1.24 E18 ph/cm²/s**
- Power ⇒ **22W**

Champion Data

Source Characteristics II

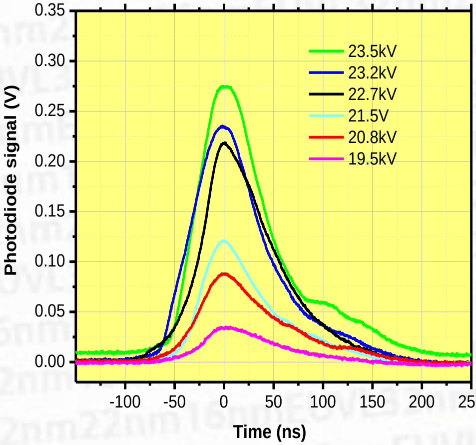
- irradiance & power vs stored energy



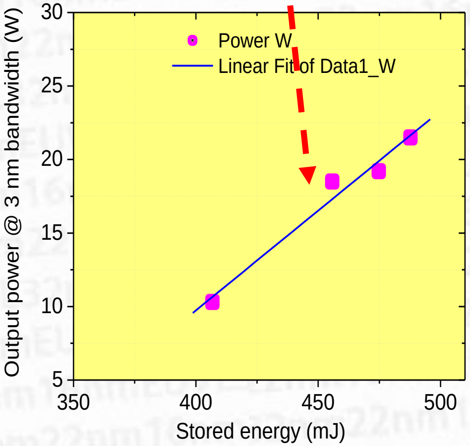


At 74 cm, 22.6 kV, 450mJ, 1 kHz, (3nm EUV band):

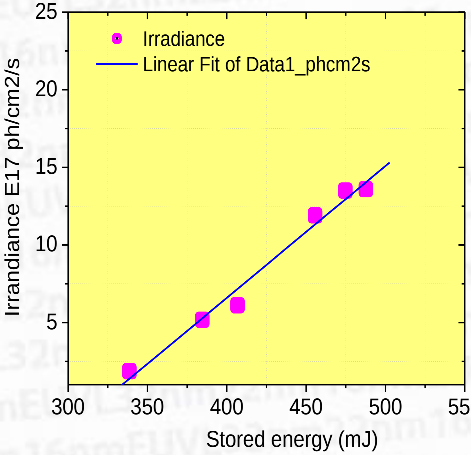
- **Peak irradiance 1.19 E18 ph/cm²/s**
- **Sigma: 4.01 mm**
- **Power: 18.5W**



Photodiode pulse over 16 shots



3nm EUV band power versus stored energy



Irradiance versus stored energy

Output power and irradiance increase with increasing stored energy

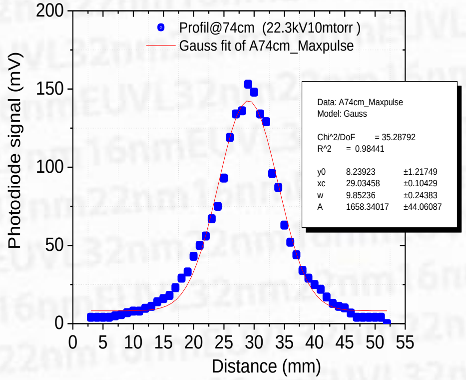
Source Structure Tuning

- different cathode materials

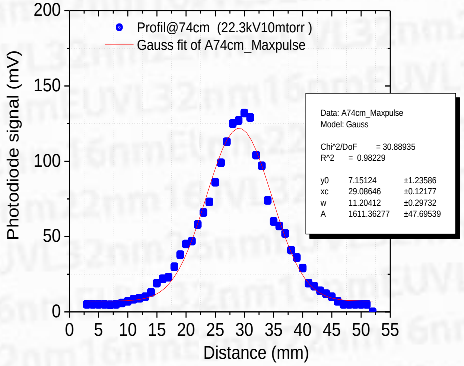
Measured Parameters

SXUV20 A Mo/Si (350/500 nm) filtered diode from IRD, 3 nm EUV band (12.4 nm - 15.4 nm), Al coated (110 nm) on Si_3N_4 (250 nm) to reject OoB, typical etendue 1.7 E-2 mm^2.sr, discharge in $He/N_2/Xe$ admixture with a total Flow 3.2 sccm/min, Cell capacity 1.7nF, Stored energy 440mJ.

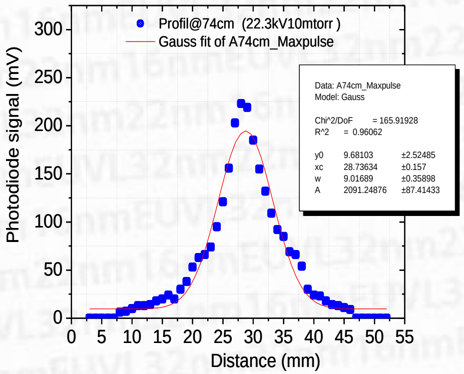
Al -alloy cathode



SS cathode



Sn-alloy cathode



- irradiance at 74cm, 10mtorr and <u>**22.3kV**</u>- **7.4e17 ph/cm²/s at 1 kHz**

  Power= 13.7W

  Sigma= 4.92mm

- irradiance at 74cm, 10mtorr and <u>**22.3kV-**</u> **6.9e17 ph/cm²/s at 1 kHz**

  Power= 16.3W

  Sigma= 5.6mm

- irradiance at 74cm, 10mtorr and <u>**22.3kV**</u>- **1.1e18 ph/cm²/s at 1 kHz**

  Power= 18W

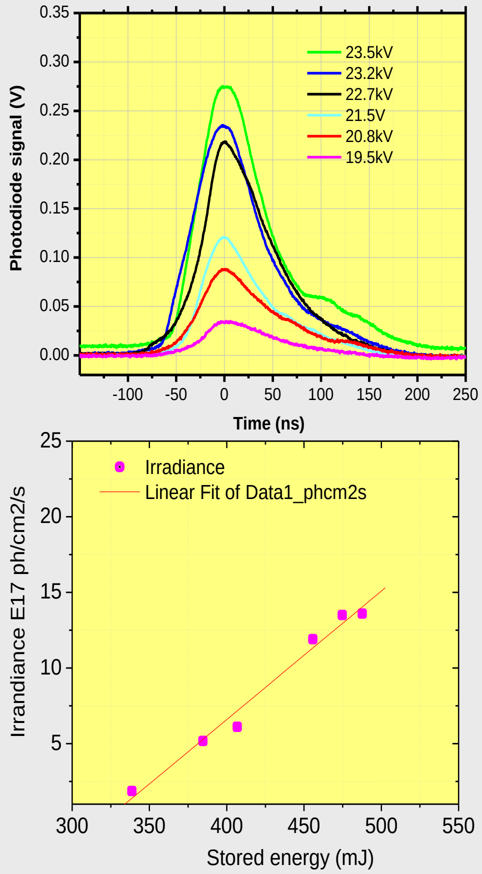
  Sigma= 4.5mm

Sn alloy cathode improves radiation output

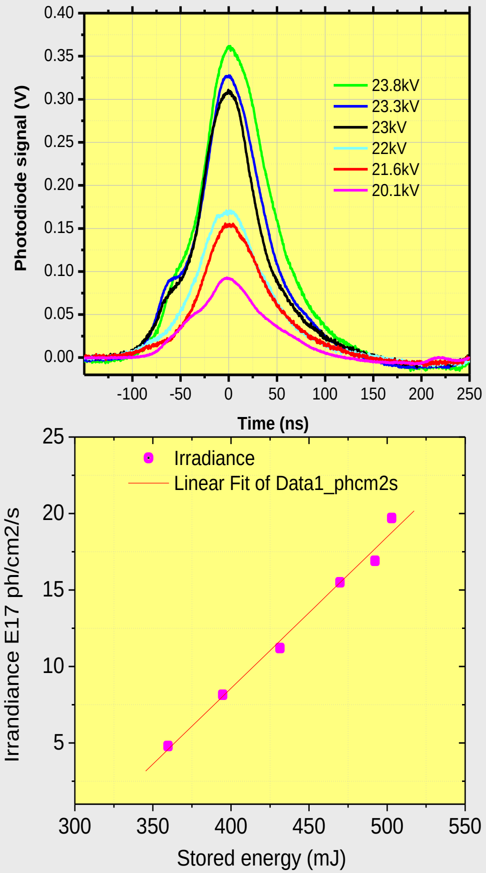
Tin addition to the gas admixture

- different Tin alloy cathode

Voltage scan using Sn-alloy cathode 1



Voltage scan using Sn-alloy cathode 2
higher Sn content



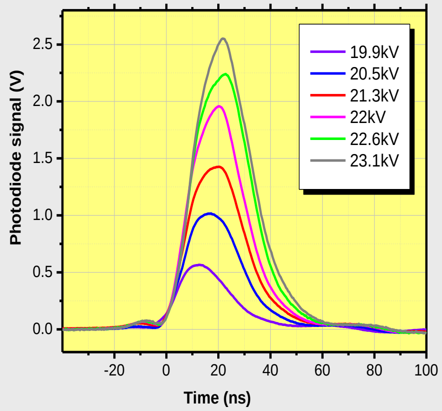
At high energy, radiation output > 1.25x using Sn alloy 2 compared to Sn alloy 1

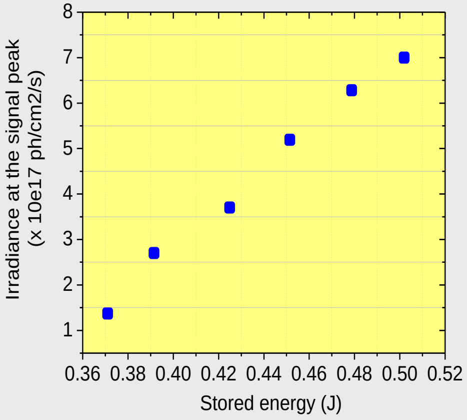
Need to assess life time issues

**2011
International
Workshop
on EUV
Lithography
June 13-17
Maui, Hawaii,
USA**

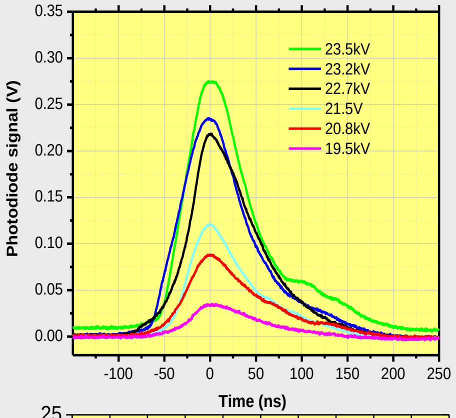
Progress

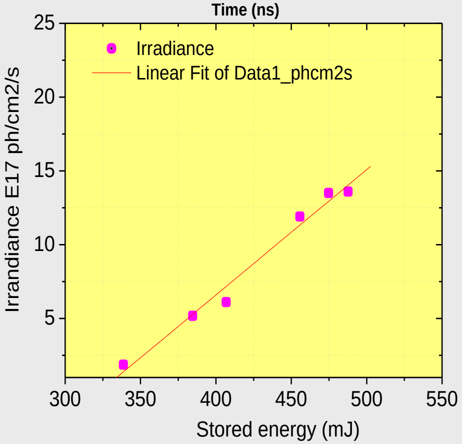
Results presented at EUVL october 2010





Current Results





At same operating voltage

- ✓ **Improvement on the fuel gas mix and flow rate**

- ✓ **2 fold increase in the irradiance**
- ✓ **3 fold increase on power**

Scaling to higher power demonstrated with Sn admixture

Multiplexing

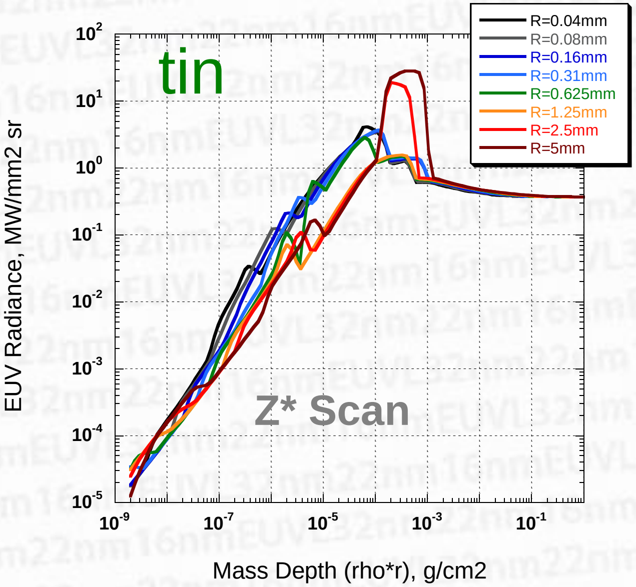
- a solution for high power & brightness

- Small size sources, with low enough etendue $E_1 = A_s \Omega << 1\ mm^2\ sr$ can be multiplexed.
- The EUV power of multiplexed N sources is

$$P_{EUV} \propto \sqrt{E \cdot N \cdot \Omega} \cdot \tau \cdot f$$

⇒ The EUV source power meeting the etendue requirements increases as $N^{1/2}$

- This allows efficient re-packing of radiators from 1 into *N* separate smaller volumes without losses in EUV power



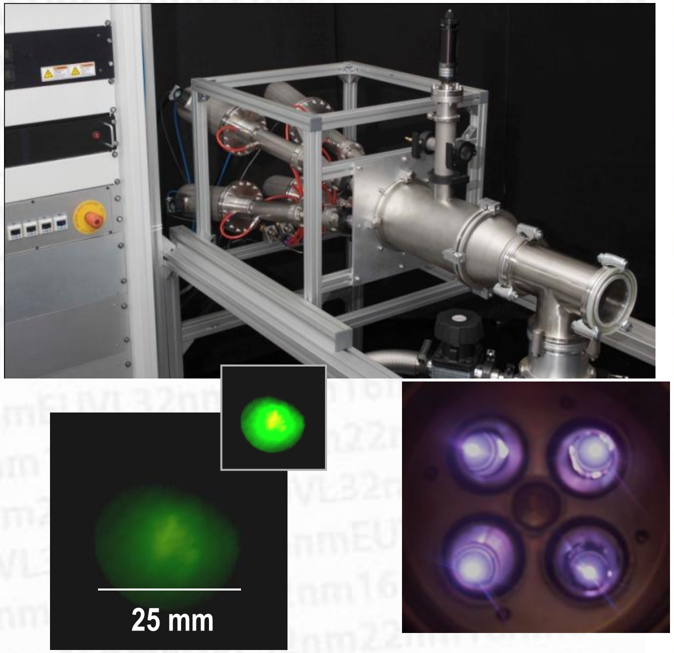
- **Spatial-temporal multiplexing:** The average brightness of a source and output power can be increased by means of spatial-temporal multiplexing with active optics system, totallizing sequentially the EUV outputs from multiple sources in the same beam direction without extension of the etendue or collection solid angle

- compct physical size of SoCoMo ?

2011
International
Workshop
on EUV
Lithography
June 13-17
Maui, Hawaii,
USA

HYDRA™-ABI
- spatial multiplexing for blank inspection

- Design Specifications
  - 60 W/mm^2.sr in-band 2% EUV radiant brightness at the IF
  - 0.6 W at the IF
  - etendue 10^{-2} mm^2.sr
  - source area - 31 mm^2 / TBD
  - **optimized for mask blank inspection**
  - **4x** i-SoCoMo™ units working at 3 kHz each
  - no debris / membrane filter
  - **close packed pupil fill**
- Current Status
  - 4 units integration & characterization
  - single unit optimization
  - ML mirrors evaluation & modelling

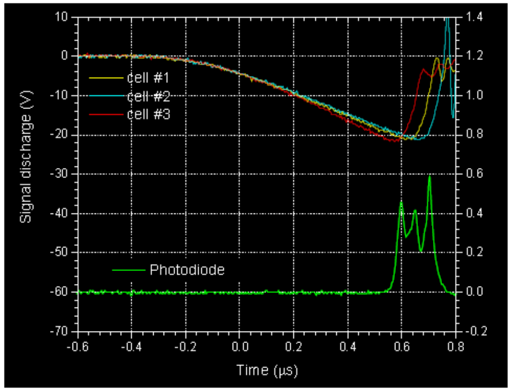


All 4 sources aligned to a point without use of any solid optical collector

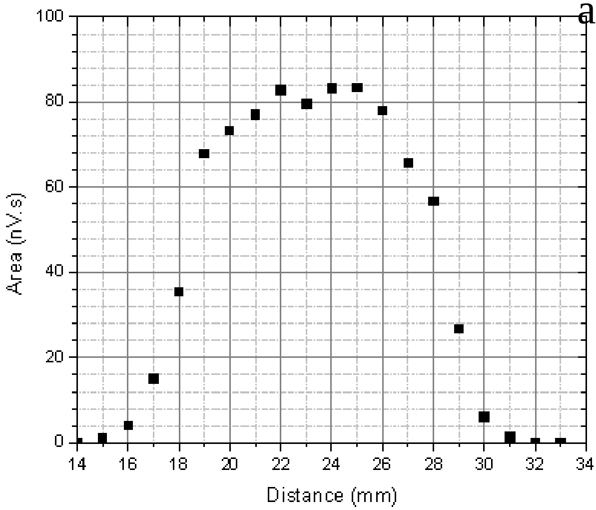
HYDRA4-ABI™

- spatial multiplexing

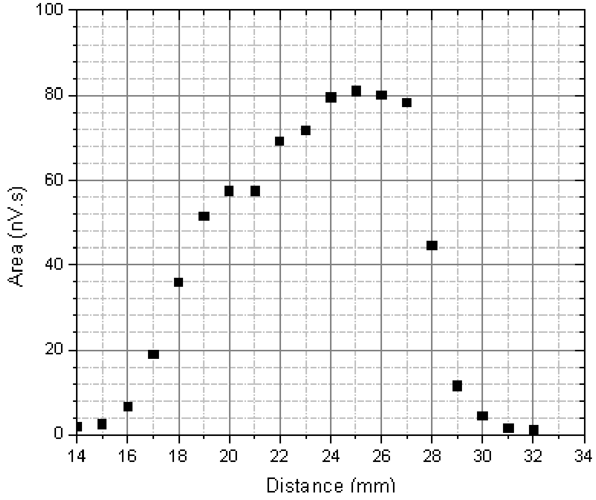
- 4 cells operating @ 1 KHz @ 22 KV
- Cells capacity : 1.2nF each
- Operating Pressure ; 30mTorr



Profile scans (3nm EUV band) @ 70 cm perpendicular to the optical beam axis



Summation of 4 single Beams



4 Beams simultaneous

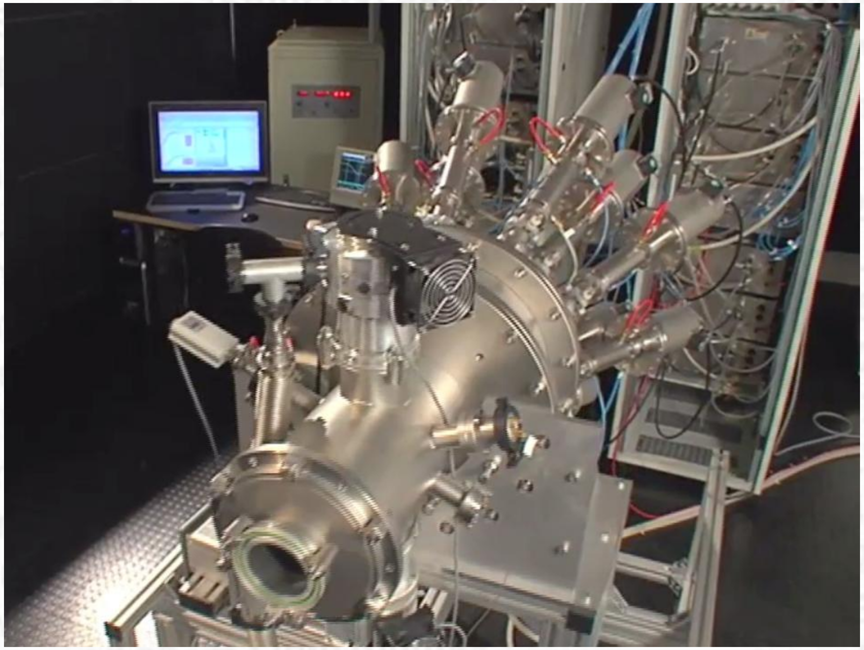
$9.6\ 10^{13}$ ph/pulse ➔ 1.4mJ/pulse ➔ 1.4 W @ 1 KHz

2011 International Workshop on EUV Lithography
June 13-17
Maui, Hawaii, USA

HYDRA™ - 12P

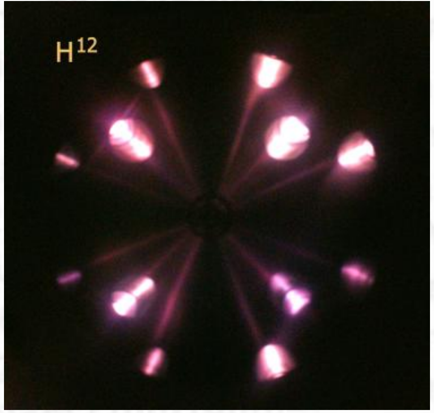
High Power Configuration

- prototype system



A multiplexed EUV Source optimized for High power

Viewing into the 12 Units operating @ 1KHz



- System integration successful
- Beam alignment needs automation
- Crosstalk between cells
- Power adding achieved
- Optical steering in preparation

HYDRA™-APMI
- unique temporal & spatial multiplexing

- Design Specifications
  - 1200 W/mm^2.sr in-band EUV radiant brightness
  - 2.4 W at the IF
  - etendue - 2. 10^{-3} mm^2.sr
  - source area - 20 mm^2
  - **optimized for patterned mask inspection**
  - 8x i-SoCoMo™ units working at 3 kHz each
  - 24 kHz temporally multiplexed
  - no debris / membrane filter
  - **Gaussian output spot**
- Current Status
  - optics design & modelling
  - single unit optimization
  - mechanical design

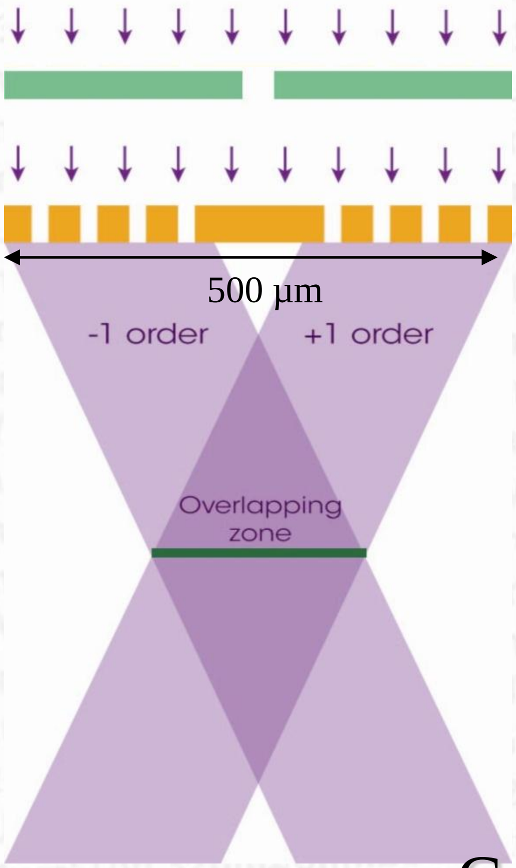
GeNI™ - for EUV Interference Lithography

Single slit (pin-hole)

10 µm x 1 mm

Double Grating

10 % DE at first order



Flux

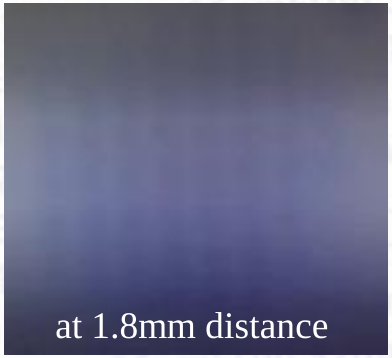
10^{16} ph/cm²/s

$2\cdot10^{14}$ ph/cm²/s

$4\cdot10^{13}$ ph/cm²/s

Dose on wafer: $6\cdot10^{-4}$ J/cm²/s

Resist Wafer


at 1.8mm distance

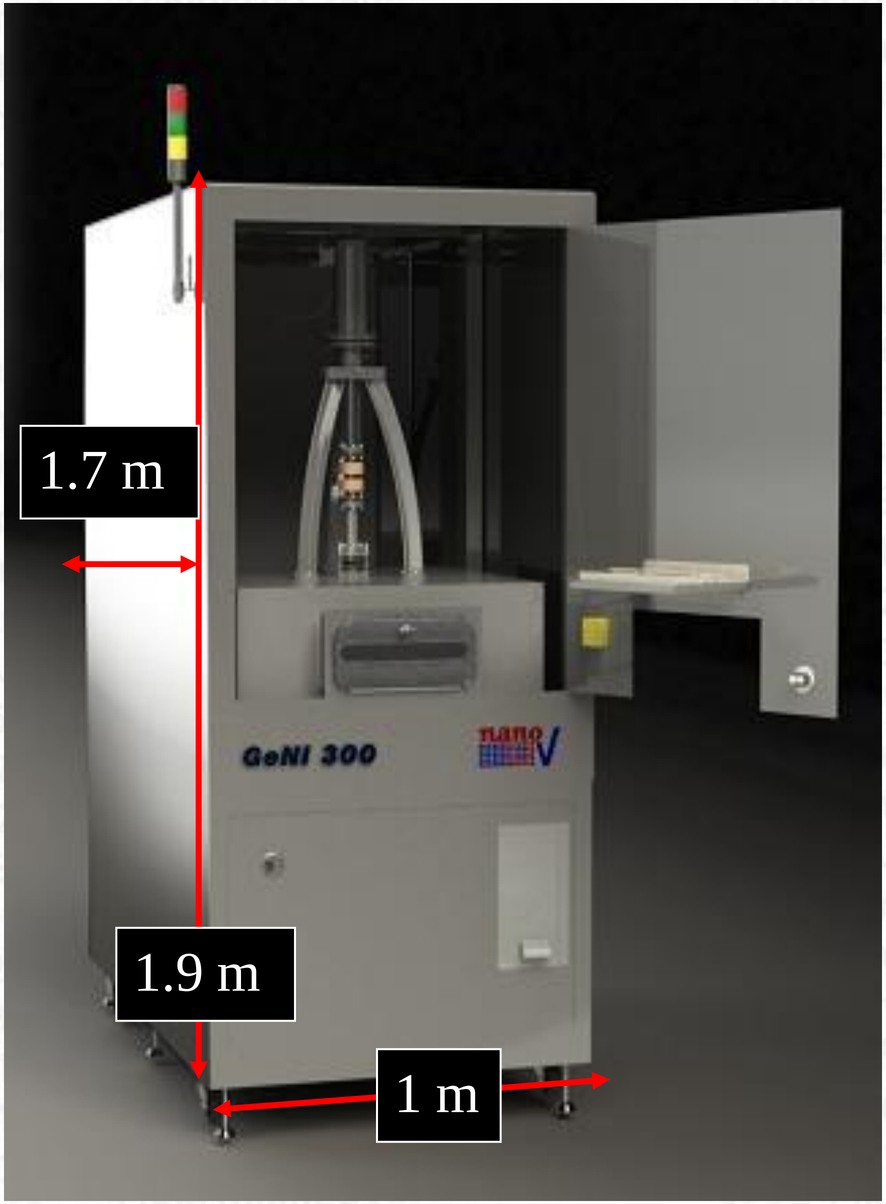
Resist sensitivity	100 mJ/cm²
Required exposure	>3 min

Grating used in evaluation

	1st order	2nd order
EUV spectral band	<5%	<3%
Grating (mesh) Period (nm)	80	80
Line feature width (nm)	40	20
Efficency	10%	3%
Material	Nickel	Nickel

2011
International
Workshop
on EUV
Lithography
June 13-17
Maui, Hawaii,
USA

GeNI™ II- Product Design



Features:

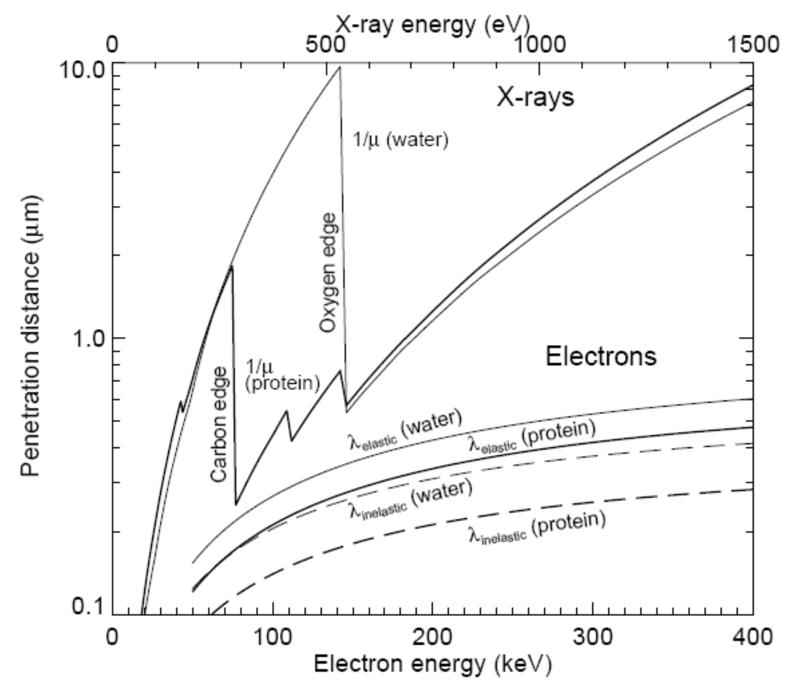
- 20 nm printing
- 150 mm, 200 mm & 300 mm wafer size
- Scan rate : 2h/wafer
- Load lock handling system
- Small footprint system
- Easy system integration
- Low cost of ownership
- High quality system adaptable to user needs
- High reliability
- Minimized downtime
- Process reproducibility

Upgradeable Features:

- 300 mm Dual FOUP Wafer Handling System
- Integrated wafer staging
- Sub 20 nm printing

Soft X-ray Microscopy

deep penetration & high contrast



Penetration distances in water and protein for electrons and X-rays

Soft X-ray microscopes and their biological applications
Janos Kirz, Chris Jacobsen & Malcolm Howells
- Q. Rev. Biophys. 28, 33{130 (1995)

Water Window
Soft X-ray

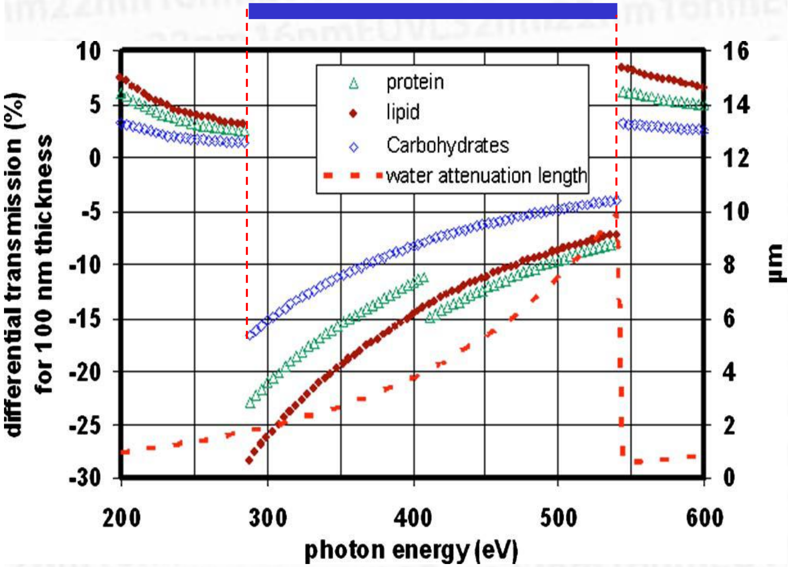
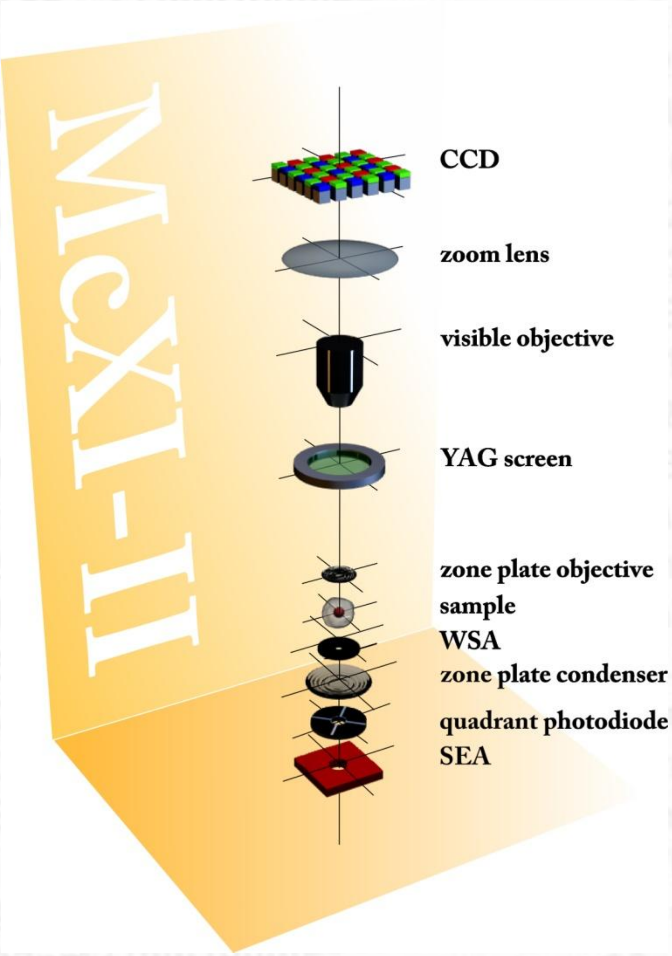


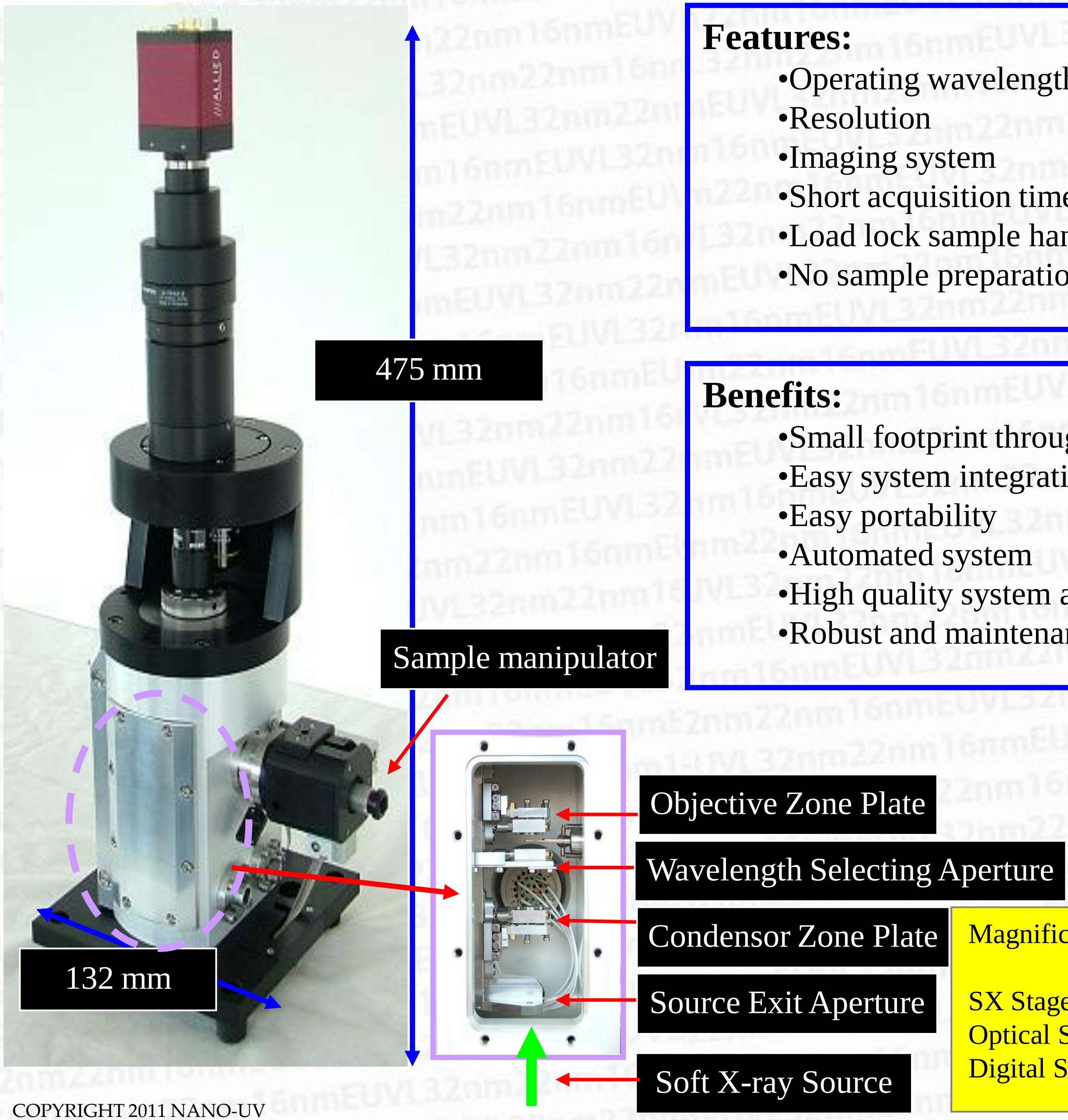
Table-top water window transmission x-ray microscopy: Review of the key issues, and conceptual design of an instrument for biology.
Jean-François Adam and Jean-Pierre Moya, Jean Susini
- Rev. Sci. Instrum. 76, 091301 2005

McXI™ - for Soft X-ray Microscopy



- Hydrated Structure Radiographic Imaging
- 20 nm resolution over Large Inspection Field (25μm x25μm)
- Real time Inspection
- In Vitro / In Vivo
- Local Environment Sample Cell
- Chemical Element Sensitive Imaging
- Hyper-Spectral Image Map
- Variable Magnification to x 20 000
- Short Set-up time
- Compact Footprint

McXI™ II – Product Design



Features:

- Operating wavelength : 2.2-4.4 nm
- Resolution : < 30 nm
- Imaging system : X-ray/Optical/Digital
- Short acquisition time
- Load lock sample handling system
- No sample preparation

Benefits:

- Small footprint through compact design
- Easy system integration
- Easy portability
- Automated system
- High quality system adaptable to user needs
- Robust and maintenance free X-ray source

Magnification

SX Stage : x 25 – x 50 (λ dependent)
Optical Stage : x 4 - x 20 (selectable)
Digital Stage : x 10 - x 20 (selectable)

2011
International
Workshop
on EUV
Lithography
June 13-17
Maui, Hawaii,
USA

- Microscope X-ray In Vivo

Summary

- Time resolved measurements show substantial power/ irradiance increase achievable in GEN II cell EUV band
- (12.4nm-15.4nm) power deliverable to a spot of under 1 cm diameter ~ 20W averaged at 1 kHz, with 0.5J stored energy per pulse
- Extrapolation suggests higher operating voltage and frequency can deliver 3 W in 2% band around 13.5 nm
- etendue increases with increasing energy stored and EUV output but remains < 10^{-2} mm^2.sr at the maximum parameters tested
- True divergence of the radiation is low from space resolved near field measurements
- zone plate based actinic EUV microscope can be constructed using a CYCLOPS™ source to provide a stand-alone instrument
- multiplexed HYDRA™-P source structure can supply a cost effective, scalable light source with requisite power for HVM scanner deployment

Acknowledgements

- Collaborators
  - Pontificia Universidad Catolica de Chile
  - NRC Kurchatov Institute, Moscow, Russia
  - Keldysh Institute of Applied Mathematics RAS, Moscow, Russia
  - University College Dublin
  - King's College London
- Sponsors - EU & French Government
  - FP7 IAPP
  - OSEO-ANVAR
- Investor – RAKIA
- EUV LITHO, Inc

2011 International Workshop on EUV Lithography
June 13-17
Maui, Hawaii, USA