High Brightness EUV Light Source for Actinic Inspection & Microscopy


Nano-UV
EPPRA
EUV Sources for EUV Lithography

Diffraction restricts the resolution

\[ r \geq k_1 \frac{\lambda}{NA} \]

λ ⇒ 13.5 nm (h=92 eV) ⇒ 6.λ nm?

δλ/λ ⇒ 2%

Nano-Age World

NOW EUV for HVM beyond 16 nm

• For HVM: > 200 W of in-band power @ IF within < 3 mm²·sr etendue
• For mask inspections ABI→AIMS→APMI: 30 → > 100 W/mm²·sr within etendue of 4·10⁻³ → 5·10⁻⁴ → 1.5·10⁻² mm²·sr

LPP & DPP can produce Sn, Xe… plasma radiating at EUV range

EUV sources are still the main issue of EUVL deployment
i-SoCoMo™ - GEN II cell

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, N₂ and Xe: 3 bar inlet
MPP Discharge Experiment
- plasma discharge emission from a channel produced by hollow cathode electrons

- pulse charged local energy storage
- sub-mm diameter capillary
- hollow cathode e-beam for on-axis discharge initiation
- rapid current heating
- ultra-bright high energy density radiator
Nano-UV: EUV Source

**MPP Performance @ 21kV**

- with SXUV20 A Mo/Si (350/500 nm) filtered diode from IRD in 3 nm EUV band (12.4 nm - 15.4 nm)
- Al coated (110 nm) on Si$_3$N$_4$ (250 nm) to reject OoB
- 200µm pinhole aperture in front of the diode
- typical etendue < 10$^{-3}$ mm$^2$.sr
- Discharge in He/N$_2$/Xe admixture, total Flow 3.2 sccm/min
- Cell capacity 1.7nF
- The low charge energy resolves heat-loading issues

**Estimated in-band brightness is of 31 W/mm$^2$ sr per kHz**
Source Characteristics
- measurement schematics

• Set up

  - Aperture: 2 mm + grid
  - Filtered Photodiode
  - Pinhole: 500 µm
  - CCD Camera

  - Cell
  - 17 cm
  - 49 cm
  - 56 - 98 cm
  - 62 cm
  - 68 cm
  - 80 cm
  - 104 cm

• Pinhole scan
  - time averaged source diameter; size & stability
  - angular emission properties
  - source etendue

• Photodiode scan
  - filtered (Mo350nm/Si500nm) SXUV_20A diode with 3 nm band (12.5-15.4 nm) with Al coated Si$_3$N$_4$ to reject Oob
  - CCD with Spectral Purity Filter (SPF) or Al coated Si$_3$N$_4$ filter
  - scan diode to get radiation profile and power delivered
  - fold with pinhole scan source image data to get radiant brightness

EUV filter Phystex SPF

0 10 20 30 40
Source Characteristics I
- irradiance & power vs stored energy

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

- Peak irradiance 1.19 E18 ph/cm²/s
- Sigma: 4.01 mm
- Power: 18.5W (3nm band)

Output power and irradiance increase with increasing stored energy
Source Characteristics
– higher resolution source projection

Pinhole scan – EUV SPF filter, F4 mesh grid over SEA (2mm)
- far field image showing collective features

The measured source size is less than Ø 180um

pinhole-scan image profile - 500 μm pinhole, 0.5 mm scan step, 50s exposure, 2x2 bin on CCD, 1 kHz EUV pulses, image sensor to source 104 cm, untreated raw data
Source Characteristics II - wavefront measurement

HASO™ X-EUV Shack Hartmann wavefront sensor - (from Imagine Optic)

- EUV beam diameter \( d = 9.75 \text{ mm} \) at 1890 mm from source
- Beam divergence half angle = 0.19°
- Solid angle \( \Omega = 0.0345 \text{ msr} \)
- Etendue \( E = 5 \cdot 10^{-5} \text{ mm}^2\text{sr} \)

Acquired image
60s exposure, source at 1 kHz

Derived wavefront
166 nm RMS (12 \( \lambda \)) & 760nm PV (58 \( \lambda \))

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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 Si₃N₄ (250 nm) to reject OoB, typical etendue 1.7 E⁻² mm².sr, discharge in He/N₂/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

* 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
Progress in experiment - irradiance vs stored energy

Results presented at EUVL october 2010

Current Results

At same operating voltage by optimisations made 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
Gen II EUV Source
- characteristics & optimization from Z* modelling

EUV source scan by stored electrical energy

Optimization by gas mixture pressure

Resistive regime

for more details, at theoretical talk (S44): S.V.Zakharov et al
Aerial Image Microscope System (AIMS) tool source

• Design Specifications
  - 100 W/mm².sr in-band 2% EUV radiant brightness
  - 50mW within etendue - 5 \times 10^{-4} \text{ mm}^2\text{.sr}
  - IF source area < 9 mm²
  - optimized for aerial image measurements
  - i-SoCoMo™ unit, 5 kHz working
  - energy stability < 10%
  - no debris / membrane filter

• Current Status
  - system characterization
  - stability optimization
  - life time components testing
Multiplexing
- a solution for high power & brightness

- Small size sources, with low enough etendue $E_1 = A_s \Omega \ll 1 \text{ mm}^2 \text{ sr}$ can be multiplexed.

- The EUV power of multiplexed N sources is

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

$\Rightarrow$ 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

- compact physical size of SoCoMo is required
HYDRA\textsuperscript{4}-ABI\textsuperscript{TM} - spatial multiplexing for blank inspection

Actinic Blank Inspection (ABI) tool source

• Design Specifications
  – 60 W/mm\textsuperscript{2}.sr in-band 2\% EUV brightness
  – 0.6 W at the IF
  – effective etendue 10\textsuperscript{-2} mm\textsuperscript{2}.sr
  – source area - 31 mm\textsuperscript{2} / TBD
  – optimized for mask blank inspection
  – 4\times i\textsuperscript{-SoCoMo\textsuperscript{TM}} 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
HYDRA$^4$-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 $\Rightarrow$ 1.4mJ/pulse $\Rightarrow$ 1.4 W @ 1 KHz
HYDRA™ - 4-beams flatness optimization

Overlapping of 4 suitably appertured Gaussian beam at a given flatness of 0.2%

An efficiency with flatness of 0.2% is of 22%.
HYDRA-APMI™
- unique temporal & spatial multiplexing

Actinic Patterned Mask Inspection (APMI) tool source

• Design Specifications
  – 60 - 120 W/mm².sr in-band EUV brightness
  – 0.6 - 1.2 W at the IF
  – etendue – 10⁻² mm².sr
  – IF source area - 20 mm²
  – optimized for patterned mask inspection
  – 4-8x i-SoCoMo™ units working at 3 kHz each
  – 12 - 24 kHz temporally multiplexed
  – no debris / membrane filter
  – Gaussian output spot

• Current Status
  – optics design & modelling
  – single unit optimization
  – mechanical design
Multiplexing

- Spatial & Temporal

Technically NOT challenging
- needs development
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