High Brightness Next Generation EUV Lithography Light Source

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OUTLINE

- Remaining challenges to EUVL deployment
- Plasma radiation sources
- Z*-code EUV source plasma parameter scan
- Extra EUV Emission from Xenon Plasma
- Multiplexed source for high power & brightness
- NANO-UV’s source solution:
  - the i-SoCoMo™
  - multiplexer HYDRA™-BE18 for mask metrology
EUVL

- EUVL lithography considered as the NGL tool holding the most promise for industrial application at 22 nm hp is at a cross road today.

- For HVM EUV lithography applications, EUV powers in the range of 200-500 W in IF are required.

- Actinic mask blank defect inspection and aerial imaging tools are key to enable yielding masks for 22 nm node and beyond that requires EUV sources with extremely high radiant brightness.

- The top challenge to EUVL deployment is the availability of a powerful and reliable light source and the associated optics to collect the EUV photons, the SoCoMo (source collector module)
EUV Brightfield Metrology - Requirements

- Mask defect inspection - the source required
  - relative defect response $> N$ photon statistics
    \[ \frac{D}{A} > \frac{2\sqrt{N}}{N} \] (K. Goldberg, Hawaii, 2008)

Consider a CCD array $(n \times n)$ detector, pixel size $A_p$, being used to image the area of the mask under inspection
- magnification of imaging optics, $m$, hence area to detect a defect is now $A_i = A_p / m^2$, and the total illuminated patch area on mask observed is $A = A_i \cdot n^2$
- total illumination time:
  \[ t = t_A \cdot M \cdot m^2 / n^2 \cdot A_p \]
- illuminating irradiance required:
- then for defect size 10 nm, a $(9 \mu m)^2$ pixel size, 2048$^2$ CCD array and full size $(4^2 \times (26 \times 33)$ mm$^2$) mask inspection:

<table>
<thead>
<tr>
<th>Magnification, m</th>
<th>40</th>
<th>80</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patch area, $A$ (um$^2$)</td>
<td>5.06E-02</td>
<td>1.27E-02</td>
<td>3.16E-03</td>
</tr>
<tr>
<td>Illuminating flux density (ph/cm$^2$)</td>
<td>5.47E+15</td>
<td>1.37E+15</td>
<td>3.42E+14</td>
</tr>
<tr>
<td>$N_A$ illuminating $A$</td>
<td>1.16E+13</td>
<td>7.26E+11</td>
<td>4.54E+10</td>
</tr>
<tr>
<td>Irradiance at mask needed, 10 shots exposure (ph/s cm$^2$)</td>
<td>2.74E+18</td>
<td>6.84E+17</td>
<td>1.71E+17</td>
</tr>
<tr>
<td>Mask exposure time (min)</td>
<td>2.16E+00</td>
<td>8.62E+00</td>
<td>3.45E+01</td>
</tr>
</tbody>
</table>

*additional time for positioning and alignment needed in each exposure

(reflectivity $R \approx 60\%$)
EUV Light Source

- Sn, Xe, Li ... High Energy Density plasma is the EUV light source in narrow 2% band @ 13.5nm
- High pulsed power LPP & DPP to produce the right conditions HED plasma

\[ t = \text{4.7614E+00 ns} \]

- For HVM - X00 W of in-band power @ IF with etendue < 3mm²·sr
- For AIM and ABI – Y0 W/mm²·sr at wavelength radiance

- kW (source) \(\Rightarrow\) W (IF) is the source of the problem -
ZETA → Z* RMHD Code → Z* BME tool
model required: nonLTE, multicharged ion plasma

Table (Te, ρ) for solid matter & for LTE, non-LTE plasmas of ion compositions:
EOS; ionization distribution; rates; non-maxwell electrons; spectral group radiation & transport coefficients

RMHD with energy supply:
(r, z+φ) plasma dynamics in (E, B)_{r, φ, z}; nonstationary, nonLTE ionization;
spectral multigroup radiation transport in nonLTE with special spectral groups (for EUV, laser); solid elements sublimation, condensation, expansion into plasma

EEMHD in real cylindrical geometry:
dynamics of electrons → change to 3D PIC;
ionization of weekly ionized plasma (hollow cathode ionization wave)

Spectral postprocessing:
3D ray tracing; detailed spectra

Data: (r, z, ν, T_e, I, p, E, B, Z, U, ω, etc);
Time evolution (I, P_ω, W, F_ω, etc);
Visualization

Heat flux postprocessing:
element lifetime estimation;
fast particle flux, 3D PIC

- Improved
- new
- coming
Optimized EUV Efficiency of a Source

- Plasma self-absorption defines the limiting brightness of a single EUV source and required power at given limiting etendue of the optics.

- The plasma parameters where EUV radiance is a maximum are not the same as that when the spectral efficiency is a maximum.

- The spectral efficiency is high SE=11-12% at plasma density $\rho = 10^{-4} \div 10^{-3} \text{g/cm}^3$.

- The optimum Conversion Efficiency@IF (CE@IF) of in-band radiation is maximal at target radius value smaller than $R < 0.38 \text{mm}$ and decreases like $R^{-2}$ at larger one.

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What is achievable with a single source?
- LPP

- Critical density for Nd:YAG laser ($\rho_{cr} \approx 2 \cdot 10^{-2}$ g/cm$^3$) is in the region of low spectral efficiency (SE).

**Example:** to obtain 150W the in-band power $P_{EUV} = L_{EUV} E \cdot \tau \cdot f (\tau \approx R / C_s )$ in conventional source with 2$\pi$-collector the laser power $P_l \approx P_{EUV} \cdot 16 \pi A_s / (\eta_{rad} \cdot E \cdot SE)$ in optimum $P_l > 50kW (\eta_{rad} \approx 0.5; \ CE_{IF} = P_{EUV} / P_l \approx 0.3\%)$ operating with frequency $f > 140kHz$ at $L_{EUV} = 2.5MW/mm^2sr$ and $R = 63\mu m$.

- Increasing the target size the operating frequency may be reduced, but the Nd:YAG laser power should be increased.

- For LPP source based on CO$_2$-laser the critical density is 100 times less.

**Example:** the spectral efficiency may be higher, up to SE $\approx 11\%$, but lower $L_{EUV}$ resulting in $CE_{IF} \approx 0.7\%$ and laser power $P_l > 22kW$ operating with many kHz $f \propto R^{-4}$. CO$_2$-laser EUV source requires an additional spectral purity filter and anti-fast-ion protection that reduces the effective $CE_{IF}$. 

![Z* Scan graph](image)
What is achievable with a single source? - DPP

- In conventional single DPP source of Z-pinch type the plasma is heated up and compressed by magnetic field energy and pressure \((B^2/8\pi)\). From Bennet ratio
  \[\rho R \leq M_i \cdot R \cdot B^2/(8\pi T(Z+1)) \approx 0.5 \cdot 10^{-15} \cdot \frac{I^2}{R}\]
- The collectable in-band EUV power for given etendue \(E_{[\text{mm}\cdot\text{sr}]}\) is
  \[P_{\text{EUV}}(W) \leq 0.16 \cdot 10^{-10} \cdot I^2 \cdot E \cdot f\]
- The joule heating should provide enough power:
  \[3 \cdot 10^4 \cdot I^2 / (\pi \sigma) \cdot f > P_{\text{EUV}} \cdot 16 \pi^2 R^2 / (E \cdot SE)\]
  \[\Rightarrow R_{[\text{cm}]} < 0.13 \cdot SE^{0.5}\]
- For high \(P_{\text{EUV}}\) from a single source in the optimal regime of high EUV radiance, the current is very high \(I_{[A]} \approx 4.5 \cdot 10^5 \cdot R^{0.5}\) supplied during short time \(\tau(s) \approx 1.7 \cdot 10^{-6} \cdot R_{[\text{cm}]}\). i.e. \(dI/dt \approx 2.6 \cdot 10^{11}/R_{[\text{cm}]}^5\) (A/s).
- Reducing the current, plasma size or pulse duration increases rapidly the necessary operation frequency and decreases the Conversion Efficiency.

Example: to obtain 150W of collectable in-band EUV power with \(\pi\)-collector for \(R=0.3\text{mm}\), the current is \(I=8\text{kA}\) operating with \(f=160\text{kHz}\). This current should be supplied to the small size plasma during 50ns time.

- By the way, spatial multiplexing \(N=40\), \(f=4\text{kHz}\) each and \(I=8\text{kA}\) provides that 150W
EUV IF Power Limitation:

- Xenon plasma EUV emission

Experimental observation of limitation of the EUV power at IF from xenon DPP source

Xenon Revisited - extra EUV emission from xenon plasma

- There are two regimes in transparent plasma of xenon: Low - Temperature (LT) with XeXI and High - Temperature (HT) with XeXVII-XeXXX ions contributing into 2% bandwidth in the spectral region 13-14nm.
- For small size xenon plasma, the maximum EUV radiance in the HT can exceed the tin plasma emission.

EUV Emission
from xenon plasma with e-beam

Emission of Xe XXII in plasma with fast electrons of various portions (from 1% to 2%) in comparison with the emission of Xe XI from equilibrium plasma

Energy of fast electrons
E = 5 keV

Plasma temperature
T = 40 eV

Plasma electron density
N_e = 10^{17} 1/cm^3
Non-equilibrium Kinetic Modeling of xenon plasma with e-beam

EUV emission spectra of various Xenon ions from non-equilibrium plasma at 80 eV with 2% of fast electrons at 3 keV in comparison with emission spectrum of Xe XI ions from plasma at 33 eV (black). Electron density = $10^{17} \text{ cm}^{-3}$

Note: X% Y keV means fast electrons at Y keV temperature and X% relative portion

- Xe XI @ 33 eV
- Xe XXI @ 80eV + 2% 3keV
- Xe XXII @ 80eV + 2% 3keV
- Xe XXIII @ 80eV + 2% 3keV
- Xe XXIV @ 80eV + 2% 3keV

Wavelength, nm
Total Emission of Xe XXI-Xe XXIV ions from plasma with e-beam

Total EUV emission spectra of Xe XXI - XXIV ions from non-equilibrium plasma at 80 eV with 2% of fast electrons at 3 keV in comparison with emission spectrum of Xe XI ions from plasma at 33 eV (black). Electron density $N_e = 10^{17}$/cm$^3$
**Multiplexing**

- a solution for high power & brightness

- For small size source, the intensity of the in-band emission is maximal in almost transparent plasma at 
  \[ \rho R = (\rho R)^*, \text{near } \kappa_\omega R \sim 1 \]

- The etendue from a single small size source is low enough \( E_j = A_s \Omega \ll 3 \text{ mm}^2 \text{ sr} \) to be multiplexed.

- The EUV power of multiplexed \( N \) sources is
  \[ P_{EUV} = Np_{EUV} \propto \frac{4}{3} \pi R \cdot N \cdot (\rho^2 R^2)^* \cdot \Omega \cdot t \cdot f; \]
  as \( n'_i \propto n_i n_e \)

Finally:
  \[ P_{EUV} \propto \sqrt{E \cdot N \cdot \Omega \cdot t \cdot f}, \text{ as } R \sim \sqrt{E/(N \cdot \Omega)} \]

- To increase the power significantly we have to increase the plasma dimension \( R \), or operation frequency \( f \), or number of sources \( N \).

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

- Decreasing the plasma size doesn’t reduce the EUV radiance (if the plasma optical depth is kept constant).

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

- problem is the physical size of SoCoMo
High Brightness EUV Source

- Pilot production unit spec
  - compact form factor
  - mm spot size at up to 1 m distance
  - $10^{16}$ photons/cm$^2$/s/ @ 4% BW in-band EUV irradiance
  - 3 kHz continuous
  - 3.3 kW average power consumption
  - 1 Gshot lifetime to service
  - in-build photon collection & projection plasma structure - PlasmaLens$^\text{TM}$

CYCLOPS$^\text{TM}BE-16
Hollow cathode triggered capillary discharge

a beam of run-away electrons $\Rightarrow$ e-beam gas

ionization $\Rightarrow$ ionization wave $\Rightarrow$ radiation-MHD

Fast electrons shift the xenon plasma ionization equilibrium increasing the in-band EUV emission from capillary discharge
CYCLOPS™ BE-16 for Metrology

- Exceptional source brightness* and power** at 3 kHz

* irradiance - greater than $4 \times 10^{16}$ EUV photons/cm²/s measured at 64 cm from the source over a 5 mm² area, 13.5 nm, 4% BW

** equivalent source power - more than 30 kW (2π sr, 13.5 nm, 4% BW)

In-band pulse

$V_{\text{peak}} = 21.1$ kV

He/Xe/Ar mixture, 160 mJ per shot

$r = 24$ ns

Si₃N₄ membrane of 0.25 mm²

Distance - 64 cm

$N_{\text{ph}} = 1.5 \times 10^{13} \text{ph/cm}^2/\text{pulse}$

$N_{\text{ph}} = 4.5 \times 10^{16} \text{ph/cm}^2/\text{s} @ 3$ kHz

XIL beamline at the Swiss Light Source

<table>
<thead>
<tr>
<th>Energy range</th>
<th>10 - 135 eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux (91 eV)</td>
<td>$2.4 \times 10^{15} \text{ph/s/cm}^2/2.8%\text{BW}$</td>
</tr>
<tr>
<td>Spot size</td>
<td>4 mm x 4 mm</td>
</tr>
</tbody>
</table>
Source Characteristics

- Emission properties measured
  - time averaged source diameter
    0.6 mm FWHM
    1.02 mm² spot size (1/e²)
  - emission angle
    0.32° half angle
    9.5 e-5 steradian
  - source etendue
    9.7 e-5 mm².sr
  - EUV radiant brightness*
    4.5 e18 photons/(mm².sr.s)/4% BW [1s average]
    8.3 e22 photons/(mm².sr.s)/4% BW [1 pulse peak]
  - a very bright source for metrology

* using average signal on SXUV5 diode of 10¹¹ photons (91 eV) after 2 ML reflection

Source image through 400 μm pinhole
- 1 min exposure, 6 E4 shots integrated
image sensor at 108 cm from source

Guassian fit of emission profile recorded
- Optical properties
  - single Gaussian profile fitting to obtain radiation half width
  - source diameter (1/e² spot size) 2.5 mm at 44 cm from exit of PCS; 69 cm from plasma source

- very small etendue: < 10⁻⁴ mm².sr
Exposure time = 60s at 1kHz repetition rate

HASO™ X-EUV Shack-Hartmann wavefront sensor measurements *

Wavefront Characteristics

Beam divergence half angle = 0.18°
EUV beam diameter = 9.1mm at distance between CCD and focal spot = 1430mm
Etendue = 4.4e-5 mm² sr

* with support of G. Dovillaire, E. Lavergne from Imagine Optic and P. Mercere, M. Idir from SOLEIL Synchrotron
HYDRA™-12BE18 - a EUV source for mask metrology

• Design Specification
  – $10^{18}$ photons/cm$^2$/s/2% BW in-band EUV irradiance
  – 12x i-SoCoMo™ units working at 5 kHz each
  – configurable pupil fill
  – etendue $\sim 10^{-2}$ mm$^2$.sr
HYDRA™-12BE18 - demonstrating spatial multiplexing

9 x 5.26 kHz \Rightarrow 47 \text{ kHz}
HYDRA™-12BE18

- a 40 kHz continuous source

• System Performance
  - spatial multiplexing well behaved
  - small cross talk in sequential operation
  - plug and play
  - needs to tune individual cell
  - 10x i-SoCoMo™ units

End-on view of 10 sources

GEN-II CYCLOPS™ cells
Summary

- Knowledge of the behaviour of multicharged ion non-equilibrium plasma with ionization phenomena, radiation and fast particles transfer is critical for EUV source development.

- Self-absorption defines the limiting brightness of a single EUV source, required for the HVM and AIM tools with high efficiency at given the limiting etendue of the optics.

- The required irradiance can be achieved by spatial multiplexing, using multiple small sources.

- Extra EUV in-band emission may be achieved from highly charged Xe ions in plasma with fast electrons.

- NANO-UV presents a new generation EUV light source unit, incorporating the i-SoCoMo™ technology, together with early experiences of operating sources in a multiplexed configuration, which can satisfy the source power and brightness requirements for an at-line mask inspection tool, and in future for HVM.
Acknowledgements

• Collaborators
  – Pontificia Universidad Catolica de Chile
  – RRC Kurchatov Institute, Moscow, Russia
  – Keldysh Institute of Applied Mathematics
    RAS, Moscow, Russia
  – University College Dublin
  – King’s College London
  – Imagine Optic

• Sponsors
  – EU & French Government
  – ANR- EUVL
  – OSEO-ANVAR

• RAKIA

• EUV LITHO, Inc.