Beam expander and homogenizer for 13.5 nm application

Ladislav Pina

Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, 115 19 Prague 1, Czech Republic
Outline

• Motivation
• Applications
• EUV/SXR sources
• Properties of LPP, DPP and FEL radiation
• EUV/SXR optics
• Collector optics for EUV lithography
• Beam expansion and homogenisation
Motivation

- Collector optics for EUV/SXR lithography
- Experimental tools for EUV/SXR lithography
- Diagnostic tools for EUV/SXR lithography
- Novel optical systems for EUV/SXR lithography
- Novel optical systems for EUV/SXR/XR microscopy
- Novel optical systems for EUV/SXR/XR tomography
Applications

• EUV / SXR lithography
• EUV / SXR radiography
• EUV / SXR high contrast imaging
• EUV / SXR optics metrology
• EUV / SXR optics alignment
Electromagnetic radiation spectrum


13.5 nm – 92 eV
Laser Produced Plasma – solid (liquid) target

- solid target
- focused high-power laser beam
- expanded low density plasma
- Nd:glass
- Nd:YAG
- KrF
- CO₂

- cold (~ 10 eV), high density (10^{22} cm⁻³) plasma
- hot (100-1000 eV), low density (10^{20} cm⁻³) plasma

- Ablation surface
- Critical surface

Laser plasma parameters for maximum EUV emission

~ 40 eV, ~ 10^{19} cm⁻³
Pinching Plasmas
Capillary Discharge Plasma

Charging circuit

- Ceramic Capacitors (1.25 ÷ 31 nF).
- Al₂O₃ capillary, 3.2mm dia., 20cm long.
- Low inductance -> high $dI/dt$.
- Pulse-charged: 1x Marx + coil.
- RL Rogowski coil.

Main discharge unit

duralumin housing
HV
capacitive divider
ceramic capacitors bank
preionization
capillary shielding
capillary
gas filling
Rogowski coil
self-breakdown spark-gap
to vacuum

Design and construction of new experimental capillary discharge apparatus (A. Jancarek, M. Nevrkla)
CTU Prague, Faculty of Nuclear Sciences

EUVL Dublin 03-06 November 2014
Laser Produced Plasma – gas puff target

• electromagnetic valve system

• X-ray backlighting images


EUV/ SXR SOURCES
Characteristics of Synchrotron Radiation

- High brightness: synchrotron radiation is extremely intense (hundreds of thousands of times higher than conventional X-ray tubes) and highly collimated.
- Wide energy spectrum: synchrotron radiation is emitted with a wide range of energies, allowing a beam of any energy to be produced.
- Synchrotron radiation is highly polarised.
- It is emitted in very short pulses, typically less that a nano-second.
Synchrotron radiation

\[ K = \frac{eB\lambda_w}{2\pi m_e c} \]

- \( K \gg 1 \) \( \Rightarrow \) wiggler
- \( K \ll 1 \) \( \Rightarrow \) undulator
Free Electron Laser radiation

FEL Radiation characteristics:

- Highest brightness of all laboratory sources
- Collimation
- Polarisation
- Coherence
- Emitted in very short pulses, typically femto seconds.
EUV/SXR/XR sources peak brilliance evolution
Speckle pattern dependence on
- wavelength
- surface microroughness
- optical system geometry

surface microroughness $\ll$ wavelength

Speckle pattern intensities exponential distribution

$$P(I)dI = \frac{1}{\mu} \exp(-I/\mu)$$
FEL and plasma source comparison

Temporal pulse structure

SASE FEL (FLASH)  LPP Sn plasma

Optimization of high average power FEL for EUV lithography application
Akira Endo, Kazuyuki Sakaue, Masakazu Washio (Waseda University), Hakaru Mizoguchi (Gigaphoton Inc.)
FEL Conference 2014 Basel, Switzerland
FEL and plasma source comparison

Spatial coherence

**SASE FEL**
~ 0.5

**Plasma source**
~ $3.2 \times 10^{-9}$
FEL and plasma source comparison

1. High divergence sources (LPP and DPP plasma sources)

Radiates in $2\pi$ steradian
ns – μs pulses typ., but ...
Low repetition
Low spatial and temporal coherence

2. Low divergence (synchrotron, FEL, HHG, hot plasma laser)

Radiates in narrow beam
fs – ps pulses
High repetition
High spatial and temporal coherence
Next step – FEL as a EUV/SXR source for lithography

Subjects to be further studied:

- Suppression of diffraction effects
- Suppression of speckle patterns
- Optics for quasi parallel input beam
- Sub micrometer IF
- High E field intensities phenomena with fs – ps pulses
- Photoresist exposure process physics with fs – ps pulses
What optics is potentially relevant?

- Grazing incidence mirrors
- ML mirrors
- Multi foil mirror systems
Kirpatrick-Baez system

- Double reflection X-ray Optics
- Two mirror sets vertical and horizontal
- Mirrors in both sets have to be curved parabolically
- Single focal point is formed in the intersection of the horizontal and vertical focal planes
- Quality of the focal spot depends on quality of substrates (shape, microroughness)
- Technology is not necessarily based on precise and expensive mandrel
- Classical manufacturing technology of laboratory KB optics is expensive

http://imagine.gsfc.nasa.gov/
What optics is potentially relevant?

Wolter system

[Diagram showing Wolter system with labels for paraboloid, hyperboloid, focal surface, and incident paraxial radiation.]
Ellipsoidal Mirror

ELLIPSOIDAL MIRROR

What optics is potentially relevant?

EUVL Dublin 03-06 November 2014
What optics is potentially relevant?

Paraboloidal Mirror

Highly parallel beam (< 1 mr)
Large area
Hole in the middle

Beam profile
Multilayer optics

Multilayer Mirror
What optics is potentially relevant?

Montel system

http://www.x-ray-optics.de
What optics is potentially relevant?

Wolter system

Hyperbola

Ellipse

F₁

F₂
What optics is potentially relevant?

Wolter systems

Rotationaly symmetric nested mirrors Wolter system

2D mirrors nested Wolter system

http://www.x-ray-optics.de
What optics is potentially relevant?

Schwarzschild-optics

http://www.x-ray-optics.de
Polycapillary optics

What optics is potentially relevant?

Lobster Eye multifoil optics
What optics is potentially relevant?

Lobster eye & multifoil optics

- Wide FOV
- Glass and/or silicon substrate for soft X-rays
- Planar & ellipsoidal mirrors
- Foils 3x3 mm to 300x300 mm
- Foil thickness from 30 μm to 1 mm
Combined MFO – nested paraboloids X-ray optical system

- Non-functional (blind) central area of Flower system can be filled with thin rotationally symmetric foils (classical nested mirrors with parabolic shape)

  => improvement of Flower optical system aperture effective area for higher energies

- Patent pending (PV 2011-297)

- Advantages:
  
  - the largest effective aperture in SXR region
  
  - higher efficiency in XR region
  
  - precise expensive mandrels are not needed for Flower part (silicon or glass thin planar mirrors can be used)

- Application in X-ray telescopes, XRF analysis, EUV/XUV microscopy, tomography and EUV/XUV lithography, focusing of electrons/neutrons, ...
X-ray optical systems - comparison

- Size limited by the critical angle – the same maximum incident angle for all systems at a given photon energy
  (reflectivity 70% after 1st reflection, 50% after 2nd reflection)
- Wolter I and KB systems have the same aperture size
- KBF system has more than two times larger aperture than the others
X-ray optical systems - comparison

What optics is potentially relevant?

=> COMBINATION
KBF and P
(in SXR - XR region)
Ray tracing – intensity map behind the LE mirror

Ray tracing – Homogenization of X-ray beam
Ray tracing – intensity map behind the LE mirror
Ray tracing – intensity map behind the LE mirror
Ray tracing – intensity map behind the LE mirror

INTENSITY PROFILE  LE-18  L =6  X1 = 85  Xd = 90
Ray tracing – intensity map behind the LE mirror

What optics is potentially relevant?

INTENSITY MAP
LE-18
L = 6
X1 = 85
Xd = 200
Ray tracing – intensity map behind the LE mirror

INTENSITY PROFILE  LE-18  L =6  X1 = 85  Xd = 200
Ray tracing – intensity map behind the LE mirror

INTENSITY MAP

LE-18 inclined

L = 6

X1 = 85

Xd = 200
Ray tracing – intensity map behind the LE mirror

INTENSITY PROFILE

LE-18 inclined  \( L = 6 \)  \( X_1 = 85 \)  \( X_d = 200 \)
Ray tracing – intensity map behind the LE mirror

INTENSITY MAP  TRUE POSITION  LE-18 inclined  L = 6  X1 = 85  Xd = 200
Ray tracing – Homogenization of X-ray beam

What optics is potentially relevant?
Ray tracing – Homogenization of X-ray beam

INTENSITY PROFILE  LE-50  L =6  X1 = 250  Xd = 265
Ray tracing – Homogenization of X-ray beam

What optics is potentially relevant?

INTENSITY MAP  LE-50  L = 6  X1 = 250  Xd = 750
Ray tracing – Homogenization of X-ray beam

INTENSITY MAP (11 mm detector sweep) LE-50 L = 6 X1 = 250 Xd = 750
Ray tracing – Homogenization of X-ray beam

INTENSITY PROFILE (11 mm detector sweep) LE-50 $L = 6$ $X_1 = 250$ $X_d = 750$

EUVL Dublin 03-06 November 2014
Ray tracing – Homogenization of X-ray beam

INTENSITY MAP  (rotating LE mirror)     LE-50    L =6    X1 = 250    Xd = 750
Ray tracing – Homogenization of X-ray beam

INTENSITY PROFILE (rotating LE mirror) LE-50 L = 6 X1 = 250 Xd = 750

Czech Technical University in Prague

EUVL Dublin 03-06 November 2014
Ray tracing – Homogenization of X-ray beam

INTENSITY MAP (rotating LE mirror + sweeping detector)  LE-50  L = 6  
X1 = 250  Xd = 750
Ray tracing – Homogenization of X-ray beam

INTENSITY Profile (rotating LE mirror + sweeping detector)  LE-50  L = 6  
X1 = 250  Xd = 750
Ray tracing – intensity map behind the LE mirror
Homogenization of X-ray beam

Summary

Lobster Eye INTENSITY MAP    LE-50   L =6   X1 = 250   Xd = 750

Lobster Eye INTENSITY MAP (11 mm detector sweep) LE-50   L =6   X1 = 250   Xd = 750

Lobster Eye INTENSITY MAP (rotating LE mirror) LE-50   L =6   X1 = 250   Xd = 750

Lobster Eye INTENSITY MAP (rotating LE mirror + sweeping detector) LE-50   L =6   X1 = 250   Xd = 750
Potential optical scheme for FEL based EUV lithography

Key components:

- Grazing incidence Kirkpatrick-Baez collector or better
- Axisymmetric ellipsoidal collector grazing incidence mirror
- Pinhole spatial filter at IF
- Optics for diffraction effects and speckle suppression (optional)
- Optics for beam homogenization (optional)
- Mask illumination optics
- Demagnifying imaging optics
Summary

• Possible optical systems for FEL based EUV lithography were studied.
• Key features of FEL radiation were compared to LPP and DPP radiation
• Quasi parallel input beam, small beam size and possibly submicron size IF make potential optics solutions different from plasma source solutions.
• Diffraction effects and speckle suppression are needed.
• Homogenization of the beam was studied and one example of relevant optical system was modeled.
• Main building blocks of the FEL lithography optical system were identified.
THANK YOU FOR ATTENTION