Overview of EUV Lithography

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(http://www.coe.berkeley.edu/AST/sxr2009)
Extreme Ultraviolet (EUV) Lithography Based on Multilayer Coated Optics

Reflective mask
Multilayer mirror

Absorber pattern

λ = 13 nm

4:1 reduction optics, aspheric, multilayer coated

Wafer to record 30 nm features or smaller, over cm² dimensions

6.7 nm period

Mo Si

λ = 13 nm

Ch10_08_June08.ai
EUV Lithography Will Use a Step and Scan Ring Field System
## International Technology Roadmap for Semiconductors

<table>
<thead>
<tr>
<th>First year of volume production</th>
<th>2003*</th>
<th>2005*</th>
<th>2007*</th>
<th>2009*</th>
<th>2011*</th>
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<tbody>
<tr>
<td><strong>Technology Generation</strong> (half pitch, 1:1, printed in resist)</td>
<td>90 nm</td>
<td>65 nm</td>
<td>45 nm</td>
<td>32 nm</td>
<td>22 nm</td>
</tr>
<tr>
<td><strong>Chip Frequency</strong></td>
<td>2.5 GHz</td>
<td>4.9 GHz</td>
<td>9.5 GHz</td>
<td>19 GHz</td>
<td>36 GHz</td>
</tr>
<tr>
<td><strong>Transistors per chip (HV)</strong> (3 × for HP ; 5 × for ASICs)</td>
<td>190 M</td>
<td>390 M</td>
<td>770 M</td>
<td>1.5 B</td>
<td>3.1 B</td>
</tr>
<tr>
<td><strong>DRAM Memory</strong> (bits per chip)</td>
<td>1.1 G</td>
<td>2.2 G</td>
<td>4.3 G</td>
<td>8.6 G</td>
<td>34 G</td>
</tr>
<tr>
<td><strong>Field Size (mm × mm)</strong></td>
<td>22 × 32</td>
<td>22 × 32</td>
<td>22 × 32</td>
<td>22 × 32</td>
<td>22 × 32</td>
</tr>
<tr>
<td><strong>Wafer Size (diameter)</strong></td>
<td>300 mm</td>
<td>300 mm</td>
<td>300 mm</td>
<td>450 mm</td>
<td>450 mm</td>
</tr>
</tbody>
</table>

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

*Possible 2-year cycle for leading edge companies.*
The Engineering Test Stand (ETS): A Pre-manufacturing EUV Stepper

Mask stage

Projection optics

Wafer stage

Collection optic

EUV Plasma source

Condenser optics

Courtesy of R. Stulen / Sandia
The ASML EUV alpha demo tool

Courtesy of Dr. Hans Meiling, 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

- $\lambda_{\text{euv}}/50$ figure
- Low flare
- Ultrasmooth finish
- 10 $\mu$m 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 Sasa 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

NA = 0.25
RFW = 2.0 mm
Dist. < 1 nm
RMS = 0.025λ
(λ = 13.4)

1390.0 mm

Courtesy of R. Hudyma and D. Sweeney, LLNL.
EUV Source Candidates for Clean, Collectable 13-14 nm Wavelength Radiation

Laser Produced Plasma Source

- Liquid jet or droplets (Xe, other)
- Hot (~60 eV), EUV emitting plasma, 1-3% conversion to in-band EUV, $2\pi$ steradians
- Focused laser light
- Large solid angle, EUV collection optic, $\Delta\Omega \approx 0.6 (2\pi)$
- $\lambda = 1.06 \mu m$
- (from high average power, diode pumped, Nd laser, P = 10 kW, 10 kHz)

Electrical Discharge Plasma Source

- Xe (1 Torr)
- Capillary
- High voltage
- Rear electrode
- Front electrode
- Hot, EUV emitting plasma

Courtesy of Neil Fornaciari and Glenn Kubiak, Sandia.
EUV Spectrum of Capillary Discharge Plasma with Nine Mirror Optical System

![Graph showing EUV spectrum of capillary discharge plasma with nine mirror optical system.](image)

**Multilayer Mirror Parameters:**
- 40 bilayers, $\sigma = 0.5$ nm rms, $\Gamma = 0.44$, FWHM of curve centered at 13.5 nm

(Courtesy of Jason Dimkoff, Sandia)
Typical EUV spectrum from a Xenon plasma in a capillary electrical discharge

References:
Comparative Spectra: Xe and Sn

Xenon

\[ 4p^5 4d^9 \rightarrow 4p^6 4d^8 \]
\[ 4p^6 4d^7 (4f + 5p) \rightarrow 4p^6 4d^8 \]

Tin

\[ 5p \rightarrow 4d \]

- Debris is the issue

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

**Buffer layer**

**Capping layer**

**Multilayer Coating**

**Substrate:**
Low thermal expansion material (LTEM)
(6" square × 1/4" thick)

- Typically Mo/Si multilayer (d = 6.7 nm) with 30 nm SiO₂ 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
At-Wavelength Mask Blank Defect Inspection

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

![Diagram of Kirkpatrick-Baez (KB) EUV focusing optics with reflected EUV beam ("bright field") and scattered EUV ("dark field")](image)

50 µm

![Image: Dark Field](image)

60 nm defect

50 µm

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

Annular

When will EUV resists be available with combined high spatial resolution (20 nm), high sensitivity (10 mJ/cm²), 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.
Plasma sources for EUV lithography exposure tools

Vadim Banine and Roel Moors
ASML, De Run 1110, 5503 LA Veldhoven, The Netherlands

Received 28 May 2004
Published 19 November 2004
Online at stacks.iop.org/JPhysD/37/3207
do:i:10.1088/0022-3727/37/23/001

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.

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>EUV power (in-band, 2π)</td>
<td>1.0 kW</td>
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<tr>
<td>Transmission and collection efficiency</td>
<td>0.02%</td>
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<tr>
<td>Resist sensitivity</td>
<td>5 mJ cm⁻²</td>
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<tr>
<td>Exposure time per wafer</td>
<td>23 s</td>
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<tr>
<td>Scan speed</td>
<td>170 mm s⁻¹</td>
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<tr>
<td>Throughput</td>
<td>100 wph</td>
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</table>
EUV Source Power Requirements are Set by Wafer Throughput Models

Updated EUV power and wafer throughput:

- Collectable EUV power: 250 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

10 µm/cm² resist
- 300 mm wafers
- 89 fields/wafer

Original courtesy of Jos Benschop and Vadim Banine, ASML.

J. Benschop et al., SPIE 3997, 34 (2000),
### Ionization Energies for Xenon

<table>
<thead>
<tr>
<th>Element</th>
<th>1 (H)</th>
<th>2 (He)</th>
<th>3 (Li)</th>
<th>4 (Be)</th>
<th>10 (Ne)</th>
<th>11 (Na)</th>
<th>12 (Mg)</th>
<th>27 (Co)</th>
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**Xenon (J. Gillaspy, NIST)**

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**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

Xenon

\[ \begin{align*}
4p^54d^9 & \rightarrow 4p^64d^8 \\
4p^64d^7(4f+5p) & \rightarrow 4p^64d^8
\end{align*} \]

\[ 5p \rightarrow 4d \]

Tin

\[ \text{Xe+10} \]

\[ \text{Sn+10} \]

- 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

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 $I \sim 10^{11} \text{ W/cm}^2$

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

at 13.5nm, CE = 2%

at 13.6nm, CE = 2.25%

CE = 5.5 % with solid tin!

CE = 3% achievable with droplet source

--- for 30 kHz, 140 mJ laser

120 W / 2\pi
We can now manipulate the UTA emission spectrum
**Conversion efficiency - Tin with other laser wavelengths**

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

\( \lambda = 0.35 \mu \text{m} \):
- Higher laser intensities required
- Emission comes from lower \( n_e \) region

\( \lambda = 1.0 \mu \text{m} \):
- \( n_e \) and \( T_e \) show different trends compared to 0.35µm

\( \lambda = 10 \mu \text{m} \):
- 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
- Collector
  - Lifetime/Cost
  - Manufacturability
  - Debris Mitigation
  - MLM Average Reflectivity
  - MLM Stability
- Source Material/Delivery
  - CE
  - Droplet stability
  - Material purity
  - Serviceability
- Laser
  - Cost/CoO
  - Extraction Efficiency
  - Rep-rate
  - Pulse Width
  - Beam Quality
  - Pointing Stability
- Other
  - Compliance Requirements
  - Alignment
  - Metrology
  - System complexity
Liquid Metal Droplet Generator Developed

- 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

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

Ref: Poster #5751-108, Algots, Cymer
Philips’s EUV Source:
Update and Issues

J. Pankert,
EUV Source Workshop
San Jose 2005
Schematics of the source

- Tin supply
- Excess tin removal
- Cooling channel
- Laser

Philips Extreme UV
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)