EUVL Development in J APAN
~ Challenge, Idea, and Latest Achievement ~

Iwao Nishiyama

Semiconductor Leading Edge Technologies, Inc.
EUVL Development in Japan

<table>
<thead>
<tr>
<th>Year</th>
<th>Light Source</th>
<th>Exposure Tool</th>
<th>Metrology</th>
<th>Mask &amp; Resist</th>
<th>Integration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>Leading Project (LPP source) Supported by MEXT</td>
<td>EUVA Source Pj Supported by NEDO</td>
<td>EUVA Tool Pj Supported by NEDO</td>
<td>ASET EUV Basic Technologies Supported by NEDO</td>
<td>SFET Wavefront measurement Supported by NEDO</td>
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<td>1999</td>
<td>EUVA Source Pj Supported by NEDO</td>
<td>High Reliability Source Supported by NEDO</td>
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<td>Wavefront measurement R&amp;D by company</td>
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<td>Wavefront measurement R&amp;D by company</td>
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<td>Wavefront measurement R&amp;D by company</td>
<td>Wavefront measurement R&amp;D by company</td>
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<td>2003</td>
<td>EUVA Source Pj Supported by NEDO</td>
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<td>Wavefront measurement R&amp;D by company</td>
<td>Wavefront measurement R&amp;D by company</td>
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<td>Wavefront measurement R&amp;D by company</td>
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<td>2005</td>
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<td>Wavefront measurement R&amp;D by company</td>
<td>Wavefront measurement R&amp;D by company</td>
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<td>Wavefront measurement R&amp;D by company</td>
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<td>2008</td>
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<td>2009</td>
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<td>Wavefront measurement R&amp;D by company</td>
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<td>Wavefront measurement R&amp;D by company</td>
<td>Wavefront measurement R&amp;D by company</td>
</tr>
</tbody>
</table>

Legend:
- National Foundation
- Company Pj
Source
First proposal of Tin Target

G. O’Sullivan and P.K. Carroll

Fig. 5. Dependence of 4d–4f transition energies on atomic number Z. Open circles, this paper (Table 1); crosses, data from plasmas of tin through iodine; open triangles, assigned to tungsten in Tokomak plasma; filled squares, absorption of neutral vapors.

Tomie, EUVL Workshop 2000 (San Francisco)

High CE of Tin target was firstly proposed.

Tanuma, EUVL Symposium 2006 (Barcelona)

Charge selective spectra were directly measured.

Charge selective spectra were directly measured.
Feasibility of CO2 laser driven LPP was firstly demonstrated.


K. Nishihara, EUVL Symposium 2004 (Miyazaki)
Pre-pulse laser crash Tin droplet, which enables efficient absorption of main pulse power. CE increases up to 2.5%.

Main pulse beam quality is improved at 7.9kW operation.
## System operation data (1)

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Brightness (@l/F)</td>
<td>25 W</td>
<td>69 W</td>
<td>104 W</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>100kHz</td>
<td>100kHz</td>
<td>100kHz</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>0.25mJ</td>
<td>0.69mJ</td>
<td>1.04mJ</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>10%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Max. non stop op. time</td>
<td>3 hr</td>
<td>1h</td>
<td>-</td>
</tr>
<tr>
<td>Experiment time</td>
<td>7 hr</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Average CE</td>
<td>1.5%</td>
<td>2.3%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Dose stability (simulation)</td>
<td>-</td>
<td>(+/-0.15%)</td>
<td>(+/- 0.15%)</td>
</tr>
<tr>
<td>Droplet diameter</td>
<td>60μm</td>
<td>60μm</td>
<td>60μm</td>
</tr>
<tr>
<td>CO2 laser power</td>
<td>5.0kW</td>
<td>5.6kW</td>
<td>7.9kW</td>
</tr>
</tbody>
</table>
Optics
New-concept interferometers were developed for $\lambda/30$ projection optics.
At-wavelength wave-front metrology of optics

Purpose: Development of standard for WFE metrology

10 m in Diameter, 20 ton in Weight

EUV Illumination

First Pin-hole 650nm

Test Optics

Gratings

Projection

Vacuum Pump

Camera

Large Window and 2nd Pinhole of 50-80nm

Interference fringes obtained by PDI

The System was installed at Hyogo Pref. Univ.

Accuracy of 0.1nm rms was achieved

Schematic View of 6 Mirror System
Tool
EUVL Tool development in Japan
- Small Field Tool -

1986 NTT

5X, 8X Schwartz Child, 11nm/12.4 nm


2001 ASET (HiNA)

Nikon

5X NA0.32


1993 SORTEC

32X Schwartz Child, 13 nm / 4.5 nm


2007 Selete (SFET)

Nikon

5X NA0.32

H. Tanaka, EUVL Symposium 2007 (Sapporo)

Canon

50 nm hp

0.1 μm
EUVL Tool development in Japan
- Full Field Tool -

1997 HIT(ETS)

5X, NA 0.1, SR Source
3 aspheric mirror system

2008 Nikon-Selete(EUV1)

4X, NA 0.25, Xe-DPP
6 aspheric mirror system


Mask
**EUV Mask Development in Selete**

**Mask Infrastructure**
- Actinic Blank Inspection
- Pattern Inspection
- Pattern Repair

**Particle free mask handling**
- MPE-tool
- Blank Inspection M3350
- Double pod
- 0.008 defects/transfer ⇒ 0.002 particles/transfer

- Semi standardization of double pod

**Mask defect printability**
- Phase defect
- Pattern Defect
- Defect repair

**Contamination control**
- Carbon analysis
- Printability
- Cleaning
- Resist outgas

**Model of carbon contamination**
- Carbon analysis
- Printability
- Cleaning
- Resist outgas
### Sensitivity of Pattern defect inspection

**Low reflectivity absorber (R4%)**

<table>
<thead>
<tr>
<th>Base pattern</th>
<th>Defect type</th>
<th>Illumination</th>
<th>Defect size [nm] (Square root of area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>hp32nm (hp128nm)</td>
<td>extrusion</td>
<td>C-pol.</td>
<td>80 75 70 65 60 55 50 45 40 35 30 25 20 15 10 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P-pol.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>intrusion</td>
<td>C-pol.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>P-pol.</td>
<td></td>
</tr>
<tr>
<td>hp27nm (hp108nm)</td>
<td>extrusion</td>
<td>C-pol.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>P-pol.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>intrusion</td>
<td>C-pol.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>P-pol.</td>
<td></td>
</tr>
<tr>
<td>hp22nm (hp88nm)</td>
<td>extrusion</td>
<td>C-pol.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>P-pol.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>intrusion</td>
<td>C-pol.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>P-pol.</td>
<td></td>
</tr>
</tbody>
</table>

- **hp32nm (128nm@mask)**
  - Both of c- and P- polarizations have enough sensitivity
- **hp27nm (108nm@mask)**
  - p-polarization has enough sensitivity
- **hp22nm (88nm@mask)**
  - p-polarization has potential for hp22nm application, but further improvement is needed

**Defect size:**
- hp32nm: 41nm
- hp27nm: 35nm

**LR absorber (R4%)**

- LR= Low Reflectivity
- LR*: TaSi (51nm)
- CrN buffer (10 nm)
- ML (Mo/Si 40 pairs)
- Si cap
- Substrate

**Allowable defect size (10 % CD change)**
Defect printability test by programmed Defect

Multi-shot images were averaged to reduce resist LER

H^32 nm (7 shots averaging)

Mask Defect

Printed images

Shot1

Shot2

Shot7

Exposure

(Edge intrusion)

Comparison between Simulation and Printed CD change

Edge Opaque Defect

Edge Clear Defect

Using the CD Averaging Method, simulated results were verified by actual PD printing test.
Actinic Blank Inspection

POC tool (MIRAI I and II) (Top view)

- YAG Laser
- 532nm, 10Hz
- Collector Mirror
- 6025 Mask Blank
- Schwarzschild Optics (20x or 26x, NA=0.2)

Full-field Inspection tool (Front view)

- EUV light source (DPP, 1.9 kHz)
- Schwarzschild optics (26X)
- 6025 Mask blank

In house LPP EUV light source (10 Hz)
Mask stage stroke: X,Y: 10 mm, 2 mm (Manual operation)
Static imaging mode

Commercial available EUV source (1.9 kHz)
Mask stage stroke: X,Y: 169 mm, 169 mm (Automatic controlled)
TDI mode & Static imaging mode
Detection probability improvement

<table>
<thead>
<tr>
<th>1Q 2009</th>
<th>2Q 2009</th>
<th>1Q 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>One FOV (0.5mm sq.)</td>
<td>Full-field of mask blank</td>
<td></td>
</tr>
<tr>
<td>1 false defect</td>
<td>80,000 false defects</td>
<td>1 false defect</td>
</tr>
</tbody>
</table>

Defect capture rate (%)

- Detection probability improvement:
  - 1Q 2009
  - 2Q 2009
  - 1Q 2010

Defect volume (nm³)

Noise Filter
Defect Map of Multilayered Blank

**Multilayer phase defect**

- Height: 2.5 nm
- Width: 1.5 nmH, 60 nmW

Detection of Programmed defects

- Wx:108nm, Wy:102nm, H:1.9nm
- Wx:40nm, Wy:43nm, H:1.8nm
- Wx:19nm, Wy:20nm, H:1.1nm
- Wx:28nm, Wy:16nm, H:2.8nm

**Defect signal intensity**

- Critical for hp 32 nm
- Critical for hp 22 nm

**Defects critical for hp 32 nm**

**Defects critical for hp 22 nm**
Resist
Change of resist chemistry by excitation energy

Absorption spectra of simple organic molecule

Absorption cross section ($10^{-18} \text{cm}^2$) vs. PHOTON ENERGY (eV)

- METHANE
- ETHANE
- PROPANE
- BUTANE

DUV resist
- Transmittance is a key factor for DUV lithography. ($248 \rightarrow 193 \rightarrow 157 \text{ nm}$)
- Reaction occurs by electronic excitation (Photochemistry)

EUV resist
- All DUV and EB resists technologies can be used for EUV lithography
- Reaction occurs by ionization of molecules (radiation chemistry)
Reaction mechanisms of EB and photo resists

- **EB resists (Main process)**
  
  **Ionization channel**
  
  \[
  \text{RH} \xrightarrow{\text{ionization}} \text{RH}^+ + e^- \xrightarrow{\text{ionization}} \text{R}^+ + \text{RHH}^+ + e^- \]

  \[
  \text{Ph}_3\text{S}^+\text{X}^- \xrightarrow{e^-} \text{Ph}_2\text{S} + \text{Ph}^+ + \text{X}^- \xrightarrow{\text{H}^+} \text{Ph}_2\text{S} + \text{Ph}^+ + \text{H}^+\text{X}^- \]

  
  
  

- **Photoresists (Main process)**
  
  **Excitation channel**
  
  RH: Solvent

  \[
  \text{Ph}_2\text{S}^+ + \text{Ph}^+ + \text{X}^- \xrightarrow{\text{cage-escaped}} \text{Ph}_2\text{S} + \text{Ph}^+ + \text{H}^+\text{X}^- \]

  Homolysis

  \[
  \text{Ph}_2\text{S}^+ + \text{Ph}^+ + \text{X}^- \xrightarrow{\text{in-cage}} \text{Ph}_2\text{S} + \text{Ph}^+ + \text{X}^- \]

  \[
  \text{Ph}_3\text{S}^+\text{X}^- \xrightarrow{\text{Heterolysis}} \text{Ph}_2\text{S} + \text{Ph}^+ + \text{X}^- \xrightarrow{\text{RH}} \text{Ph}_2\text{S} + \text{PhR} + \text{H}^+\text{X}^- \]

  o-PhPhSPh + H^+X^-  

  m-PhPhSPh + H^+X^-  

  p-PhPhSPh + H^+X^-  

  \[
  \text{Ph}_2\text{S}^+ + \text{Ph}^+ + \text{X}^- \xrightarrow{\text{in-cage}} \text{Ph}_2\text{S} + \text{Ph}^+ + \text{X}^- \]

  \[
  \text{Ph}_2\text{S} + \text{Ph}^+ + \text{X}^- \xrightarrow{\text{RH}} \text{Ph}_2\text{S} + \text{PhR} + \text{H}^+\text{X}^- \]
Pattern Collapse Improvement by New Developer

**TMAH 0.26N** (Tetramethyl Ammonium Hydroxide)

**TBAH 0.26N** (Tetraethyl Ammonium Hydroxide)

**New Developer**

**Short-range LWR**

Pattern Collapse Improvement by New Developer

Short-range LWR: 3σ (nm)

- SSR2
- SSR3
- SSR4+Process
- SSR4

**E_{size} of hp32nm (mJ/cm²)**

- 0
- 2.5
- 5.0
- 7.5
- 10.0
- 12.5

**Resolution limit (nm)**

- 0
- 5
- 10
- 15
- 20

**Pattern Collapse**

- hp 26 nm
- hp 25 nm
- hp 24 nm

**Swelling**

- New Developer

**TMAH 0.26N**

- N+
- HO⁻

**TBAH 0.26N**

- N+
- HO⁻
Latest performance of EUV resist

**SSR4**

- hp 28 nm
- hp 26 nm
- hp 24 nm
- hp 22 nm
- hp 21 nm
- hp 20 nm

Dose: 11.9mj/cm²
LWR: 7.2nm

**SMR569**

- hp 19 nm

Dose: 16.0mj/cm²
LWR: 5.4nm

SFET NA0.3
Illumination: X-slit
50nm Thick.
Developer: TBAH
Molecular Resist (Fullaren derivatives)

SMR567 based on M100
M100-bulky E/BBI-nf 30wt%/TOA 3wt%
Substrate: under-layer F (UL-F) 20nm
Film thickness: 50nm
SFET (x-slit)
PAB 110°C/PEB 110°C
Dev.: TMAH 0.26N 30 sec

Protecting group: bulky ester

SMR567: 保護基の最適化
SMR601: 保護比率の増加

Cross sectiona view before/after etching (SMR567)

Litho-pattern
Resist(60nm¹)
/UL(20nm¹)

After Etching
Resist(60nm¹)
/UL(20nm¹)
/Poly-Si(50nm¹)
/SiO₂(4nm¹)/Si

Etcher: U-8150 (Hitachi)
Condition: Cl₂, 0.4Pa, 500W

Normalized Etch-rate

<table>
<thead>
<tr>
<th>Etch-rate</th>
<th>ArF resist (dry)</th>
<th>SMR377 (PHS-tBOC)</th>
<th>MET-2D</th>
<th>SMR567 (Fullerene)</th>
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</thead>
<tbody>
<tr>
<td>hp 26 nm</td>
<td>1.00</td>
<td>0.81</td>
<td>0.53</td>
<td>0.37</td>
</tr>
<tr>
<td>hp 28 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>hp 32 nm</td>
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</table>
Full Field Exposure
Performance of EUV1 (1)

CD accuracy

hp 28 nm

In-field homogeneity

Mean = 29.5 nm
3σ = 3.7 nm

35 nm ホール

Mean = 37.0 nm
3σ = 3.3 nm

Overlay accuracy

Via 1 to Metal 1

Frequency

Overlay accuracy from V1 to M1 (nm)

Mean x y
1.0 0.6
3σ 11.3 8.9

Metal 2 to Via 1

Frequency

Overlay accuracy from M2 to V1 (nm)

Mean x y
1.1 -1.9
3σ 9.8 9.9

CD accuracy

Performance of EUV1 (1)
Performance of EUV1 (2)

Resolution performance by dipole illumination

SSR4:
45 nm thick
Dose:
11 mJ/cm²
Yield improvement of hp 3X nm PL-TEG

1st RUN ('09/1)

Yield was improved by resist performance

2nd RUN ('09/6)

3rd RUN ('09/10)

Yield improvement of hp 3X nm PL-TEG

SSR3

SSR4

SMR73

tiny bridge

collapse

Yield was improved by resist performance
Summary

- History of Japan EUVL development was reviewed.
- Source power is approaching 100 W level based on understanding of plasma physics under the collaboration with university and national laboratories.
- Wavefront error of optics is drastically improved by introduction of new metrology techniques in this decade, and become to satisfy the requirement to pre-production exposure tool.
- EUV1 shows resolution of 22 nm hp with dipole illumination.
- Mask infrastructure is now developing at Selete.
  - Signal to noise ratio of actinic blank inspection tool (ABI) is improved. We applied ABI tool to whole-area bank inspection, and successfully demonstrated the sensitivity as small to 1.1nmH and 20nmW defect.
  - DUV (199 nm)-based pattern inspection technique is applicable to hp 2X by using polarized illumination and low reflectance absorber material.
  - Defect printability are studied using above infrastructures and calculation.
- Resist performance has improved steady based on the improvement of materials and processing technologies.
- We are now developing the $\alpha$-stage EUVL processing, and will be transferred to $\beta$-stage processing in next phase and also manufacturing in company.
- We are now developing BEOL-TEG(hp35nm) process, and PL-TEG(hp3Xnm and hp2Xnm) process. We learn the issues for high volume production.
A part of technologies shown in this presentation are developed by the support of **NEDO** (New Energy and Industrial Technology Development Organization) under the management of **METI** (Ministry of Economy, Trade and Industry).

The author thanks to all co-workers for assistance of presentation.