Advanced Issues and Technology (AIT) Modules

Purpose: Explain the top advanced issues and concepts in optical projection printing and electron-beam lithography.

- **AIT-1**: LER and CAR
- **AIT-2**: Resolution Enhancement and PSM
- **AIT-3**: Small Features and Defects
- **AIT-4**: Aberrations

* **AIT-5**: Maskless, High-NA, Immersion, EUV, Imprint

- **AIT-6**: Electron Beam Lithography

Each module is a 20-25 min presentation of about a dozen slides.

Suggested reading:

- Griffin: Plummer, Deal and Chapter 5
- Wong: 31-45, 55-58, 71-90, Fig 4.1, Fig. 4.10
Reducing Masks Costs in Development by Sharing and by Shuttle

- Shared Masks
  - TSMC: Snipits of several designs on same mask

- Shuttle Masks (4 to 9 layers on one mask)
  - LSI: Reduced volume reticles (Production usage of 4 layers and chips ¼ of field)
  - Cypress: Multiple layers of circuit snipit on the same mask (Balasinski BACUS 04 Best Paper Award)

- Lithography tool overlay issue: blade off most of mask and deal with locally asymmetrical mask runout to still align and print sub-area.
Maskless Lithography

Maskless Lithography Implementation

Physical Details

- A single mirror cell is optically focused to a spot size of 25nm with a critical dimension using two spots (45nm)

- Tilting comb or parallel plate mirrors are controlled electro-statically via which have generally a non-linear displacement response to voltage

- Analog modulation allows high CD control and 1nm edge placement
Grayscale Interface

- Analog modulation allows mirrors to generate various lithography patterns
- Throughput to the mirror array is a primary constraint in this design
  - 5-6 bit data must be compressed off-chip and sent to the chip
  - Data is then decompressed and converted to analog form
  - Due to the slow response time of the mirror (~1us/mirror), a DRAM with a faster response time sits beneath the mirror and stores the analog voltages

Optical analysis of mirror based pattern generation
Yashesh Shroff., Yijian Chen, W. G. Oldham, Department of EECS, UC Berkeley
Optical Constraints at Element Level: Through Focus Symmetry

Software Solutions

(g) tilt

Element Solutions

(c) 2-piston

(a) 1-piston

(d) 3-piston

(e) 4-piston

Jen-Shiang Wang, EIPBN 05
Pareto of Issues

1. Data Management
   - Rate: 10 Terabytes/sec, $10^4$ to $10^7$ elements; Compression: 200X, local decompression

2. Implementation Issues
   - DUV damage to electronics/mirrors, flare, recalibration, aberrations, non-standard circuits, multiple decoding schemes

3. Image Synthesis - elements and software
   - A lot of cool things but Integration Issues: Double grid; Multiple exposure for process window through focus; focus insensitive elements; PSM; Local optimization of illumination

4. System Implementations – few Wafers per Hour
   - Micronic with MEMS array from Fraunhofer Institute
   - ASML 12 mirror arrays with $10^8$ elements (2-4 multiple exposures in one pass)
Depth of Focus at High NA

Rayleigh Quarter Wave Phase Constraint  \( d - d \cos \Theta = \lambda / 4 \)

a) Small angle approx  \( \cos \Theta = \sqrt{1 - \sin^2 \Theta} \approx 1 - (\sin^2 \Theta) / 2 \)

\[ d_1 = \lambda / (2 \sin^2 \Theta) = \lambda / (2NA^2) \]

b) Large Angle Formula  \( 1 - \cos \Theta = 2 \sin^2 \left( \Theta / 2 \right) \)

\[ d_2 = \frac{\lambda}{8 \sin\left(\Theta / 2\right)} = \frac{\lambda}{8 \sin\{\arcsin(NA) / 2\}} \]

<table>
<thead>
<tr>
<th>NA</th>
<th>0.3</th>
<th>0.5</th>
<th>0.63</th>
<th>0.75</th>
<th>0.85</th>
<th>0.93</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 ( \lambda / NA ) nm</td>
<td>322</td>
<td>193</td>
<td>153</td>
<td>129</td>
<td>114</td>
<td>104</td>
</tr>
<tr>
<td>( \Theta ) deg</td>
<td>15.6</td>
<td>30</td>
<td>39.1</td>
<td>48.6</td>
<td>58.2</td>
<td>68.4</td>
</tr>
<tr>
<td>( d_1 / \lambda )</td>
<td>5.6</td>
<td>2.0</td>
<td>1.26</td>
<td>0.89</td>
<td>0.69</td>
<td>0.58</td>
</tr>
<tr>
<td>( d_2 / \lambda )</td>
<td>5.4</td>
<td>1.87</td>
<td>1.12</td>
<td>0.74</td>
<td>0.53</td>
<td>0.40</td>
</tr>
<tr>
<td>( d_2 ) in nm</td>
<td>1024</td>
<td>361</td>
<td>216</td>
<td>143</td>
<td>102</td>
<td>77</td>
</tr>
</tbody>
</table>
Immersion Lithography

- Concept
  - Imaging in a liquid medium with refractive index $n$ offers an $n$ factor of $n$ reduction in resolution
  - $n_{\text{WATER}} @ 193 \text{ nm} = 1.44$ to $1.46$
  - $n_{\text{FUTURE}} @ 193\text{nm} = 1.7$?

- Implementation: Drop and Drag
  - Dispense water from front side of lens, use the surface tension to make the drop follow the lens, and suck in the liquid on the back of the lens.
Immersion Lithography: Results and Promise

- Promise
  - Improve resolution of 193 to that of 157 using a lower NA (0.9 => 0.77) and an increase (1.5X) in DOF.
  - NA = 1.25 for 45 nm generation
  - NA = 1.55 for 32 nm generation

- Issues
  - Liquid (optics), liquid (resist), liquid (machine)
Resolution and Depth of Focus with Immersion

Snell’s Law

\[ \sin \Theta_{AIR} = n_{LIQUID} \sin \Theta_{Liquid} \]

\[ NA_{LIQUID} = \frac{NA_{AIR}}{n_{LIQUID}} \]

For Water at 193 \( n_{LIQUID} = 1.44 \)

<table>
<thead>
<tr>
<th>( NA_{AIR} )</th>
<th>0.85</th>
<th>0.95</th>
<th>1.05</th>
<th>1.15</th>
<th>1.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 ( \lambda/NA ) nm</td>
<td>114</td>
<td>102</td>
<td>92</td>
<td>84</td>
<td>77</td>
</tr>
<tr>
<td>0.35 ( \lambda/NA ) nm</td>
<td>79</td>
<td>71</td>
<td>65</td>
<td>59</td>
<td>54</td>
</tr>
<tr>
<td>( NA_{LIQUID} )</td>
<td>0.59</td>
<td>0.66</td>
<td>0.73</td>
<td>0.80</td>
<td>0.87</td>
</tr>
<tr>
<td>( \Theta_{LIQUID} )</td>
<td>36.2</td>
<td>41.3</td>
<td>46.8</td>
<td>53.0</td>
<td>60.2</td>
</tr>
<tr>
<td>( d_2/\lambda_{AIR} )</td>
<td>1.30</td>
<td>1.0</td>
<td>0.79</td>
<td>0.63</td>
<td>0.50</td>
</tr>
<tr>
<td>( d_2 ) nm</td>
<td>251</td>
<td>193</td>
<td>153</td>
<td>153</td>
<td>97</td>
</tr>
</tbody>
</table>
Polarization Effects at High NA

Parallel Orientation

Vector Addition

$E_x \sim \cos \theta$

$E_z \sim \sin \theta$

$I_{\text{MAX}} \sim (\cos \theta)^2$

$I_{\text{MIN}} \sim (\sin \theta)^2$

$\vec{E}_{\text{total}}$

Perpendicular Orientation

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Module: AIT-5    Ver: 04/09/06

Polarization State

(a) Linear phase grating

(b) Radial phase grating (RPG)

(c) Proximity effect polarization analyzer (PEPA)

(a) Monitoring the nulls of an alternating phase periodic linear grating provides a polarization dependent signal. (b) The image center of a periodic radial grating offers a 2x improvement in signal strength. (c) The optimum pattern is derived from proximity effects enabling a 3-4x signal improvement.

Greg McIntyre, SPIE 06
Illumination Polarization for 193 nm tools

Off-Axis dipoles with polarization perpendicular to off-axis direction.

Illumination Polarization Monitor

Phase-Shifting Masks with 4 phases

Monitor via dose to print central spot

A complete polarimeter is comprised of a minimum of six analyzers designed either for (a) on-axis or (b) off-axis illumination. (c) The image center provides the measurement and is detected in photoresist.
EUV Projection (X-Ray) Lithography

13.5 nm Sn
13.4 nm wavelength

$\lambda/NA = 31$ nm

NA = 0.3

$TFR = \lambda/NA^2 = 149$ nm

Figure 9.24  An x-ray projection lithography system using x-ray mirrors and a reflective mask (after Zorpette, reprinted by permission, © 1992 IEEE).
Exitech MS-13

- 0.30NA, 5x demag
- 200x600um field
- <1nm RMS wavefront
  (0.61nm pred.)
- <10% flare (6% pred.)
- 15 exposure field reticle on translation stage
- 35nm dense and 23nm iso resolution target
- Frequency doubling could test resist to 15nm
EUV Issues

• Source Power
  – Need > watt to wafer to get throughput
  – Difficult collection, low reflectivity => 100W in

• Masks
  – Height
    • Absorber stacks from 100 to 180 nm high
    • Produce horizontal vs. vertical bias 4-6 nm
    • Image placement error 5-8 nm
  – Defect Free

• Difficult to get NA > 0.35
### EUV Mask Absorber Stacks

<table>
<thead>
<tr>
<th>Absorber</th>
<th>Absorber Thickness (nm)</th>
<th>Buffer layer</th>
<th>Buffer layer thickness (nm)</th>
<th>Total height (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>70</td>
<td>SiO2</td>
<td>80</td>
<td>150</td>
</tr>
<tr>
<td>TaN</td>
<td>100</td>
<td>SiO2</td>
<td>90</td>
<td>190</td>
</tr>
<tr>
<td>TaBN</td>
<td>50</td>
<td>Cr</td>
<td>50</td>
<td>100</td>
</tr>
</tbody>
</table>

\[ \theta \approx 6^\circ \]

\[ W = M^*(CD-bias) - \text{shadow} \]

Simulation domain

FBC replaces multilayer stack in 3D simulations

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Near Field at EUV Mask

- Cr 70nm / SiO2 80nm, CD = 45nm, pitch = 90nm, $\theta = 6^\circ$
Simulation of Oblique Mask Illumination Effects for 30 nm EUV

Due to the use of reflective optics in EUV the illumination of masks will be slightly off-normal and electromagnetic effects of slightly oblique incidence result in H-V bias, H-V shift and even polarization dependence that is related to the mask absorber stack height.

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Nano-imprint Lithography

Step&Flash Imprint Lithography

(a) 30 nm dense

(b)

(c)

(d) 20 nm isolated

(e)

(G. Willson, UT Austin)

Issues: Masks, Alignment, Inspection
Printing Over Topography is Possible

MOS Device

Planarization/Imprint

Breakthrough Etch

Transfer Etch

Two Layer Optical Element
Alignment

Typical Step & Scan tool

- Mask
- ~ tens of inches
- Wafer

Requires calibration

The SFIL process

- Template
- ~ 0.25 μm
- Wafer

In situ error measurement and correction

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Mask Making

• e-beam writing (example Applied ETEC system)
  – < 100 nm resolution, 15 – 5 nm grid
  – 50 nm overlay (due to butting)
  – very high cost ($50K/layer)

• optical writing (example ATEQ 4300)
  – 180 nm resolution
  – 25 nm overlay
  – high cost ($20K/layer)
Status: Node by Node

• **2003: 90 nm node: Gates 65 nm**
  – Advanced semiconductor companies 90 nm Using 193 nm NA = 0.85 4X systems
  – Lines => assist or phase-edges
  – Contacts => multiple phase assist patterns

• **Status 2006: 65 nm node: Gates 48 nm**
  – Use 193 nm NA = 1.05-1.10 4X systems
  – Lines => assist or phase-edges
  – Contacts: e-beam or multiple phase-assist

• **Status 2009 45 nm node: Gates 32 nm**
  – Use 193 NA = 1.30 immersion with new liquid
  – Lines => Phase-edge
  – Contacts: e-beam
  – Or EUV 13.4 nm NA = 0.25

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