Zone-Plate Array Lithography: Enabling Nanotechnology from Research through Production

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Was Dali painting with electrons?

Salvador Dali, *The Disintegration of the Persistence of Memory*, 1954
Photons Vs. Electrons

Long Wavelength
  Poor DOF
  Resolution Limit (???)

Short Wavelength
  High resolution
  Depth of focus
Photons Vs. Electrons

Long Wavelength

- Poor DOF
- Resolution Limit (???)

- Fast & Cheap
  - Low Photon Energy
  - No limit to photon density
  - Ambient atmosphere
  - Low-cost optics
  - Photons unperturbed by fields
  - Multi-beam is easy

Short Wavelength

- High resolution
- Depth of focus

But....

- Very Challenging Engineering

- Shot Noise in exposure dose
- Vacum, Slow thermal stabilization
- Deflection by ALL electric & magnetic fields!!!
  - beam current
  - substrate charging
  - column charging
  - scanning stages

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Next Generation of What?

Key Metric not bleeding edge performance, but flexibility, cost, ease-of-use. Access.

- Research
- Defense
- Biotech (tissue scaffolds microarrays)
- Photonics, CGH
- Photomasks, inverse litho

ZPAL lowers barriers to entry for high-resolution lithography.
Barriers to Entry
Barriers to Entry

Complexity
- Chemically Amplified Resist
- Excimer Lasers
- Tool Size, Footprint
- Vacuum
- Proximity Effects

Cost
- Money & Time

Flexibility
- Non-Manhattan Geometries
- Large-area Devices

Inspection
State-of-the-art

Electron Beam

Laser Pattern Generator
ZP-150A Alpha Tool

Affordable, high-throughput high-resolution patterning emphasizing flexibility and ease of use for research, prototyping and low-volume manufacturing.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Feature Size</td>
<td>150nm Dense, 120nm Isolated</td>
</tr>
<tr>
<td>Numerical Aperture:</td>
<td>NA=0.85</td>
</tr>
<tr>
<td>Parallel Beams:</td>
<td>1000</td>
</tr>
<tr>
<td>Writing Speed:</td>
<td>1.7mm²/sec (@0.85 NA)</td>
</tr>
<tr>
<td></td>
<td>~1hr per Ø100mm wafer,</td>
</tr>
<tr>
<td></td>
<td>~2hrs per Ø150mm wafer</td>
</tr>
<tr>
<td>Design Grid:</td>
<td>1nm</td>
</tr>
<tr>
<td>Positioning Resolution:</td>
<td>1.2nm</td>
</tr>
<tr>
<td>Maximum Pattern Area</td>
<td>150mm x 150mm</td>
</tr>
<tr>
<td>Overlay</td>
<td>&lt;20nm</td>
</tr>
<tr>
<td>Field Size</td>
<td>Unlimited</td>
</tr>
<tr>
<td>Wavelength:</td>
<td>405nm (I-line, G-line compatible)</td>
</tr>
<tr>
<td>Minienvironment:</td>
<td>ISO Class 5</td>
</tr>
<tr>
<td>Pattern Layout:</td>
<td>GDS II</td>
</tr>
<tr>
<td>Optimization:</td>
<td>MaskPlus PEC software</td>
</tr>
<tr>
<td>Tool Size:</td>
<td>35” x 53” x 61”</td>
</tr>
</tbody>
</table>

Specifications
Examples of ZPAL Patterns

- \( k_1 = 0.38 \)
- \( k_1 = 0.32 \)

180nm  
150nm

Prototype
MRAM
memory

NA = 0.9

190 nm

Array of contact holes

Optical
Ring
Resonator

CD=230nm

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Zone Plate: A Simple Diffractive Lens

Why diffractive optics?
- Abberation-free on-axis.
- High-NA at low cost.
- Fabricated with planar process.
- Focus uniformity across array.
- Wavefront engineering.

Simple Diffraction:
\[
\sin(\theta) = \frac{\lambda}{p}
\]

Incident Radiation

Zone Plate

\[
\text{NA} = 0.85 \\
\lambda = 400\text{nm}
\]

FWHM = 262nm


SPIE Advanced Lithography 2009
Zone-Plate-Array Lithography

Arbitrary patterns in a dot-matrix fashion as substrates are scanned beneath a fixed array of diffractive microlenses known as zone-plates.

Beamlets individually turned on and off with micromechanics.

Each ZP focuses radiation to a spot.
ZP-150A System Overview

**Spatial Light Modulator**
- Silicon Light Machines Grating Light Valve, 1088 Pixels, 290 kHz, 8-bit grayscale.

**Data Delivery Electronics**
- Custom FPGA design.
- Synchronizes data with motion.
- Position-clocked laser trigger.

**Optics**
- 405nm GaN Laser.
- Beam Mapped to GLV.
- GLV mapped to ZPA.

**Data Preparation**
- GDSII Pattern.
- PEC & Fracturing.
- Optimized bitmap.
- ~4 Tb / 150mm wafer.

**Precision Metrology**
- Direct ZPA-Wafer Measurement minimizes Abbe error, drift.
- 2D Grid Encoder, min res 0.3nm.
- 3-5nm repeatability, 50nm global.
- 1nm position @ 20MHz.

**Scanning Air Bearing & Position Control System**
- 6" x6" Hi-res travel
- ~3nm RMS Error
- 20mm/sec velocity

**ZPA Fabrication**
- e-beam lithography
- HSQ on Fused Silica
- 1000 lens monolithic array
- 0.85NA, ~135μm diameter

**ISPI Gapping & Overlay**
- Direct Measurement of ZPA to Wafer Distance.
- Overlay Detection <1nm
# Design for Accuracy

<table>
<thead>
<tr>
<th>Design</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Static Lens Array</strong></td>
<td>- Accurate Stitching</td>
</tr>
<tr>
<td>Monolithic zone-plate array fixes relative positions of all beams on wafer.</td>
<td>- Loose Tolerances for beams to ZPA.</td>
</tr>
<tr>
<td></td>
<td>- Location of beams on wafer determined only by stage position relative to ZPA.</td>
</tr>
<tr>
<td><strong>Direct Metrology</strong></td>
<td>- Directly measures ZPA relative to wafer, not to machine frame</td>
</tr>
<tr>
<td>ZPA, wafer chuck integrated in metrology frame with 2D encoder.</td>
<td>- Reduces Abbe error, simplifies overall system.</td>
</tr>
<tr>
<td></td>
<td>- More robust than laser interferometer</td>
</tr>
<tr>
<td><strong>Position-clocked data</strong></td>
<td>- Only errors normal to scan are printed.</td>
</tr>
<tr>
<td>Timing of exposure determines location of exposed pixels on wafer.</td>
<td>- Position and velocity errors along scan compensated by exposure timing.</td>
</tr>
</tbody>
</table>
Scanning System

Only Cross-Scan error, not along scan, contributes to pattern error

- Custom XY Air Bearing on Granite Base
- 1nm resolution at 20MHz
- 2kHz Control Loop

RMS=2.8nm

Read Head
Wafer Chuck
Air Bearing Stage
Granite
Pattern Optimization

Proprietary software ensures pattern fidelity, CD linearity by optimizing dose level to every pixel. Also corrects illumination inhomogeneity.

Line-Edge Control

Propriety software ensures pattern fidelity, CD linearity by optimizing dose level to every pixel. Also corrects illumination inhomogeneity.

Proximity-Effect Correction

PEC is computationally easier for ZPAL (incoherent) than coherent imaging (e.g. projection litho).

~200 gray-levels for every exposure pixel allows sub-pixel line control.
Problem of Inspection in Maskless Lithography

Inspection for direct-write litho is a harder problem than for photomasks. Common to ALL maskless schemes.

- No Amortization
- No Repair
- Throughput requirement

Solution: Inspection on the fly = Hard Output

Record in photoresist of dose at all positions on substrate. + Soft Output

Digital record of dose at all positions on substrate.

★ Tool provides additional soft output to enable localization and characterization of errors prior to guide inspection of hard output.

★ Capture of true position of all beams simultaneously with dose information critical for practical implementation.
Interferometric Spatial-Phase Imaging

ISPI encodes position in the spatial-phase disparity between a matched pair of interferometric moiré patterns that magnify displacement.

sub-1 nm via phase-analysis

Benefits of ISPI

Directly measure working distance.
Direct ZPA-wafer overlay.
Dark Field Imaging for High-SNR.
Low-NA (0.06) optics.
Robust through multiple layers.

Absorbance Modulation Optical Lithography (AMOL)

- Annulus at $\lambda_2$ in competition with bright spot at $\lambda_1$ creates localized sub-wavelength aperture
- Bright spot at $\lambda_1$ transmits through aperture exposing photoresist

AMOL Proof-of-Concept

Dichromatic Zone Plate

Absorbance Modulation Photochemistry

$\lambda_1 = 325\text{nm}$

$\lambda_2 = 633\text{nm}$

Focal spot at $\lambda_1$

Focal ring at $\lambda_2$

1.23 $\mu$m

396 nm

426 nm

35nm

42nm

1.70 nm

350nm

Thanks to H.Y. Tsai, Massachusetts Institute of Technology and T. Andrew, Massachusetts Institute of Technology
Zone-Plate Array Lithography (ZPAL): Leveraging new technologies for low-cost, high-performance lithography

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