LUMARRAY

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

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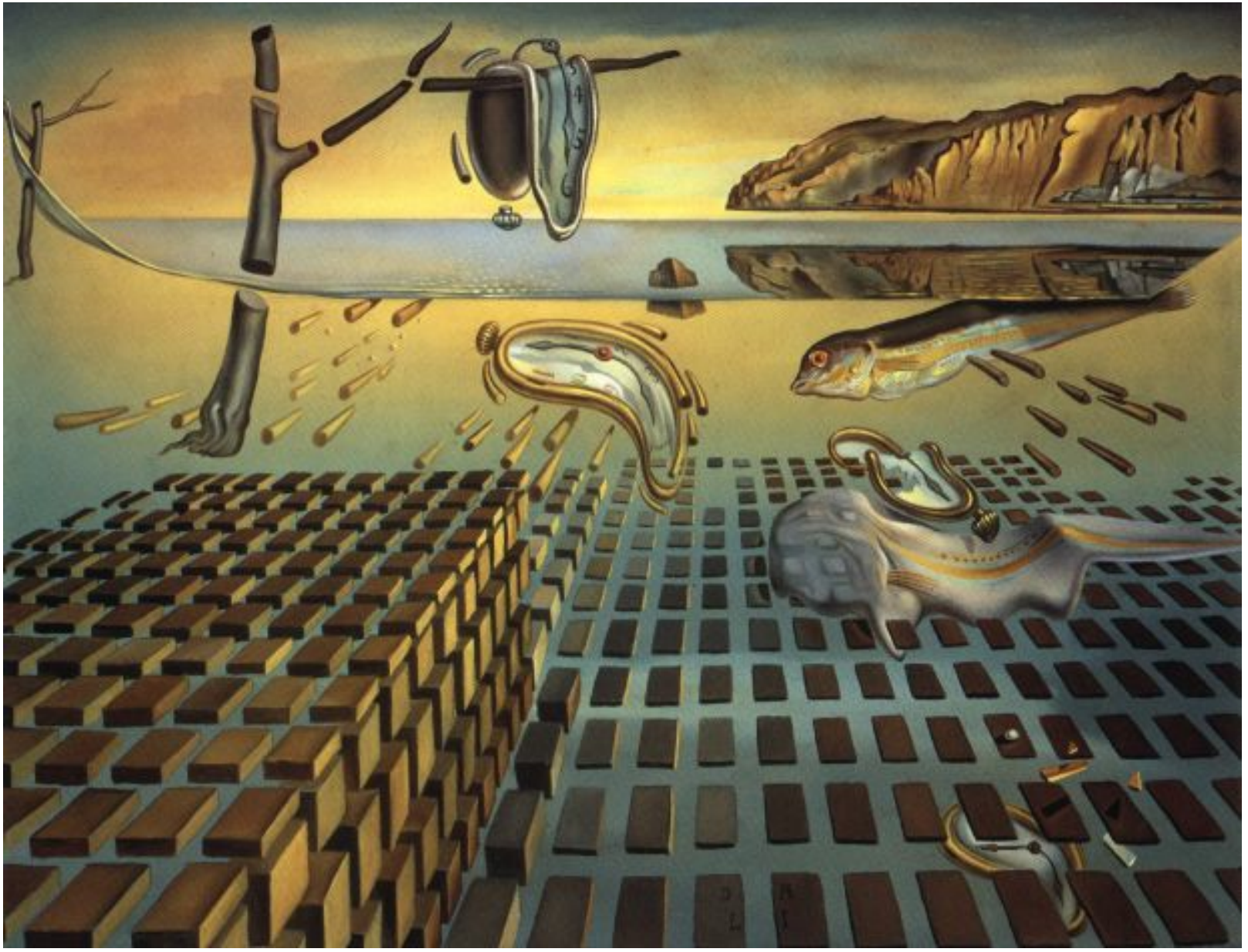
Was Dali painting with electrons?



Salvador Dali, *The Disinegration 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 (???)

Short Wavelength

High resolution

Depth of focus

But....

Fast & Cheap

Low Photon Energy

No limit to photon density

Ambient atmosphere

Low-cost optics

Photons unperturbed by fields

Multi-beam is easy

Very Challenging Engineering

Shot Noise in exposure dose

Vaccum, Slow thermal stabilization

Deflection by ALL electric & magnetic fields!!!

beam current

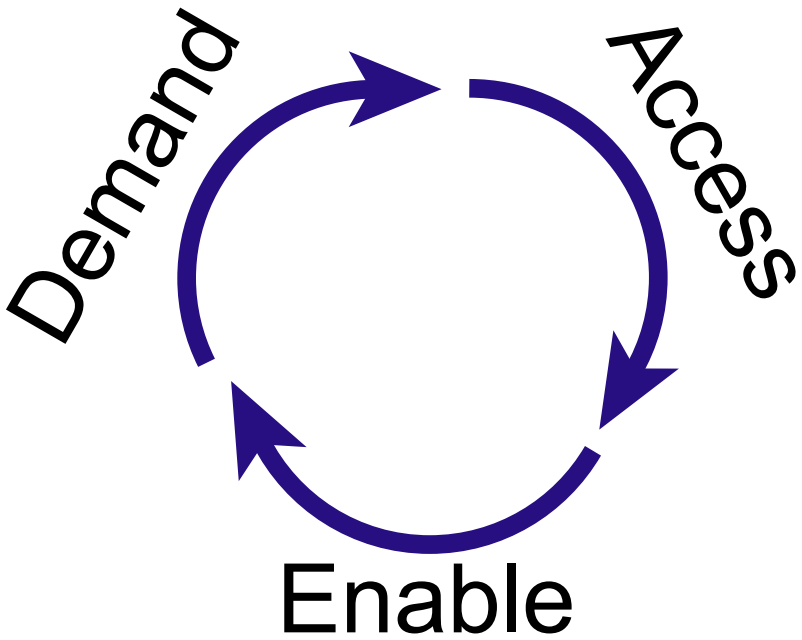
substrate charging

column charging

scanning stages

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

Inspection

Cost

Money & Time

Flexibility

Non-Manhattan Geometries

Large-area Devices

State-of-the-art

Laser Pattern Generator

Electron Beam

ZP-150A Alpha Tool

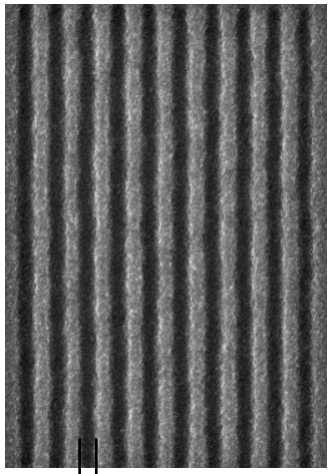
Affordable, high-throughput high-resolution patterning emphasizing flexibility and ease of use for research, prototyping and low-volume manufacturing.

Specifications

Minimum Feature Size	*150nm Dense, 120nm Isolated*
Numerical Aperture:	*NA=0.85*
Parallel Beams:	*1000*
Writing Speed:	*1.7mm²/sec (@0.85 NA)* *~1hr per Ø100mm wafer,* *~2hrs per Ø150mm wafer*
Design Grid:	*1nm*
Positioning Resolution:	*1.2nm*
Maximum Pattern Area	*150mm x150mm*
Overlay	*<20nm*
Field Size:	*Unlimited*
Wavelength:	*405nm (I-line, G-line compatible)*
Minienvironment:	*ISO Class 5*
Pattern Layout:	*GDS II*
Optimization:	*MaskPlus PEC software*
Tool Size:	*35" x53" x61"*

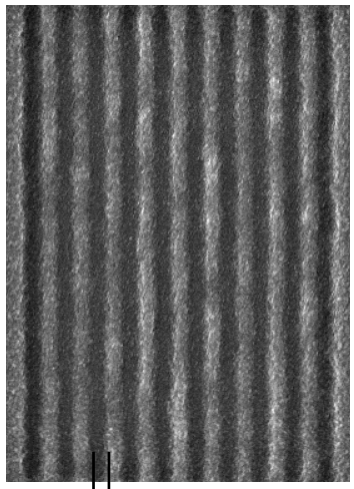
Examples of ZPAL Patterns

$k_1 = 0.38$



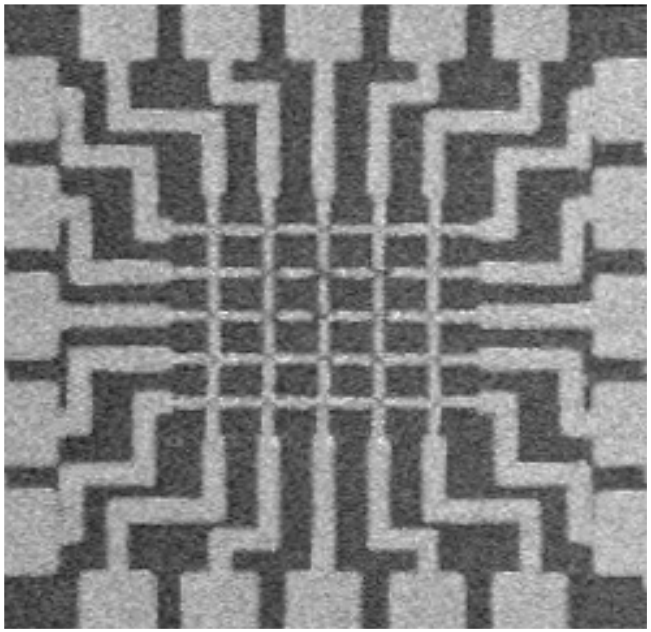
180nm

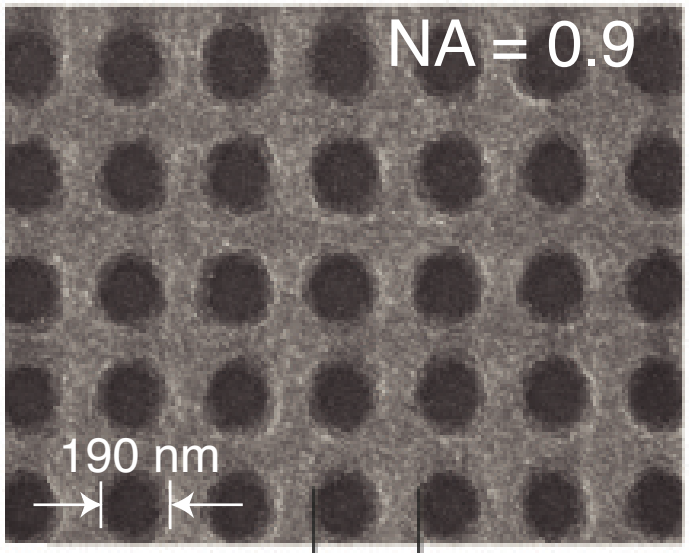
$k_1 = 0.32$



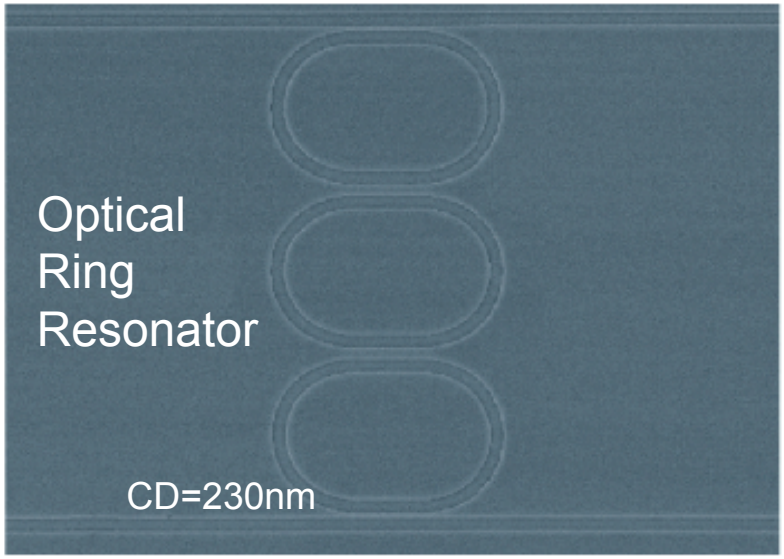
150nm

Prototype MRAM memory

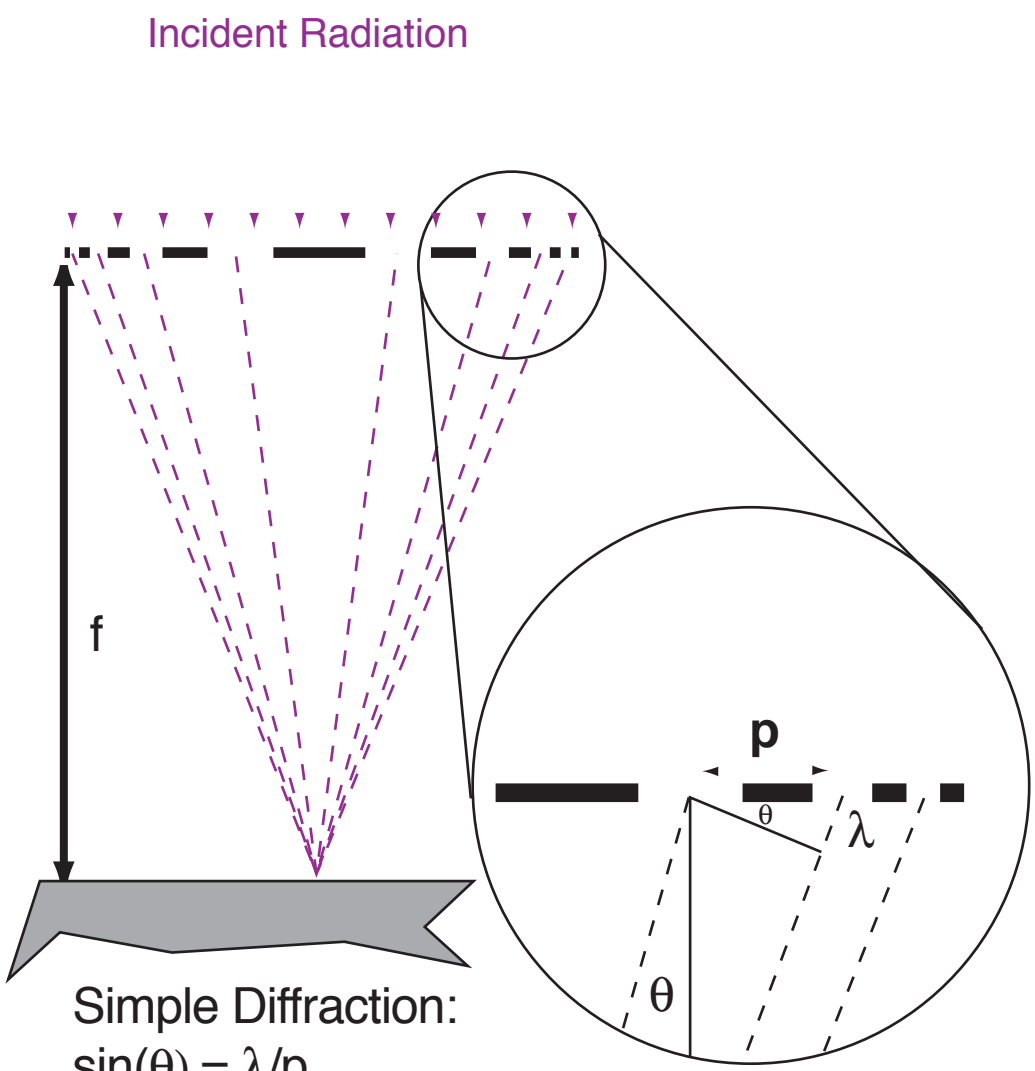




Array of contact holes



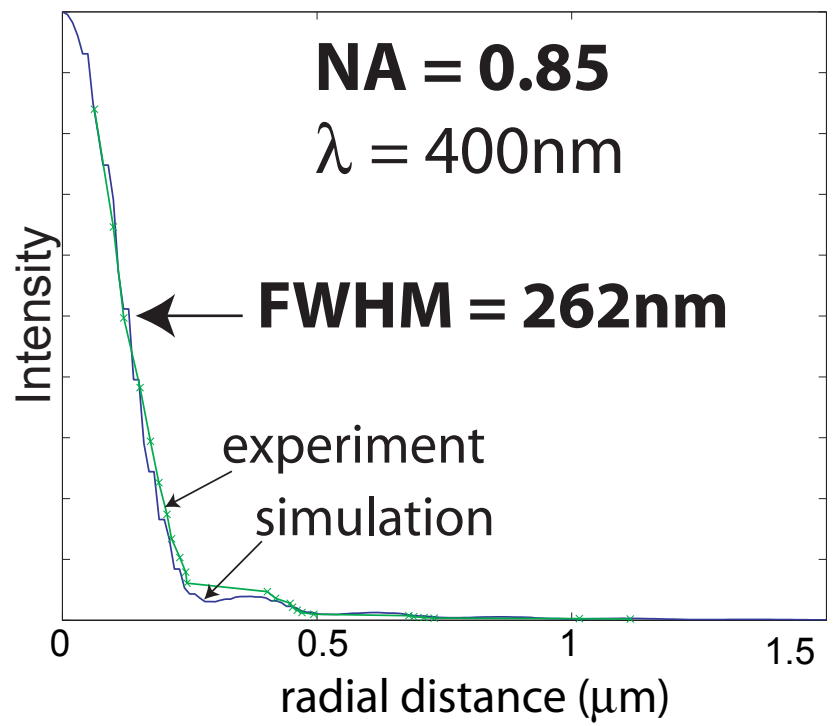
Zone Plate: A Simple Diffractive Lens



Simple Diffraction:
$\sin(\theta) = \lambda/p$

Why diffractive optics?

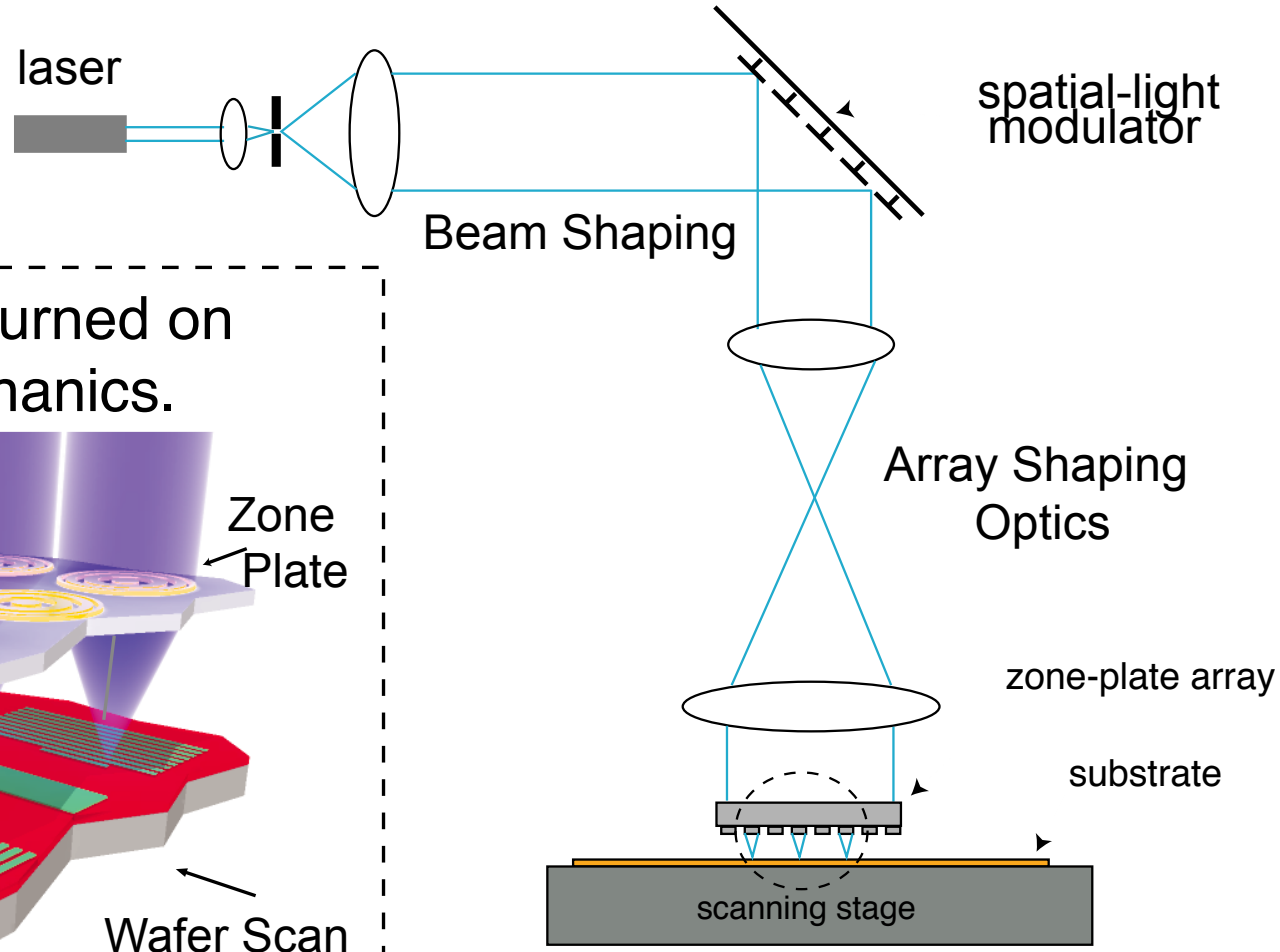
- Abberation-free on-axis.
- High-NA at low cost.
- Fabricated with planar process.
- Focus uniformity across array.
- Wavefront engineering.



D. Gil, et al. 'The Case for Diffractive Optics in Maskless LIthography,' J. Vac. Sci. Technol B 21(6) 2003

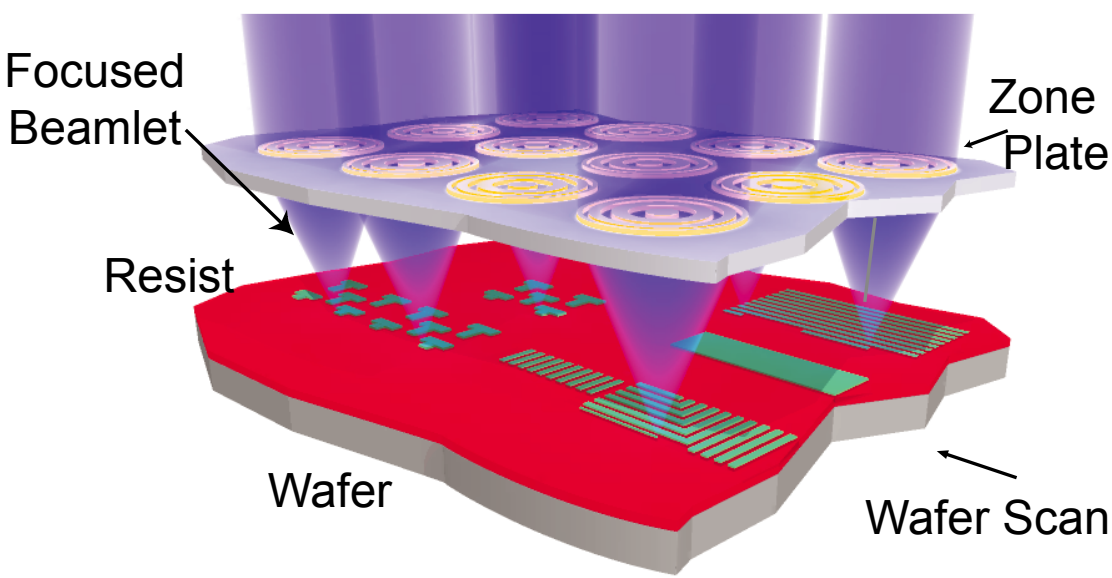
Zone-Plate-Array Lithography

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



Serpentine, constant-velocity wafer scan.

Beamlets individually turned on and off with micromechanics.



Each ZP focuses radiation to a spot.

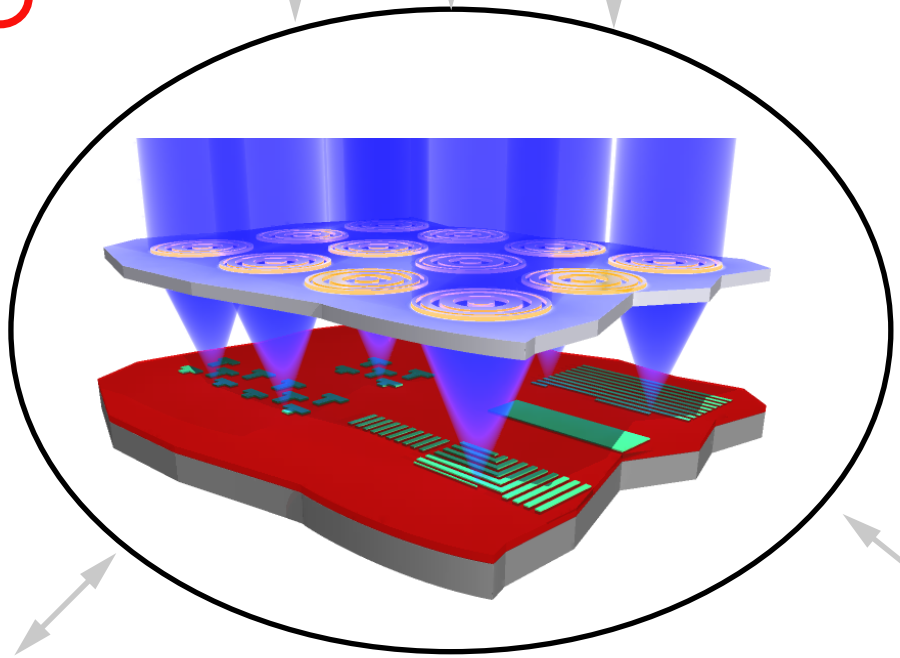
LUMARRAY

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 wafe.r

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

1nm position
@ 20MHz

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

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

ISPI Gapping & Overlay
Direct Measurement of
ZPA to Wafer Distance.
Overlay Detection <1nm

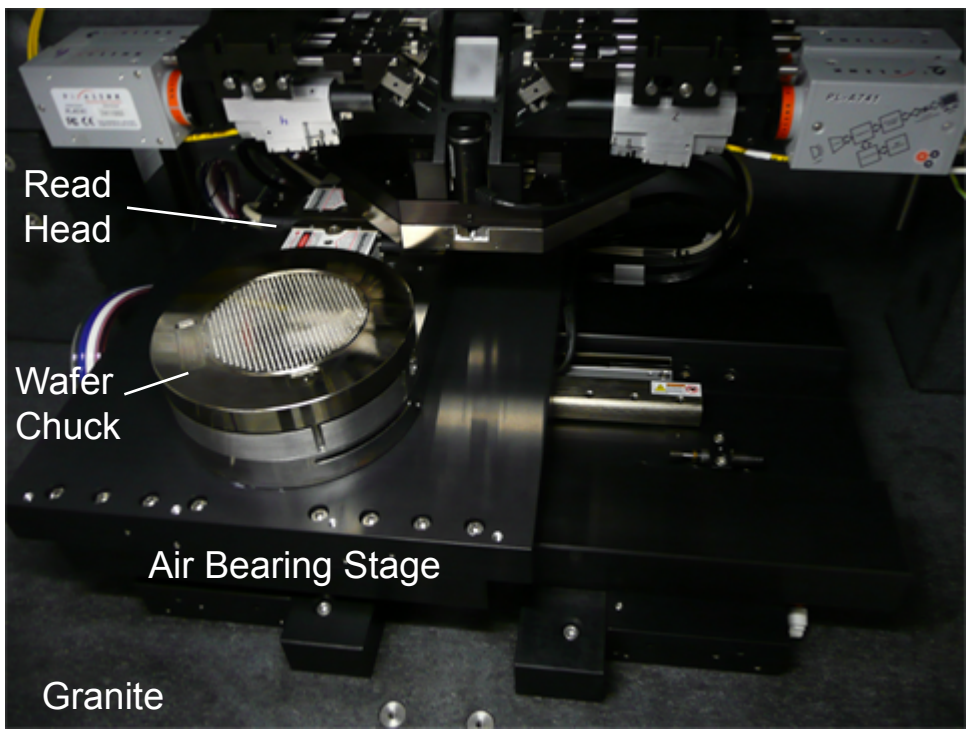
Design for Accuracy

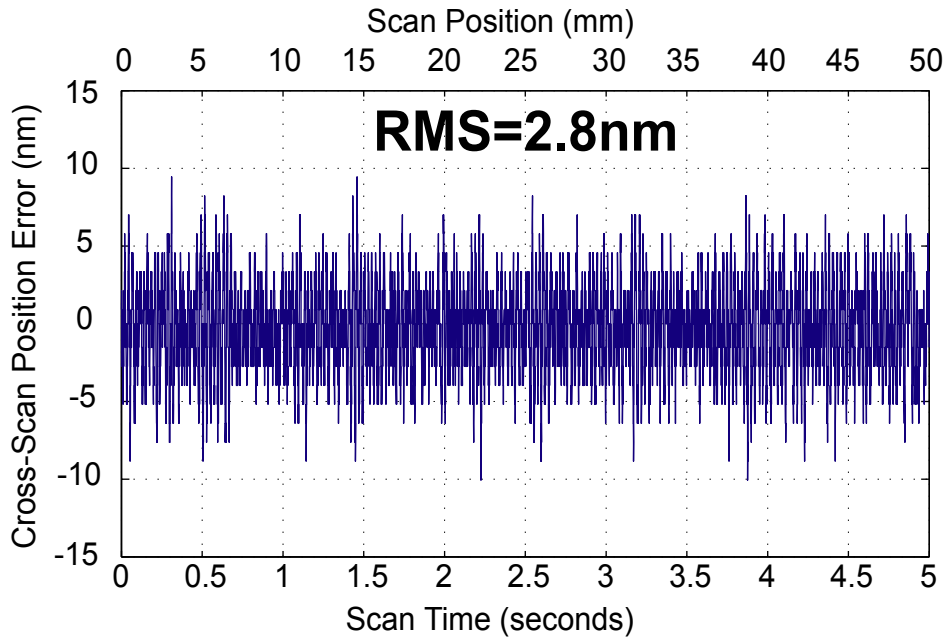
Design	Benefit
Static Lens Array Monolithic zone-plate array fixes relative positions of all beams on wafer.	★ Accurate Stitching ★ Loose Tolerances for beams to ZPA. ★ Location of beams on wafer determined only by stage position relative to ZPA.
Direct Metrology ZPA, wafer chuck integrated in metrology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

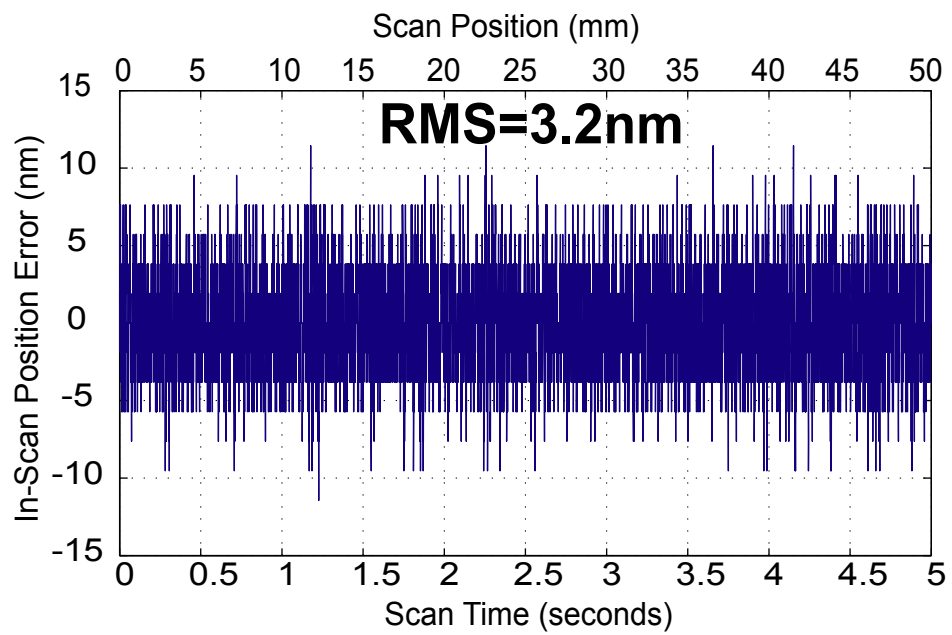
Scanning System

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

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



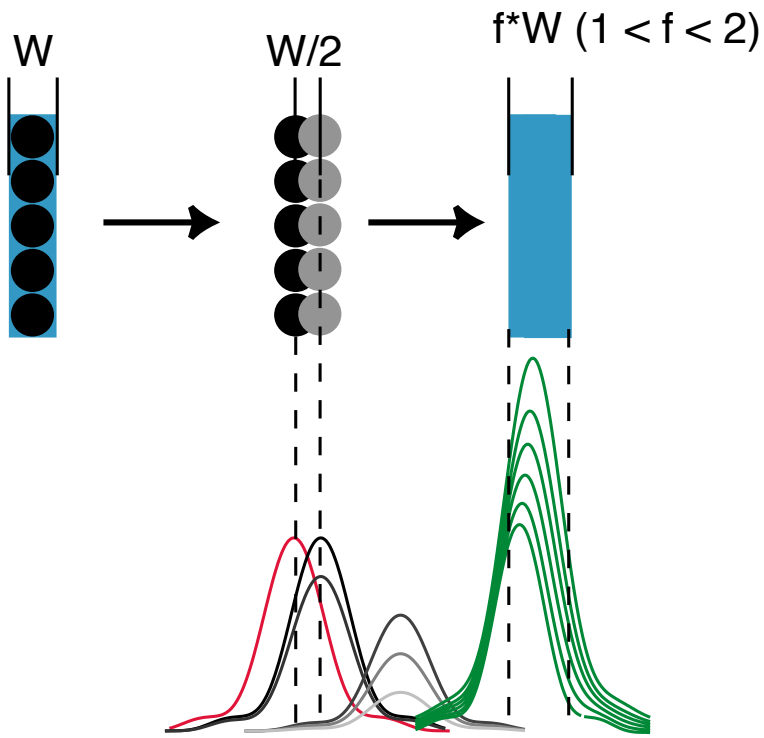




Pattern Optimization

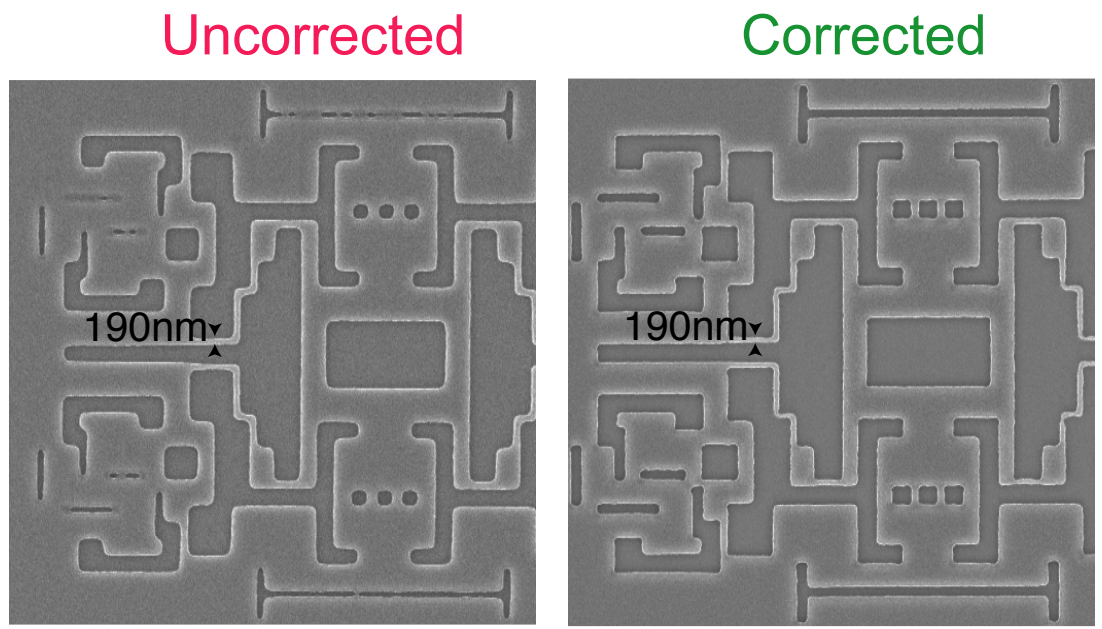
Proprietary software ensures pattern fidelity, CD linearity by optimizing dose level to every pixel. Also corrects illumination inhomogeneity.

Line-Edge Control



~200 gray-levels for every exposure pixel allows sub-pixel line control

Proximity-Effect Correction



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

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 susbstrate.*

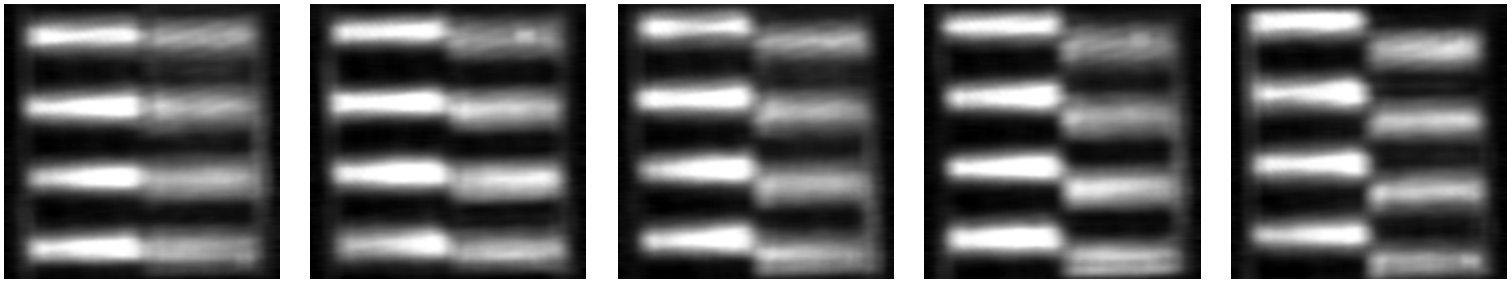
★ Tool provides additional soft output to enable localization and characterization of errors prior to guide inspection of hard output.

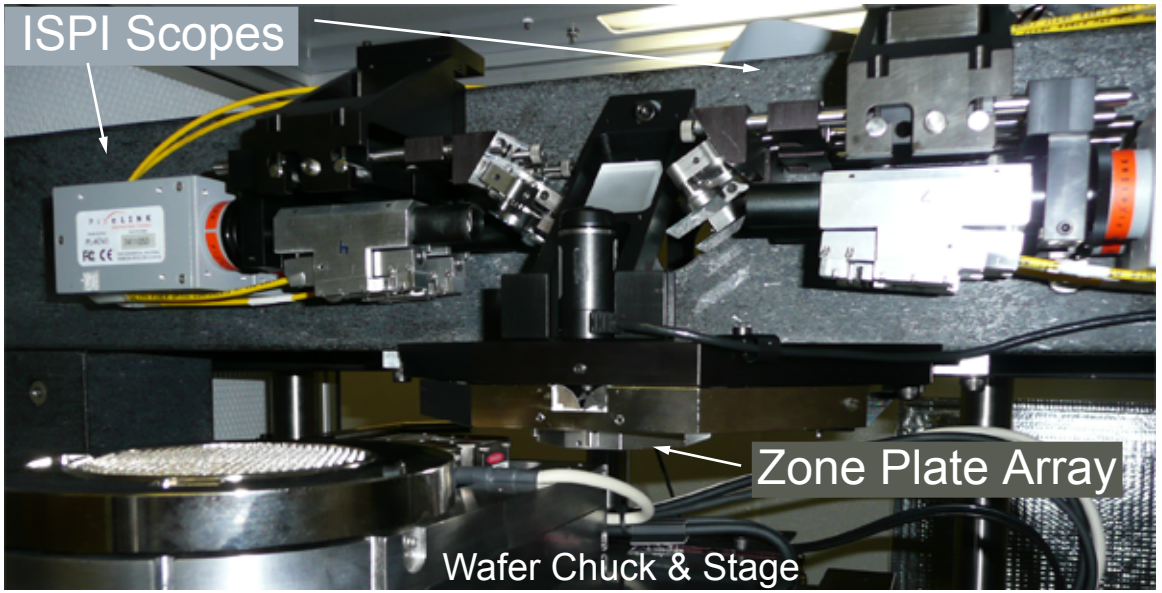
★ Capture of true position of all beams simultaneously with dose information critical for practical implementation.

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.

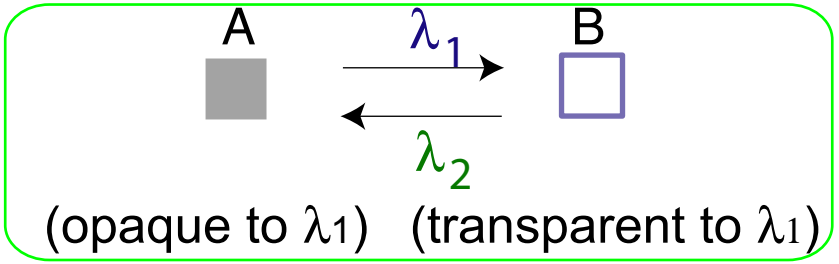
Dark Field Imaging for High-SNR.

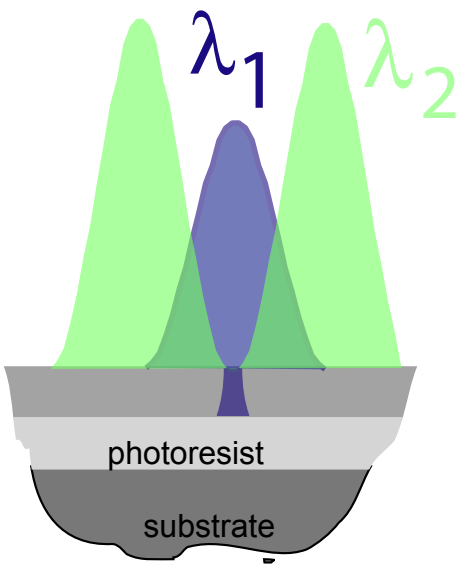
Low-NA (0.06) optics.

Robust through multiple layers.

E.E. Moon et al, *J. Vac Sci. Technol. B* 21(6) 3112 (2003)

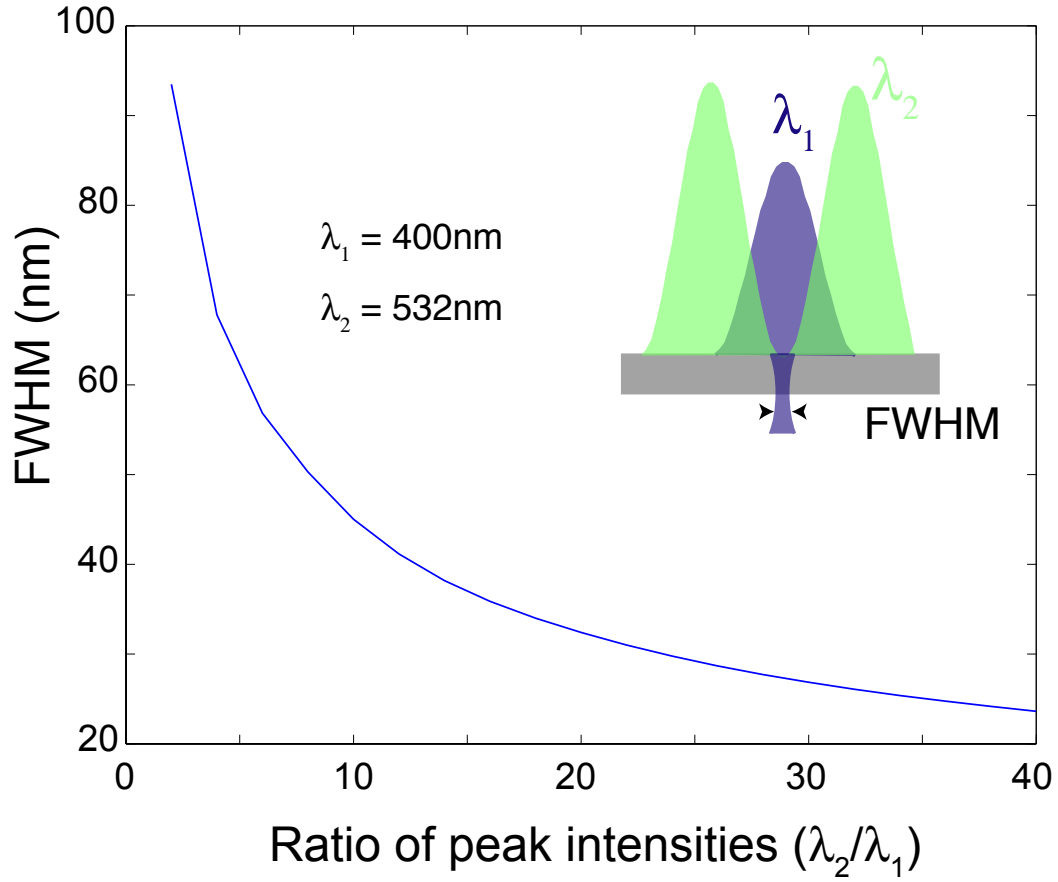
Absorbance Modulation Optical Lithography (AMOL)





absorbance modulation layer (AML)

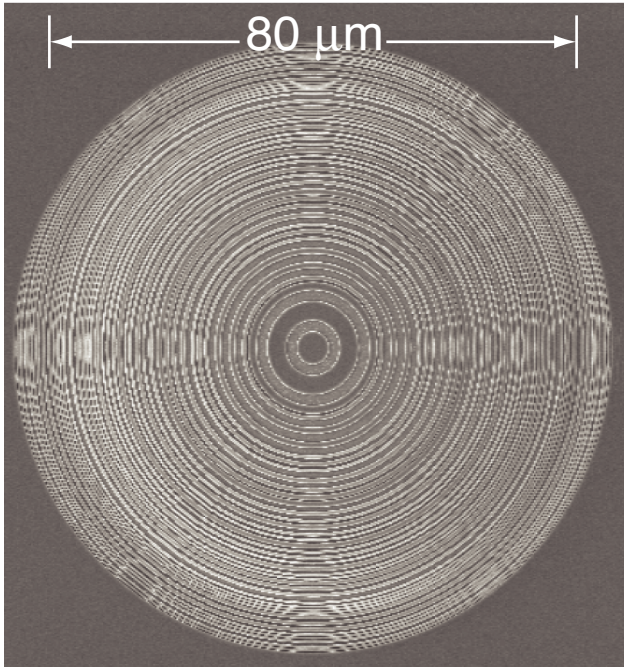
R. Menon, et al, J. Opt. Soc. Am A, 23, 2290 (2006).



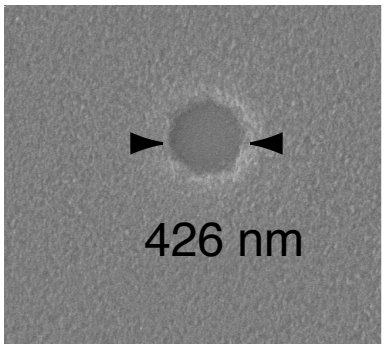
- Annulus at λ_2 in competition with bright spot at λ_1 creates localized sub-wavelength aperture
- Bright spot at λ_1 transmits through aperture exposing photoresist

AMOL Proof-of-Concept

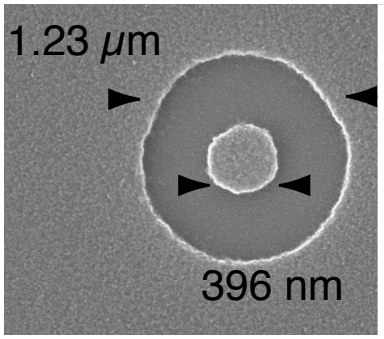
Dichromatic Zone Plate



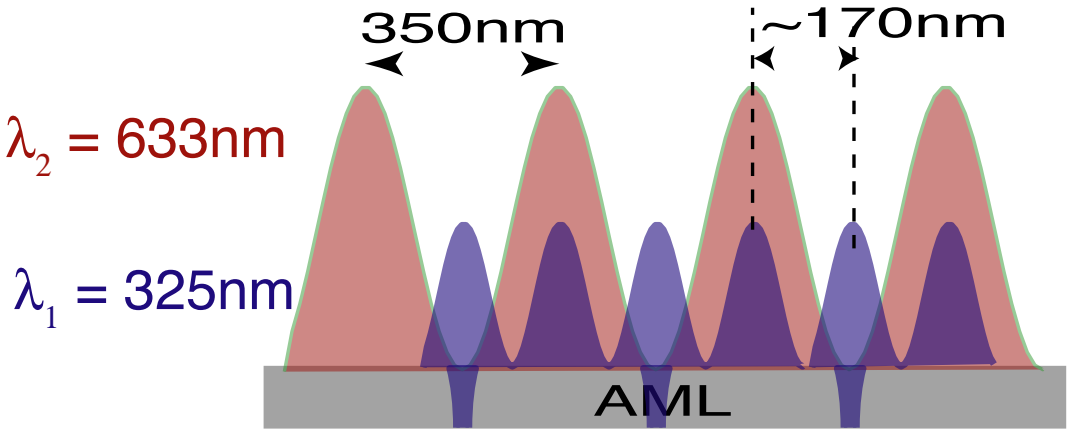
Focal spot at λ_1

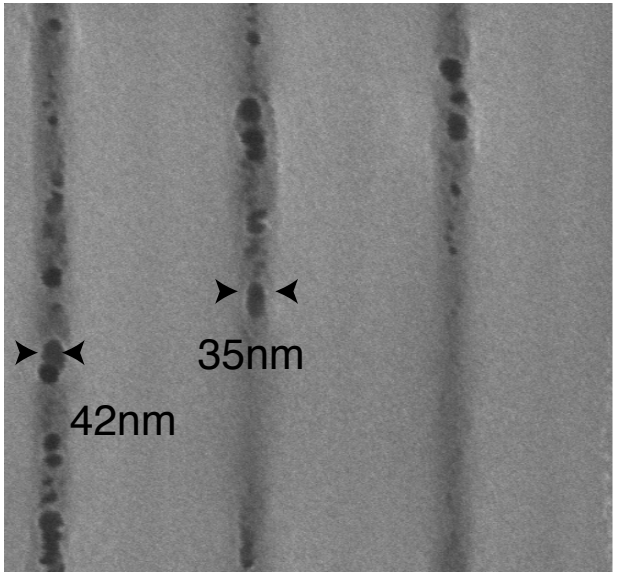


Focal ring at λ_2



Absorbance Modulation Photochemistry



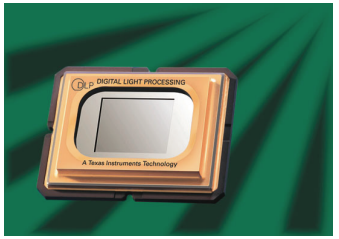


Thanks to H.Y. Tsai, Massachusetts Institute of Technology and T. Andrew, Massachusetts Institute of Technology

Zone-Plate Array Lithography (ZPAL): Leveraging new technologies for low-cost, high-performance lithography

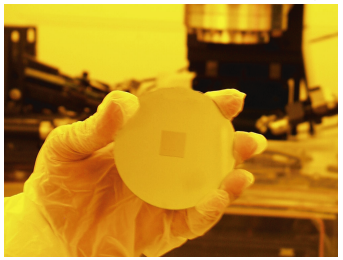
Photomask

Light Multiplexer



Stepper Lens

Zone-Plate Array



Printing Press Model

Laser Printer Model

Thanks to :

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MIT NanoStructures Lab
Sidny Tsai
Euclid Moon
Trisha Edwards