Maskless Photolithography for Customization

by

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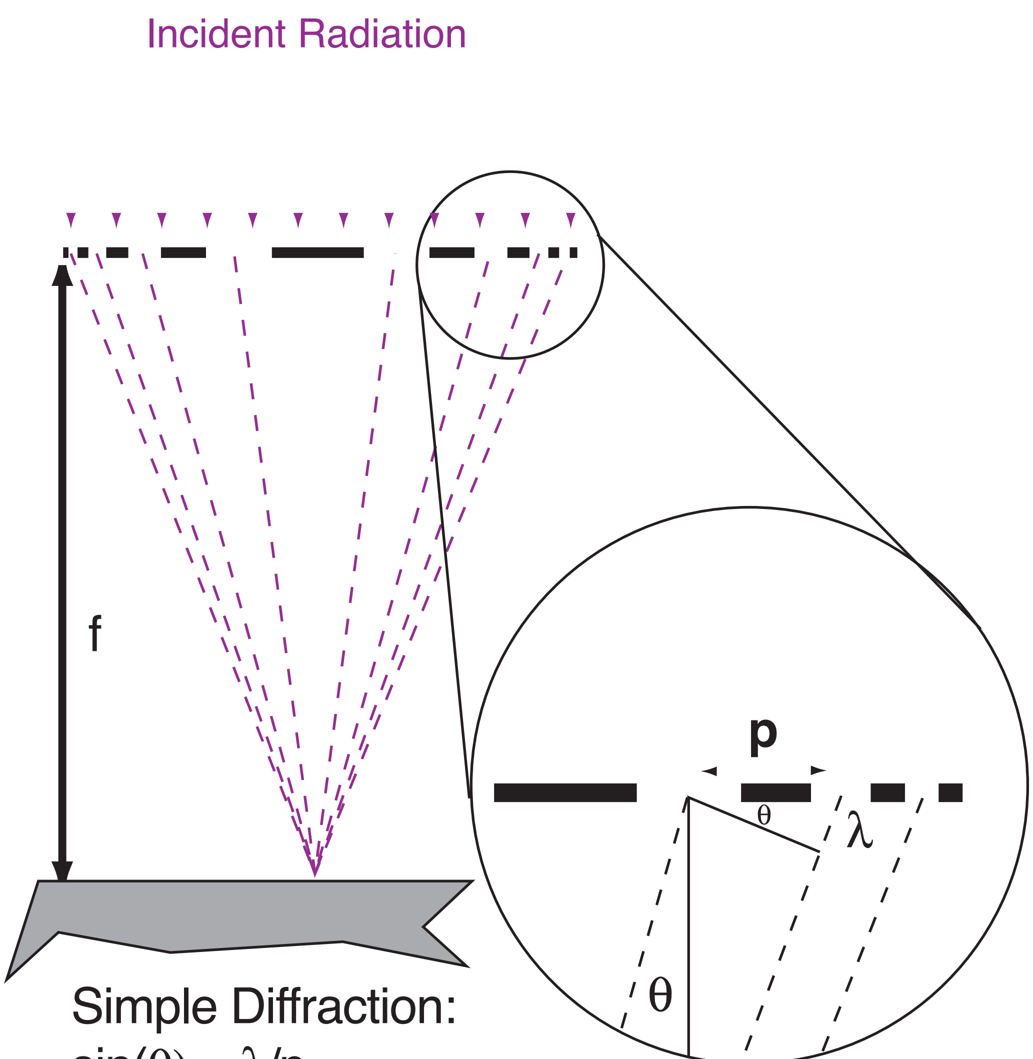
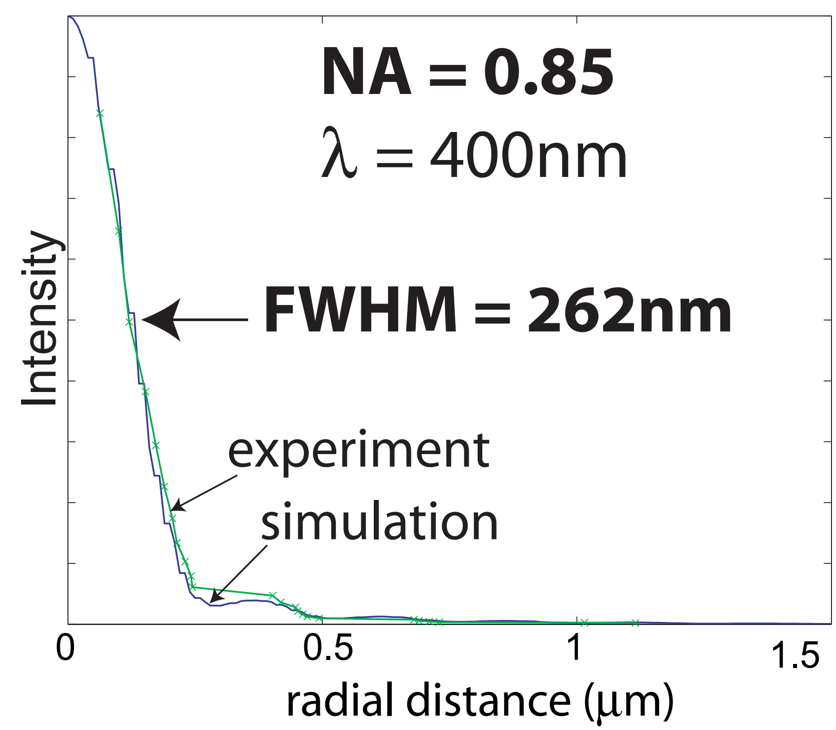
Zone Plate: A Simple Diffractive Lens



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

Why diffractive optics?

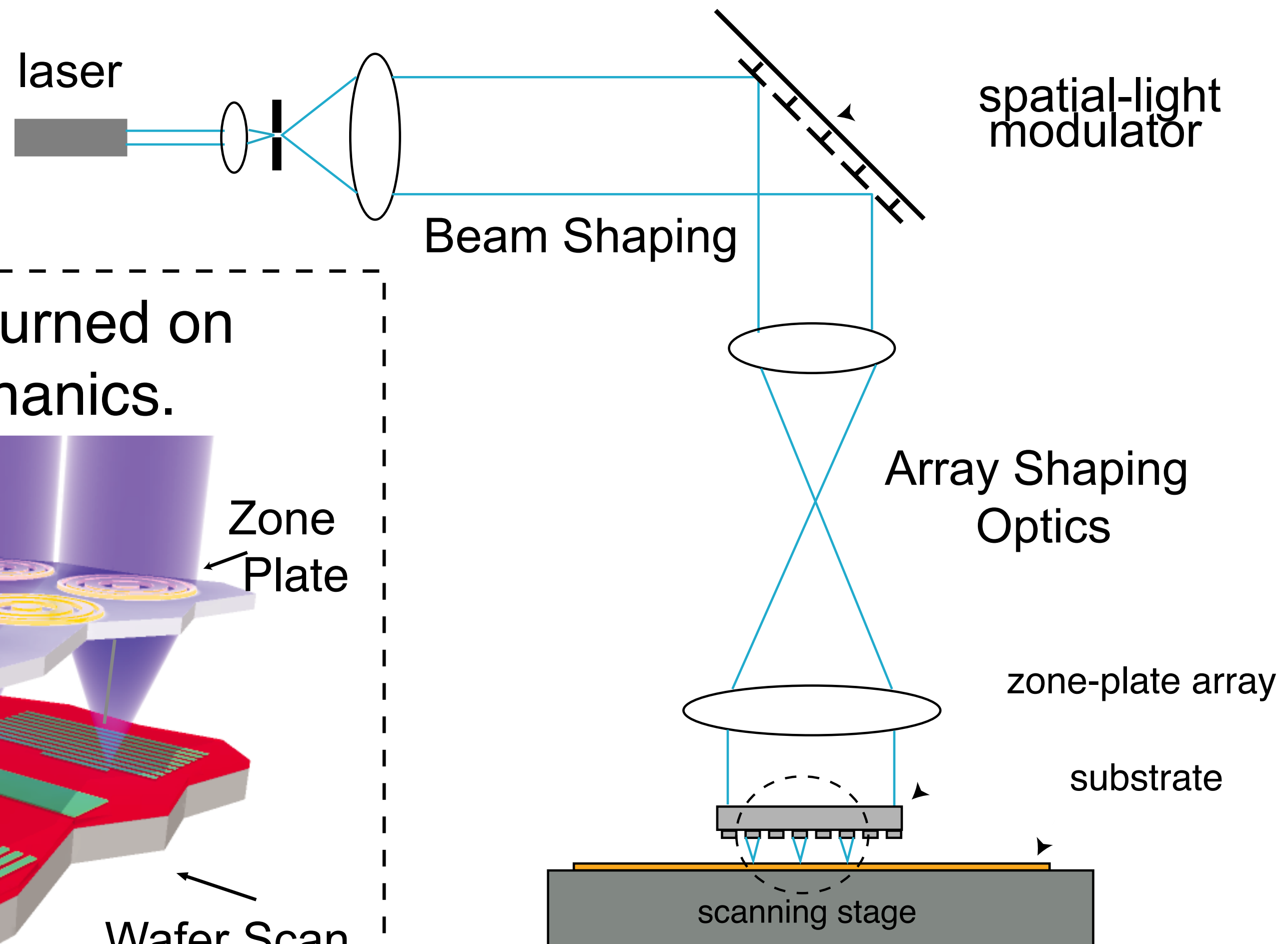
- Abberation-free on-axis.
- High-NA at low cost.
- Fabricated with planar process.
- Focus uniformity across array.
- Wavefront engineering.



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

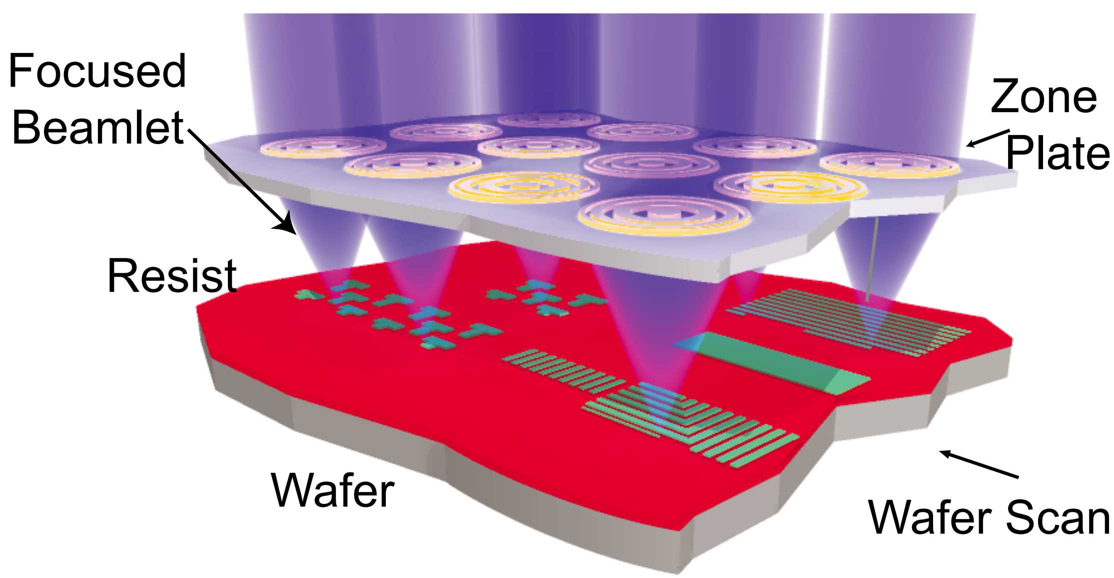
Zone-Plate-Array Lithography

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



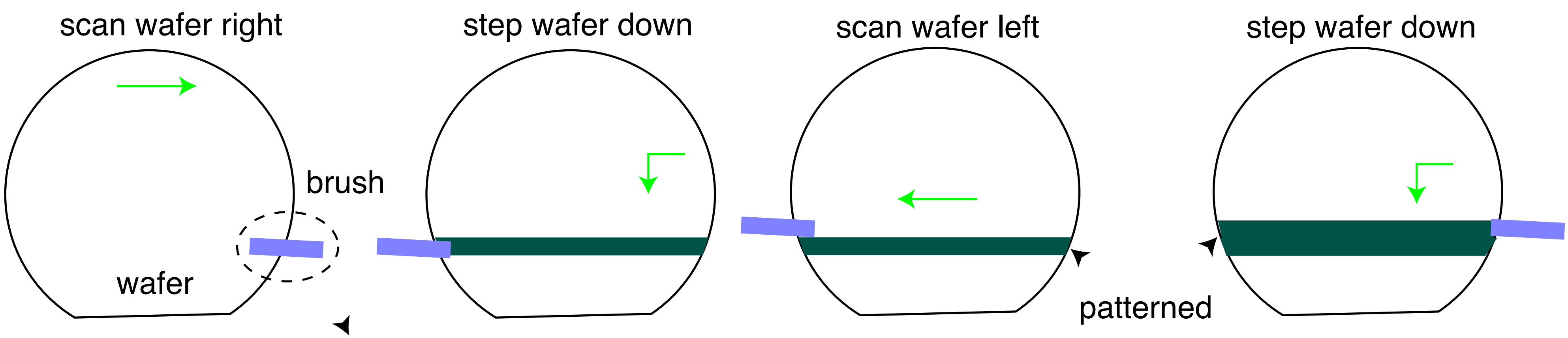
Serpentine, constant-velocity wafer scan.

Beamlets individually turned on and off with micromechanics.

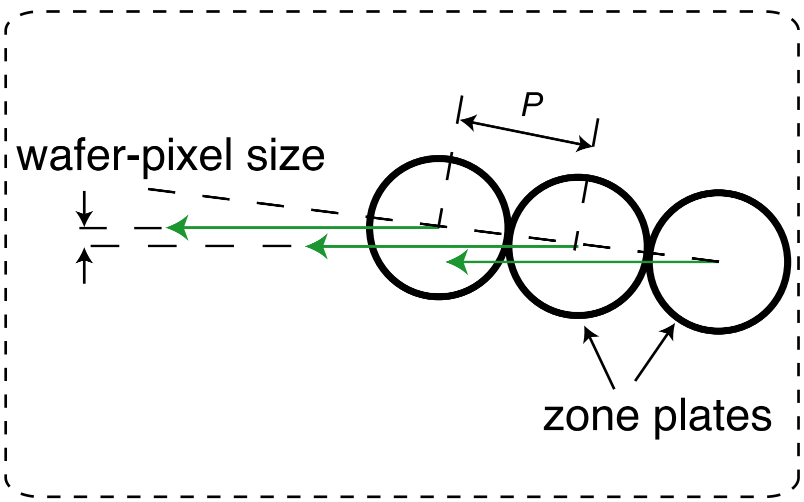


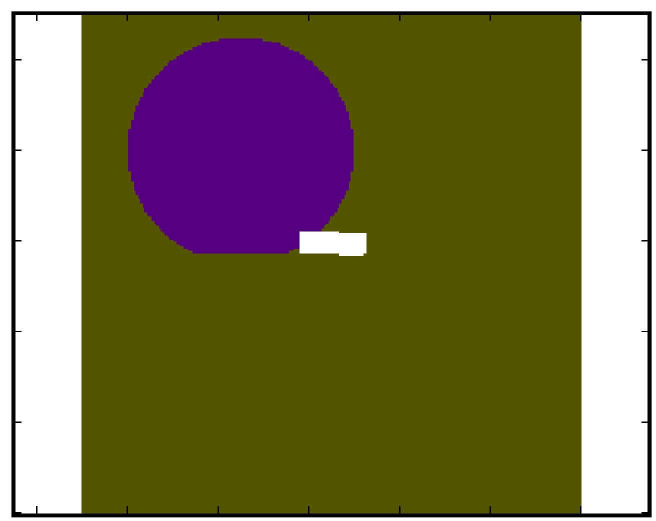
Each ZP focuses radiation to a spot.

Scan Strategy



The Brush

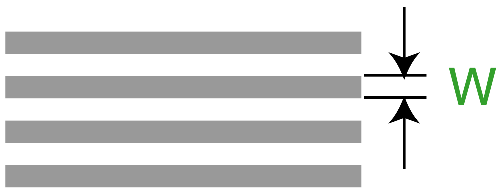




- Similar to “scanner” but much slower scan speed (~ 30 to 375 mm/s)
- Brush is fixed. Only wafer scanned --> placement, overlay, stitching determined by stage
- Laser-interferometer-controlled stage for nanometer-level precision

Resolution: $k_1 < 0.3$

minimum feature size:



$$W = \frac{k_1 \lambda}{NA}$$

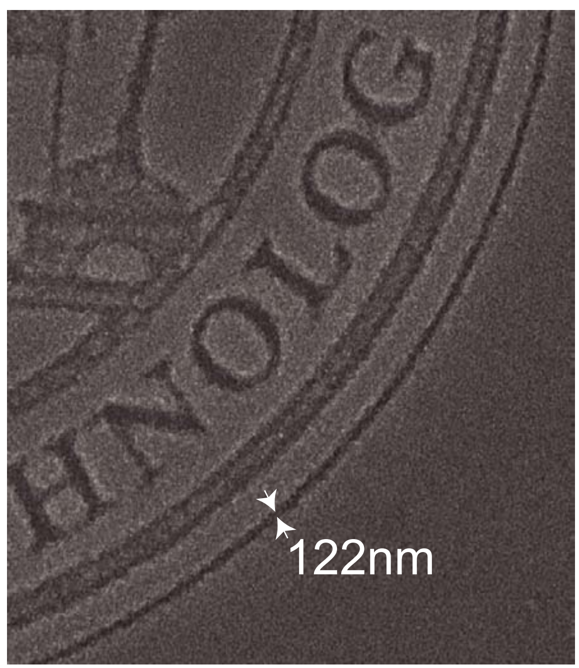
Address unit = W/2 + 8 bits of gray-levels
Linewidth control = W/512
= 0.29 nm (W = 150nm)

λ = 400nm, NA = 0.85

Patterns of Arbitrary Geometry

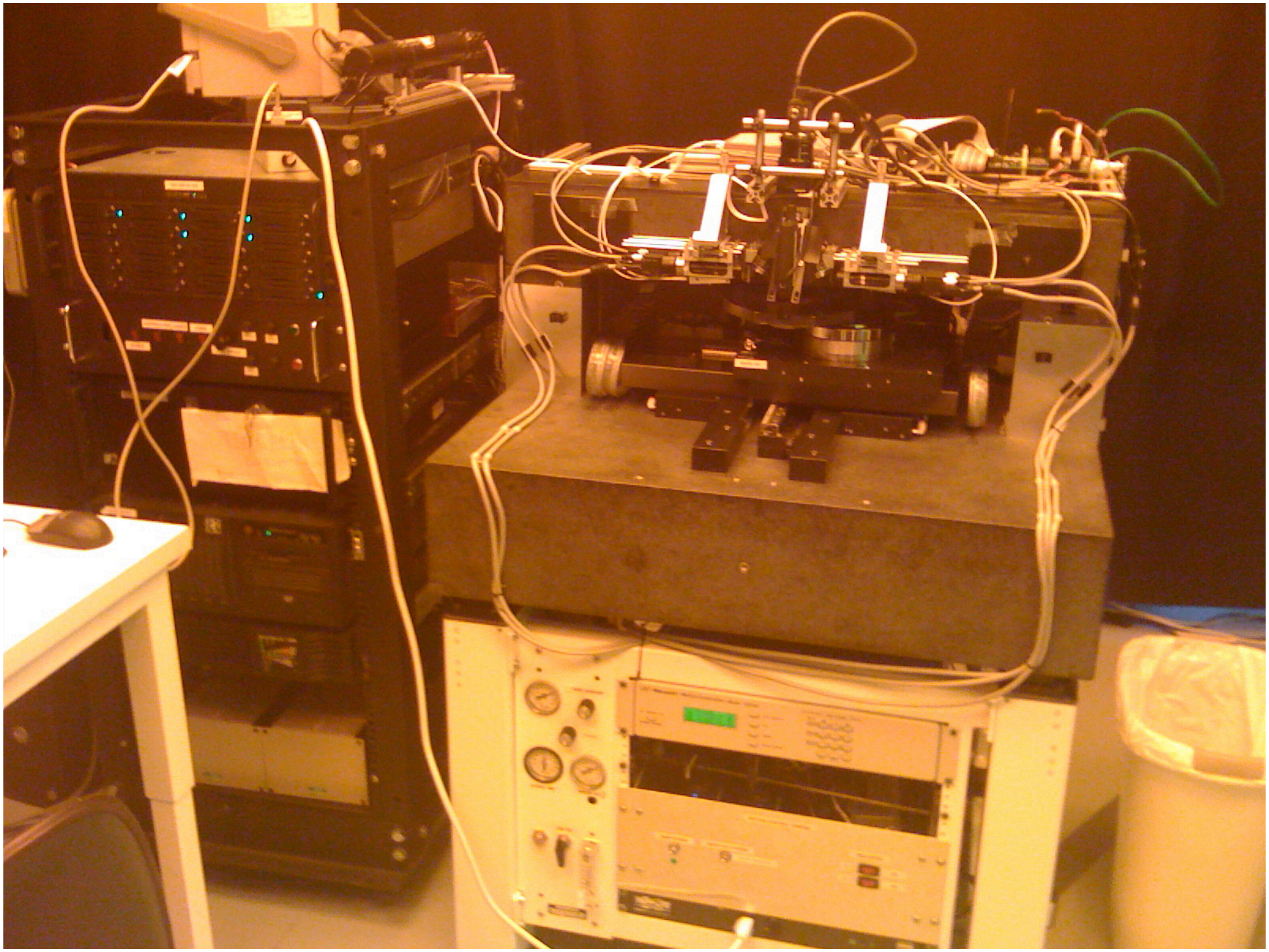
NA = 0.85

λ = 400nm

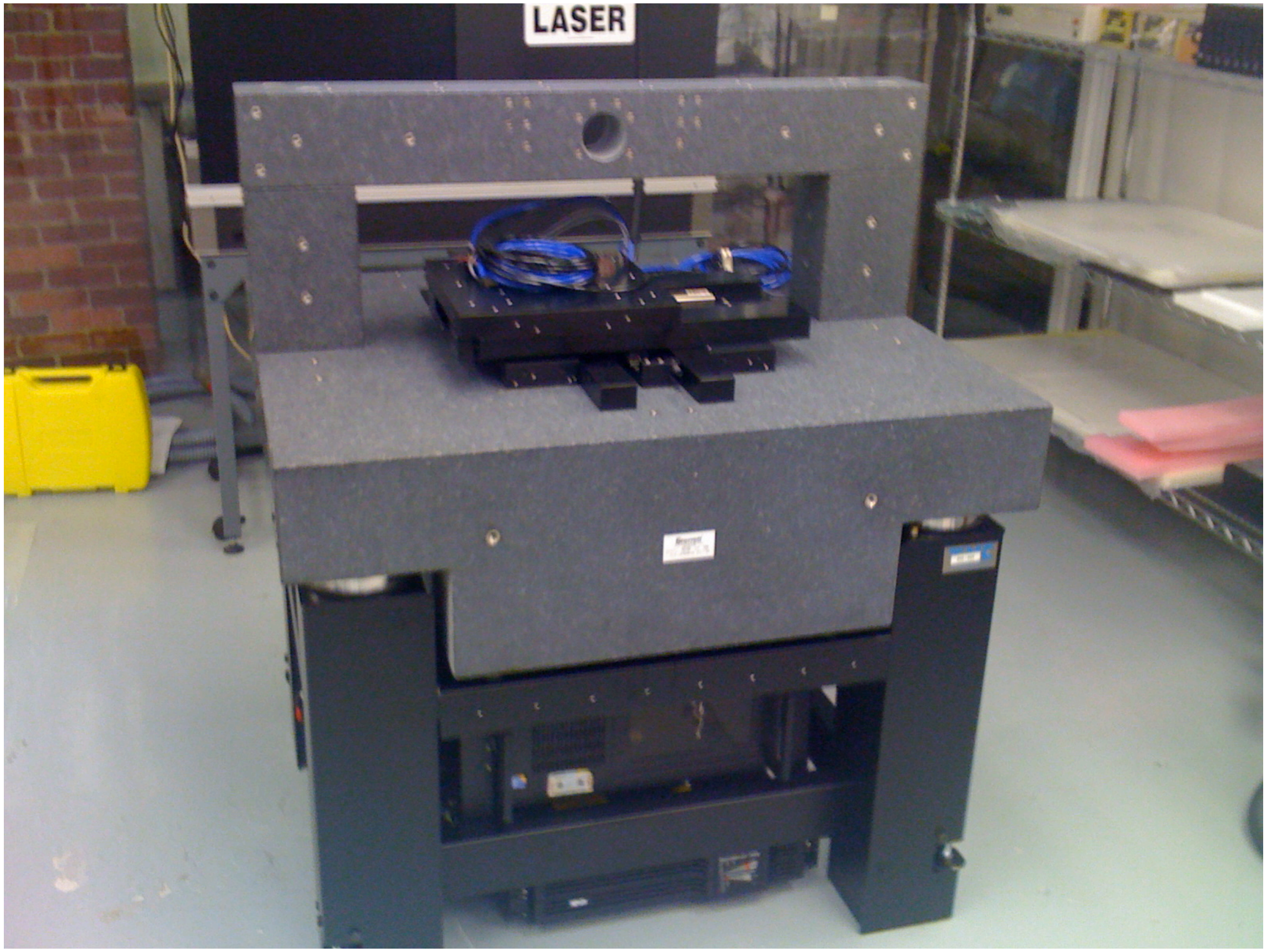


k1 = 0.259

alpha system, ZP-150A



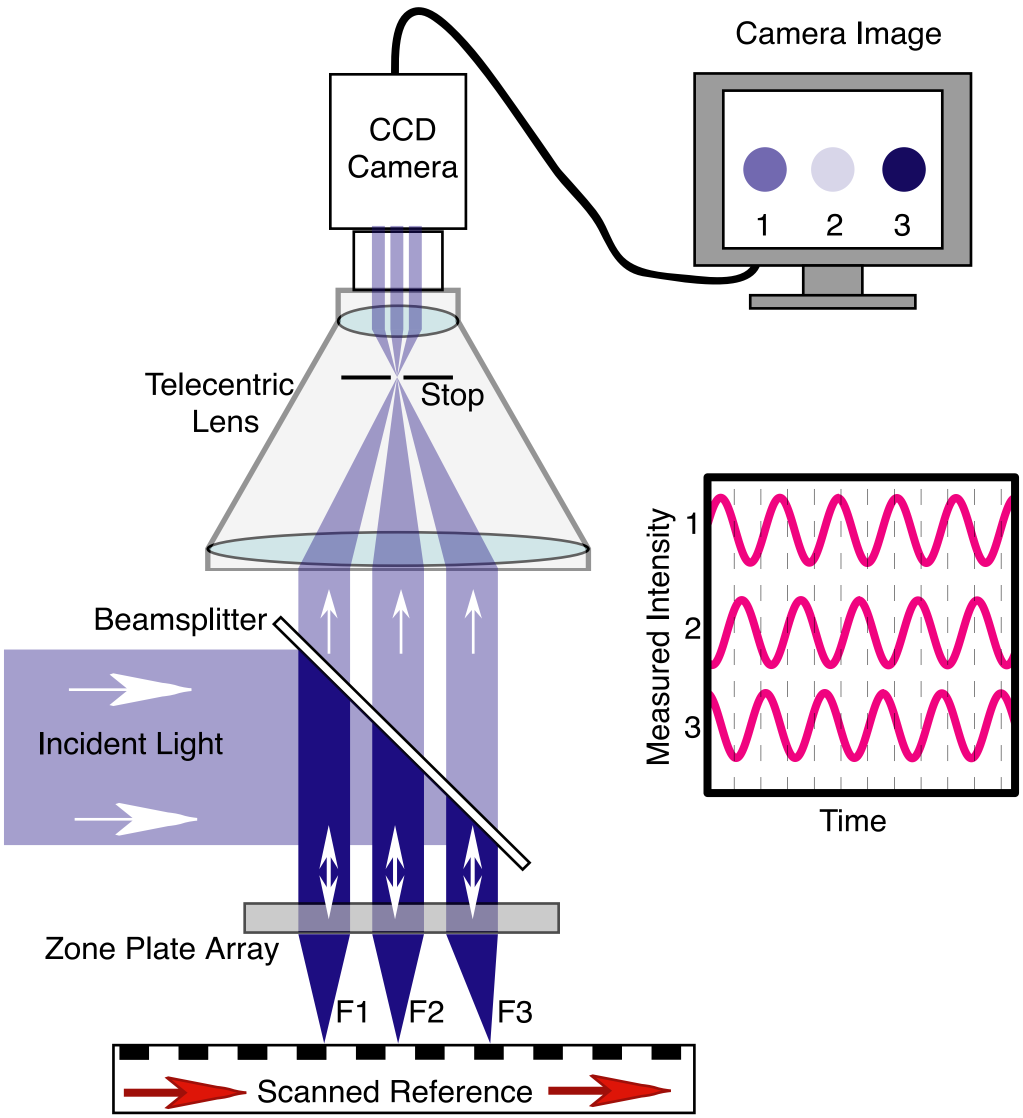
ZP-150B, under construction



Will deliver a tool to NIST in December for making computer-generated holograms

Will deliver a tool in January to Defense Microelectronic Activity (DMEA)

Zone-Plate Array Calibration

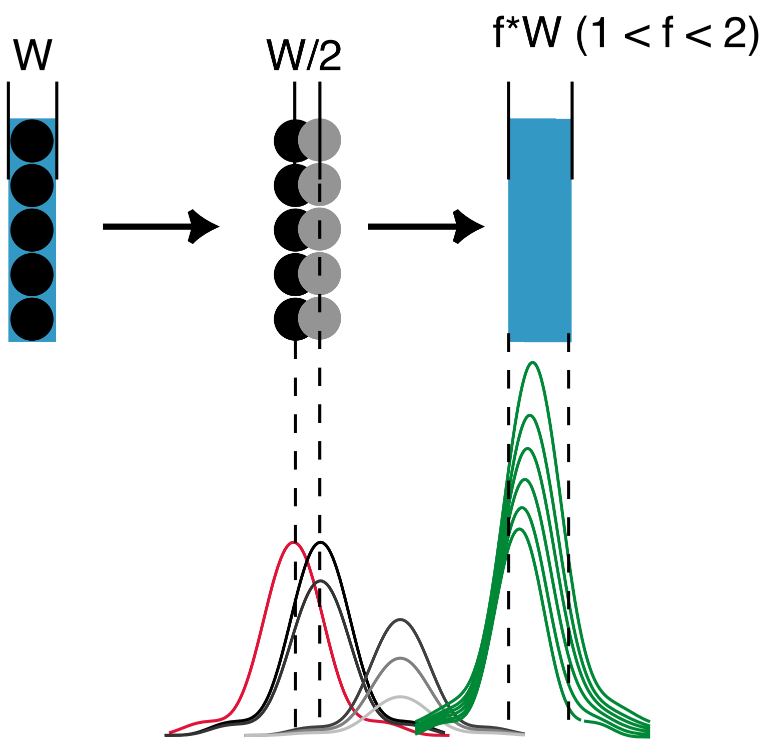


- Position of all focal spots must be known with nm-accuracy.
- High-Quality Grating Reference used to calibrate focal spot positions.
- Phase-based measurement immune to scan errors.
- Single measurement for all spots.

Pattern Optimization

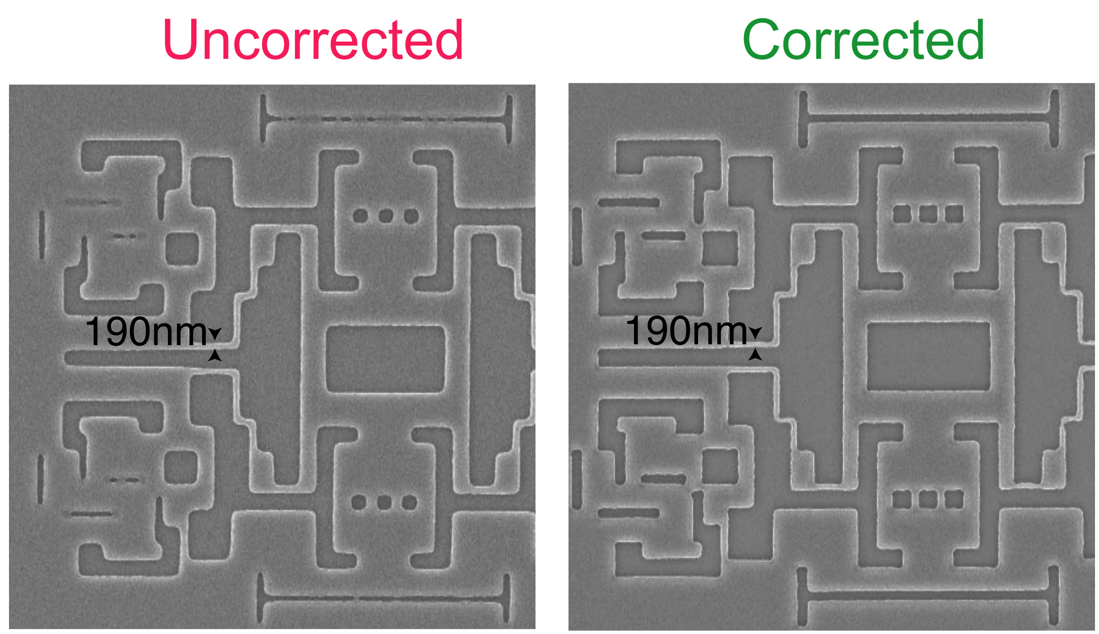
Proprietary software ensures pattern fidelity, CD linearity by optimizing dose level to every pixel. Also corrects illumination inhomogeneity.

Line-Edge Control

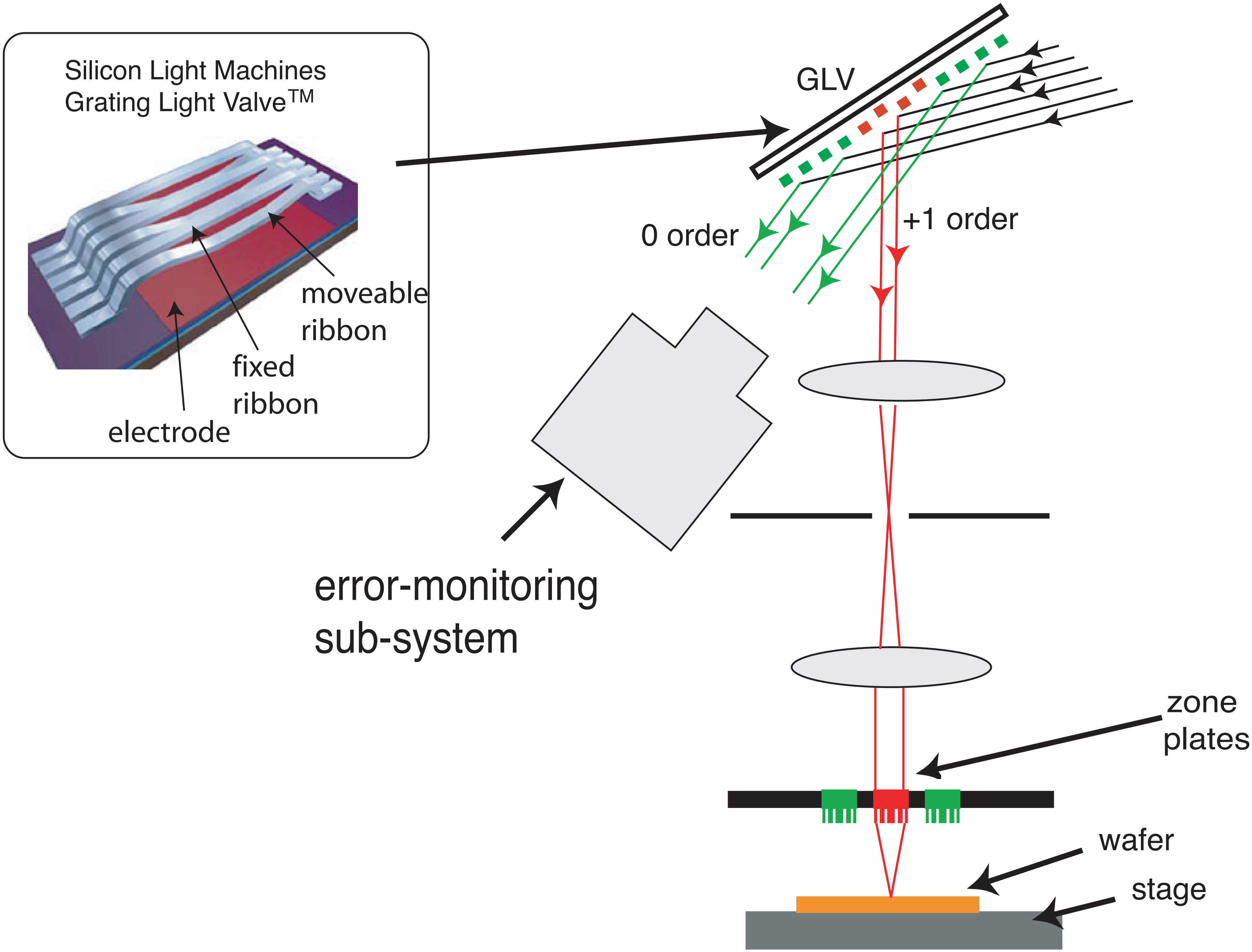


~200 gray-levels for every exposure pixel allows sub-pixel line control

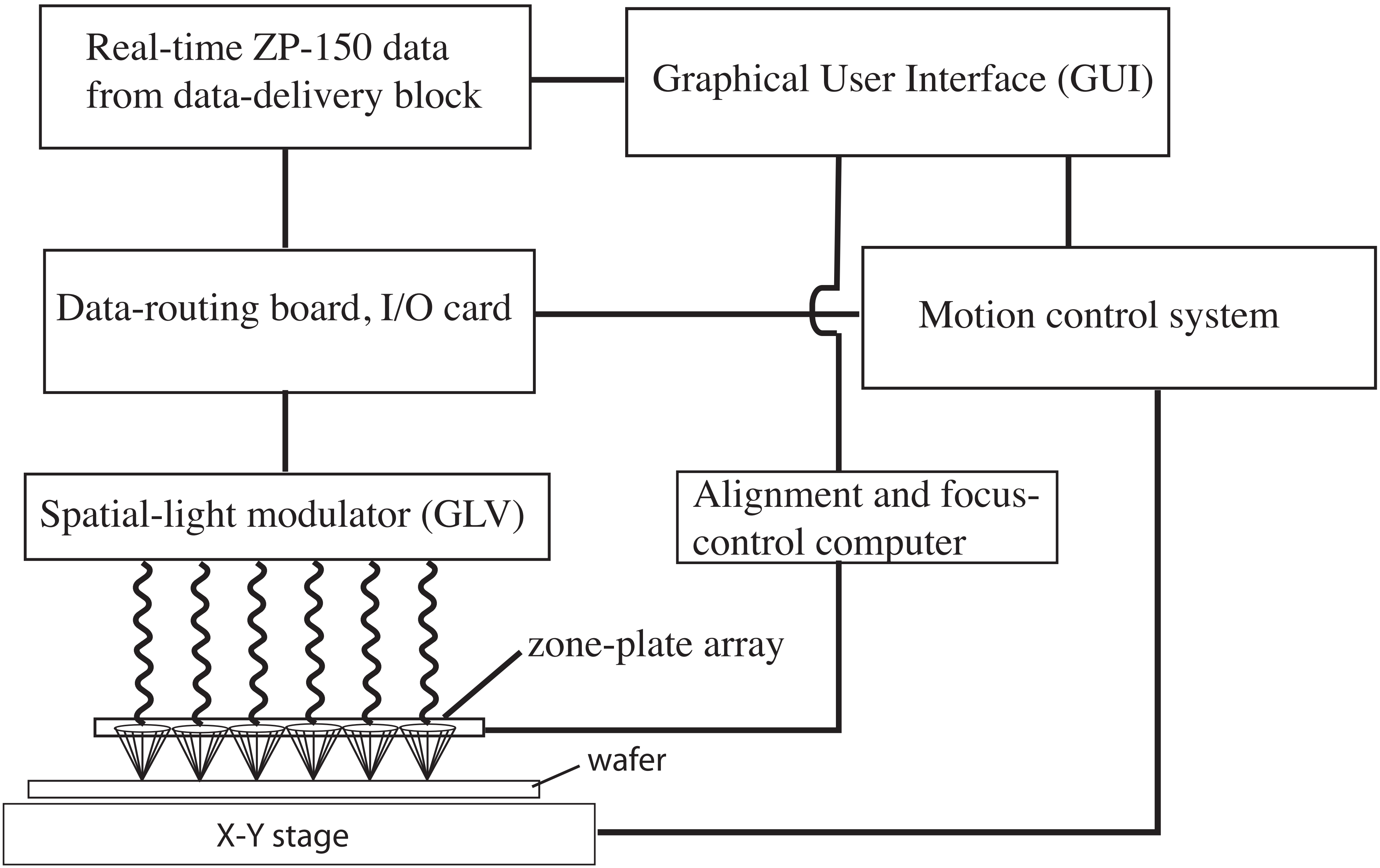
Proximity-Effect Correction

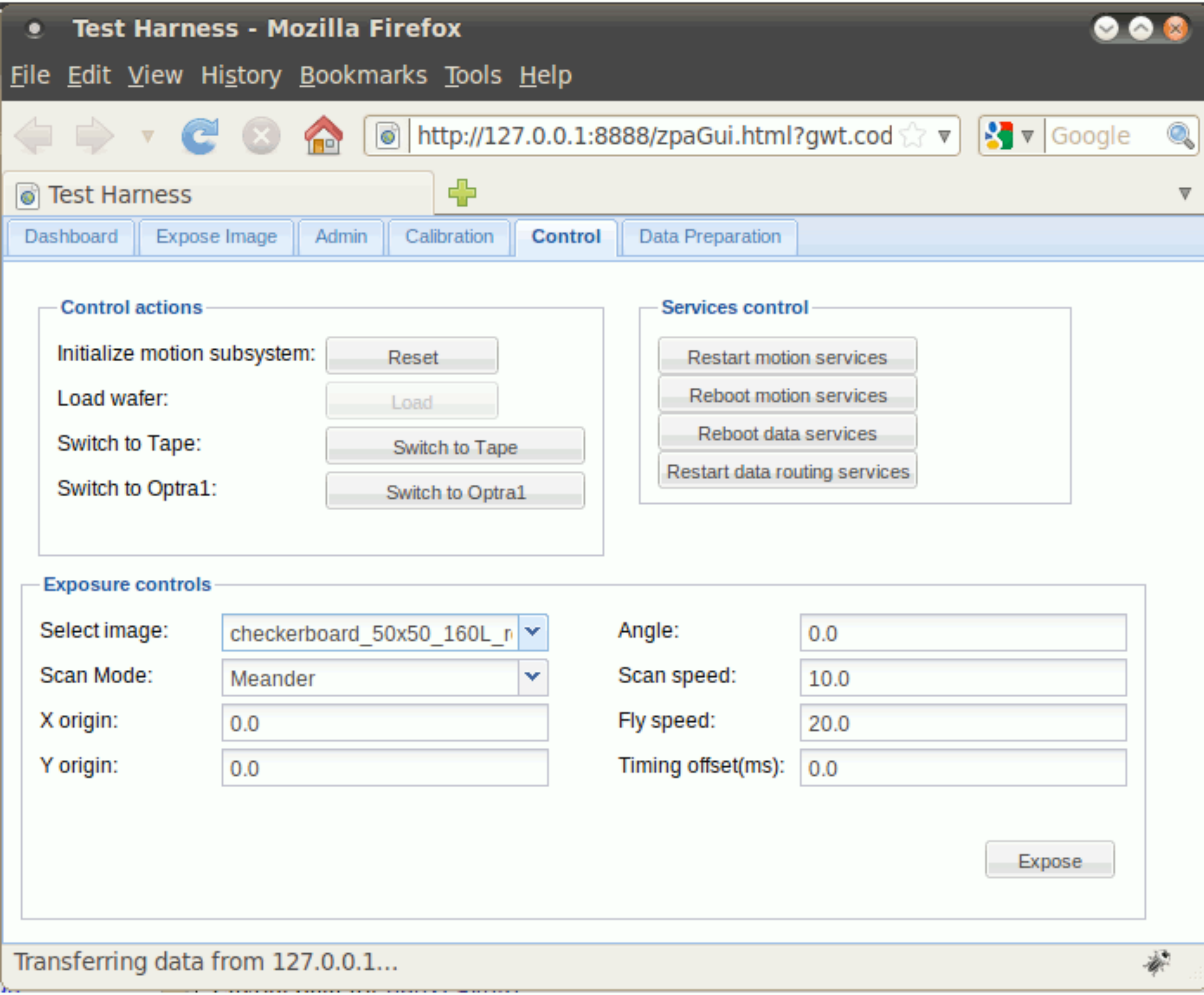


PEC is computationally easier for ZPAL (incoherent) than coherent imaging (e.g. projection litho).


Silicon Light Machines
Grating Light Valve™
moveable
ribbon
fixed
ribbon
electrode
GLV
0 order
+1 order
error-monitoring
sub-system
zone
plates
wafer
stage

Data Delivery and Pattern Writing




Test Harness - Mozilla Firefox
File Edit View History Bookmarks Tools Help
http://127.0.0.1:8888/zpaGui.html?gwt.cod
Google
Test Harness
Dashboard
Expose Image
Admin
Calibration
Control
Data Preparation
Control actions
Initialize motion subsystem:
Reset
Load wafer:
Load
Switch to Tape:
Switch to Tape
Switch to Optra1:
Switch to Optra1
Services control
Restart motion services
Reboot motion services
Reboot data services
Restart data routing services
Exposure controls
Select image:
checkerboard_50x50_160L_r
Scan Mode:
Meander
X origin:
0.0
Y origin:
0.0
Angle:
0.0
Scan speed:
10.0
Fly speed:
20.0
Timing offset(ms):
0.0
Expose
Transferring data from 127.0.0.1...

Thruput

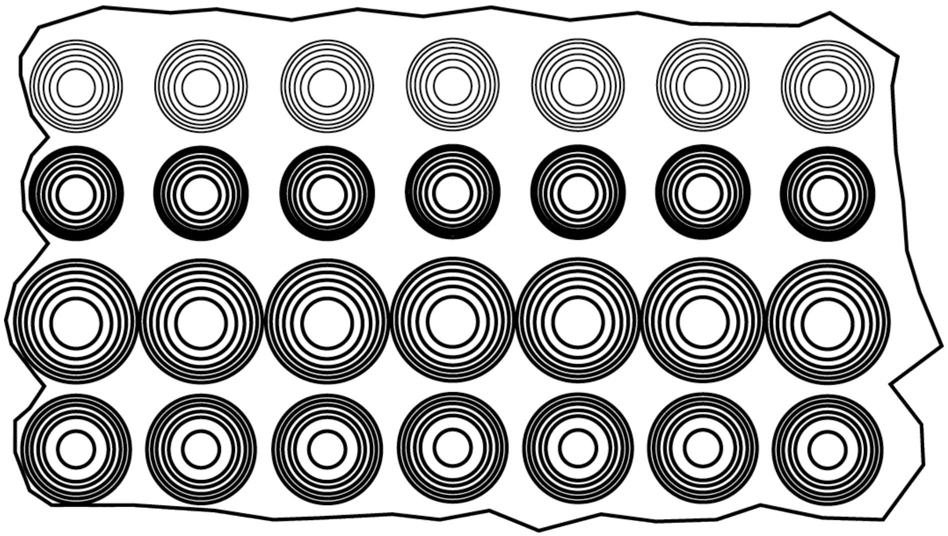
Area/sec = N R d^2

- N = # of focal spots – currently 1000
- R = modulator update rate – currently 290 kHz (with 8-bit gray scale)
- d = exposure grid spacing – currently 75 nm, adjustable

@ d = 75nm, 150 mm wafer => 4 x 10^{12} bytes, 1.5 mm^2/sec, 2 hours.

Higher thruput => modulatable laser array to replace current modulator; still a problem of data handling

array of zone plates



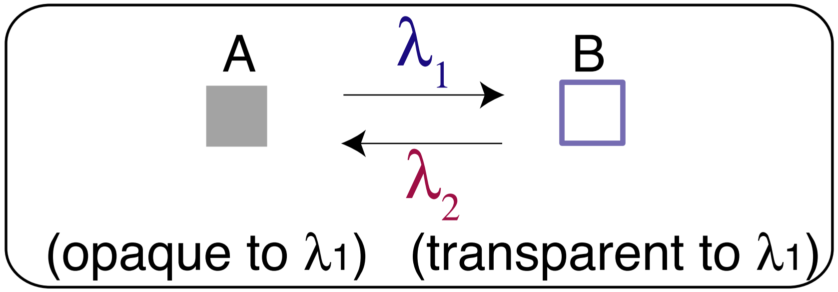
FZP array at 500 nm resolution

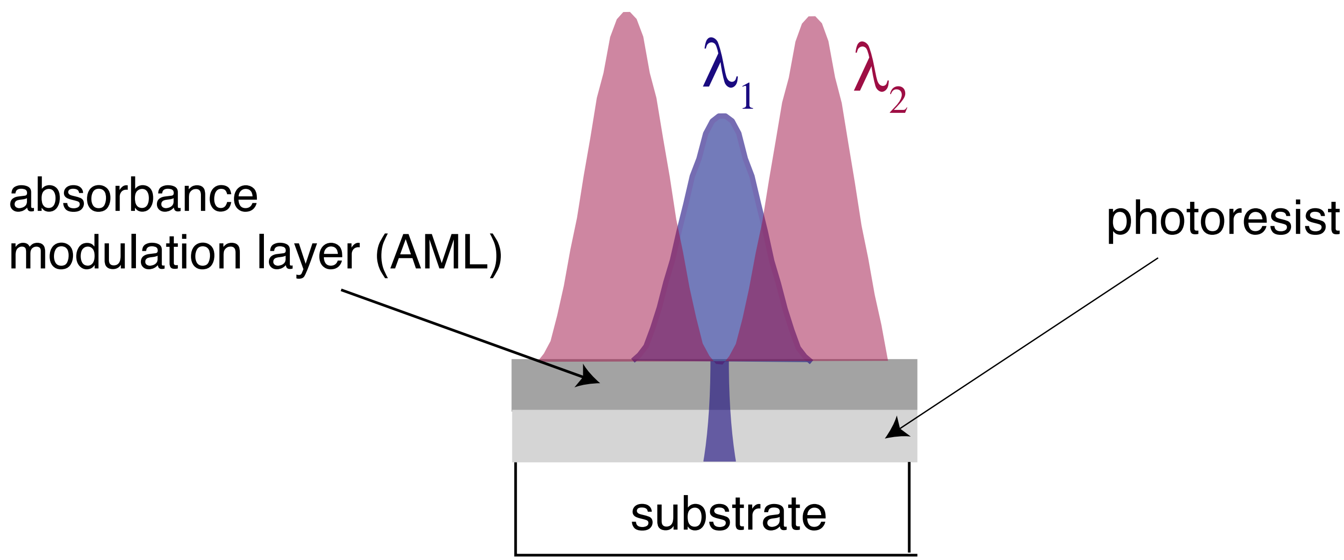
FZP array at 250 nm resolution

FZP array at 100 nm resolution

PSZP array at 50 nm resolution

Absorbance Modulation Optical Lithography (AMOL)



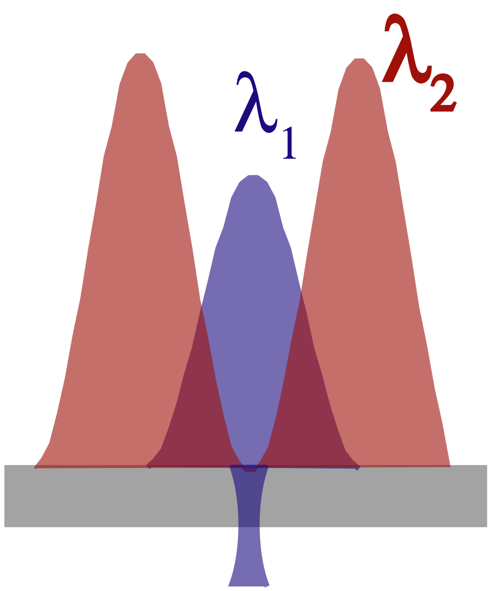


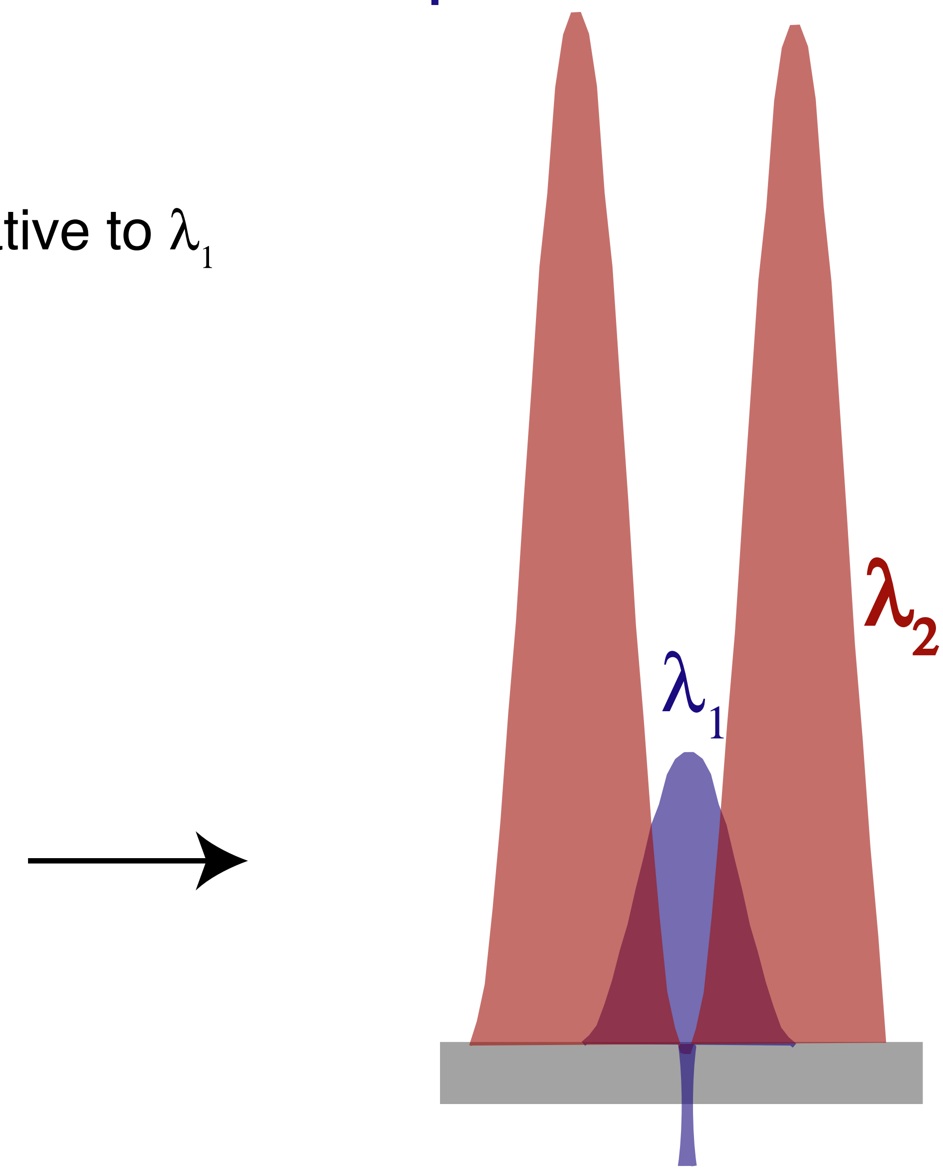
- Dark-ring at λ_2 in competition with bright spot at λ_1 creates localized sub-wavelength aperture
- Bright spot at λ_1 transmits through aperture exposing photoresist
- Incoherent imaging --> resolution almost unlimited

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

“Squeezing” the Nanoscale Optical Probe

Increasing power density at λ_2 relative to λ_1 “squeezes” the transmitted “spot”

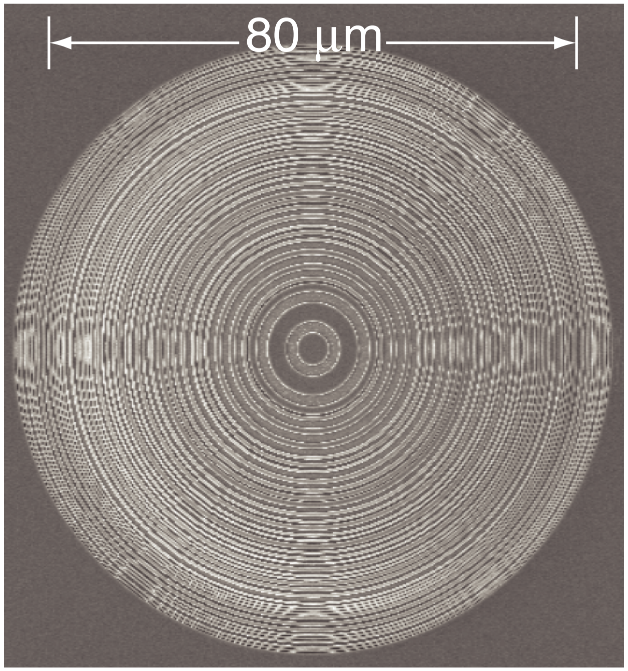




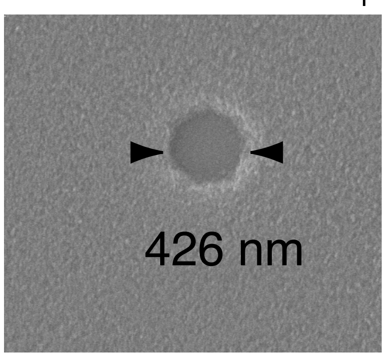
Nanoscale Optical Probe → nanopatterning, nanoscopy & nanoscale trapping

AMOL Proof-of-Concept

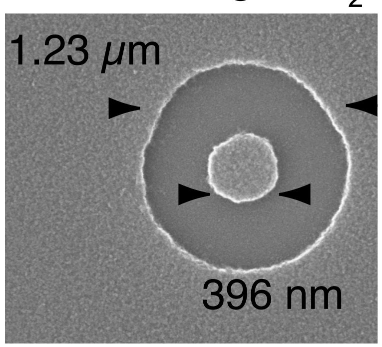
Dichromatic Zone Plate



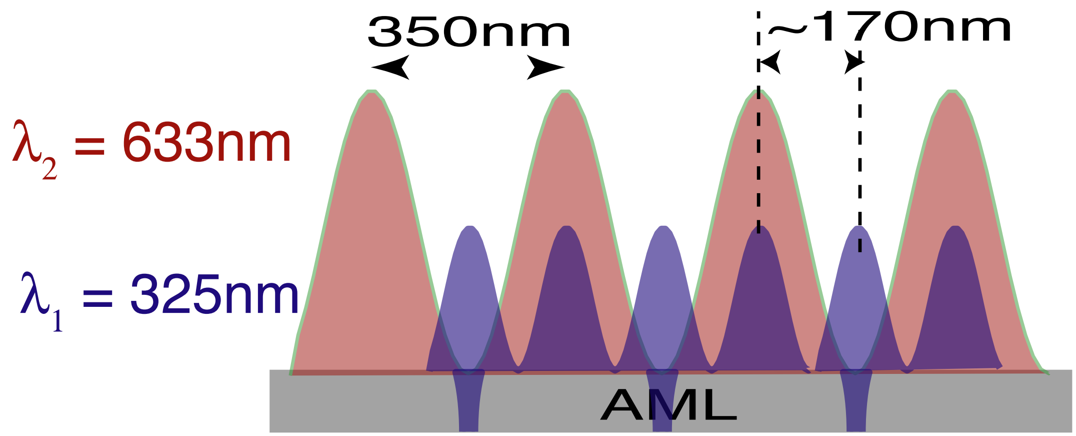
Focal spot at λ_1

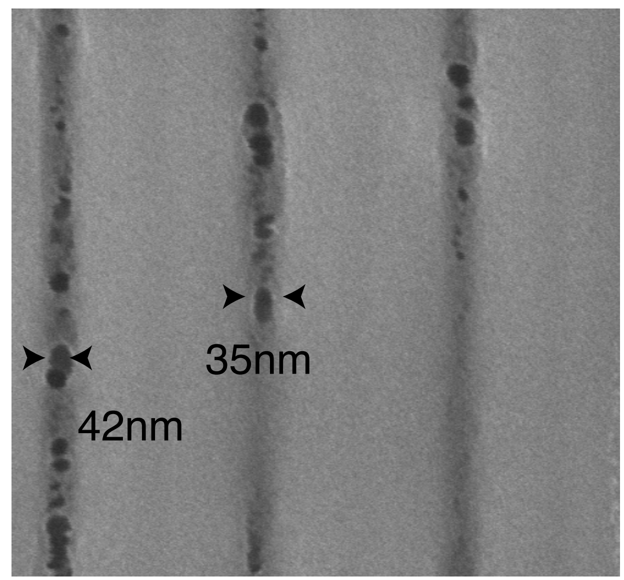


Focal ring at λ_2



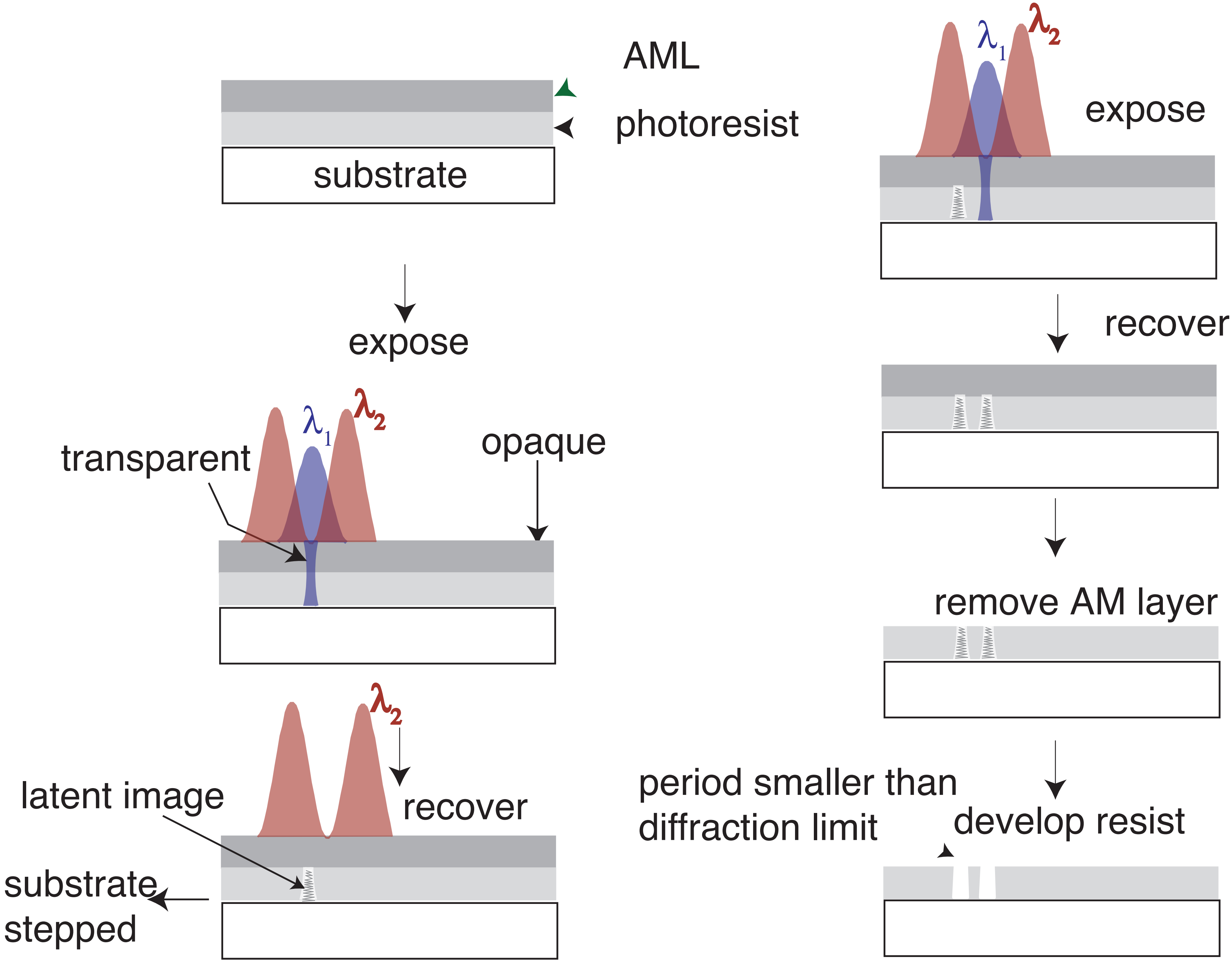
Absorbance Modulation Photochemistry





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

Patterning via Absorbance Modulation

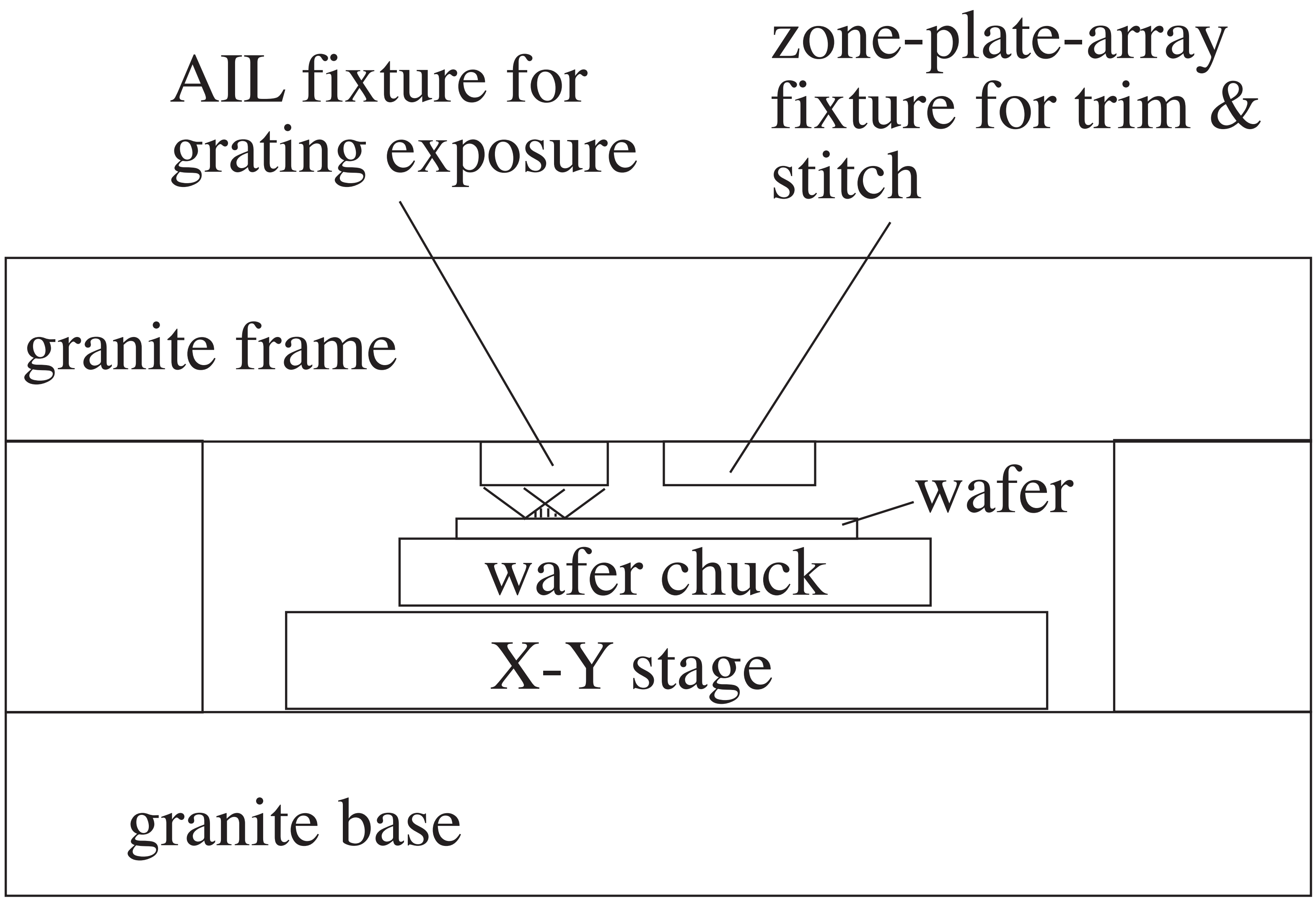


R. Menon, *et al*, *J. Opt. Soc. Am A*, 23, 2290 (2006).

Role of ZPAL in the semiconductor industry?

- Mask making (faster, higher accuracy, lower cost)
- Chip size not limited to 26x33 mm
- Alter the expensive design cycle? Change design from chip to chip? Converge to optimal design?
- Photonics and photonic integration with CMOS.
- Stimulate innovation in design => competition in the performance realm.

A single system for grating exposure and Trim and stitch



Summary

Summary

- Diffractive optics => high NA; arrays; focus engineering
- Scan the stage for full wafer & sub-nm precision
- Software correction of systematic errors => sub-nm accuracy
- Incoherent imaging => easy proximity correction & linewidth control; contacts no problem
- Web based protocols
- Wavelength-selective chemistry => break diffraction barrier (20nm)
- Error reporting during exposure
- Ideal for trim and stitch
- Initial markets => low volume manufacturing, research, mask making, MEMS, tissue scafolds, etc.
- Path to higher thruput
- With AMOL, ZPAL will supplant E-beam litho

Back up slides

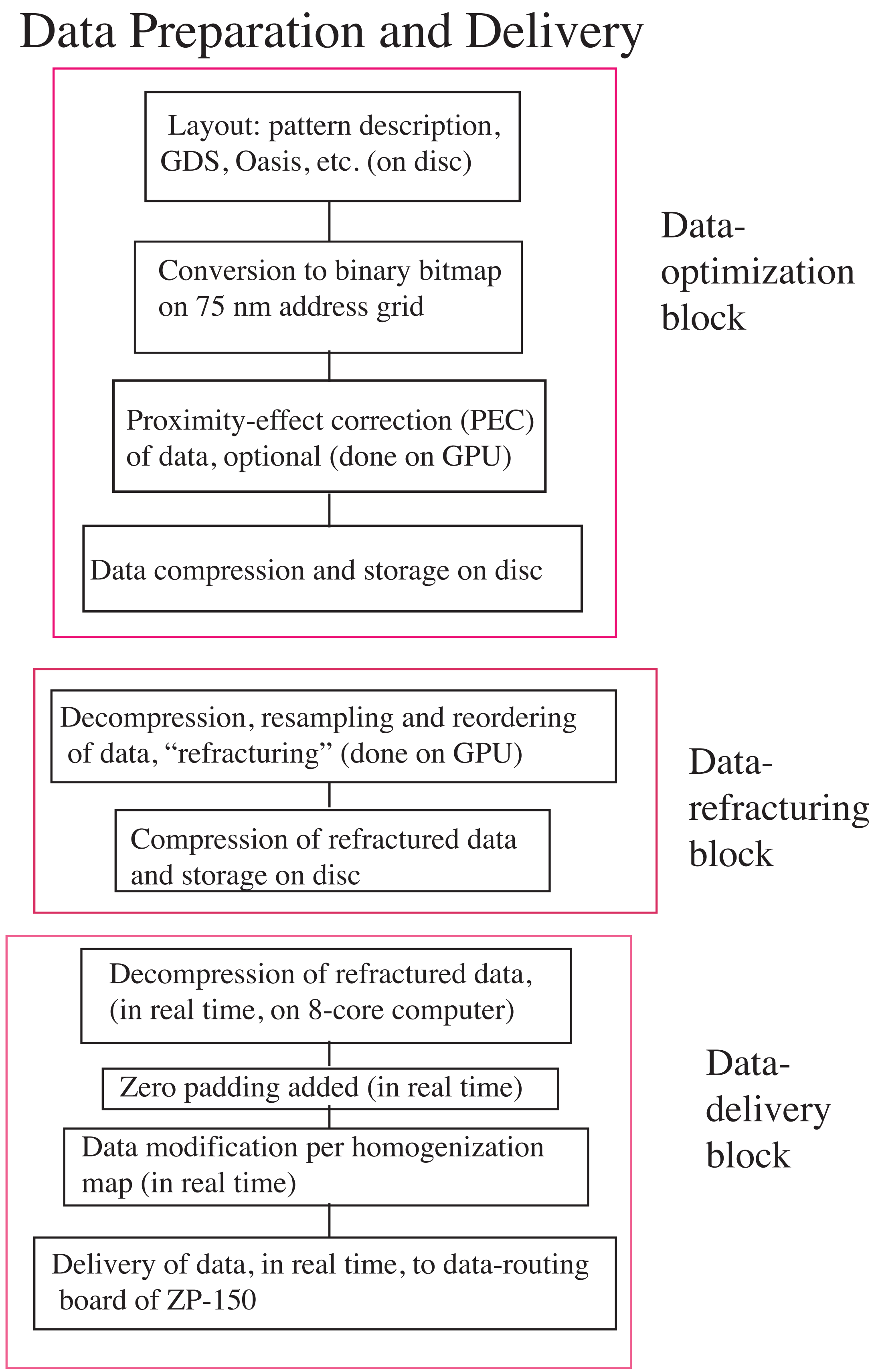
ZP-150A Alpha Tool

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

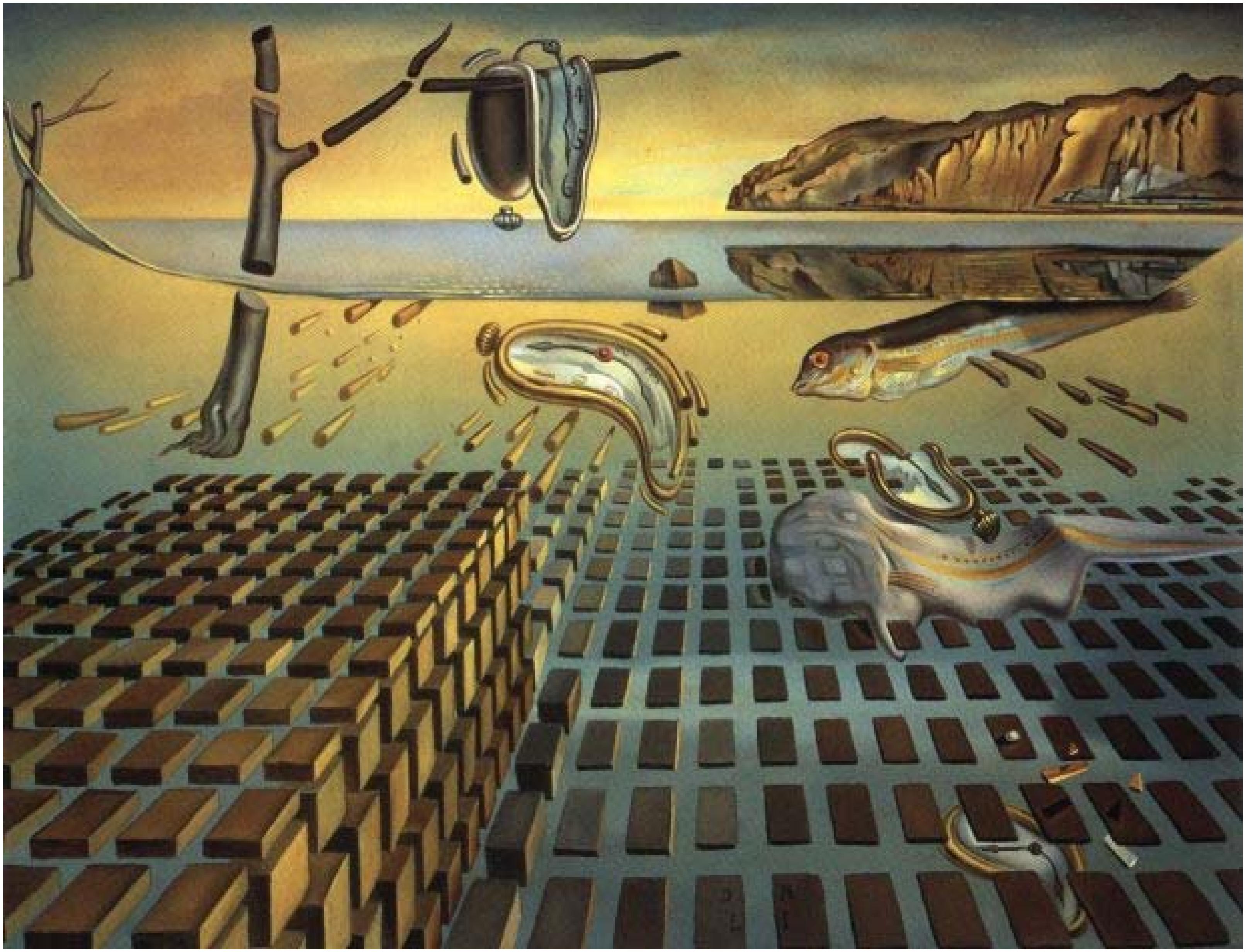
Specifications

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”*

Figure 7


Data Preparation and Delivery
Layout: pattern description, GDS, Oasis, etc. (on disc)
Conversion to binary bitmap on 75 nm address grid
Proximity-effect correction (PEC) of data, optional (done on GPU)
Data compression and storage on disc
Data-optimization block
Decompression, resampling and reordering of data, “refracturing” (done on GPU)
Compression of refractured data and storage on disc
Data-refracturing block
Decompression of refractured data, (in real time, on 8-core computer)
Zero padding added (in real time)
Data modification per homogenization map (in real time)
Delivery of data, in real time, to data-routing board of ZP-150
Data-delivery block

If we saw the world with electrons instead of photons...



Salvador Dali, *The Disinegration of the Persistence of Memory*, 1954

Advantage of e-beams in litho

- Electrons are easily deflected by E or M fields

Advantage of e-beams in litho

- Electrons are easily deflected by E or M fields

Disadvantage of e-beams in litho

- Electrons are easily deflected by E or M fields

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

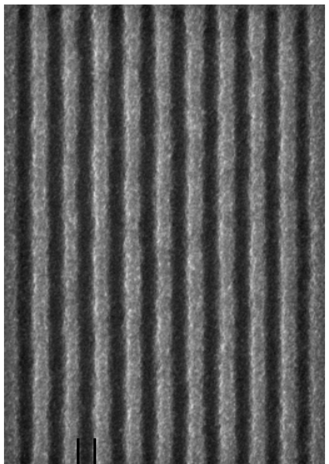
Vaccum, Slow thermal stabilization

Deflection by ALL electric & magnetic fields!!!

beam current
substrate charging
column charging
scanning stages

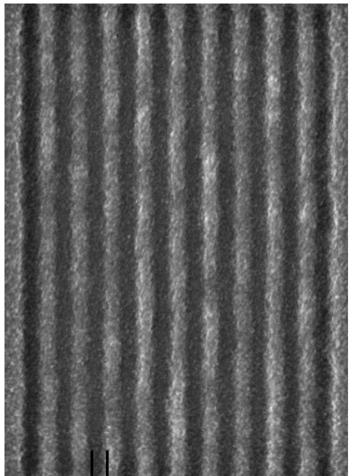
Examples of ZPAL Patterns

$k_1 = 0.38$



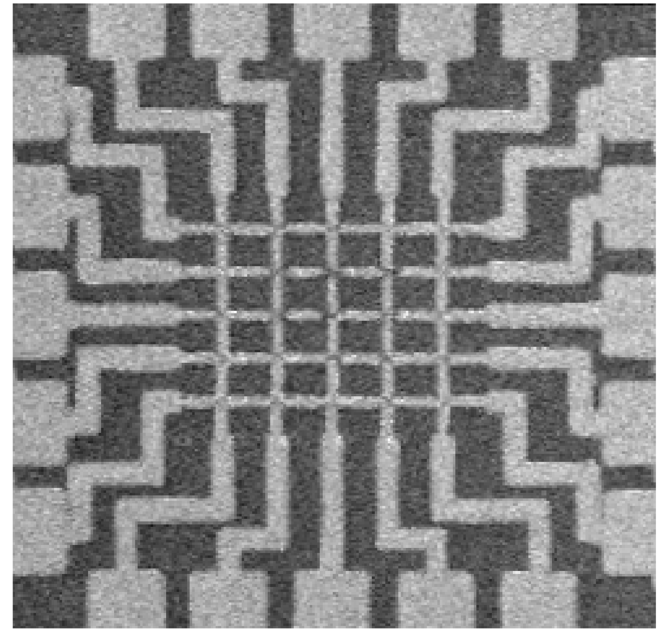
180nm

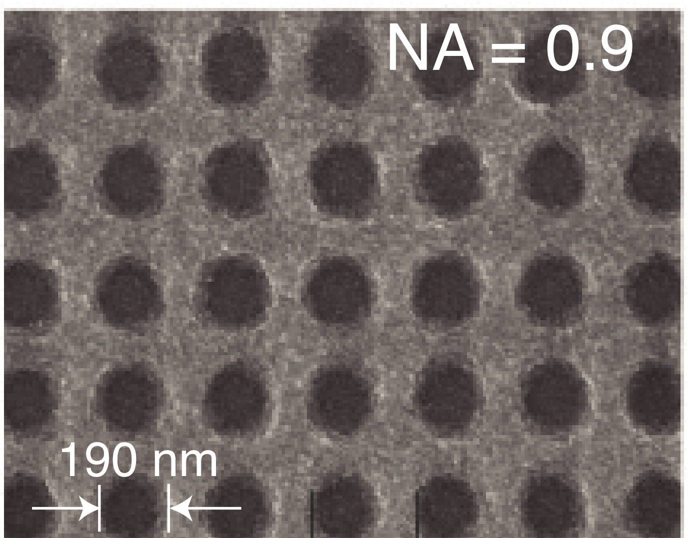
$k_1 = 0.32$



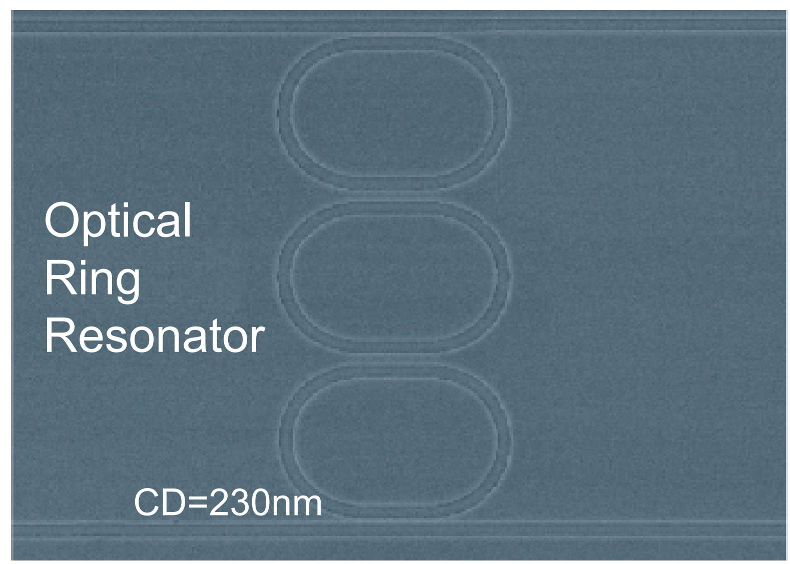
150nm

Prototype MRAM memory





Array of contact holes



LUMARRAY

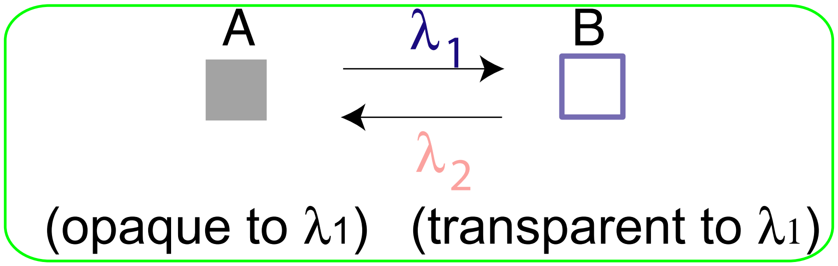
Design for Accuracy

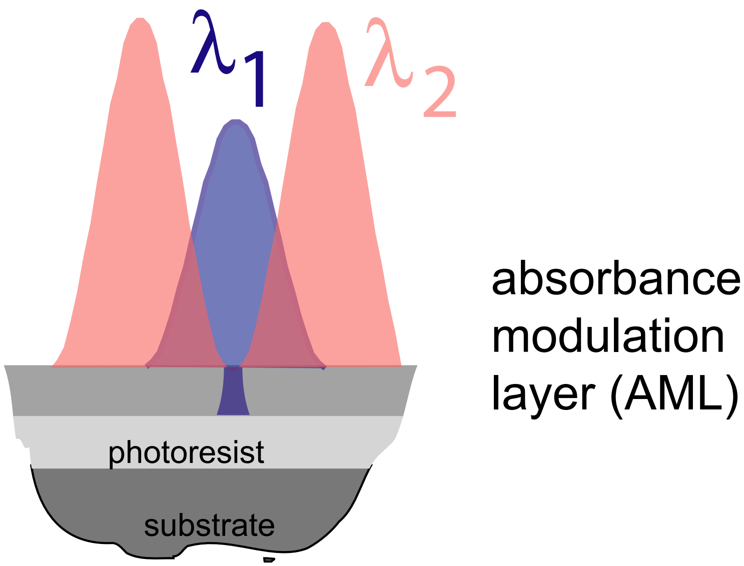
Design	Benefit
Static Lens Array Monolithic zone-plate array fixes relative positions of all beams on wafer.	★ Accurate Stitching ★ Loose Tolerances for beams to ZPA. ★ Location of beams on wafer determined only by stage position relative to ZPA.
Position-clocked data Timing of exposure determines location of exposed pixels on wafer	★ Only errors normal to scan are printed. ★ Position and velocity errors along scan compensated by exposure timing.
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

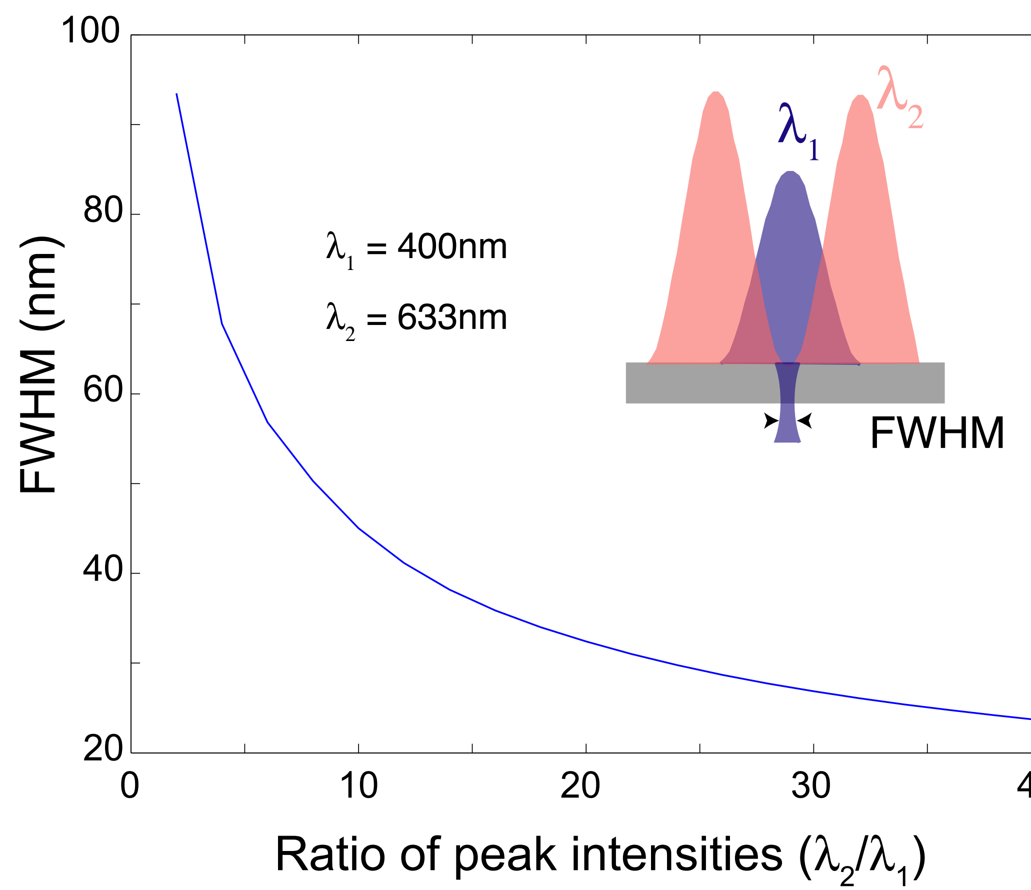
ADVANTAGES OF ZPAL

- Maskless => fast turn around (laser-printer analog)
- Any arbitrary pattern, i.e., non-Manhattan
- Multiple chip designs on 1 wafer
- No limit on chip size, e.g., full wafer
- Nanometer-level placement accuracy
- Software intensive => correction of systematic distortion in stage or zone plate foci locations
- Incoherent imaging => simple proximity-effect correction
- Incoherent imaging => precision linewidth control
- Extendable to sub-20 nm via photochromic chemistry
- Applications: electronics, photonics, biochips, tissue scafolds, mask making, imprint templates, MEMS, NEMS, nanotechnology

Absorbance Modulation Optical Lithography (AMOL)







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

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