Exploring the limits of optical lithography in MEMs and nano device fabrication

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Advanced Lithography Research Group

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Topics

- Basic concepts
- Photoresists
- Reflection control
- Exposure tools
- Optical enhancements
- MEM's specific processing
- Projects
- What's next

What is Lithography?

Lithography -- (a method of planographic printing from a metal or stone surface)
(the process of printing from a surface on which the printing areas are not raised but are ink-receptive (as opposed to ink repellent)[1])

Optical Lithography:
The enabling technology for virtually all IC and MEMs production

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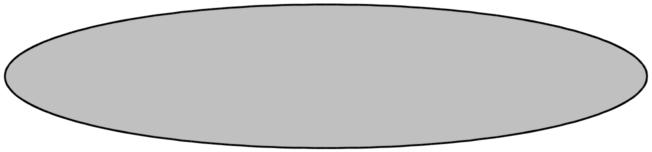
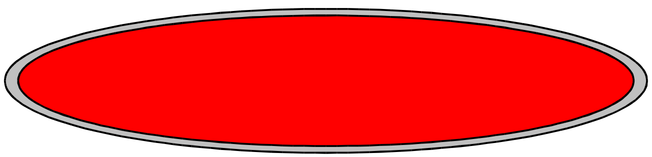
1.Definition from The Princeton University Wordnet

The basic lithography process

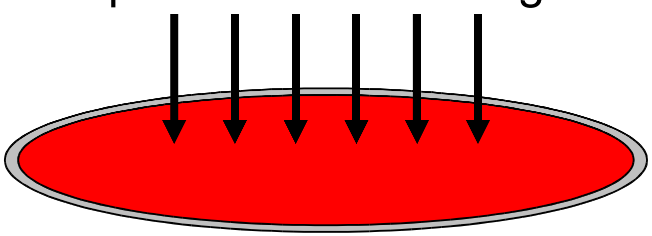
Substrate (wafer)



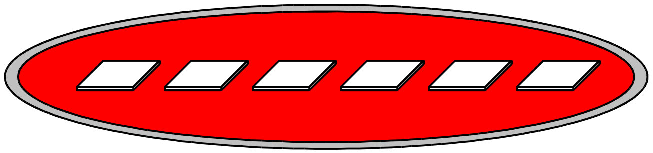
Coat with light sensitive polymer (photoresist)



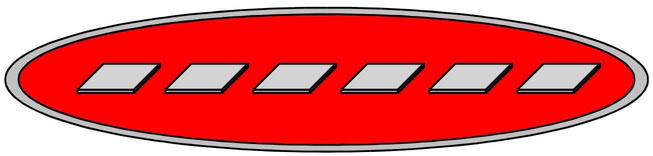
Expose to ultraviolet light



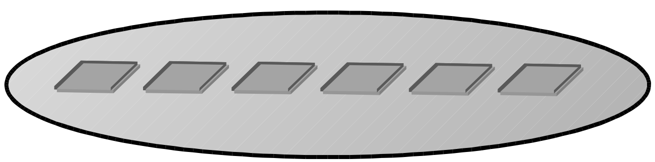
Develop pattern



Etch substrate (exposed areas)



Strip photoresist



Major factors/considerations in selecting the lithography process:

Process functionality: Etch mask, Implant shield, Plating mold

Substrate characteristics: Silicon, LiNb, GaAs, InP

Topography: Resist coating uniformity, step coverage

Selectivity: Selectivity of resist vs. layer to be etched

Aspect ratio: Mechanical stability/integrity

Resolution: Minimum feature size

Alignment tolerance: Overlay control/nesting tolerance

Resolution limit – Rayleigh criterion

Minimum feature size (CD – critical dimension) is determined by a modified form of Rayleigh's criterion:

$$Cd_{min} = K_1\lambda/NA$$

NA= numerical aperture

λ= wavelength

K_1= empirical constant (typically 0.4 or less in today's IC technology)

By examining the the Rayleigh criterion for DOF vs Resolution we can understand the driving force toward shorter wavelength exposure tools

Resolution		DOF
$Cd_{min} = K_1\lambda/NA$	vs	$K_2\lambda/NA^2$

Quadratic relationship (λ vs. NA) drives us to shorter wavelengths

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Depth of Focus for Various Exposure Wavelengths/NA DOF= K2 * λ/NA^2

$$K_2 \frac{\lambda}{NA^2} = \frac{\mathbf{436}\ \textit{(G line)}}{0.35^2} = 3559\text{nm}$$ **(620nm min feature)**

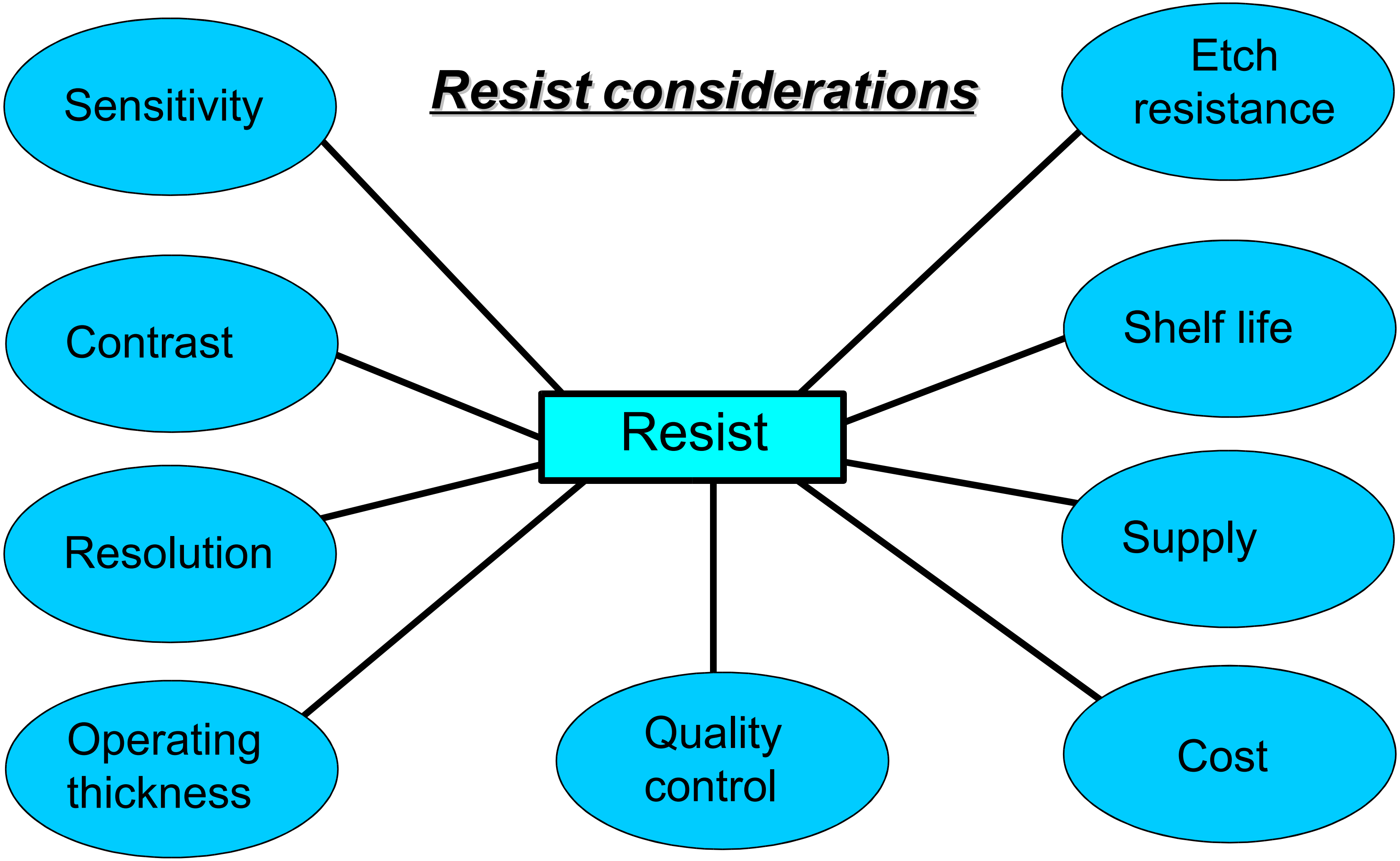
$$K_2 \frac{\lambda}{NA^2} = \frac{\mathbf{365}\ \textit{(I line)}}{0.55^2} = 1206\text{nm}$$ **(331nm min feature)**

$$K_2 \frac{\lambda}{NA^2} = \frac{\mathbf{248}\ \textit{(248nm DUV)}}{0.68^2} = 536\text{nm}$$ **(182nm min feature)**

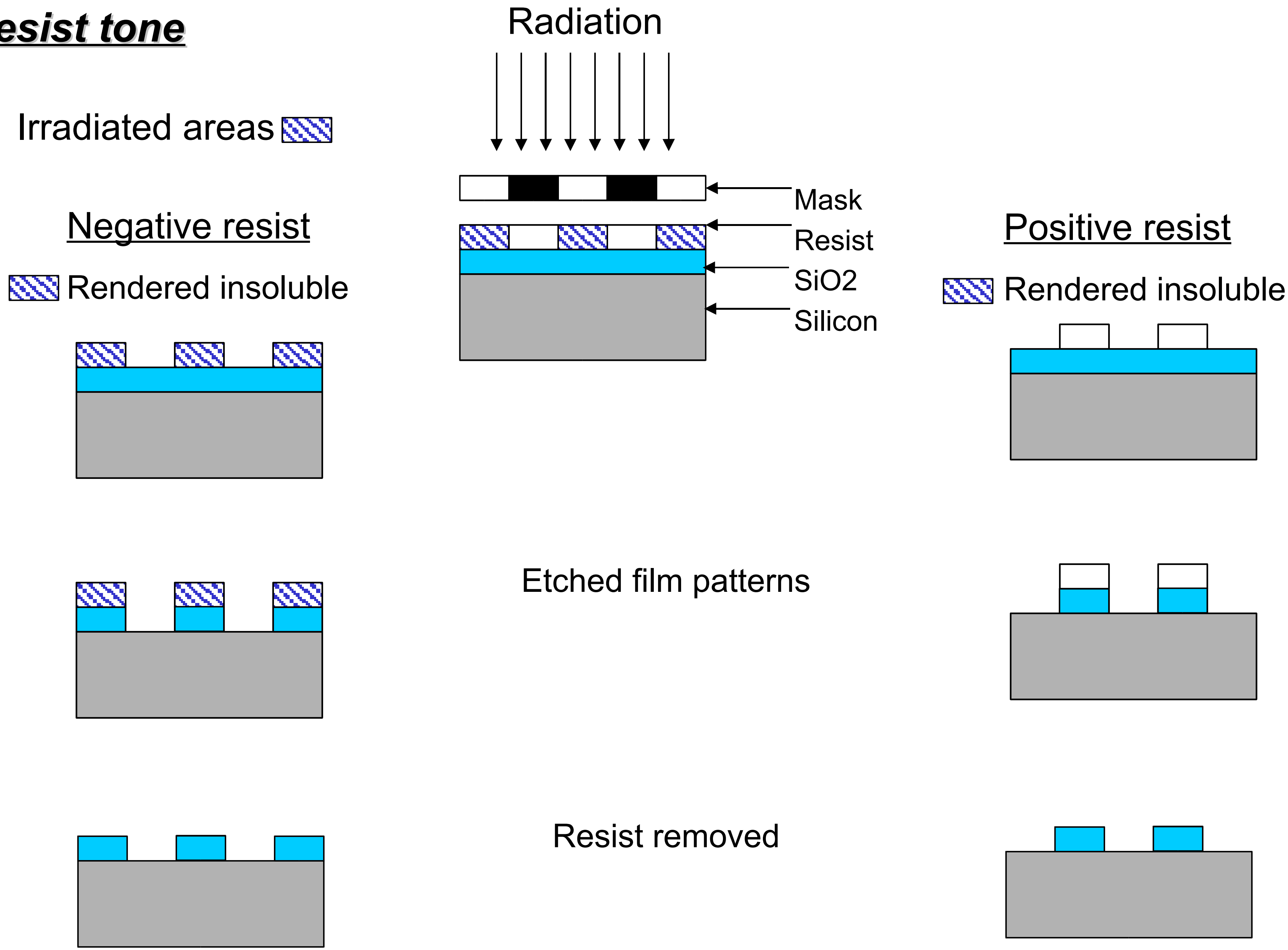
Depth of Focus for Various Exposure Wavelengths/NA DOF= K2 * λ/NA^2

λ	NA	DOF/min CD
***436**(G line)*	0.35	= 3559nm **(620nm min feature)**
***365**(I line)*	0.55	= 1206nm **(331nm min feature)**
248 KrF	0.68	= 536nm **(182nm min feature)**
193 ArF	0.85	= 264nm **(113nm min feature)**

Resist considerations



Resist tone



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Resist Materials and Processes for 193 nm Lithography

- **Single Layer Resist Systems**
- **New polymer resins are required as the novolacs (G- and I-line) and poly (hydroxy styrene) (deep-UV) polymers are unsuitable because of intense absorption of aromatics and olefins**
- **Since 193 nm resists are Chemically Amplified because of photospeed considerations, new PAGs may also be required**
- **The challenge is to synthesize new resins that are structurally different but functionally same (or better) as novolacs and PHS**
- **Key Resist Properties: Absorption, Plasma Etch stability, 0.262 N TMAH compatibility, Sensitivity, Thermal Stability, Adhesion, Low Metal ions , Manufacturability and Cost**

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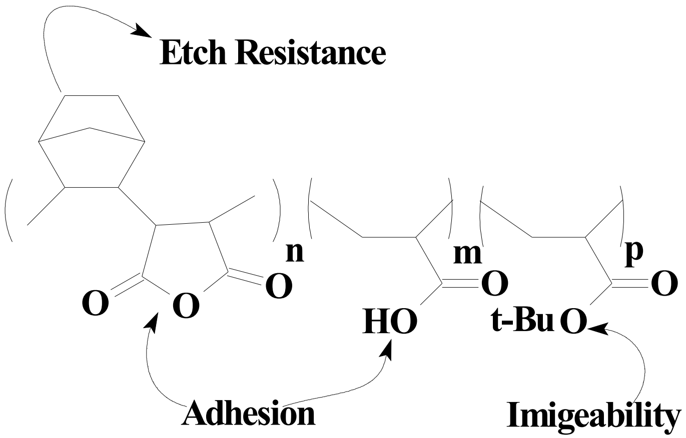
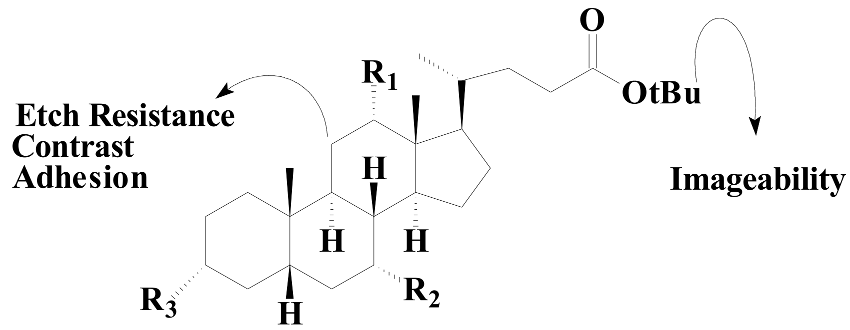
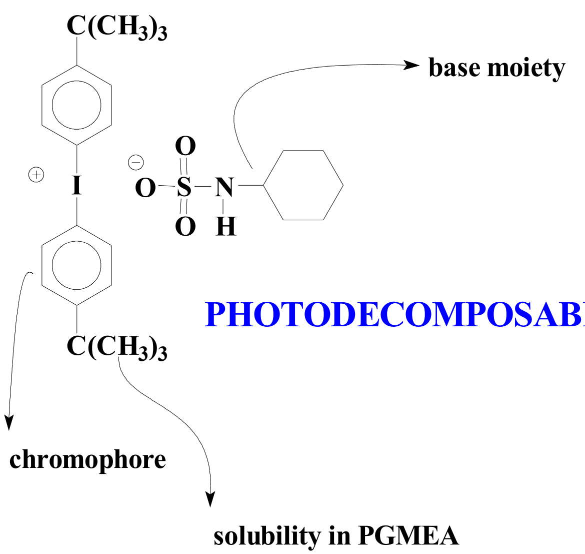
193 nm Single Layer Resist



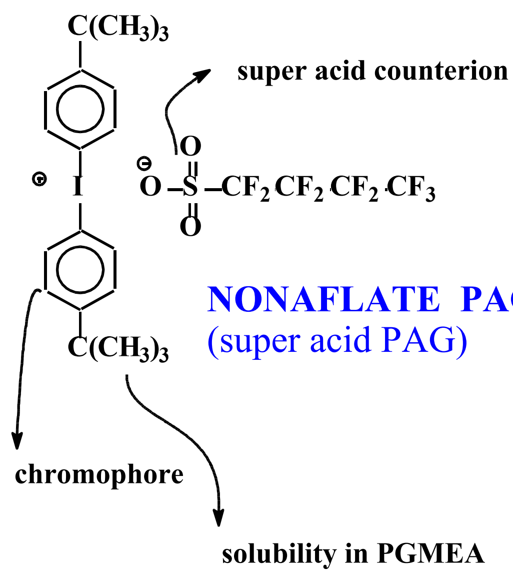
POLYMER



CHOLATE BASED DISSOLUTION INHIBITOR



PHOTODECOMPOSABLE BASE



NONAFLATE PAG
(super acid PAG)

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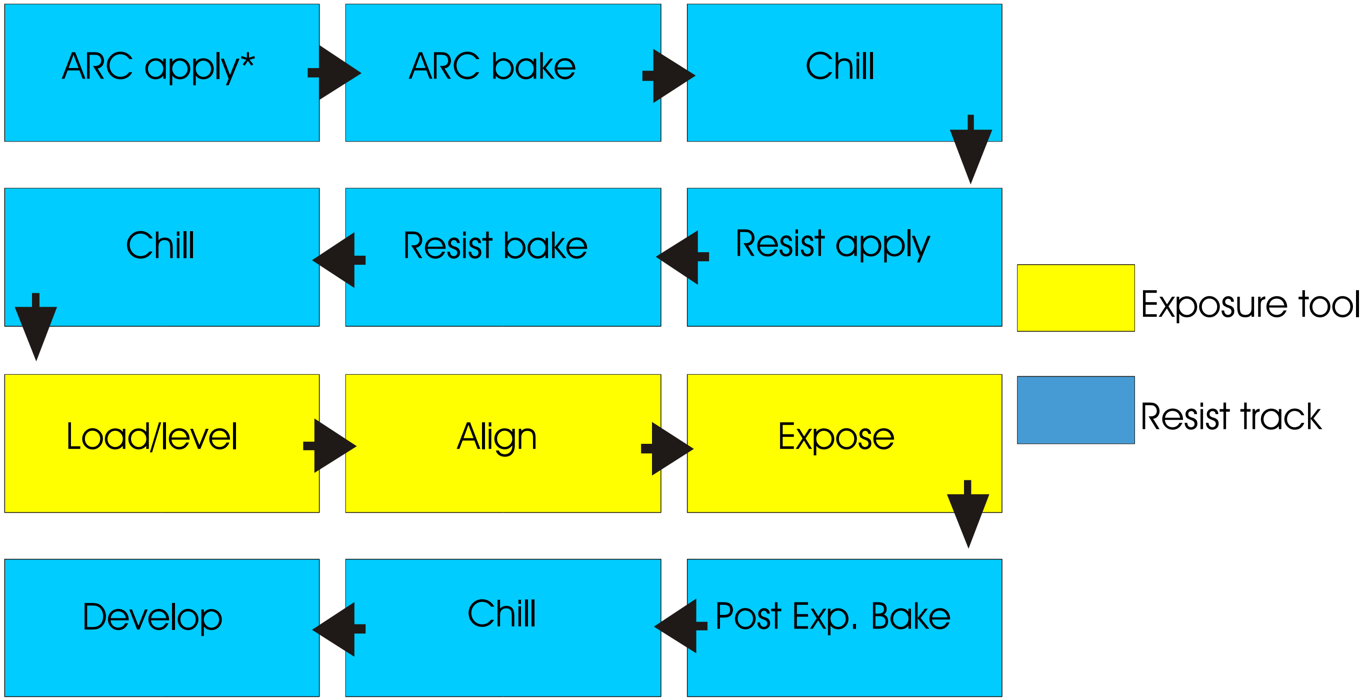
Lithocell process flow:



*HMDS adhesion promoter can be substituted

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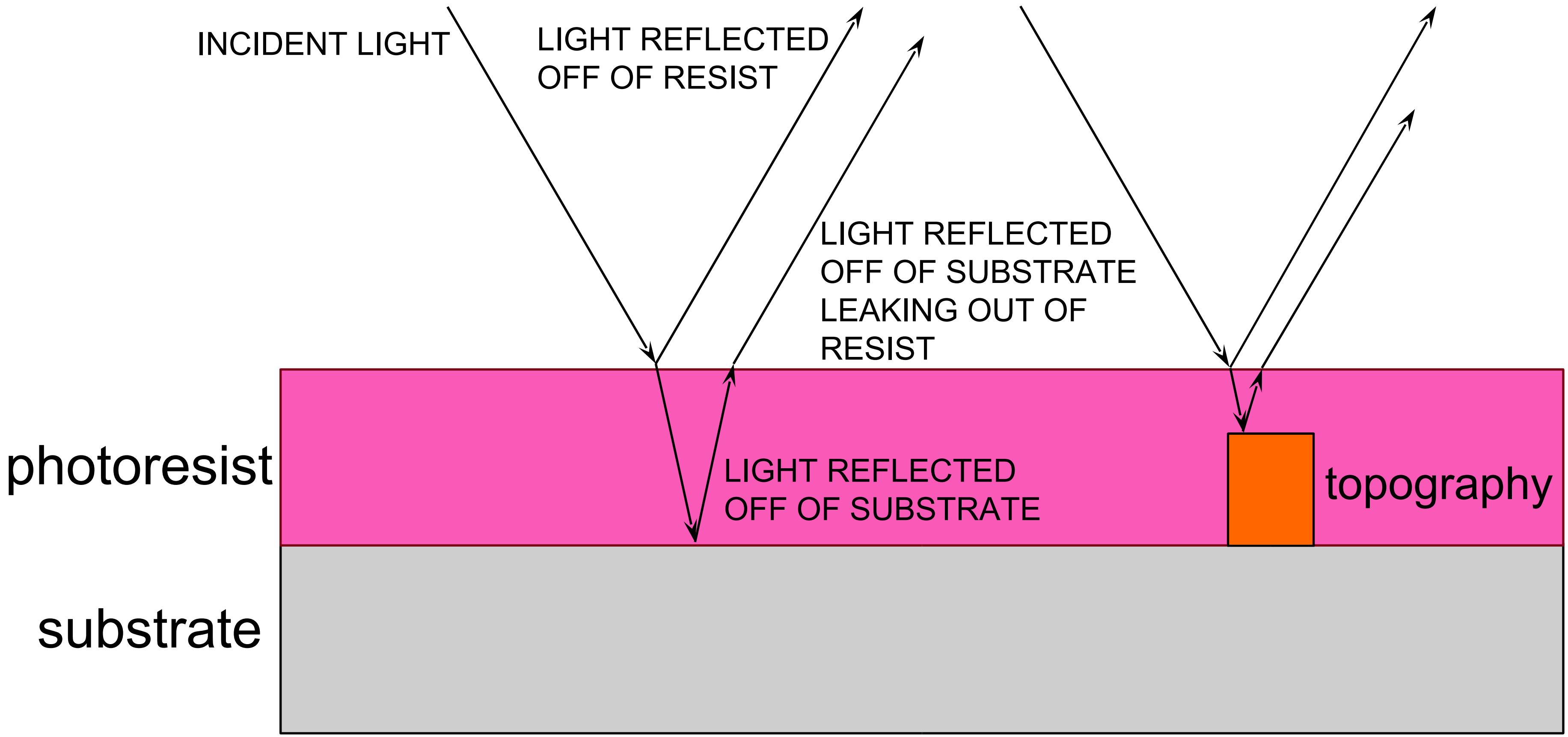
Reflection control

SWING EFFECT FROM HIGHLY REFLECTIVE SUBSTRATE

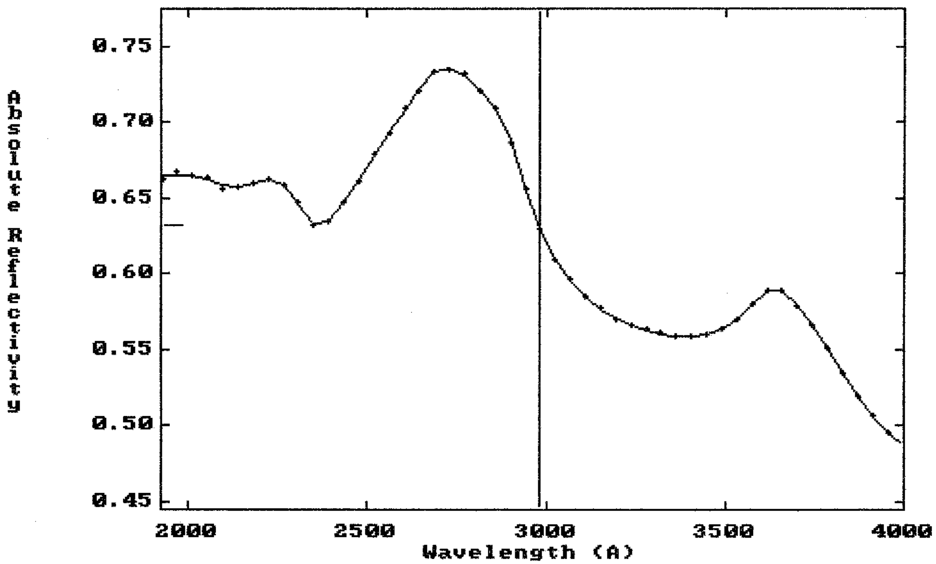


Absolute Reflectivity

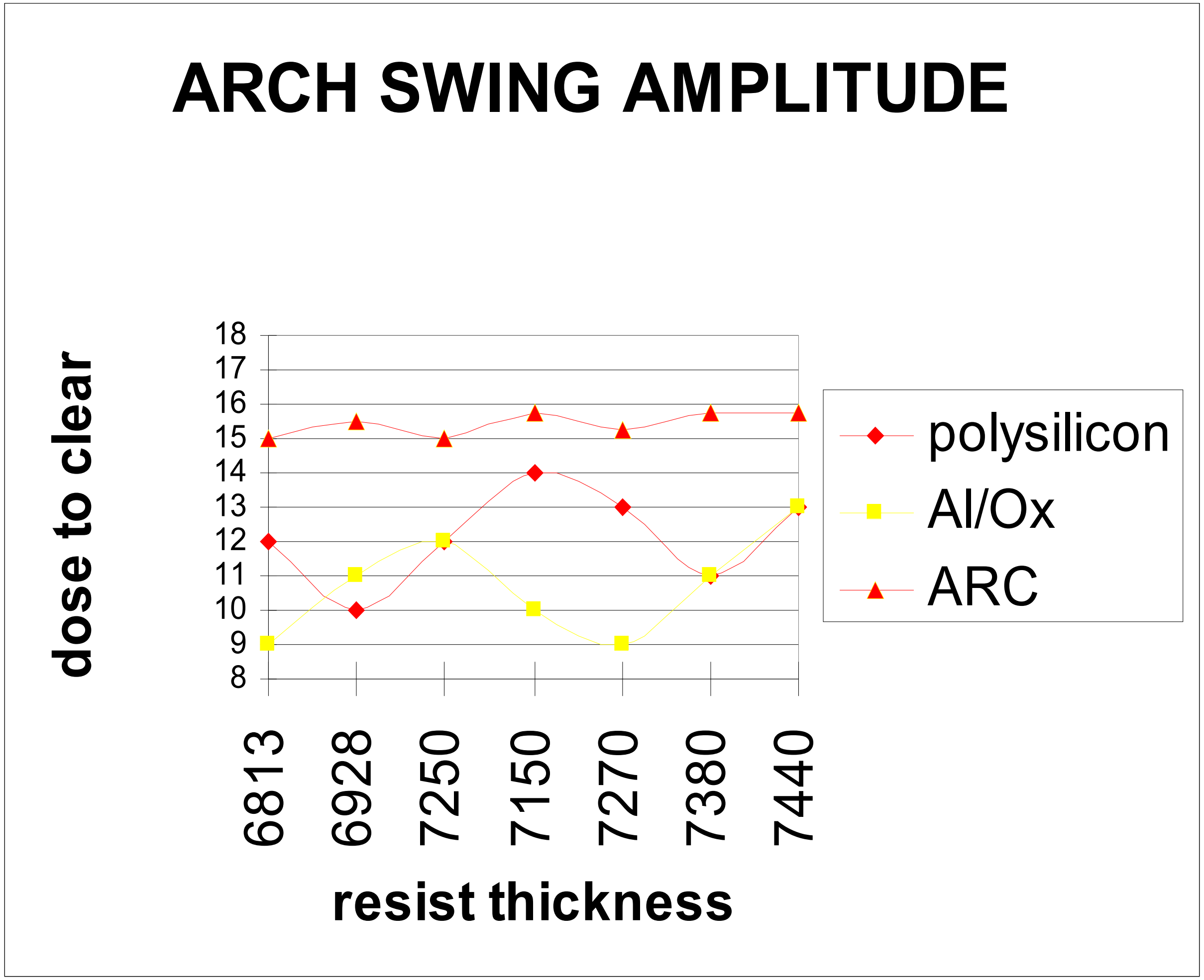
Bare Silicon

Experimental Data

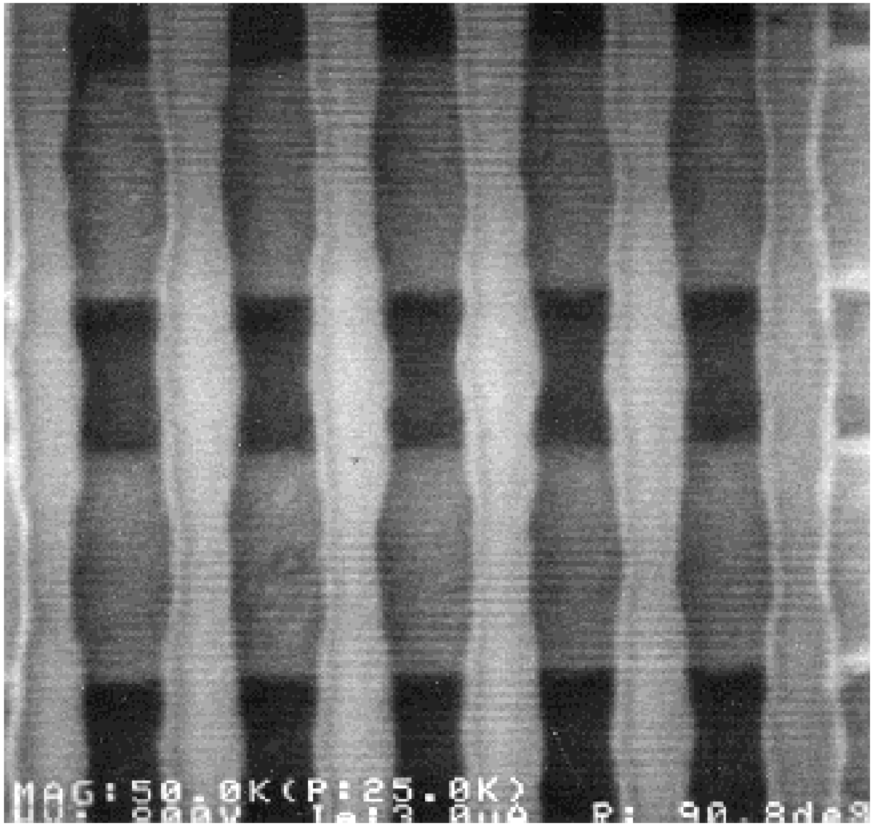
Thermawave



Swing Amplitude for Various Film Stacks



Linewidth variations caused by a highly reflective substrate



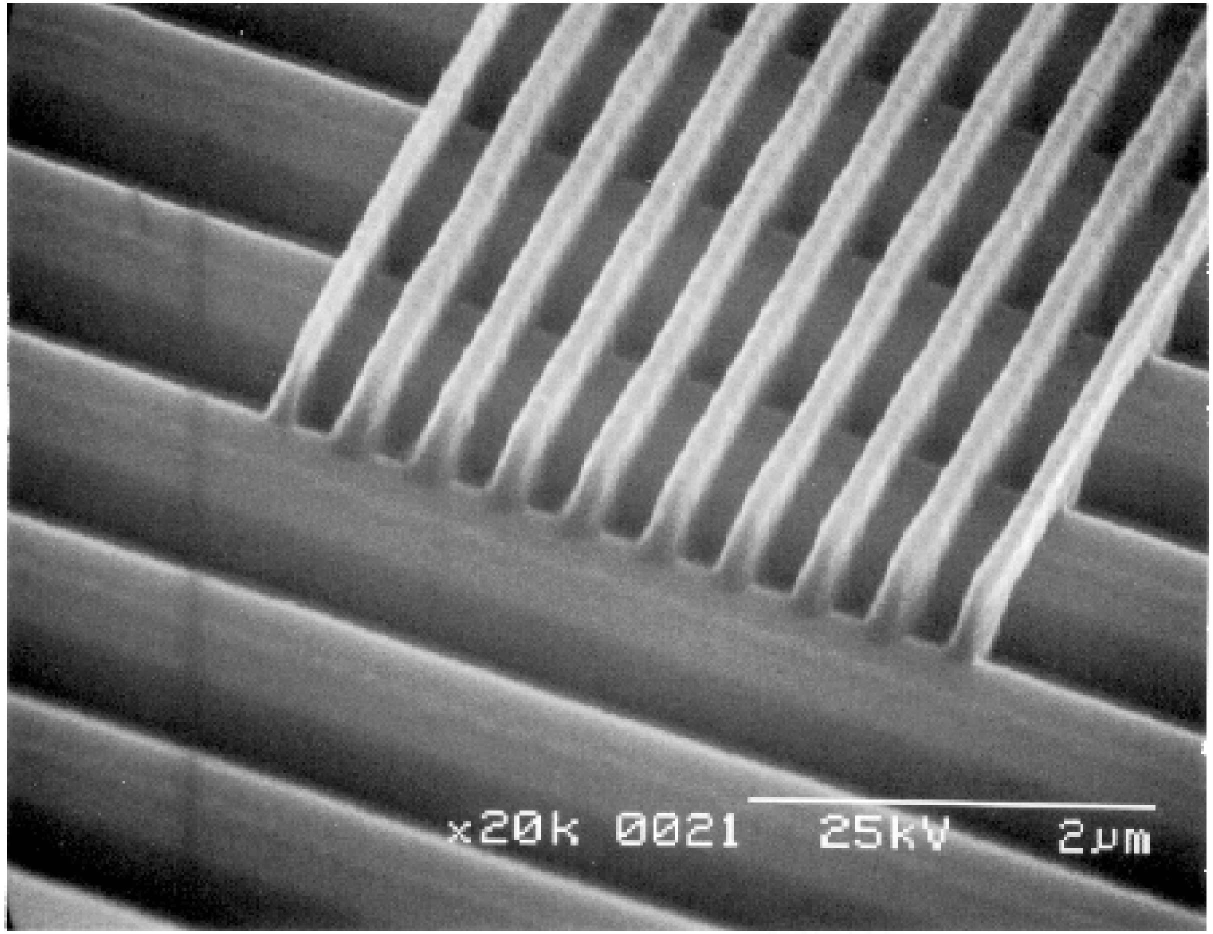
0.40µm L/S pattern

Polysilicon substrate

COMPARISON OF VARIOUS ARC SCHEMES

TYPE	ADVANTAGES	DISADVANTAGES
ORGANIC TOP ARC	COMPATIBILITY WITH MOST PROCESS LEVELS, USES STANDARD ETCH PROCESSES	NOT COMPATIBLE WITH ALL RESISTS, REFLECTIVE NOTCHING, ADDS PROCESS STEPS
ORGANIC BOTTOM ARC	COMMERCIALLY AVAILABLE, SIMPLE APPLICATION ON RESIST TRACK	ADDS PROCESS STEPS, LINEWIDTH CONTROL PROBLEMS AFTER ETCH
INORGANIC BOTTOM ARC	CAN BE APPLIED ON PE-CVD TOOL, EFFICIENT ENOUGH TO USE ON HIGHLY REFLECTIVE SUBSTRATES (Al,etc.)	PROCESS COMPATIBILITY MAY BE A PROBLEM

200nm lines over 150nm topography (Multilayer ARC on Poly)



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Exposure tools

Evolution of Lithography Tools (production)

1970's Contact Printers

Late1970's 1X Scanners (Perkin Elmer)

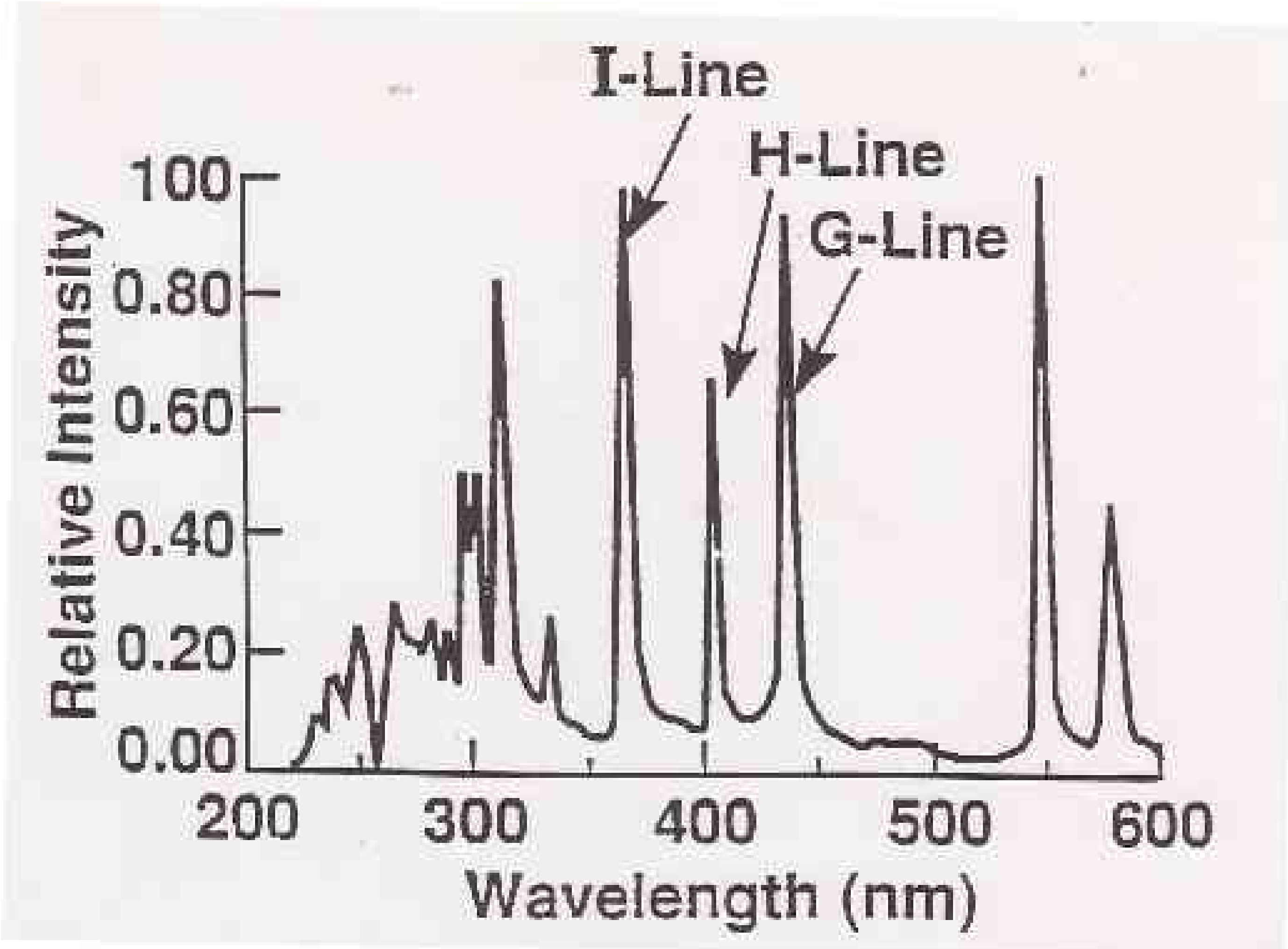
1980's Step And Repeat Tools With Reduction Optics-Mercury Arc Lamp Illumination (GCA)

Early 1990's Step And Repeat Tools With Reduction Optics-248nm KrF Laser Illumination

Mid 1990's to present Step And Scan Tools With Reduction Optics (typically 4X) 248nm KrF or 193nm Arf Laser or Mercury Arc Lamp Illumination introduction of 157 Arf

Mercury Arc lamp spectrum

The light source that virtually all lithography tools were designed around until the integration of excimer lasers in the mid 80's (research)



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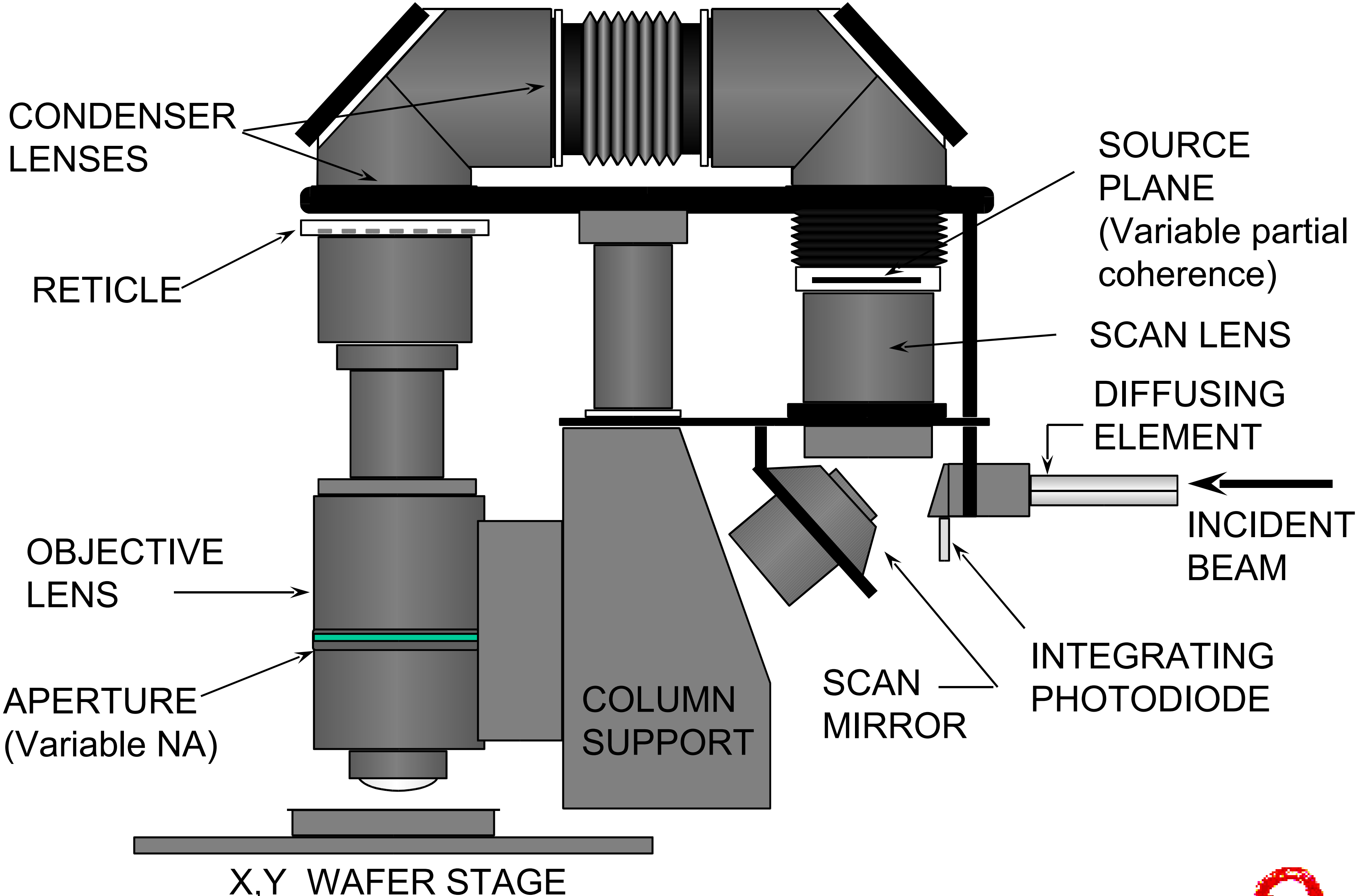
DUV-1 1984



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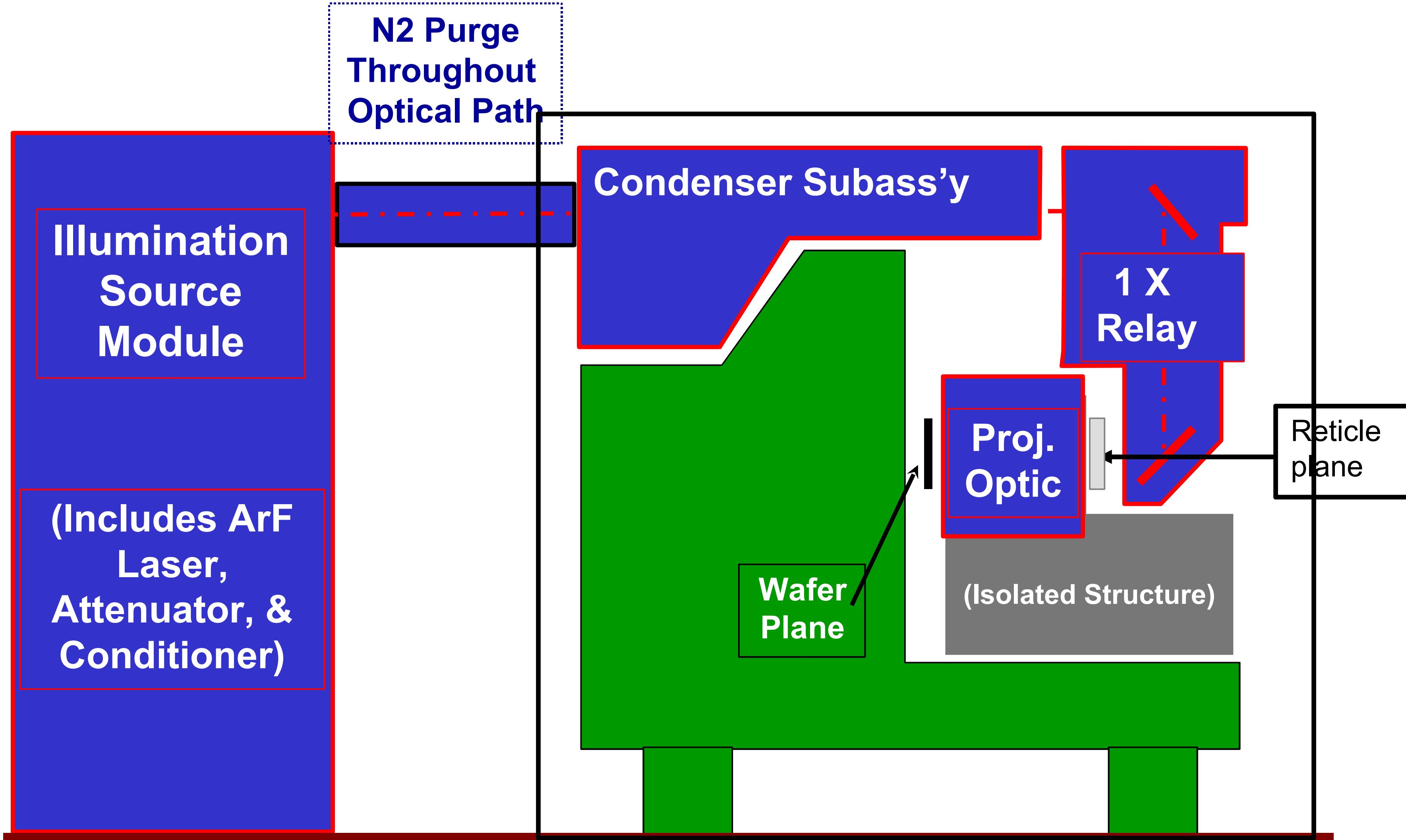
ASML

SVGL 193nm full field scanner System Architecture



Catadioptric Projection Optics.

Benefits of the Catadioptric lens design

The Micrascan utilizes a catadioptric lens design which provides:

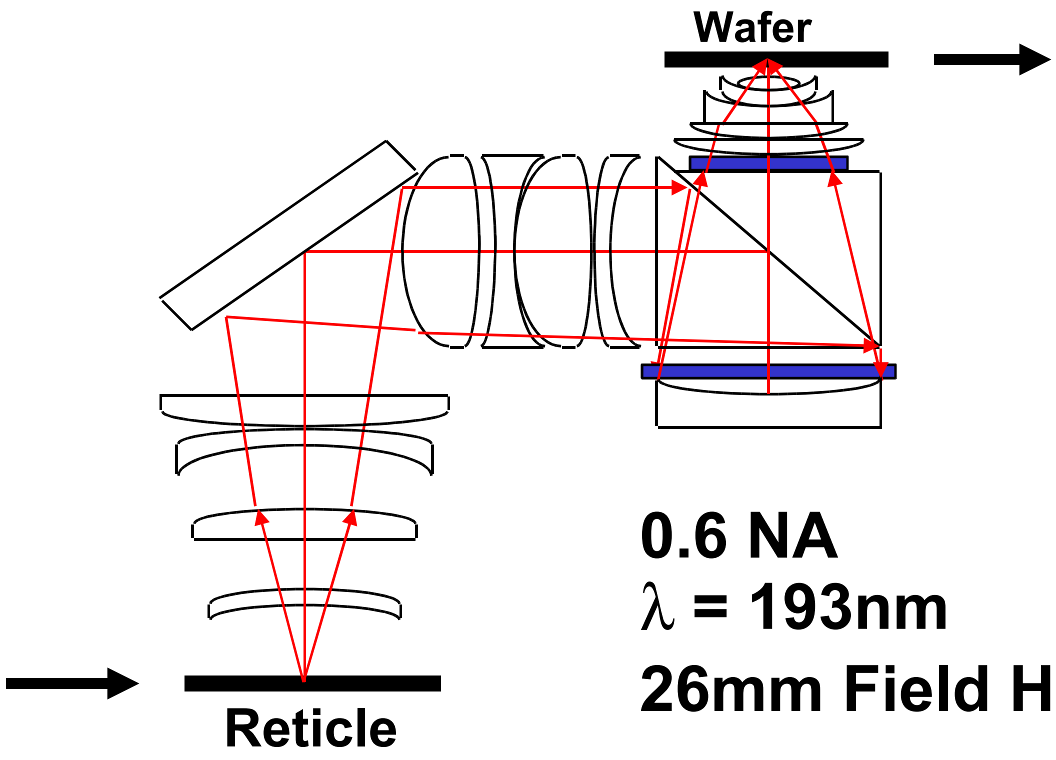
•A reflective element for the reduction power of the lens

•Greatly decreases the sensitivity of the lens to environmental variances

•A significantly smaller lens assembly

•A broadband lens when compared to all refractive designs

•Reduces the criticality of wavelength optimization, source to lens



0.6 NA

λ = 193nm

26mm Field Height

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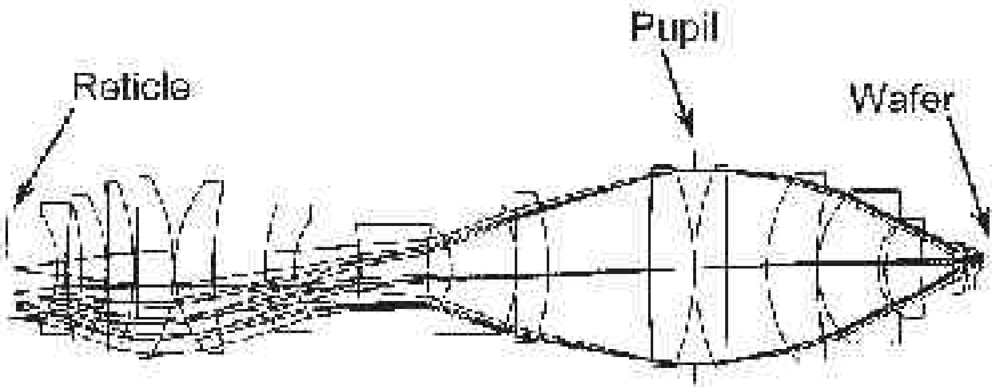
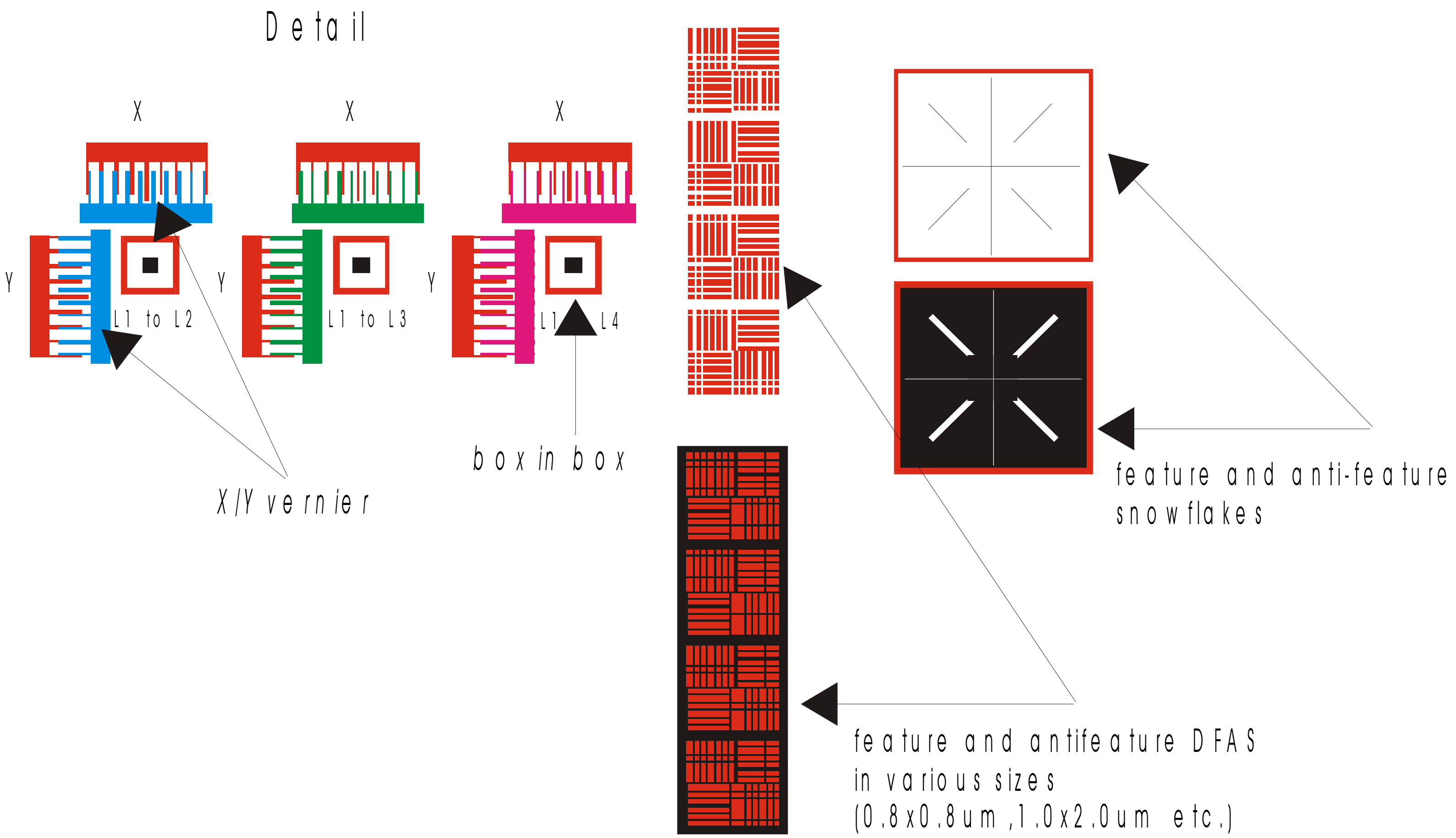
4. Chromatic Dioptric 4x



Wafer alignment marks



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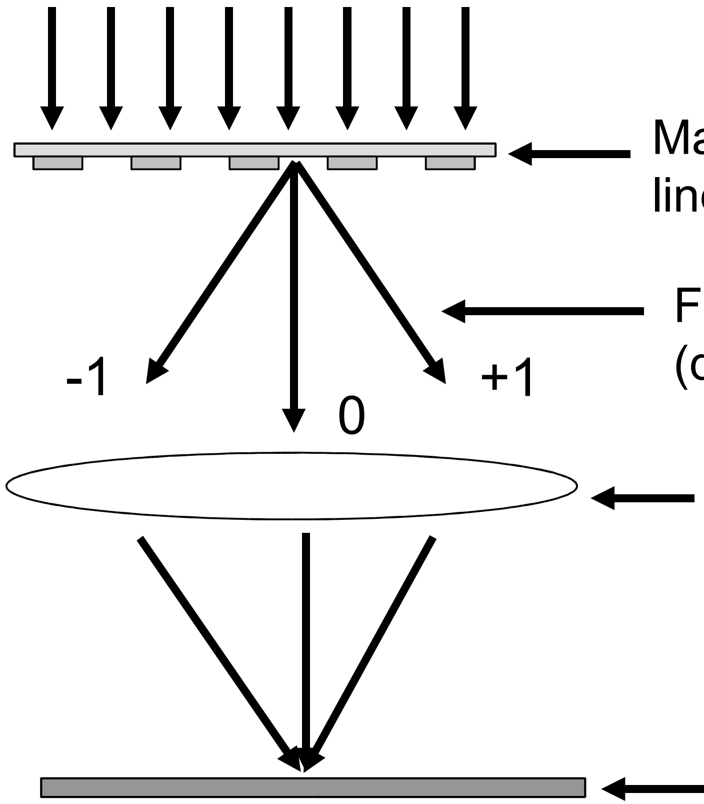
Optical enhancements

- Off axis illumination
- Variable transmission illumination
- Phase shifting
- Dual mask phase shift

Diffraction limited imaging

A stepper lens can be considered a low pass filter of the mask image onto a wafer



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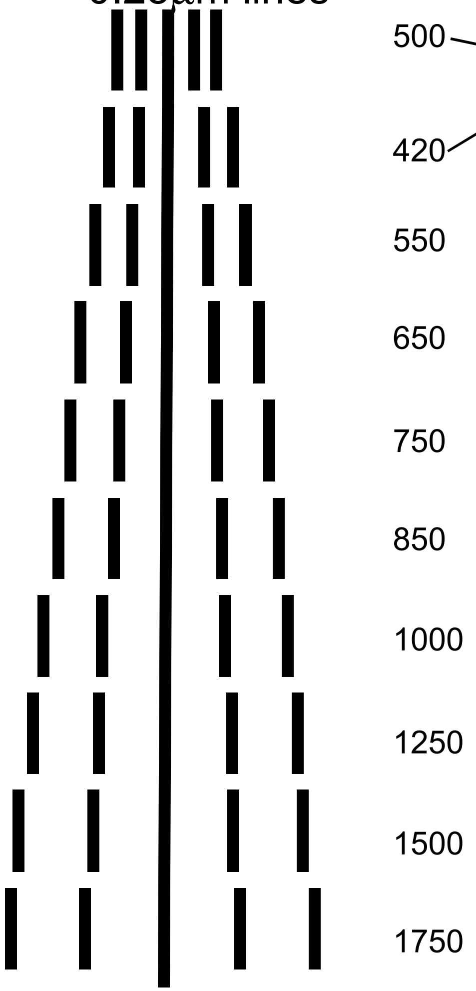
Proximity effects (Experimental data)

Mask Pattern

Proximity tree test structure



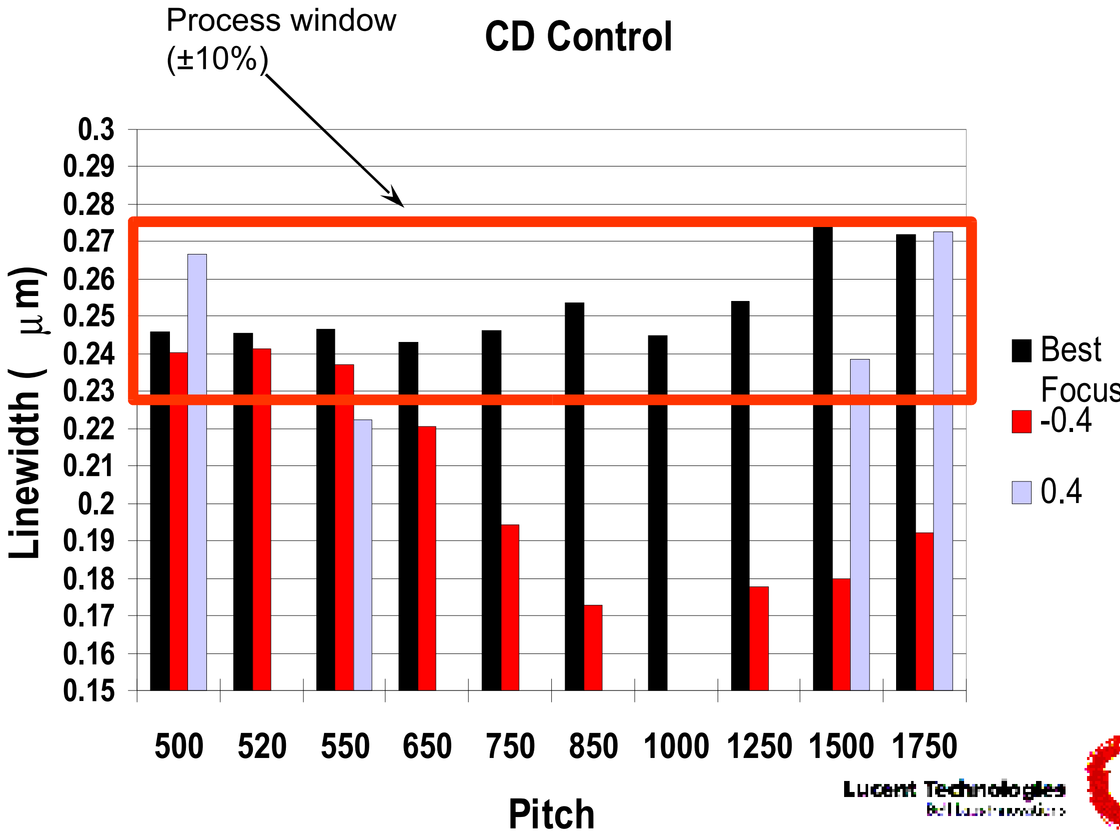
Substrate: Multilayer ARC on Si

Resist: Olin ARCH2

Thickness 760n

NA: 0.53

Sigma: 0.74



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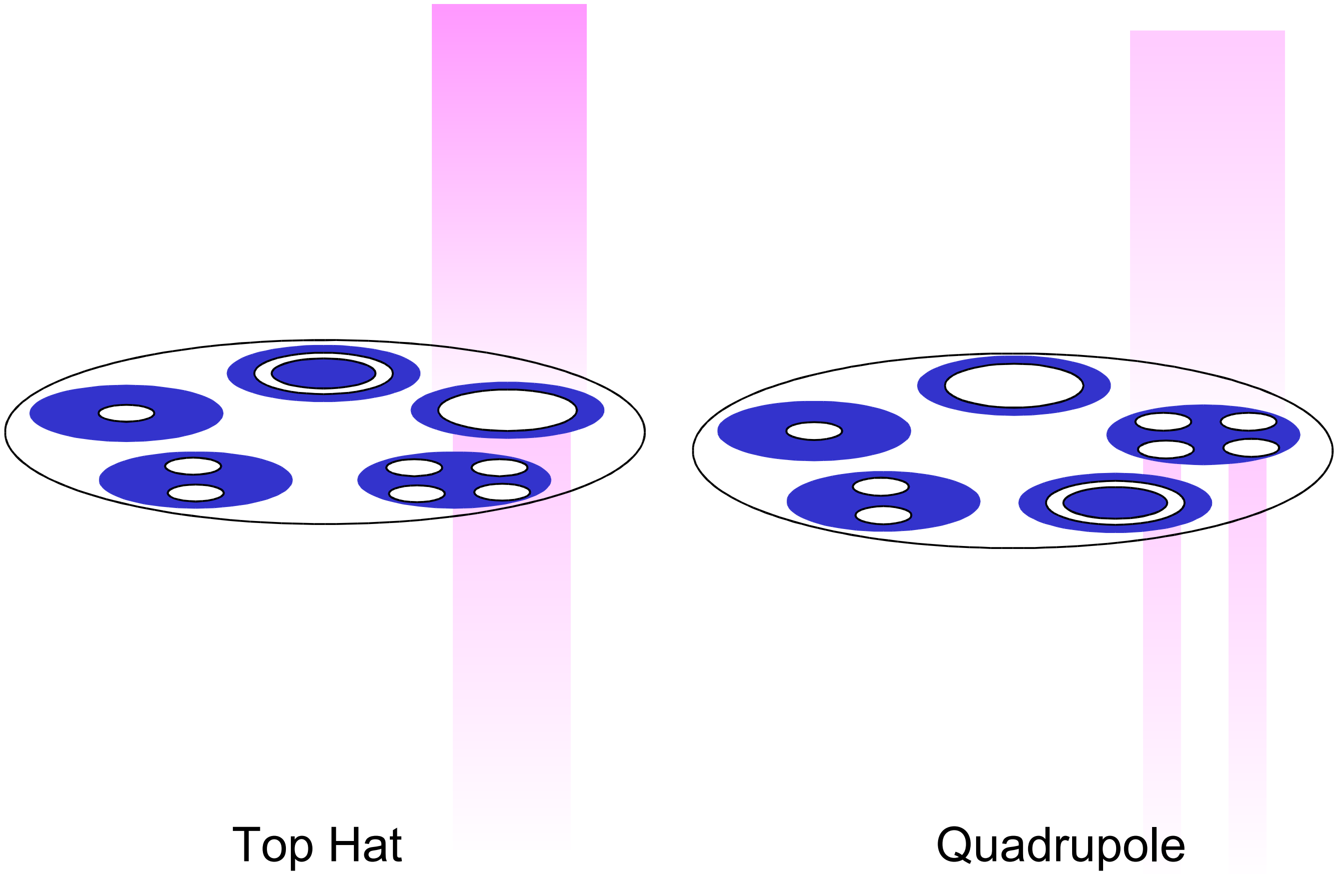
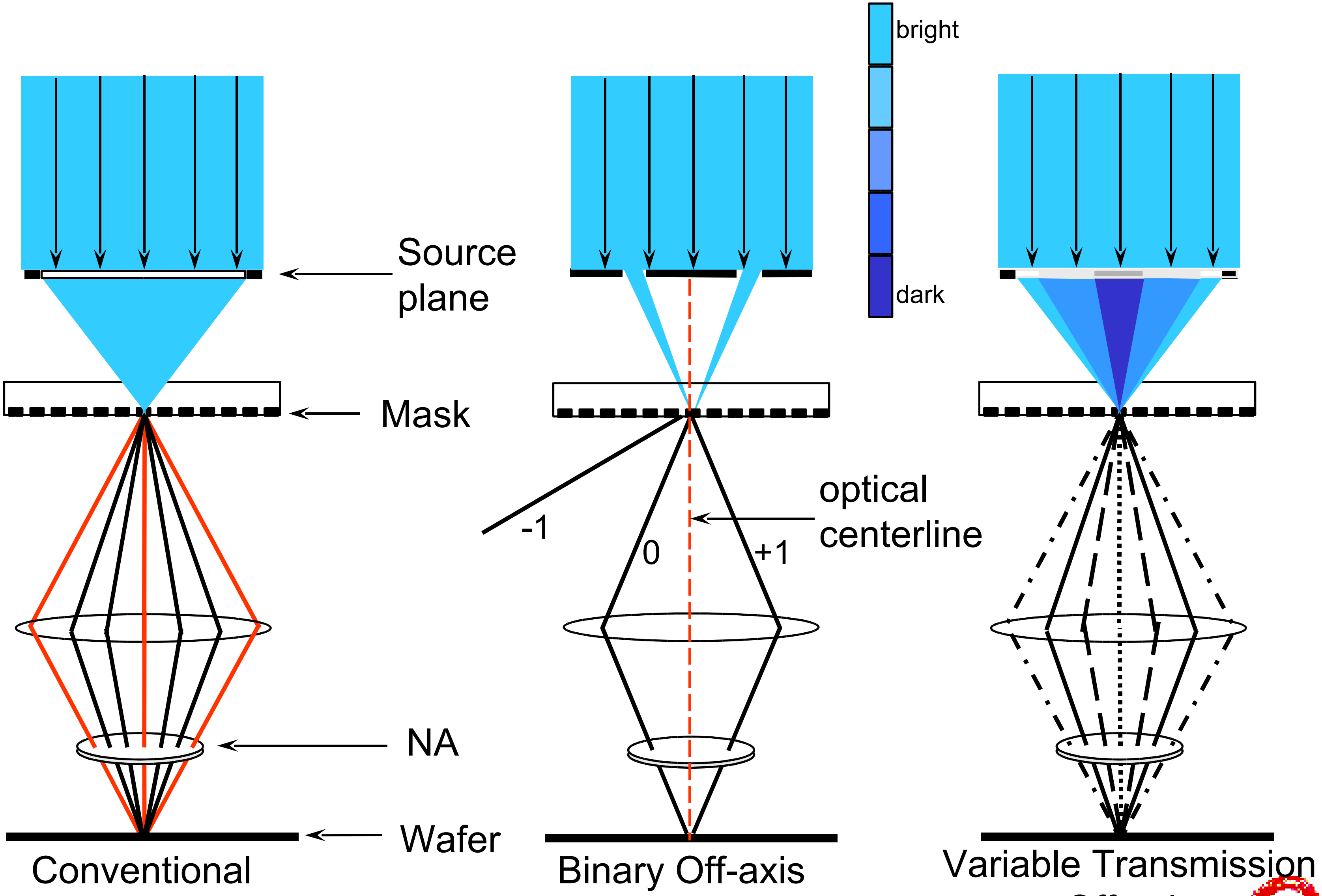
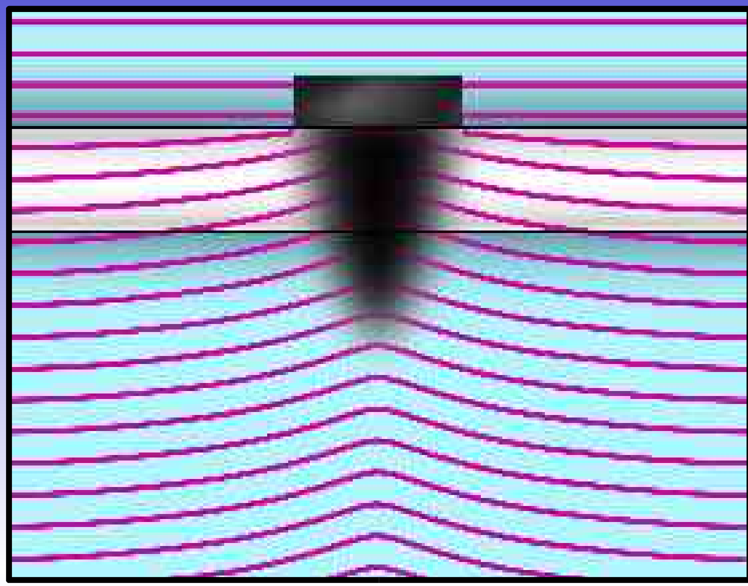
“Clean–up aperture” operation

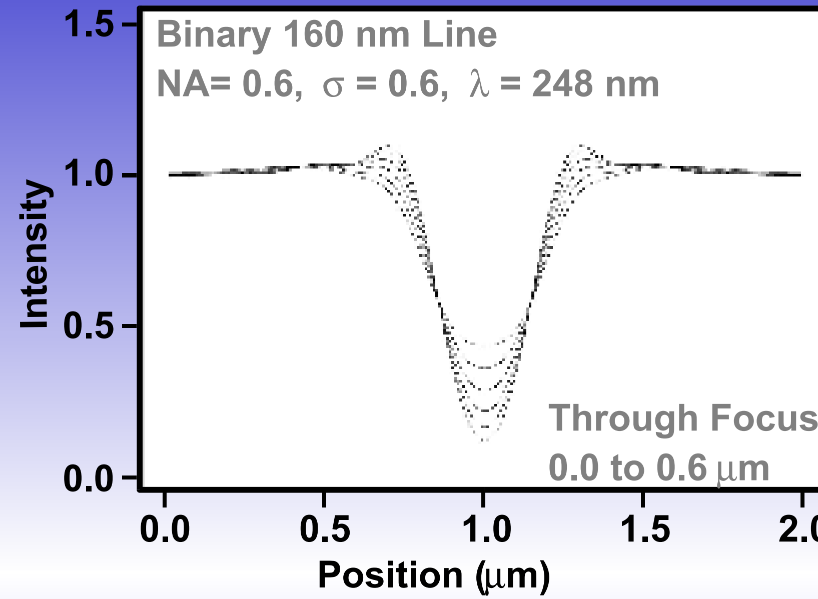


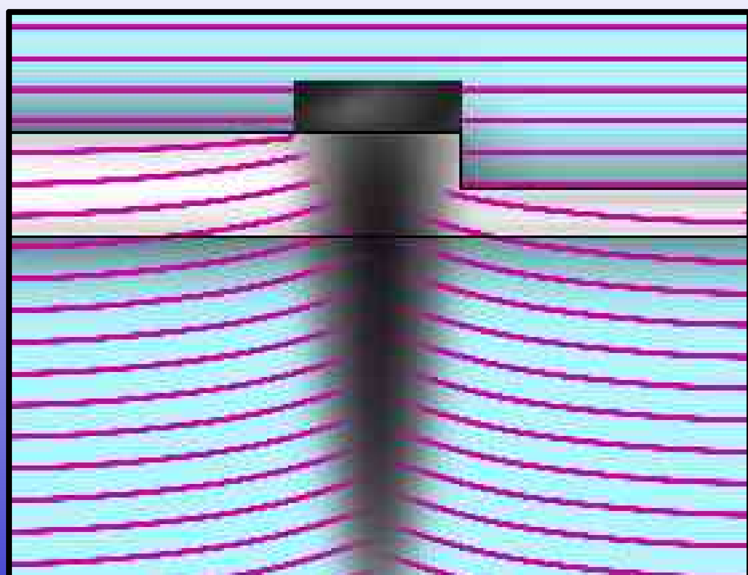
Conventional and Binary Off-axis vs. Variable Transmission

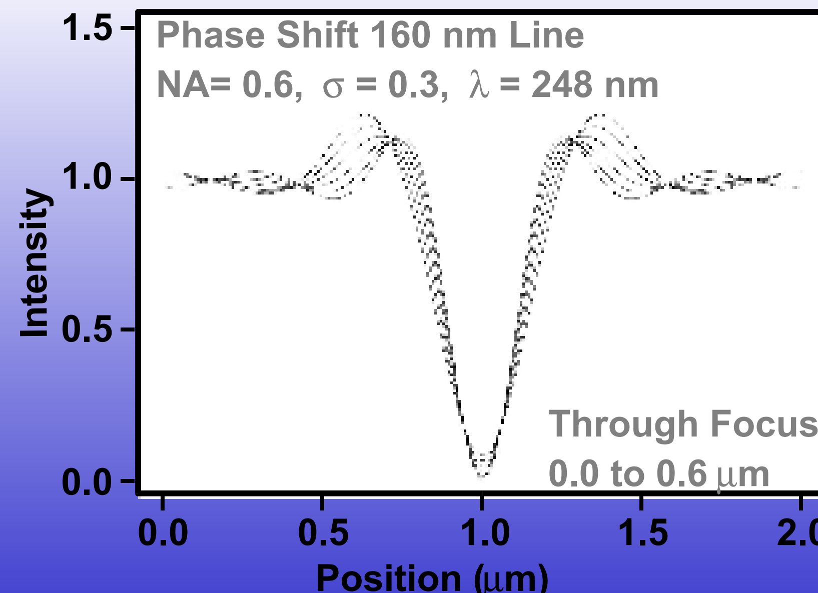


Principle of Phase Shifting



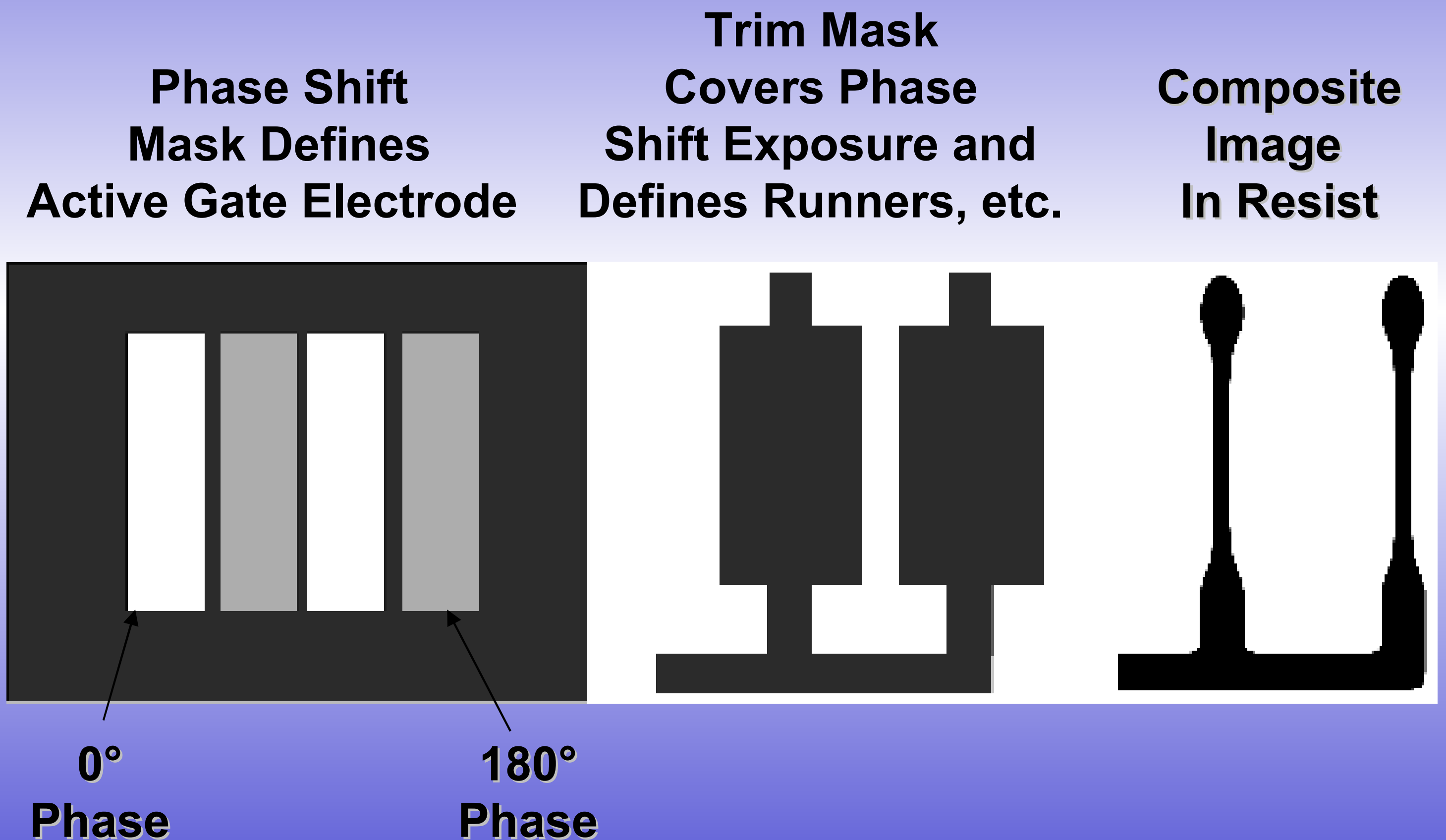






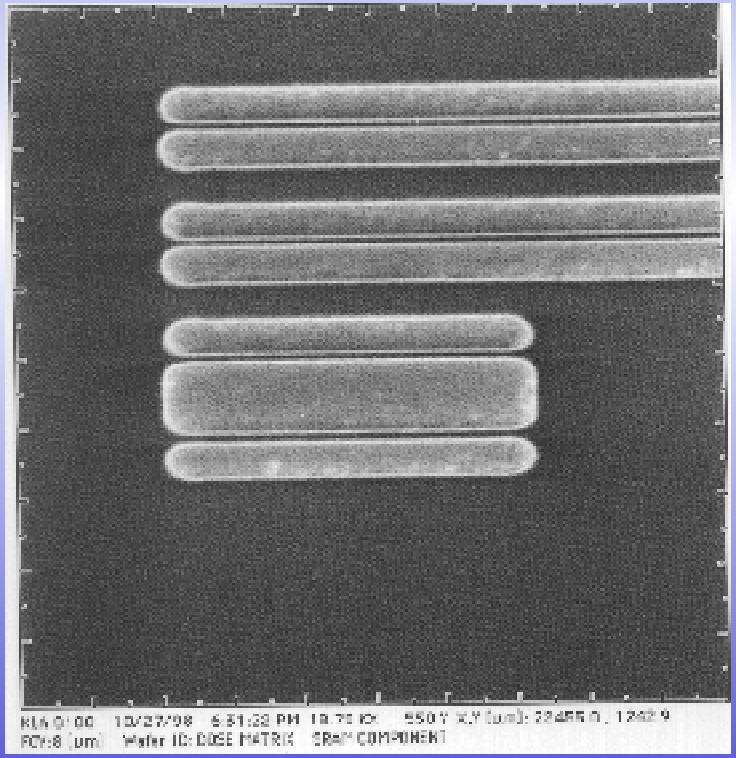
Dual Mask Approach

Gate Level Exposure

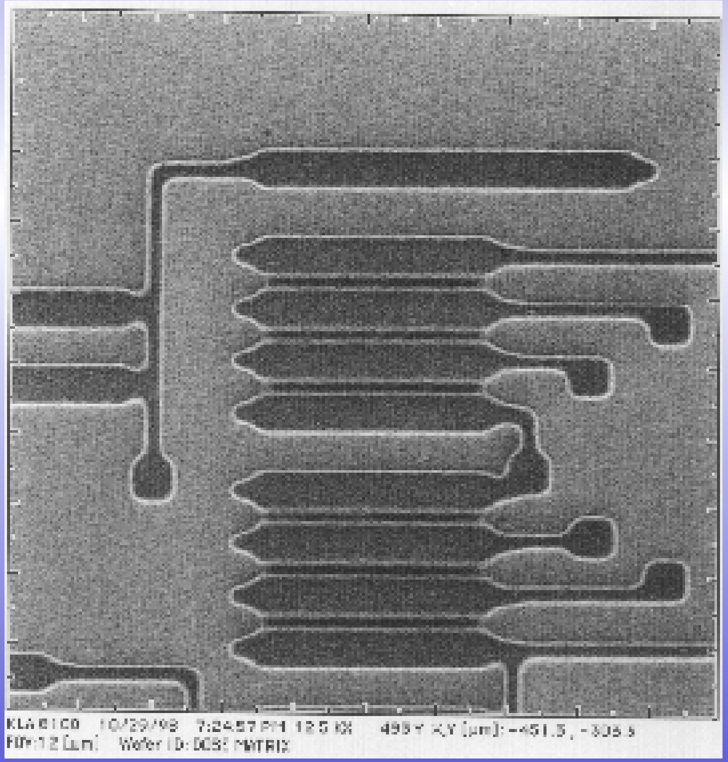


Dual Mask – Individual Exposure

248 nm Wavelength, 0.53 NA Step and Repeat Tool
P.S. Partial Coherence 0.3
Binary Partial Coherence 0.74
600 nm UV6 Resist
Multilayer inorganic ARC

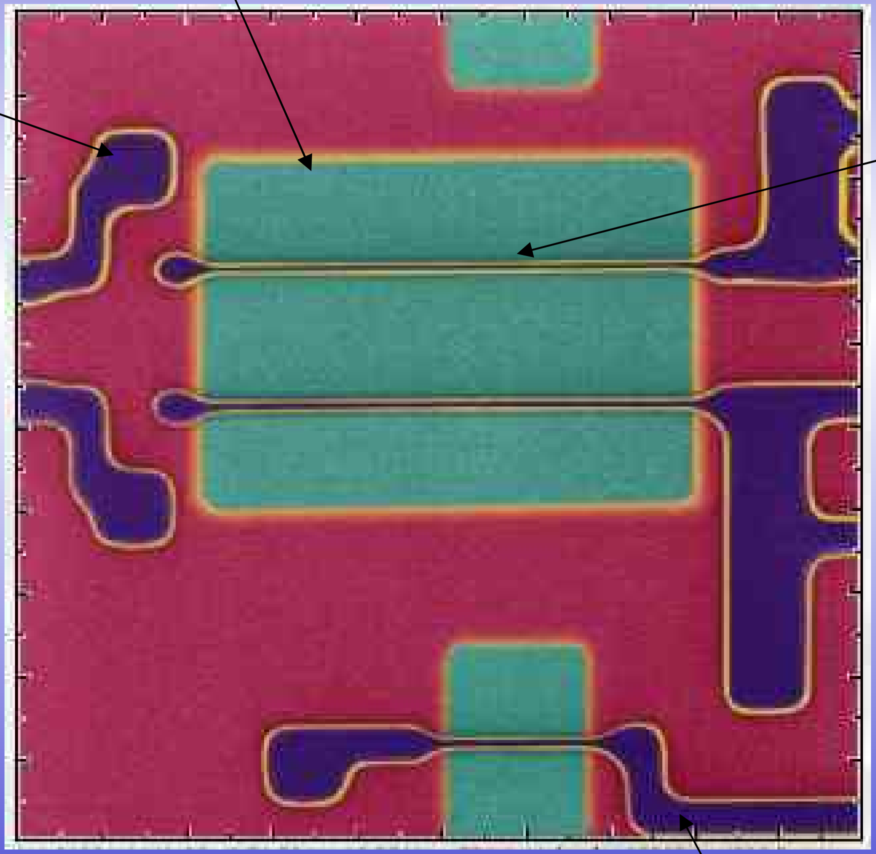


Phase Shift Mask

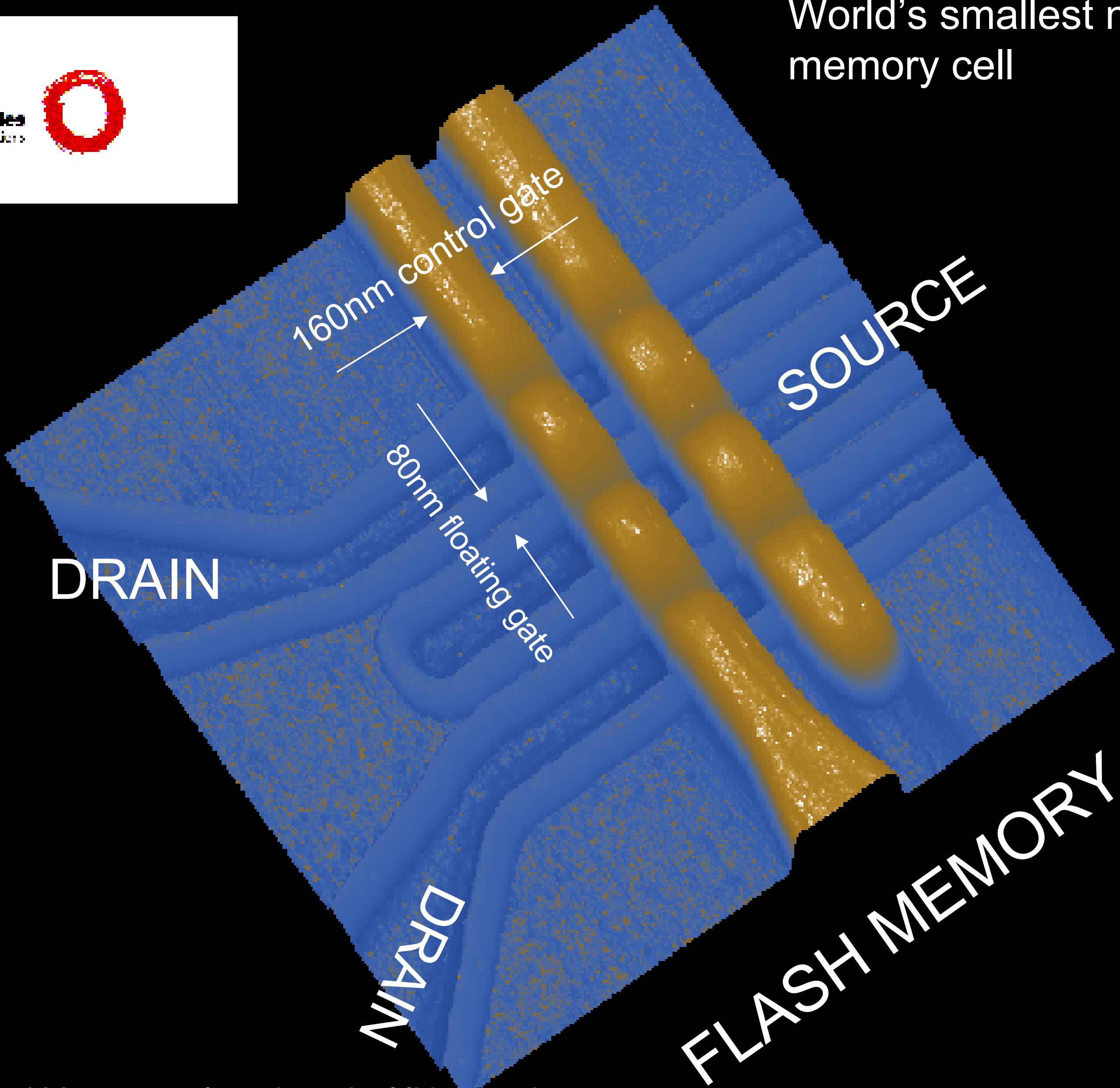


Binary (Trim) Mask

Dual Exposure (Composite)



World's smallest non-volatile memory cell



Fabricated with 193nm wavelength optical lithography

60nm features

_with alternating aperture phase shift mask

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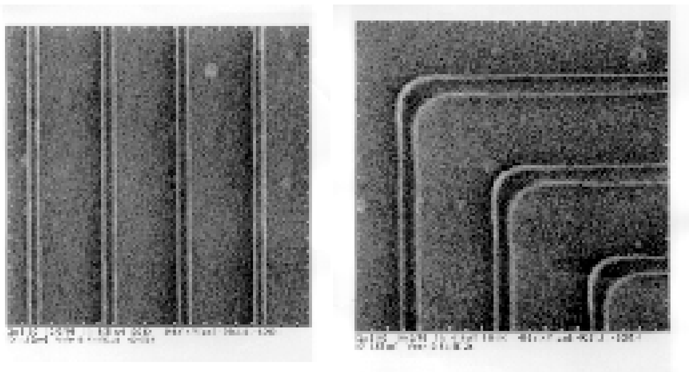
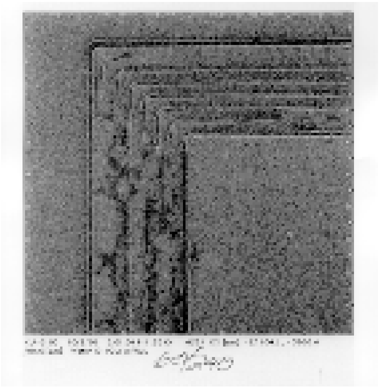
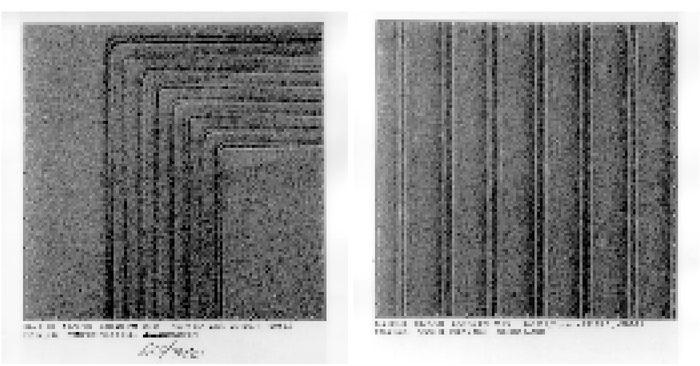


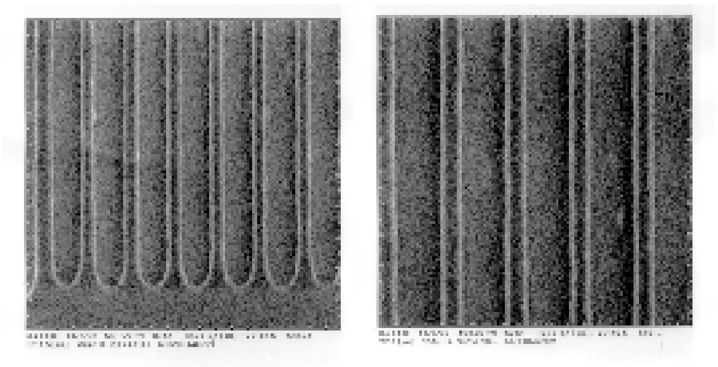
60nm/360 pitch



60nm/240 pitch



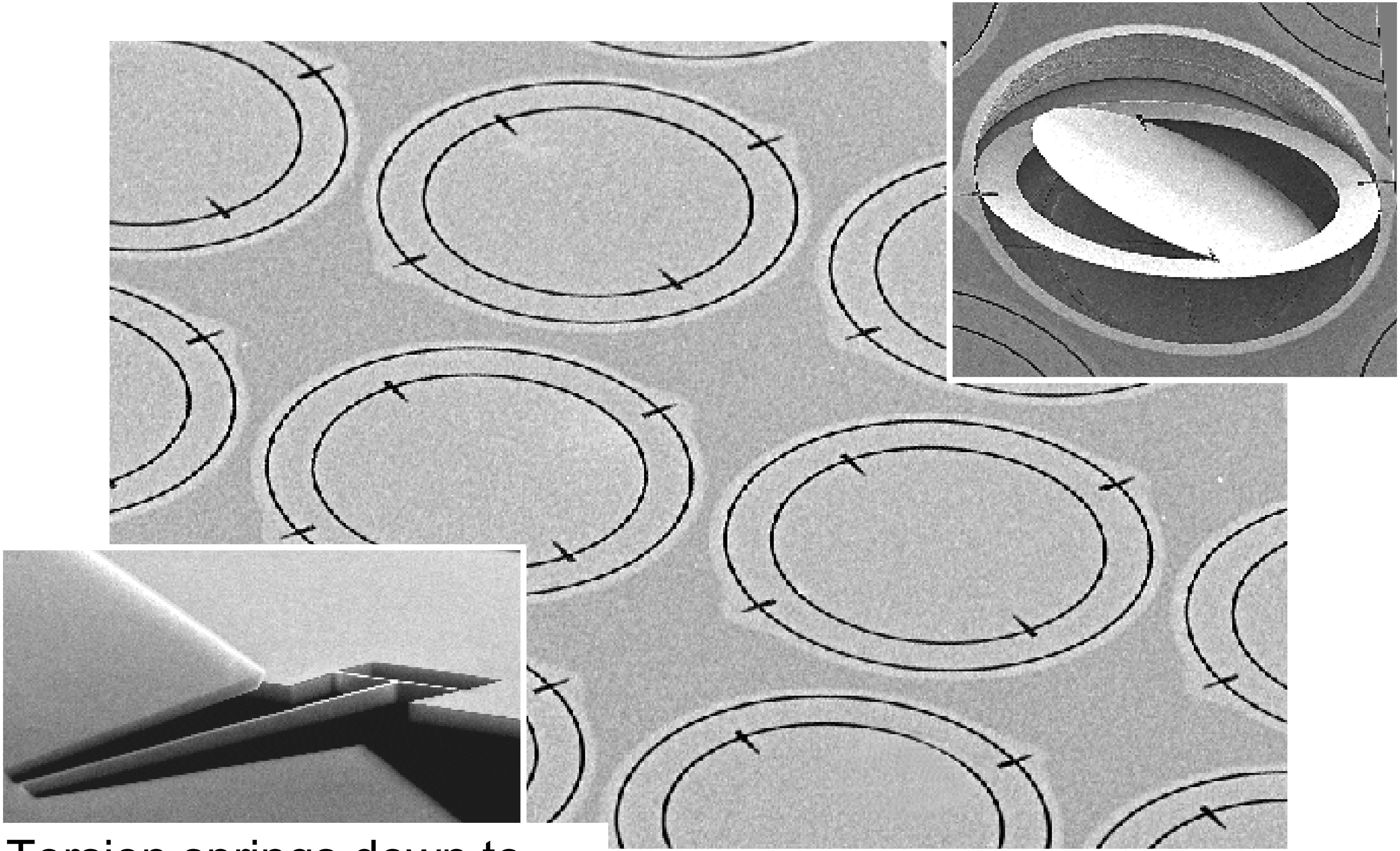
60nm/300 pitch



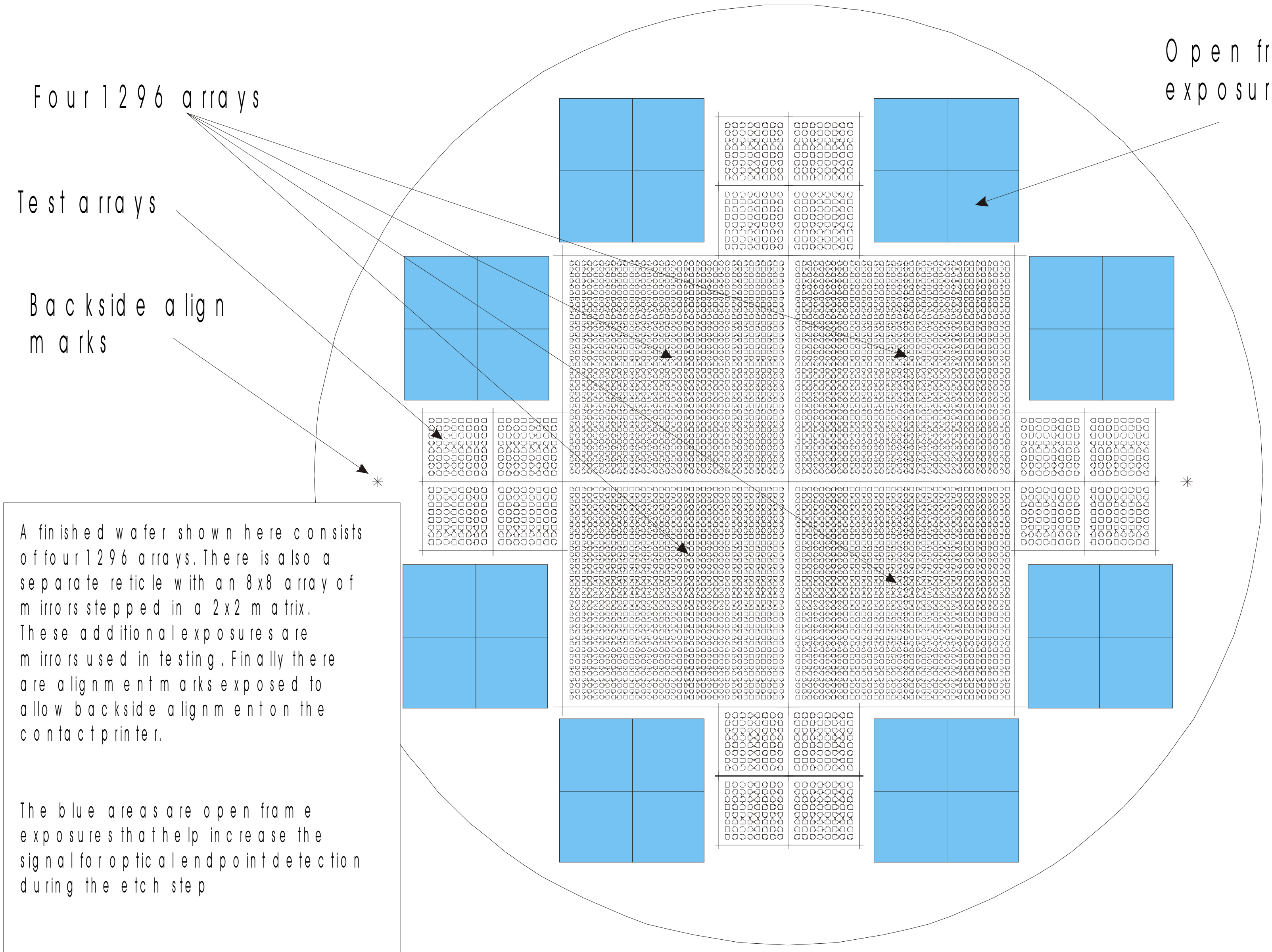
60nm/200 pitch

MEMs Lithography

SOI Lambda Router Mirrors

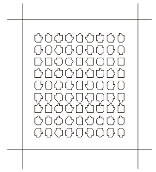


Torsion springs down to 0.4μm



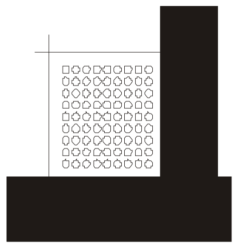
A finished wafer shown here consists of four 1296 arrays. There is also a separate reticle with an 8x8 array of mirrors stepped in a 2x2 matrix. These additional exposures are mirrors used in testing. Finally there are alignment marks exposed to allow backside alignment on the contact printer.

The blue areas are open frame exposures that help increase the signal for optical endpoint detection during the etch step



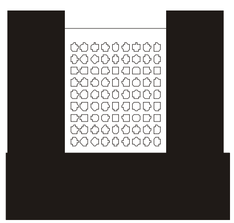
Starting reticle for "active device" consists of a 9x9 array of mirrors. This reticle is used to construct the final 1296 mirror array

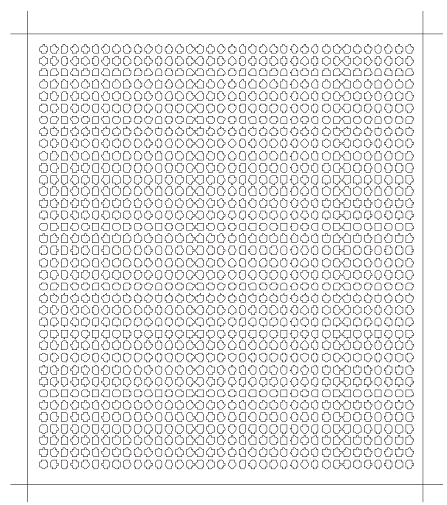
Corner blade setting (four separate settings are used)

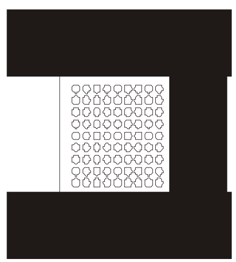


Scribe bars are exposed by manipulating aperture blades. There are 9 reticle passes and 9 exposure passes for each device. A total of 72 passes are needed to expose a quad array.

Top blade setting

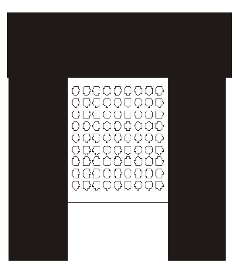


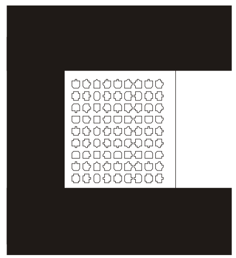




left blade setting

Bottom blade setting





right blade setting

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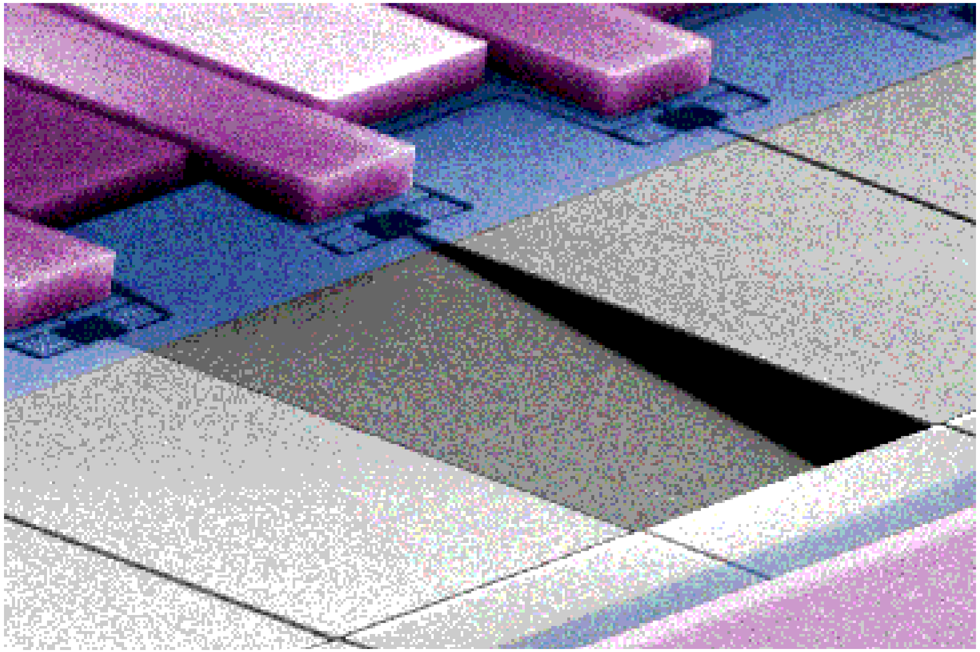
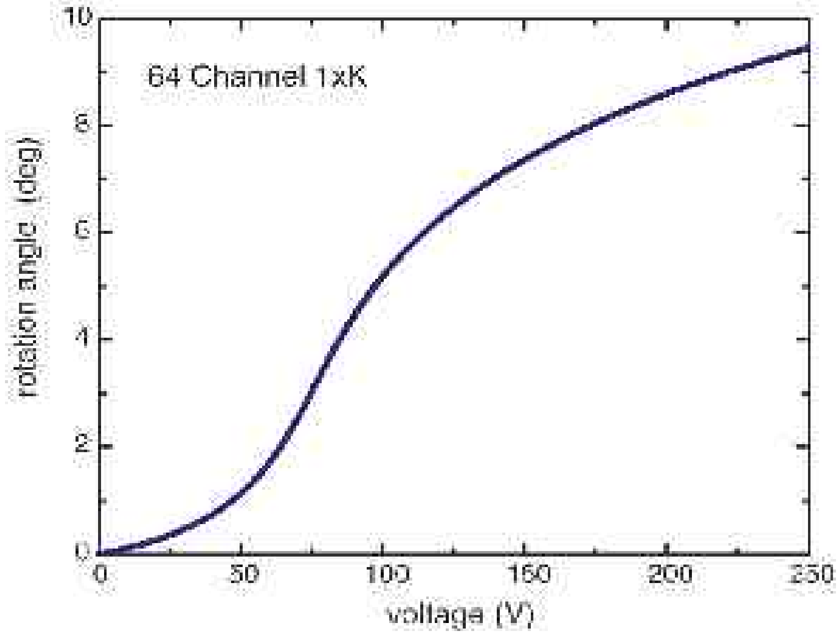
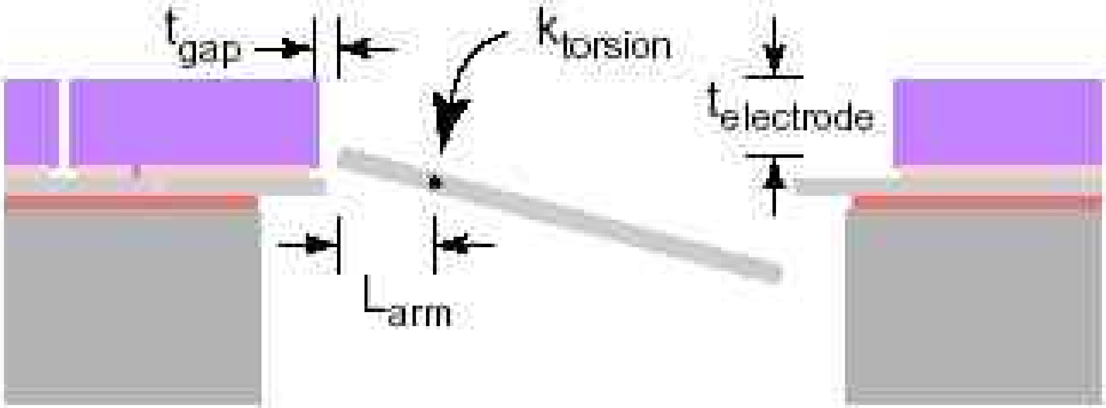
Monolithic Fringing-Field 1xN Switch







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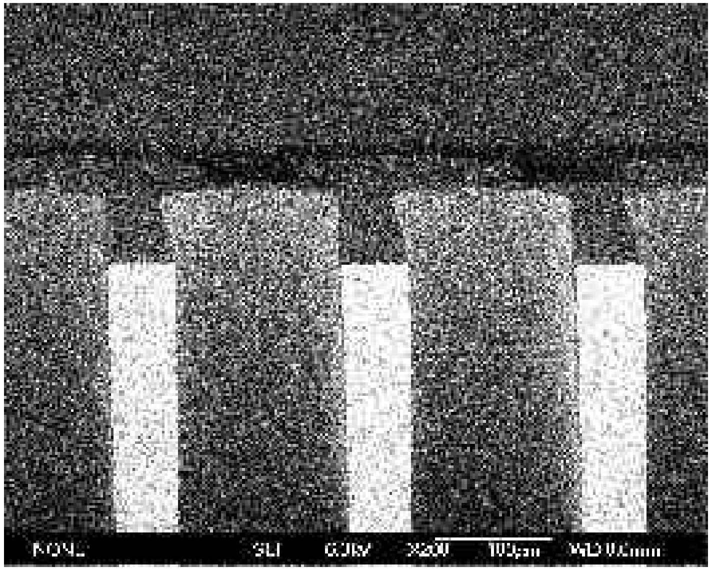
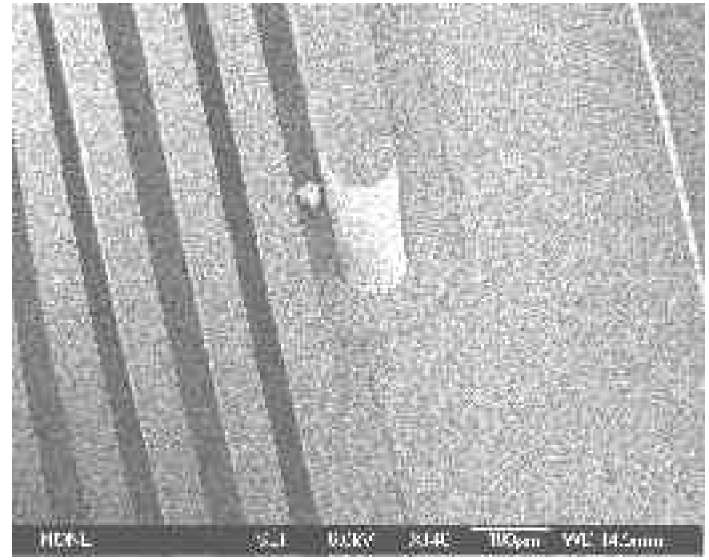
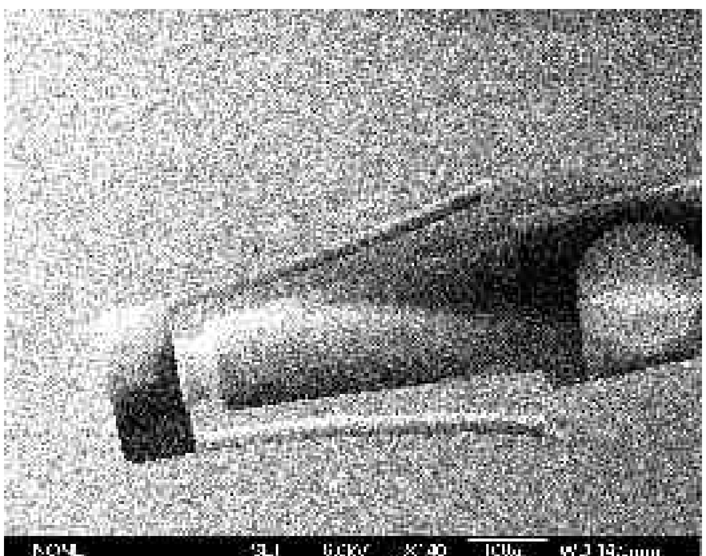
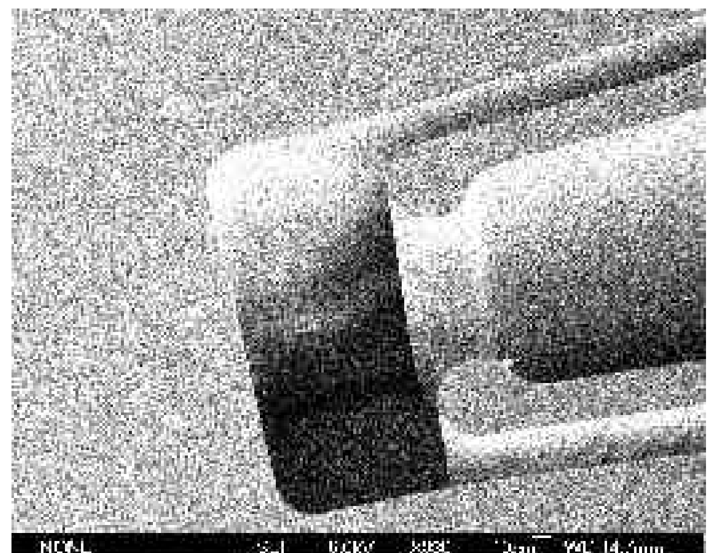
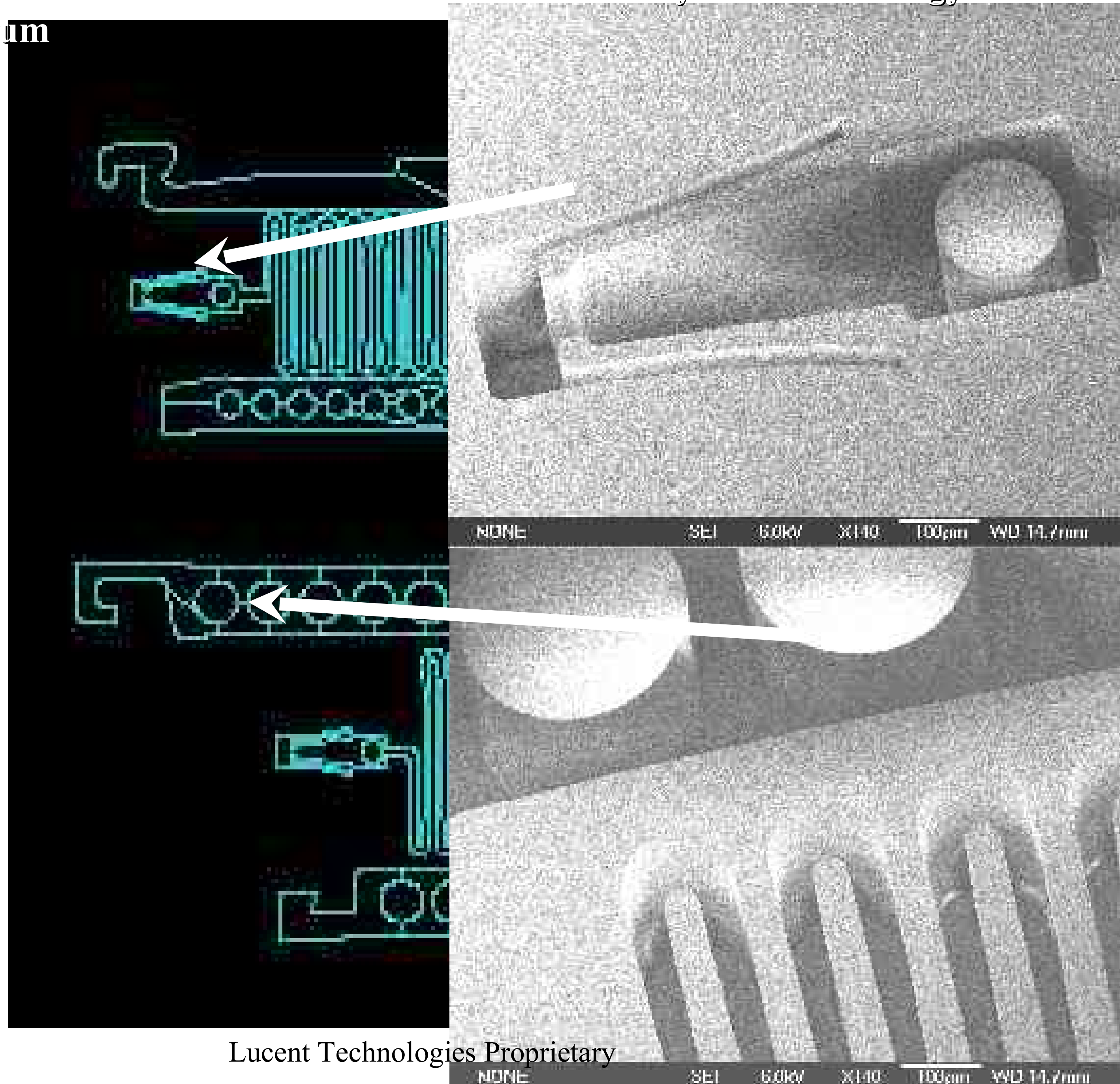
SU-8 280μm thick







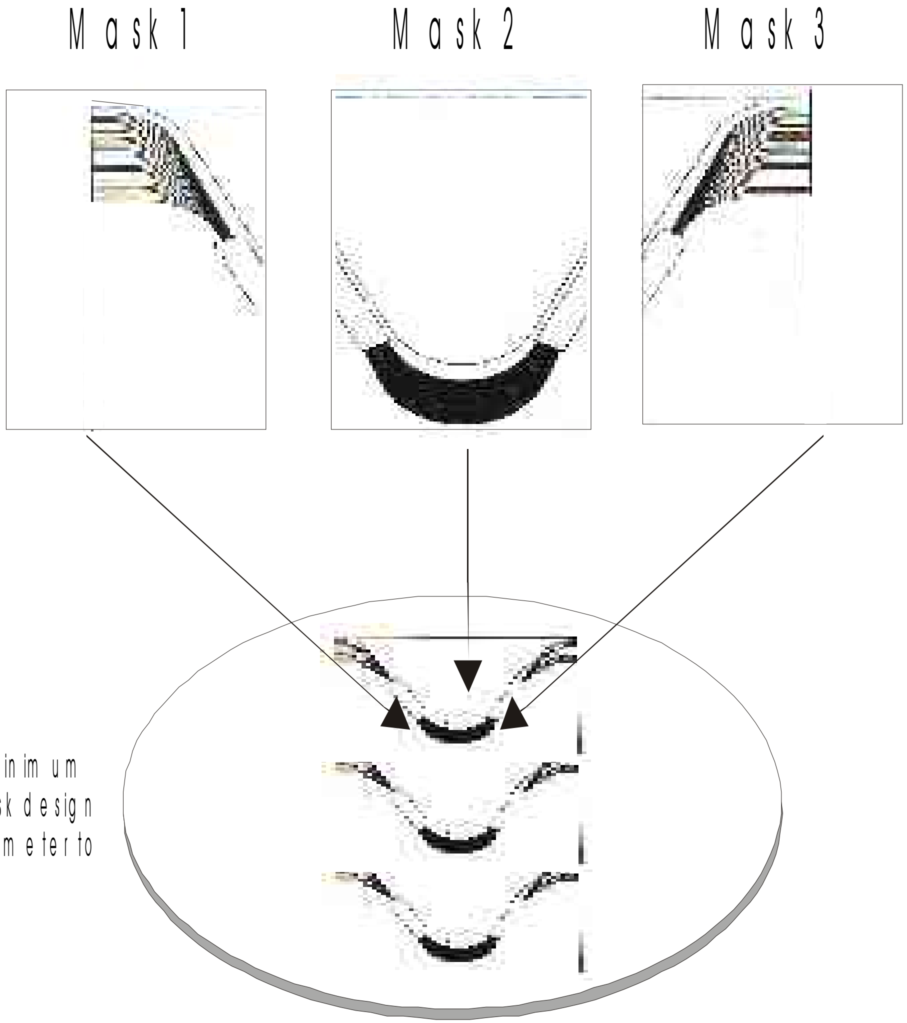



NONE SEI 6.0kV X140 100µm WD 14.7mm
NONE SEI 6.0kV X140 100µm WD 14.7mm

AWG device fabrication with step and repeat lithography

The stepper is limited to a field size of 22X22mm vs. the device which is over 60mm

The solution is to separate the device into three sections and "stitch" the fields together to make a complete device



Stitching errors are held to a minimum through a combination of mask design and utilizing the stage interferometer to align the masks

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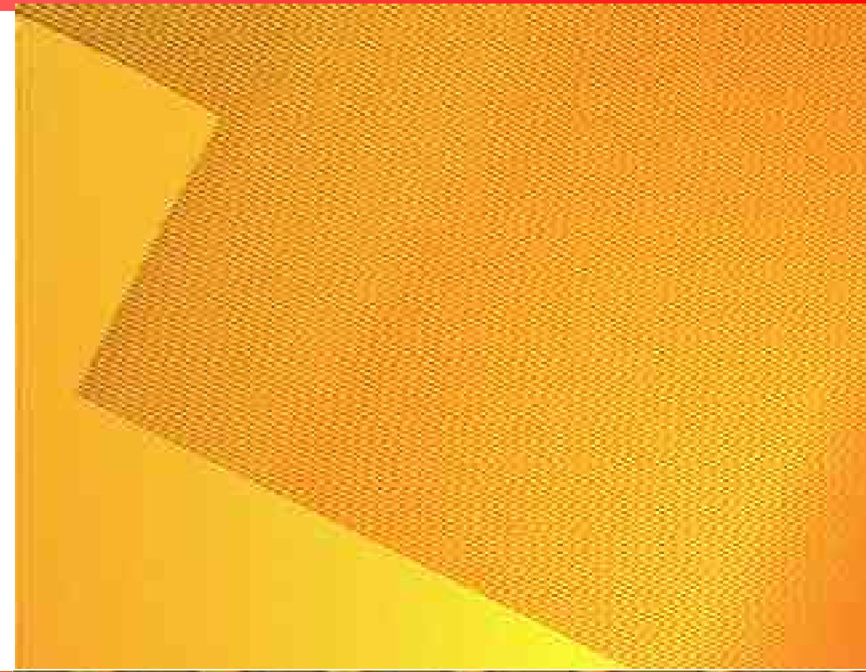
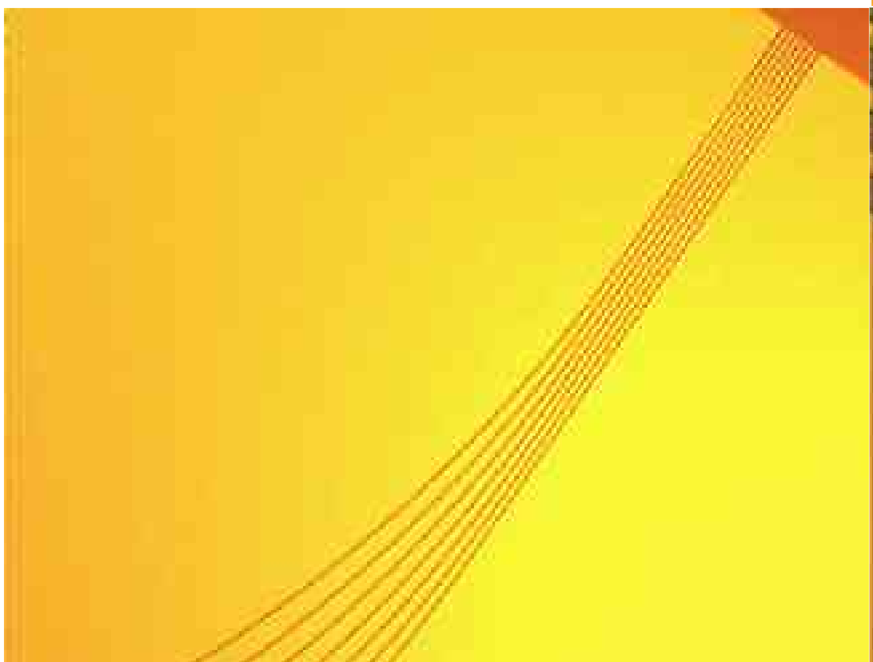
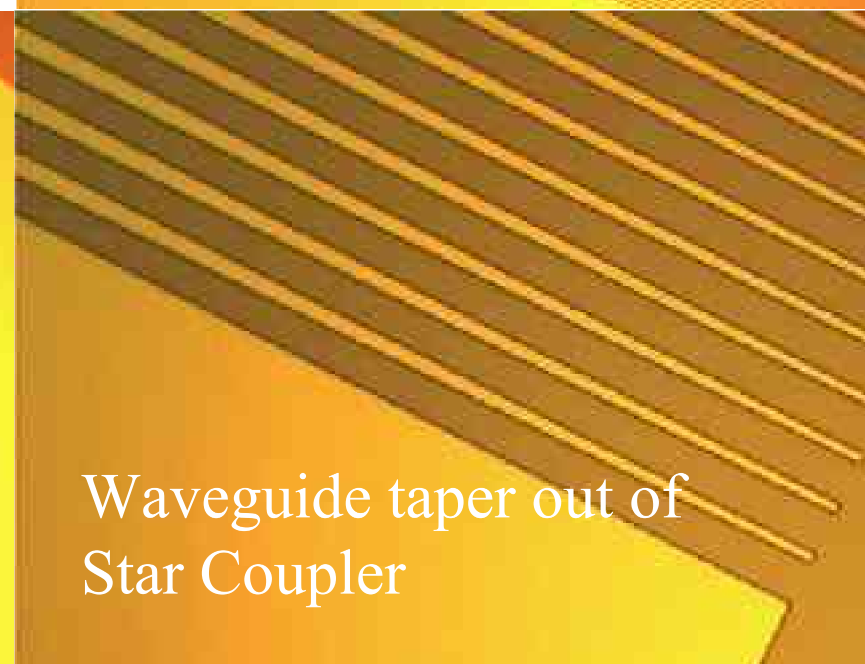
Waveguide lithography

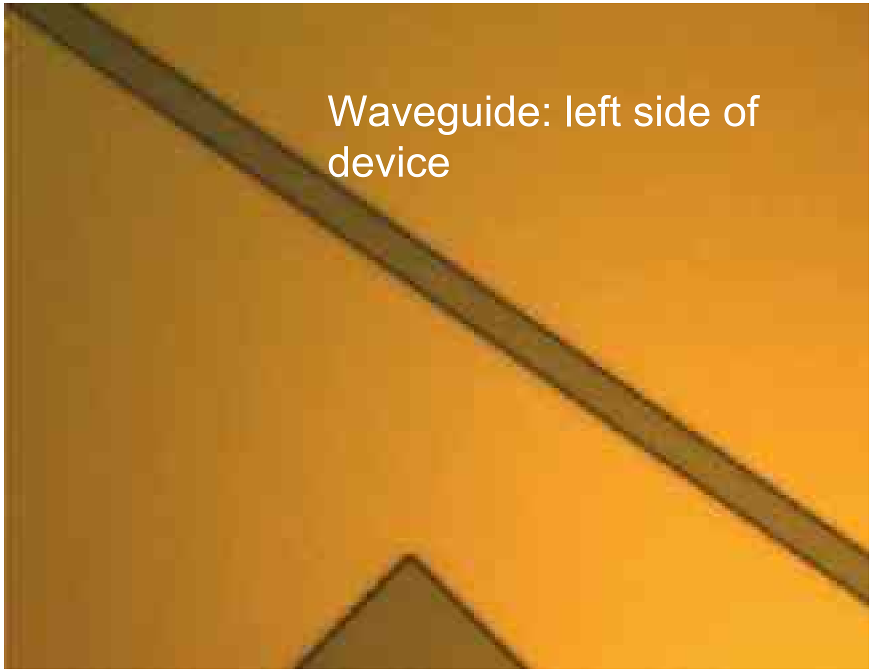


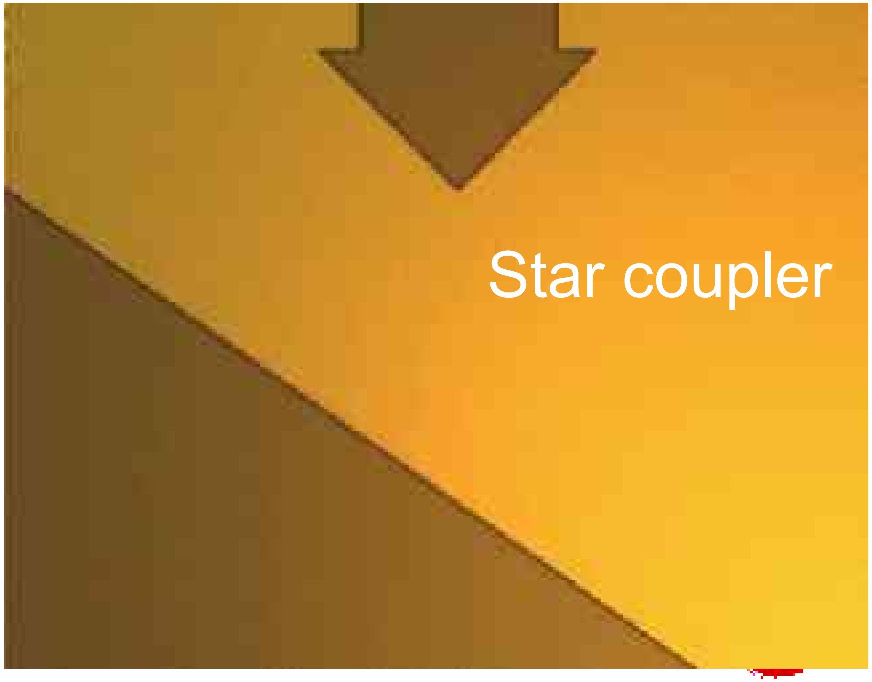


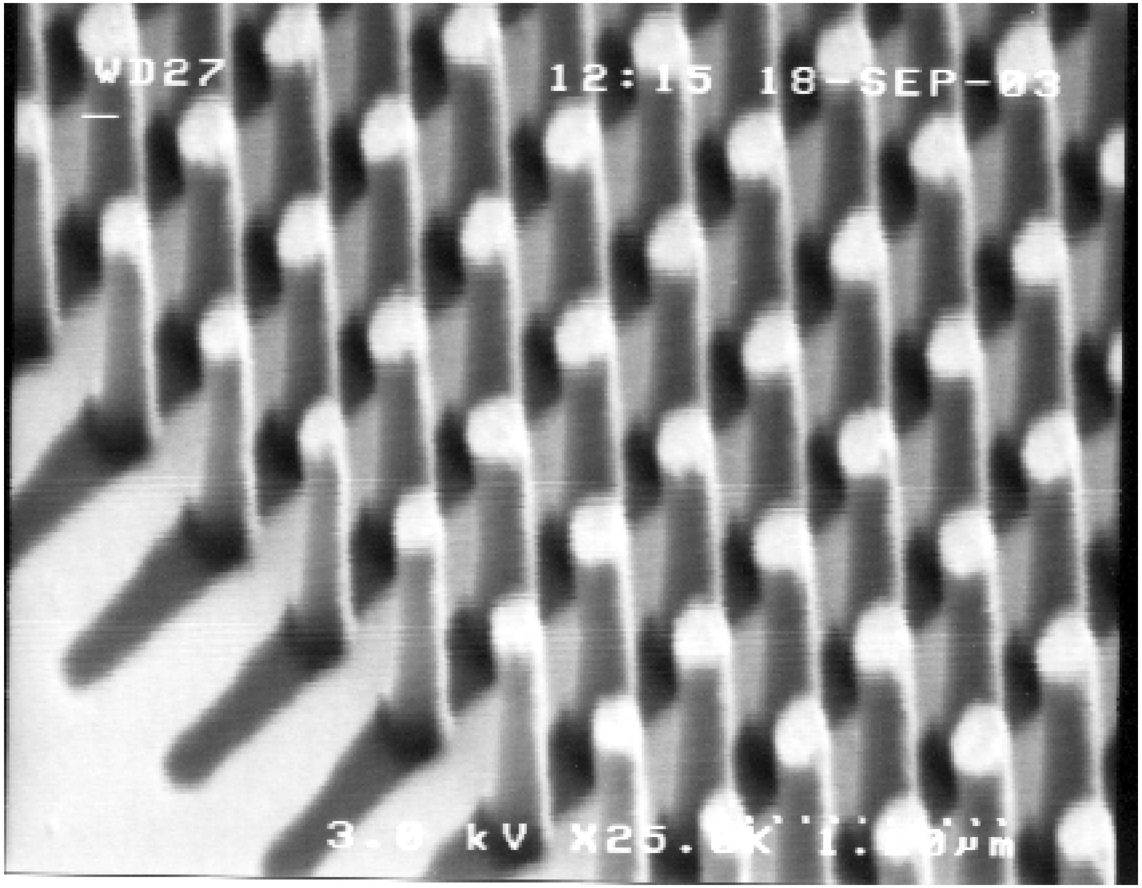


Field stitching

Arrows mark the area where two stepper fields meet







“nanograss”

(250nm pillars 2um tall)

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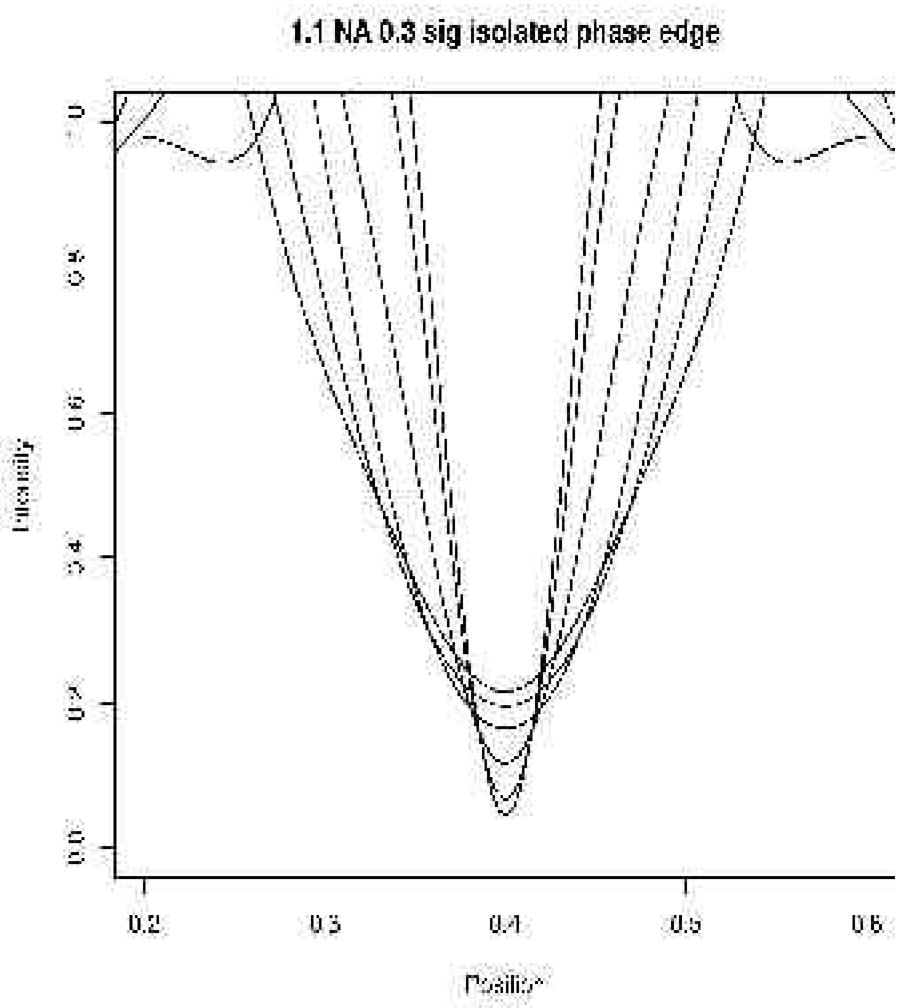
How Do We Prototype 45 nm Node Devices?



Strong phase shifting must be employed for 193 nm wavelength lithography at 45 nm node

Threshold 0.3 – CD ~60nm

Threshold 0.2 – CD < 40 nm

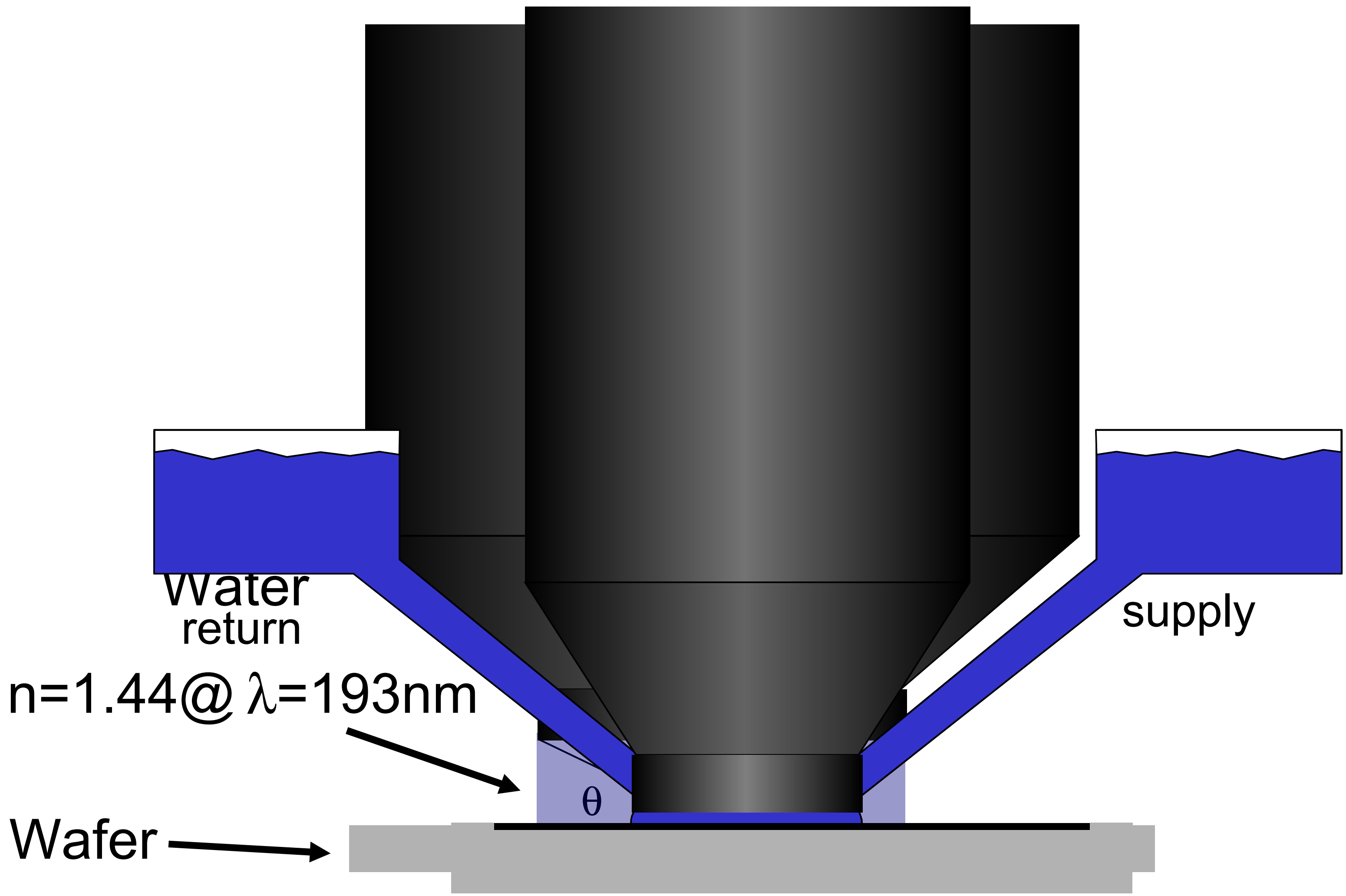
DOF ~ 0.4 microns with reasonable contrast even at 40 nm feature size

What's next?

- E-beam: (too slow, great for research, breakthroughs in optical litho may challenge it
- EUV: problems with source, mask
- X-ray not on the road map any longer
- Ion beam: most major programs have been disbanded
- 157 ArF on hold mainly because of imaging materials issues

157nm immersion with high index fluids

Immersion lithography



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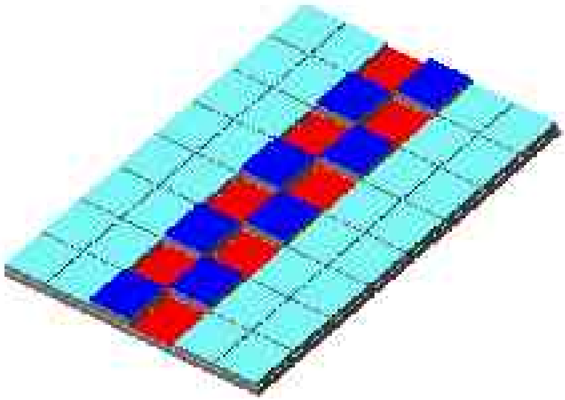
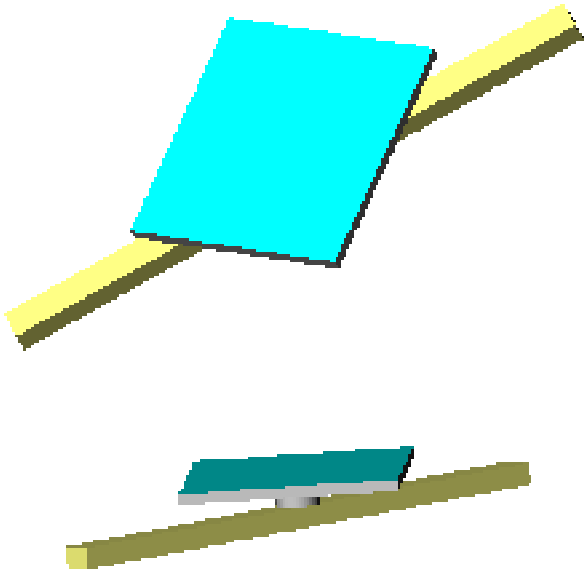
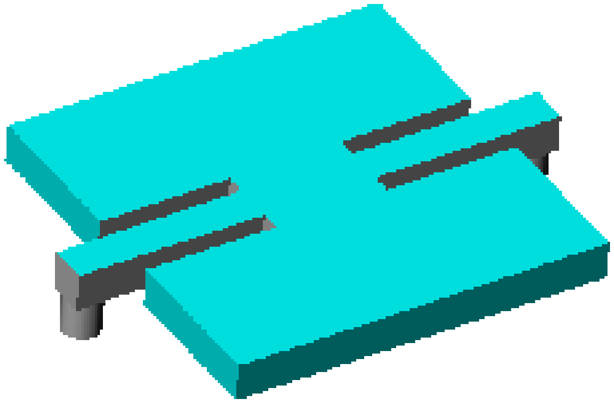
Scaling Down Mirrors: SLM's for lithographic imaging

- Tilt Mirrors
  - As mirror size is reduced, torsion arms must scale as well
  - Torque required to twist tilt mirror increases
  - Twist axis must remain on x or y axis
- Piston Mirrors
  - Bending structure can be oriented at any angle – can be longer than mirror dimensions







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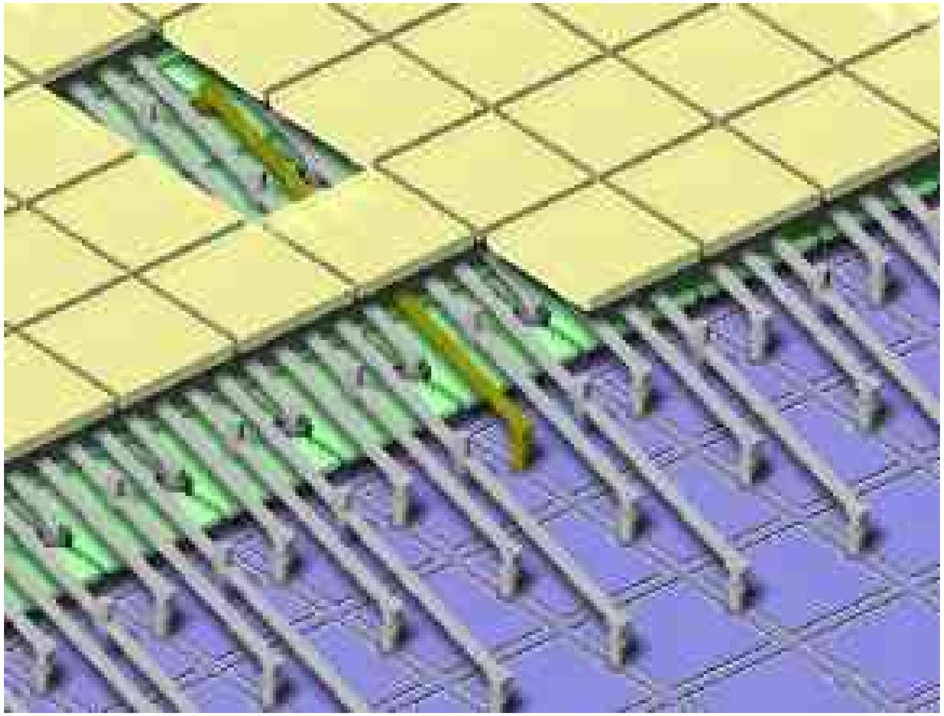
Maskless Lithography



Partial cut-away view of the MEMS piston pixel array

Acknowledgements:

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