Resolution-enhanced Technology (RET)

Resolution Enhanced Technology (RET)

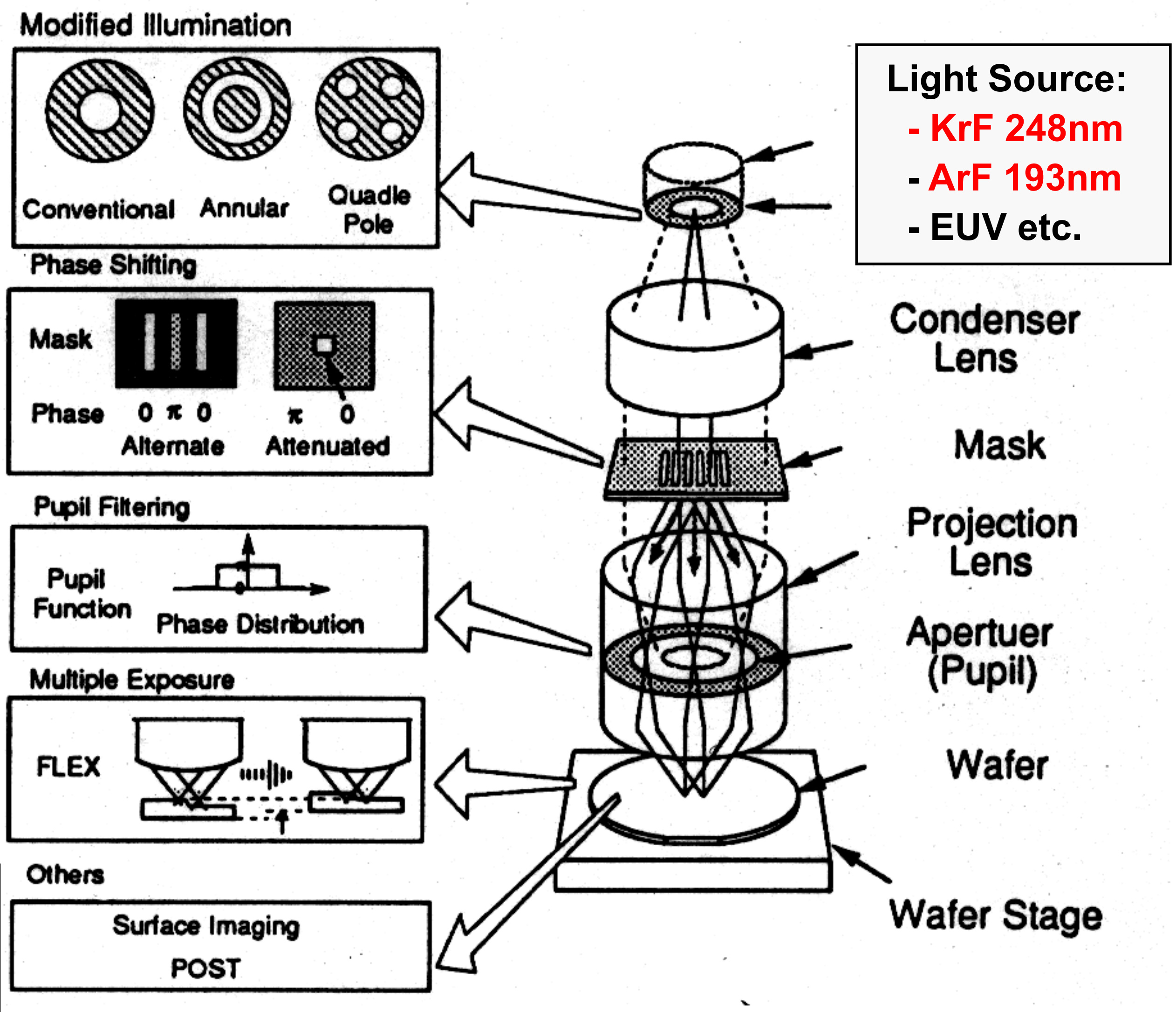
- Off-Axis Illumination (OAI)

- Phase shift mask (PSM)
- Optical proximity correction (OPC)

- Pupil filtering

- Immersion
- Multiple exposure
- FLEX

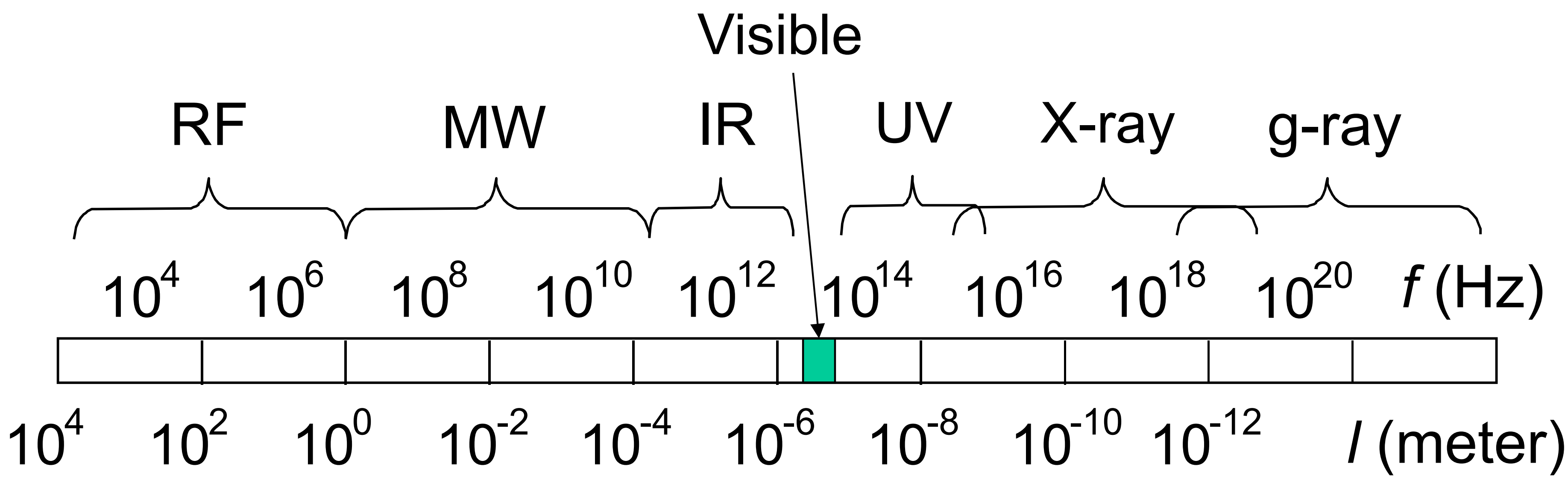
- Advanced resist process
- Anti-reflection coating
- Multi-patterning



Light Source

- Mercury I-line, 365 nm
  - Commonly used in 0.7~0.35 μm lithography
- DUV KrF excimer laser, 248 nm
  - 0.25 μm, 0.18 μm and 0.13 μm lithography
- ArF excimer laser,193 nm
  - Applications: 90 nm ~ 14 nm (immersion + double patterning)
- F_2 excimer laser 157 nm
  - Unlikely used
- EUV 13.5 nm
  - Laser produced plasma (LPP) or discharge produced plasma (DPP) source
  - Sub-7 nm nodes
- BEUV 6.5 nm
  - Beyond EUV

Electromagnetic Wave Spectrum

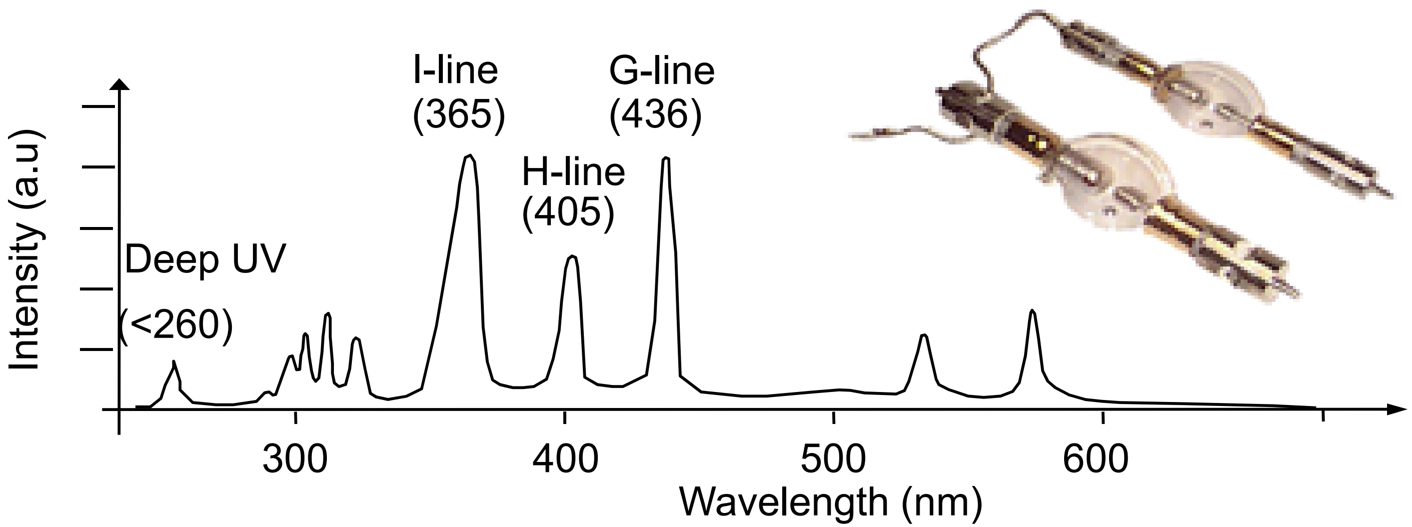


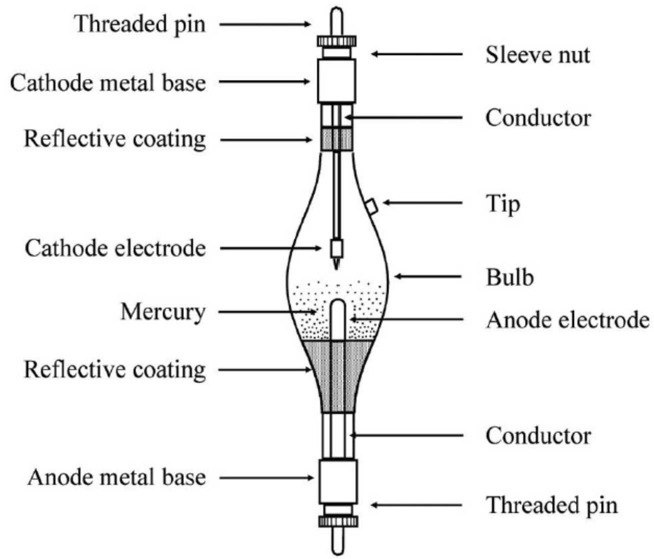
RF: Radio frequency; MW: Microwave; IR: infrared; and UV: ultraviolet

Hard x-ray: 0.01 ~ 1 nm; Soft X-ray: 1~25 nm; **EUV:10~100 nm**; **Deep UV: 100~300 nm**

Arc Lamps

- High pressure (20~40 atm).
- Filled with mercury (Hg) or a mercury-xenon (Hg-Xe) mixture.
- Distribution of the emitted spectrum depends on the partial pressures of Hg and Xe.
  - For a high-pressure Hg lamp, the minimum emitted wavelength of significant intensity is about 300 nm.
  - By adding Xe to the Hg gas, the limit can be reduced to about 240 nm.

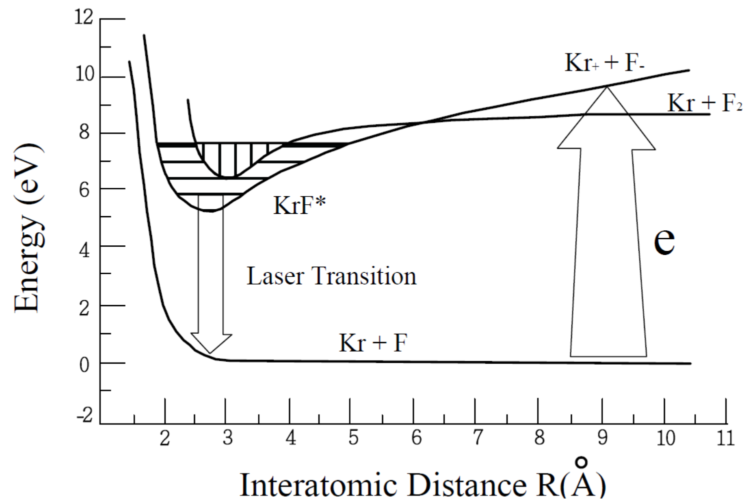




Excimer Lasers

- Excimer means "excited dimer".
  - Rare gas halides, e.g., KrF, XeF, XeCl, ArF.
- For KrF laser

$F_2 + e^- \rightarrow F^- + F$	Negative fluorine production
$Kr + e^- \rightarrow Kr^* + e^-$ $Kr^* + e^- \rightarrow Kr^+ + 2e^-$	Two-step positive krypton production
$Kr^+ + F^- + Ne \rightarrow KrF^* + Ne$	Excimer formation
$KrF^* \rightarrow Kr + F + h\nu$	Spontaneous emission
$KrF^* + h\nu \rightarrow Kr + F + 2h\nu$	Stimulated emission
$F + F + Ne \rightarrow F_2 + Ne$	Recombination



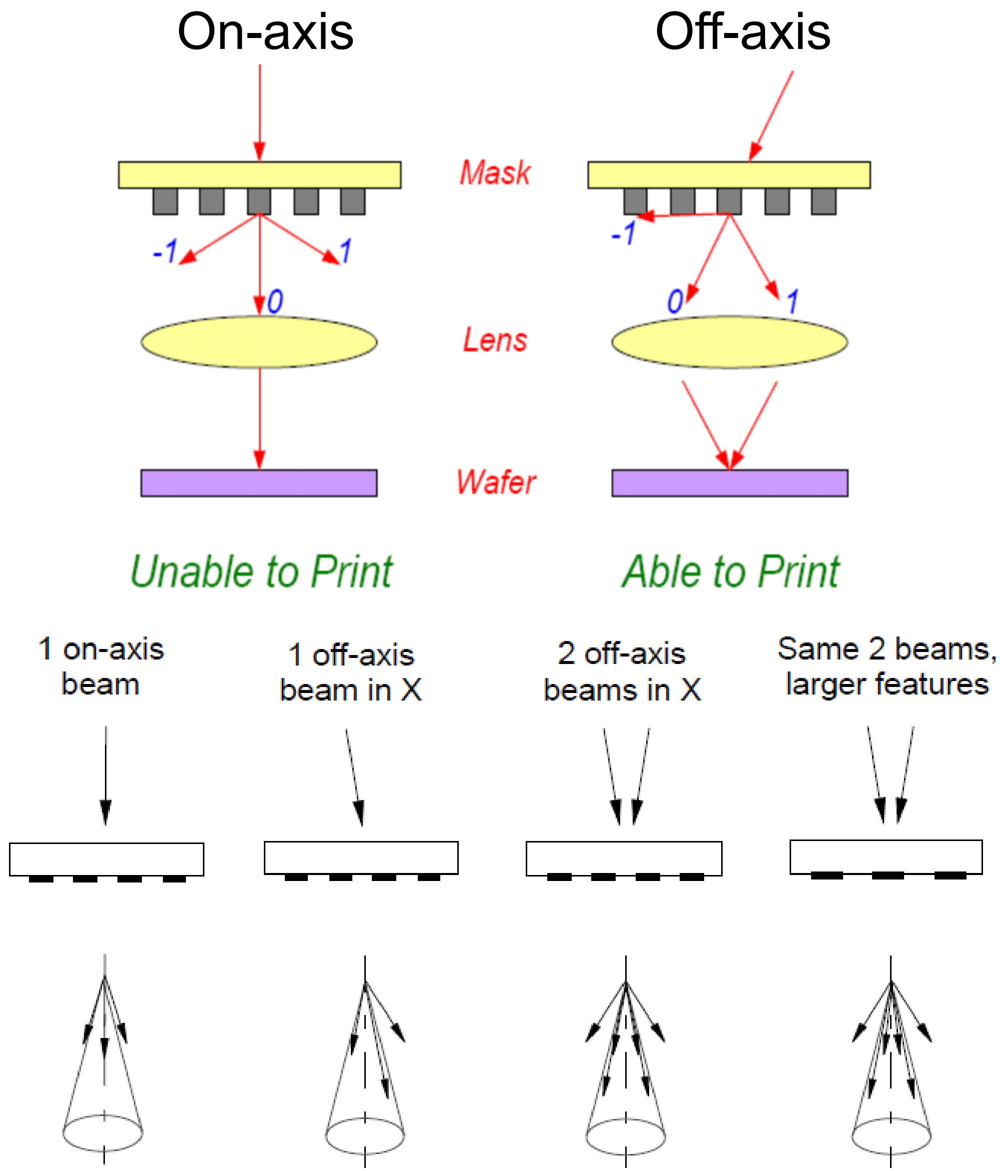
- Wavelength: XeF = 351 nm, XeCl = 309 nm, KrF = 248 nm, ArF = 193 nm.
- Excimer laser has also been employed for re-crystallization of amorphous semiconductors and junction annealing.

Advantages of Excimer Laser

- High power output.
- Spatial incoherence (results in no speckle).
- Make the task of developing suitable PR materials simpler.
- Narrow spectral line width (~ pm).
- The most powerful among all UV laser sources.
- Supplier: Cymer, Gigaphoton.

Off-axis Illumination

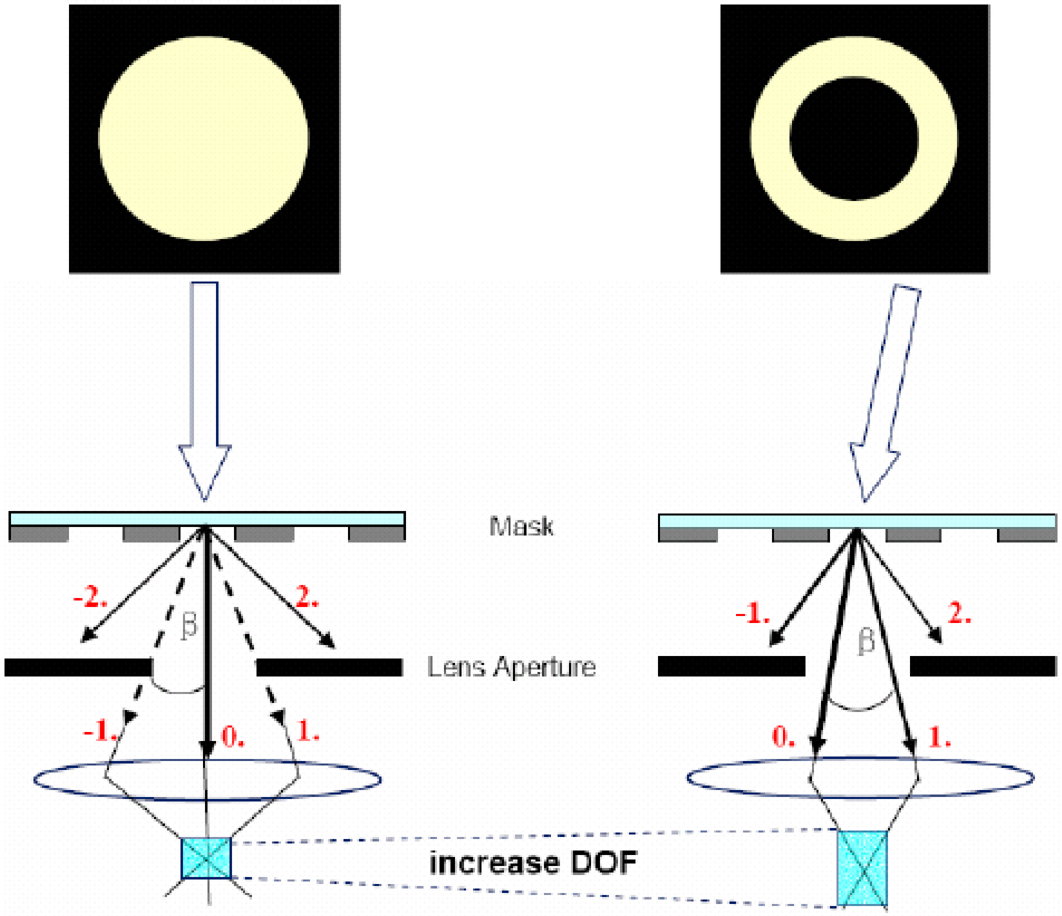
- Capture some of higher order diffracted light which would be lost through normally incident radiation.
- Resolution can be somewhat improved.
- Idea is similar to the use of partially coherent illumination.
- Techniques include
  - Ring illumination
  - Quasa and quadruple illuminations
  - Dipole illumination

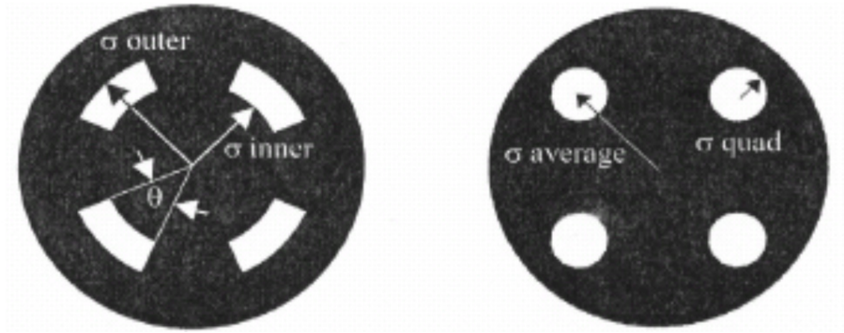


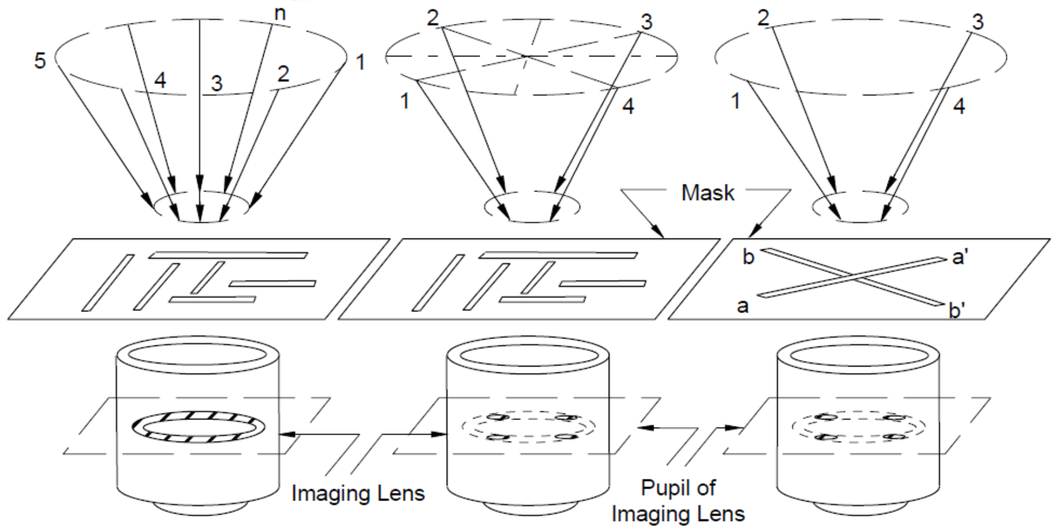
Types of OAI

- DOF can also be increased.

Conventional | Annular (Ring) | Quasar | Quadruple







(a) Ring Illumination: Each line orientation sees a mixture of off-axis and on-axis illuminations

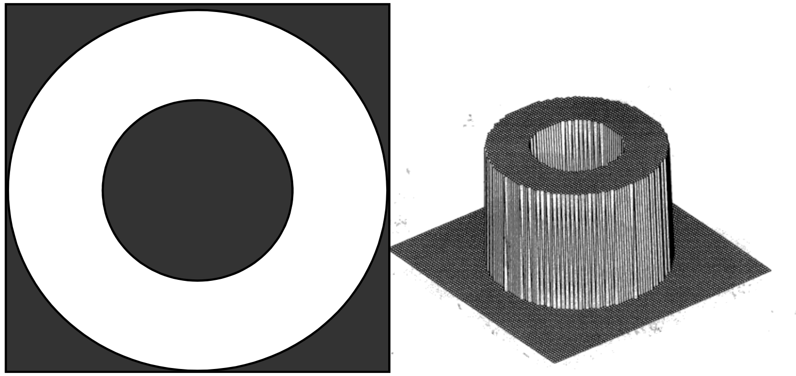
(b) Quadrapole Illumination: All beams are off-axis to all vertical and horizontal lines

(c) Quadrapole Illumination: Beams 2, 4 off-axis to aa' but on-axis to bb'

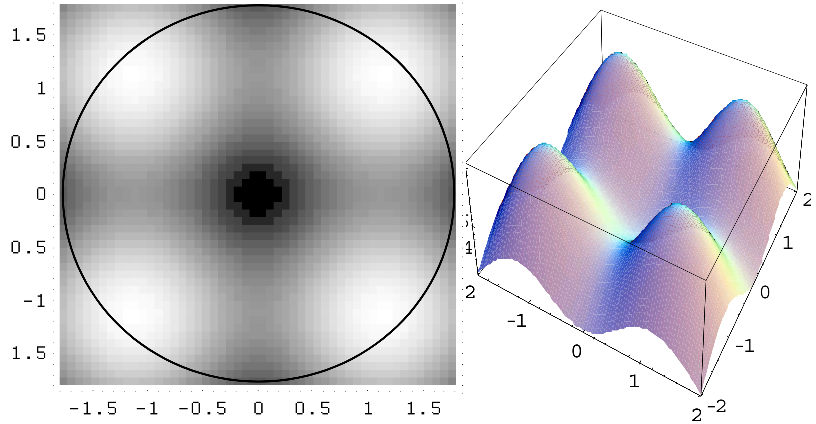
Aggressive OAI

-Customized Illumination Filter

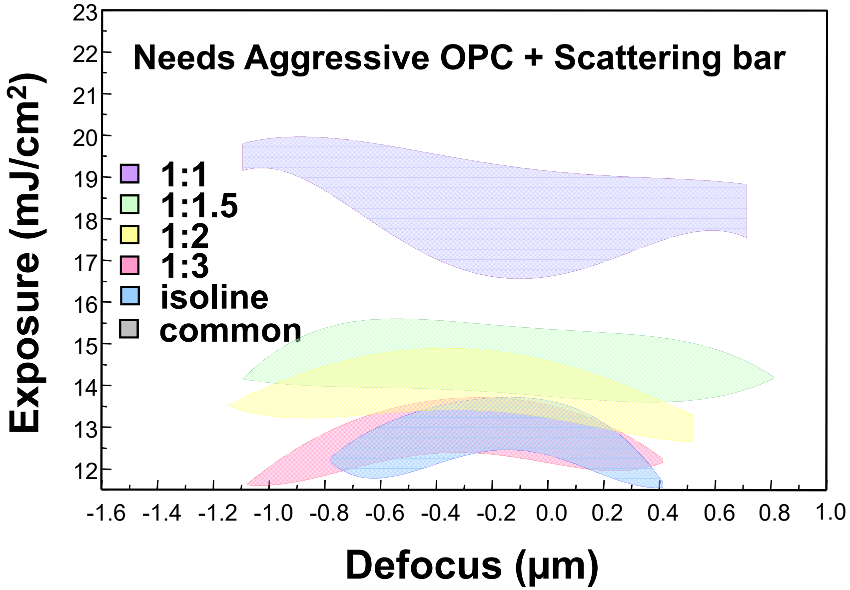
Ring Illumination



Customized Illumination Filter

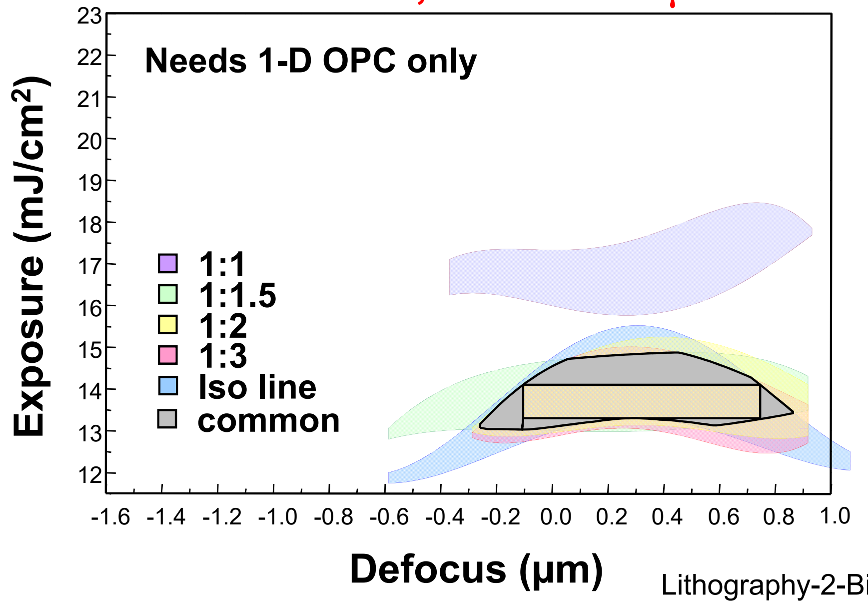


No common window



Common window

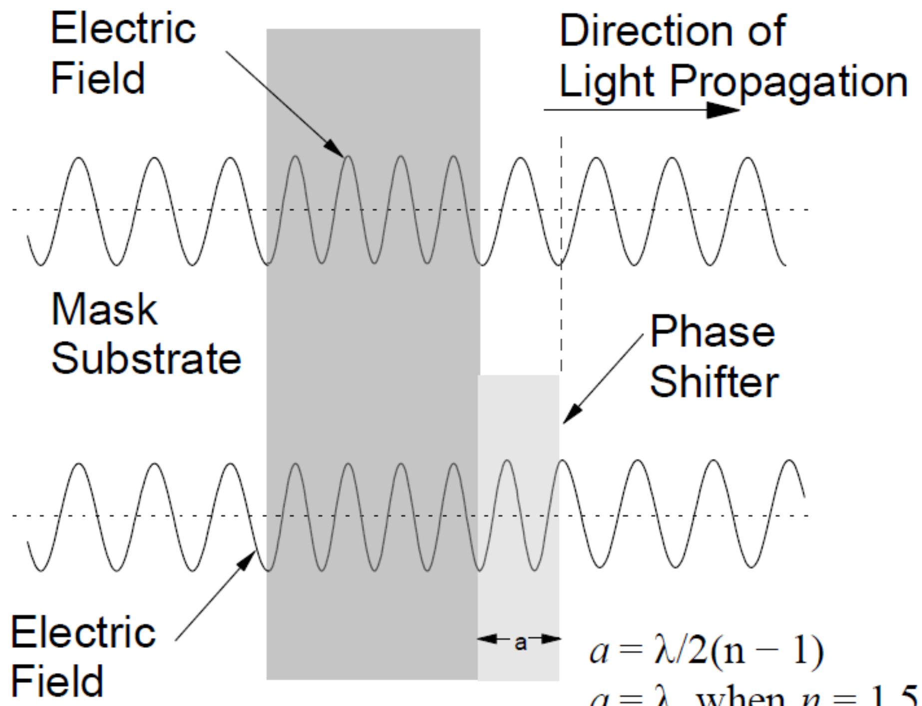
E.L.=6.0%, DOF=0.86 μm



Phase-shifting Mask (PSM)

- A mask that contains phase-shifting areas with or without energy-absorbing areas.
  - PSMs take advantage of the interference effect in a coherent or partially coherent imaging system to reduce the spatial frequency of a given object and/or to enhance its edge contrast, resulting in a combination of higher resolution, larger exposure latitude, and DOF.
  - The shifting of phase is accomplished by adding an extra patterned layer of transmissive material on the mask.

$$\theta = 2\pi \frac{a}{\lambda}(n-1)$$



$a = \lambda/2(n-1)$

$a = \lambda$, when $n = 1.5$

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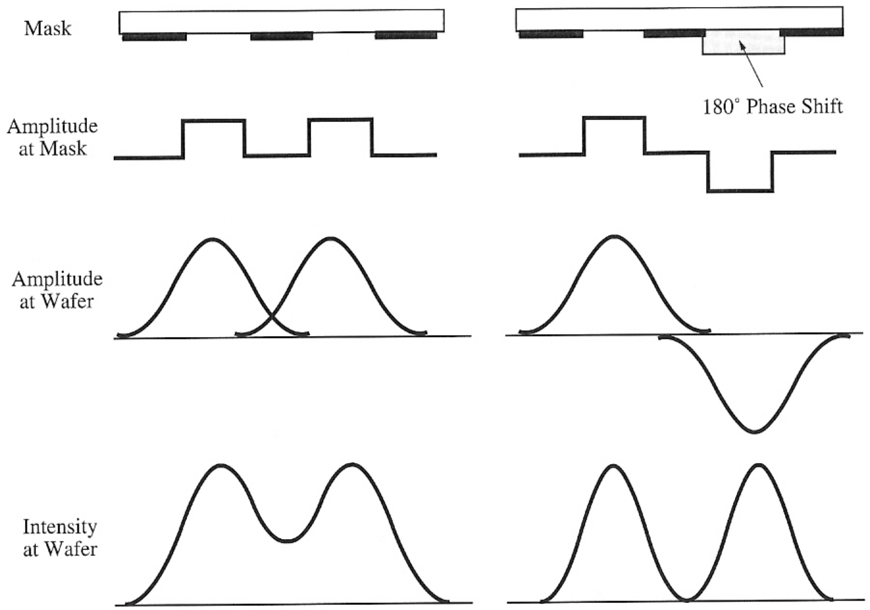
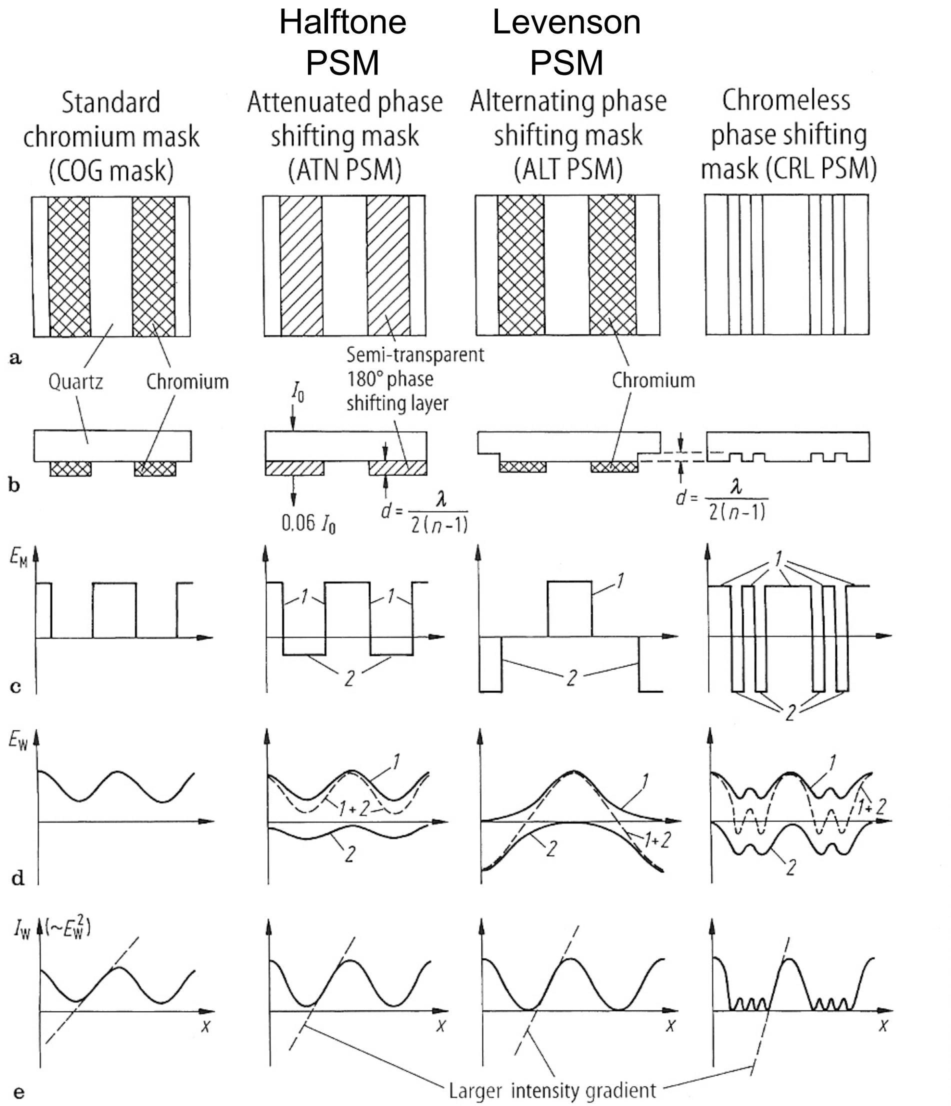
Phase Shift Masks

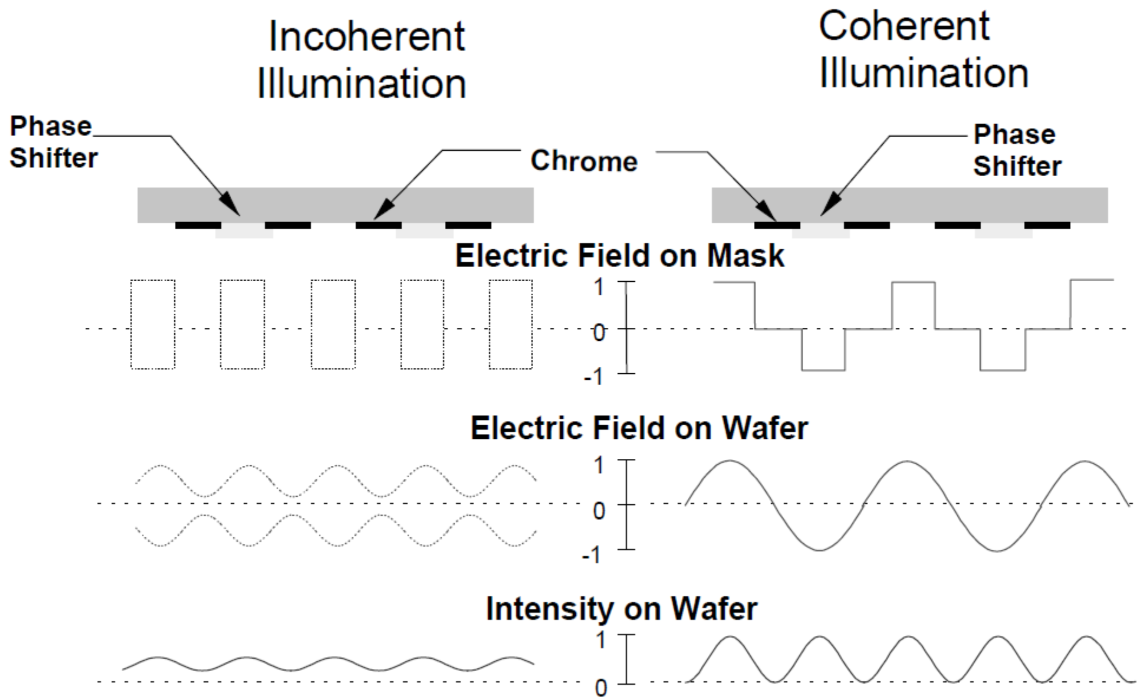
- Proposed by Levenson in IEEE T-ED, p.1828,1982.
  - Light intensity ~ (E-field)^2.
  - MTF at PR plane increases with PSM, thus resolution can be improved.





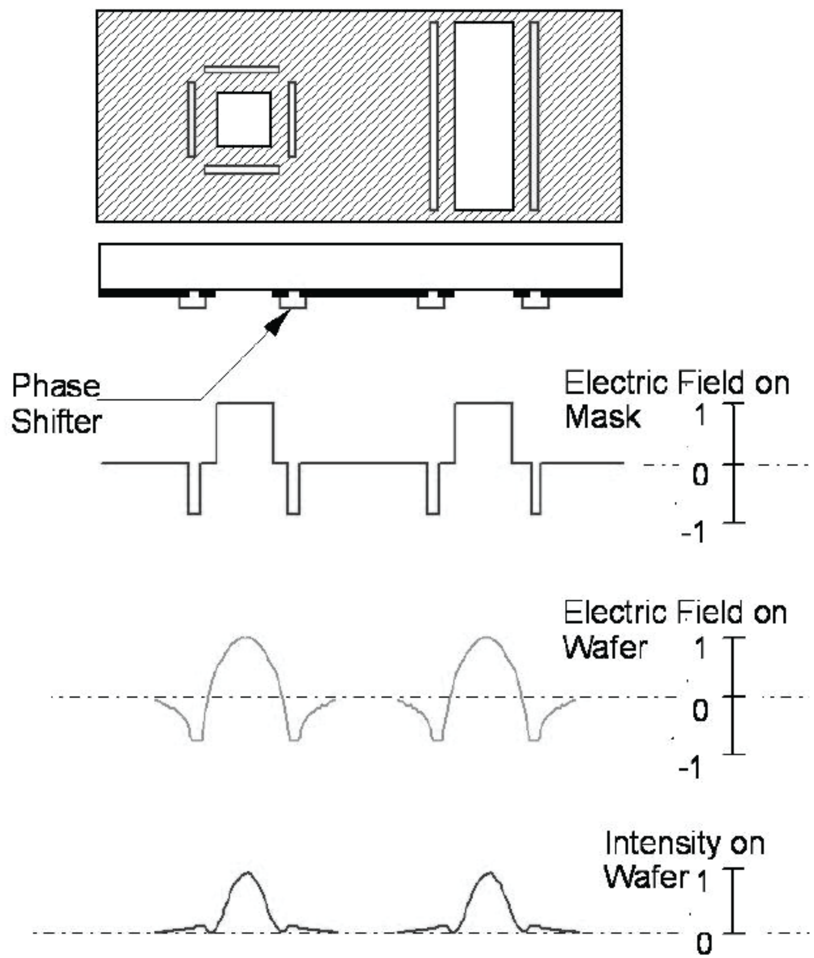
Alternating Phase-shifting Mask (AltPSM)

- AltPSM (Levenson PSM)
  - AltPSM requires closely packed patterns to be effective.
  - With incoherent illumination the electric field fluctuates randomly in phase, and the spatial frequency doubling effect is not possible.
  - If coherence is lost, an AltPSM just becomes binary image mask (BIM).



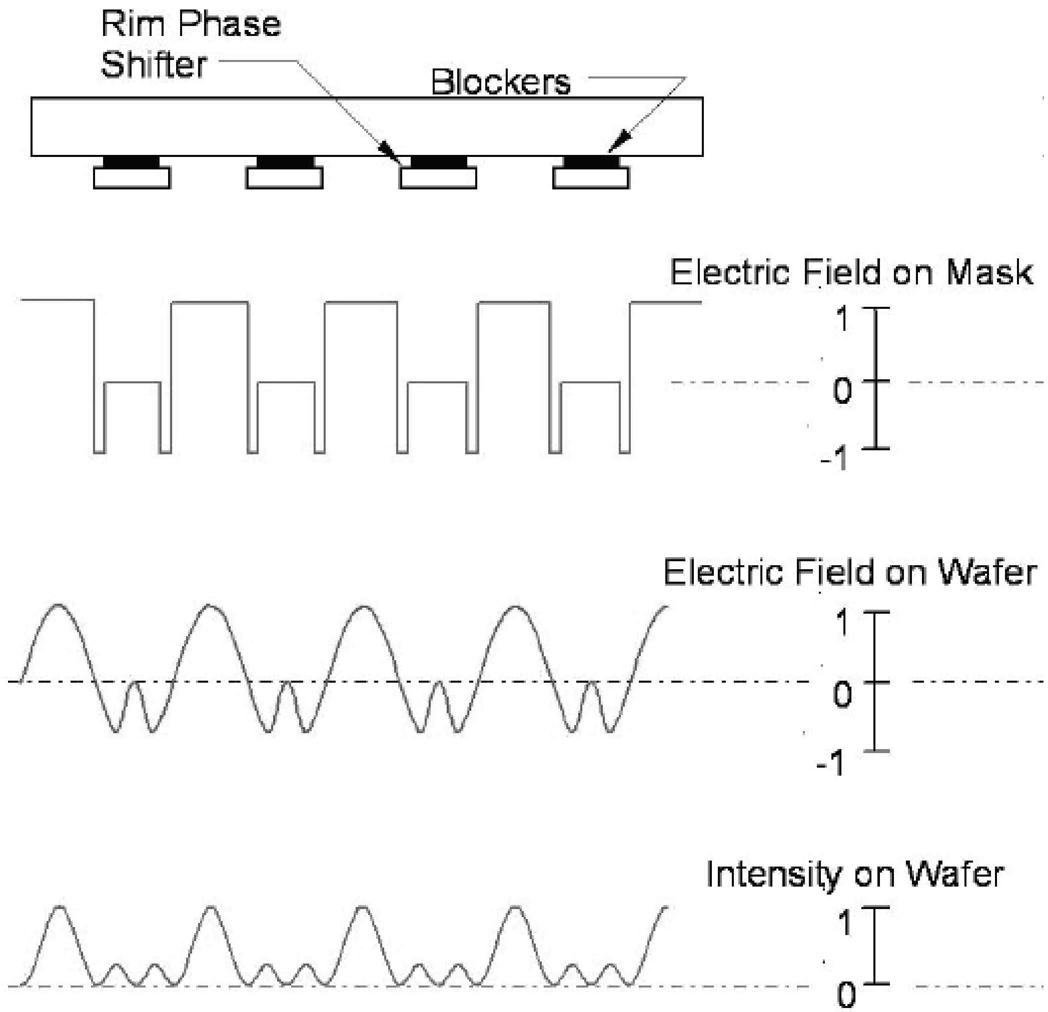
Subresolution-assisted Phase Shifting Mask (SA PSM)

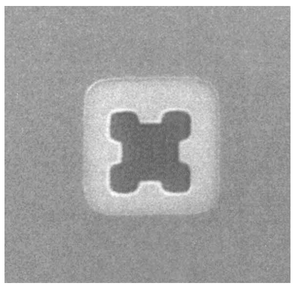
- SA PSM
  - In order to provide phase shifting for isolated openings, such as contact holes and line openings, another form of BIM uses sub-resolution phase shifters near isolated openings.
  - These phase shifters are smaller than the resolution limit of the optical imaging system; thus, they cannot be printed. Their sole function is to enhance the edge contrast of the pattern of interest.

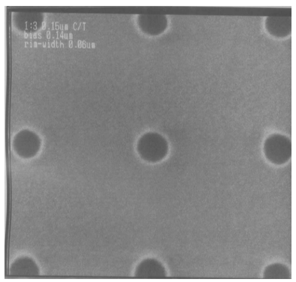


Rim Phase Shifting Mask (Rim PSM)

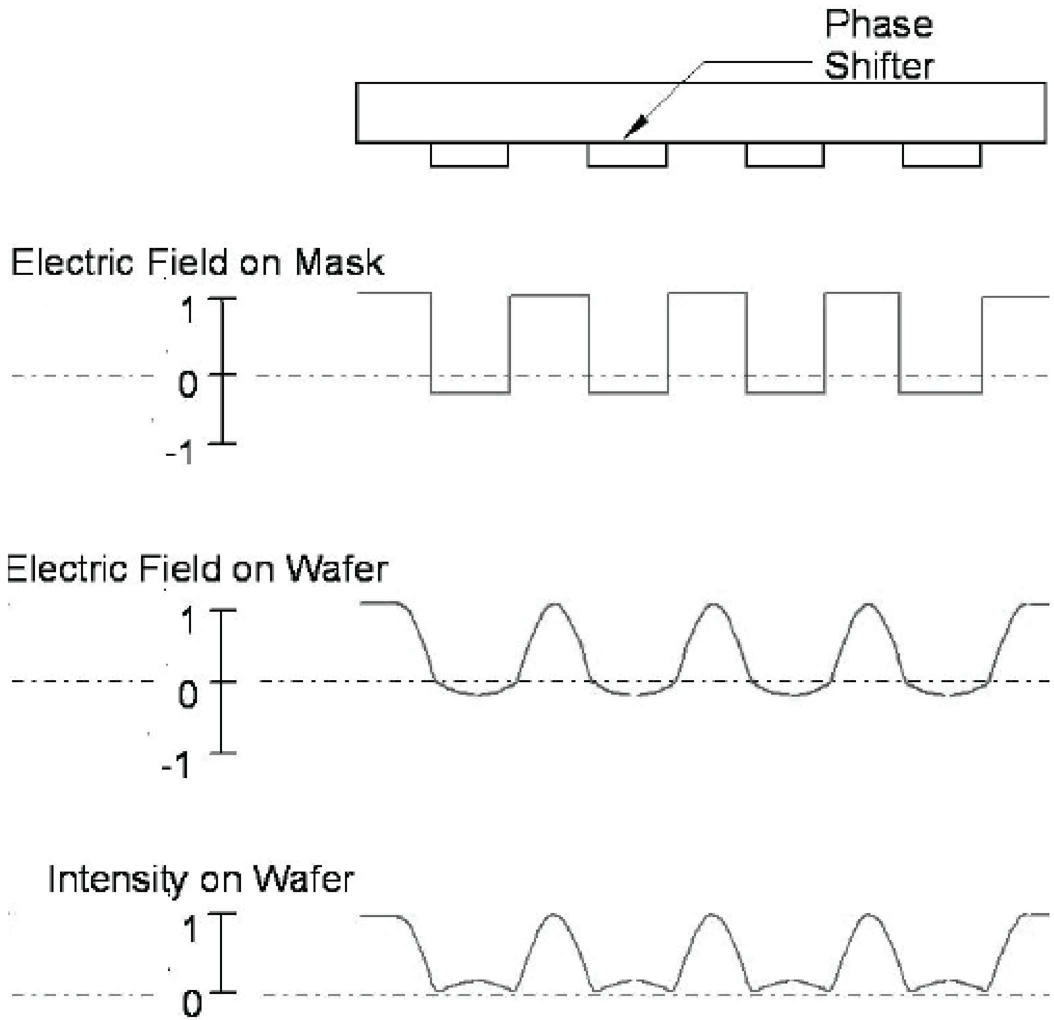
- Rim PSM
  - SA PSM and AltPSM are still limited by their inability to provide phase shift to opaque patterns.
  - Phase shifting only takes place at the rim of the mask patterns. The center of the patterns is blocked by the absorber to prevent large areas of negative amplitude from producing bright areas where they are supposed to be dark.







Attenuated Phase-shifting Mask (AttPSM)



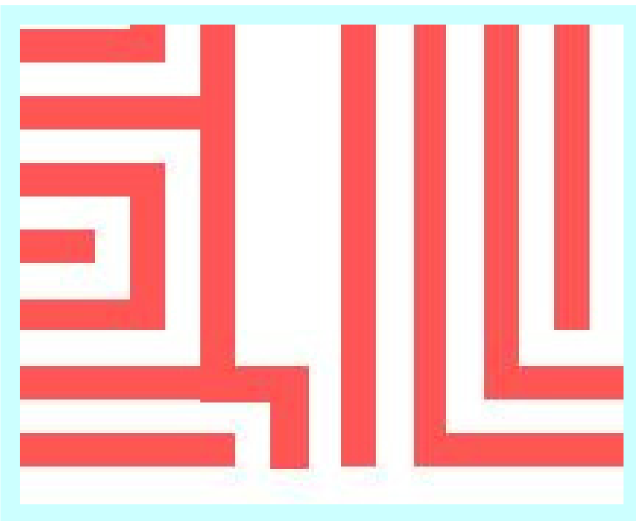
AttPSM (Halftone PSM)

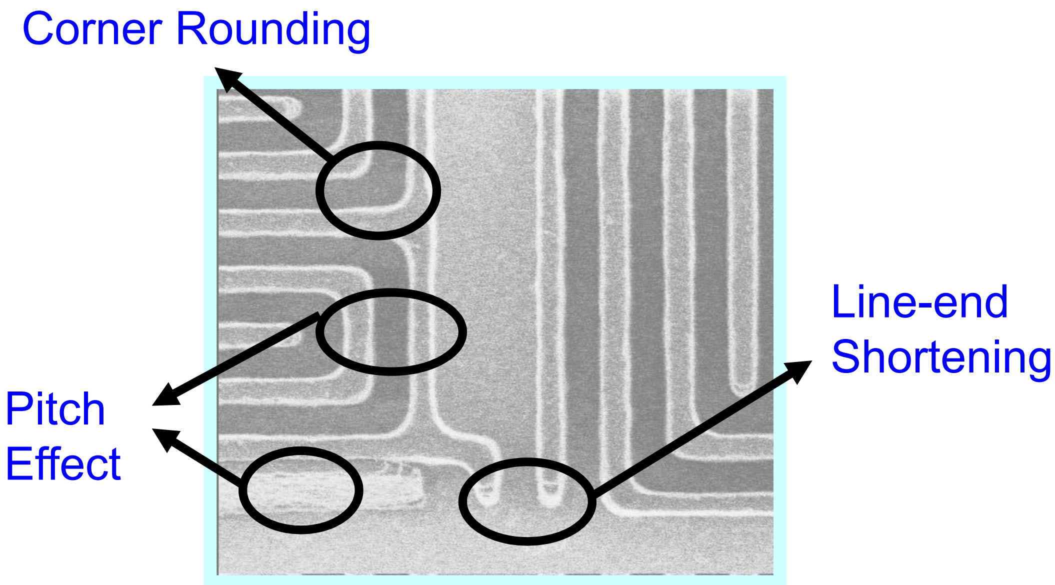
- The AttPSM applies to arbitrary mask layouts. The dark areas of the mask can be phase shifted to π but with an attenuated amplitude to prevent producing too much light in these areas.
- Regular absorbers often must be included at the borders of the mask plate to block off light at the boundary of the exposure field and to provide regular reticle alignment marks.

Optical Proximity Effect (OPE)

➢ What is Optical Proximity Effect ?

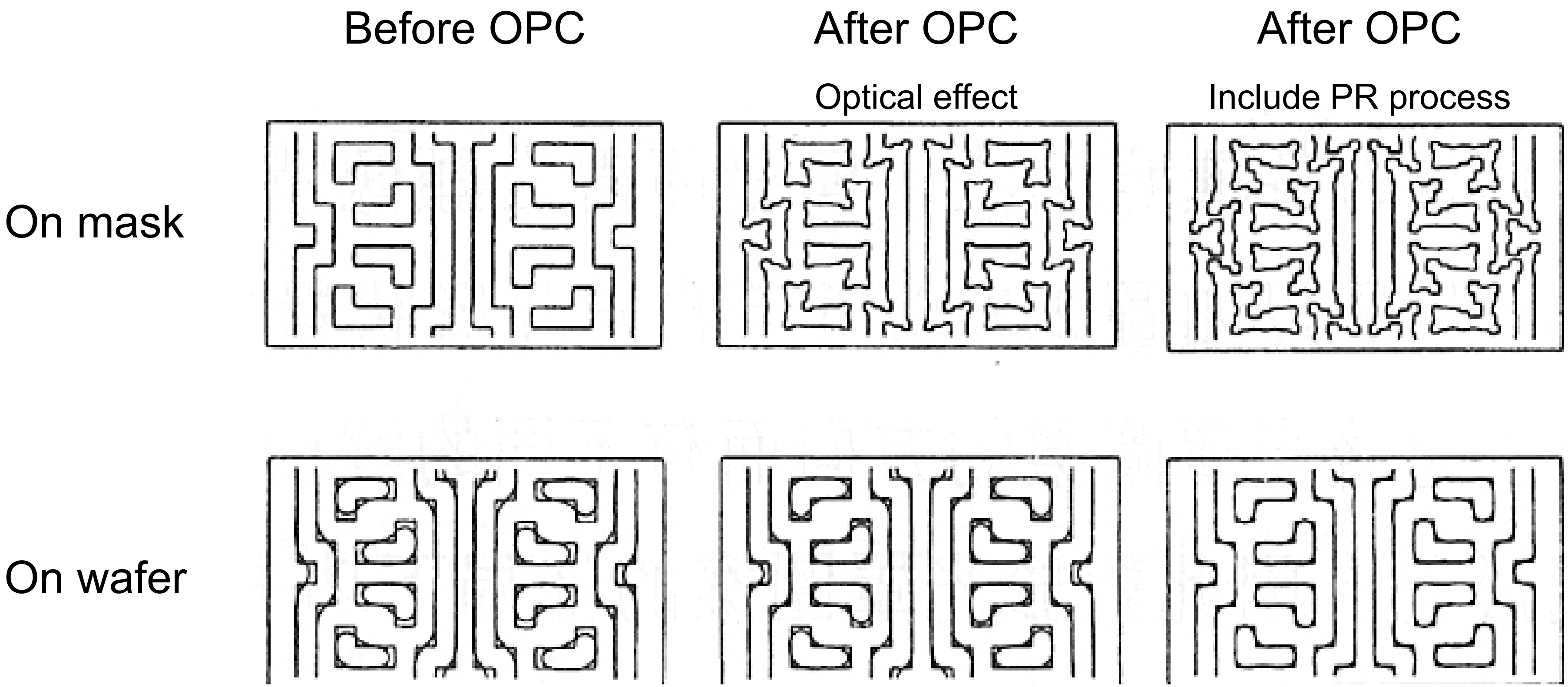
- Feature distortion (edges of printed or etched features do not conform to those of the designed patterns) incurred in the pattern transfer process.
- Manifest itself as line-width bias, line-end shortening, corner rounding, etc.
- Mainly caused by loss of high spatial frequency components in imaging. Non-uniformity in the etch process also contribute to OPE.





Optical Proximity Correction (OPC) - 1

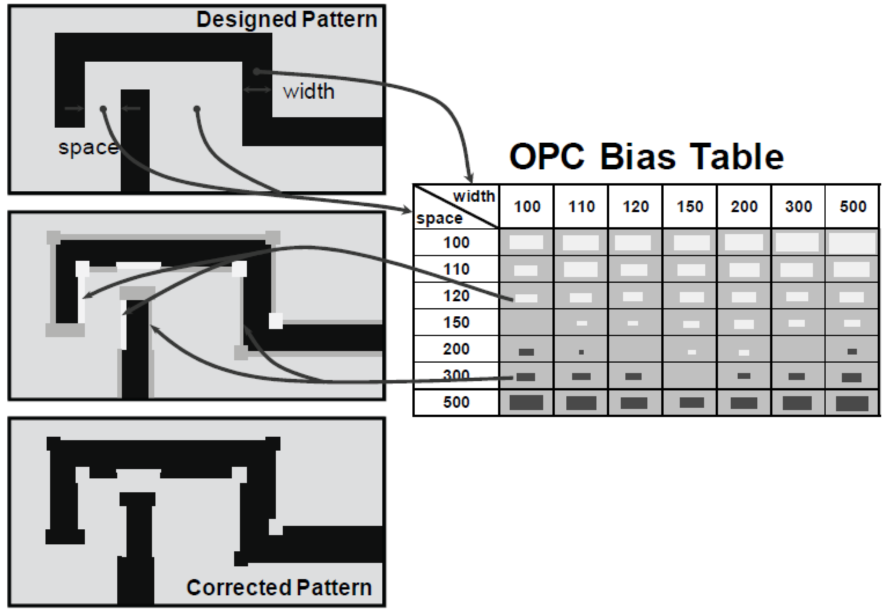
- How to Minimize OPE ?
  - Pre-distort the patterns on the mask to minimize OPE.



Optical Proximity Correction (OPC) - 2

➢ Rule-based correction

- Correction according to correction rules
  - Manual correction by designer
  - Automatic correction using DRC like software
  - Automatic correction using rule-based OPC software
- Bias lines, add/subtract serifs, and add hammer-head according to the rule table determined experimentally or by experimentally calibrated simulation.



➢ Advantages

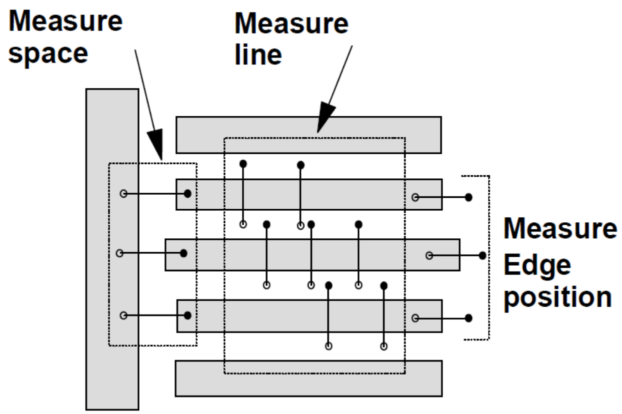
- Simple rules are applied to all features. Fast correction approach !

➢ Disadvantages

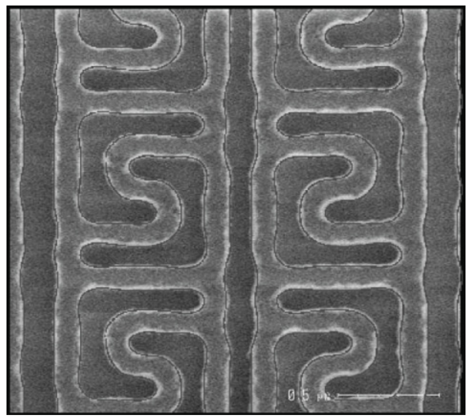
- Various test patterns must be designed, fabricated, and measured.
- Correction can not be optimized for all features.

Optical Proximity Correction (OPC) - 3

- Model based (simulation based) correction
  - Simulation of image using original mask -> comparison of the image to original layout -> correction -> simulation using corrected mask
  - Automatic correction using model based OPC software
  - Edges in resist are segmented and determined by a model for the pattern transfer process. Iterative calculations are carried out in real time to minimize the difference between these edges and the desired ones.
- Advantage
  - Precise correction for all features.
- Disadvantage
  - It is very time consuming !
  - Expansion of data volume.
  - Difficult in mask-making and inspection.



OPC Test Site

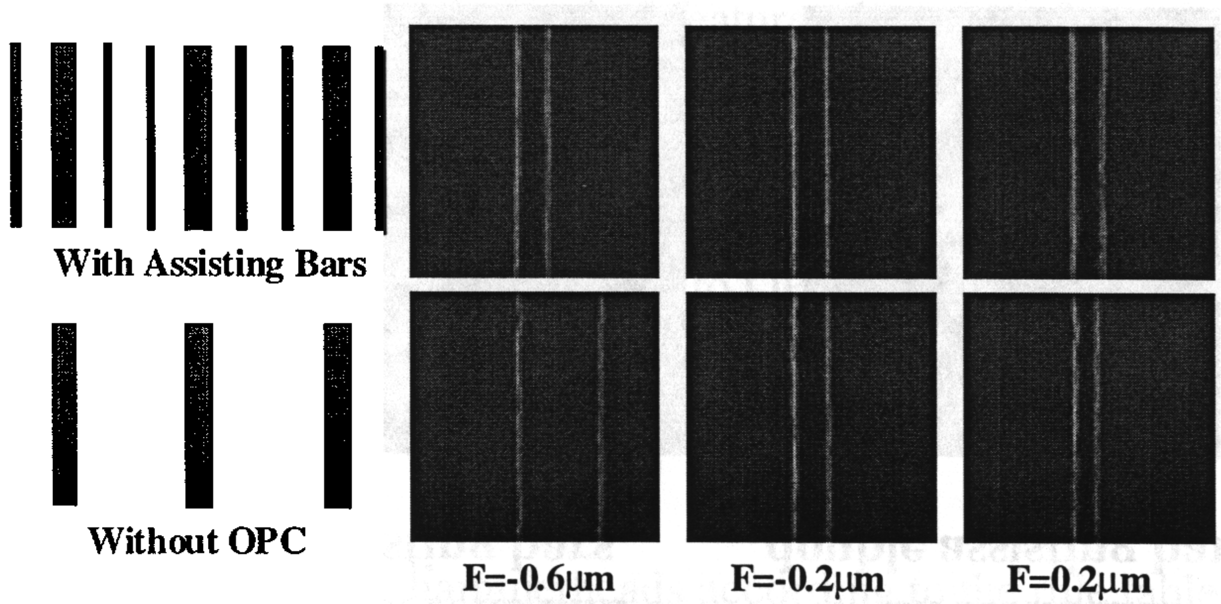


Model-generated edge contour superimposed on the resist image

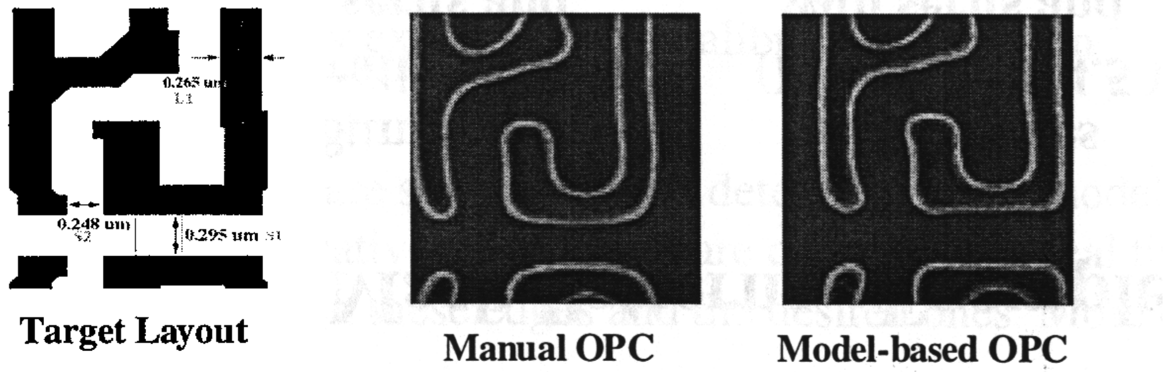
Optical Proximity Correction (OPC) - 4

- OPC strategy ?

Rule-based OPC (with assisting bars) applied to random logic



Model-based OPC applied to memory circuits



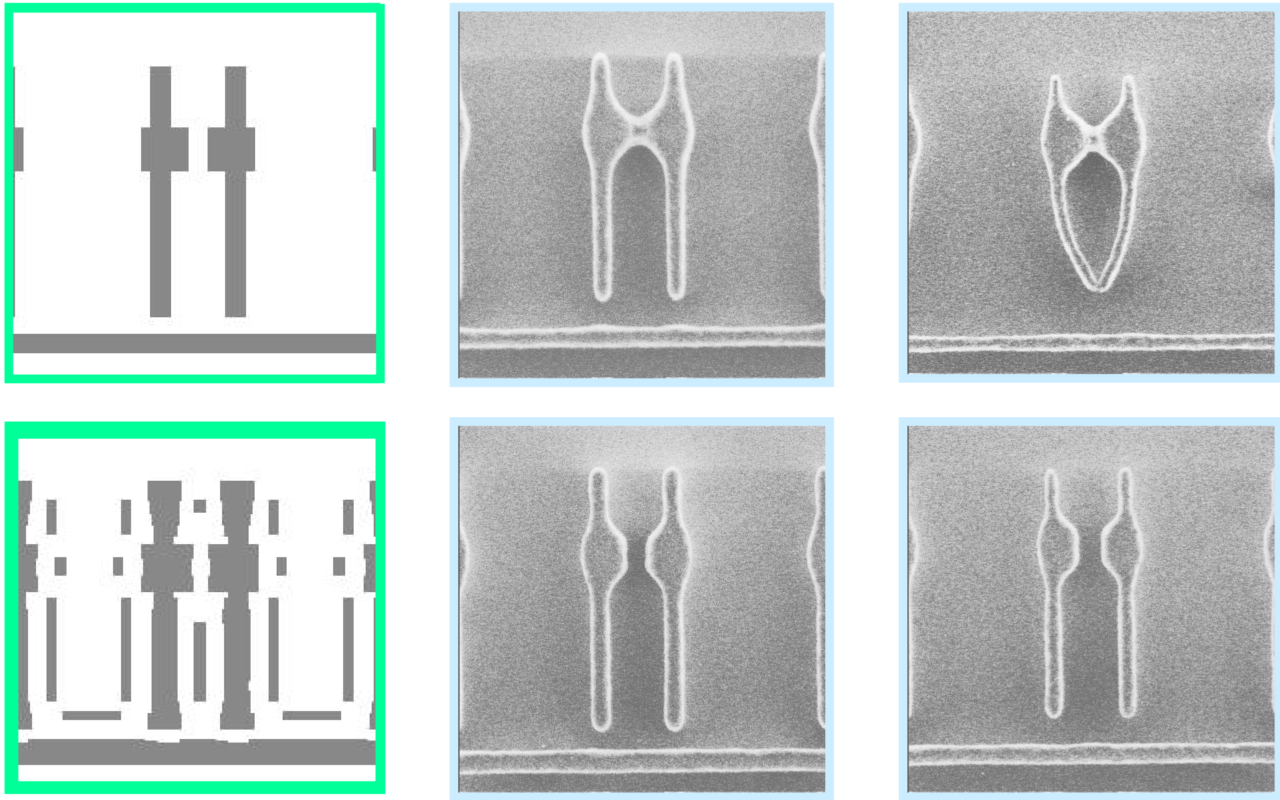
Example of OPC - 1

On Focus

Defocus

Before OPC

After OPC

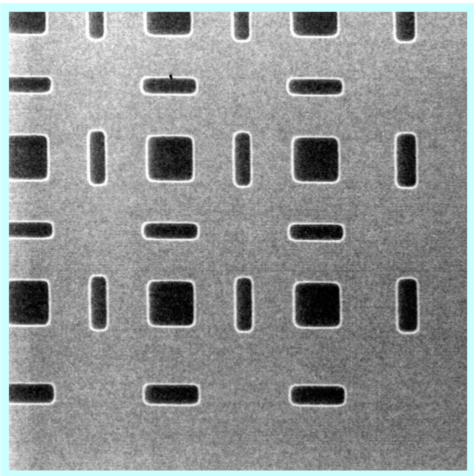


On mask

SEM pictures

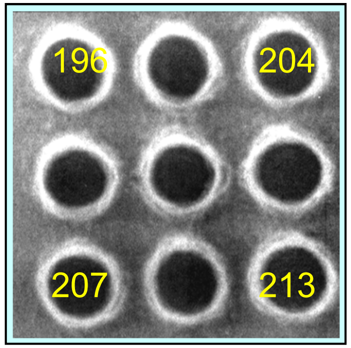
Example of OPC - 2

Mask Patterns

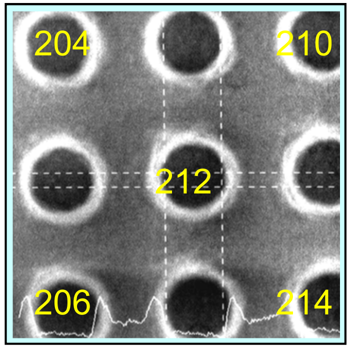


Wafer Patterns

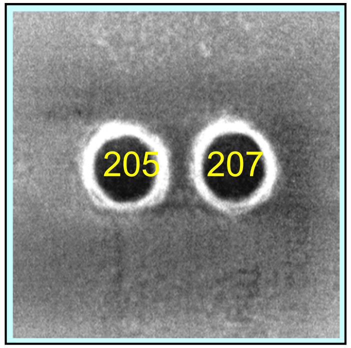
0.20 μm 1:1
3X3



0.20 μm 1:2
3X3

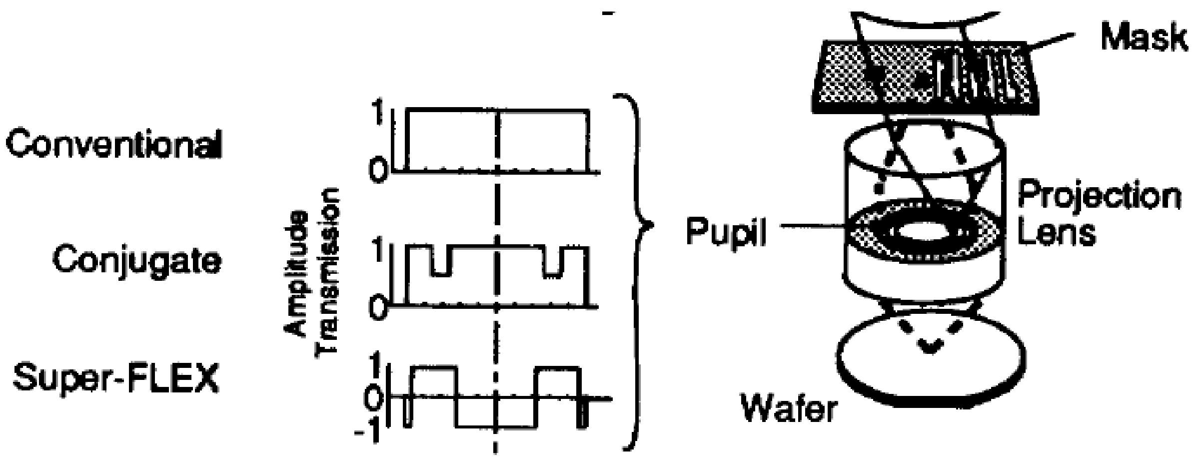


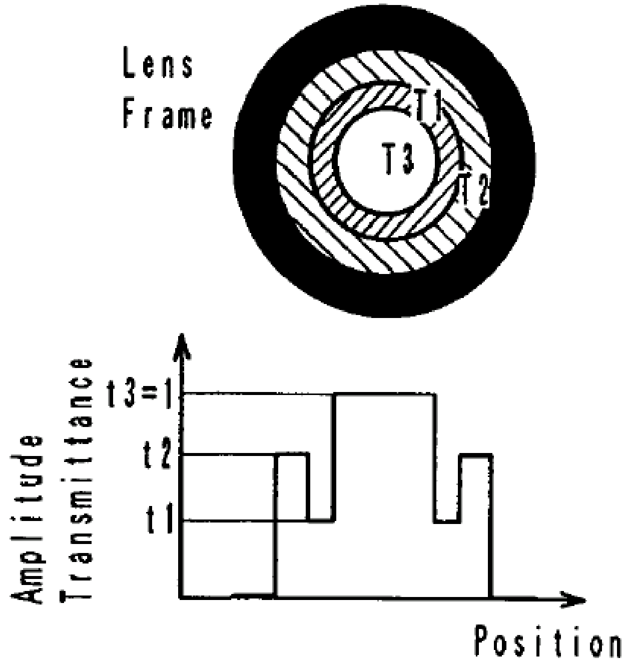
0.20 μm 1:1
2X1



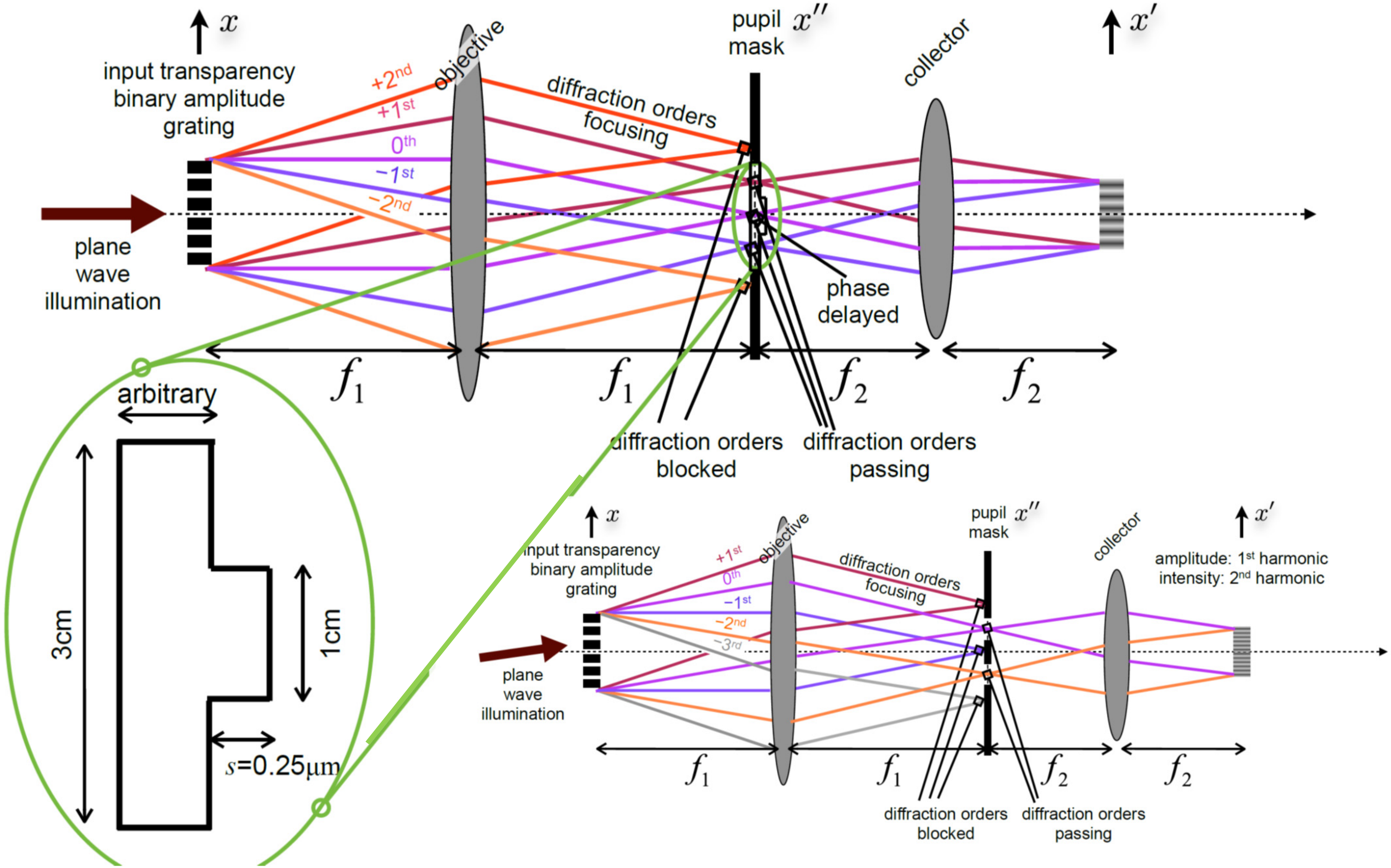
Pupil Filter

- It is not easy to apply PSM to complicated mask patterns, such as ASIC, microprocessor, etc.
- Pupil filter can be applied without PSM.



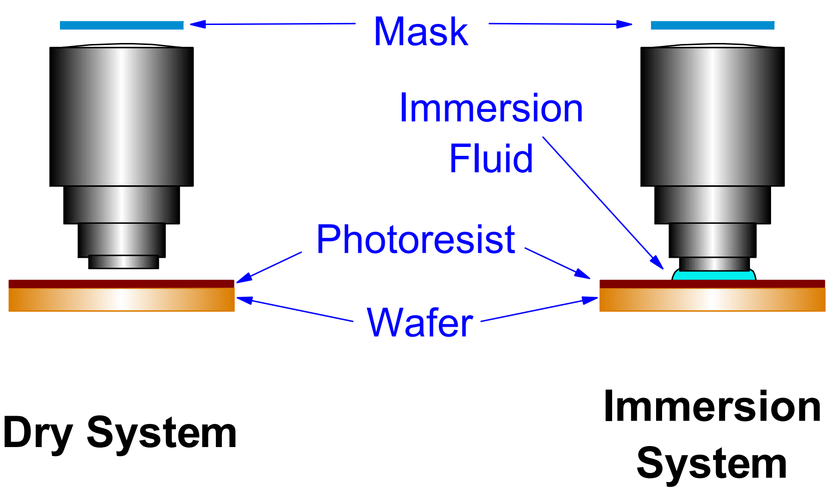


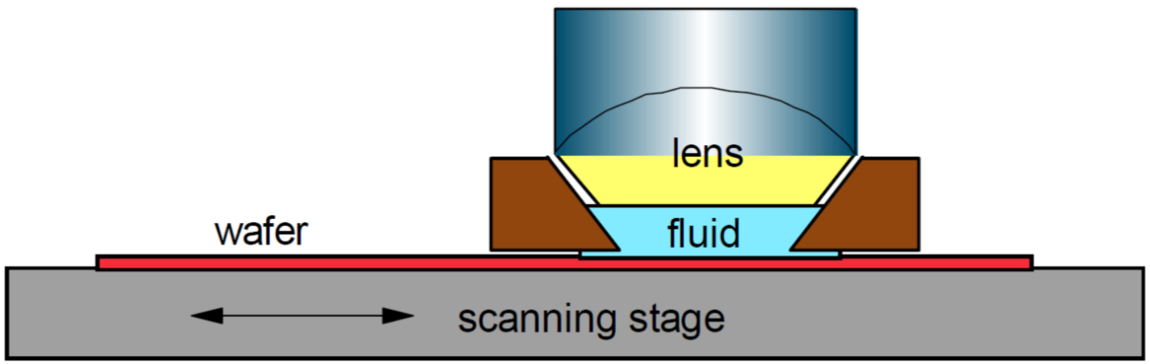
Pupil Filter



Immersion Lithography

- The water is confined to the area on the wafer immediately below the exposure head, while the rest of wafer stays dry.
- Therefore, the immersion has no conflict with the wafer alignment and the leveling sensors.





Why is Water ?

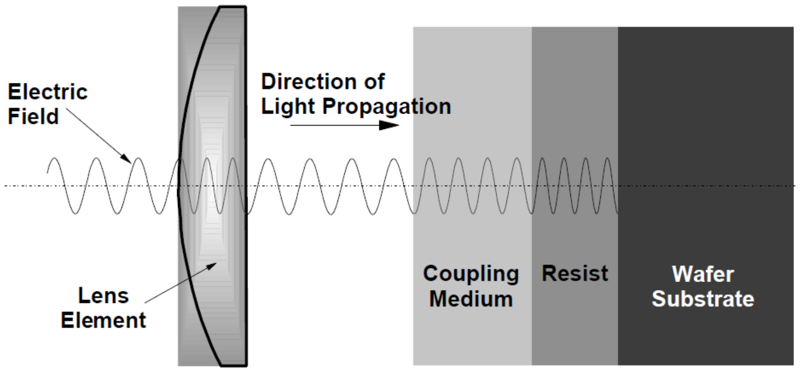
- The semiconductor industry has considerable experience in producing ultrapure water inexpensively.
- Water is nontoxic, which has implications for both worker safety and disposal costs.
- Water is compatible with resist and materials commonly used to fabricate lithography tools.
- The surface tension between water and many materials facilitates containment.
- Water is stable under exposure to 193-nm light.
- Water has sufficiently low viscosity to permit fast scanning.

Material	Index of refraction at $\lambda = 193$ nm
Water	1.44
Fused silica[21]	1.56
Calcium fluoride[21]	1.50
Aluminum oxide[22]	1.92
Lutetium aluminum garnet (LuAG)[23]	2.14

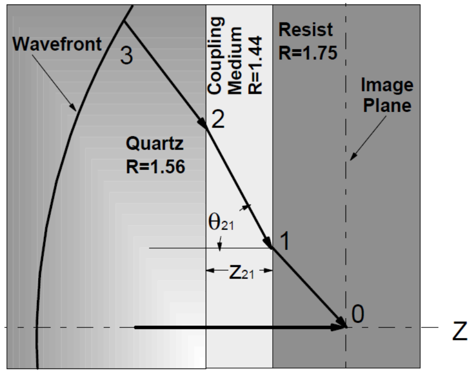
Resolution Improvement

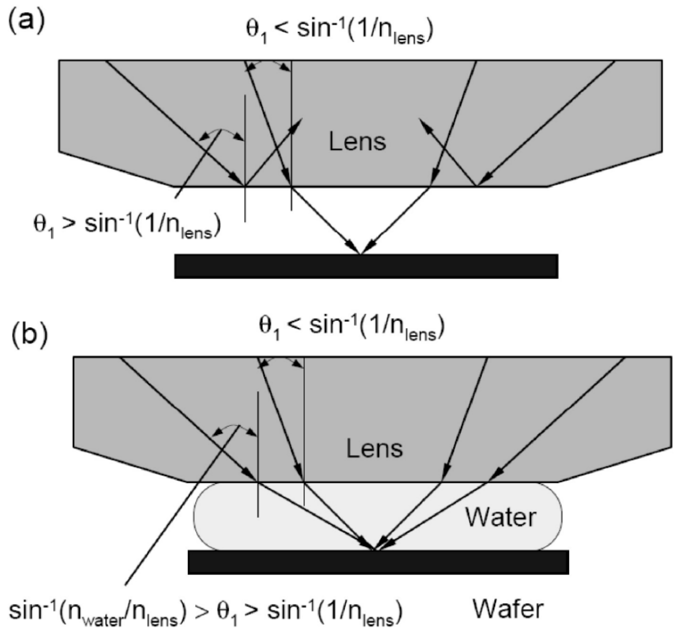
- Effective wavelength of the exposure light is reduced by the high index medium. The medium also changes the optical paths of the exposure light beams.
  - Larger spatial frequencies for higher resolutions sustain a larger θ.
  - The maximum incident angle at the lens-air interface is $\sin^{-1}(1/n_{lens})$. Beams with incident angle > $\sin^{-1}(1/n_{lens})$ are totally reflected. (40° from quartz to air)
  - With water in the gap, the maximum incident angle increases to $\sin^{-1}(n_{water}/n_{lens})$.

$$n_1\lambda_1 = n_2\lambda_2 = n_3\lambda_3$$



$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$





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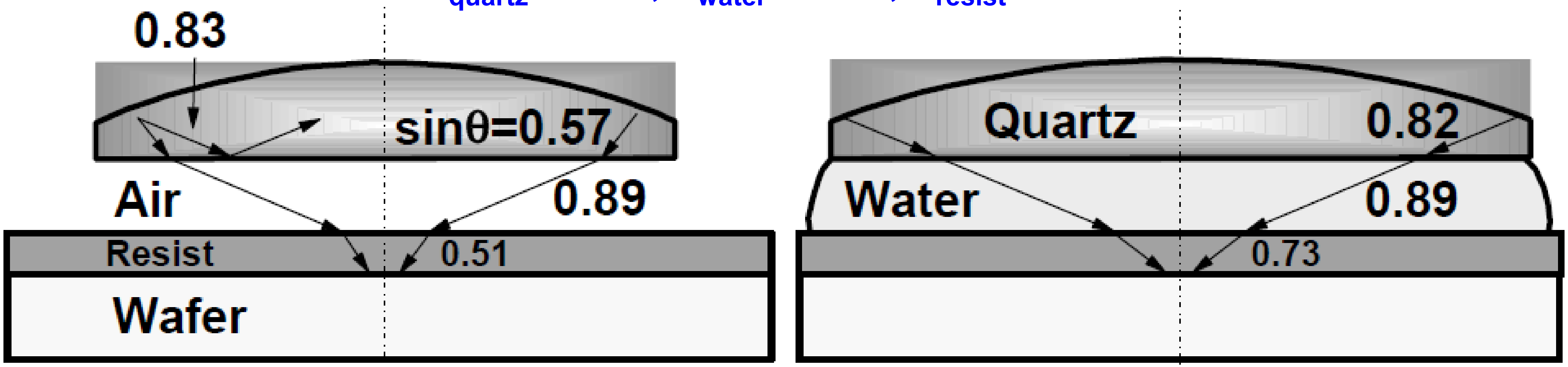
Resolution Improvement

- The higher index medium couples higher spatial frequencies to the resist.
  - Preserving the physical angle in the coupling medium to improve resolution.
  - The actual imaging performance of the immersion system is slightly worse than that of an equivalent reduced vacuum wavelength due to polarization-dependent stray light.

n_{quartz} = 1.56, n_{water} = 1.44, n_{resist} = 1.75.



DOF Improvement

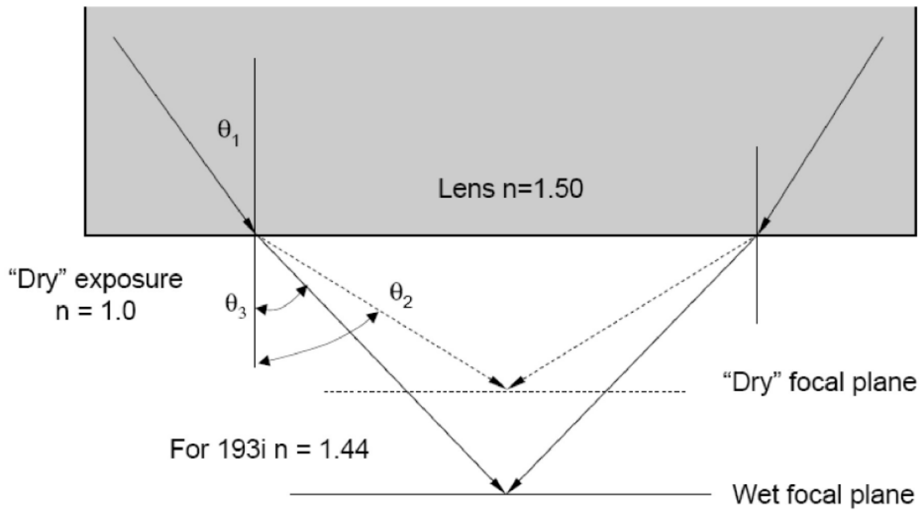
- The refractive index of water alone does not change the NA. However, the water does reduce the refractive angle, i.e., $\theta_2 > \theta_3$, significantly increasing the DOF.
- Smaller angle in the coupling medium is less sensitive to longitudinal displacement in wafer.

$$n_{lens}\sin\theta_1 = n_{air}\sin\theta_2 = n_{water}\sin\theta_3 = NA$$

$$\text{High NA: } DOF = \frac{k_3}{2}\frac{\lambda}{n - \sqrt{n^2 - NA^2}}$$

$$\text{Low NA: } DOF = k_3\frac{n\lambda}{NA^2}$$

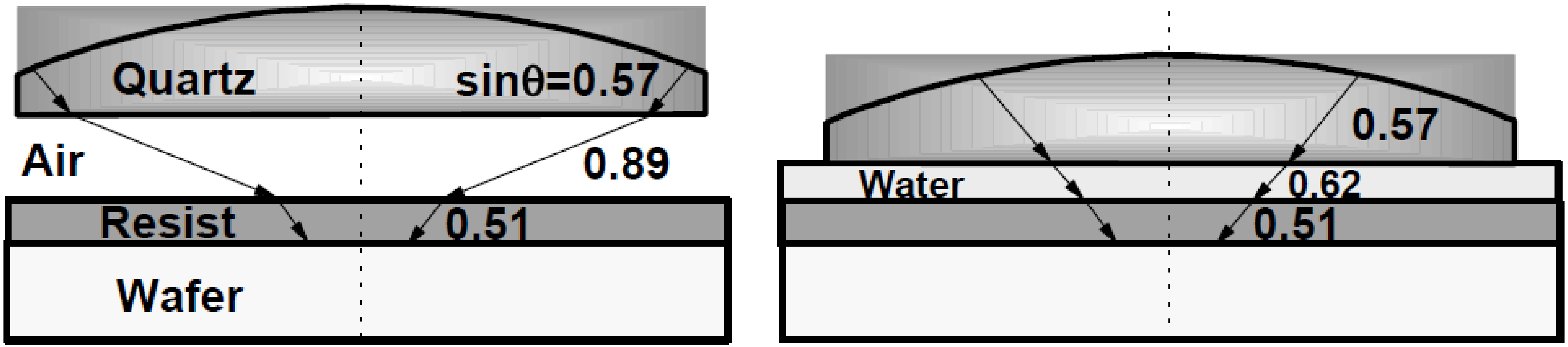
$$\frac{\text{DOF193i}}{\text{DOF dry}} = \frac{n_{air} - \sqrt{n_{air}^2 - NA^2}}{n_{water} - \sqrt{n_{water}^2 - NA^2}} = \frac{n_{air}\left[1 - \sqrt{1 - \left(NA/n_{air}\right)^2}\right]}{n_{water}\left[1 - \sqrt{1 - \left(NA/n_{water}\right)^2}\right]} \approx \frac{n_{water}}{n_{air}}$$



DOF Improvement

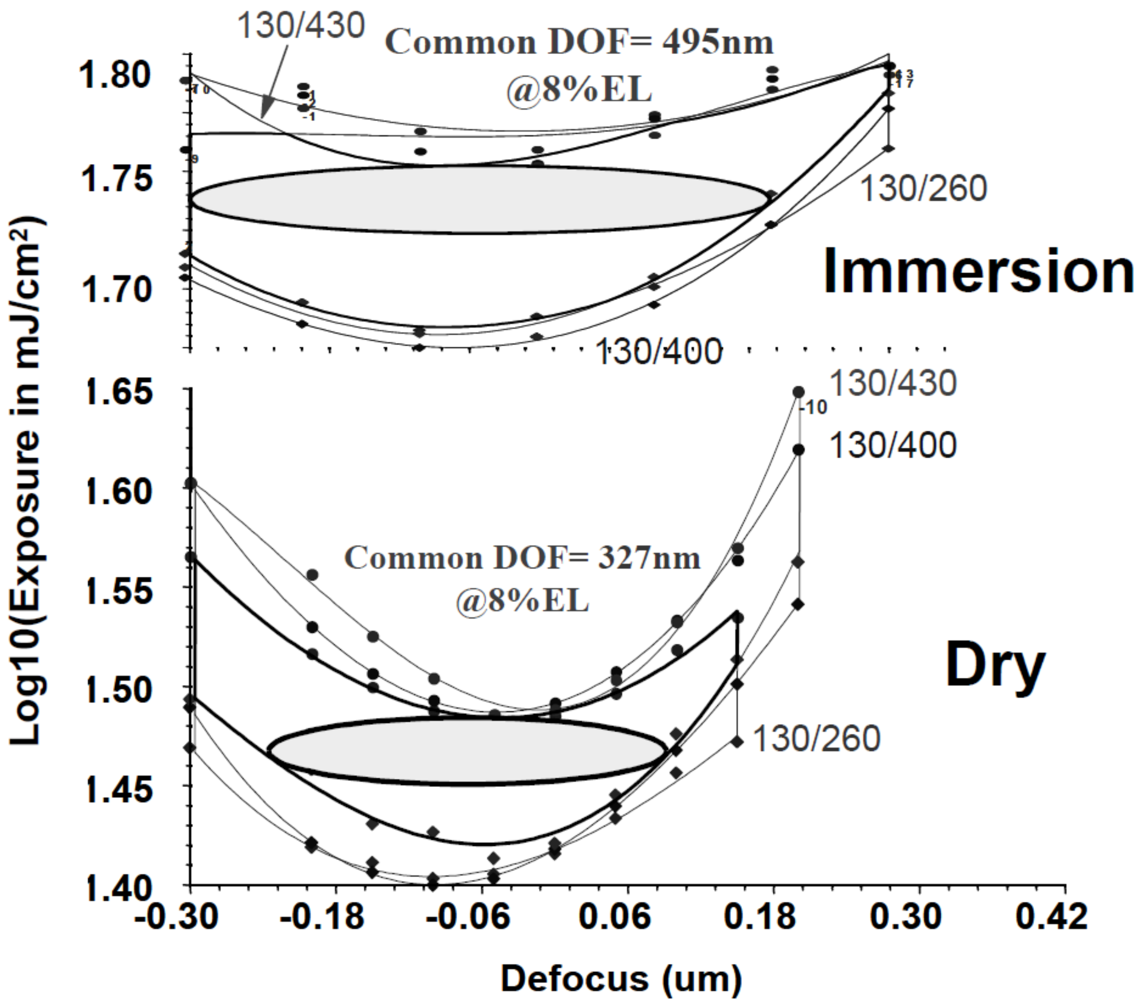
- Let a system whose resolution is adequate but marginal in DOF. In this case, the image-forming angle in the resist does not have to increase.
- The angle in the coupling medium is reduced due to the water, making focusing less sensitive to any physical longitudinal displacement of the wafer.

n_{quartz} = 1.56, n_{water} = 1.44, n_{resist} = 1.75.



Example

- The DOF of 130-nm contact holes determined with an E-D window.
  - Axial illumination at σ = 0.6, 0.75 NA, and a 6% AttPSM mask were used.
  - Individual and common E-D windows at 260-, 400-, and 430-nm pitches were plotted.
  - The DOF improvement for each individual window is between 30% and 50%, and for the common window it is 51%.



Special Consideration – Resist Leaching

➢ Resist Leaching and Water Uptake

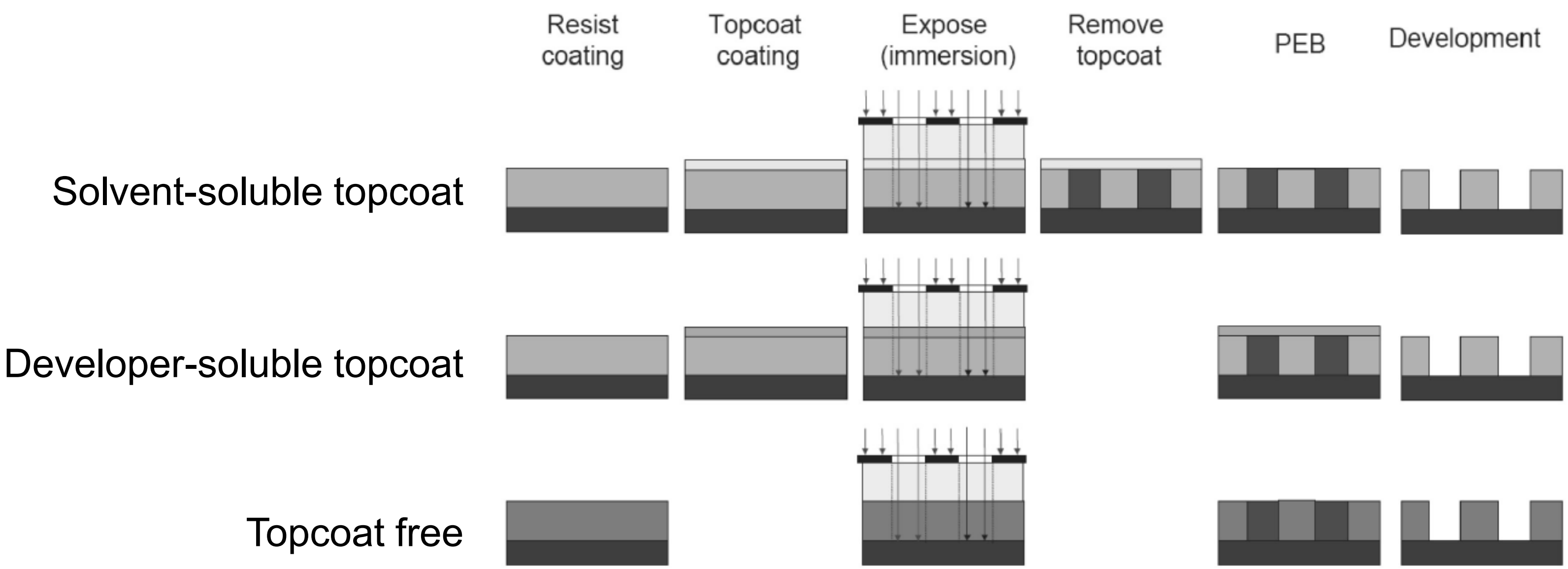
- The resist stack (with or without topcoat) on the wafer is dynamically exposed through water with the step-and-scan process.
- The photoacid generator (PAG), quencher, and other small molecular components of the resist may leach into the water.
- These leached components contaminate the water and may degrade resist performance.
- The contaminated water can additionally contaminate the lens and wafer stage of the scanner.

	ASML	Canon	Nikon
PAG leaching	1.6×10^{-12} mol/cm^2/s	1.0×10^{-11} mol/cm^2/s	5×10^{-12} mol/cm^2/s
Amine leaching	-	-	2×10^{-12} mol/cm^2/s

Special Consideration - Topcoat

➢ Topcoats

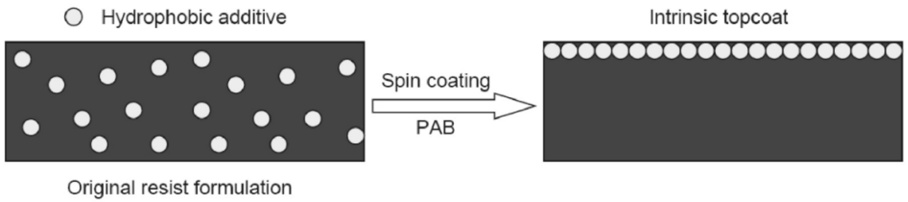
- Topcoats were a practical and viable solution to avoid resist leaching.
- The developer-soluble topcoat processes were relatively easy to integrate into manufacturing lines and remain the most commonly used processes today.
- In contrast, solvent-soluble topcoats have never been used in mass production because they are made from fluoropolymers that require toxic solvents for removal. Additionally, solvent-soluble topcoats require dedicated modules for coating and removal.



Special Consideration – Topcoat Free

- Resist process without top protection coatings is thought to be the ultimate solution for 193-nm immersion lithography.
  - In order for a resist to be suitable for use without a topcoat, it must simultaneously meet the requirements of low leaching and superior lithographic performance.

Embedded barrier layer (EBL) technology



Factors	Items	Recommended values	Comments
Surface hydrophobicity	Static CA	$>90^0$	To prevent the water leakage from the meniscus
	Receding CA	$>70^0$	
Leaching	Dynamic leaching rate	Meet the requirements of scanner suppliers	See, for example, Table 1 in Chapter 3
Defectivity	Defect count after coating	$<0.01/cm^2$	Totally ~50 defects per 300mm wafer
	Defect count with pattern	$<0.03/cm^2$	
Litho performance	Thickness	70-150nm	Meet the imaging requirements of 45nm hp node
	LWR	$3\sigma<2.4$nm	
	Resolution	~45nm hp	
Etch	Etch selectivity	Similar to current "dry" resist	

Advanced processes for 193-nm immersion lithography byYayi Wei and Robert L. Brainard., SPIE, p.104.

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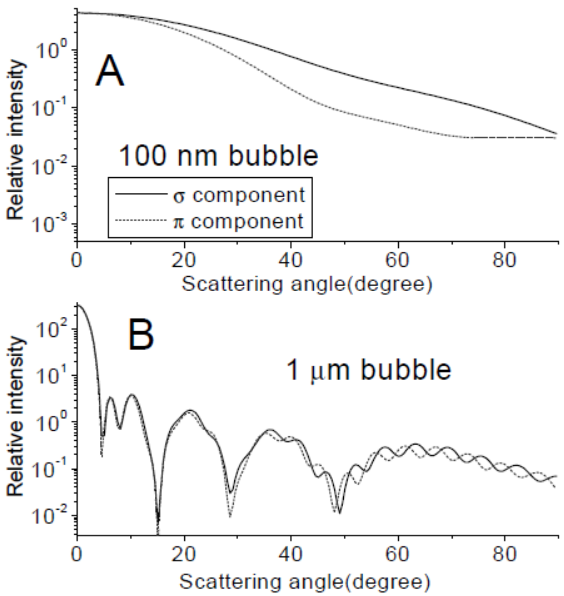
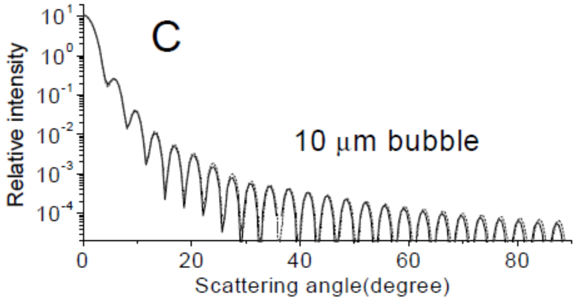
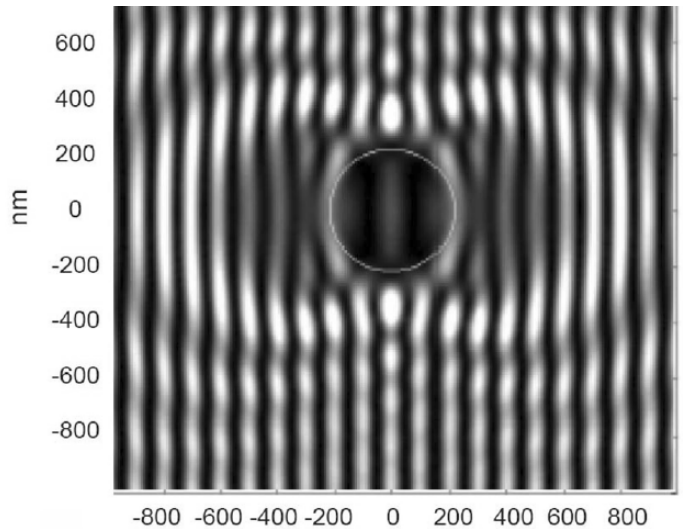
Special Consideration - Bubble

- The effect of bubbles in the water is mostly in redirecting the imaging light in the form of scattering.
  - The scattering effect is a strong function of the size and quantity of the bubbles, as well as the distance from the resist surface.
  - Small free-floating air bubbles in the immersion water do not cause imaging defects.



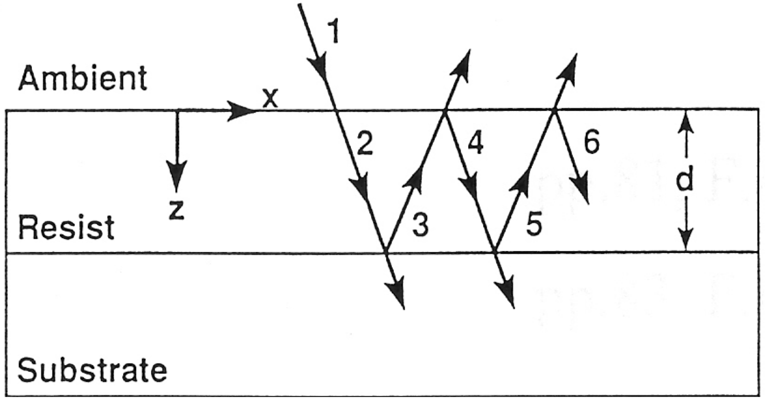
σ: TE polarization
π: TM polarization

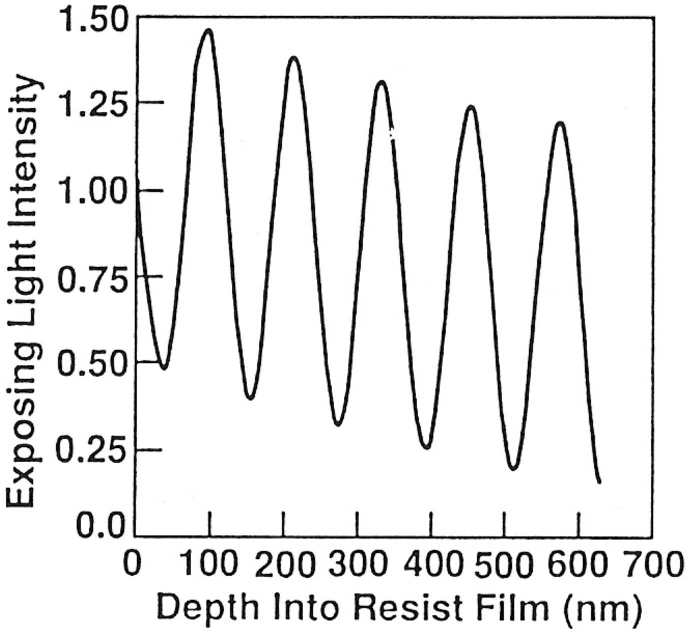


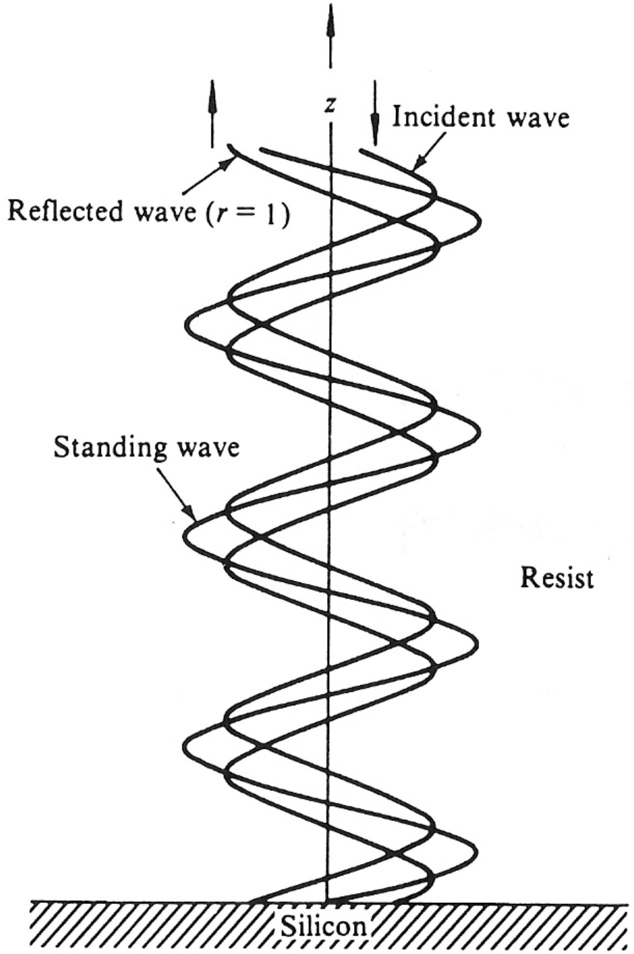


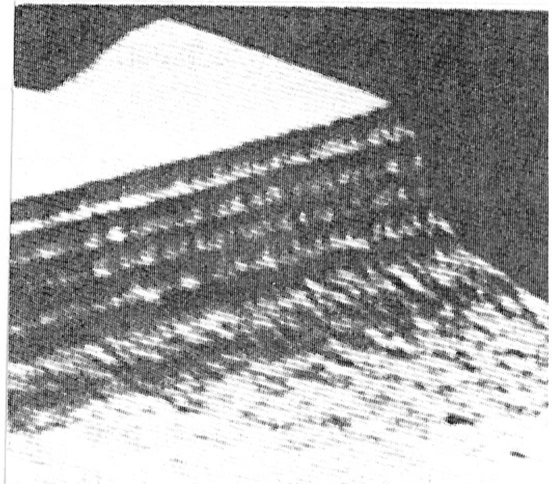
Aerial image of 100-nm dense lines at the resist surface in the vicinity of an 400 nm air bubble.

Reflection Problem



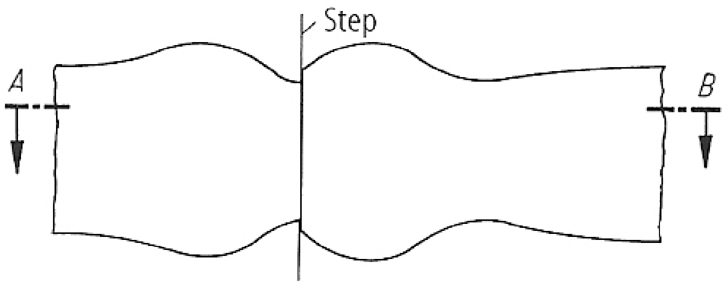




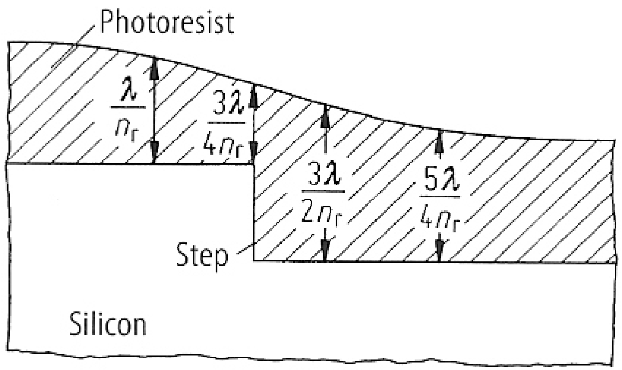


Necking and Notching

Necking

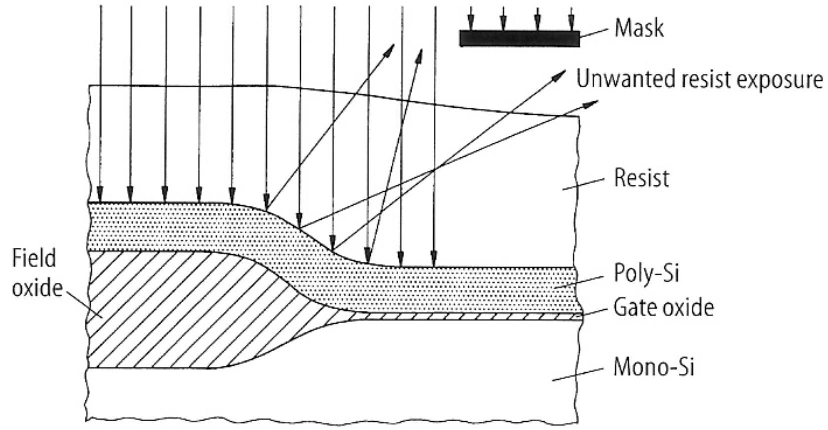


a Photoresist pattern (plan view)

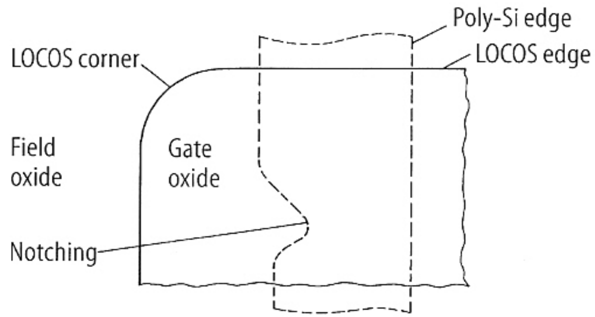


b Section A-B

Notching



a Cross-section



b Plan view

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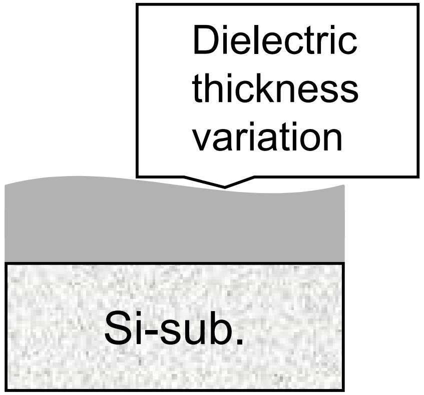
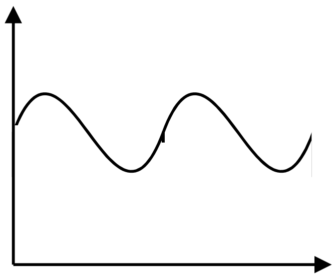
Anti-Reflecting Coating

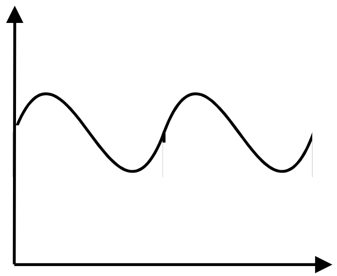


• Trench or via lithography on transparent dielectric layer

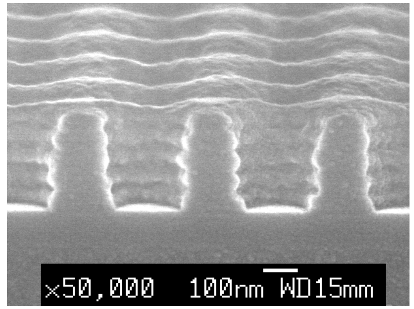
Reflectivity swing curve



CD swing curve



Standing wave



Solution Option

Single BARC and/or TARC

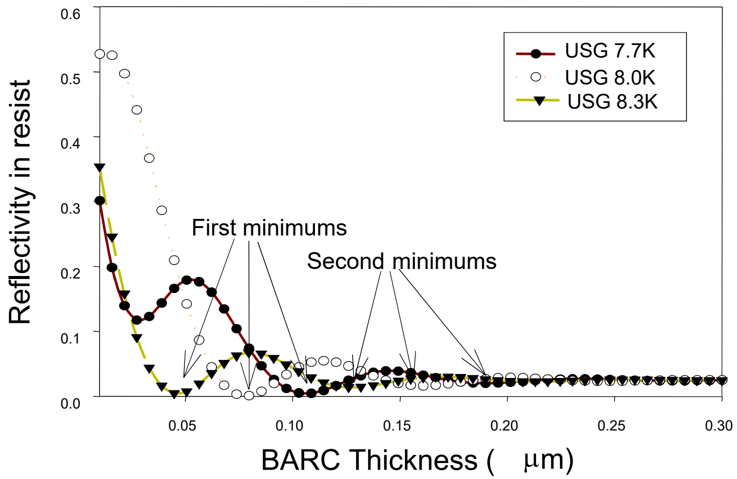
Single DARC

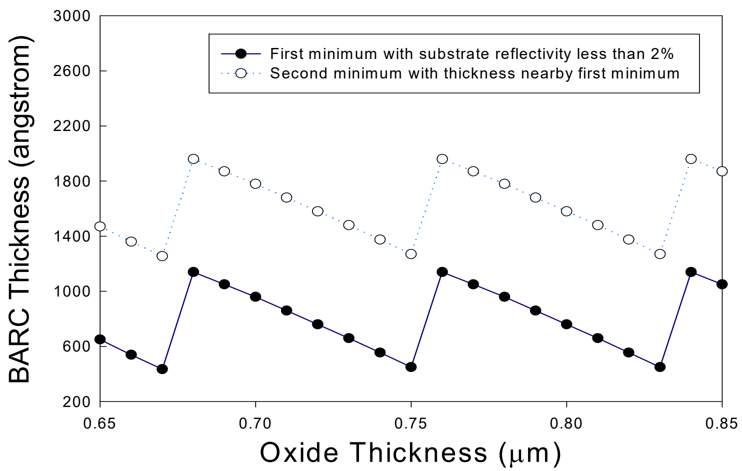
Single DARC + single BARC and/or TARC

Dual DARC

Tri-layer DARC

Reflection Issues

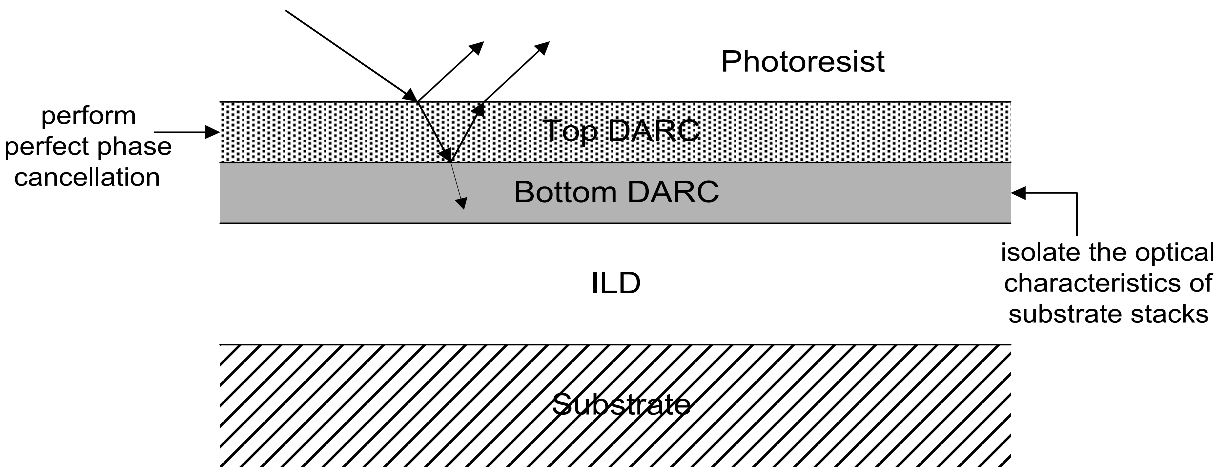


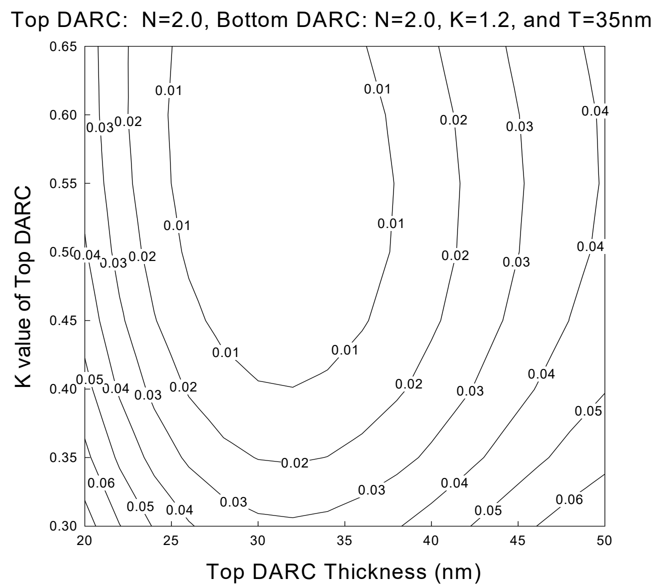


- Transparent oxide thickness variation makes CD control more difficult.
- Different oxide thickness has different 1st minimum.
- Cannot find suitable BARC thickness for different oxide thickness except very thick BARC.
- Thick BARC→ etch/clean problem

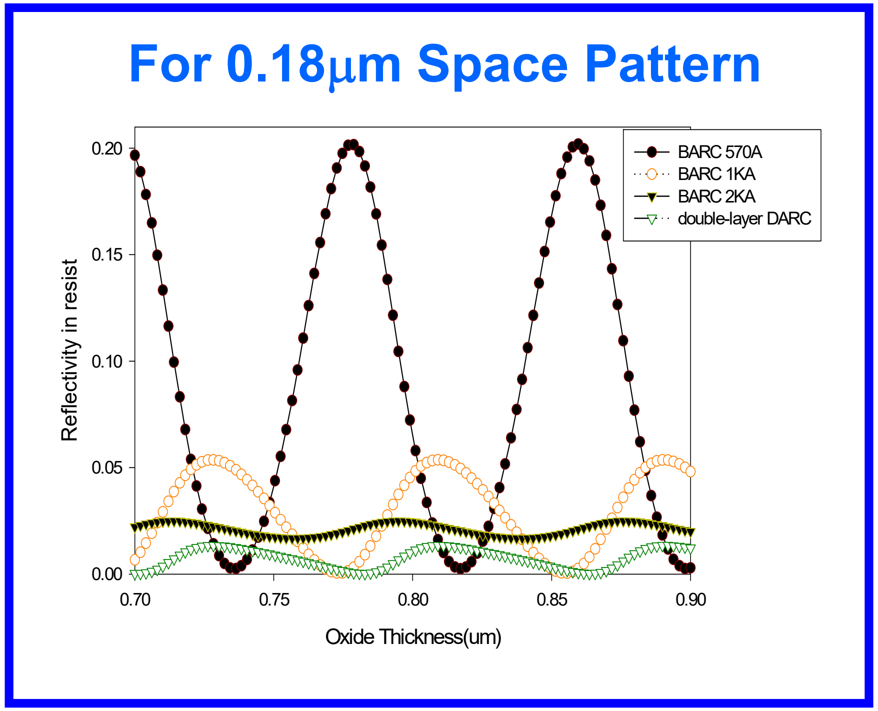
Dual DARC Approach

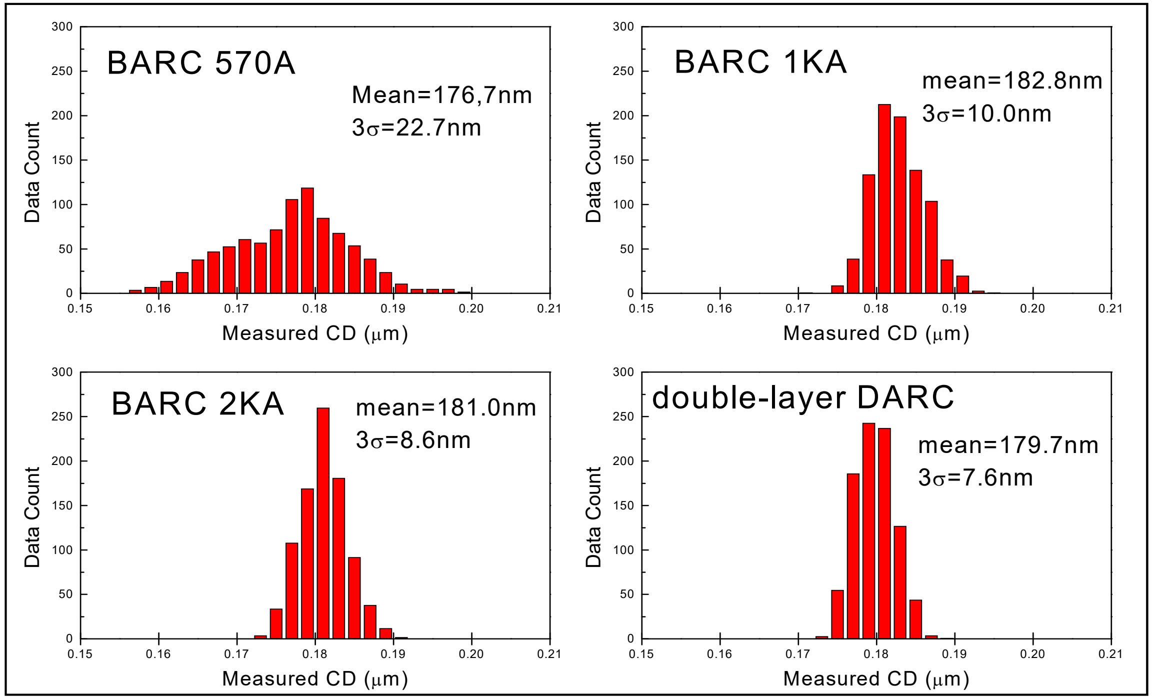
- Bottom DARC
  - Isolate the optical characteristics of underlying films.
- Top DARC
  - Annihilate intrinsic reflective light by phase cancellation.
- Optimized dual DARC design - substrate reflection less than 1%





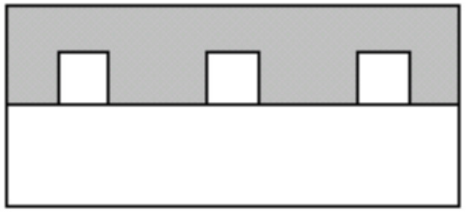
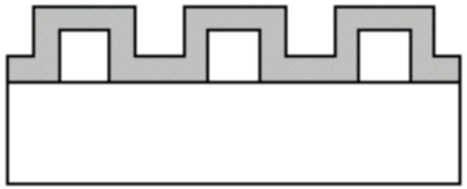
Example of Dual DARC





- 57 nm BARC - worse CD control caused by larger swing
- Dual DARC - better CD control caused by minimum swing

Organic versus Inorganic BARC

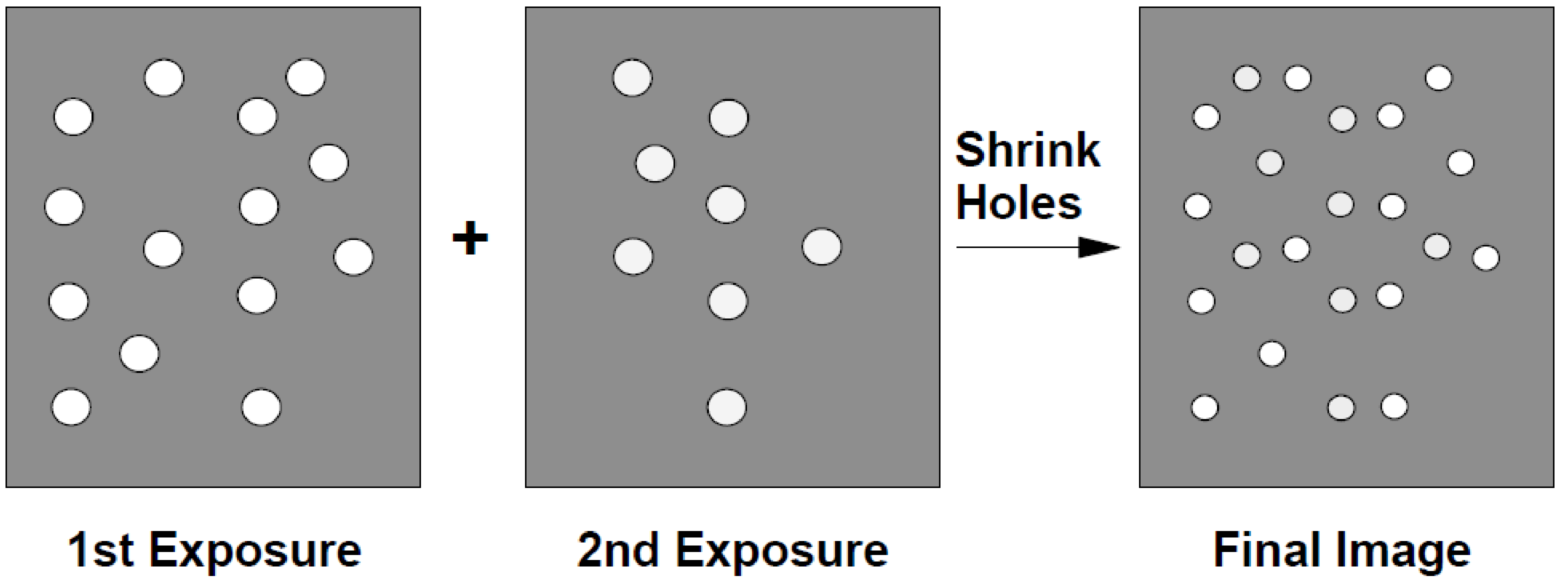
Film type / Compared items	Organic film	Inorganic film
Coating method	Spin-on	CVD
Working principle	Absorption of reflected light	Phase-shift cancellation of specific wavelength
Thickness	1000~2000A	Can be less than 1000A
Tunability	Difficult	Easier
Conformal on topographic substrates?		

Multi-Patterning

- The limitations of the resolution of optical lithography are constraints on the minimum pitch that can be printed, not the size of individual features.
  - Double exposure and pitch splitting
  - Double exposure and double dipole lithography (DDL)
  - Double patterning technology (DPT)
  - Double patterning technology (DPT) + Spacer image transfer
  - Other innovative combinations

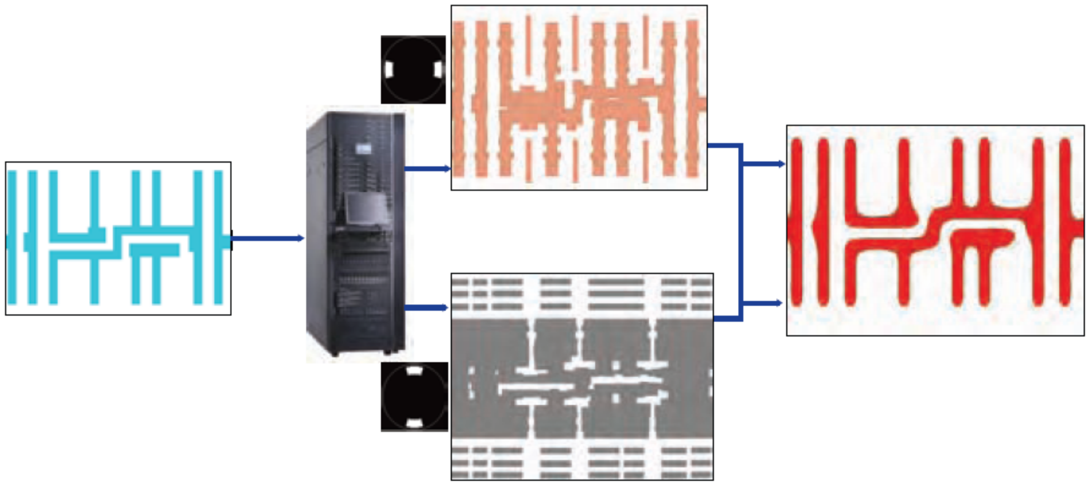
Double Exposure and Pitch Splitting

- After the minimum pitch is reached, the limit can be extended by splitting the mask pattern into larger pitches to delineate them separately without cross-exposure interference onto the same areas on the wafer.



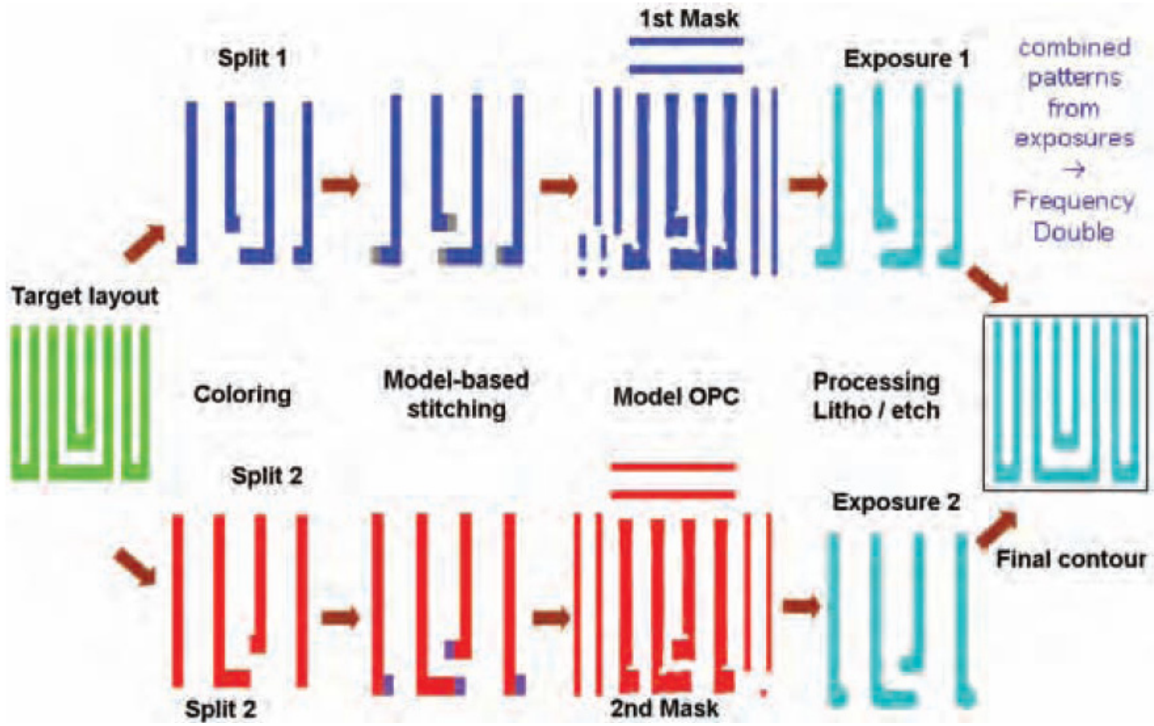
Double Dipole Lithography (DDL)

- Using extreme off-axis illumination, such as X-dipole illumination for imaging vertical features and Y-dipole for horizontal features, there is a sufficient imaging contrast.
  - For manufacturing to use double dipole illuminations, it requires proper decomposition of the intended mask into corresponding H- and V- oriented component patterns. This is followed by using two respective X- and Y-dipole exposures in two consecutive exposures on the same wafer.
  - For DDL mask decomposition, it is most critical to form a proper mask "shield" to protect from the unwanted dipole exposure.



Double Patterning Technology (DPT)

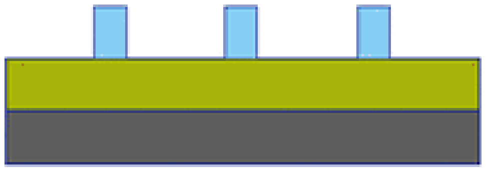
- For DPT, after the first mask exposure, the wafer is sent to the develop and/or etch processes. Then it is to come back for a second mask exposure. The intended mask pattern is formed by two independent patterning steps.



DPT with Litho-Freeze-Litho-Etch (LFLE)

Litho quality yet below required 32 nm performance but lowest cost opportunity: wafer will not leave the litho cell between the 2 exposures

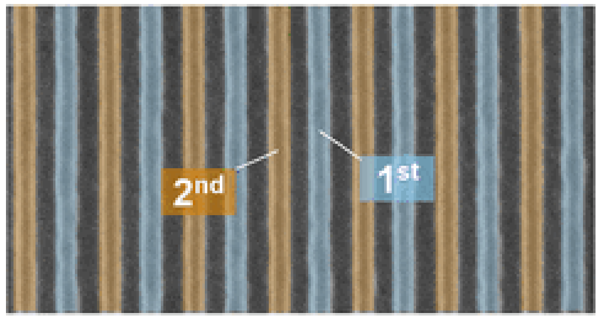
Litho1
Standard resist



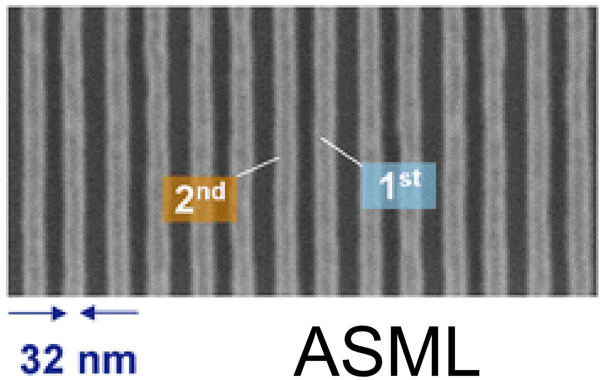
"Freezing" process first developed image:
1) Coat first developed (shown)
2) Thermal treatment
3) Pos/Neg resist
4) Other post development treatment

Litho 2
Coat, expose, develop 2nd pattern

Litho1 + Litho2

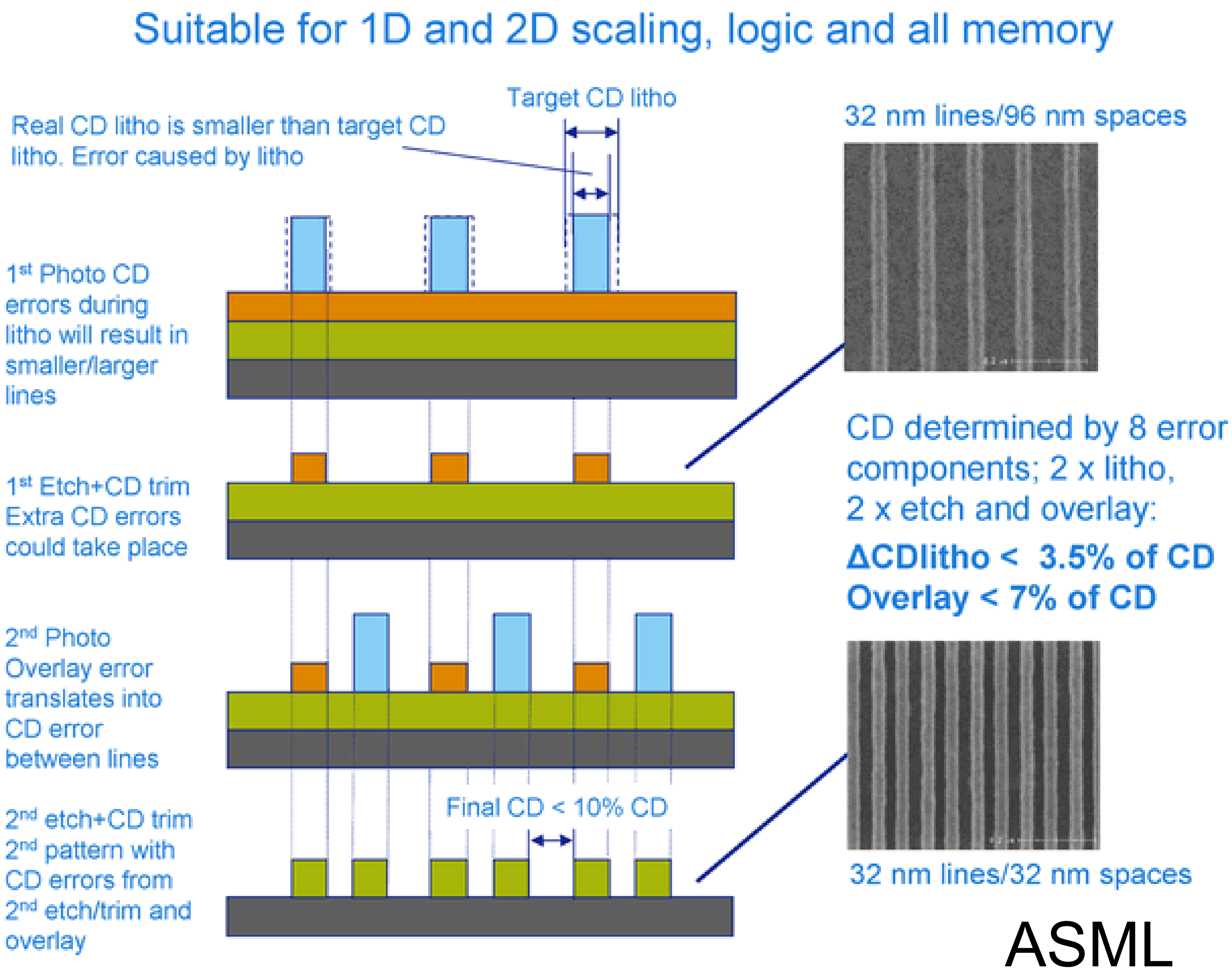


After etch into 60nm poly



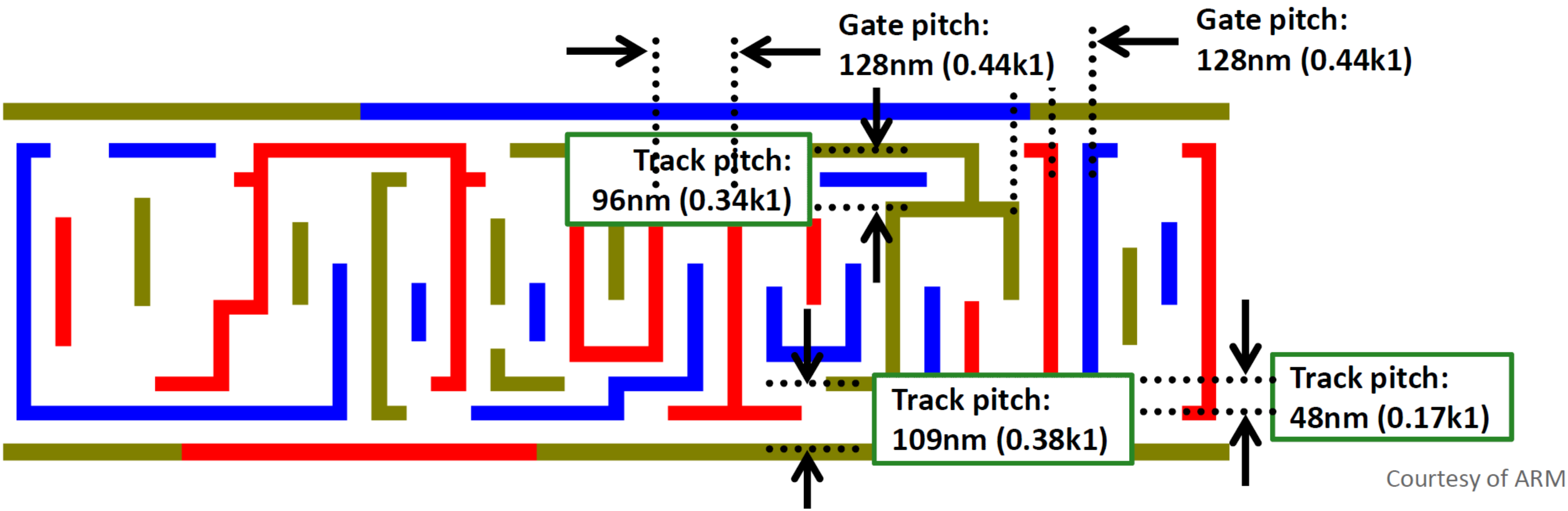
ASML

DPT with Litho-Etch-Litho-Etch (LELE)



ASML

Triple Patterning for N10 ?



Effect of Overlay Error

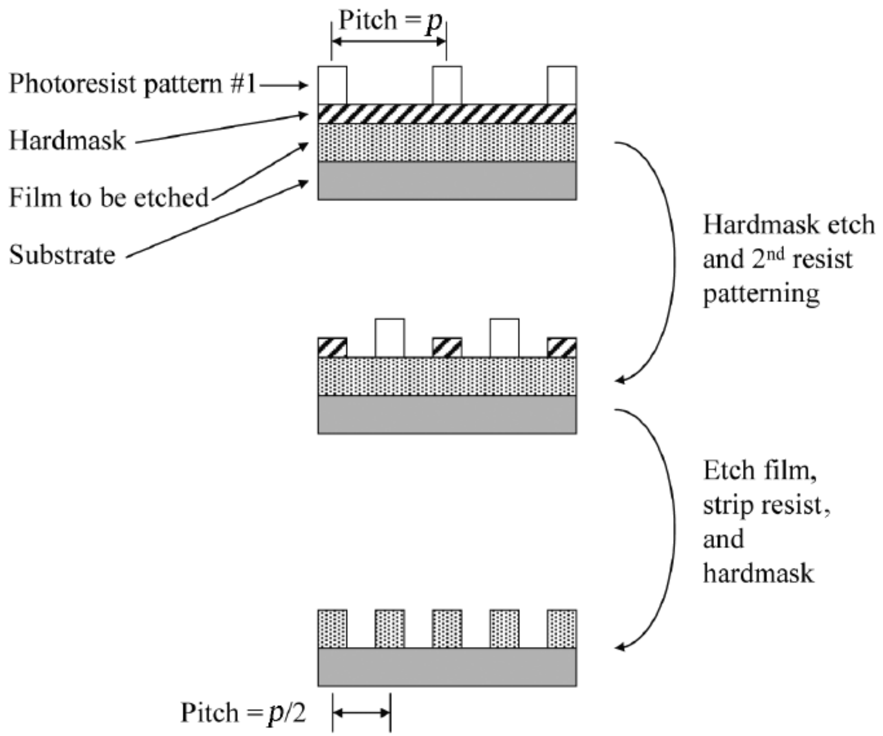
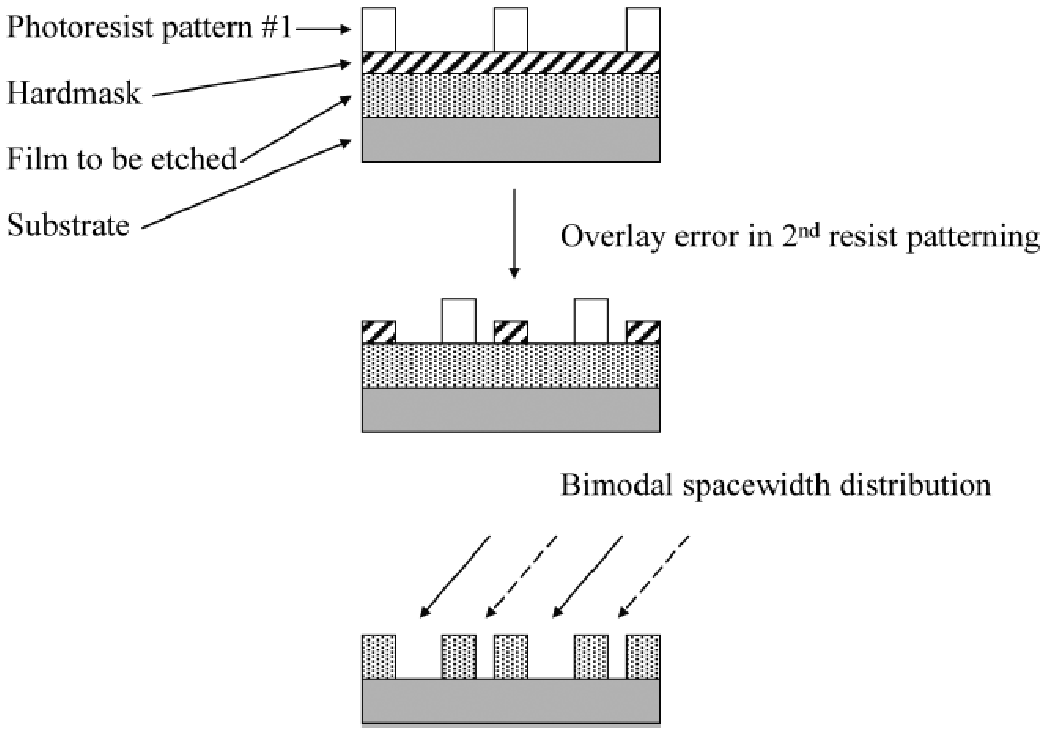
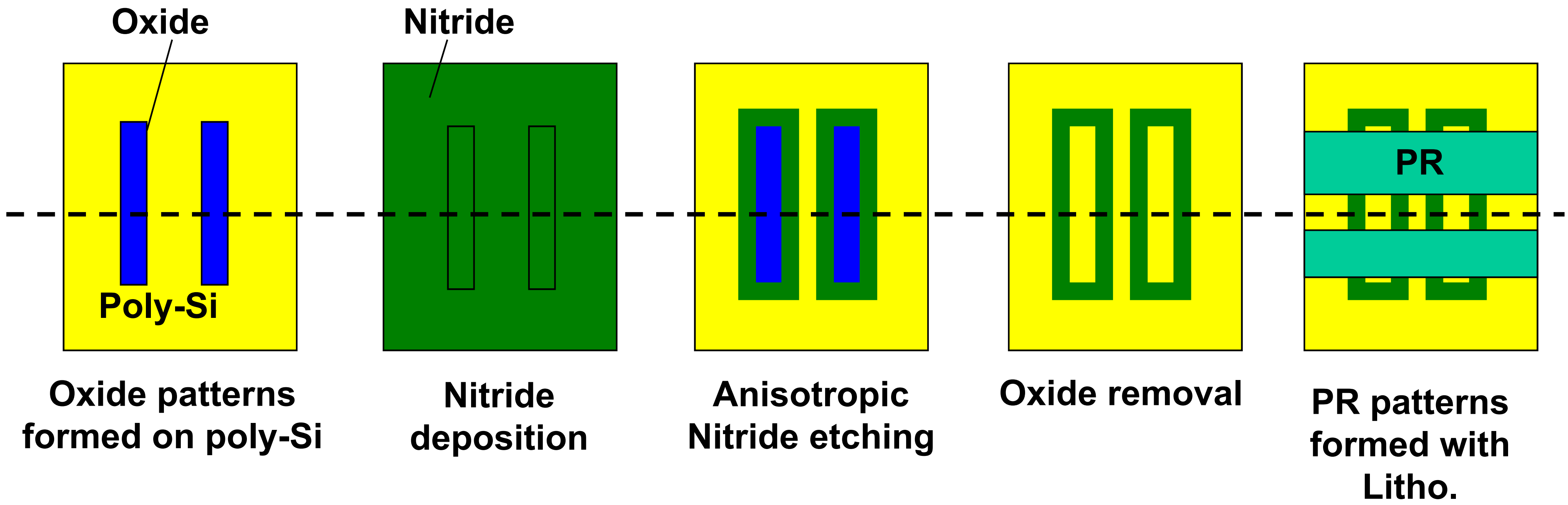


Illustration of a double-patterning process that incorporates a hardmask and two etches.

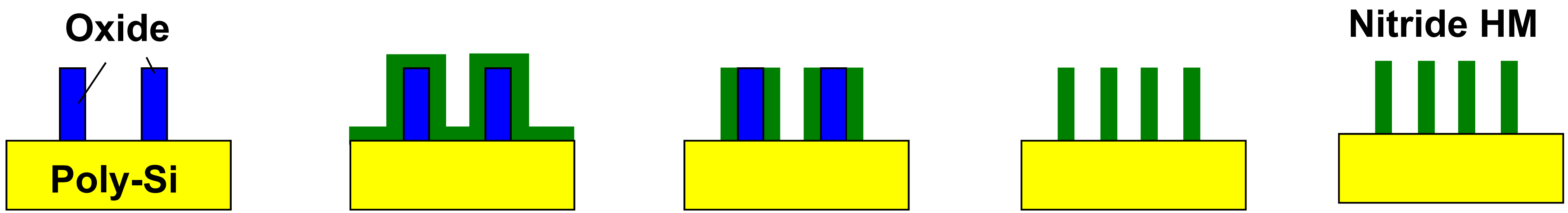


A double-patterning process with an overlay error.

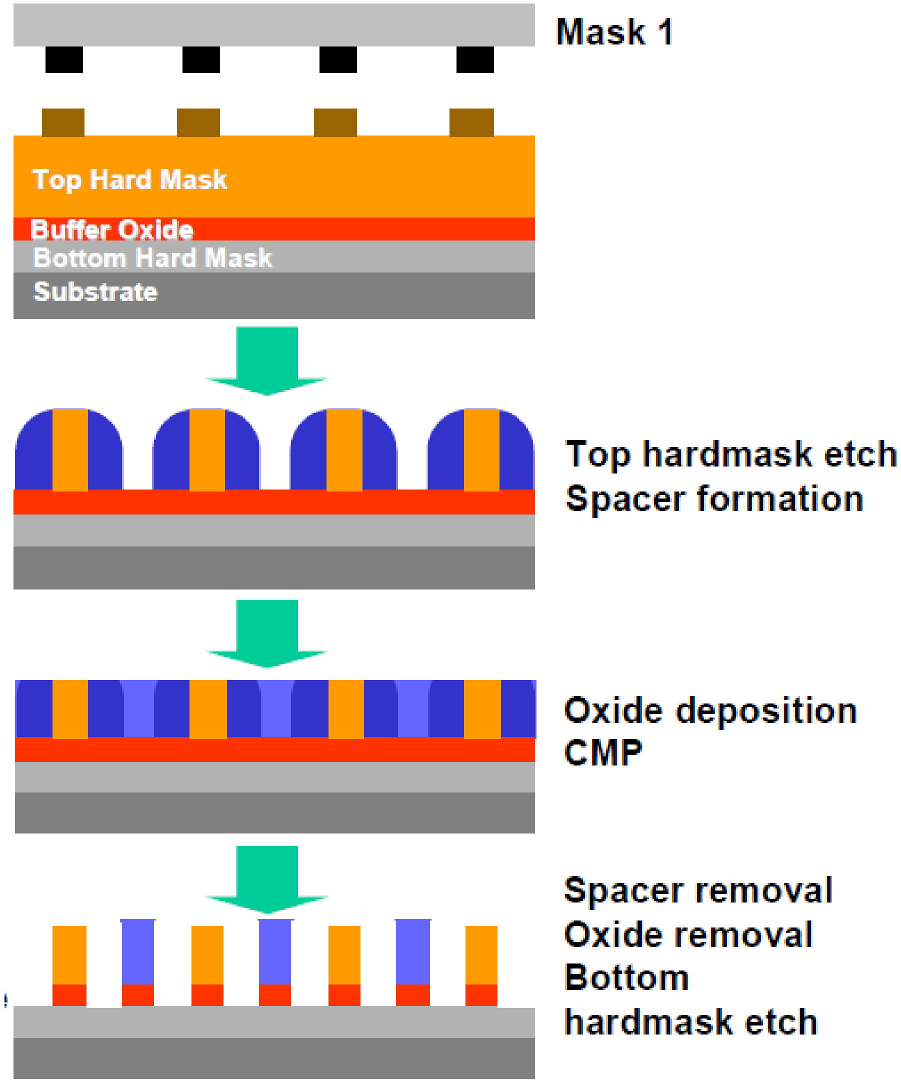
DPT with Self-aligned Sidewall Spacers



Cross-sectional views along the dashed line



Self-aligned DPT with Spacer/CMP

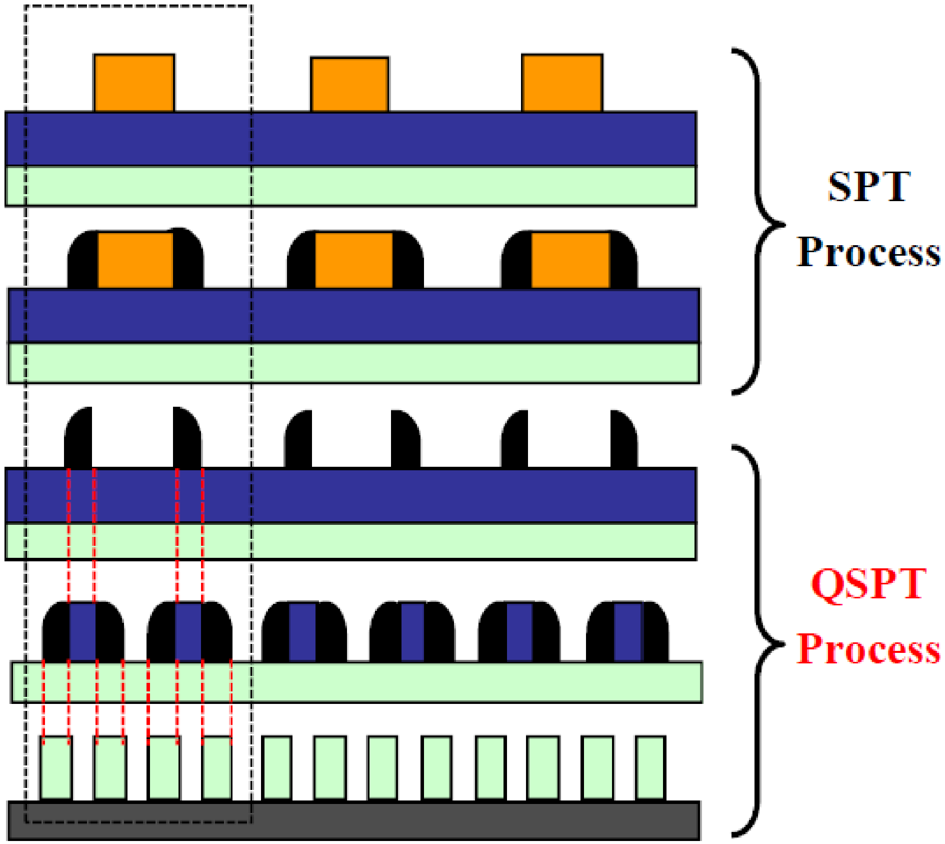


(2009 ITRS)

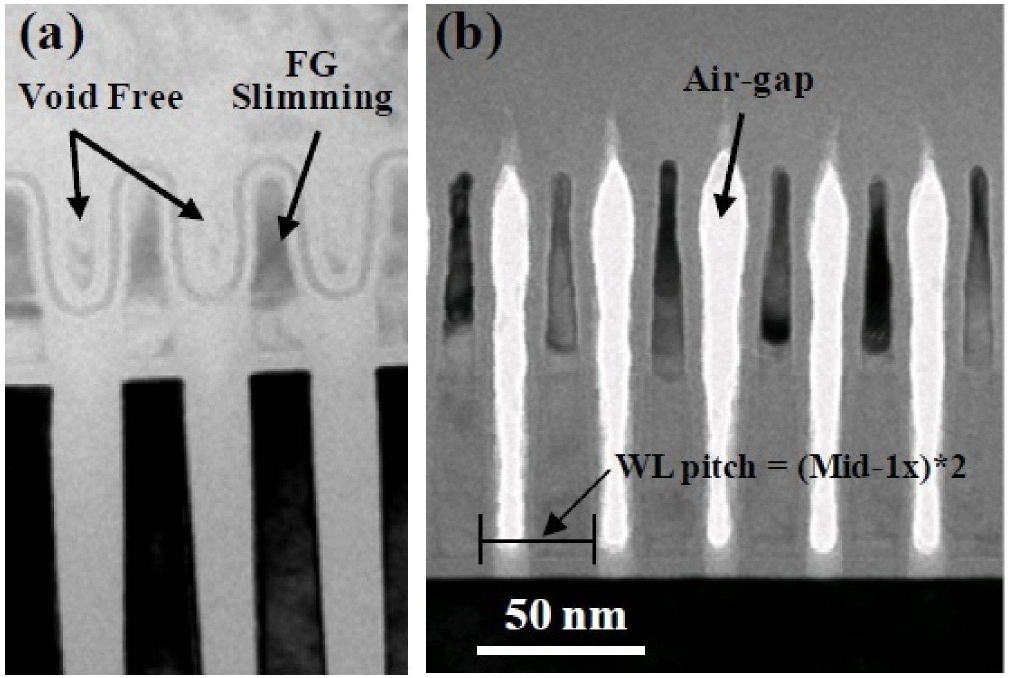
- Advantages
  - Only one mask required.
  - Cut the line pitch by half.
  - Suitable for NAND Flash manufacturing.
- Disadvantages
  - Processing complexity
  - Not suitable for random logic.

Middle-1x nm NAND Flash Memory Cell

(IEDM'11, S. 9.1, p.199)



QSPT: Quad Spacer Patterning Technology



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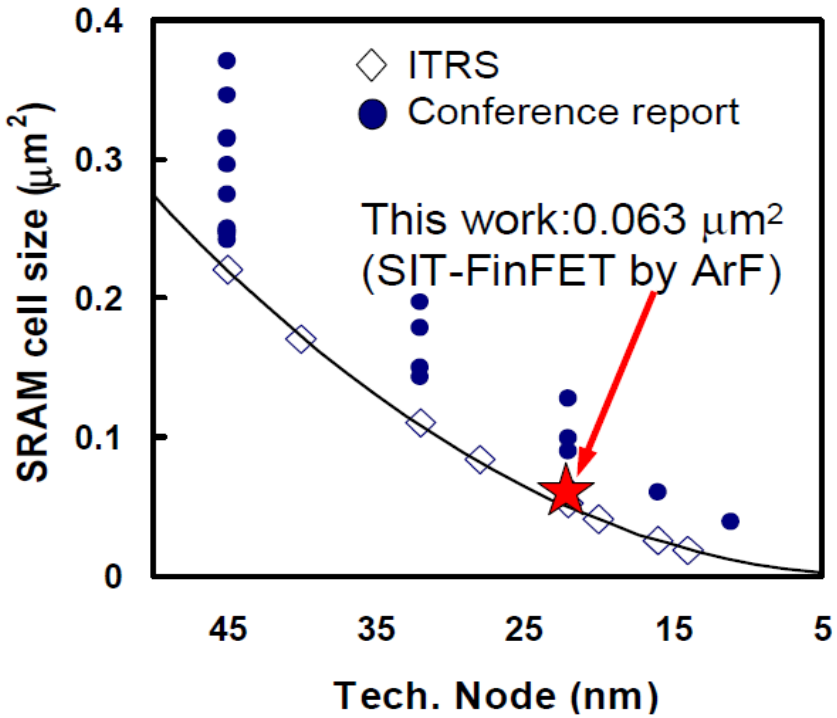
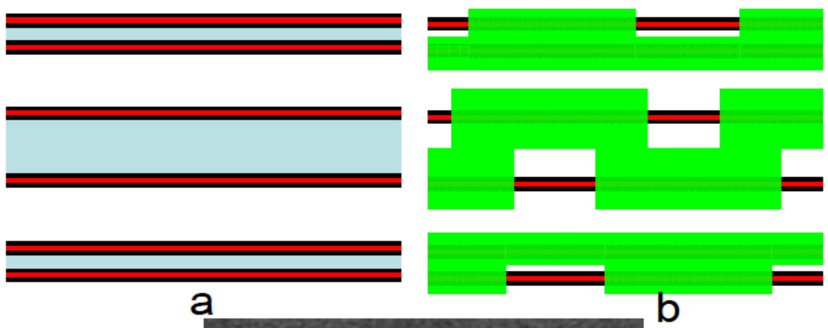
Double-exposure Double-etching Spacer Image Transfer

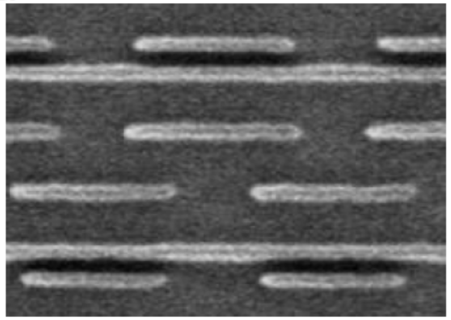


A 0.063 μm^2 FinFET SRAM Cell

(VLSI'10, S.2.2, p.19)

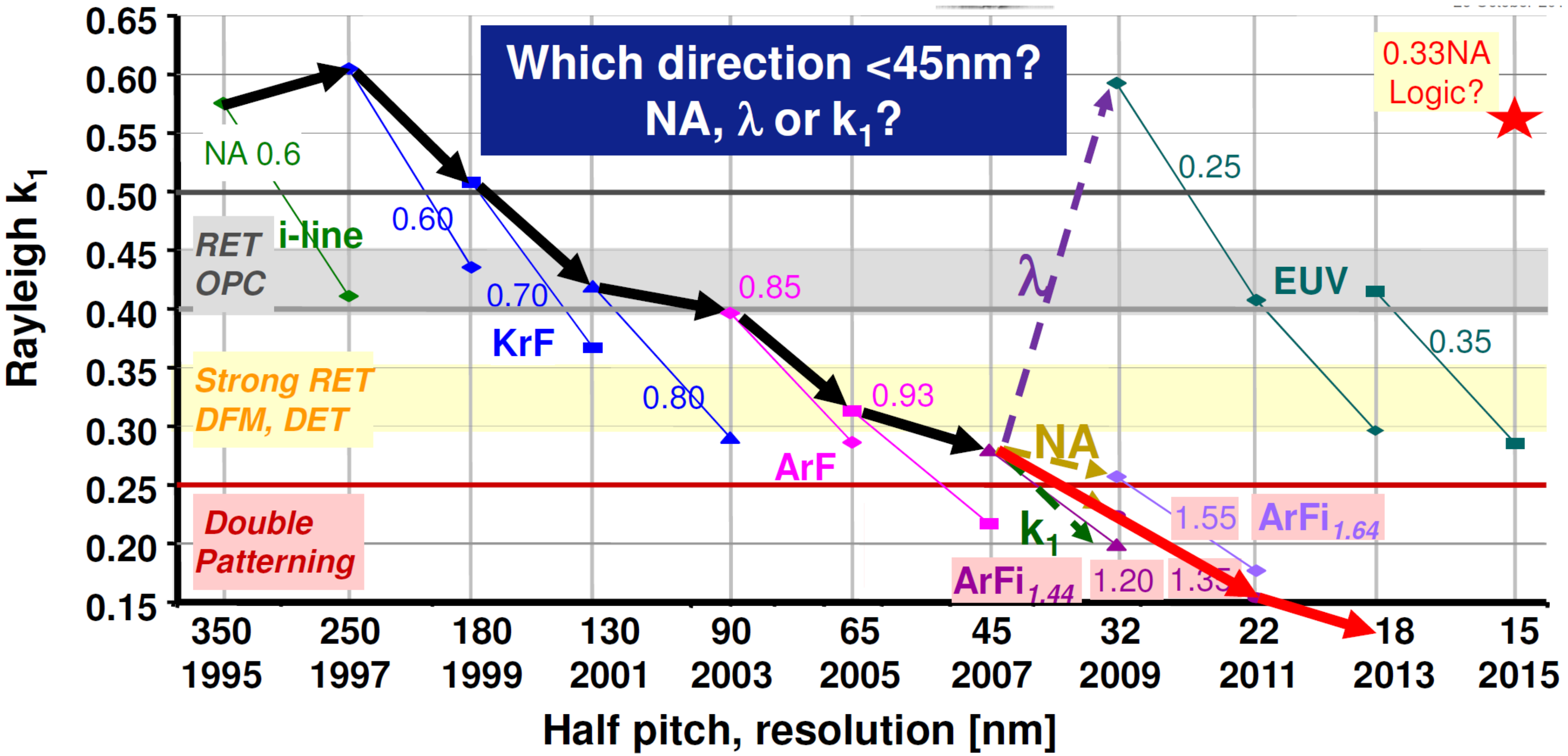


- Fin formation by DE^2 SIT process
- HK/MG Gate Stack formation
- Spacer 1 formation
- Extension formation and EPI fin merge
- Spacer 2 formation
- S/D I/I
- Silicidation
- Contact and Metal formation


c

Next Generation Lithography (NGL) Technology

NGL Direction



DFM: Design For Manufacture

DET: Double Exposure Technology

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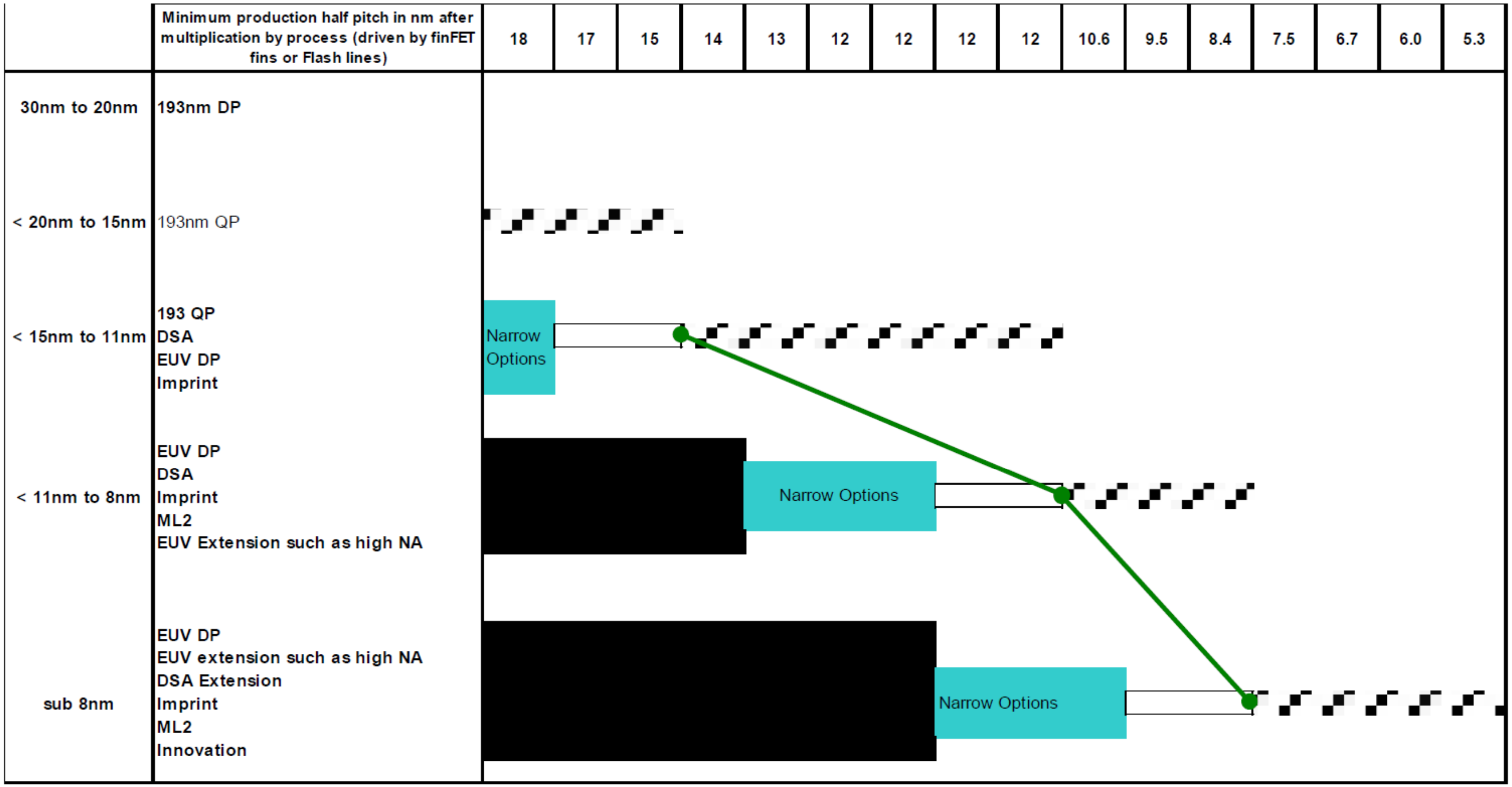
NGL Choices

2013 ITRS Roadmap, http://www.itrs.net



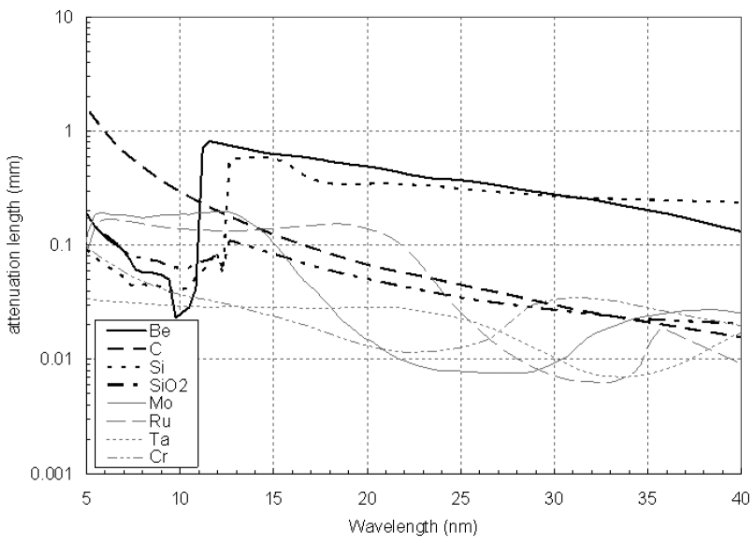
Legend indicates the time frame in which research, development, and qualification/pre-production should be taking place for a given half pitch range for the solution.

Research Required
Development Underway
Qualification / Pre-Production
Continuous Improvement

DSA: Directed Self-Assembly
ML2: Maskless lithography

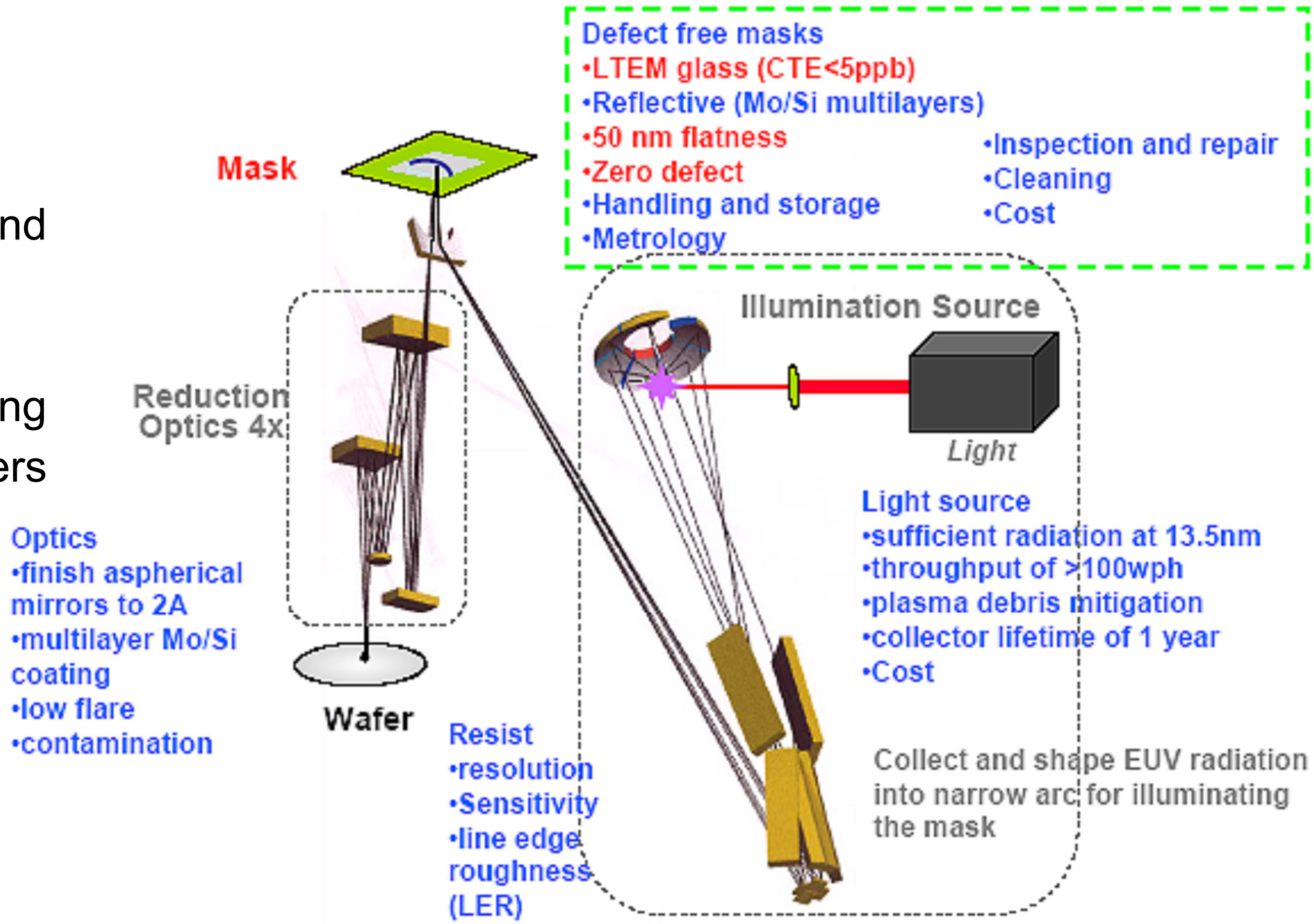
Extreme Ultra-Violet Lithography (EUVL)

- Optical lithography in the regime of $k_1 = 0.3$ is very complicated.
  - EUVL using a 13.5-nm wavelength. This wavelength offers an order of magnitude reduction in wavelength from the water-immersed ArF wavelength.
  - It presents an opportunity to bring k_1 back to above 0.5.
- With such a dramatic drop in wavelength, the imaging system is substantially different from existing systems.
  - Any substance heavily absorbs EUV light, even gases; therefore, the optical path must be in vacuum.
  - Following its heavy absorption characteristics, there is no transmitting material; EUV imaging depends on reflection.



EUV Lithography Overview

- Key elements
  - Light source
  - Illuminator optics
  - Projection optics
  - Precision wafer and reticle stages
  - Alignment system
  - Mechanical handling systems for wafers and reticles.



Source: Intel report

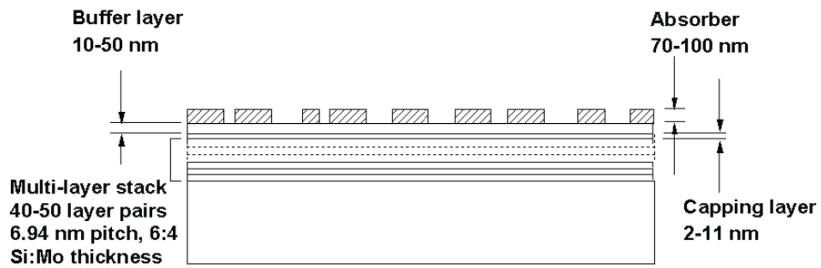
Special Requirements

- Exposures must take place in a vacuum.
  - The transmission of 13.5-nm light through 0.1 mm of air at atmospheric pressure is only 7%.
  - The vacuum must be very good, because photon-induced carbon deposition on mirror and mask surfaces or surface oxidation can result from the presence of very low levels of hydrocarbons in the system.
  - All components within the vacuum chamber be constructed of ultrahigh vacuum-compatible materials.
  - We must prevent optics from becoming contaminated by the inevitable out-gassing from resists.
- EUV absorption results in thermal issues.
  - Masks will also absorb an appreciable amount of light energy, which could lead to expansion and contraction of masks with attendant overlay errors.
  - EUV masks are fabricated from ultralow expansion materials, with coefficients of thermal expansion measured in parts-per-billion.

EUV Mask - 1

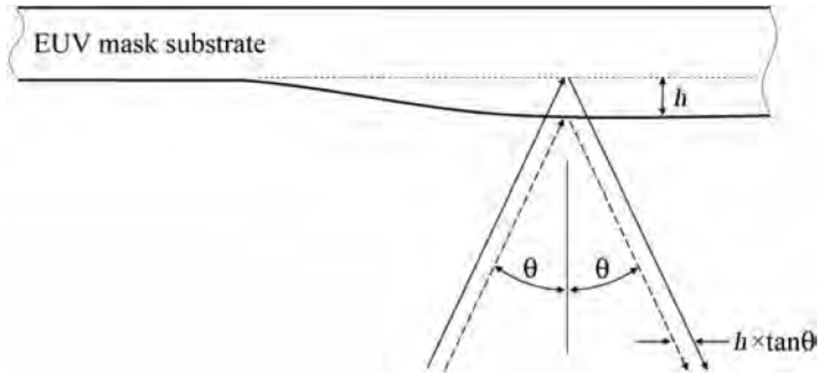
➢ Reflective masks are necessary.

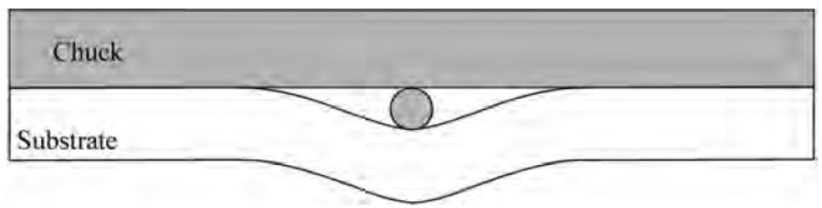
- Reflector: Mo/Si multilayer is commonly used. It can reach 70% reflectivity.
- Absorber: Cr, TiN or TaN could be used. Higher absorption coefficient results in thinner absorber.
- Buffer layer: SiO_2 layer to facilitate etching and repair without damaging the multilayer.



➢ Flatness

- Mask nonflatness leads to image-placement errors.
- The lateral displacement $h \times tan\theta$ is reduced on the wafer by the reduction of the projection optics.
- A 36-nm peak-to-valley mask flatness contributes an overlay error of ~1 nm for systems which illuminate the mask at an angle of 6° and have projection optics with a reduction ratio of 4:1.
- Particles would degrade flatness severely.

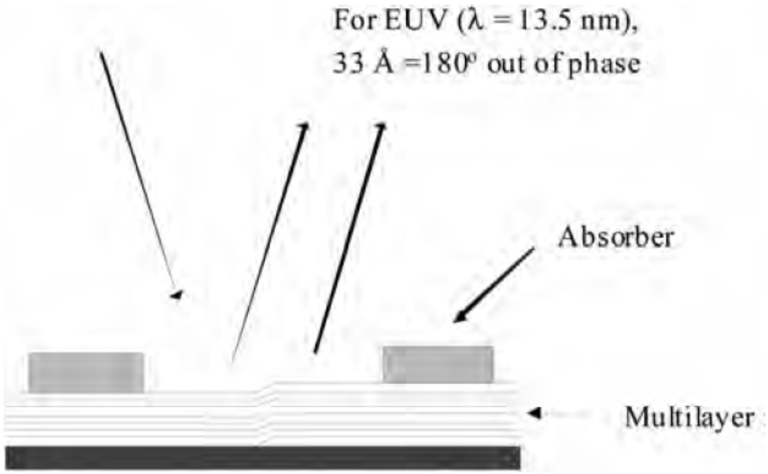


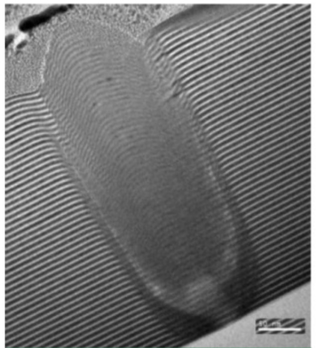


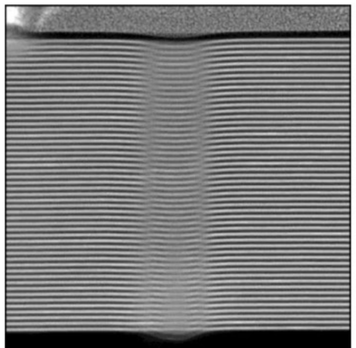
EUV Mask - 2

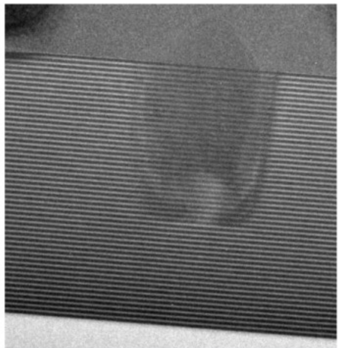
➢ Mask defects

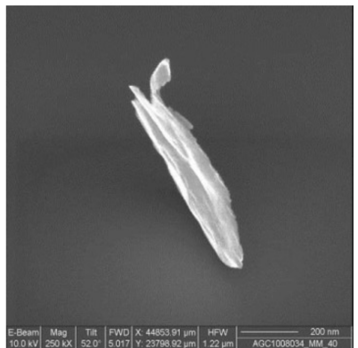
- Steps can result from particles or scratches on the substrate surface on which the multilayer film is deposited, and these steps can form phase defects.
- A 3.375 nm step results in 180° out of phase.
- Defects have been detected using actinic inspection tools that could not be found with conventional visible-light defect inspection tools.
- Consequently, it may be necessary to inspect masks with tools that use EUV light to provide sensitivity to phase defects.
- The absence of highly transparent materials at EUV wavelengths implies that conventional pellicles cannot be used.




Blank defect caused by substrate bump


Blank defect caused by substrate pit


Blank defect added during ML deposition


Particle added on top of EUV Multilayer (ML)

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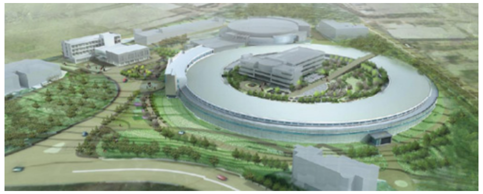
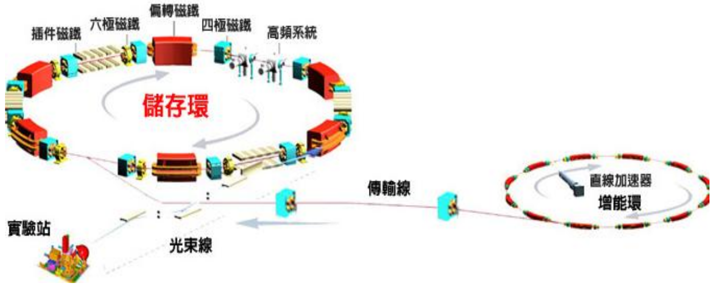
Department of Electronics Engineering &
Institute of electronics

EUV Sources - 1

- Synchrotrons are commonly used as sources of EUV light for R&D and metrology.



NSRRC

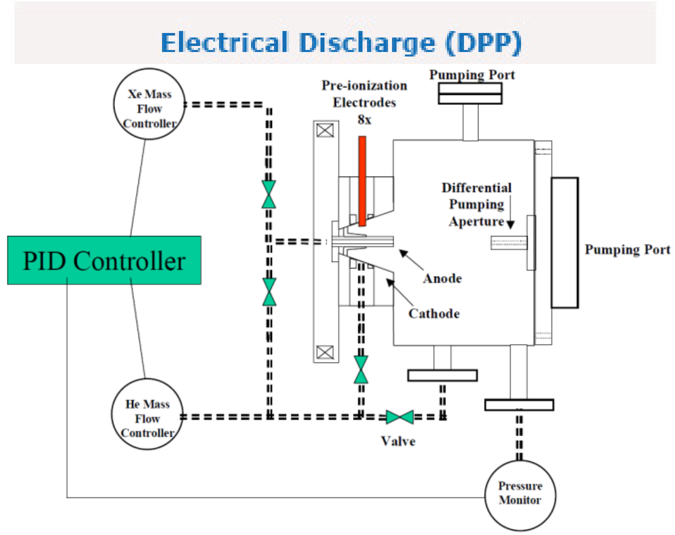


- More compact sources have been developed
  - EUV light is generated by the deposition of laser or electrical energy into a source element, such as xenon (Xe), tin (Sn), or lithium (Li), creating ionized gas micro-plasma at electron temperatures of several tens of electron volts.
  - As these highly excited ions decay, energetic radiation is emitted in all directions. For EUV lithography, the 13.5 nm radiation is collected by a mirror (either grazing incidence or normal incidence)
  - Discharge-produced-plasma (DPP) sources
  - Laser-produced-plasma (LPP) sources

EUV Sources - 2

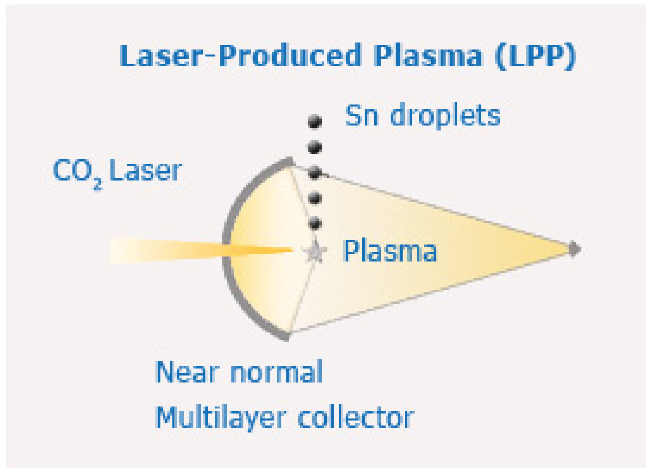
DPP source

- The main features of these DPP sources are the anode and the cathode. Electric energy is stored between them. When a discharge is triggered, it produces the plasma to emit EUV light.
- DPP sources tend to generate more debris than do LPP sources. The debris damages the collector mirror and shortens its lifetime.

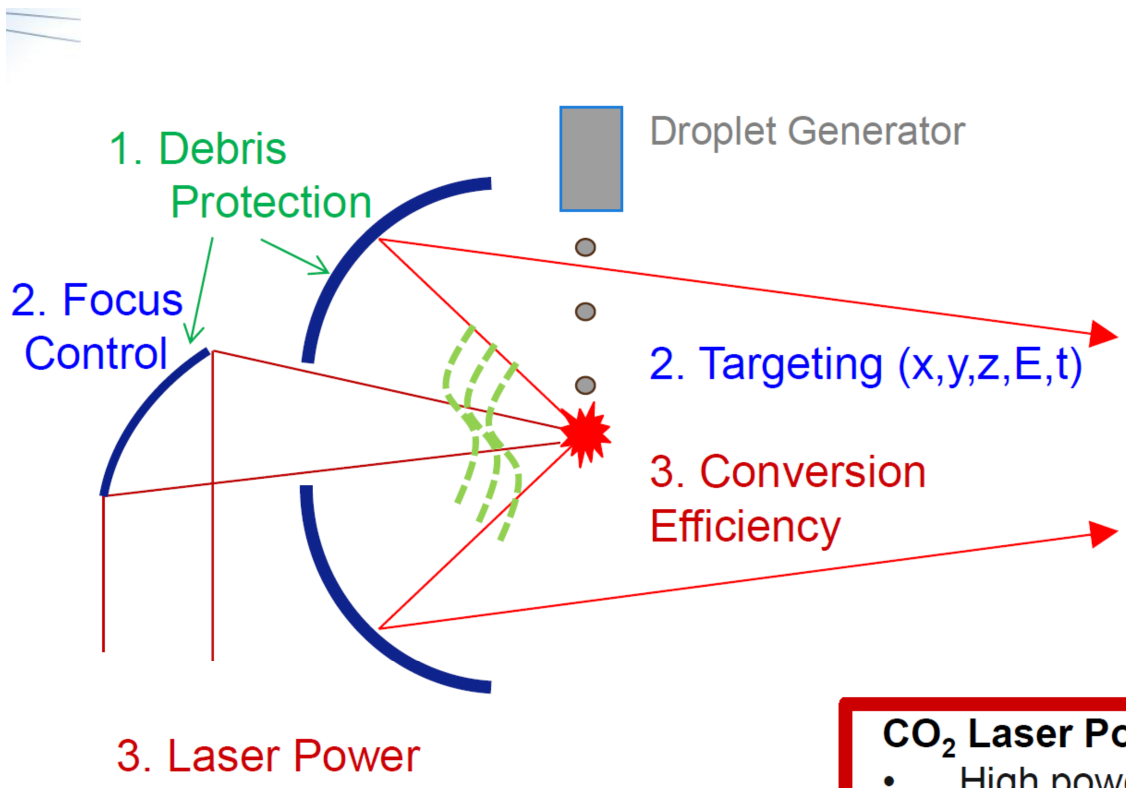


LPP source

- Very-high-intensity pulsed-laser light is focused onto a material, which creates a plasma containing very highly charged ions. When electrons recombine with the ions, high-energy photons are emitted.
- The high efficiency of laser produced plasma is the key to a low cost architecture.
- CO_2 lasers and Sn are currently used.



EUV Sources - 3



Collector Protection (Debris Management) ①
- Collector protection by H_2
- In-situ collector cleaning
- Collector capping layers

Availability / CoO

Targeting Dynamics ②
- Target conditioning
- Focus Control
- x,y,z, E & t control

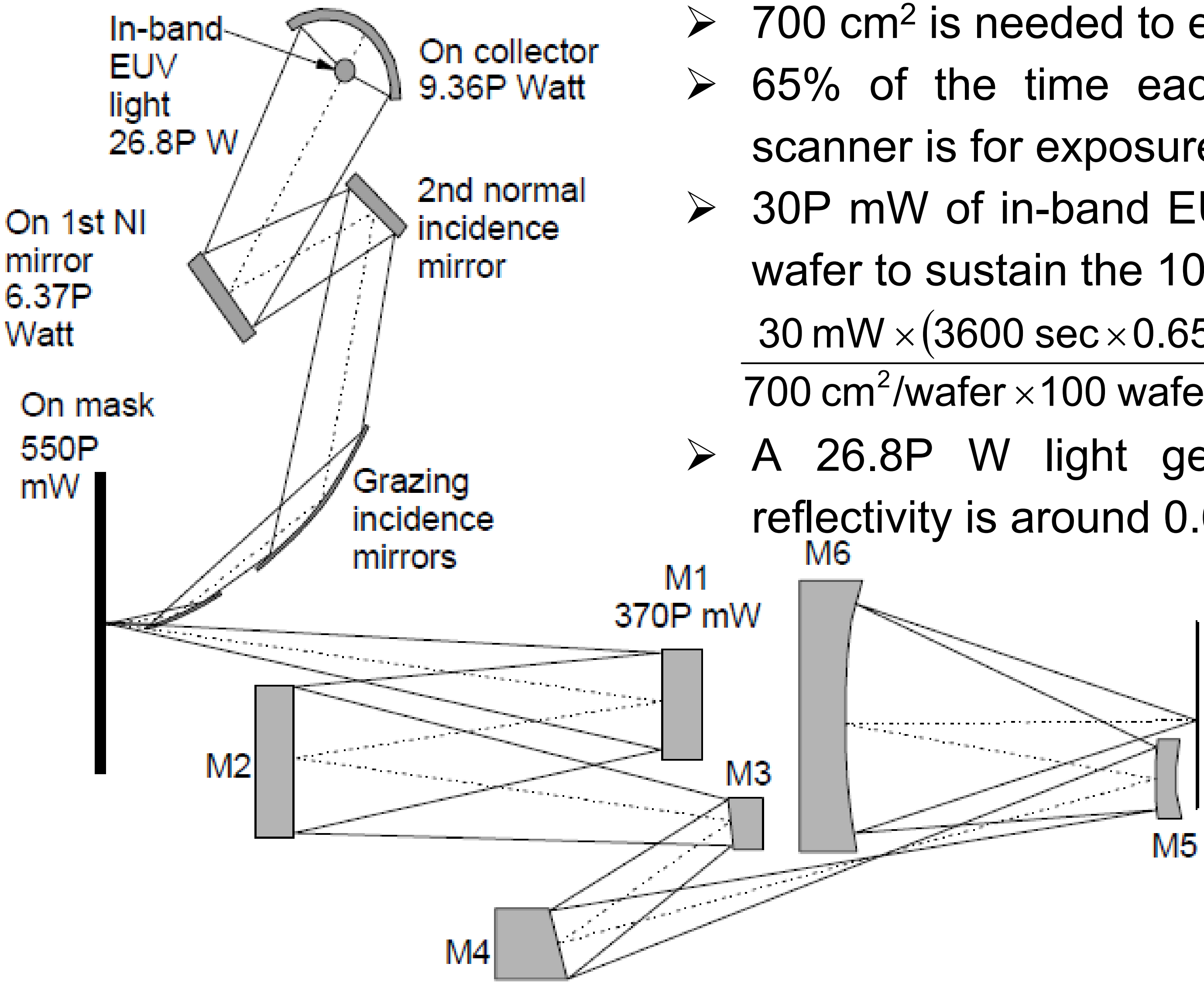
Dose Control / Yield

CO_2 Laser Power ③
- High power drive laser

Conversion Efficiency
- Prepulse

EUV Power / Throughput

Power Loss



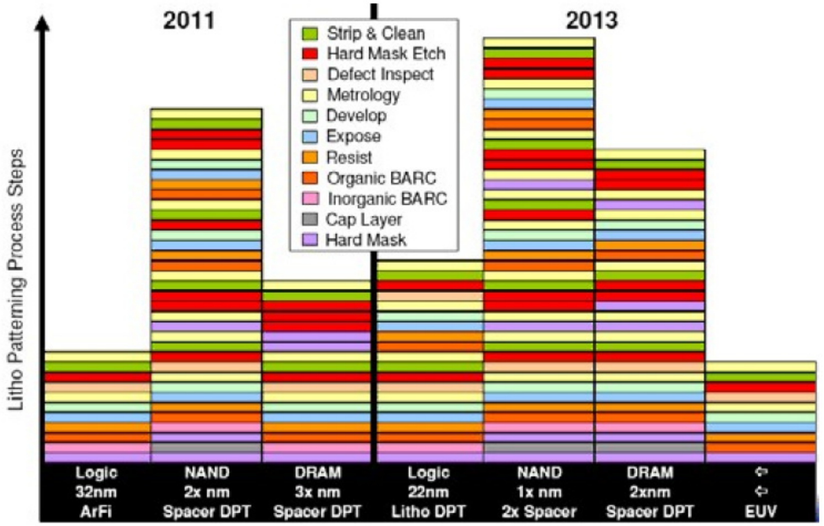
- P mJ/cm^2 is needed to expose the resist.
- 700 cm^2 is needed to expose a 300-mm wafer.
- 65% of the time each wafer spends in the scanner is for exposure.
- 30P mW of in-band EUV power is needed per wafer to sustain the 100-wph throughput.

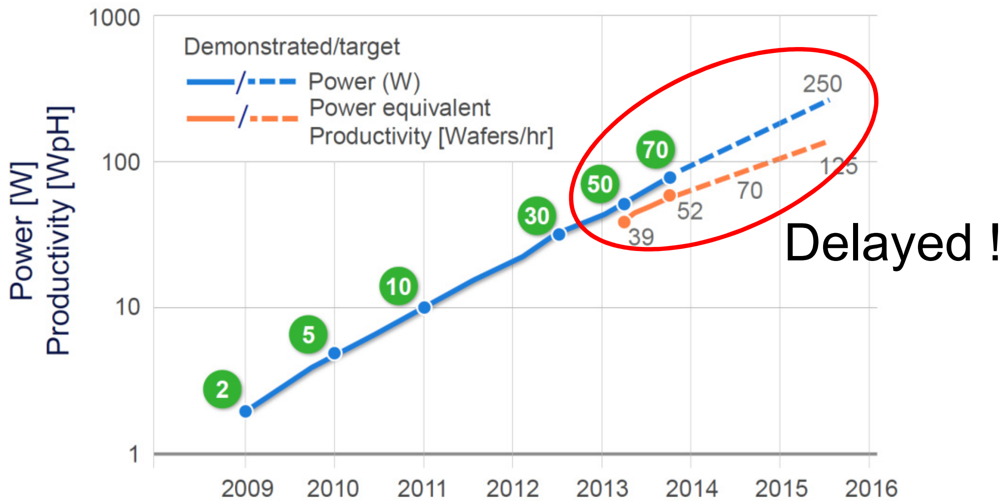
$$\frac{30\ \text{mW}\times(3600\ \text{sec}\times 0.65)}{700\ \text{cm}^2/\text{wafer}\times 100\ \text{wafers}} = 1\,\text{mJ/cm}^2$$

- A 26.8P W light generation is required if reflectivity is around 0.66.

EUV or 193i MP

- 193i MP will get more expensive and complex than EUVL at every next node.
- EUVL has been proven to be capable but it continues to slip due to lack of adequate source power and will not be ready for high volume manufacture for a few more years.
- 193i MP is getting to be very complicated and expensive so chip makers have to have a backup, and that is EUVL.





EUV Resist - 1

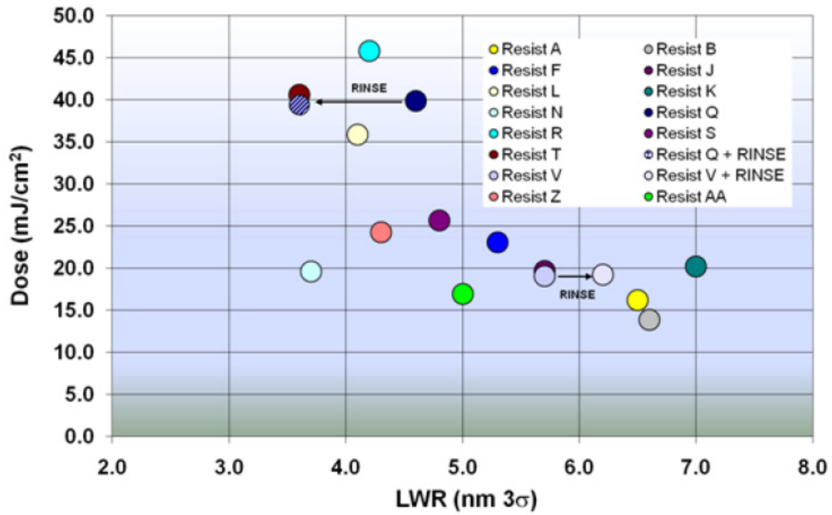
- Resists very similar to conventional DUV materials are used for EUV lithography.
  - Development of EUV resists is facilitated by the fact that most absorption at EUV wavelengths is dominated by atomic absorption, and the particulars of the molecular bonding have only a very small effect on optical absorption.
  - In EUV resists, the initial step is the generation of photoelectrons.
  - A photoelectron will propagate from its point of origin and subsequently scatter, which can result in the generation of additional energetic electrons. Many of these secondary electrons also have the potential to induce chemical reactions.

Short acid diffusion length PAG	High Tg resin	High absorption resin
Acid diffusion control	Acid diffusion control	High acid yield
LWR & Resolution	LWR & Resolution	Sensitivity

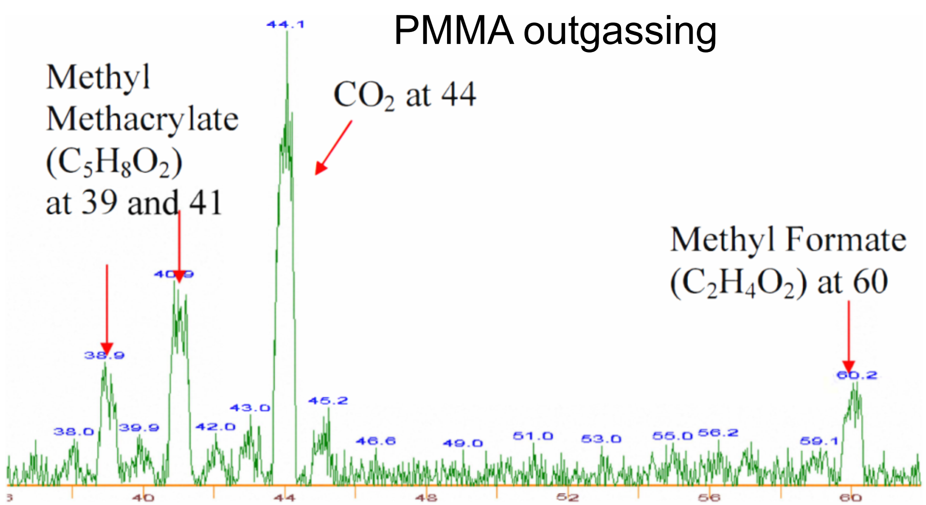
EUV Resist - 2

- High resolution and low LER for sub 1x nm technology node.
  - The energy per EUV photon (91.85 eV) is much higher than that for photons with wavelengths of 248 or 193 nm, there are far fewer EUV photons for the same doses as measured in mJ/cm^2.

$$LER = \frac{1}{ILS}\frac{4.08}{d\sqrt{E}},$$ where ILS is the image log slope, d is the length for LER measurement, and E is the exposure dose.



- High sensitivity to improve throughput.



- Low out-gassing to avoid contamination on the optical system.

R&D Cost and System Price

ASML

Public

Significant R&D required to support lithography tool development – "the shrink engine"

R&D: ~50 mln €

1980's:
PAS 2000/5000
Resolution:
<500 nm Overlay
>100nm

R&D: ~400 mln €

1990s:
PAS 5500 steppers/scanners
Resolution: 400 to 90 nm
overlay: > 12 nm

R&D: ~1.5 bln €

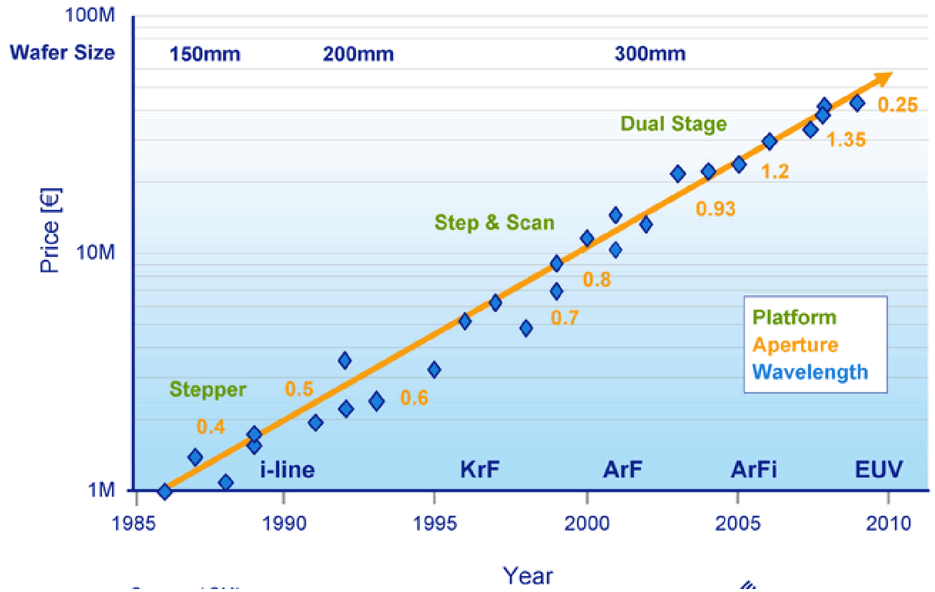
2000s:
Twinscan
Resolution:
>1X nm
overlay: > 2 nm

R&D: ~2 bln €

2010s:
NXE EUV systems
Resolution:
<15 nm
overlay: <2 nm

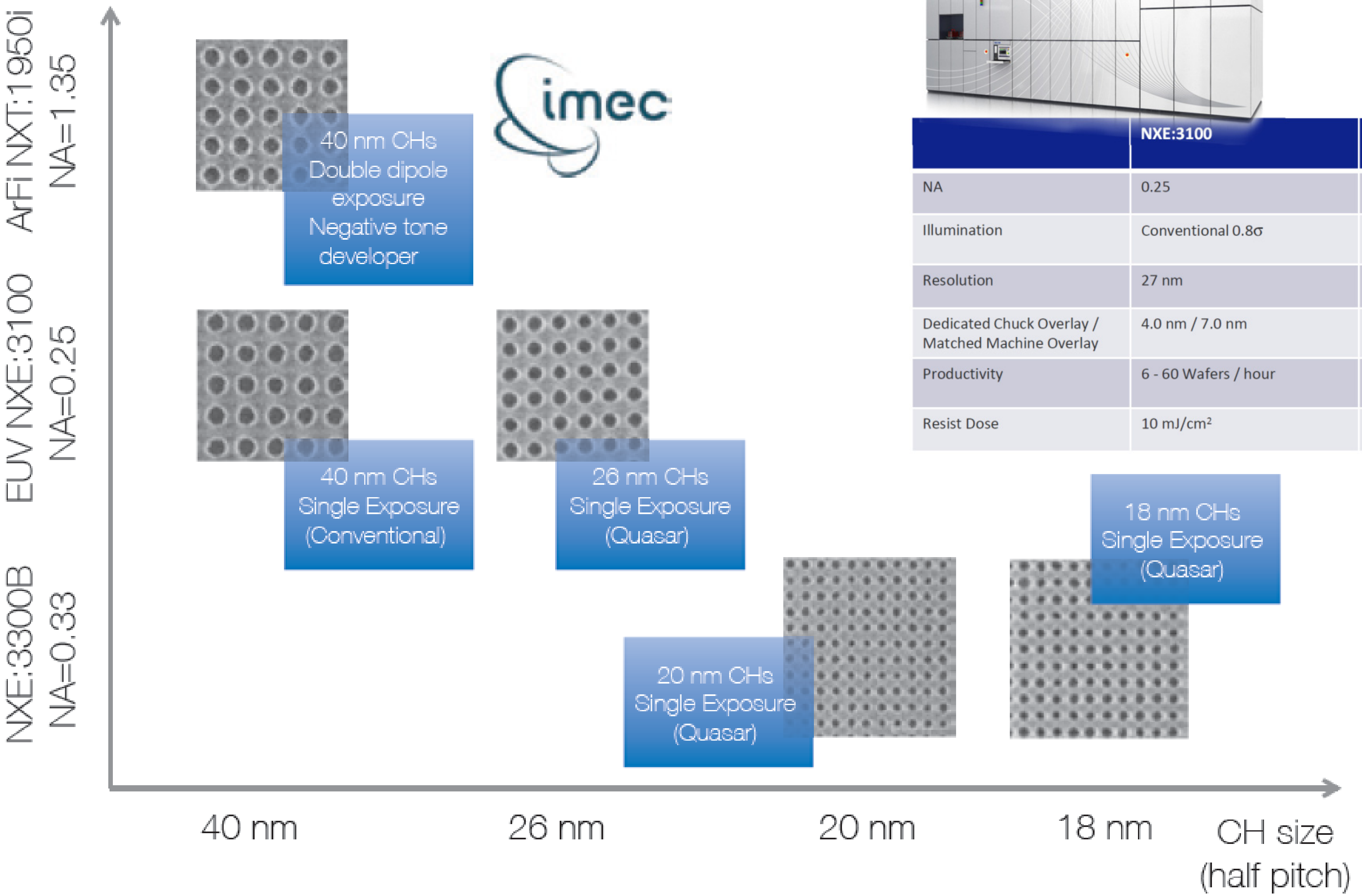
R&D: ? bln €

2015s:
450 mm systems
Resolution:
KrF, Immersion, EUV
overlay: <2 nm



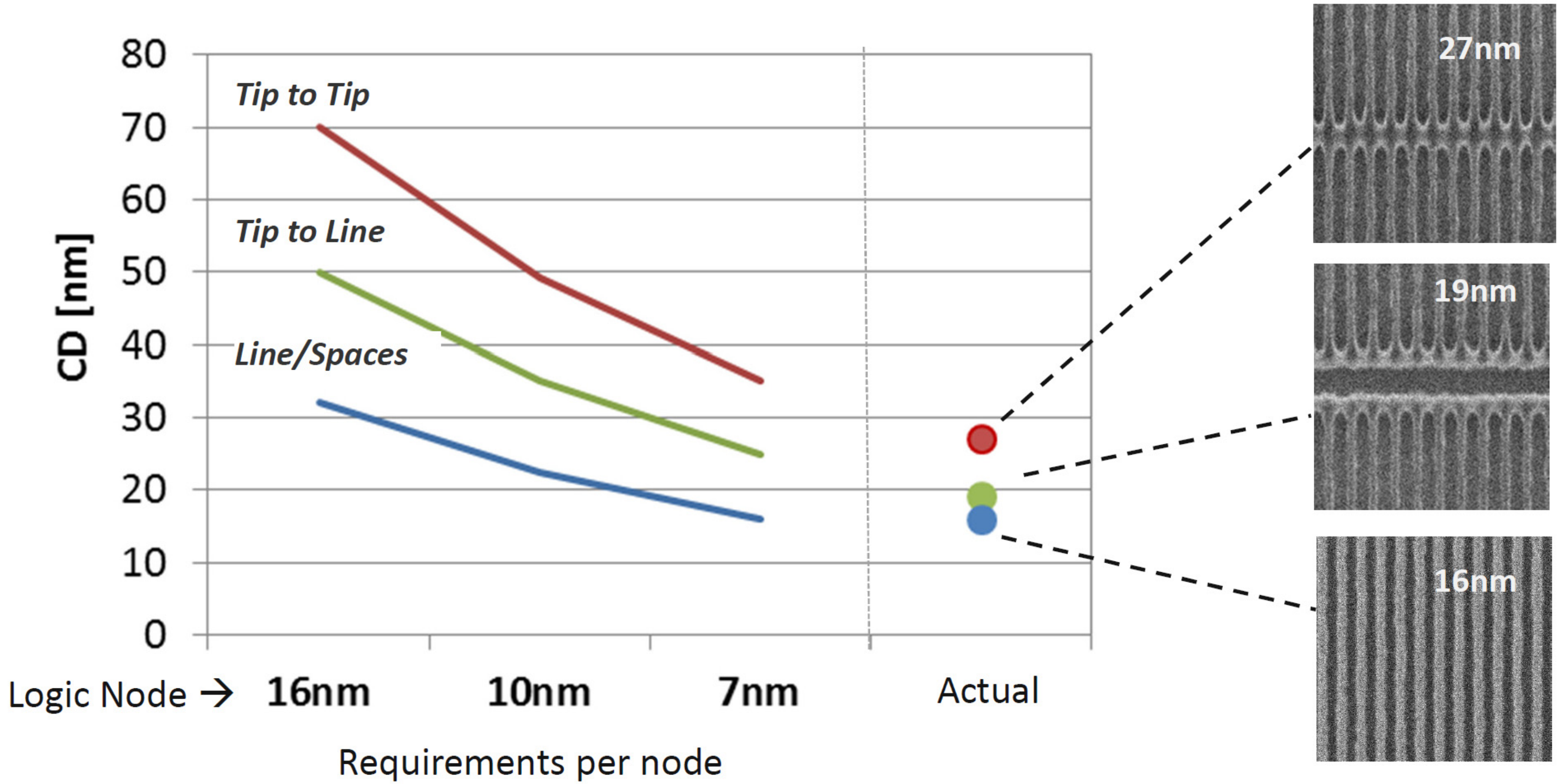
Performance of EUVL - 1

NXE:3300B dense-CH imaging down to 18 nm hp



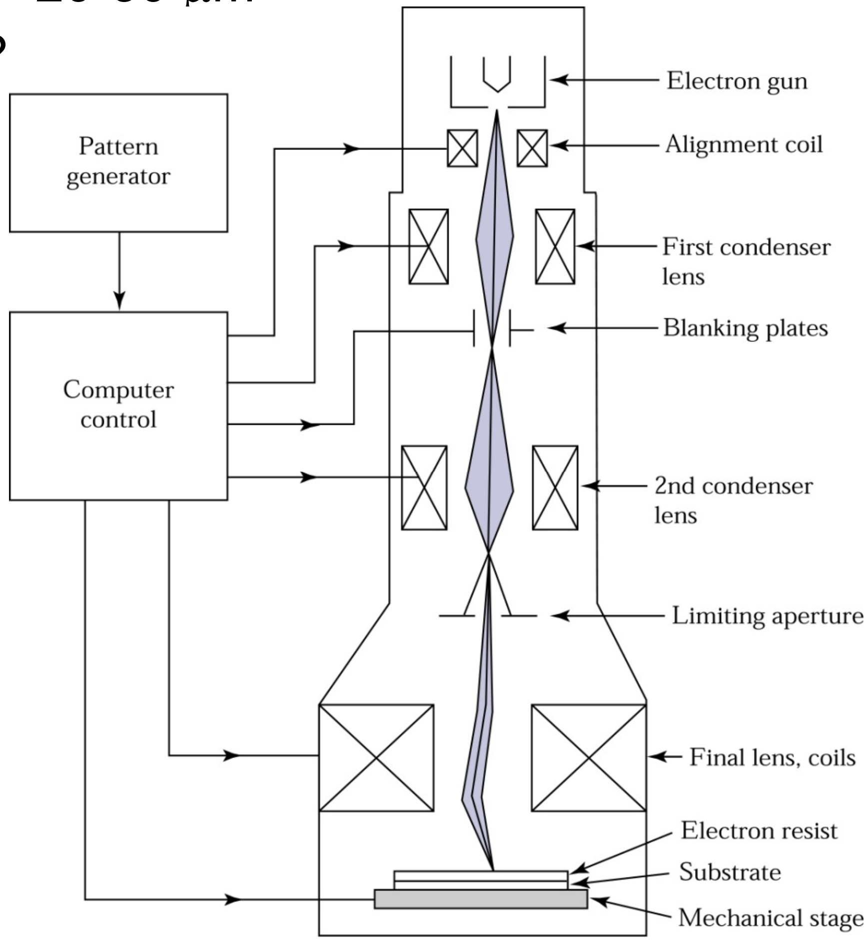
	NXE:3100	NXE:3300B shipments started 2013
NA	0.25	0.33
Illumination	Conventional 0.8σ	Conventional 0.9σ, 6 off-axis pupil settings
Resolution	27 nm	22 nm
Dedicated Chuck Overlay / Matched Machine Overlay	4.0 nm / 7.0 nm	3.0 nm / 5.0 nm
Productivity	6 - 60 Wafers / hour	55 - 125 Wafers / hour
Resist Dose	10 mJ/cm²	15 mJ/cm²

Performance of EUVL - 2



E-Beam Lithography

- Advantages
  - High resolution~30 nm
  - Large DOF~20-30 μm
  - Maskless ?



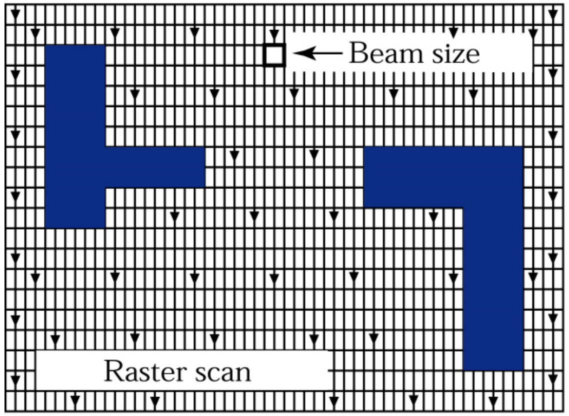
W or LaB_6 thermionic-emission tip

Focus beam diameter to 10-25 nm

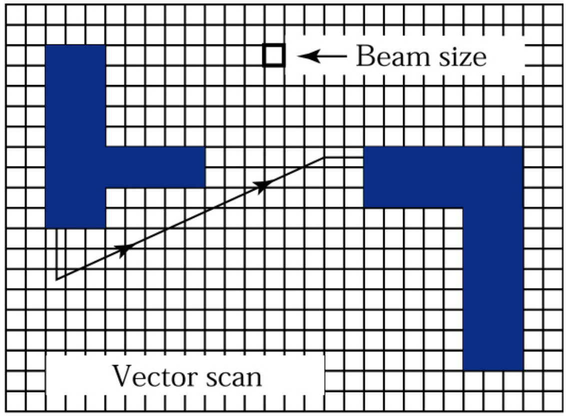
Turn on/off beam

Computer controlled to direct the beam.
Scan field ~ 1 cm

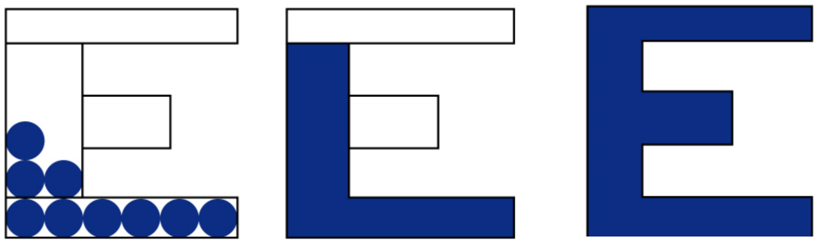
E-Beam Scanning



Raster Scan



Vector Scan



Round

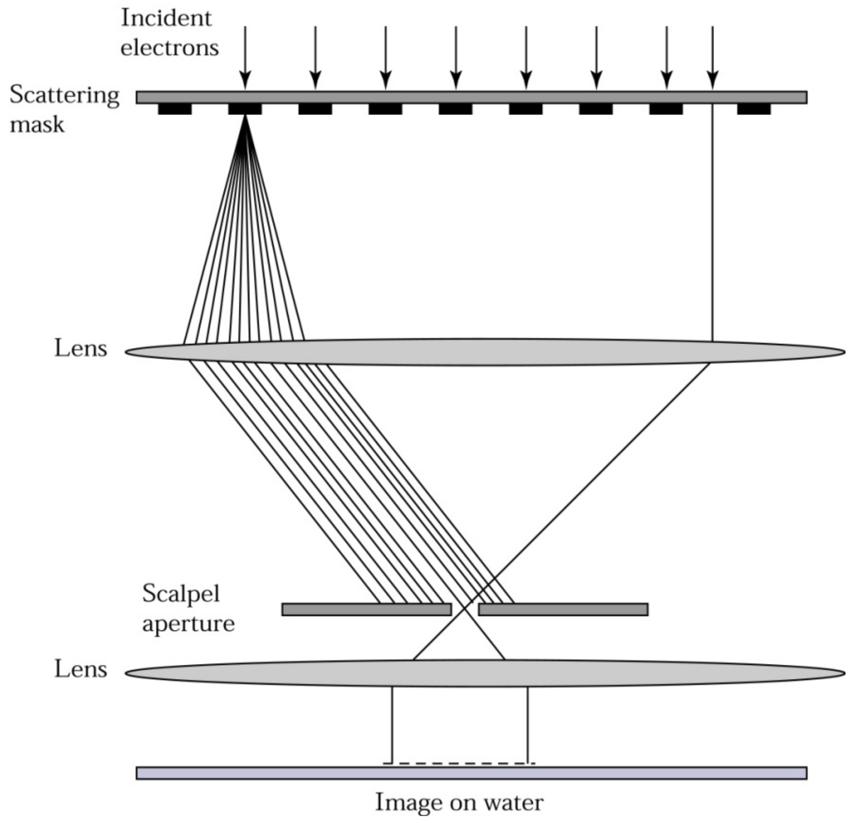
Variable

Cell Projection

Shaped Beam

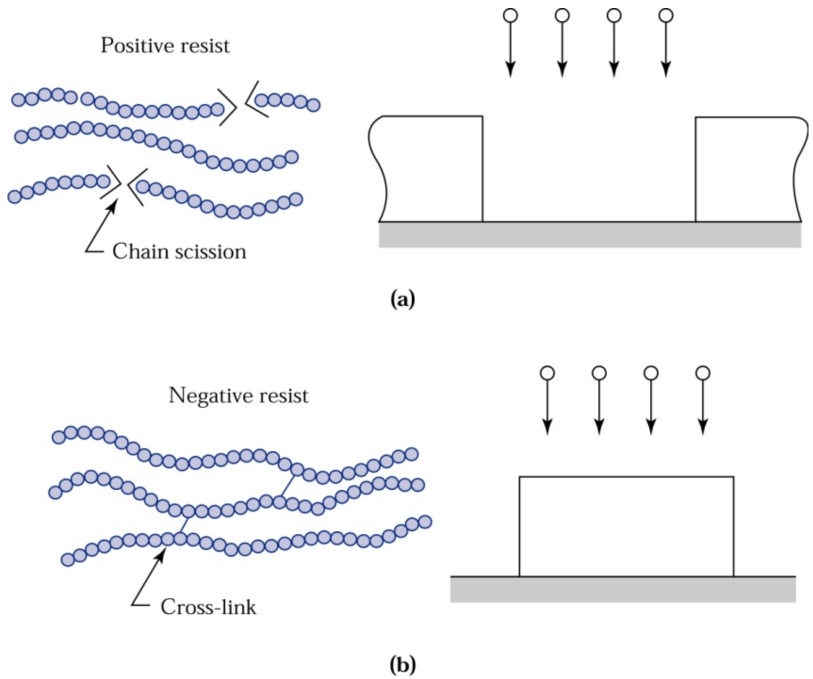
SCALPEL System

- SCALPEL
  - Scattering with Angular Limitation Projection Electron beam Lithography
- A new mask design consists of
  - Low atomic number membrane (Si_3N_4, 100-150 nm)
  - High atomic number pattern (Cr or W, 30-60 nm)
  - Mask is uniformly illuminated by a parallel beam of 100 keV electron over a 1 mm^2 area.
  - Mask is completely electron transparent at the energy of 100 keV.
  - Pattern layer scatters most electrons strongly with high angles.



E-Beam Resist

- Positive resist
  - The polymer-electron interaction causes chemical bonds to be broken (chain scission) to form shorter molecular fragments.
  - Poly-methyl methacrylate (PMMA) or poly-butene-1 sulfone (PBS)
- Negative resist
  - Irradiation causes radiation-induced polymer linking to create a complex three dimensional structure.

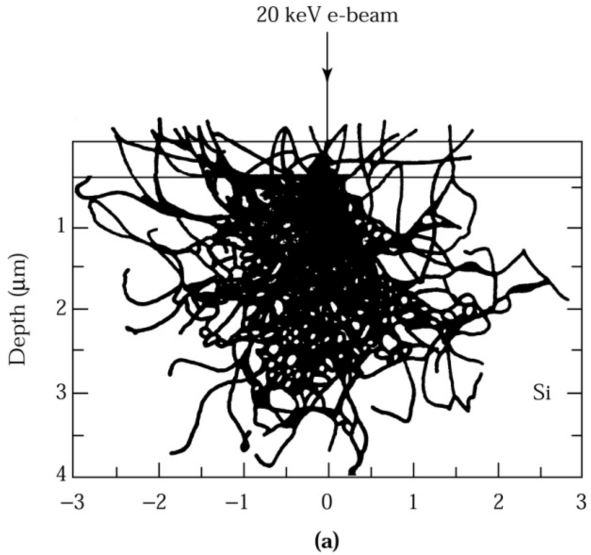


(a)

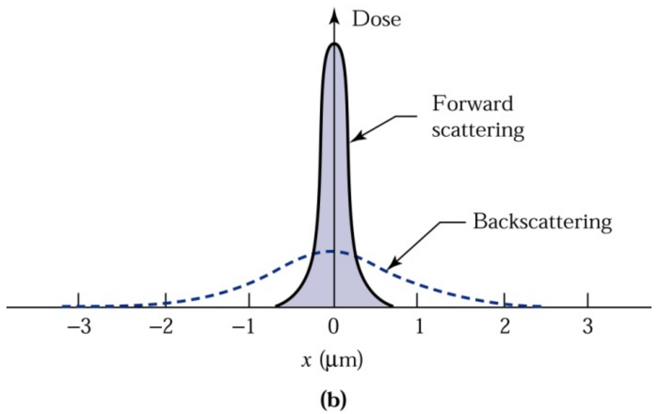
(b)

Electron Scattering

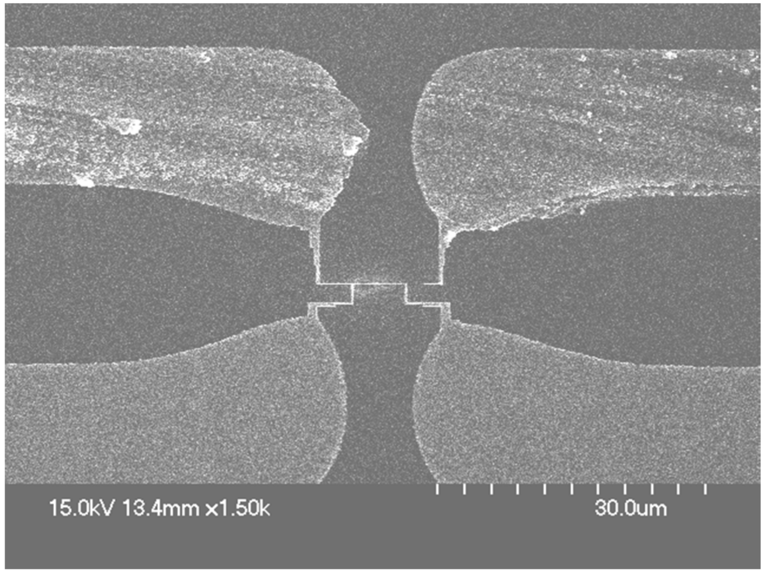
- Scattering but not diffraction is the main reason of proximity effect.



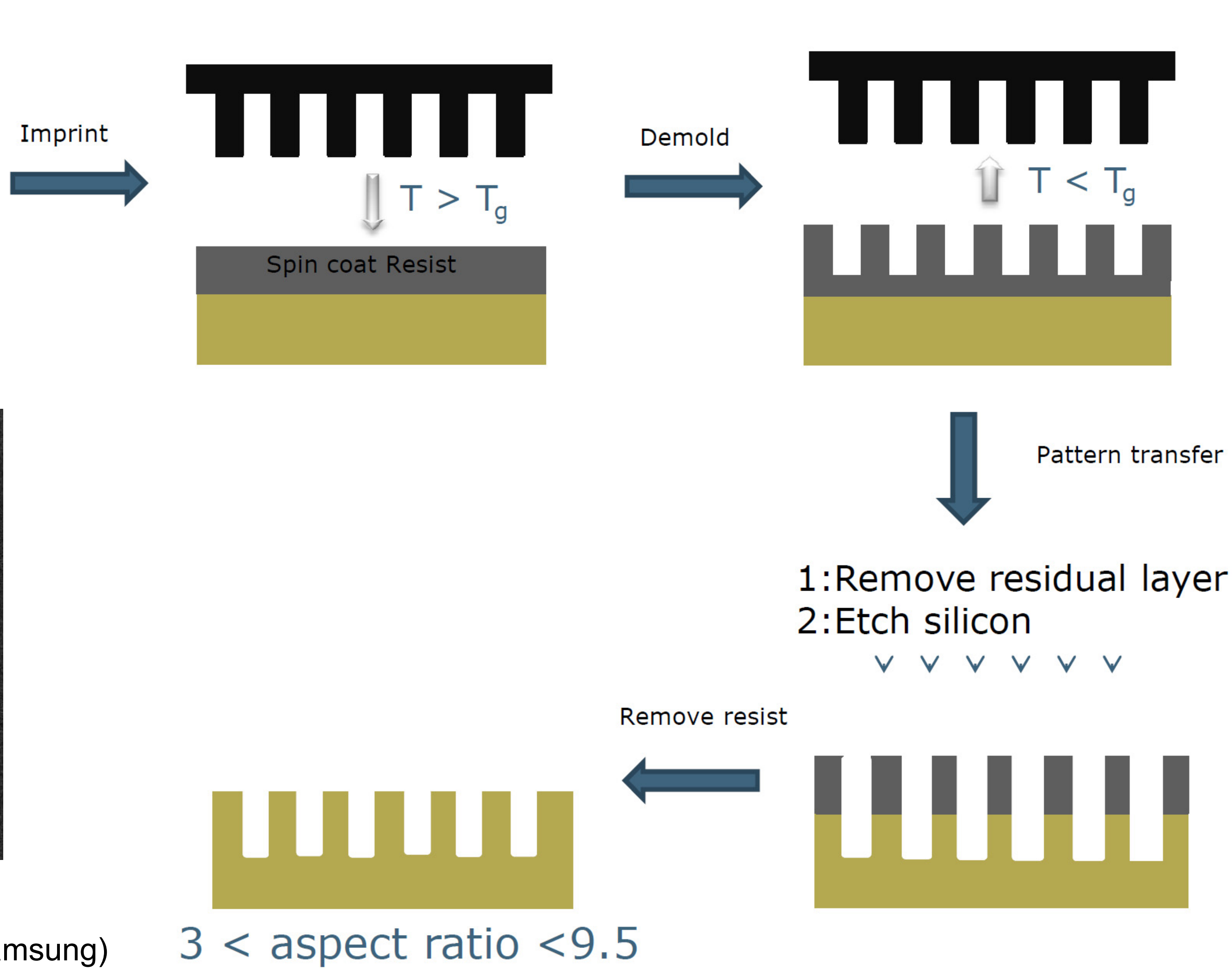
(a)

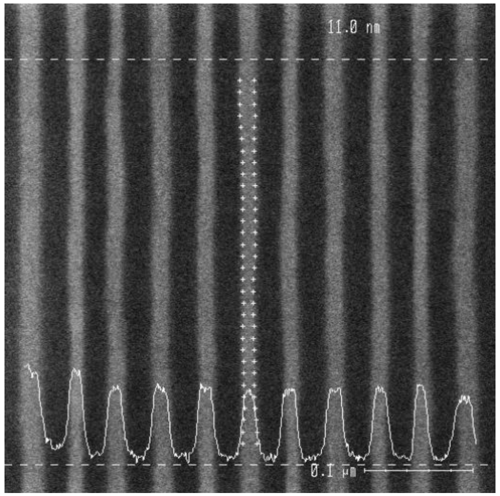


(b)



Concept of Nano Imprint



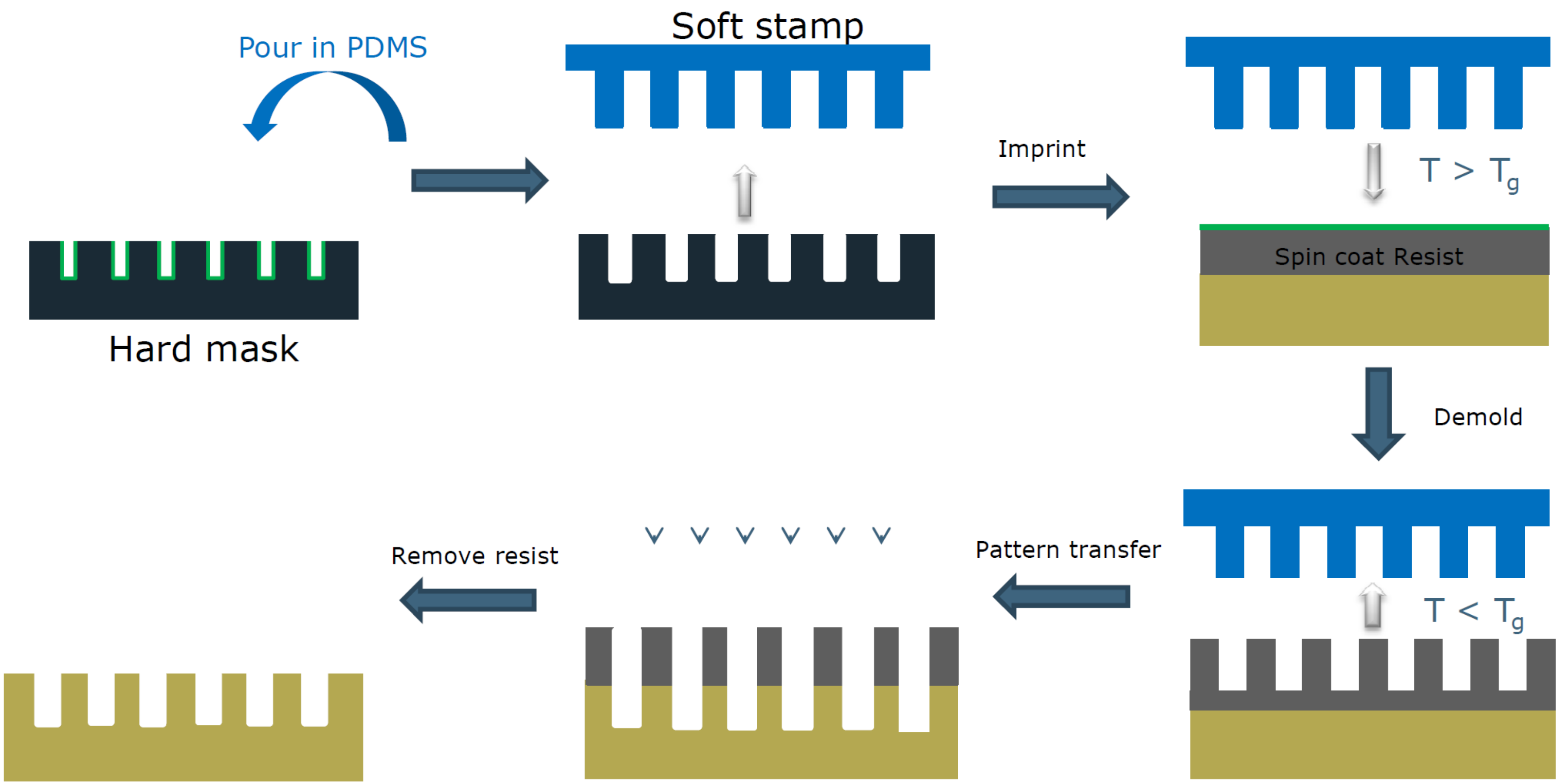


11 nm line width
(Image courtesy of SEMATECH and Samsung)

Concept of Soft Nano Imprint

1: PDMS=Silicone Elastomer

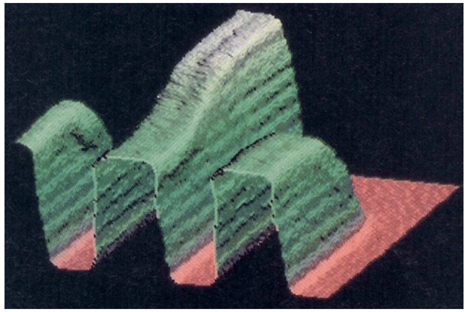
2: With anti-sticky layer coating when fabricating soft stamp and imprinting

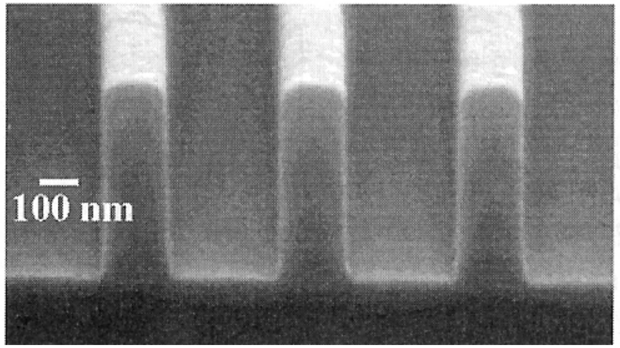


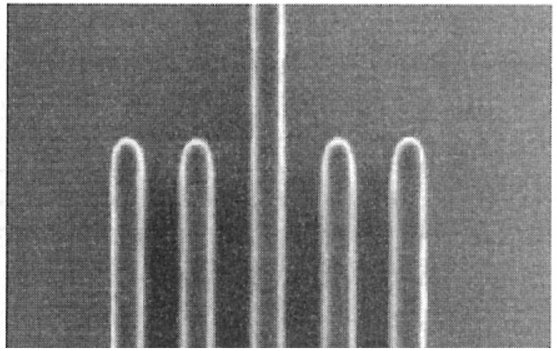
Inspection

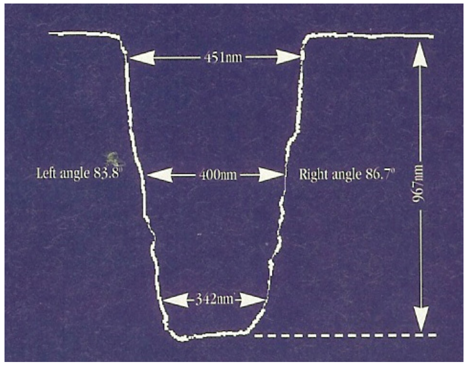
CD Measurement

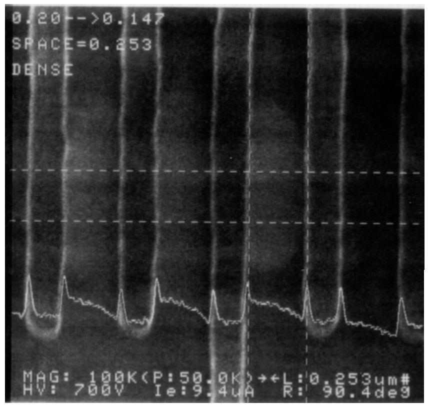
- In-line SEM plane-view (tilted angle) inspection
- Off-line SEM cross-sectional inspection
- CD AFM











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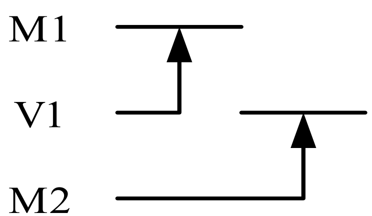
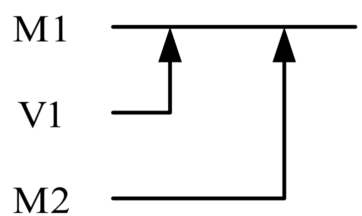
Overlay Errors

- Errors generated mainly in two steps: alignment and exposure.
  - Direct alignment : depends on machine and mask
  - Indirect alignment : also depends on alignment sequence



$$OL_{3-1} = \sqrt{OL_{2-1}^2 + OL_{3-2}^2}$$



Overlay

	Back layer			
Front layer		M1	V1	M2
	M1	/	/	/
	V1	0.07	/	/
	M2	0.10	0.07	/

→Overlay of M2 to V1 is 0.07μm

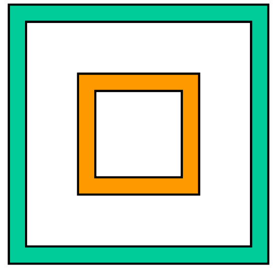
Overlay

	Front layer			
Back layer		M1	V1	M2
	M1	/	/	/
	V1	**0.07**	/	/
	M2	**0.07**	0.10	/

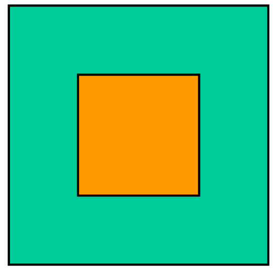
→Overlay of M2 to V1 is 0.1μm

Overlay Monitor

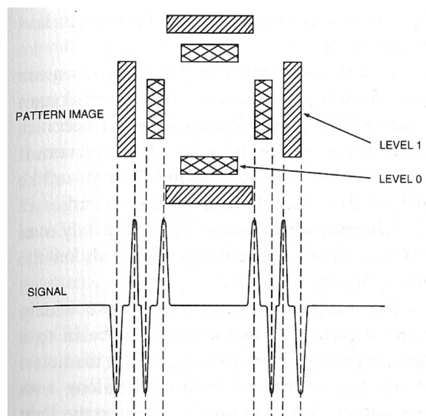
- Automatic reading - overlay target
  - The purpose of overlay target is to precisely measure overlay by overlay machine.
  - Frame-in-frame, box-in-box, and bar-in-bar patterns can be used. The outer one is the front layer, the inner one is the back layer which will be resist pattern on wafer.
    - Frame-in-frame and bar-in-bar have 4 edges at each layer
    - Box-in-box has two edges at each layer
  - Image is detected by a CCD camera and is numerically processed to determine overlay.
  - Overlay as good as 10 nm can be resolved.
  - Various designs are used by various machine.
  - Any process results in asymmetrical structure will degrade reading validity.
  - Frame and box must not be fully planarized.



frame-in-frame



box-in-box



bar-in-bar

Defects Inspection

- Un-patterned wafer
  - Light scattering
    - Optical microscope
  - Image comparison
    - Optical microscope or scanning electron microscope
- Patterned wafer
  - Periodic pattern
    - Pattern comparison with pre-selected area
  - Random pattern
    - Pattern comparison with on-mask pattern or layout
- Defects identification
  - Precision SEM or TEM inspection plus another analysis