PSM: Phase Shifted Masks

- Physics
- Performance to date
- ***<u>Types:</u>***
- Embedded Attenuated (leaky chrome) (Att-PSM): : EAPSM
- Alternating aperture (Alt-PSM): AAPSM and SCAAM
- Unattenuated (Chromeless): UAPSM
- Rim Shifters
- Multi-phase
- ***<u>Low k1 PSM processes</u>***; Double exposure techniques: IDEAL, GRATEFUL

PSM: Phase Shifted Masks

http://www.kla-tencor.com/company_info/magazine/autumn00/AutumnMag00.pdf

- RET Reticle enhancement techniques by Node
- Embedded Attenuated (leaky chrome) (Att-PSM): : EAPSM
- Alternating aperture (Alt-PSM): AAPSM

Node		180nm	130nm	100nm	70nm
KrF Lithography	Feature size / Wavelength Ratio	73%	53%	40%	28%
	Binary	OPC / Serif	OPC / Assist Bar	-	-
	Att-PSM*	3- 8%	15- 25%	-	-
	Alt-PSM**	-	Shifter Edge Type (Logic Gate)	Shifter Edge Type (Logic Gate)	-
		-	Hidden Shifter Type (Memory)	-	-
ArF Lithography	Feature size / Wavelength Ratio	93%	67%	52%	36%
	Binary	-	OPC Serif	OPC / Assist Bar	-
	Att-PSM	-	3- 8%	15- 25%	-
	Alt-PSM	-	-	Shifter Edge Type (Logic Gate)	Shifter Edge Type (Logic Gate)
		-	-	Hidden Shifter Type (Memory)	-
F_2 Lithography	Feature size / Wavelength Ratio	115%	83%	64%	45%
	Binary	-	-	OPC / Assist Bar	-
	Att-PSM	-	3- 8%	3- 8%	15- 25%
	Alt-PSM	-	-	-	Shifter Edge Type (Logic Gate)
		-	-	-	Hidden Shifter Type (Memory)

High-transmission and Tri-tone type Att-PSM

*Att-PSM = Attenuated Phase Shifting Mask

**Alt-PSM = Alternating Phase Shifting Mask

Phase Shifted Masks: PSM

http://www.gbhap.com/Science_Spectra/20-2-article.htm

- ***P***hase ***S***hifted ***M***ask IDEA 180^{o} phase shift between spaces on mask grating (Alt-PSM)

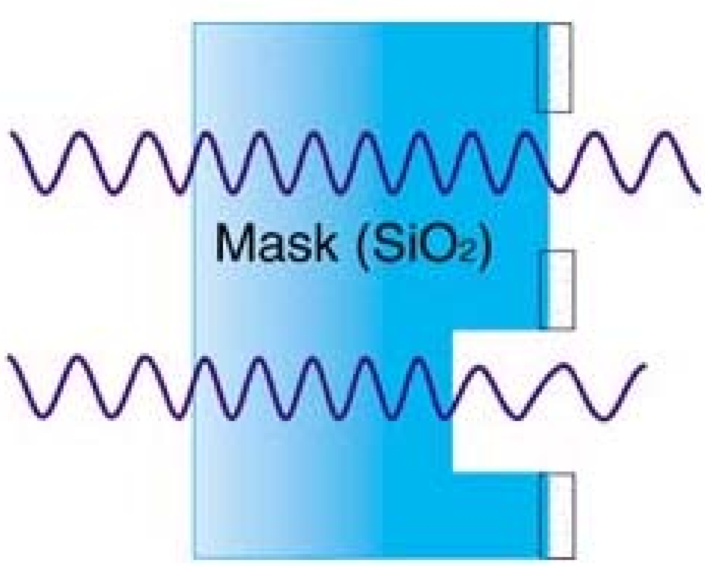
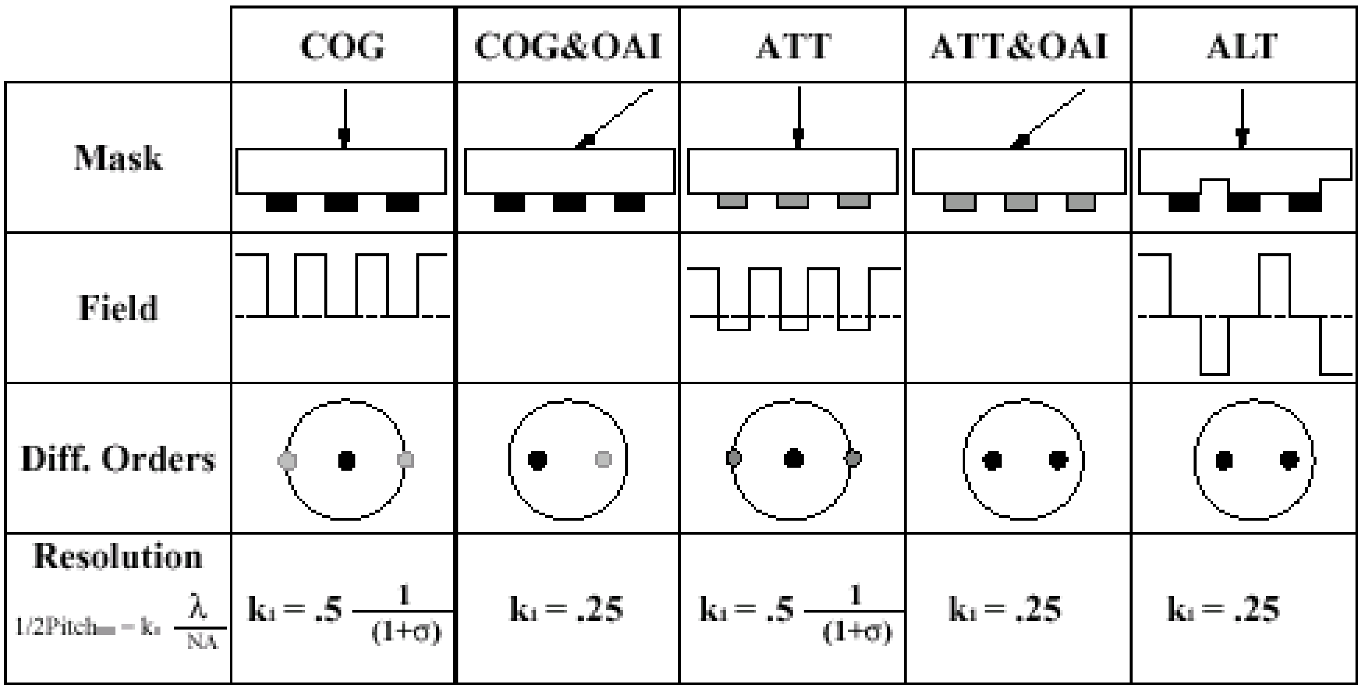


Figure 5: Passage of light through two openings of a phase-shifting mask, shown in cross-section. The two light rays enter in phase from the left-hand side, and exit 180 degrees out of phase from the right. The depth to which the SiO2 has been recessed from the lower opening controls the magnitude of the phase difference.

PSM:

- RET techniques



	COG	COG&OAI	ATT	ATT&OAI	ALT
Mask					
Field					
Diff. Orders					
Resolution $1/2Pitch_{min} = k_1 \frac{\lambda}{NA}$	$k_1 = .5 \frac{1}{(1+\sigma)}$	$k_1 = .25$	$k_1 = .5 \frac{1}{(1+\sigma)}$	$k_1 = .25$	$k_1 = .25$

Table 1, Concept, electric field amplitude, diffracted orders in the pupil plane, and k_1 limits of popular RET.

PSM: Phase Shifted Mask Basics: Physics

OPD: to create 180^o phase shift at edges

Phase shift is given by: ***$\theta = 2\pi t\ (n-1)\ /\lambda$***

n = refractive index of shifter material

λ = wavelength of exposure radiation

t = thickness of shifter material

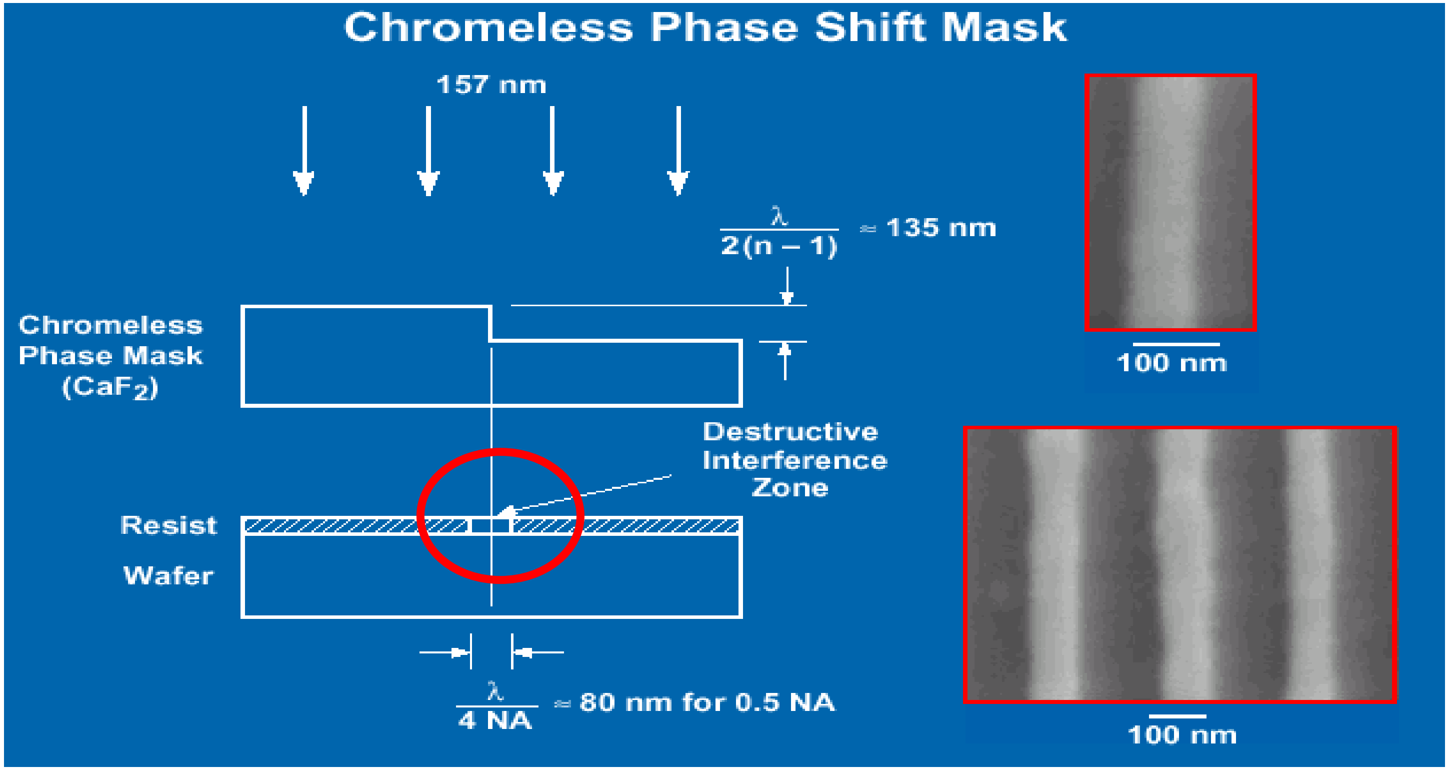
180^o Phase shift is given by: $\theta = \pi = 2\pi t\ (n-1)\ /\lambda$

then shifter thickness (depth): ***$T\ (\pi) = \lambda\ /[2 * (n-1)]$***

So one can tune a given material with refractive index n to be a PSM at a specific wavelength by adjusting the thickness.

PSM: Phase Shifted Mask Basics: Unattenuated *Chromeless*

180º Phase shift is given by: $\theta = \pi = 2\pi t(n-1)/\lambda$ then shifter thickness (depth): ***$T(\pi) = \lambda/[2*(n-1)]$***



PSM: Alternating Aperture

- Levenson idea (IBM):

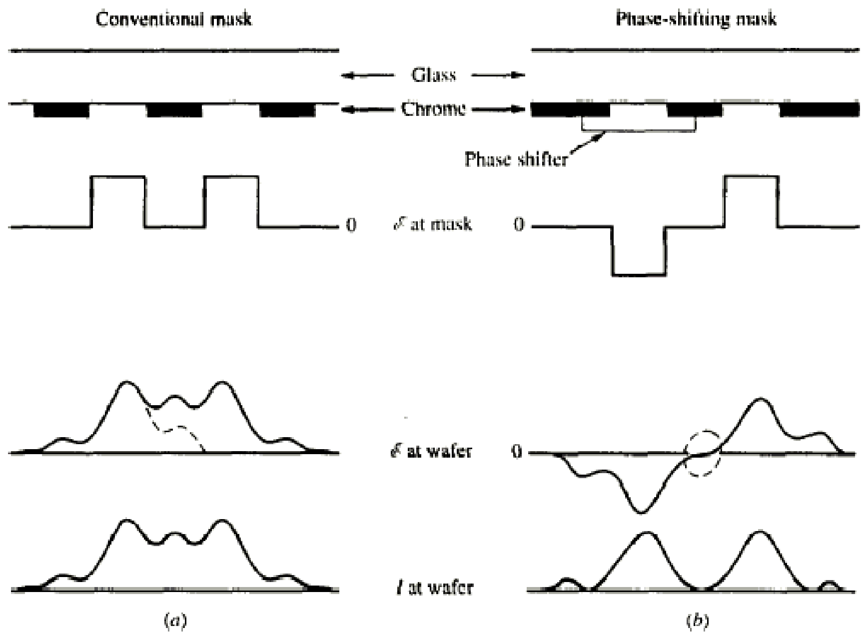
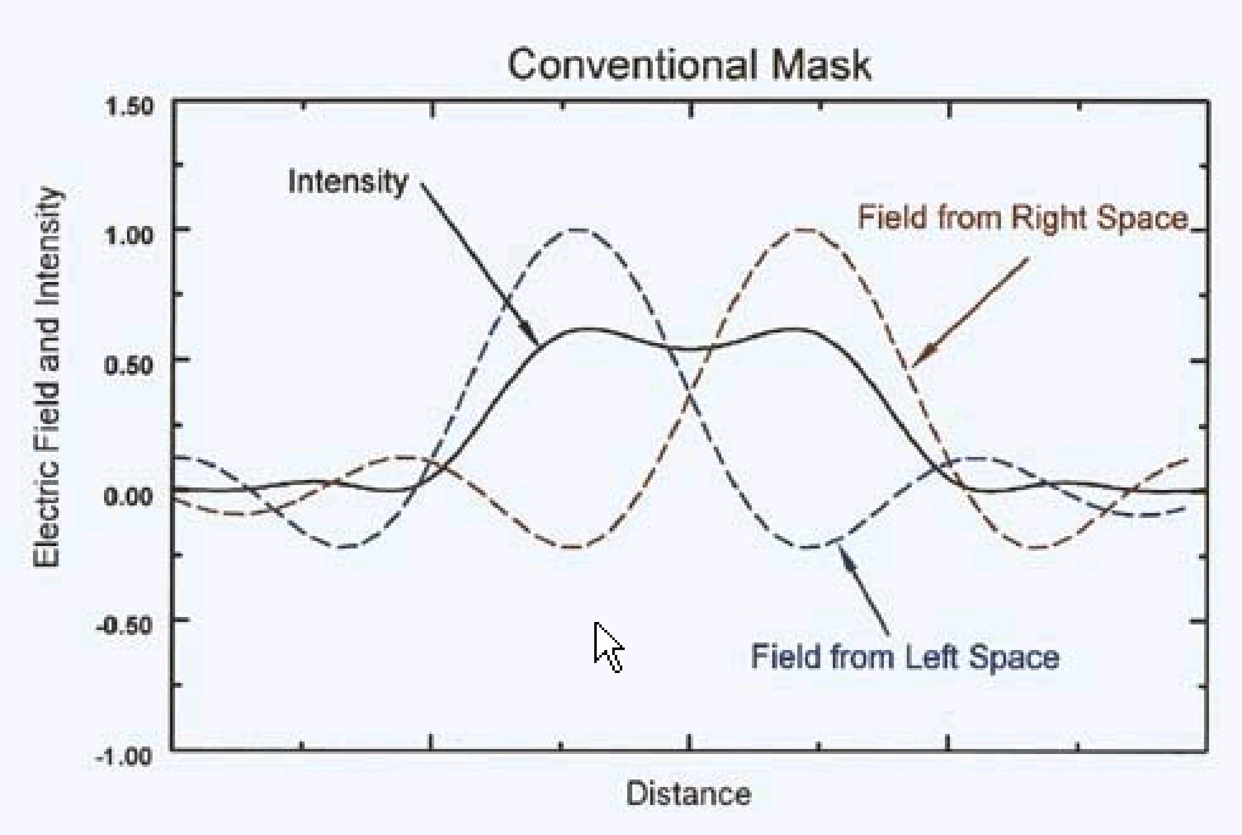


Figure 5.8: The principle of phase-shift technology. (**a**) Conventional technology. (**b**) Phase-shifting technology.

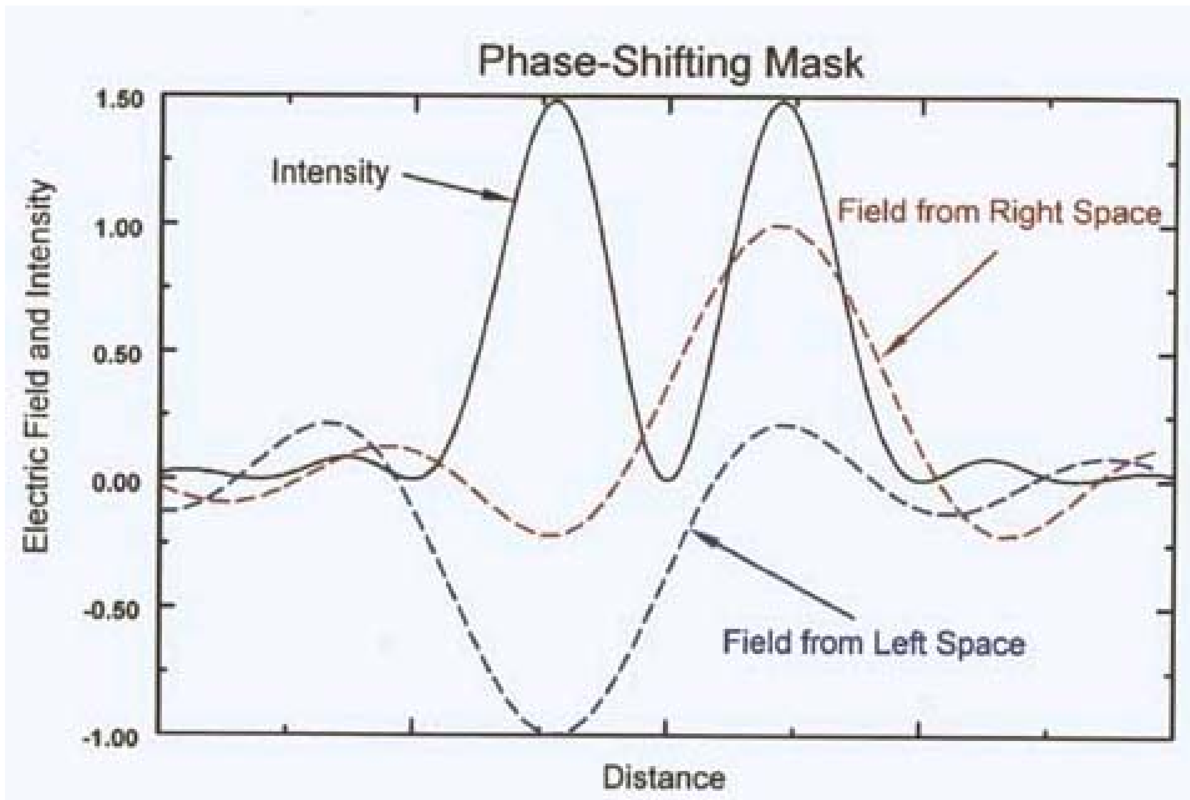
PSM: Alternating Aperture

- ***Binary mask*** electric field and intensity: $I = E^2$



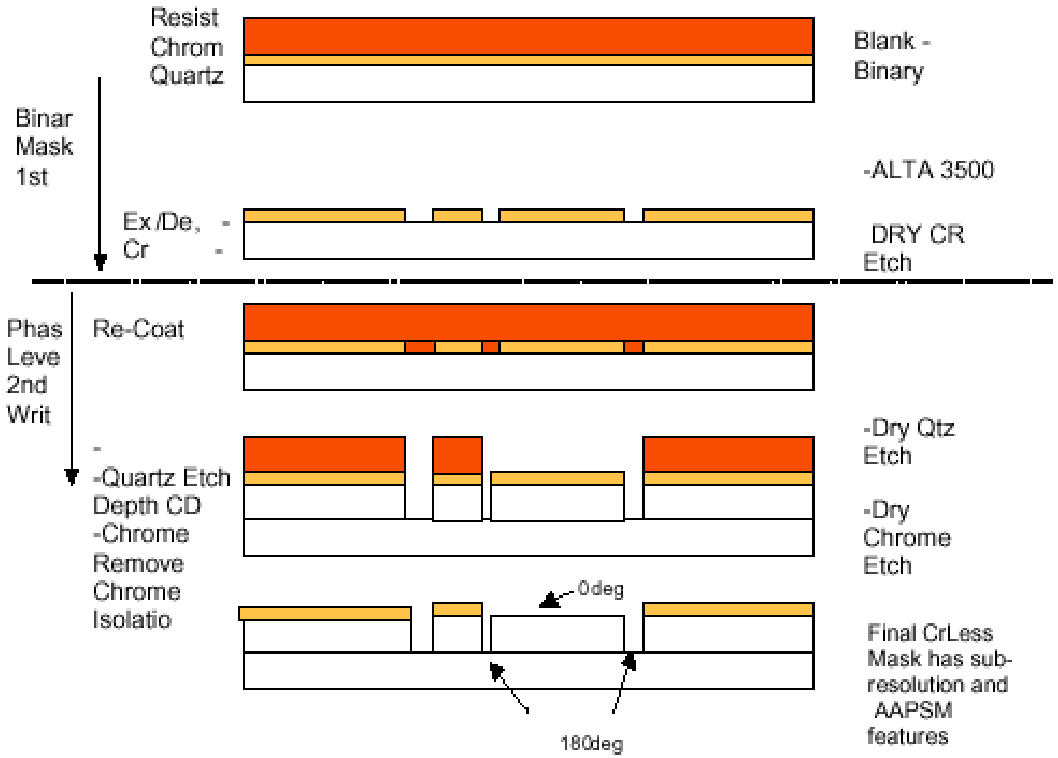
PSM: Alternating Aperture

- ***Phase shifted mask*** electric field and intensity



Alt-PSM: Alternating Aperture

- AAPSM fabrication process



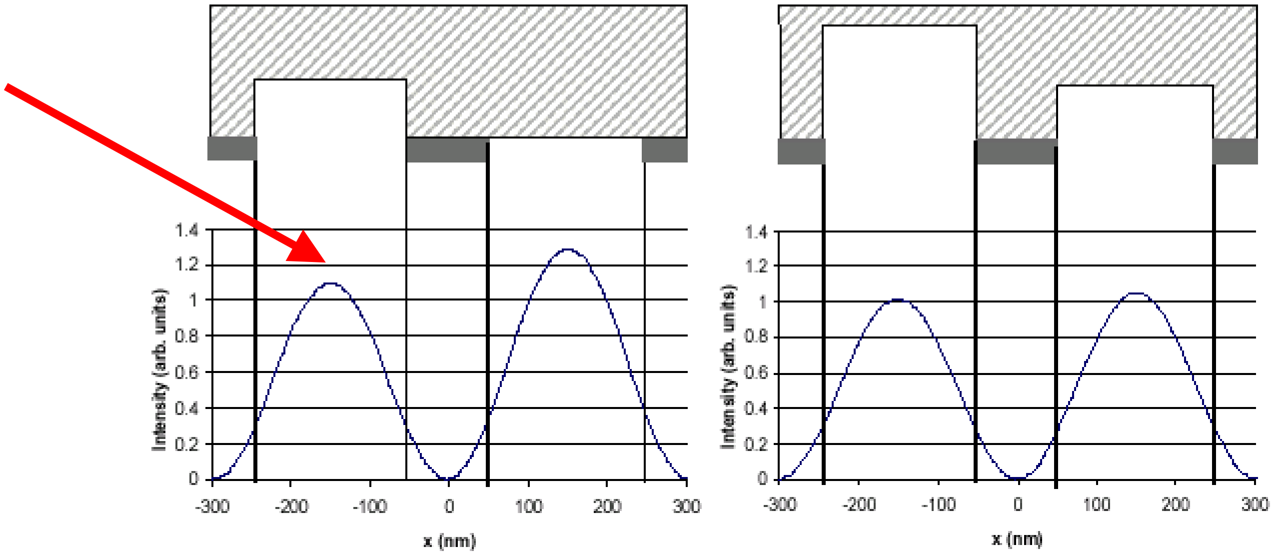
PSM: Alternating Aperture

http://www.advlitho.com/content/Papers/4346-72.pdf

- AAPSM Issue: ***Intensity*** difference between apertures

PSM Topography and Dual Trenches

- A perfectly manufactured phase-shifting mask has an intensity imbalance between the shifted and unshifted intensity peaks.
- Adding a dual trench corresponding to a global phase shift of π radians can equalize the peaks.



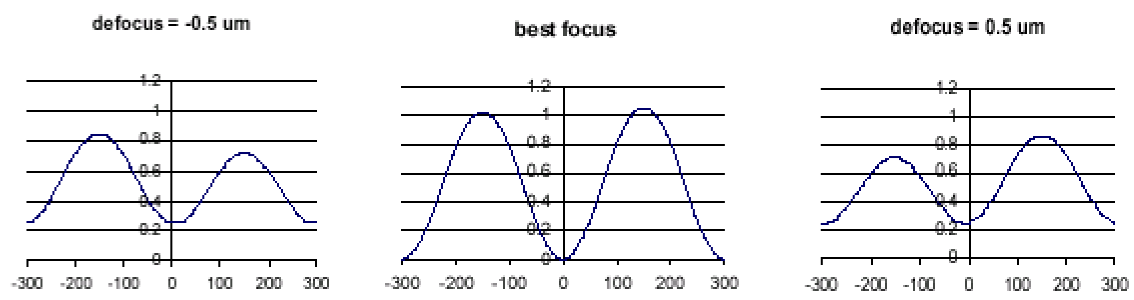
PSM: Alternating Aperture

http://www.advlitho.com/content/Papers/4346-72.pdf

- AAPSM Issue: ***Focus issue***

Phase Error

- More important, however, is the behavior of the shifted and unshifted peaks through focus.
- Note that the dual trench has shifted the intensity peaks apart. The peak equalization is therefore stymied out of focus.
- This means $\Delta\phi = 2\pi t(n-1)/\lambda$ is an insufficient model.

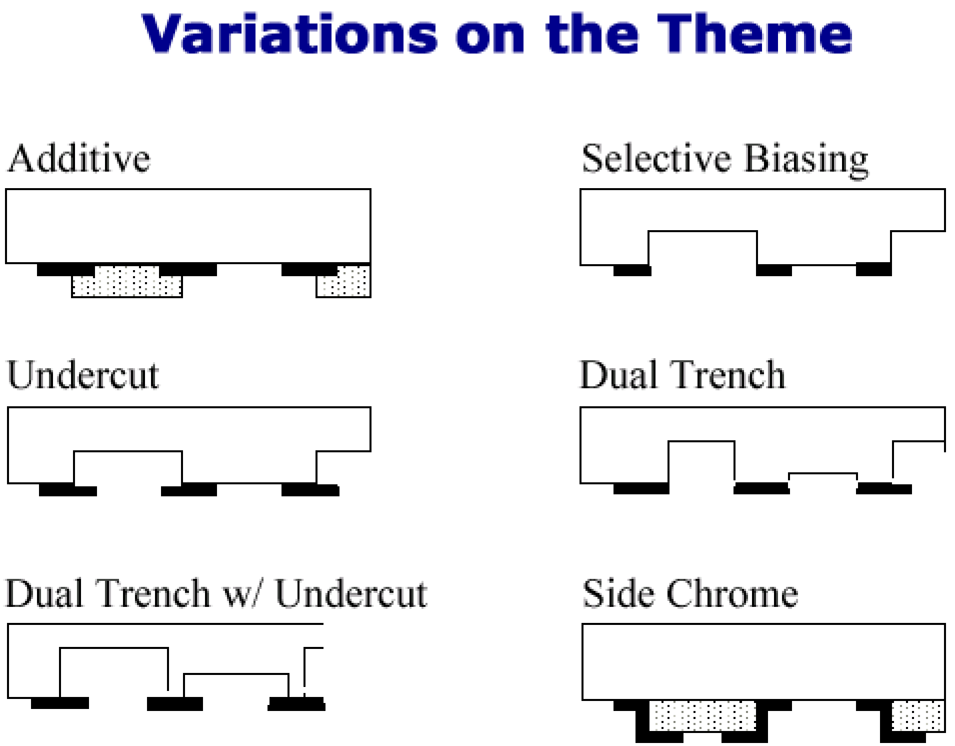


J. S. Petersen, et.al., SPIE Vol. 3564, p. 288 (1998)

PSM: Alternating Aperture

http://www.advlitho.com/content/Papers/4346-72.pdf

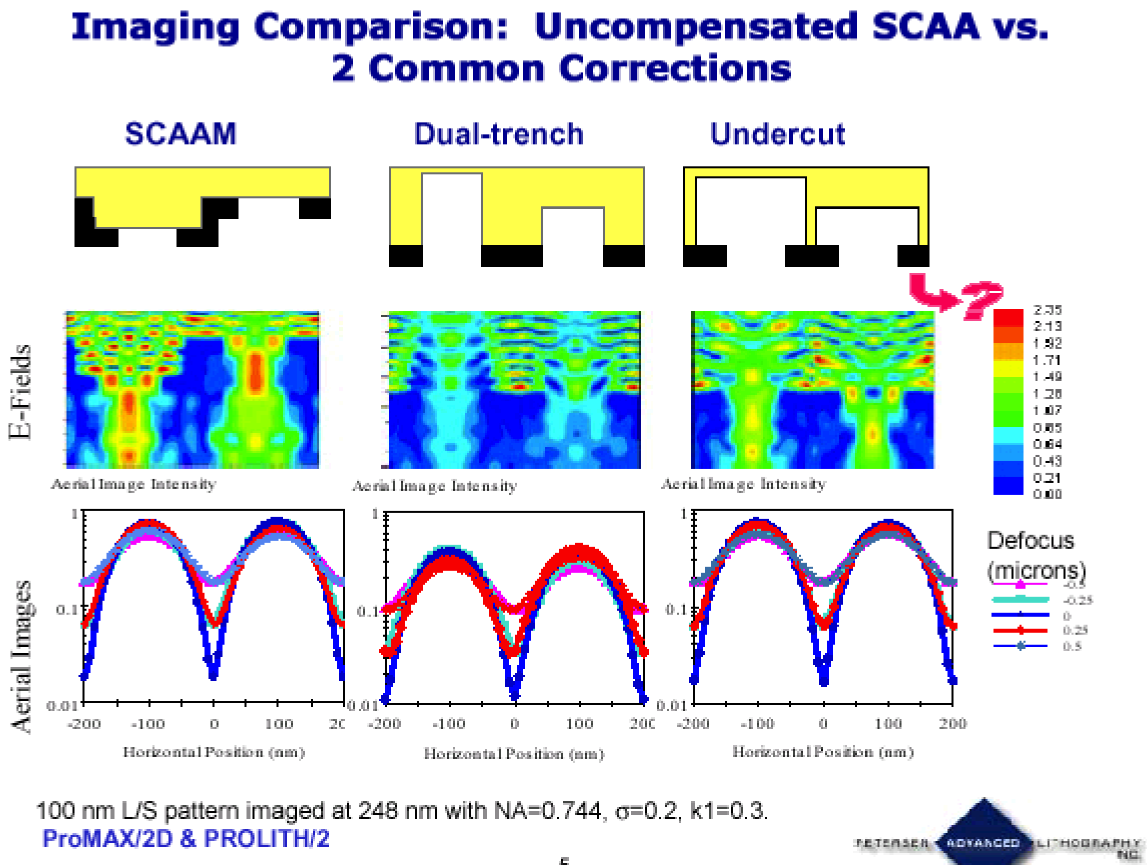
- AAPSM : correction for focus and intensity issue



PSM: Alternating Aperture

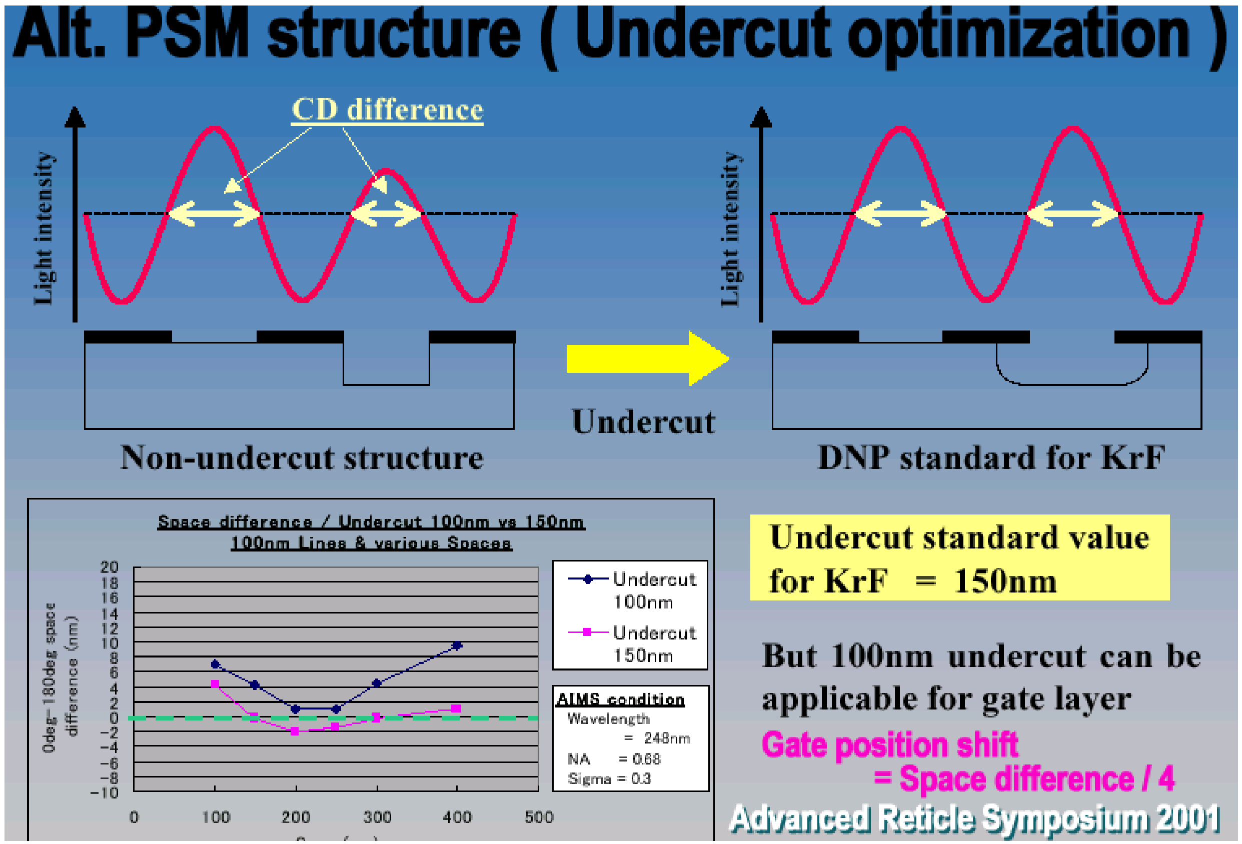
http://www.advlitho.com/content/Papers/4346-72.pdf

- ***AAPSM Issue: Focus and intensity mismatch***



PSM: Alternating Aperture

- AAPSM improved CD control = Aerial image intensity by undercutting

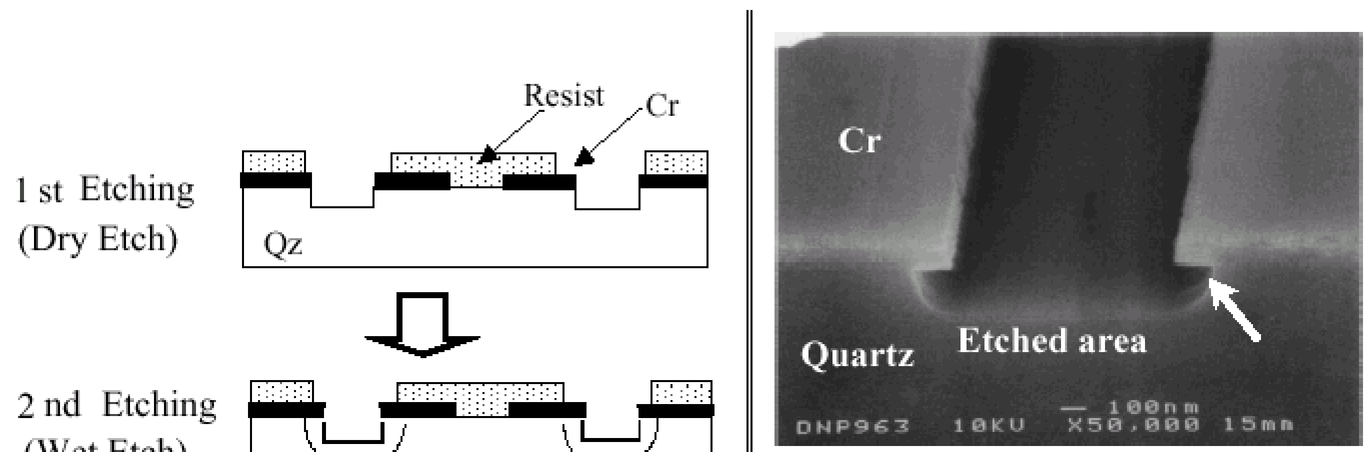


PSM: AAPSM Alternating Aperture

http://www.numeritech.com/download/files/53/ntiprsn.pdf

- Alternating Aperture PSM (hard Phase shifting): Quartz etch fabrication

Two-step Quartz Etching Process

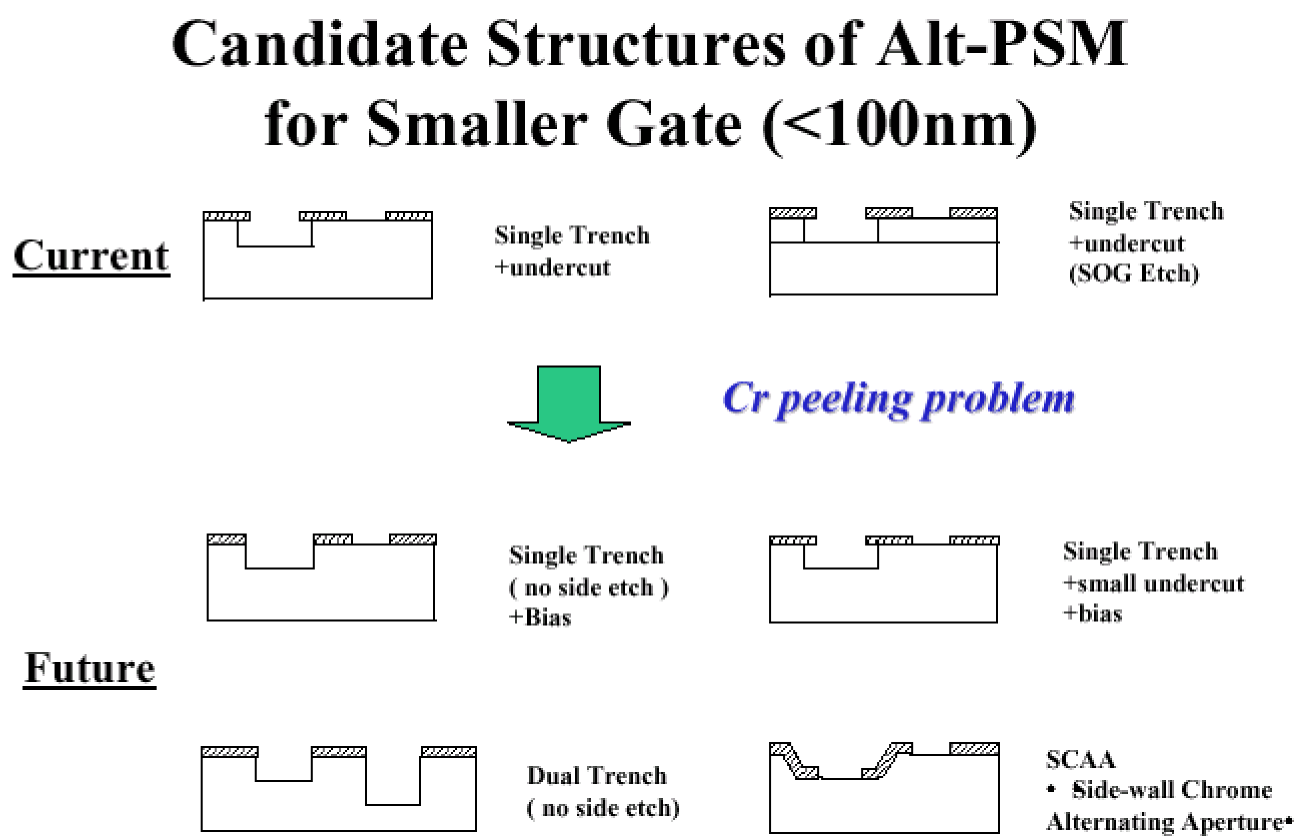


Cross-section SEM Image of Side-etched Structures

Advantages
- (1) It is easy to make the side-etched structures.
- (2) It is possible to control a phase angle precisely.
- (3) Defect density is small.

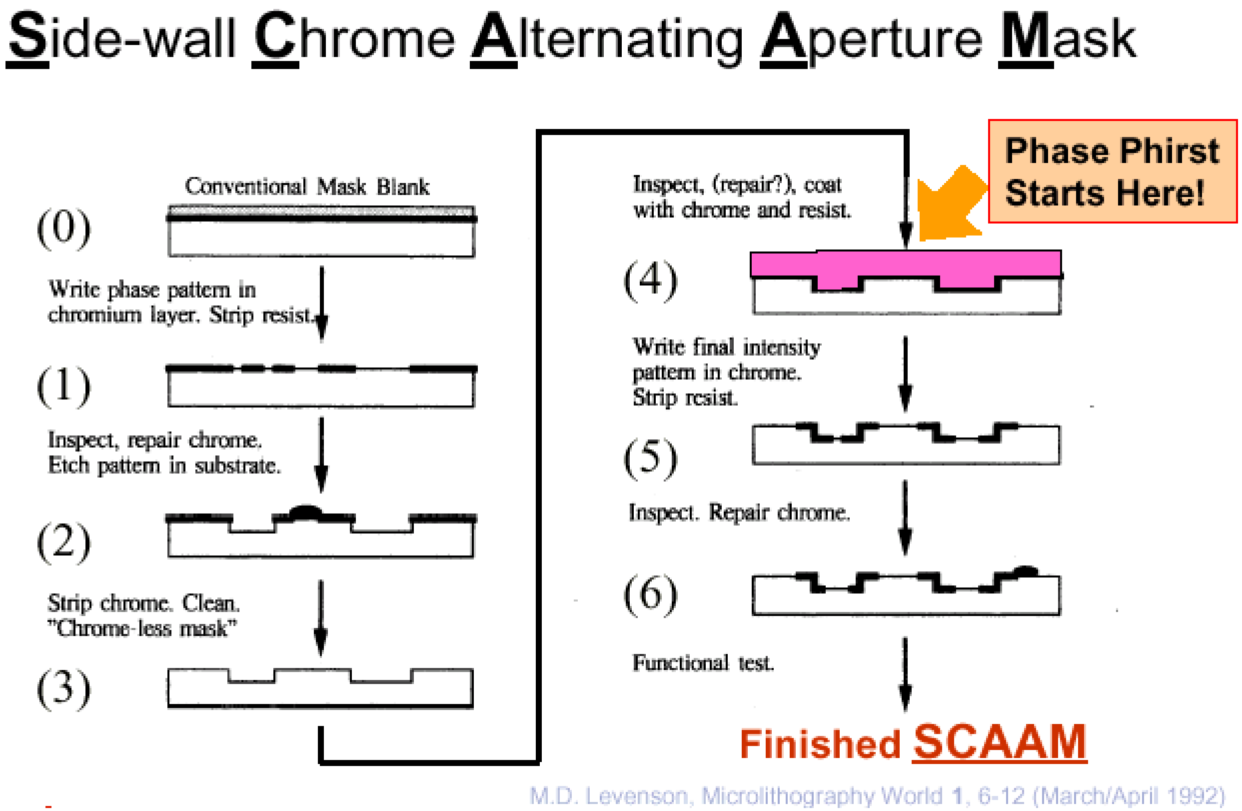
PSM: AAPSM Alternating Aperture: undercut issue

http://www.numeritech.com/download/files/53/ntiprsn.pdf



PSM: SCAAM Process

http://www.ultratech.com/about/presentations/T.Ebihara.PDF

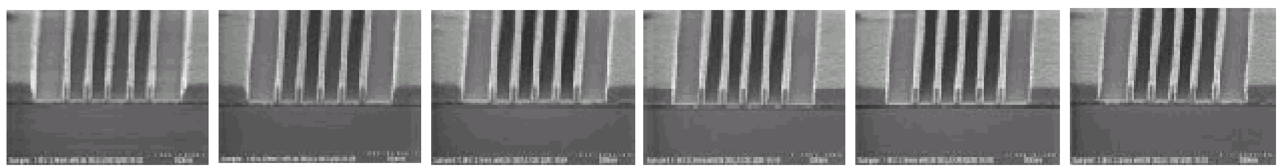


PSM: SCAAM Process

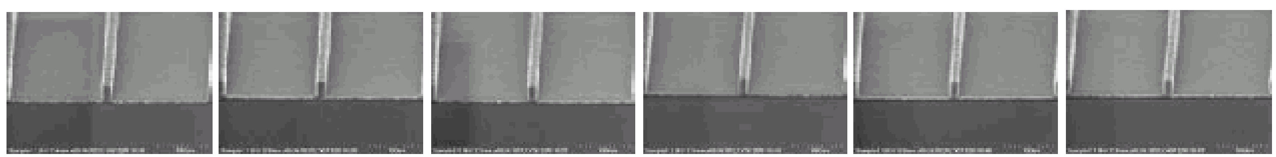
http://www.ultratech.com/about/presentations/T.Ebihara.PDF

73nm Semidense L/S and 106nm Isolated Line

220nm pitch Semidense: 72.9nm ± 2.5nm (1σ) linewidth; k_1 = 0.19



Isolated: 105.7nm ± 4.3nm (1σ) linewidth; k_1= 0.27



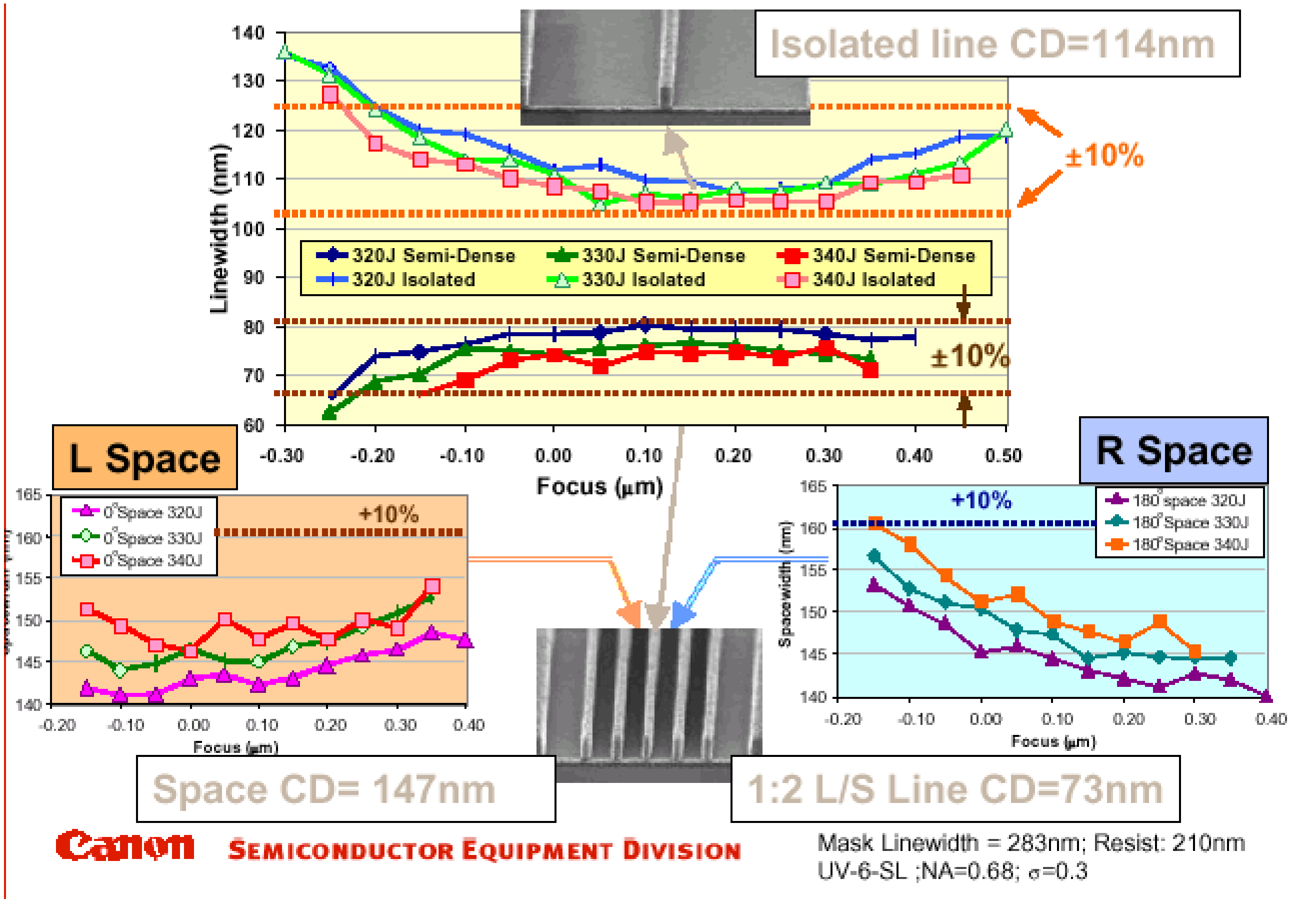
- 0.2 µm   - 0.1 µm   Best focus   + 0.1 µm   + 0.2 µm   + 0.4 µm

Focus Offset

Printed on Canon ES3, Resist: Shipley UV6-SL (2100Å), **NA= 0.63 σ= 0.3**
with 320J dose from SCAA mask patterns with 280nm linewidth @ 4 ×.

PSM: SCAAM Process

http://www.ultratech.com/about/presentations/T.Ebihara.PDF



Att- PSM: EAPSM Embedded Attenuated Phase shift:

http://www.advlitho.com/content/Papers/4000-126.pdf

Attenuated Phase shift: also called leaky chrome, weak shifter, and EAPSM(Embedded Attenuated Phase Shifted Mask): Typically $MoSi_2$ with a 6-8% transmission at a thickness that causes a 180^o phase shift. Most manufacturable Phase shift mask process! ***Very common for contact layer!***

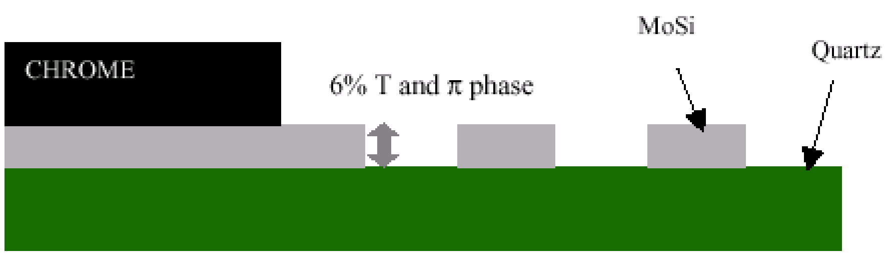


Figure 1: a) Tri-tone 6% attenuated PSM

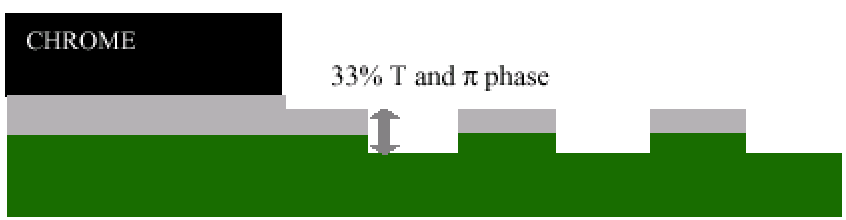
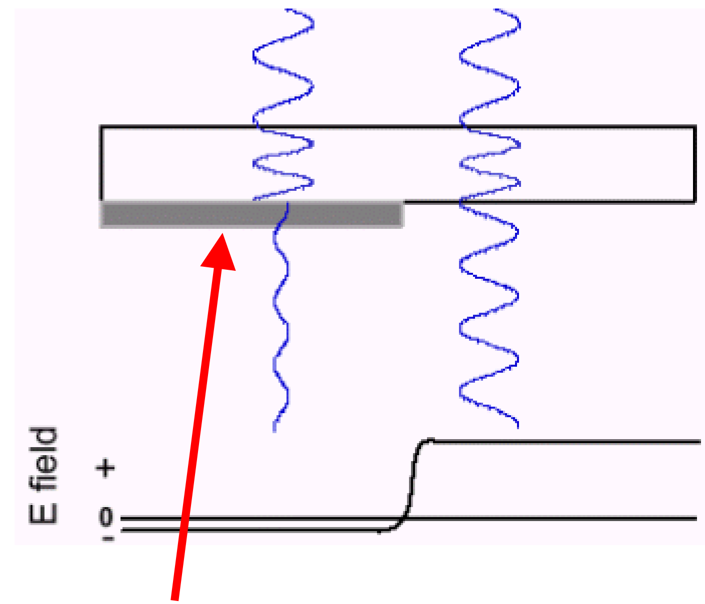


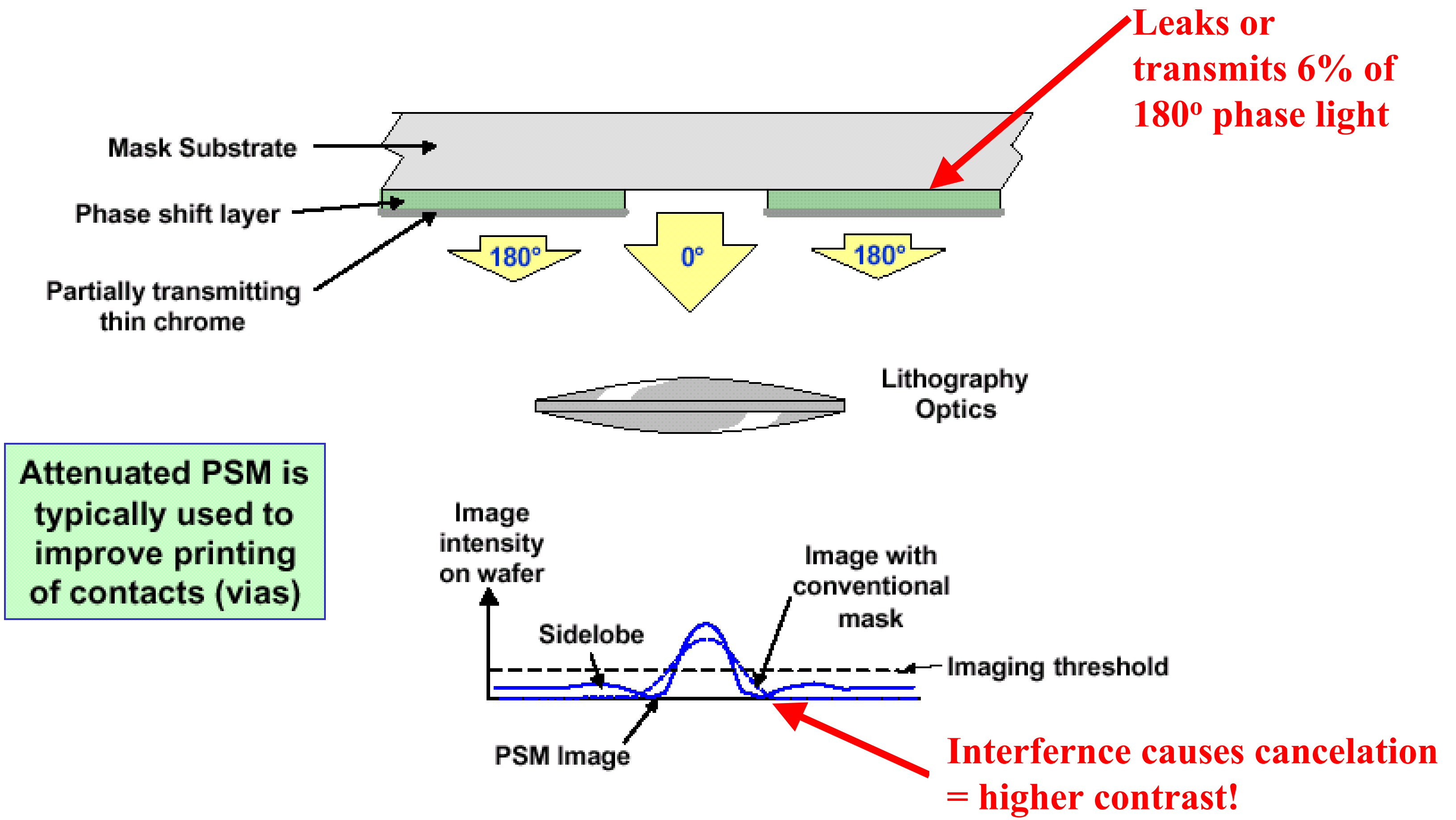
Figure 2: High transmission tri-tone PSM made by reducing the MoSi thickness,



Leaks or transmits 6% 180^o phase light = weak shift at edge!

PSM: EAPSM Embedded Attenuated Phase shift:

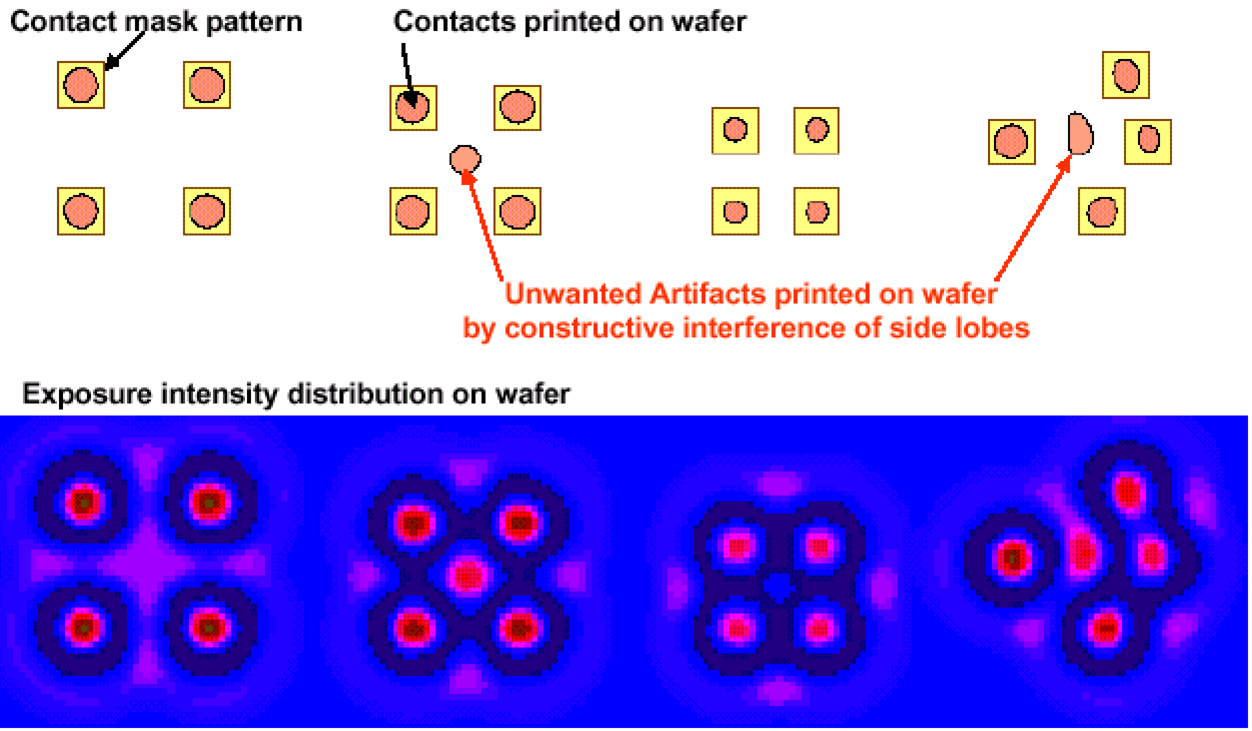
Attenuated Phase shift: weak shifter, and EAPSM :$MoSi_2$ most common



PSM: EAPSM Embedded Attenuated Phase shift:

Unwanted constructive interference

EAPSM : Printing unwanted features>> Side lobe issue Unwanted constructive interference!



**Avoid configurations where side lobes reinforce each other.
Model-based methods may be required to find problem configurations.**

Att-PSM: EAPSM Embedded Attenuated Phase shift:

http://www.ultratech.com/about/presentations/Y.Morikawa.pdf

EAPSM Future materials for Phase shift and partial transmission: Need to consider the non-zero extinction coefficient (k) slight phase impact and reflectivity!

Attenuating PSM shifter materials - DNP original -

Exposure	I-line	KrF	ArF	ArF	F_2
Wavelength	365nm	248nm	193nm	193nm	157nm
Blank structure	CrO_xN_y / CrNx / Qz	CrF_xO_y / Cr / Qz	CrF_xO_y / Cr / Qz	$TaSi_xO_y$ / Ta / Qz	$TaSi_xO_y$ / Ta / Qz
Film thickness	140nm	140nm	135nm	135~155nm	130nm
Transmission	4-8%	3-6%	<6%	<20%	<15%
	Production		Under Development		

Issues for ArF , F_2 Att.PSM material

- **Transparency**
  - adaptability for ArF and F_2 lithography
- **Chemical durability / Irradiation durability**
- **Inspection capability**
  - keep lower transmittance at inspection wavelength

Advanced Reticle Symposium 2001

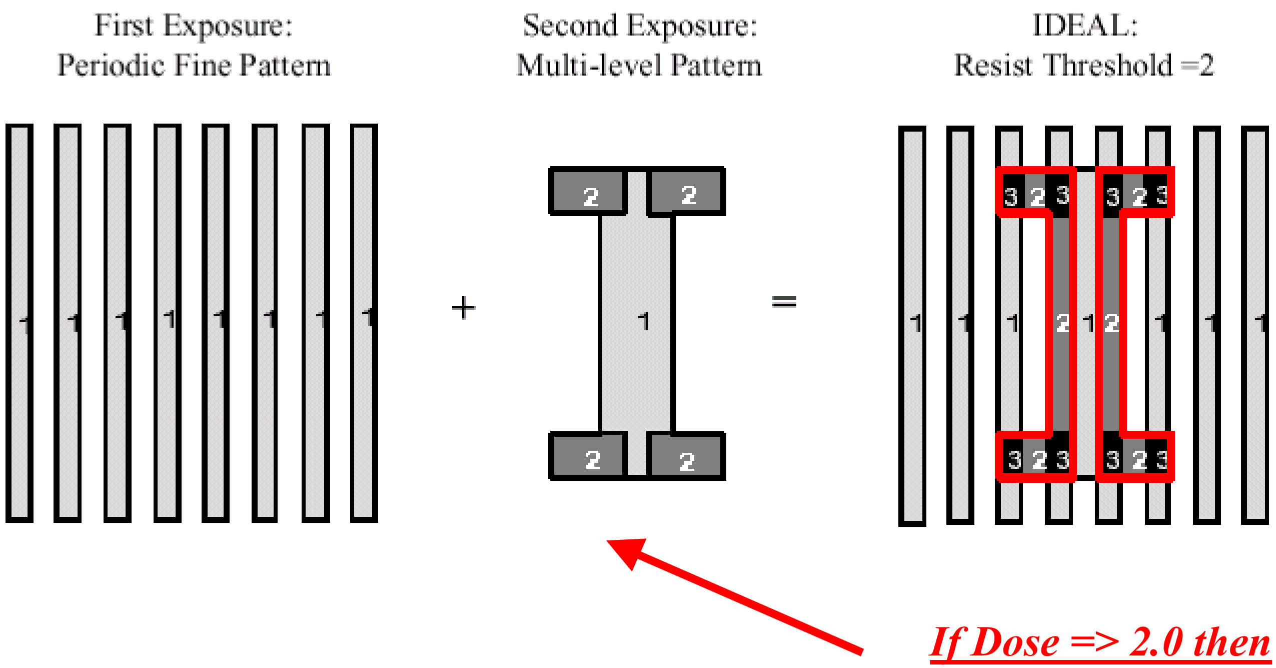
PSM: Double Exposure Process

- ***IDEAL:*** (Canon): **I**nnovative **D**ouble **E**xposure by **A**dvanced **L**ithography >. 100- 130nm gates!!
- Uses 2 reticles:
- ***1. PSM Levenson*** (master can re-use)
- ***2. Binary*** (custom trim)
- ***Exposure 1*** using AAPSM with sub- threshold dose
- ***Exposure 2*** using BIN is sub-threshold, but dose is additive in areas of overlapping exposure(double) creating a resist pattern.

PSM: Double Exposure Process: ***Low k1 processing***

Canon Process Development

Dose distributions: Resist threshold 2 or greater

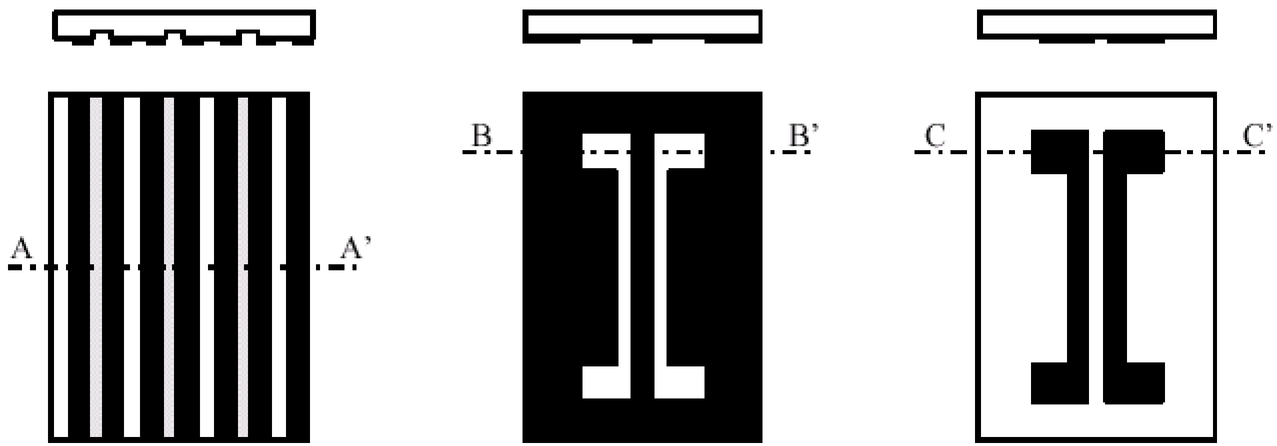


If Dose => 2.0 then photoresist reacts!!

PSM: Double Exposure Process: ***Low k1 processing***

Canon Process

- IDEAL for logic gates



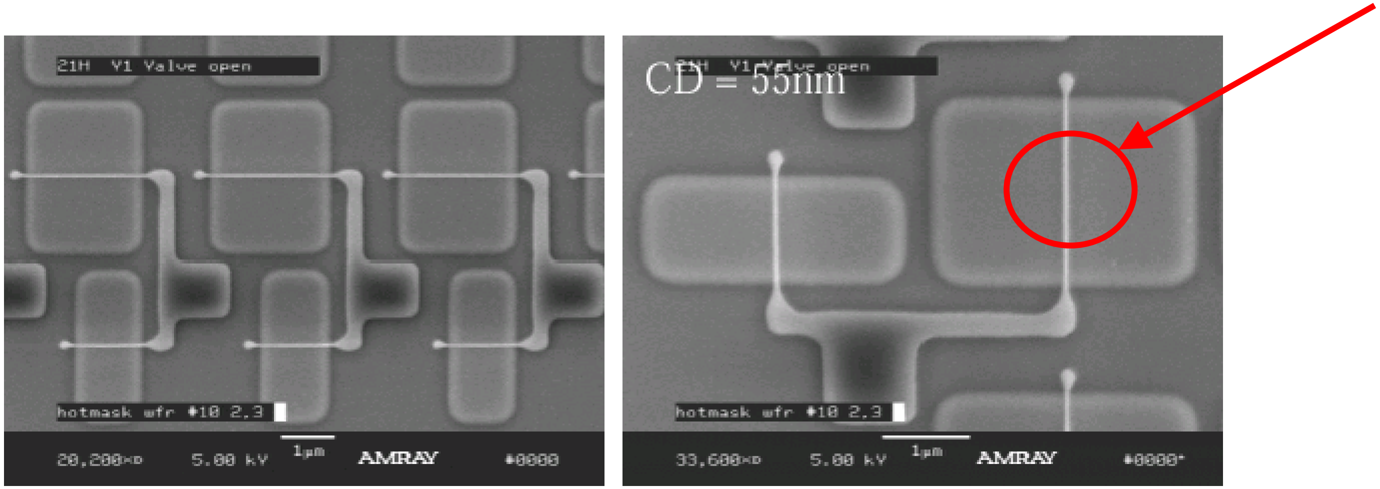
(a) Fine Pattern Mask
[Levenson PSM]

(b) Rough Pattern
Mask for Negative Resist

(c) Rough Pattern
Mask for Positive Resist

PSM: Double Exposure Process: ***Low k1 processing***

55-nm Gates Made By 248-nm Phase-Shift Double Exposure



Resist on poly on patterned 60 nm islands
Canon EX-4 248 nm Stepper 0.6NA 0.3 Sigma
UV-5 resist on AR-3 ARC
(Courtesy M. Fritze, MIT Lincoln Laboratory)

PSM: Double Exposure Process: ***Low k1 processing***

- Aerial Image simulations of Canons IDEAL
- T = Resist Threshold

Positive Photoresist (lines) **Negative Photoresist (lines)**

1st dose

2nd dose

Addition 1 + 2

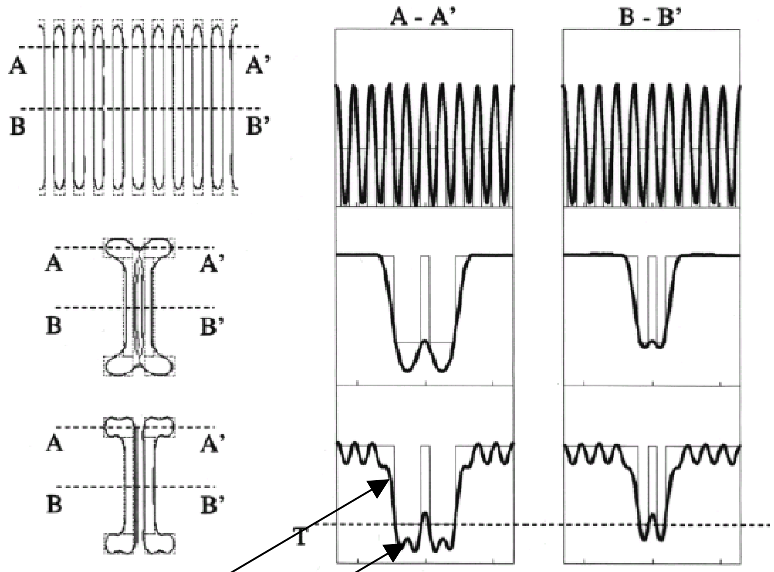


Figure 3 Simulated aerial images of 130 nm logic gate pattern with KrF NA 0.60 illumination of positive resist.

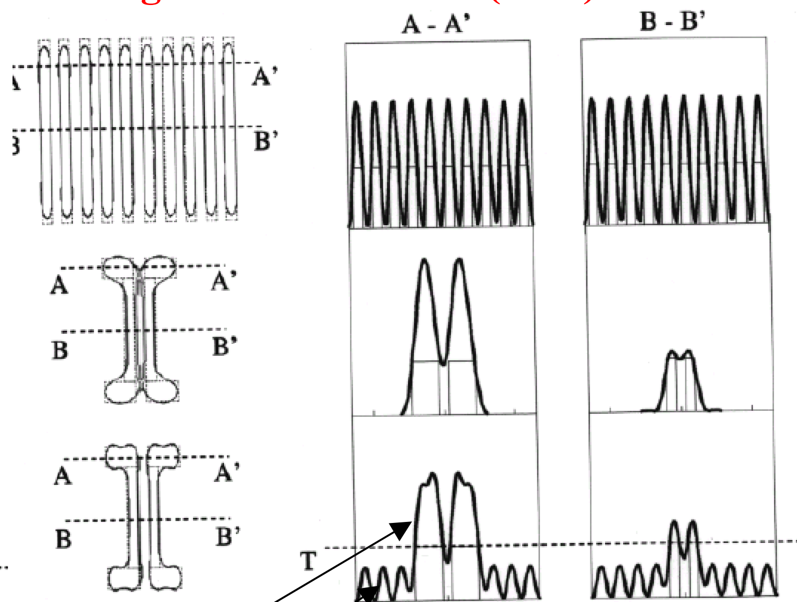


Figure 4 Simulated aerial images of 130 nm logic gate pattern with KrF NA 0.60 illumination of negative resist.

Exposure (no photoresist)

No exposure

Exposure

No exposure (no photoresist

PSM: Double Exposure Process: ***Low k1 processing***

http://www.usa.canon.com/indtech/semicondeq/news_ideal.html

- Aerial Image simulations of IDEAL

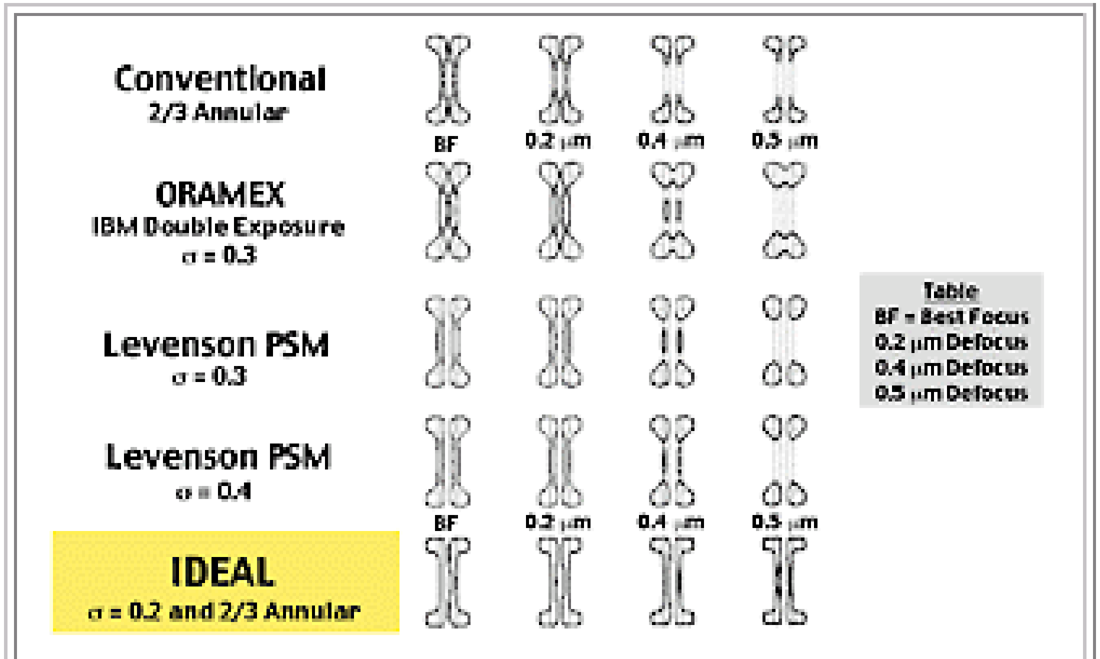
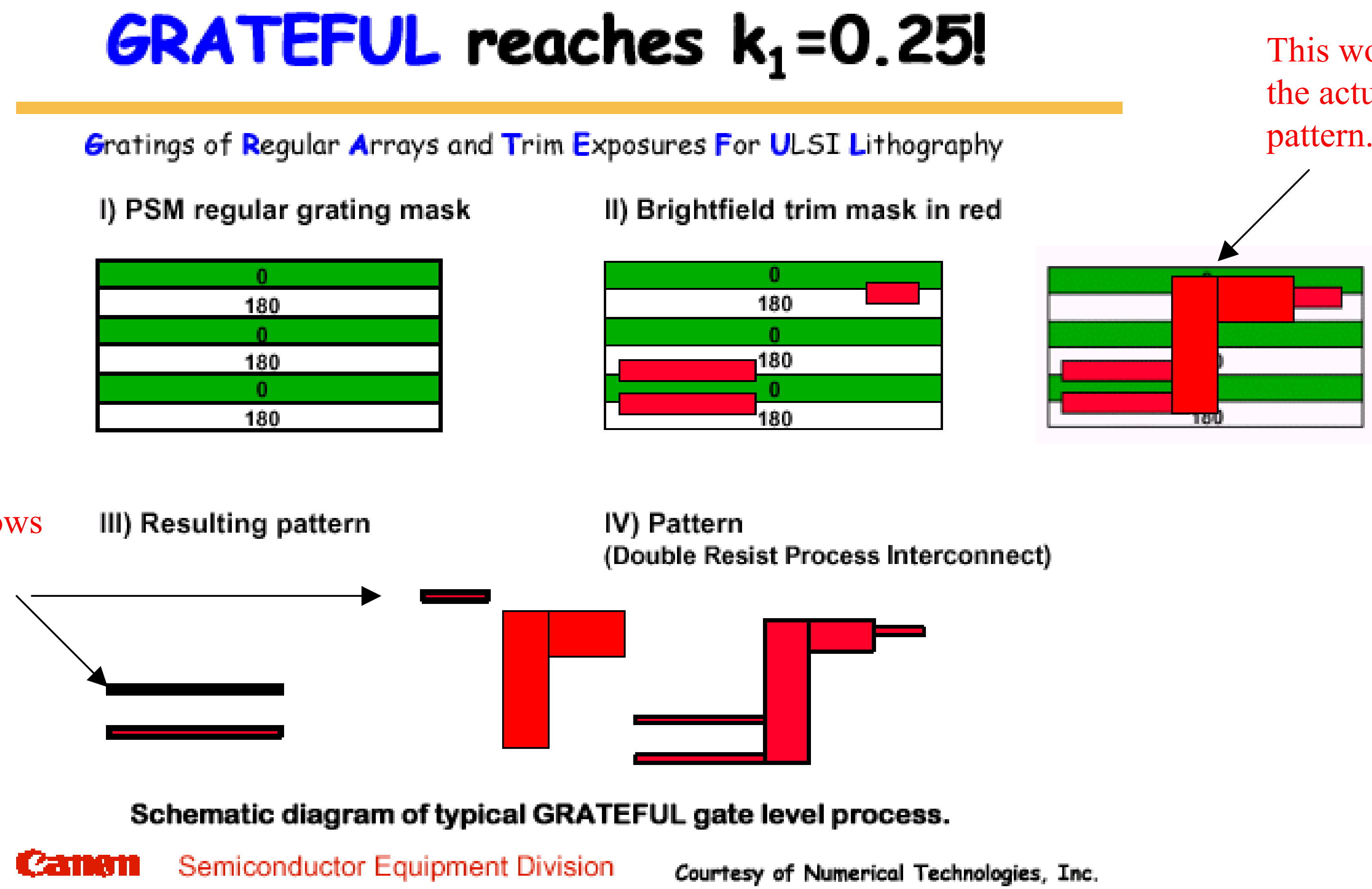


Figure 4. Simulated aerial images of 120nm gate pattern with negative resist on a 0.60 NA KrF lens. IDEAL technology is compatible with both positive and negative resists.

PSM: GRATEFUL Process *Low k1 processing*

http://www.fsi-intl.com/products/ware.pdf



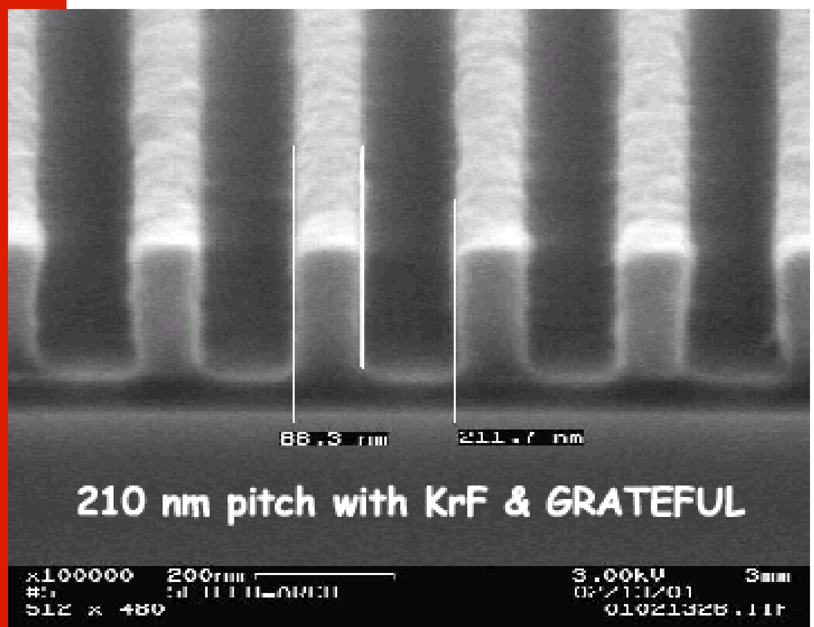
This would be the actual pattern.

This just shows the trim exposures!

PSM: GRATEFUL Process *Low k1 processing*

http://www.fsi-intl.com/products/ware.pdf

100nm imaging with GRATEFUL and KrF!



GRATEFUL achieves excellent profiles for some of the smallest pitch gratings ever obtained from 248 nm optical lithography...

Resist: 289 nm ARCH GKR-5104 **ARC:** 50 nm Brewer DUV-32
Tool: Canon EX-6 248 nm NA=0.65, Sigma=0.3 **Mask:** Chromeless PSM

Canon Semiconductor Equipment Division

Courtesy of Numerical Technologies, Inc.

PSM: GRATEFUL Process *Low k1 processing*

http://www.numeritech.com/download/files/42/gratefulcomplete.pdf

Creation of PSM contacts with double exposure using negative photoresist.

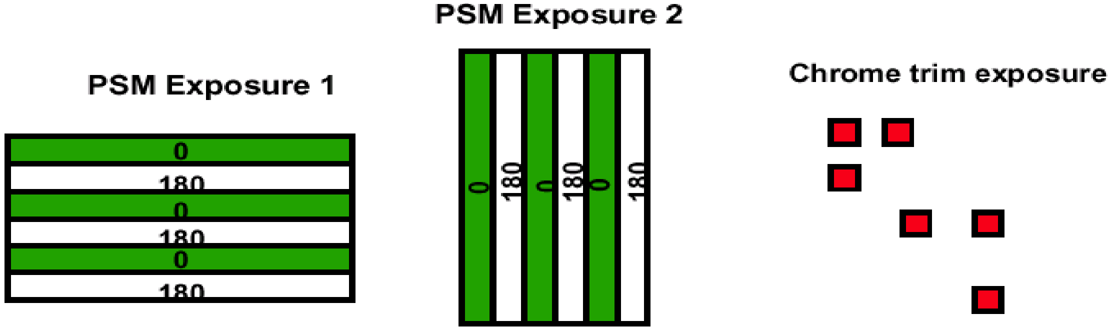
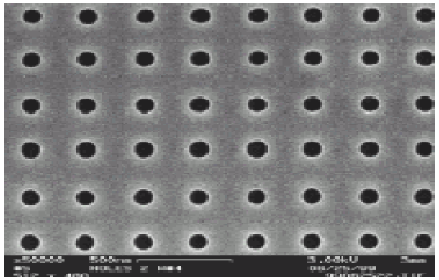


Fig. 8) Schematic diagram of triple exposure contact process in GRATEFUL.



PSM: GRATEFUL Process *Low k1 processing*

ht f

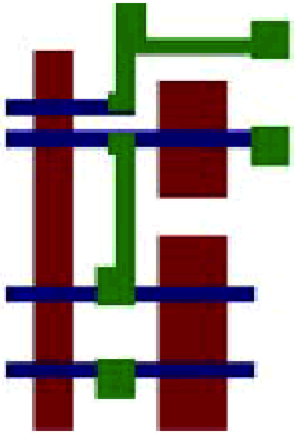


Fig. 11) Schematic diagram of typical gate level pattern to be printed by GRATEFUL

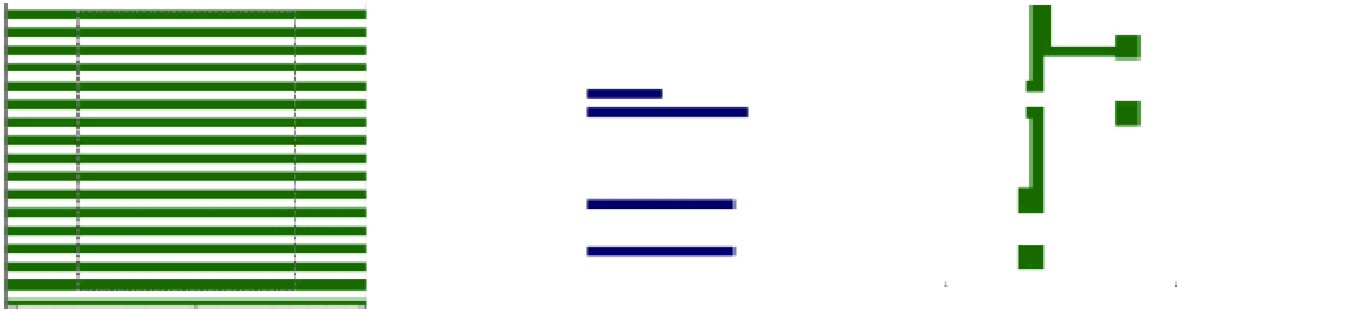


Fig. 12) Decomposition of above mask into three GRATEFUL exposures

PSM: GRATEFUL Process *Low k1 processing*

100nm Node Lithography with KrF?? Paper:
M.Fritze etal. MIT

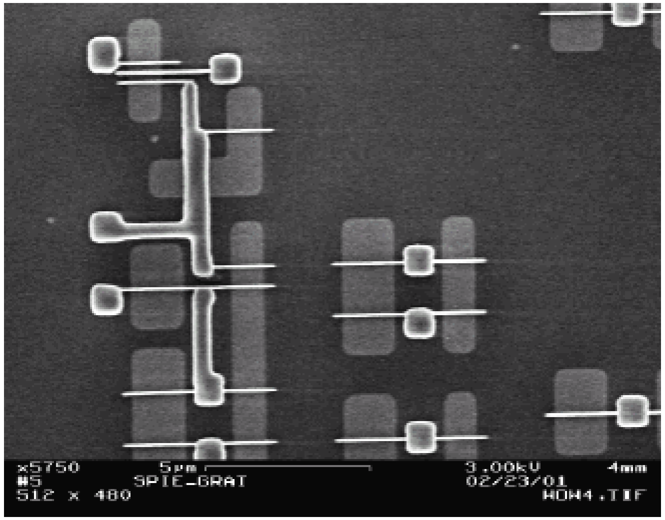
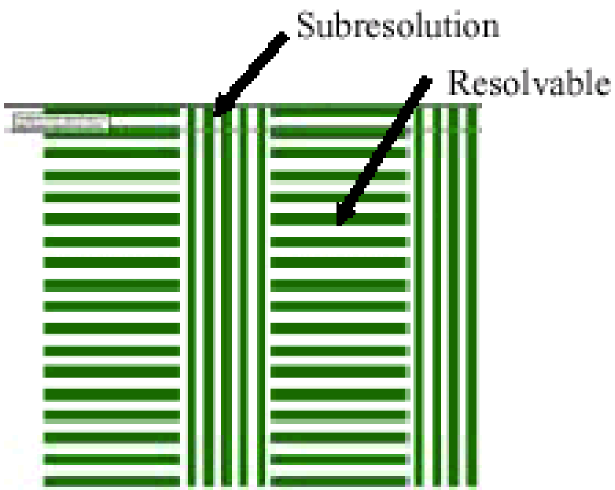


Fig 15) Experimental result after a double resist process placed the poly interconnect features on the above gates. In this SEM, 65 nm gate features have been imaged through pitch values ranging from 250 nm to isolated *without* proximity effects or OPC correction. The 248-nm stepper used had NA=0.6 and sigma=0.3.

PSM: GRATEFUL Process *Low k1 processing*

100nm Node Lithography with KrF?? Paper:
M.Fritze etal. MIT



L1: PSM Grating Cell

L2: PSM Trim

Fig. 17) GRATEFUL decomposition of the above gate pattern into two exposures.

PSM: GRATEFUL Process *Low k1 processing*

100nm Node Lithography with KrF?? Paper:
M.Fritze etal. MIT

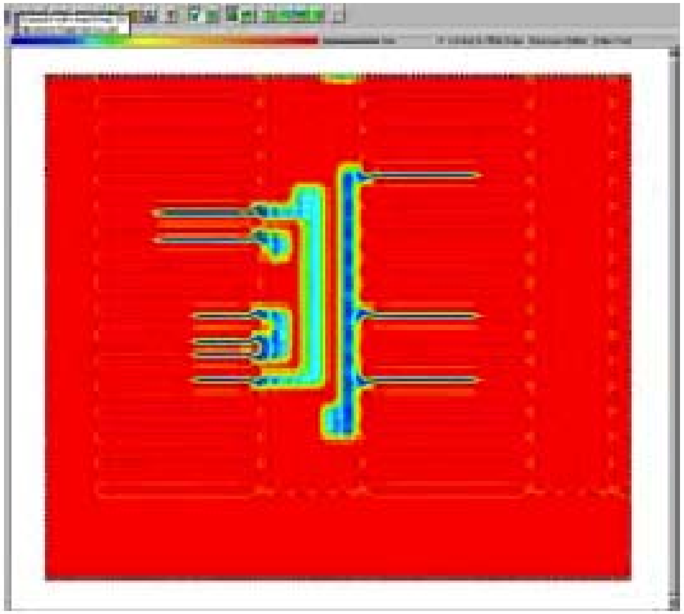


Fig 18) Optical simulation of GRATEFUL double exposure process for the pattern above. Note the absence of proximity effects for pitch values from 250 nm through isolated. NA=0.6 and sigma=0.3 here.

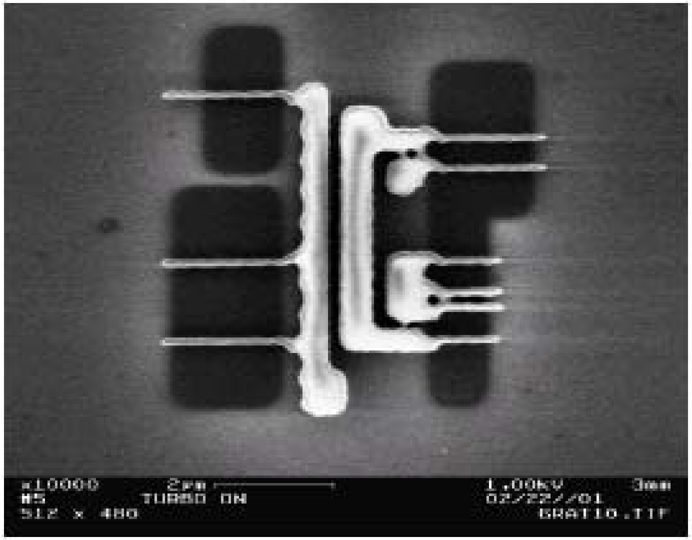


Fig 19) Experimental result corresponding to the simulation on the left. The pattern is mirrored compared with the simulations. The dose was incorrect but the principle is illustrated here. The stepper NA=0.6 and sigma=0.3.