EUV Lithography at Insertion and Beyond

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Acknowledgements

Kenny Toh for help with Rigorous EM modeling

Robert Bristol and Mark Phillips for fruitful discussion and comments

Outline

Intel Technology Cadence

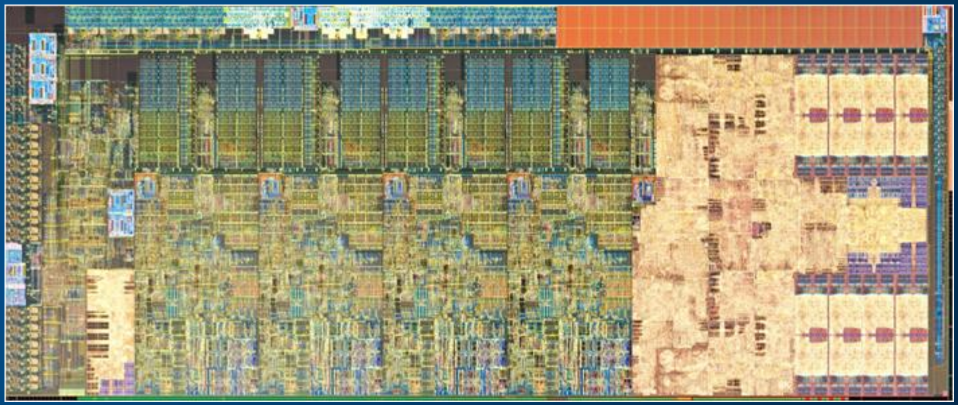
EUV HVM Insertion
- Timing
- Method
- Tooling
- Materials
- Priorities

EUV beyond Insertion

Conclusions

Intel Technology Cadence

Process Name	P1266	P1268	P1270	P1272	P1274
Lithography	45nm	32nm	22nm	14nm	10nm
1st Production	2007	2009	2011	2013	2015

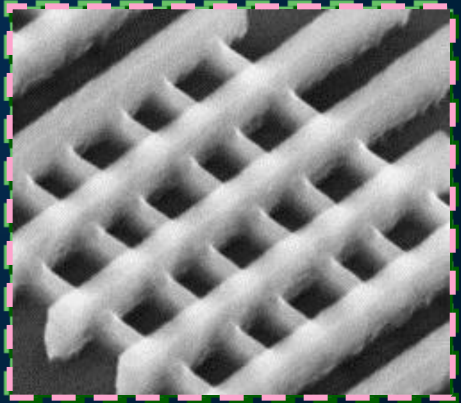


Ivy Bridge

22nm

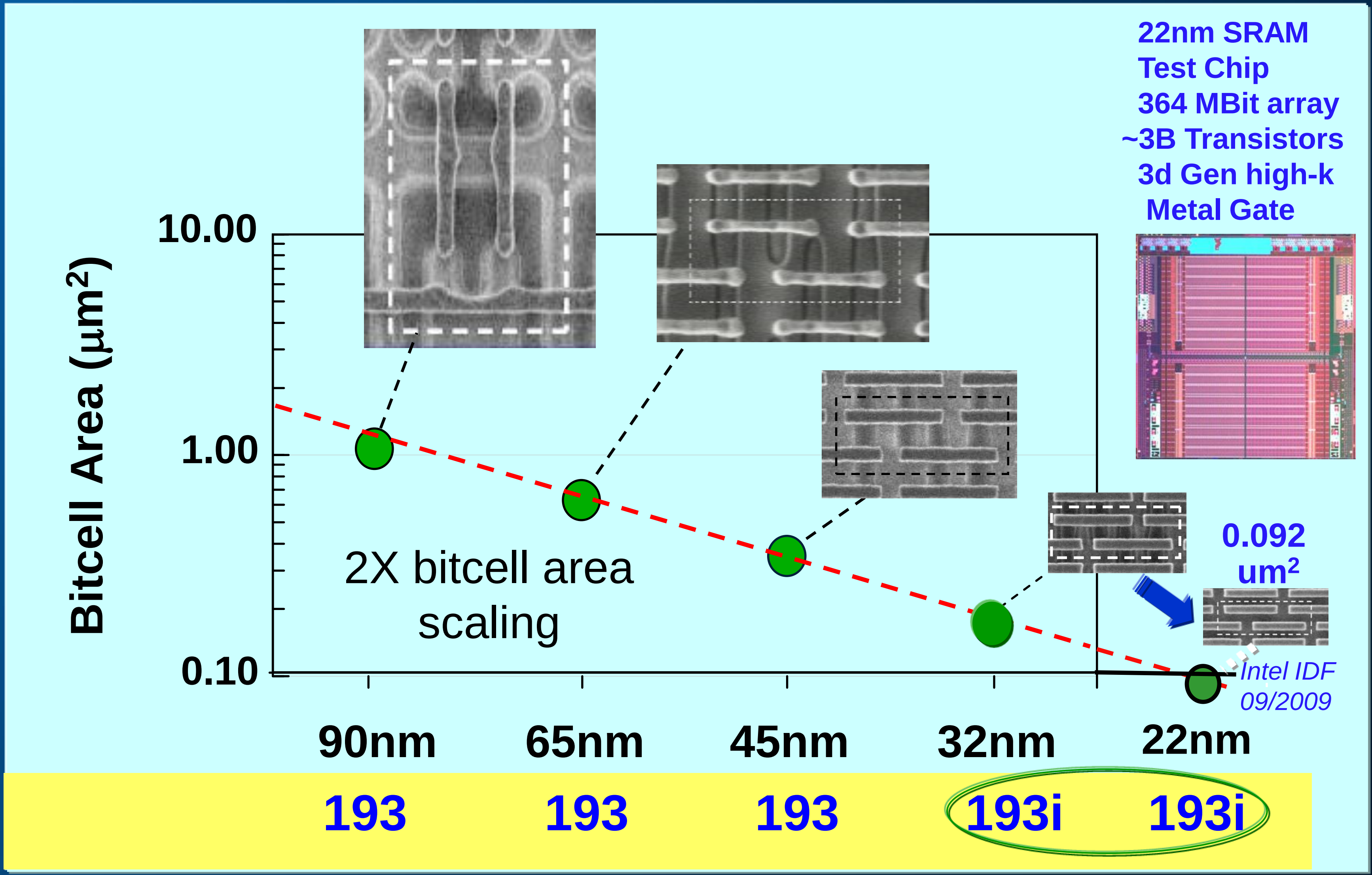
1.4B TriGate

193i Litho

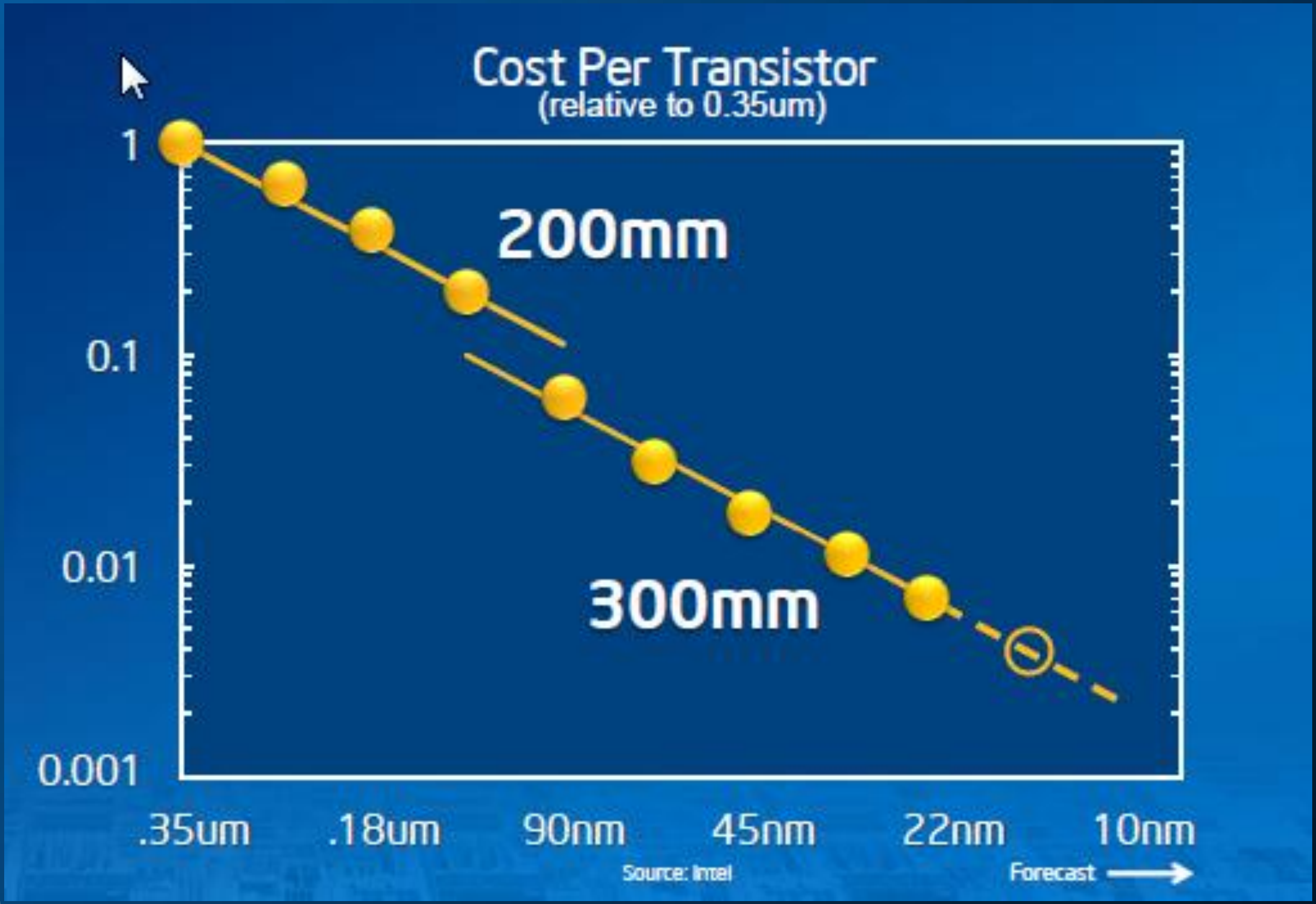


Intel continues introducing a new technology generation every 2 years

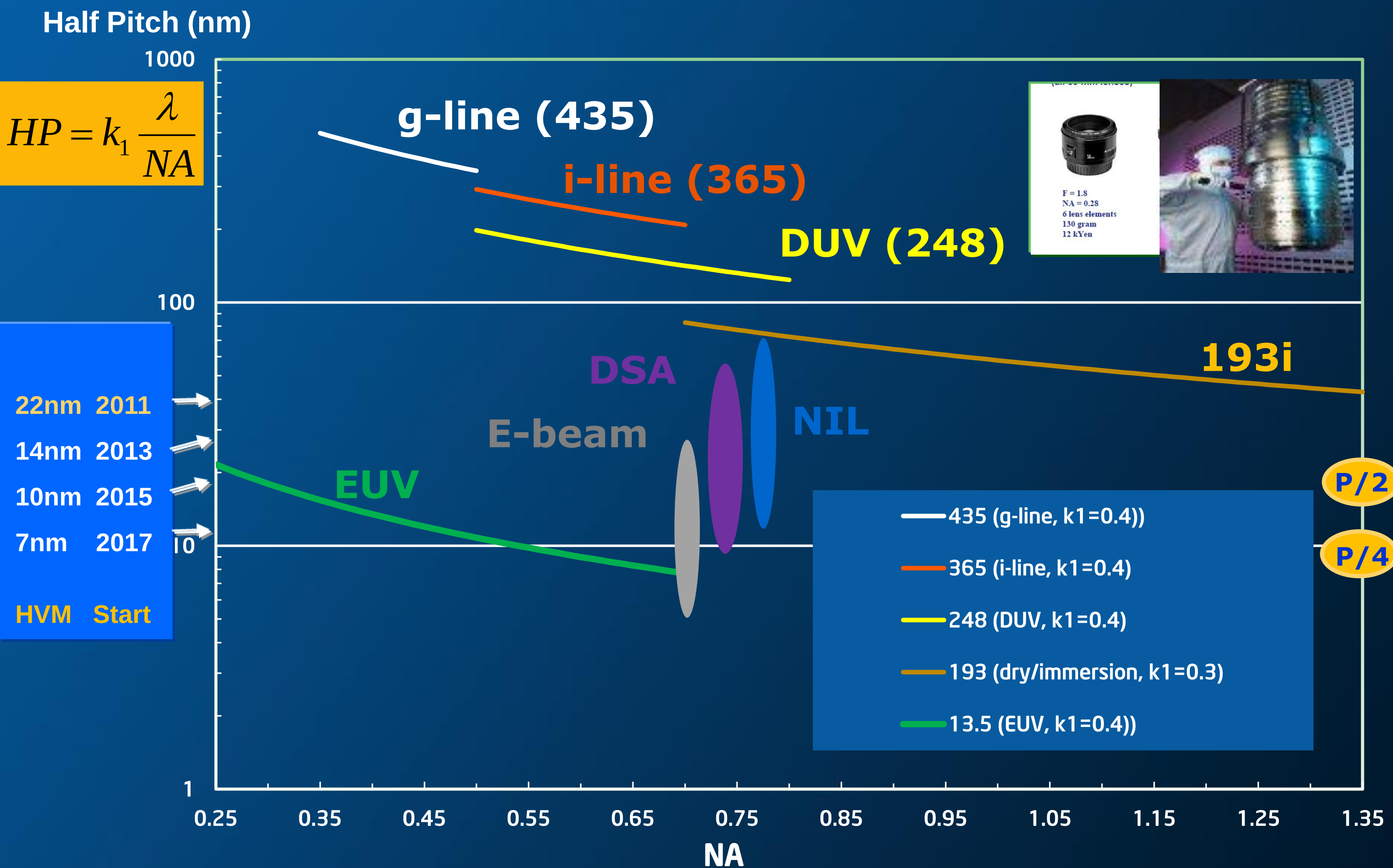
2X Area density Scaling at Intel – Last 10 Years



Cost per Transistor Trend sustained with TriGate and 193i Pitch Divided Lithography

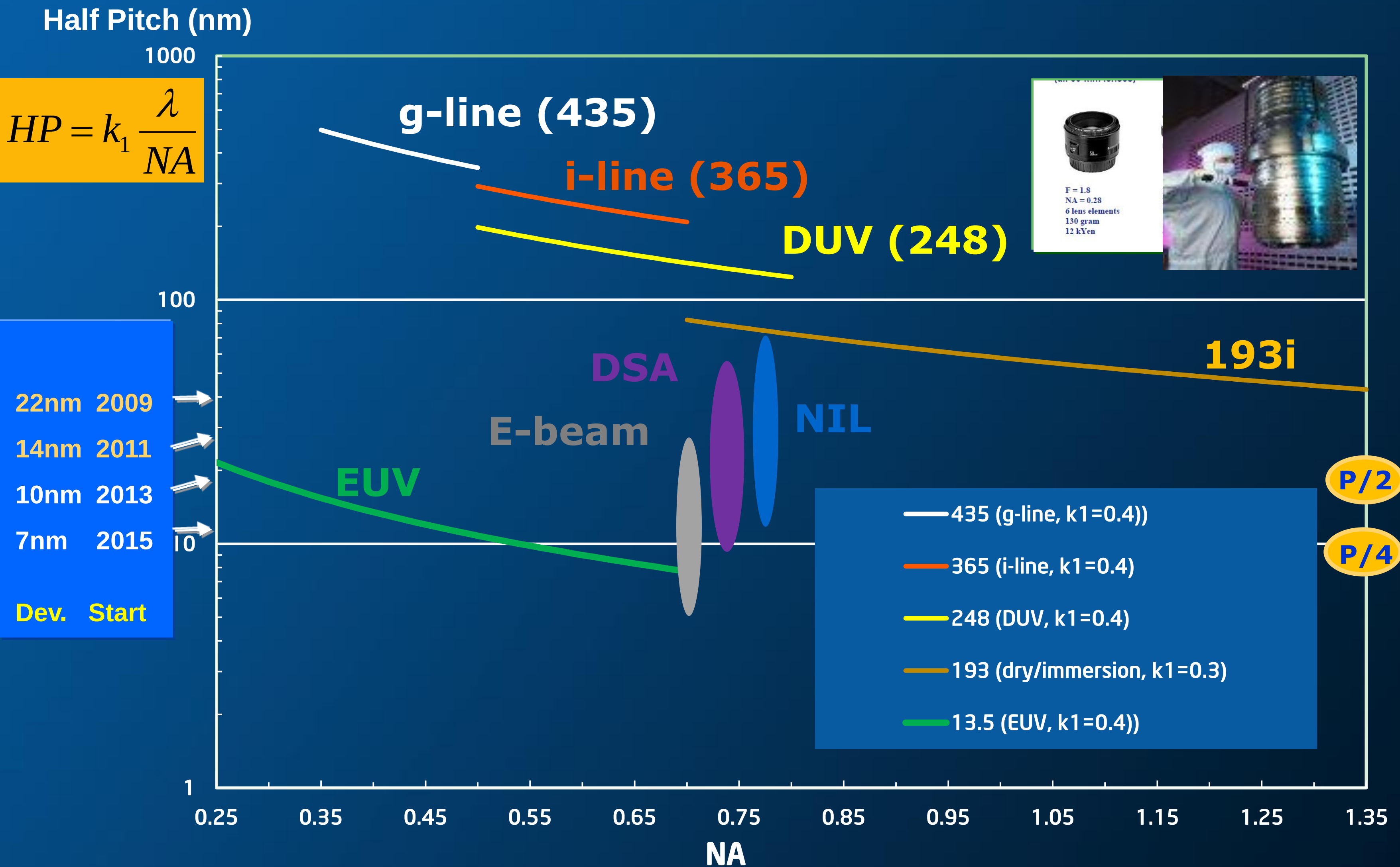


22nm node HVM Litho – 193i



14nm HVM Litho – 193i

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



Yan Borodovsky, Intel, 2012 International Workshop on EUV Lithography, Maui, Hi

EUV HVM Insertion Method Complementary Patterning

Com·ple·men·ta·ry

Definition: **1. completing:** completing something else

2. making whole, making a pair or whole

MSN Encarta dictionary

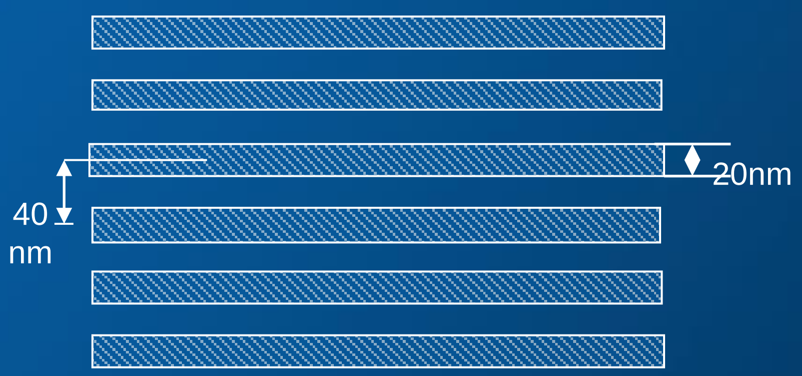
Step 1. Use mature High Throughput 193i with Pitch Division to define CD Critical parts of layout by patterning continuous gratings.

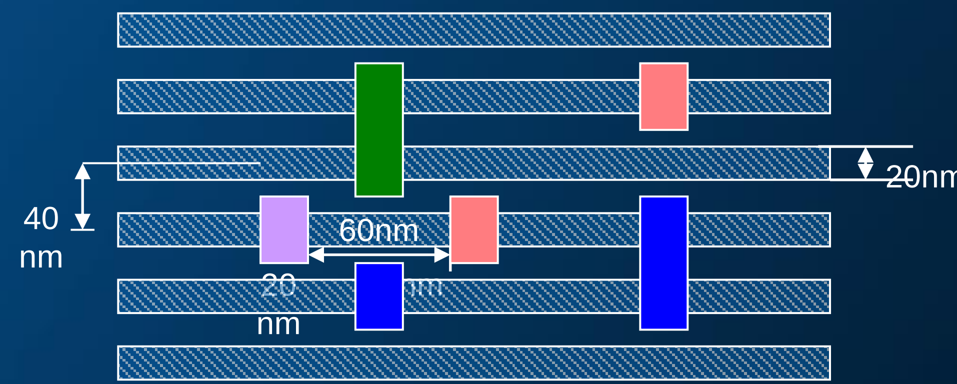
Complement Step 1 by Step 2

Step 2. Use High Resolution High Throughput Imaging to break continuity of gratings defined in Step 1.

40nm Pitch Example

ArF Only Patterning





1 193i w/PD to form gratings + 4 193i Masks/Exposures to form Pattern = 5 Mask
5 Exposures

Complementary Patterning

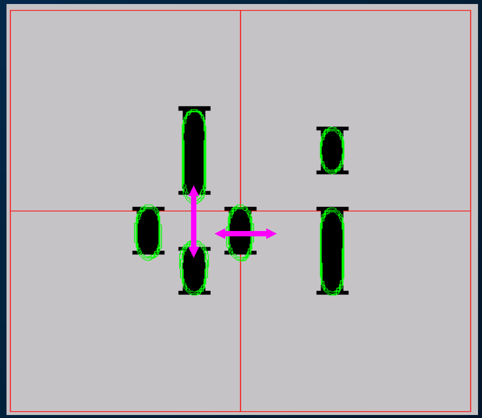
CD, LWR <2nm 3s

1 Mask/1 193i Expose

+

CD, LWR <4nm 3s

1 Mask/1 EUV Expose

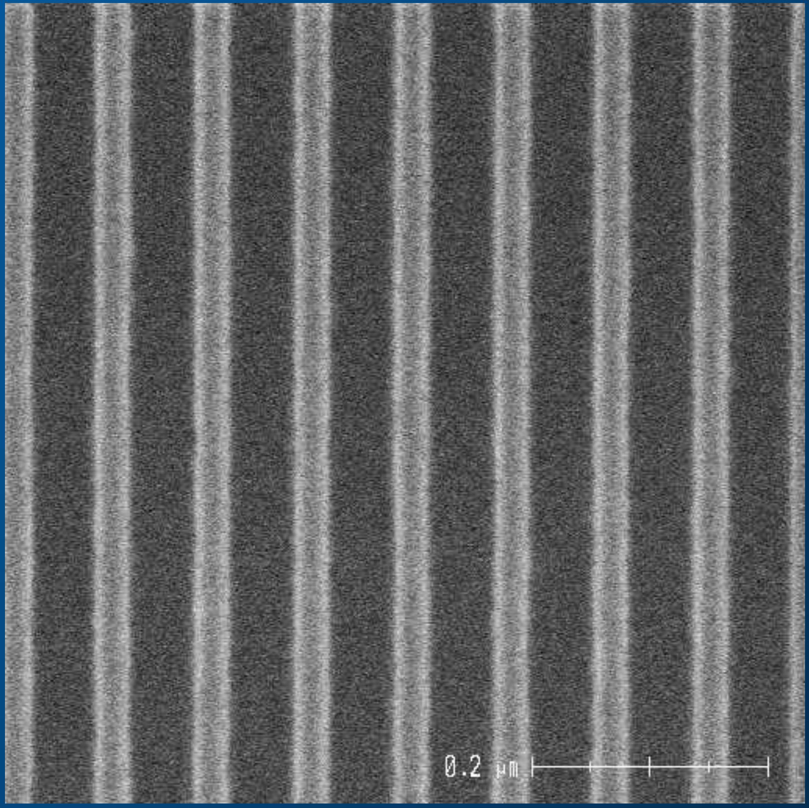


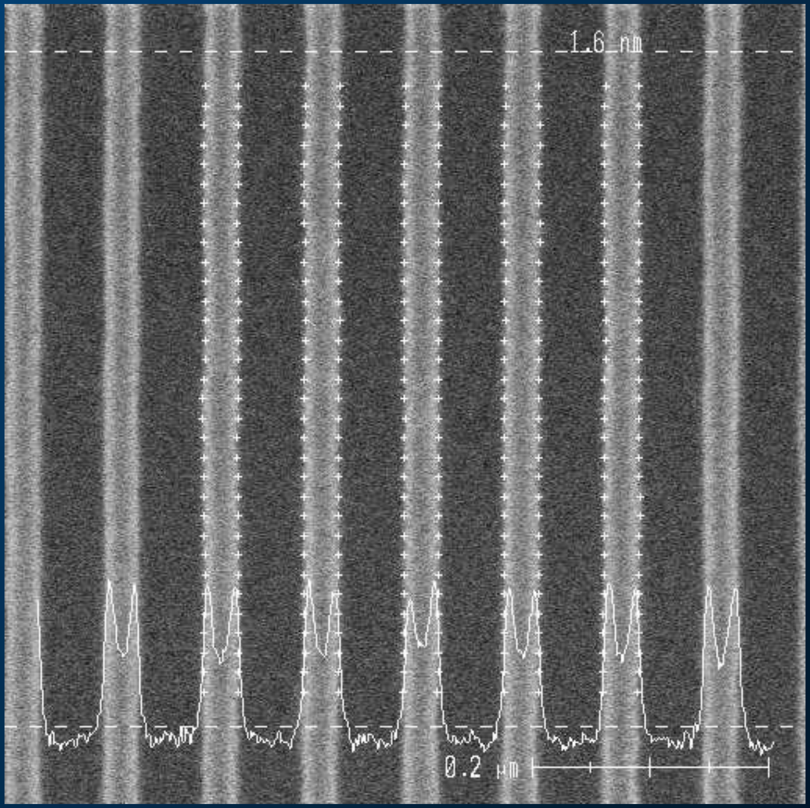
1 193i w/PD to form gratings + 1 EUV Masks/Exposure

Total 2 Masks/2 Exposures

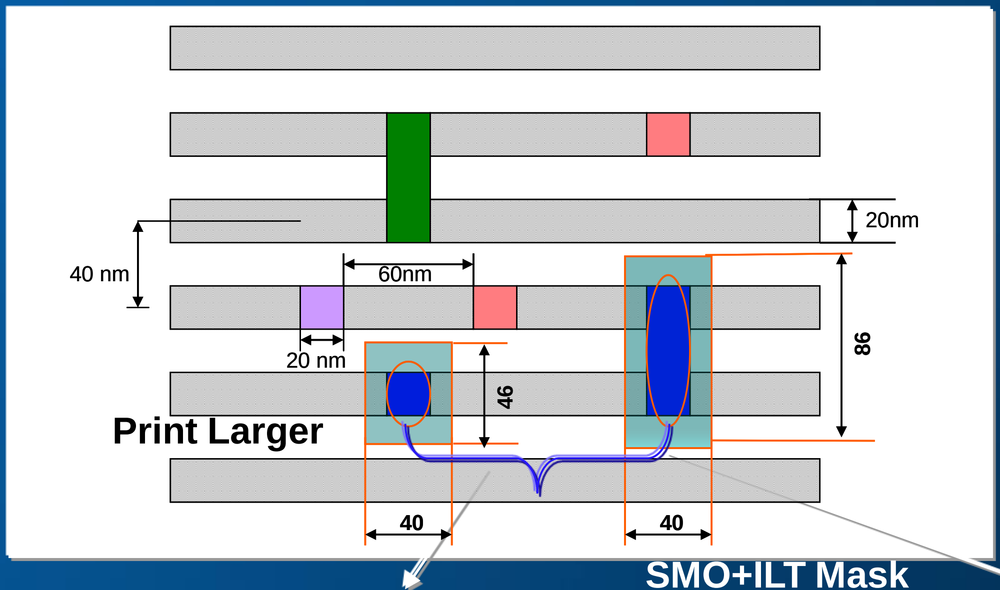
193i Allows for better LWR Starting Control then EUVL

Images in 193i Resist with 1.35NA
Pitch = 84nm, LWR 3σ=1.6nm



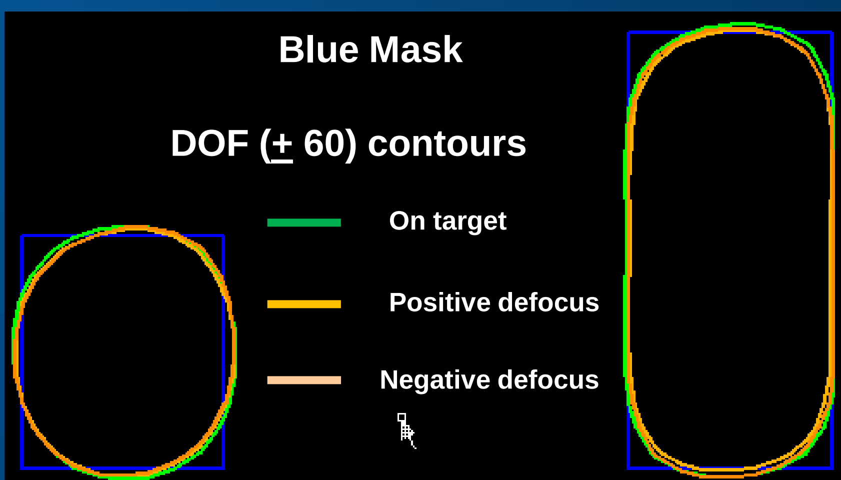


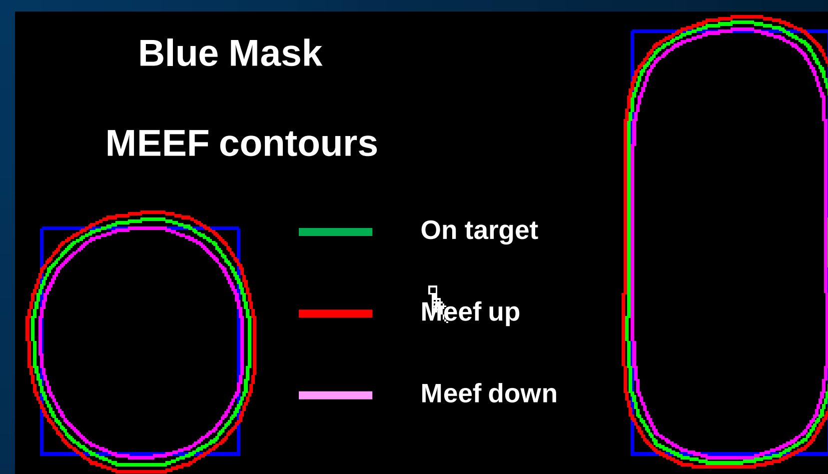
40nm Pitch Example - **ArFi Can do Cuts (with 4 masks)**



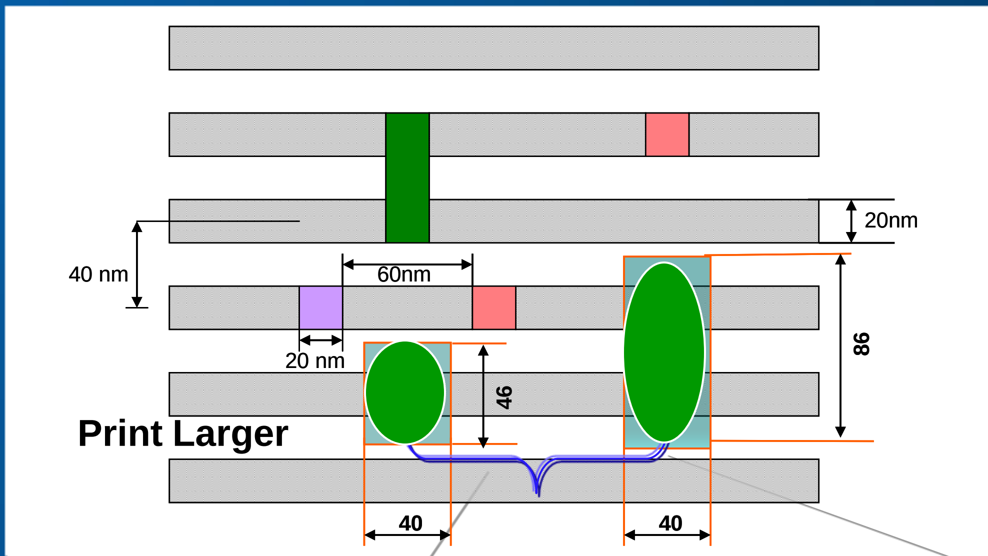
On Target – Upsized 10nm/long side
13nm/short side
To be followed by chem trim 10nm/side

Location	MEEF
Short side left	2.26
Short side right	2.45
short side top	3.05
short side bottom	2.97
long side left	1.42
long side right	1.73
long side top	2.54
long side bottom	2.04





40nm Pitch Example - **ArFi Can do Cuts (with 4 masks + Print Bias and Shrink)**



SMO+ILT Mask

On Target – Upsized 10nm/long side
13nm/short side
To be followed by chem trim 10nm/side

Location	MEEF
Short side left	2.26
Short side right	2.45
short side top	3.05
short side bottom	2.97
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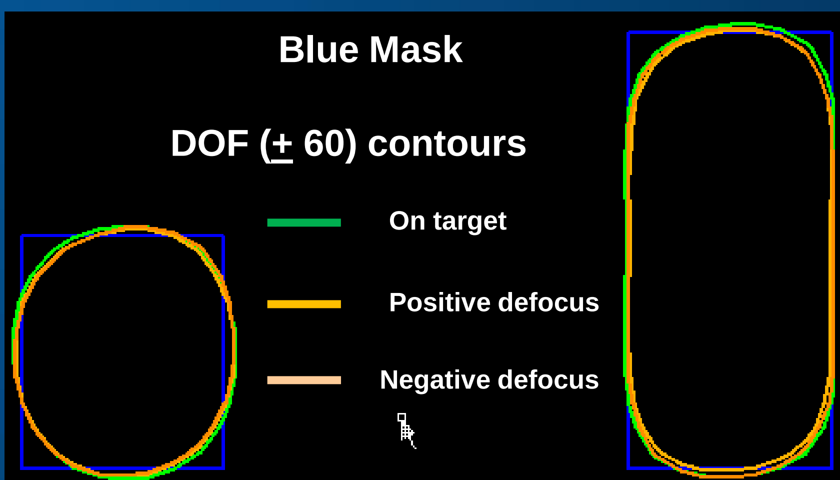
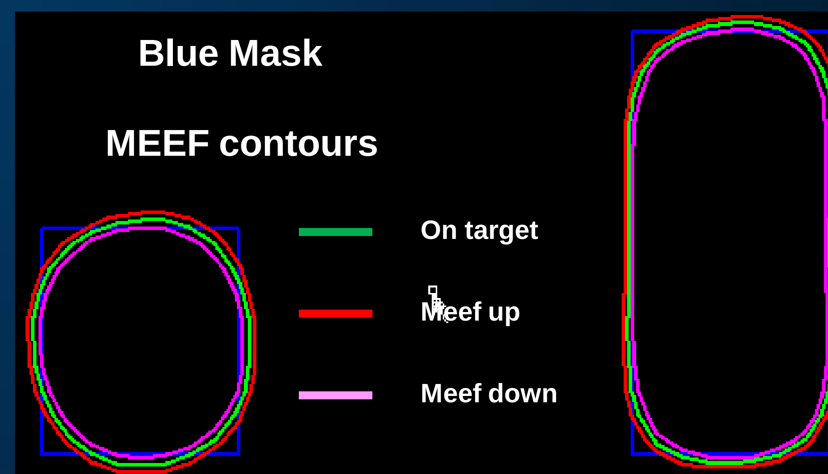
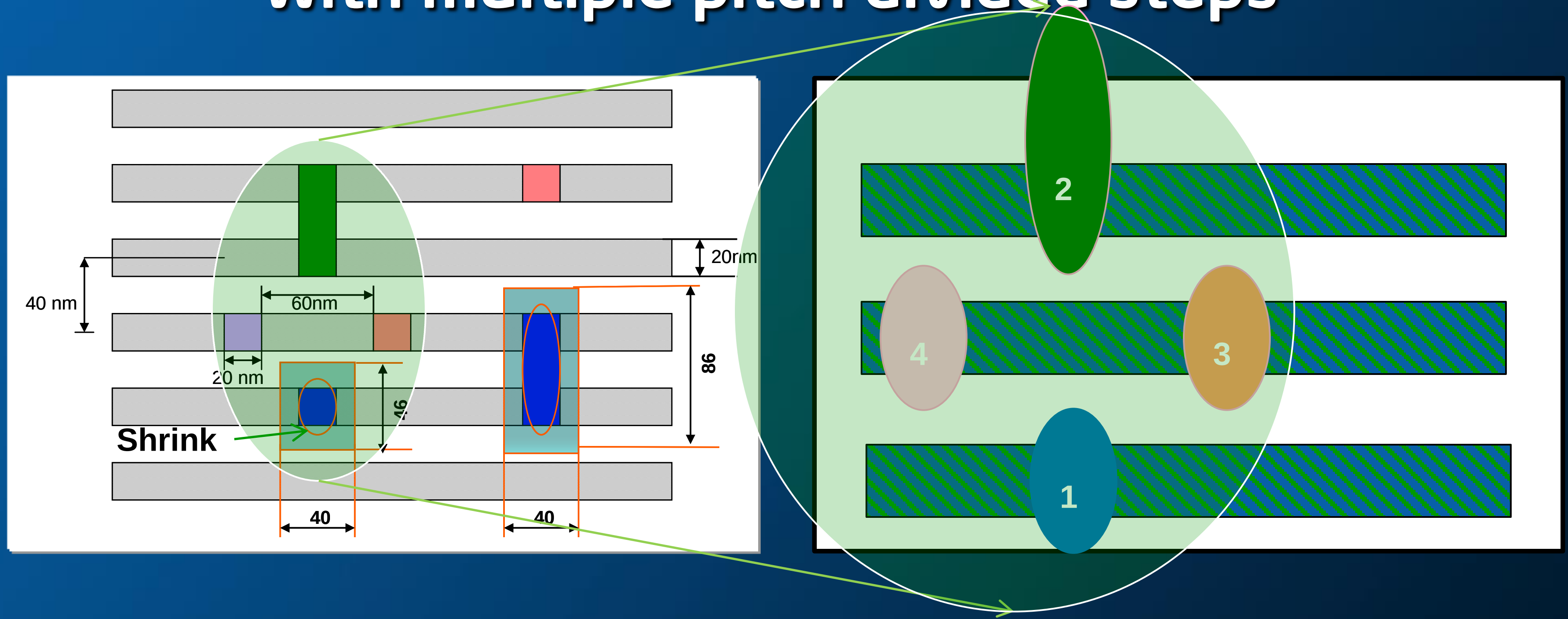


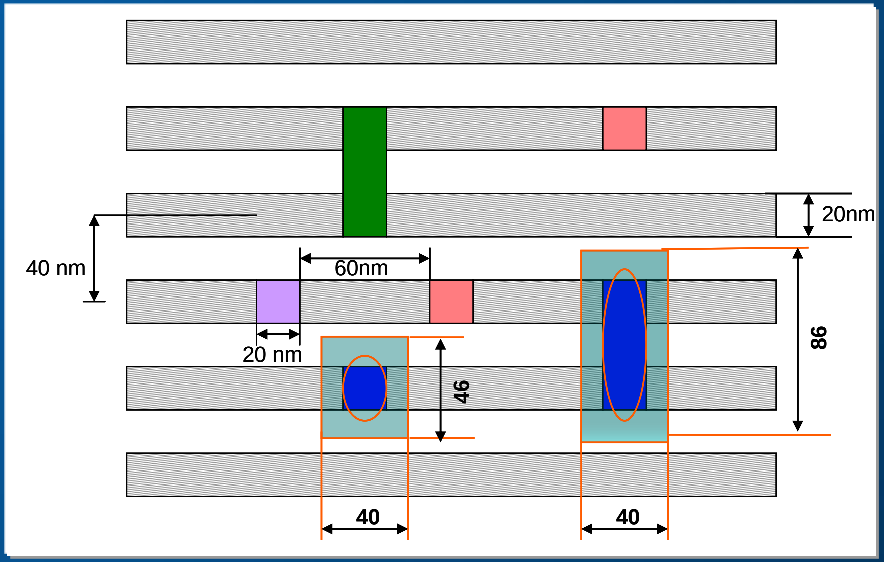


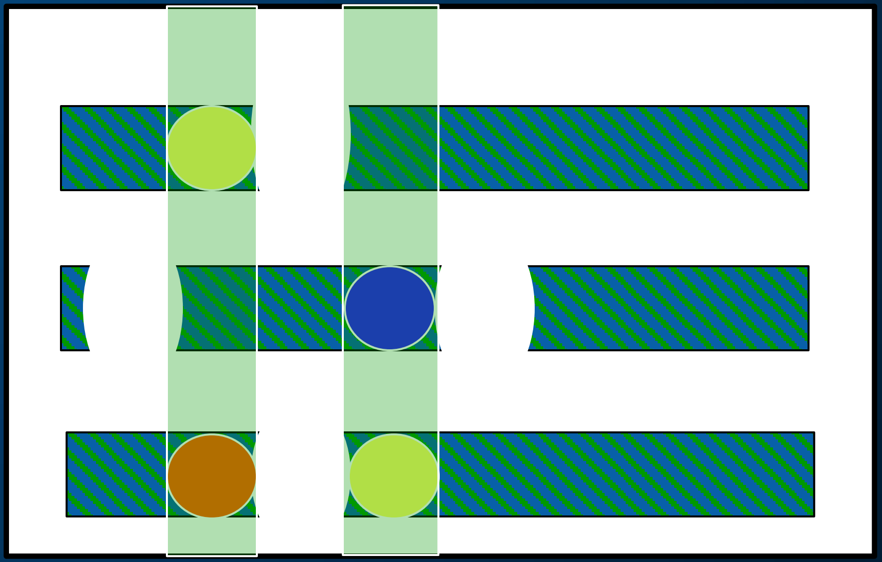
Edge Placement Error might be an issue with multiple pitch divided steps



That's how enlarged grating cuts are suppose to go on the wafer if placement and dimensions of all 4 cuts exposed in 4 separate exposures are ideal

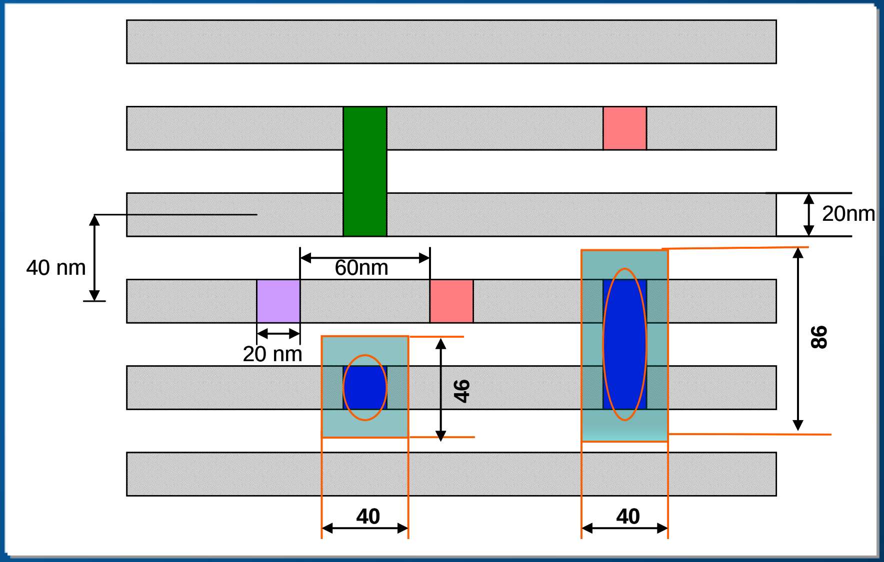
Edge Placement Error might be an issue with multiple pitch divided steps

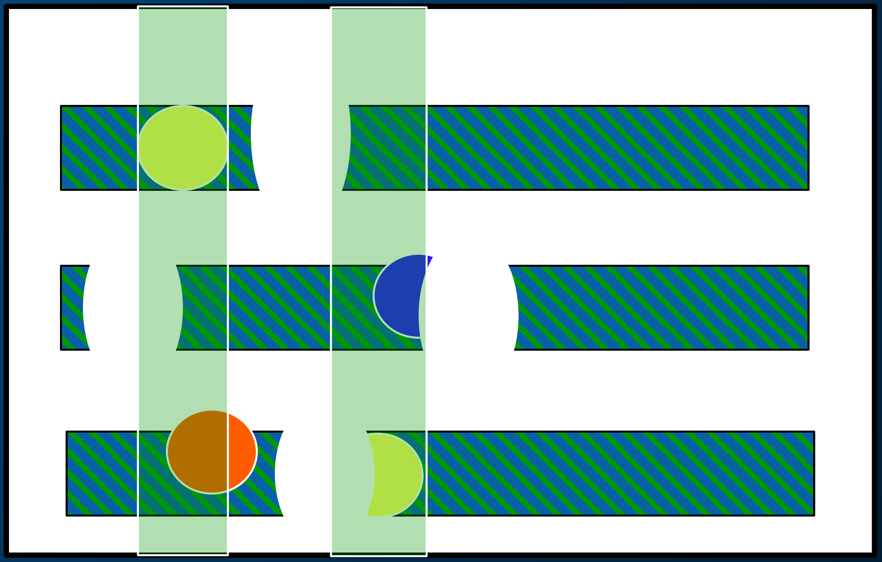




That's how next interconnect and vias are suppose to go on the wafer if placement and dimensions of next layer interconnect and vias grating are ideal

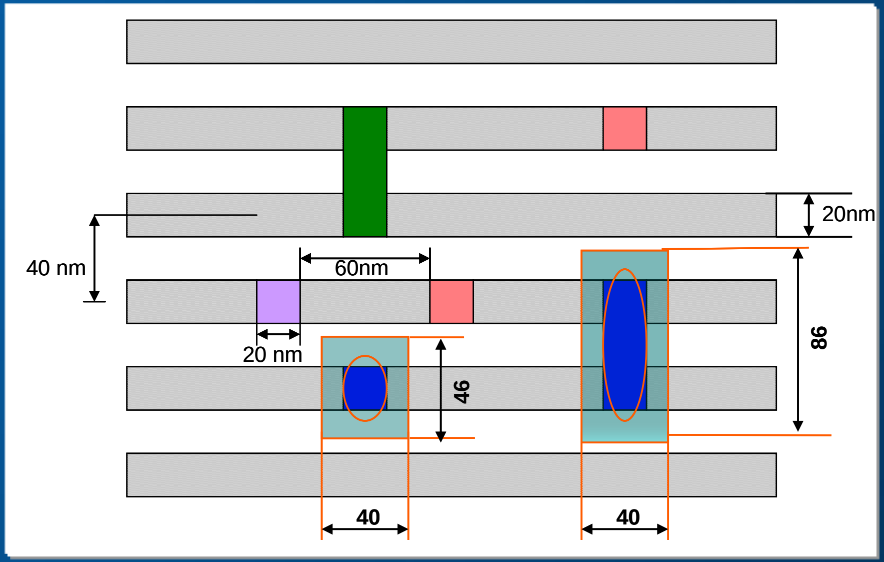
Edge Placement Error might be an issue with multiple pitch divided steps

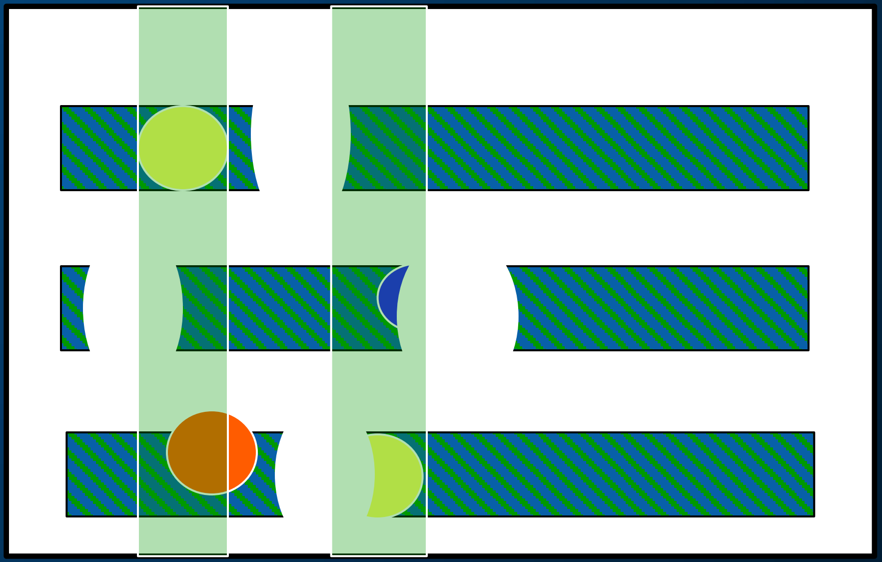




That's what happens if some exposure steps introduce 5-7nm overlay errors

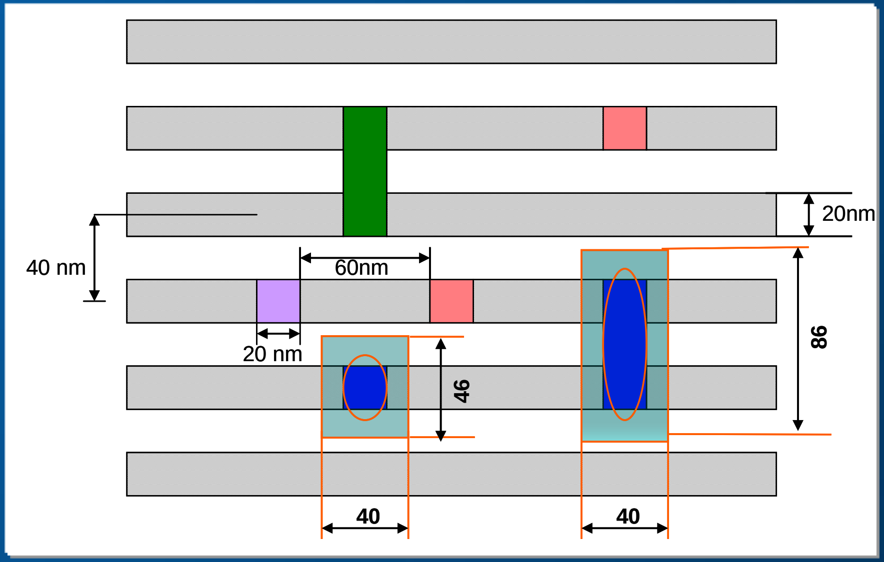
Edge Placement Error might be an issue with multiple pitch divided steps

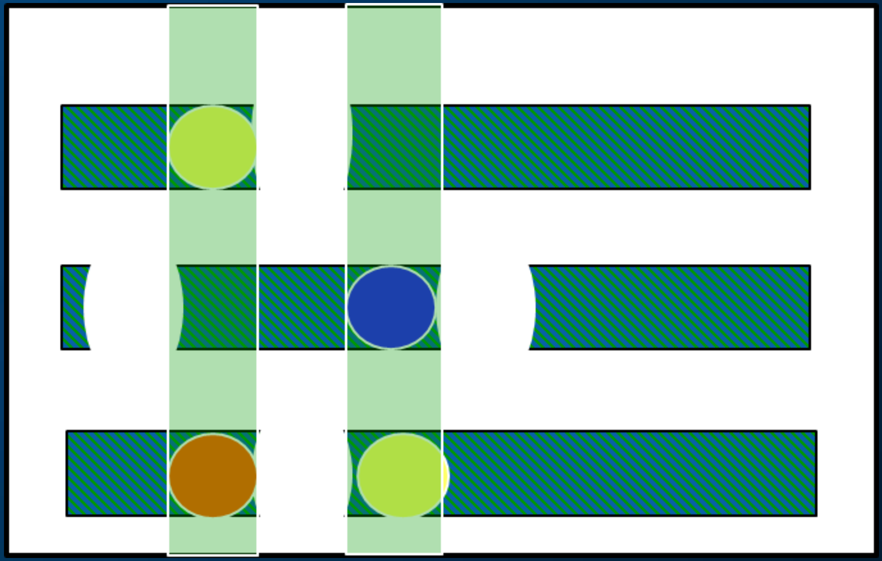




That's what happen if some exposure steps introduce 5-7nm overlay errors and
OPC imperfections, Defocus, Dose instability add to Edge Placement Error (EPE) resulting in yield loss

Edge Placement Error might be an issue with multiple pitch divided steps





Combining divided exposures in one will help minimize one of major contribution to EPE budget.

EPE improvement is one of key benefits we expect for EUV to bring to future technologies

EUV HVM Insertion

In addition to widely discussed EUV infrastructure Issues following capabilities have to be present in support of EPE and Yield requirements for EUV HVM Insertion at Intel:

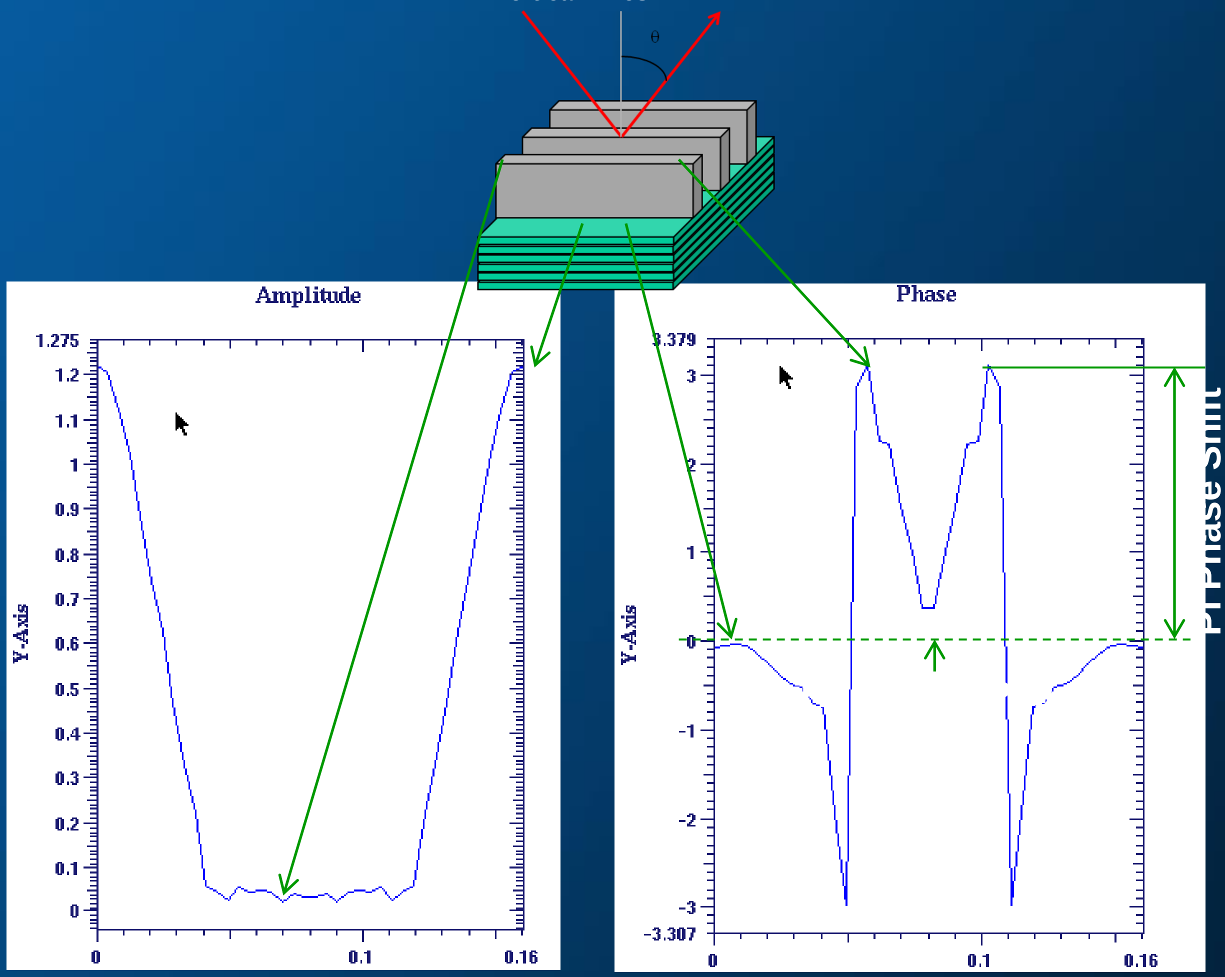
Tooling - Sophisticated OPC

Materials - Stochastics Suppression

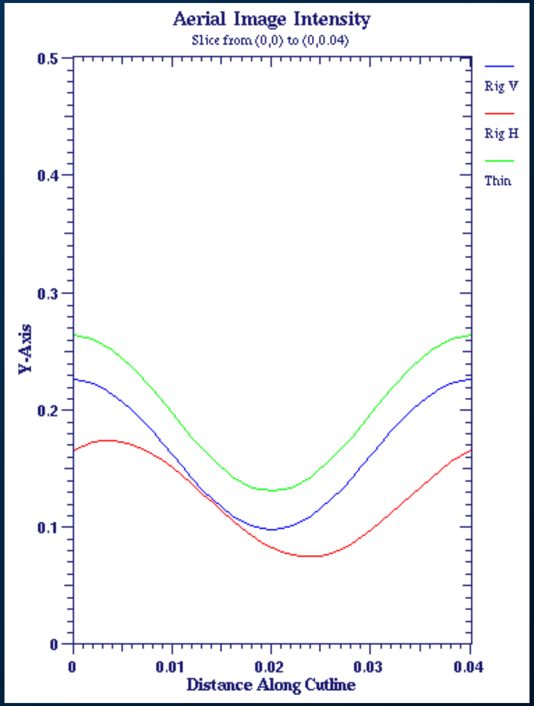
Vertical Lines

EUV is complex PSM (Thick) Mask.
Fast Thick Mask Tooling needed for OPC

Vertical Lines



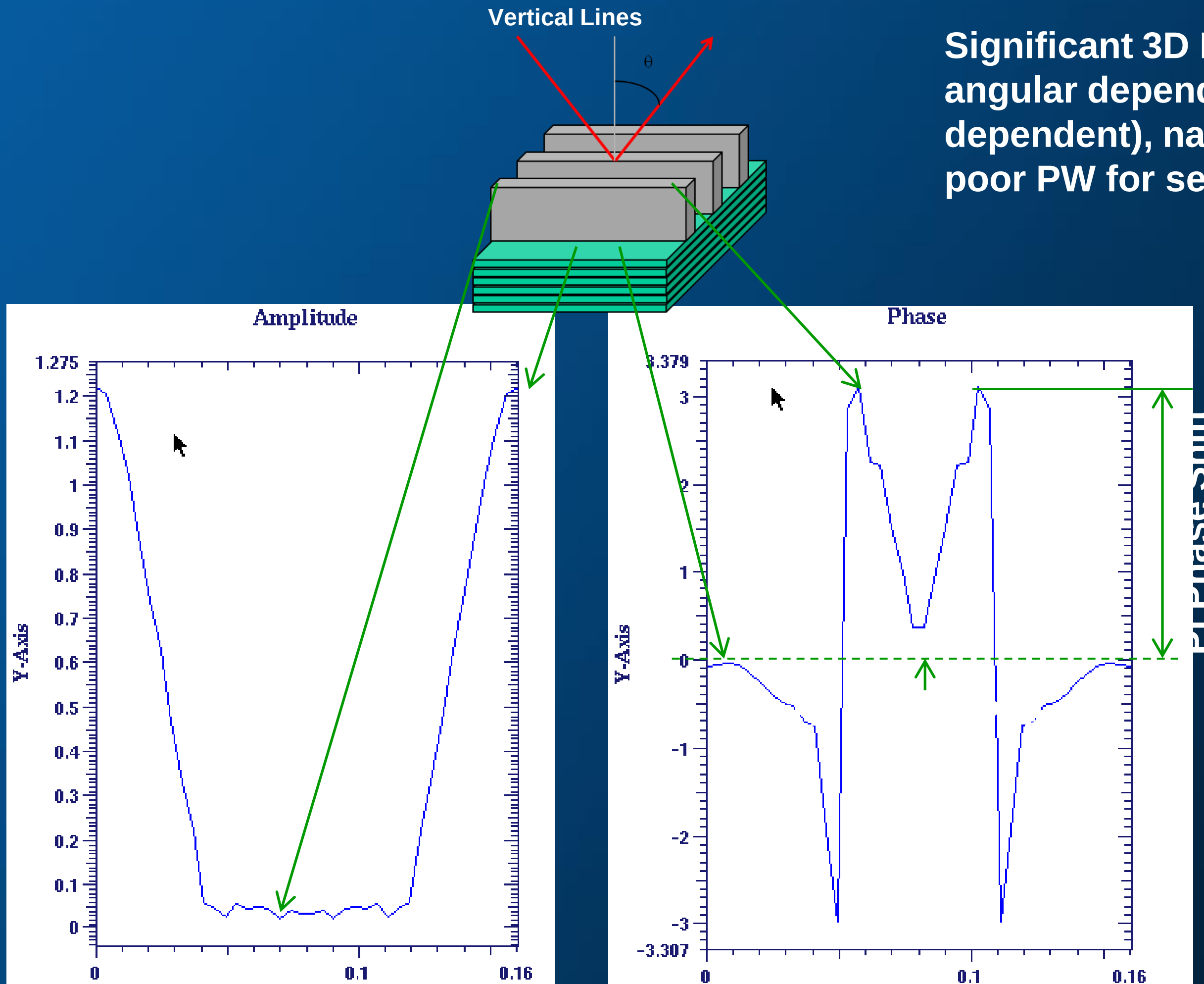
Big Imin and Imax Deltas



Thick Mask Vertical: Near Field E-Field

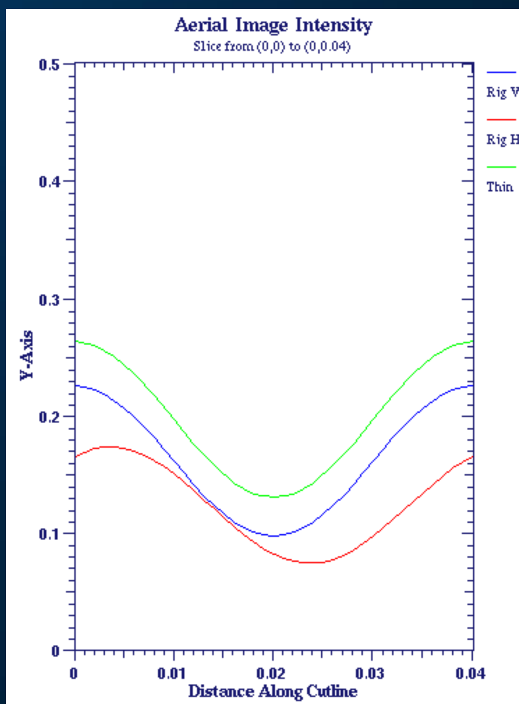
Vertical Lines

EUV is complex PSM (Thick) Mask. Fast Thick Mask Tooling needed for OPC



Significant 3D EPE due to: mask source angular dependencies (EPE - Slot position dependent), narrow DOF (Pitch dependent BF), poor PW for semi-isolated features

Big Imin and Imax Deltas



Thick Mask Vertical: Near Field E-Field

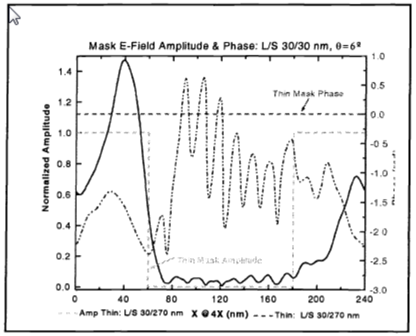
EUV HVM Insertion
Need for Sophisticated OPC

I. INTRODUCTION In this discussion, we show that the masking layer does not behave like a simple binary filter but rather that the illuminating radiation is diffracted and propagates in the multilayer in a very complex way before being reflected out of the mask, affecting the system imaging.

Imaging properties of the extreme ultraviolet mask

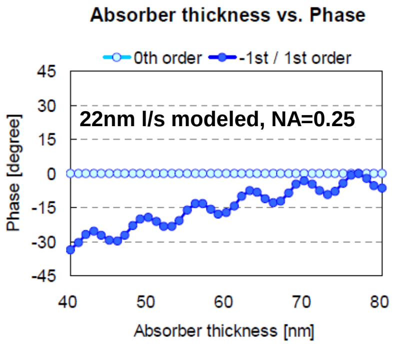
B. S. Bollepalli, M. Khan, and F. Cerrina

J. Vac. Sci. Technol. B 16(6), Nov/Dec 1998



b) θ = 6°

The Impact of the EUV mask Phase Response
Proceedings of SPIE Vol. 4343 (2001)
Christof Krautschik *et al*



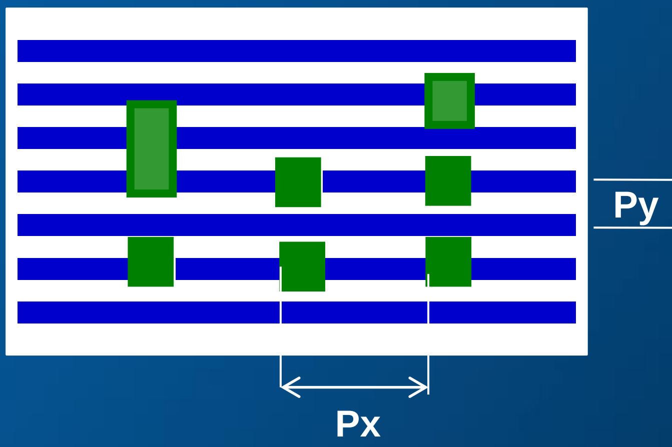
Aberration Budget in Extreme Ultraviolet Lithography
Yumi Nakajima, Takashi Sato, Ryoichi Inanami,
Tetsuro Nakasugi, Tatsuhiko Higashiki
Proc. of SPIE Vol. 6921, 69211A, (2008)

Image EPE is multivariate function of 3D EUV mask scattering, i.e.:
- features placement and dimensions through field (slot) are
source shape and
mask tone and
pitch and
feature size dependent

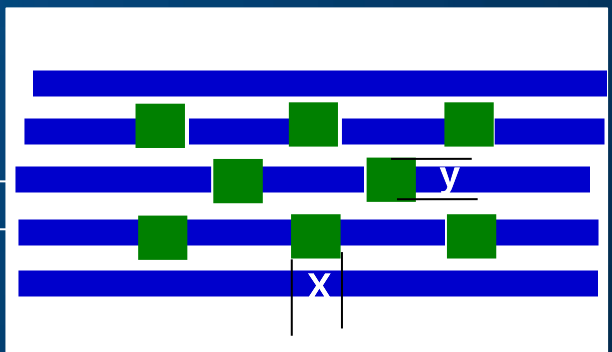
3D nature of EM reflection/absorption/scattering on EUV Mask will require Fast and Accurate non-Kirchhoff approach for EUV OPC modeling and corrections

EUV HVM Insertion
Need for Sophisticated OPC

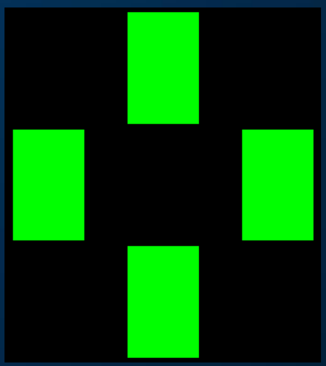
Example 1, 1b, 3



Example 2

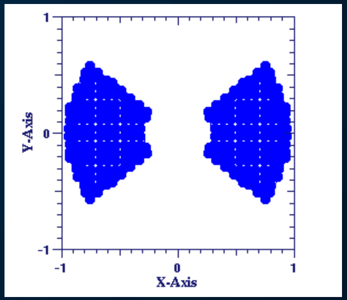


Example 4a,b,c



	1	1b	3	2	4a	4b	4c
Px	80 50	108 84	68 44	108 64	54 42	54 42	54 42
x	20 14	20 14	20 14	20 14	34 26	46 34	20 14
Py	34 22	34 22	54 42	34 22	34 22	34 22	34 22
y	34 22	34 22	54 42	34 22	30 16	18 12	34 22

Source



All features are on the same mask and need to be printed at the same time

All dimensions in nm

Simulation Conditions

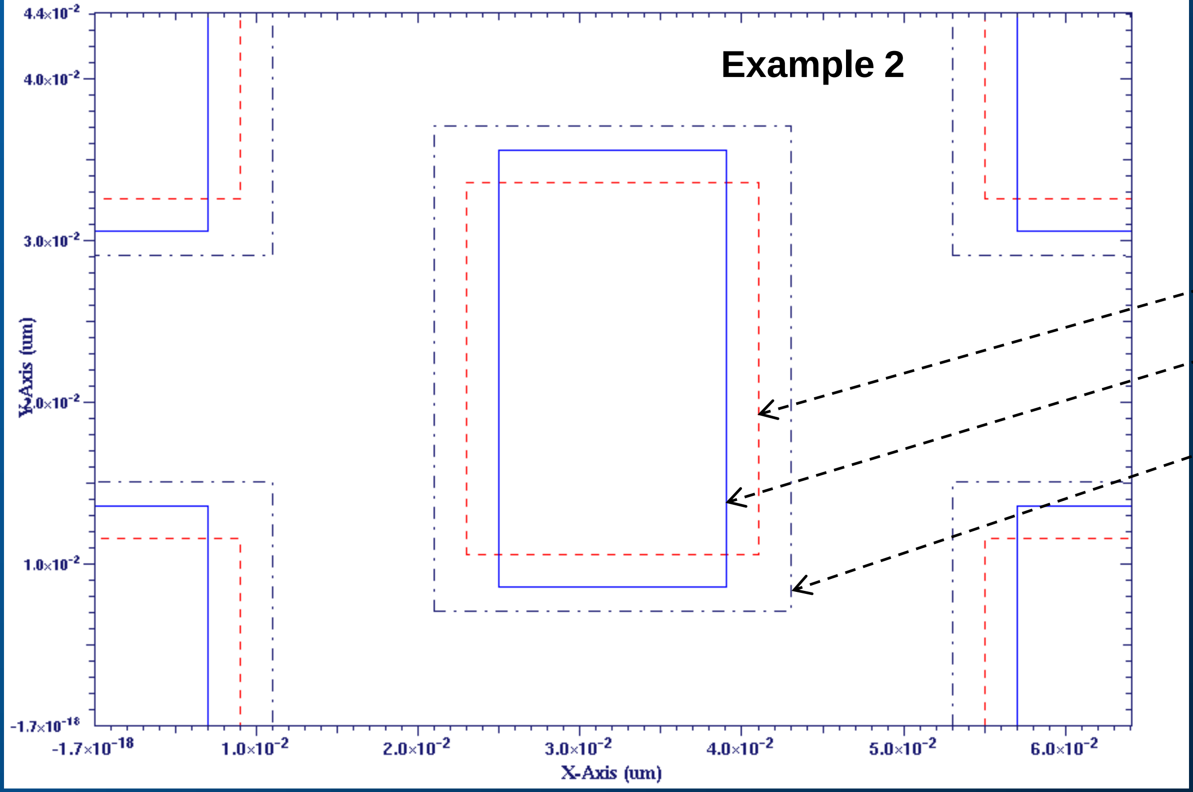
Simulator	Intel's Rigurous EM
Simulation Model	Vector, FDTD
Imaging	NA=0.33, X-Dipole 0.9/0.2
Wavelength	13.5nm
CRAO	6 deg
Aberrations, Flare, OOB	All 0
Mask Absorber	n=0.9394; k=0.0410
Multilayer Si	n=0.9988; k=0.0018
Intermix Layer	n=0.9691, k=0.0044
Multilayer Mo	n=0.9235; k=0.0065
Edge Placement	Mask Tone Specific Threshold

EUV HVM Insertion
Need for Sophisticated OPC
Sensitivity Study

1. Size up features to improve contrast and stochastics until MEEF=3
2. Use Kirchhoff to find starting mask OPC dimensions
3. Use Rigorous EM modeling to run near field/far field imaging around starting OPC dimensions to find correct mask sizing
4. Define common focus and dose threshold for all features
5. Characterize slot position EPE sensitivities for all features
6. Characterize focus dependent EPE sensitivities for all features

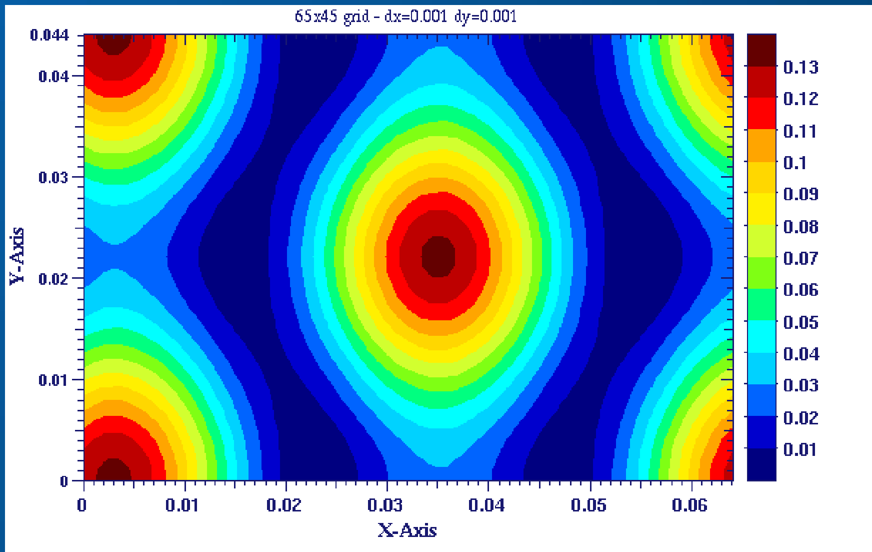
Assess both Dark field and Bright field sensitivities.

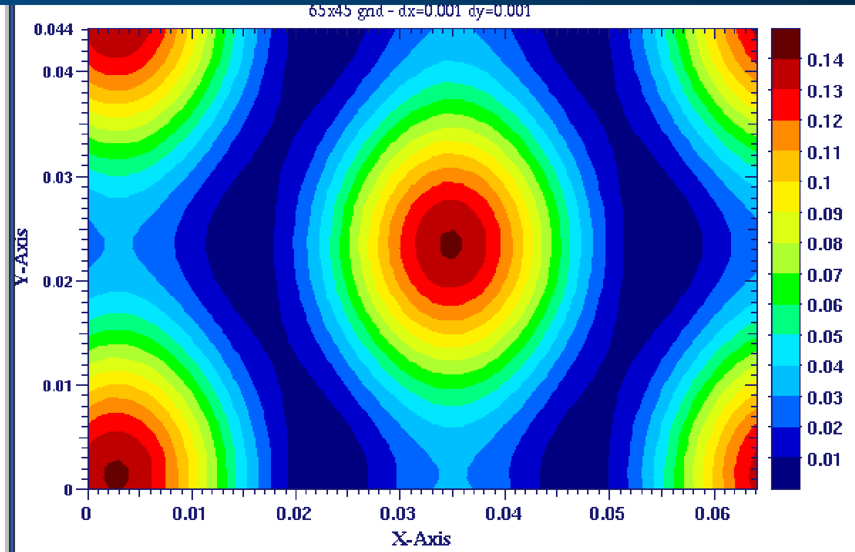
EUV HVM Insertion
Need for Sophisticated OPC



	W	H
OPC (Ideal Mask)	18	23
OPC (Thick Mask)	14	27
Target	22	30

Example2 (blue) : Dark Field, Aerial Image with OPC, CRAO along x-axis

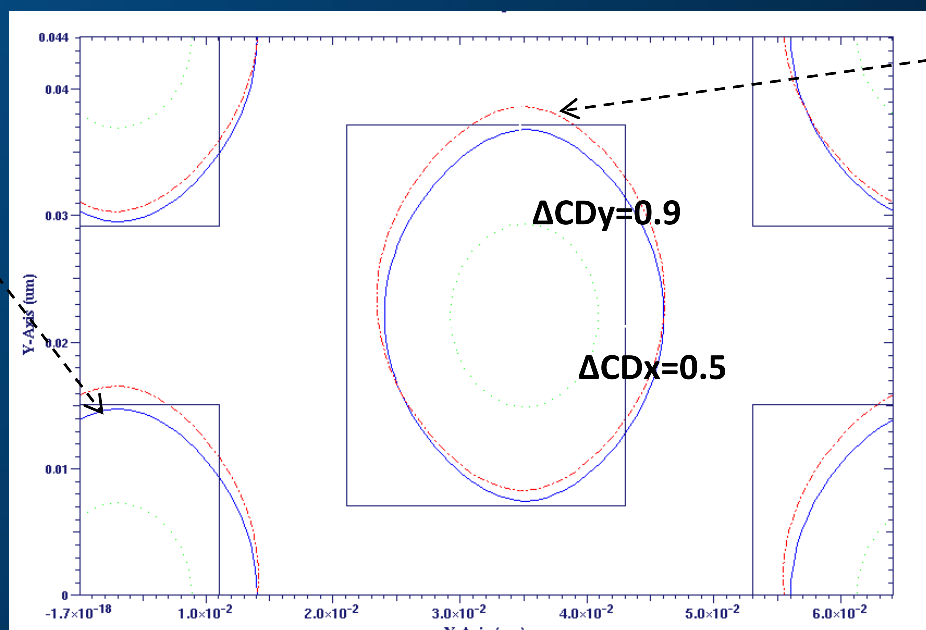




Φ=0 Slot Center (Blue Solid line)

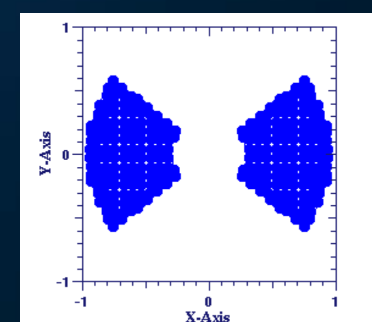
Contrast = 0.846

Φ=25 , Slot Edge (Red dashed line)

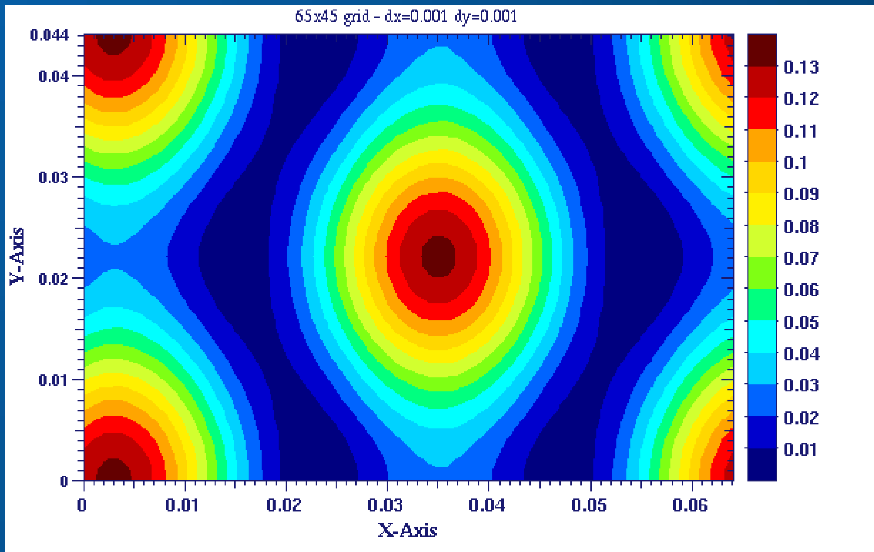


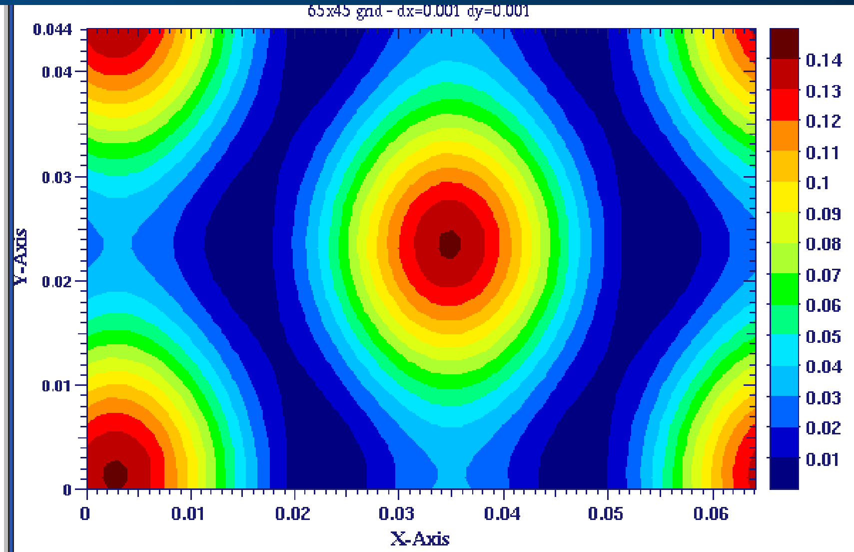
CRAO along x-axis

Threshold → 0.05 for ϕ=0 we get, CDx = 22 CDy = 29.3



Example2 (blue) : Dark Field, Aerial Image with OPC, CRAO along x-axis





Φ=0 Slot Center (Blue Solid line)

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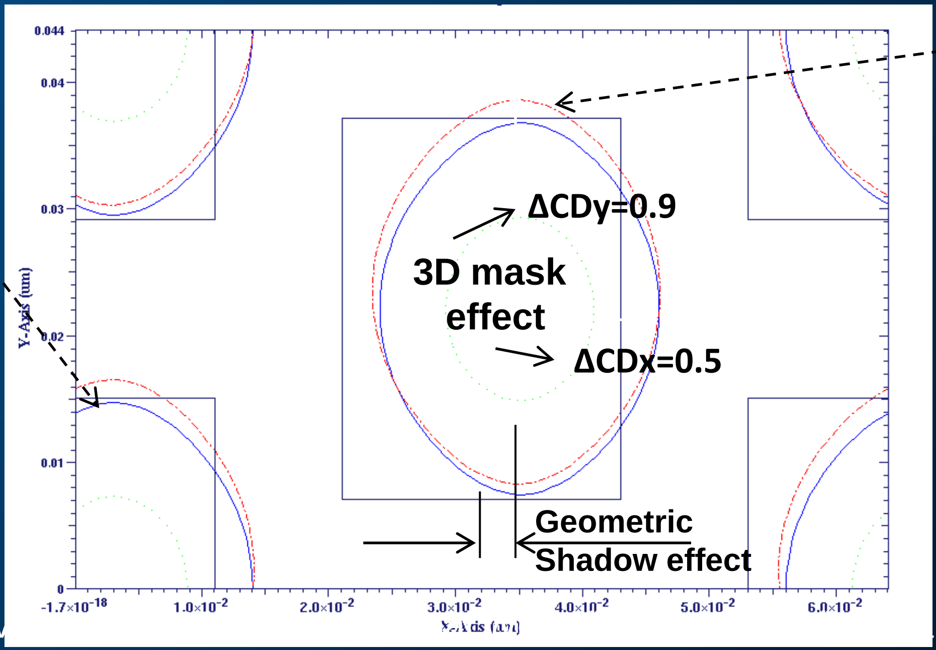
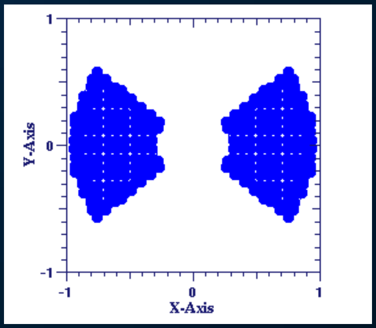
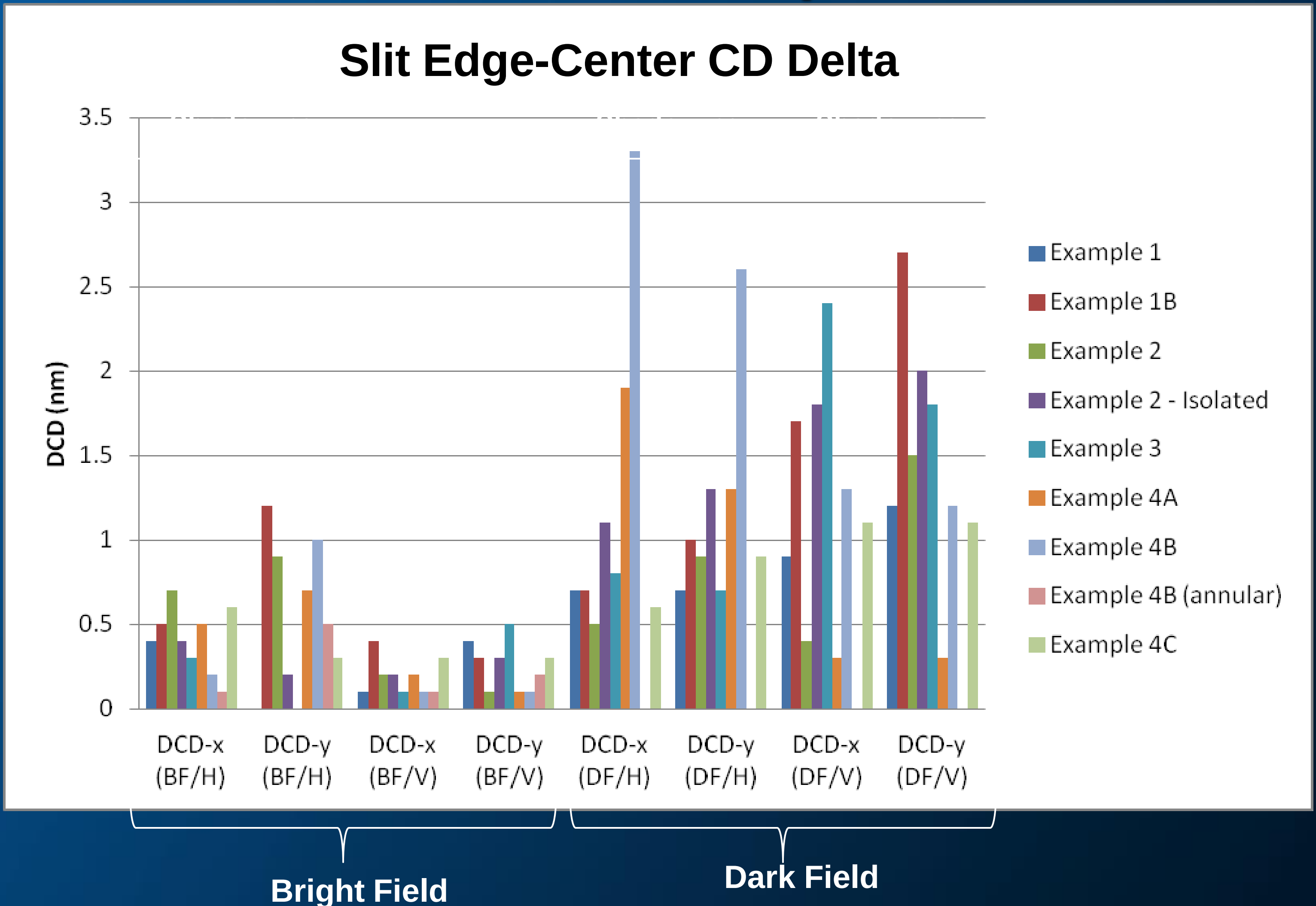




Through-Slit 3D Mask EPE effects are source shape , mask tone, feature pitch and feature size Dependent



Example2 (blue): Dark Field, Through focus results

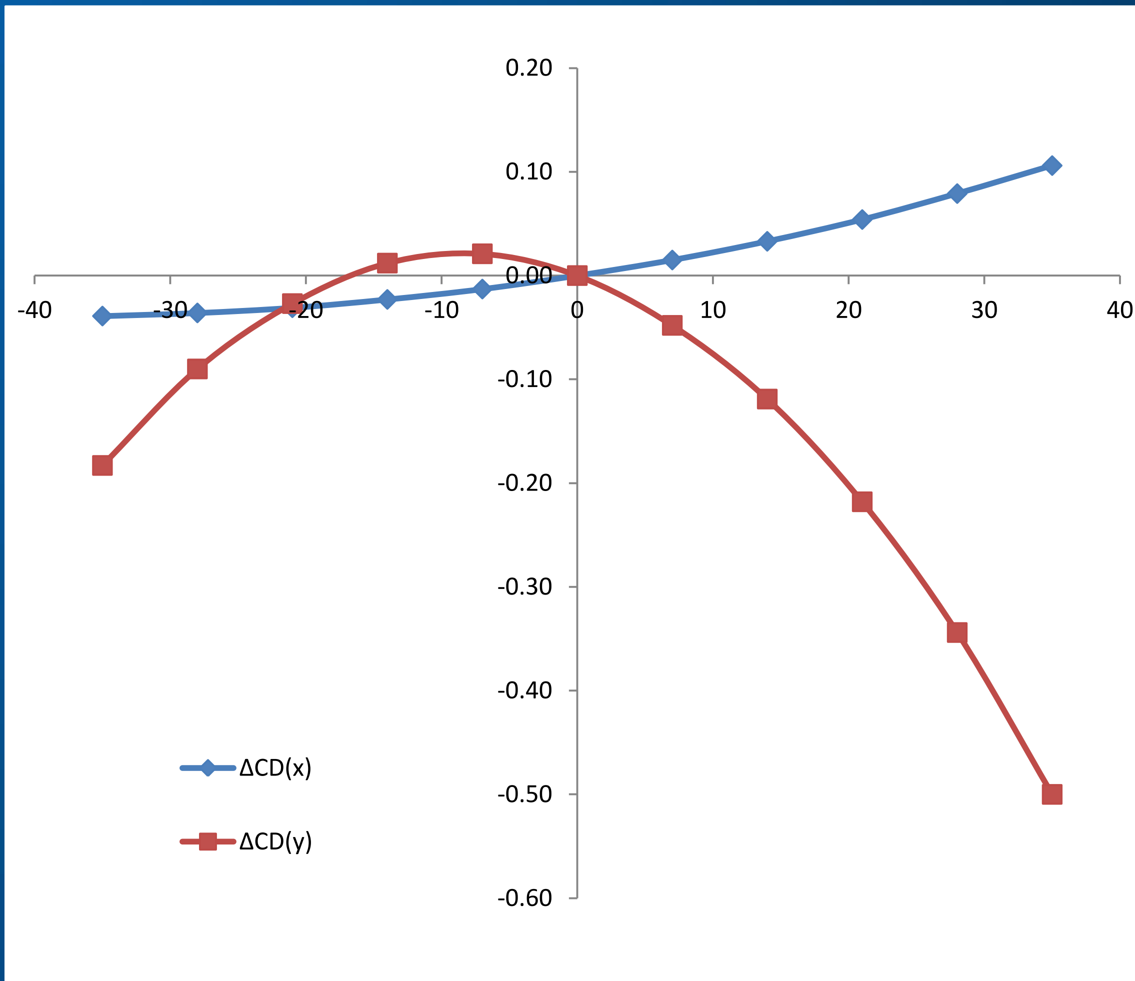
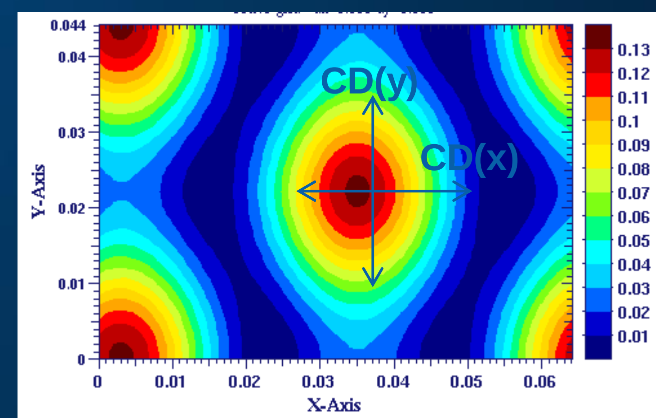
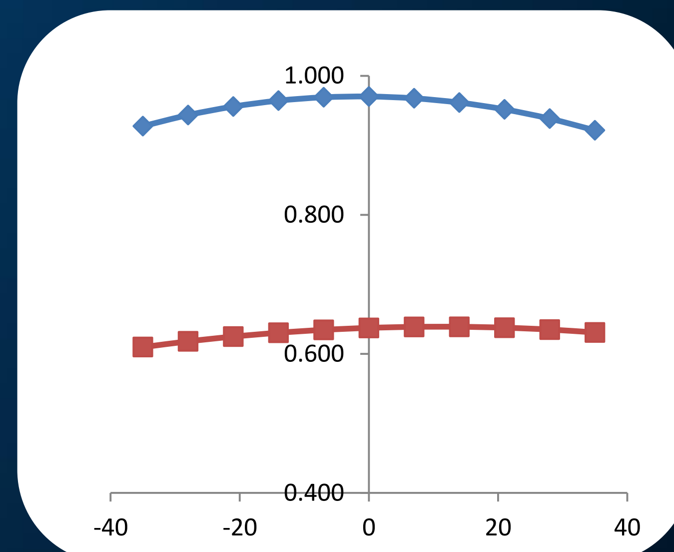


Image Contrast

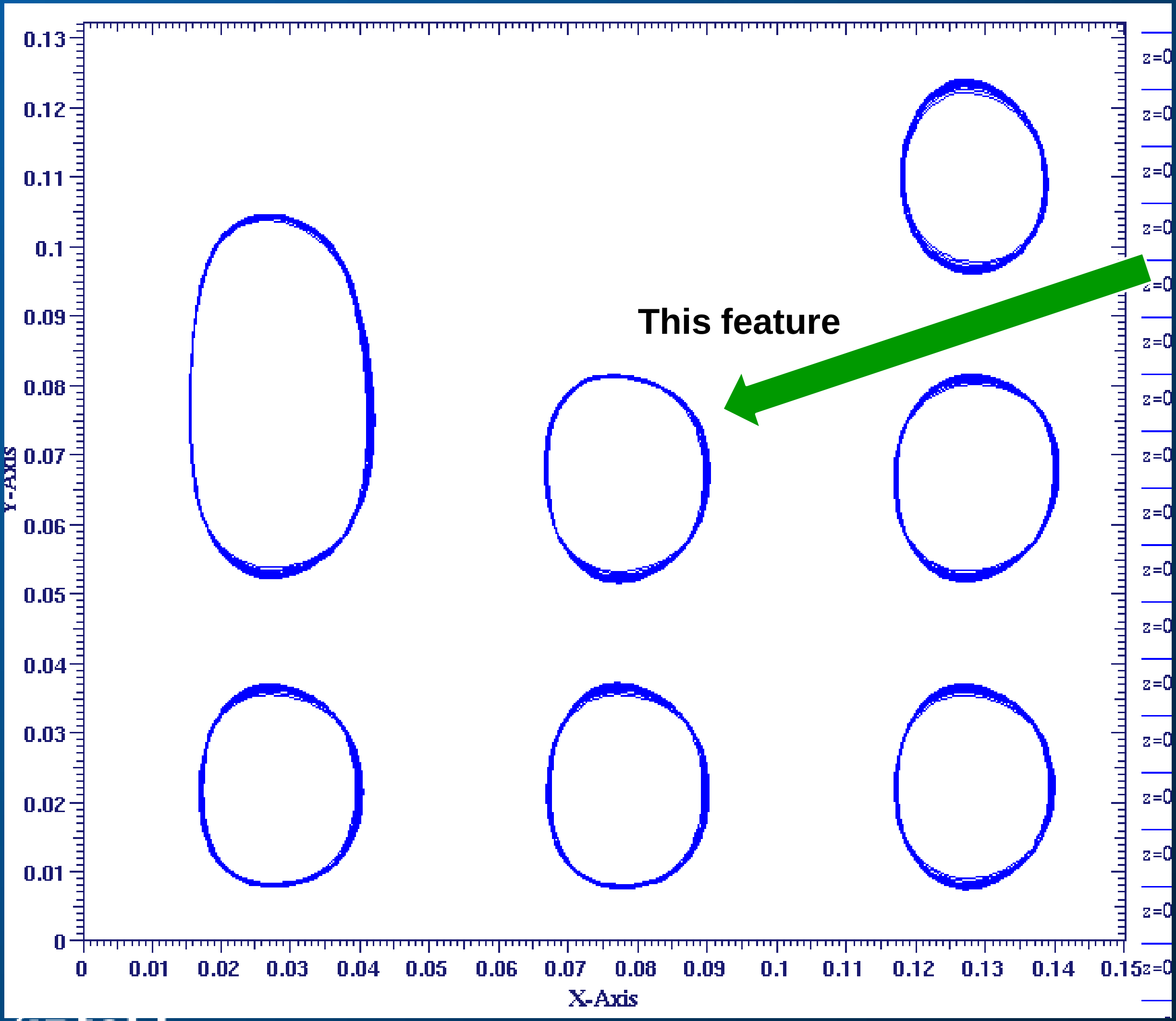




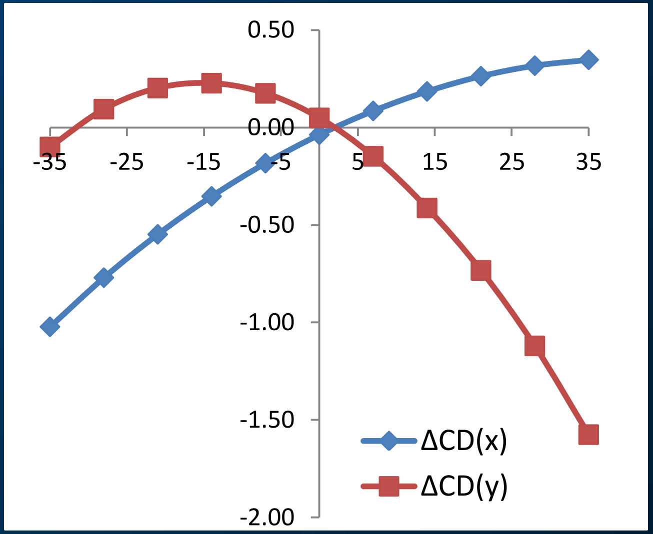
ΔCD (x) = CD (x, focus) - CD (x, focus=0)
ΔCD (y) = CD (y, focus) - CD (y, focus=0)

3D Mask dependent EPE Changes through Focus are Tone, Pitch and Feature size specific and significant for most features

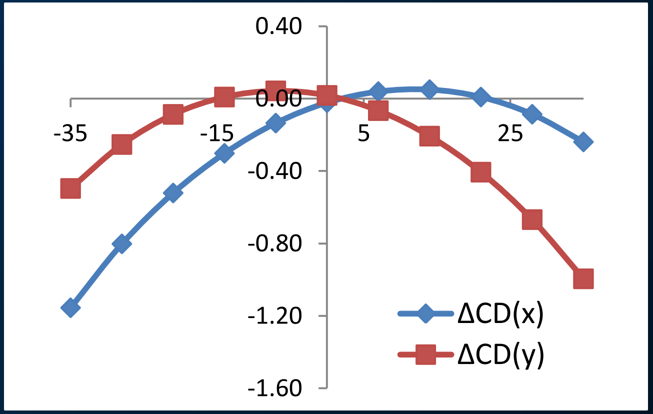
Example1 (Blue) : Through focus contour



Bright Field

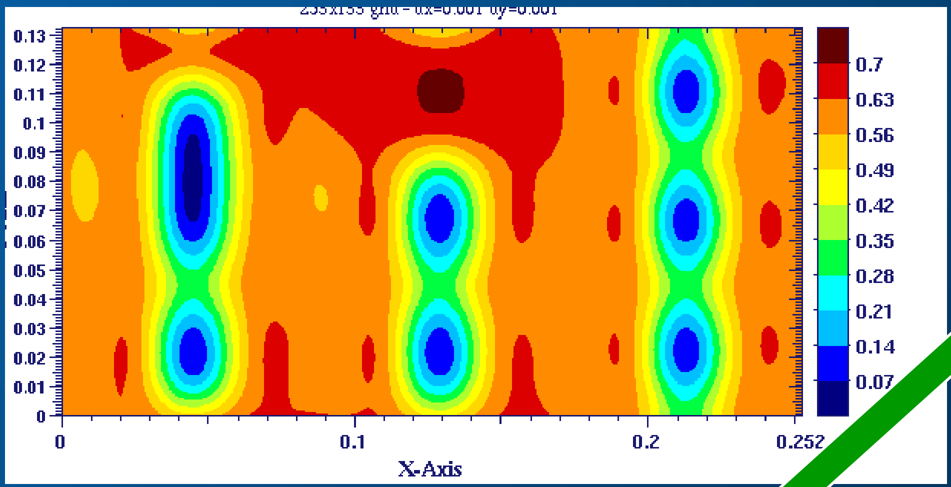


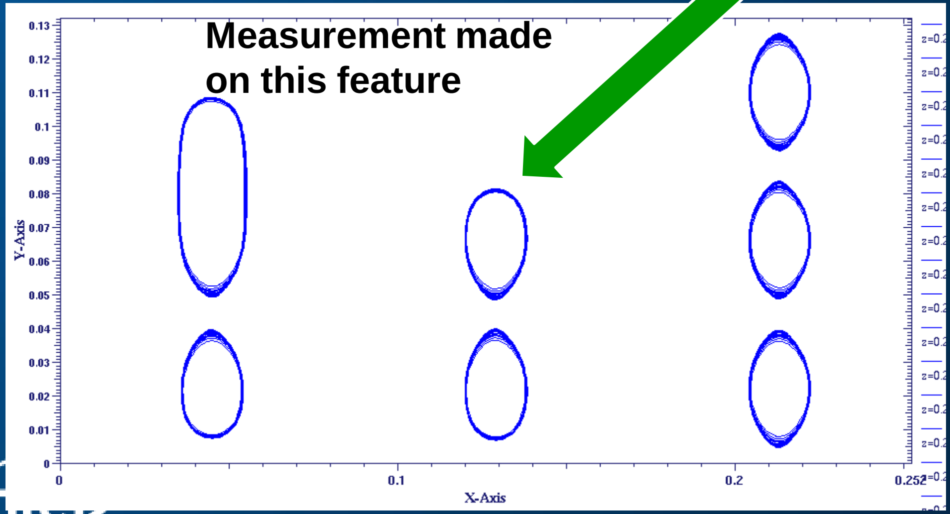
Dark Field



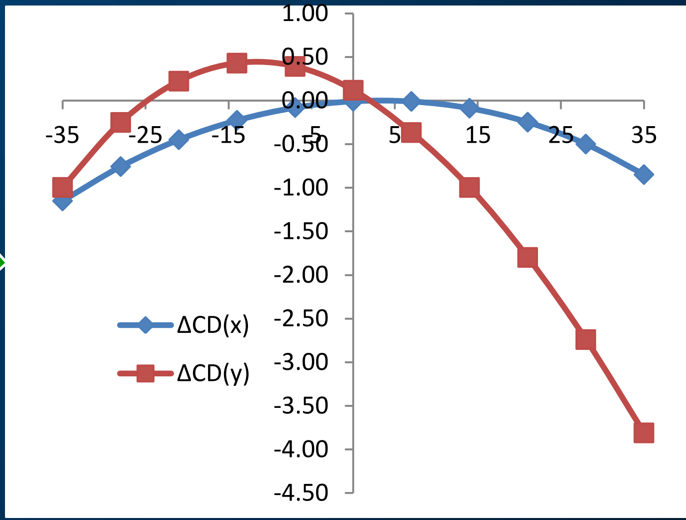
3D Mask dependent EPE Changes through Focus are Tone, Pitch and Feature size specific and significant for most features

Example1B (blue) : Through focus contours

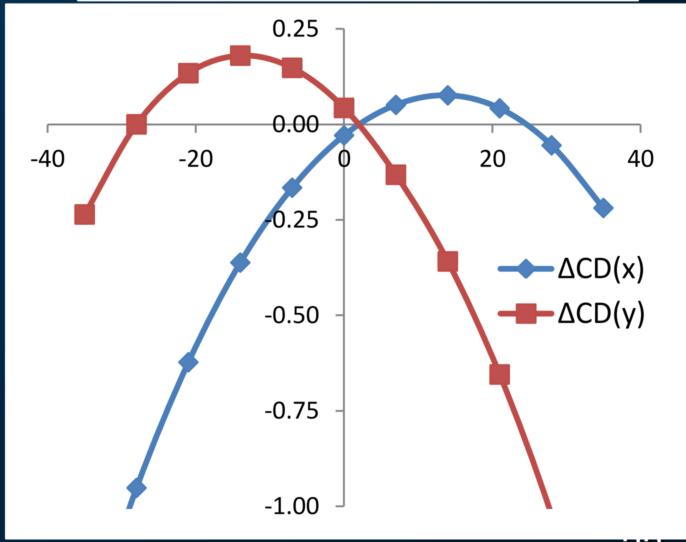




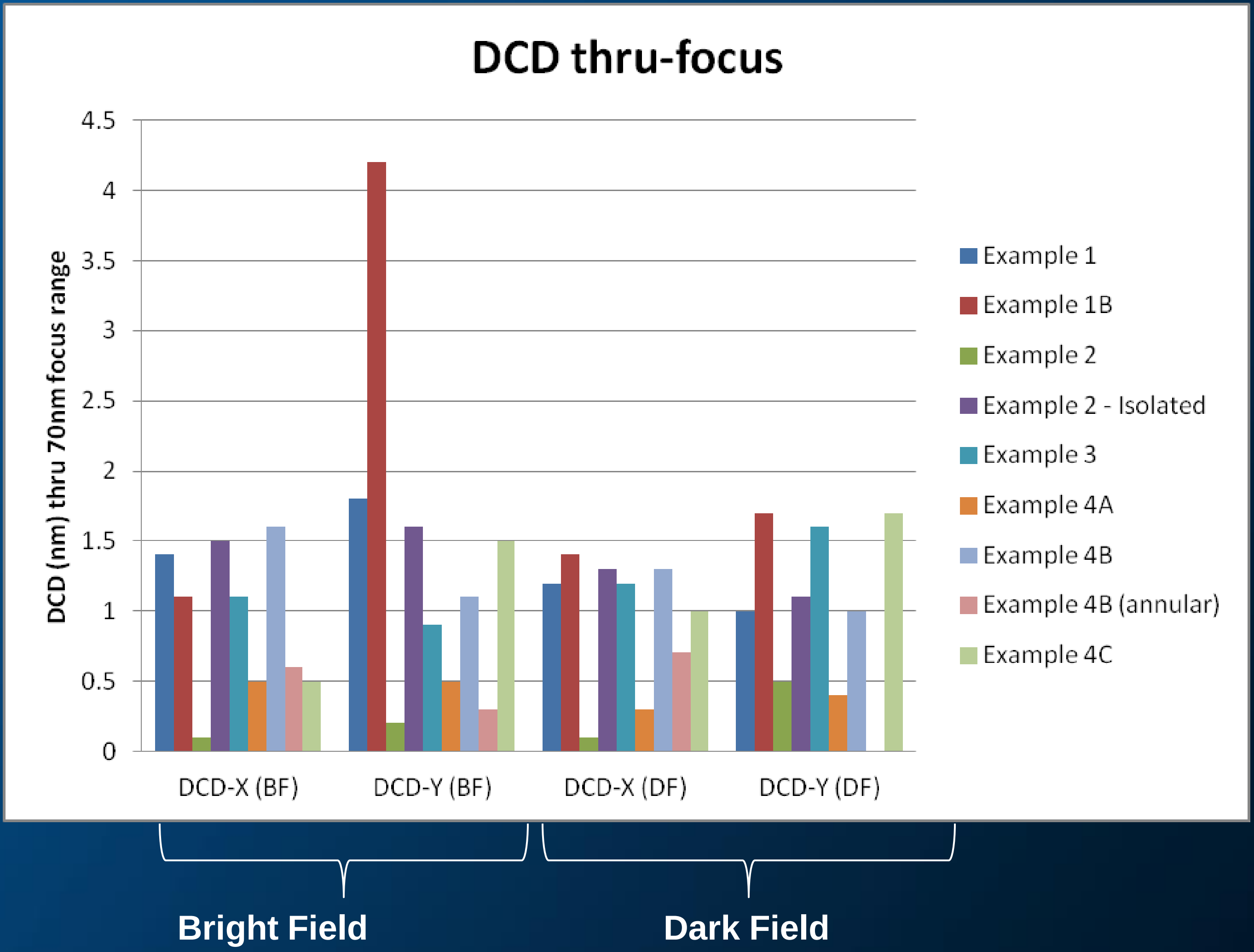
Bright Field



Dark Field



Through-Focus 3D Mask EPE effects are source shape , mask tone, feature pitch and feature size Dependent



EUV HVM Insertion - Tooling Need for Sophisticated OPC

Interaction of oblique EUV Radiation with 3D geometries formed by reflective and absorptive layers of EUV Mask leads to complex near field phase and amplitude behavior of reflected EUV radiation.

Complexity of referred interaction manifest itself in properties usually associated with phase shifted masks: I_{min} lower than I_{min} for "thin mask", sizable "Best Focus" shifts between different features and pitches and strong dependence on radiation source choice.

Referred dependencies, if not corrected, will result in Edge Placement Errors that will consume exceedingly large portion of CD Control Budget

Accurate and Fast Approximation of Rigorous EM modeling and corresponding model calibration procedures are necessary to provide EUVL OPC support for HVM Insertion.

EUV HVM Insertion – Materials Stochastics Suppression

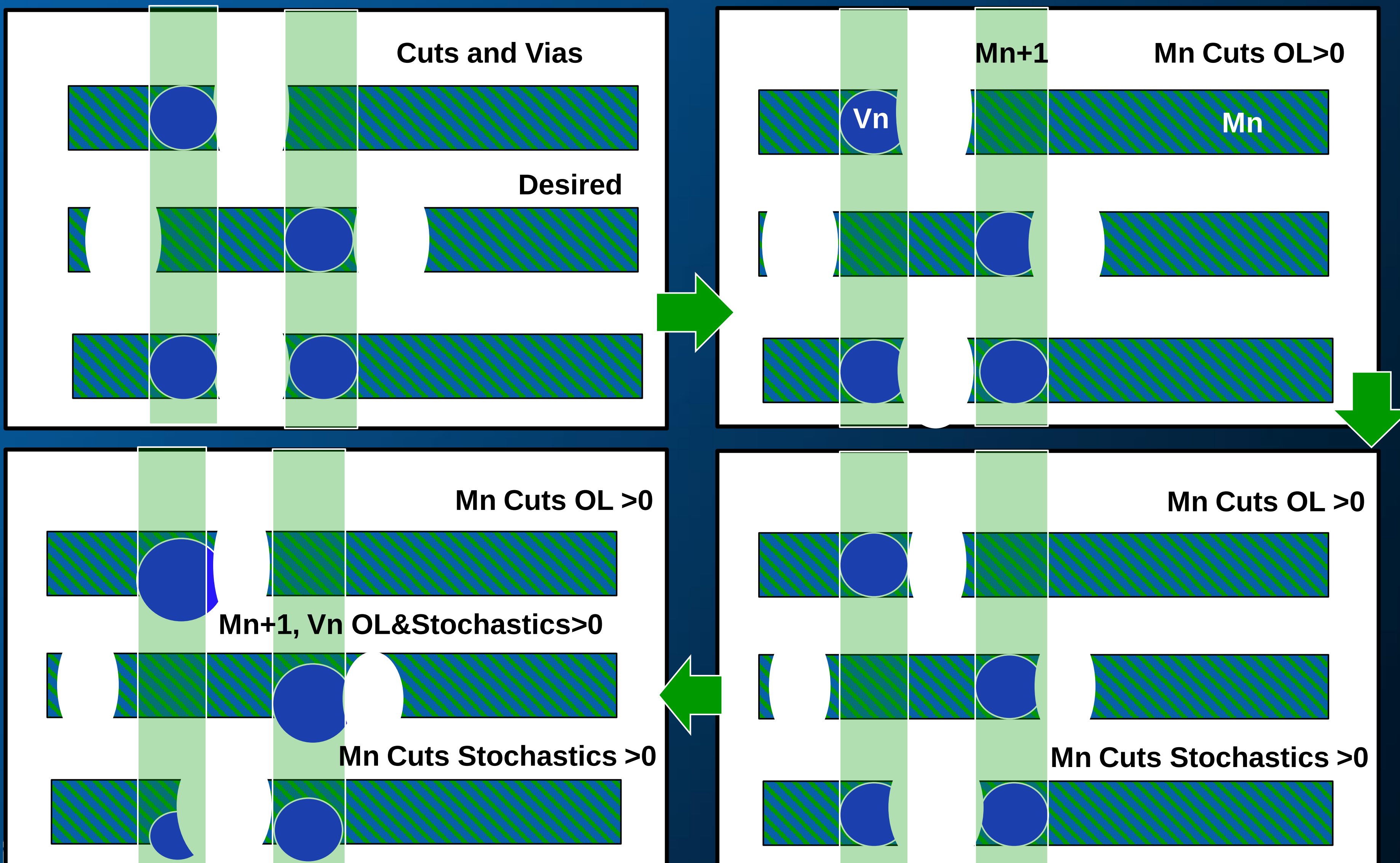
Given actual and expected 193i and EUV Tools respective Productivity one have to conclude

Overlay	Throughput
16-point Alignment	300 mm Wafers 30 mJ/cm2 (125 shots)
2.5 nm*	175 wph **>250 in 2013**

that NXE33XX must have TPT>100wph at HVM insertion

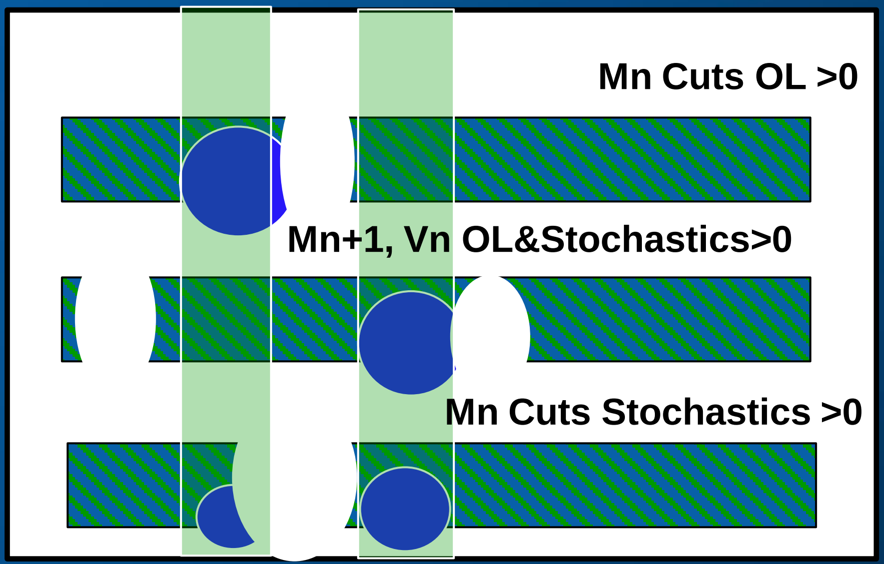
Sources ASML.COM, SPIE 2012Vol. 8326 83260L-14

EUV HVM Insertion
Materials Requirements

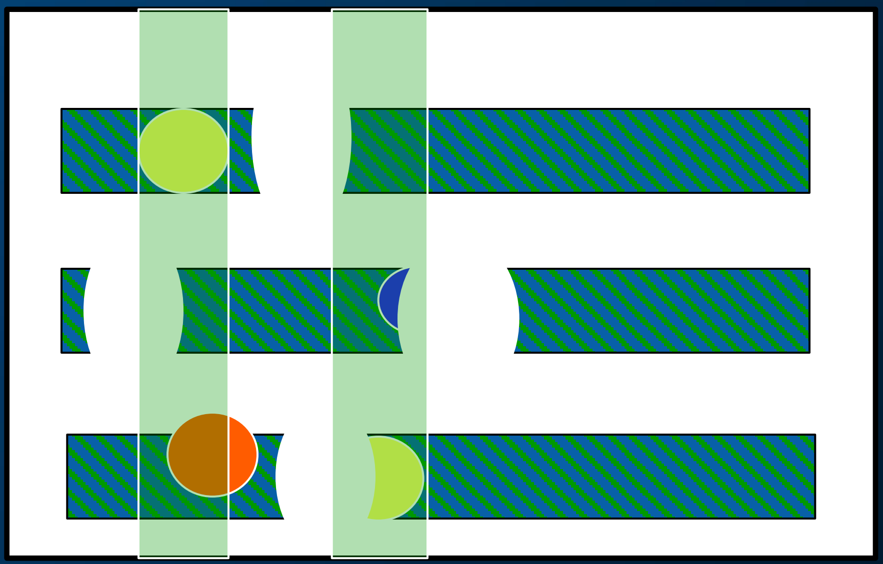


EUV HVM Insertion - Materials Stochastics Suppression

EUV Cuts and Vias

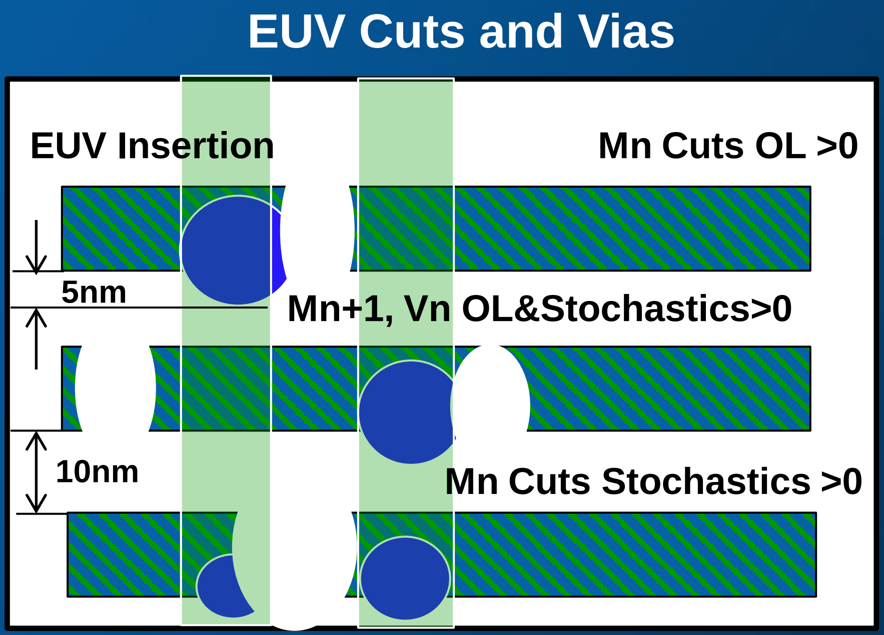


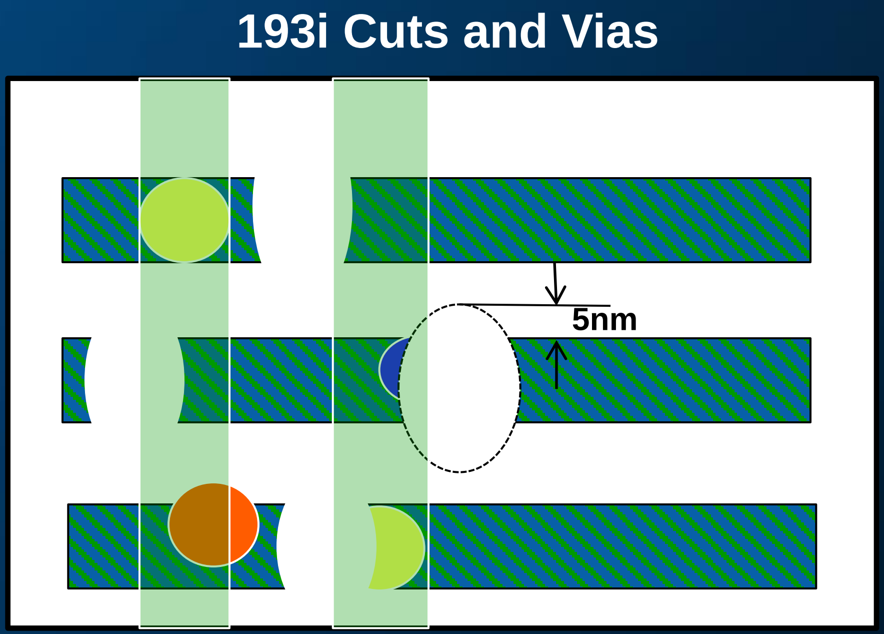
193i Cuts and Vias



EPE (EUV/193i OL) ≤ EPE (N*193i/193i)
EPE EUV Stochastics ≥ EPE 193i Stochastic
Assuming everything else = We would want at EUV Insertion
EPE EUV (OL, Stochastics) < EPE 193i (OL, Stochastics)

EUV HVM Insertion - Materials Stochastics Suppression





EPE (EUV/193i OL) ≤ EPE (N*193i/193i)

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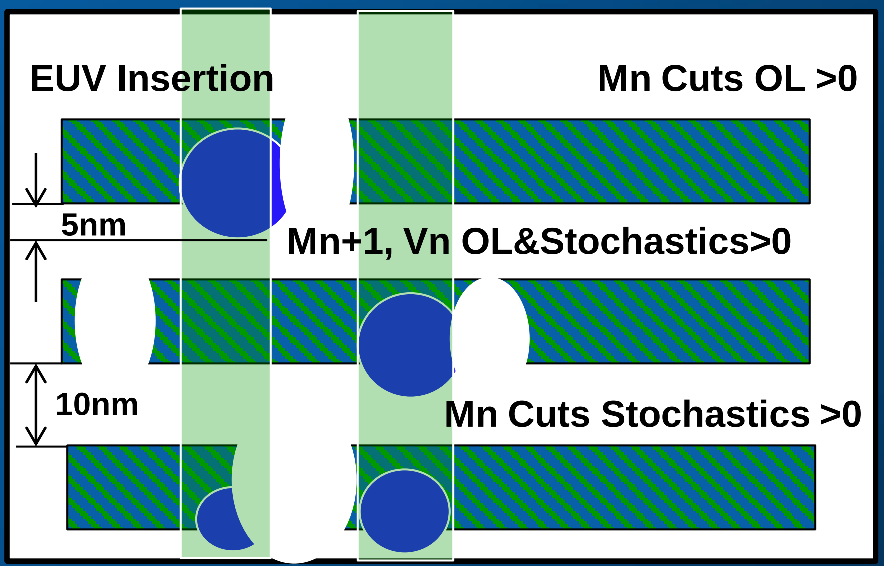
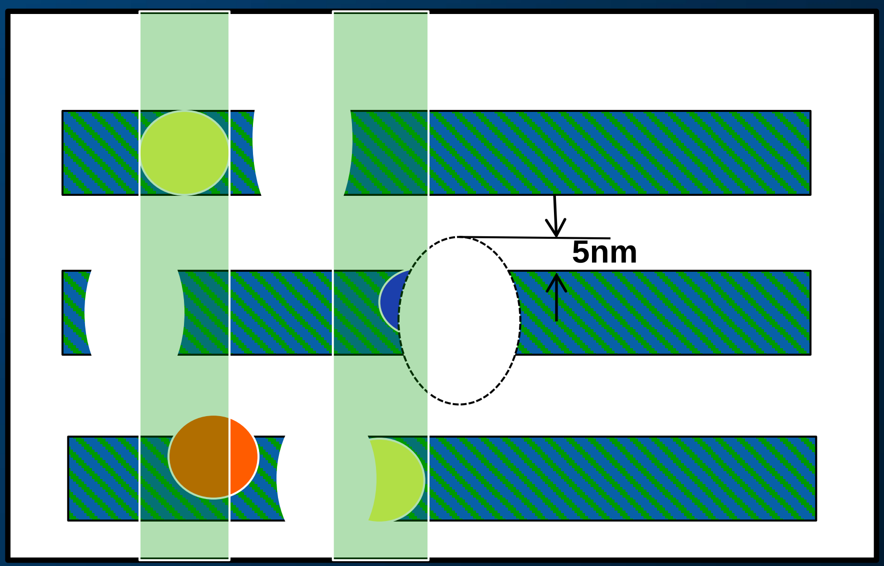
EUV HVM Insertion - Materials Stochastics Suppression

EUV Cuts and Vias



193i Cuts and Vias



EPE (EUV/193i OL) ≤ EPE (N*193i/193i)
EPE EUV Stochastics ≥ EPE 193i Stochastic
Assuming everything else = We would want at EUV Insertion
EPE EUV (OL, Stochastics) < EPE 193i (OL, Stochastics)

Given 5nm EPE limit what does it mean for EUV Stochastics?

EUV HVM Insertion - Materials Stochastics Suppression

$EPE_{all} = EPE_{OL} \pm ½\ CD3\sigma$

$|EPE_{all}| = EPE_{OL} + ½\ CD3\sigma$

$CD3\sigma$ = f(resist stochastics, focus and dose errors, OPC residuals, mask errors with MEEFs, Etch Biases, etc, etc, etc)

Assuming for simplicity for EUV :

σ(resist stochastics) = σ(focus and dose errors, OPC residuals, mask errors with MEEFs, Etch Biases, etc, etc, etc)

$|EPE_{all}|=EPE_{OL}+½\ CD3\sigma = EPE_{OL}+½CD3\sigma(2\text{resist stochastics})$

or, keeping it simple,

$|EPE_{all}|= EPE_{OL}+CD3\sigma(\text{resist stochastics}) = 5nm$

Assuming EUV/193i EPE_{OL}=2nm

$CD3\sigma_{EUV}(\text{resist stochastics}) = 5nm – EPE_{OL} = 5nm-2nm = 3nm$

EUV HVM Insertion - Materials Stochastics Suppression

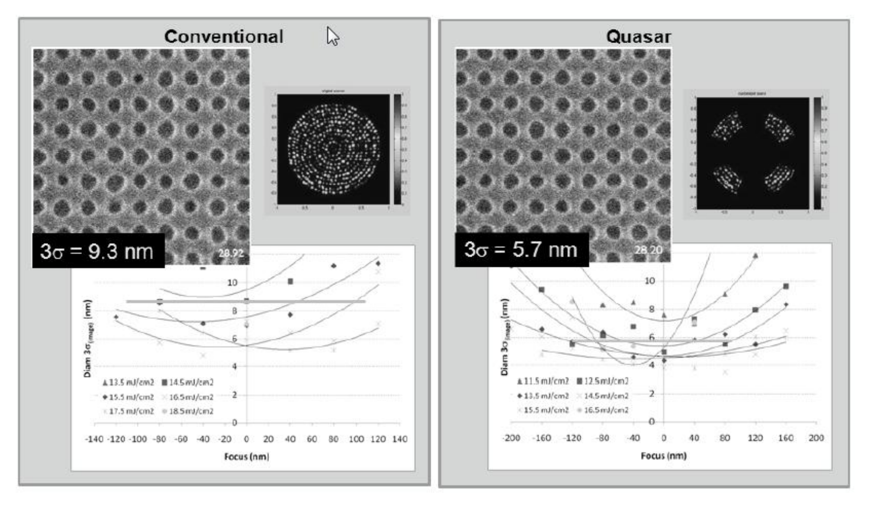
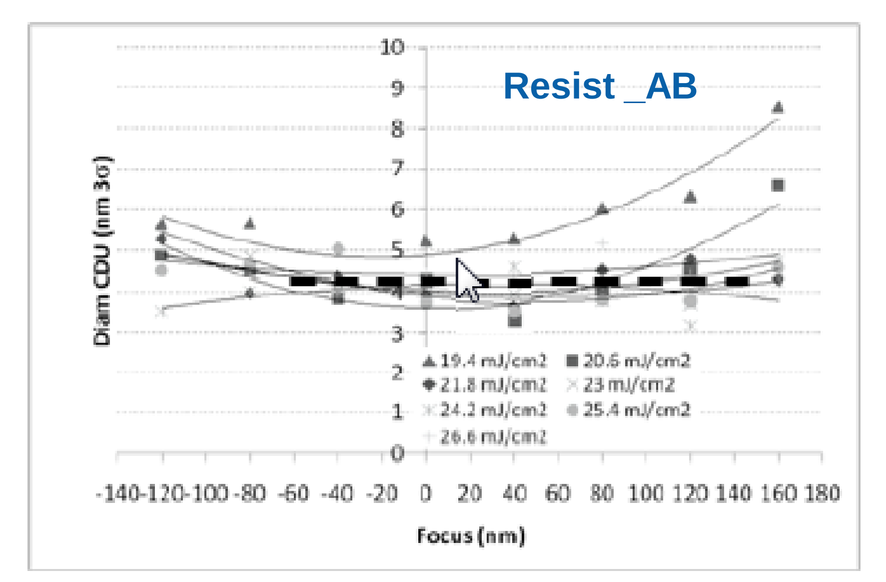


Figure 8. Comparison of $\sigma_{(image)}$ Bossung plots for NXE:3100 conventional vs. Quasar illumination. Litho targets are 1:1 Contacts at 54 nm pitch; IMEC setup POR.



EUV resist performance: current assessment for sub-22 nm half-pitch patterning on NXE:3300

T. Wallow[1*], D. Civay[1], S. Wang[2], H.F. Hoefnagels[2], C. Verspaget[2], G. Tanriseven[2], A. Fumar-Pici[3], S. Hansen[4], J. Schefske[5], M. Singh[5], R. Maas[2], Y. van Dommelen[6], J. Mallmann[2]

Proc. of SPIE Vol. 8322, 83221J · © 2012 SPIE

$CD3\sigma_{EUV}$(resist stochastics) =3nm=CD3σ(focus and dose errors, OPC residuals, mask errors, Etch Biases etc, etc, etc) will be very tough

EUV HVM Insertion - Materials
Stochastics Suppression

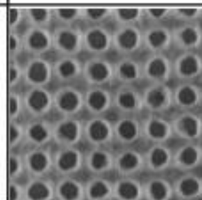
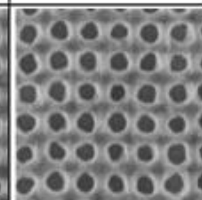
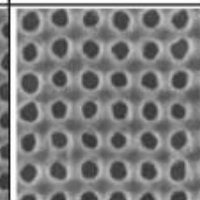
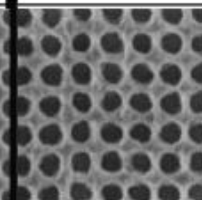
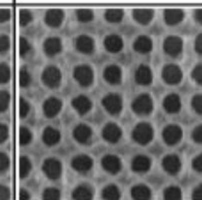
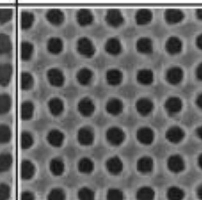
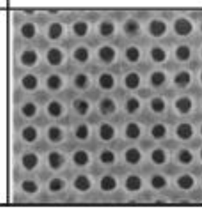
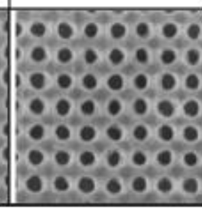
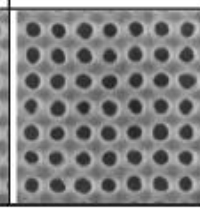
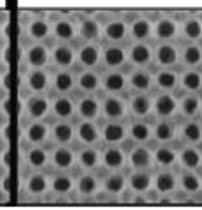
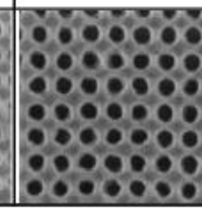
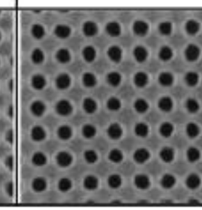
		Resist A	Resist B	Resist C	Resist D	Resist E	Resist F
Protecting group size		Bulky	Bulky	Bulky	Small	Small	Small
Protecting group ratio		Low	Middle	High	Low	Middle	High
35nm CH	Sensitivity	46.0mJ	55.9mJ	61.4mJ	53.2mJ	54.6mJ	56.1mJ
	CDU	9.7nm	5.8nm	3.6nm	Overdose	Overdose	3.8nm
	Top-down						
30nm CH	Sensitivity	50.1mJ	60.1mJ	70.6mJ	53.2mJ	59.5mJ	61.0mJ
	CDU	4.4nm	3.8nm	3.3nm	5.5nm	3.7nm	3.6nm
	Top-down						

Table 2. CDU values and sensitivity for different protective group ratios at 30nm HP and 35nm HP contact hole patterns. All six samples were exposed on the AMET using annular illumination. Process conditions are the same.

Key Parameters of EUV Resists for Contact Hole Applications

Proc. of SPIE Vol. 8322, 83221B

Kyoungyong Cho [1], Hiroki Nakagawa [2], Ken Maruyama [2], Makoto Shimizu [3], Tooru Kimura [3], Yoshi Hishiro [2],

[1] SEMATECH, 257 Fuller Road, Albany NY 12203
[2] JSR Micro, Inc., 1280 North Mathilda Avenue, Sunnyvale, CA 94809
[3] JSR Corporation, 100 Kawajiri-cho, Yokkaichi, Mie, 510-8552, Japan

EUV HVM Insertion - Materials Stochastics Suppression

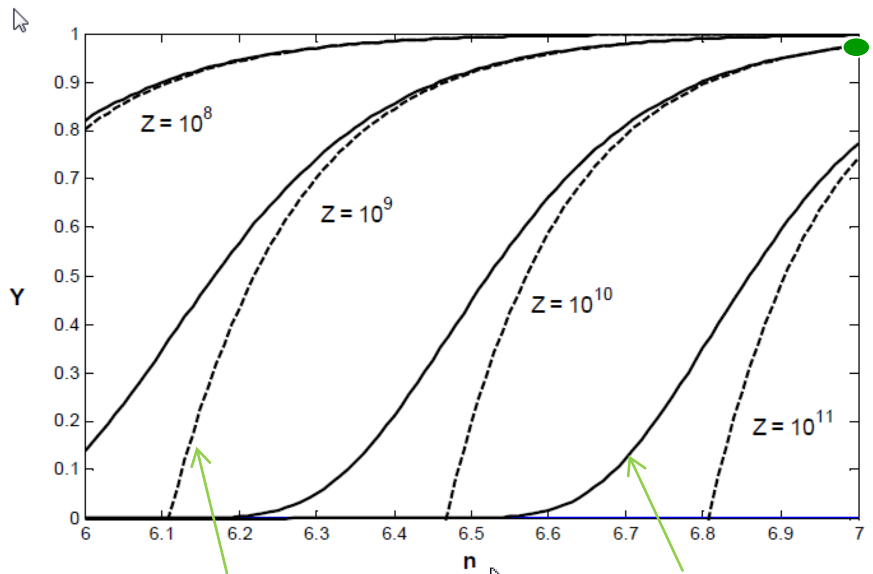
$CD3\sigma_{EUV}$(resist stochastics) =3nm=Sum (Photon, e^-, Acid, Develop Stats)

In 2003, Lee, Bristol and Bjorkholm using photon shot noise statistics considerations only, derived formula for required incoming Dose (D_{inc}) to print all of Z contacts size S (nm) with Probability (Yield) Y% within Exposure Dose variation defined by exposure latitude EL =$2\Delta N/N_0$ where $\Delta N=n\sigma$), assuming ratio of incoming radiation to absorbed by resist is given by α and quantum efficiency of photons producing species resulting in solubility change is given by ε. Plot on the right shows relation between n and Yield for large contact arrays.

To print good *all* of n*10^{10} ($3*1.4*10^9*2*^n$) contacts on 98% of the wafers require n=7 for 2ΔN absorbed EUV photons

(Ivy Bridge (22nm) has $1.4*10^9$ Transistors, assume 3 Contacts/Transistor,)

Contact Array Yield vs Photon stats Only!



$$Y = 1 - Z\left(1 - erf\left(n/\sqrt{2}\right)\right)$$

Approximation, true near unity,

$$Y = \left[erf\left(n/\sqrt{2}\right)\right]^Z$$

General Expression

Shot noise and process window study for printing small contact holes using EUV Lithography

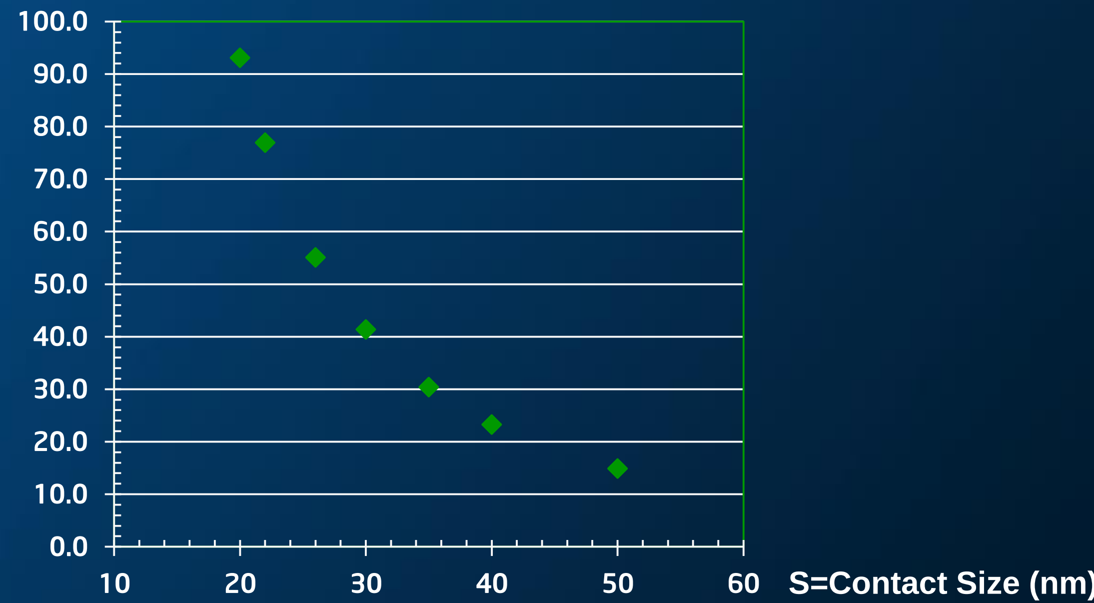
Sang H. Lee*, Robert Bristol, John Bjorkholm Proceedings of SPIE Vol. 5037 (2003)

EUV HVM Insertion - Materials
Stochastics Suppression

$CD3\sigma_{EUV}$(resist stochastics) = $3CD\sigma_{EUV}$ (Photon, e^-, Acid, Develop Stats)=3nm

In 2003, Lee, Bristol and Bjorkholm using photon shot noise statistics considerations only, derived formula for required incoming Dose (D_{inc}) to print all of Z contacts size S (nm) with Probability (Yield) Y% within Exposure Dose variation defined by exposure latitude EL =$2\Delta N/N_0$ where $\Delta N=n\sigma$), assuming ratio of incoming radiation to absorbed by resist is given by α and quantum efficiency of photons producing species resulting in solubility change is given by ε.

D_{inc} = Dose to Print (mj/cm²), Photon stats Only!



Plot on the right shows Dose needed to print good all $n*10^{10}$ contacts with 98% probability for EUV (ε=2) with EL=5% and rather generous absorption α=0.5

1

$$D_{inc} \geq \frac{1.88}{\alpha \cdot \varepsilon} \cdot \left[\frac{2n}{EL \cdot S} \right]^2 mJ/cm^2$$

n=7
α=0.5
ε=2
EL=5%

Shot noise and process window study for printing small contact holes using EUV Lithography

Sang H. Lee*, Robert Bristol, John Bjorkholm Proceedings of SPIE Vol. 5037 (2003)

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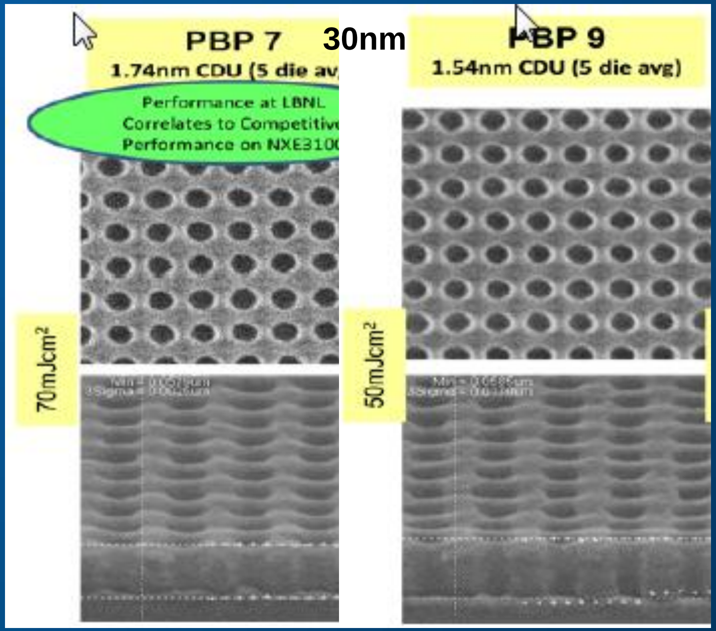
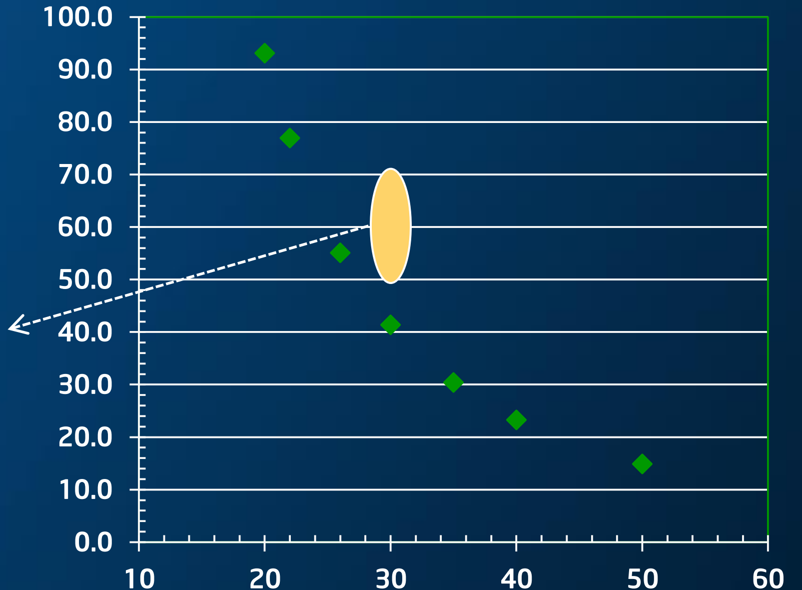
$CD3\sigma_{EUV}$(resist stochastics) =3nm = CD3σ (Photon, e^- Acid, Develop stats)



Comparison of EUV and e-Beam Lithographic Technologies for Sub 22nm Node Patterning

James Cameron et al 2012 Proc. of SPIE Vol. 8322 83222F-1

D_{inc} = Dose to Print (mj/cm²), Photon stats Only!



1

$$D_{inc} \geq \frac{1.88}{\alpha \cdot \varepsilon} \cdot \left[\frac{2n}{EL \cdot S} \right]^2 mJ / cm^2$$

n=7
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Shot noise and process window study for printing small contact holes using EUV Lithography

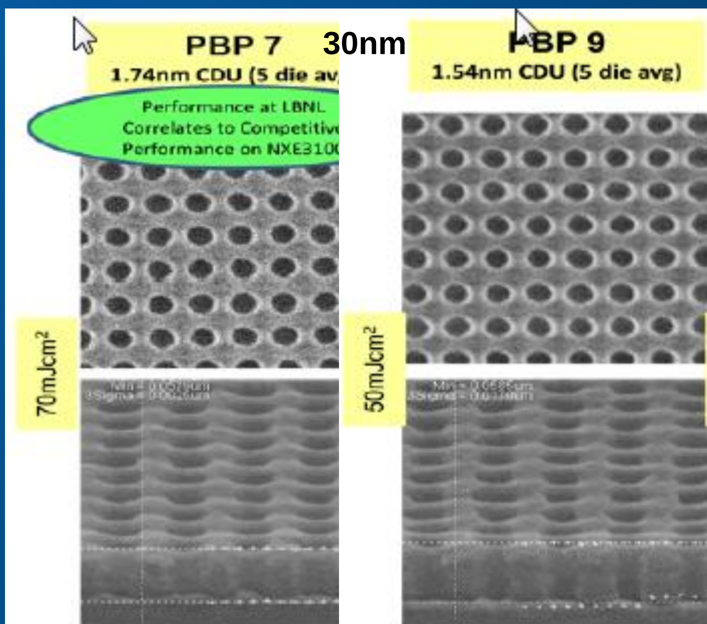
Sang H. Lee*, Robert Bristol, John Bjorkholm Proceedings of SPIE Vol. 5037 (2003)

2

Yan Borodovsky, Intel, 2012

EUV HVM Insertion - Materials Stochastics Suppression

$CD3\sigma_{EUV}$(resist stochastics) =3nm = CD3σ (Photon, e⁻ Acid, Develop stats)

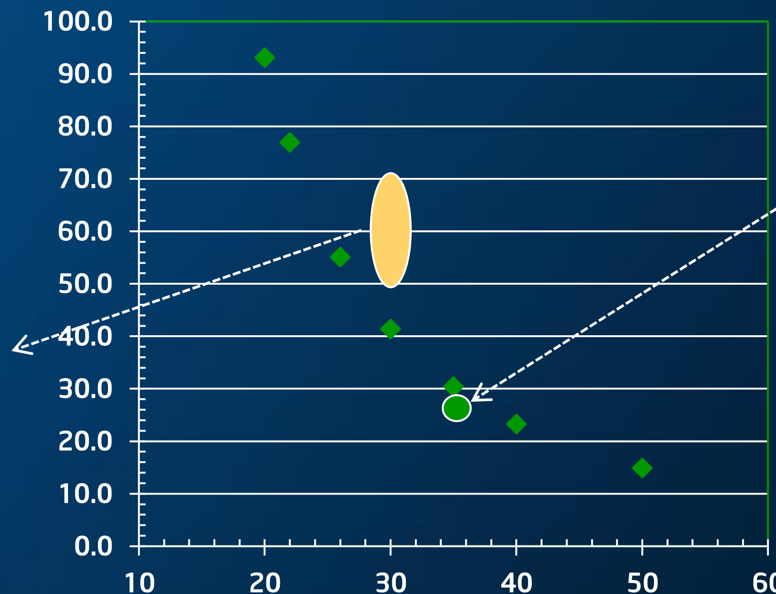


Comparison of EUV and e-Beam Lithographic Technologies for Sub 22nm Node Patterning

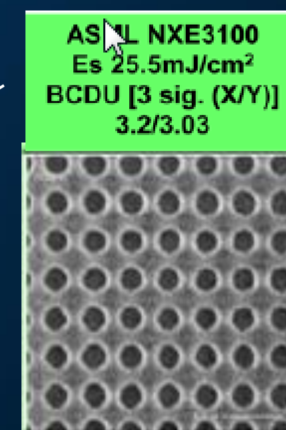
James Cameron et al 2012 Proc. of SPIE Vol. 8322 83222F-1

2

D_{inc} = Dose to Print (mj/cm²), Photon stats Only!



35nm, PBP 7



2

1

$$D_{inc} \geq \frac{1.88}{\alpha \cdot \varepsilon} \cdot \left[\frac{2n}{EL \cdot S} \right]^2 mJ/cm^2$$

n=7
α=0.5
ε=2
EL=5%

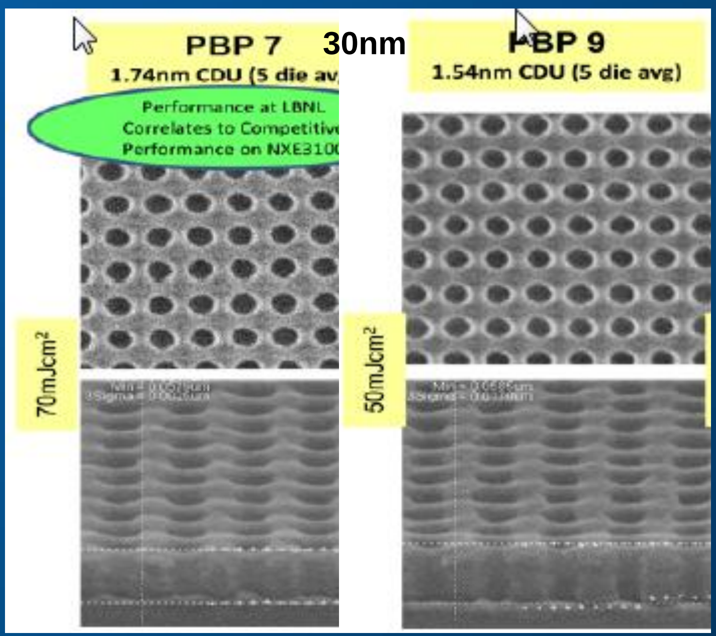
Shot noise and process window study for printing small contact holes using EUV Lithography

Sang H. Lee*, Robert Bristol, John Bjorkholm Proceedings of SPIE Vol. 5037 (2003)

Yan Borodovsky, Intel, 2012

EUV HVM Insertion - Materials Stochastics Suppression

$CD3\sigma_{EUV}$(resist stochastics) =3nm = $CD3\sigma$ (Photon, e^- Acid, Develop stats)

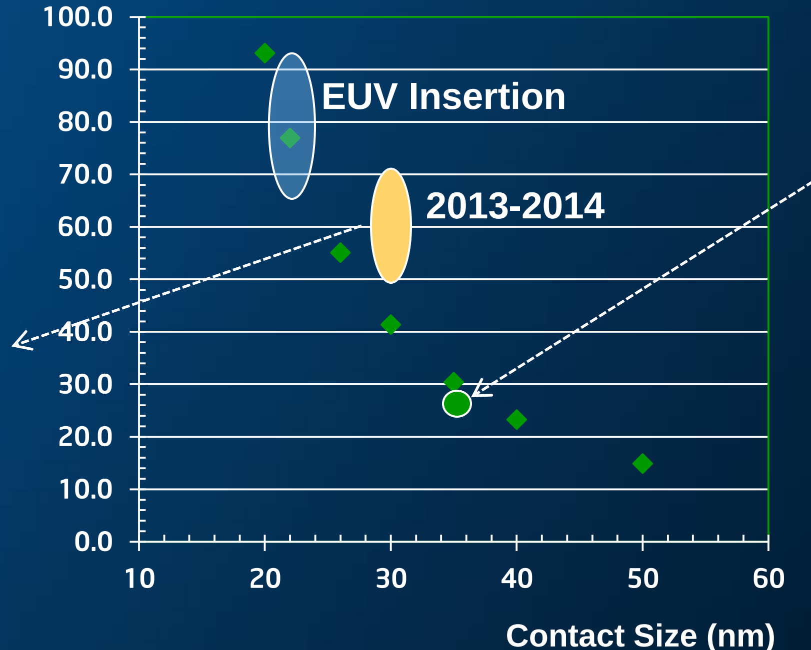


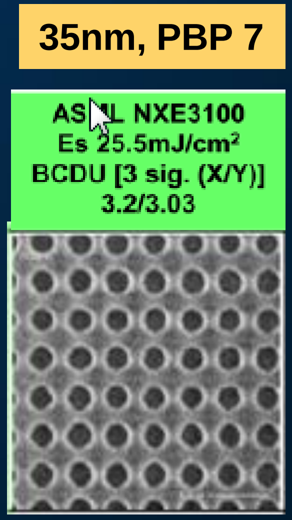
Comparison of EUV and e-Beam Lithographic Technologies for Sub 22nm Node Patterning

James Cameron et al 2012 Proc. of SPIE Vol. 8322 83222F-1

2

D_{inc} = Dose to Print (mj/cm²), Photon stats Only!





2

1

$$D_{inc} \geq \frac{1.88}{\alpha \cdot \varepsilon} \cdot \left[\frac{2n}{EL \cdot S} \right]^2 mJ / cm^2$$

n=7
α=0.5
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EL=5%

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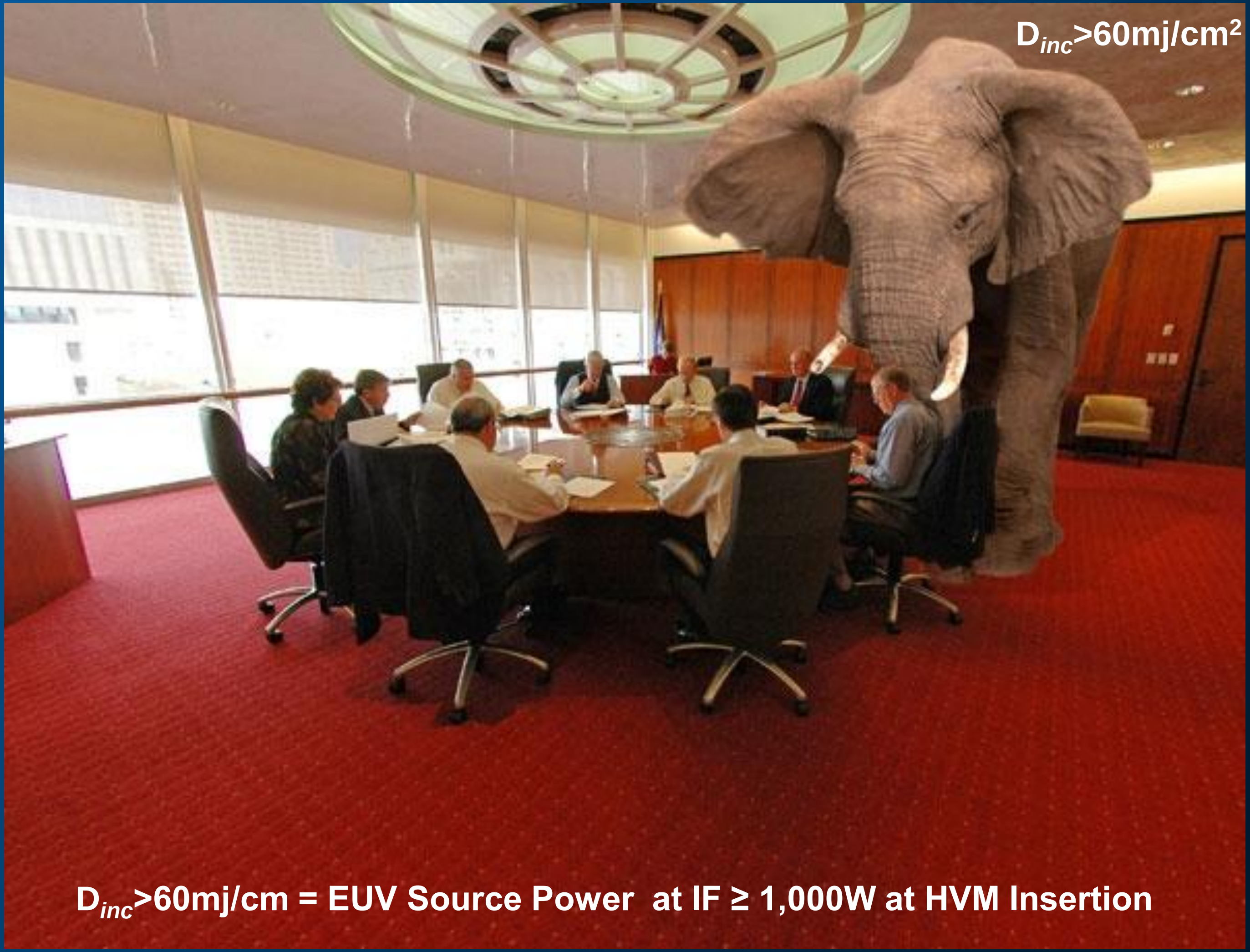
EUV HVM Insertion - Materials
Stochastics Suppression

EUV HVM Insertion - Materials Stochastics Suppression



Re-target EUV Source Power Requirements for HVM Insertion

Shot noise statistics alone leads to conclusion that source in-band average power needed to expose resist capable to meet HVM Contacts and Cuts patterning requirements might need to exceed 1,000W at Intermediate Focus (IF).

While this is 4X of current source power targeted for EUV tools in 2013-2014 it is hard to expect 4X power gain during next several years through incremental improvement of existing designs.

New ideas and focused effort is necessary to enable concept, design and implementation of such source in relatively short time

Having 1,000W average in-band power at IF source will enable resist vendors and their customers develop and select resist materials from large array of polymer and inorganic materials that already demonstrated properties close to required at suggested Exposure doses range for both Complementary and traditional lithography approaches.

Beyond Insertion

In my opinion it is critical for EUV HVM introduction to attain 100wph productivity with resists capable to limit impact of stochastic effects to $CD3\sigma<3nm$ for contacts ~20nm diameter.

This most probably will require sources 4X more powerful then currently under development.

There is no benefit in developing higher resolution EUVL through $NA>0.33$ or $\lambda=6.8nm$ unless resist stochastics effects can be reduced ~2X from current best CAR platforms levels

Priority for the resources and research dollars, euros, yens, wons and rubles available for "beyond Insertion" R&D projects should be speedy development of realistic solutions for 13.5nm Source capable of 1kW in-band Power at IF.

Conclusion

Significant OPC infrastructure development will be necessary to overcome EUV 3D Mask effects.

EUV source power targets need to be revised upwards (≥1kW average in-band @IF) to meet future Complementary Lithography and Contacts patterning technology needs.

Significant progress had been made to achieve EUV Pilot Capabilities, lets make sure opportunity for HVM insertion will not be missed.

Thank you for your attention