Evaluation of the critical dimension control requirements in the ITRS using statistical simulation and error budgets

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Acknowledge: Wei Wu and Bernie Roman (Motorola), Harry Levinson (AMD), Kevin Cummings (ASML), Chris Progler (Photronics), Janice Golda (Intel) and Dan Herr (SRC) for their helpful input

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2003 ITRS requirements are challenging

	2004	2007	2010	2013	2016	2018
DRAM ½ Pitch (nm)	90	65	45	32	22	18
MPU/ASCI Metal 1 (M1) 1/2 pitch (nm)	107	76	54	38	27	21
MPU ½ Pitch (nm) (uncontacted gate)	90	65	45	32	22	18
Overlay	32	23	18	12.8	8.8	7.2
MPU gate in resist (nm)	60	40	27	19	14	10
MPU gate length after etch (nm)	37	25	18	13	9	7
Gate CD control (3 sigma) (nm)	3.3	2.2	1.6	1.2	0.8	0.6
Mask CD uniformity (nm, 3 sigma) Isolated lines (MPU gates), Binary mask	3.8	2.2	2.0	1.3	0.5	0.4

- Gate CD control is intended to represent total CD variation
- Is it possible to meet the gate CD control values?

Major CD error sources

- Intrafield
  - **Dose uniformity**
  - **Focus uniformity**
  - **Aberration variation within the field**
  - **Flare variation for EUV**
  - **Mask CD uniformity**
- Interfield
  - **PEB temperature variations**
  - **Dose variation**
  - **Mean focus variation**
- Process window analysis lumps all focus and dose errors together
  - **Neglects the effect of various components of dose and focus on CD control**
  - **MEEF may be neglected**

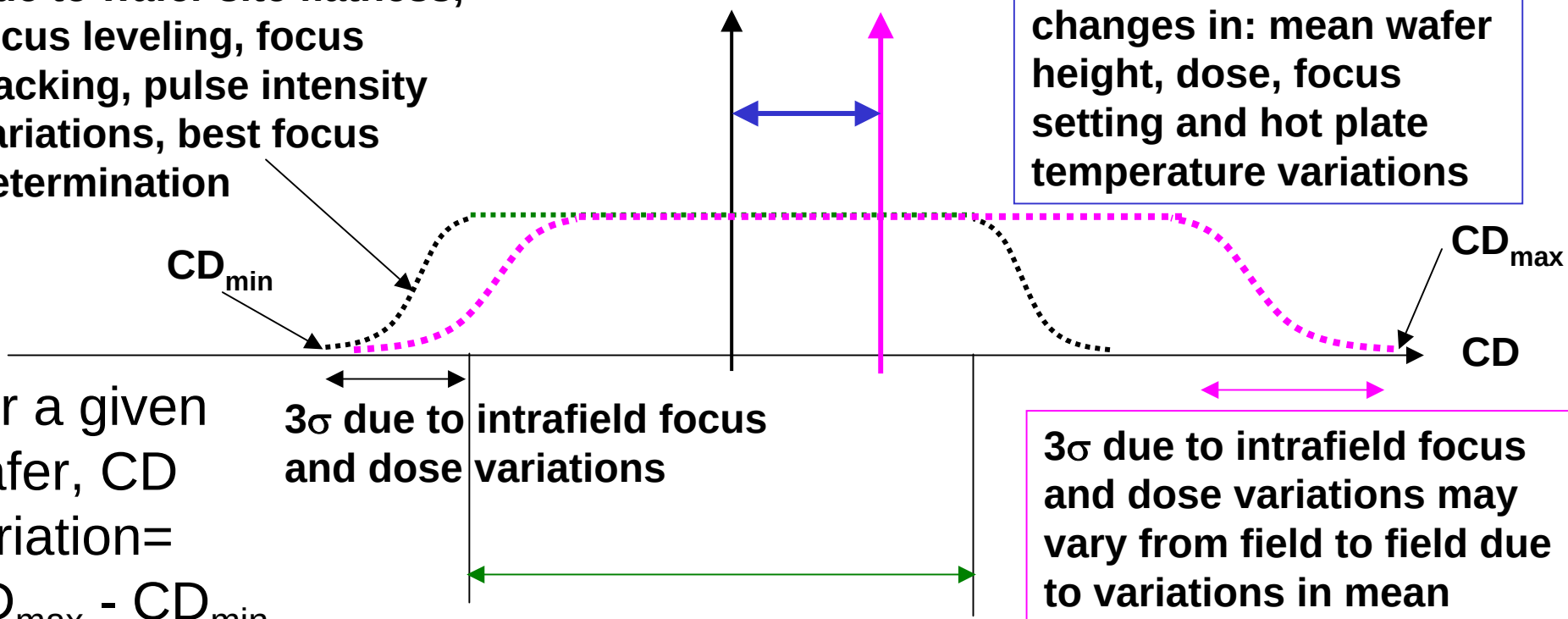
CD variation calculation approach

- CD error on wafer calculated from Monte Carlo aerial image simulations through dose and focus range on tool within a field
- Assumptions
  - **Kirchhoff boundary conditions at the mask (thin mask model)**
    - **Rigorous coupled wave analysis for mask for 65-nm and 32-nm nodes**
  - **Vector model of propagation with random polarization**
  - **Ideal illumination in pupil**
  - **500 simulations carried out for each pattern**
  - **Assumes alternating PSM or binary mask**
    - **No mask phase errors are modeled**
  - **Uses constant threshold model and aerial image (no resist effects are modeled)**
    - **Dose proportional to 1 / intensity**
  - **MEEF is calculated at each mean defocus value**
  - **No residual iso/dense bias at best focus after OPC**

Determining total CD variation

Due to wafer site flatness, focus leveling, focus tracking, pulse intensity variations, best focus determination

Due to field-to-field changes in: mean wafer height, dose, focus setting and hot plate temperature variations



For a given wafer, CD variation= $CD_{max} - CD_{min}$

3σ due to intrafield focus and dose variations may vary from field to field due to variations in mean dose and focus

CD variation due to mask CD and phase variations and MEEF, variation of aberrations, dose uniformity along slit, residual dense to isolated bias after OPC

Across wafer and across lot CD variation

- Width of CD variation distribution is *linearly* increased by:
  - **Resist CD change to due to hot plate variations**
- Field-to-field and wafer-to-wafer dose variations are systematic
  - **Assume that CD change with focus and mask CD, respectively, does not change with small changes in dose**
- Within field distribution affected by mean focus error within the field
- Lot-to-lot dose variations perfectly removed using automatic process control (APC) algorithms

Adding the terms

- Linear addition of error terms from each statistically independent random error and from each systematic error provides a worst case value
- A more representative value could be obtained using method developed by Govil et al.[1]
  - **Model systematic errors as uniformly distributed random variables and random errors as Gaussian distributed random variables.**
  - **Error is 99.7% range of the resulting distribution.**

1. Govil, P.K.; Tsacoyeanes, J.; Eron, R.; Walters, D., “Contributors to focal plane nonuniformity and their impact on linewidth control in DUV step and scan system,” *Proceedings of the SPIE 3334* p.92-103 1998.

Adding the terms (continued)

- The intrafield errors due to dose and focus have a Gaussian distribution
- Model the intrafield errors due to variation of aberrations and mask CD as uniform random variables and RSS the variances
- Model the interfield errors due to hot plate temperature and dose variation as uniform random variables and RSS the variances
  - **Linearly add the uniform portion since it changes the mean field by field**

Adding the terms (continued): the equations

$\sigma_1 = 0.5 \times [\sigma_{image}(f_{min}) + \sigma_{image}(f_{max})]$

$R_1 = 0.5 \times [MEEF(f_{min}) + MEEF(f_{max})] \times (\text{mask CD error}) / M$

$R_2 = 0.5 \times [\Sigma_{i=4 \text{ to } 11} \left| \delta CD / \delta Z_i(f_{min}) \Delta Z_i \right| + \Sigma_{i=4 \text{ to } 11} \left| \delta CD / \delta Z_i(f_{max}) \Delta Z_i \right|]$

$R_3 = \Delta CD/\Delta T \times \Delta T$

$R_4 = 0.5 \times [\Delta CD/\Delta dose(f_{min}) + \Delta CD/\Delta dose(f_{max})] \times 6\sigma_{FF_dose}$

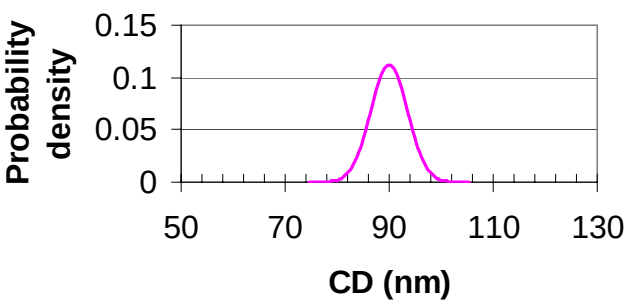
$$\text{Total CD variation } (3\sigma\, equiv.) = 3\sigma_1 + \frac{\sqrt{R_1^{\,2} + R_2^{\,2}}}{2} + \frac{\sqrt{R_3^{\,2} + R_4^{\,2}}}{2} = 3\sigma' + \frac{R'}{2}$$

Distribution of CD errors

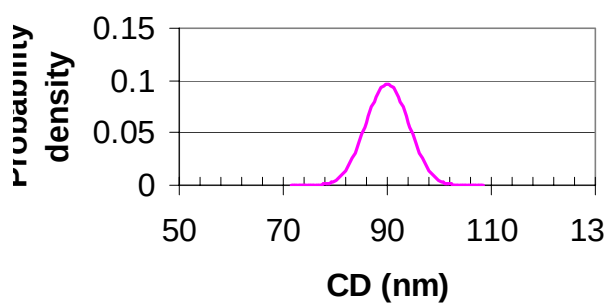
$$f(CD) = \frac{1}{2\sqrt{2}\sigma'^2 R'}\left\{\mathrm{erf}\left[\frac{CD + R'/2 - \mu}{2\sigma}\right] - \mathrm{erf}\left[\frac{CD - R'/2 - \mu}{2\sigma}\right]\right\}$$

f(CD) is the probability density function for CD
erf is the error function

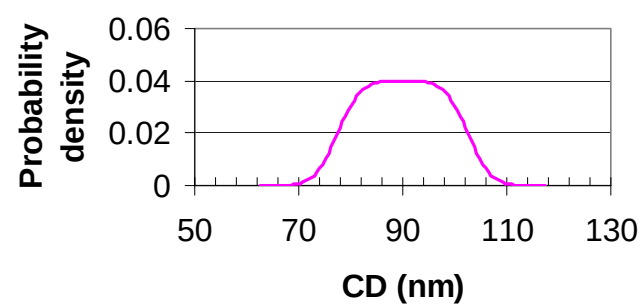
σ'=2.5 nm, R'=1 nm



σ'=2.5 nm, R'=7 nm



σ'=2.5 nm, R'=25 nm



Parameters for ACLV determination

Intrafield contributors (used to calculate σ_{image})

ITRS node (nm)	*130*	*90*	*65*
minimum MPU half pitch (nm)	160	120	76
Linewidth with minimum half pitch (nm)	100	70	40
semi-dense MPU half pitch (nm)	240	180	120
Exposure wavelength (nm)	248	193	193
NA	0.8	0.75	0.85
1sigma intrafield focus variation (nm) *	45	30	30
1sigma intrafield dose variation (%) *	0.20%	0.20%	0.20%
Minimum focus error, f_{min} (nm)	0	0	0
Maximum focus error, f_{max} (nm)	100	100	50
Mean aberration level (waves rms) ***	0.02	0.014	0.014
Aberration variation within field	10%	10%	10%
Binary masks			
Inner sigma	0.55	0.55	0.55
Outer sigma	0.85	0.85	0.85
alt PSM sigma	0.4	0.4	0.3
Flare**	2%	2%	2%

*** Gaussian distribution**

**** Flare is doubled for altPSM; assume 25% average pattern density**

- Values agreed upon by subset of the US Lithography Technical Working Group

† Because of aberrations, σ_{image}, MEEF and $\Delta CD / \Delta Z$ have slightly different values depending on whether f_{max} is positive or negative. The mean value of each quantity at the positive and negative value was taken to represent the value at f_{max}.

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Detailed aberration and flare assumptions for aerial image at a given field point

$I_{image} = (1-F) \times I_{image_no_flare} + T*F$; **F=Flare, T=1-local pattern density**

$\sigma_{aberration}^2 = \sigma_{spherical}^2 + \sigma_{coma}^2 + \sigma_{astig.}^2 + \sigma_{3\text{-}foil}^2$

$0.25\sigma_{aberration}^2 = \sigma_{spherical}^2$

$0.25\sigma_{aberration}^2 = \sigma_{astigmatism}^2$

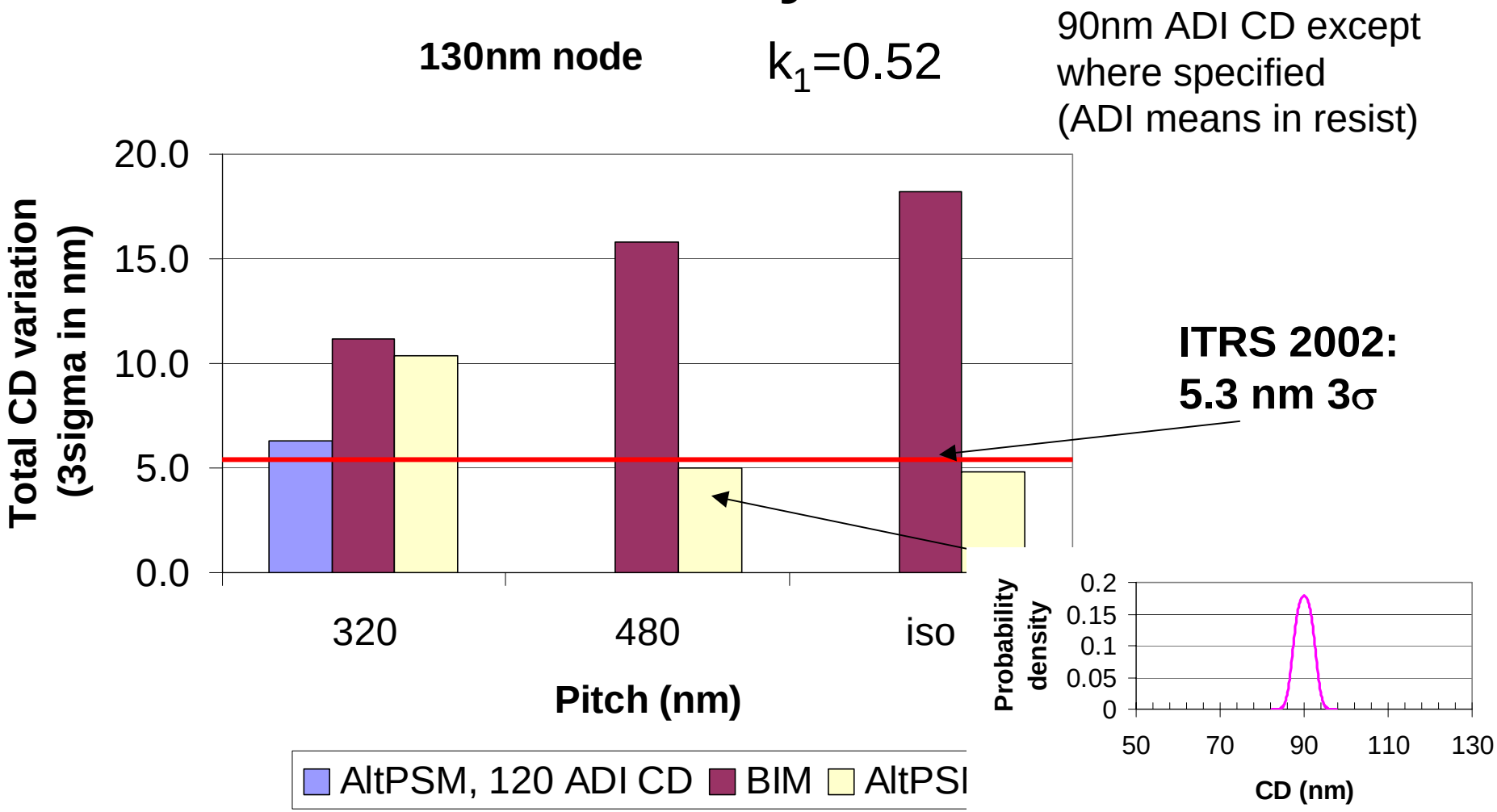
$0.25\sigma_{aberration}^2 = \sigma_{coma}^2$

$0.25\sigma_{aberration}^2 = \sigma_{3\text{-}foil}^2$

$\sigma_{aberration} = 0.02\lambda$ at the 130-nm node with a 30% reduction per node

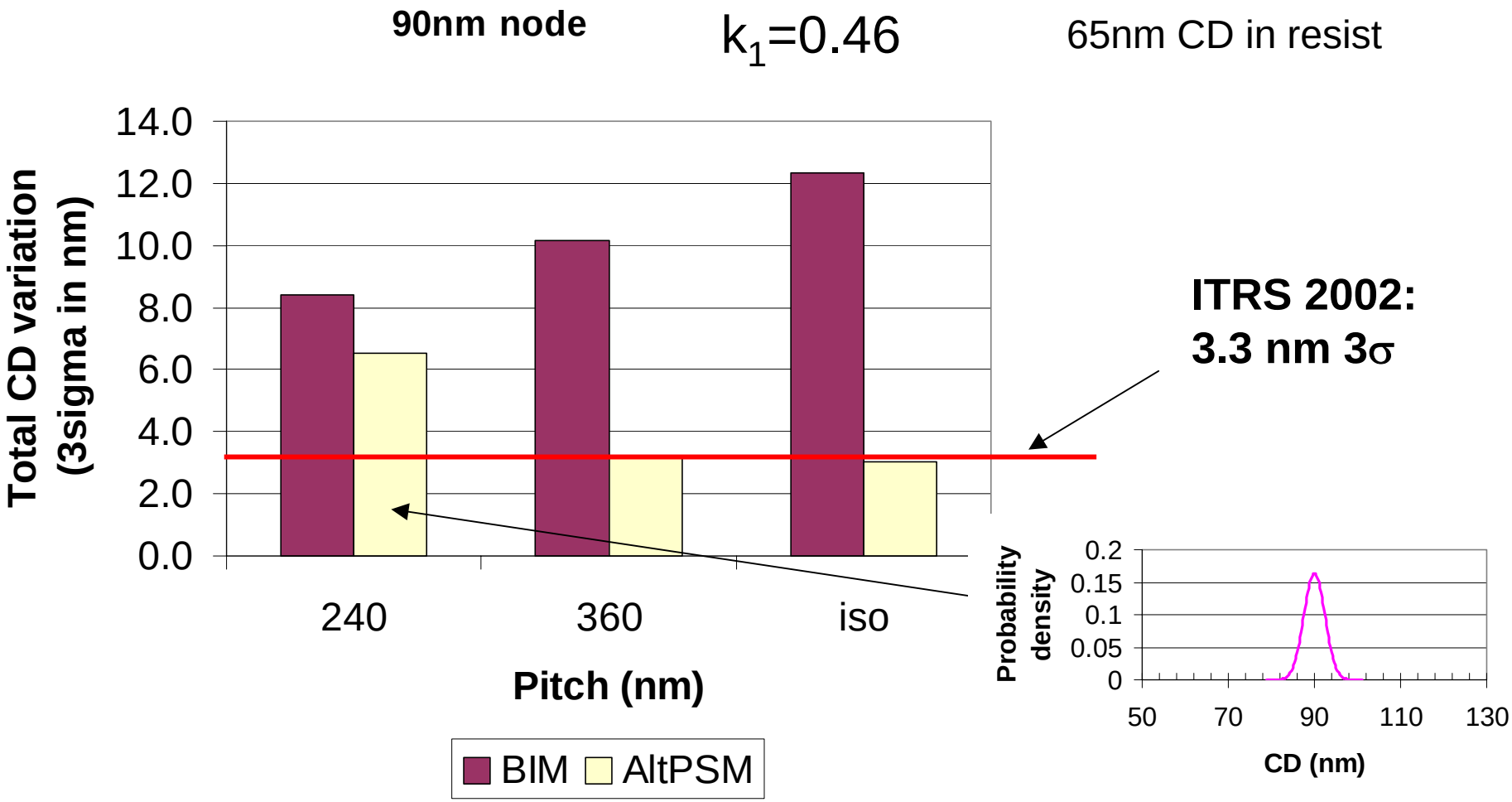
I_{image} includes the effects of aberrations.

130nm node summary



- Alternating PSM might be sufficient for ITRS 2002 130nm node requirements for CD control if larger ADI CD is used

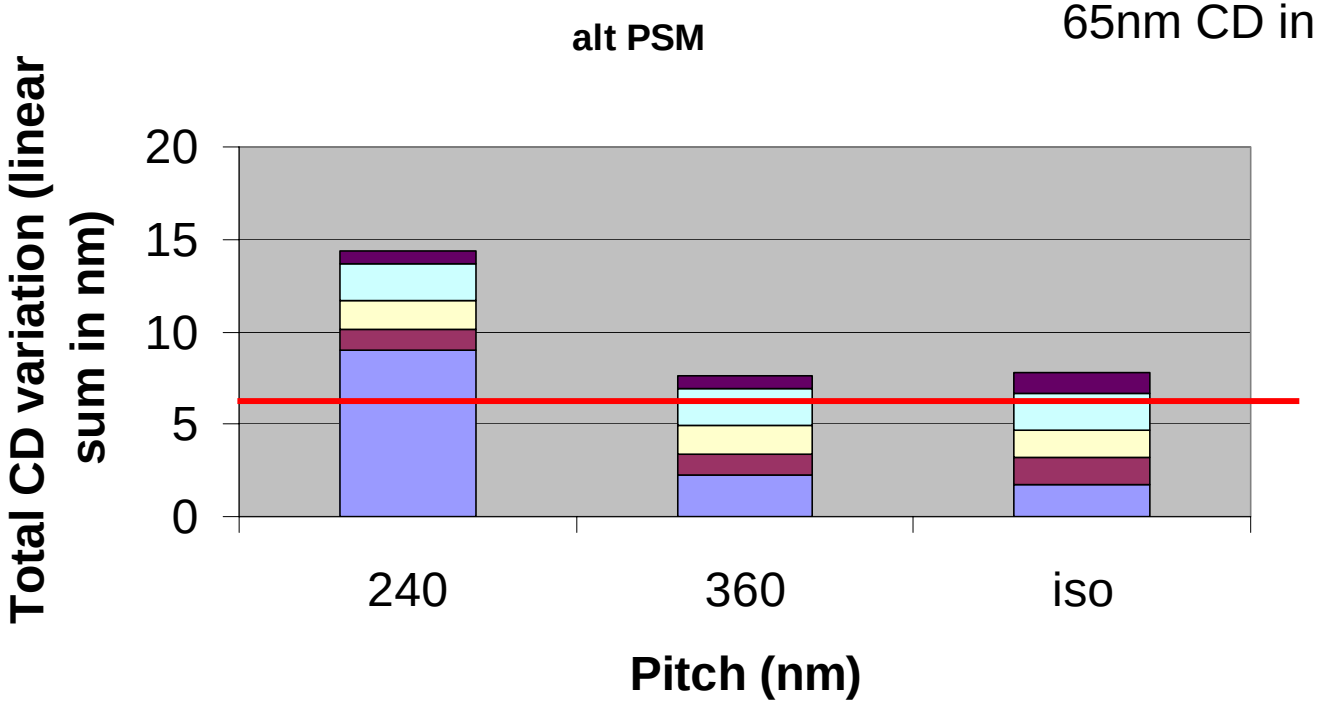
90nm node summary



- Alternating PSM might be sufficient for ITRS 2002 90nm node requirements for CD control if larger ADI CD is used and minimum pitch is relaxed

Dose and focus control errors are largest component of CD error

65nm CD in resist



90-nm node:

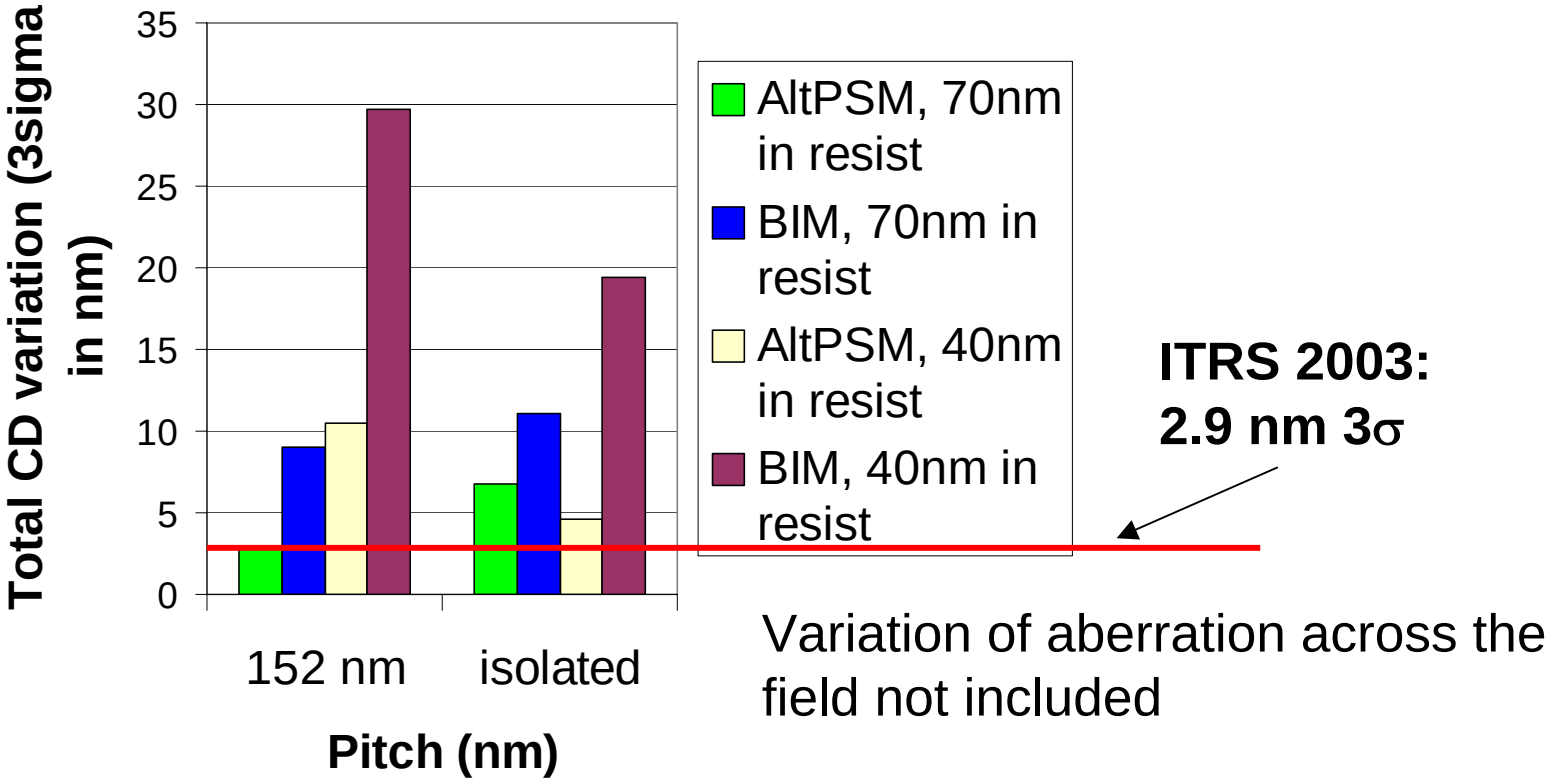
ITRS 2003: 3.3 nm 3σ

Averaged over 50-nm mean defocus

R_4	mean dose variation across wafer
R_3	hot plate temperature variation across wafer
R_1	variation of aberrations across field
R_2	mask
σ_1	intrafield focus,dose

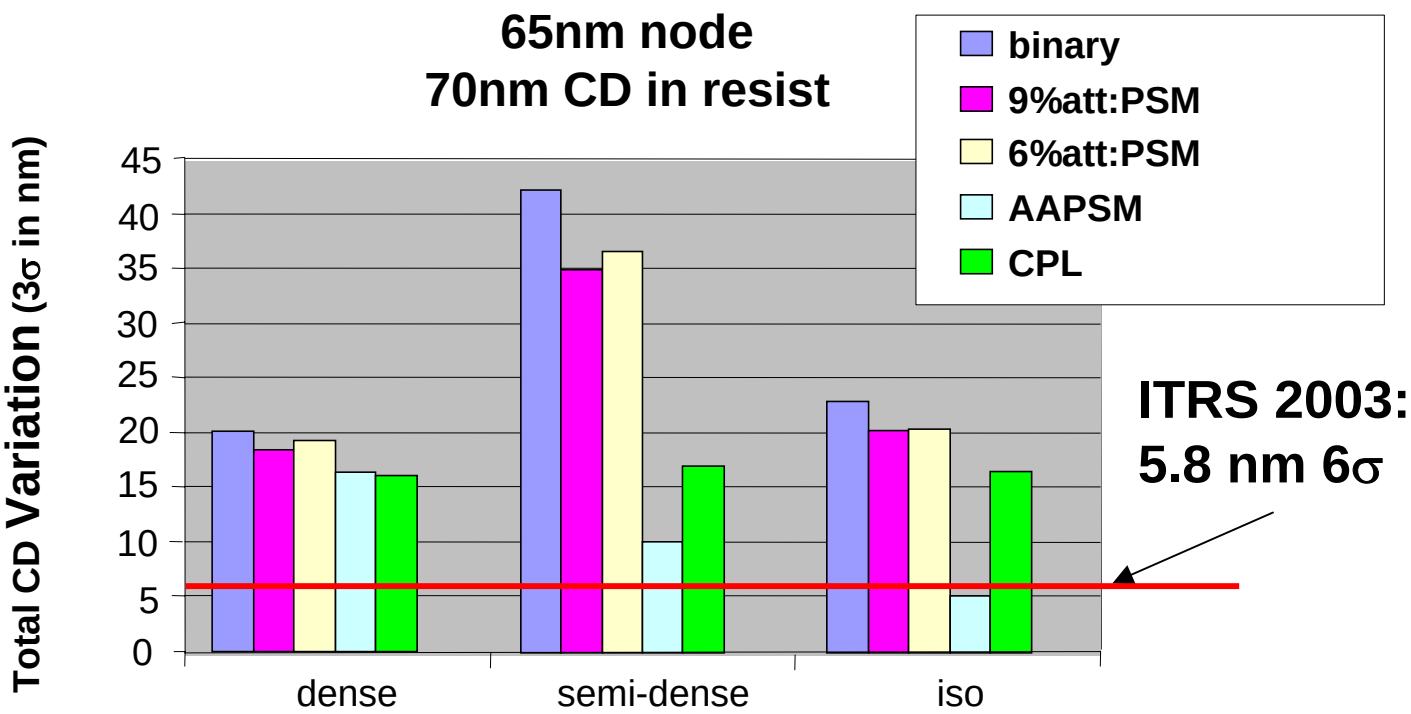
65nm node summary

k_1=0.34



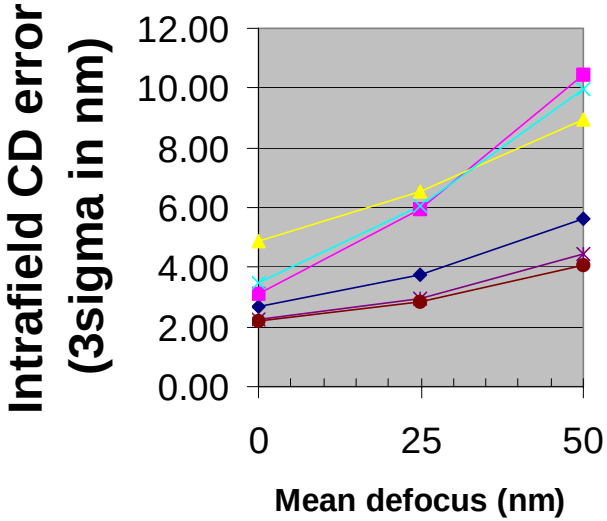
- Alternating PSM not sufficient for 65-nm node CD control requirements in ITRS

Study of various mask types indicated AltPSM provides the best CD control



- AltPSM offers the best theoretical CD control through pitch, CPL is next
- No major difference in mask options at dense pitch

EUV provides opportunity for better CD control than alternatives at 32-nm node



	NA	Mask	MEEF*
157nm dense	1.3	CPL	2.25
157nm isolated			1.48
193nm dense			5.66
193nm isolated			1.94
EUV dense	0.25	BIM	1.06
EUV isolated			1.06

45-nm half pitch

2 nm 3σ mask CD error
* At 25-nm mean defocus

- 157nm and 193nm immersion probably won't provide CD control comparable to EUV

CD error simulation assumptions for 32nm node

Intrafield contributors (used to calculate σ_{image})

Technology parameters	*193nm immersion*	*EUV*
minimum MPU half pitch (nm)	45	45
Linewidth with minimum half pitch (nm)	25 or 40	25 or 40
Exposure wavelength (nm)	193	13.5
NA	1.34	0.25
1sigma intrafield focus variation (nm) *	25	25
1sigma intrafield dose variation (%) *	0.75%	1.05%
Minimum mean focus error, f_{min} (nm)	0	0
Maximum mean focus error, f_{max} (nm)	25	25
Mean aberration level (waves rms) ***	0.02	0.045
Aberration variation within field	10%	10%
Sigma	0.3	0.7
Bias on isolated lines (nm at 1X)	-10	-1
Flare**	5%	10%
Flare variation (1sigma)	0%	1%
Mask CD control (nm 3sigma)	1.8	1.3

* Gaussian distribution

** Assume 25% average pattern density

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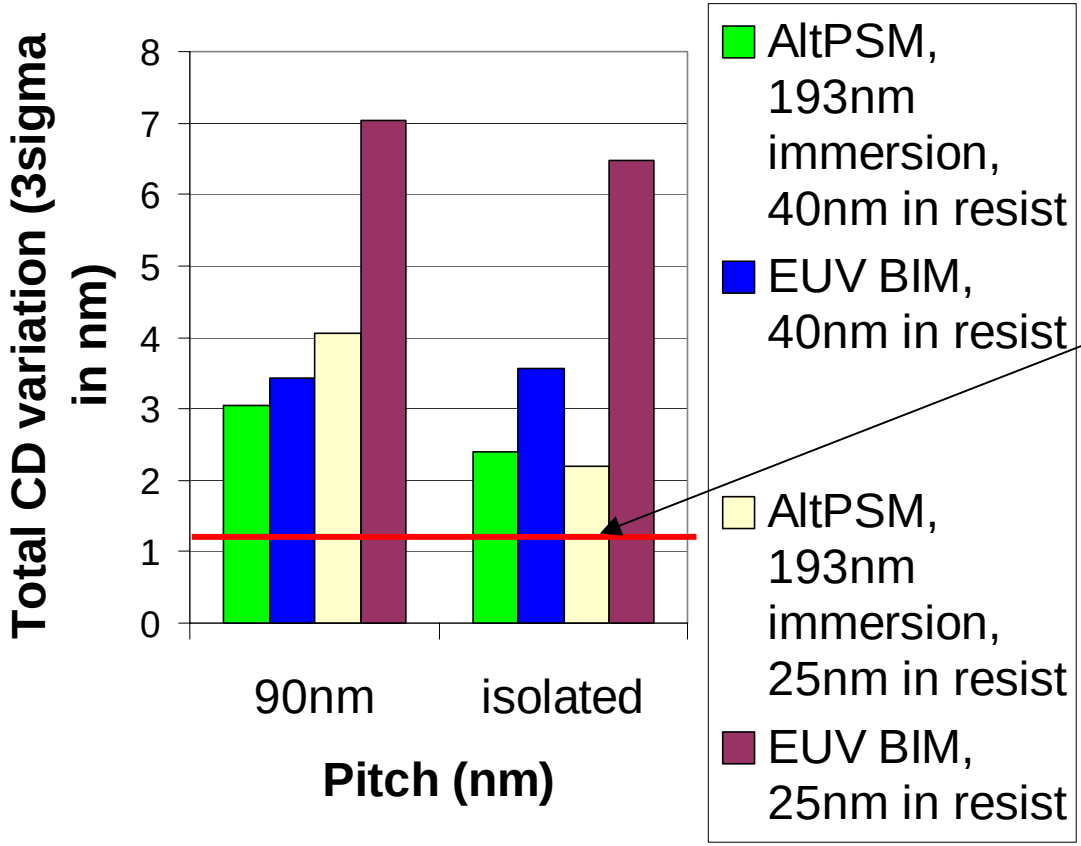
32nm node summary



ITRS 2003: 1.2 nm 3σ

Variation of aberration across the field not included

- Under near ideal optical lithography conditions, 193nm immersion at near maximum NA (k_1=0.31) may provide better CD control
  - **Analysis needs to be performed for image absorbed in resist**
- Both 193nm immersion and EUV (k_1=0.83) will probably not meet ITRS requirements

Conclusions

- Difficult to meet ITRS CD control targets for 130-nm and 90-nm nodes
- Meeting ITRS CD control requirements for 65-nm node and beyond not possible using assumptions detailed here
- Using larger CD in resist than in ITRS 2003 results in better CD control
- To approach demanding tolerances of 32nm node, mean focus must be controlled to better than 25 nm, and flare variation must be reduced