Limits of optical dimensional metrology at the nano-scale

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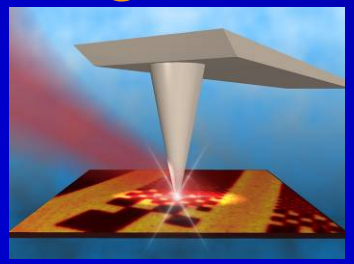
Conclusion

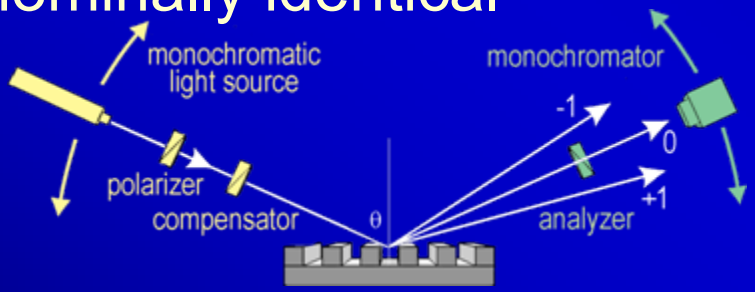
- There is no strict feature size limit to the resolution or accuracy of optical dimensional metrology at the nano-scale
- However, measurement uncertainty arising from parametric influences increases as feature sizes diminish below the wavelength.

Optical metrology techniques: Imaging and non-imaging

- Imaging *far field optical microscope*
  - Isolated and dense (proximity < few λ) features
  - Transmission or reflection
- Imaging *near field optical scanning microscope*
  - Isolated and dense features



- Non-imaging "*scatterometry*"
  - Diffraction grating technique
  - Average linewidth, pitch, etc., over an array
  - Requires dense array of nominally identical features

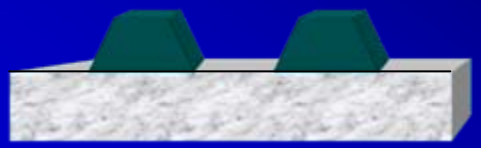


Imaging far field optical microscope

- We will concentrate here on imaging ***far field optical metrology*** techniques
  - Near field optical scanning microscopy may be considered a SPM technique
  - Scatterometry returns only average values for an array of nominally identical objects

Nano-objects of interest are 3-dimensional

- Some kind of ***contrast mechanism*** is required to create an image for any kind of dimensional metrology
  - Topography—geometric OPD



  - Optical phase change (*n*, *k*, or both)—phase OPD
  - Non-optical (magnetic, tribological, …, other property)
- Focus criterion for optical imaging
  - A focus criterion must be established
  - “best focus” must be defined
  - If the object's OPD is greater than ≈λ, “best focus” may not be unique

Scope of this presentation

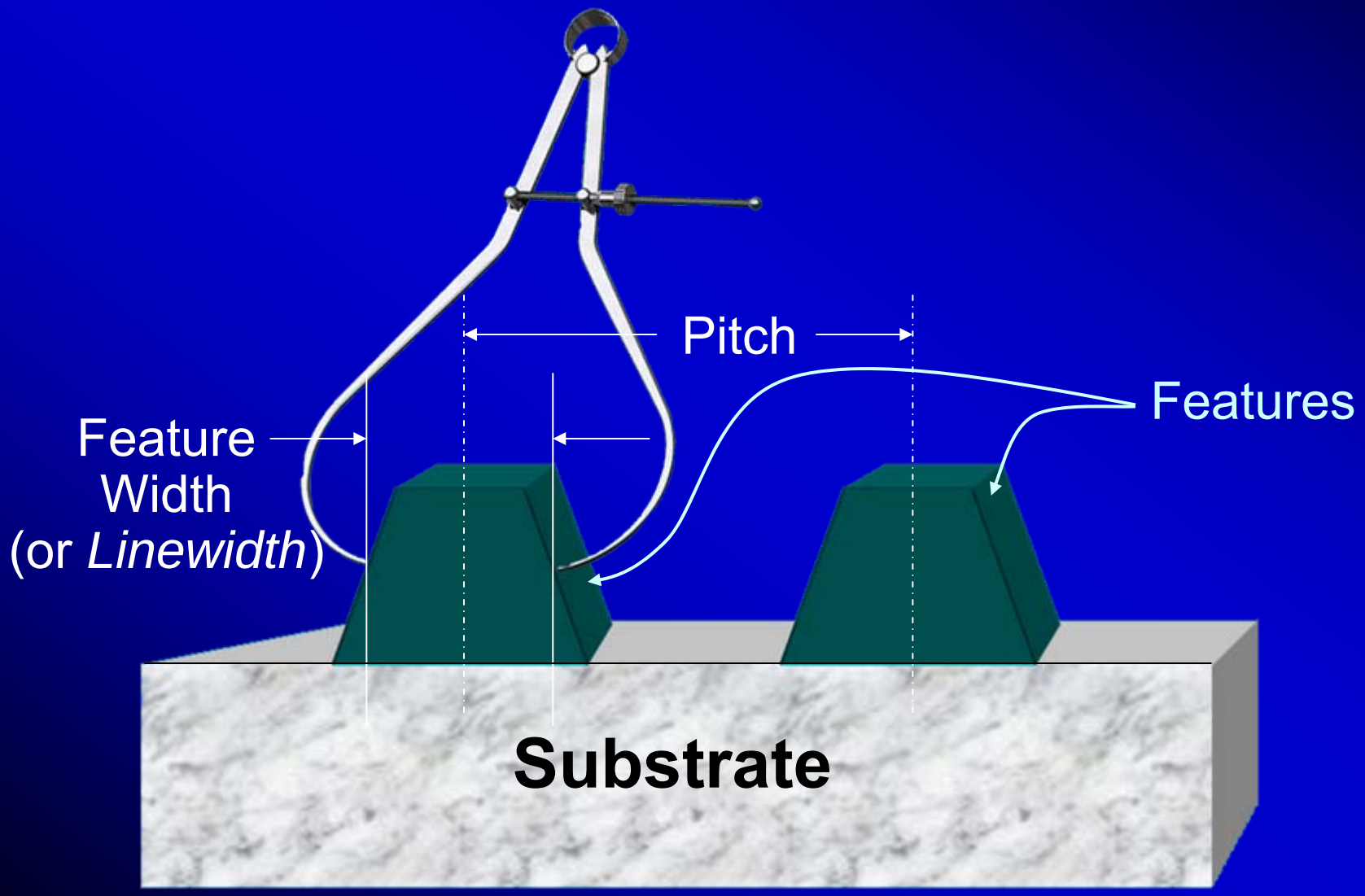
- "Optical"—imaging microscope
- "Dimensional"—feature size or placement
- "Metrology"—measurement traceable to a recognized reference

"Limits of optical dimensional metrology at the nano-scale"

Some thoughts about metrology

- “True value” of a measurand refers to the intended application of the measurement
  - May be different for different applications
- Measurements to be compared with each other must be traceable to the same reference.
  - In comparing optical, AFM, and SEM measurements, for example

Popular measurands: feature width and pitch



The microscope imaging process

- A microscope maps a contrast property
  - 3-d topography
  - optical phase change
  - combination
  - …etc
- to a 3-dimensional image
  - *image intensity* as function of *x* and *y* position
- But this mapping is ***not one-to-one***
- Similarly for SEM and AFM microscopes

Microscope imaging

- The image is not the object:

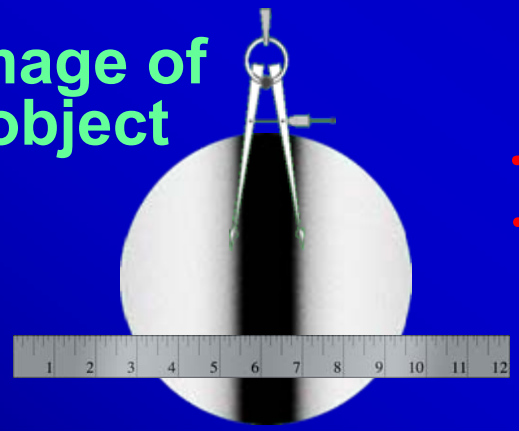
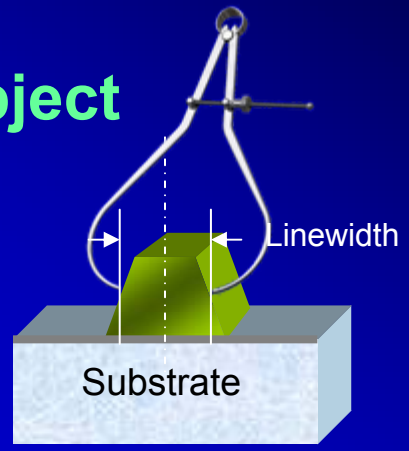
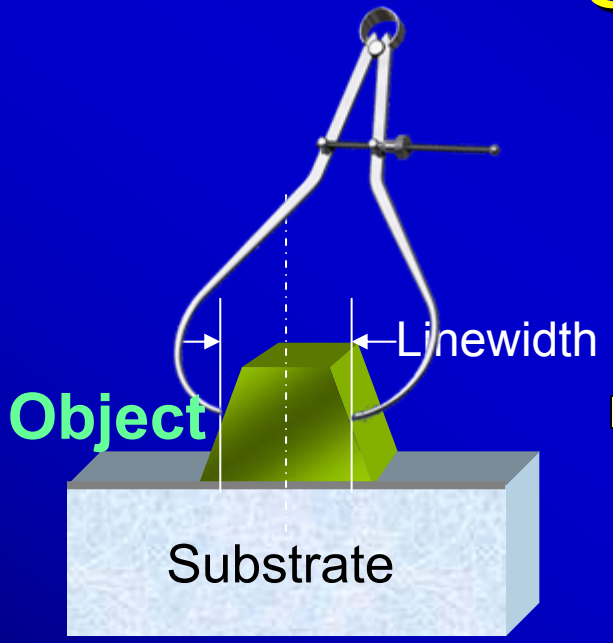


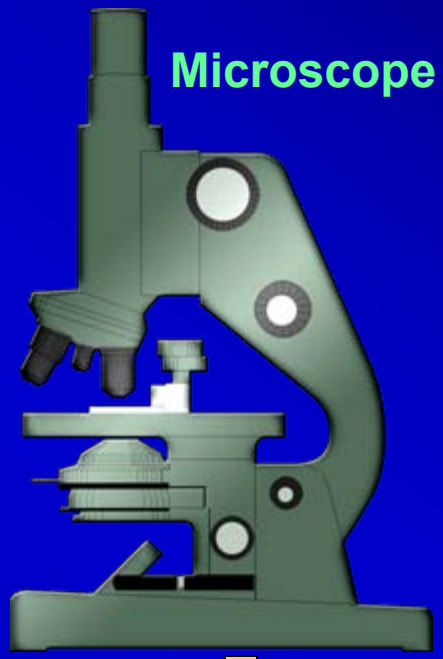
Image ≠ Object

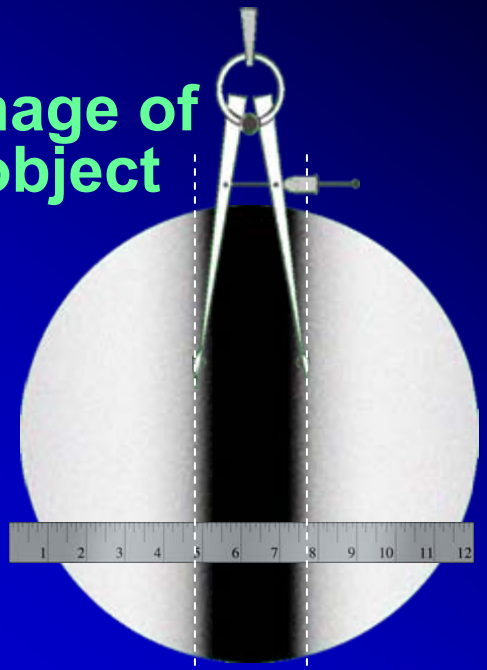


- We can measure only the ***image***, not the ***object***.
  - Consequently we must relate the image to the object
  - through a physics-based imaging model.
- Optical image modeling:
  - Maxwell's equations
  - Parameters describing the object
  - Parameters describing the microscope
- Optical metrology: measure image, infer object dimensions.

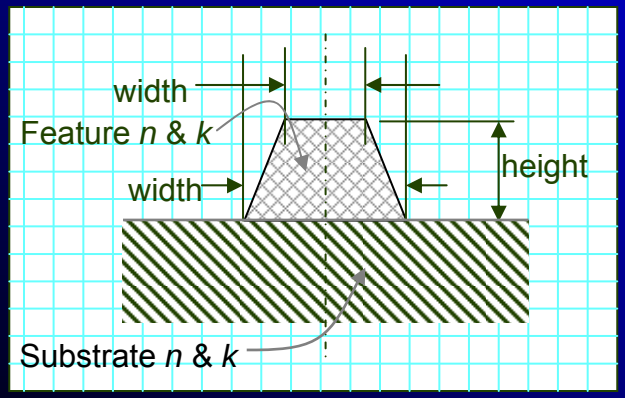
Modeling the microscope image







Parametric description of object



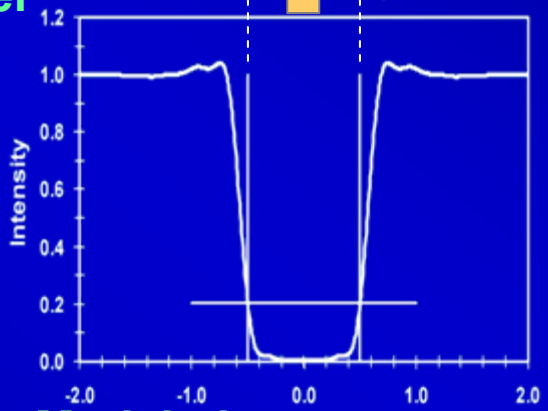
Imaging model

$$\nabla \cdot D = \rho$$

$$\nabla \cdot B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

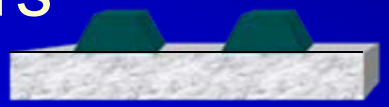
$$\nabla \times H = J + \frac{\partial D}{\partial t}$$



Modeled image

Parameters affecting the image

- Object parameters
  - Topography
  - Materials parameters (*n* & *k*)

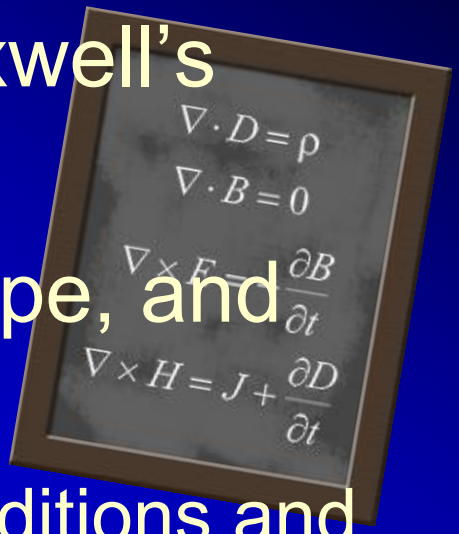


- Microscope parameters
  - Wavelength
  - Objective and condenser lens NAs
  - Illumination geometry
  - Polarization
  - Defocus
  - …more

- These parameters have uncertainties
  - These uncertainties propagate through the imaging model
  - Leading to the “parametric uncertainty” of the measurement

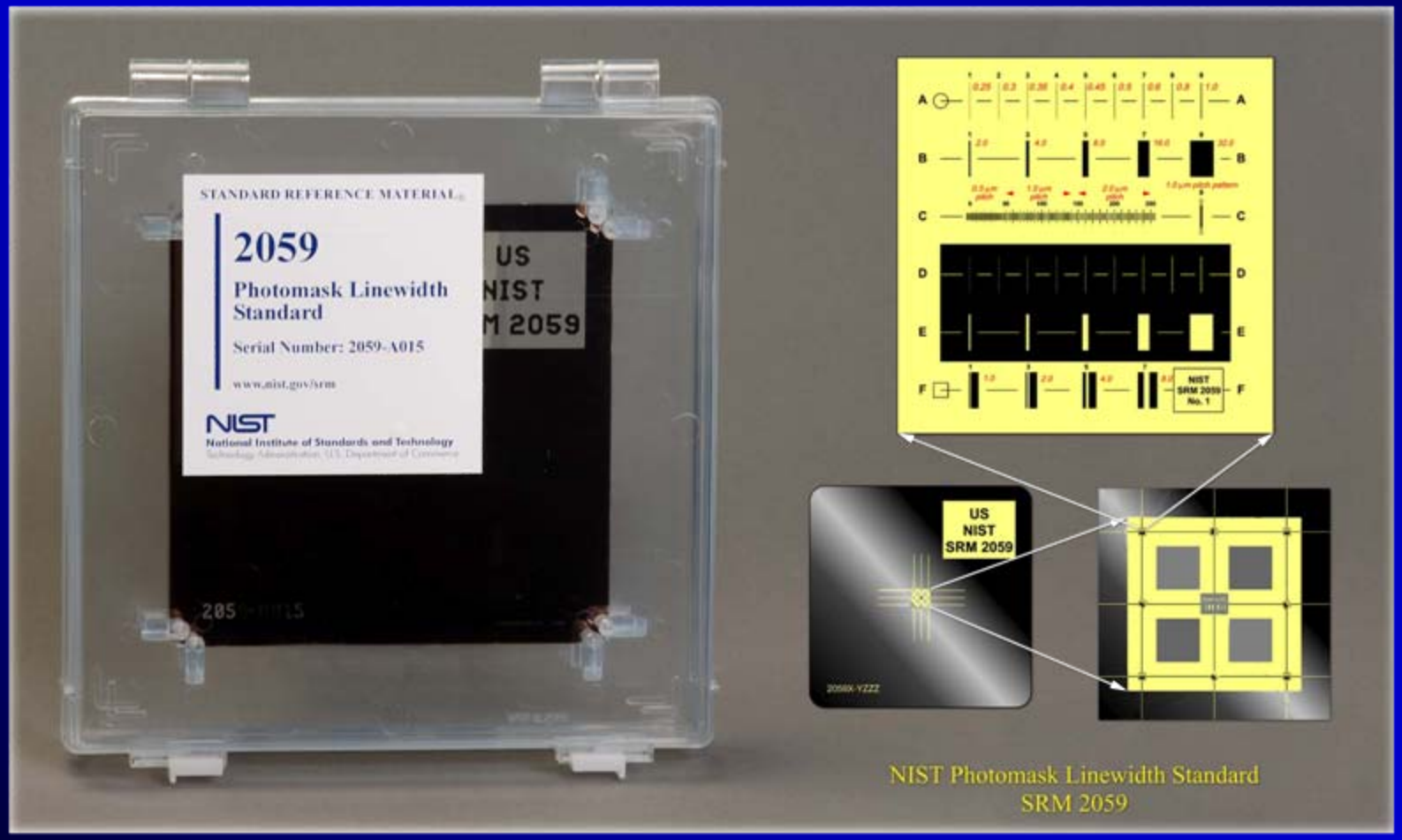
Optical imaging model

- Optical imaging is based on Maxwell's equations



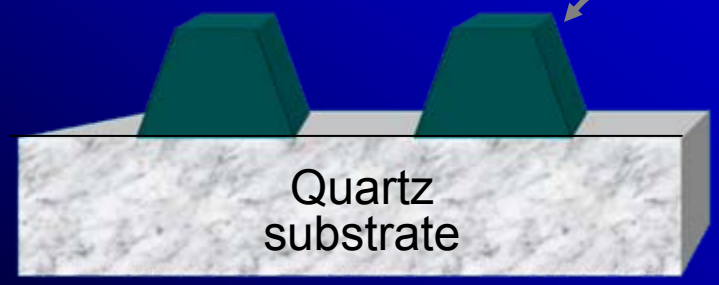
- Must reflect the object, microscope, and illumination conditions used
  - Object described by boundary conditions and complex indices of refraction
- Must reflect measurement procedures used
  - *e.g.* focus criterion

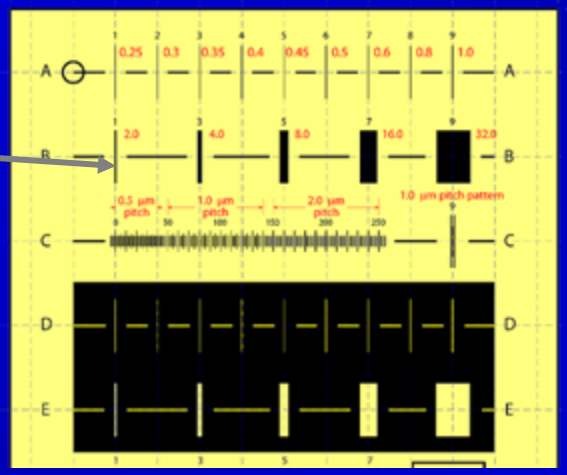
A practical example: integrated circuit photomask features



Integrated circuit photomask

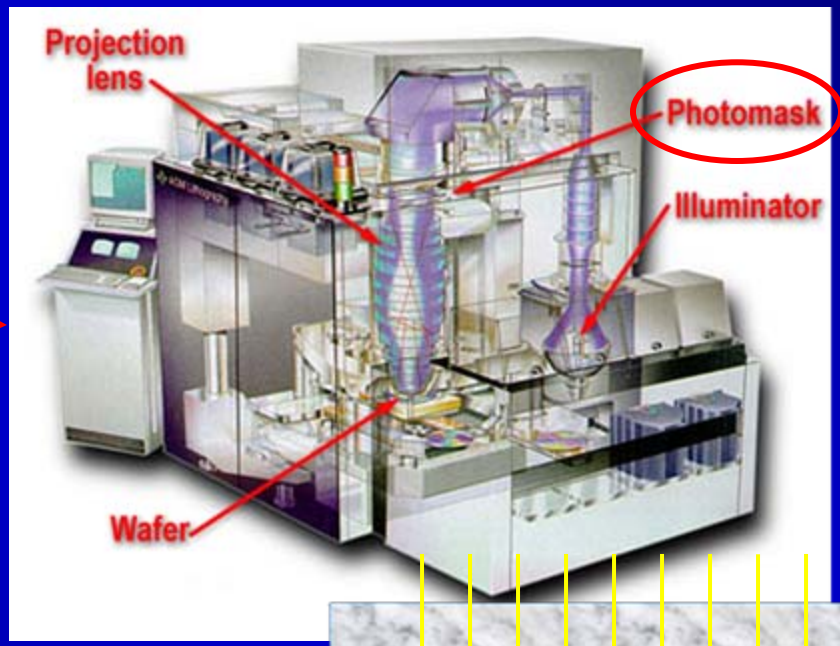
- Etched Cr/CrO_3 features on quartz substrate
- ≈100 nm to >10 μm wide lines, spaces, and contact holes (or dots, like particles on substrate)
- Isolated and dense patterns

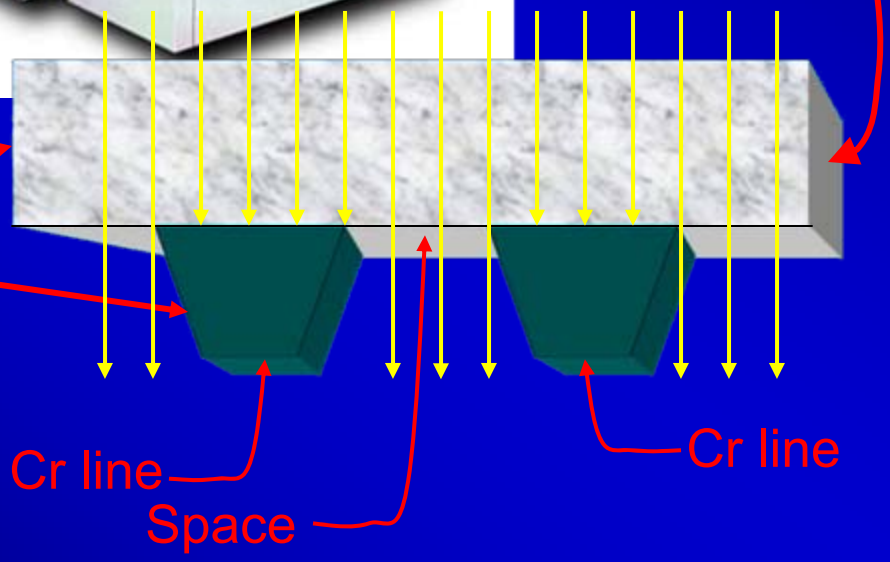




Photomask application: exposing IC wafers

- Photomask creates patterns in integrated circuit photoresist by optical projection
- Typical exposure wavelengths 193 nm to 488 nm
- Chrome ≈100 nm thick
- Qz substrate typically 6.35 mm thick, 150x150 mm square

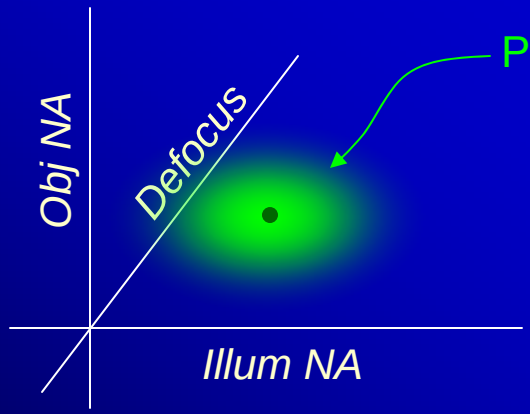




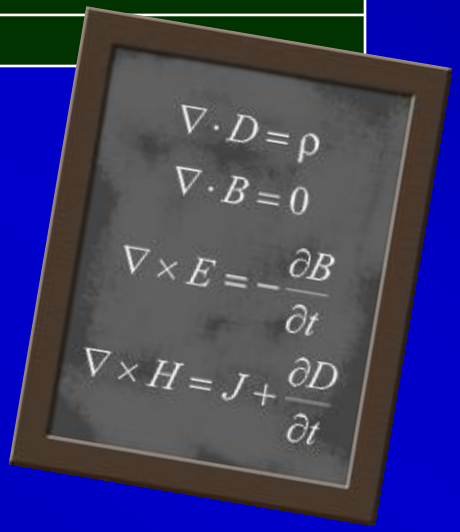
Photomask measurement parameters and parameter space

Optical imaging parameters for isolated photomask features		
Object	***Optical microscope***	***Optical imaging model***
Cr thickness	Wavelength, λ	Grid size
Cr edge shape	Illumination NA	Infinite series truncation
Cr edge roughness	Objective NA	Number of orders
Cr *n* as function of depth	Sampling aperture (pixel size)	Roundoff effects
Cr *k* as function of depth	Defocus	Number of incident angles
Substrate thickness	Illumination alignment (Köhler)	
Substrate *n*	Illumination polarization	
Substrate *k*	Illumination apodization	
	Flare light	
	High NA imaging effects	
	Field curvature, vignetting, etc.	

Example **parameter space** for 3 parameters, showing their values and uncertainties



Parameter cloud represents parameter uncertainties



Parametric uncertainty

- These parameters $\{P_i\}$ have uncertainties $u(P_i)$
  - The uncertainties propagate through the imaging model
  - leading to the "combined parametric uncertainty" of the measurement $u_p(LW)$:

$$u_p(LW) = \sqrt{\sum (\partial LW/\partial P_i)^2 \, u^2(P_i)}$$

  - Calculating ∂LW requires a metric, *i.e.*, How is the LW deduced from the image?

Parametric uncertainty

Parameter uncertainty

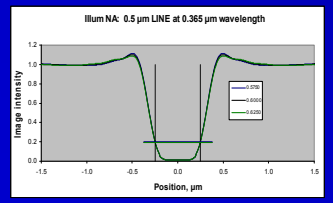
	Parameter	Nominal value	Parameter uncertainty
Instrument	***Wavelength***	547 nm, 365 nm, 193 nm	± **3 nm**
	Illumination NA	0.60	± **0.1**
	Objective NA	0.90	± **0.05**
	Aperture	100 nm	± **25 nm**
	Defocus	0 nm	± **100 nm**
Object	***Cr n***	2.100, 1.843, 1.111	± **0.5**
	Cr k	2.540, 2.195, 1.349	± **0.5**
	Cr thickness	103.5 nm	± **3 nm**

Finding linewidth from the image

- ***Inverse image modeling*** — Calculate the object directly from the image
  - Extract feature width and other parameters
  - Complex calculations
  - Uniqueness problem

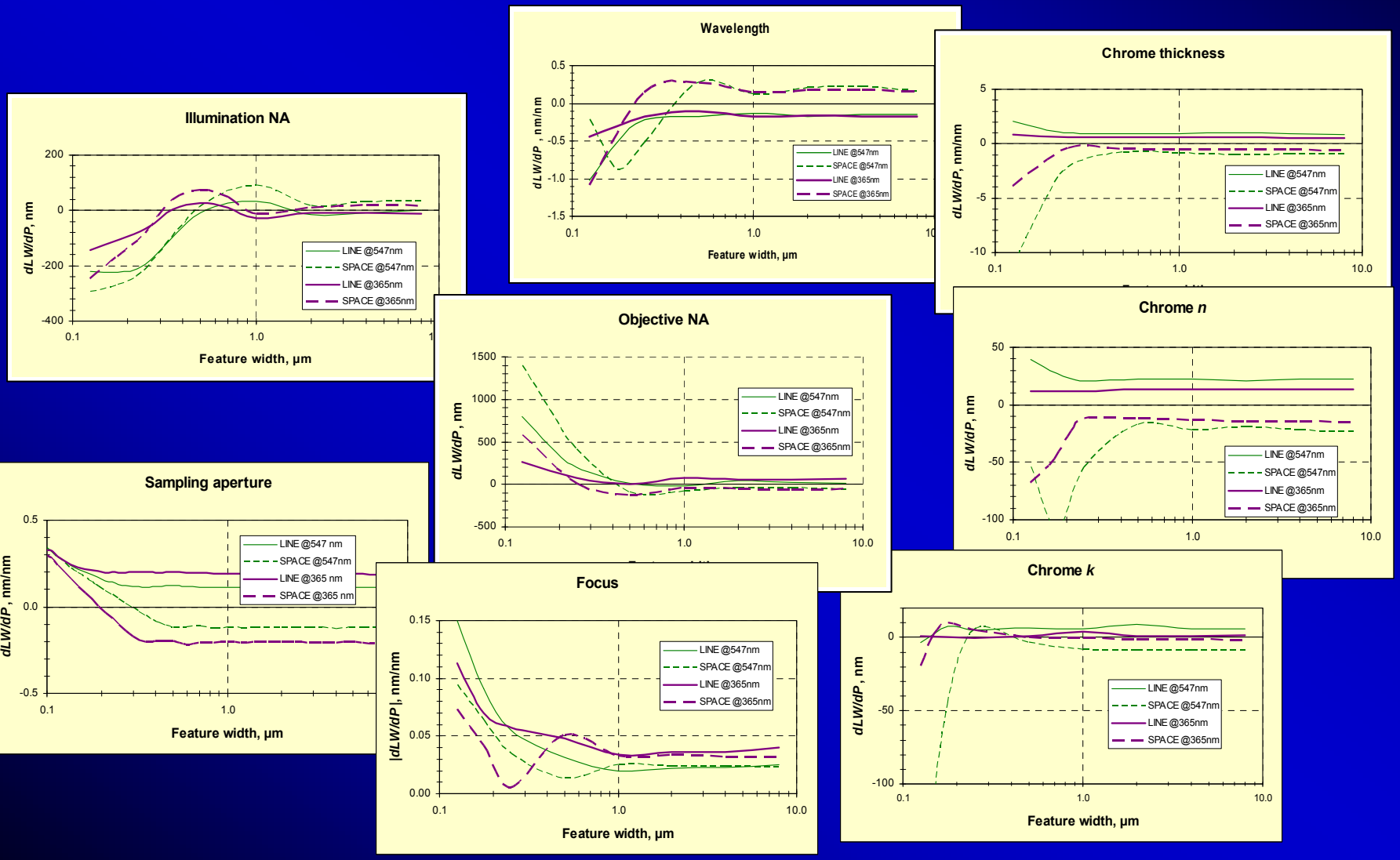
- ***Image library*** — Model feature images throughout a volume of parameter space
  - Find closest library match to real image
  - Interpolate if necessary
  - Extract feature width and other parameters from modeled image

- ***Edge threshold*** — Model the images of features using nominal parameters, over a range of linewidths
  - Subset of Image Library—1-dimensional library in feature width.
  - Find the image intensity at feature edge from model
  - Find linewidth at this intensity in real image
  - Use perturbation to derive parametric uncertainties from parameter uncertainties

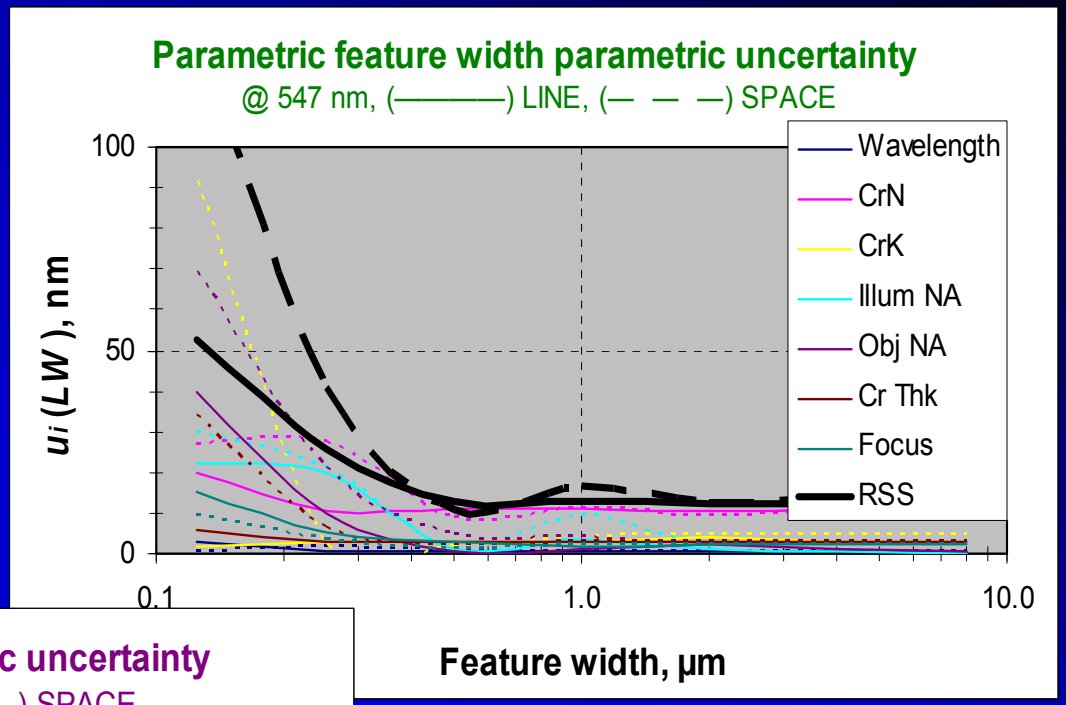


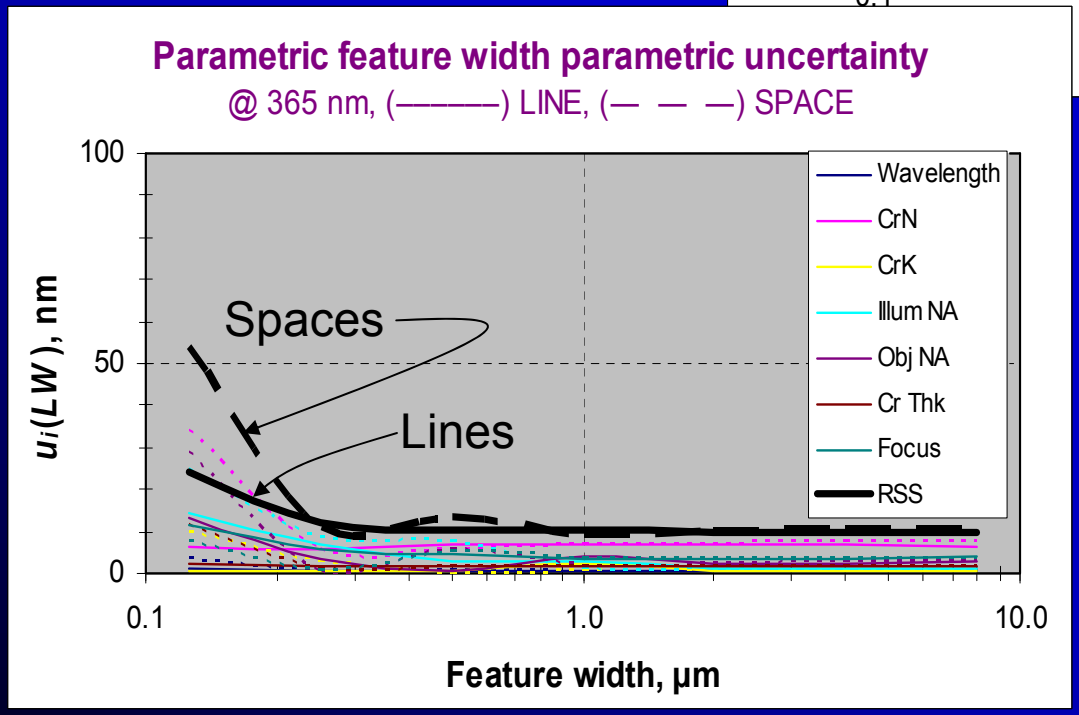
- Numerical imaging models are too slow to model images in real time.

Optical $\partial LW/\partial P_i$ as function of LW for isolated lines and spaces at 2 wavelengths for 8 parameters



Optical parametric linewidth uncertainty components

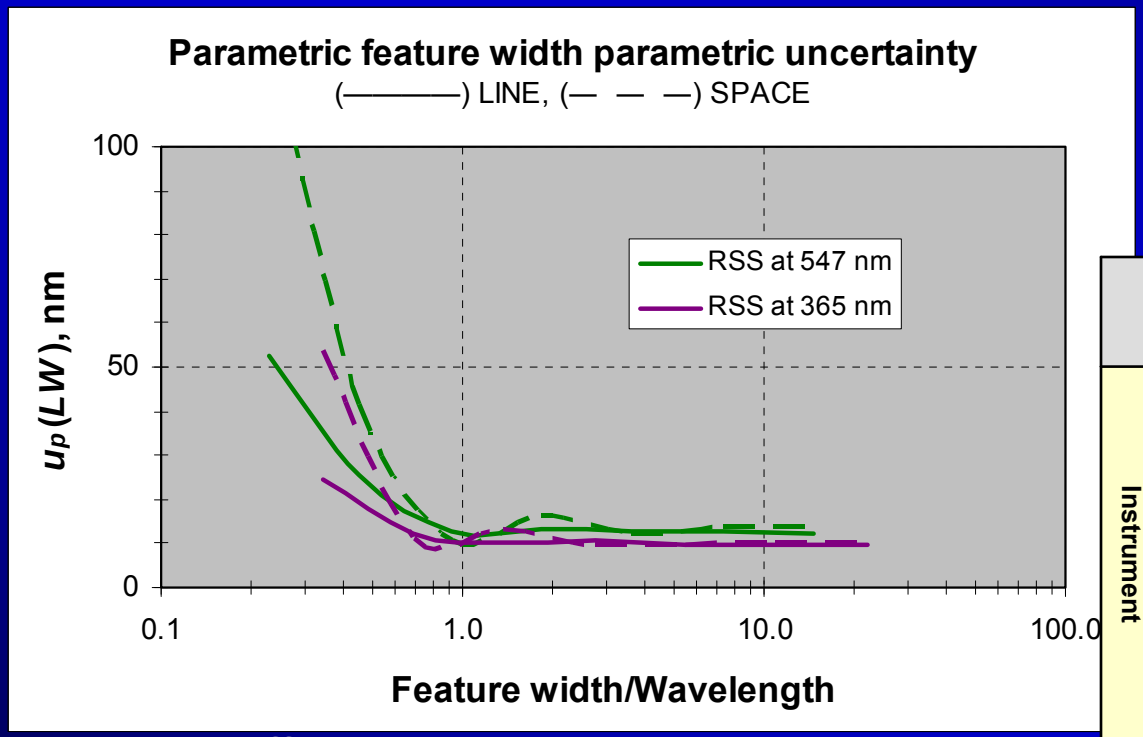




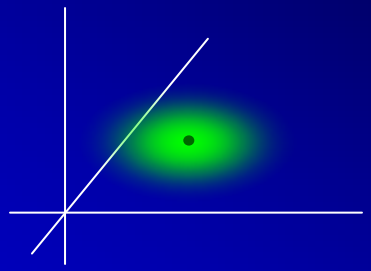
Results for isolated lines and spaces at 2 wavelengths, and their RootSumSquares $u_p(LW)$

(Note the logarithmic scale)

Combined parametric uncertainty



(Note the different scale)



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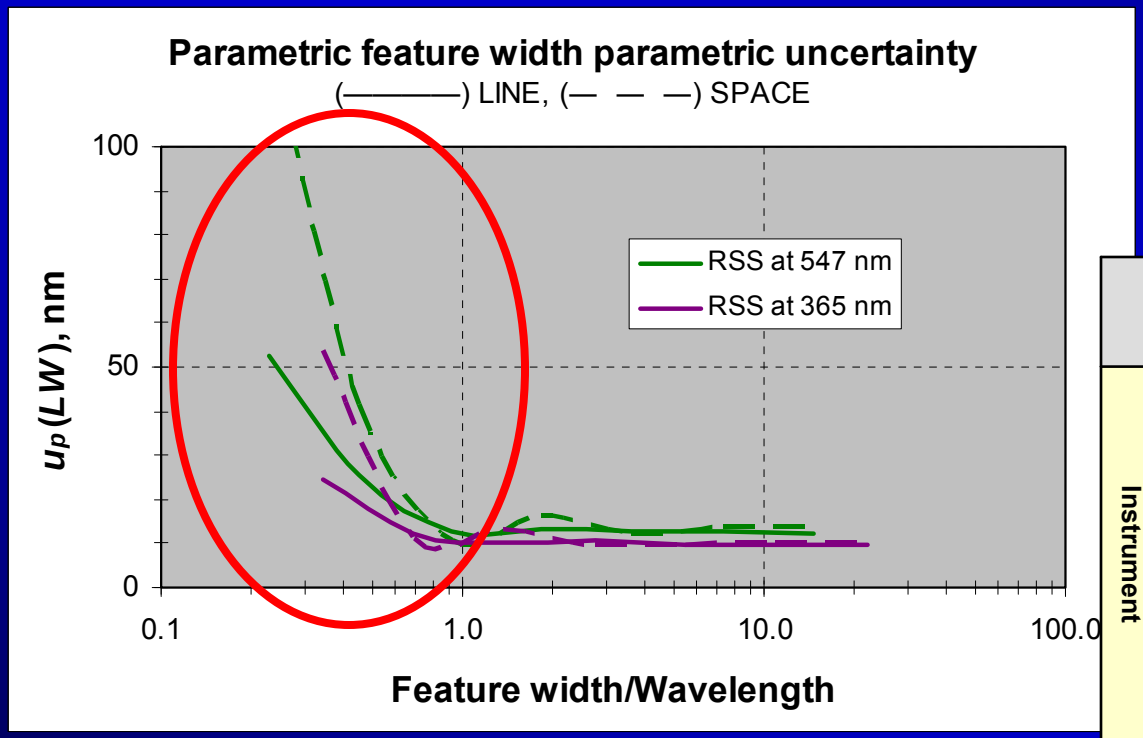
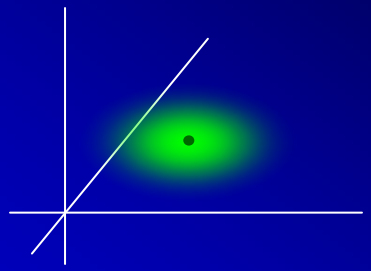
Optical parametric uncertainty explosion





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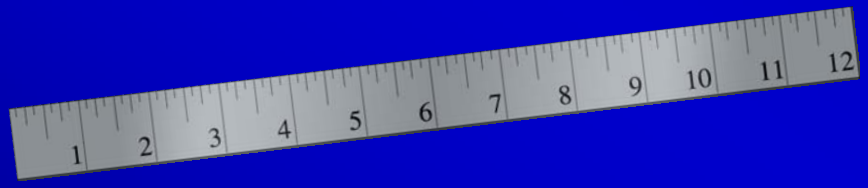
$$u_p(LW) = \sqrt{\sum (\partial LW/\partial P_i)^2\, u^2(P_i)}$$

Optical parametric uncertainty explosion

- The magnitude of the “Parametric Uncertainty Explosion” is somewhat overstated by the metric chosen
  - However, the explosion is still real
- Parametric uncertainty can be improved by
  - Better knowledge of parameter values
  - Better way of deducing LW from the image
- Combined parametric uncertainty is often the largest component
  - Others include repeatability and scale calibration



The conclusion remains…

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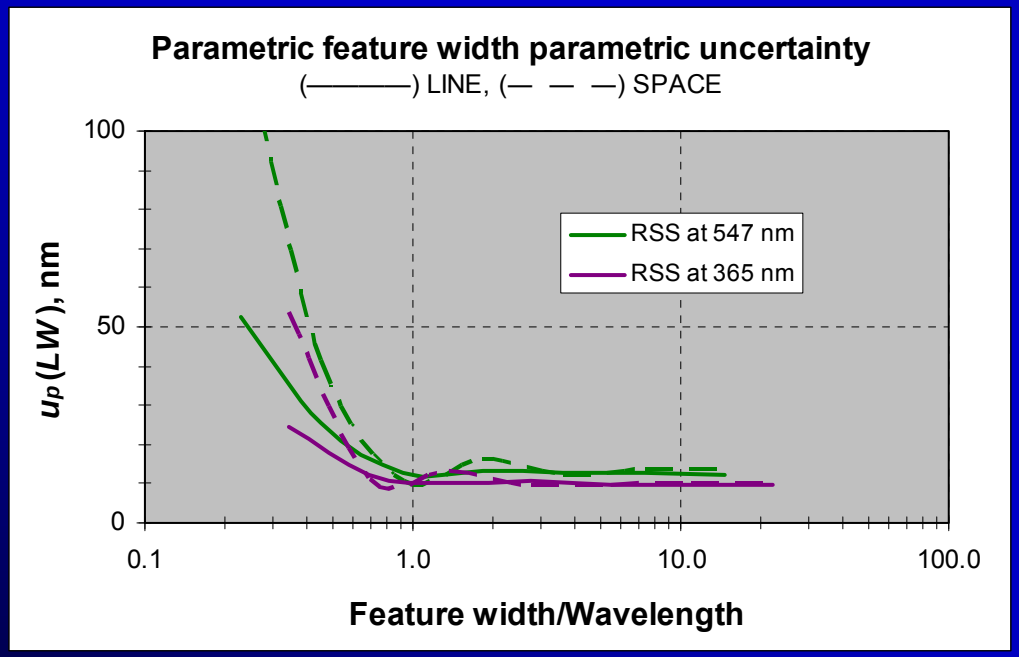
- However, measurement uncertainty arising from parametric influences increases as feature size diminishes below the wavelength.



In optical metrology

Image is everything

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Questions?