Characterizing Variation in EUV Contact Hole Lithography

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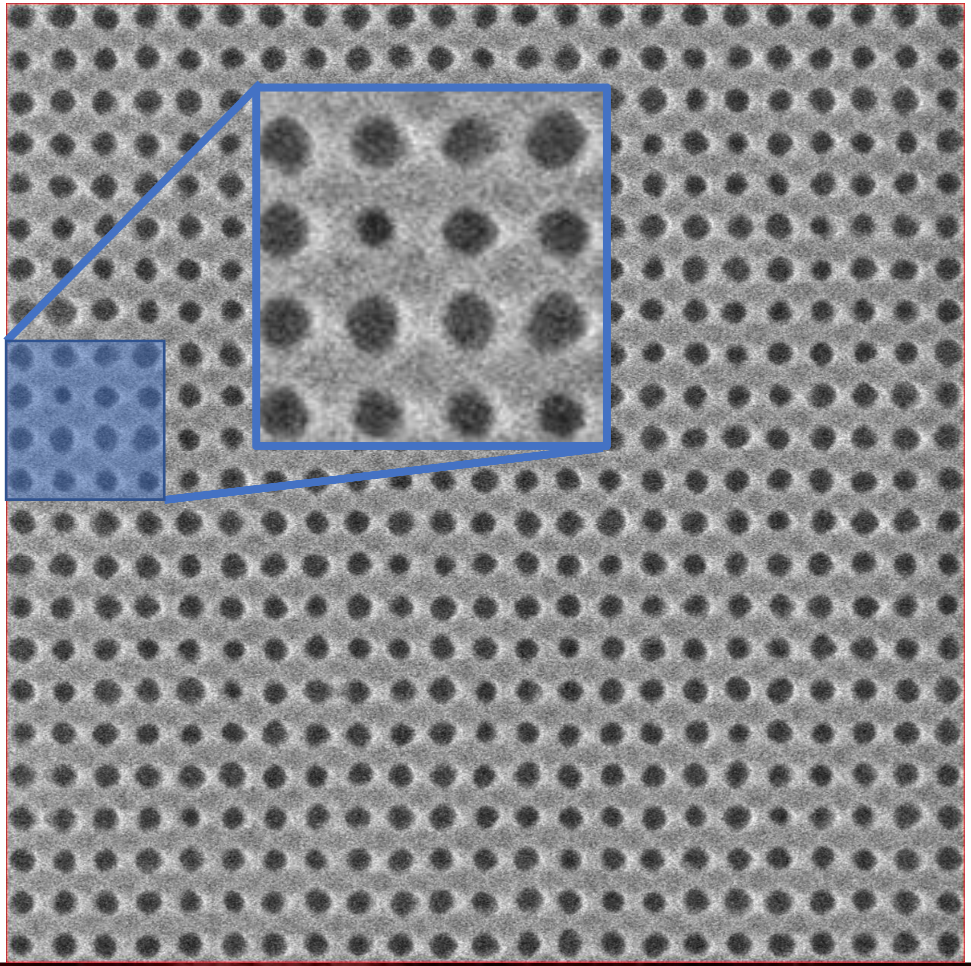
Study Goals

- Local contact hole/pillar variation has important impacts on devices and must be accurately characterized
  - Variation in size
  - Variation in shape
  - Defectivity rate (missing or merged)
- Study Goals:
  - Determine best size metrics for characterizing hole/pillar stochastic size variability
  - Determine best shape metrics for characterizing hole/pillar stochastic shape variability
  - Defectivity measures put off to future work…

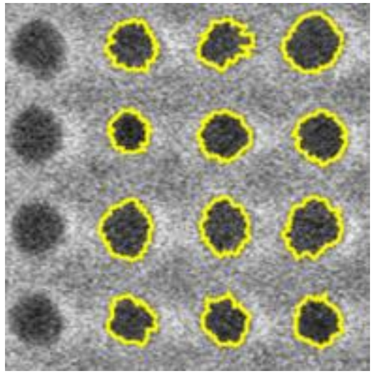
Categories of Variation

- Variations in contact hole size and shape are the result of
  - Global variations (across-wafer, across-scanner-field, etc.), the traditional focus of lithographic control
  - Local variations (as seen in a single SEM image field), mostly the result of stochastics (though mask variations can be seen)
- Local variations often dominate in EUV hole patterning due to the small feature size and dose limitations



Characterizing Hole Size and Shape

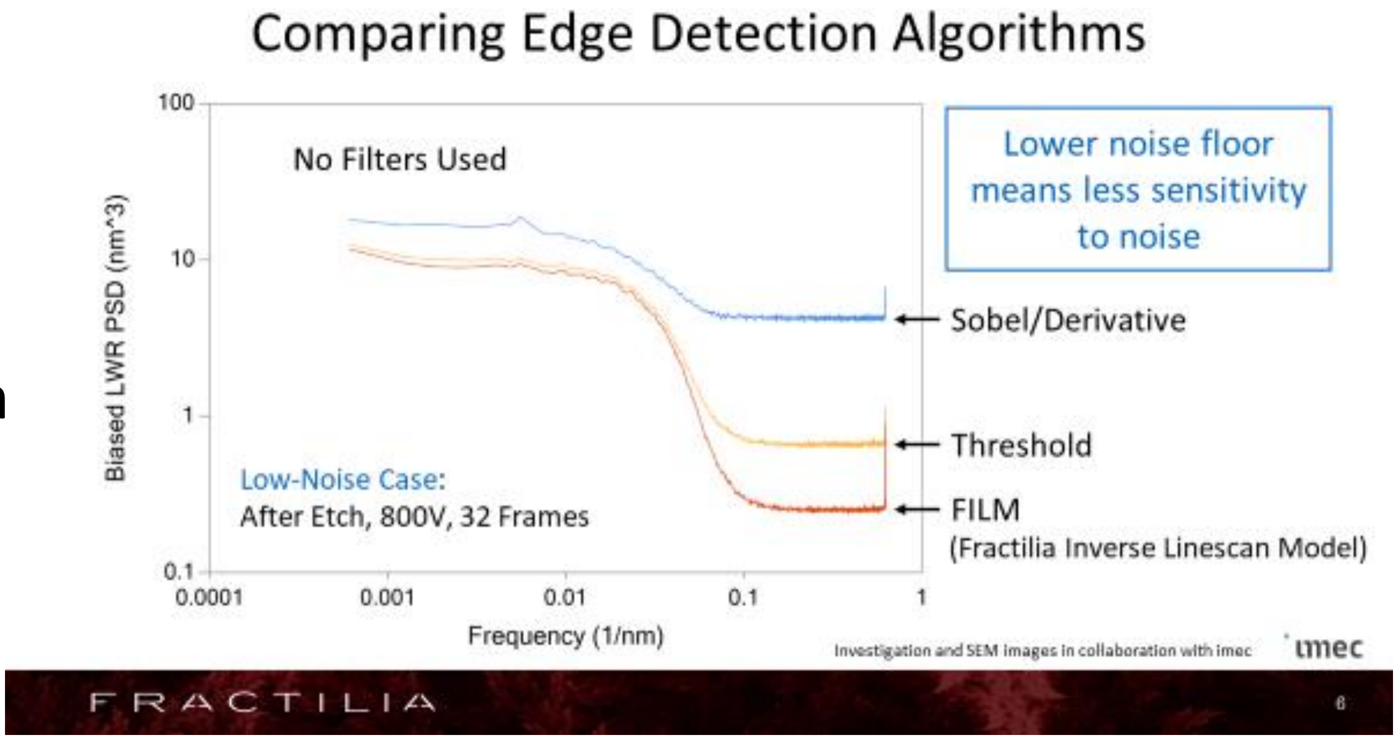
- Contact hole critical dimension ("CD") can be defined and measured in a variety of ways
  - First, edge detection creates a complex shape, with some sensitivity to image noise
  - Second, characterization of the complex shape boils it down to a single CD metric



- Contact hole shape compares the detected edges to an idealized shape (circle, ellipse, rectangle, convex hull, etc.)
  - Contact line-edge roughness is also a shape metric

Edge Detection Choice

- Different edge detection algorithms have different sensitivities to image noise
  - We want the algorithm with minimum sensitivity to noise and maximum sensitivity to signal
  - FILM will be used here
  - Typical 1σ noise is 0.5 – 1.0 nm

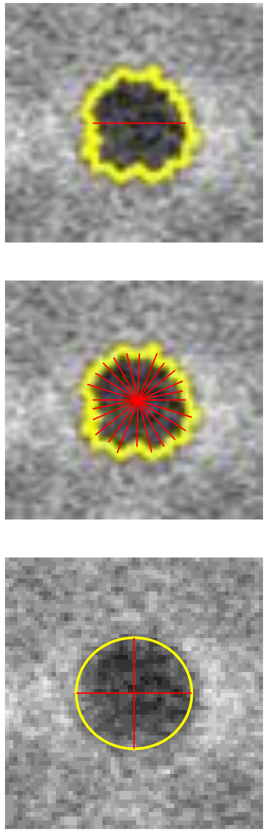

Comparing Edge Detection Algorithms

Lower noise floor means less sensitivity to noise

Chris A. Mack, “Comparing edge detection algorithms: their impact on unbiased roughness measurement precision and accuracy”, Proc. SPIE 11325, *Metrology, Inspection, and Process Control for Microlithography XXXIV*, 113250P (2020).

Defining Hole Critical Dimension

- There are many different possible ways to collapse a complex detected edge shape into a single size metric
  - Single edge-edge distance
  - Average diameter across all polar angles
  - Square root of hole area (effective CD = $2\sqrt{Area/\pi}$)
  - Size of best-fit ellipse (major axis and minor axis)
  - Other best-fit shapes (super ellipse)
- Different definitions have different sensitivities to edge detection noise



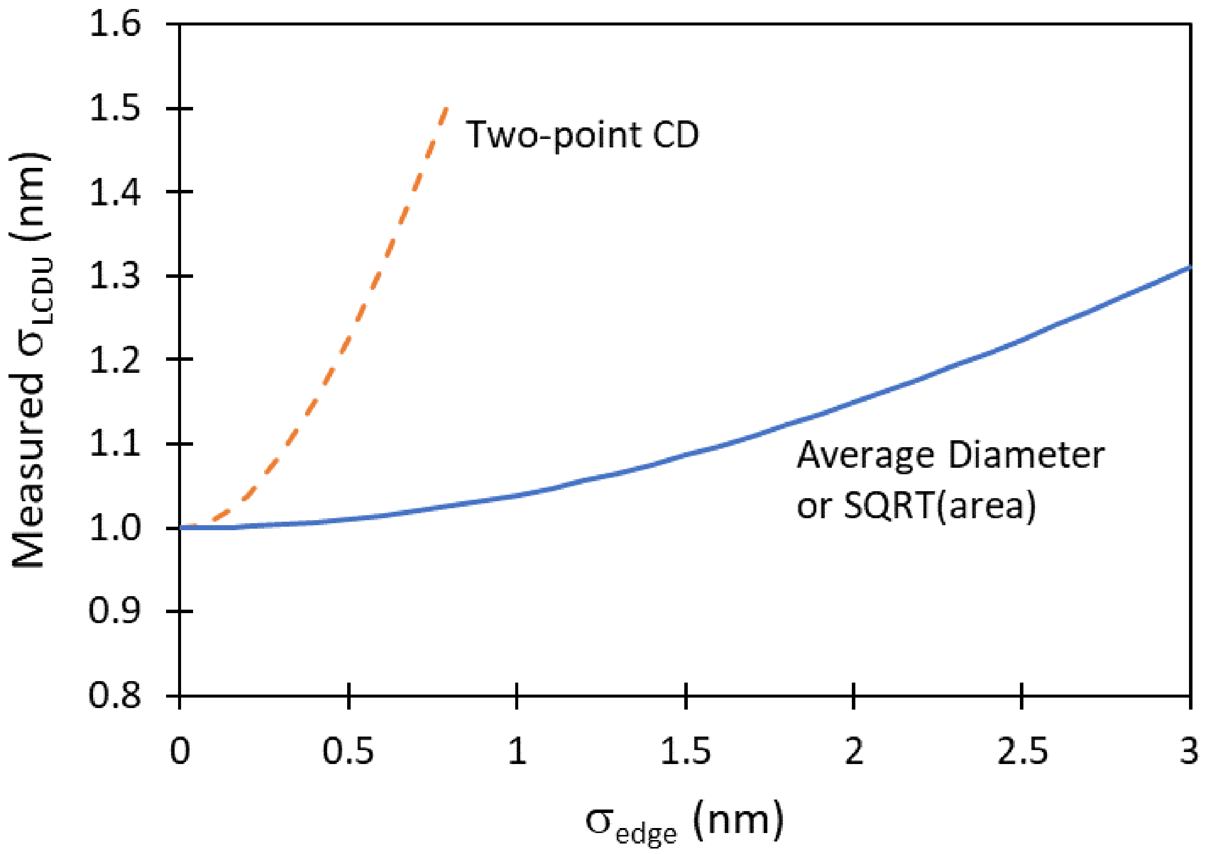
CD Definition Sensitivity to Noise

- Given N detected edge points around the hole, and σ_{edge} independent edge detection uncertainty at each point:
  - Single edge-edge distance: $\sigma_{CD(noise)} = 2\sigma_{edge}/\sqrt{2}$
  - Average diameter across all polar angles: $\sigma_{CD(noise)} = 2\sigma_{edge}/\sqrt{N}$
  - Square root of hole area: $\sigma_{CD(noise)} \approx 2\sigma_{edge}/\sqrt{N}$
  - Best fit ellipse, each independent CD direction: $\sigma_{CD(noise)} \approx 2\sqrt{2}\,\sigma_{edge}/\sqrt{N}$

Average diameter and square root of hole area are about equivalent and least sensitive to edge detection uncertainty

Note: the optimal N is such that the distance between edge points along the hole circumference is about equal to the pixel size.

Expected LCDU Sensitivity to Noise



Goals: use low-noise edge detection + CD definition that averages away some edge detection noise

$$\sigma_{LCDU(measured)} = \sqrt{{\sigma_{LCDU}}^2 + {\sigma_{CD(noise)}}^2}$$

(N = 50 for average diameter and area CD measurements)

Impact of Image Filtering on LCDU Measurement

- Can image filtering lower the impact of edge detection error without adding systematic bias to CD or LCDU?
- Filtering has two impacts:
  - reduction of image noise
  - blurring of image signal (throwing away resolution)

$$image = signal + noise$$

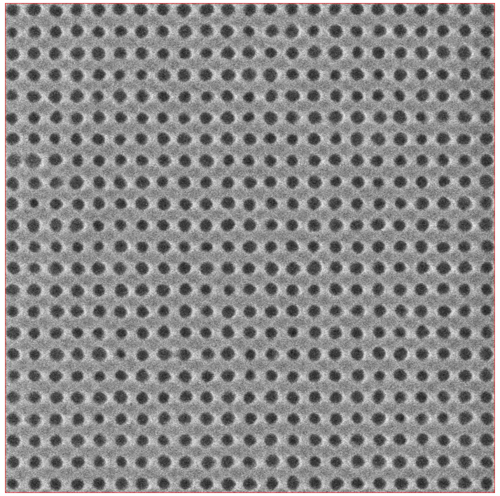
$$filter * image = \overset{}{filter * signal} + filter * noise$$

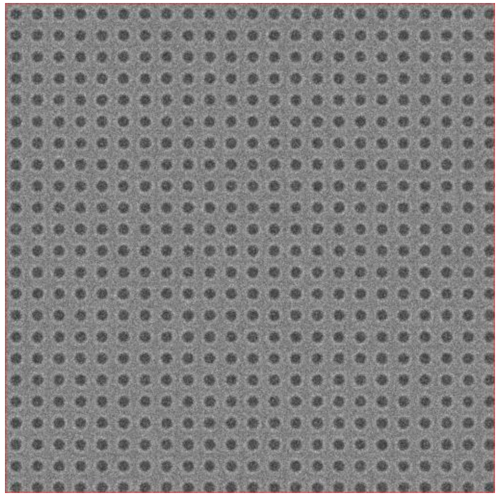
Impact depends on signal shape

Goes to 0 as filter size increases

Data to be Analyzed

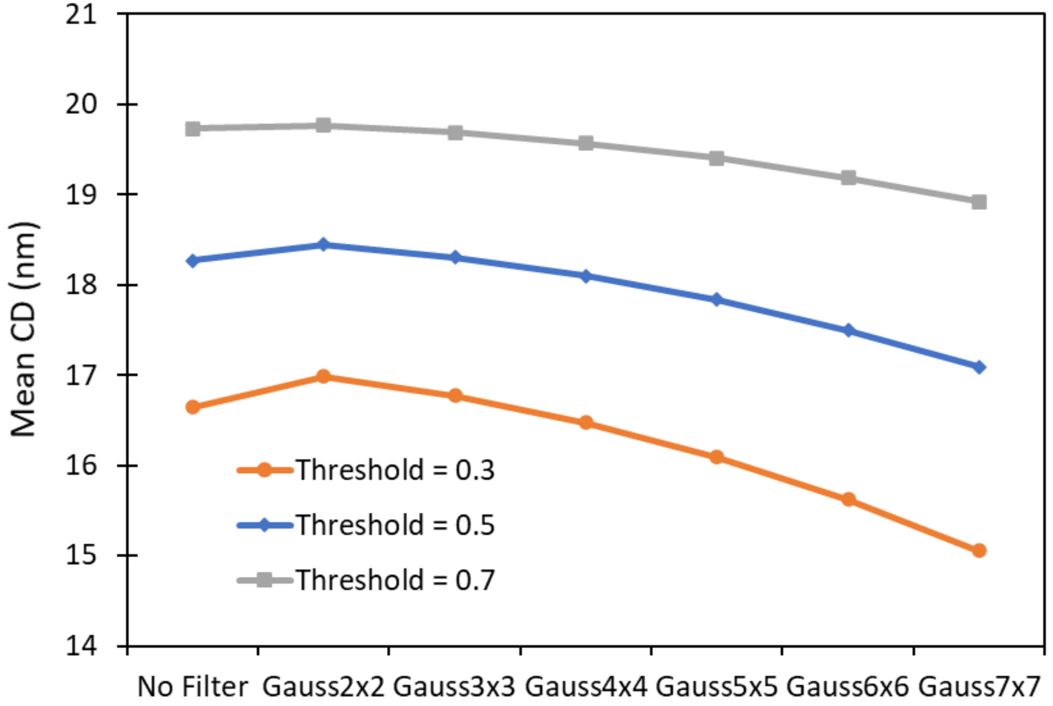
- Typical set of experimental EUV contact holes
  - Resist on underlayer, square array at 36 nm pitch
  - Pixel size = 0.8 nm x 0.8 nm
  - 316 images, 146k contact holes analyzed
- Synthetic images with no stochastic variations
  - Each hole identical except added image noise
  - Grayscale noise added (σ = 20 or 40 out of 256)
  - Square array at 36 nm pitch
  - Pixel size = 0.8 nm x 0.8 nm
  - 300 images, 145k contact holes analyzed

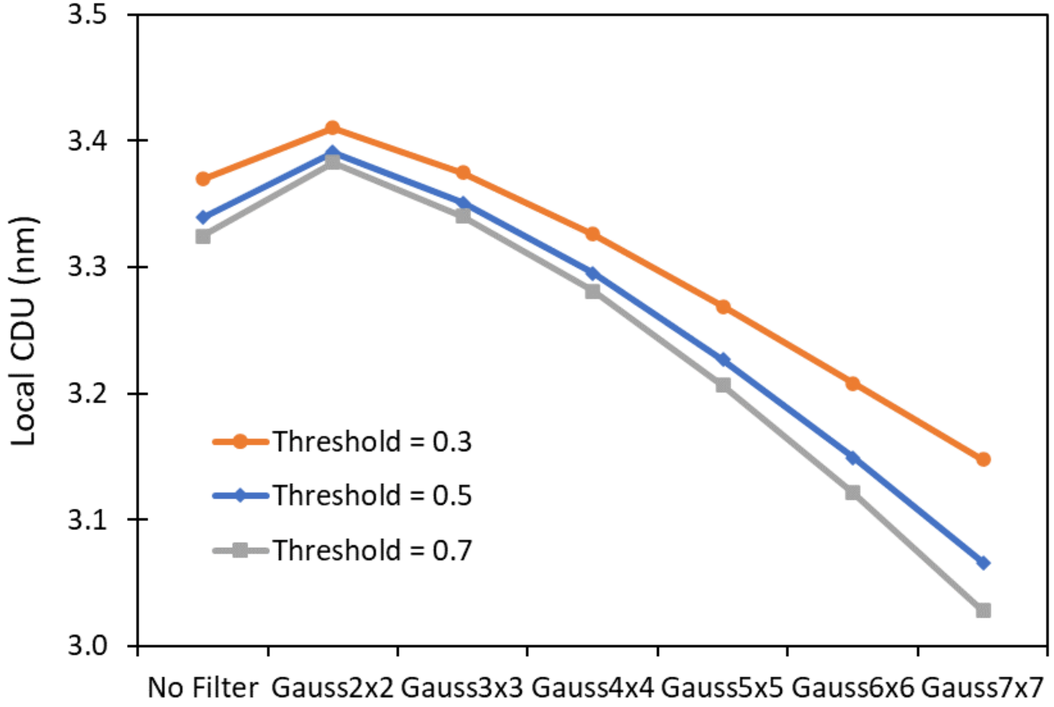




Impact of Threshold and Image Filtering

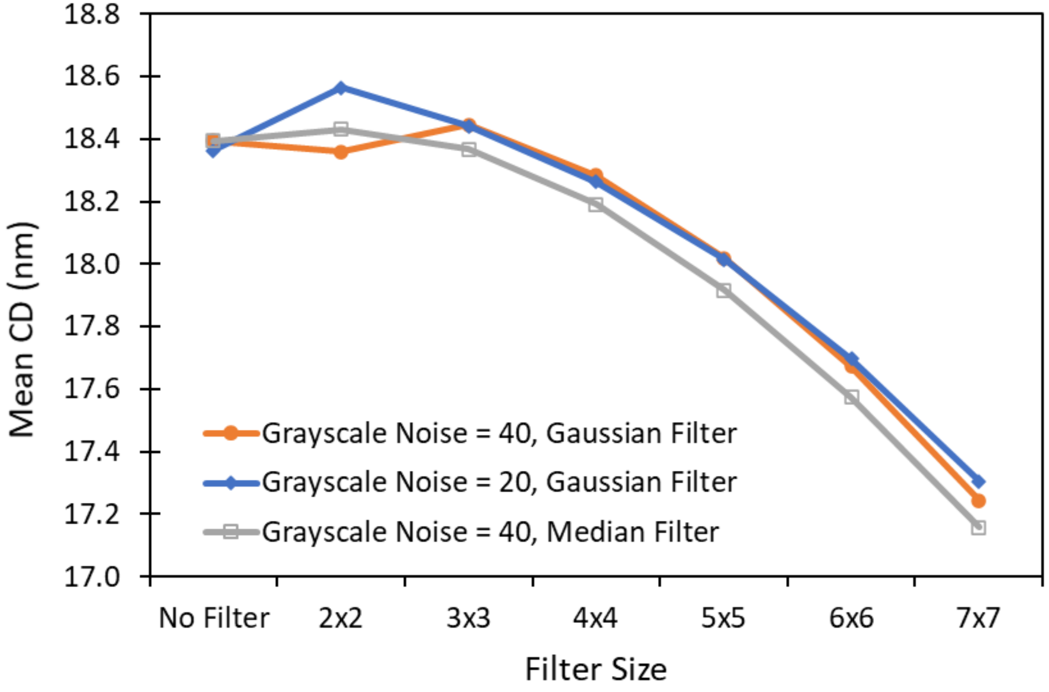
Experimental Images, measured grayscale noise = 32

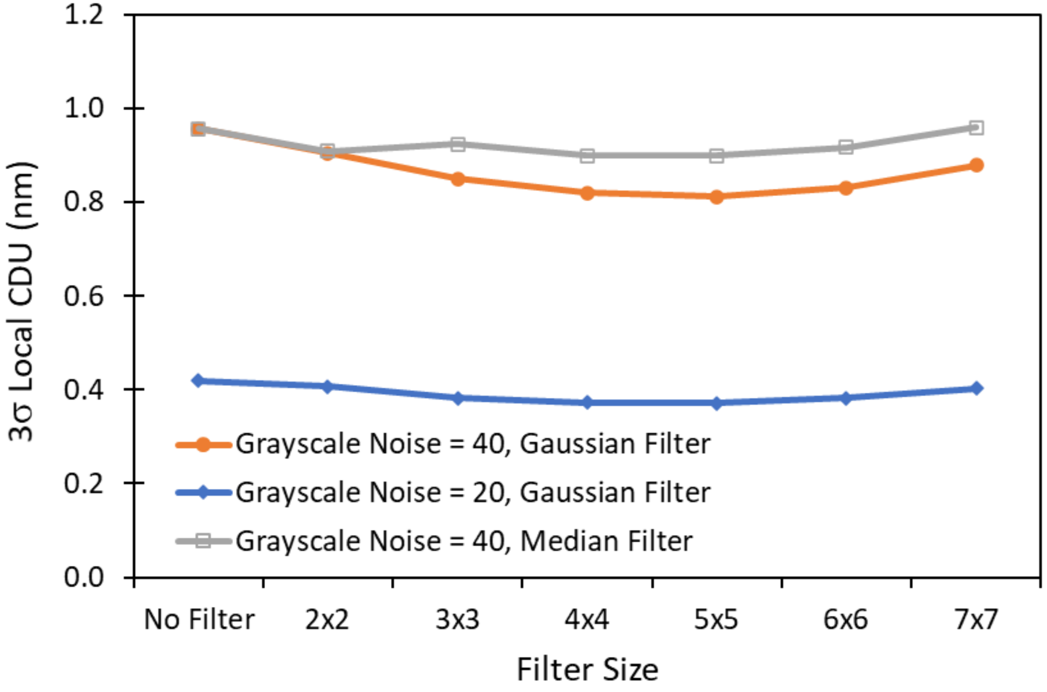




- Threshold has much larger impact on CD (17%) than on LCDU (1.4%)
- Filtering changes both CD and LCDU (LCDU/CD stays about constant)
- Filtering with Box/Mean filter produces very similar results as Gaussian filter

Synthetic Images with Only Edge Detection Noise

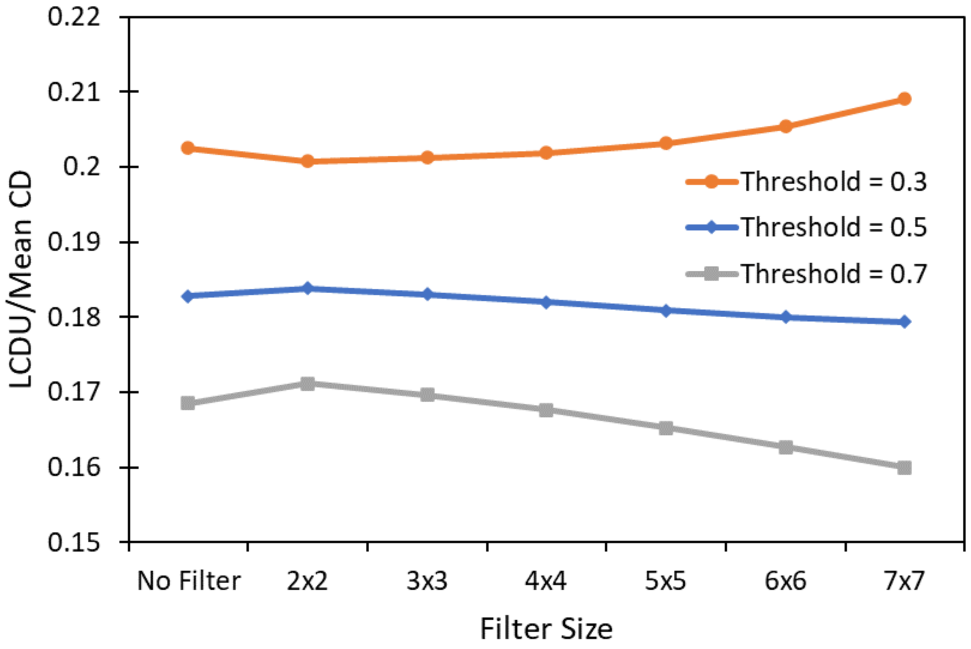




- Filtering has noticeable systematic effect on CD (1.2 nm, 7% range)
- Filtering has only small effect on measured LCDU (0.05 – 0.15 nm)
- Median (edge preserving) filter does not mitigate these effects

Filtering Conclusions

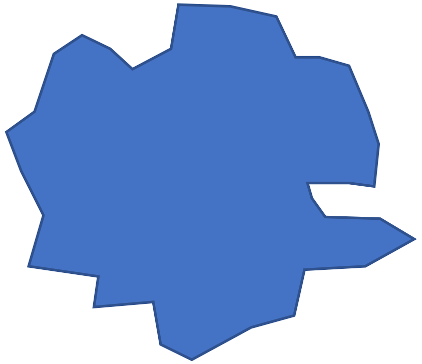
- Filtering changes CD because the linescan signal is being blurred
  - Throwing away SEM resolution
- Filtering has very little impact on edge detection noise over useful range of filter sizes
- Thus, filter impact on experimental LCDU is due to signal degradation, not noise reduction

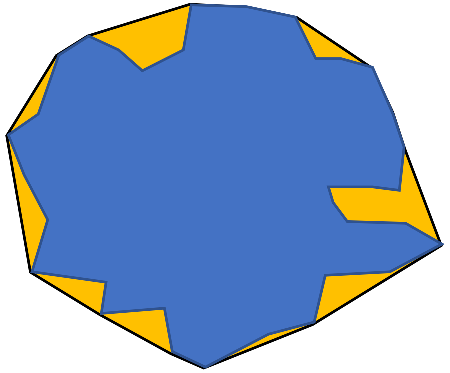


Experimental images

Shape Metrics – how "round" is your hole/pillar?

- The shape metrics either compare the hole/pillar shape (based on the detected edges) to a circle/ellipse/rectangle, or to its convex hull
  - The convex hull of feature is the smallest convex polygon that contains the feature
  - Each metric has a maximum value of 1 for a perfect circle, and is less than 1 for departures from the ideal
  - Some metrics (solidity, convexity) have a maximum value of 1 for any convex shape


Original Feature

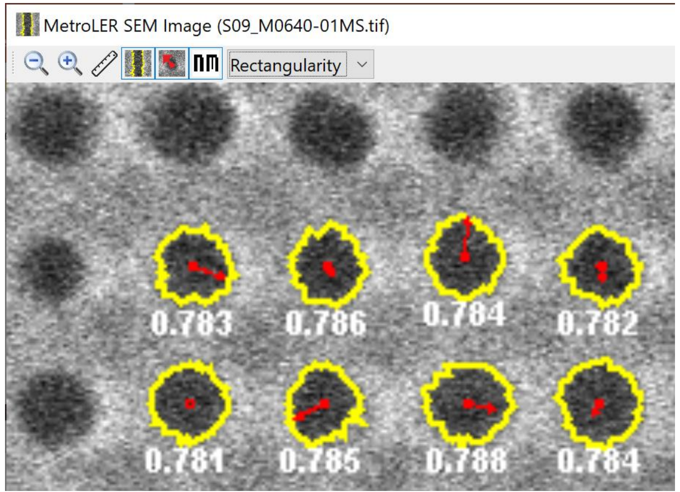

Convex Hull

Shape Metrics – how “round” is your hole/pillar?

- Solidity = Feature Area/Convex Hull Area
  - Solidity measures the “density” of the feature, with a maximum value of 1 for a convex shape. A value less than 1 indicates an irregular boundary. This metric is least sensitive to edge detection noise.
- Convexity = Convex Hull Perimeter/Feature Perimeter
  - Convexity measures the “irregularity” of the feature, with a maximum value of 1 for a convex shape. A value less than 1 indicates an irregular boundary. This metric is more sensitive to edge detection noise.
- Sphericity = Minimum Inscribed Circle/Maximum Circumscribed Circle
  - Sphericity measures how closely the feature matches a “sphere”, with a maximum value of 1 for a circle. Both inscribed and circumscribed circles are centered at the centroid of the feature. A value less than 1 indicates an irregular boundary. This metric is very sensitive to edge detection noise.
- Compactness = $4*\pi*$Feature Area / (Feature Perimeter)^2
  - Compactness is a measure of the “roundness” of the feature, with a maximum value of 1 for a circle. A value less than 1 indicates a departure from a circle. This metric can indicate an irregular boundary or an elliptical or square shape, for example.
- Circularity = $4*\pi*$Feature Area / (Convex Hull Perimeter)^2
  - Circularity is another measure of the “roundness” of the feature, with a maximum value of 1 for a circle. A value less than 1 indicates a departure from a circle. This metric is less sensitive to irregular boundaries and can indicate an elliptical or square shape, for example.

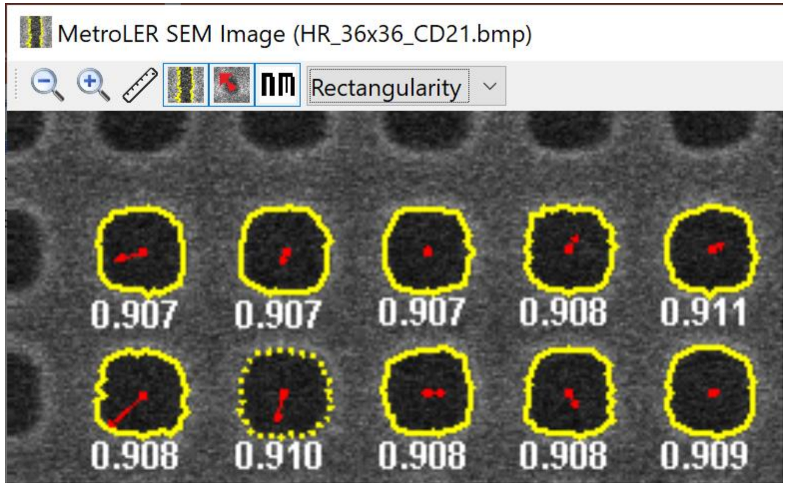
Shape Metric: Rectangularity

- Useful measure for corner rounding
  - Fit hole/pillar to ellipse (user-specified type), get Major-axis and Minor-axis CD
  - Ideal rectangle area = Major-axis CD * Minor-axis CD
  - Rectangularity = feature area/ideal rectangle area
  - Metric varies from 0.5 (diamond) to 0.785 (circle) to 1.0 (rectangle)



MetroLER SEM Image (S09_M0640-01MS.tif)

Rectangularity



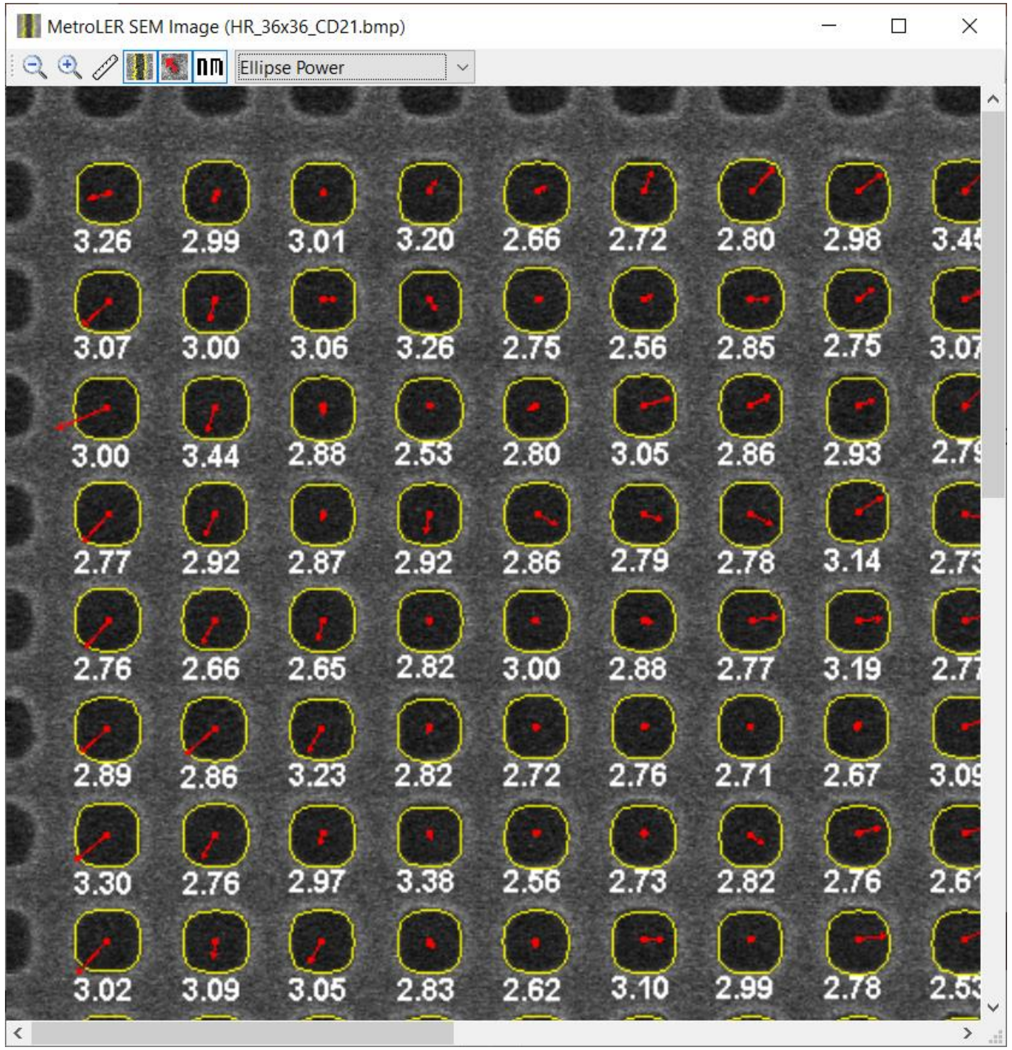
MetroLER SEM Image (HR_36x36_CD21.bmp)

Rectangularity

Fitting Super Ellipse N

- Useful measure for corner rounding
  - N = 2 is a perfect ellipse
  - Higher N approaches a rectangle

$$\left(\frac{x}{a}\right)^N + \left(\frac{y}{b}\right)^N = 1$$



Shape Metrics Example – Experimental Data

Shape Metric	Mean	Standard Deviation
Solidity	0.930	0.018
Convexity	0.923	0.029
Sphericity	0.693	0.057
Compactness	0.755	0.061
Circularity	0.892	0.024
Rectangularity	0.785	0.004
Ellipticity	0.060	0.046
Eccentricity	0.313	0.126
Super Ellipse Power	1.84	0.43

Experimental images: 36nm pitch square array, 316 images, 146k contact holes analyzed

Conclusions

- Contact/pillar LCDU is biased by edge detection noise
  - Impact depends on definition of CD used
  - Average diameter and sqrt(area) metrics are least sensitive to edge detection noise
- Image filtering is not effective at reducing edge detection noise without also degrading true LCDU measurement
- The best approach to LCDU measurement is to use :
  - CD definition that averages edge detection noise based on N, the number of edge points around the feature
  - Small pixel size to produce large N
  - Edge detection algorithms with inherently low noise sensitivity (such as FILM)
  - This produces so-called “low-noise LCDU”
- Various shape metrics are useful for characterizing hole/pillar variations

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