Overview of scatterometry applications in high volume silicon manufacturing

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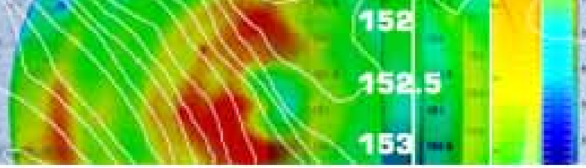
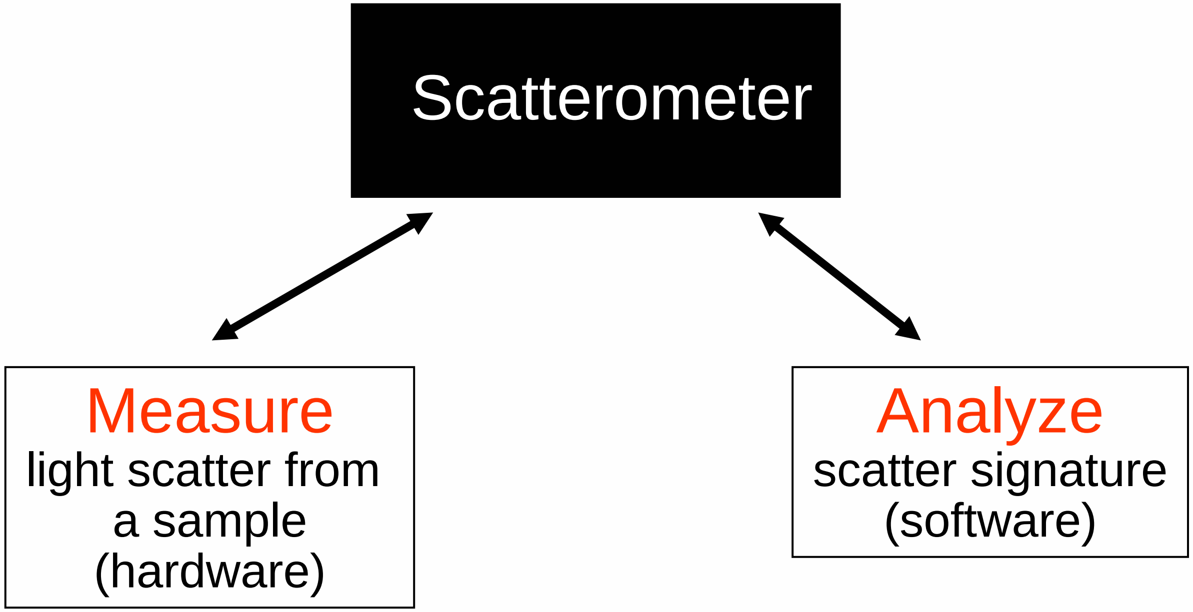


Outline

- Background
  - History of scatterometry
  - Hardware configurations
  - Analysis methods
- Applications
  - Lithography
  - Etch
- Conclusions

Scatterometry Concept

MEASUREMENT and ANALYSIS of light scattered/diffracted from a periodic sample



Scatterometer

Measure
light scatter from a sample (hardware)

Analyze
scatter signature (software)

- This *is not* classic roughness scattering
  - roughness scattering typically measures non-specular scatter from random features

History

1987 - SEMATECH/SRC funded research at UNM, proof of principle scatterometer was developed.

1990 - Focus and dose control investigated.

1993 - Patterned CD measurements investigated.

1995 - Sandia Systems develops/markets CDS-1.

Tool/process validated by SEMATECH, TI.

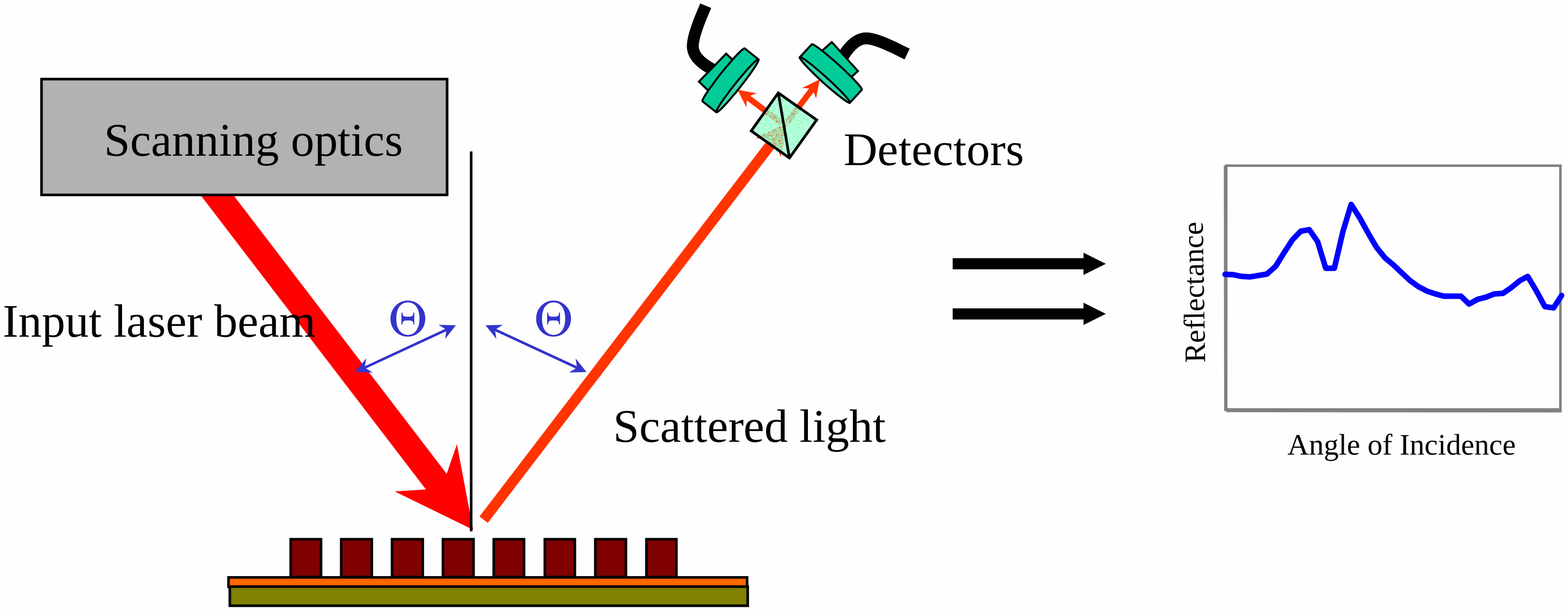
1996 - Sandia Systems acquired by Bio-Rad.

1998 - First sales and shipments of CDS-2.

2000 - First shipments of CDS200 (improved CDS-2).

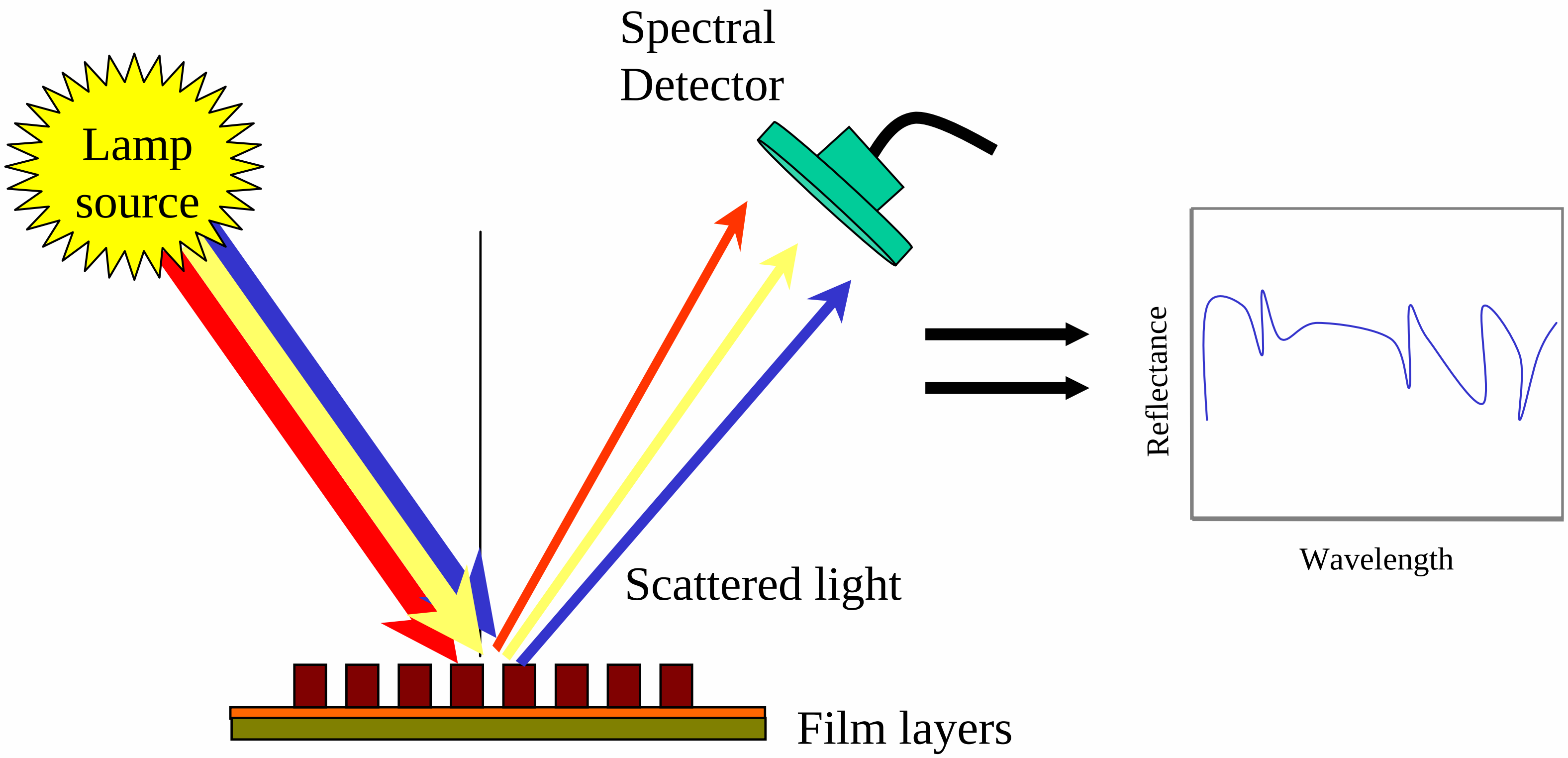
2000 - Bio-Rad Semiconductor Division acquired by Accent.

Angular Scatterometer



- Low noise “2Θ” polarized reflectometer
- Wide angle scanpath (>90º)

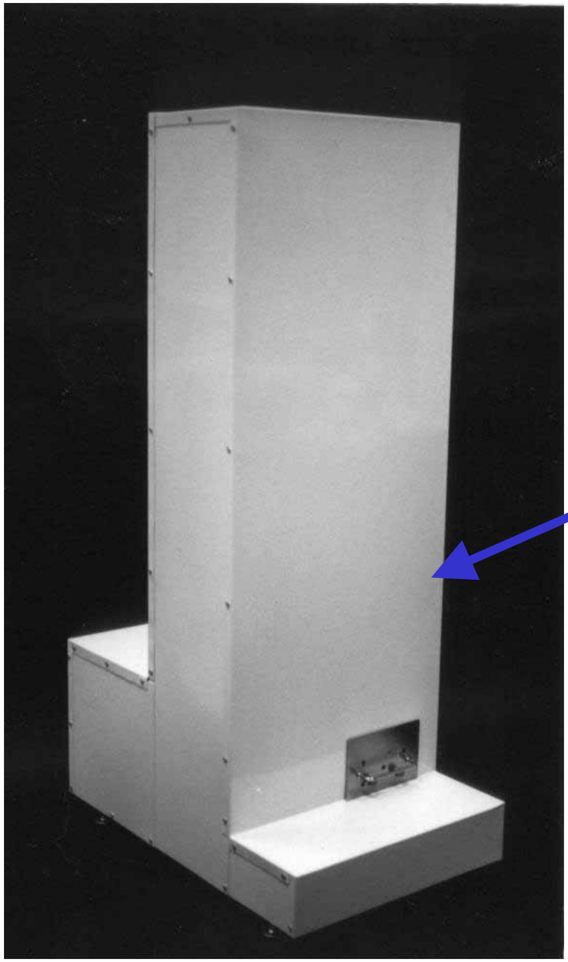
Spectral Scatterometer



- Reflectometer, polarized reflectometer, ellipsometer
- Wavelengths from ~300-800 nm
- Fixed angle scanpath (~65-70º)

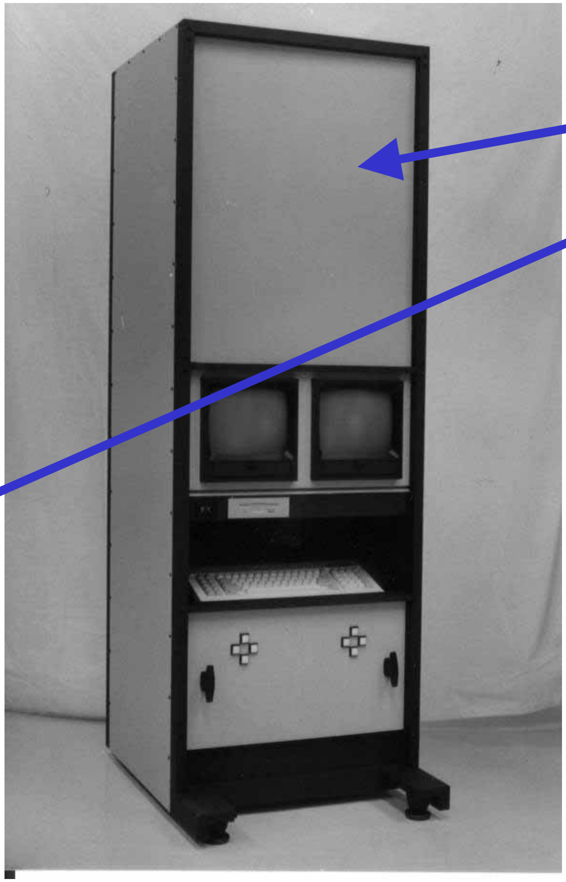
Angular Scatterometers

DINO-I



ca .1990

DINO-II



ca. 1991

Classic scattering measurement for inspection of smooth/flat surfaces

Angular Scatterometers

CDS-1

ca. 1995

CDS-2

ca. 1998

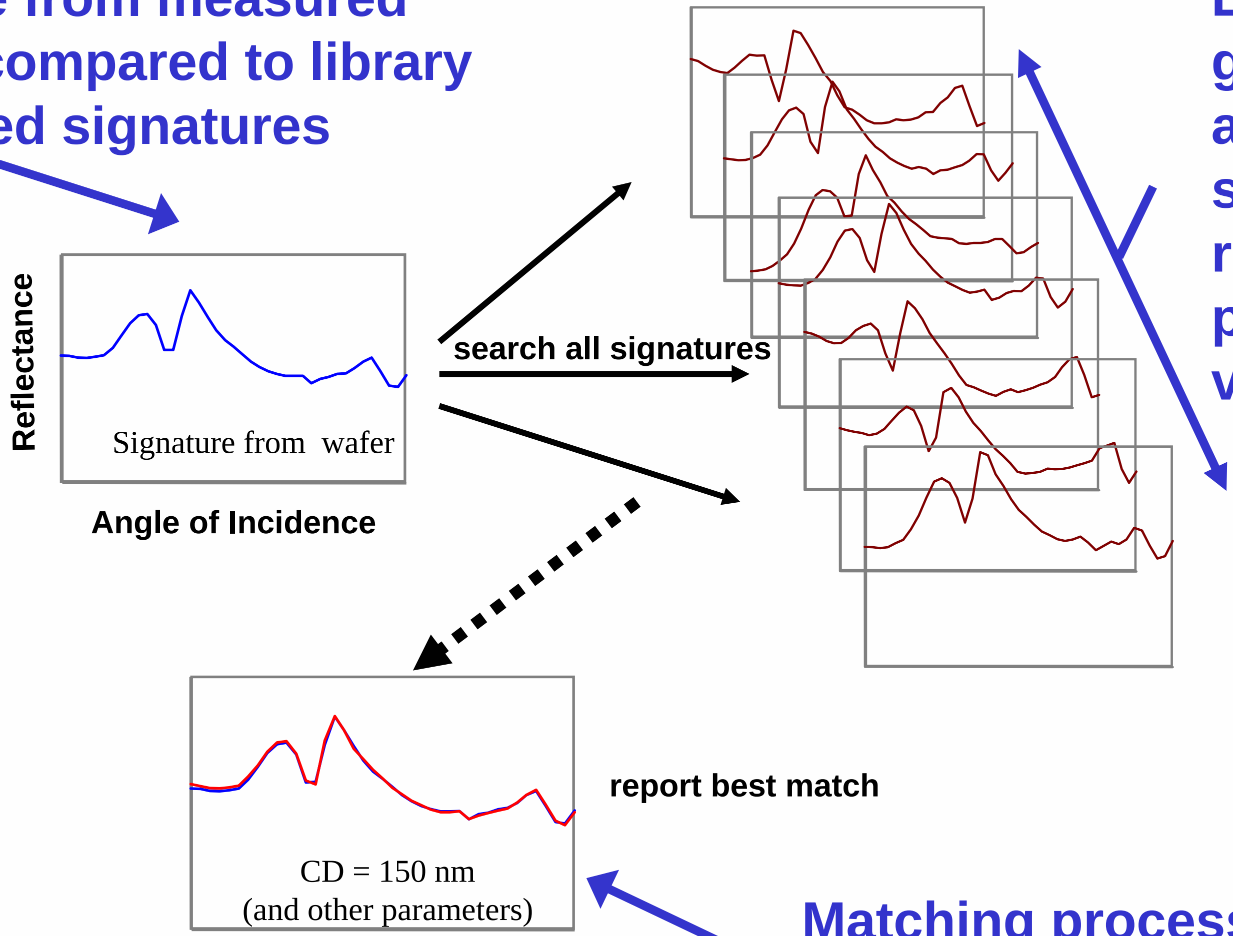
First commercial scatterometers for CD/shape metrology applications

Analysis Methods

- Library search techniques
  - Pre-generate a library of theoretically modeled reference signatures across a relevant range of variables
  - Search library for match against measured signature
  - Report best match as CD measurement answer
- Optimization methods
  - Multiple algorithms
  - Requires starting point or range to search
  - Converges on best solution
  - Reports CD measurement result at some convergence point

Analysis - Library

Signature from measured wafer is compared to library of modeled signatures

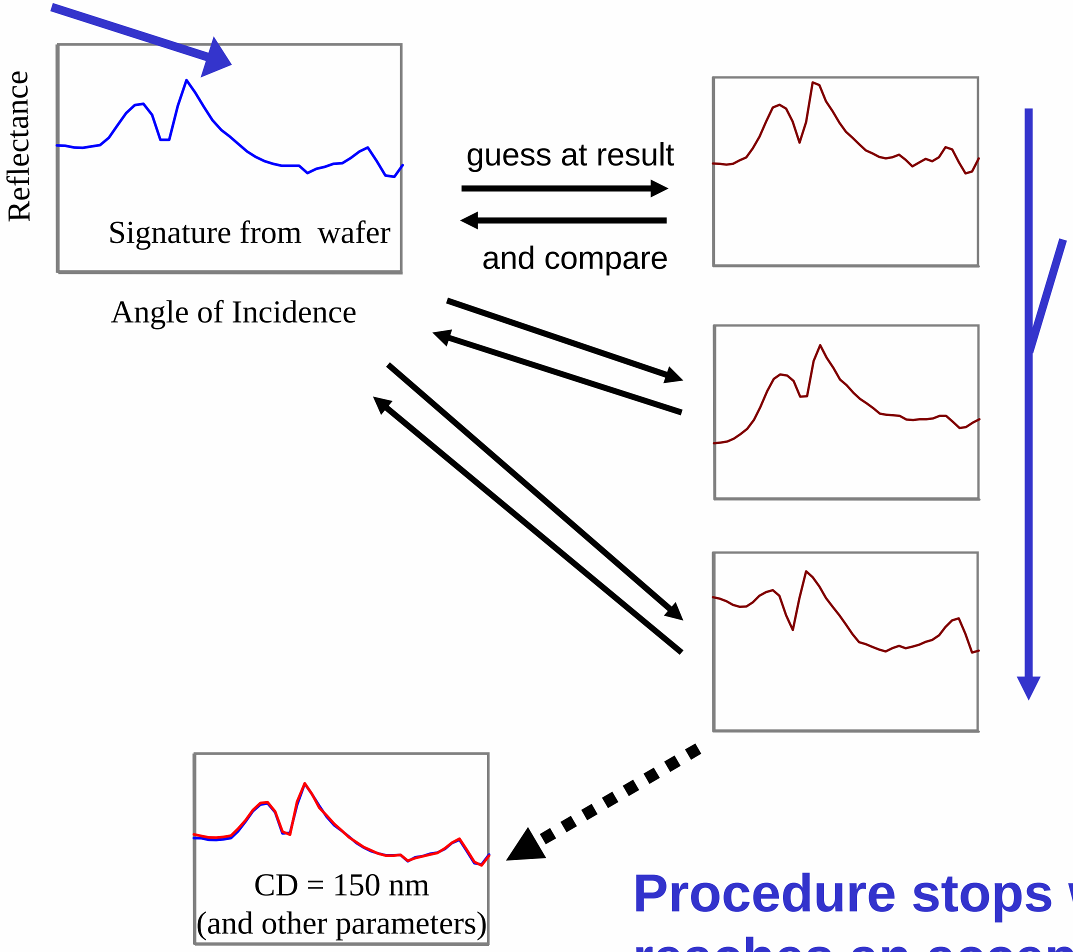


Library generated in advance to span expected range of process variation

Matching process occurs quickly and the measurement is reported

Analysis - Optimization

Signature from measured wafer is compared in “real time” to a model via dynamic simulation

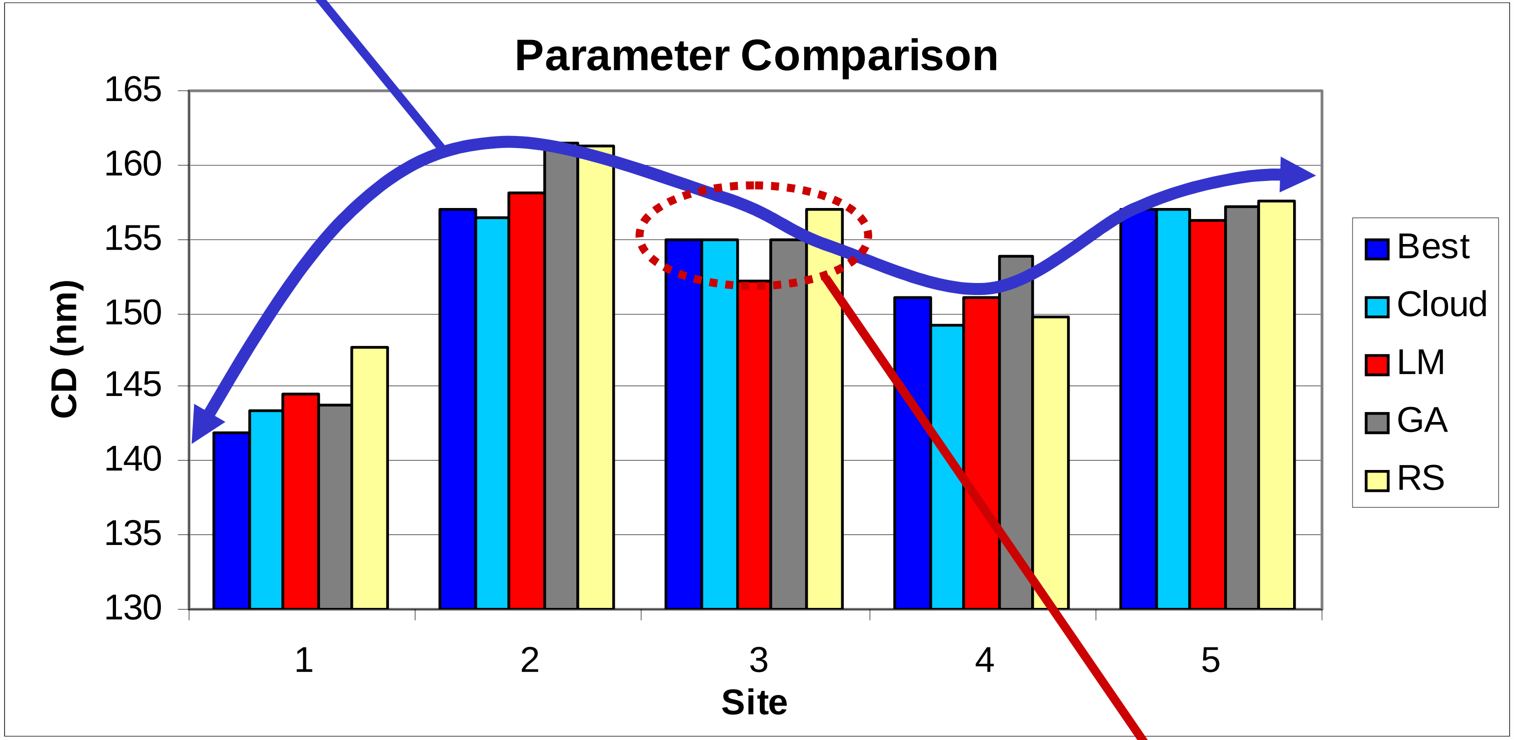


Successive model refinements, based on changing parameters to improve the match

Procedure stops when match reaches an acceptable level

CD Results - Resist

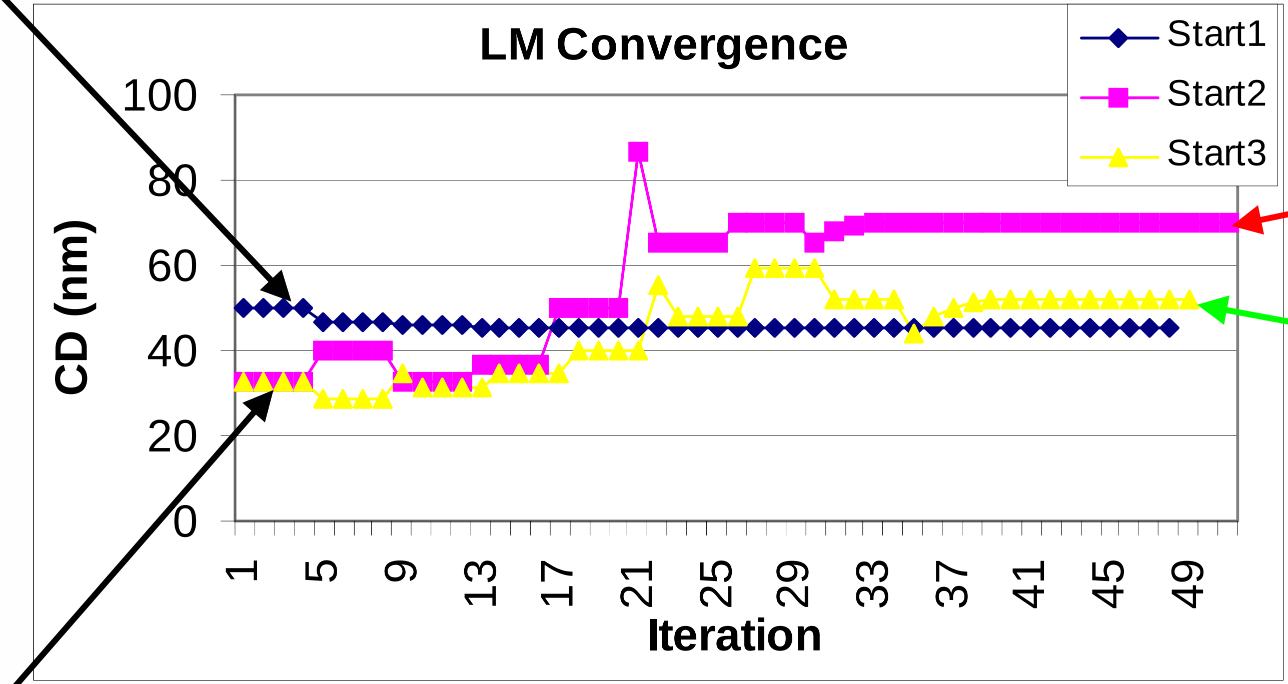
Good general cross-wafer consistency amongst the various methods



Intra-site variation is significant

Convergence Behavior - LM

Nominal CD



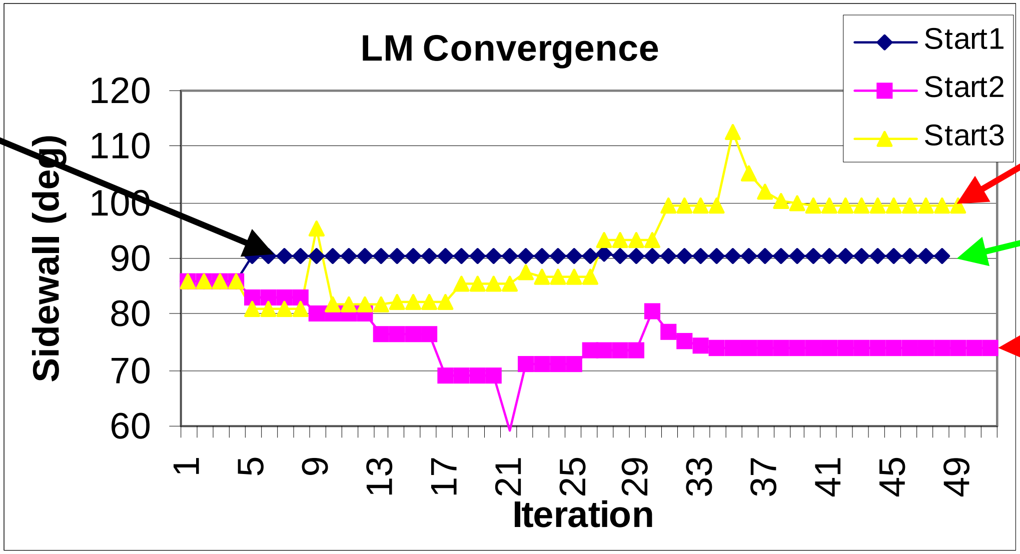
Miss

Hit

Nominal CD – 10 nm

Convergence Behavior - LM

Nominal sidewall



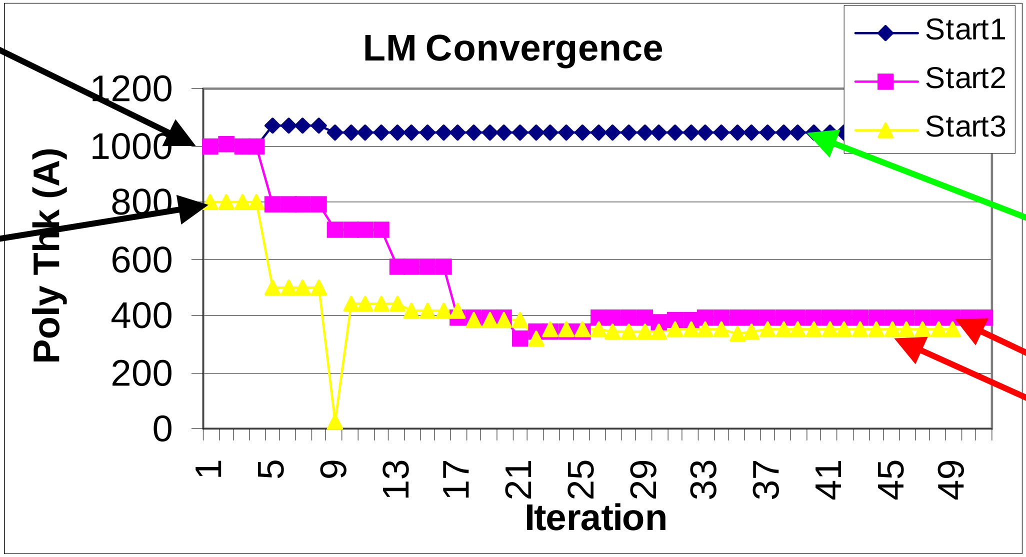
Miss

Hit

Miss

Nominal poly thickness

Nominal poly – 200 Å



Hit

Miss

ACCENT

Analysis - Summary

Method	Pros	Cons
Library	1. Good precision 2. Robust 3. Fast search time 4. Easy to use	1. Longer set-up time 2. Management
GA	1. Robust 2. Minimal set-up time	1. Slowest of the optimizers 2. Tunable
RS	1. Minimal set-up time 2. Not very tunable 3. OK precision	1. Prone to local minima
LM	1. Fast 2. Minimal set-up time 3. OK precision	1. Starting point dependence 2. Tunable

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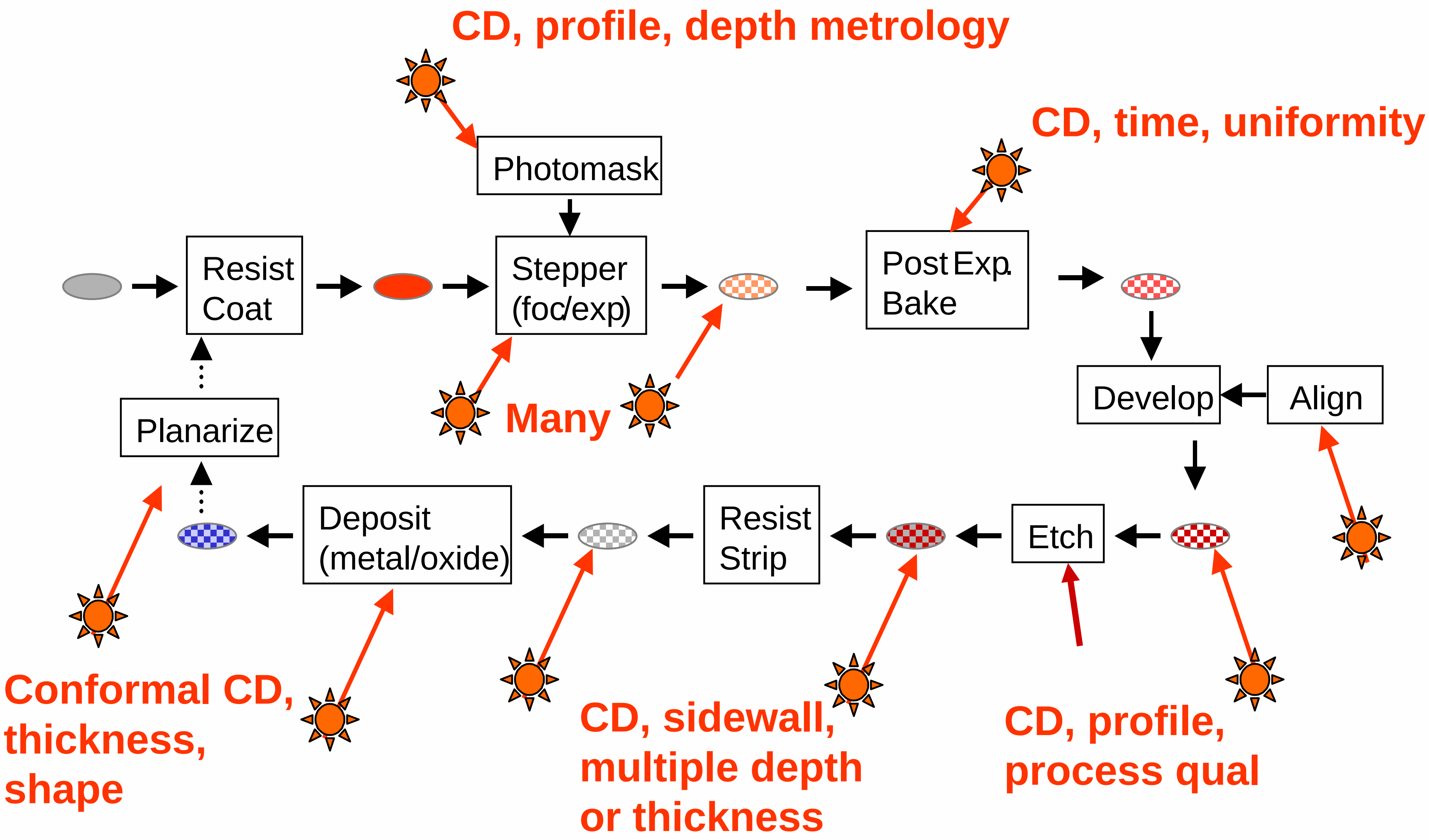
Scatterometry Applications



CD, profile, depth metrology

Photomask

CD, time, uniformity

Resist Coat

Stepper (foc/exp)

Post Exp. Bake

Develop

Align

Many

Planarize

Deposit (metal/oxide)

Resist Strip

Etch

Conformal CD, thickness, shape

CD, sidewall, multiple depth or thickness

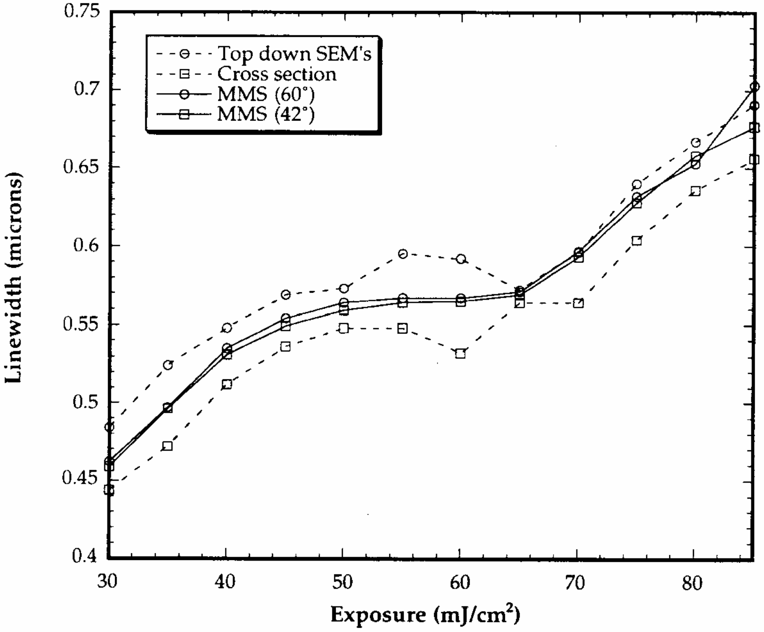
CD, profile, process qual

Why Litho Tool Control?

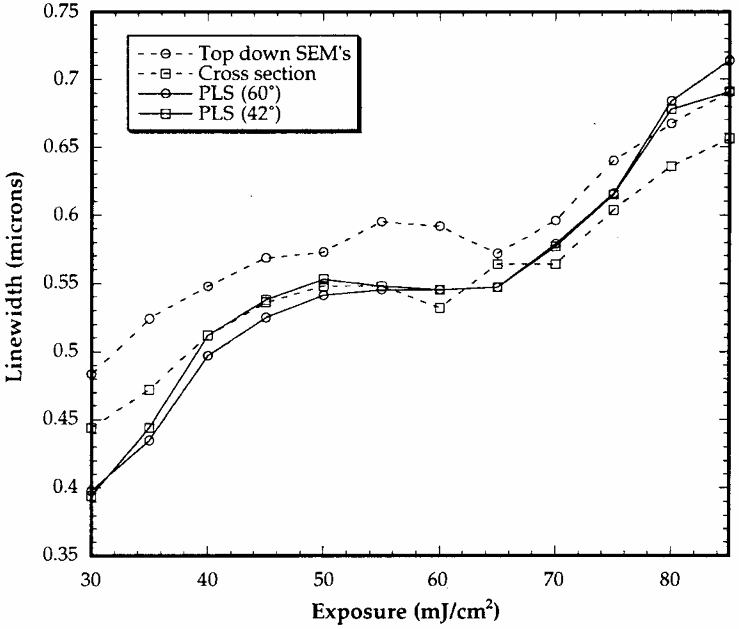
- Applications are mature
  - earliest of scatterometry applications
  - have evolved and expanded in recent years
  - focus, tilt, scan sync, illumination, aberrations, ScatterLith
- Litho tool control is challenging
  - Lots of “knobs” to turn
  - Very narrow process window
  - CDs<<λ
- Large economic impact
  - Litho tools are at the top of the process
  - Fewer alpha/beta errors due to improved precision
  - Greater lithography tool availability

Dose Monitoring

Library Match

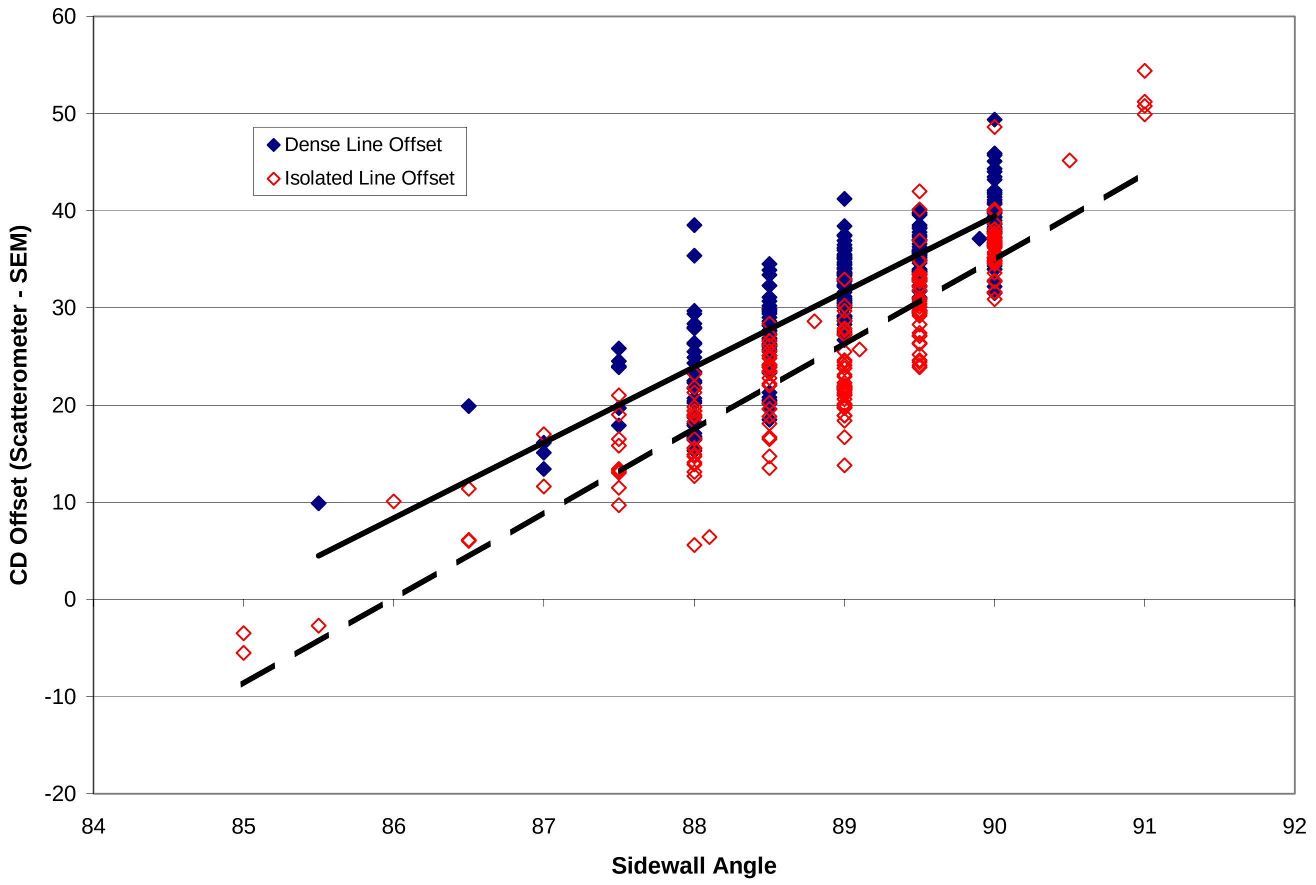


PLS Regression



- JVSTB 1995
- Note large CDs and process window
- Which SEM is right?
- Library match results trend better than regression

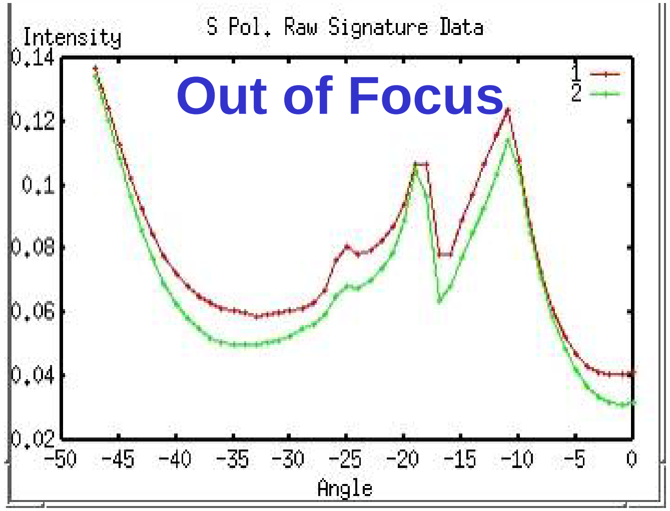
CD-SEM Sidewall Bias



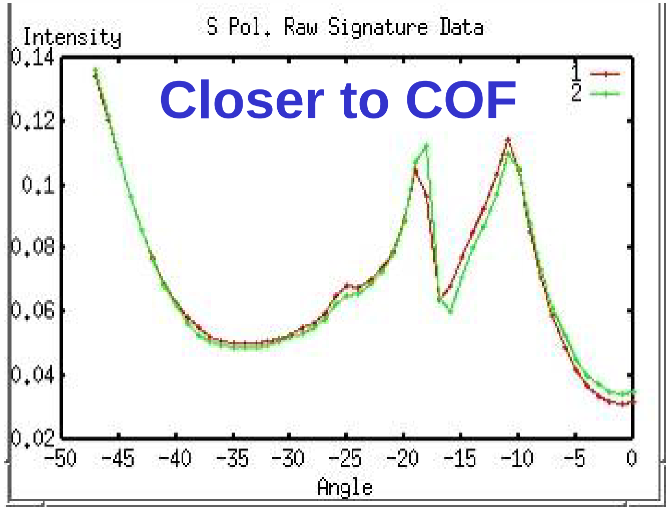
Data courtesy of
Chris Baum

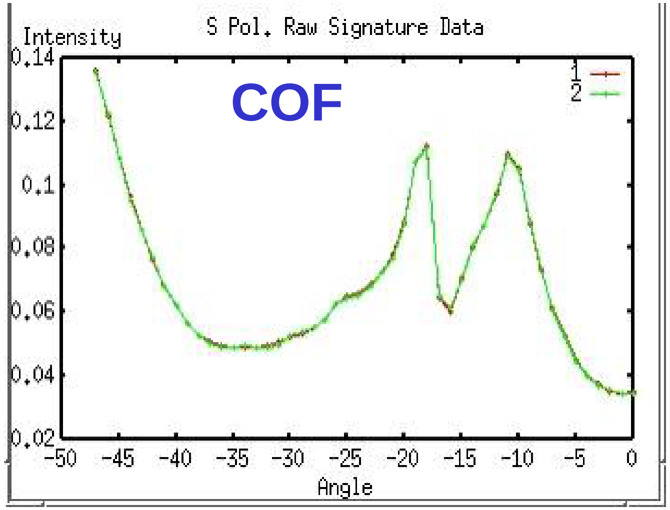
- CDSEM-Scatterometer offset is linear with sidewall
  - Calibration method for SEM?
- Now a widely published result

Model-less Focus Control



- Diffraction signatures will move closer together over focus as the center of focus is reached



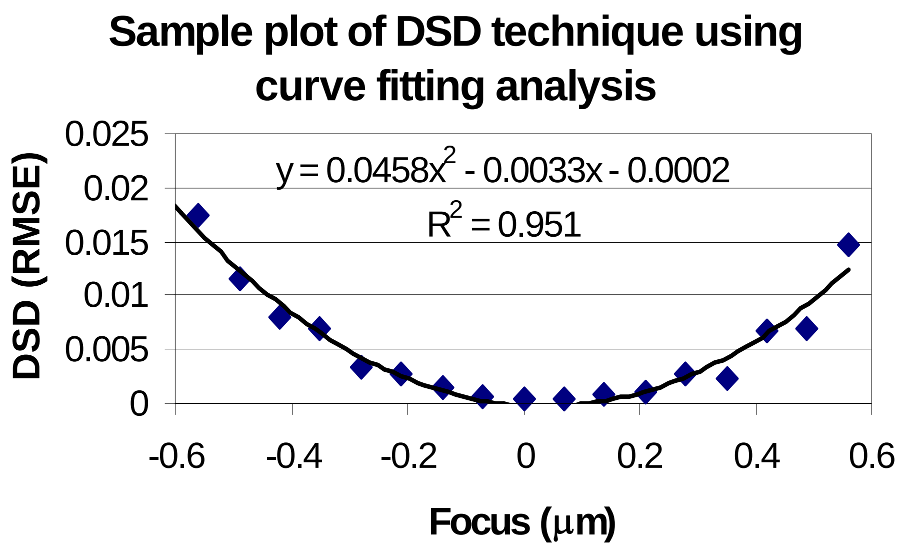


‘DSD’ Analysis Method

- Fit a parabolic curve to DSD over focus range

OR

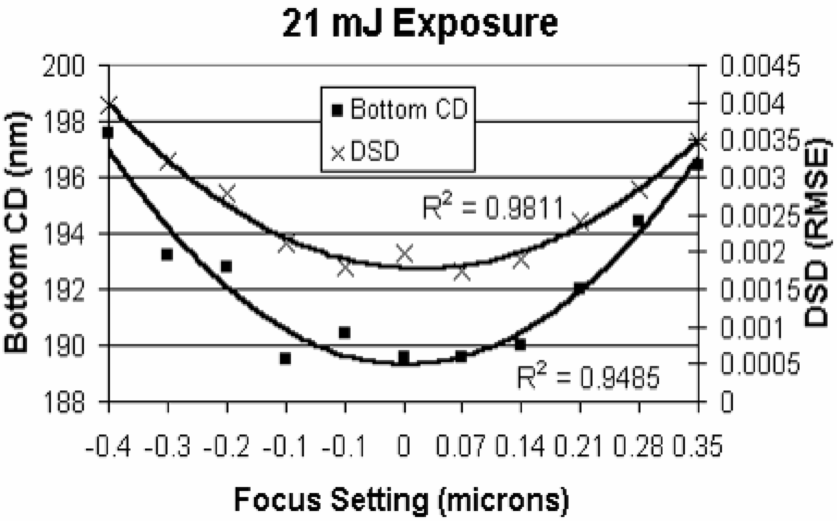
- Determine COF via a weighted average (α, β are constants)
- Average COF difference between two techniques on wafer average basis: 0.009 µm



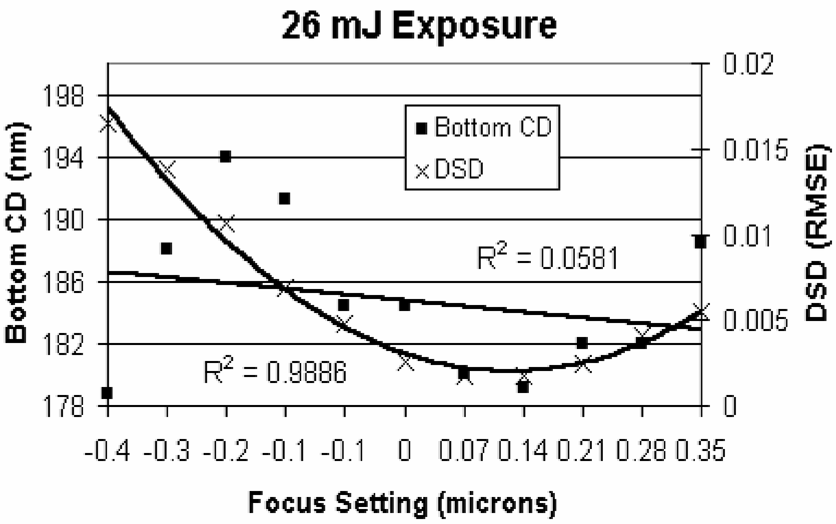
Sample plot of DSD technique using curve fitting analysis

$$\mathrm{COF}=\frac{\sum \frac{\alpha(\text{Focus Step})}{(\mathrm{DSD}_{\mathrm{RMSE}})^{\beta}}}{\sum \frac{\alpha}{(\mathrm{DSD}_{\mathrm{RMSE}})^{\beta}}}$$

DSD Response



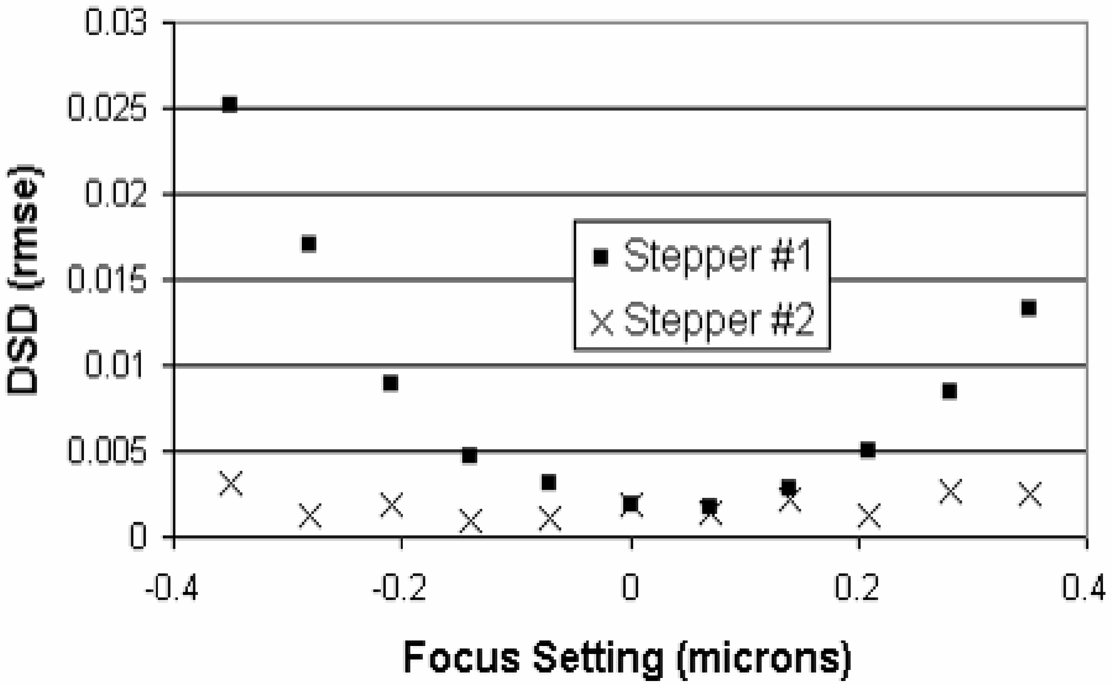
DSD shows similar center of focus to "good" CD/focus plot



DSD yields parabolic trend in case where CD/focus cannot

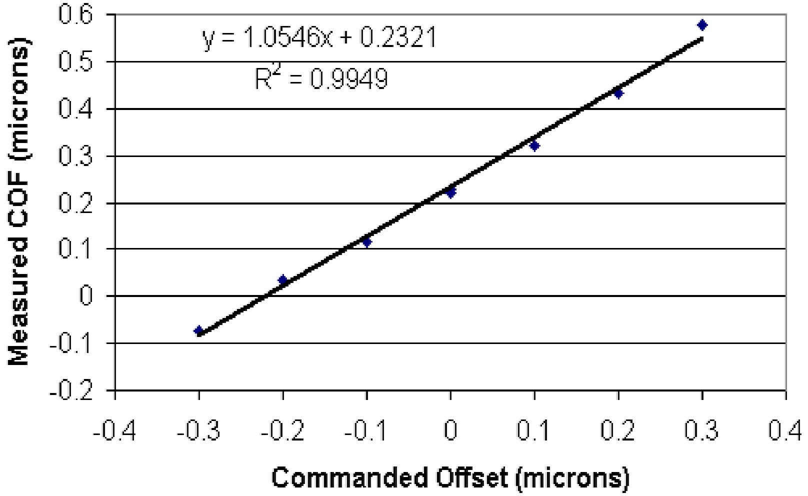
Depth of Focus

- Technique can be used to identify steppers with superior focus robustness
  - Low DSD values across wide focus range indicates better stepper depth of focus

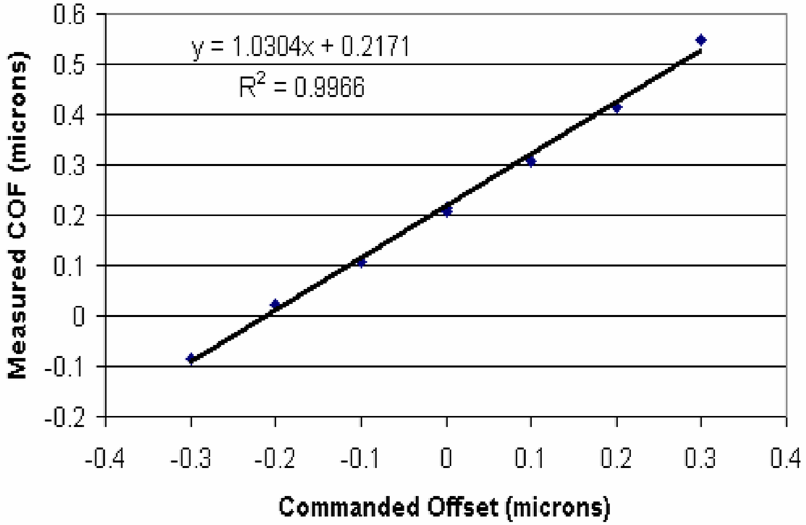


Focus Control

Dense Lines

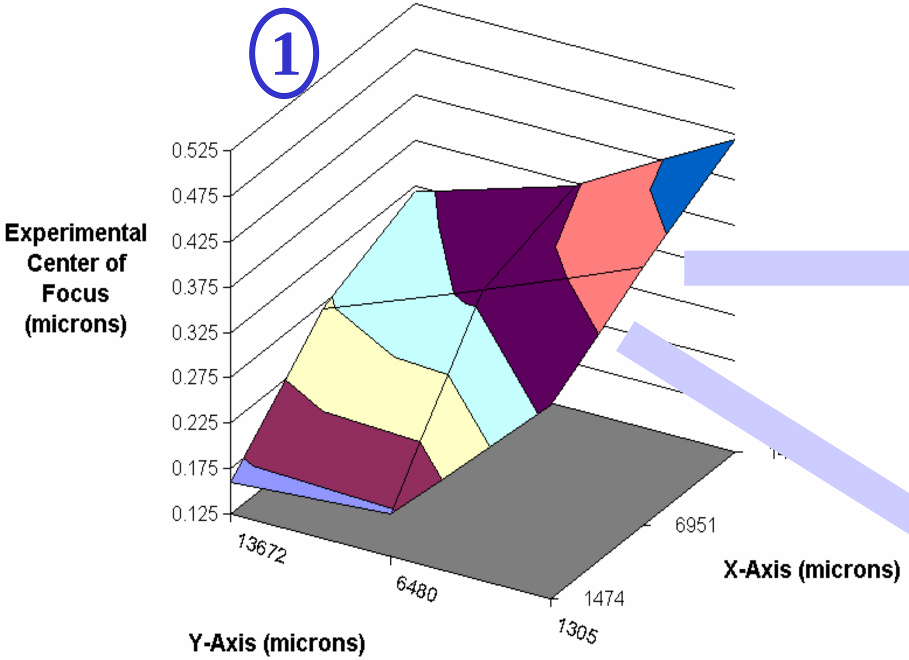


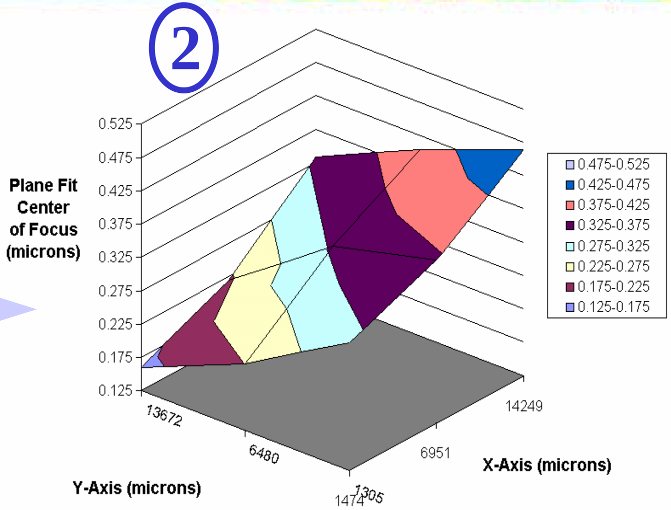
Iso Lines

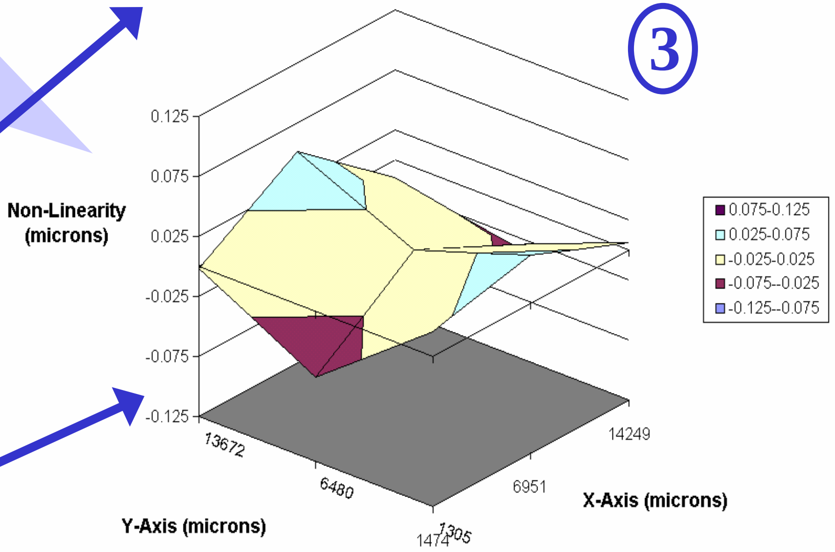


- Scatterometry measurements track commanded focus offsets
  - scatterometry technology can monitor focus
- Data shows offset in iso versus dense lines
  - impact on yield?

Sample Field Map

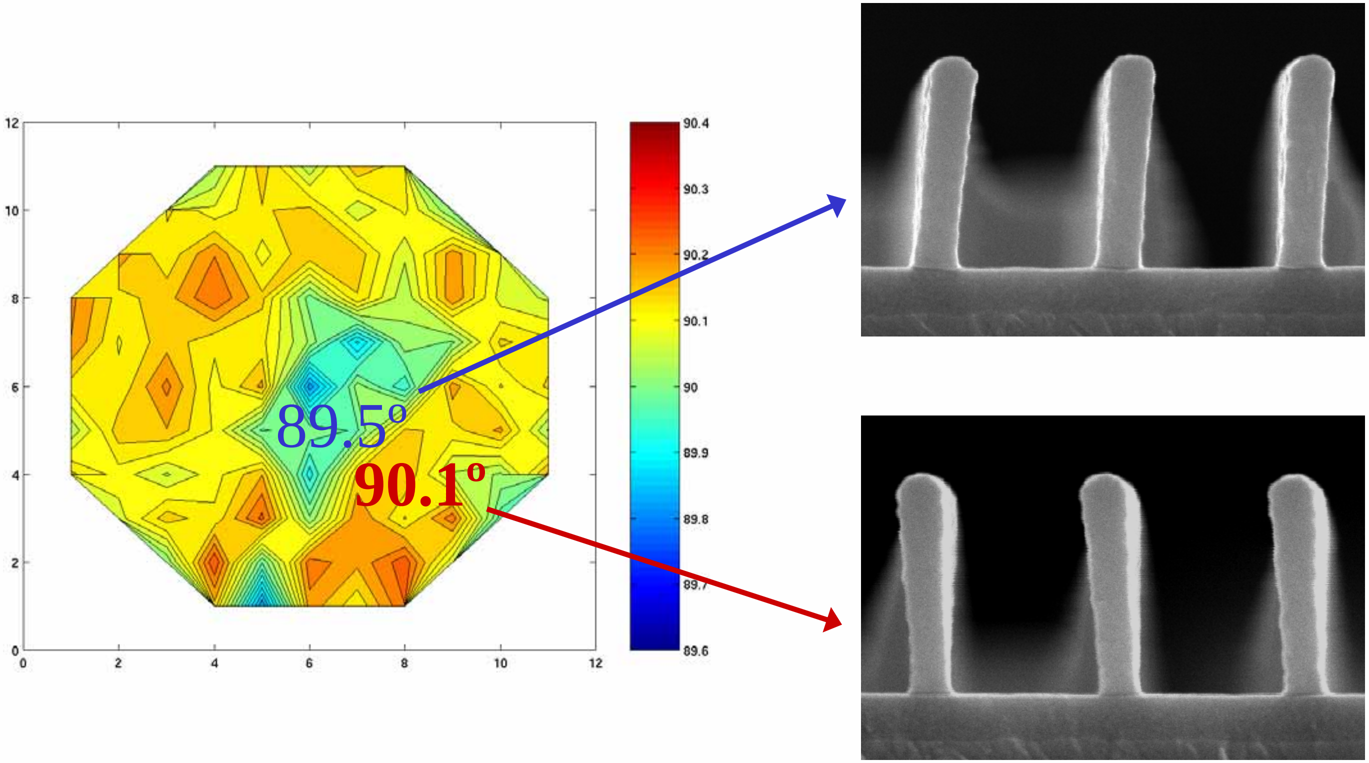






Rapid cross-field measurements of best focus (1) reveal stage tilt (2) and non-linear residual that relates to illumination non-uniformity (3).

Focus Control



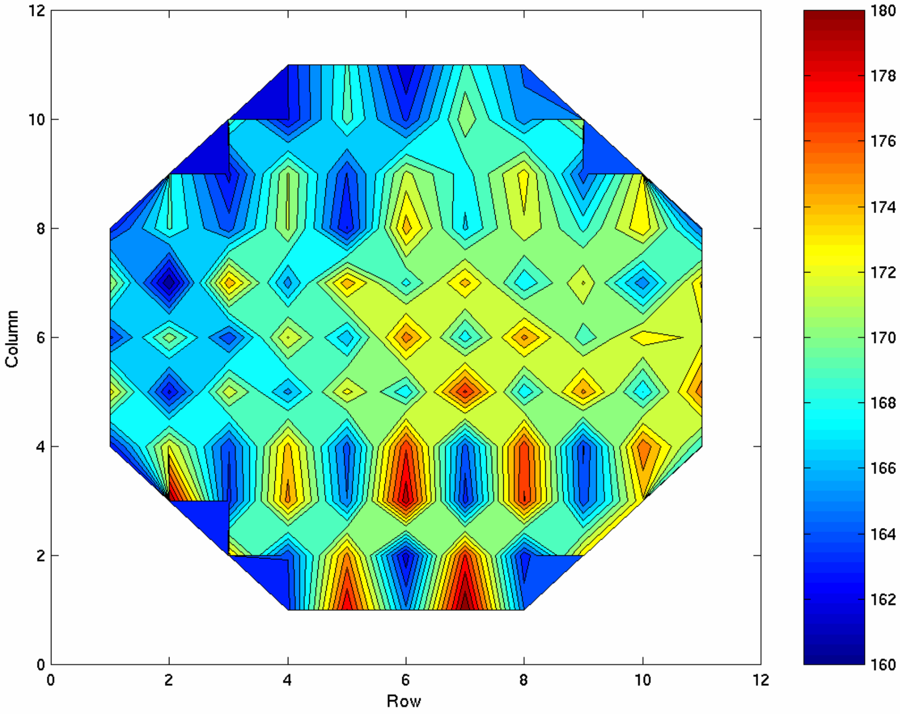
- CDSEM sees only rounded top
  - CD mis-targeted for etch
- Scatterometer correctly detected re-entrant sidewall

data courtesy of C. Baum, Texas Instruments

Focus Control

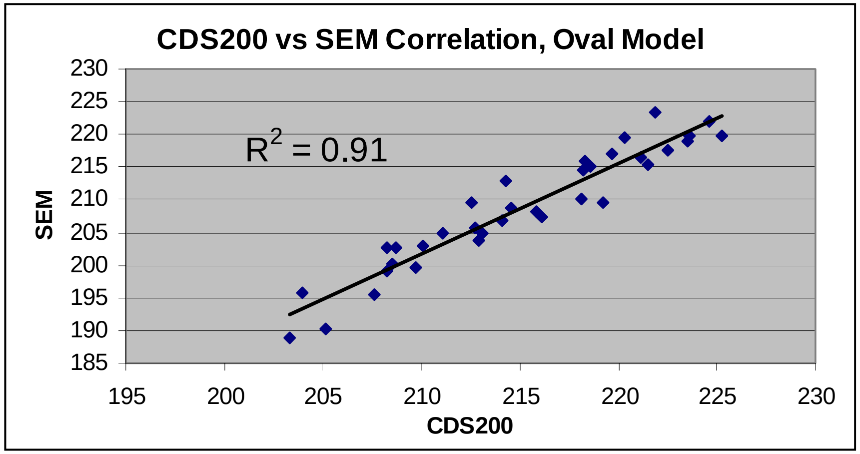
CD/Sidewall: Scan Dependence

- Die-to-Die variation is due to Scan-sync and is as large as 20nm
- Variation is mostly in sidewall angle (focus) and causes bottom CD change.
- **CD-SEM could not detect this variation, but it was apparent post-etch.**

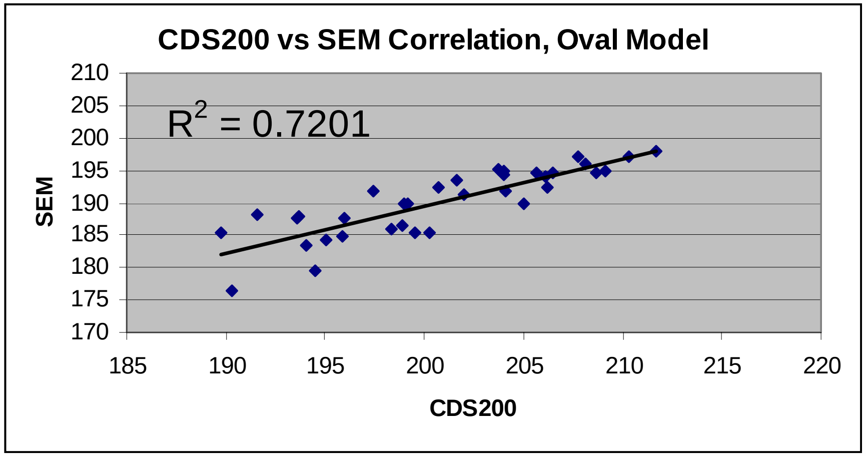


data courtesy of C. Baum, Texas Instruments

Contact Hole Application



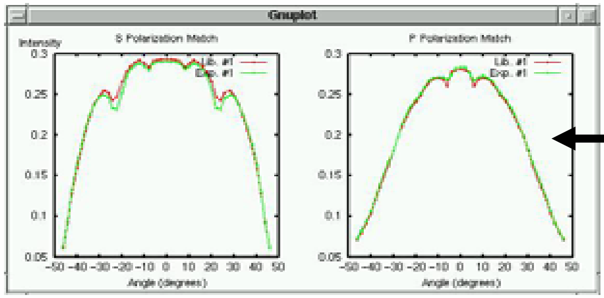
Xcd, Oval Model



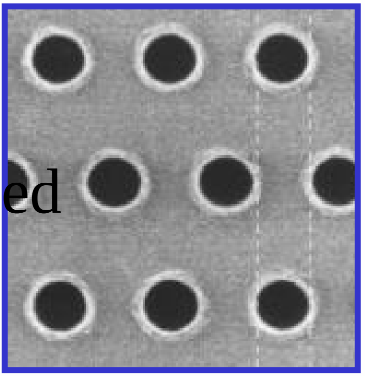
Ycd, Oval Model

NOTE: Ycd is constrained!

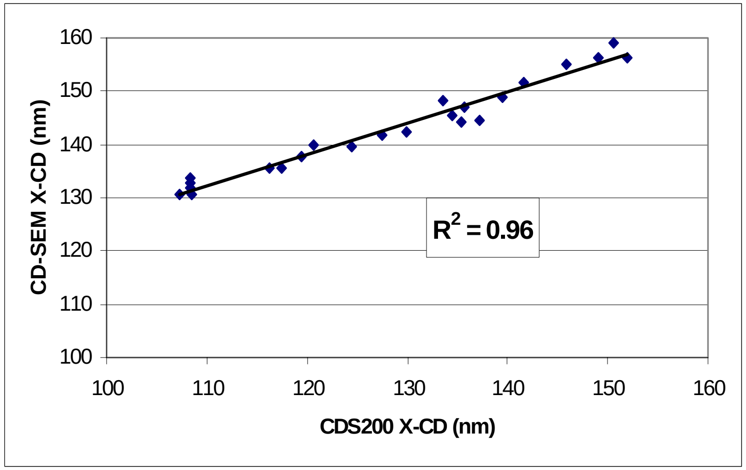
Ycd=Xcd-15 nm



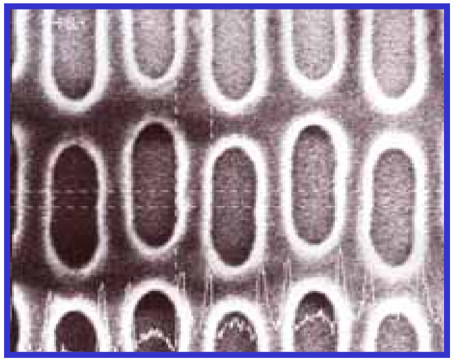
Good model fit when modeled asymmetrically

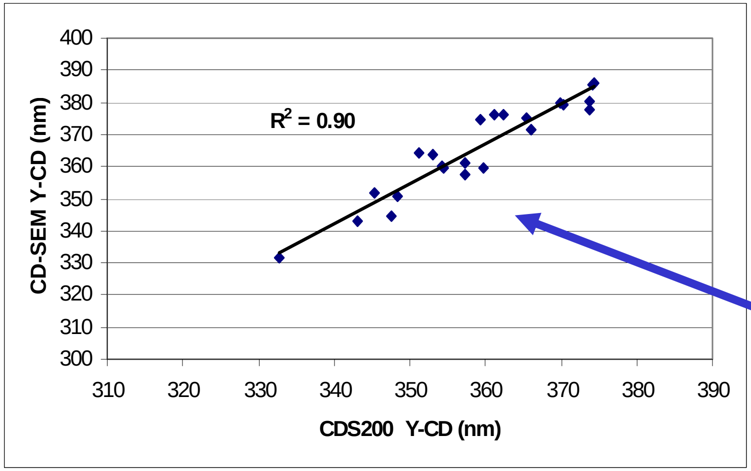


Memory Cells



X-CD data





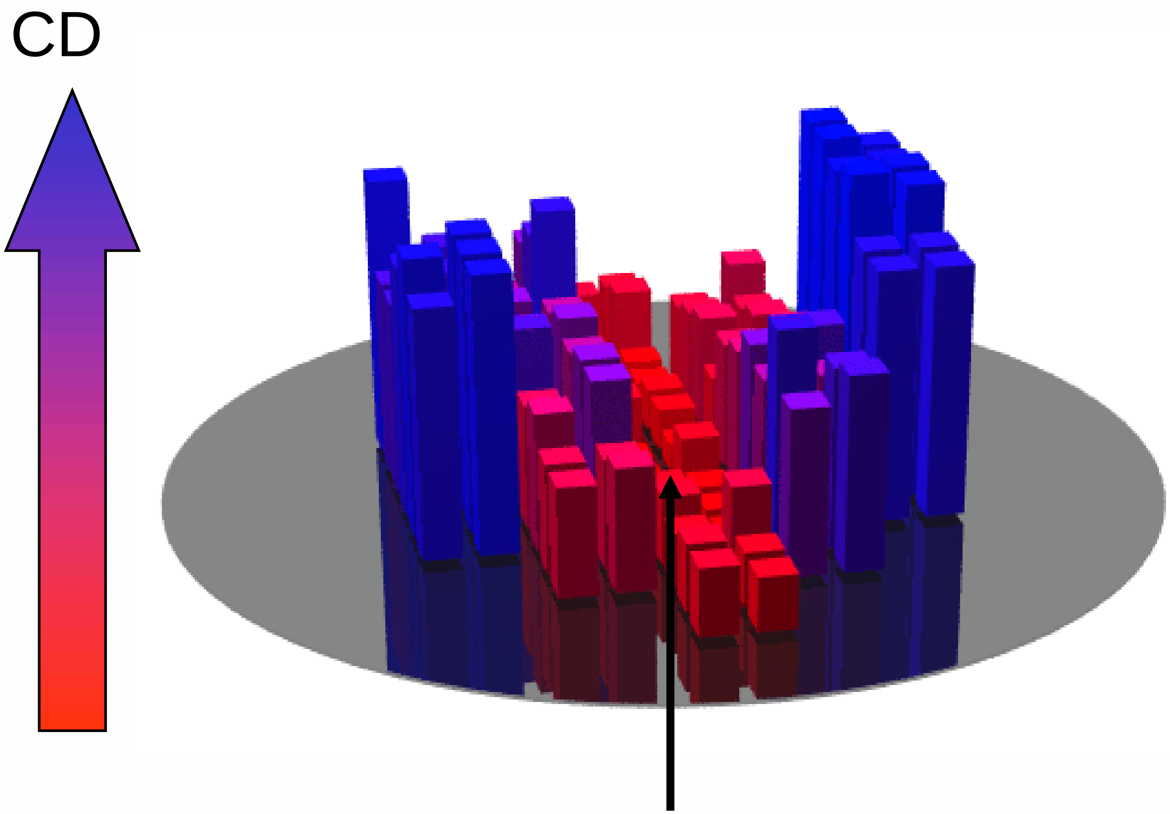
Y-CD data

Ycd less sensitive to measurement due to smaller volume change in scattering structure.

TI’s ScatterLith Capabilities

- In addition to focus information, ScatterLith can also provide information about:
  - field curvature
  - V-H bias
  - spherical aberration
  - astigmatism
  - scan dynamics
  - general lens “fingerprinting”
- See papers by Changan Wang

Bake Plate Temperature Uniformity



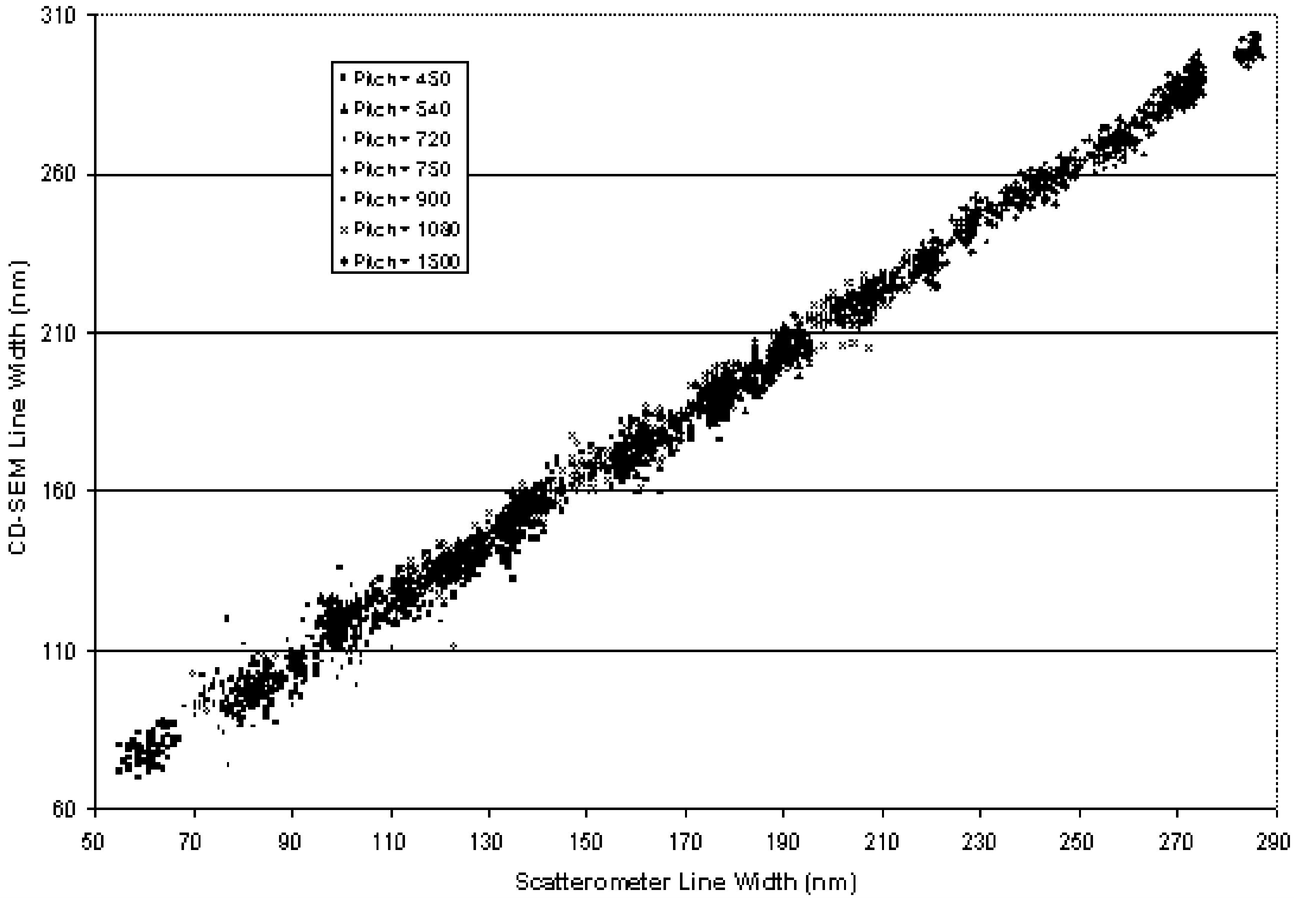
Contaminant in middle of plate!

data courtesy of Infineon

Why Etch Tool Control?

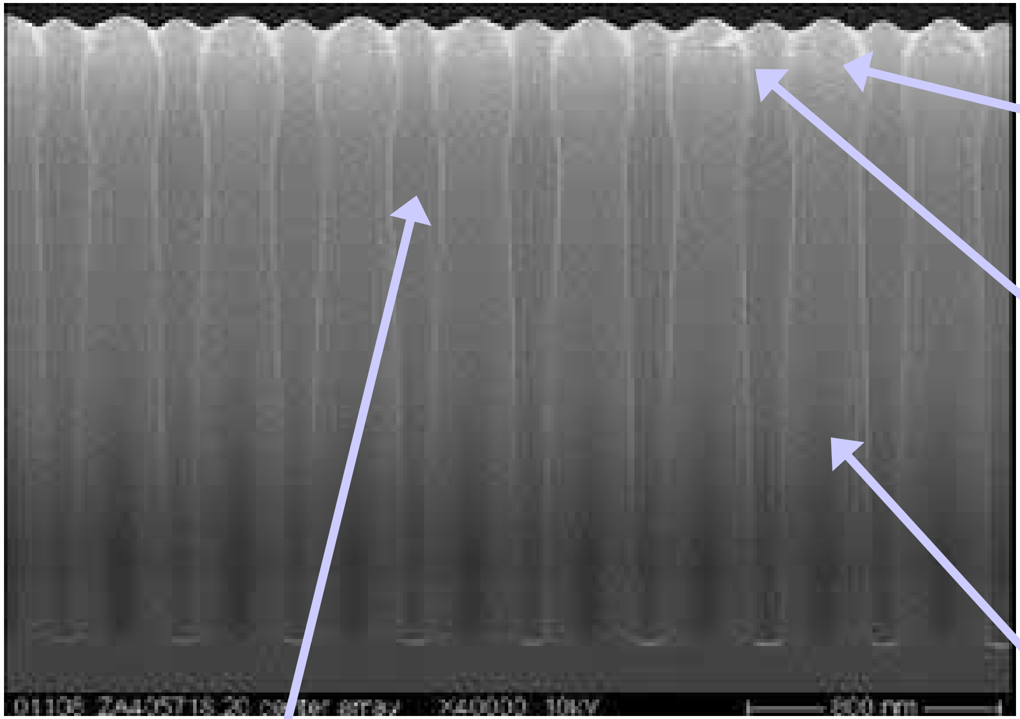
- Etch is full of unknowns
  - Cross-wafer uniformity
  - Chamber seasoning
  - Timed depth control
- Etch processes getting more complex
  - Exotic materials: oxides and metals
  - Etch-trim
- Etch is risky
  - Little chance for re-work
  - Already invested resources

Etch Gate Stack



data courtesy of Baum and Bushman, Texas Instruments

XSEM Image



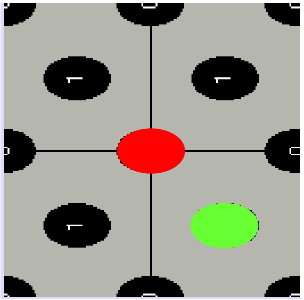
Note signficant rounding of aSi layer

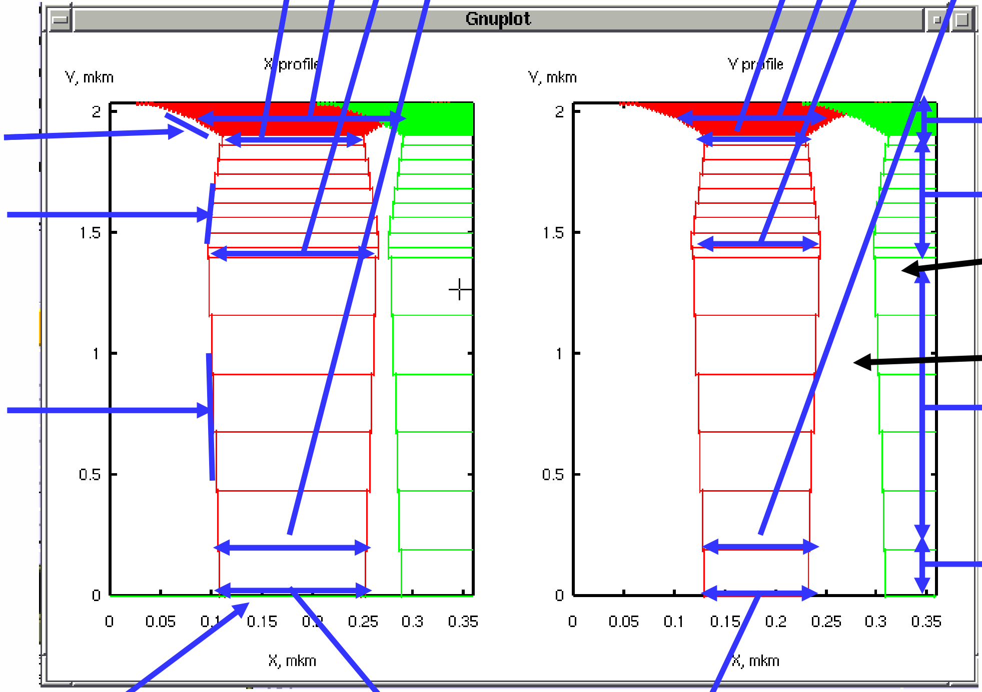
The upper aSi layer contributes a strong scattering influence due to high index of refraction

Glassy regions transmit red light well, so light interacts all the way down the profile

- Bow point vertical position and dimensions were the main focus of the application
- CD at other points, especially the bottom, were also of interest

Profile Model





x_cd_5,6_0

x_cd_4_0

x_cd_3_0

y_cd_5,6_0

y_cd_4_0

y_cd_3_0

x,y_ang_5,6_0

x,y_ang_4_0

x,y_ang_3_0

aSithk1,2

BSGthk2

Air

Material

BSGthk1

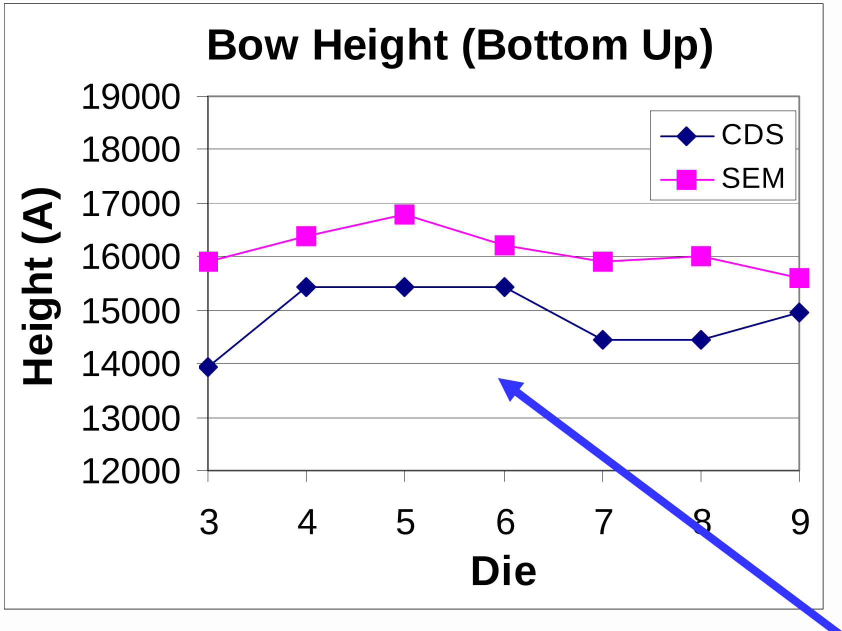
SiNthk

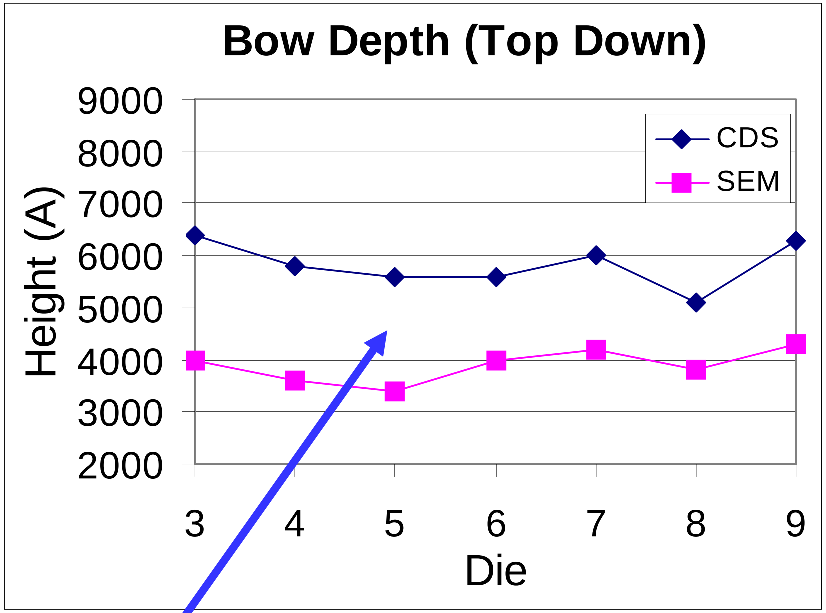
x_cd_2_0

y_cd_2_0

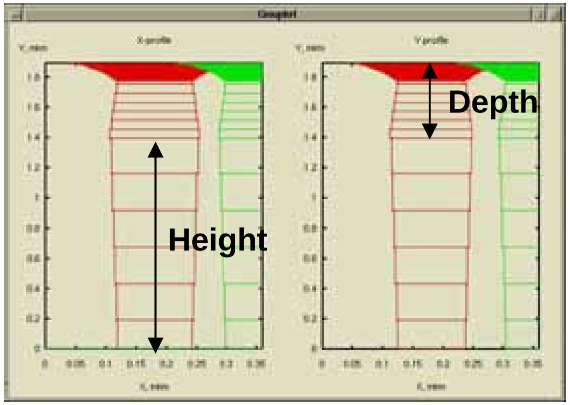
40 A oxide layer (x_cd_2_0, y_cd_2_0, etc) can’t be seen on this scale.

Bow Point Comparison



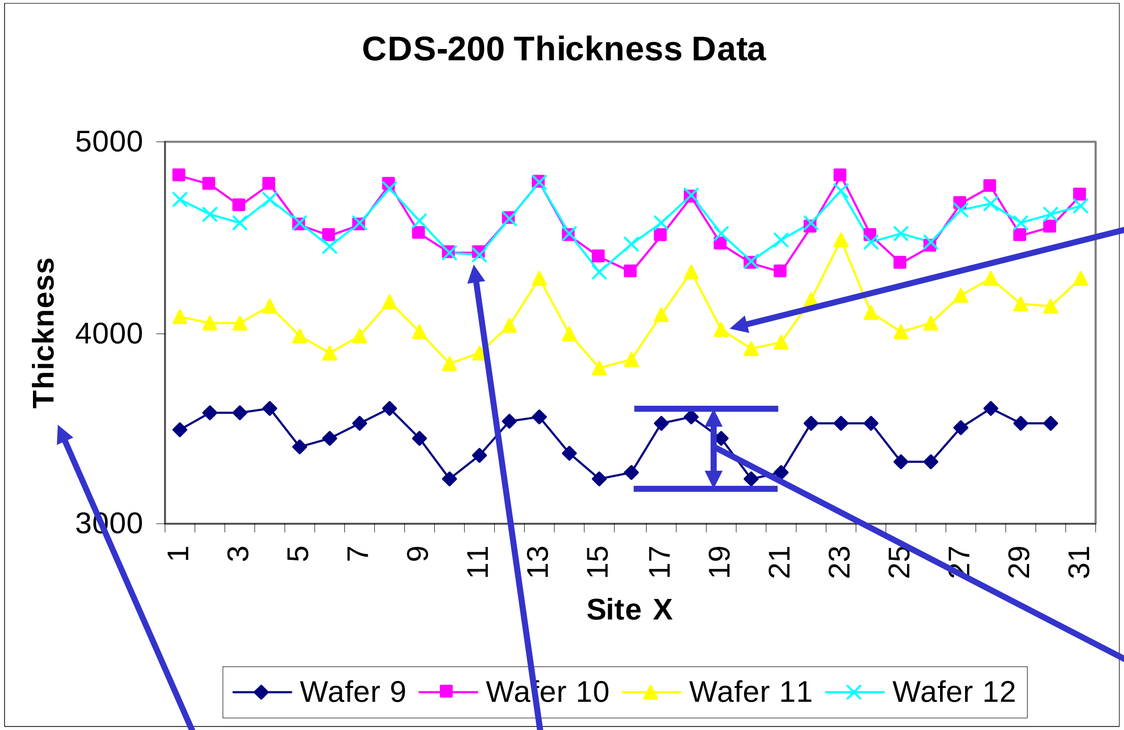


Measurement Point



CDS height is shallower but depth is deeper – bow point is lower than XSEM. Results trend nicely, however.

Metal Etcher Qualification

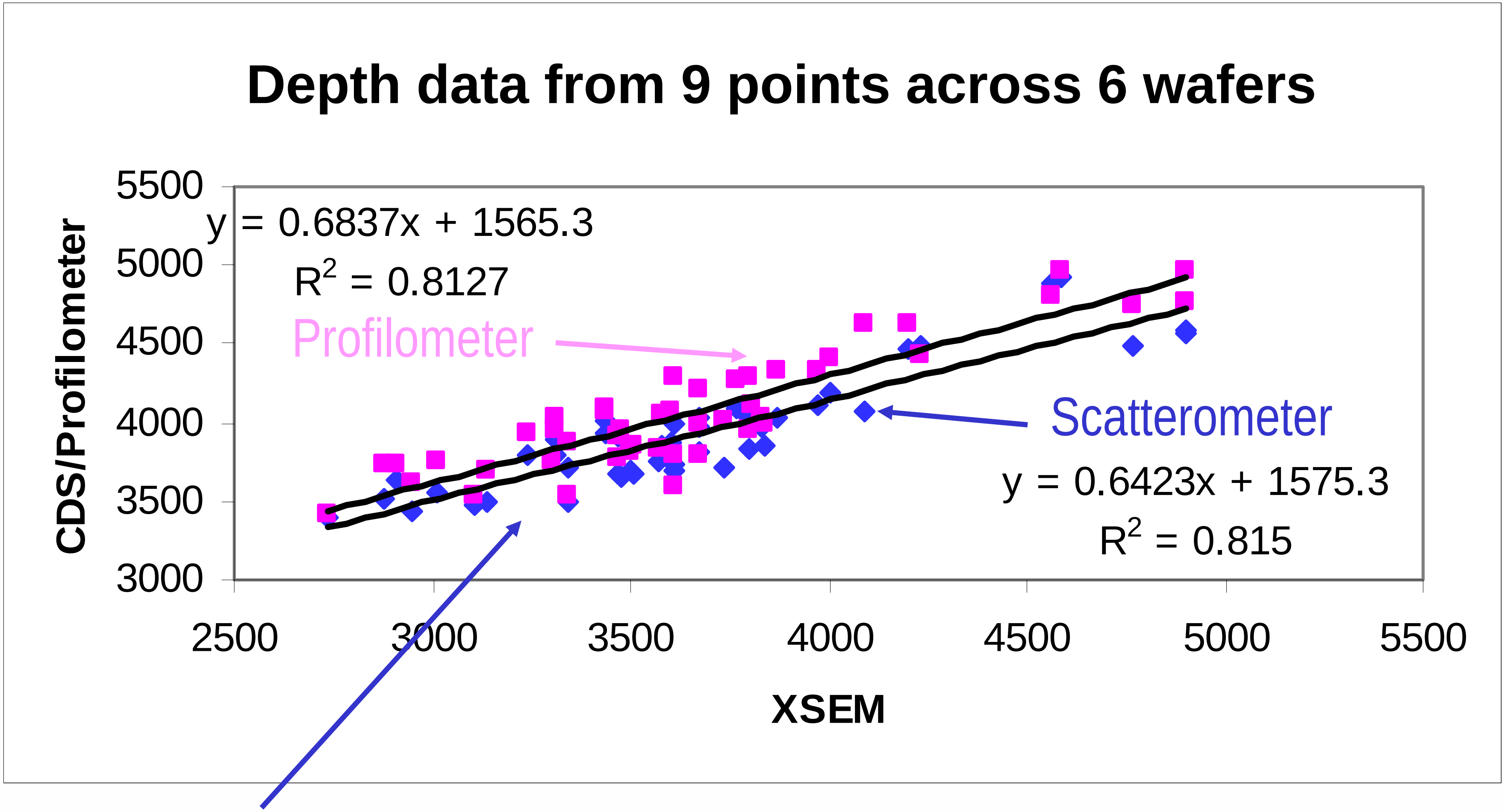


The repeating curves are a chamber signature, which in this case is a bowl-shaped pattern depth.

Cross-wafer etch uniformity is easily observed.

Three thickness splits seen clearly across 4 wafers. Wafers 10 and 12 were etched the same, but wafer 10 was not wet cleaned.

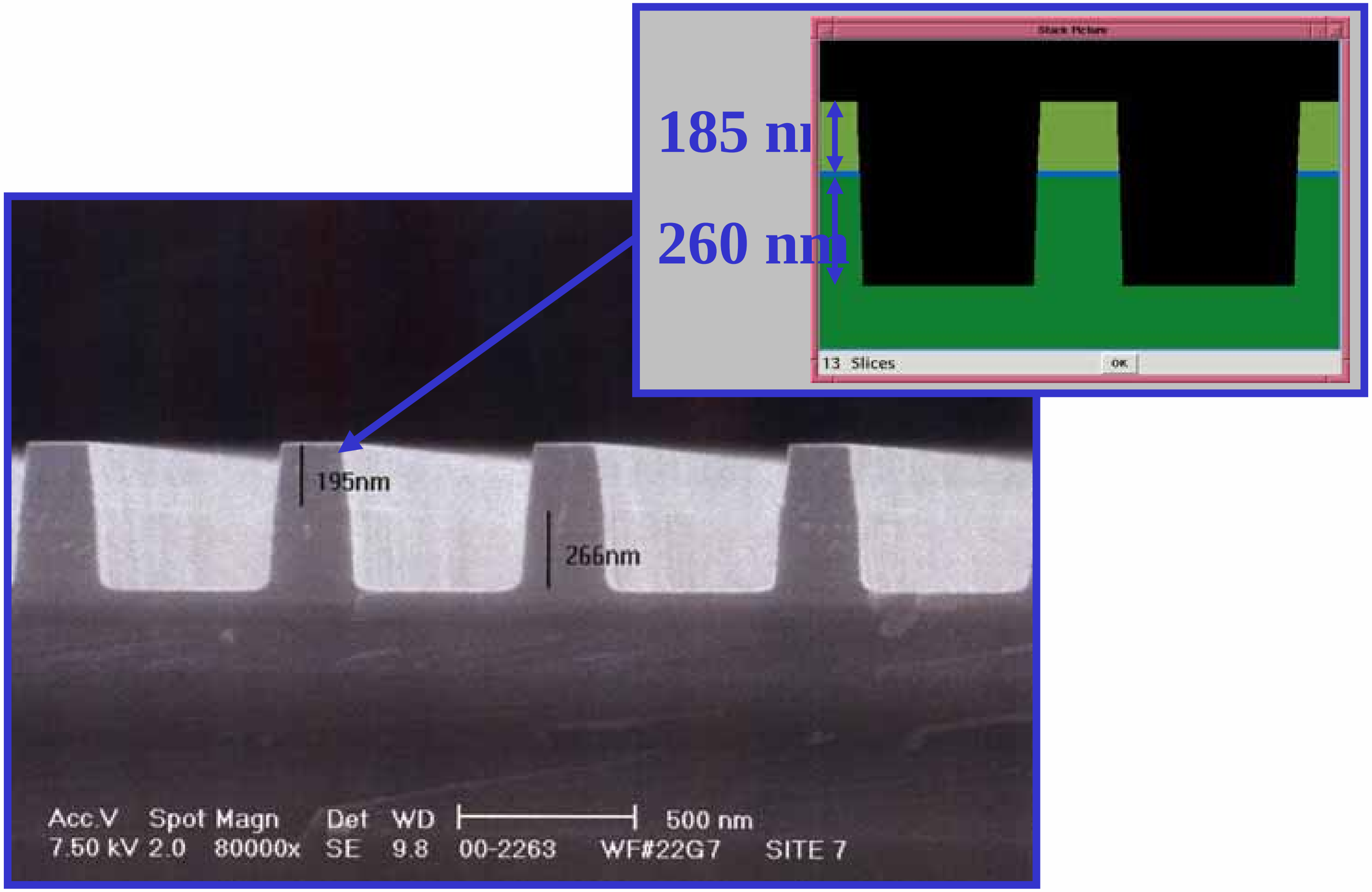
Metal Depth Comparison



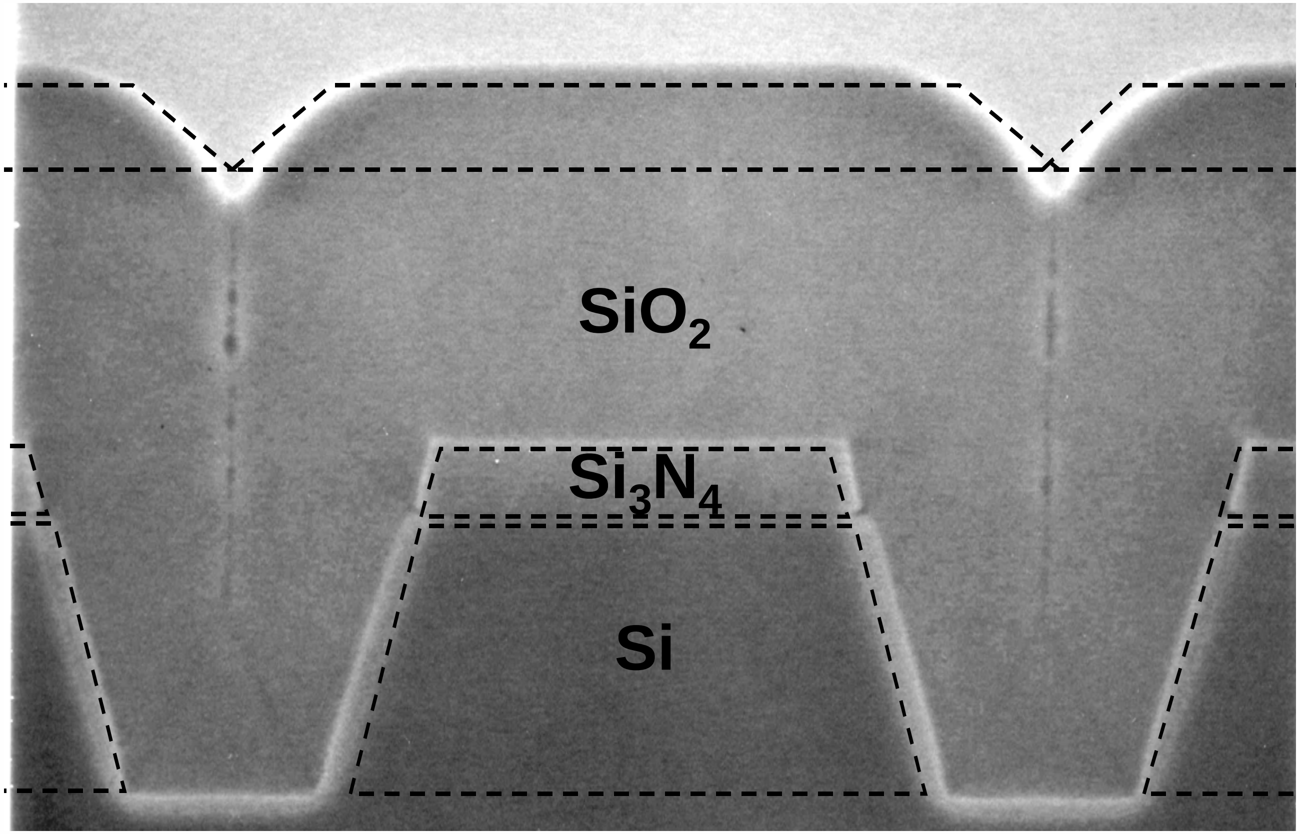
All methods show good linearity across a broad range of depth values, despite differences in measurement points and structures.

Cross-Section Comparison

(nominal etch wafer)



STI Characterization



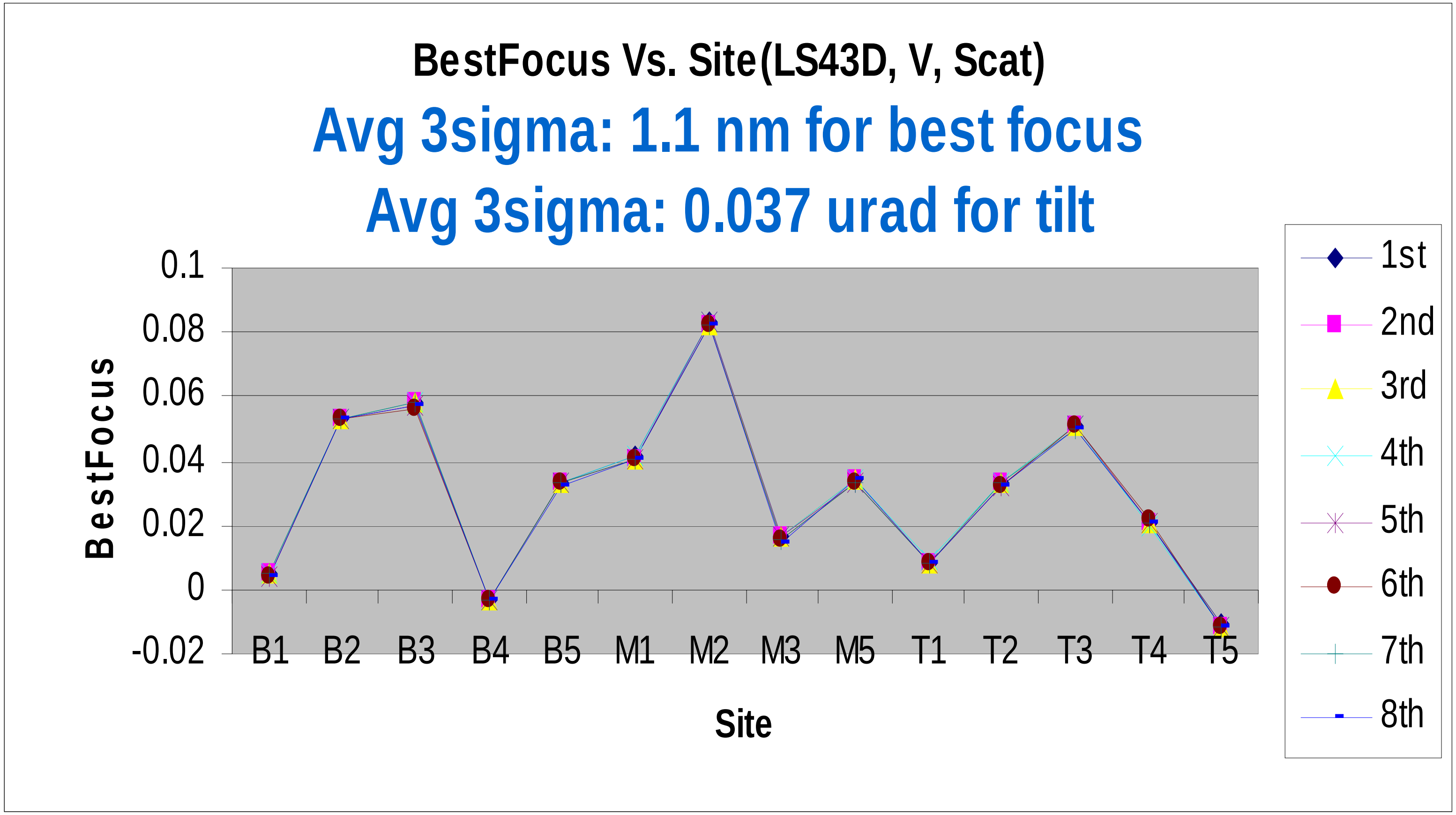
Data source: Sandia National Lab

Conclusions

- Scatterometry is mature and ready for mainstream silicon applications
  - Variety of methods and techniques which all work well
- Lithography control applications are especially compelling
  - Rapid, precise, complete measurements
  - Focus, dose, leveling, aberrations, bake, CD control…
- Etch applications also provide significant value
  - Reduced etcher qualification time
  - Better depth control with greater sampling
  - Sidewall and profile control

- **Backup slides**

Scatterlith Results - Precision

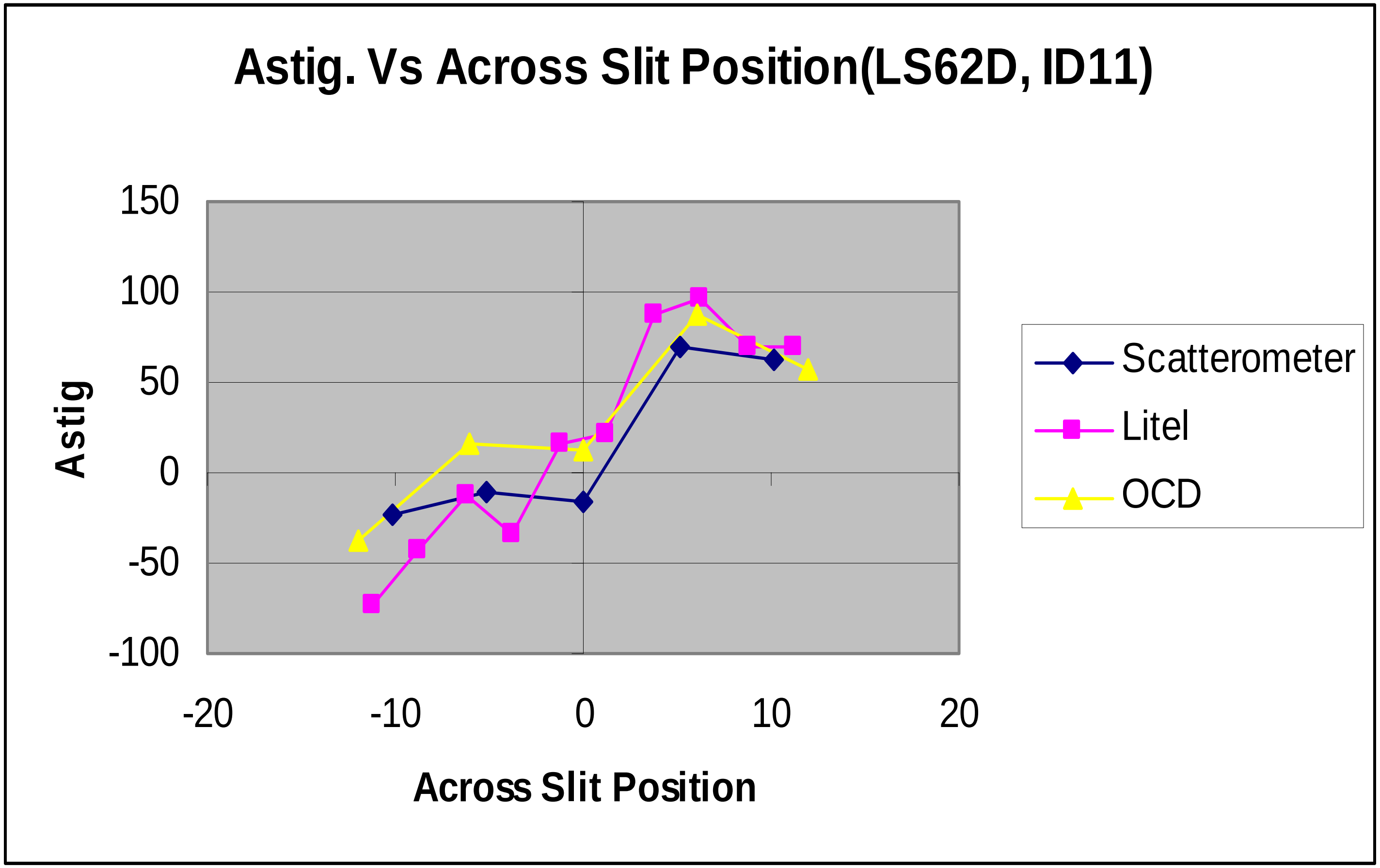


Avg 3sigma: 1.1 nm for best focus

Avg 3sigma: 0.037 urad for tilt

Data courtesy of Changan Wang, Texas Instruments

Correlation Among ScatterLith, Litel and Nikon OC



Data courtesy of Changan Wang, Texas Instruments