Nondestructive and Economical Dimensional Metrology of Deep (Truly-3D) Structures Using Through-focus Scanning Optical Microscopy (TSOM)

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Contents

- Introduction
- Method to construct TSOM images
- Characteristics of TSOM images
- Process monitoring of HAR targets

TSOM

(Through-focus scanning optical microscopy)

TSOM transforms conventional optical microscopes into 3D shape metrology tools.

TSOM is a high-throughput, low-cost, nondestructive, and easy-to-use 3D shape metrology method with 1 nm or better measurement resolution for target sizes (depths/heights) ranging form sub-nanometer to over 100 um.

TSOM compliments the other tools by filling some gaps

Through-focus Scanning Optical Microscopy (TSOM)

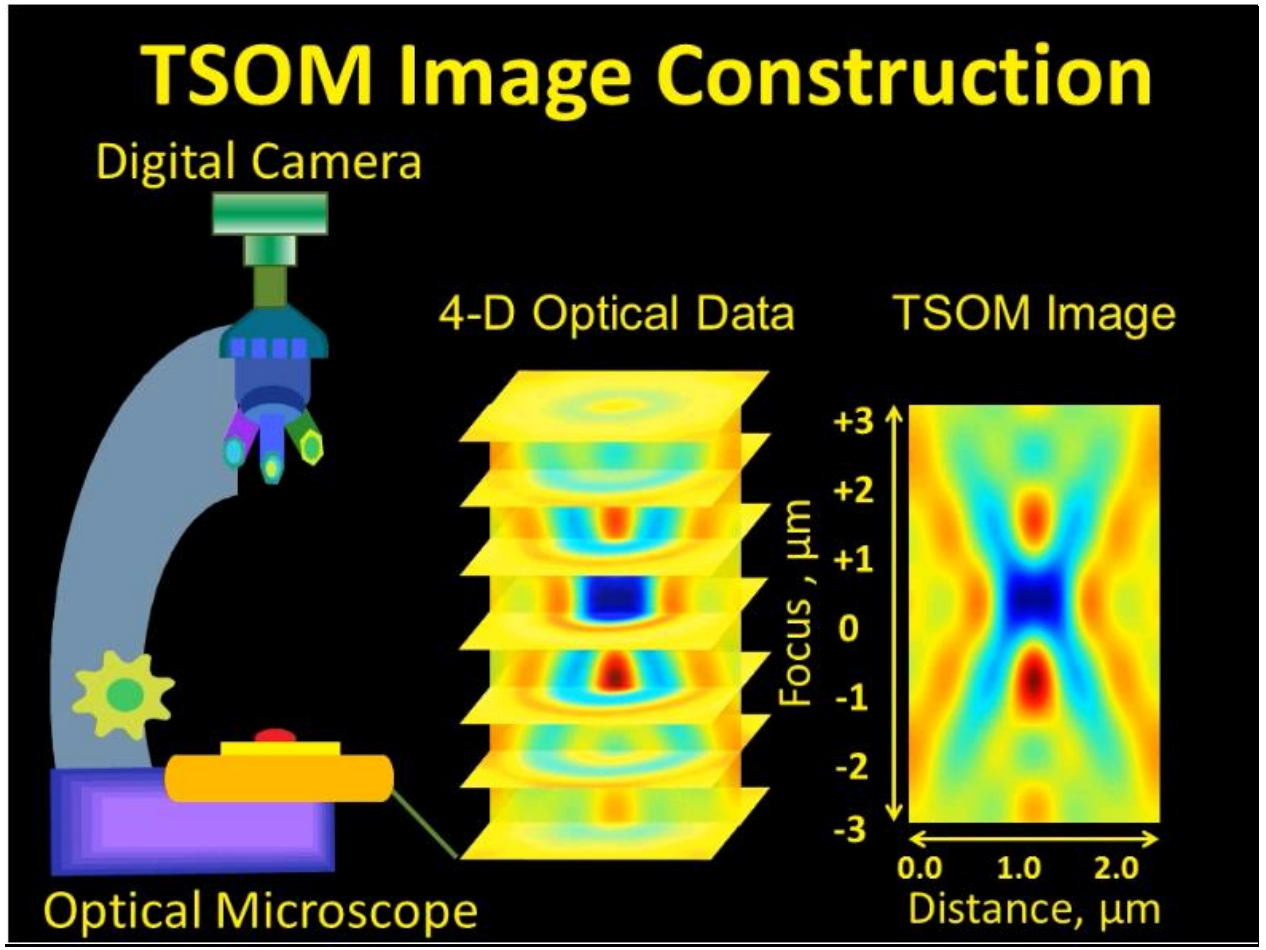
TSOM Requires

↓

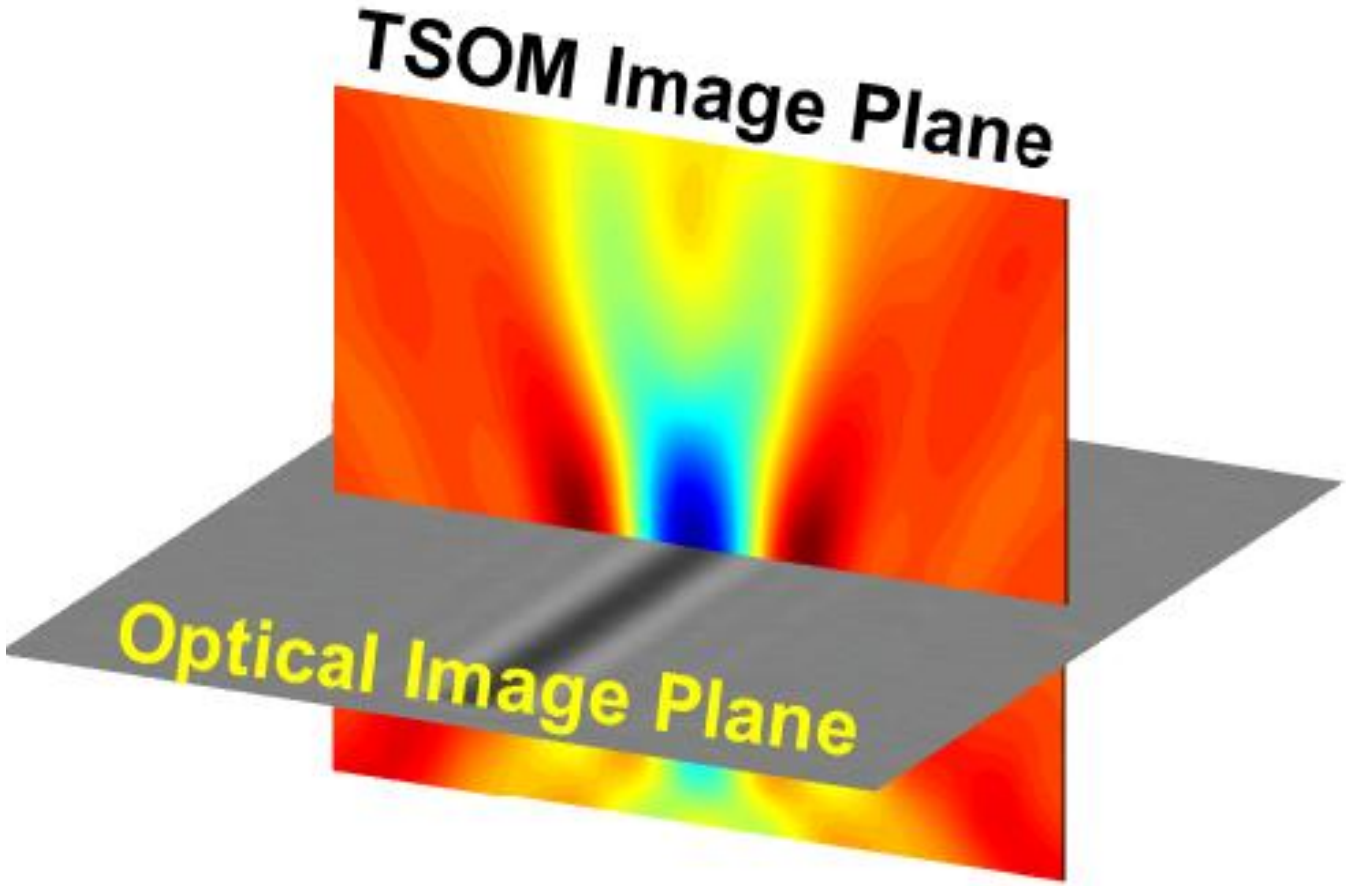
Through-focus optical data

↓

TSOM Image

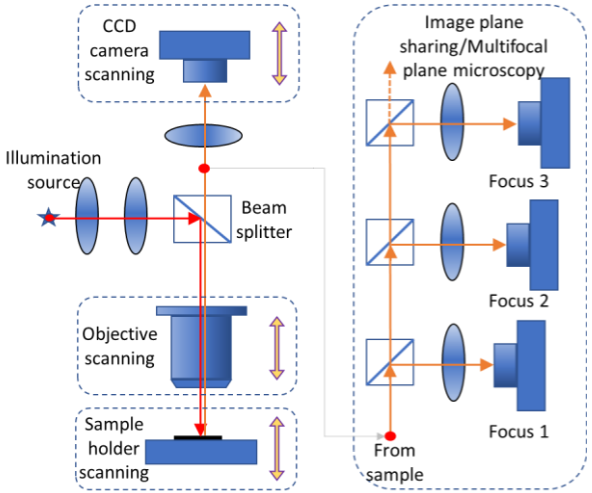


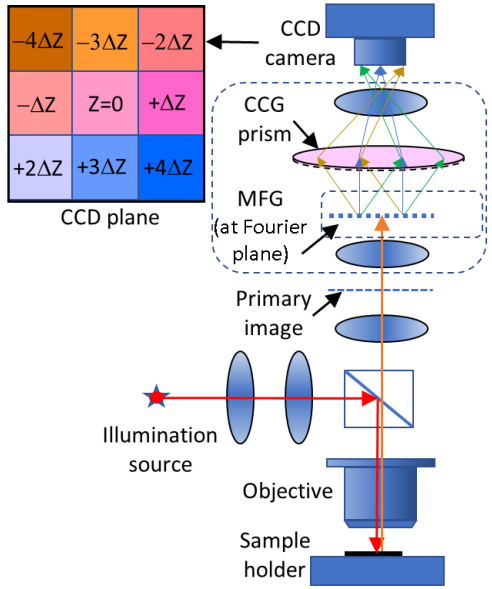
The TSOM image plane is perpendicular to the optical image plane

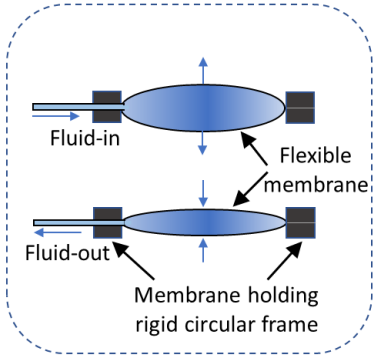


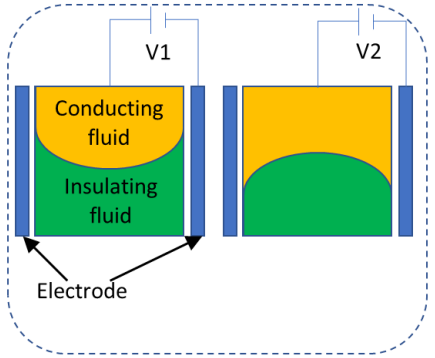
Over 15 through-focus image collection methods identified
Data collection time varies from several minuets to a millisecond

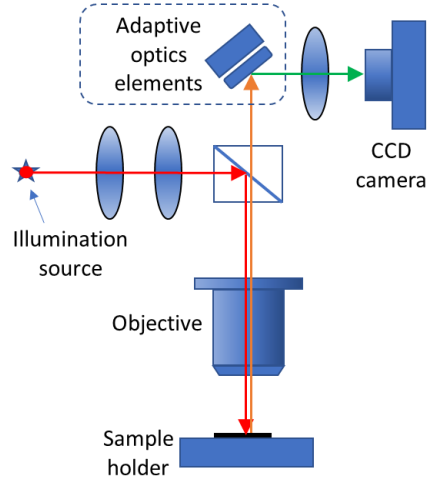
R. K. Attota, "Through-focus or volumetric type of optical imaging methods: a review," J Biomedical Optics 23, 070901, (2018).

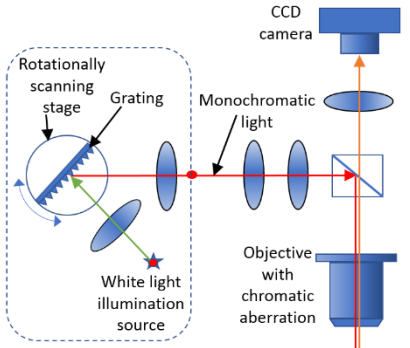


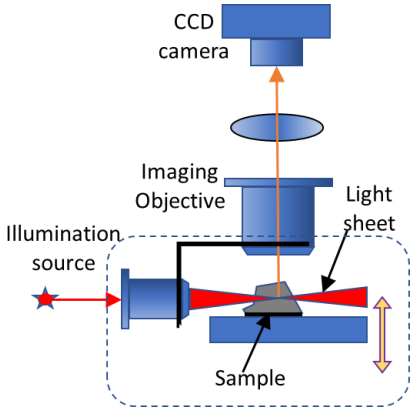


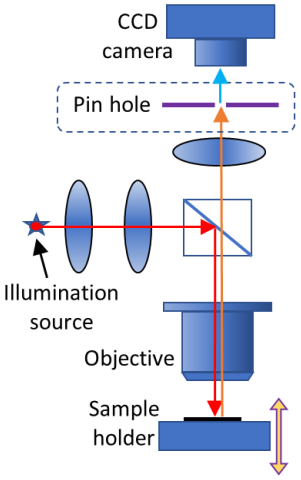


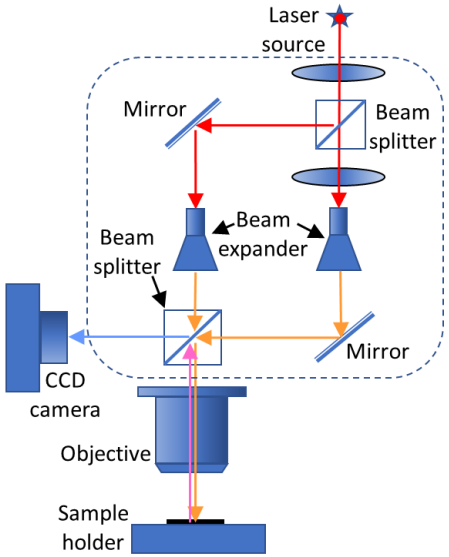


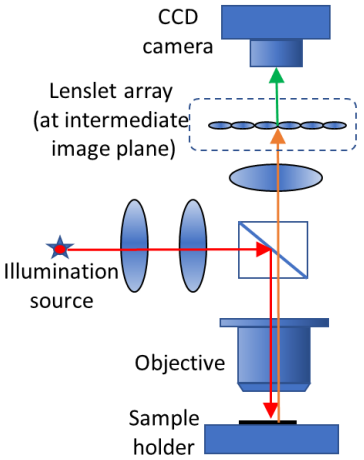






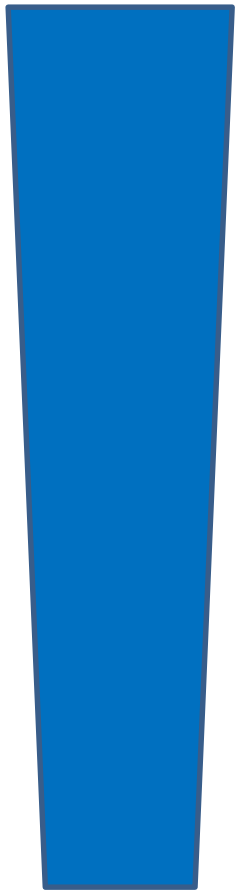


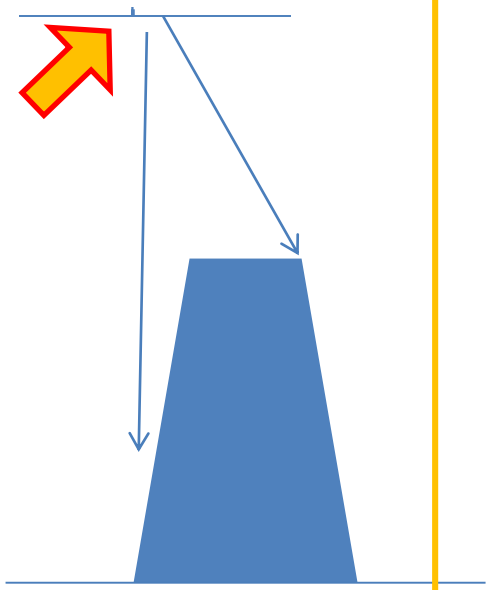




Target dimensions (depths) spanning over FIVE orders of magnitude have been studied with TSOM

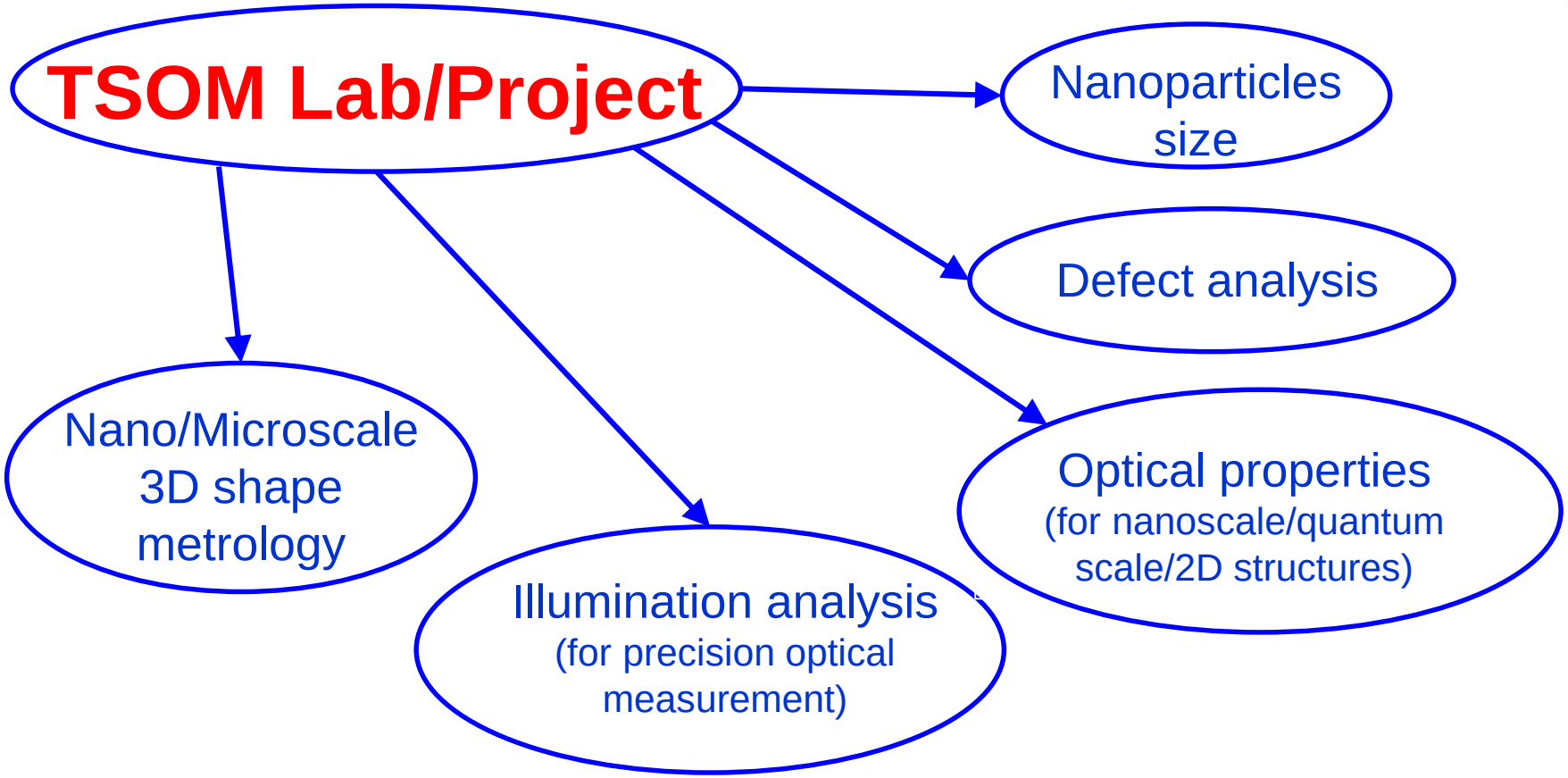
Microchannel	HAR Targets	Lines	2-D materials
Width = 200 μm Depth = **200 μm**	CD = 0.1 μm Depth = 1.1 μm	CD = 0.04 μm Height= 0.07 μm	Width = 0.4 μm Height = **3 Å**





X100
Magnified


2010
R&D
100


TSOM Lab/Project
Nanoparticles size
Defect analysis
Optical properties
(for nanoscale/quantum scale/2D structures)
Illumination analysis
(for precision optical measurement)
Nano/Microscale 3D shape metrology

TSOM Applications studied

- Optical microscope illumination analysis and improvement
- Optical properties evaluation (for nanoscale structures, 2D materials
- Quantum devices
- Flexible electronics (high speed process control)
- Nanoparticles (including irregularly-shaped) / hydrogel nanoparticles / soft nanoparticles
- Defect inspection and review
- 3D interconnects (TSV)
- FinFET
- High aspect ratio (HAR) targets
- High-throughput inspection and process control
- Critical dimension (CD) metrology
- Overlay registration metrology (Several micrometer distance between the two levels)
- Photo mask metrology
- Film thickness (2D materials)
- MEMS/NEMS metrology
- Micro/nano channels metrology

Impact

- **ITRS** (2013 to 2016) includes TSOM for defect and HAR analysis

  (ITRS - International Technology Roadmap for Semiconductors)

- **IRDS** (2018) includes TSOM for several applications

  (IRDS - International Roadmap for Devices and Systems)

- **SEMI** document (3D5-0613) on “Guide for metrology techniques to be used in measurement of geometrical parameters of through-silicon vias (TSVs) in 3DS-IC structures” – now has a TSOM section (2013)

- **SEMATECH** includes TSOM in their GAPS analysis, and for memory/HAR metrology applications

- **SAMSUNG Electronics** adopted the TSOM method and applied for two patents based on their work on TSOM. It also published several papers based on TSOM.

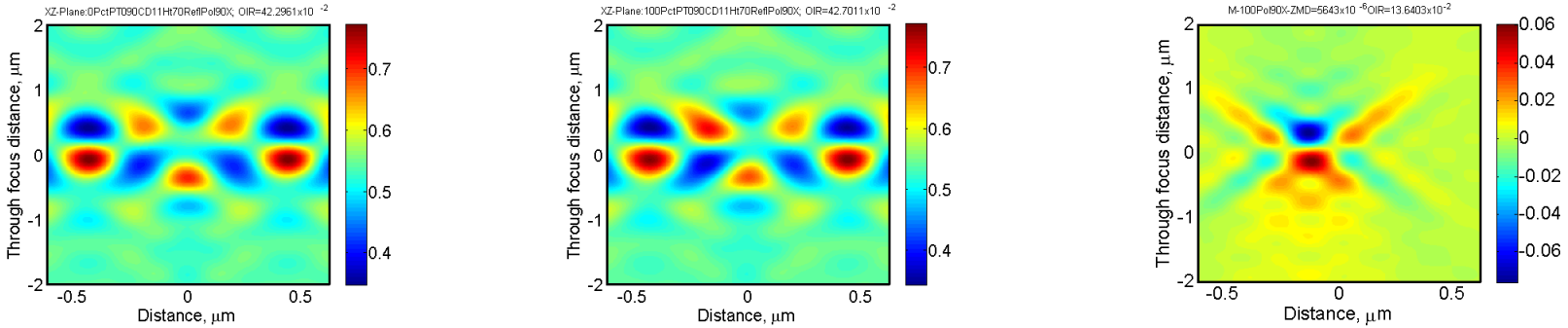
- **SPIE Newsroom** highlighted TSOM (August 2013)

Industries Expected to Benefit

- Semiconductor
- Quantum
- Photonics
- Photovoltaic
- Display
- Nanotechnology
- MEMS/NEMS
- Biotechnology
- Nanomanufacturing
- Data storage
- .....

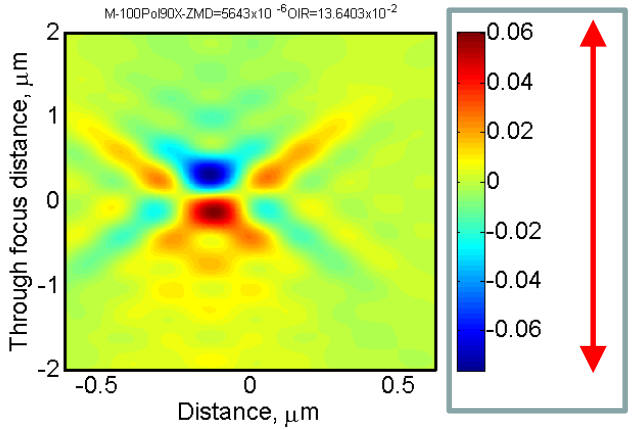
Differential TSOM (D-TSOM) image

TSOM image 1 - TSOM image 2 = D-TSOM Image



Optical Intensity Range (OIR)

Absolute difference in the maximum and minimum optical intensities present in a TSOM or a D-TSOM image. It represents signal strength.



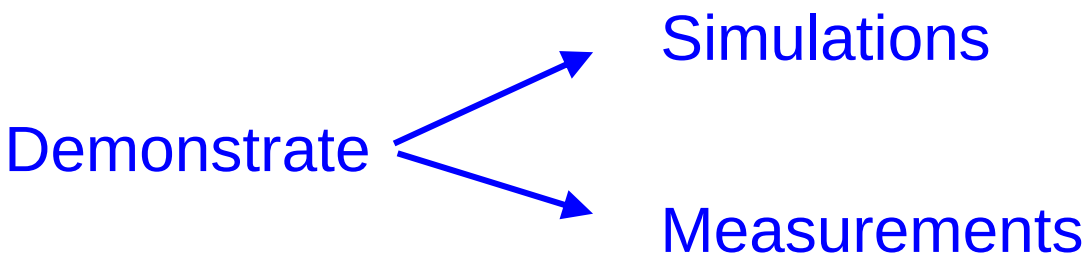
OIR = Absolute intensity range X 100

Characteristics of D-TSOM Images

1. Each dimensional difference produces a unique color pattern

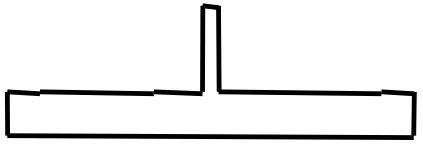
2. Optical content shows magnitude of the dimensional difference

3. Additive



Simulation Demonstration

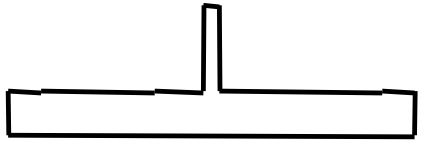
Reference target



LW = 40 nm

LH = 100 nm

Production target



LW = 40 nm ± x nm

LH = 100 nm ± y nm

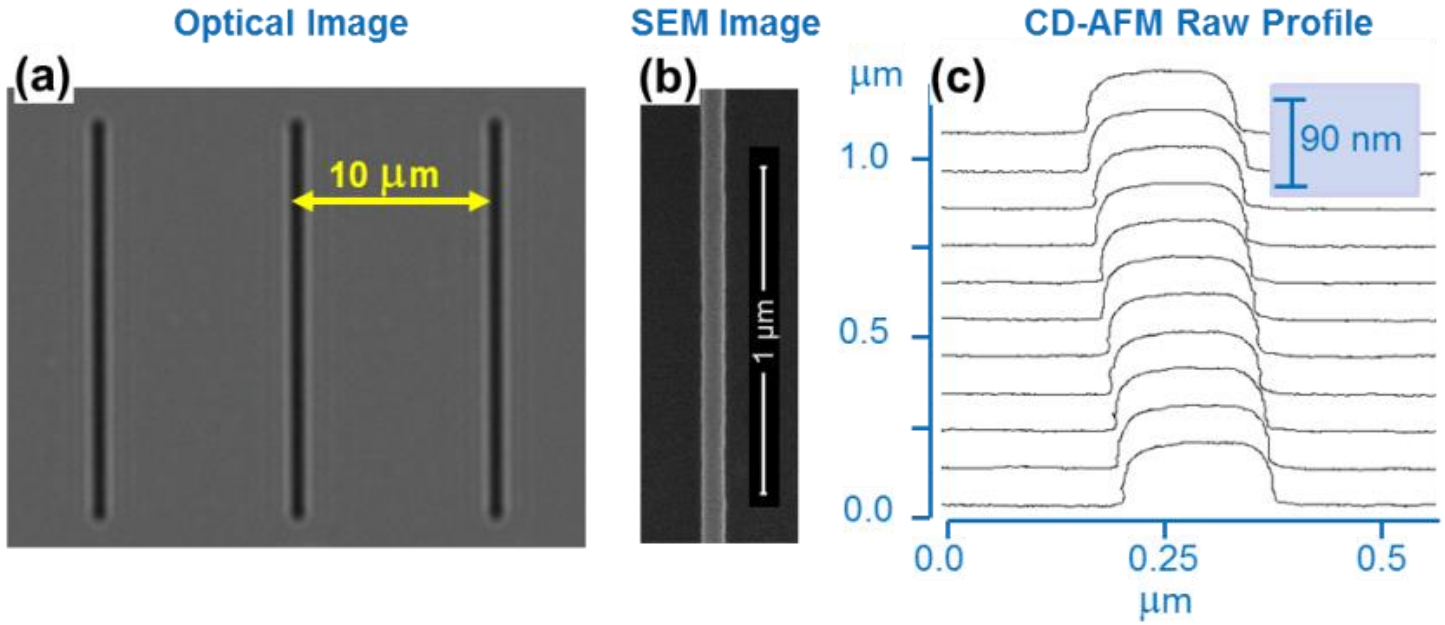
TSOM 1

TSOM 2

TSOM1 – TSOM2 = D-TSOM

Measurement demonstration

Isolated lines studied: CD ~ 40 nm; Height ~ 70 nm



1. Each Dimensional Difference Produces a Unique Color Pattern

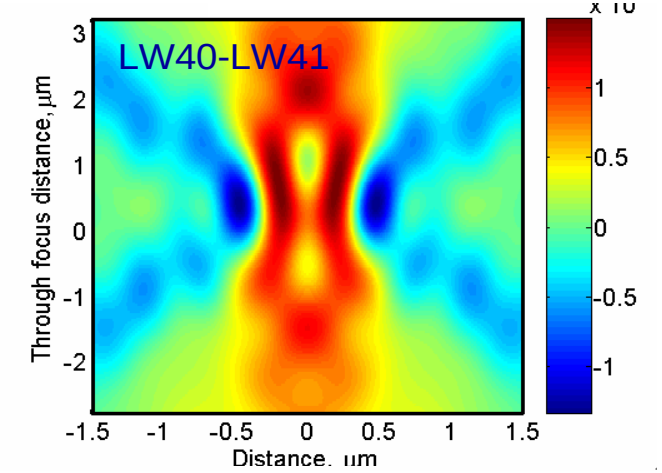
Isolated Si line on Si substrate; λ = 546 nm; LW = 40 nm; LH = 100 nm

Simulation

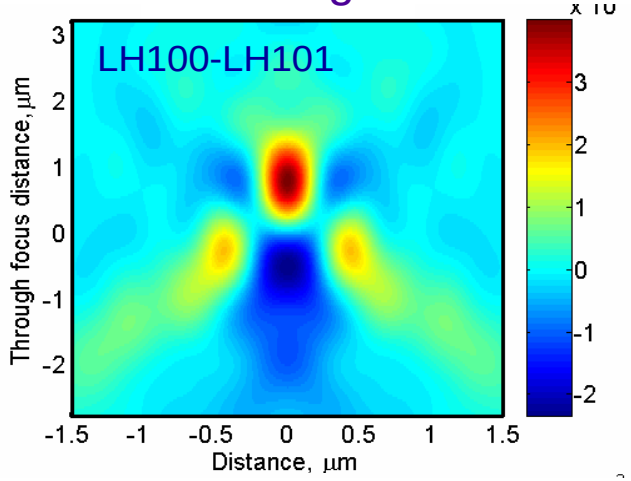
Isolated line

LW=Linewidth;
LH=Line height;
SW=Sidewall angle

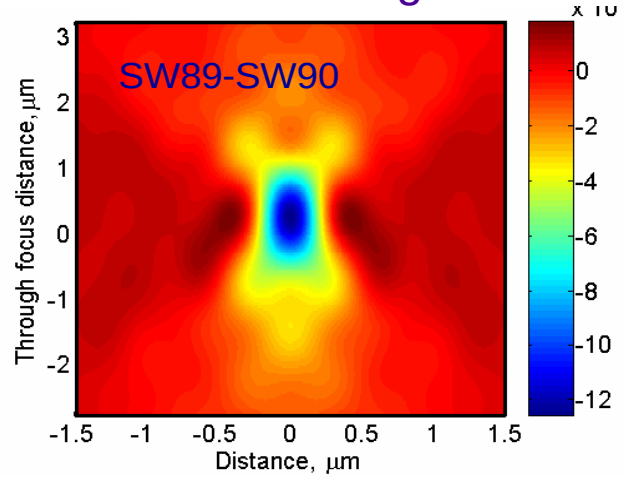
Linewidth



Line height



Sidewall angle

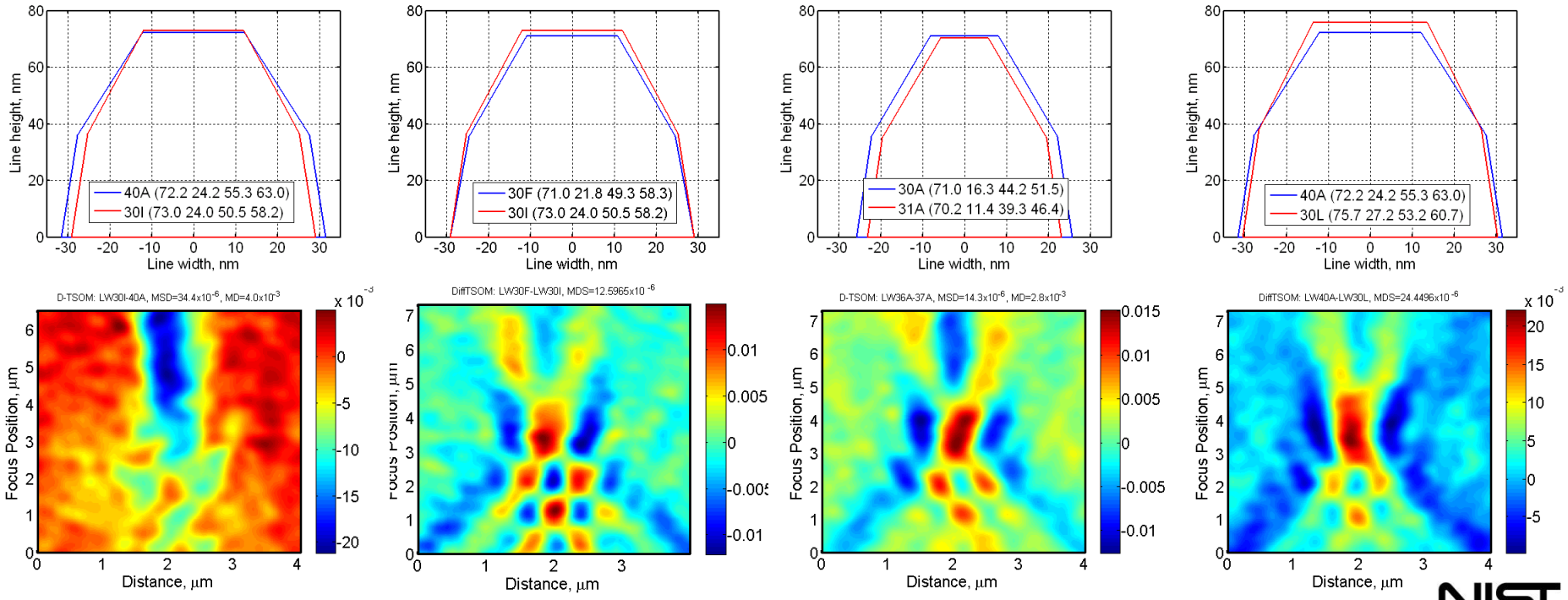


Experiment

Measurements Confirm TSOM Characteristics

1. **Each dimensional difference produces a unique color pattern**
2. Optical content shows magnitude of the dimensional difference
3. Additive

4.8 nm Bottom Difference	2.2 nm Top Difference	~5 nm Top to Bottom Difference	2.3 nm Bottom Narrow and 3 nm Top Wide



Simulation

2. Optical content/intensity shows magnitude of the dimensional difference

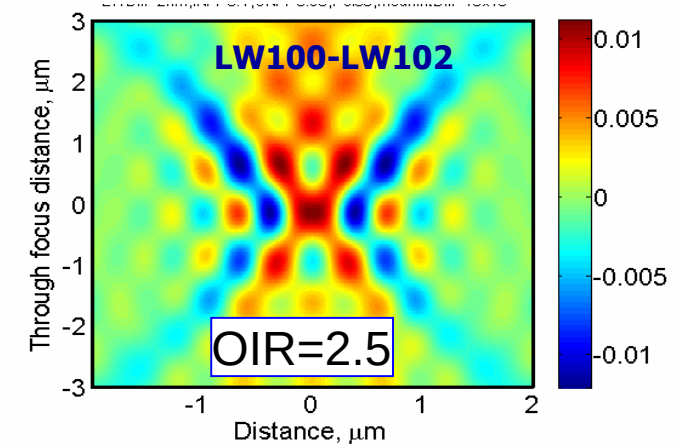
LW ~100 nm
LH ~100 nm

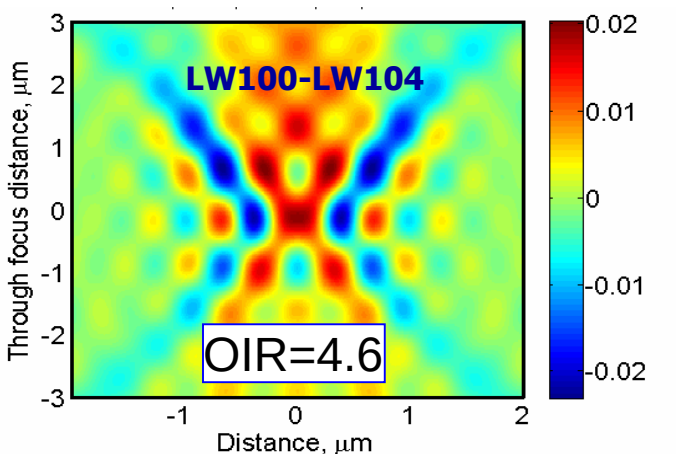
Linewidth difference

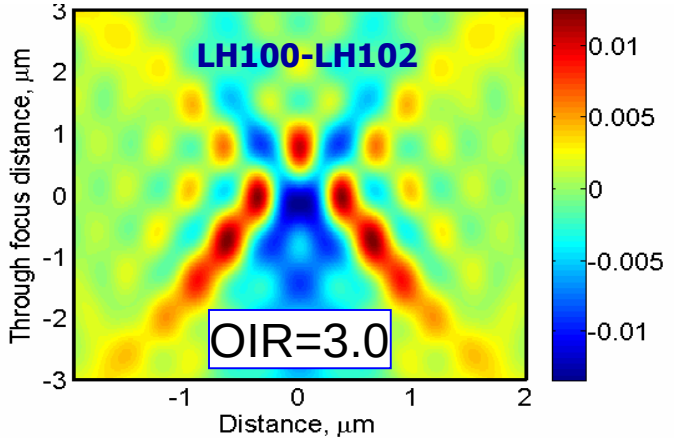
Line Height difference

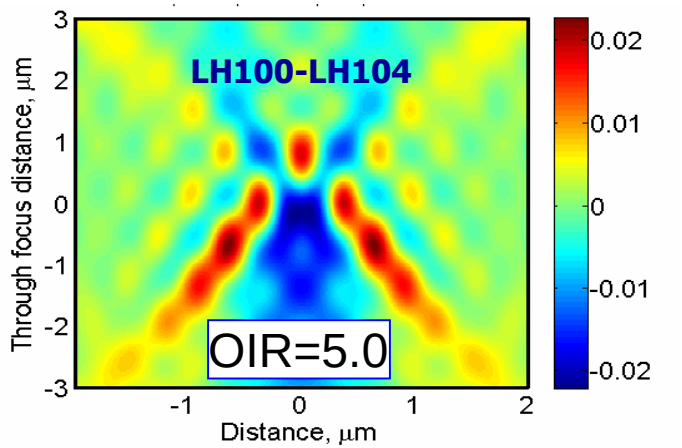
Difference = 2 nm

Difference = 4 nm









NIST

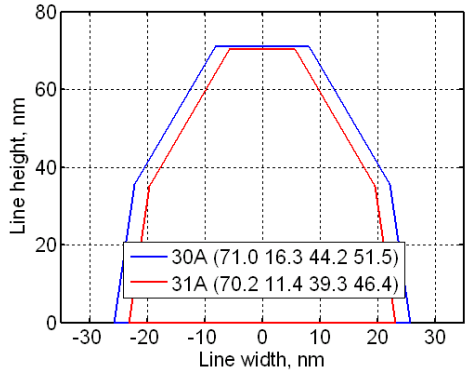
Measurements Confirm TSOM characteristics

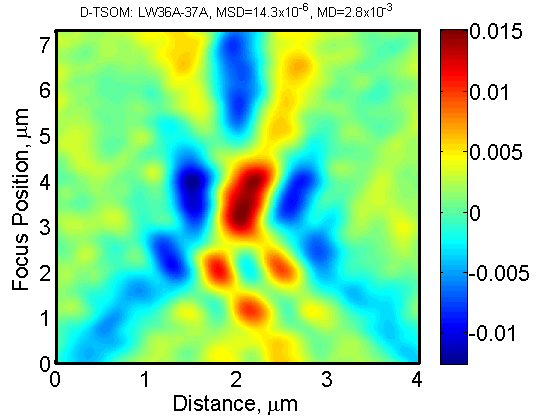
Experiment

2. Optical content shows magnitude of the dimensional difference

Top-to-bottom differences

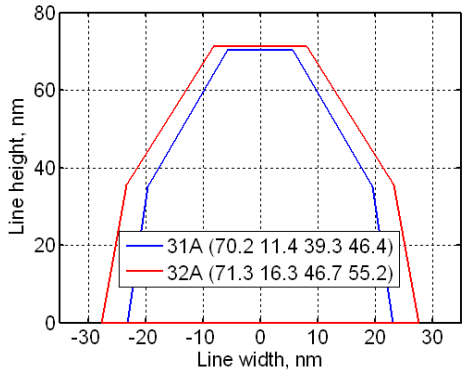
Difference ~ 5 nm

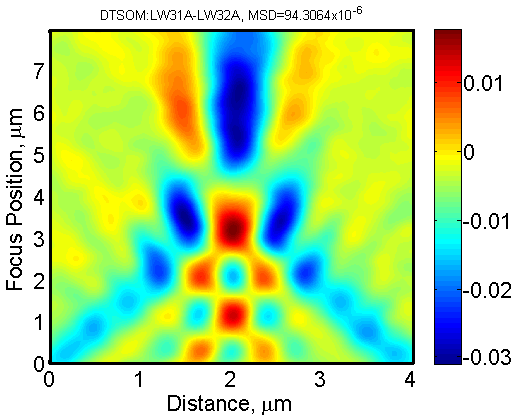




OIR=2.9

Difference ~ 7 nm



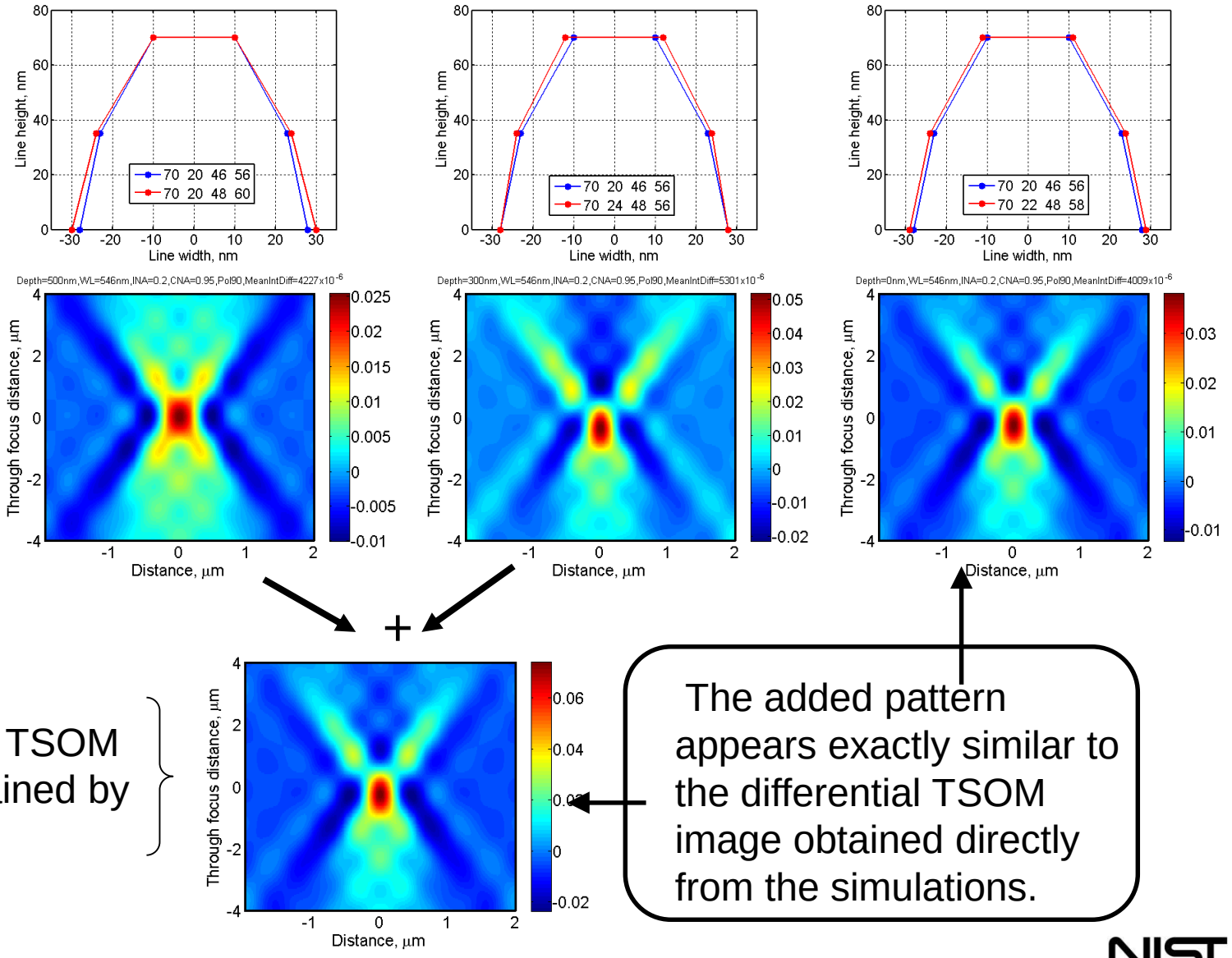


OIR=5.0

3. Additive

Simulation

Bottom difference + Top difference = Top to bottom difference



Differential TSOM images obtained directly from simulations

Differential TSOM image obtained by **addition**

The added pattern appears exactly similar to the differential TSOM image obtained directly from the simulations.

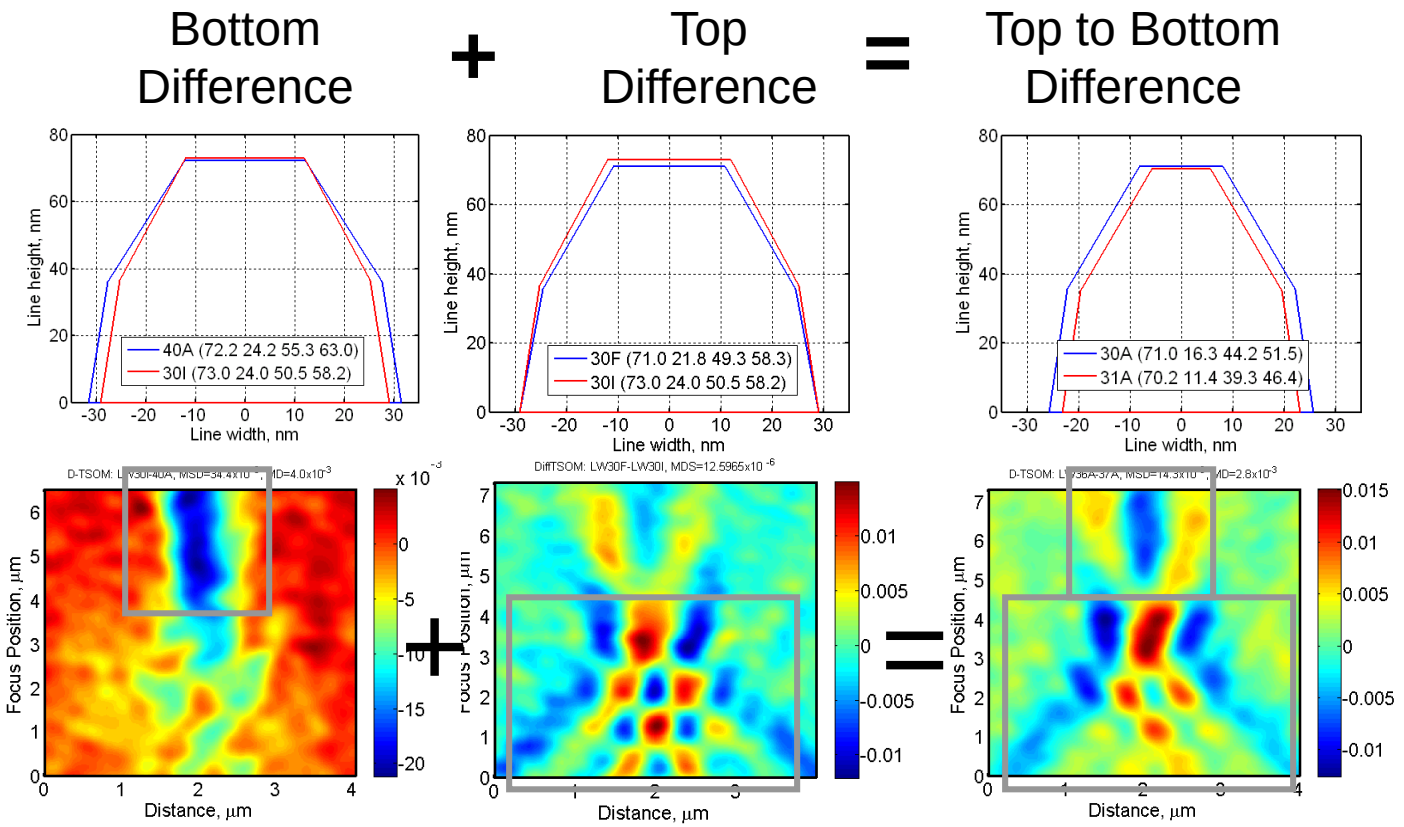
NIST

Experiment

Measurements Confirm TSOM characteristics

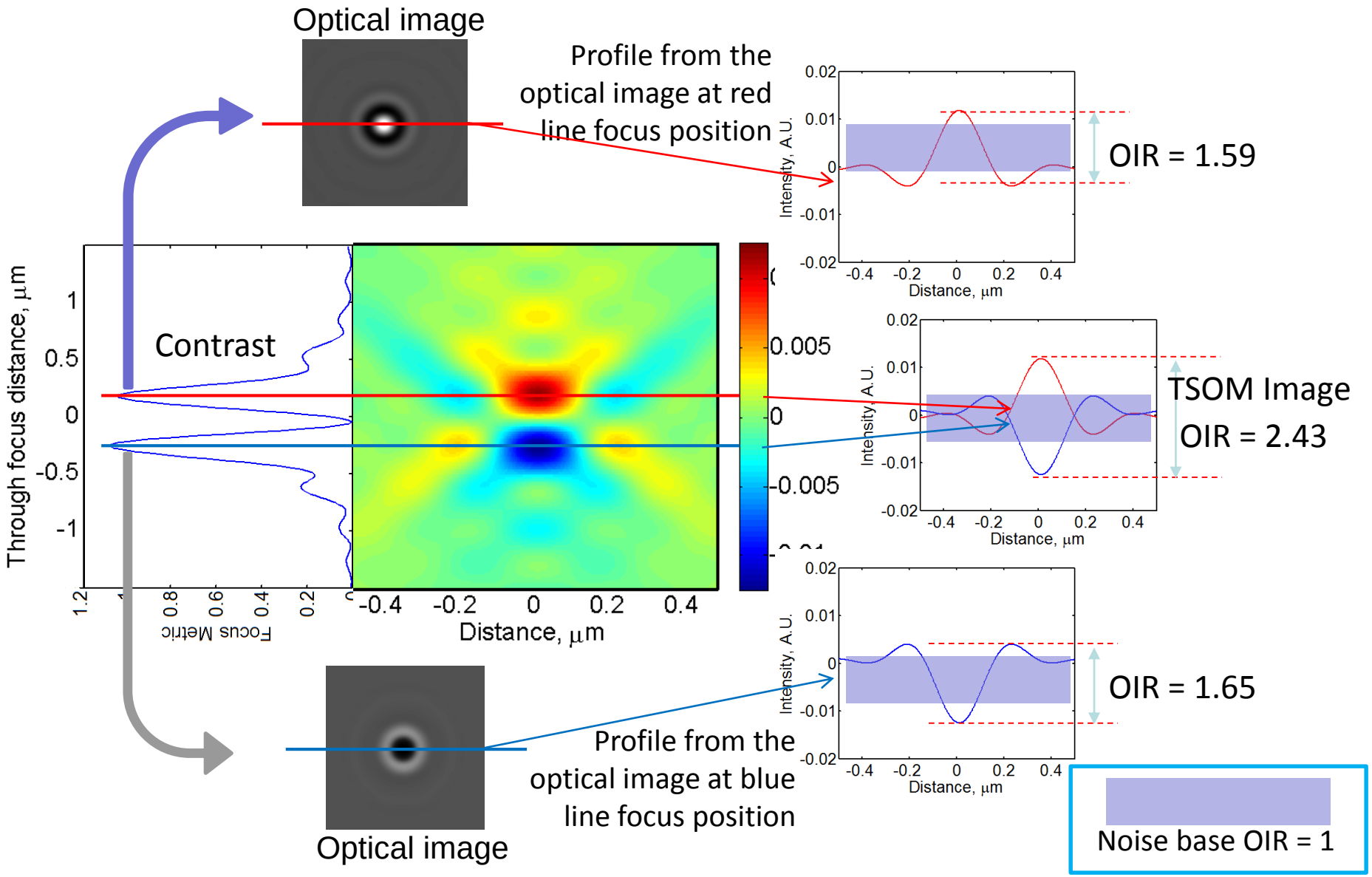
1. Color pattern shows type of dimensional difference
2. Optical content shows magnitude of the dimensional difference

3. Additive

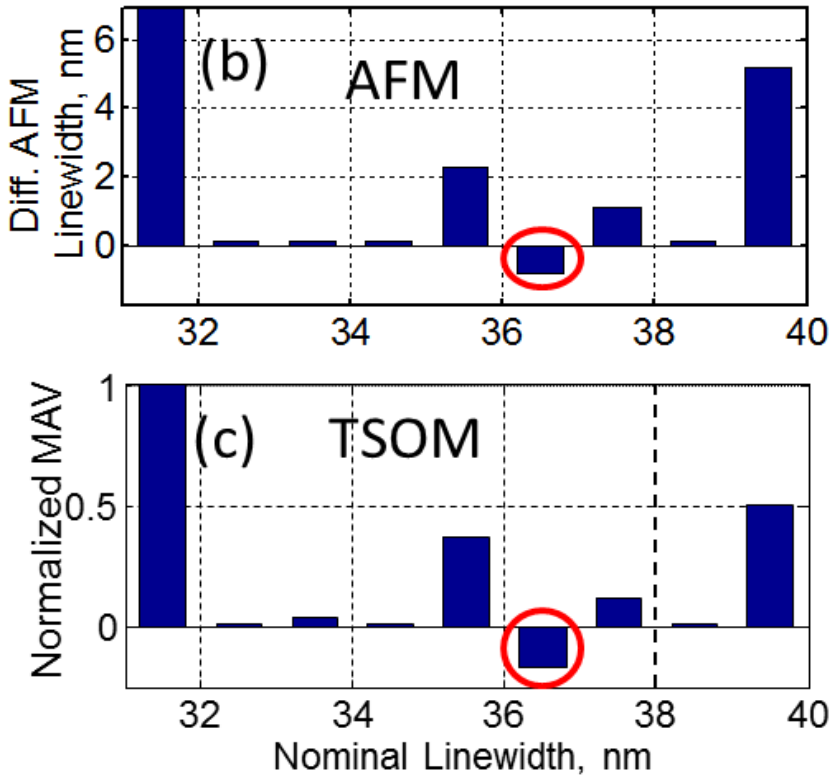


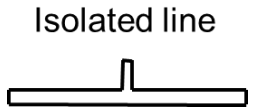
A Unique Inherent Advantage: TSOM Image Signal Strength is Stronger

Captures Both Peaks and Valleys: Useful for defect and nanoparticle detection



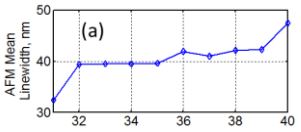
Good Correlation Between CD-AFM & TSOM



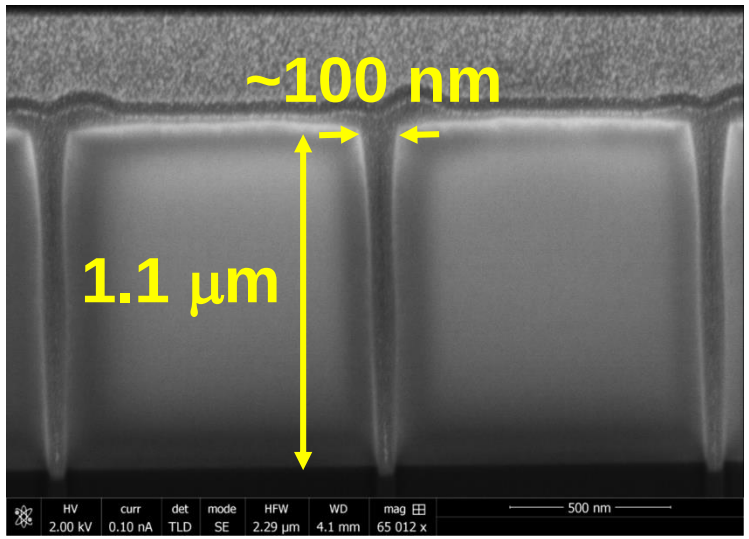


Expanded uncertainty = 1.48 nm
(for k=2)

(based on AFM measurements)

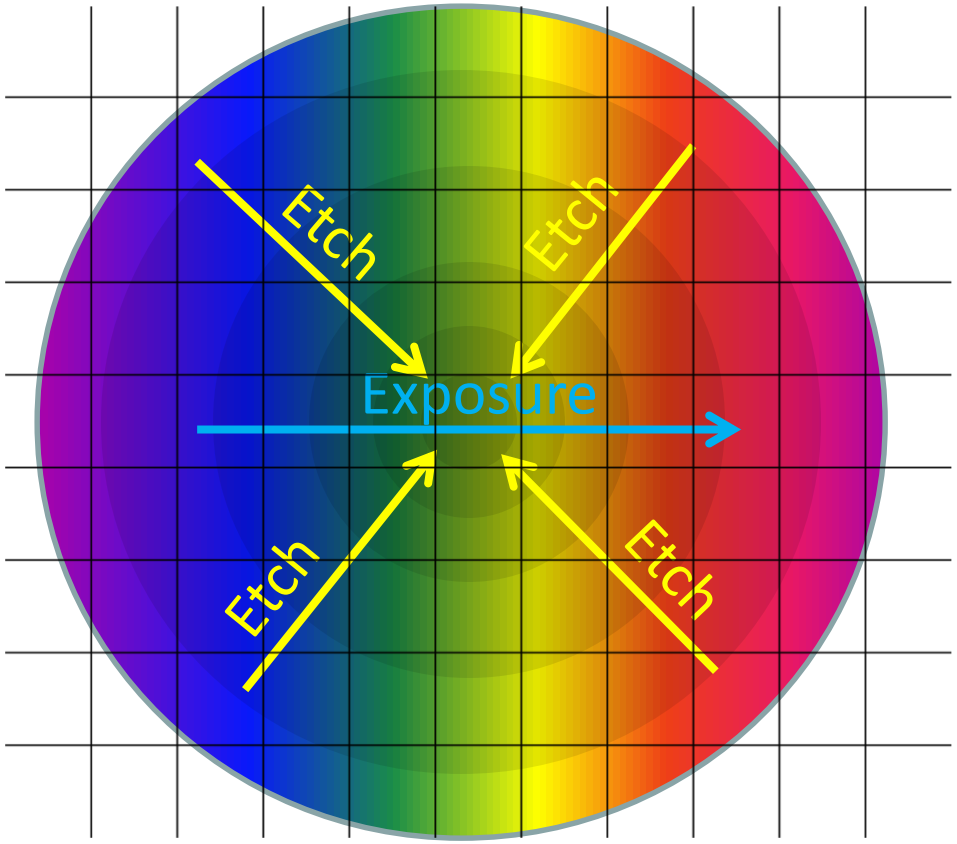


Nondestructive, High-throughput 3D Shape Process Monitoring of 1.1 μm Deep High-Aspect-Ratio (HAR) Targets Using Library Matching

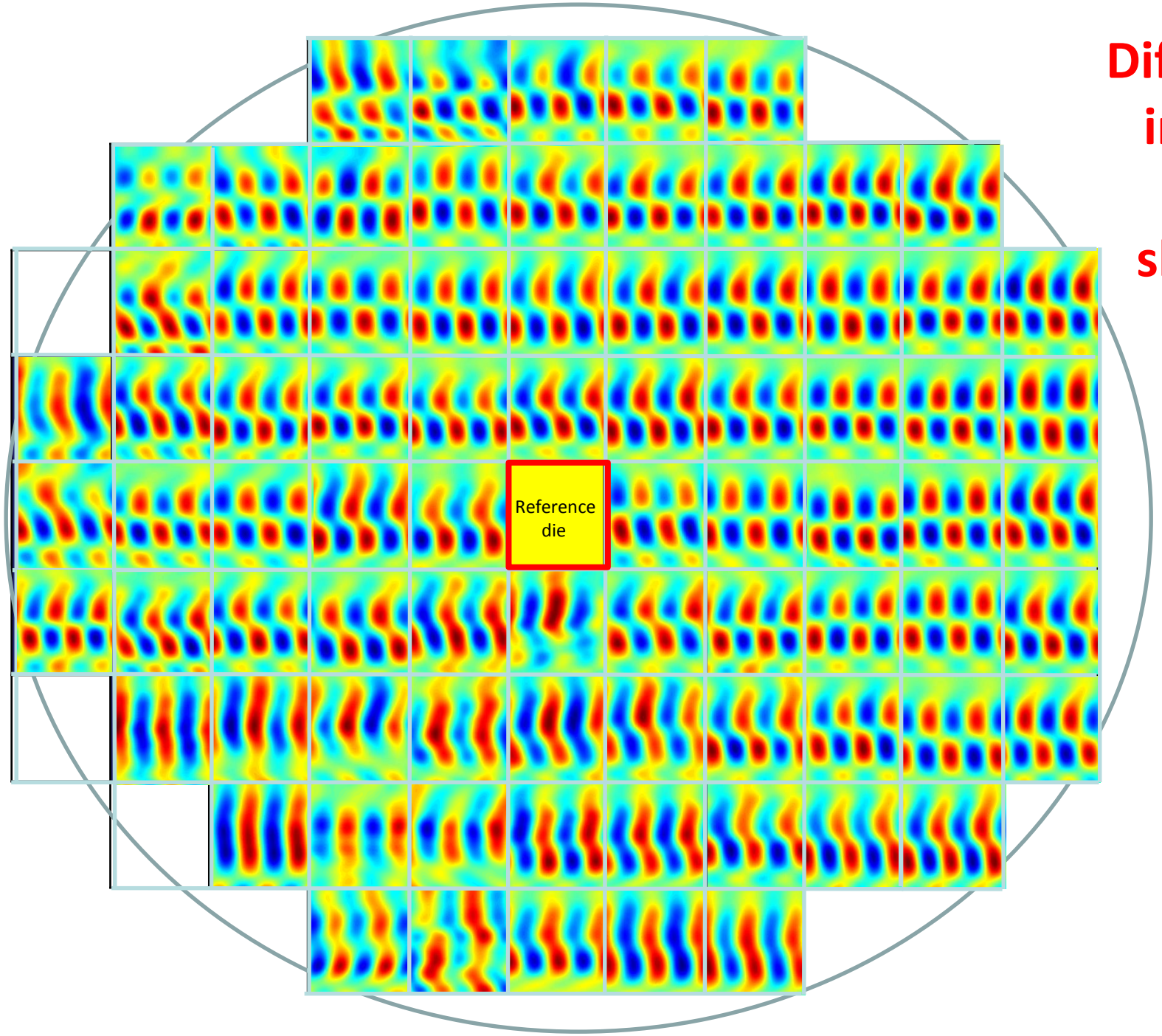


FIB SEM Image

Process Variation of the HAR Wafer

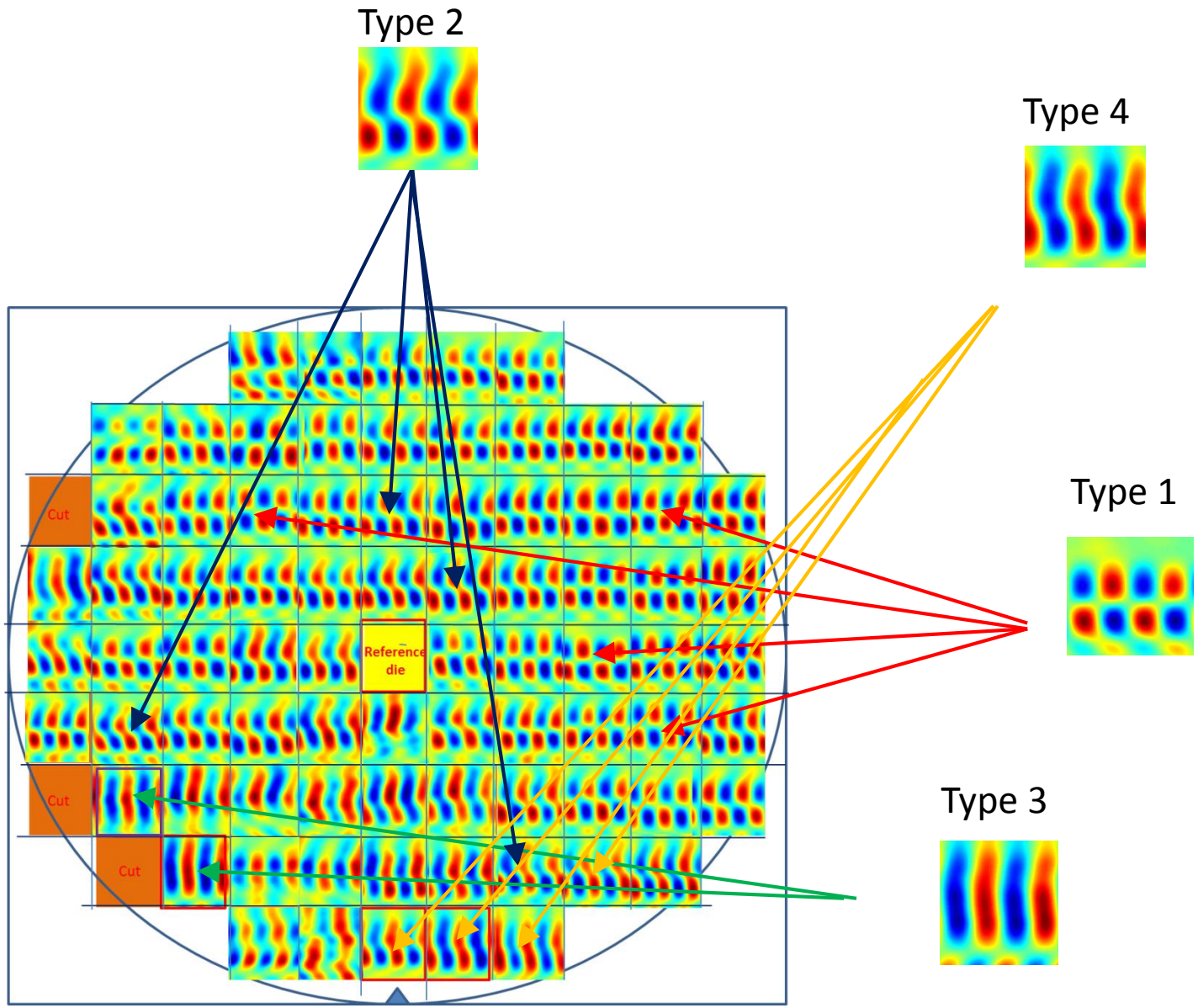


Wafer provided by SEMATECH



Differential TSOM images highlight the type of 3D shape difference

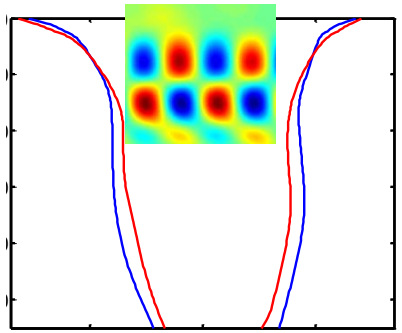
Division of the Production Targets into Four Pattern Groups



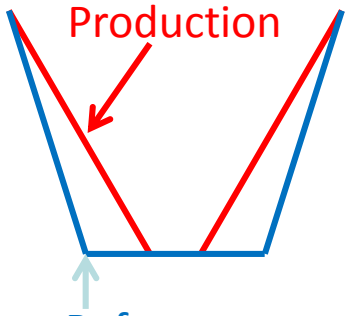
Matching Color Pattern to 3D Profile

Mostly symmetric sidewall angle differences

Type 1

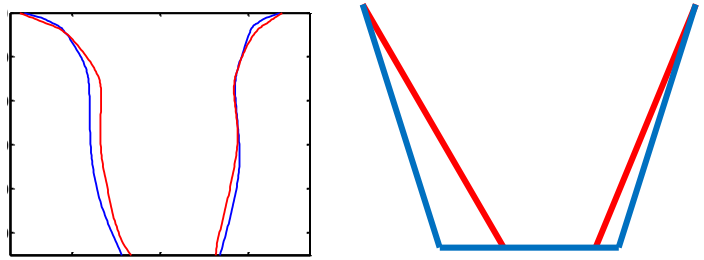


Top similar
Bottom wider

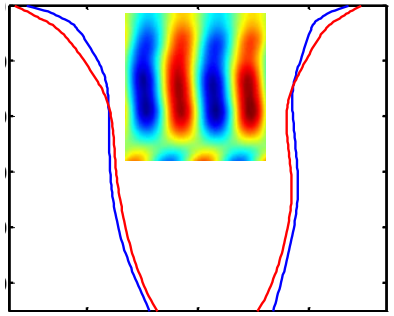


Mostly asymmetric sidewall angle differences

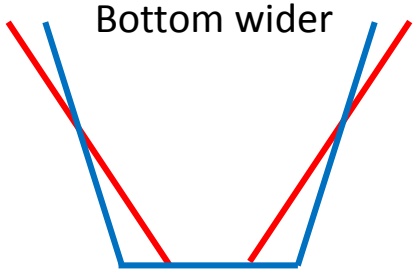
Type 2 = Type 1 + Asymmetry



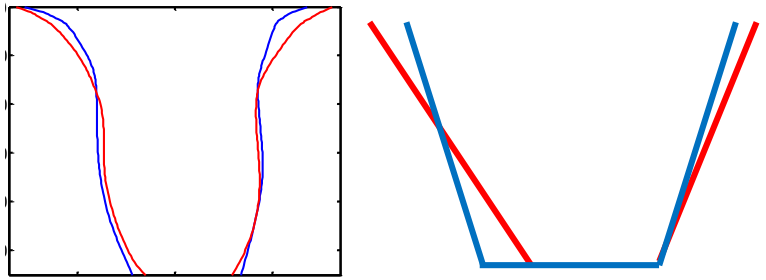
Type 3



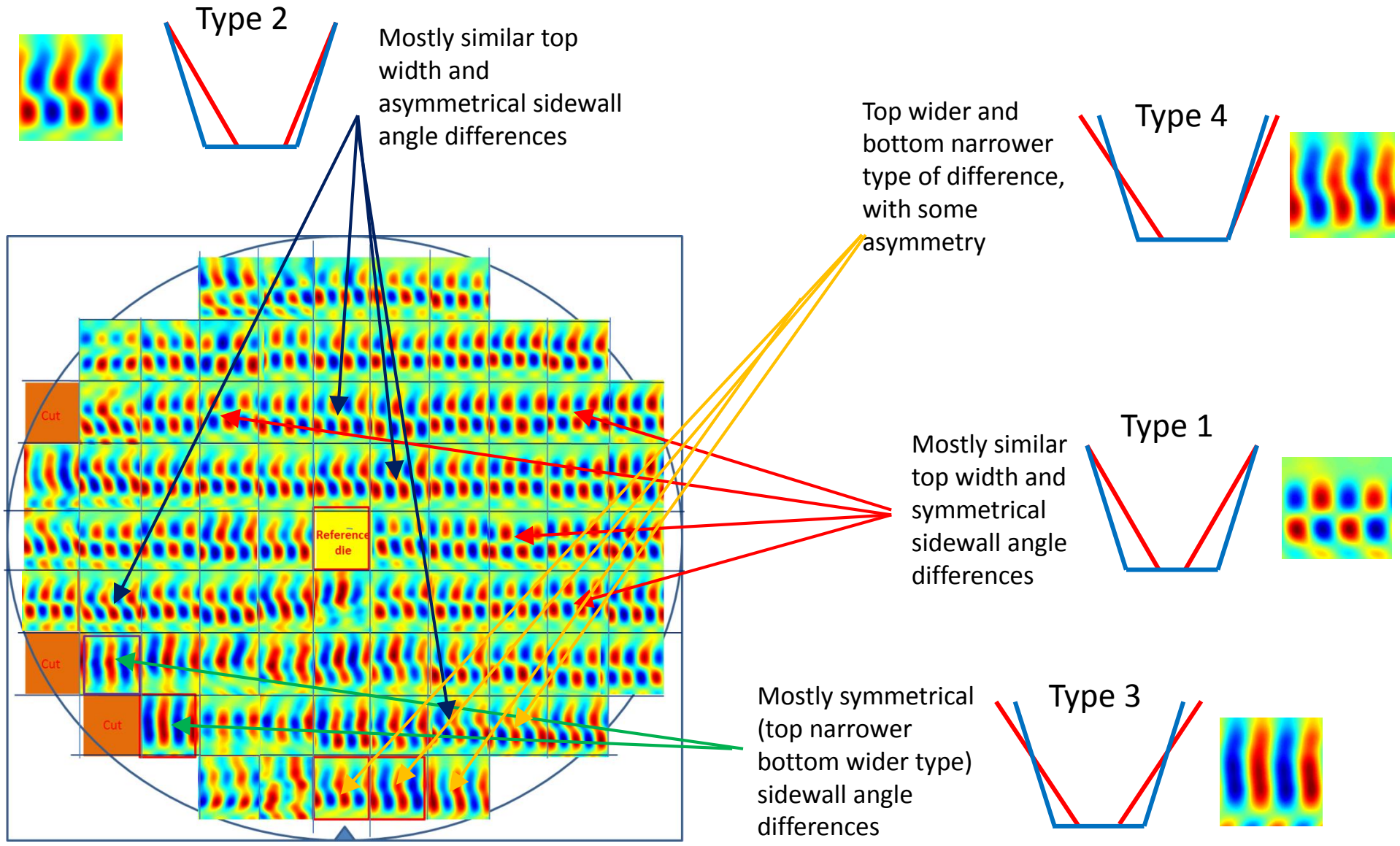
Top narrower
Bottom wider



Type 4 = Type 3 + Asymmetry



Division of the Production Targets Based on the 3D Profiles



Non-destructive, High-throughput, 3D Shape Process Monitoring Procedure

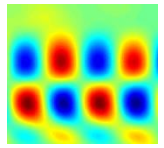
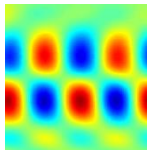
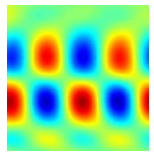
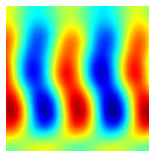
Two numbers are needed

OIR

Magnitude of the dimensional deviation

Correlation coefficient

The degree of 3D shape similarity/deviation

Target 1	Target 2	Corr. Coeff.
		**0.96**
		**0.52**

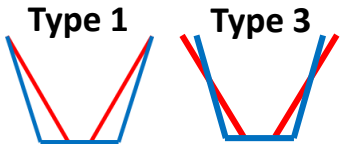
Create Rules to Accept or Reject

OIR > 12 - Reject (too much deviation)

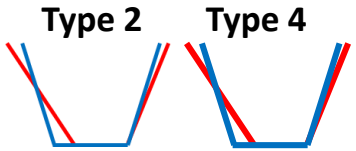
OIR < 7 - Accept (acceptable deviation)

7 > OIR < 12

If symmetrical deviation - accept



If asymmetrical deviation - reject



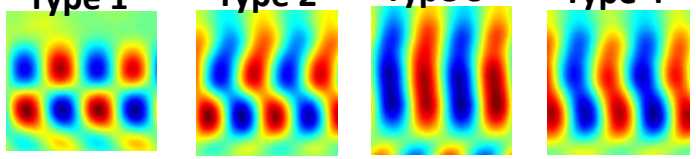
Simplified Schematic of Process Monitoring

Two numbers: (1) OIR, and (2) Correlation coefficient

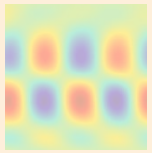
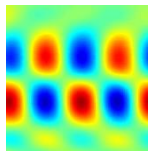
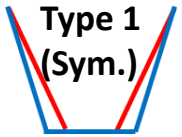
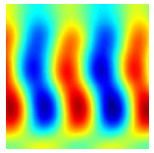
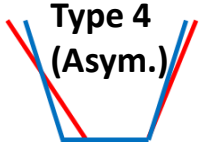
Rules for rejection:

OIR > 12 - Reject
OIR > 7 and Asymmetry – Reject

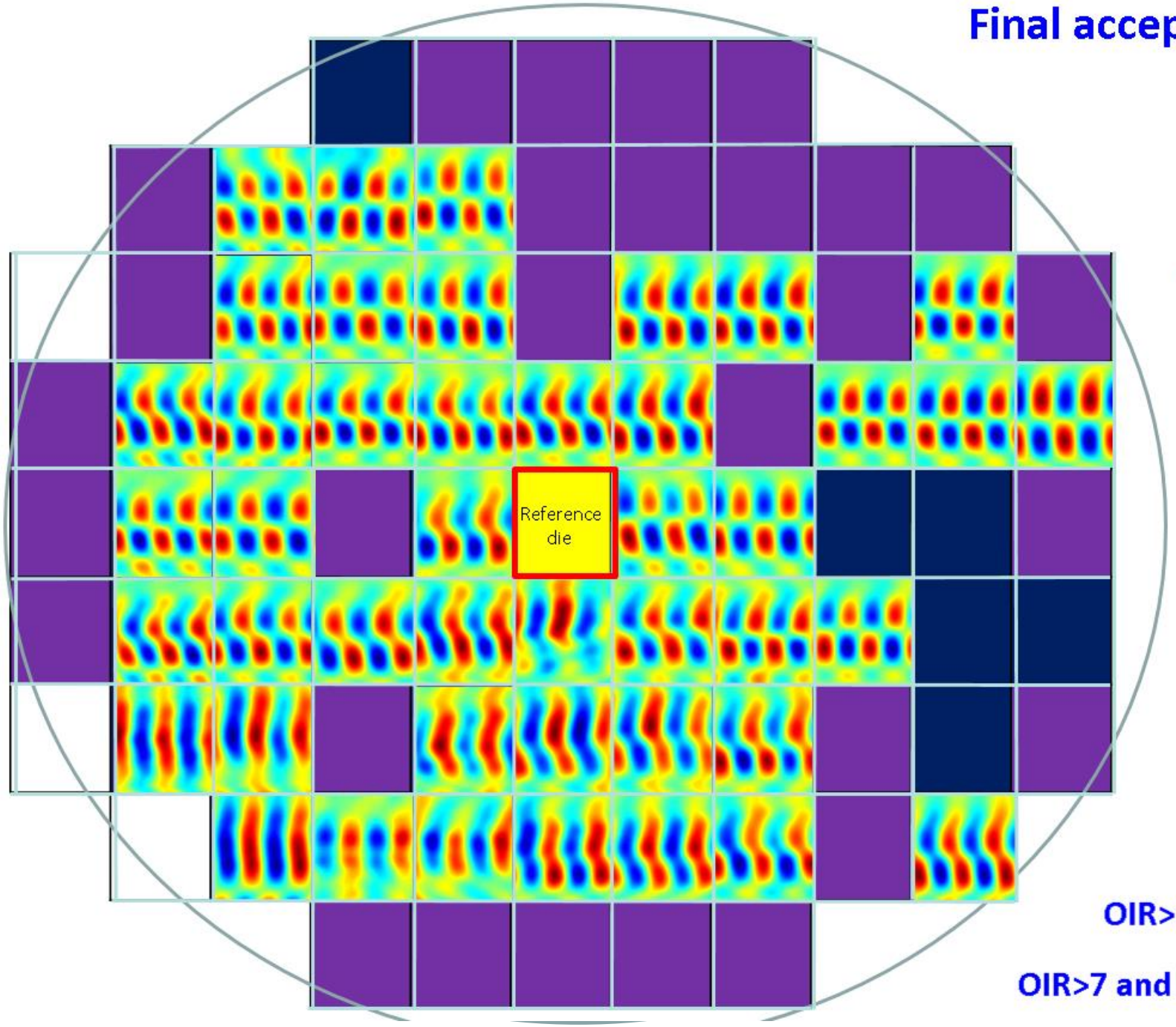
Library



(Correlation coefficients)

Unknown production target shape	OIR	D-TSOM Image	Type 1	Type 2	Type 3	Type 4	Inferred shape difference	Accept/ reject
	6.3		0.84	**0.85**	0.59	0.54	 Type 2	✓
	**13.6**		**0.9**	0.77	0.65	0.52	 Type 1	⊗
	8.4		**0.96**	0.69	0.66	0.61	 Type 1 (Sym.)	✓
	8.0		0.64	0.79	0.78	**1.00**	 Type 4 (Asym.)	⊗

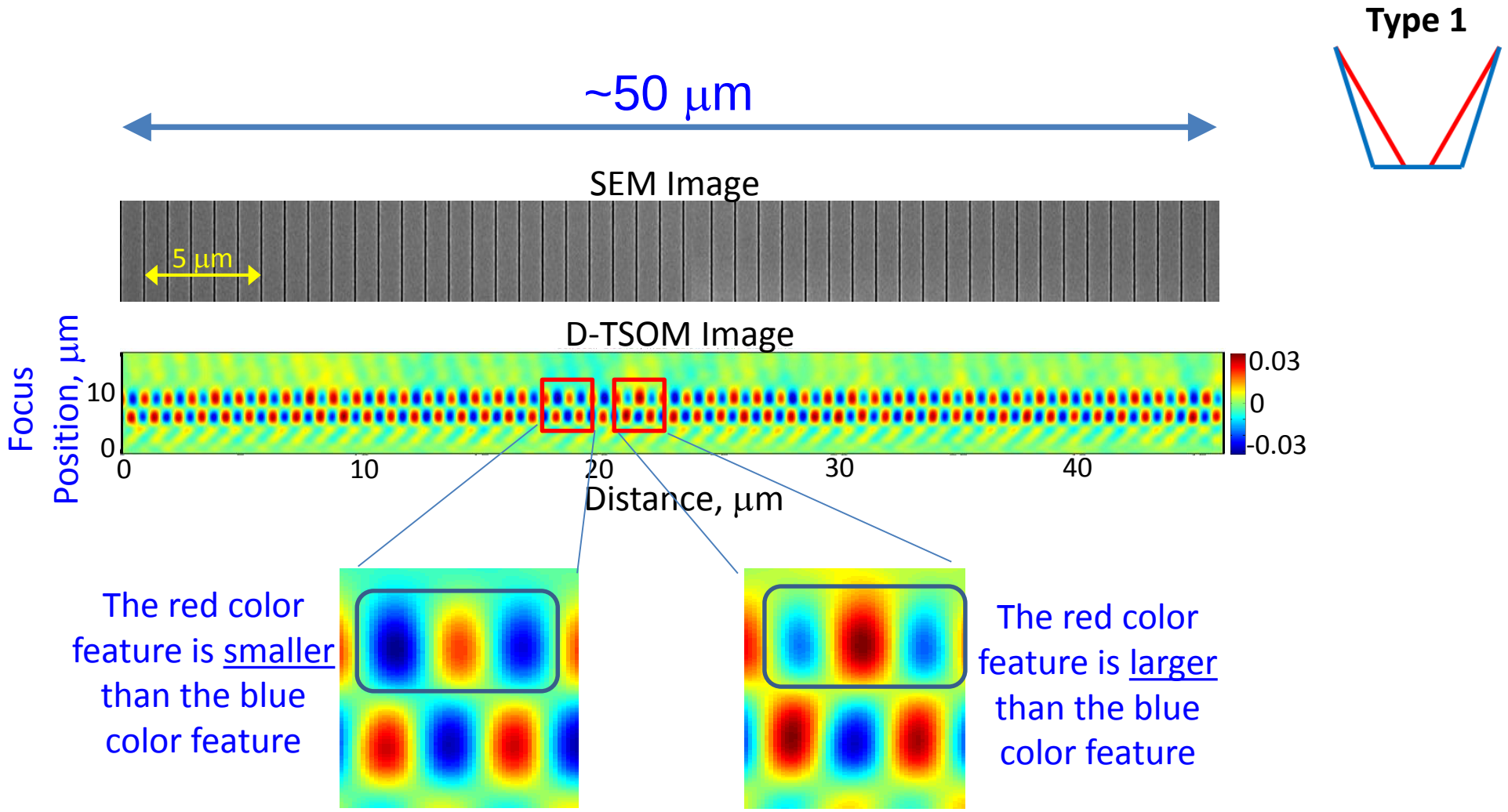
Final accepted targets



OIR>12 - Reject

OIR>7 and Asymmetric- Reject

Many Targets Can be Analyzed Simultaneously



D-TSOM image color deviations indicate dimensional variations within a die

2014 SPIE Advanced Lithography
Metrology Inspection and Process Control

5:20 pm: **Metrology and 3D shape process monitoring of HAR features using TSOM method**, Ravikiran Attota, HyeongGon Kang, John A. Kramar, National Institute of Standards and Technology (USA); Benjamin D. Bunday, Victor H. Vartanian, SEMATECH Inc. (USA) . . . . . .[9050-13]

Measurement Science and Technology

PAPER • OPEN ACCESS

Nondestructive shape process monitoring of three-dimensional, high-aspect-ratio targets using through-focus scanning optical microscopy

Ravi Kiran Attota[1,7], Hyeonggon Kang[1,5], Keana Scott[2], Richard Allen[3], Andras E Vladar[1] and Benjamin Bunday[4,6]

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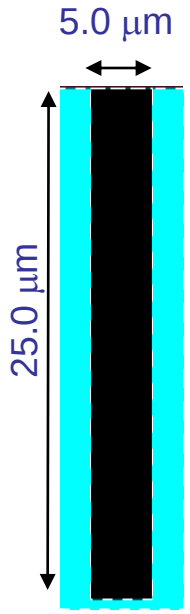
Measurement Science and Technology, Volume 29, Number 12

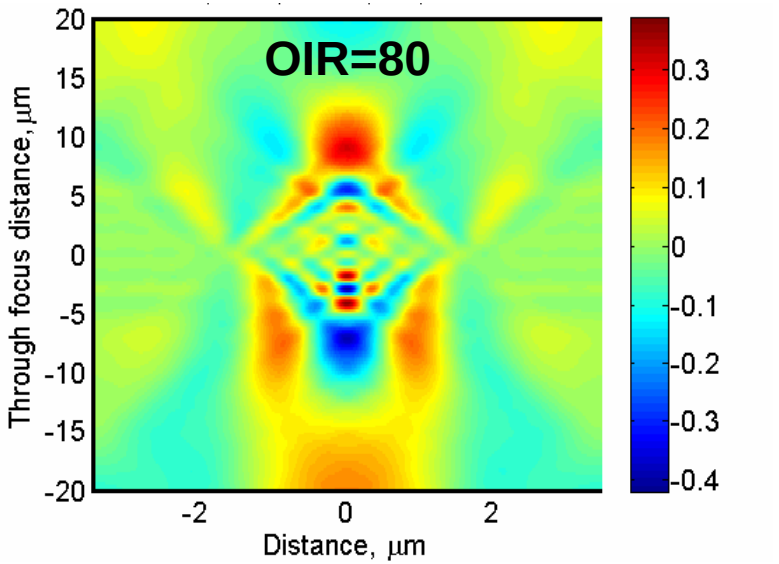
High-aspect-ratio through-silicon-via (TSV) dimensional analysis

Simulation

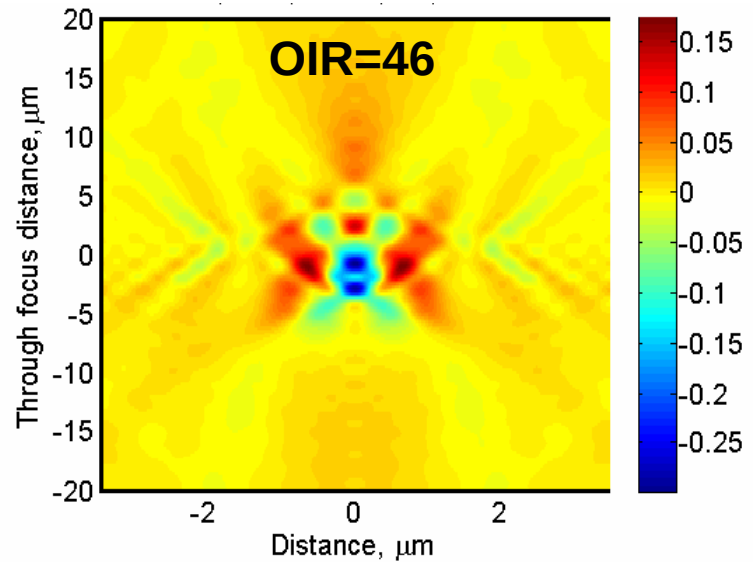
High aspect ratio through silicon via (TSV) dimensional analysis

TSV Diameter = 5 μm, Depth = 25 μm, λ = 546 nm





20 nm change in the depth



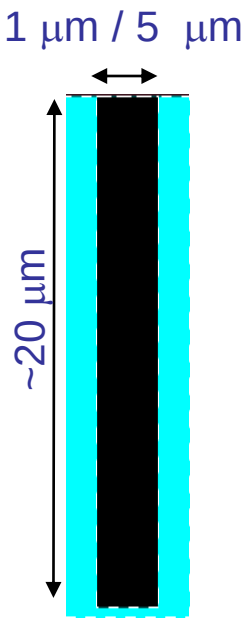
20 nm change in the diameter

NIST

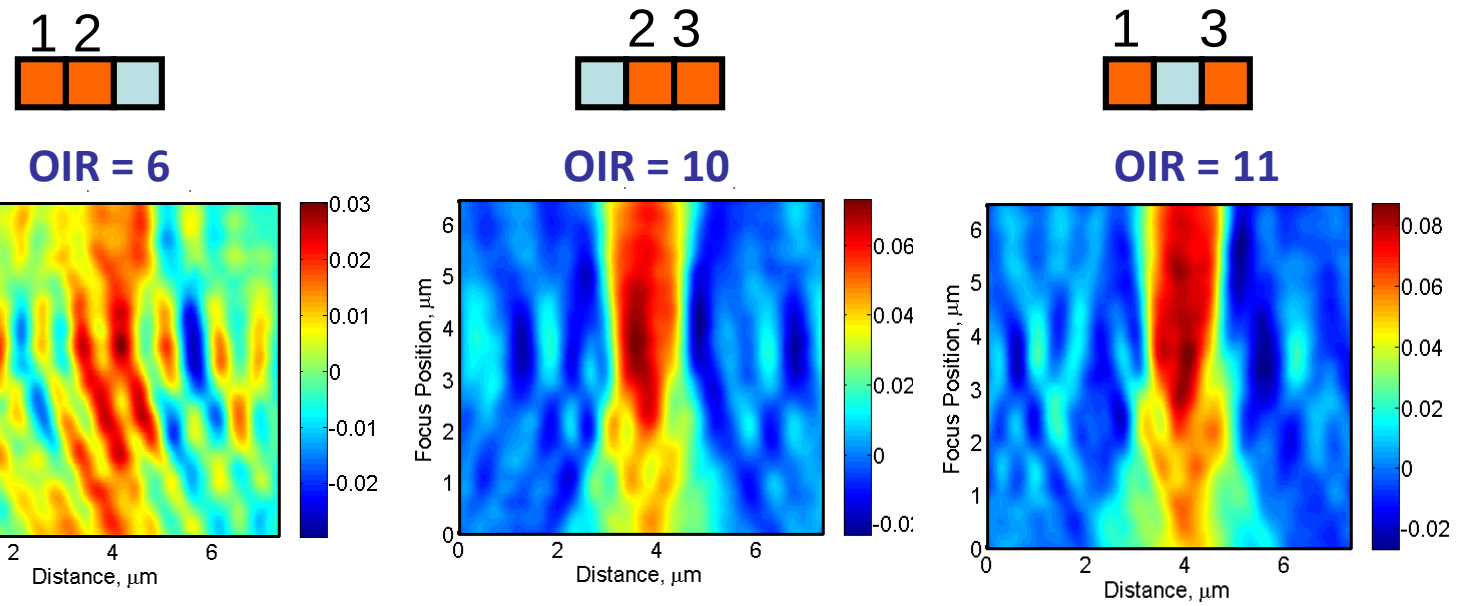
High-aspect-ratio through-silicon-via (TSV) dimensional analysis

Measurement

Depth varies from 18 μm to 25 μm



CD=1.0 um



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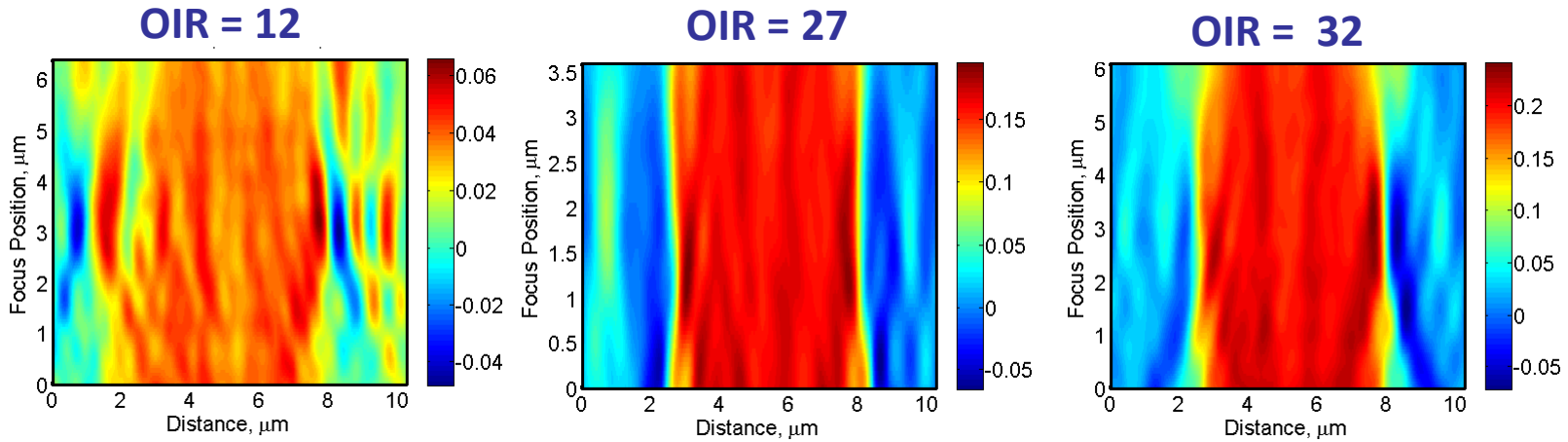

Advantages of TSOM

- Eliminates or reduces optical cross-correlations
- Nanometer scale 3D shape sensitivity
- Requirement for defining the “best focus’ is eliminated
- Ideal for defect analysis and process control
- Robust to optical and illumination aberrations
- Low cost (requires only optical microscopes)
- High throughput
- Optical simulation may not be needed for process control
- In-line metrology capable
- Minimizes the need for vibration isolation
- Non-contaminating, noncontact, nondestructive

Disadvantages of TSOM

- Requires contrast in the image

Summary

Computational process control (CPC) compatible non-destructive 3D shape process monitoring of deep structures appears feasible using through-focus scanning optical microscopy (TSOM)

Thanks

Acknowledgements:

John Kramar
SEMATECH