Extending Optical Critical Dimension Metrology into the Mid-Infrared Range

23 JUNE 2022

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FCMN 2022 June 20-23, 2022
Monterey Marriott
Monterey, California USA
International Conference on Frontiers of Characterization and Metrology for Nanoelectronics

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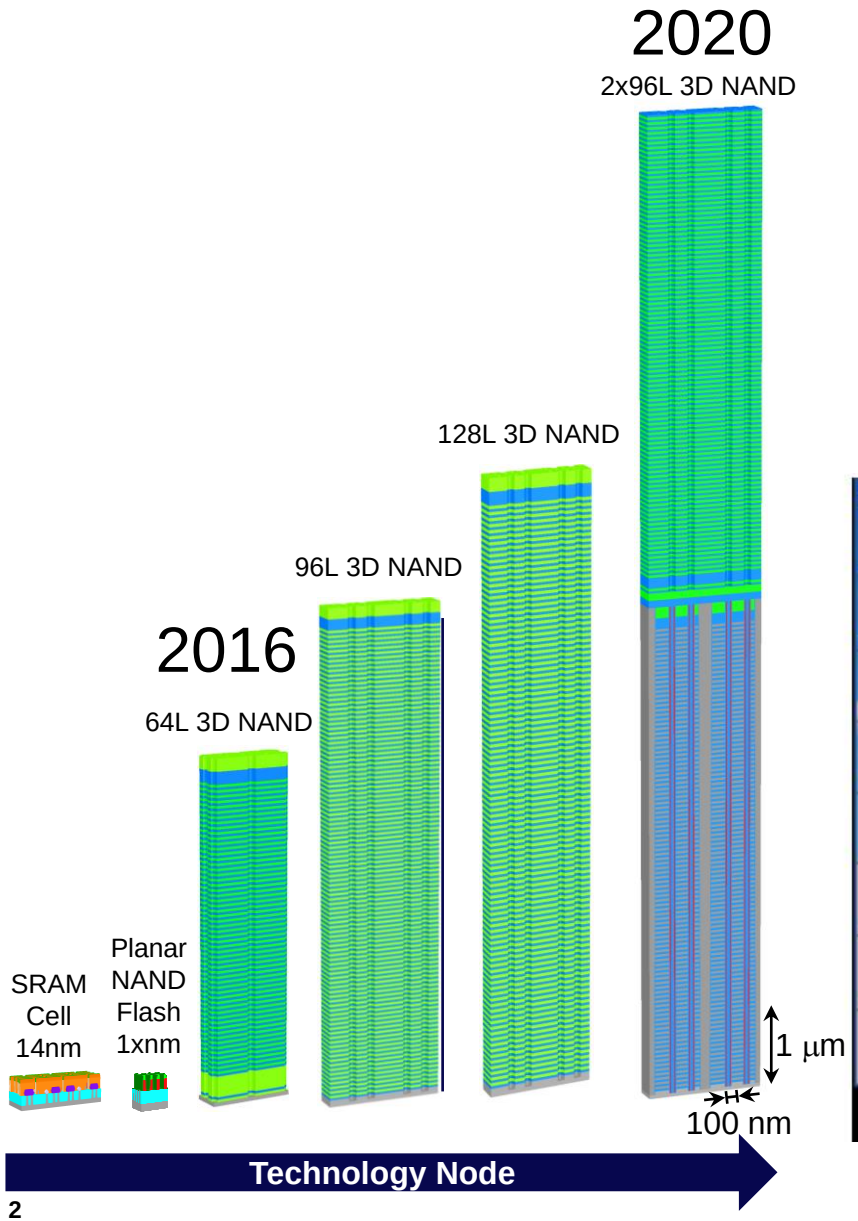
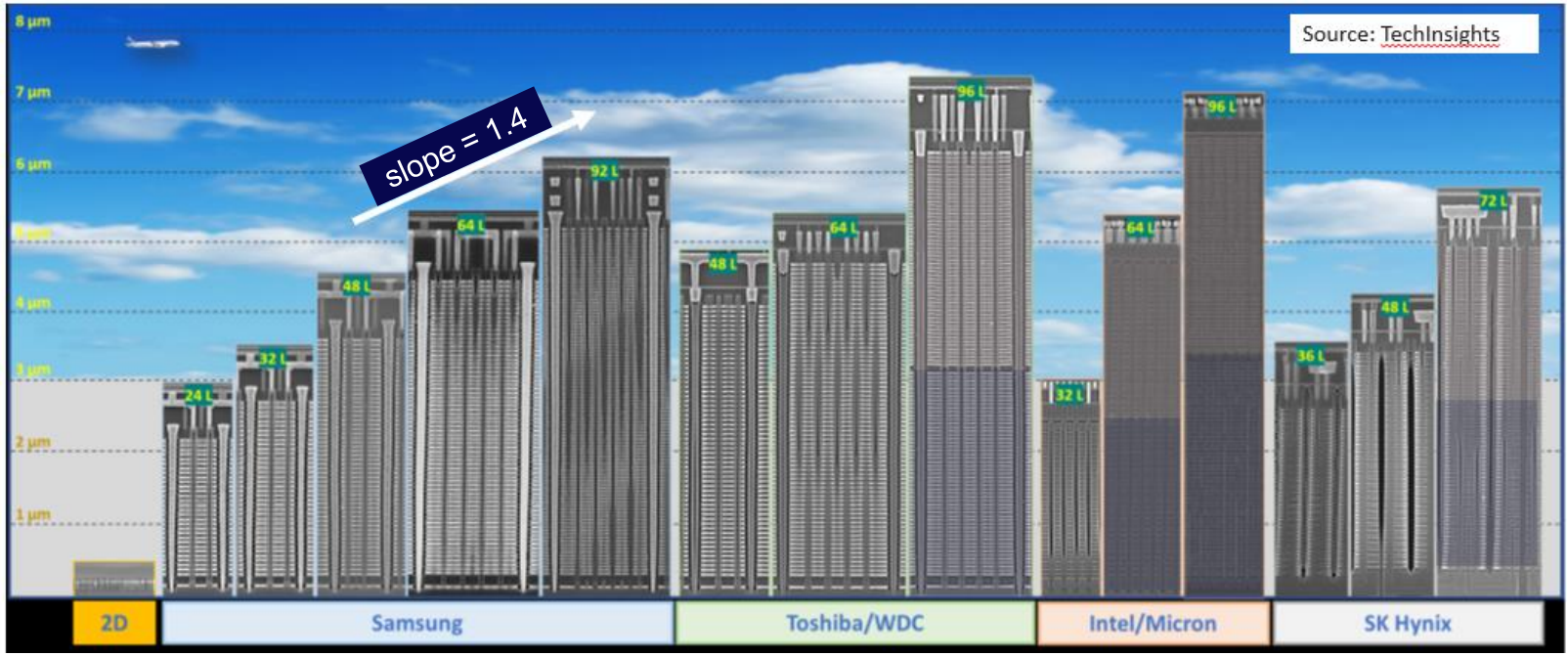
onto

Memory Devices: Plenty of Room in the Z Direction



The future will be higher and denser implying an increase in the demand for high-aspect ratio etch process control

3D memory needs 3D metrology!



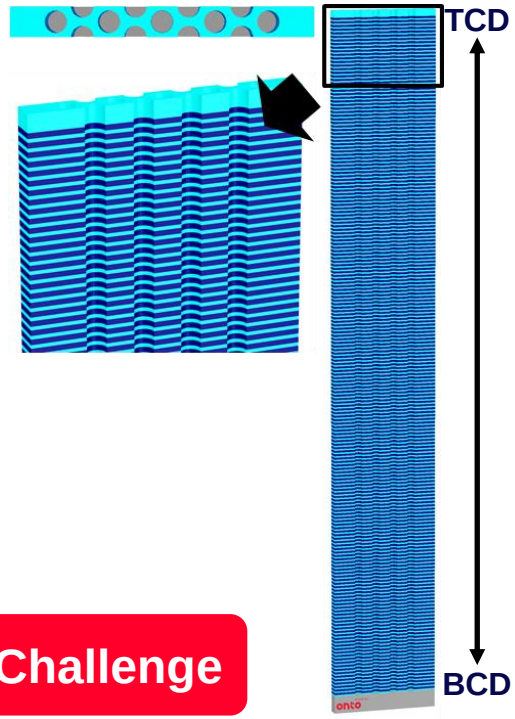
Challenges in 3D Memory Optical Metrology

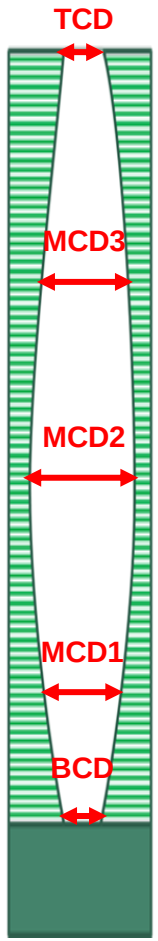
Patterning: Profile

Channel Hole Etch

Challenge:

- Sensitivity to the CD as function of channel height





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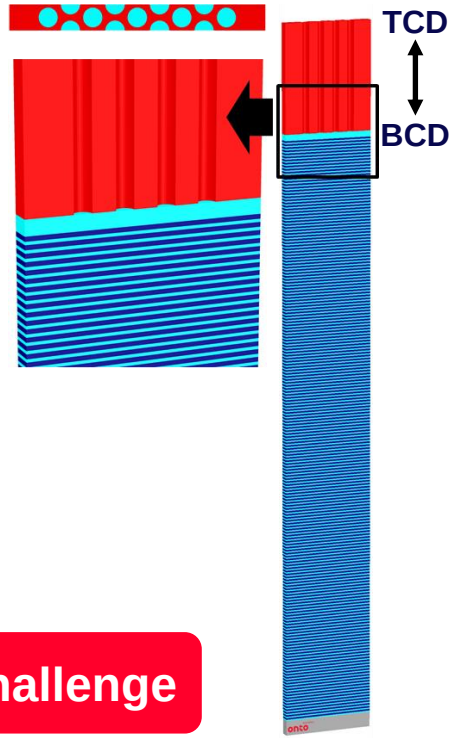

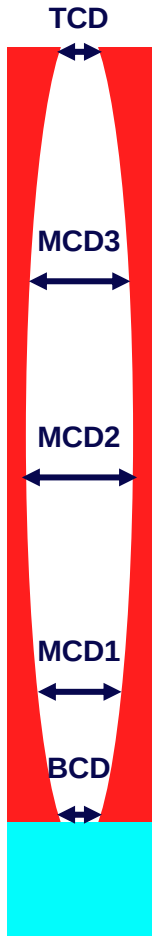

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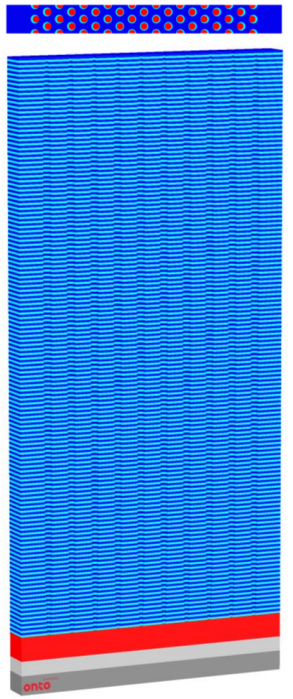
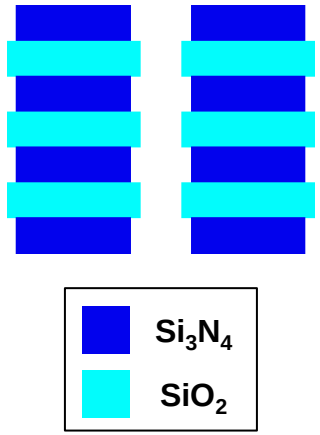
Si_3N_4 Recess

Challenge:

- Sensitivity to recess of Si_3N_4

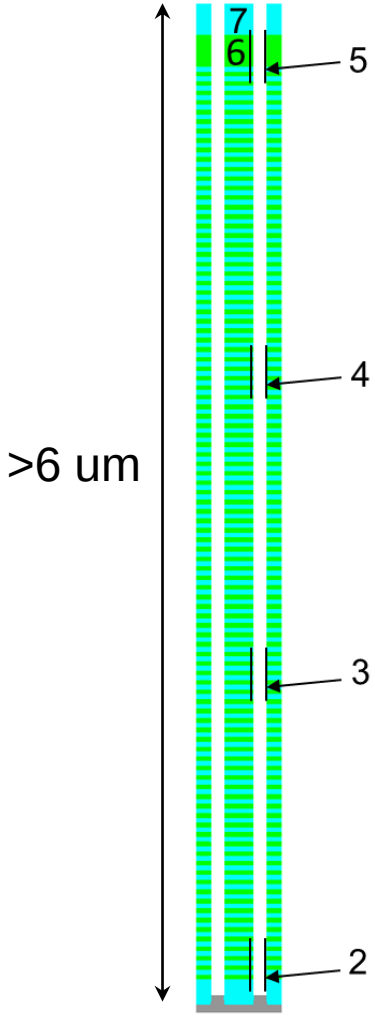


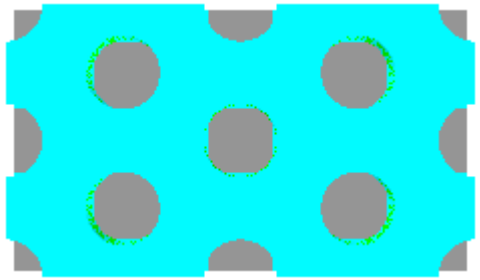


Challenge

A High Aspect Ratio Problem

Limitations of Conventional OCD





Parameter	CD
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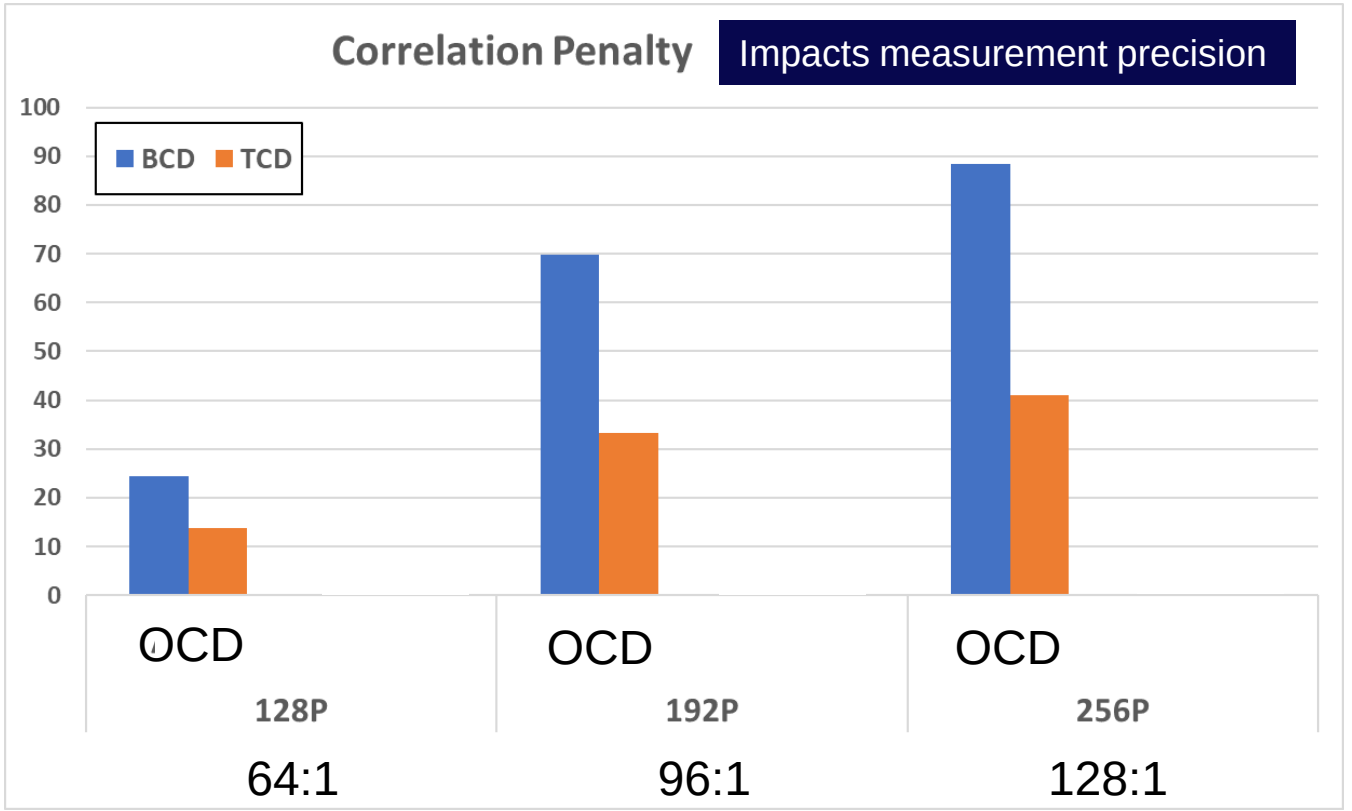
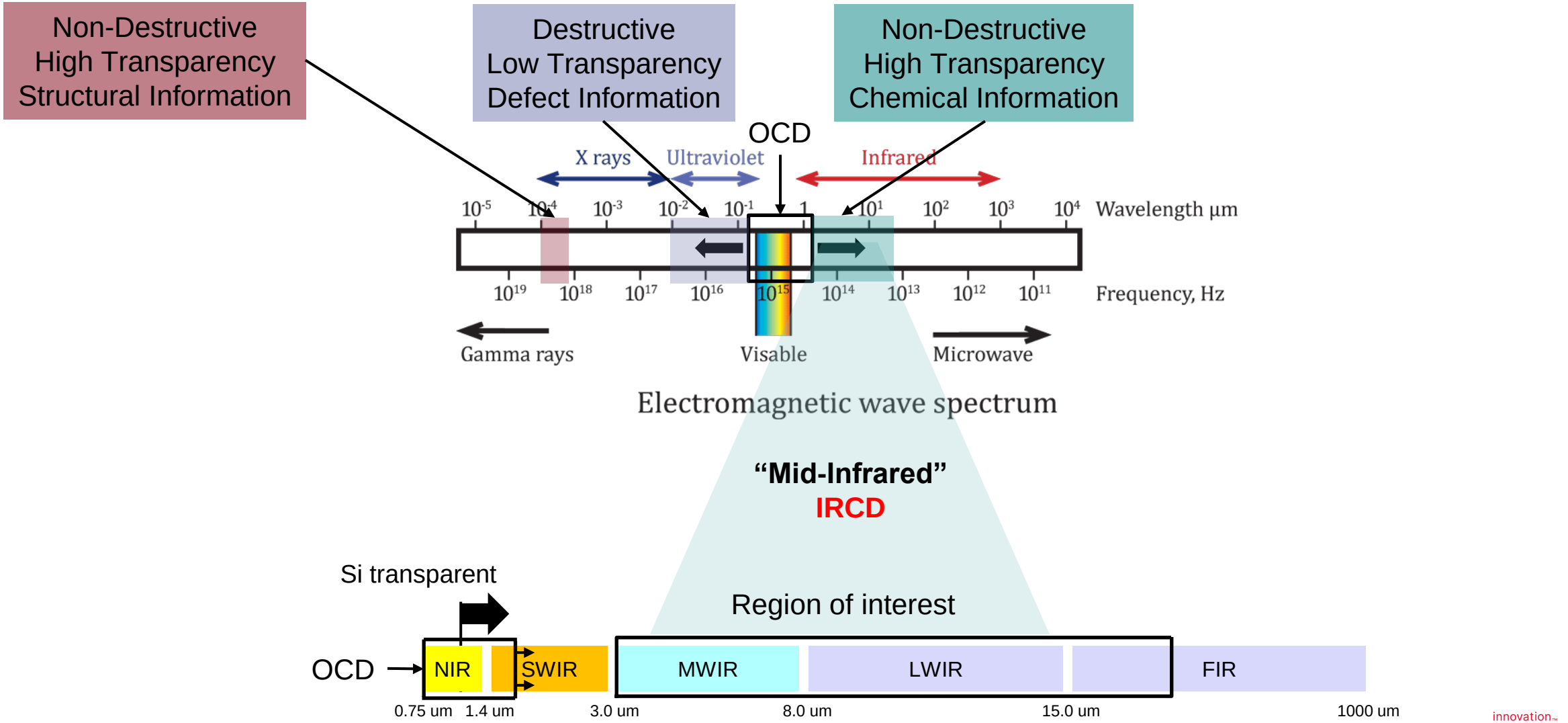


The Electromagnetic Spectrum



IRCD Simulations of Channel Hole Profile

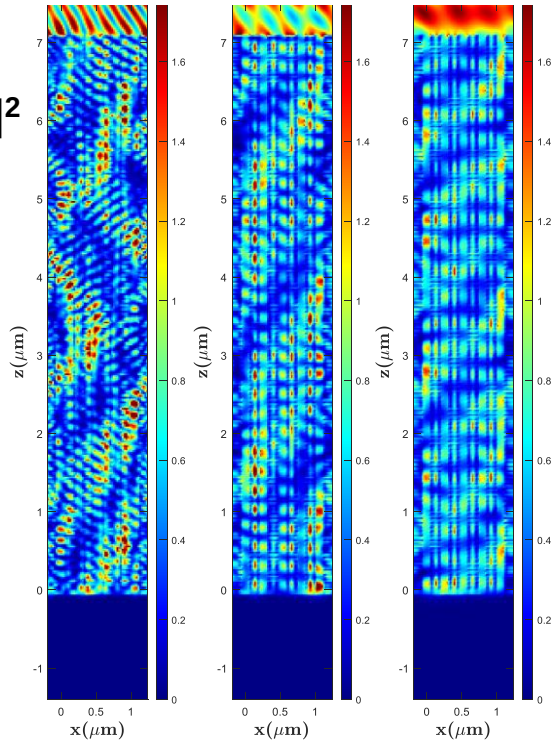
Finite difference time domain (FDTD) simulation of electric field intensity

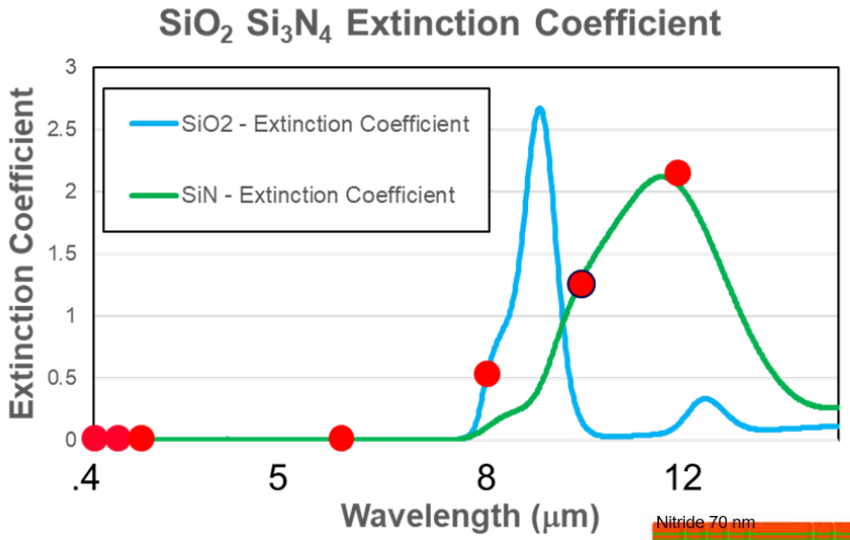
Wavelengths in **OCD** range interact similarly leading to **high parameter correlation** limiting profile sensitivity

OCD

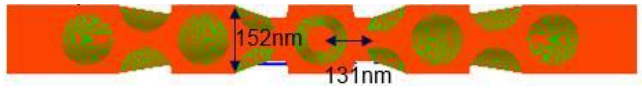
400 nm 600 nm 800 nm

$|E|^2$

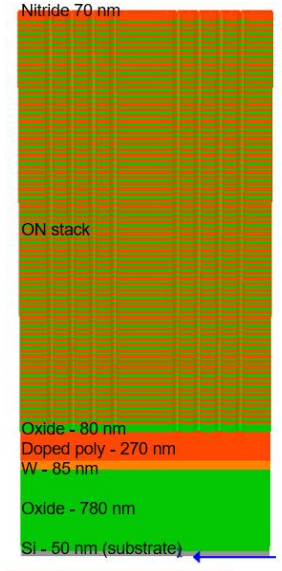




FDTD simulation of $|E|^2$ in 128L 3D NAND structure SiO_2/Si_3N_4 superlattice pair thickness 25 nm/30 nm and hole diameter of 120 nm with hexagonal lattice



Simulations executed in Lumerical FDTD package

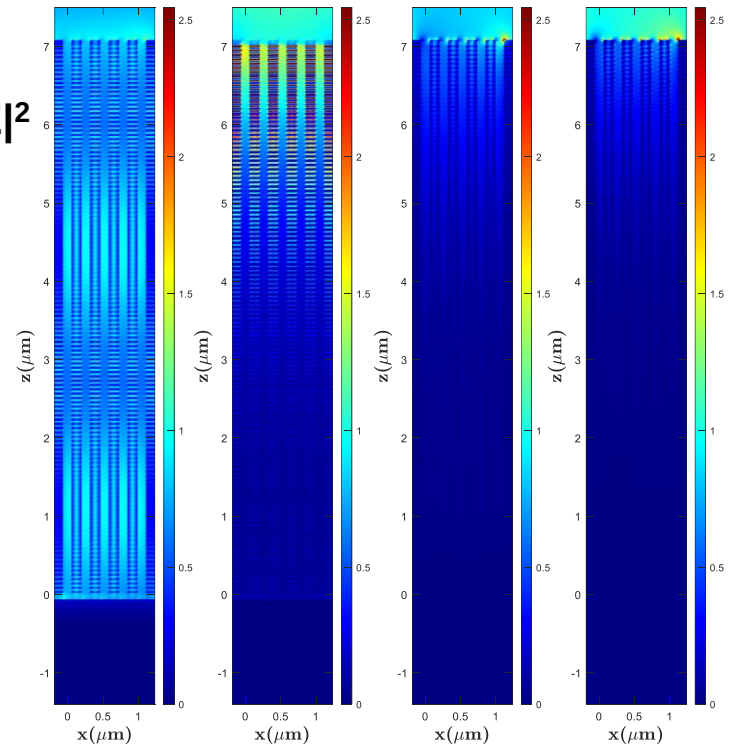


Wavelengths in **IRCD** range interact uniquely, leading to **parameter decorrelation** and **CD profile metrology**

IRCD

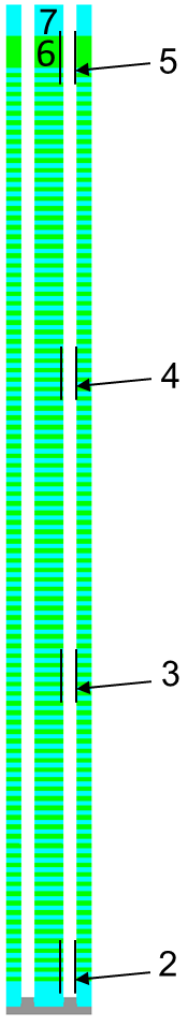
6000 nm 8000 nm 10000 nm 12000 nm

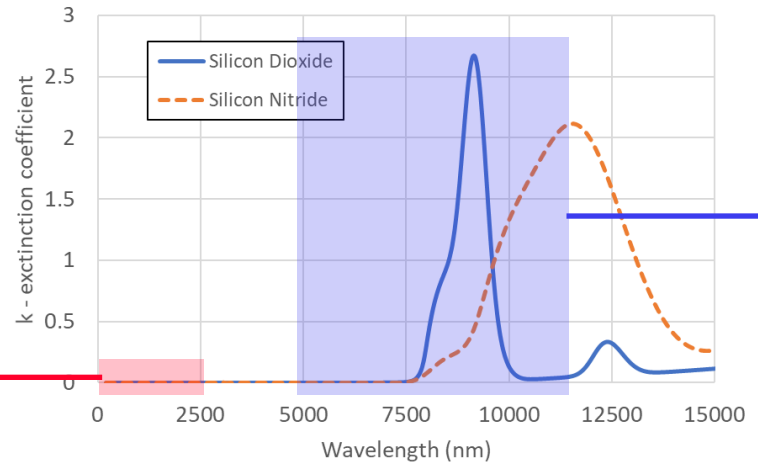
$|E|^2$



Source: Fumani, et al., Journal of Micro/Nanopatterning, Materials, and Metrology 21(2), 021205 (4 April 2022).

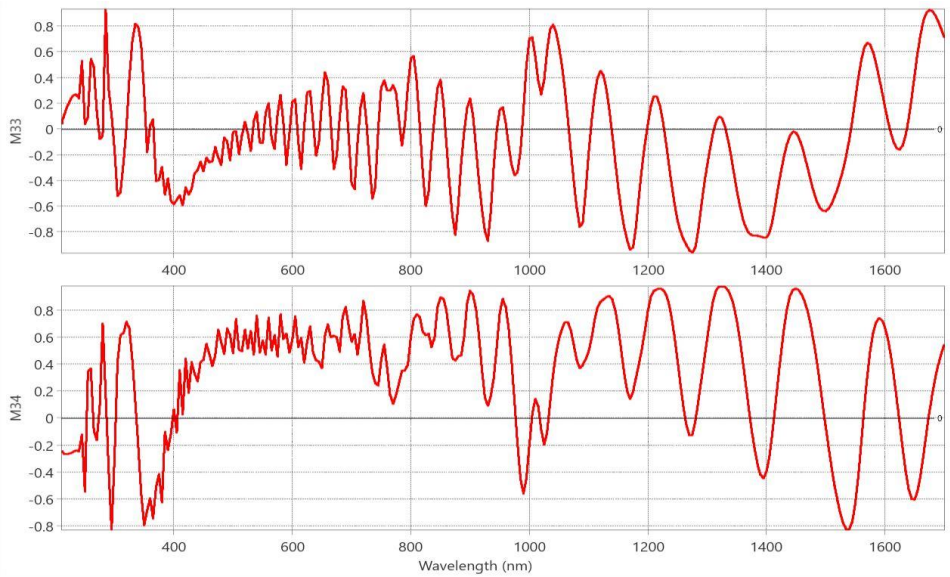
Data Comparison of OCD and IRCD

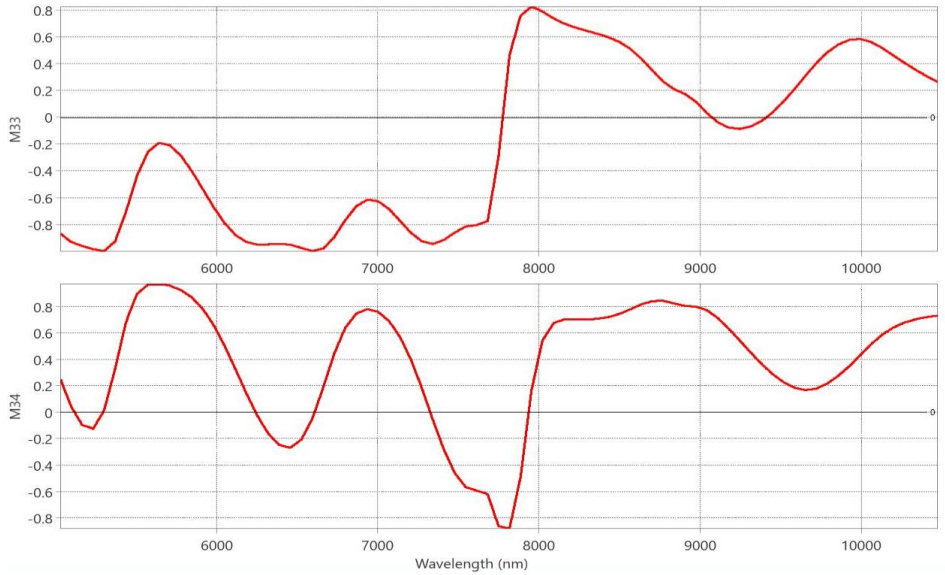




OCD

IRCD





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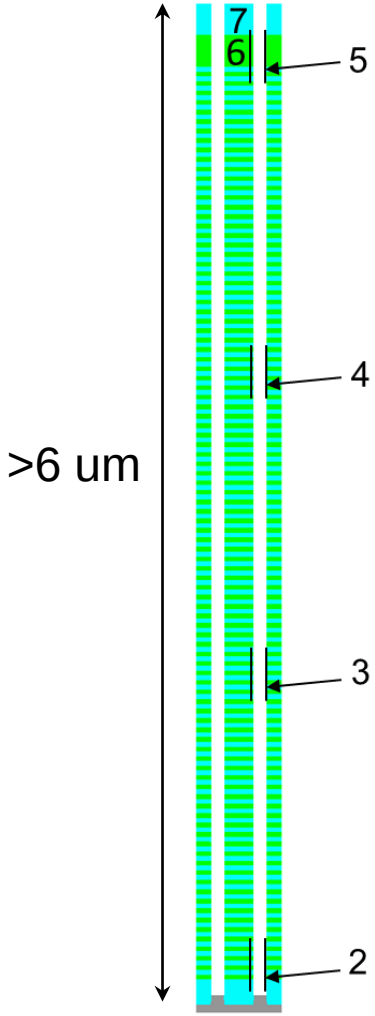

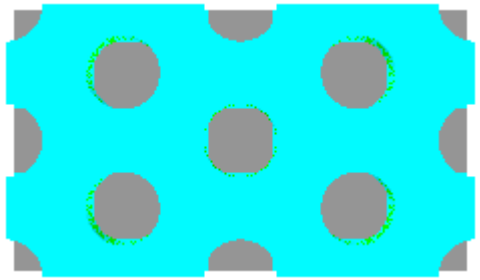

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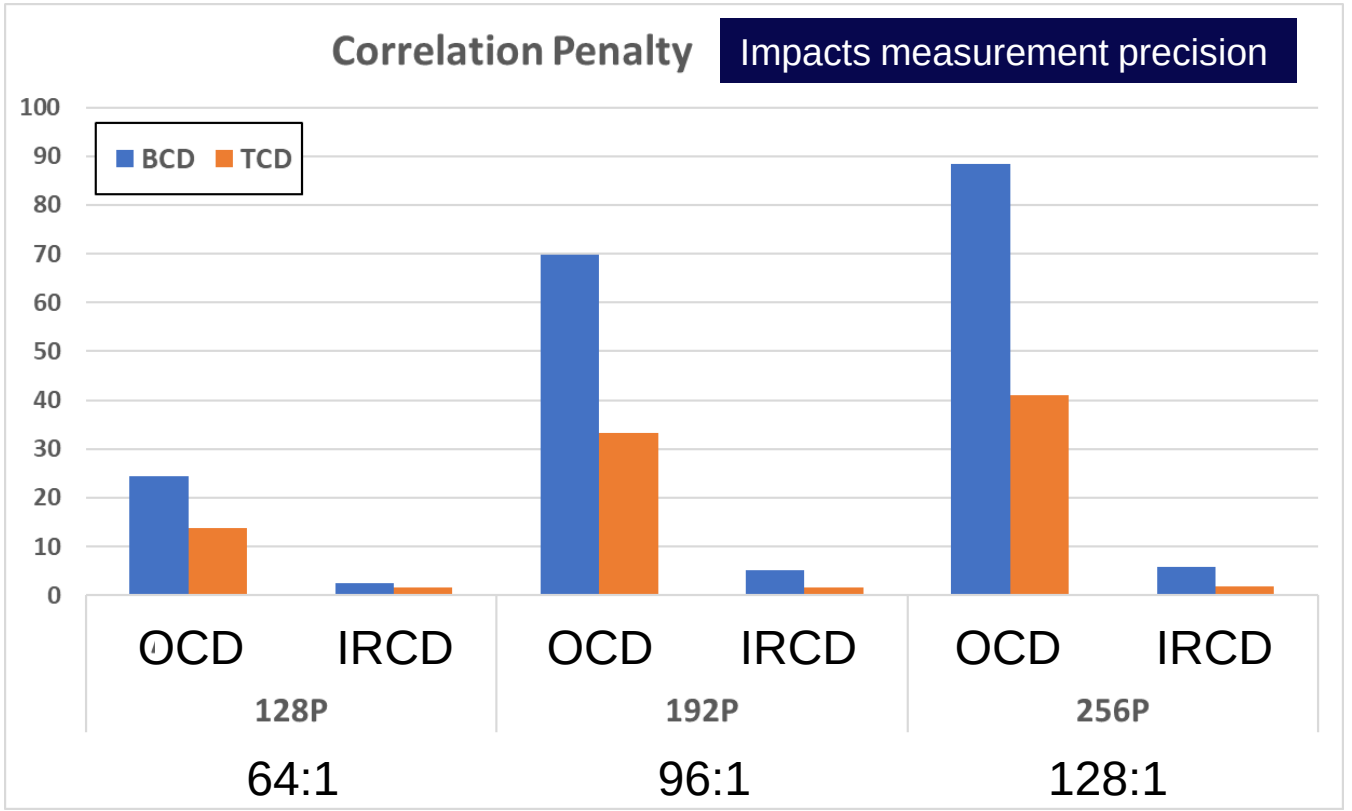

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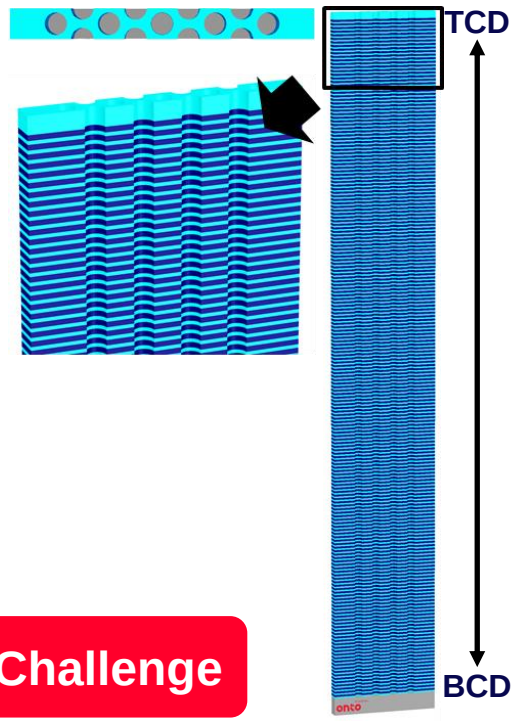

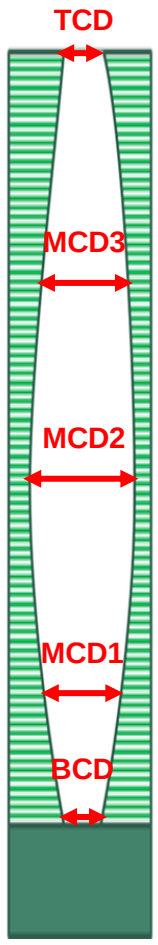

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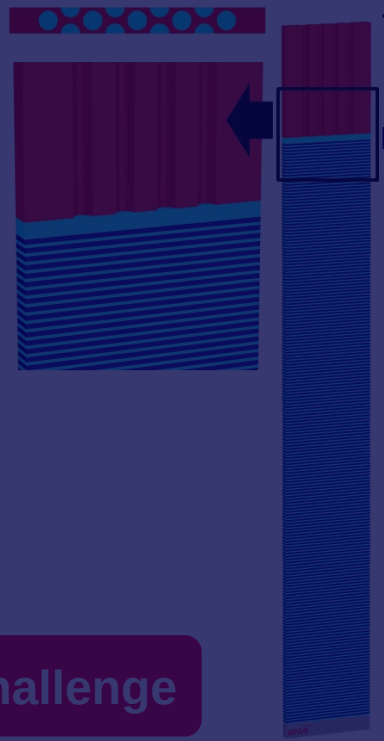

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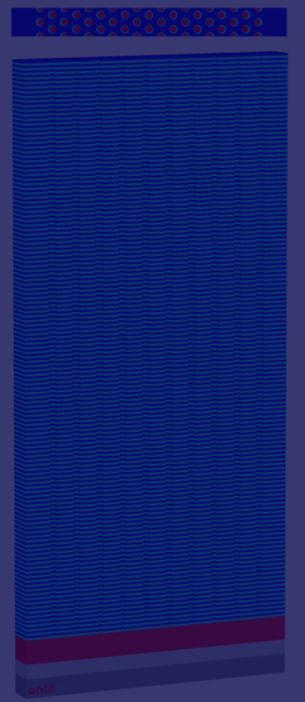
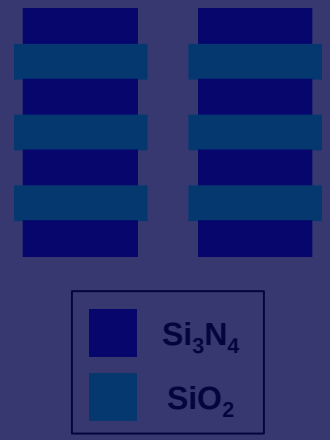
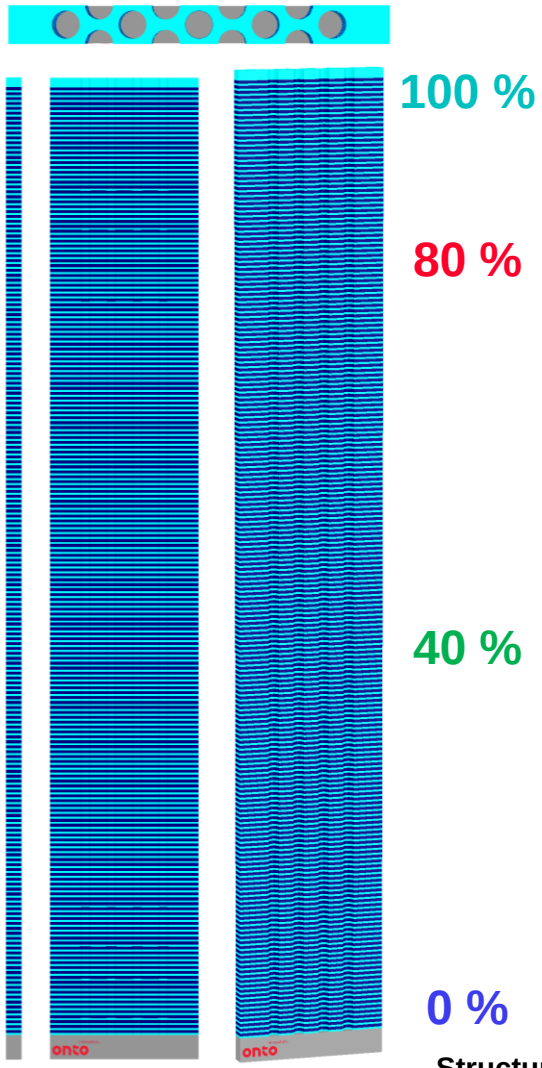




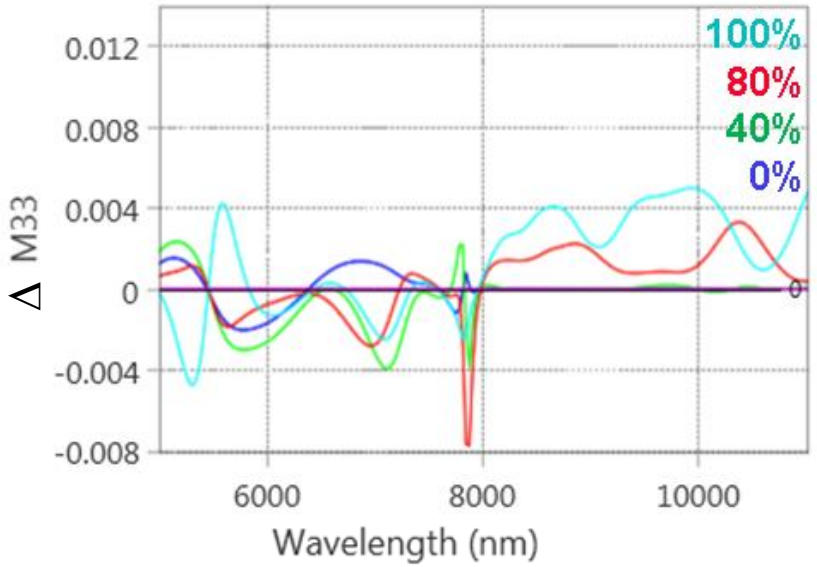
Challenge

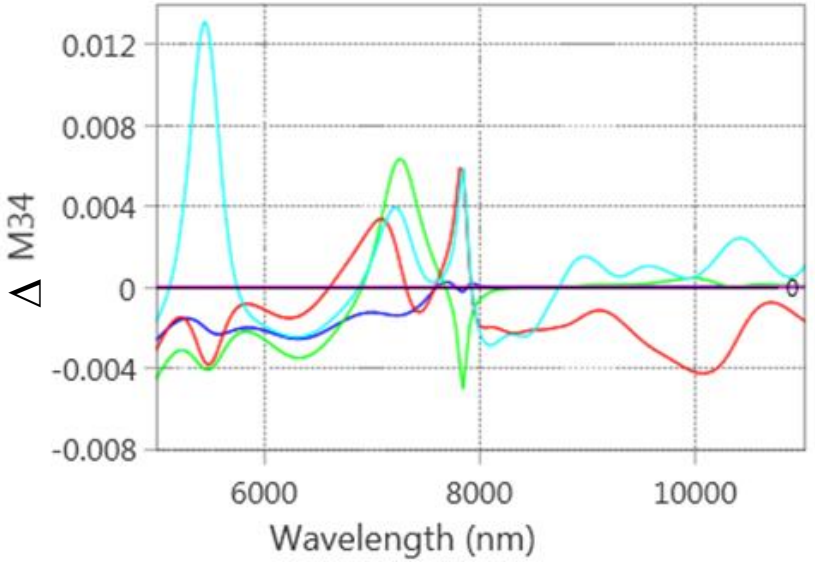
IRCD Simulations of Channel Hole Profile

Spectral sensitivity to changes in channel hole profile



Simulated mid-infrared spectral response of the M33 and M34 Mueller matrix elements





1 nm change in CD at different heights on the channel hole, where 0% indicates the bottom and 100% indicates the top

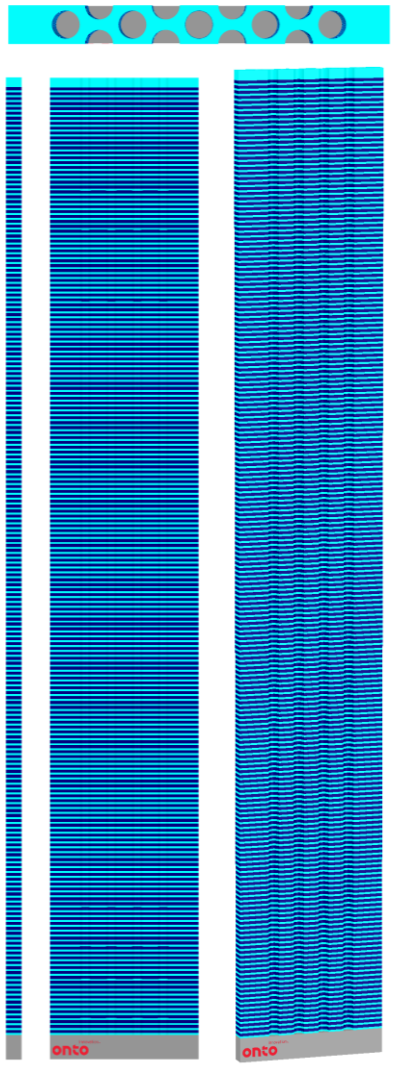
IRCD simulations indicate a high level of unique sensitivity to changes in profile

Structure: 192L 3D NAND SiO_2/Si_3N_4 superlattice pair thickness ~ 50 nm and hole diameter ~100 nm with hexagonal lattice

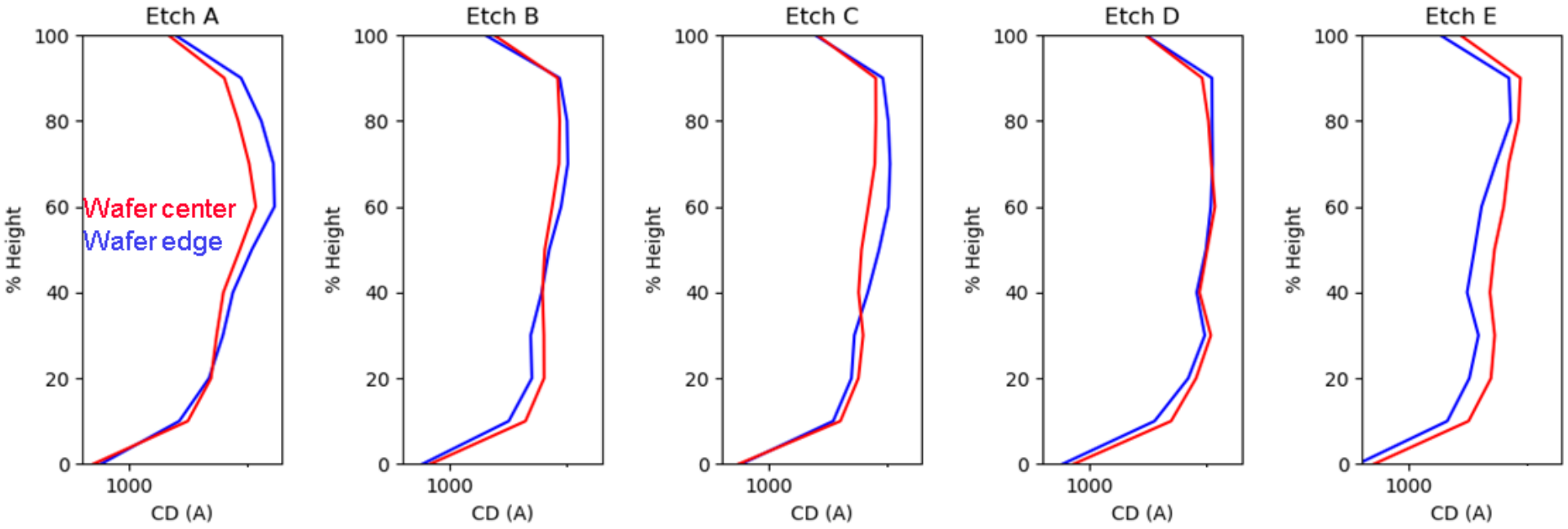
Source: Antonelli, et al. Proc. SPIE 11611, Metrology, Inspection, and Process Control for Semiconductor Manufacturing XXXV, 116111O (22 February 2021).

IRCD Measurements of Channel Hole Profile

Impact of within-wafer etch process



A, B, C, D, and E represent different etch process conditions



IRCD has no limit to the number of measured CDs

IRCD profile varies with etch process condition and wafer position

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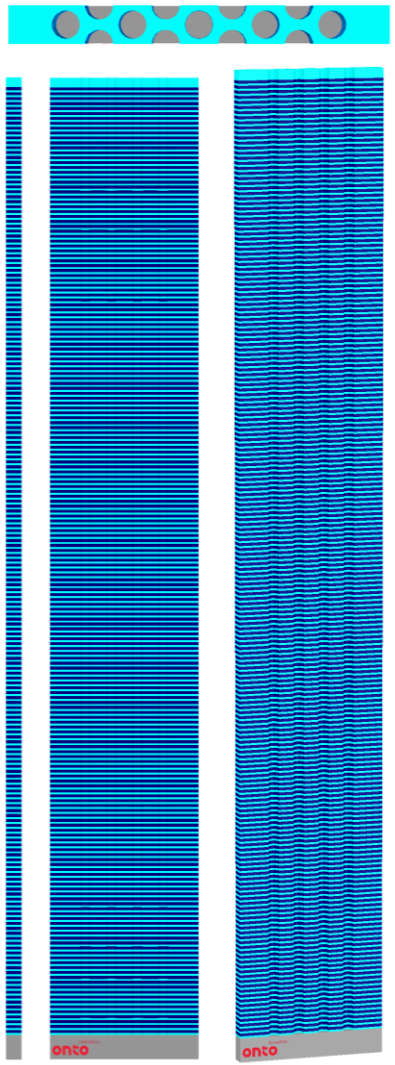

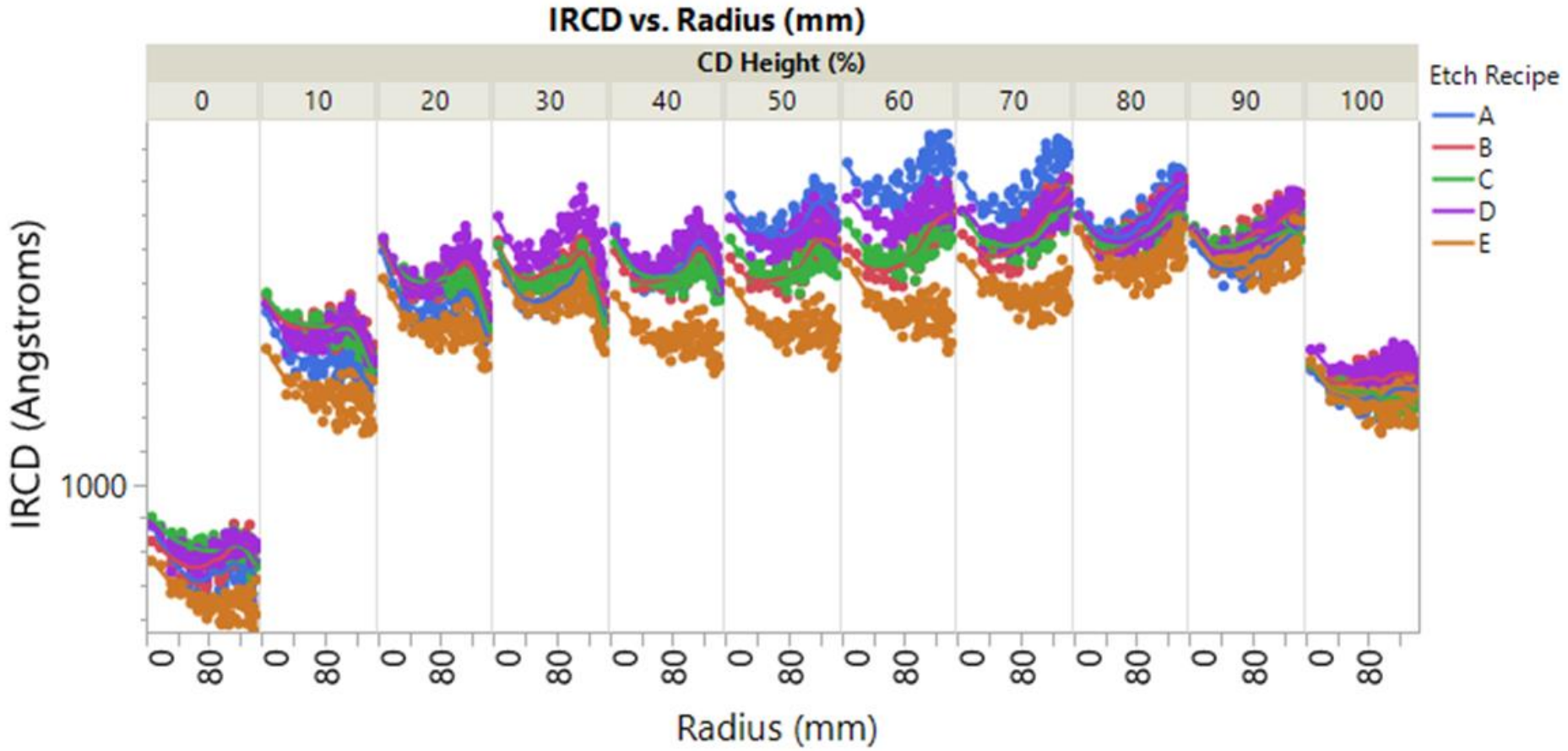

With-in wafer IRCD profile variation is continuous both with radial position and depth

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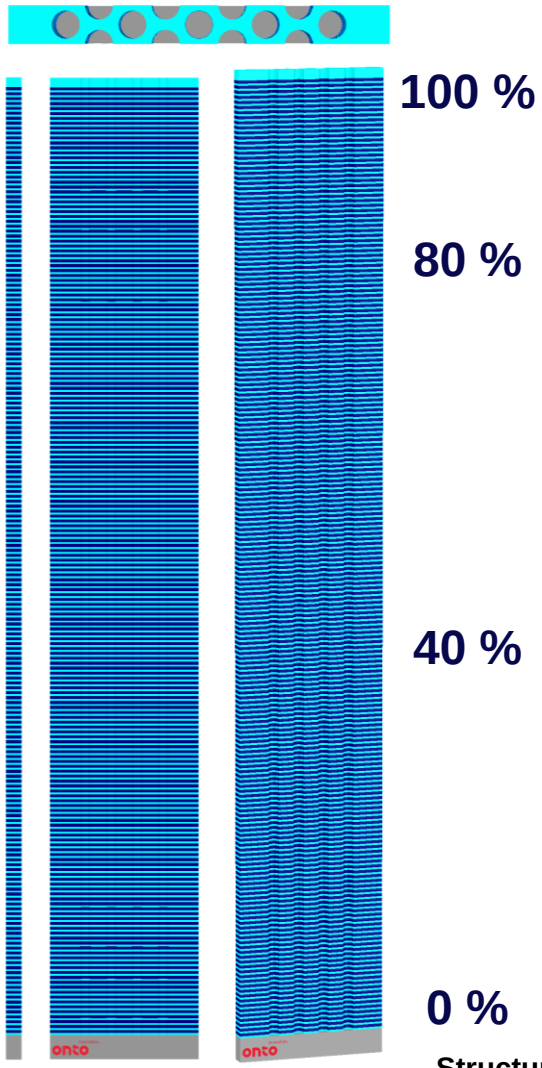
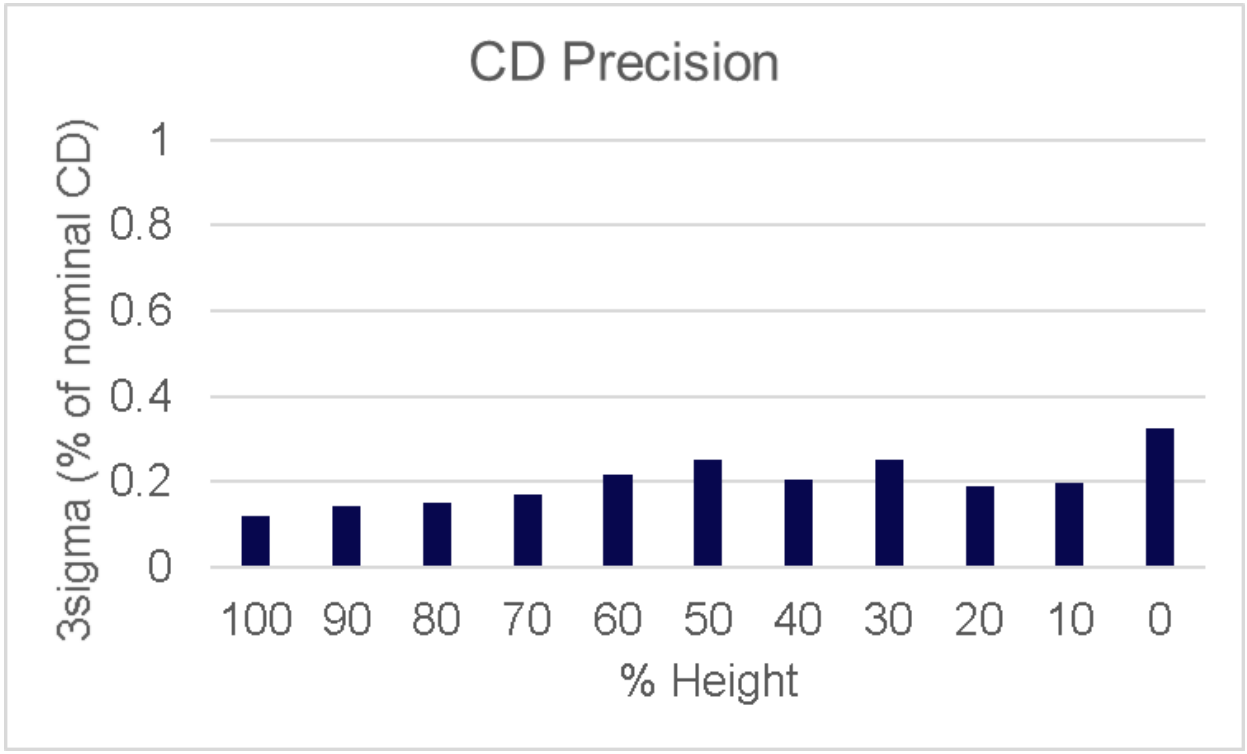
IRCD Measurements of Channel Hole Profile

Measurement precision





Pooled values from 12 sites and 5 cycles

IRCD profile measurements have Angstrom level precision

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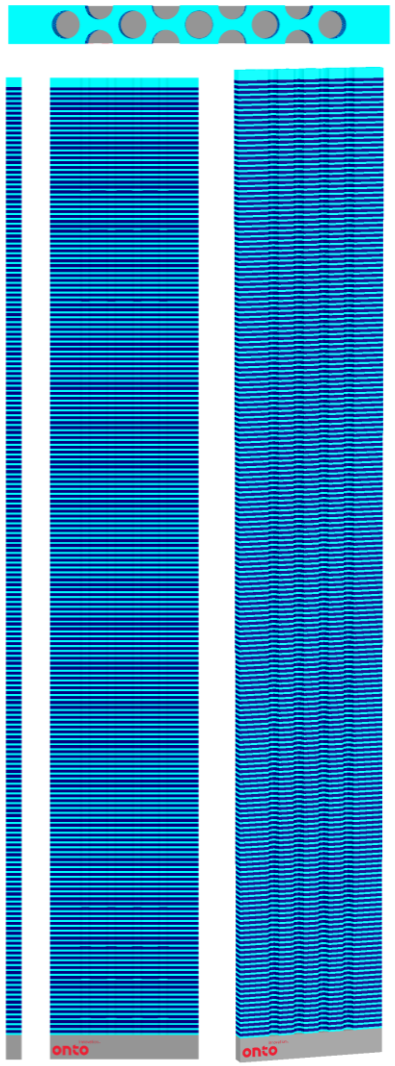
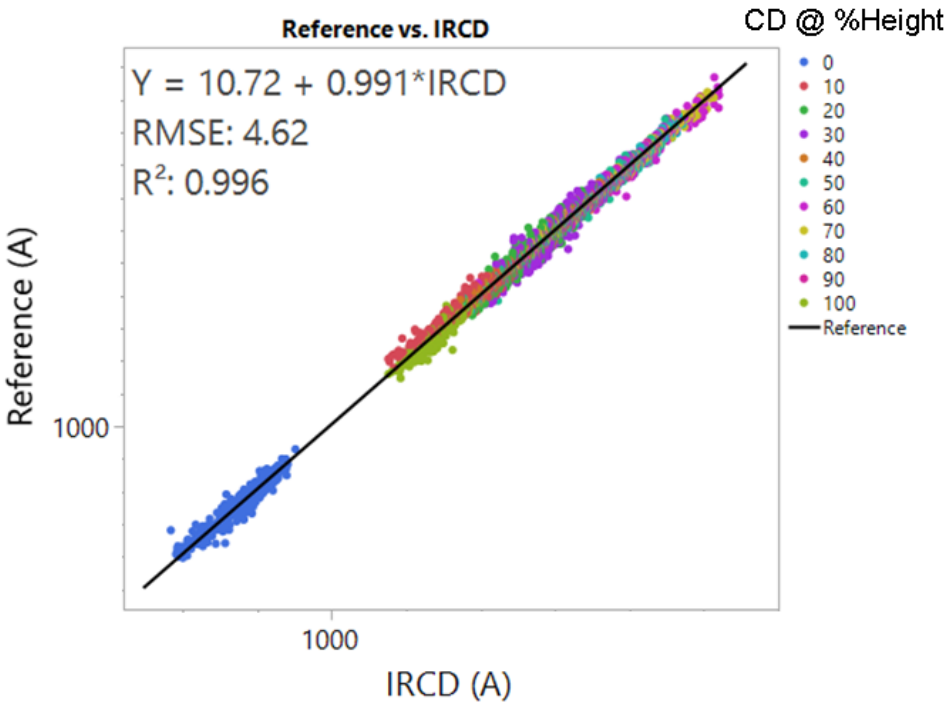
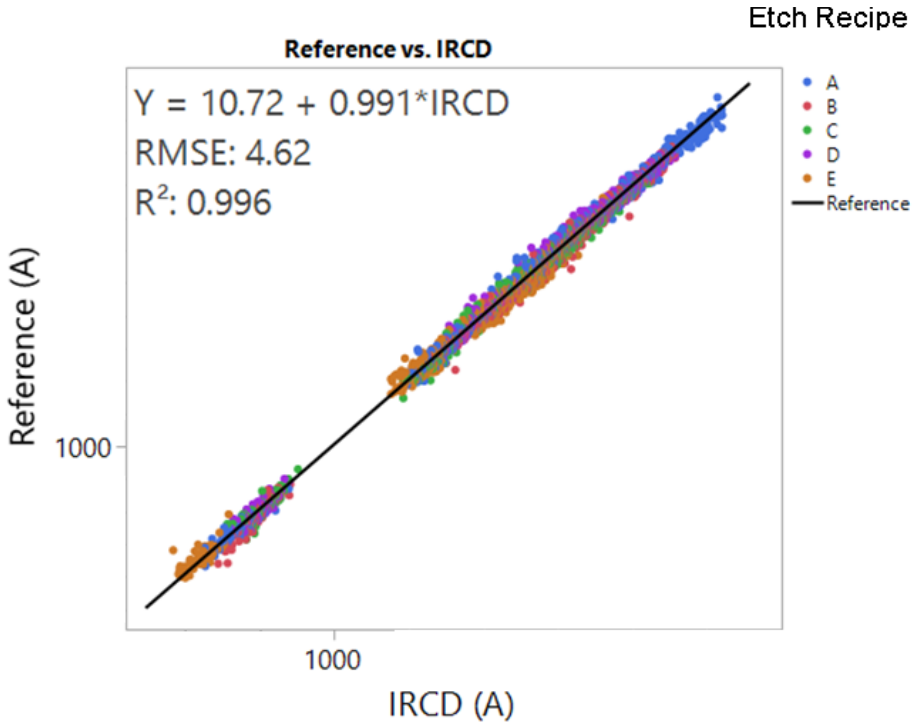
IRCD Measurements of Channel Hole Profile

Comparison of profile for IRCD and destructive reference







IRCD profile agrees well with reference profile for all etch process conditions

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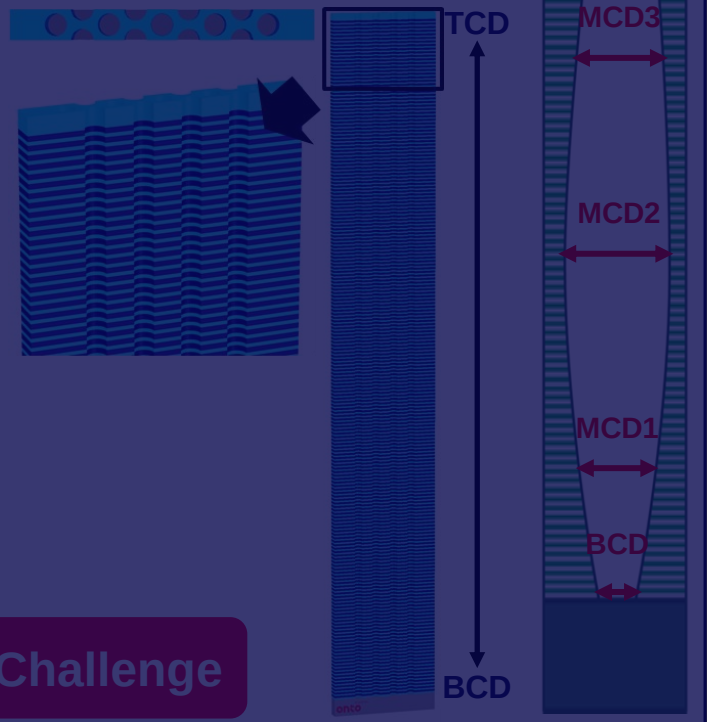

Challenge

Patterning: Profile

Hardmask Etch

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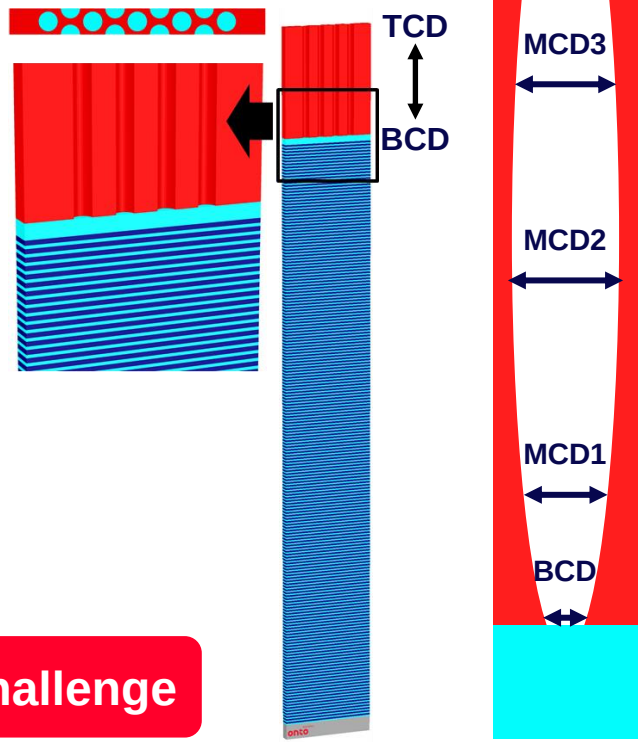

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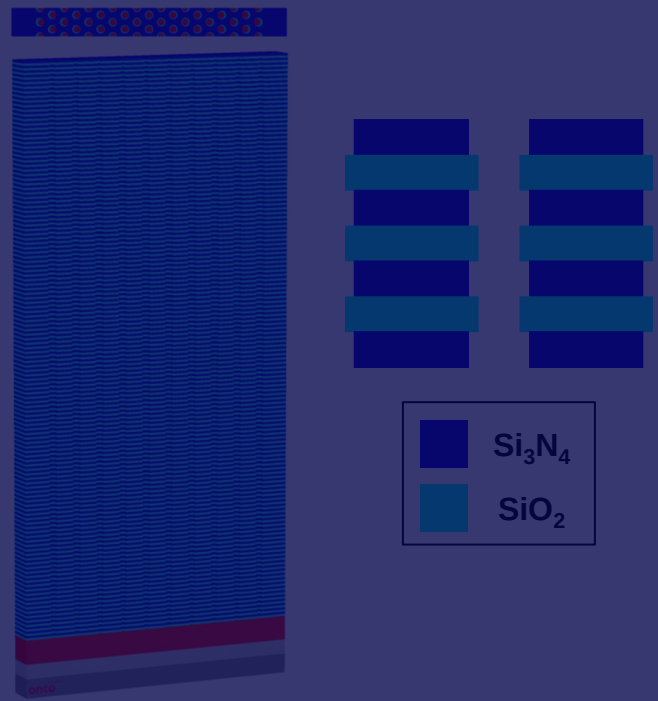


Challenge

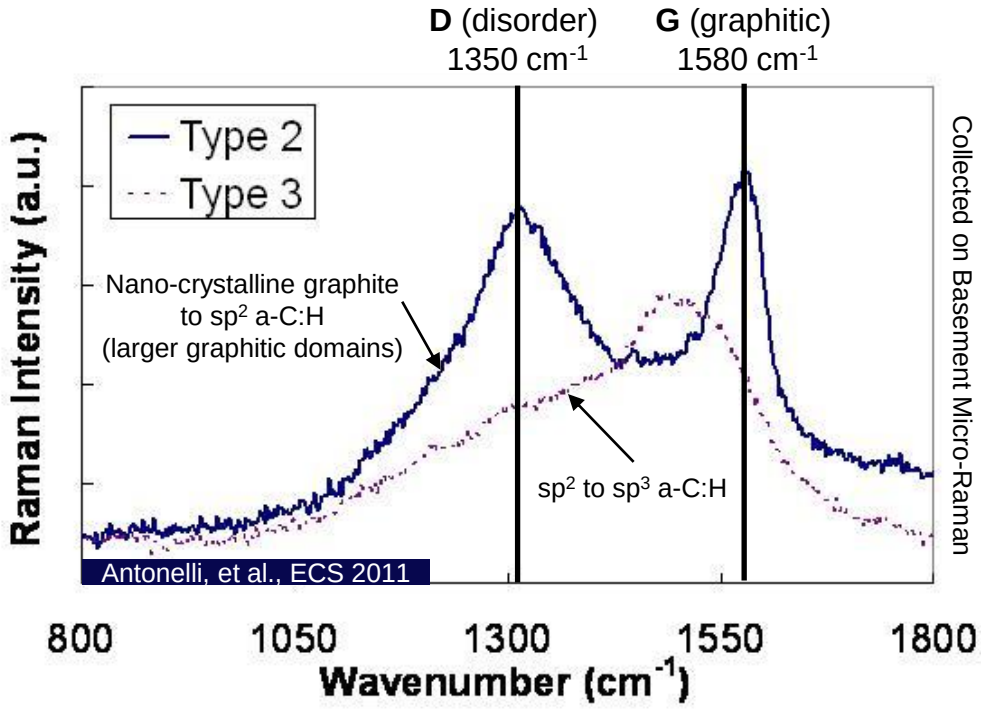
Amorphous Carbon Hardmask Materials

A complex material with only two atoms

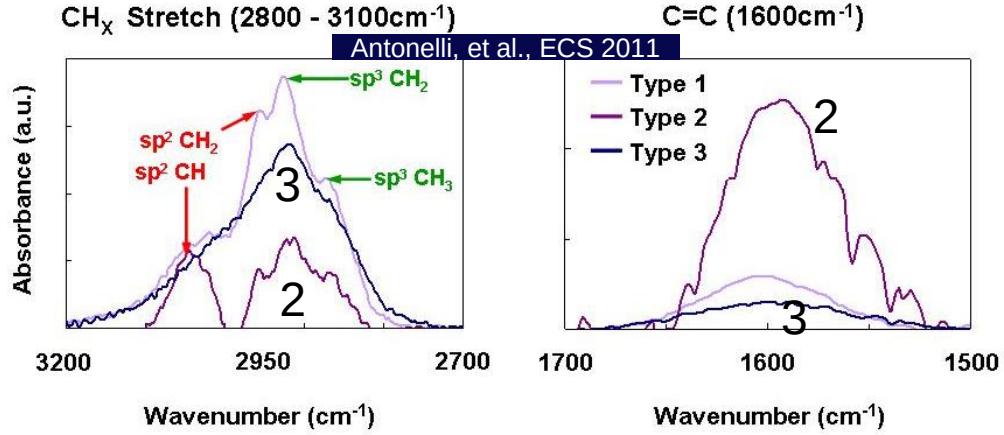
TABLE I. AHM Material Properties.

Antonelli, et al., ECS 2011

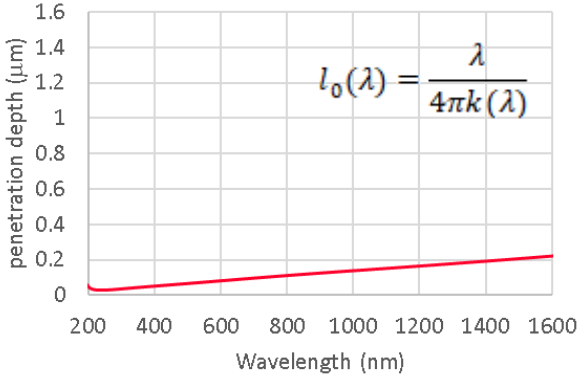
	% C by atom	% H by atom	n @ 633 nm	k @ 633 nm	Density (g cm-3)	Hardness (GPa)
Type 1	56	42	1.81	0.05	1.23	2.7
Type 2	70	27	2.00	0.38	1.44	1.8
Type 3	60	40	1.99	<0.10	1.48	9.5

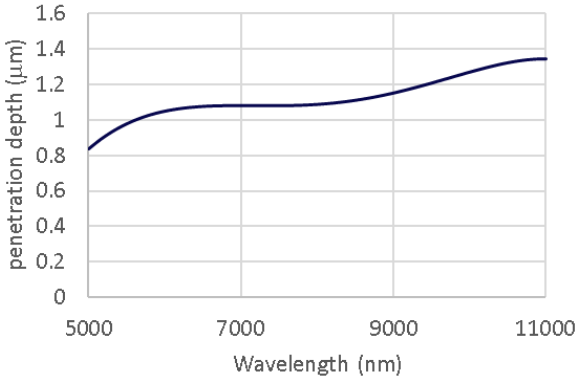


FTIR Measurements



Optical penetration depth for highly graphic a-C:H



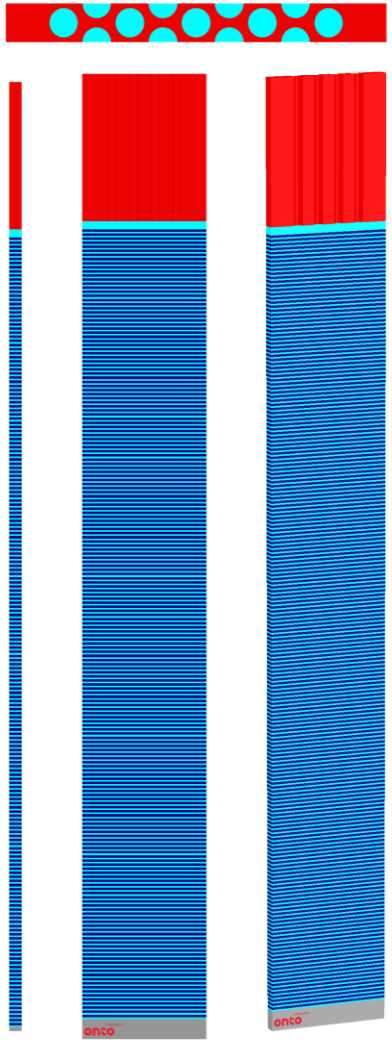


Highly graphitic a-C:H materials have much higher transparency in the mid-infrared

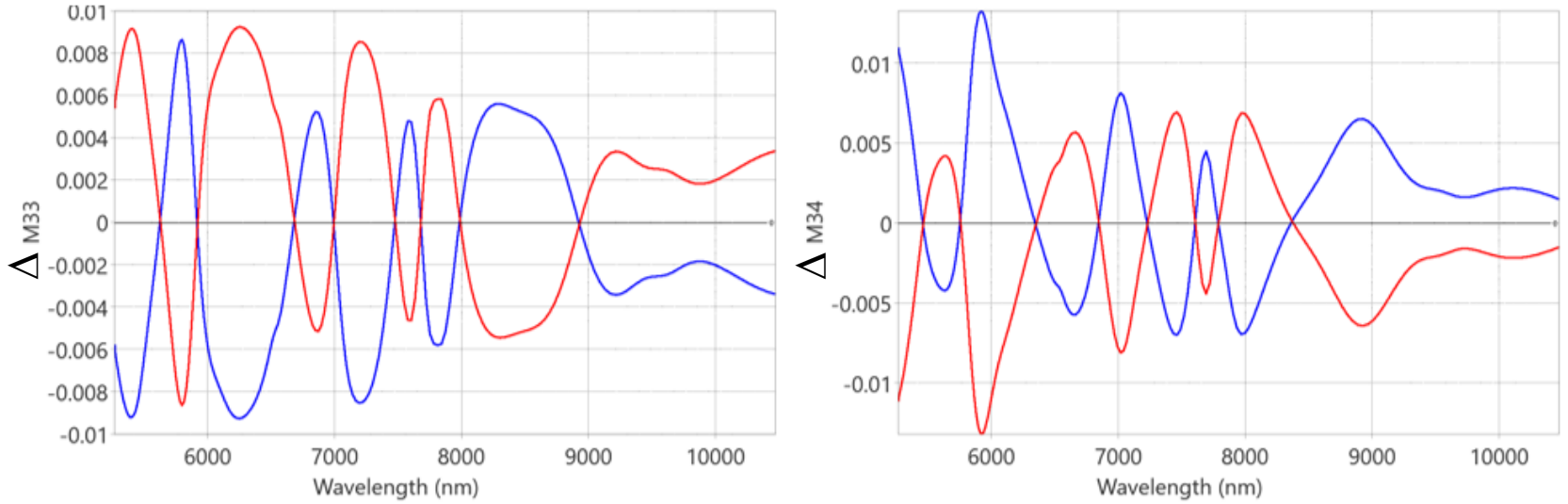
Source: G. A. Antonelli, et al., ECS Meeting, Montreal, CA, May (2011)

IRCD Simulations of a-C:H Hardmask Profile

Spectral sensitivity to changes in a-C:H hardmask



Simulated mid-infrared spectral response of the M33 and M34 Mueller matrix elements



±10 nm change in > 2.5 μm thick a-C:H hardmask on 3D NAND structure

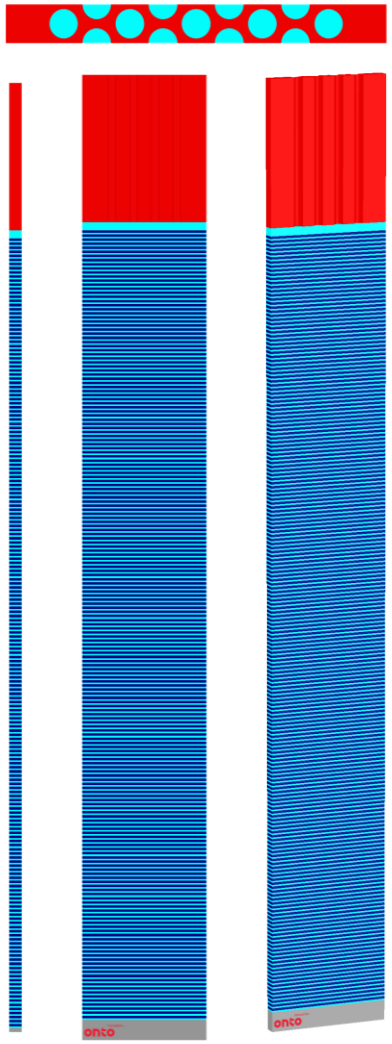
IRCD simulations indicate a high level of sensitivity to changes in a-C:H hardmask

Structure: 192L 3D NAND SiO_2/Si_3N_4 superlattice pair thickness ~ 50 nm, hole diameter ~100 nm with hexagonal lattice, and > 2 μm a-C:H hard mask

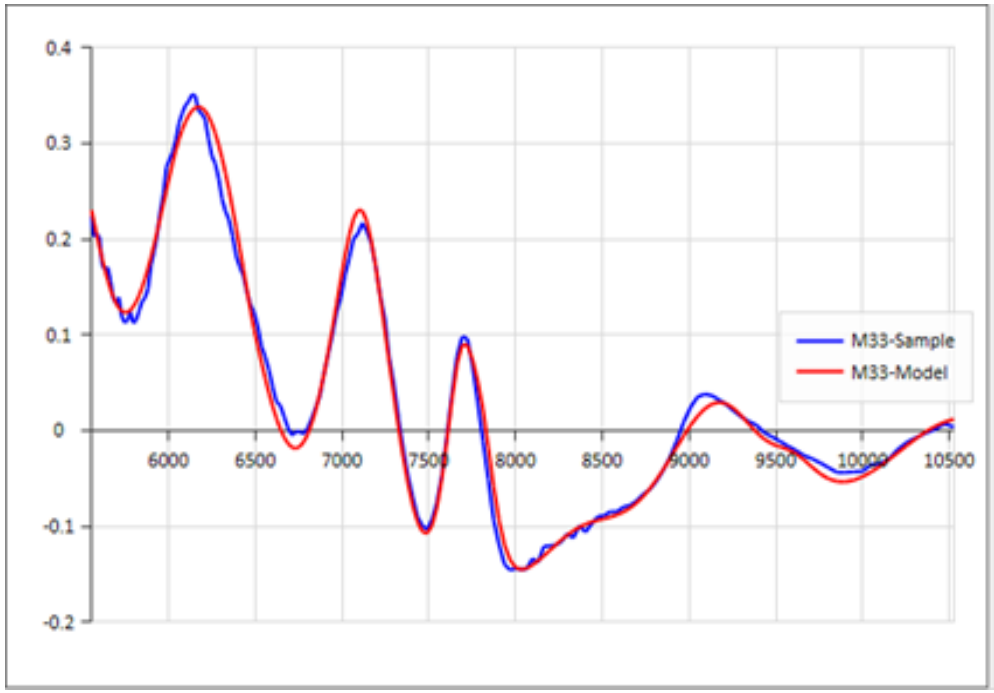
Source: Antonelli, et al. Proc. SPIE 11611, Metrology, Inspection, and Process Control for Semiconductor Manufacturing XXXV, 116111O (22 February 2021).

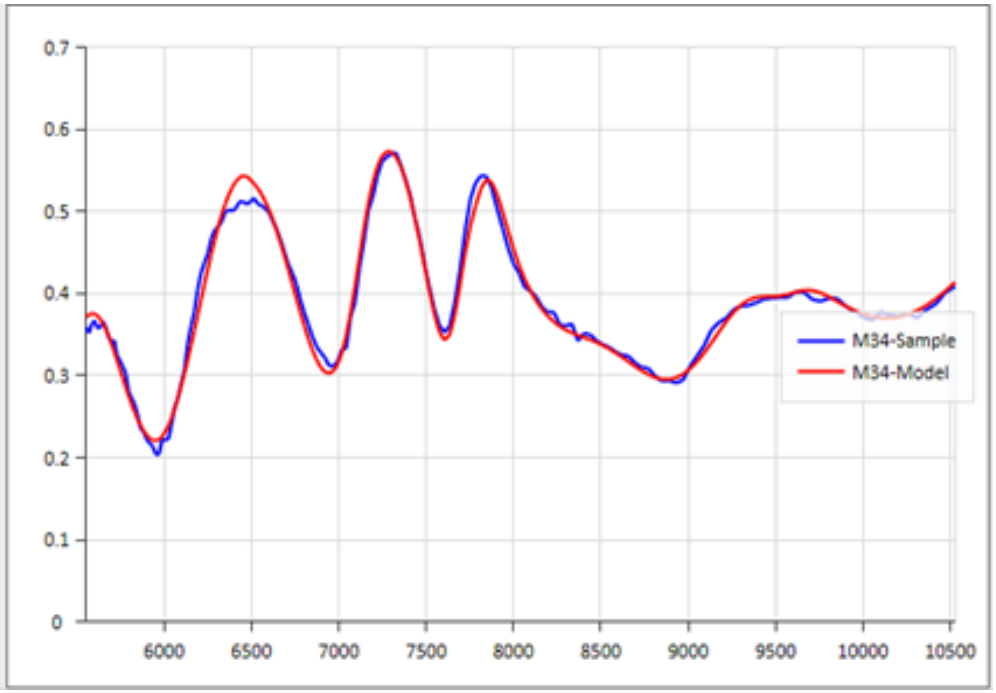
IRCD Measurements of a-C:H Hardmask Profile

Comparison of simulation and measurement



Simulation vs measurement of the M33 and M34 Mueller matrix elements





Oscillations at < 8000 nm are the result of penetration of light through the a-C:H hardmask

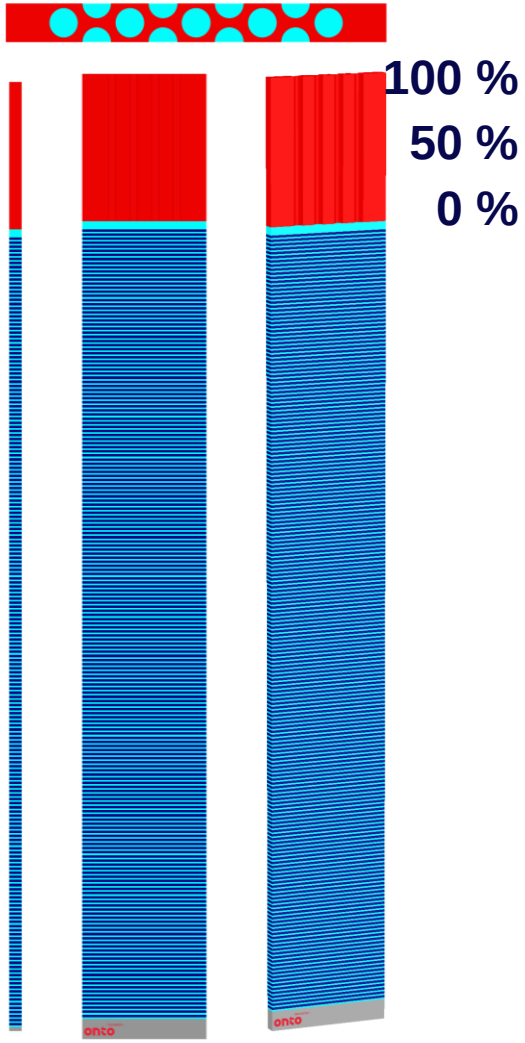
IRCD simulation and measurements agree well

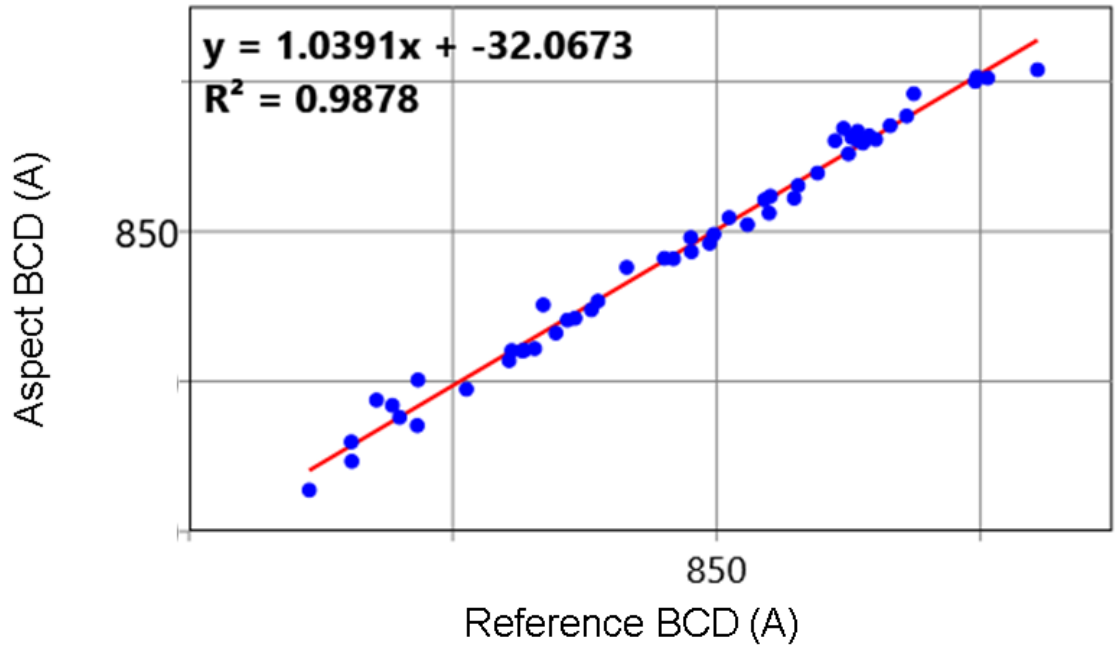
Structure: 192L 3D NAND SiO_2/Si_3N_4 superlattice pair thickness ~ 50 nm, hole diameter ~100 nm with hexagonal lattice, and > 2 μm a-C:H hard mask

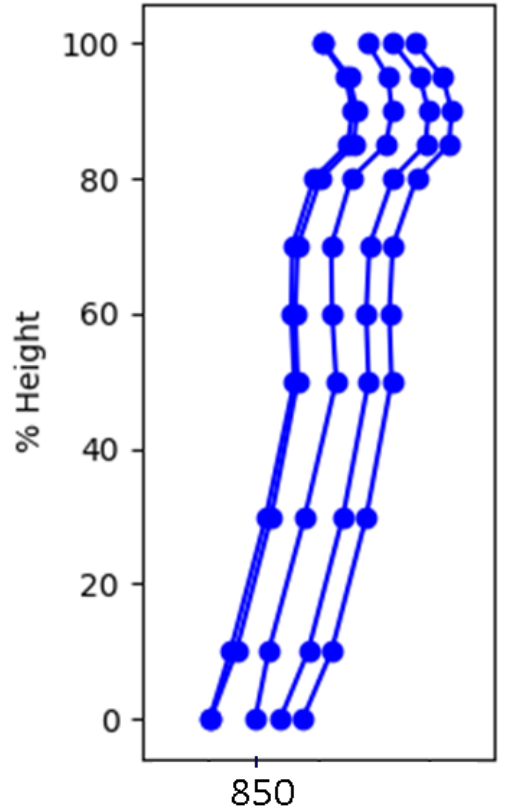
Source: Antonelli, et al. Proc. SPIE 11611, Metrology, Inspection, and Process Control for Semiconductor Manufacturing XXXV, 116111O (22 February 2021).

IRCD Measurements of a-C:H Hardmask Profile

Comparison of profile for IRCD and destructive reference







IRCD profile agrees well with reference profile

Structure: 192L 3D NAND SiO_2/Si_3N_4 superlattice pair thickness ~ 50 nm, hole diameter ~100 nm with hexagonal lattice, and > 2 μm a-C:H hard mask

Source: Antonelli, et al. Proc. SPIE 11611, Metrology, Inspection, and Process Control for Semiconductor Manufacturing XXXV, 116111O (22 February 2021).

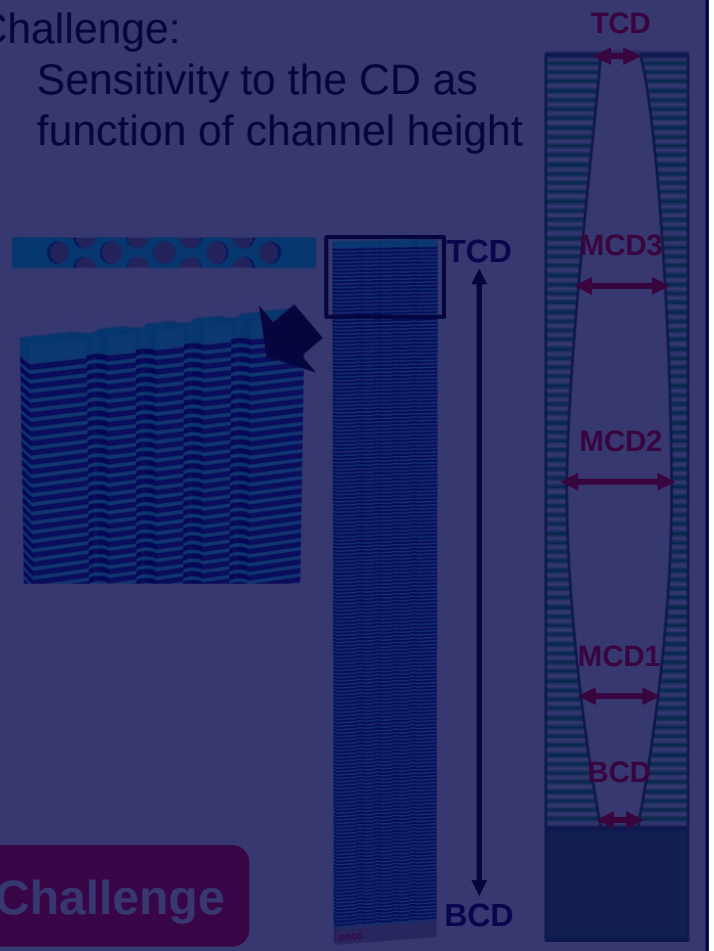
Challenges in 3D Memory Optical Metrology

Patterning: Profile

Channel Hole Etch

Challenge:

- Sensitivity to the CD as function of channel height



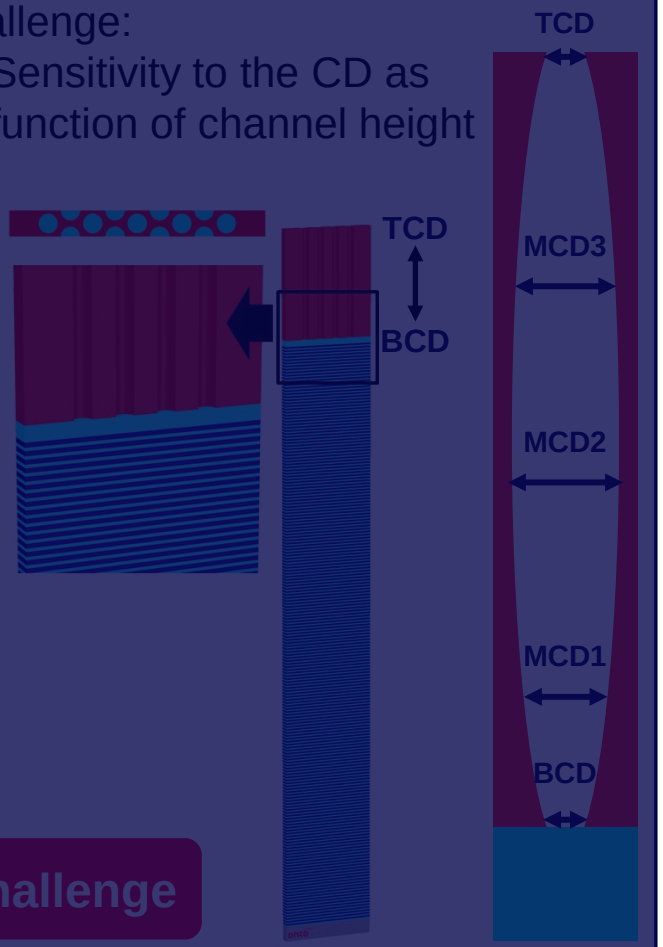
Challenge

Patterning: Profile

Hardmask Etch

Challenge:

- Sensitivity to the CD as function of channel height



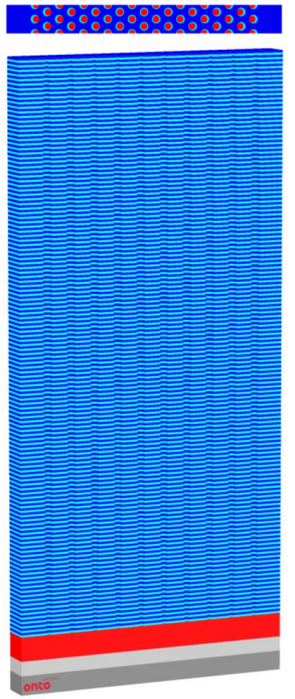
Challenge

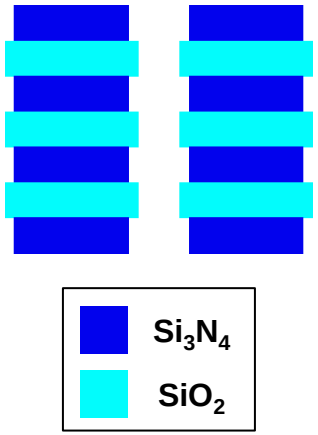
Patterning: Profile

Si_3N_4 Recess

Challenge:

- Sensitivity to recess of Si_3N_4

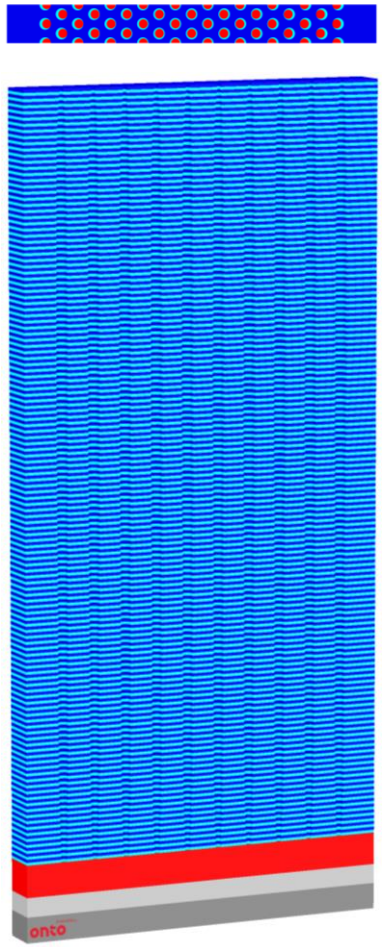




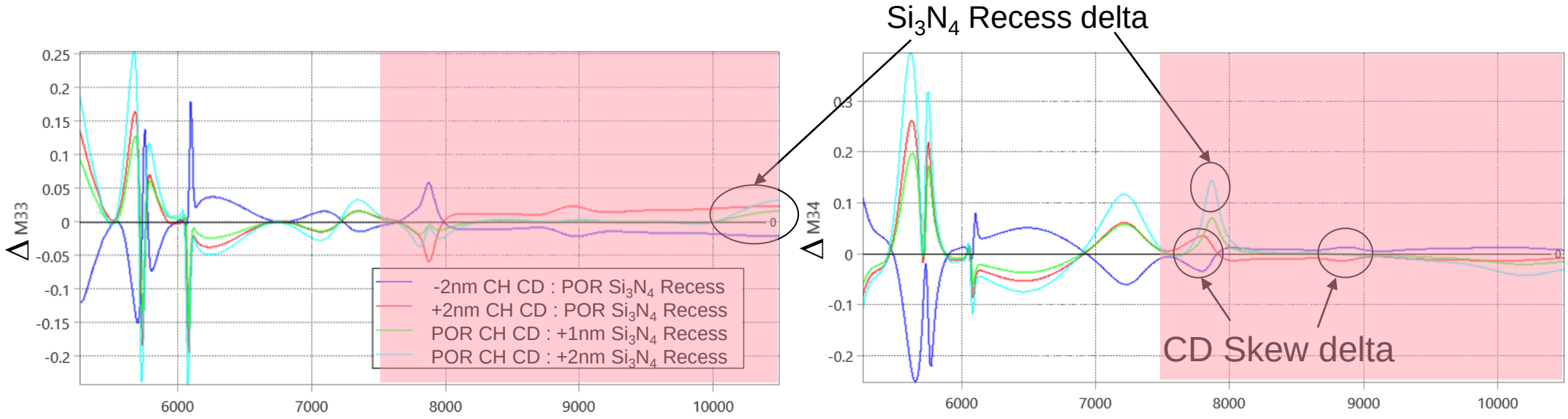
Challenge

IRCD Simulations of Si_3N_4 Recess

Spectral sensitivity to changes in Si_3N_4 recess



Simulated mid-infrared spectral response of the M33 and M34 Mueller matrix elements



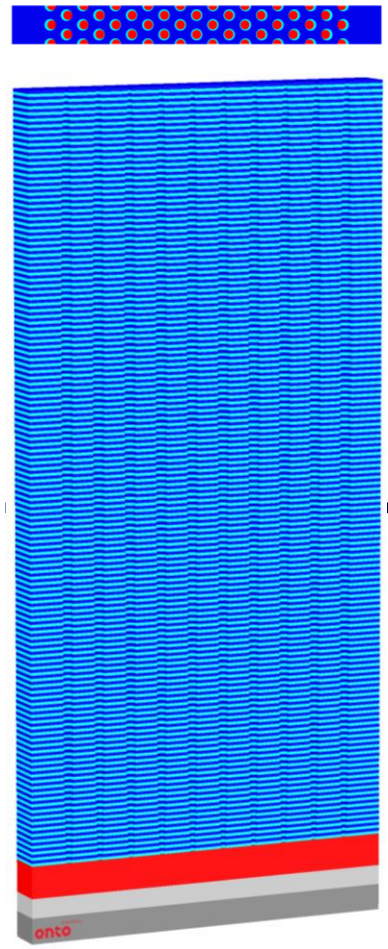
IRCD simulations exhibit a high level of decorrelated spectral response to Lateral Si_3N_4 Recess

Structure: 192L 3D NAND SiO_2/Si_3N_4 superlattice pair thickness ~ 50 nm and hole diameter ~100 nm with hexagonal lattice

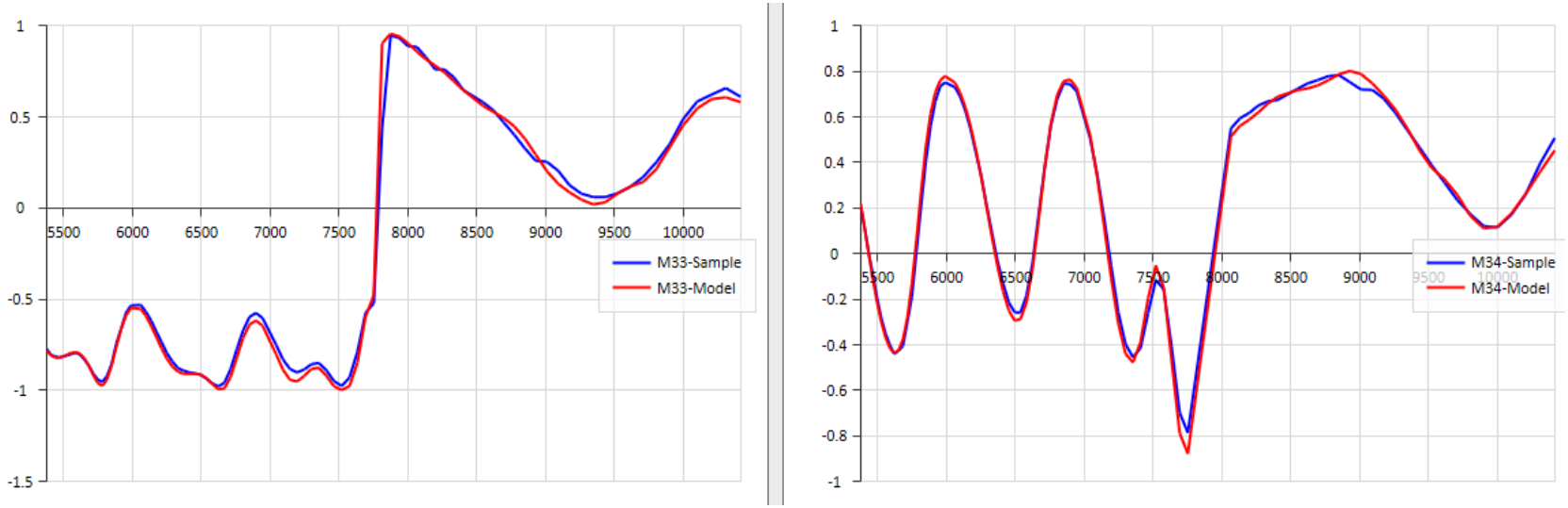
Source: Keller, et al. Proc. SPIE 12053, Metrology, Inspection, and Process Control for Semiconductor Manufacturing XXXVI, 120530T (26 May 2022).

IRCD Measurements of Si_3N_4 Recess

Comparison of simulation and measurement



Simulation vs measurement of the M33 and M34 Mueller matrix elements



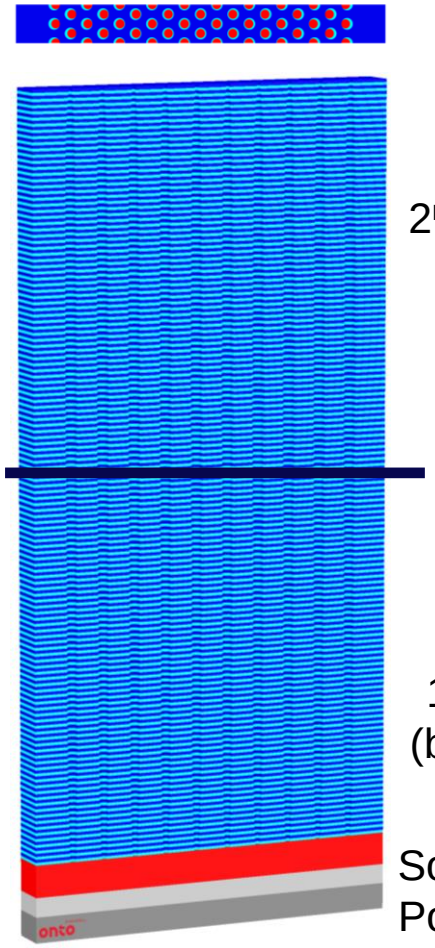
IRCD simulation and measurements agree well

Structure: 192L 3D NAND SiO_2/Si_3N_4 superlattice pair thickness ~ 50 nm and hole diameter ~100 nm with hexagonal lattice

Source: Keller, et al. Proc. SPIE 12053, Metrology, Inspection, and Process Control for Semiconductor Manufacturing XXXVI, 120530T (26 May 2022).

IRCD Measurements of Si_3N_4 Recess

Comparison of profile for IRCD and destructive reference



2nd Tier (top)

1st Tier (bottom)

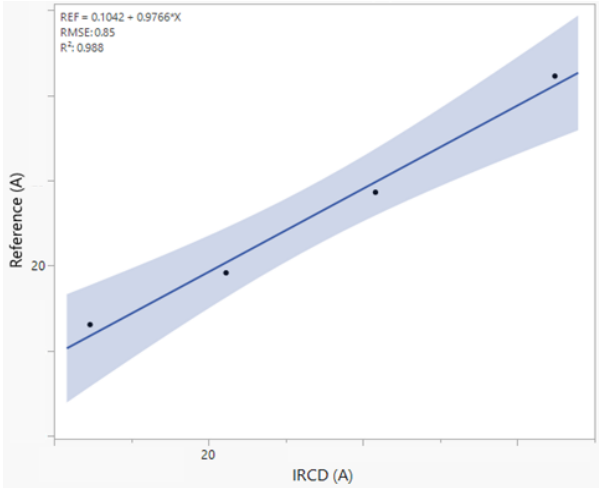
Source Poly-Si

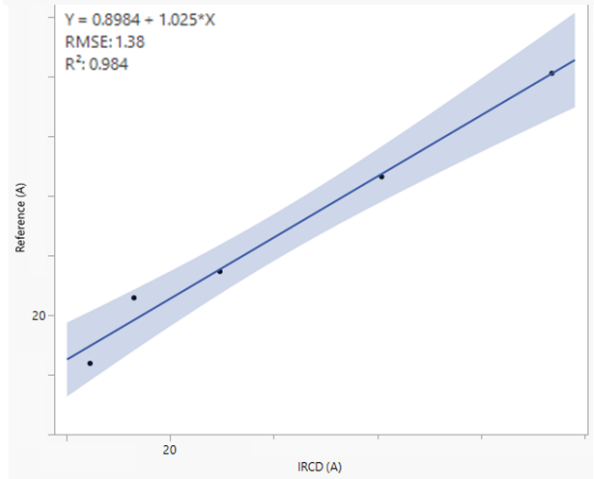
2nd Tier Post Channel Hole Etch Structure

1st Tier Post Channel Hole Etch Structure

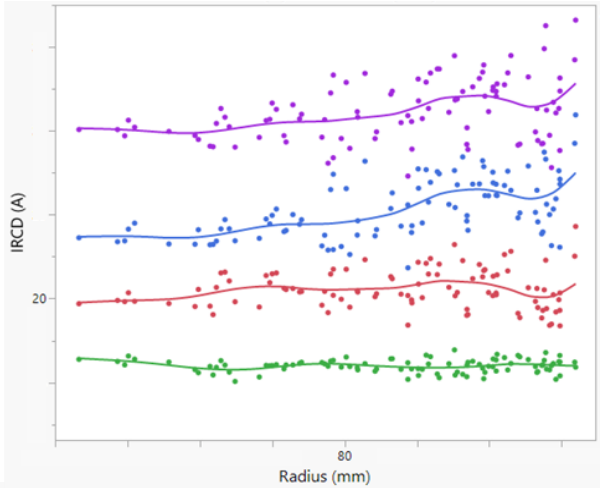
IRCD measurements agree with Reference metrology and have consistent radial trends

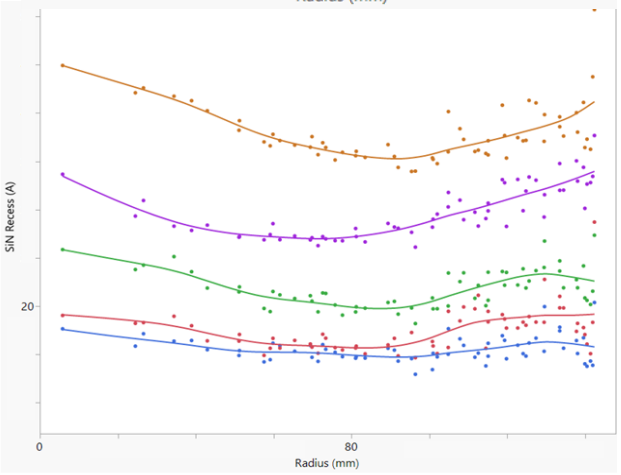
Correlation to Reference





Radial Trend





Structure: 192L 3D NAND SiO_2/Si_3N_4 superlattice pair thickness ~ 50 nm and hole diameter ~100 nm with hexagonal lattice

Source: Keller, et al. Proc. SPIE 12053, Metrology, Inspection, and Process Control for Semiconductor Manufacturing XXXVI, 120530T (26 May 2022).

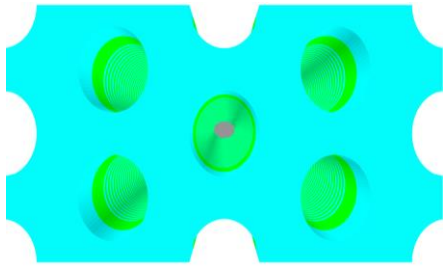
Additional Challenges in 3D Memory Optical Metrology

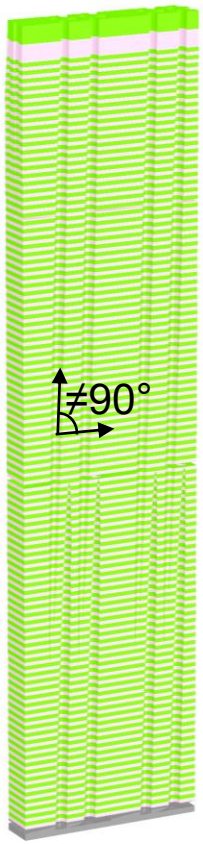
Patterning: Profile

Channel Hole Etch Tilt

Challenge:

- Sensitivity to tilt
- Sensitivity to hole shape





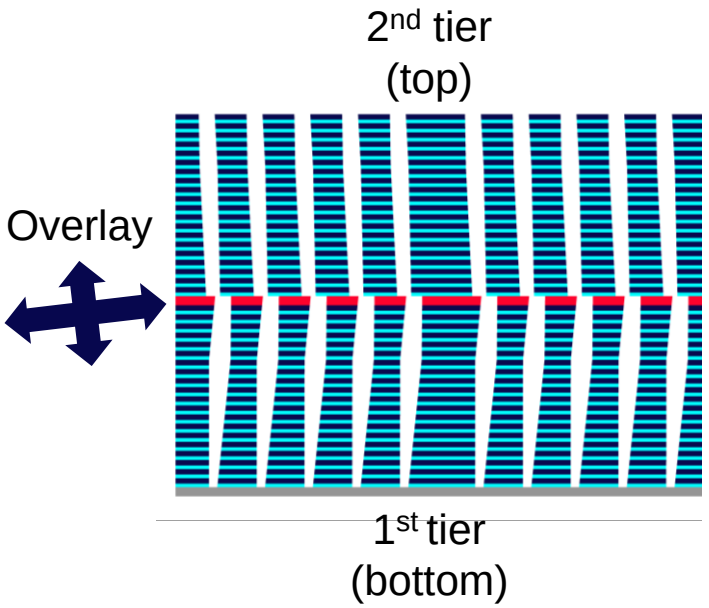
Challenge

Patterning: Overlay

Tier to Tier Overlay

Challenge:

- Sensitivity to the overlay of top and bottom tier



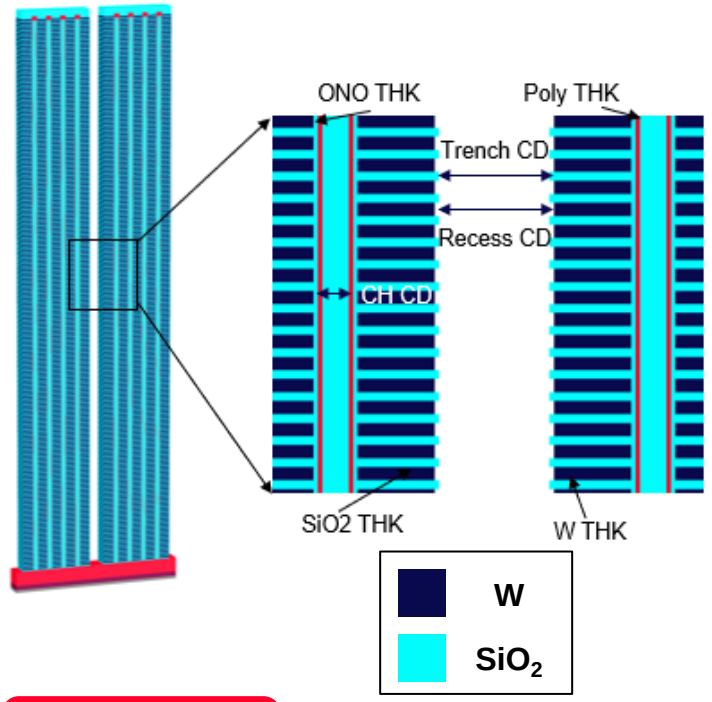
Challenge

Patterning : Profile

W Recess

Challenge:

- Sensitivity to recess of Tungsten



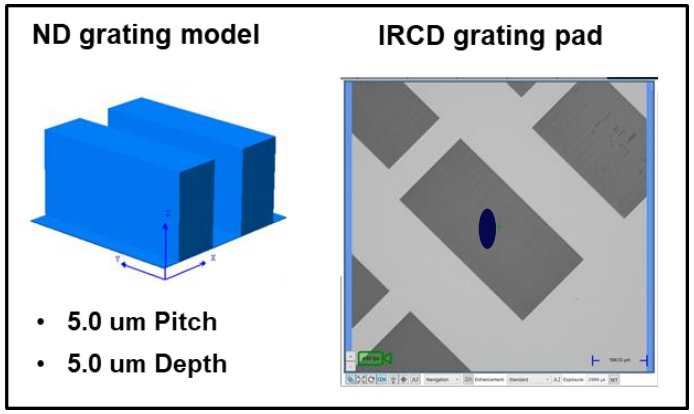
Challenge

Adding Capabilities to Address New Problems

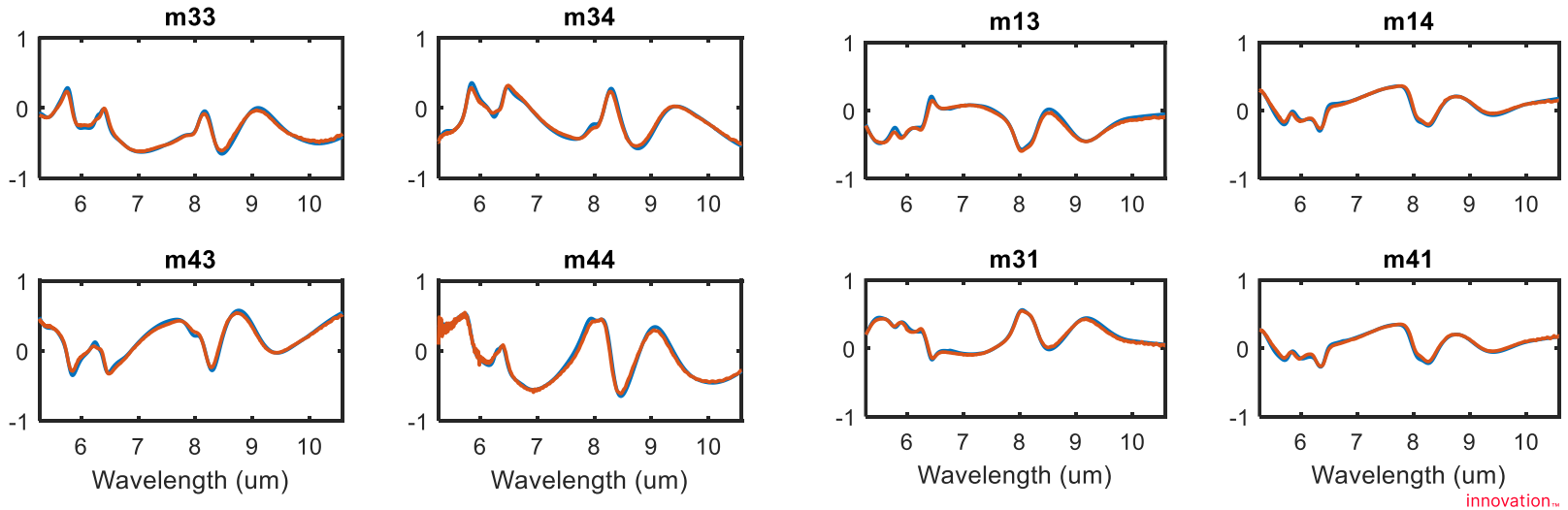
Increasing Mueller Matrix Elements

- Two phase modulation components
- Enables off-diagonal element of MM for tilt/asymmetry measurements

$$M = \begin{bmatrix} M_{11} & \blacksquare & M_{13} & M_{14} \\ \blacksquare & \blacksquare & \blacksquare & \blacksquare \\ M_{31} & \blacksquare & M_{33} & M_{34} \\ M_{41} & \blacksquare & M_{43} & M_{44} \end{bmatrix}$$



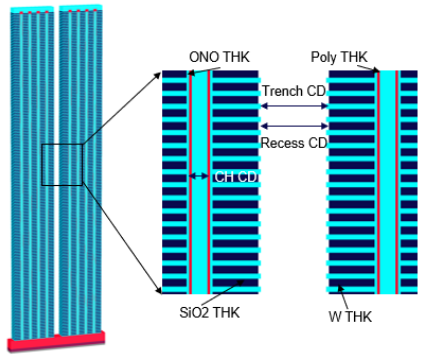
Measurement vs Model

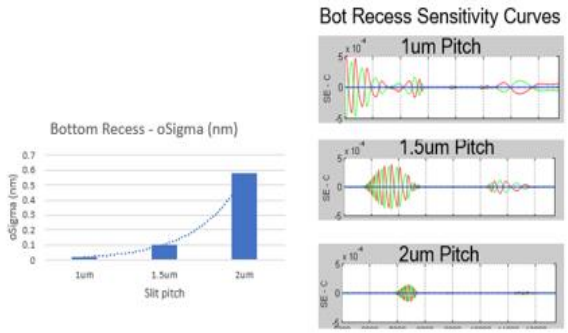


IRCD Measurements of W Recess

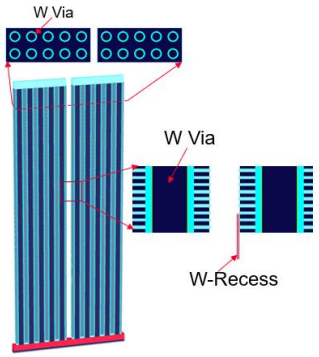
Solving High Value Problems with Innovative Target Design

- **Problem Statement**: Measure the W-Recess @ the bottom of WL Slit
  - Penetration depth decreases exponentially with pitch increase



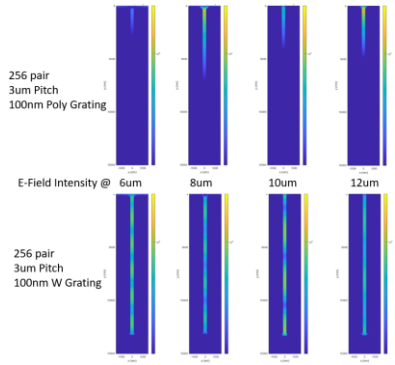


- **Solution**: Create a design rule compliant target that utilizes W though-array vias to couple MIR light to the bottom of the slit

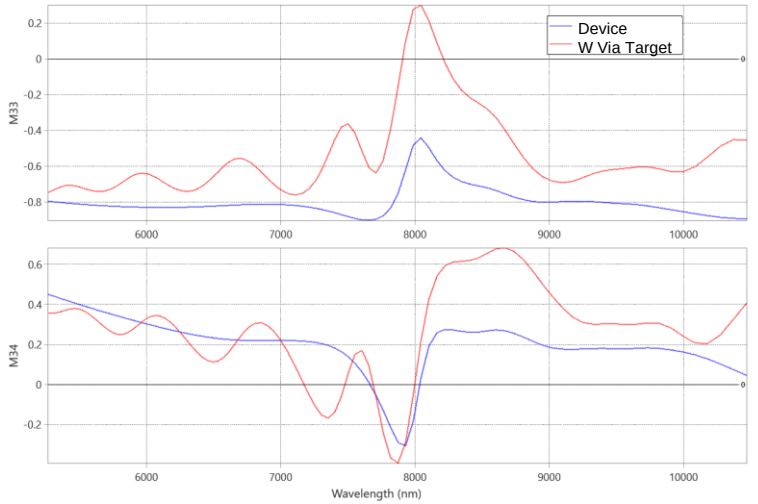


VtP Target Structure

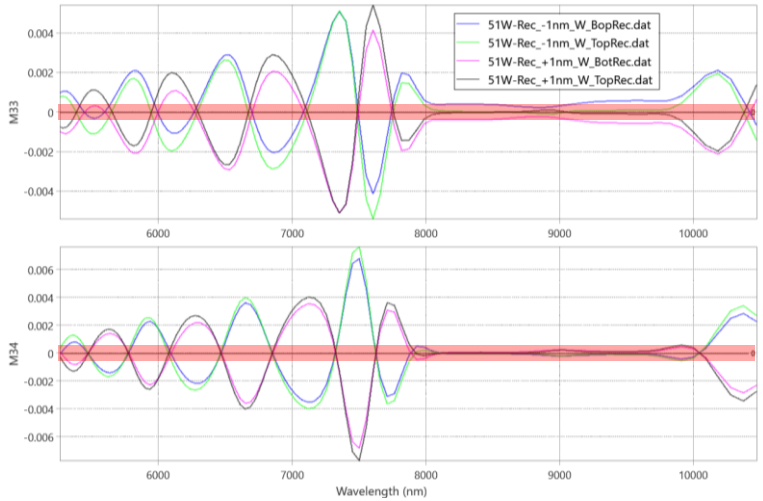
FDFD E-Field Simulation



W Recess - Device vs Target



W Recess Target Sensitivity (+/-1 nm)



Source: N. Keller & G.A. Antonelli, US Patent Application # 17/231,508

Conclusions

- 3D NAND has a wide variety of unique and challenging metrology problems
- OCD can address a broad subset but not all challenges
- IRCD is a fast and non-destructive metrology complementary to OCD
- Profile interrogation with IRCD for channel hole, hardmask etch, and Si_3N_4 recess demonstrated
- Composition as contrast mechanism could have far-reaching applications

Thank You

谢谢 | 謝謝	ありがとう	Obrigado
Danke	감사합니다	Merci

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