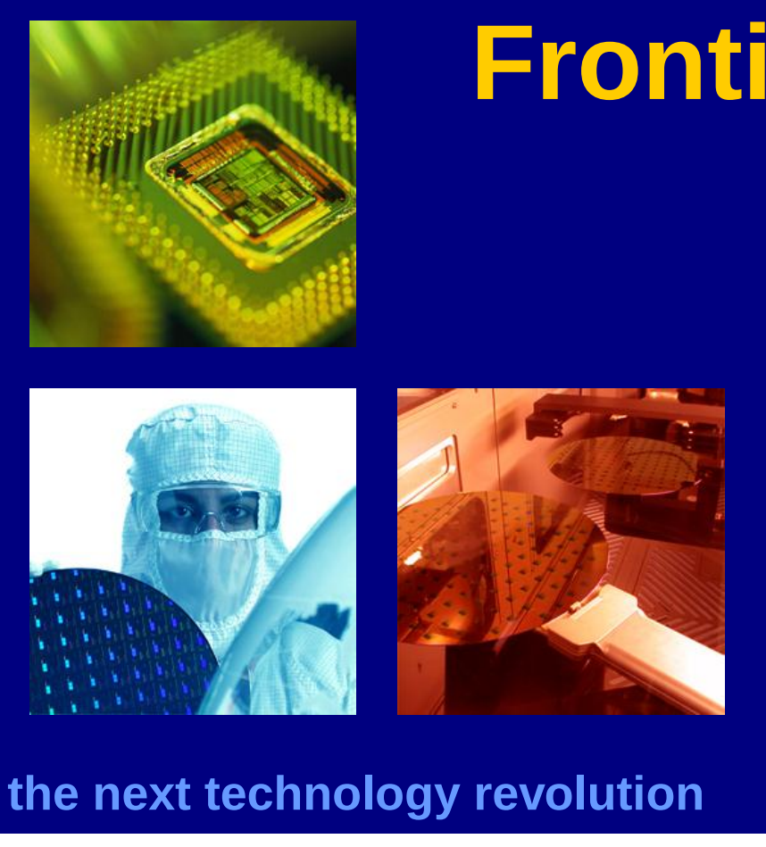
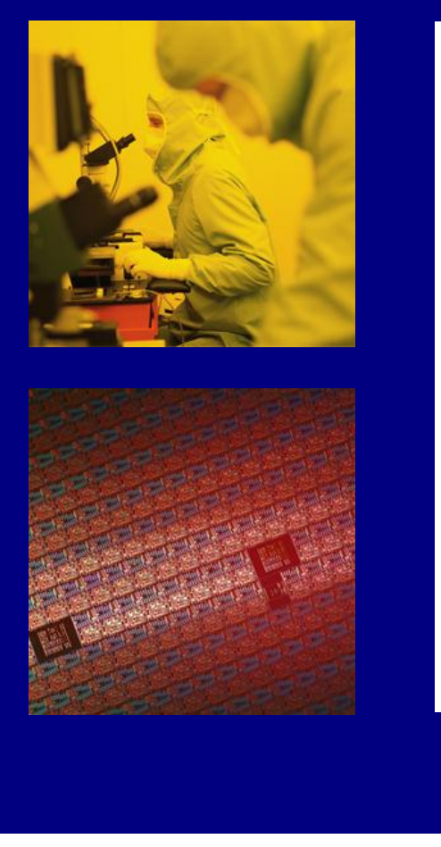
CD Metrology Gaps Analysis from the 22 nm Node Onwards

Frontiers of Characterization and Metrology for Nanoelectronics, Gaithersburg, MD, March 28, 2013

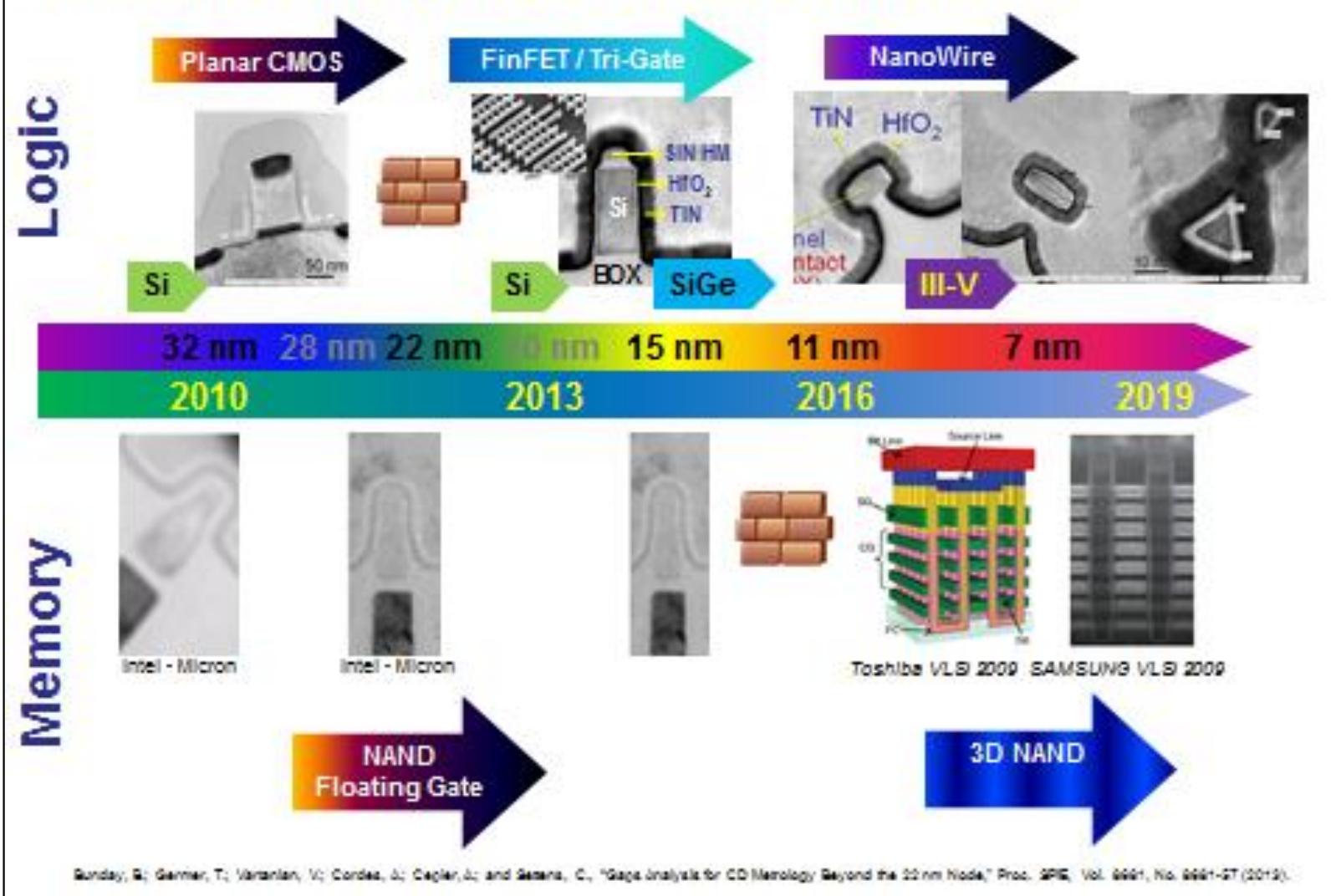
Benjamin Bunday, CD Metrology Project Manager, SrMTS
Thomas Germer, NIST, Gaithersburg, MD, USA
Victor Vartanian, Aaron Cordes, & Aron Cepler, SEMATECH Metrology, Albany, NY, USA
Charles Settens, CNSE, Albany, NY, USA

Accelerating the next technology revolution





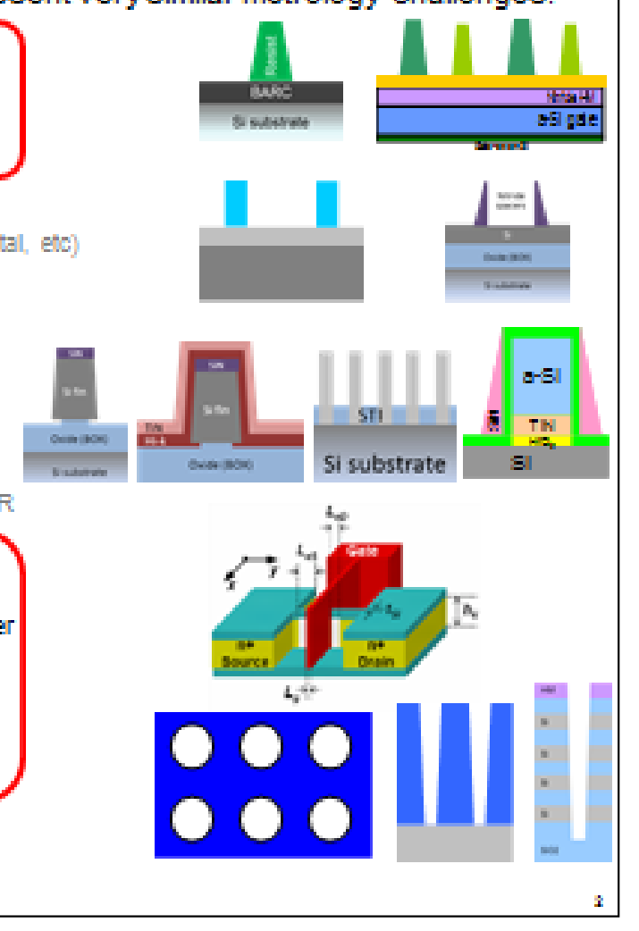
Transition to Advanced Architectures



Bunday, B.; Germer, T.; Vartanian, V.; Cordes, A.; Cepler, A.; and Settens, C., "Gaps Analysis for CD Metrology Beyond the 22 nm Node," Proc. SPIE, Vol. 8681, No. 8681-57 (2013).

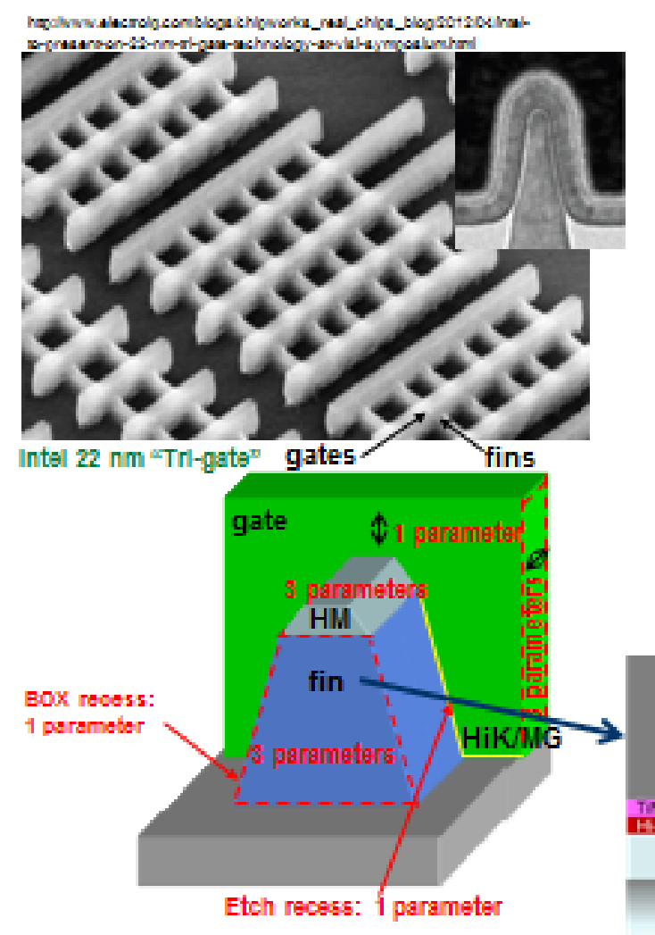
Application Families

- Many important applications require HVM process control.
- Separate cases, but broadly, several groupings represent very similar metrology challenges.
- **2D/3D Litho applications**
  - EUV (or older) resist patterns of Line/space & contact holes
  - CD, SWA, h, LER (or CER)
  - In dual litho cases, 2 populations, plus pitchwalk
- 2D Planar Etch applications
  - Etch of a single layer (Si, SiO_2, SiN, planar gates, STI trench, metal, etc)
  - Includes hardmasks & spacers in spacer double patterning
  - CD, LER, SWA, h, undercut, maybe TCR
- 2D+ Multilayer Planar Etch
  - Etch through multiple layers
  - Includes deposited conformal layers
  - Includes fins of FinFETs (SOI & bulk, also planar MG)
  - CD, recess/undercut, LER, SWA, h, maybe pitch walk, TCR, SWR
- **3D FinFET** & Nanowire
  - Gate-on-fin
  - Gate 1st steps: gate dep & CMP, gate litho, gate etch, gate spacer
  - Next page...
- **3D HAR / Memory**
  - HAR holes and trenches in single layer or multilayers
  - Later page...
- 2D/3D DSA apps



3D FinFET Gate-on-Fin applications

http://www.electroiq.com/blogs/chipworks_real_chips_blog/2012/04/intel-to-present-on-22-nm-tri-gate-technology-at-vlsi-symposium.html



FinFETs require monitoring of 12+ dimensional parameters

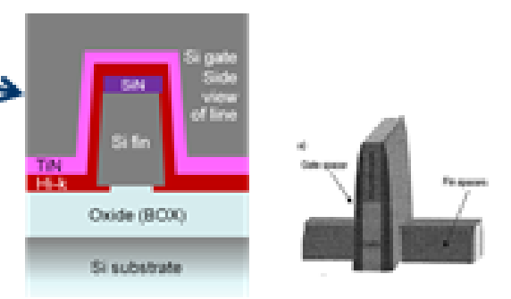
- Fin
  - CD
  - Undercut
  - LER (maybe SWR)
  - SWA
  - Height
  - TCR, especially for Tri-gate
  - Pitch / Pitch walk
  - Hi-k thickness
  - TiN thickness

Fin profile

- Gate
  - CD
  - LER
  - SWA
  - height above fin

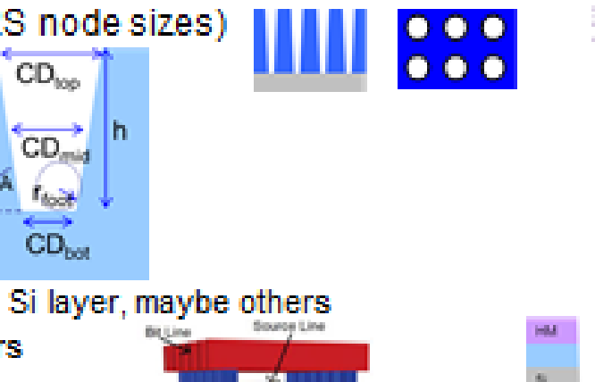
Integration Schemes

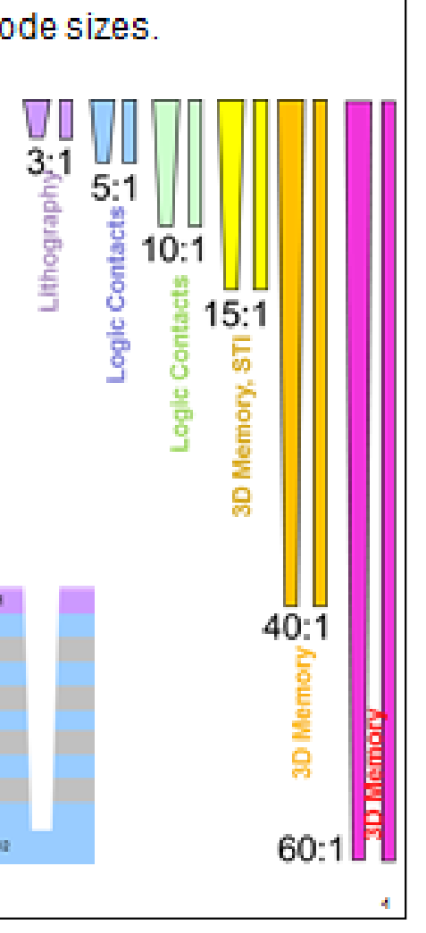
- Gate 1st steps
  - gate dep & CMP
  - gate litho
  - gate etch
  - gate spacer
- Gate last steps
  - Dummy gate removal
  - HiK, TiN, Al dep
  - Gate stack CMP / etch

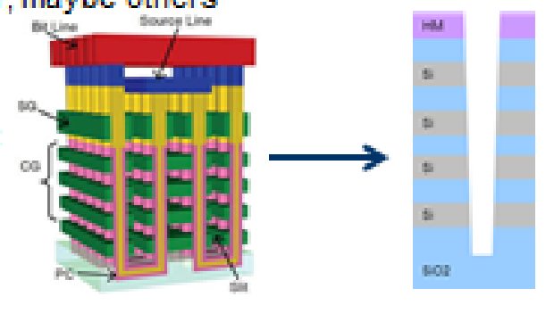


3D High Aspect Ratio (HAR) / Memory applications

- Many different possible architectures—very diverse, closely-guarded IP.
- 3D memory structures include many HAR features, at ITRS node sizes.
- Difficult to measure relevant parameters on deep holes and HAR structures for memory using AFM/SEM.
- Situation will become more dire as aspect ratios increase.
- HAR Etched Si, SiO_2 or multi-layer, trench or hole (20:1, 40:1, 60:1 AR at ITRS node sizes)
  - Bottom CD
  - SWA
  - Depth
  - TCR
  - LER or CER
  - Multi-layer: CD at bottom Si layer, maybe others
  - 4, 8, 16... (256?) Si layers







Toshiba Pipe-shaped Bit Cost Scalable (PBICS)

R. Katsumata et al. Symp. on VLSI Tech. Dig., pp.136-137, (2009).

Design rules used here

Rather than show too many tables, blanket rough assumptions:

- All design rules considered are extensions of the ITRS, with fair assumptions:
  - Height: ~3:1 AR for resists, fins & non-HAR or STI etched structures
  - SWA: 88°–90°, 85° for spacers
  - FinFET gates: double the fin pitch (gates not double patterned)
  - HAR / memory: AR of depths given with apps, height = AR × bottom CD

ITRS MET3 Lithography Metrology (Wafer) Technology Requirements

Year of Production	2012	2015	2018	2021	2024	2026
R&D Start Year	2006	2009	2012	2015	2018	2020
Design Rules						
Flash ½ Pitch (nm) (un-contacted Poly)	20	15	12	9	8	8
MPU Printed Gate Length (GLpr) (nm)	32	22	16	11	8	6
pitch (nm)	64	44	32	22	16	12
MPU Physical Gate Length (GLph) (nm)	22	17	13	10	7	6
Wafer minimum contact hole (nm, post etch) from lithography tables Flash	32	23	16	11	8	6
Resist thickness (nm, single layer)	40-75	30-55	20-45	15-35	15-30	15-30

HVM CD Metrology Needs & Potential Solutions

Needs

- Non-destructive HVM CD metrology for advanced architectures at future nodes
- For the many different applications
- HVM considerations: automation, high throughput, non-destructive
- Sampling: Area of measurement also important

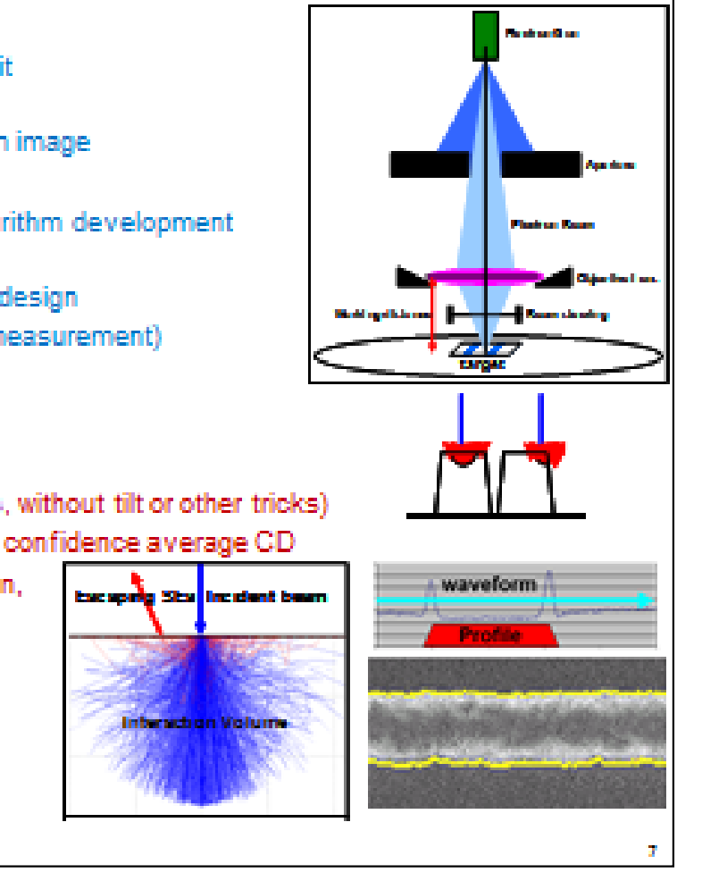
Existing & New Solutions

- No one technology can do everything—very application specific. Must look case-by-case at challenging applications.
- Important: have both imaging solution & spectroscopic solution
  - Imaging & spectroscopic solutions quite complementary
  - Imaging solutions for discrete features, variation & roughness
  - Spectroscopic solutions for process average & profile
- Existing:
  - CD-SEM
  - CD-AFM
  - OCD (Scatterometry)
    - SE, Mueller Matrix, Normal Inc RP, Multi-Angle SE, etc.
  - MBIR
- "New":
  - HeIM (or other ion)
  - HV-SEM or E-SEM
  - CD-SAXS
    - Transmission & Grazing Incident
  - TSOM
  - Others

& Hybrid combinations

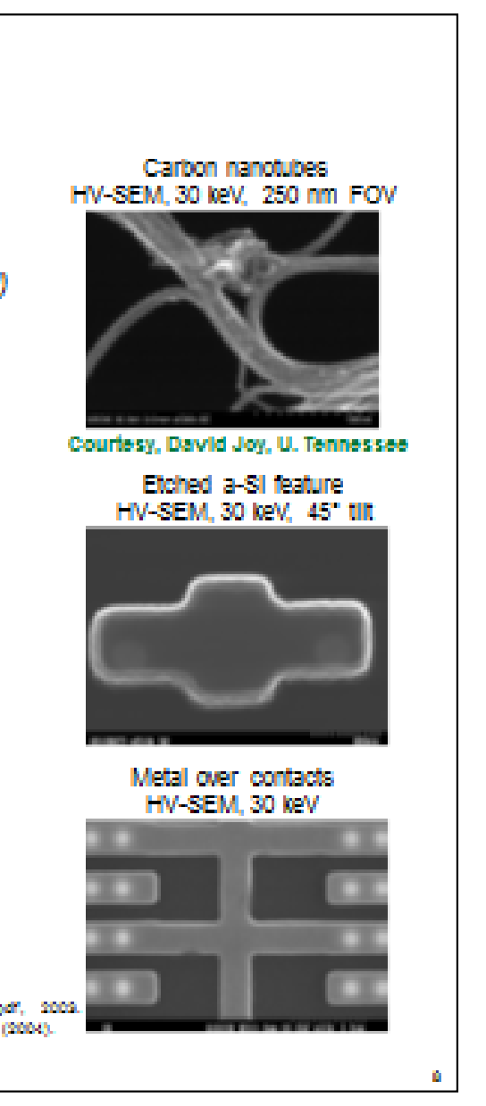
CD-SEM

- CD-SEM has been / is the main image-based workhorse CD metrology tool for 20+ years
  - R&D, process window mapping, process control & centering, OPC model inputs & validation
- CD-SEMs generate x-y projection maps of SE's as seen from topdown (or tilt); many more SE's from edges.
- Pros:
  - Measures complex shapes of discrete features in circuit → local CD, contours, CD variation, LER/LWR
  - "What you see is what you get" – known accuracy from image
  - Valuable image information about process excursions
  - Extremely flexible, no modeling *required* (although algorithm development important), move & image, "instant gratification"
  - No need for specialized target, planned in advance on design
  - Surface sensitive (buried features don't interfere with measurement)
- Cons:
  - Difficult to measure 3D profile
  - Becoming somewhat resolution-challenged
  - Surface sensitive (cannot see re-entrance or undercuts, without tilt or other tricks)
  - Local measurement → more sampling needed for high confidence average CD
  - Minor (non-fatal) sample damage: carbon contamination, resist shrinkage
- **Vital that CD-SEM, in some form, continue to be useful.**
  These capabilities are indispensable.



HV-SEM, LL-BSE, E-SEM

- Traditionally, SEM with $V_{acc} \geq 30$ keV , but also ≥ 5 keV
- *Variants:*
  - *Low Loss BSE (different detector scheme)*
  - *E-SEM (low vacuum, small partial pressure of H_2O for charge control)*
- Pros:
  - Much improved resolution, excellent edge definition
  - Interaction volume mostly deep within sample
  - Improved DOF & bright source
  - Possible depth profiling & overlay
  - Significant SE & BSE
  - Some think shrinkage low, but FA SEMs always severely shrink resist
  - No knock-on damage until much higher keV
  - *LL-BSE: HV BSE's might escape HAR*
  - *E-SEM: charge control on insulator targets*
- Cons:
  - Known electrical damage, oxide traps, leakage current increase (Rice, SPIE 2004)
  - Might have to deal with unwanted signals from buried features

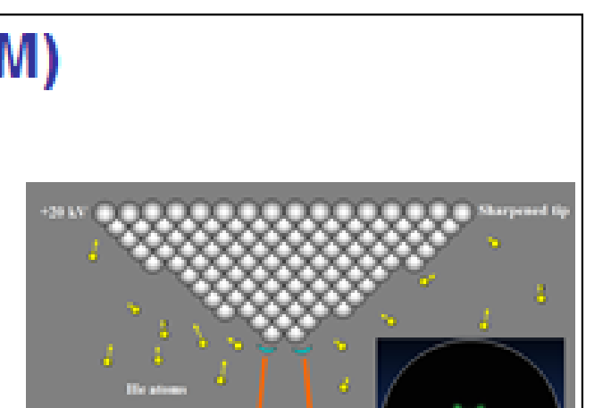


Carbon nanotubes HV-SEM, 30 keV, 250 nm FOV
Courtesy, David Joy, U. Tennessee
Etched a-Si feature HV-SEM, 30 keV, 45° tilt
Metal over contacts HV-SEM, 30 keV

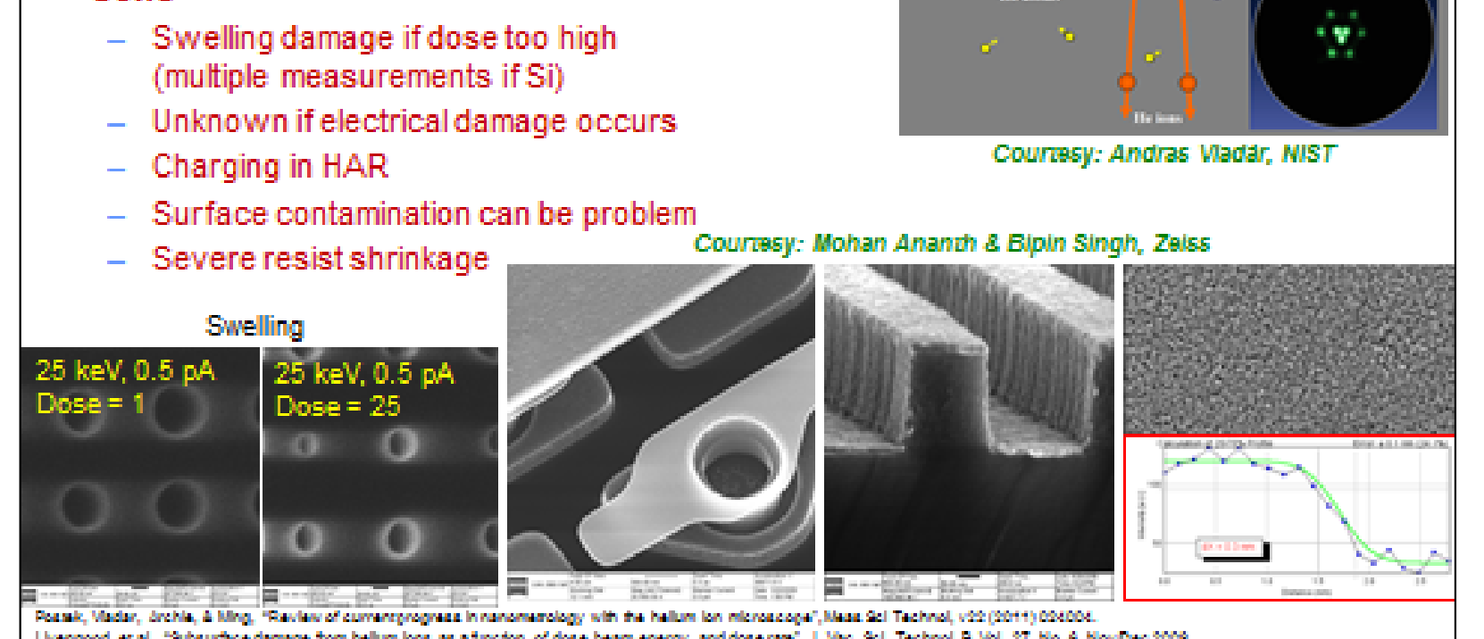
D. C. Joy, "The CD-SEM – and Beyond," NIST Frontiers , available online at http://www.nist.gov/pml/div683/conference/upload/Joy_2003.pdf, 2003.
B. Rice, A. Danilevsky, M. Grumski, S. Koshihara, et al. "Prospects for Using Primary Electron-based CD Metrology", Proc. SPIE, v5375, (2004).

Helium Ion Microscopy (HeIM)

- Pros
  - 0.35 nm resolution demonstrated
  - Very surface sensitive
  - Large DOF
  - Charging control at surface (electron flood gun)
- Cons
  - Swelling damage if dose too high (multiple measurements if Si)
  - Unknown if electrical damage occurs
  - Charging in HAR
  - Surface contamination can be problem
  - Severe resist shrinkage



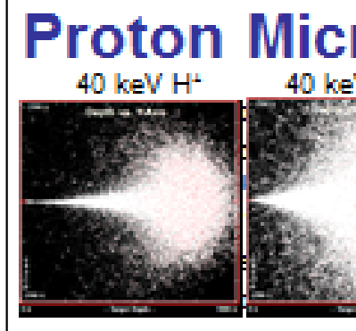
Courtesy: Andras Vladár, NIST



Courtesy: Mohan Ananth & Bipin Singh, Zeiss

Postek, Vladár, Archie, & Ming, "Review of current progress in nanometrology with the helium ion microscope", Meas. Sci. Technol. v22 (2011) 024004.
Livengood, et al., "Subsurface damage from helium ions as a function of dose, beam energy, and dose rate", J. Vac. Sci. Technol. B Vol. 27, No. 6, Nov/Dec 2009

Proton Microscope



...ion to date in keV range
...emission electron gun,
...d of vacuum)
...aller DOF
damage expected
...oton Microscope in bio applications (MeV)

R. Levi-Setti, "Proton Scanning Microscopy: Feasibility and Promise," In Proceedings of the Seventh Annual Scanning Electron Microscope Symposium, 1974.
D. C. Joy, "Protons, Ions, Electrons and the Future of the SEM," Journal of Physics: Conference Series, vol. 241, pp. 1-8, 2010.

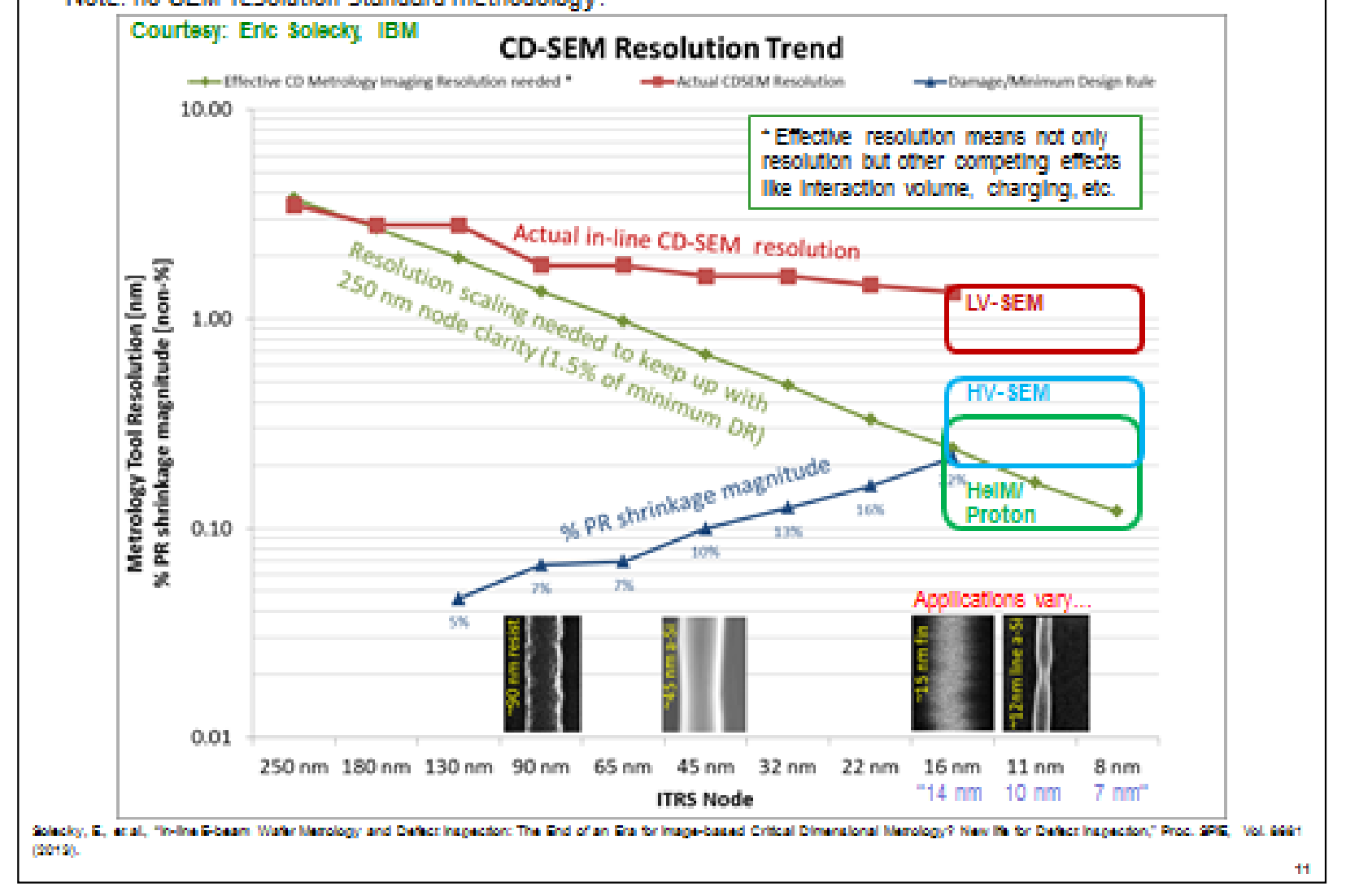
Comparison of CD-SEM & Alternatives

Charged particle imaging technique comparison table, all values openly published, references in paper

Technique	Resolution (best publicly reported)	Resolution Limit (best predicted)	Rayleigh Diffraction Limit (floor to predicted limits)	DOF (512 × 512 Pixels, 500 nm FOV)	Source	Brightness (A/cm² sr)
Conventional CD-SEM 800 eV	1.35 nm	0.75 nm	0.66 nm, 40 mR	~50 nm	Proprietary, assume Schottky FE	Proprietary, assume ~5E+07
High Voltage SEM 50 keV	0.5 nm	0.2–0.5 nm	0.22 nm, 15 mR	~100 nm	Schottky FE	1E+08
Low vacuum SEM 10 keV	1–1.25 nm	0.5–1.0 nm	0.50 nm, 15 mR	~100 nm	Schottky FE	1E+08
HeIM 50 keV	0.35 nm	0.1–0.25 nm	0.04 nm, 1 mR	1950 nm	Gas field ion Source	5E+09
Proton Microscopy 50 keV	None yet reported, likely similar to HeIM if beam optics similar	Likely similar to HeIM if beam optics similar	0.005 nm, 15 mR	Not yet commercially or experimentally available		
TEM (for baseline)	<0.1 nm (atoms resolved)	<0.1 nm (atoms resolved)				

CD-SEM: Resolution Improvement Needed

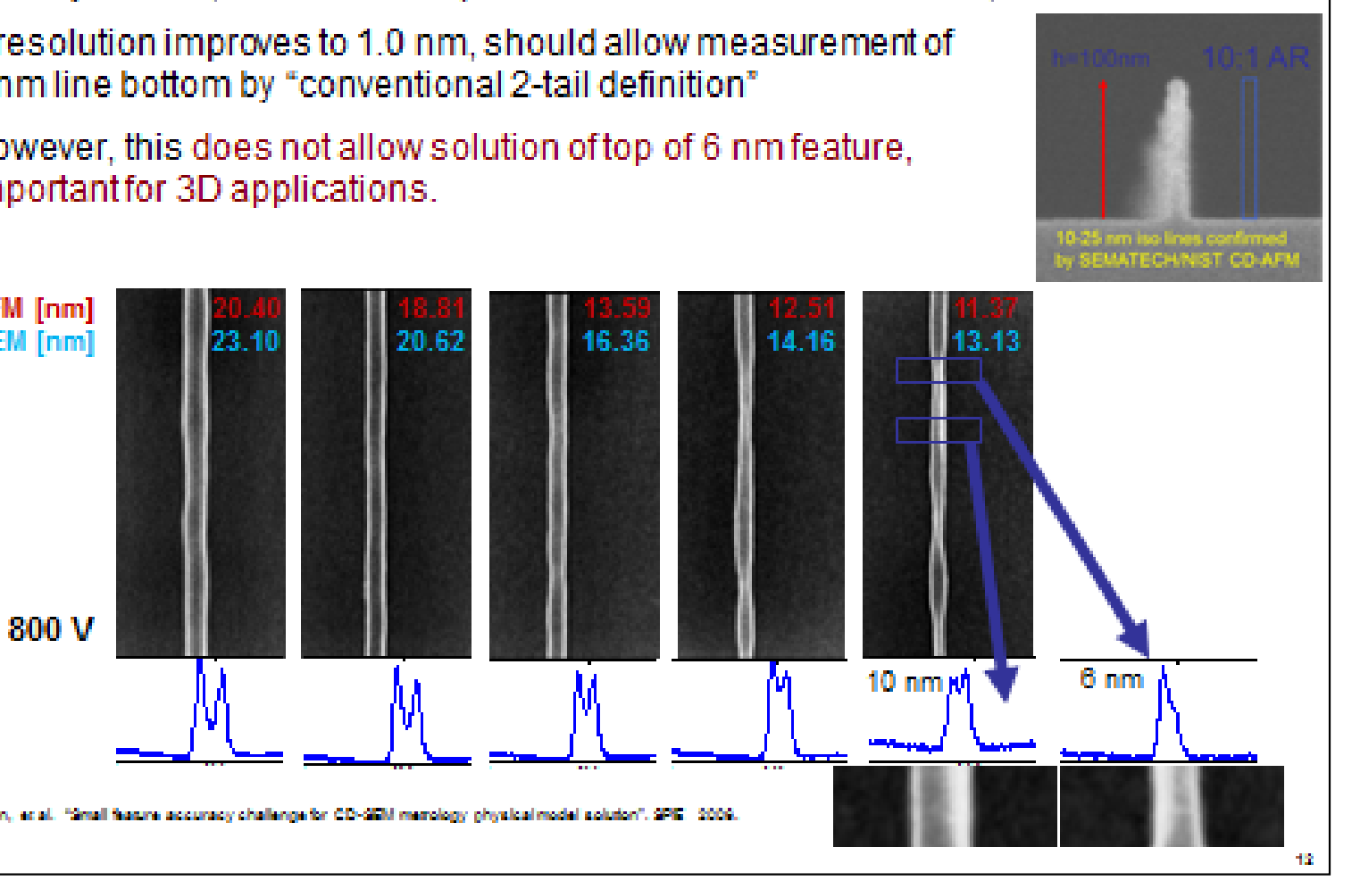
- Note: no SEM resolution standard methodology.



Solecky, E., et al., "In-line E-beam Wafer Metrology and Defect Inspection: The End of an Era for Image-based Critical Dimensional Metrology? New life for Defect Inspection," Proc. SPIE, Vol. 8681 (2013).

LV-CD-SEM Small Feature Limits

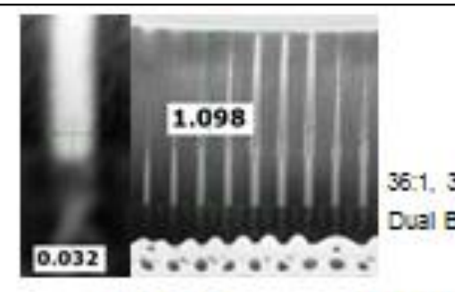
- 13 nm & 10 nm isolated etched a-Si lines, 100 nm tall
- Bunday & Adan, SPIE 2006: experiment with ~1.5 nm resolution, older tool
- If resolution improves to 1.0 nm, should allow measurement of 6 nm line bottom by "conventional 2-tail definition"
- However, this does not allow solution of top of 6 nm feature, important for 3D applications.



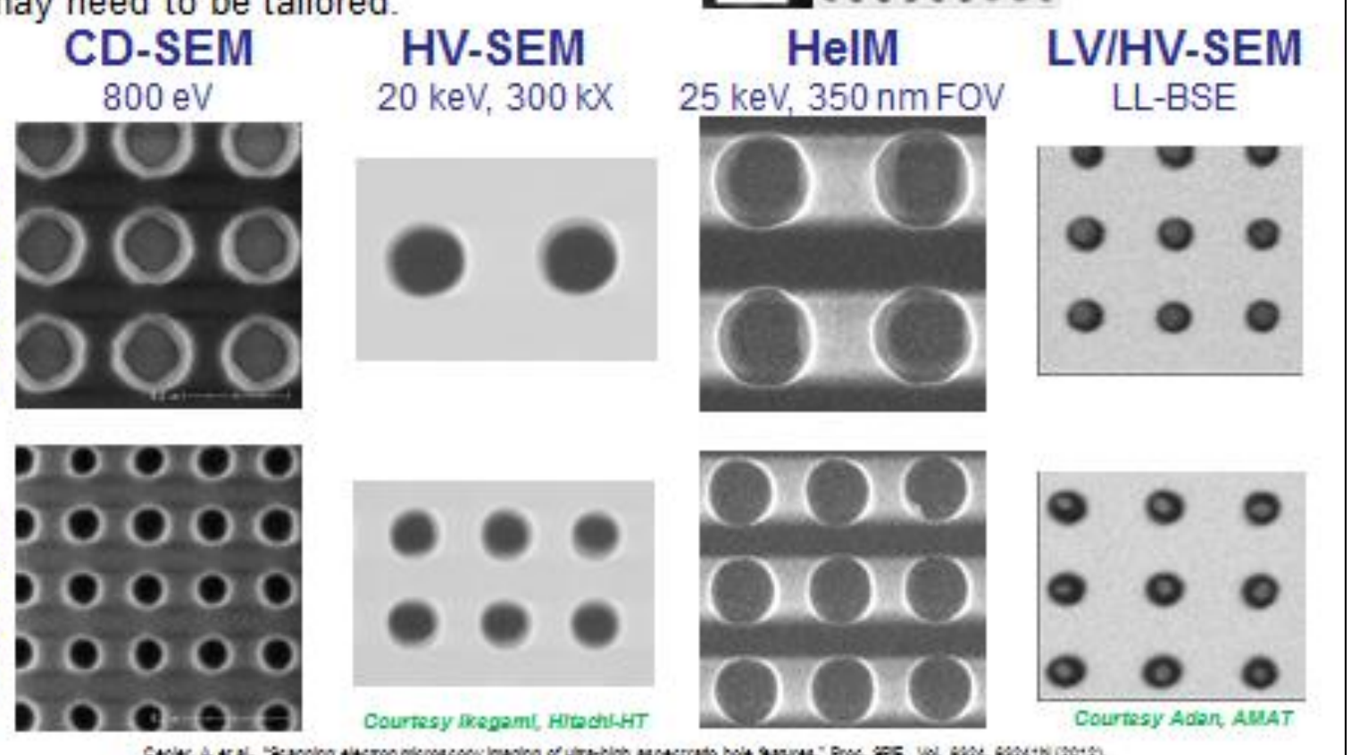
Bunday, Adan, et al. "Small feature accuracy challenge for CD-SEM metrology physical model solution". SPIE 2006.

36:1 HAR Oxide Holes

- There are solutions to HAR and contact hole imaging! HV-SEM, 2 flavors.
- Multi-layers charge differently, solutions may need to be tailored.



36:1, 3X nm bottom CD
Dual Beam FIB

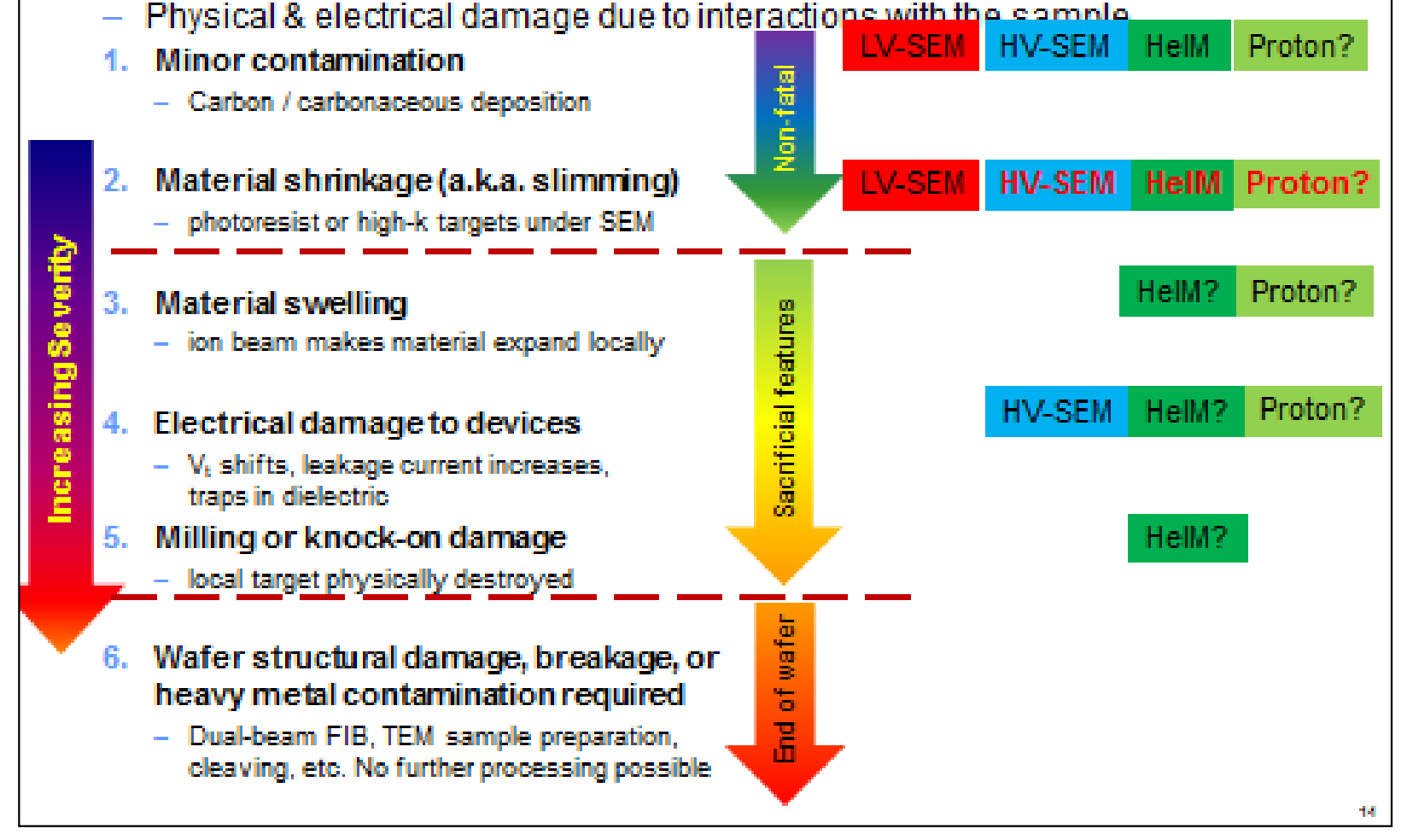


Courtesy Ikegami, Hitachi-HT
Courtesy Adan, AMAT

Cepler, A. et al., "Scanning electron microscopy imaging of ultra-high aspect ratio hole features," Proc. SPIE, Vol. 8324, 83241N (2012).

Damage Phenomena by Charged Particles

- All electron & ion beam techniques can change sample to varying degrees
  - Physical & electrical damage due to interactions with the sample

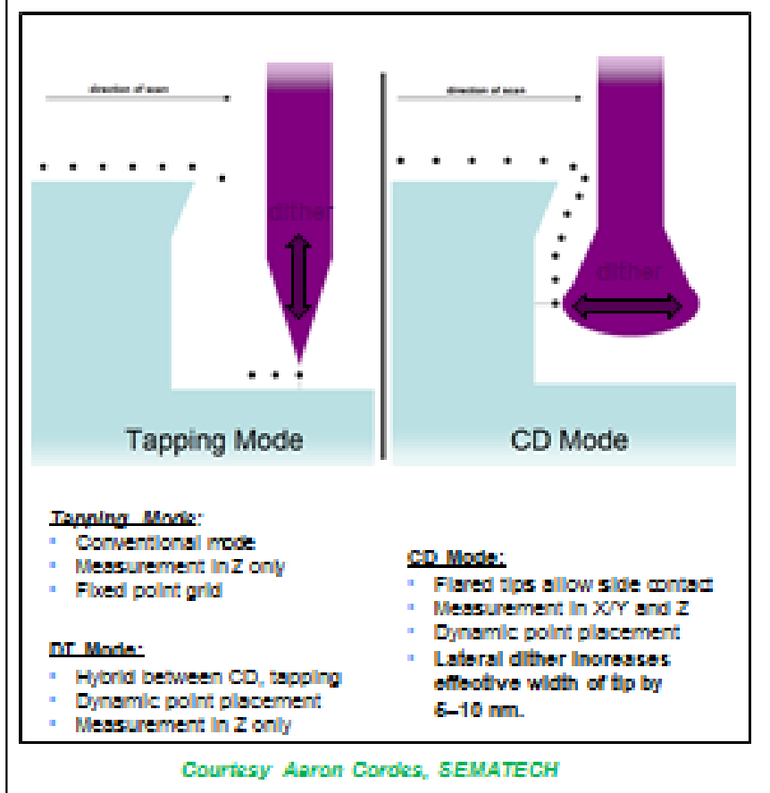


1. Minor contamination
   - Carbon / carbonaceous deposition
2. Material shrinkage (a.k.a. slimming)
   - photoresist or high-k targets under SEM
3. Material swelling
   - ion beam makes material expand locally
4. Electrical damage to devices
   - V_t shifts, leakage current increases, traps in dielectric
5. Milling or knock-on damage
   - local target physically destroyed
6. Wafer structural damage, breakage, or heavy metal contamination required
   - Dual-beam FIB, TEM sample preparation, cleaving, etc. No further processing possible

CD-AFM

Limit is primarily imposed by tip dimensions, somewhat adjusted by measurement parameters.

Measurement Mode Overview



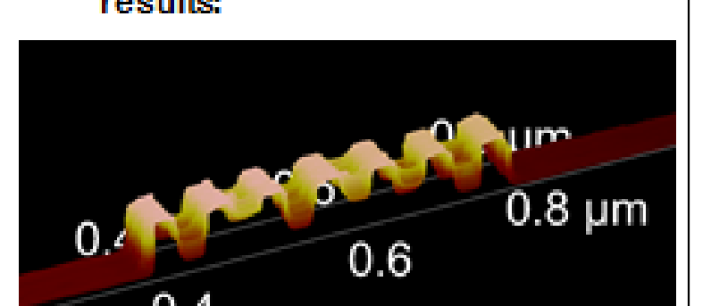
Tapping Mode:
- Conventional mode
- Measurement in Z only
- Fixed point grid

DT Mode:
- Hybrid between CD, tapping
- Dynamic point placement
- Measurement in Z only

CD Mode:
- Flared tips allow side contact
- Measurement in X/Y and Z
- Dynamic point placement
- Lateral dither increases effective width of tip by 6–10 nm.

Courtesy Aaron Cordes, SEMATECH

- As tip width approaches available feature space, measurement steadily becomes harder, leads to messy results:

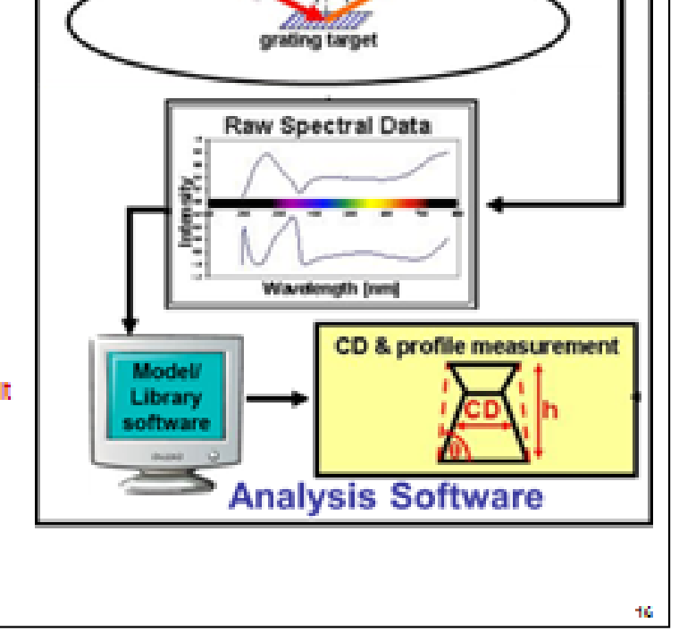


28 nm fin array measured in CD mode. Although the probe was nominally 20 nm wide, mechanical effects make the practical width broader. Measurements under these constraints are difficult to make robust.

- Current functional limit for CD probes is 20 nm. Structural limits constrain the probes; hard to see better than 15 nm.

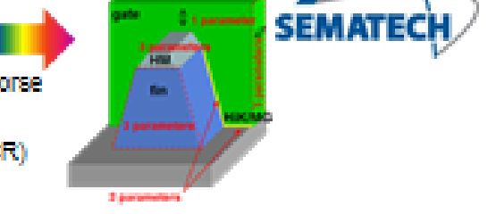
Optical Scatterometry (OCD)

- Ellipsometers/Reflectometers measure optical scattering
  - Software to solve CD/profile
- Measures average CD/profile within illuminated spot on grating target
  - Metrics are result of model-based or library solutions
  - Average, non-localized information
- Pros
  - High confidence measurement of average CD/profile (3D) up to ~12 parameters of 3D structures
  - Fast
  - Non-destructive
  - Inexpensive (relatively...)
  - Non-vacuum → small size → Standalone or integrated
  - Good matching
  - No abrupt resolution cutoff as with OM—features well sub-λ, but material acts as effective medium
- Cons
  - Accuracy known only after verification to other reference
  - Difficulties measuring across-grating-variation & roughness
  - Repeating unit cell target required, often not applicable in-circuit
  - Cannot measure discrete features
  - Issues when n & k shift away from modeled process
  - Some features: parameter cross-correlations
  - Model build time can be significant (although improving)



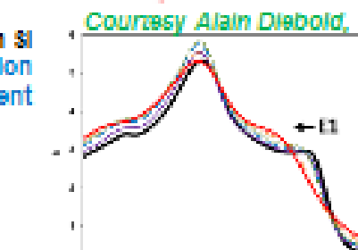
Optical Scatterometry (OCD) Challenges

- Difficult to solve too many parameters in complex features (without improvement or hybrid inputs)
  - As nodes or complexity progress, parameter cross-correlation issues get worse
  - Full FinFETs or 3D memory structures need ~12, possibly more in future
  - Optical volume of some critical features becoming extremely small (Ex: TCR)
  - Vaid, SPIE 2011 & 2012

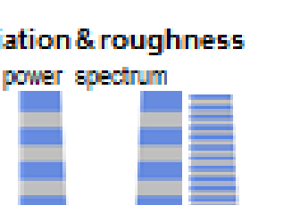


- n & k of Si shifts as features get very small
  - predicted significant at 11 or 8 nm nodes.
  - effects reported for films, may increase for small CD patterns
  - Kamineni & Diebold, "Evidence of the phonon confinement on the linear optical response of nanoscale silicon films," Applied Physics Letters, Vol. 99, 151903 (2011).
  - Diebold, SPIE 2011.

Ultra-Thin Si
Blue shift for E1 transition due to Quantum Confinement

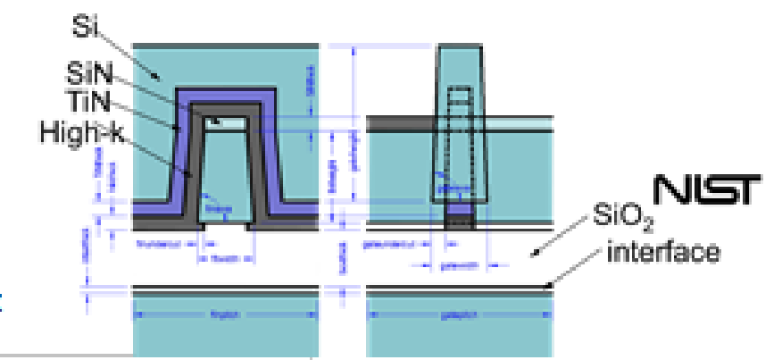


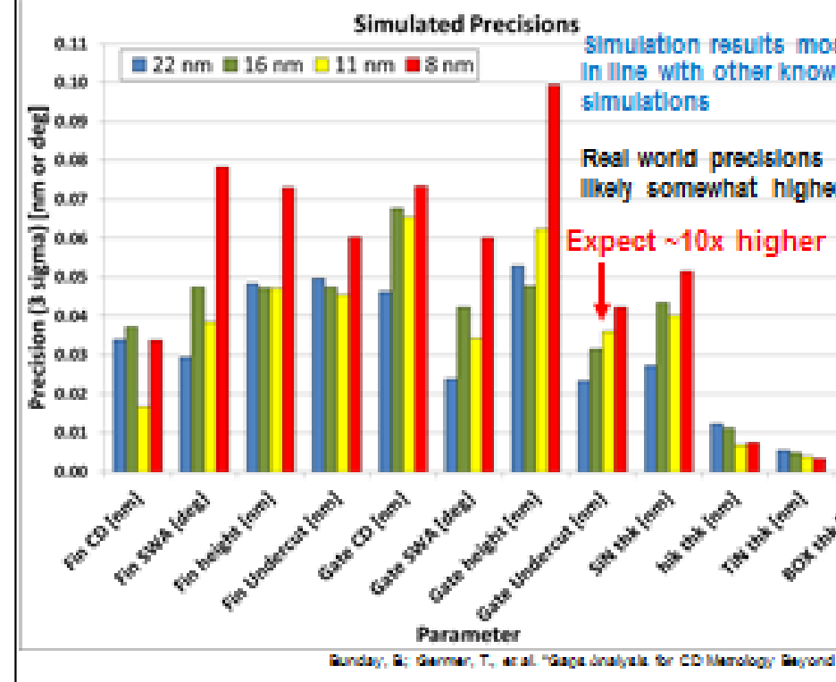
- OCD has difficulties measuring within-grating variation & roughness
  - Uncertain if sensitive to broadband random roughness or power spectrum
- May be challenging for OCD to measure future HAR 3D memory features with many layers
- Insensitive to ~0 nm pitch walk on DP
- Predicted insensitivity to SWA/profile with thinner EUV resists (h < 40 nm)
  - Bunday, Ella & Liu, et al, SPIE 2011
- New source may help many of these, more data needed
  - Shaughnessy & Shchegrov et al, SPIE 2013



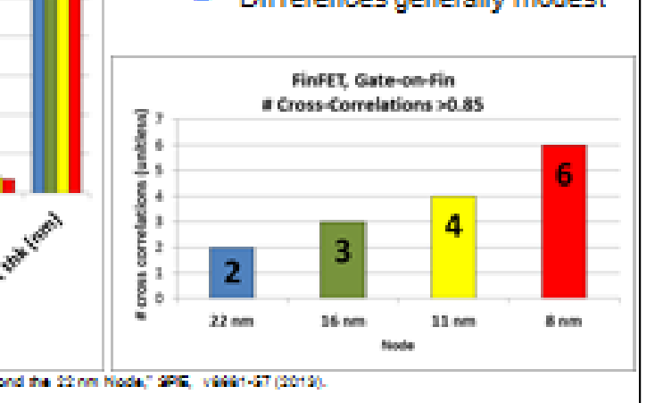
OCD simulation study FinFET (Gate-on-Fin)

- OCDsense sims (Germer, SPIE 2009)
- 13 floating parameters:
  - Fin: CD, h, SWA, undercut, pitch (fix)
  - Gate: CD, h, SWA, undercut, pitch (fix)
  - Film thicknesses: SiN, HiK, TiN, BOX, BOX interface





- 108 tools simulated
  - SE, NI-RP, NI+Obl-RP, Multi-θ, Multi-θ / multi-λ, etc.
- Average of SE, NI-RP, NI+Obl-RP
  - Differences generally modest



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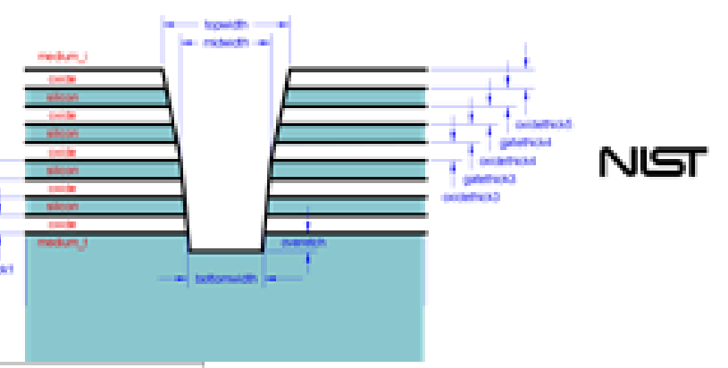
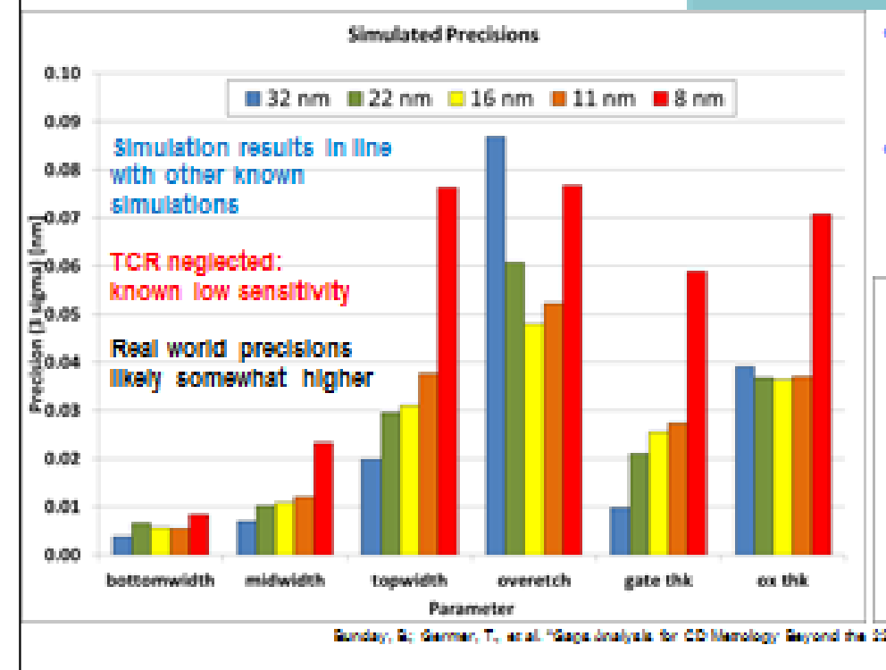
OCD simulation study
20:1 HAR multi-layer

- OCDsense sims (Germer, SPIE 2009)
- 13 floating parameters:
  - Pitch (fix)
  - Trench CD: Top, Mid, Bottom
  - Over-etch
  - Film thicknesses: 4 Si gate, 5 oxides





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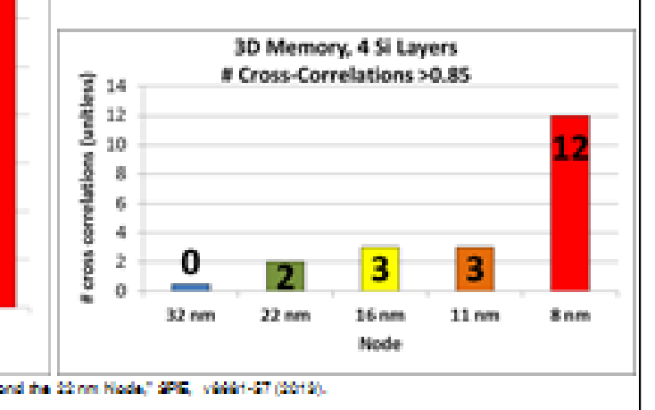
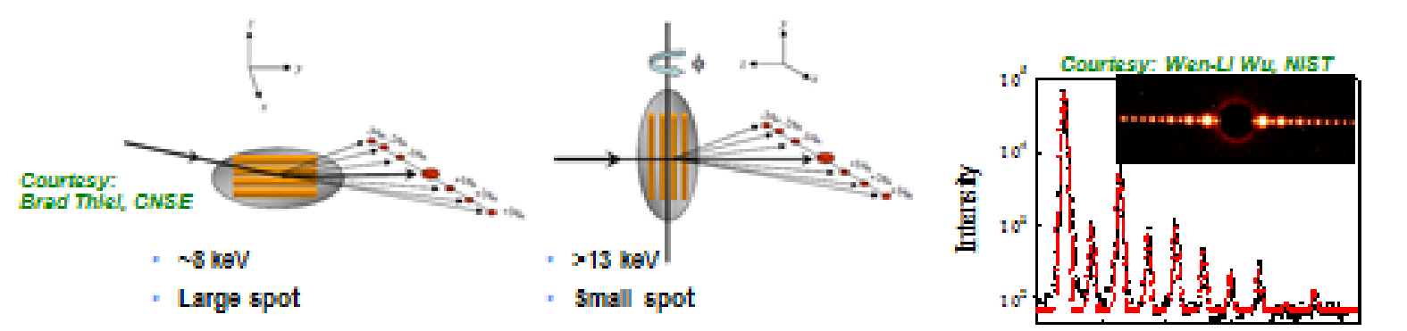


Bunday, B.; Germer, T., et al. "Gaps Analysis for CD Metrology Beyond the 22 nm Node," SPIE, v8681-57 (2013).

CD-SAXS (X-ray Scatterometry)



Grazing Incidence:
- ~8 keV
- Large spot
- Z-dimension probed by examining scattering in $+q_z$ direction

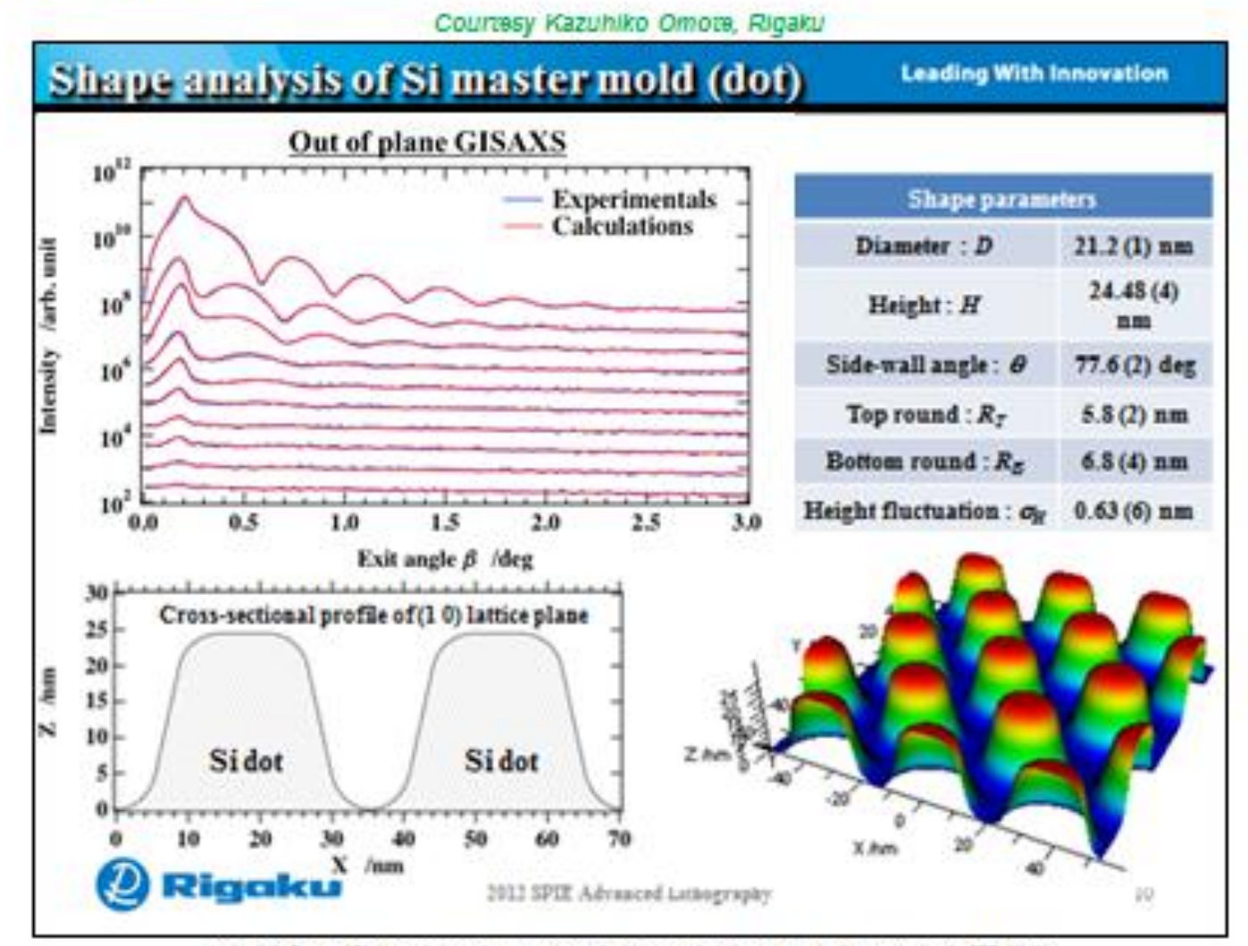
Transmission:
- >13 keV
- Small spot
- z-dimension probed by varying angle of incidence ϕ

- Pros
  - Classical X-ray scattering (no n & k issues)
  - Sensitive to electron density contrast
  - Capability improves in future nodes
  - Demonstrated solution of 13 parameters (δ-trap)
    - Wen-Li Wu et al, NIST, SPIE 2011
  - Can measure pitchwalk & roughness
    - Ronald Jones, Wu et al, NIST, SPIE 2006
  - Can measure non-planar film thicknesses on sidewalls
    - Chengqing Wang, Wu et al, NIST, SPIE 2009
- Cons
  - GI-SAXS:
    - TP ~ okay, but spot size too large for many applications
    - Insensitive at large depths (HAR)
  - T-SAXS:
    - Currently too slow for HVM, but spot size can be ~okay
    - Must transmit through wafer (effects speed, interference from deep underlayers, can measure HAR)

Thiel, B.; Cepler, A.; Diebold, A. and Matyi, R., "Advances in CD Metrology (CD-SAXS, Mueller Matrix based Scatterometry, and SEM)," AIP Conference Proceedings, Vol. 1395, 298 (2011).

GI-SAXS

Courtesy Kazuhiko Omote, Rigaku

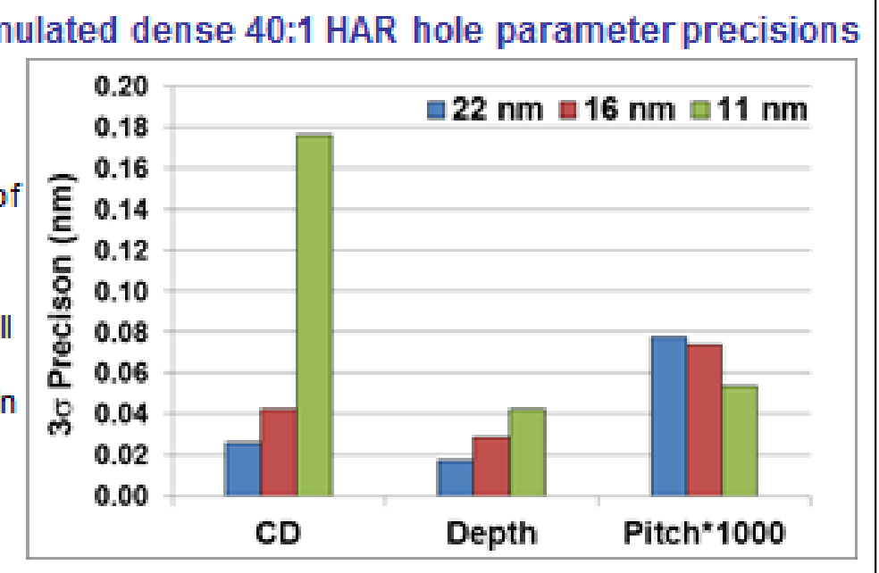


Shape parameters	
Diameter : D	21.2 (1) nm
Height : H	24.48 (4) nm
Side-wall angle : θ	77.6 (2) deg
Top round : R_T	5.8 (2) nm
Bottom round : R_B	6.8 (4) nm
Height fluctuation : σ_H	0.63 (6) nm

Y. Ito & K. Omote, "Characterization of nanostructures for imprinted dot/hole patterns by X-ray metrology", SPIE 2012.

T-CD-SAXS HAR contact hole simulation
3σ repeatability for 22/16/11 nm nodes

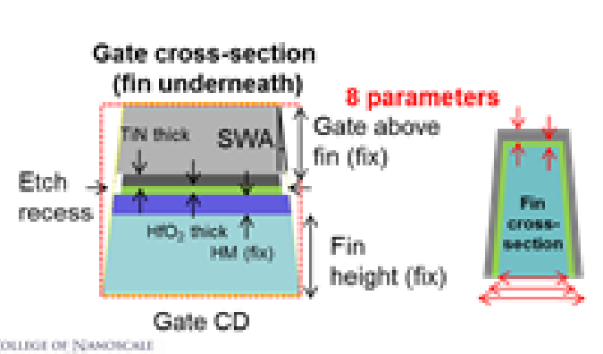
- 30 fits to simulated data + noise
  - Synchrotron beam & noise conditions
- Demonstrates predictive capability of key structural parameters for HAR hole metrology
- Parameter 3σ precision is very small for dense features (more features contributing to the scattered signal in same beam area)
- 3σ SWA < 0.01°
- No significant cross-correlations

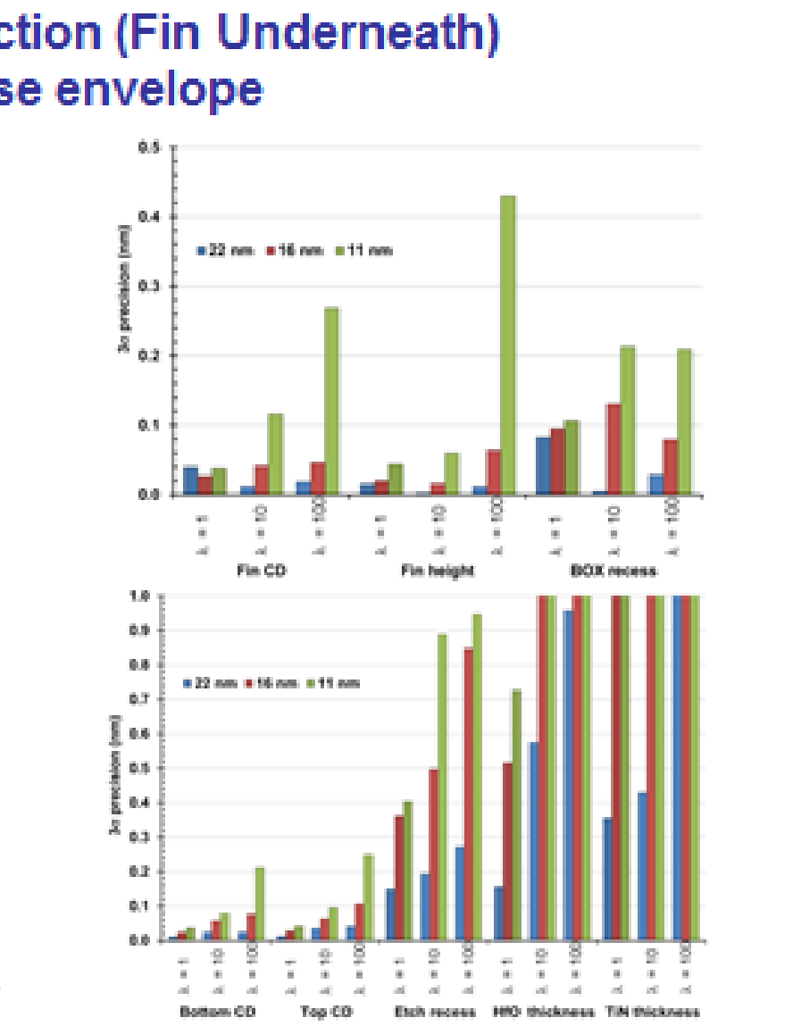


Settens, C.; Bunday, B.; Thiel, B.; Kline, J.; Sunday, D.; Wang, C.; Wu, W. and Matyi, R., "Critical dimension small angle X-ray scattering measurements of FinFET and 3D memory structures," Proc. SPIE, Vol. 8681, No. 8681-20 (2013).

T-CD-SAXS Gate cross-section (Fin Underneath)
Precision with varying noise envelope

- 30 fits to simulated data + noise
  - Synchrotron beam & noise conditions
- Demonstrates predictive capability of key structural parameters for FinFET metrology
- 3σ SWA < 0.01°
- No significant cross-correlations
- Noise & background introduced
- Experimental synchrotron BG = 20 counts, → noise envelope of 1 < λ < 10
- HfO_2 & TiN thickness 3σ large due to analysis of thickness in z-direction only (i.e. film not patterned in gate direction)



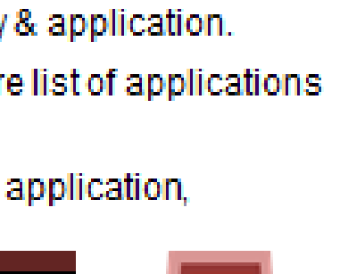


Gaps Analysis – Fin Example (March 2013)

- Using all information presented, and other info omitted for brevity, we can populate a table of expectations for each technology & application.
- SEMATECH Advanced Metrology has done this for the entire list of applications shown earlier.
- We show the Fin application as an example of an individual application, and the results by family on the next page.

<—Imaging Techniques | Spectroscopic Techniques—>

Application	LV CD-SEM	E/LLBSE/HV-SEM	HeIM	CD-AFM	OCD (SE or MM)	OCD (normal inc)	T-CD-SAXS	GI-CD-SAXS	TSOM	MBIR
Fin, SOI										
CD	8/11	6	≤ 6	16 dns <6 iso	8/11 small CD n&k	8/11 small CD n&k	≤ 6	≤ 6	sims predict maybe	needs study
recess / undercut		BSE?			8/11 small CD n&k	8/11 small CD n&k	≤ 6	≤ 6		needs study
roughness	8/11	6	≤ 6	16 dns <6 iso			≤ 6	≤ 6		needs study
SWA	tilt?	tilt or EW?	tilt or EW?	16 dns <6 iso	8/11 small CD n&k	8/11 small CD n&k	≤ 6	≤ 6	sims predict maybe	needs study
height	tilt?	tilt?	tilt?	16 dns <6 iso	8/11 small CD n&k	8/11 small CD n&k	≤ 6	≤ 6	sims predict maybe	needs study
pitch walk	8/11	6	≤ 6	16 dns <6 iso	new source helps?	new source helps?	≤ 6	≤ 6	sims predict maybe	needs study
FinFET HK dep	pre/post 8/11	pre/post 6/6	pre/post 6		11 very thin layer	11 very thin layer	6	6	needs study	needs study
FinFET TiN dep	pre/post 8/11	pre/post 6/6	pre/post 6		6	6	≤ 6	≤ 6	needs study	needs study



Color Key:
- ≤6 nm limit
- 6nm limit
- 8nm limit
- 11nm node limit
- 16nm node limit
- ≥22nm node limit
- not possible
- unknown
- sims predict maybe

SEMATECH CD Metrology Gaps Analysis (March 2013)
High Level Summary

<—Imaging Techniques | Spectroscopic Techniques—>

Application	LV CD-SEM	E/LLBSE/HV-SEM	HeIM	CD-AFM	OCD (SE or MM)	OCD (normal inc)	T-CD-SAXS	GI-CD-SAXS	TSOM	MBIR
2D/3D Litho apps	8/11 * shrinkage, need profile	severe shrinkage	severe shrinkage	16 dns <6 iso	8/11 thin PR, small CD n&k	8/11 thin PR, small CD n&k	≤ 6	≤ 6	needs study	
2D Planar Etch apps	8 * need profile	6 * need profile	≤ 6 * need profile	16 dns <6 iso	8/11 small CD n&k	8/11 small CD n&k	≤ 6	≤ 6	sims predict maybe	needs study
2D+ Multi-layer planar etch apps	8/11 * need profile	6 * need profile	≤ 6 * need profile	16 dns <6 iso	8/11 small CD n&k	8/11 small CD n&k	≤ 6	≤ 6	sims predict maybe	needs study
3D FinFET & Nano wire apps	8/11 * need profile	6 * need profile	≤ 6 * need profile	16 dns <6 iso	8/11 * small CD n&k	8/11 * small CD n&k	≤ 6	≤ 6	needs study	needs study
3D HAR apps	22 *	8 *	16 *		8/11 * small CD n&k, large depth limit?	8/11 * small CD n&k, large depth limit?	≤ 6		sims predict maybe	11 * no depth limit

Color Key:
- ≤6 nm limit
- 6nm limit
- 8nm limit
- 11nm node limit
- 16nm node limit
- ≥22nm node limit
- not possible
- unknown
- sims predict maybe

* significant gaps for some metrics within the family of applications (ex: SEM issues with measuring profile)

Other HVM Considerations

<—Imaging Techniques | Spectroscopic Techniques—>

Application	LV CD-SEM	E/LLBSE/HV-SEM	HeIM	CD-AFM	OCD (SE or MM)	OCD (normal inc)	T-CD-SAXS	GI-CD-SAXS	TSOM	MBIR
MAM time	🟩	🟩	🟩	🟨	🟦	🟦	🟥	🟨	🟦	🟩
Area of measurement	🟦	🟦	🟦	🟦	🟩	🟩	🟥	🟩	🟩	🟩
Destructiveness	🟩	🟥	🟨	🟦	🟦	🟦	🟦	🟦	🟦	🟦

Color Code Key:
- 🟦 excellent
- 🟩 okay
- 🟨 high
- 🟥 very high

CD Metrology Gaps Analysis Conclusions
(March 2013)

- **Defined scheme of classifying main CD metrology applications into 5 broader families.**
- **Technical challenges shown for all main potential CD metrology technologies:**
  - **These are current best-known projections—improvement is needed but possible.**
  - **SEM, in general:** flexible capability indispensable; resolution improvement needed—make it work!
    - If not LV, damage. If lateral range of damage limited, users may have to learn to work with sacrificial features.
  - **LV-CD-SEM:** still needed for photoresist measurements. Needs resolution improvement.
  - **HV-SEM:** HAR memory opportunity; known electrical damage; severe resist shrinkage.
  - **HeIM:** resolution improvement we need; severe resist shrinkage.
    - Swelling of Si reported to be at large doses, what of other materials? Electrical damage unknown.
  - **Proton SEM: possible** alternative to HeIM with lower predicted damage.
  - **CD-AFM:** challenged with tight spaces, but still useful on relaxed pitch.
  - **OCD:** n & k shift issue due to quantum confinement may be a challenge. Cross-correlations and small optical volumes of profile subtleties also possible challenges.
    - Can suppliers address?
  - **CD-SAXS:** much potential, but needs to be made practical.
  - **TSOM:** Simulations predict some capability, but experimental verification needed, at λ = 248 nm.
  - **MBIR:** precision somewhat higher, but could be reliable standby for HAR multi-layers due to infrared material transparency.
- **Gaps analysis matrix shown, reflecting expected limits of different techniques (best known to date) for the various application families.**
  - Also rated each technology for other important HVM considerations.
  - Remember, very important to have both imaging & spectroscopic solutions.

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