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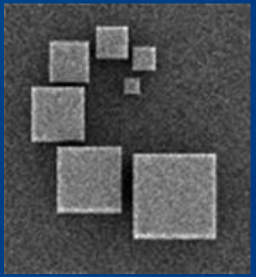
5:00PM-5:20PM PST

Simulating HV-SEM imaging of HAR and buried features



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https://www.amagnm.com/

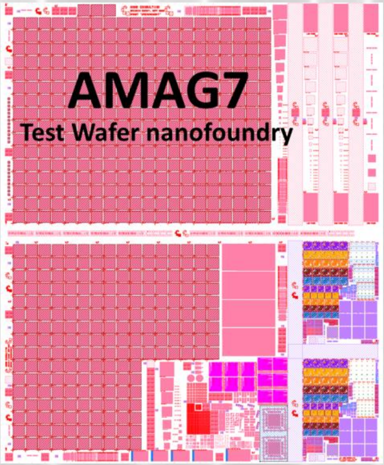
AMAG nanometro
AMAGnm.com

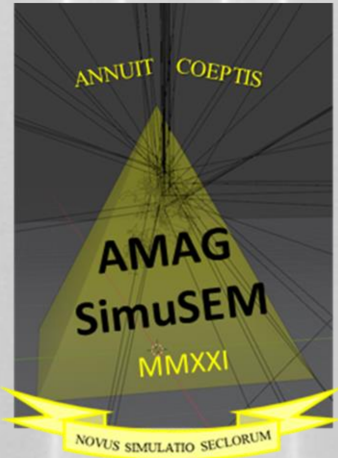
AMAGnm Mission:

- Enable semiconductor metrology sector progress through addressing critical infrastructure gaps & enabling collaboration.

AMAGnm Products:

- Thoroughly-characterized IP-neutral metrology-centric test wafer nanofoundry with AMAG7 reticle
- Physically-accurate SEM simulation made practical with AMAG SimuSEM software
- Semiconductor metrology expertise & consulting
- AMAG nanomart at AMAGnm.com





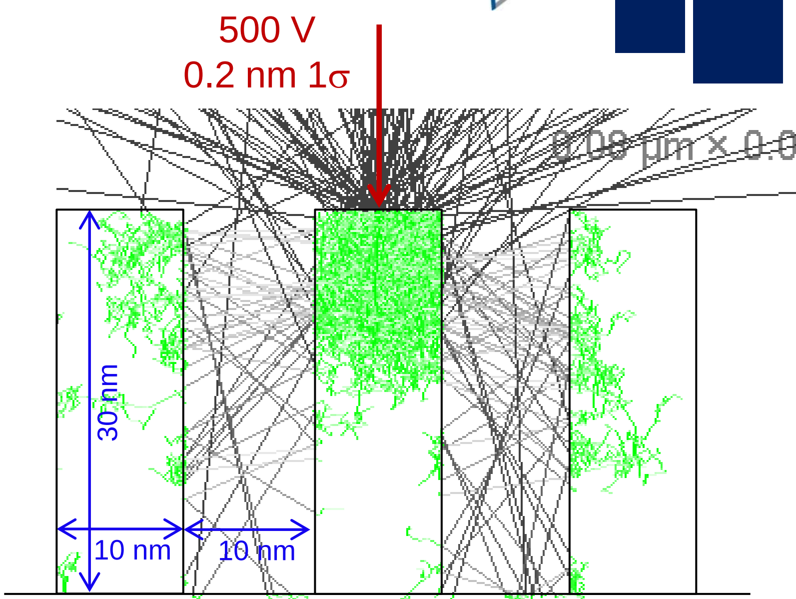
AMAG nanometro is DBA name for AMAG Consulting, LLC. All legal and financial interactions still refer to AMAG Consulting, LLC.

Introduction

- HV-SEM is becoming mainstream in fab metrology ecosystem for detecting/locating & measuring HAR or buried features:
  - Imaging down HAR holes & trenches
  - Calibrating optical overlay through thick interlayers
  - Defect metrology—buried void/particle detection
- HV-SEM setup involves time-consuming exploration for best conditions
  - Expensive tool downtime
  - Expensive perfect samples with perfect advanced foreknowledge
- Simulation is far superior for such important application work
  - Tool BKMs & parameters
  - DOEs of perturbations of critical sample parameters
- Complex features are modeled using AMAG SimuSEM, which transforms NIST's JMONSEL into a simulated-virtual SEM tool by providing full versatile sample definition workbench.
- Simulation DOEs for these applications will demonstrate prediction of best conditions/performance for:
  - HAR hole bottom imaging, including experimental validation
    - 1-5um deep HAR holes, including AMAG7
  - See-thru imaging of buried gratings
    - As for optical overlay calibration
  - DI-SEM detection of buried voids, particles & surface defects down holes/trenches
    - 3D ONO VNAND IDA

JMONSEL by NIST

- **JMONSEL is a 3-D simulating program**
  - Java MONte Carlo Simulator for Secondary ELectrons
- **Written by John Villarrubia (NIST) for SEMATECH AMAG as 1st principles SEM simulator**
  - Open source, transparently implements best known physical models
- **The program follows electrons as they…**
  - Enter material
  - Scatter
  - Lose energy
  - Exit material
  - Captured by detector
- **By monitoring electrons that exit material and are captured, electron yields found**
  - SEM Line scans (waveforms) or full images
- **User definable targets**
  - Lines, traps, triangular wedges, cylinders, spheres (full, cut or hollow), cones, pyramids, prisms, multiplanar shapes, films, substrate, Boolean operations, stretch, skew, z-height map shapes like AFM images, roughened planes
  - ~40 materials of interest, validated to Joy electron yield database
- **Beam & Scan parameters**
  - Beam energy up to 150 keV
  - Dose (# incident electrons per pixel)
  - Pixel size (set as scan locations at coordinates x,y)
  - Spot size (1sigma of Gaussian-profile, and/or divergent hourglass
  - Incident beam angle (beam "tilt")



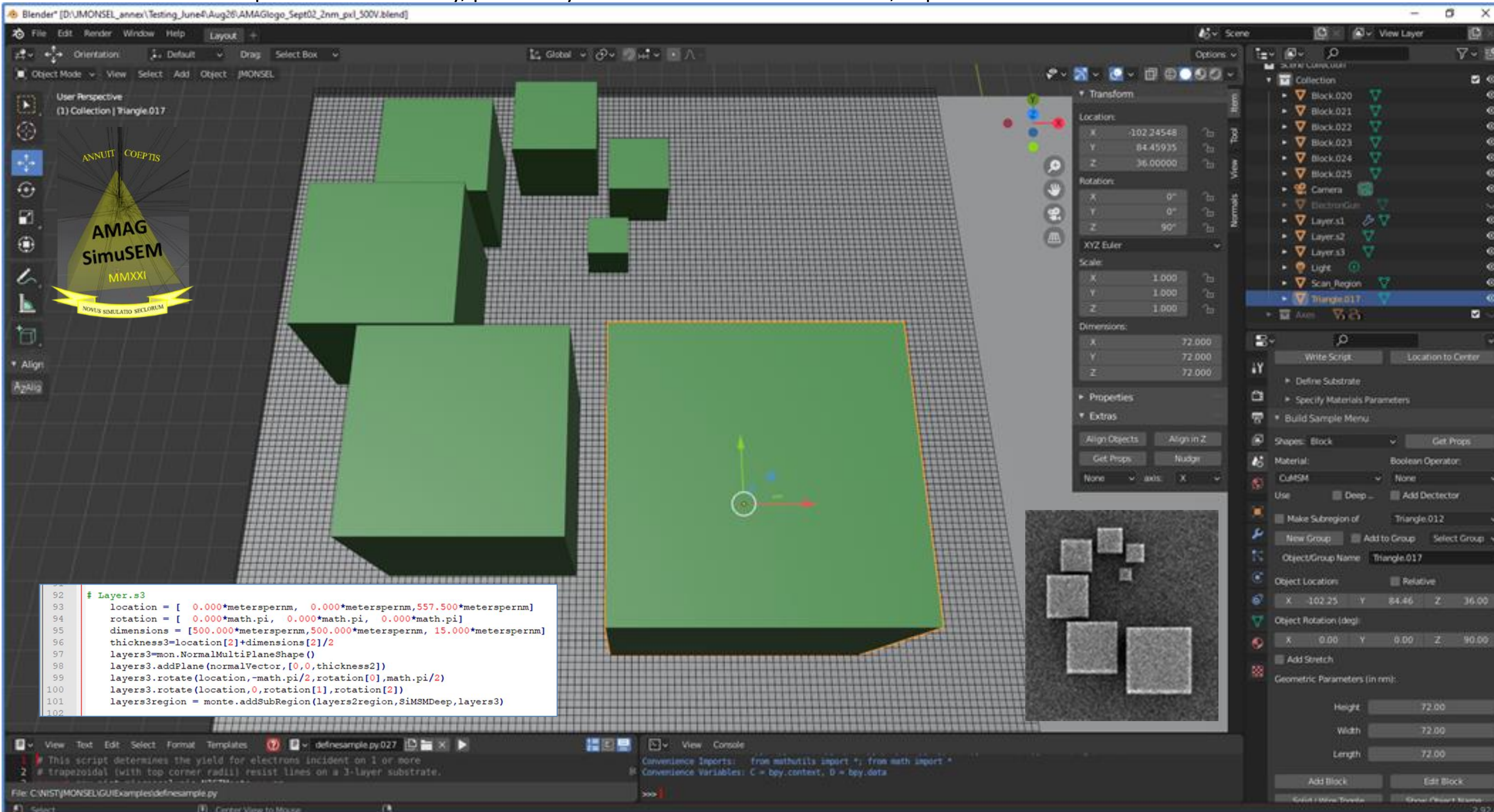
Simulated trajectories,
500 V beam on 10 nm line/space

```
# Layer.s3
    location = [  0.000*meterspernm,  0.000*meterspernm,557.500*meterspernm]
    rotation = [  0.000*math.pi,  0.000*math.pi,  0.000*math.pi]
    dimensions = [500.000*meterspernm,500.000*meterspernm, 15.000*meterspernm]
    thickness3=location[2]+dimensions[2]/2
    layers3=mon.NormalMultiPlaneShape()
    layers3.addPlane(normalVector,[0,0,thickness2])
    layers3.rotate(location,-math.pi/2,rotation[0],math.pi/2)
    layers3.rotate(location,0,rotation[1],rotation[2])
    layers3region = monte.addSubRegion(layers2region,SiMSMDeep,layers3)
```

But, coding JMONSEL scripts is challenging and hard to visualize for detailed features.

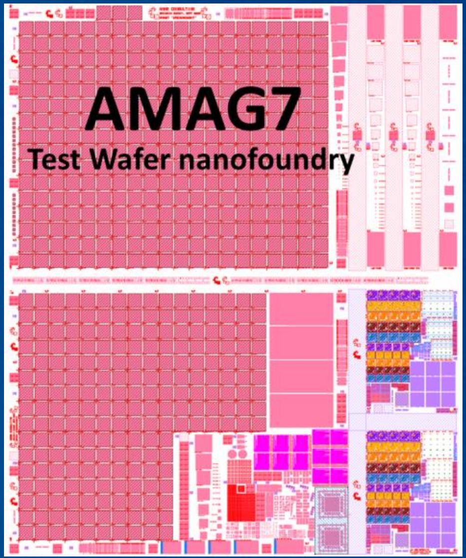
AMAG SimuSEM / JMONSEL GUI

- AMAG SimuSEM is total overhaul, enhancement & modernization extension to JMONSEL.
- Powerful yet intuitive GUI achieved by building NIST JMONSEL and rigorous sample definition capabilities into 3D Blender interface. Complex samples now possible. Core physics is still original JMONSEL code, although code is speed optimized and enhanced with new & evolving features & outputs.
- Greatly increased utility, productivity, flexibility, visualization, accessibility, & achievable complexity of designed features with 5000x simulation speed with scalability, plus many other refinements & additions, superior results access & visualization.

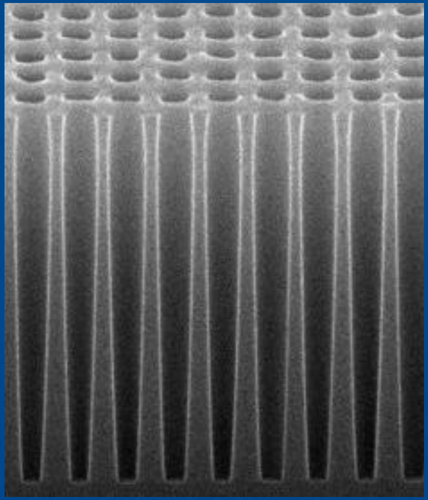


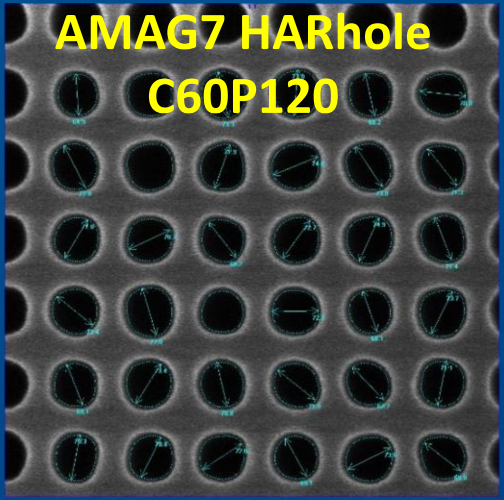
AMAG nanometro

ANNUIT COEPTIS
AMAG SimuSEM
MMXXI
NOVUS SIMULATIO SECLORUM



HAR hole simulation validation

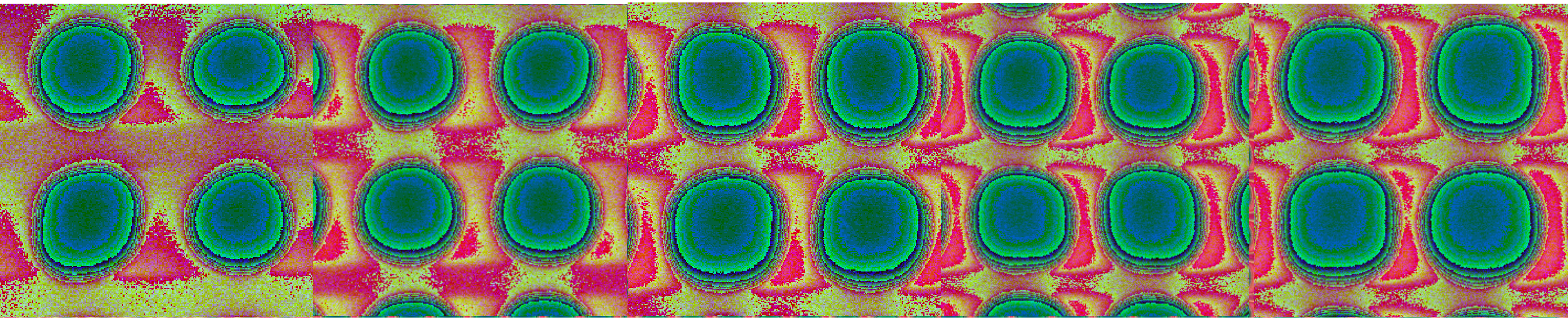




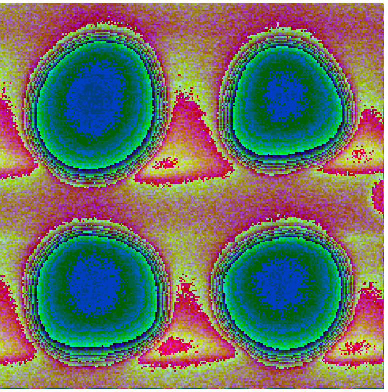
HAR hole HV-SEM images of AMAG7

- Experiments:

1. HV-SEM of AMAG7 HARhole 1um & 1.5um C60P120
   - AMAG7 wafers imaged in NGR5000 HV-SEM @ 10kV
   - Alternate color scales show much concentric structure to signal at hole bottoms.



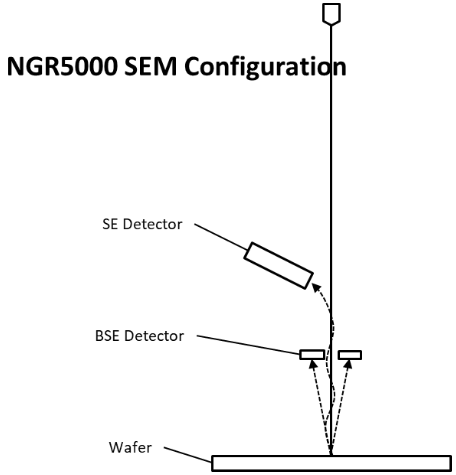
C60P120 HAR1um | C62P124 HAR1um | C64P128 HAR1um | C67P134 HAR1um | C70P140 HAR1um



C60P120 HAR1.5um

- Column & Gun configuration of NGR5000 HV-SEM

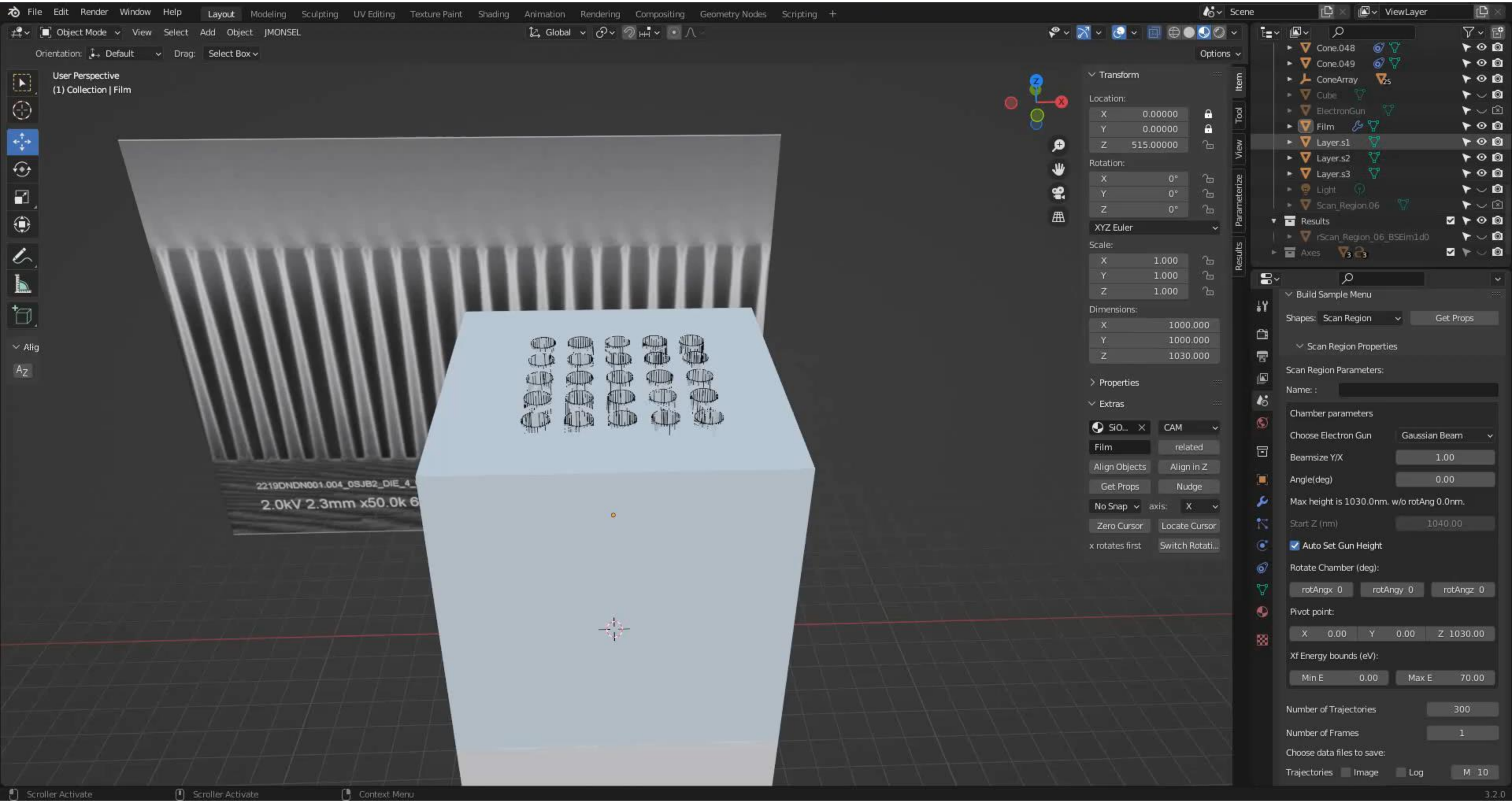
Acceleration Voltage	-15kV
Wafer Bias	-15kV ~ 0V
Landing Energy	100eV ~ 15kV
Probe Current	0.01 ~ 4.0nA
Pixel Size	0.5nm ~ 10.0nm
Image Size	256 ~ 32,000 pixels
Pixel Rate	3M ~ 100MHz



TORAY TASMIT, Inc.

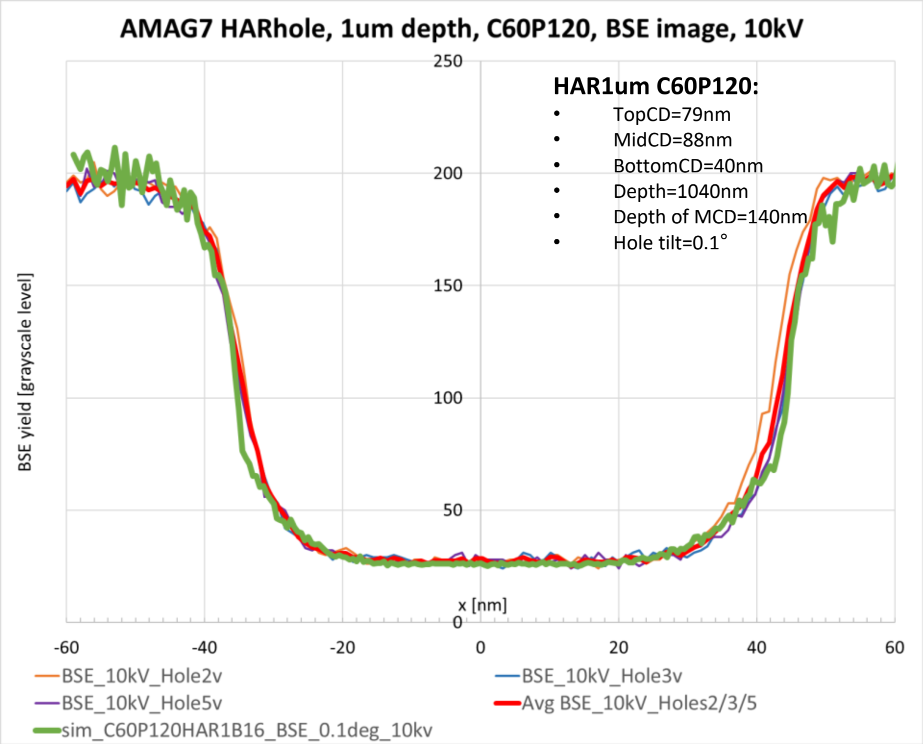
2-cone HAR hole profile setup

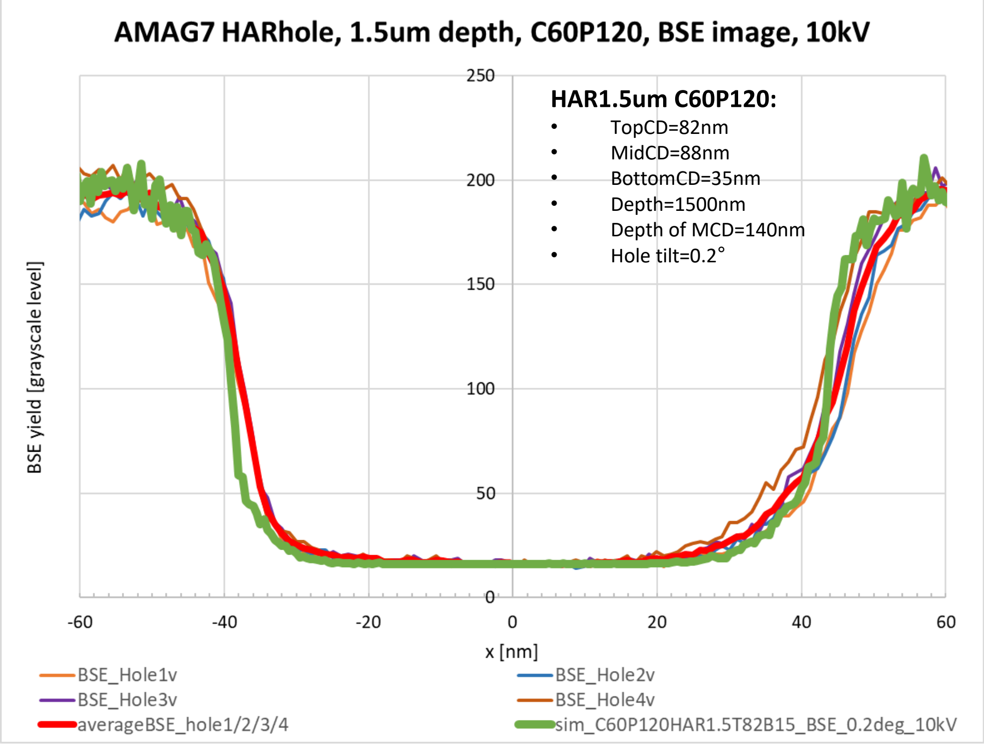
- Dual cone model for bowing hole set directly to XSEM image
- Varied bottom CD and hole tilt to converge on observed HV-SEM BSE signal



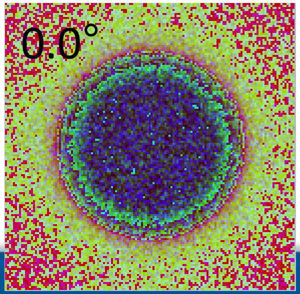
HARhole C60P120 validation

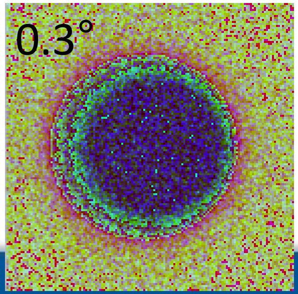
- Identified linescan segments over multiple holes of similar size on 10kV images and found average linescan.
- Iterated simulations to match linescan, simulation to experiment, as model validation.

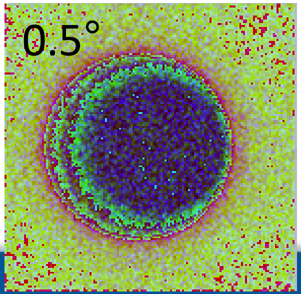


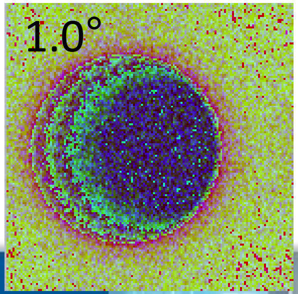


Sims, HAR1 C60P120 10kV→



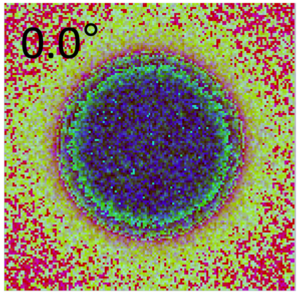


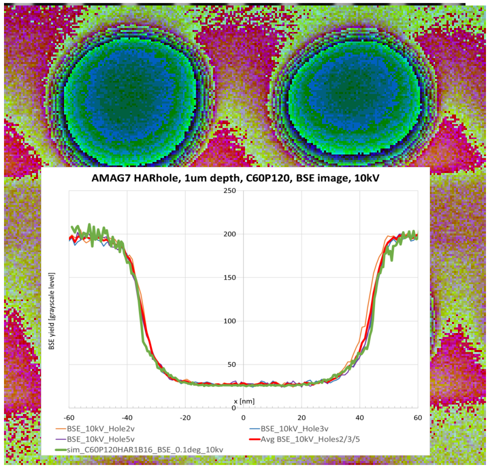




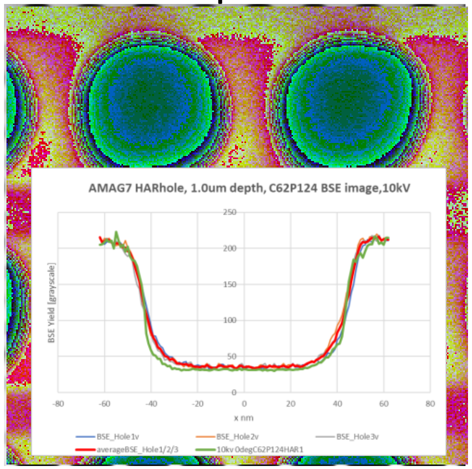
HAR hole HV-SEM images of AMAG7

- Linescan matches achieved for:
  - 5 different hole sizes in HAR hole 1um depth features
  - C60P120 HAR hole with 1.5um depth.

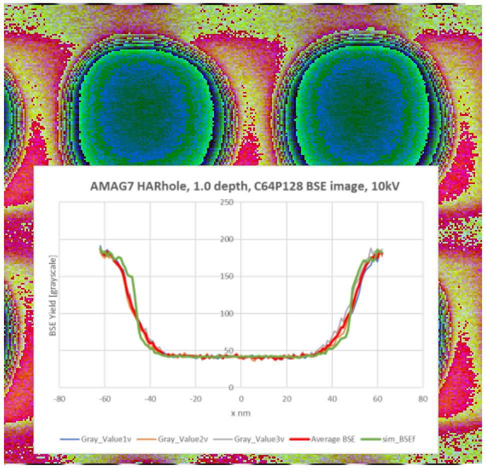




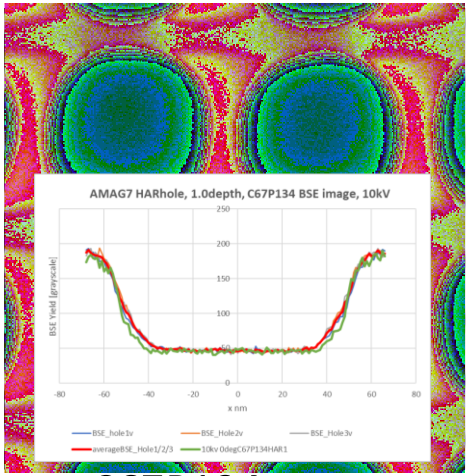
C60P120 HAR1um



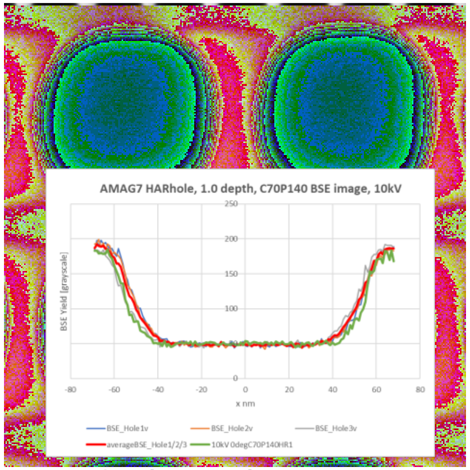
C62P124 HAR1um



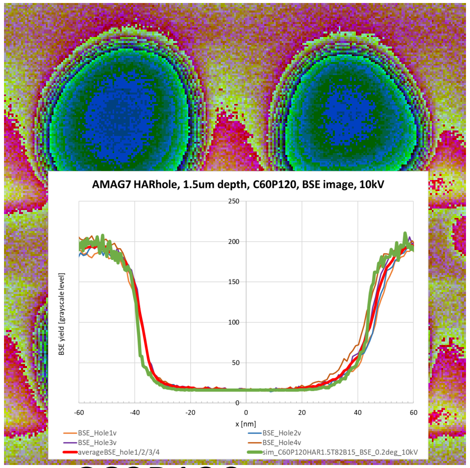
C64P128 HAR1um



C67P134 HAR1um



C70P140 HAR1um



C60P120 HAR1.5um

HAR hole HV-SEM simulation

- Experiments:

2. Replicate Fig. 4 experiment from recent paper (Sun, Hitachi)
   – Paper explored HAR hole HV-SEM imaging in detail by experiment & simulation, demonstrated exponential signal vs hole depth.

Top CD: 100 nm
Depth: 5 um
Bottom CD = 60nm
0.16 deg SWA

V_acc: 30kV/ 35kV/ 40kV

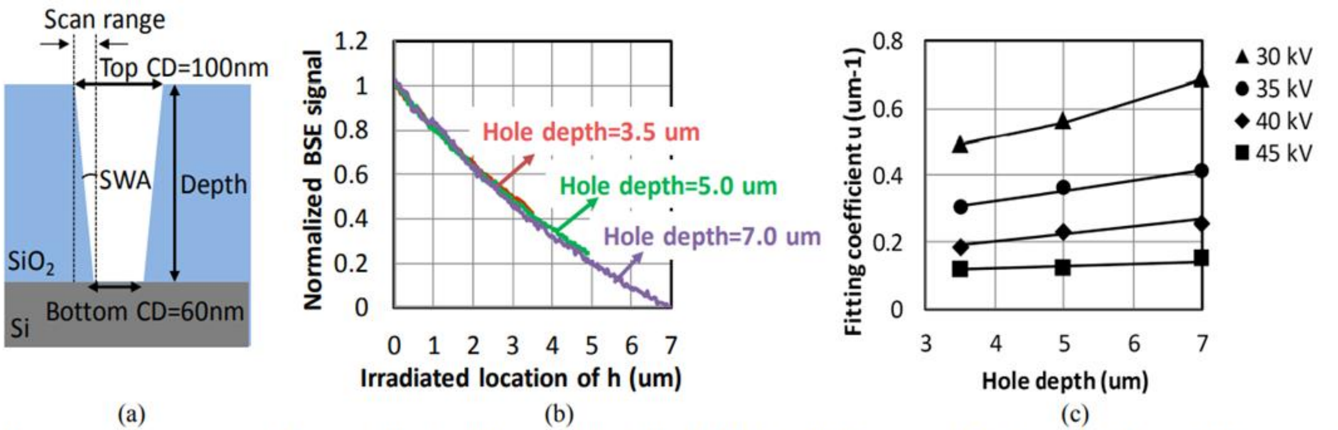
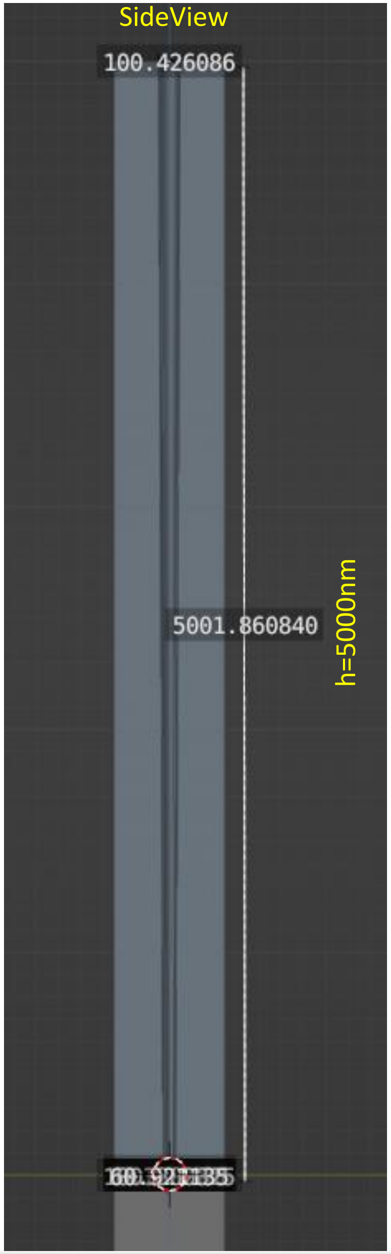


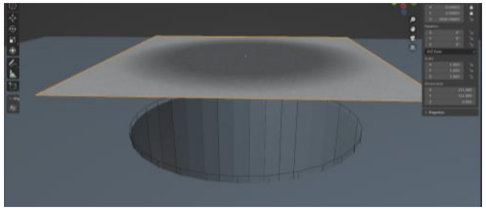
Figure 4. (a) Cross-sectional view of the simulation models of the HAR holes (b) Examples of the normalized signal intensity as a function of the irradiation depth location in a hole with different depths at electron energy of 45 keV. The hole density is 35% and the SWA is 0.16 degrees for all. (c) Comparison of the dependence of the fitted coefficient of μ on the depth of the hole, for the electron energy ranging from 30 to 45 keV.

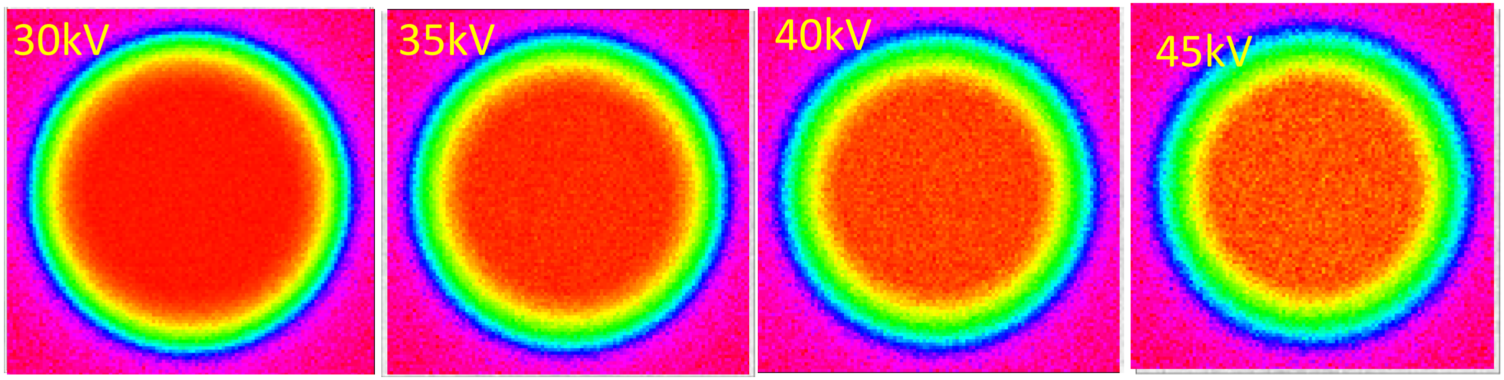
Wei Sun, Yasunari Sohda, Hiroya Ohta, Taku Ninomiya, Yasunori Goto, "High voltage CD-SEM based metrology for 3D-profile measurement using depth correlated BSE signal," Proc. SPIE 10959, Metrology, Inspection, and Process Control for Microlithography XXXIII, 1095915 (26 March 2019); doi: 10.1117/12.2511272

5um HAR hole

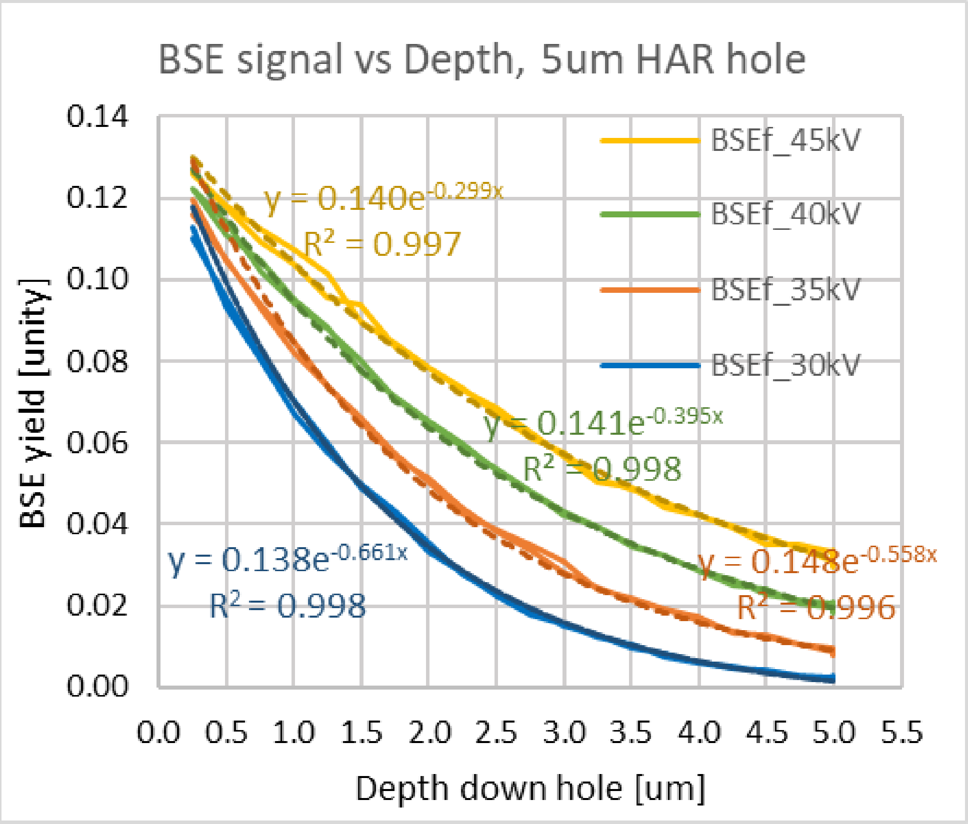


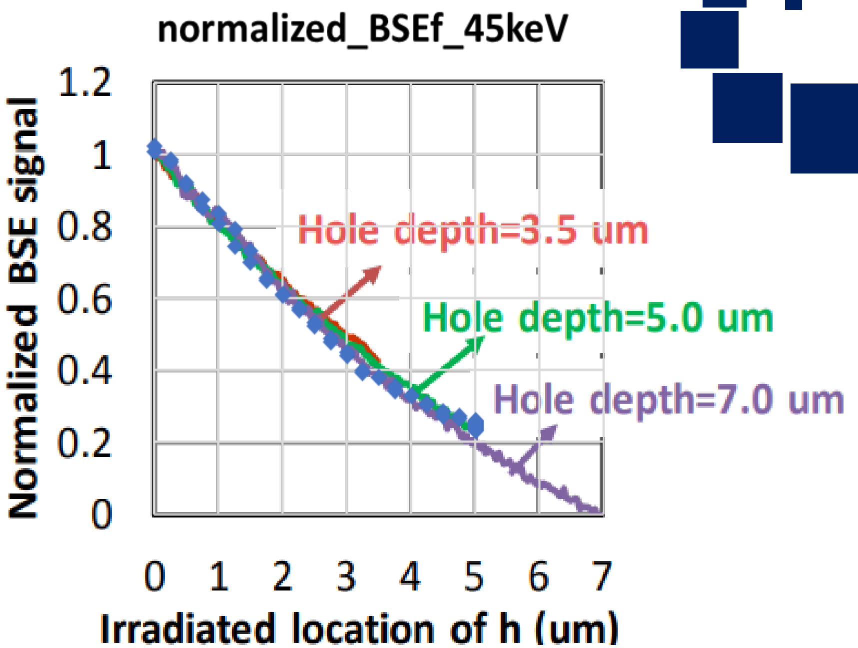
- 5000nm deep SiO_2 film on Si substrate
- Truncated cone Boolean-cut from film to make hole
  - –Top radius 50nm
  - –Bottom radius 30nm
  - –Height 5000nm
- BSE images are noisy so N=10000 trajectories.
- Conditions:
  - –1nm square pixels
  - –N=10000
  - –V=30kV/35kV/40kV/45kV





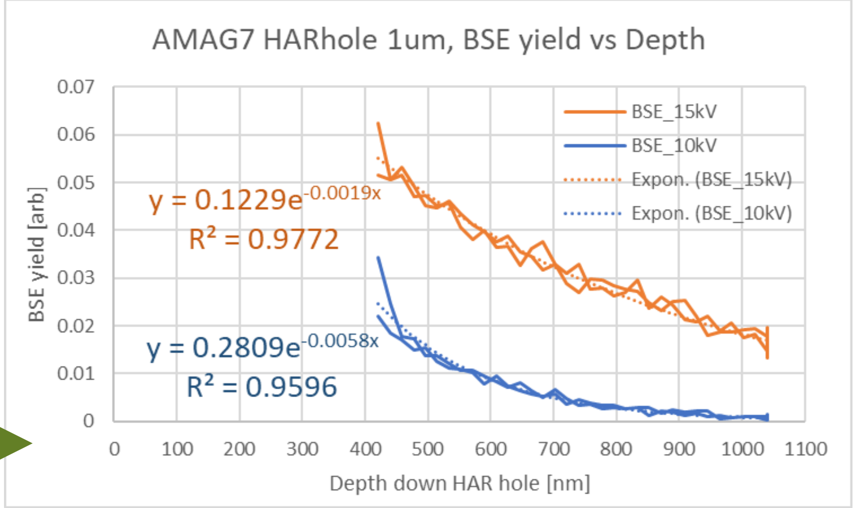
5um HAR hole results





- Normalized 45kV results directly match Sun's experimental & simulation results.

- Sun paper demonstrated (both by simulation & experimentally):
- BSE(h)/BSE(0) = exp(-μh)
- **Conclusive Exponential fits achieved**
- **Confirmed on AMAG7 results**

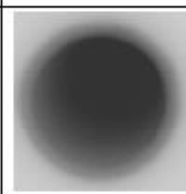
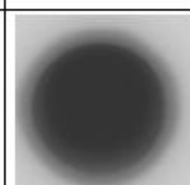
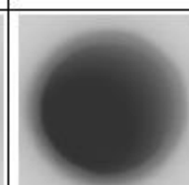


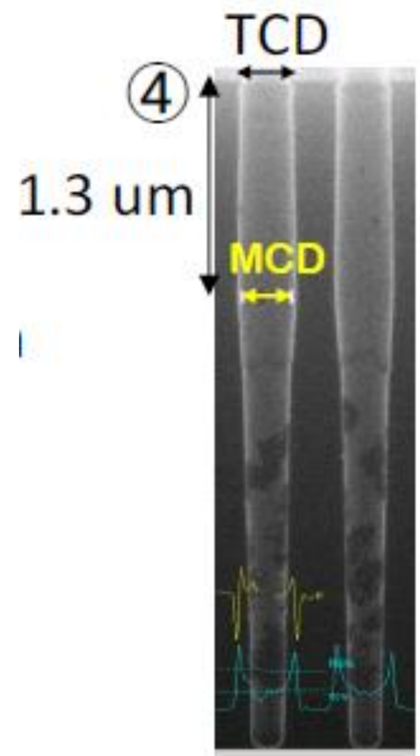
HAR hole HV-SEM simulation

- Experiments:

3. Replicate Fig. 6 experiment from recent paper (Sun, Hitachi)

- Demonstrate ability to explore complex profiles by building bowing holes model for fig 6(d) and demonstrate tilt imaging:
  - TCD: 276 nm
  - MCD = 300 nm in depth of 1.3 um
  - Bottom CD = 140 nm
  - Pitch: 600 nm
  - Depth: 3.5 um
- Vacc = 30kV, BSE tilt images, 0° & ±1°

Bowing holes	Tilt angle (degree)		
	1.0	0	-1.0
④ MCD=300 nm			

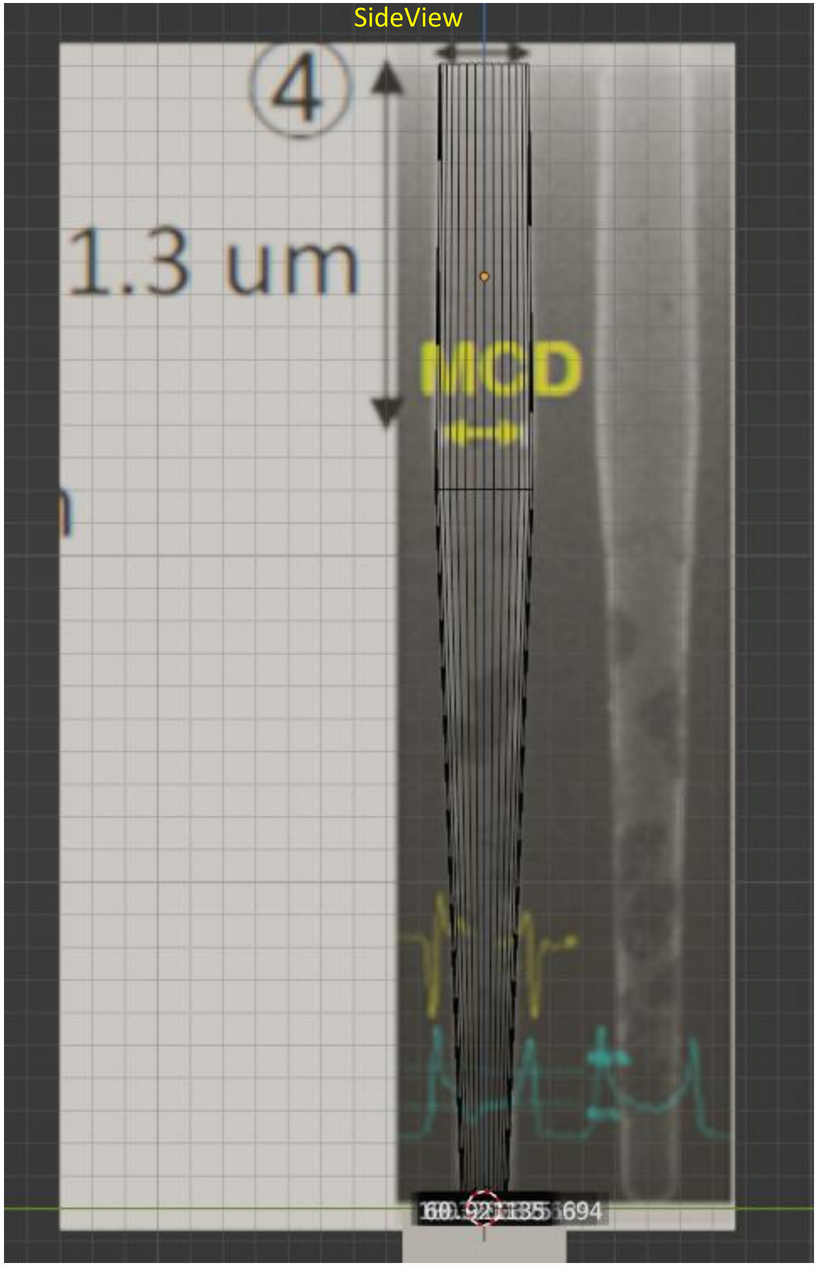


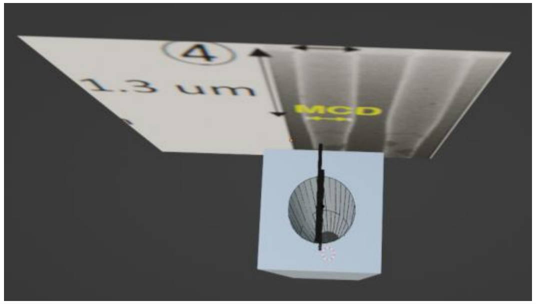
(d)

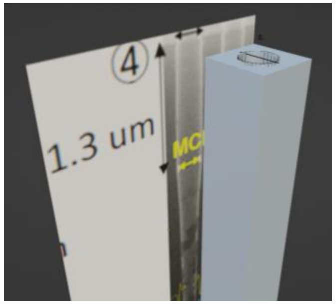
Wei Sun, Yasunari Sohda, Hiroya Ohta, Taku Ninomiya, Yasunori Goto, "High voltage CD-SEM based metrology for 3D-profile measurement using depth correlated BSE signal," Proc. SPIE 10959, Metrology, Inspection, and Process Control for Microlithography XXXIII, 1095915 (26 March 2019); doi: 10.1117/12.2511272

2-Cone profile setup

- 3500nm deep SiO_2 film on Si
- 2 truncated cones Boolean-cut from film to make hole
  - –Top section:
    - Top radius 138nm (diameter 276)
    - Bottom radius 150nm (diameter 300)
    - Height 1300nm
  - –Bottom section:
    - Top radius 150nm (diameter 300nm)
    - Bottom radius 70nm (diameter 140nm)
    - Height 2200nm
- Profile directly matched to XSEM image in GUI to show fidelity of designed profile



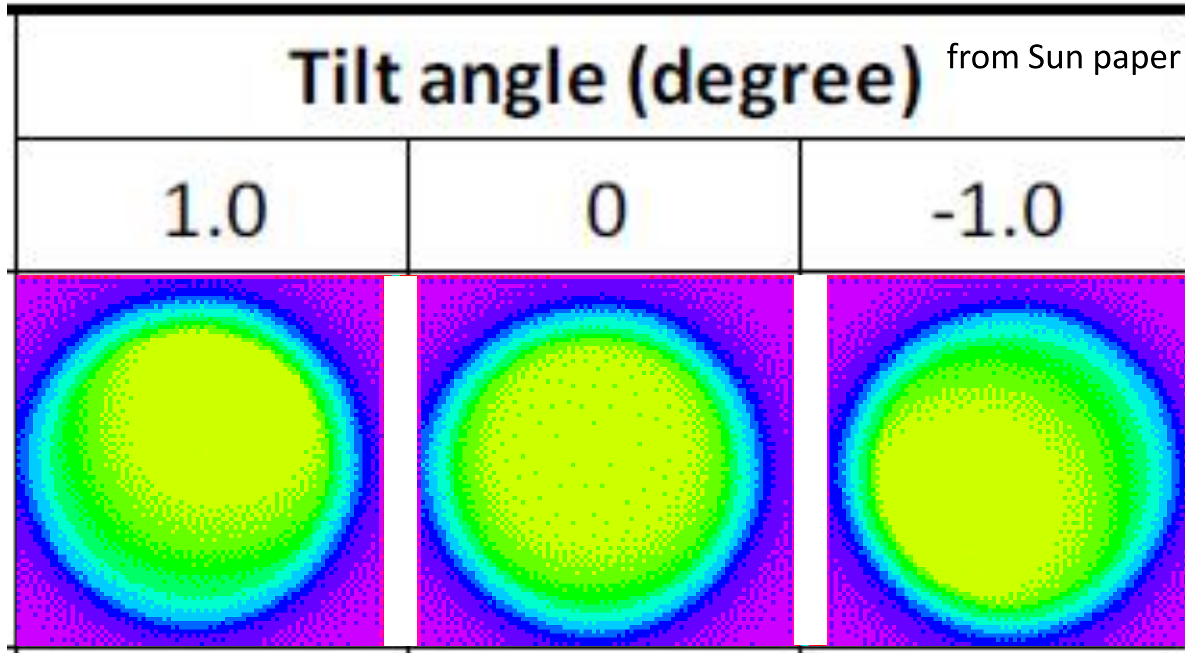


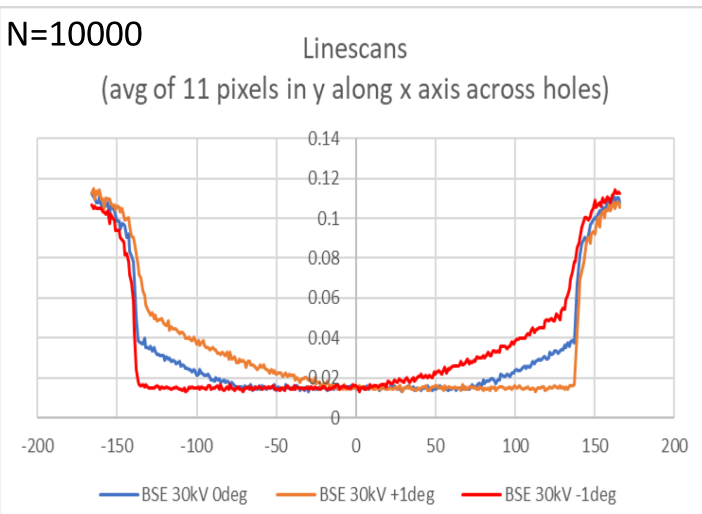


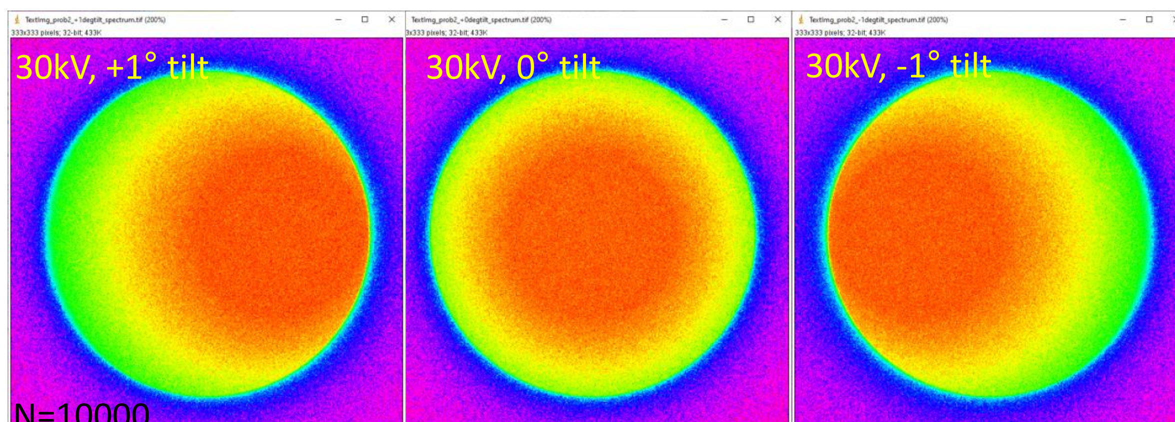
HV-SEM HAR hole tilt images

- HV-SEM images are noisy for BSE, N=10000 trajectories suppresses noise.
  - N=1000 does give okay results but with less certainty. Part of the nature of the HAR hole / HVSEM problem.
- Conditions:
  - 1nm square pixels
  - N=10000 (very high SNR)
  - V=30kV at -1°/0°/+1° beam tilt
  - Axes not same alignment, brightness/contrast difference from images in paper, but **good match achieved and expected linescan behavior**

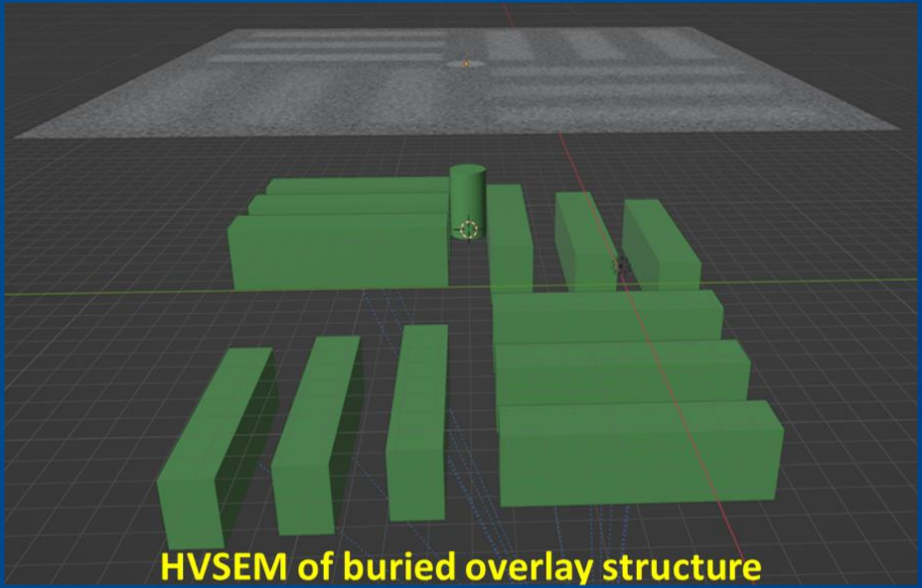
from Sun paper







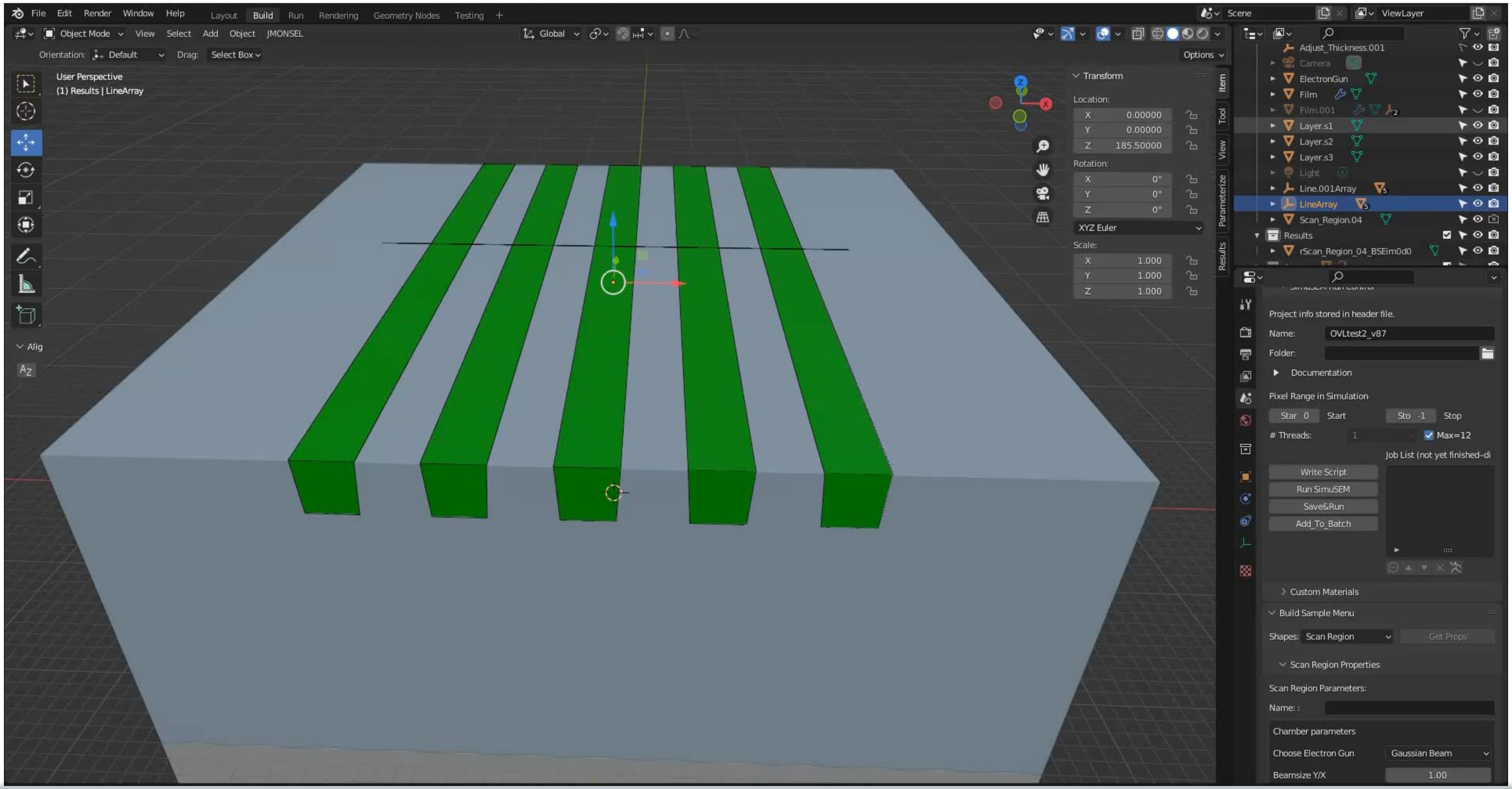
HV-SEM See-through imaging



HVSEM of buried overlay structure

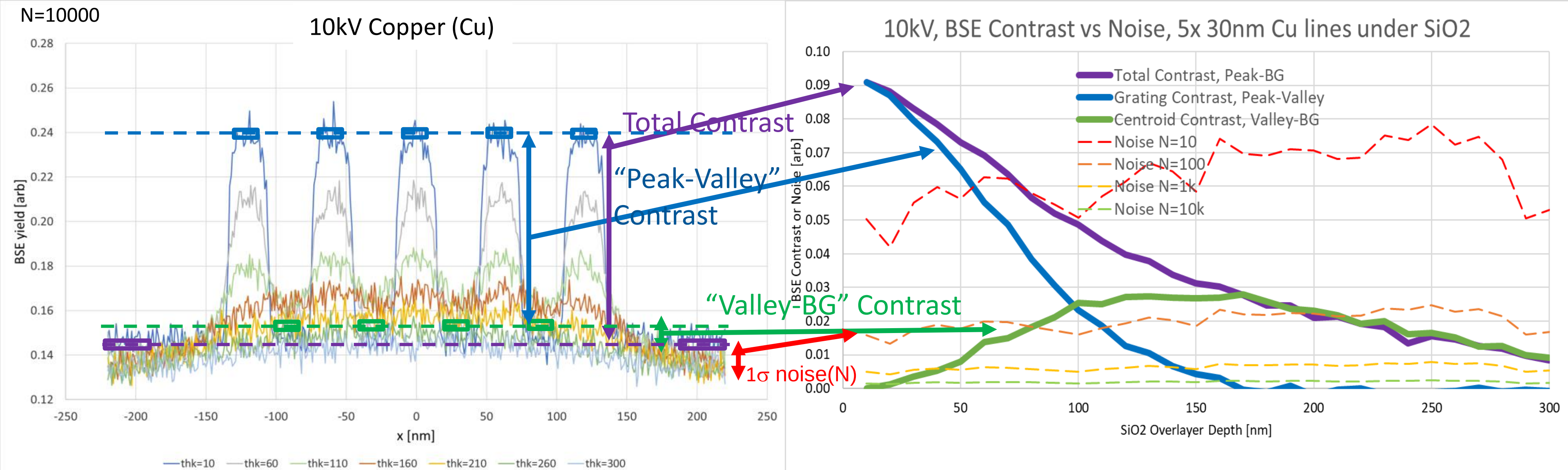
HV-SEM See-thru simulation

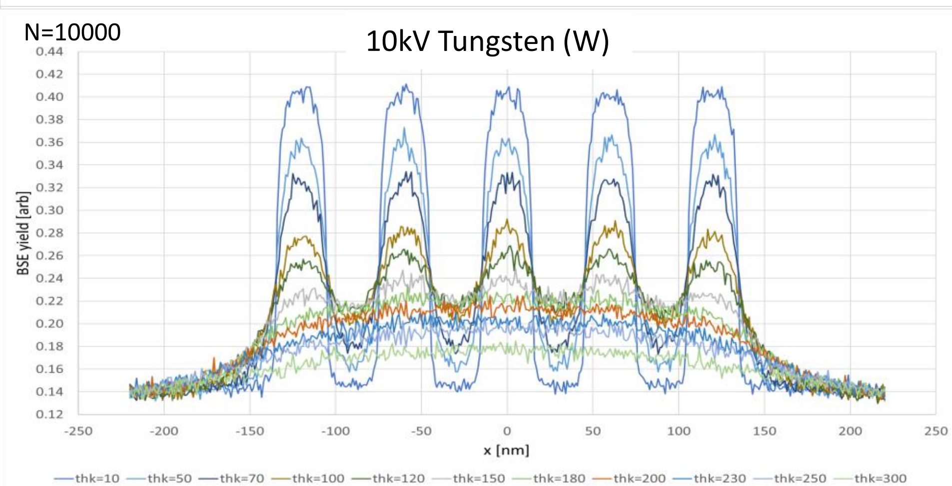
- Optical overlay has calibration issues when aligning thru thick overlayer films (i e oxide).
- Basic HV-SEM See-thru overlay problem: **What beam V to accurately detect center location of buried feature under x nm of oxide film?**
- Many sample layouts one could try (dense line group, iso line, more complex marks, 2 levels, etc), we choose simple 5 line grouplet of 30nm wide 60nm pitch lines. Damascene Cu & W.
- Sophisticated simulations can explore any cases of above.
- Varied SiO_2 overlayer, 10-300nm step 10nm.
- 1nm pixels, 10/15/20/25/30kV, N=10000.

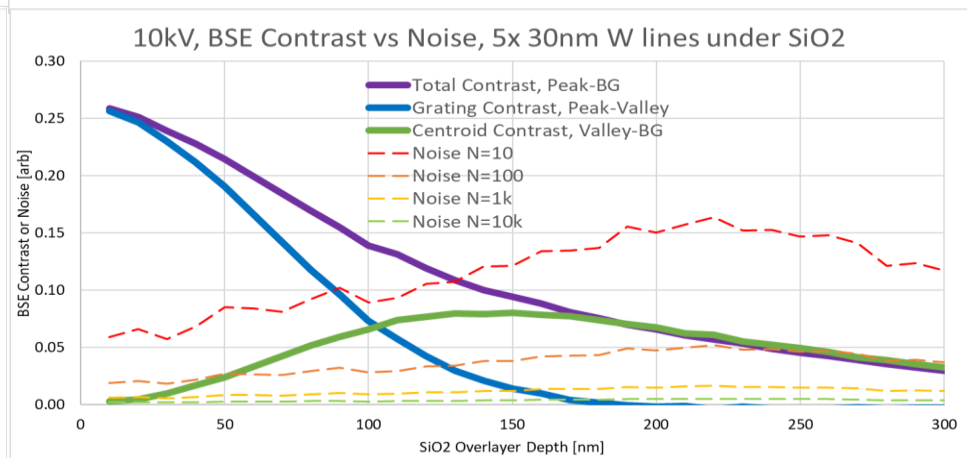


BSE Signal Contrast vs Depth

- Determine best conditions for contrast and noise for detecting 5x 30nm wide 60nm pitch Cu or W lines thru x nm SiO_2 overlayer.
- DOE of linescans at different V and different oxide overlayer thickness.

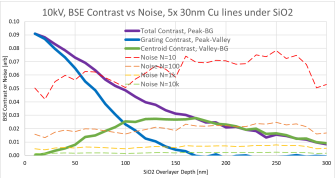


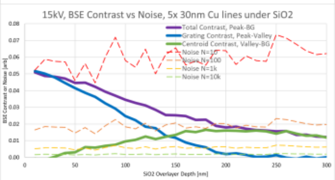


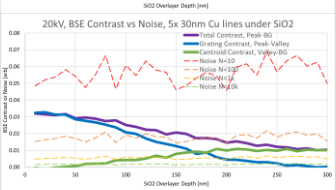


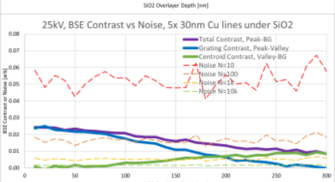
SNR of Buried Copper Grating in Oxide

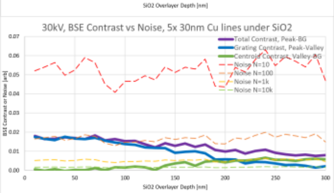
- At 10kV, limit seems to be ~200nm depth with N=100 per pixel dose.
- Can enhance with higher N.

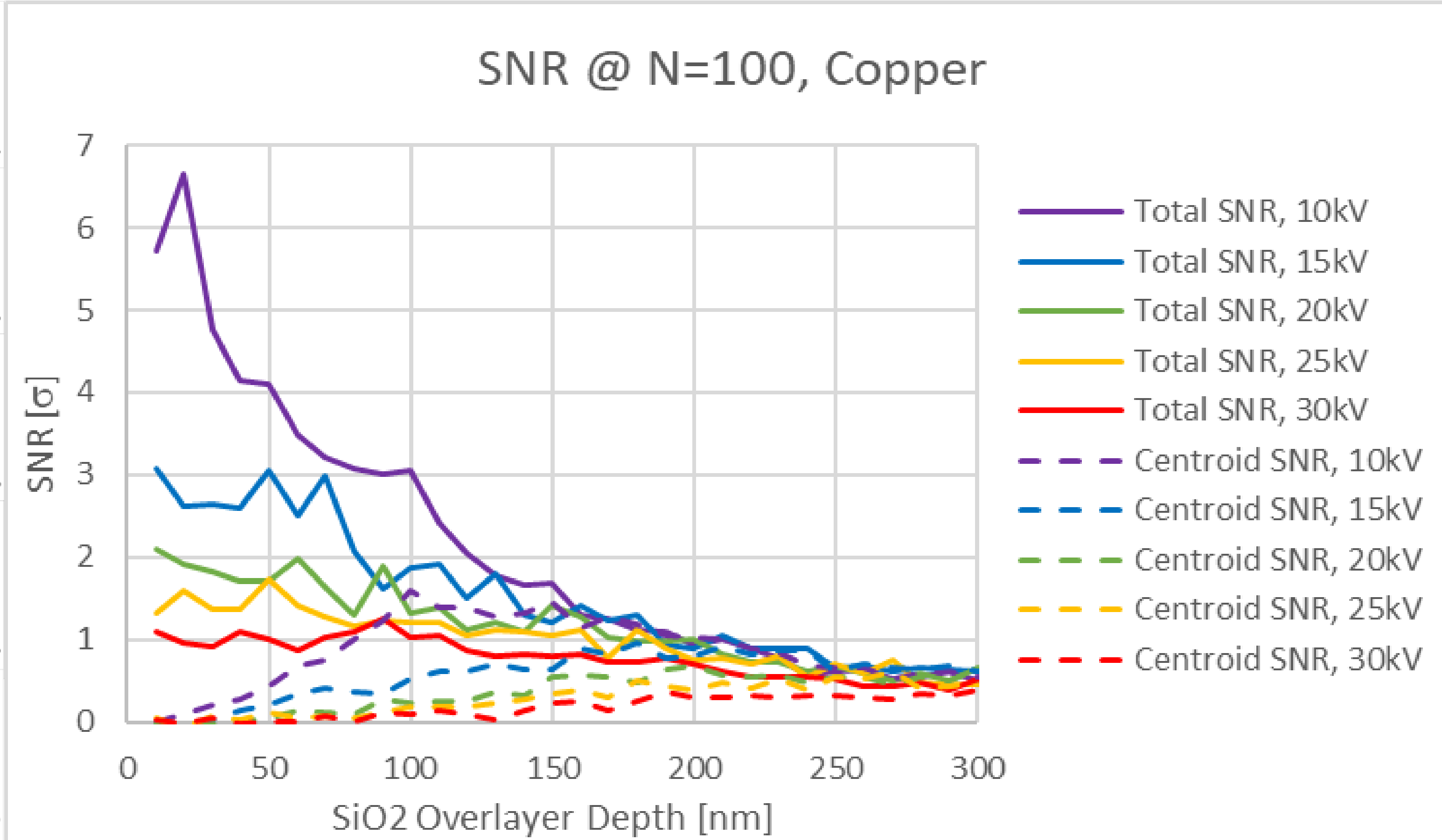






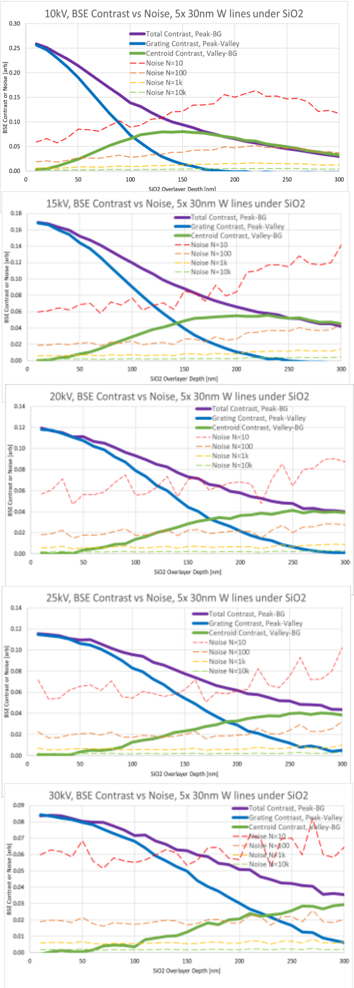


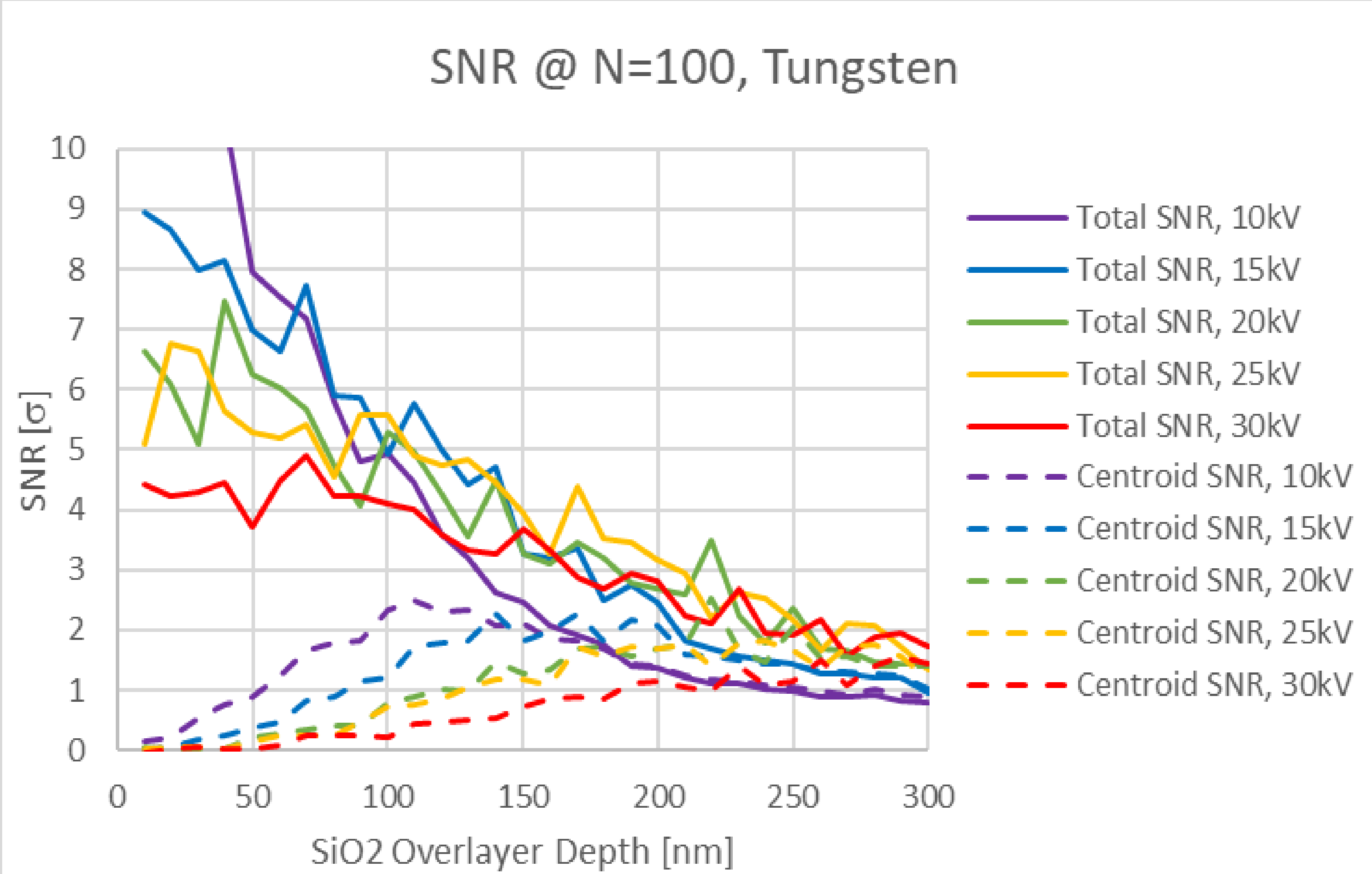




SNR of Buried Tungsten Grating in Oxide

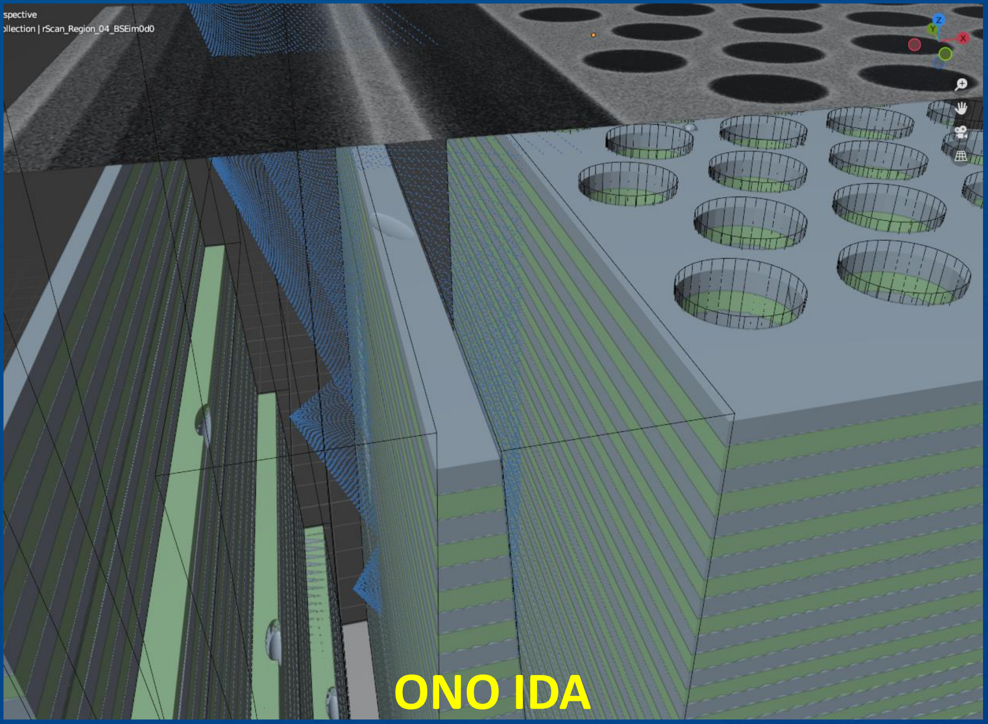
- At ≥20kV, limit seems to be >300nm depth if using N=100 per pixel. SNR seems decreasing with higher thicknesses so not much thicker than 300nm is limit.
- Can enhance with higher N.





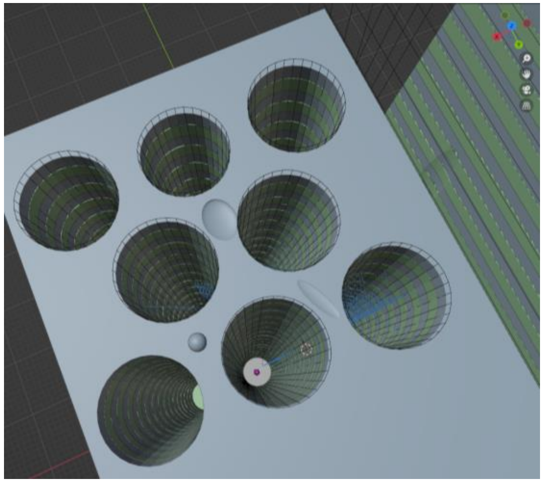
- Higher beam V should go deeper and attain centroid of grating. More simulation studies required to find limit.

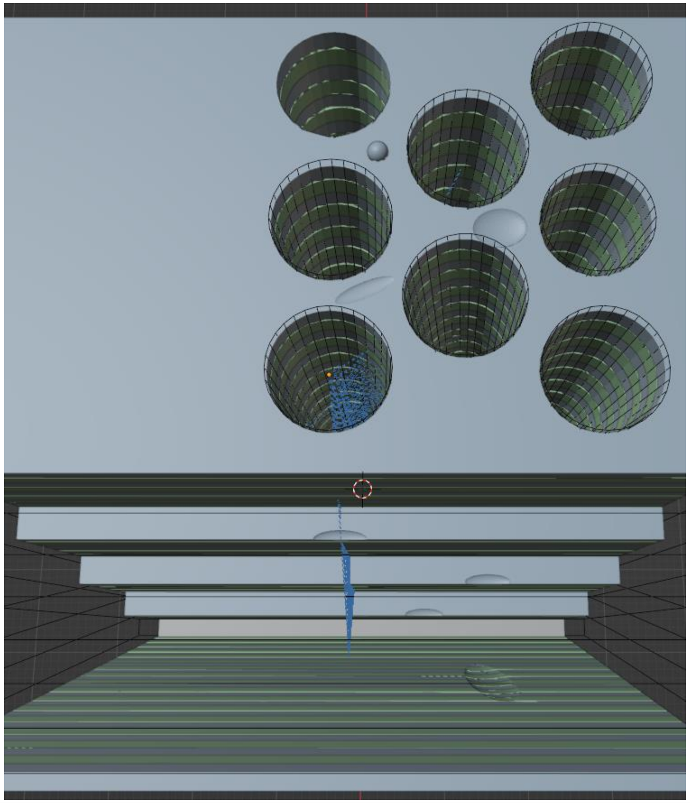
HV-SEM & Defectivity

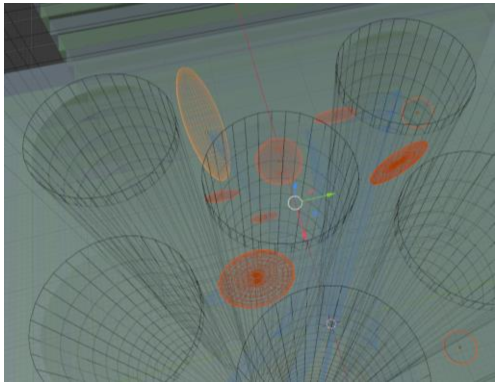


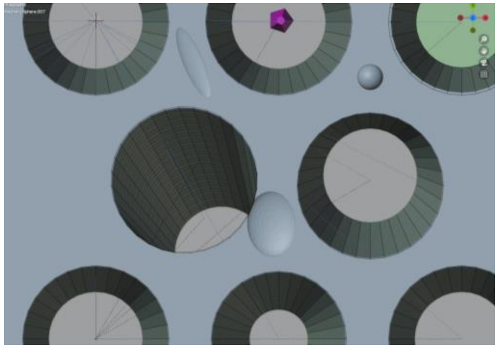
HV-SEM simulation for defects

- Defectivity is a large yield detractor and is only getting harder to detect with complex 3D structures.
- HV-SEM see-through techniques can detect buried voids, buried particles, surface damage or particles in trenches or holes.
- ONO IDA set up to demonstrate how simulation can now define & explore such defects.
- This topic will be explored in greater detail in future, but just looking at the simulated images without SNR analysis at different beam V, much can be learned about feasibility of detecting different defect types in such a complex matrix.









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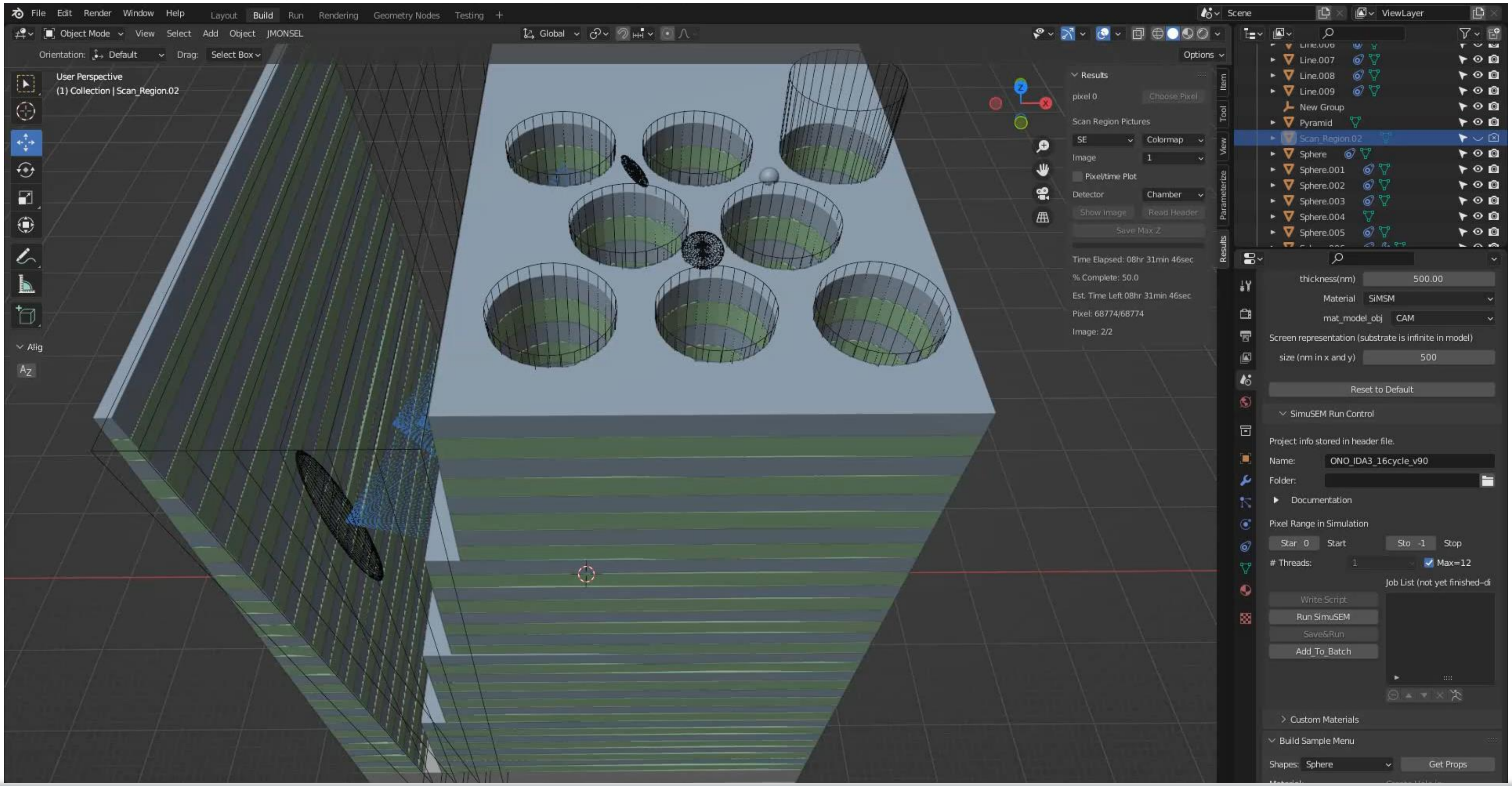
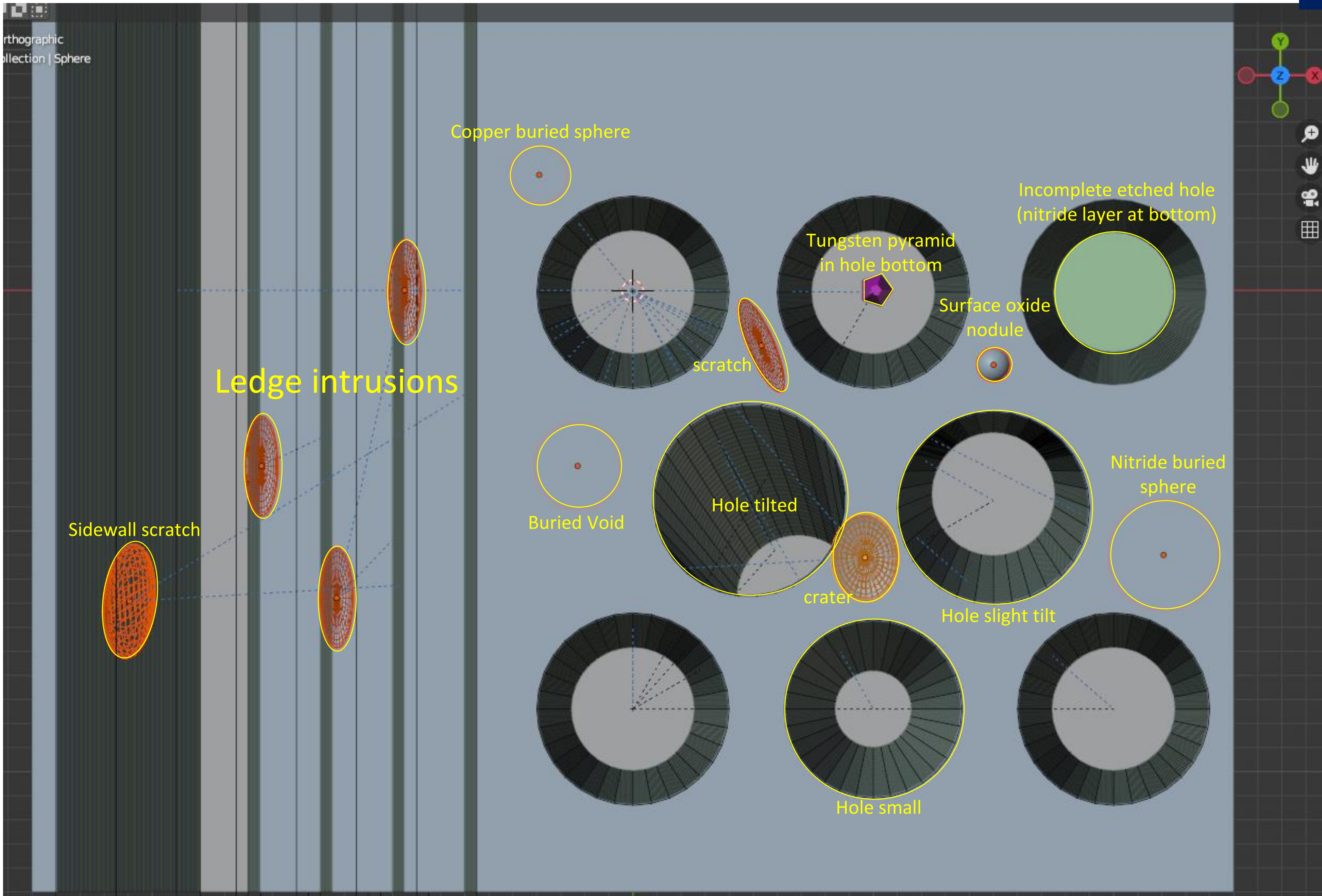


HV-SEM BSE images of ONO IDA



- Quantitative comparative SNR analysis will be in paper.

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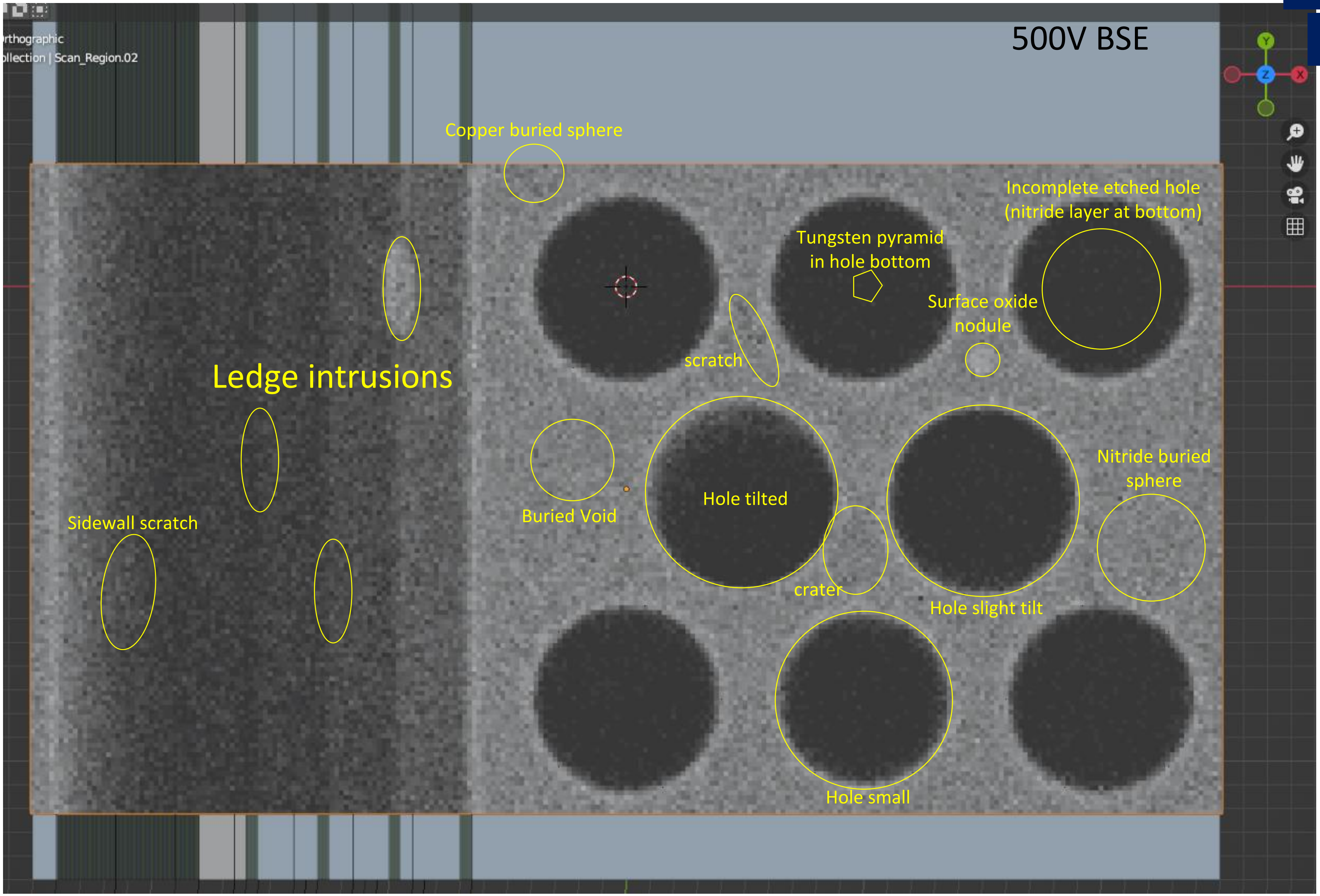

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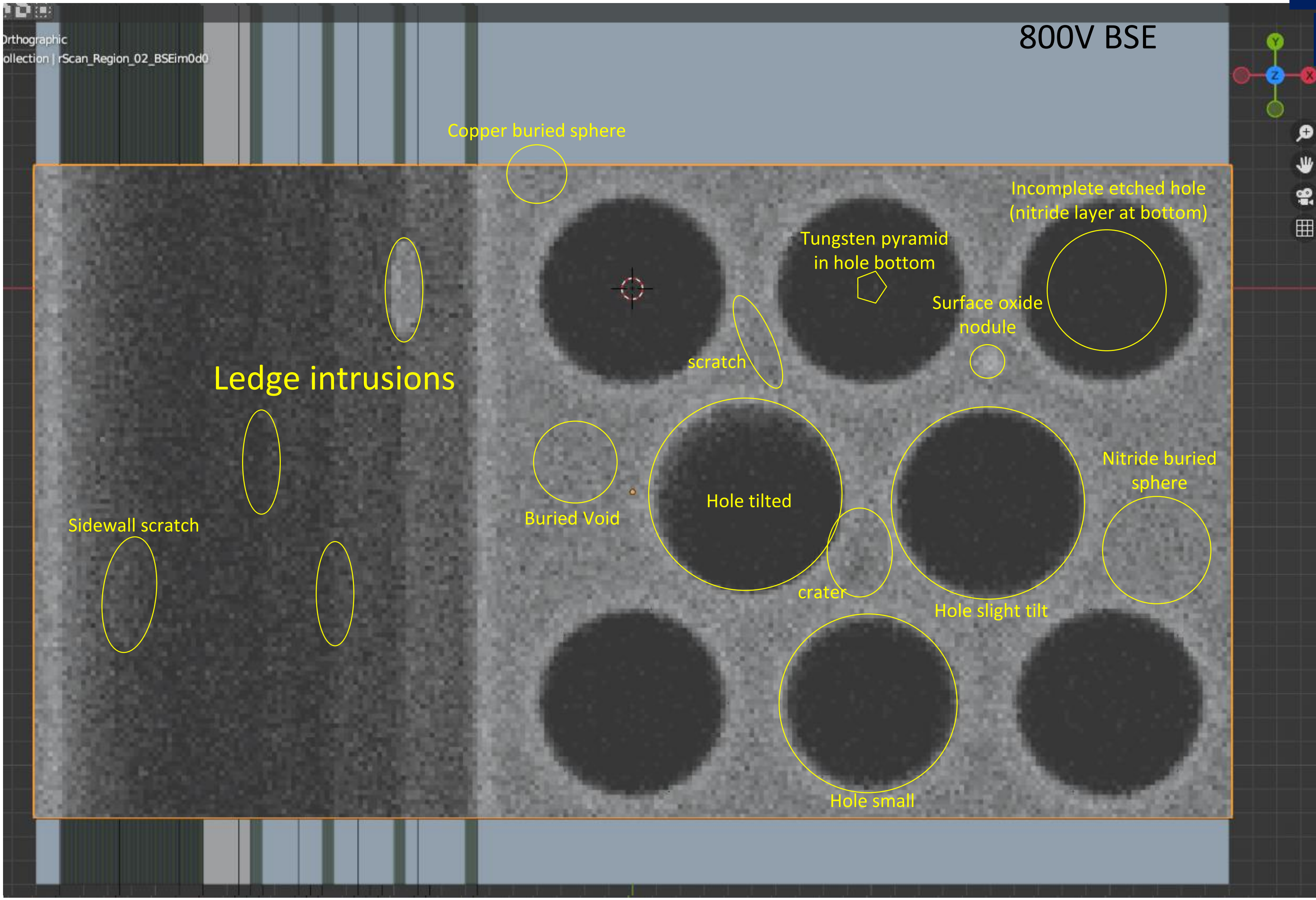

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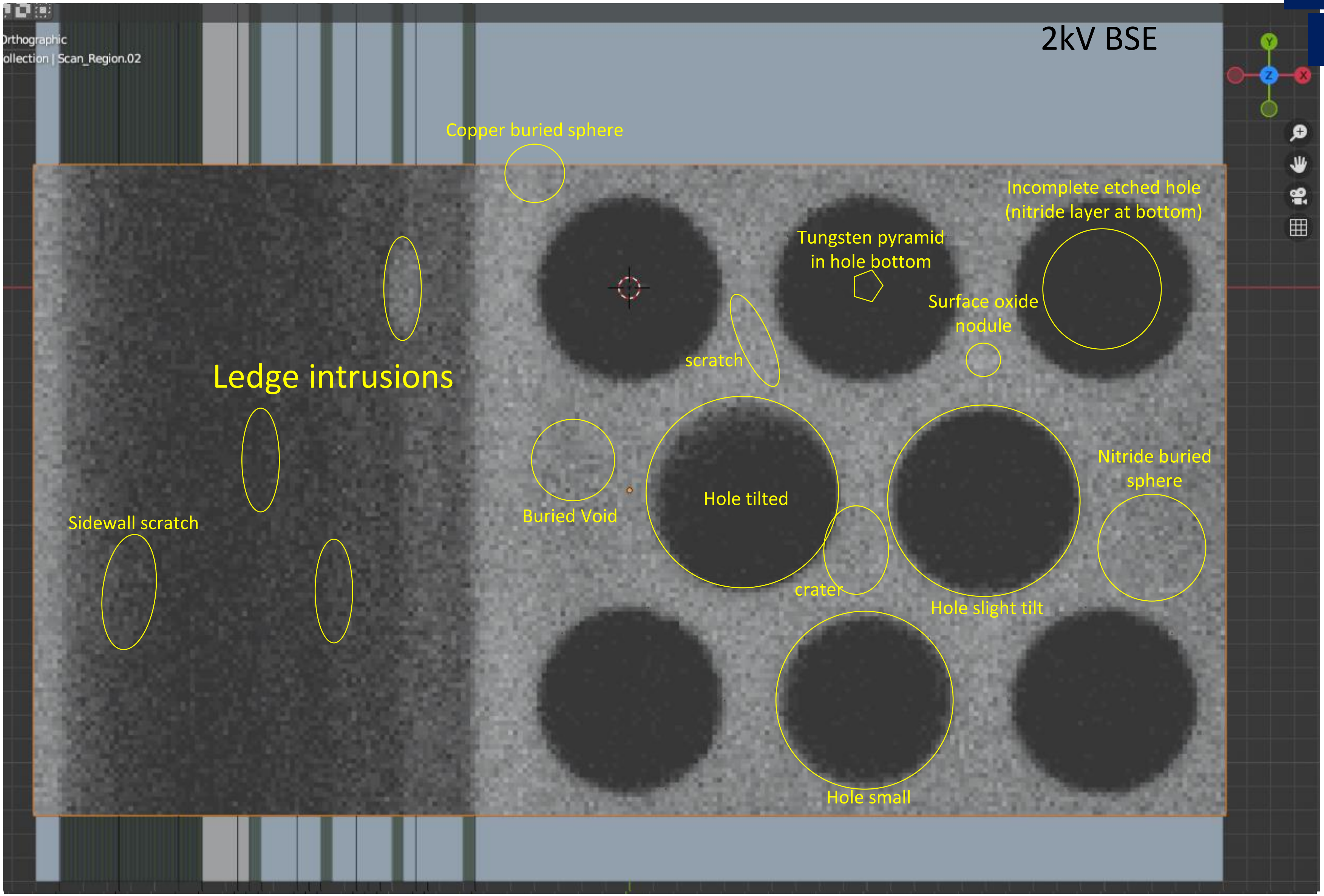

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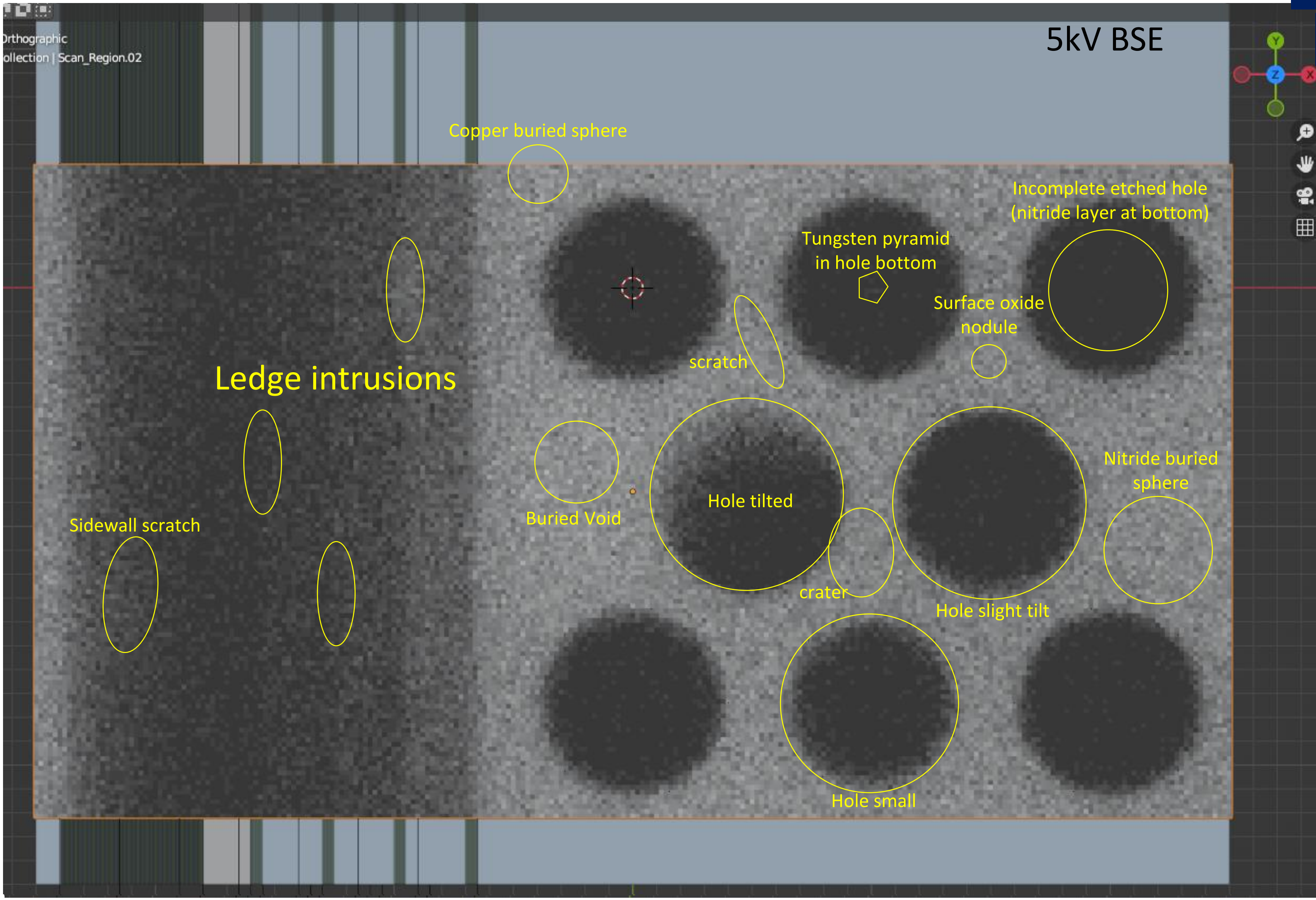

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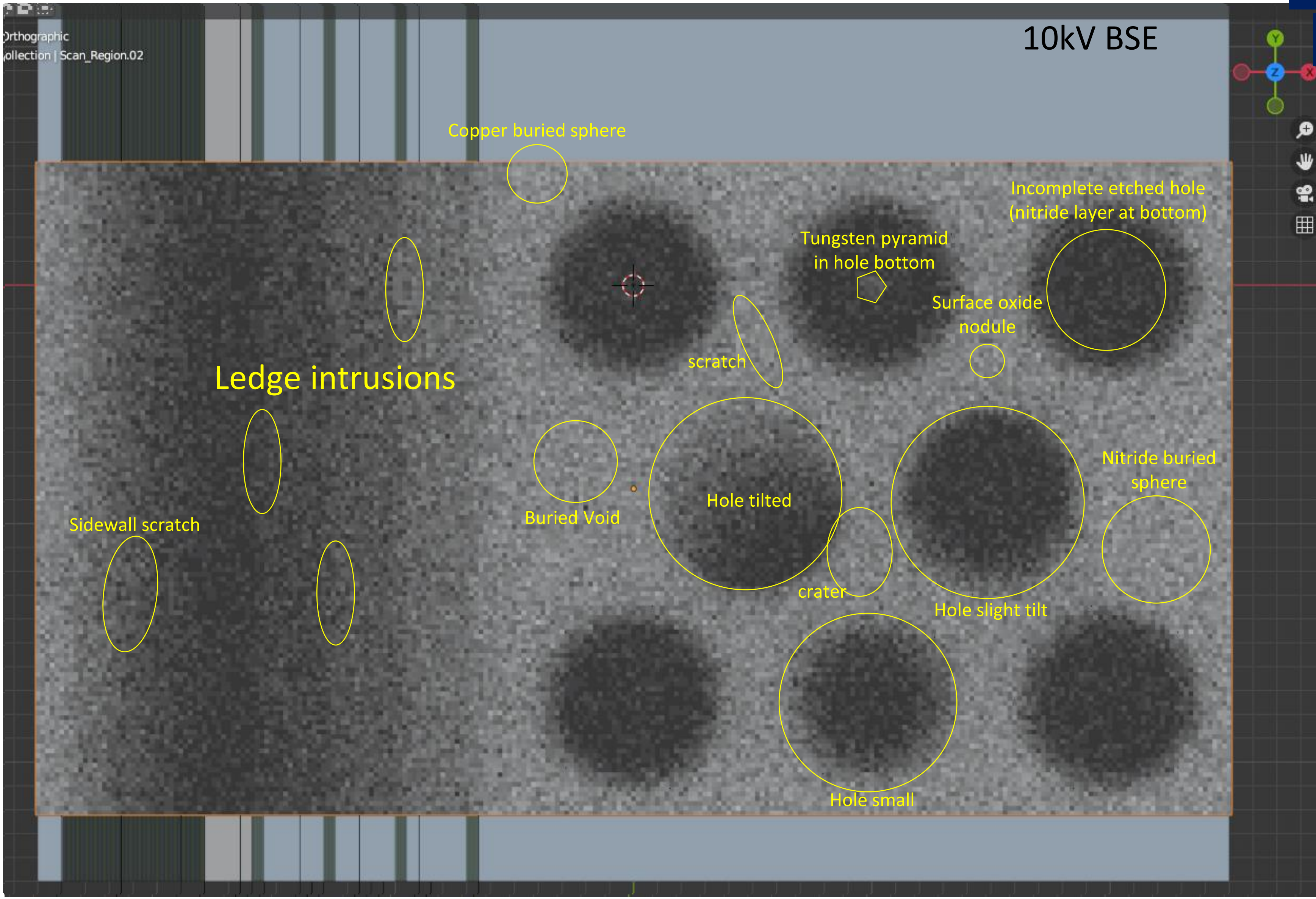

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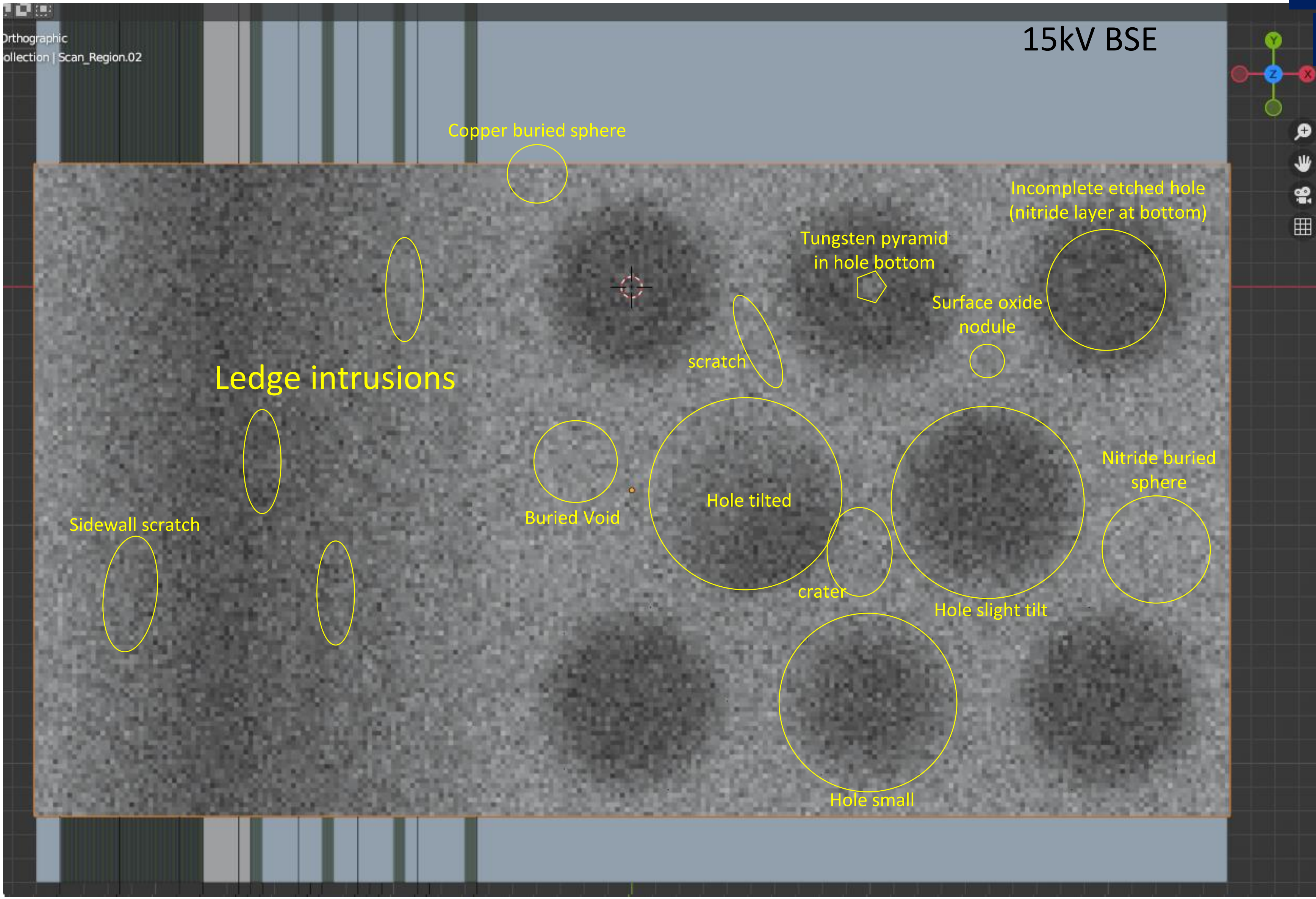

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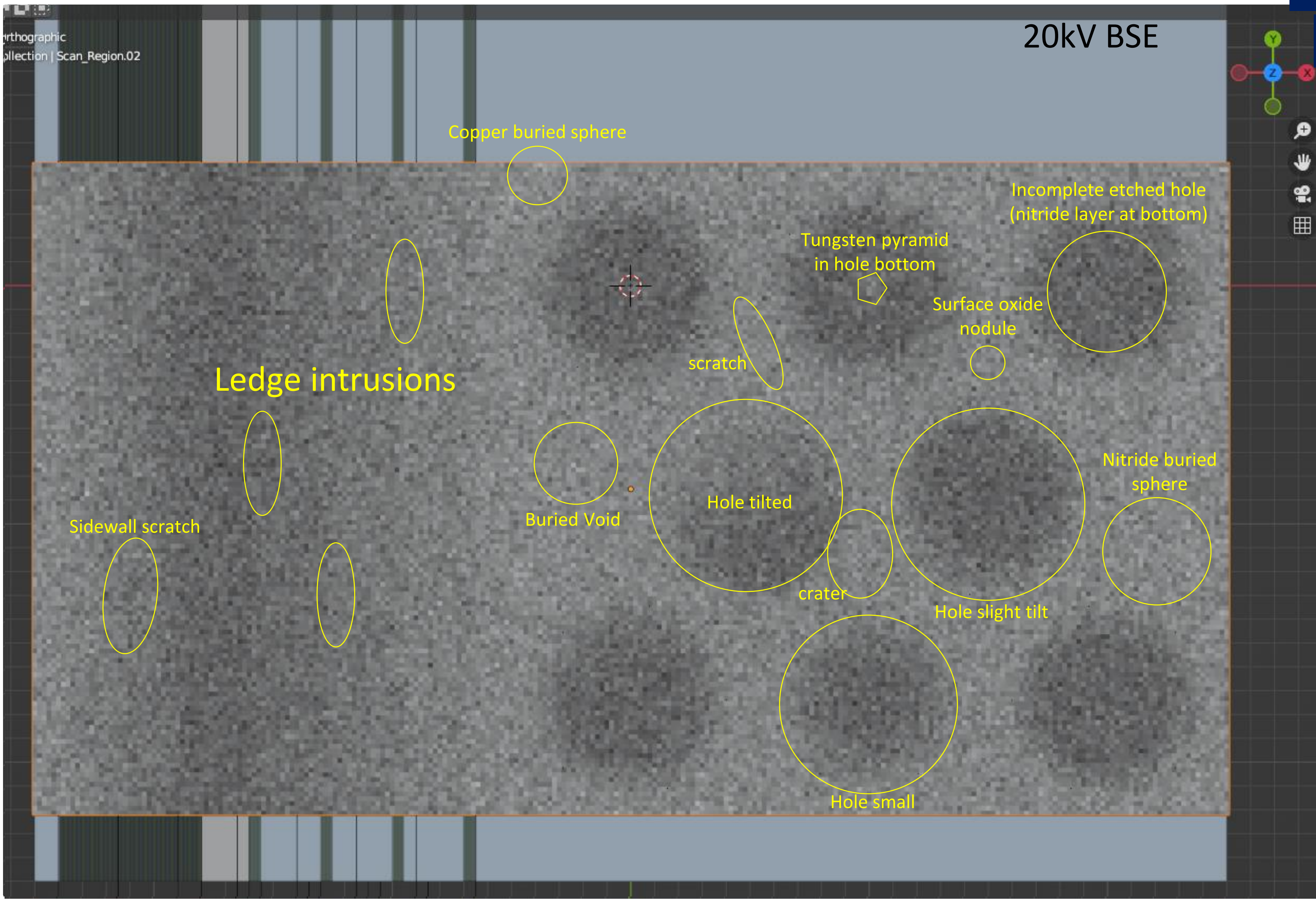

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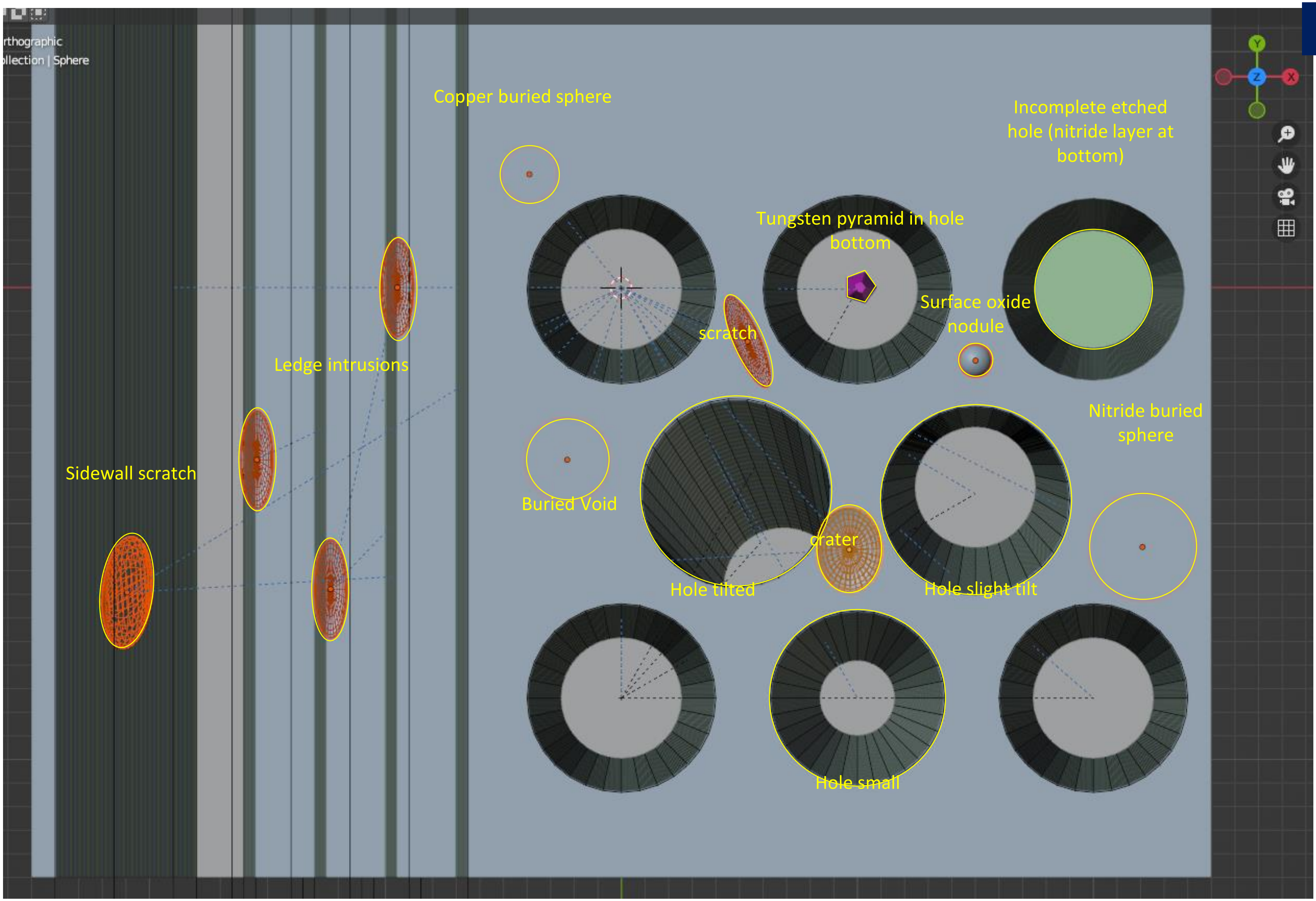
HV-SEM SE images of ONO IDA



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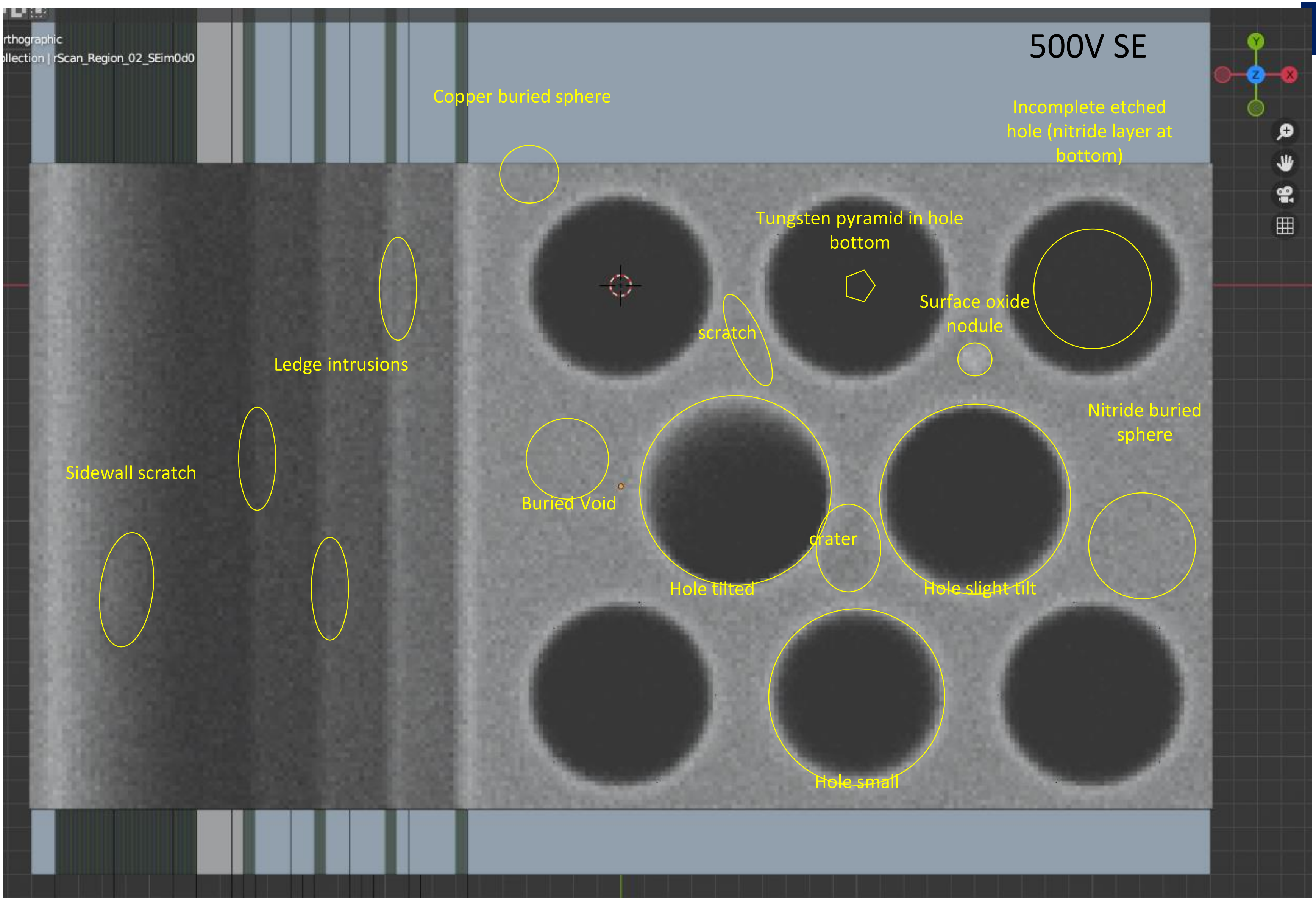

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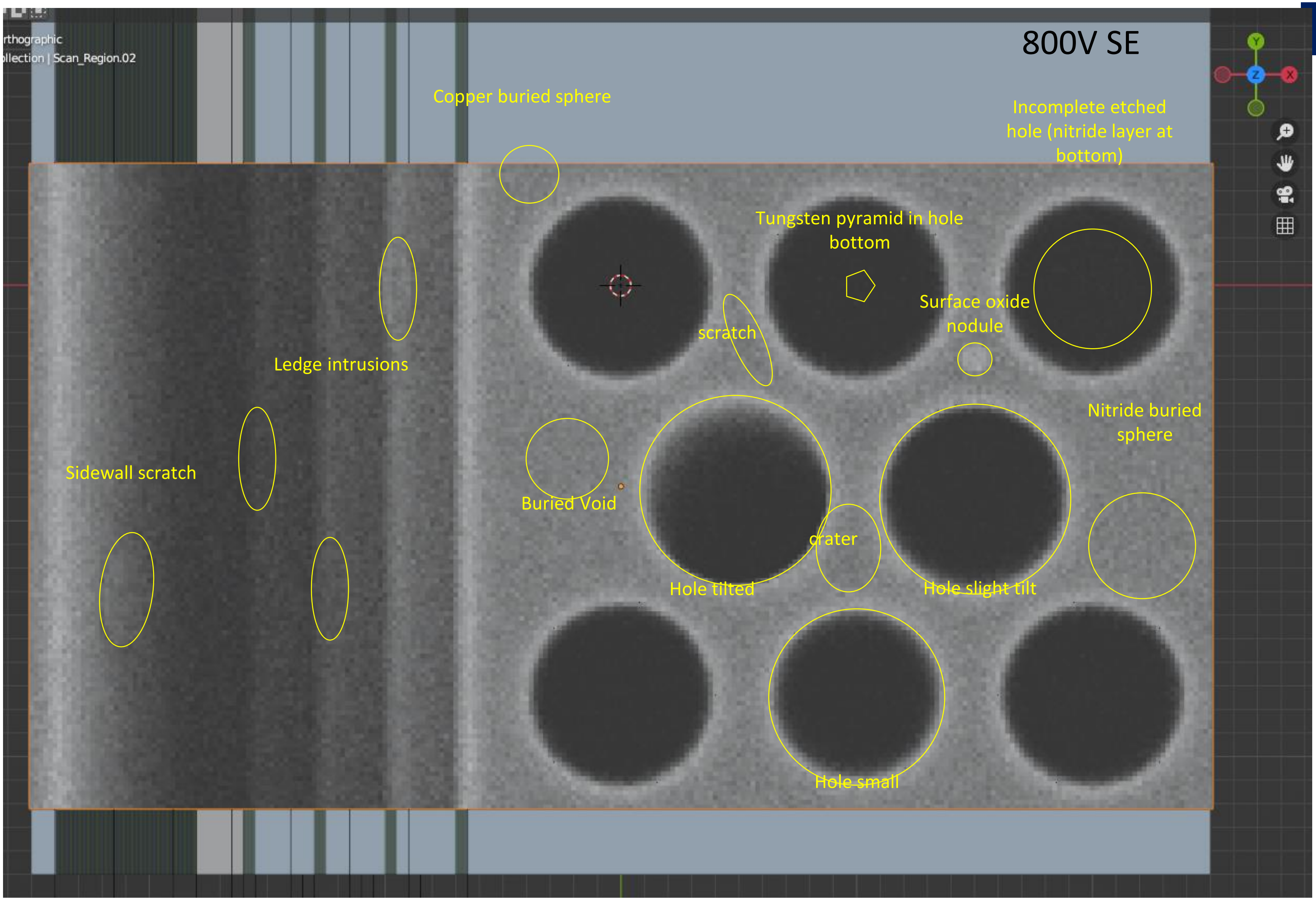

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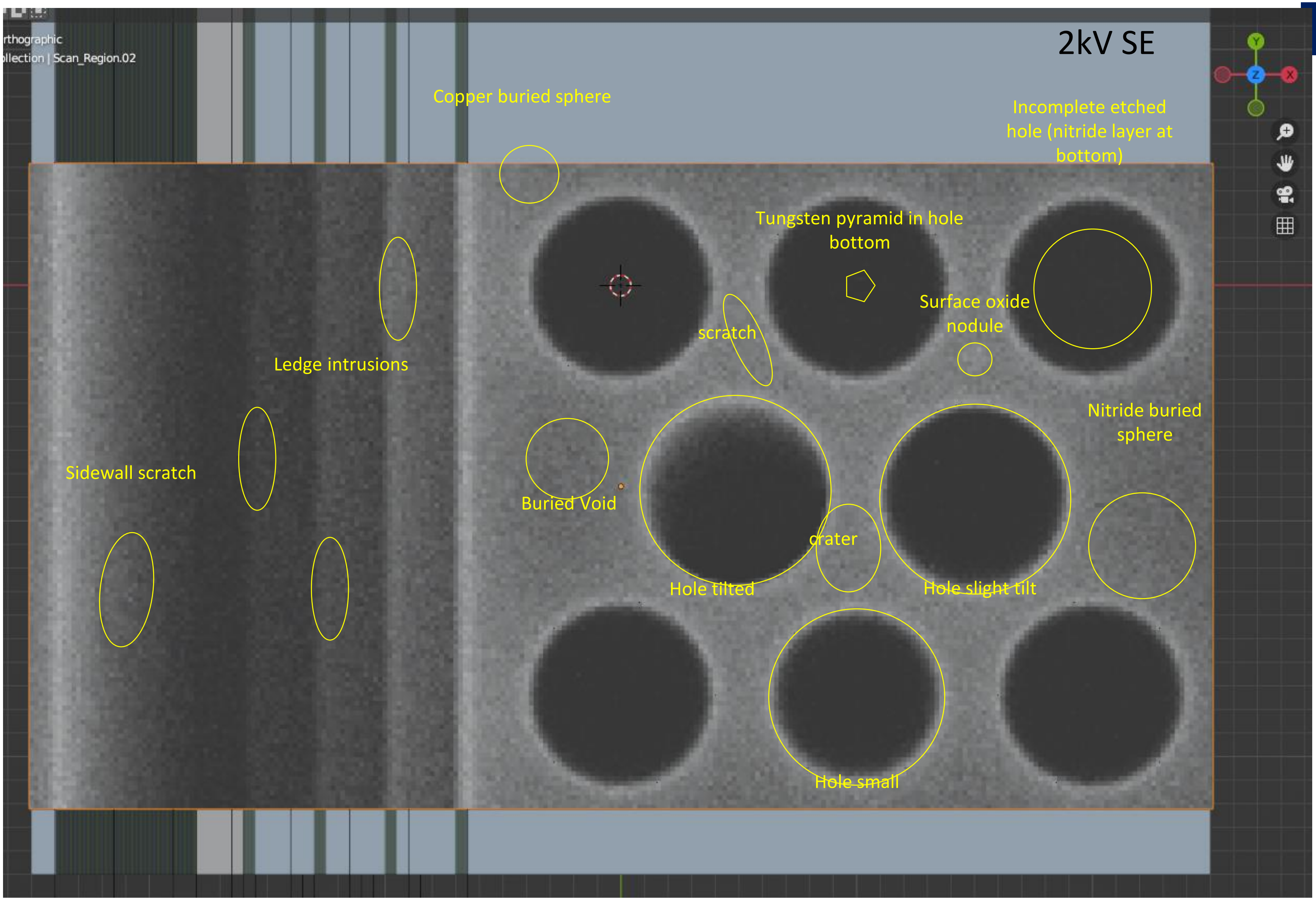

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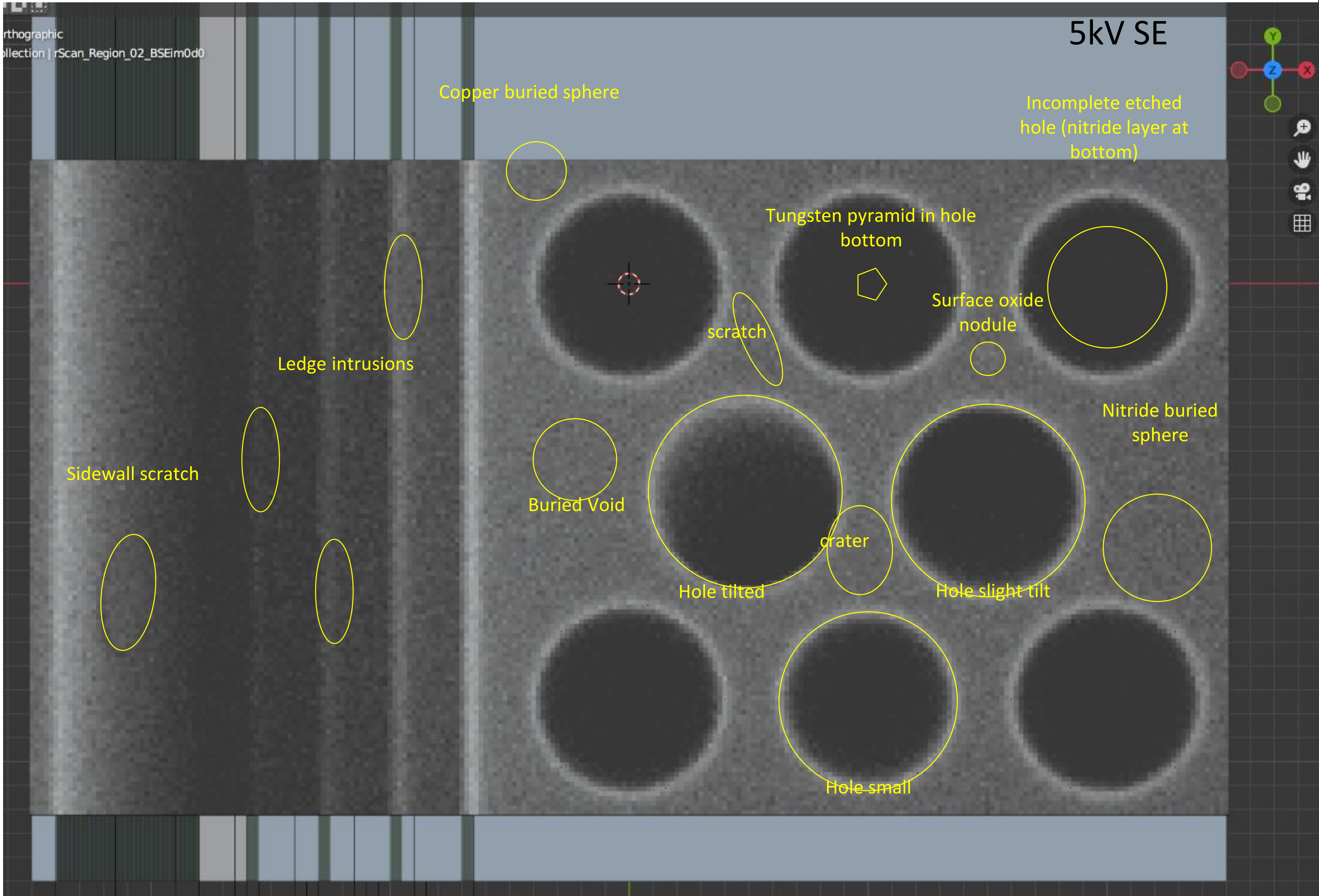

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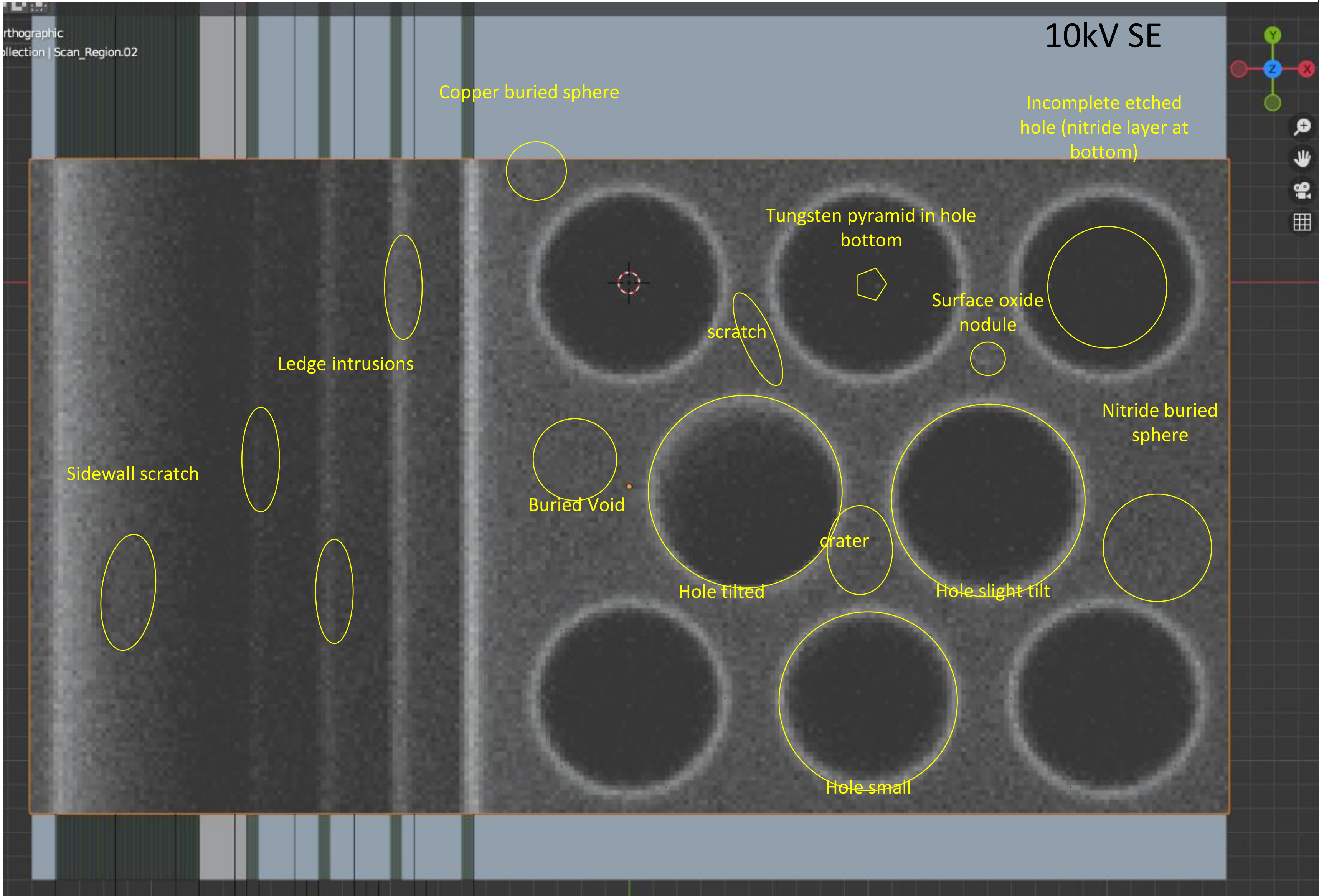

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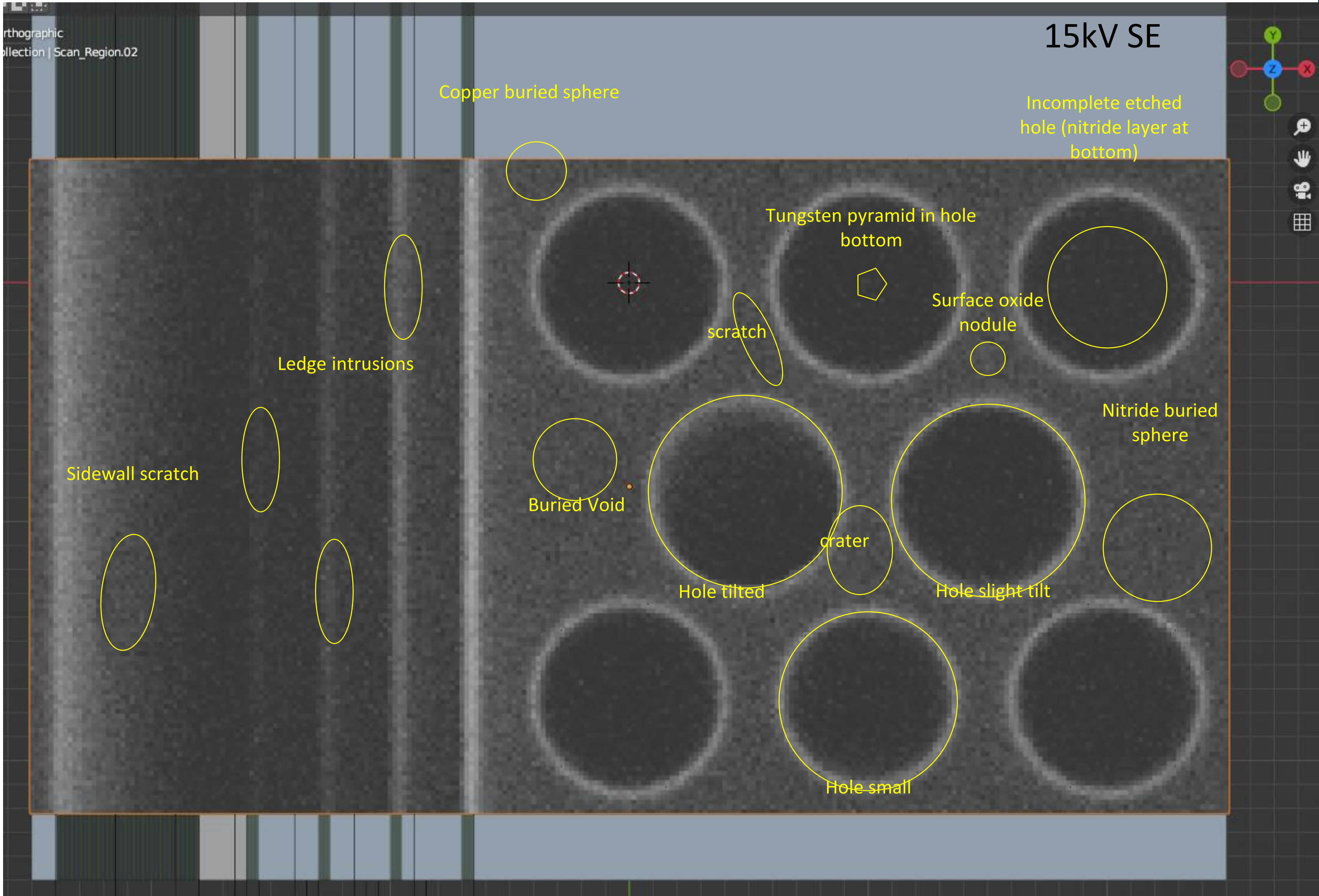

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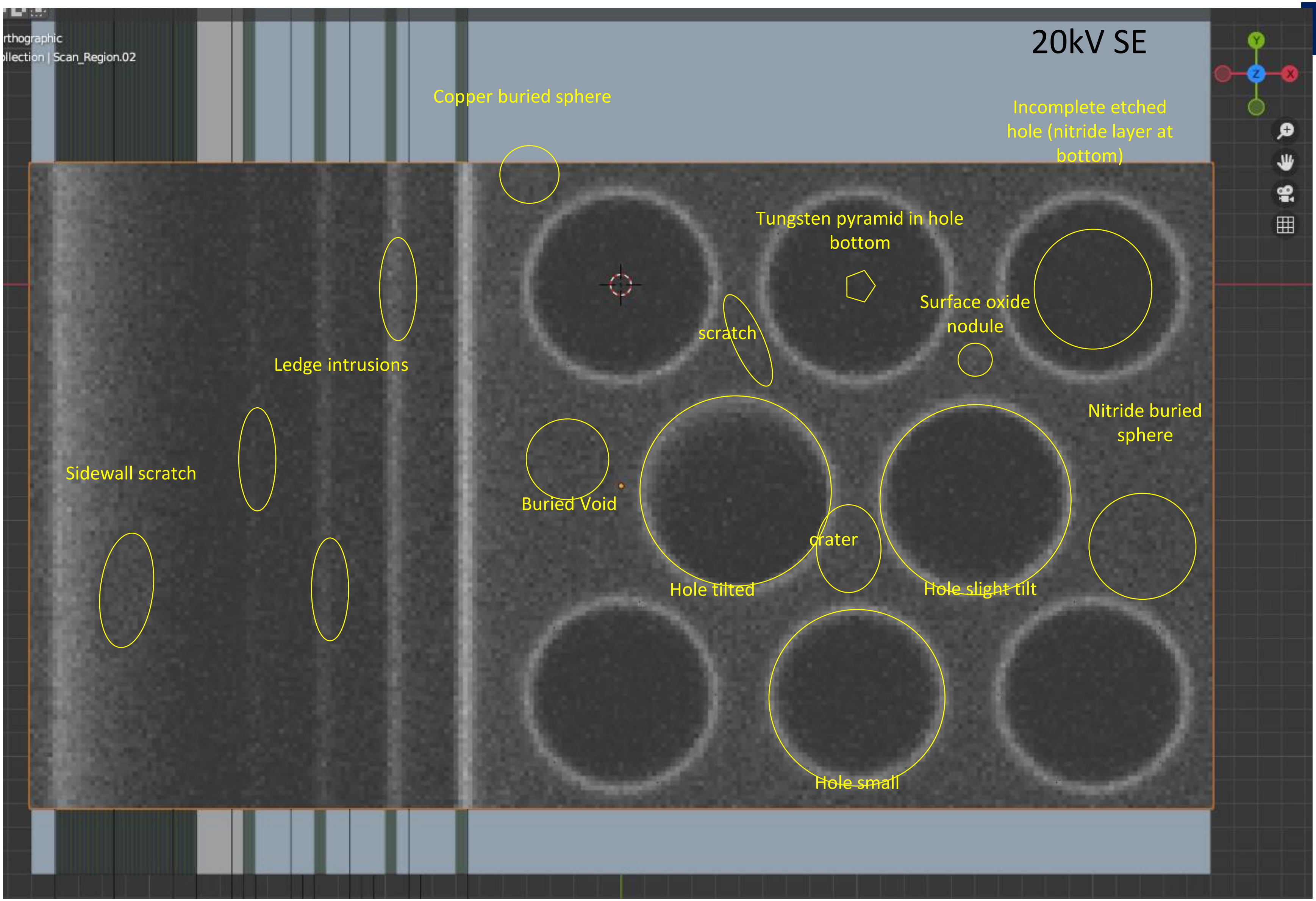

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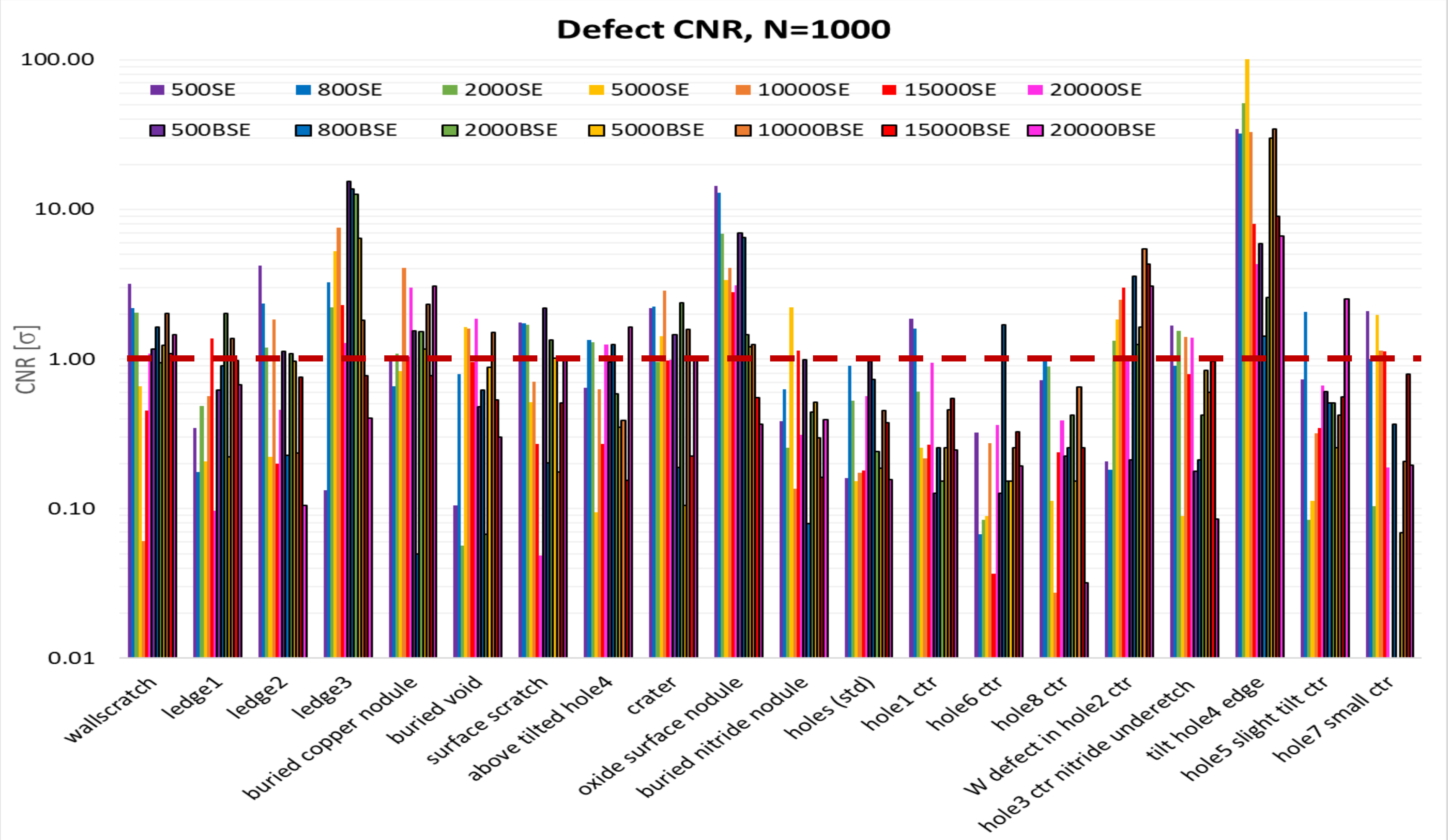
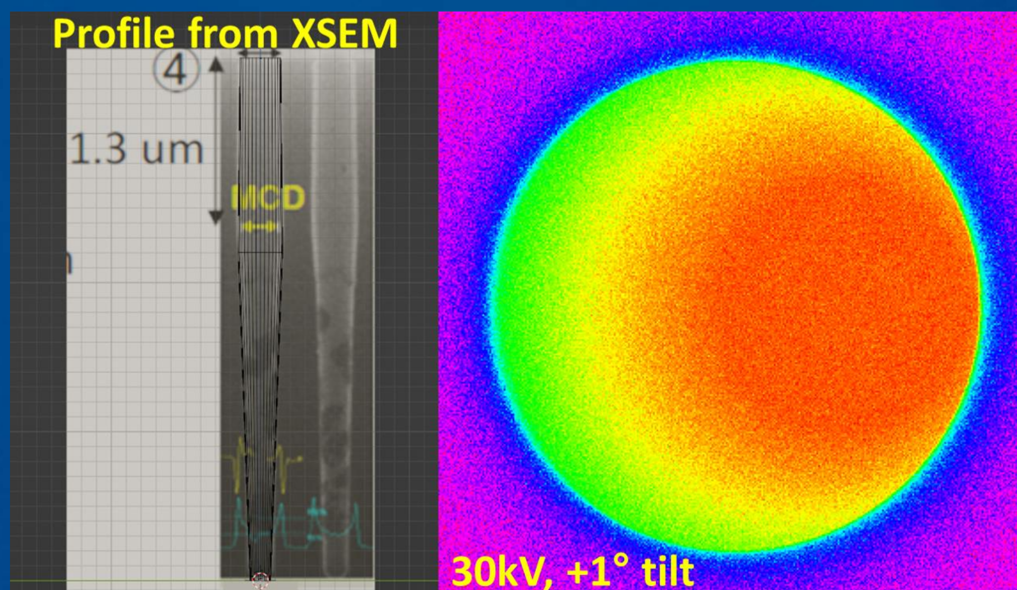
ONO IDA CNR results

- Most defects had at least one condition where CNR > 1 so in theory detectible.
- This includes both SE and BSE signals from the applies beam energies.
- Higher N can be used to increase detectability.



Conclusions



Conclusions

- In this work, we provide simulation studies of these important HV-SEM use cases, including:
  - HAR hole imaging of many depths & profiles
  - See-thru imaging of buried gratings for optical overlay calibration
  - Feasibility of defect detection of buried voids, particles and surface defects down holes/trenches in complex 3D ONO IDA
- HAR hole models proved tunable to match to experimental results at 10kV beam.
- In both AMAG7 1-1.5um HAR and deeper 5um HAR holes, BSE signal as function of depth was confirmed to follow exponential decay.
- HV-SEM see-thru imaging of oxide-buried gratings identify 160nm as a limit with good SNR at N=100 for copper gratings, and a little over 300nm for tungsten gratings.
- Feasibility of advanced defect detection simulations was demonstrated on a complex 3D ONO IDA; buried voids appear to be detectible, buried nitride stack defects maybe not—more simulation studies required.

Acknowledgements

- Dr. John Villarrubia of NIST for JMONSEL, and Dr. Andras Vladar of NIST for HV-SEM discussions.
- Mark Raymond, Patrick Kearney, Harlan Stamper, Brian Martinick, Ilyssa Wells, Dominic Ashworth & Frank Tolic of NYCreates for AMAG7 HARhole wafer process development & production.

Product: AMAG7 HARhole, available from AMAG Consulting, LLC

Thank you for your Attention!

Note image cropped on right.

AMAG nanometro (AMAGnm)

Established December, 2019 as AMAG Consulting, LLC

Available via AMAG nanometro:

- AMAG test wafer nanofoundry with AMAG7 reticle (details at AMAGnm.com)
- SEM simulation with AMAG SimuSEM software
- Semiconductor metrology expertise & consulting

About AMAG:

- SEMATECH AMAG (Advanced Metrology Advisory Group) for 20 years was very influential in guiding semiconductor metrology to keep pace with the ITRS roadmap.
- Strong collaboration among IC manufacturers, equipment suppliers, laboratories & universities identified critical industry metrology problems and formulated/executed consensus solutions.
- AMAGnm's Benjamin Bunday was AMAG Chair from 2001-2015, and led the team that developed such AMAG items and can still leverage industry-crucial products of those efforts such as test wafers & SEM simulation software.
- AMAGnm builds upon the SEMATECH AMAG legacy to address current critical industry enablement needs.

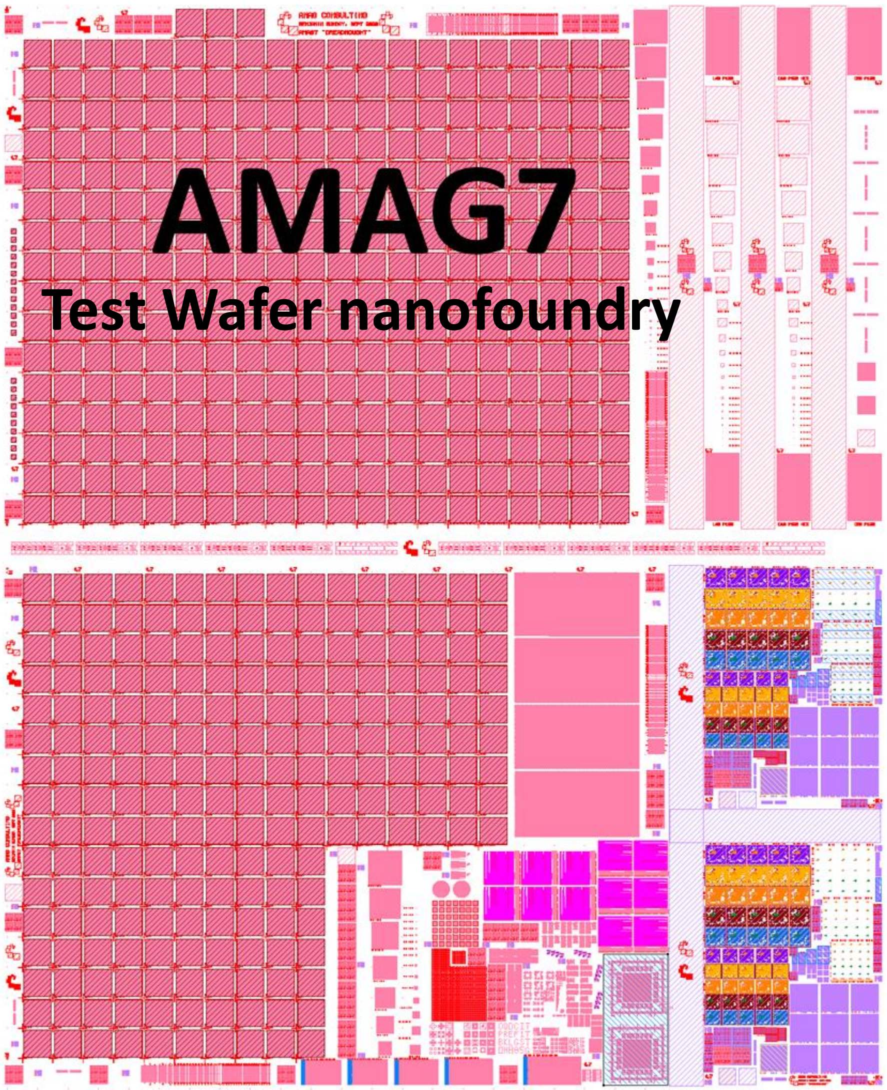
Goal of AMAGnm:

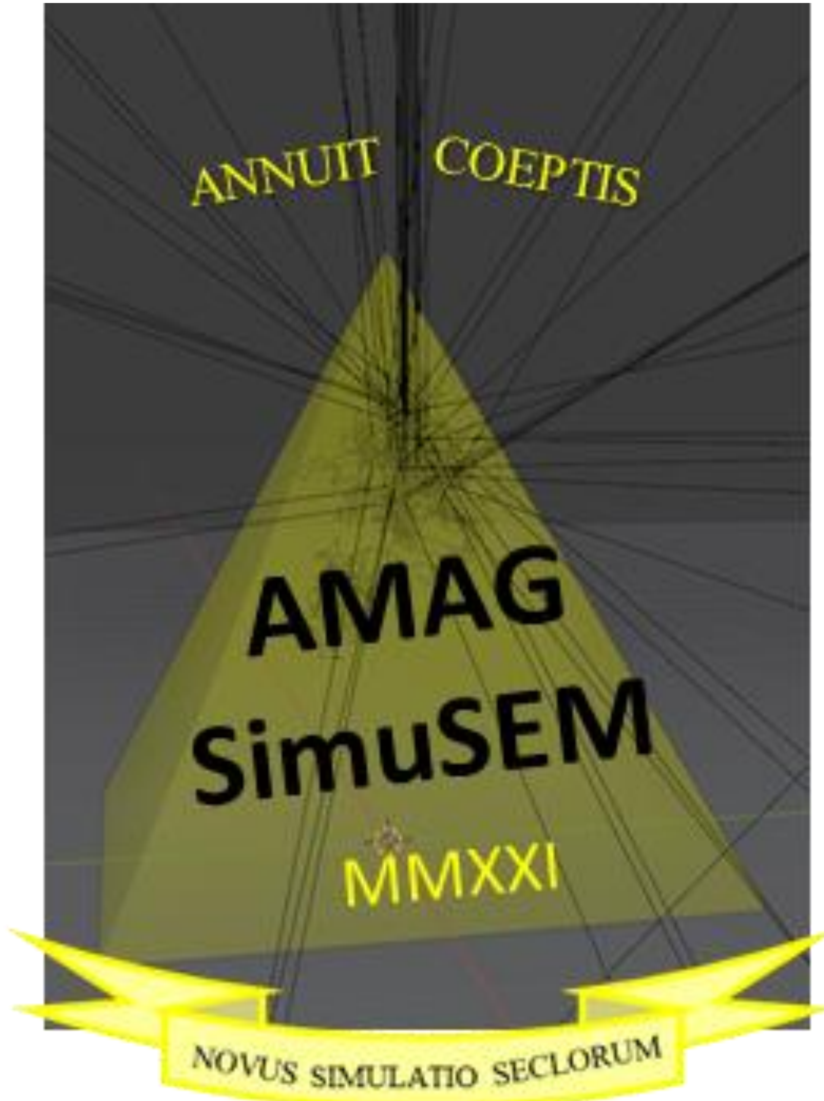
- **Enable metrology sector progress through addressing critical infrastructure gaps and enabling collaboration.**

AMAGnm

Products

For details, see AMAGnm.com, coming Oct 2022!





AMAG SimuSEM / JMONSEL GUI

- AMAG SimuSEM is total overhaul, enhancement & modernization extension to JMONSEL.
- Powerful yet intuitive GUI achieved by building NIST JMONSEL and rigorous sample definition capabilities into 3D Blender interface. Complex samples now possible. Core physics is still original JMONSEL code, although code is speed optimized and enhanced with new & evolving features & outputs.
- Greatly improved utility, productivity, flexibility, visualization, accessibility, & achievable complexity of designed features while improving simulation speed, plus many other refinements & additions, superior results access & visualization.