Direct To Digital Holography For High Aspect Ratio Inspection of Semiconductor Wafers

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Work presented is a collaboration of nLine[a] and ORNL[b] team

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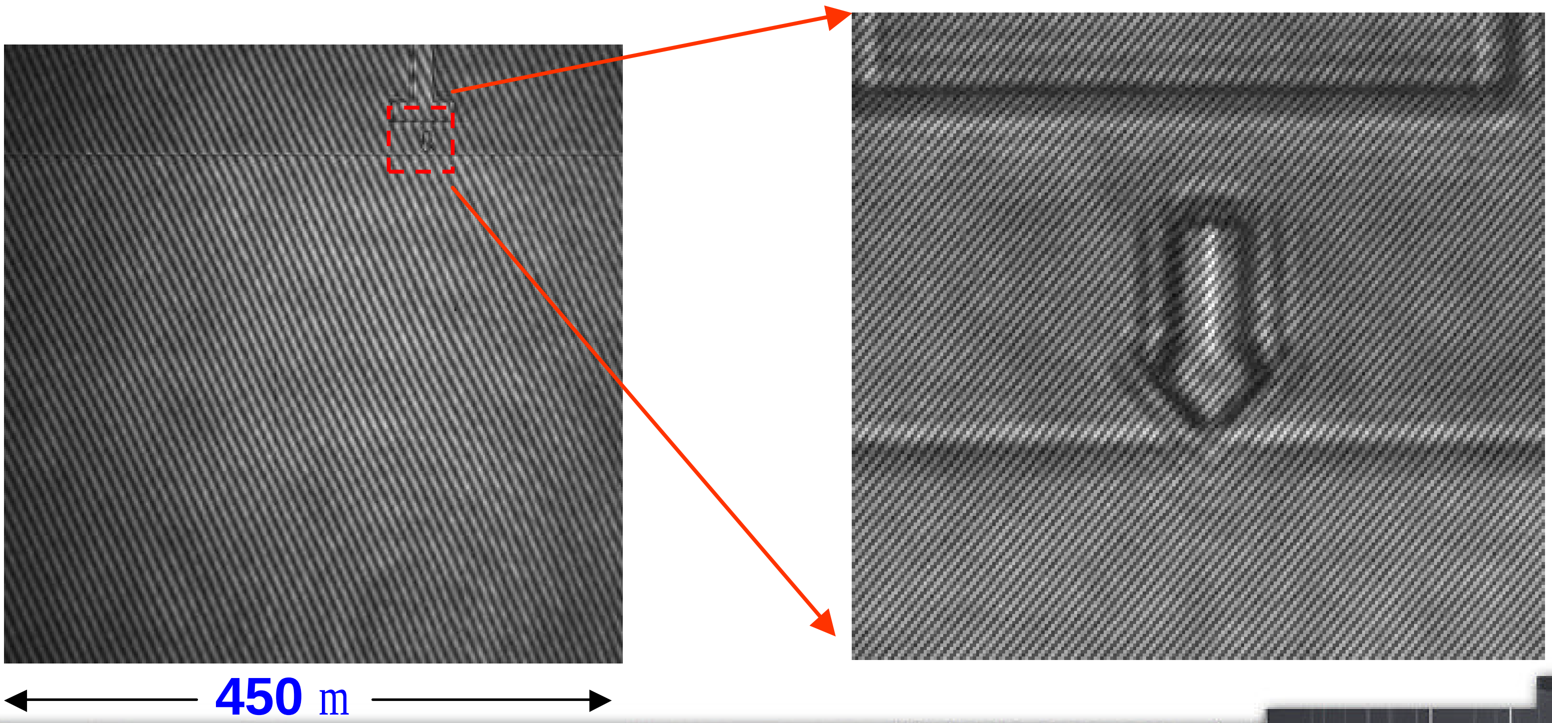
Presentation will give an overview from concept to examples

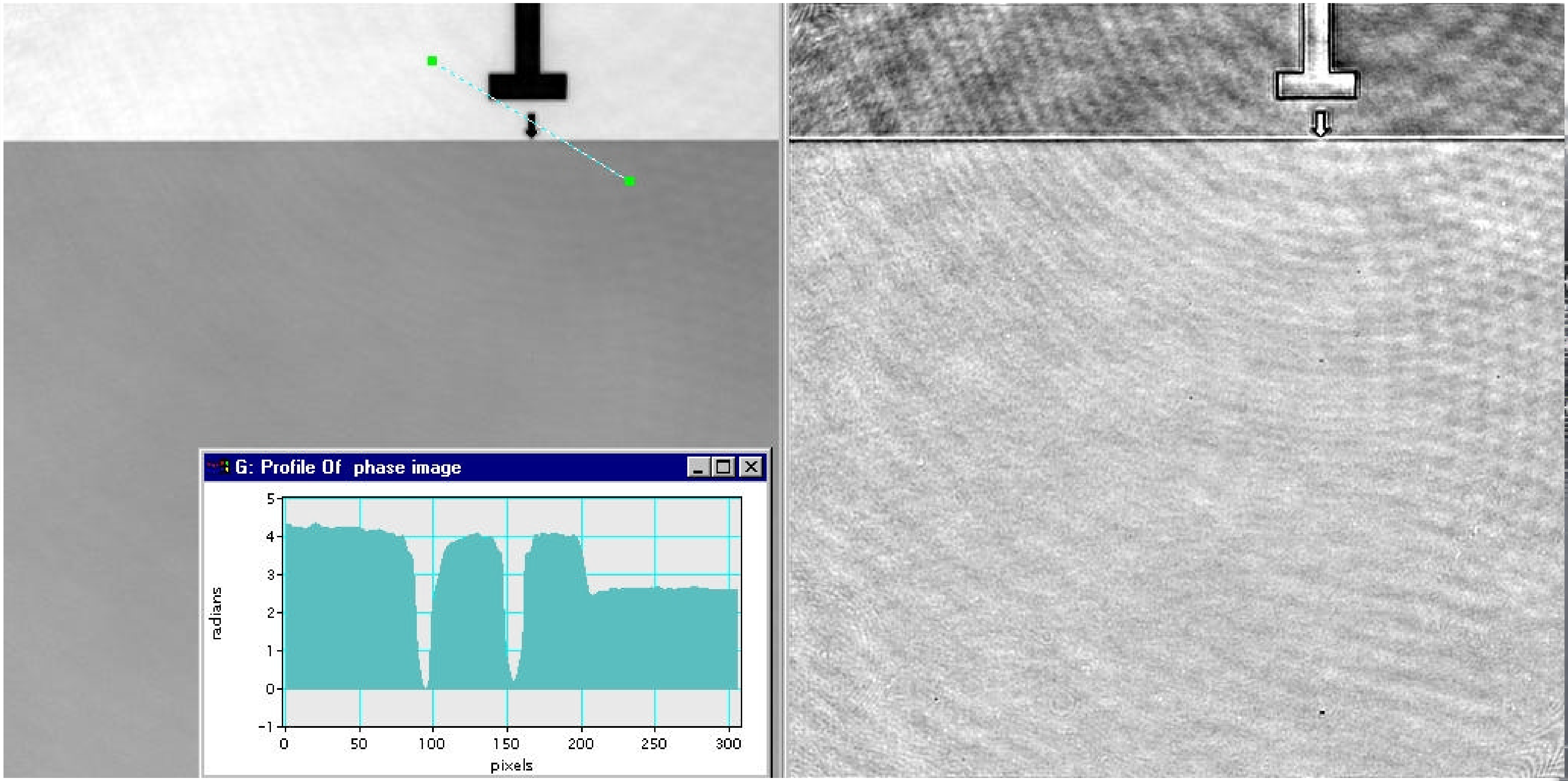
- **Overview of digital holography**
- **Summary of distinguishing features**
- **Advantages of technology for HARI and phase objects**
- **Calculation of signal levels**
- **Identification of possible noise sources**
- **Signal to noise ratios and expected sensitivity**
- **Example wafer inspections**
- **Summary**

What do we mean by digital holography?

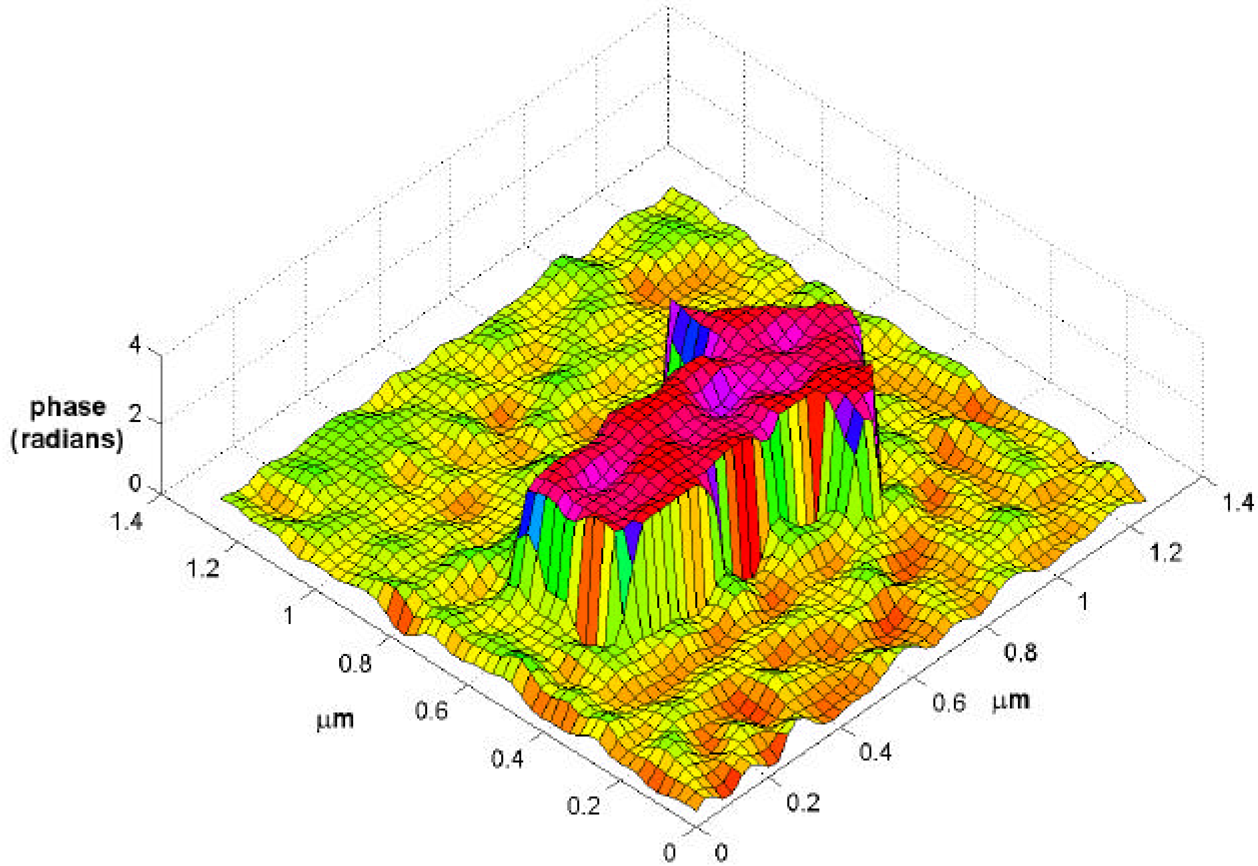
- We have an built an optical system that enables the capture of a true hologram with a digital camera
- Interference between reference beam and target beam encodes complex wavefront reflected from wafer surface



Capture and process hologram to recover phase and amplitude of wavefront



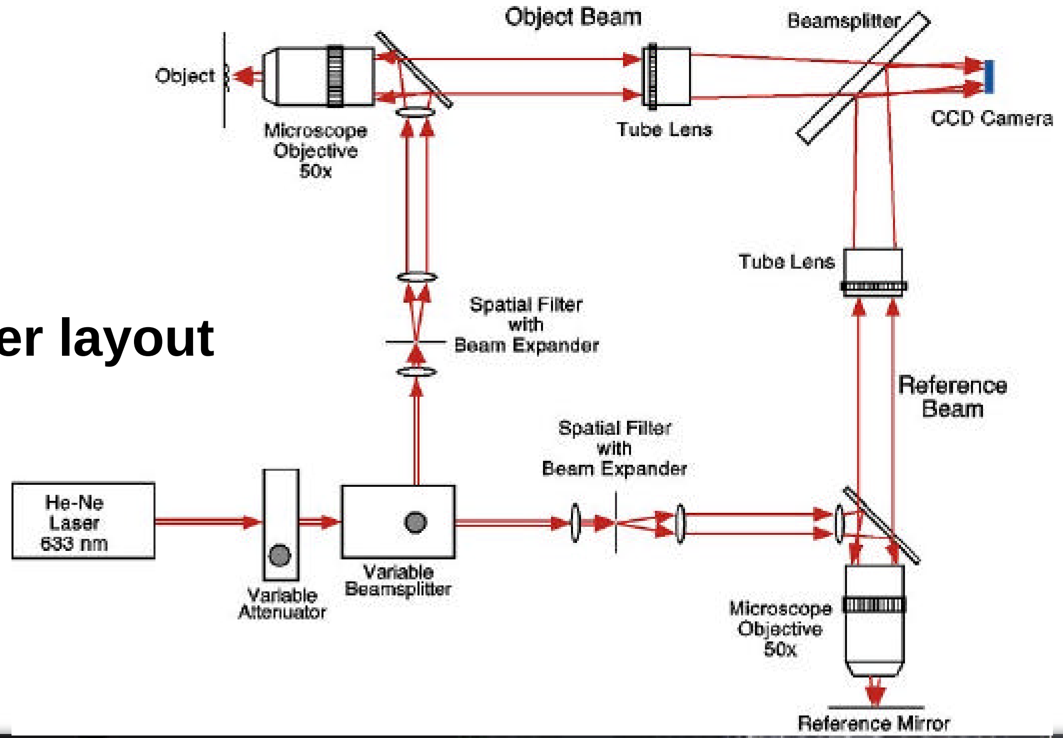
Surface plot shows the difference between traditional imaging and digital holography



Several key features enable viable production inspection tool

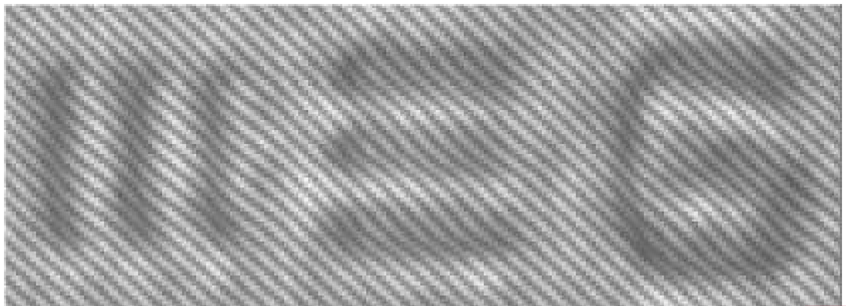
- Optical system design
  - Focus the target image at the camera recording plane
  - Small angle between reference and target beams: fringes can be adequately sampled with CCD
  - Magnification to match resolution to fringe density

Mach-Zehnder layout

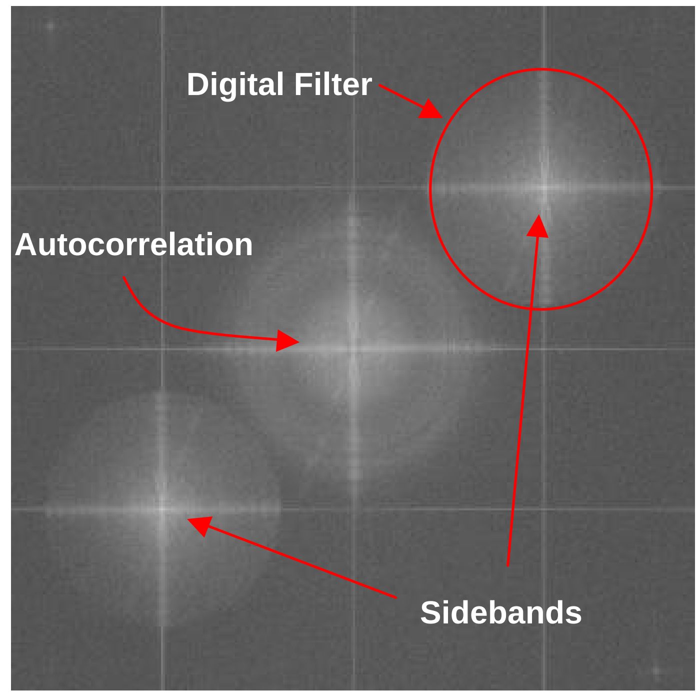


Fourier domain processing enables the extraction of the complex wavefront

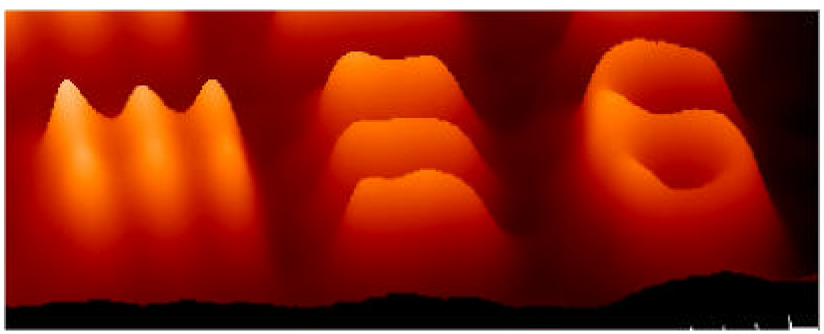
Input intensity image



2-D FFT



Output phase



2-D IFFT of filtered & centered sideband

Digital holography has unique advantages for high aspect ratio and phase object defects

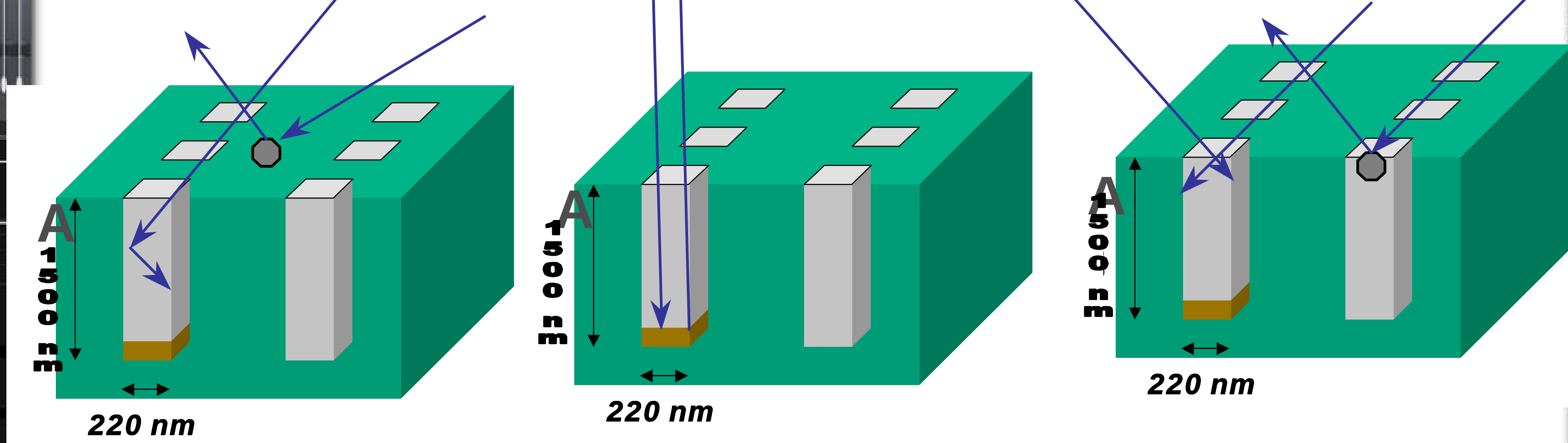
- Head-on illumination geometry with collimated laser beam
  - Best penetration of high aspect ratio (HAR) structures
- Target signal is combined with reference signal in a spatial heterodyne method
  - Total signal in hologram is proportional to reference beam electric field times the target beam electric field
  - Higher signal power as compared to bright-field or scattering approaches
- Phase sensitive
  - Resolution in the z (coincident with illumination) is very high with potential for 1/1000th wavelength
  - Topology and material properties contribute to phase measurement
  - Do not require that defect be resolved
- Low incident power
  - Combination of heterodyne and phase sensitivity reduces energy on wafer

High-Aspect-Ratio Inspection Optical Methods Comparison

Collimated laser light (DDH) penetrates and returns from high aspect ratio structures

Scattered Light (dark-field) tools are not optimized for high-aspect ratios (but good for surface particles)

Bright field tools: Incoherent (broadband) light is poorly collimated and can only isolate surface defects well



Expected return signal can be modeled using a range of techniques

- Simple phase difference estimates are based on the phase change due to wave passing through one material (defect) vs. another (desired), e.g. SiO_2 vs. air
  - Can include correction for diffraction by spreading phase change over the resolution of the imaging optics
- Exact 1-D solution using transmission-line (TL) equations
  - Accounts for multiple surface interfaces
  - Need dielectric constants (real and imaginary) for materials
  - Same method as above can be used to include diffraction effects
- Investigating using full wave 3-D finite difference time domain approach
  - For example Tempest

Comparison of 1-D TL theory with experimental measurements

Dielectric stack down to Si
(SiO2/SiN/SiO2/SiN/SiO2/SiN/SiO2/Si)

A=0.928 V (scale 1 V)
Ph=0.364 rad (scale -pi to pi)

Dielectric Stack to Cu
(Sio2/SiN/SiO2/SiN/Cu)

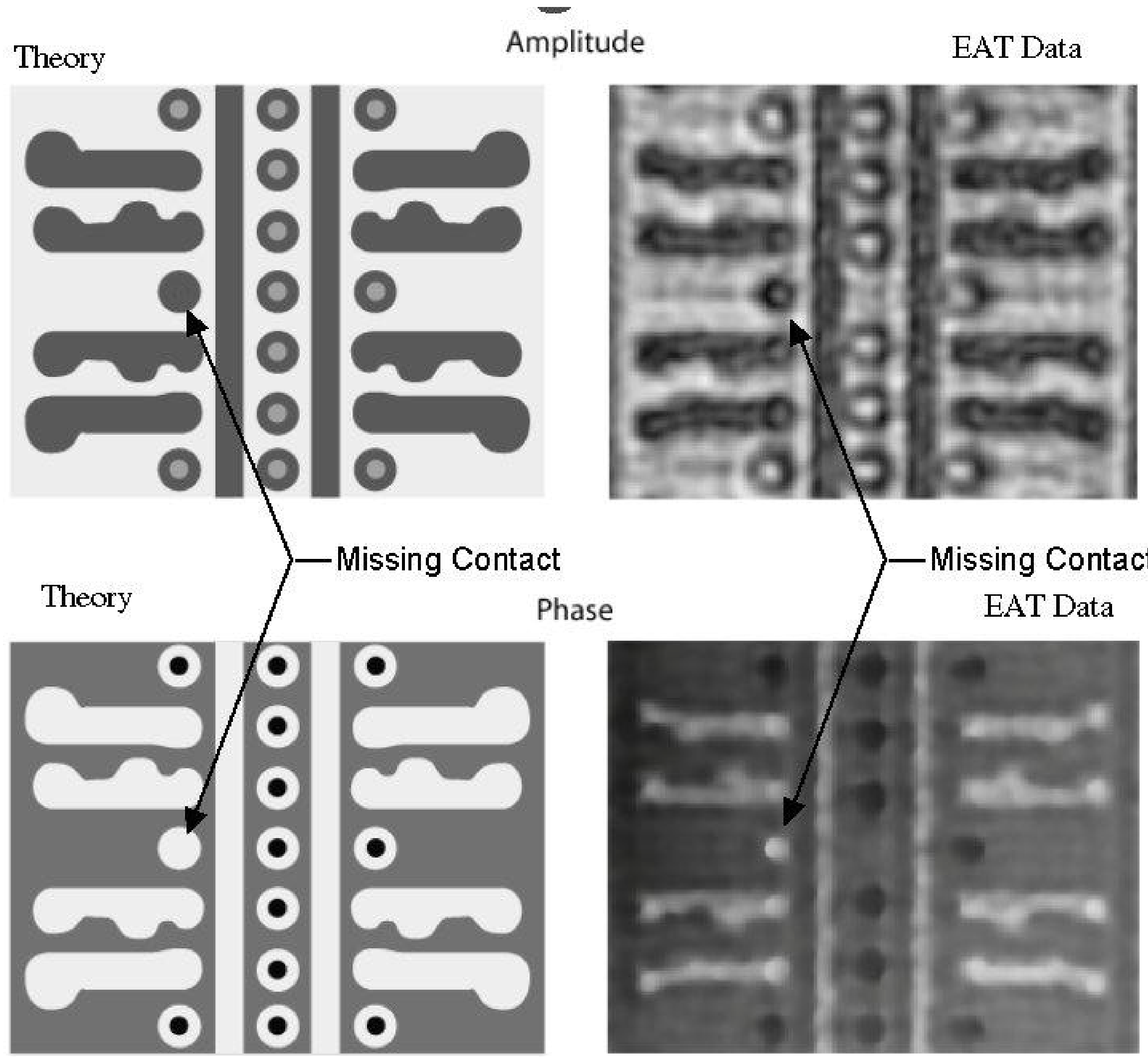
A=0.353 V (scale 1 V)
Ph=-2.73 rad (scale -pi to pi)

Via to Cu
(air/Cu)

A=0.626 V (scale 1 V)
Ph=2.95 rad (scale -pi to pi)

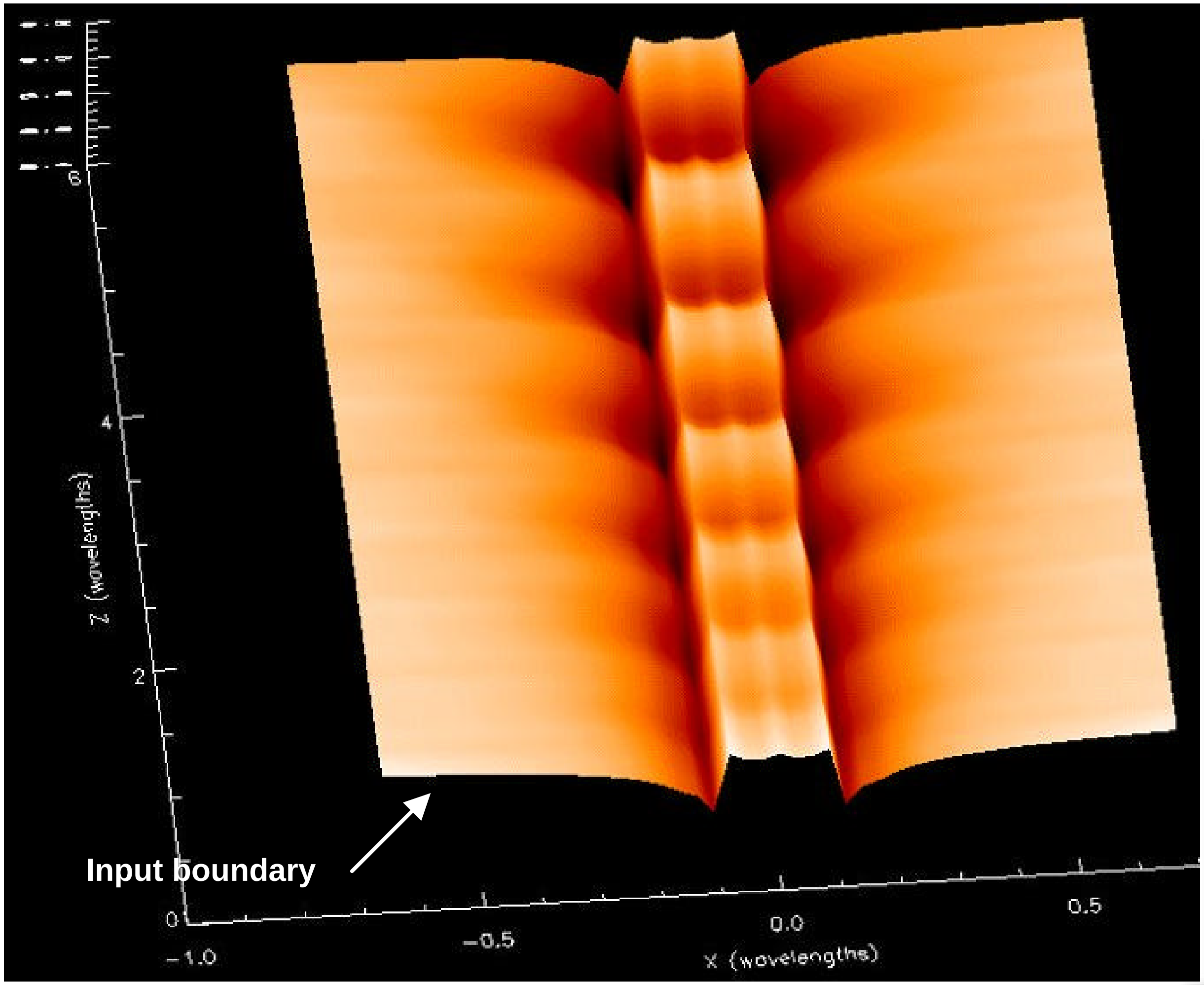
Via to BARC/SiN/Cu
(air/BARC/SiN/Cu)

A=0.255 V (scale 1 V)
Ph=0.717 rad (scale -pi to pi)



Simulation of EM wave propagation into HAR contact verifies return signal

- Contact hole is ¼ of the illumination wavelength
- Aspect ratio is 12:1
- Exit (return) electric field is 64% of input



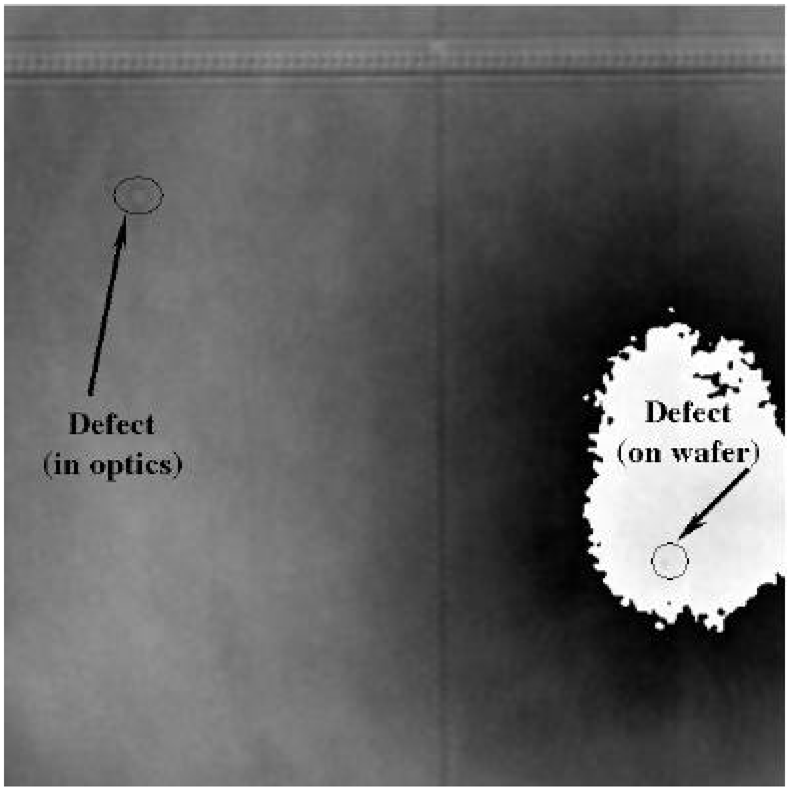
Noise sources have been characterized and minimized

- **Back-reflections and Ghosts**
  - Only want interference between target and reference, all other coherent reflections are noise sources
  - Use low reflectance coatings to minimize unwanted reflections
  - Also use a polarizing beam splitter and quarter wave plate to reduce back-reflections
- **Vibrations**
  - Motion of the target or reference during the exposure will reduce fringe visibility
  - Reduce exposure time and use a stiff, well-damped opto-mechanical design
- **Image to image registration**
  - Must register to an accuracy of at least 1/10 of a pixel

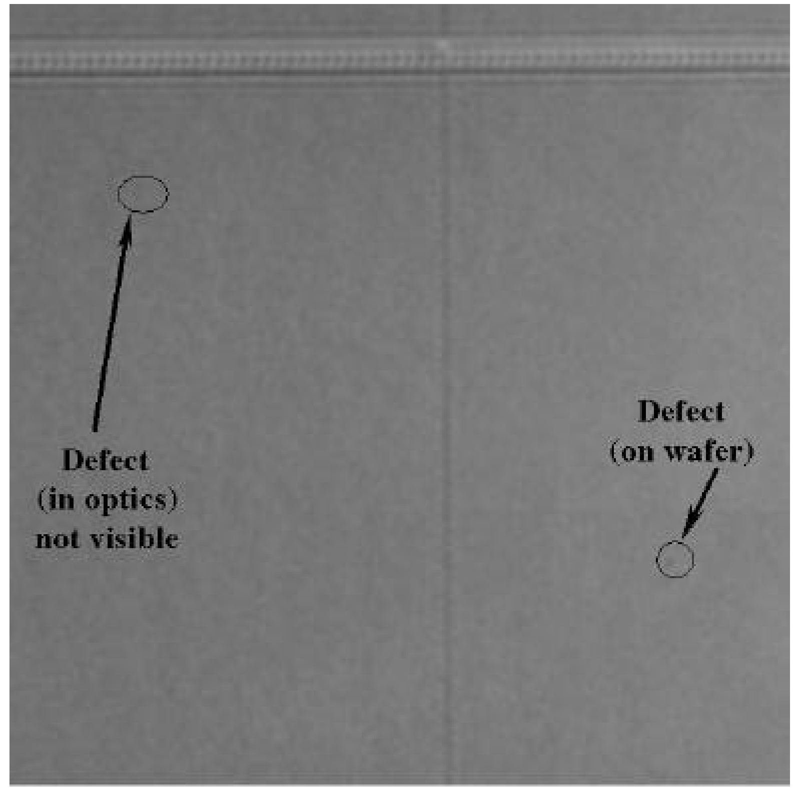
Noise sources have been characterized and minimized (cont.)

- **Stray light**
  - Reduce optical surface roughness to under 2nm
  - Eliminate clipping or baffle stray light
- **Camera noise**
  - Relatively short exposure and low readout noise
  - Map gain non-uniformities and operate over linear range of sensor
- **Optical imperfections**
  - Minimize during manufacturing and remove with flat field
- **Photon statistics**
  - Fundamental limit of sensitivity: 1/1000th of a wavelength

Example of flat-field correction to reduce optical imperfections



Raw phase reconstruction



Flat-field phase reconstruction

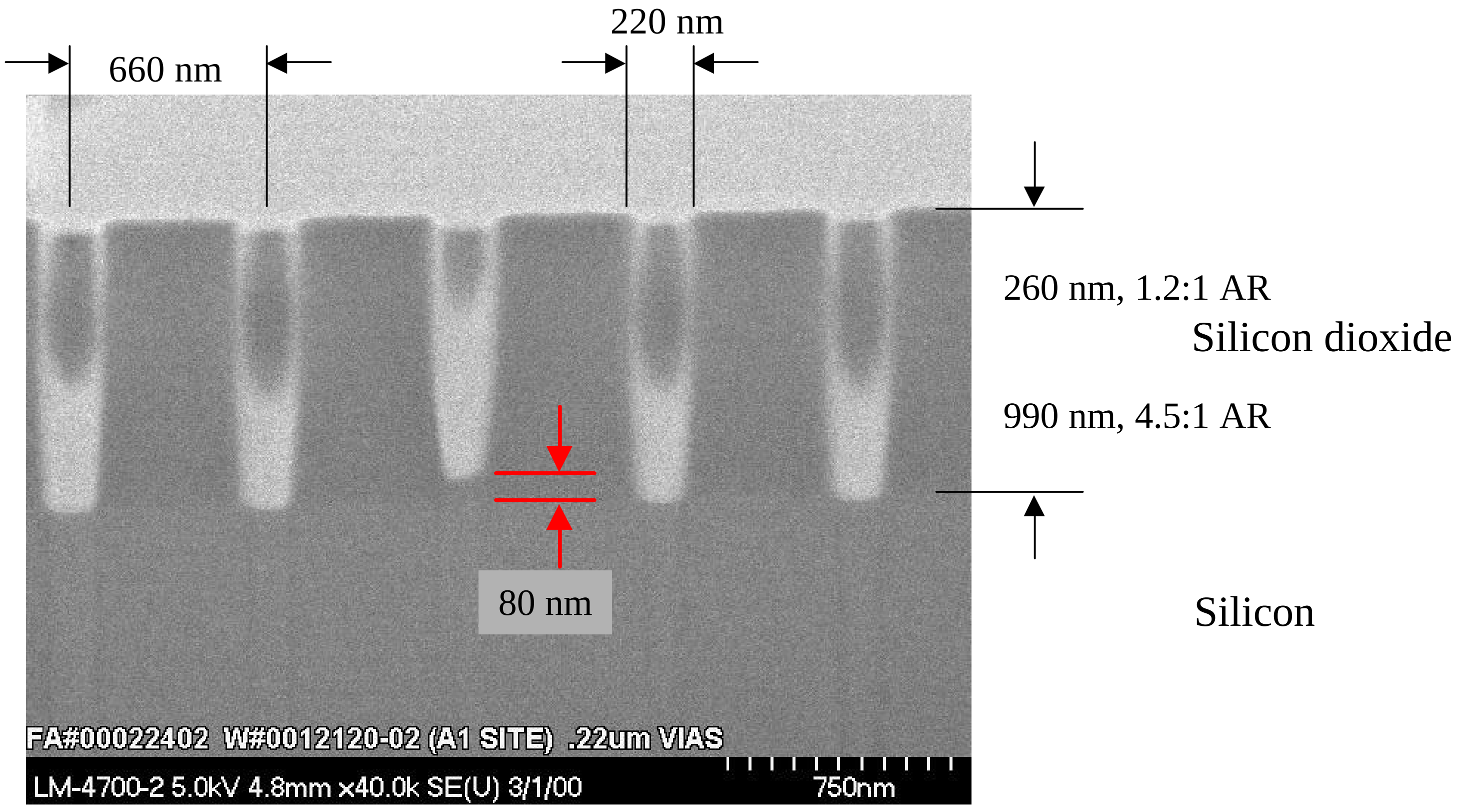
Expected sensitivity with different noise levels (as percentage of wavelength)

Objective	Sensitivity—Noise=1.4%, SNR=4	Sensitivity—Noise=0.84% SNR=4	Sensitivity—Noise=0.45% SNR=4.0
0.5 NA	55 nm	41 nm	31 nm
0.2 NA	136 nm	102 nm	76 nm
0.1 NA	270 nm	165 nm	152 nm

266 nm illum., same material (only height, different material increases sensitivity), defect volume x by 1.5x by 500 nm

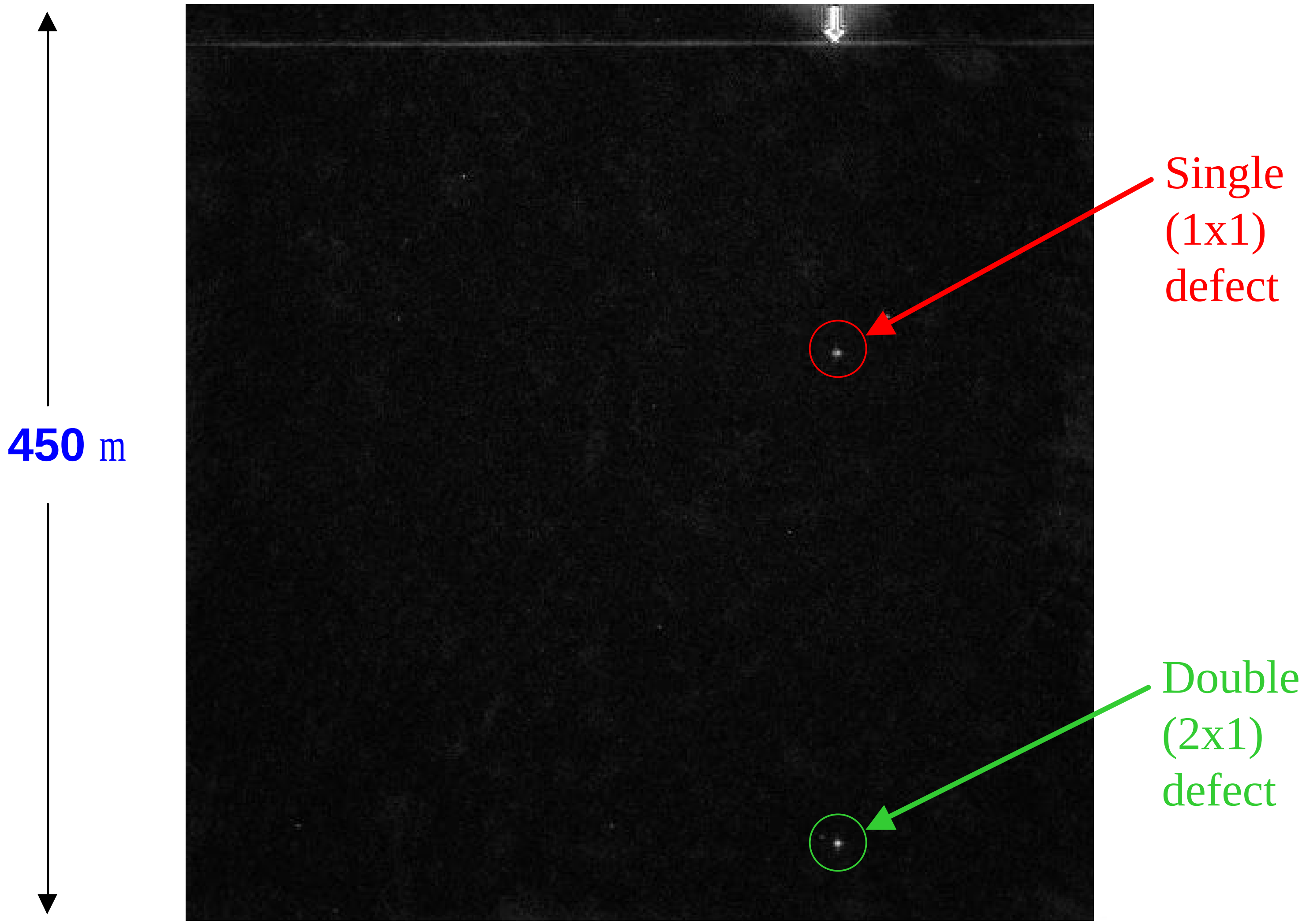
High Aspect Ratio Defect Test Wafer
(International SEMATECH)

Cross section of single under etched contact



Single and double under etched contacts

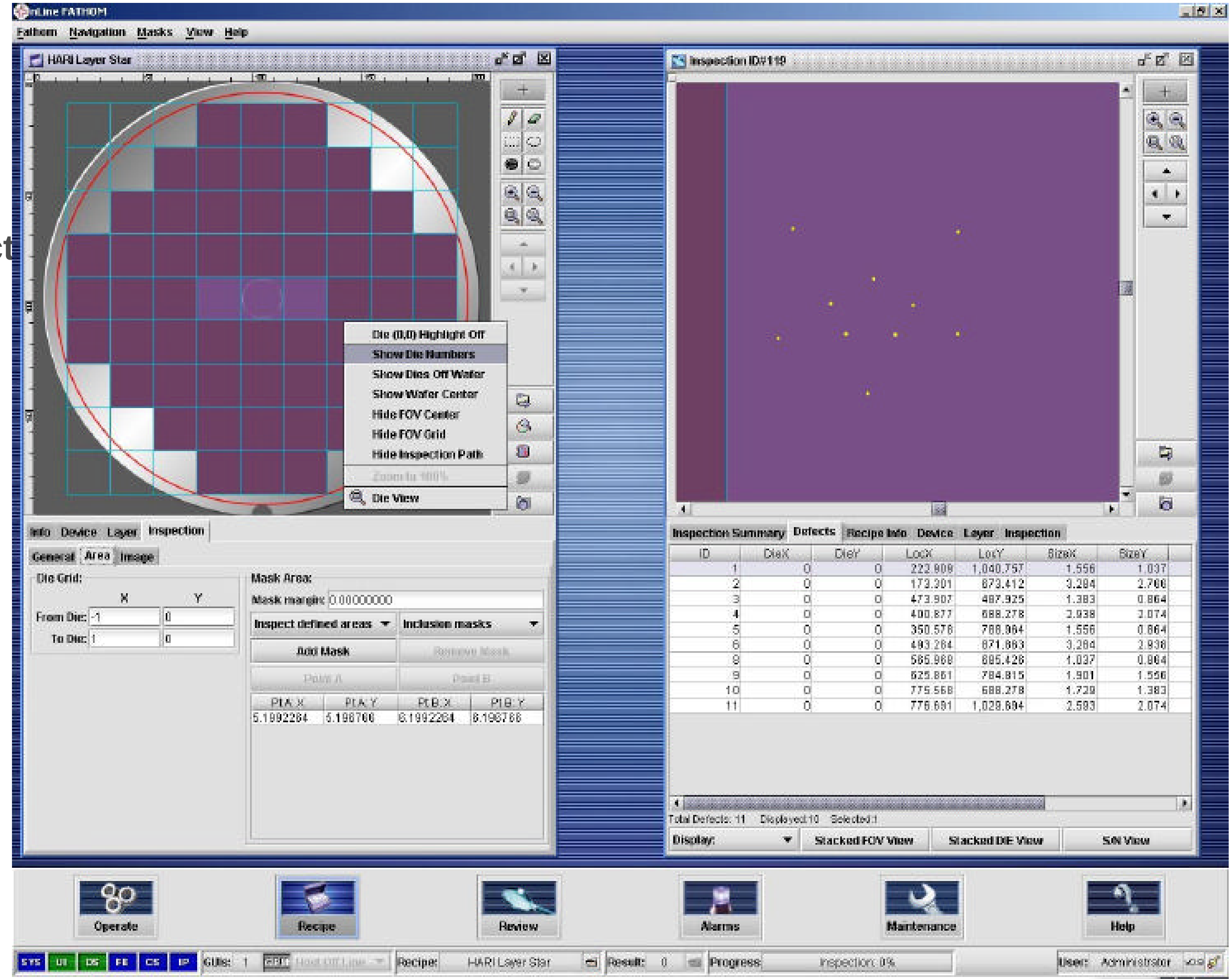
Difference image for defect detection (low mag.)



Star of Texas

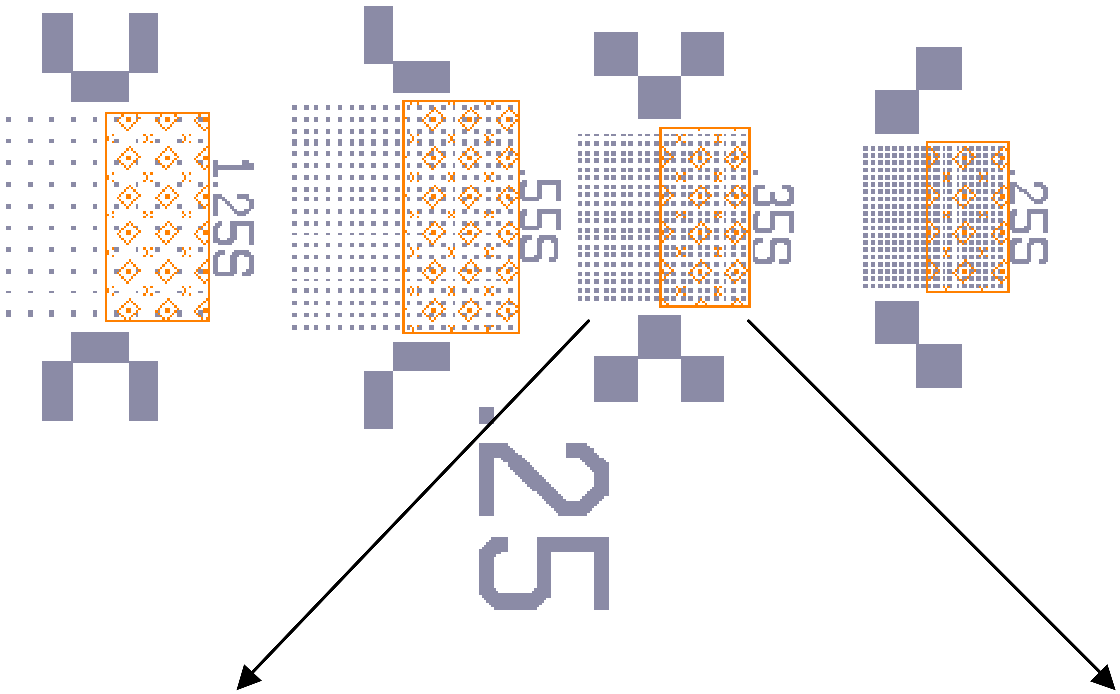
"Star of Texas" from Sematech HARI wafer test wafer 6.8:1 aspect ratio

Inspection using 266nm laser, 0.2 NA objective

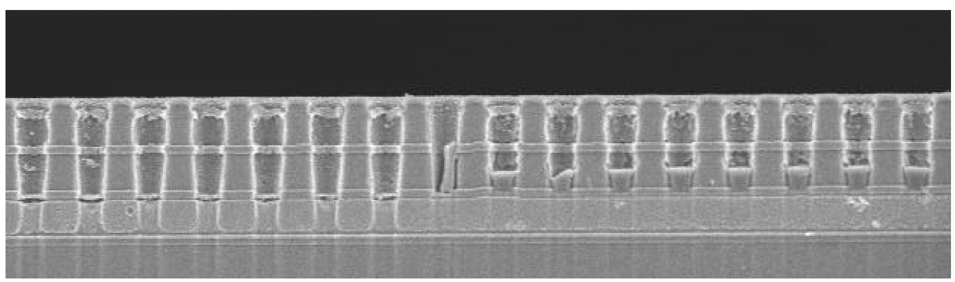


Test structures in street contain half partially etched (BARC) and fully etched vias in an array layout

(wafer and cross section courtesy International Sematech)



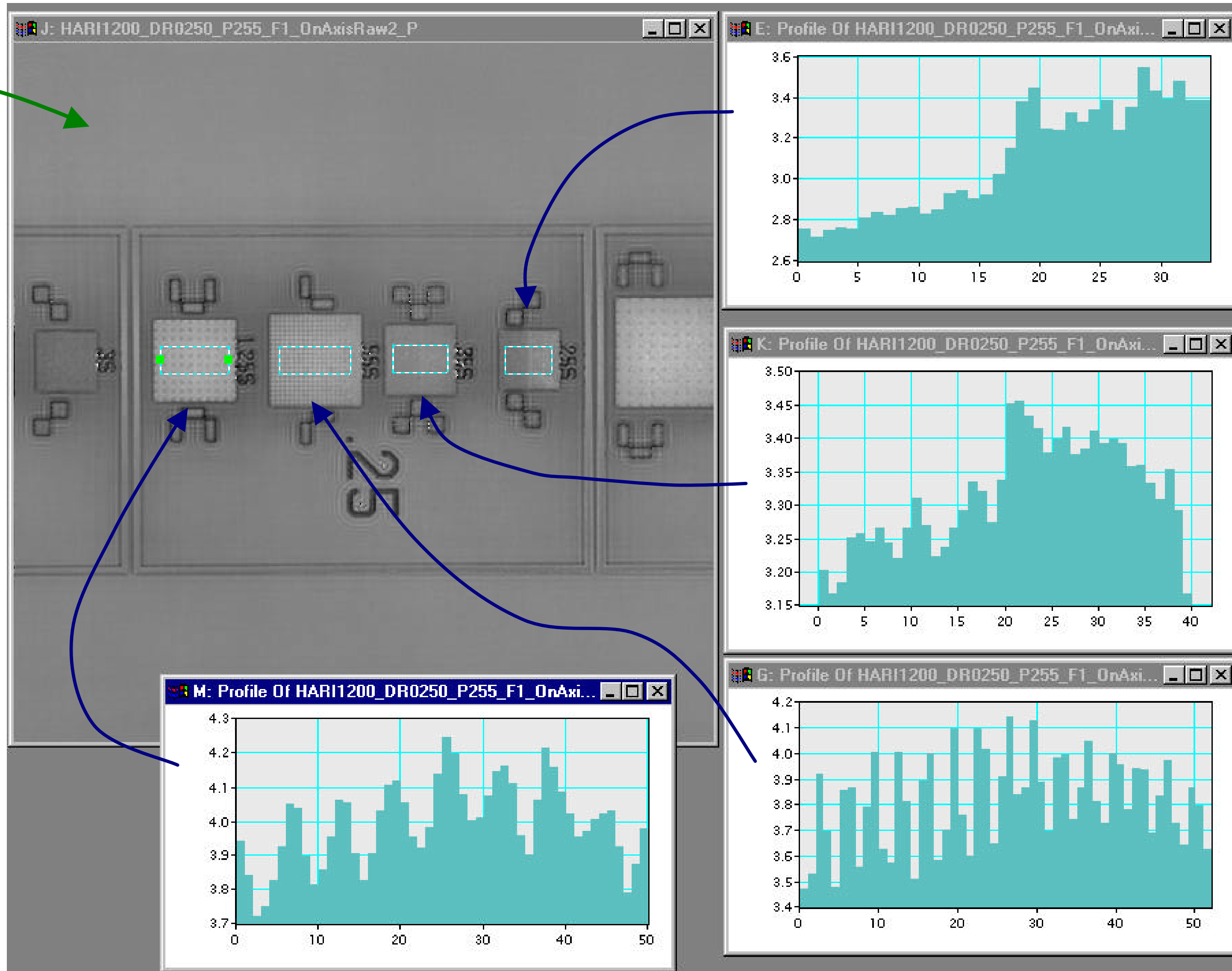
Reticle image



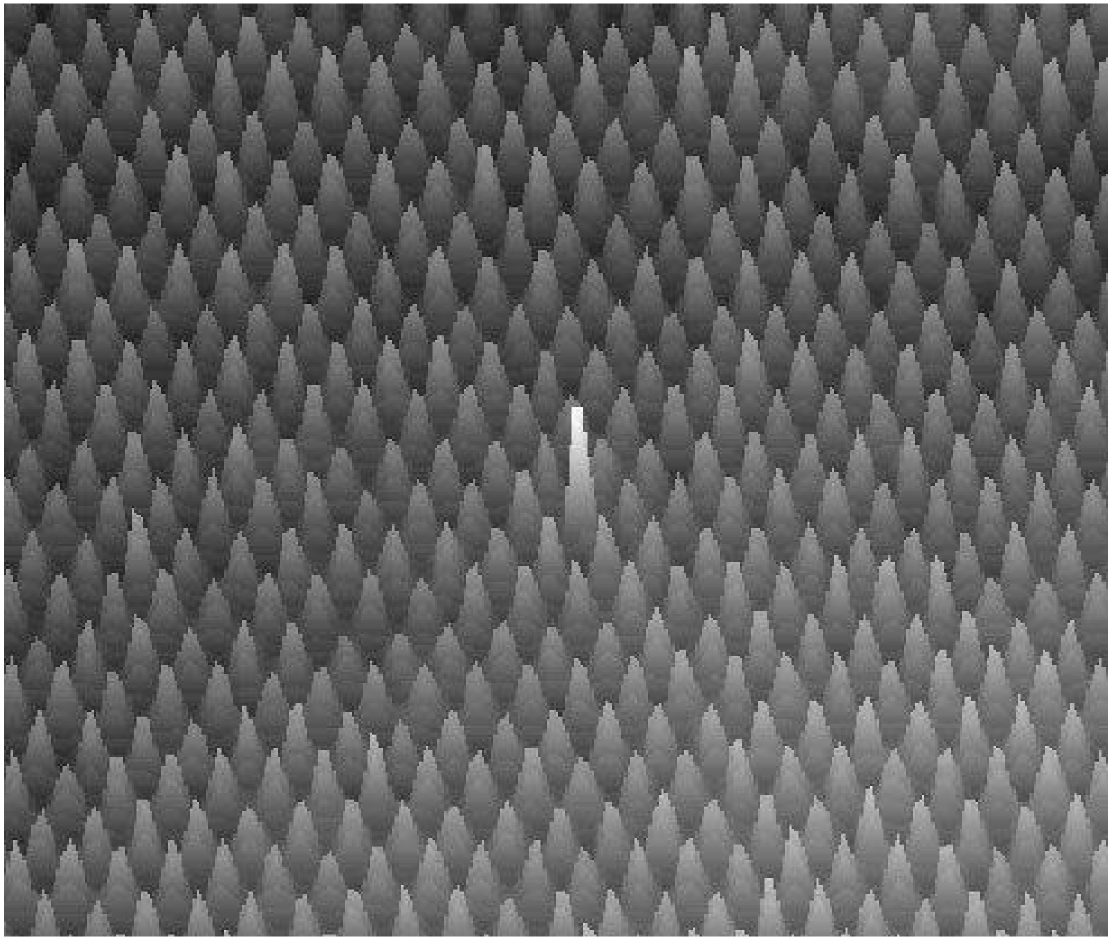
Cross section image
(0.25µ dia. via,
0.35µ spacing)

Horizontal phase profile generated by averaging columns in the vertical direction

Flat field corrected phase reconstruction

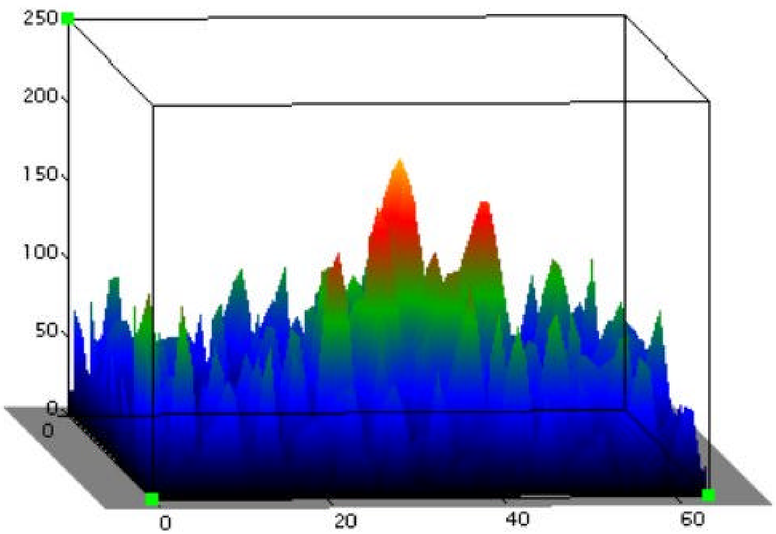


Single bad contact on a production wafer with 200 nm contacts at top



Example of optical detection of defective contact verified with voltage contrast SEM

DDH S/N 3D Difference Image (S/N >10)



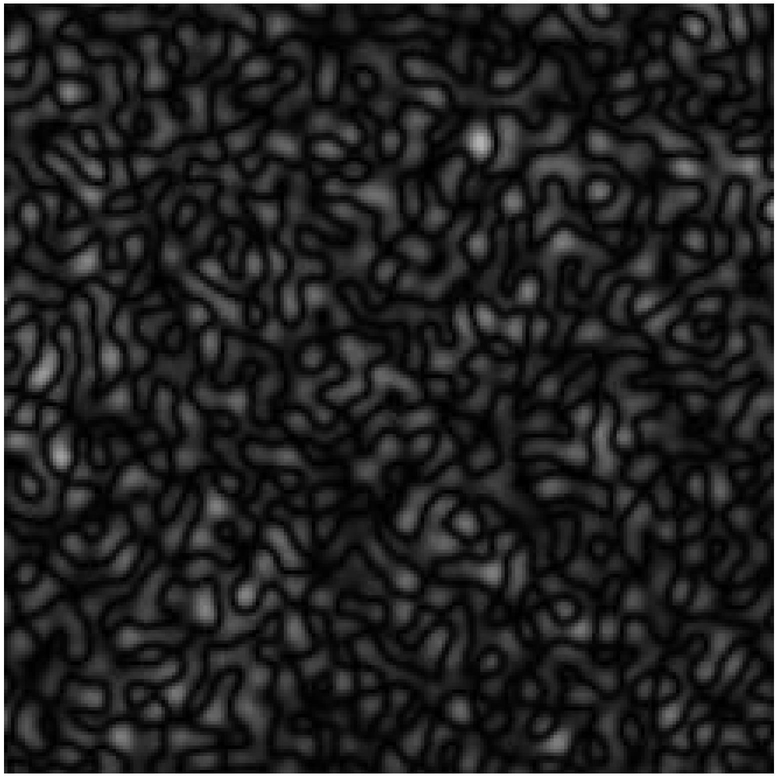
Partial Heights Extensions

- **Partial height defects all of the same material (*e.g.*, oxide on oxide) are difficult to detect on conventional brightfield tools because they are primarily found by edge effects**

- **Fathom also gathers surface height information via phase measurement from the hologram**
  - **For oxide on oxide partial height defects, the defect signal from phase is much greater than the signal from amplitude**

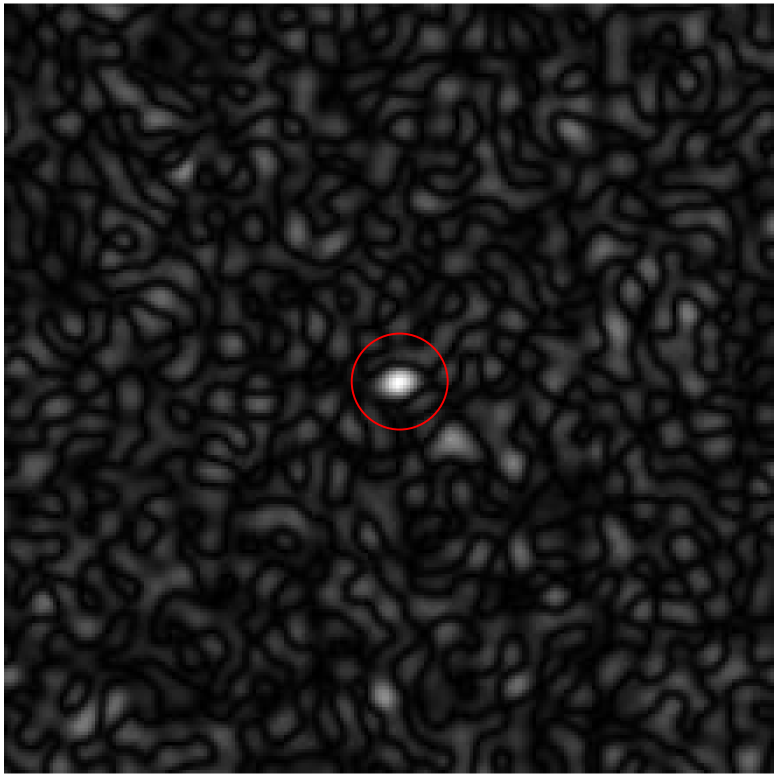
Partial Height Extensions

Amplitude difference



Defect not visible

Phase difference



Defect easily detected in phase

Defect not detected without holography

Digital holography technology shows tremendous potential for semiconductor process diagnostics

- **HARI continues to be a critical unmet need according to the ITRS**
- **Partial height defects such as stringers have also been identified by manufactures as a inspection need**
- **Digital holography offers unique advantages over competing technologies for inspection of these defect types**
  - **Head-on illumination penetrates high aspect ratio structures**
  - **Spatial heterodyne acquisition increases signal power**
  - **Phase measurements increase sensitivity and remove lateral resolution requirements**
  - **Low incident power on wafer, less risk of material damage**
  - **No vacuum required**
  - **Large area inspection in one frame, thus faster than SEM**

Product Roadmap

HARI 1

- Demo Q4 2003, production 1H 2004
- Sub 70 nanometer defect detection
- Throughput ~0. 1 up to ~1 wafer per hour @ <=70 nm defect
- Throughput ~ 1 to 3 wafers per hour @ 200 nm defect

HARI 2 (NIST ATP)

- Demo TBD, production TBD
- Sub 70 nanometer defect detection
- Initial Throughput ~4 wafers per hour @ 70 nm defect (then 10 wph)
- Initial Throughput ~ 12 wafers per hour @ 200 nm defect (then 30 wph)