OPTIQUIVER: NOVEL METROLOGY SOLUTION FOR IN-SITU WAFER SHAPE MEASUREMENTS

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ENGINEERING FORWARD

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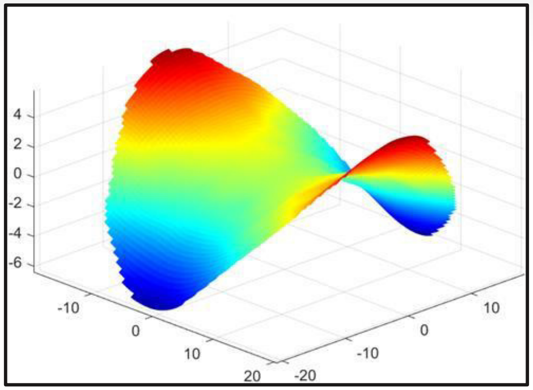
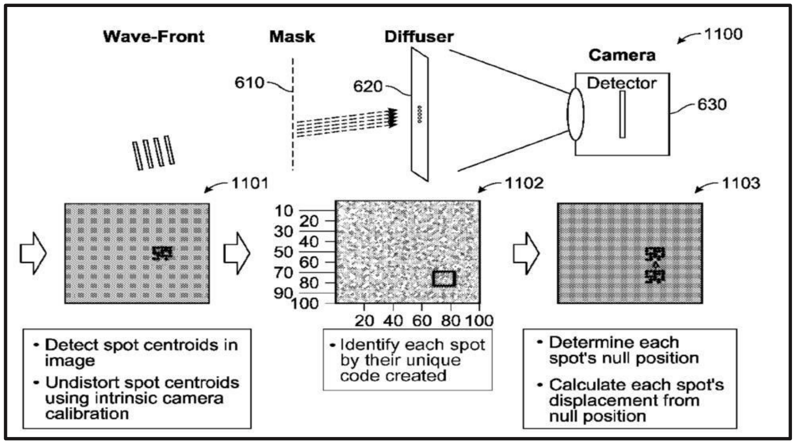
INTRODUCTION

- The OptiQuiver is a novel metrology solution to support high-throughput wafer inspection by measuring wafer shape during the semiconductor manufacturing process
- Wafer bow can impact uniform material removal during the CMP process – a metrology tool coupled with other mitigation strategies can improve yield
- Current configurations of OptiQuiver cannot fully capture shape information of 300 mm wafers
- Studies performed to demonstrate that the 2” OptiQuiver produces similar results to conventional metrology equipment
- Numerical simulations used to support analysis-driven design of 12” OptiQuiver, resulting in fewer design iterations needed to meet target optical performance



Sample Wavefront Measurement



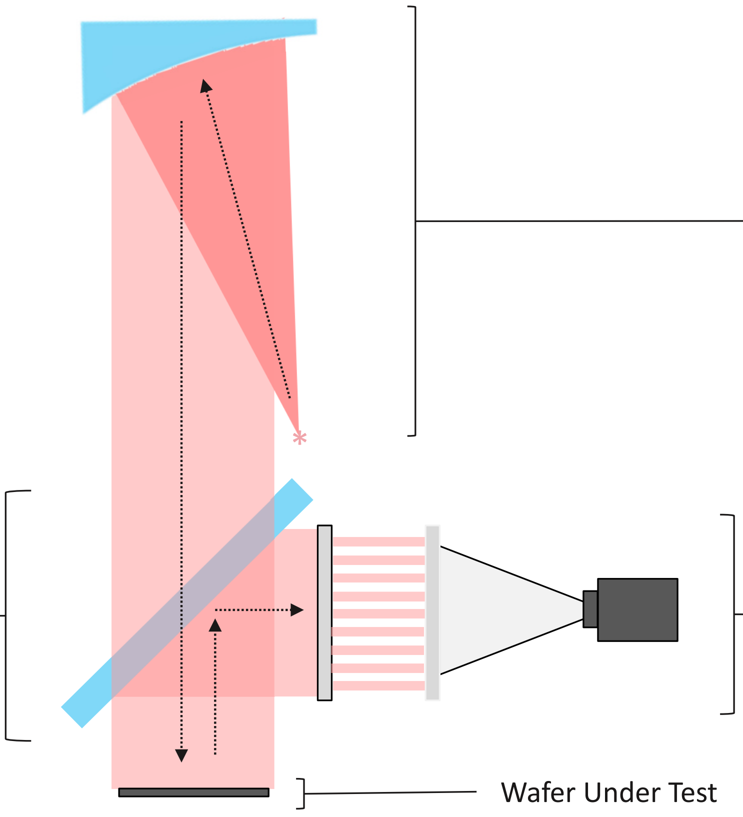
- Detect spot centroids in image
- Undistort spot centroids using intrinsic camera calibration

- Identify each spot by their unique code created

- Determine each spot's null position
- Calculate each spot's displacement from null position

Patent WO 2022/132797 A1

BACKGROUND | OPTIQUIVER CORE TECHNOLOGY



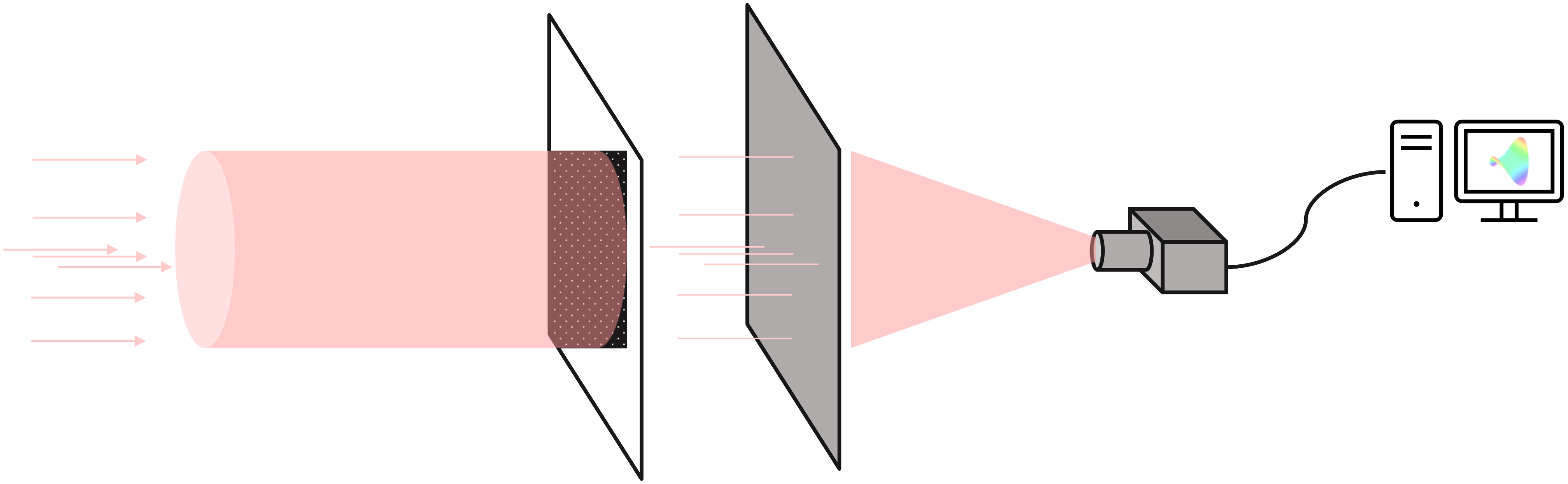
Transmit Module
Collimated Reference Beam

Optical Beam Splitter

Receive Module
Spot Mask, Screen, Camera

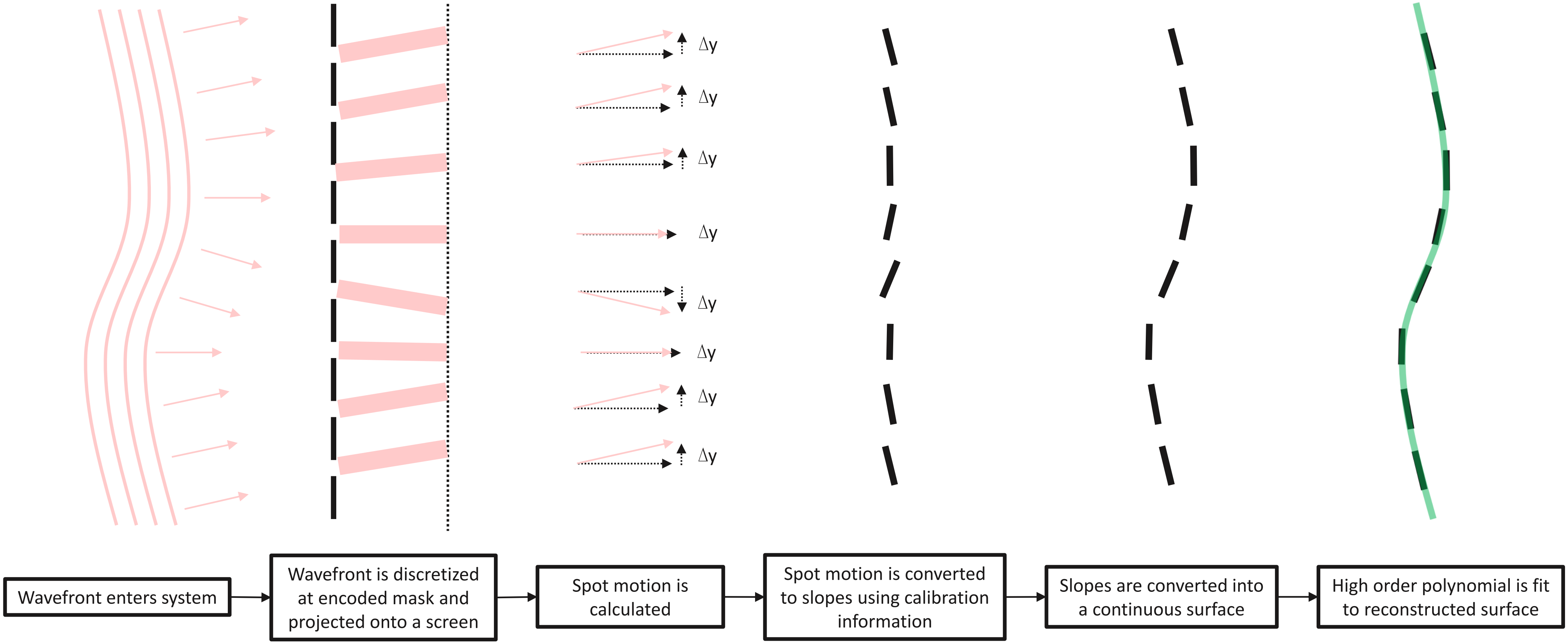
Wafer Under Test

BACKGROUND | OPTIQUIVER CORE TECHNOLOGY



Wavefront enters system → Wavefront is discretized at encoded mask → Spots are projected onto a screen → Camera images screen → Spot displacement is used to calculate tilt and wavefront error

BACKGROUND | OPTIQUIVER CORE TECHNOLOGY



Wavefront enters system

Wavefront is discretized at encoded mask and projected onto a screen

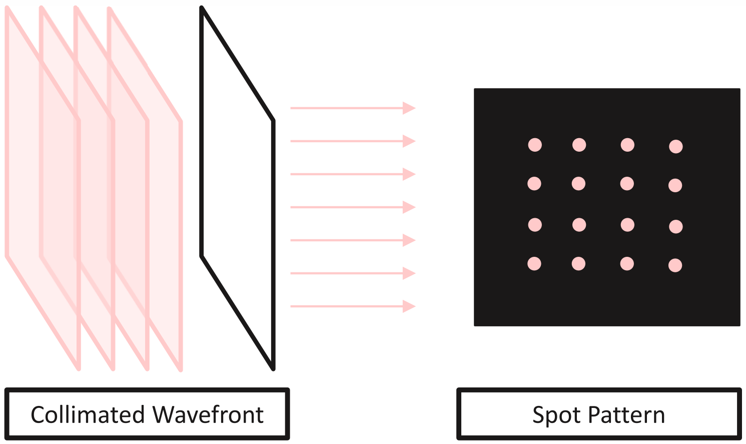
Spot motion is calculated

Spot motion is converted to slopes using calibration information

Slopes are converted into a continuous surface

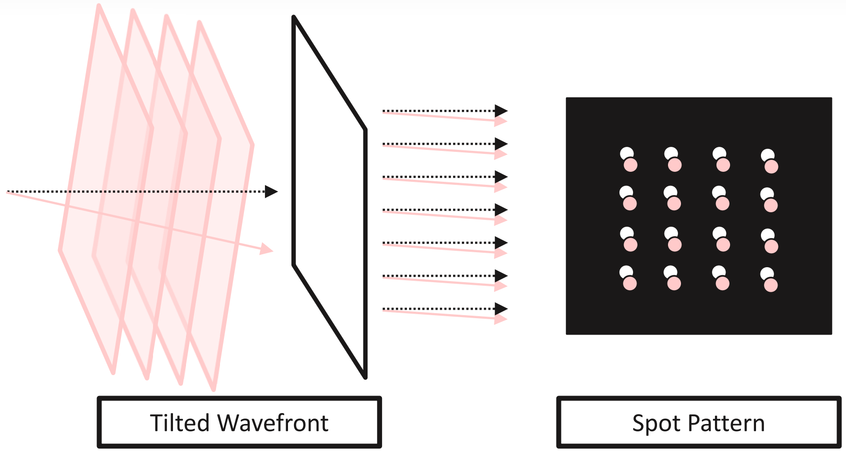
High order polynomial is fit to reconstructed surface

BACKGROUND | OPTIQUIVER CORE TECHNOLOGY



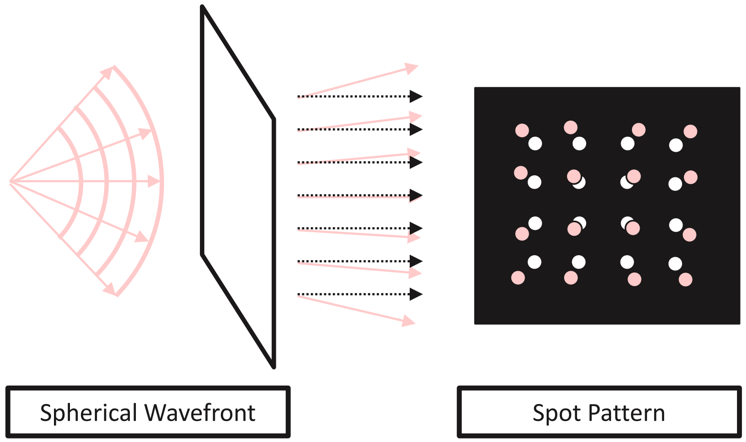
Collimated Wavefront

Spot Pattern



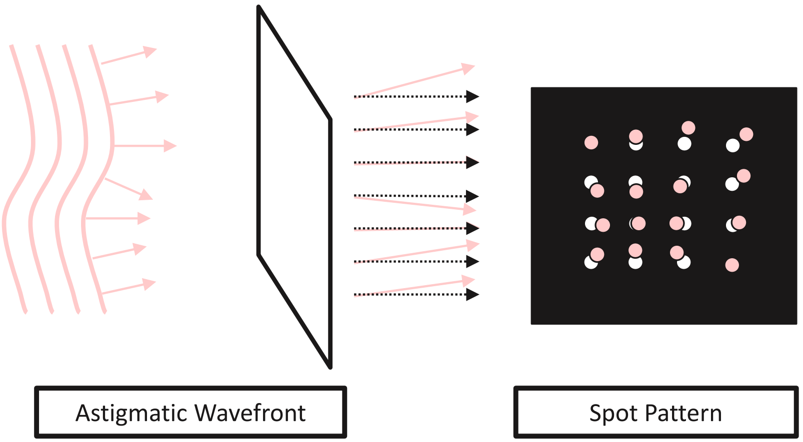
Tilted Wavefront

Spot Pattern



Spherical Wavefront

Spot Pattern

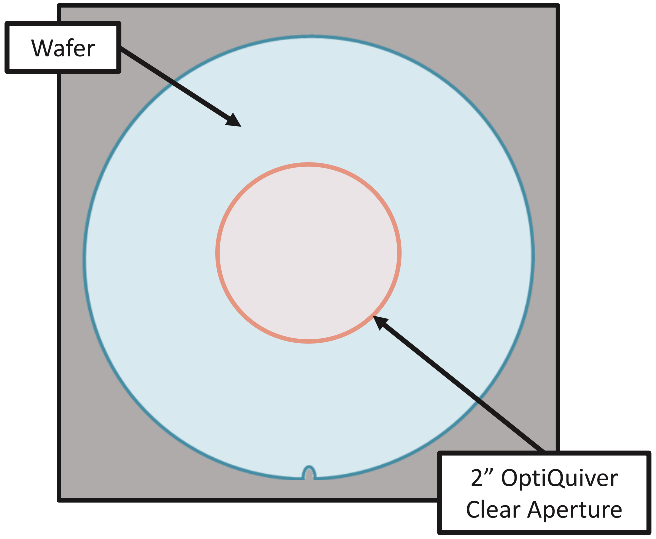


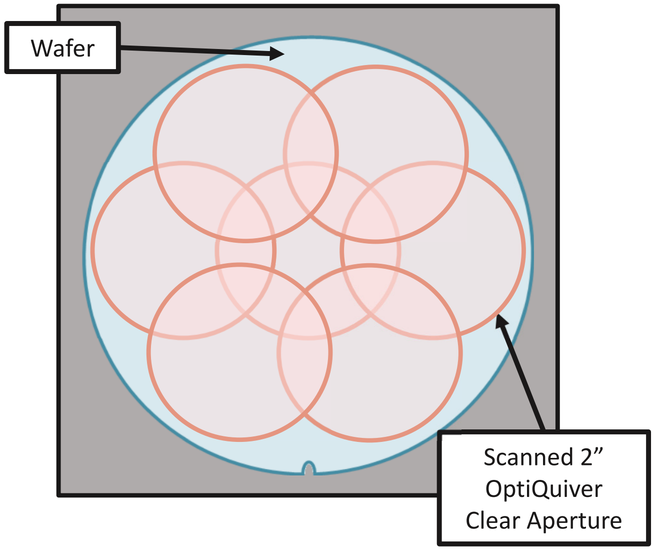
Astigmatic Wavefront

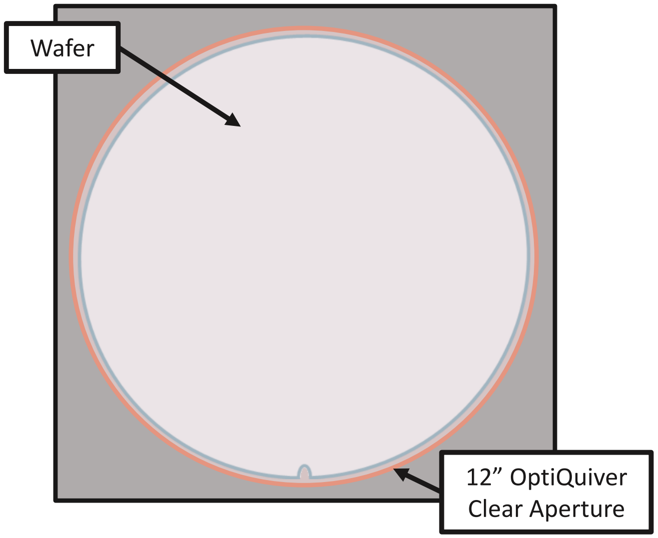
Spot Pattern

BACKGROUND

- Why scale up from a 2” to 12” OptiQuiver?
  - Sub-aperture measurement may not reveal the true shape or maximum deflection for a wafer
  - Scanning introduces additional measurement error and increases measurement time
  - Full aperture measurement captures true wafer shape in single image, for very fast measurement time



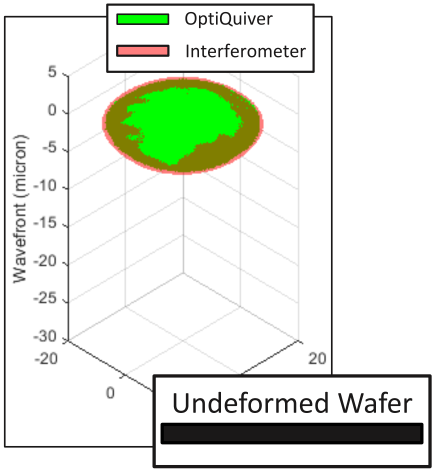


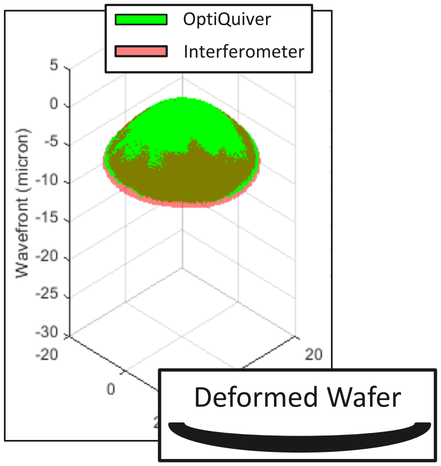


EXPERIMENT OVERVIEW

Wafer Deformation Study

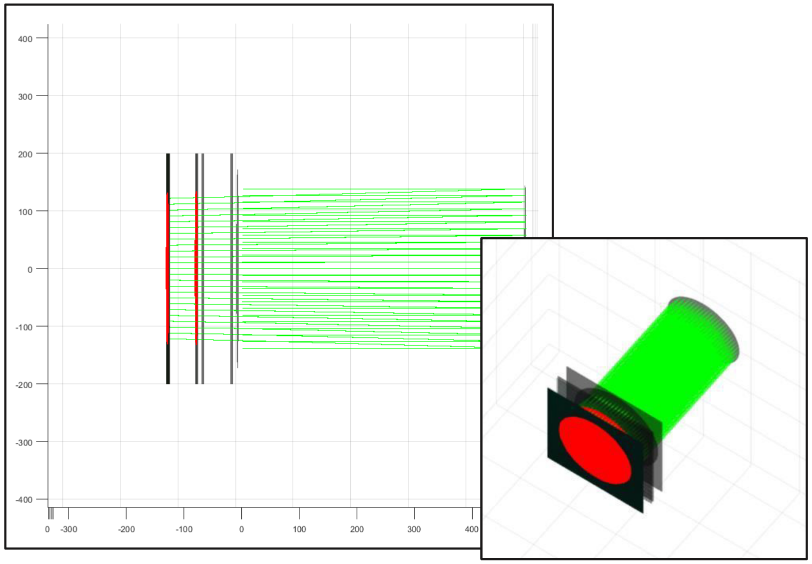
- Validate that the 2” OptiQuiver captures similar wafer shape and wavefront information compared to conventional metrology equipment
  - Mechanically deform sample wafer
  - Capture shape and wavefront information with 2” OptiQuiver and Interferometer





Numerical Simulations

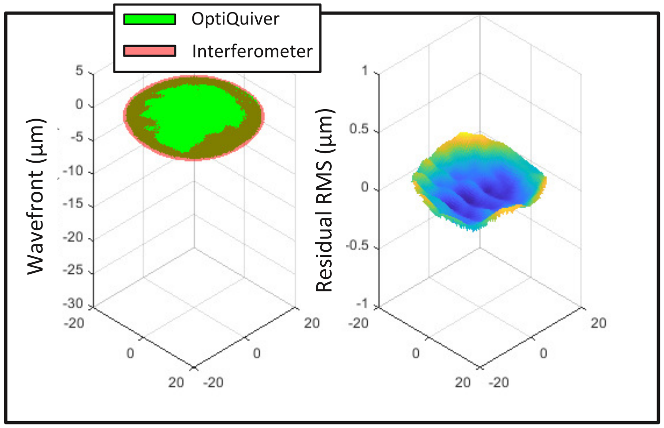
- Quantify the effect of OptiQuiver design parameters on RMS error and dynamic range of 12” System
  - Trade study conducted with numerical simulations to minimize design iterations needed for system to reach target optical performance



EXPERIMENTAL PROCEDURE

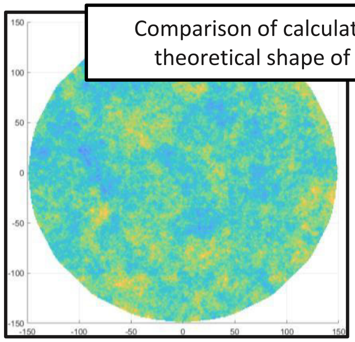
Wafer Deformation Study

- Capture undeformed wafer shape with interferometer and 2” OptiQuiver
- Mechanically deform wafer, repeat data capture
- Repeat 9 times with progressively increasing wafer deformation
- Plot wavefront information from 2” OptiQuiver and Interferometer
  - Calculate peak-to-valley (PV), and residual root mean square (RMS) values



Numerical Simulations

- Numerical simulations using OptiMetrika, an open-source MATLAB library [1]
  - Implements ray tracing approximation to optical image formation
- Evaluate parameters needed to achieve desired optical performance
  - Camera resolution – 20, 80, 180, 320 MP
  - Mask pitch (spot spacing) – 0.5, 1, 1.5, 2 mm
  - Mask-diffuser distance – 50, 100, 150 mm
- Determine wavefront given design parameters against theoretical shape of optic in simulation
  - Calculate the RMS error and dynamic range of system

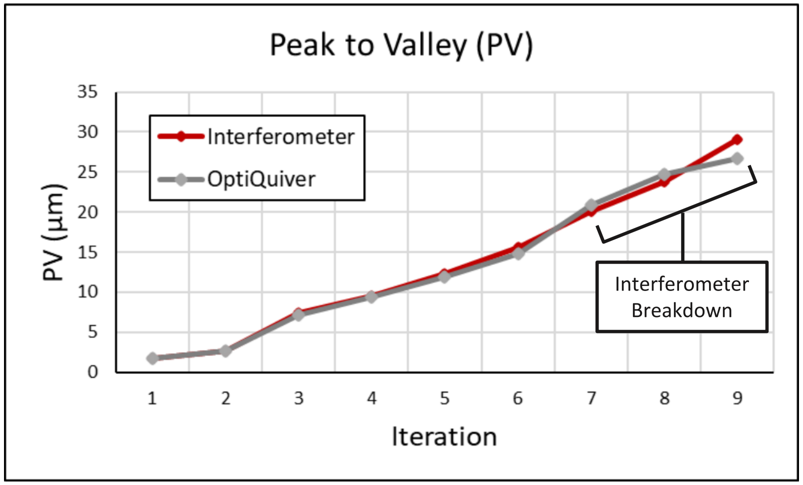


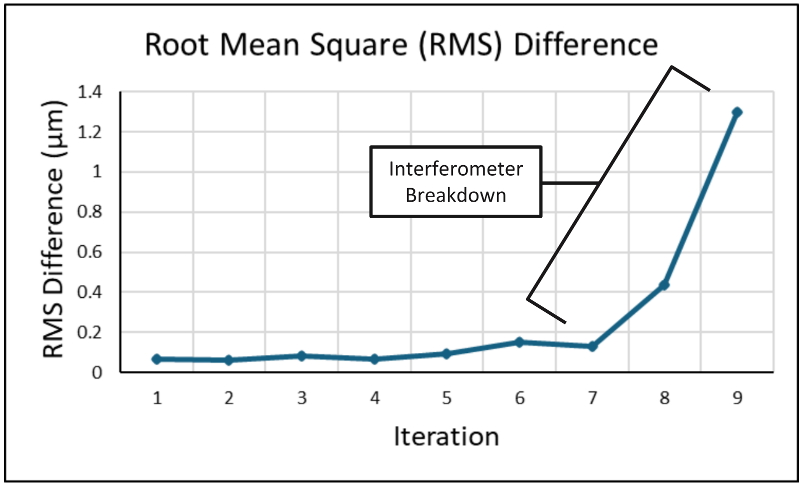
Comparison of calculated and theoretical shape of optic

[1] A. Schultze and Y. Petrov. OptoMetrika -Open source ray tracer for MATLAB. 2021. DOI: 10.13140/RG.2.2.10027.98081/2

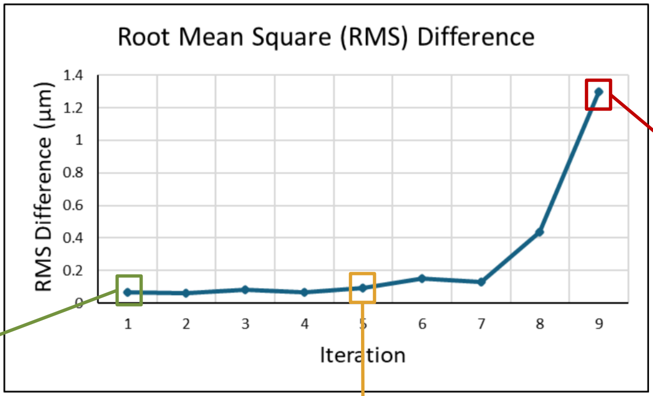
RESULTS | WAFER DEFORMATION

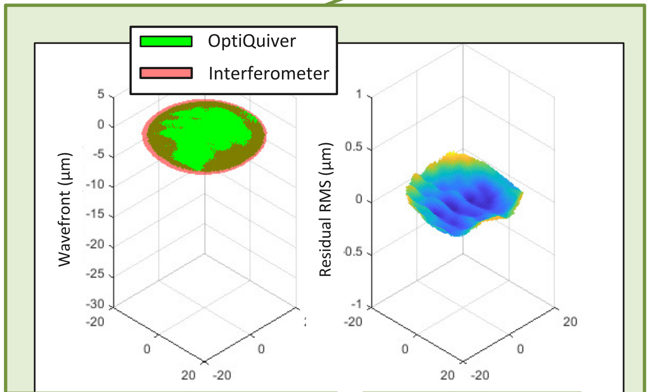
- Good agreement of wavefront information between interferometer and OptiQuiver
- Approach dynamic range limitations of interferometer, breakdown region where interferometer results are no longer reliable
  - Trend expected to continue with continued mechanical deformation
  - Interferometer breakdown region is more significant with RMS value, indicating that RMS is more sensitive to dynamic range as compared to PV due to higher frequency content





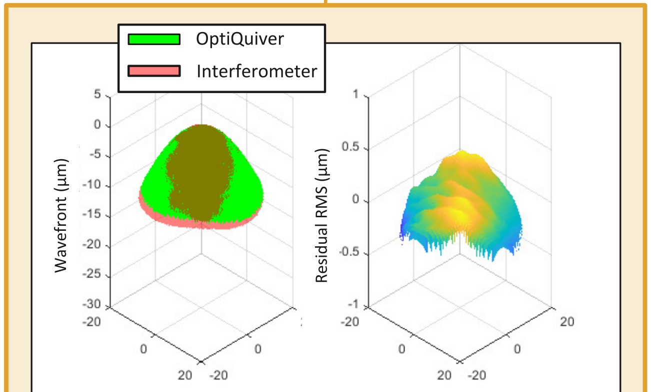
RESULTS | WAFER DEFORMATION





OptiQuiver PV: 1.676 µm
Interferometer PV: 1.719 µm

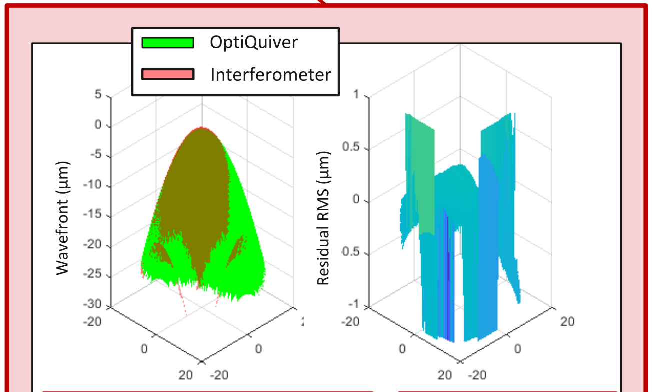
RMS Difference:
0.056 µm



OptiQuiver PV: 11.521 µm
Interferometer PV: 12 µm

RMS Difference:
0.093 µm

Approaching fringe contrast limit on Interferometer



OptiQuiver PV: 28.779 µm
Interferometer PV: 25.105 µm

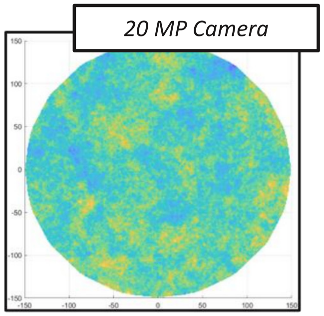
RMS Difference:
1.081 µm

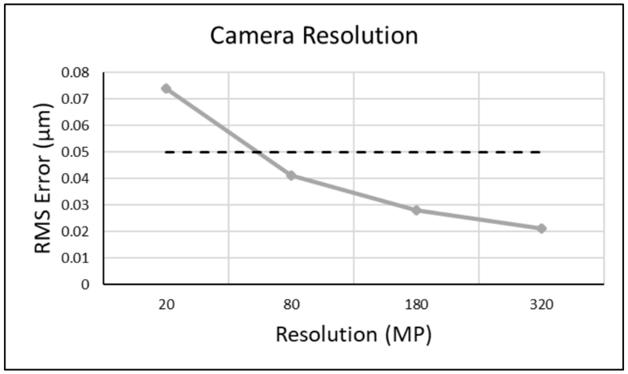
Interferometer software unable to calculate data

RESULTS | NUMERICAL SIMULATIONS

Camera Resolution

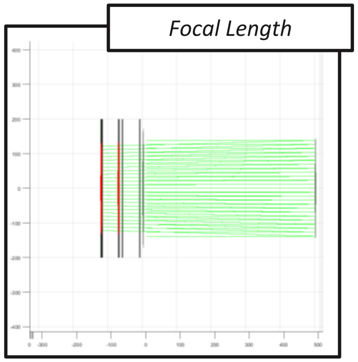
- Acceptable RMS error of 50 nm, any resolution beyond 80 MP is sufficient to meet optical performance requirements
  - Achieves 1/10 wave error at 12” diameter
- RMS error decreases with increasing camera resolution
  - 44% improvement in RMS error between 20 and 80 MP
  - Anticipated asymptote with increasing camera resolution beyond 320 MP

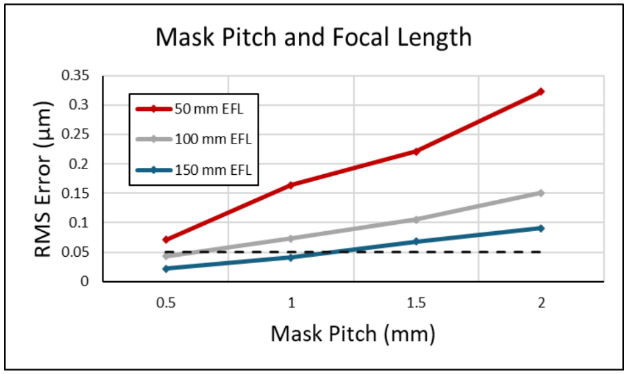




Mask Pitch and Focal Length

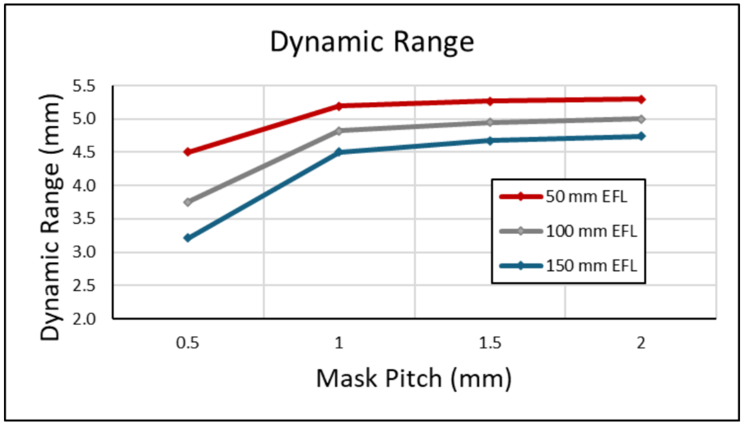
- Acceptable RMS error of 50 nm, 50 mm of effective focal length (EFL) will not meet optical performance requirements
- With a mask pitch of 0.5 mm, RMS error improves by 39% by changing EFL from 50 to 100 mm
  - Improves further with an EFL of 150 mm
- EFL and mask pith effect max dynamic range, a critical metric for this metrology system



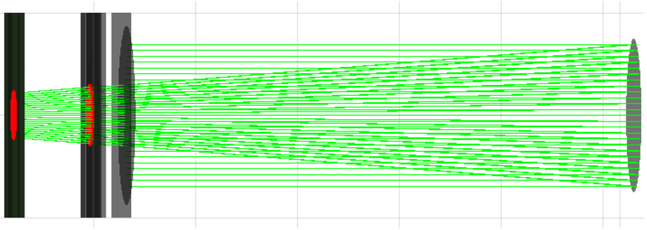


RESULTS | NUMERICAL SIMULATIONS

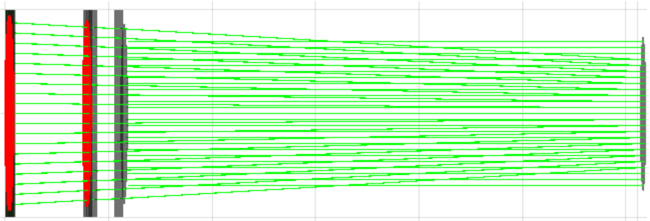
- At a mask pitch of 0.5 mm, dynamic range increases by 30% when reducing EFL from 150 to 50 mm
- Each EFL converges to a maximum dynamic range with increasing mask pitch
- Longer EFL correlated to lower dynamic range, optimization of system required to reach maximum dynamic range while minimizing RMS error



Ray Trace Simulations at Various Mask Pitch and EFL Configurations



Spots can cross over each other and no longer be distinguished from one another



Spots can move off the diffuser or outside of the camera FOV

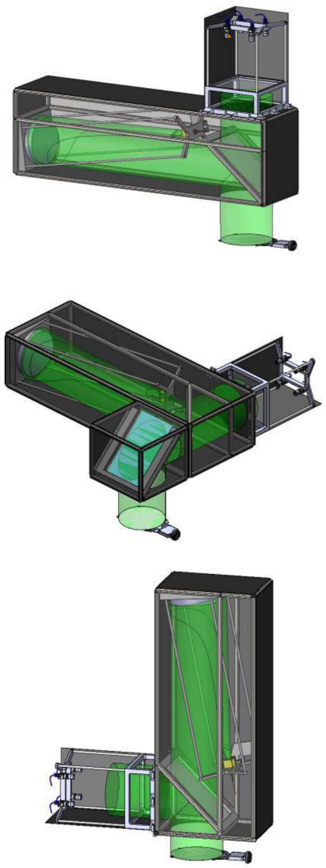
CONCLUSIONS AND FUTURE WORK

Conclusions

- Negligible difference in OptiQuiver wafer shape measurements as compared to interferometer
  - As wafer distortion increases and dynamic range of the interferometer is approached, the measurements deviate
  - OptiQuiver core technology allows for accurate calculation of wafer shape for large wafer deformations
- A camera resolution of 80 MP meets the requirements for optical performance when scaling up to a 12” OptiQuiver
- RMS error can be minimized by longer EFL and lower mask pitch, but dynamic range improves significantly with a shorter EFL
- EFL will asymptote to a maximum dynamic range with increasing mask pitch
  - Trade-off between EFL, mask pitch, and dynamic range should be considered when determining form-factor of 12” OptiQuiver

Future Work

- Compare results from numerical simulations to actual optical performance of the 12” OptiQuiver to understand model fidelity
- Repeat wafer deformation study on 12” OptiQuiver and compare results to interferometer of the same aperture



Potential 12” OptiQuiver Configurations

For additional information, please contact:

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CITATIONS

[1] Schultze, Alexander & Petrov, Yury. (2021). OptoMetrika -Optical ray tracer for MATLAB. 10.13140/RG.2.2.10027.98081/2.

Additional references informing study:

[2] Mansfield, E. , Barnes, B. , Kline, R. , Vladar, A. , Obeng, Y.
and Davydov, A. (2023), INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMSTM 2023 EDITION METROLOGY, *International Roadmap for Devices and Systems (IRDS™),* https://irds.ieee.org/editions/2023

[3] P. Vukkadala, K. T. Turner, and J. K. Sinha, “Impact of Wafer Geometry on CMP for Advanced Nodes,” Journal of The Electrochemical Society, vol. 158, no. 10, p. H1002, 2011, doi: https://doi.org/10.1149/1.3615988.

[4] B. Zhang and Z. Zhu, “Wafer bow effects on CMP performance.” Accessed: Oct. 29, 2024. [Online]. Available: https://nccavsusergroups.avs.org/wpcontent/uploads/2023/01/P41-BZhang.pdf