Fabrication of EUVL Micro-field Exposure Tools with 0.5 NA

EUV Litho, June 15th, 2016

Luc Girard[1], Lou Marchetti[1], Jim Kennon[2], Bob Kestner[2], Regina Soufli[3], Eric Gullickson[4]

[1] *Zygo Corporation, Extreme Precision Optics (EPO), Richmond, CA*
[2] *Akumen Engineering, LLC. (former employees of Zygo EPO)*
[3] *Lawrence Livermore National Laboratory, Livermore CA*
[4] *Lawrence Berkeley National Laboratory, Berkeley, CA*

AMETEK ULTRA PRECISION TECHNOLOGIES

Outline

- Introduction
  - Application
  - Design considerations
- Mirror Fabrication
  - Component testing
  - EUV fabrication / development / CCOS and IBF
  - Component fabrication results
    - Figure, MSFR, HSFR ranges
- Opto-mechanical assembly and alignment
  - Assembly process
  - Alignment performance
- Coating
- Final transmitted wavefront performance
- Summary

Introduction

ZYGO corporation got contracted to build several EUV-L Micro-Field Exposure Tools with 0.5NA, *known as MET5*.

- Those tools are used for infrastructure development required for the EUV lithography industry to support printing at the ~12nm node and below.
  - Example: resist development.

- The lithography industry drive to print smaller feature sizes requires a shift towards smaller wavelengths and higher NA… **and ultimately to tighter optical surface specifications.**

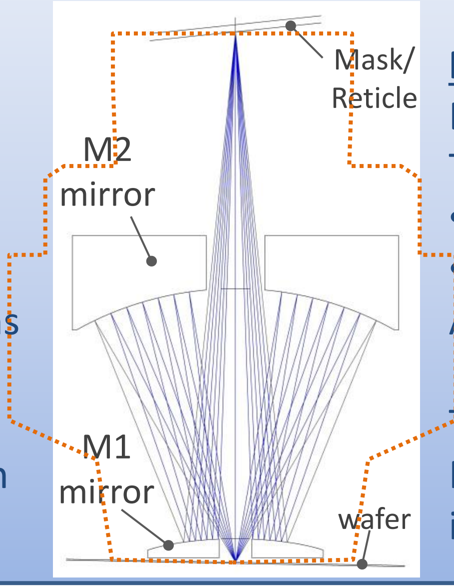
Design Features:

Modified Schwarzschild Design

- 13.5nm wavelength
- 0.5NA
- 5X reduction
- Field dimension 30 x 200microns

Reticle plane tilted by 6 degrees.

- Reticle (Mask) used in reflection at EUV wavelengths



Performance Requirements:

Diffraction limited Imaging with Transmitted wavefront error:

- Center of the field < **0.5nm RMS**
- Edge of the field < **1.0nm RMS**

And Flare < **5%**

This is an upgrade to existing 0.3NA tools. Fitting the PO in existing platform volume is a design and manufacturing challenge.

Mirror Fabrication

- ZYGO Extreme Precision Optics (EPO) group in Richmond, California is a leader in optical surfacing development.
  - 40 years of Computer Controlled Optical Surfacing (*CCOS*) use and development.
  - Over 15 years of Ion Beam Figuring (*IBF*) experience.
  - Over 20 years of EUV optics fabrication.
    - During that period, EUV optics specs got tighter by a factor of 5
      - For all Ranges: Figure, MSFR, and HSFR

← CCOS **IBF →**

Technologies used in fabrication of the EUV optics for the MET5 Projection Optic Box

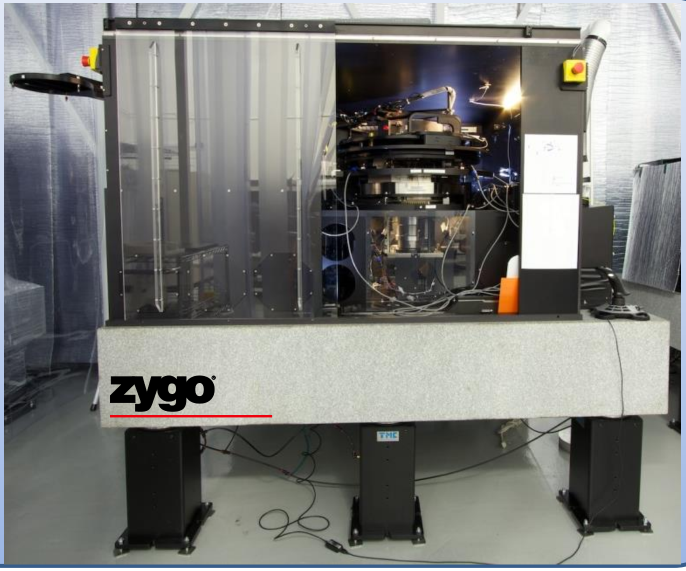
- The M1 and M2 Mirrors are fabricated using a combination of conventional and discrete computer controlled polishing techniques.
  - Aspheric departures of 46 and 51 microns.
  - Aspheric slopes of 8.6 microns/mm and 3.6 microns/mm

← Extremely high
← for EUV optics

ULTRA PRECISION TECHNOLOGIES

Mirror Metrology

- Figure Metrology
  - Custom built, full aperture test station
  - Zygo Verifire™ MST
  - High precision computer generated holograms (CGH's)
  - **Reproducibility of 20pm RMS**
    - Including mount deformations
  - **Total Accuracy of both tests < 0.2nm RMS**
    - Verified when first POB assembly was tested in our POB system test.
- Full Spatial Range of metrology instruments
  - Figure test station
  - SASHIMI (custom built sub-aperture interferometer)
  - Optical Profilometer
    - 2.5x and 50x objectives
  - Atomic Force Microscope (AFM)



Mirror Fabrication Results

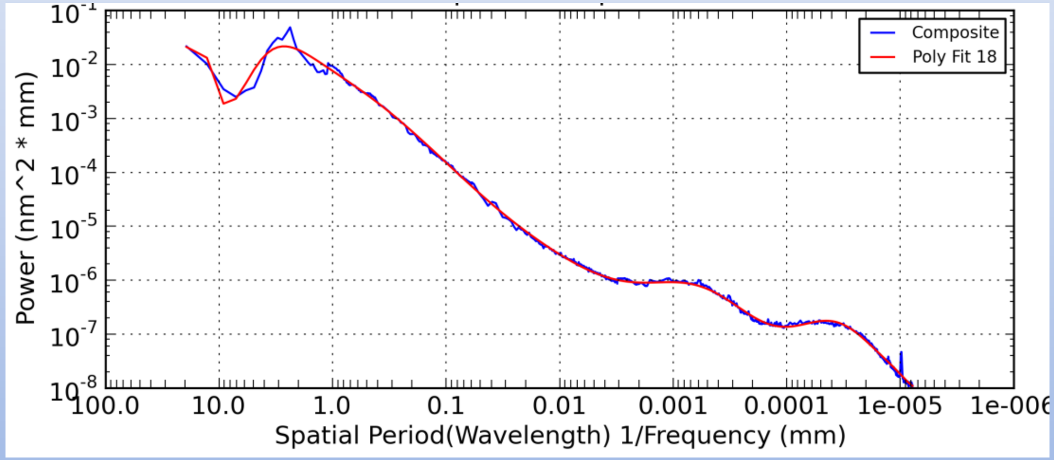
- Average achieved RMS for 3 sets of mirrors (i.e. 3 complete systems)

		Figure	MSFR	HSFR	Entire range
M1 mirror	**Ranges**	CA - 3mm	3mm to 0.43μm	1μm - 10nm	CA - 10nm
	Results	***0.050*** nm RMS	***0.128*** nm RMS	***0.088*** nm RMS	**0.163** nm RMS
M2 mirror	**Ranges**	CA - 8mm	8mm to 1.2μm	1μm - 10nm	CA - 10nm
	Results	***0.066*** nm RMS	***0.123*** nm RMS	***0.085*** nm RMS	**0.163** nm RMS

  - The MSFR and HSFR are evaluated by stitching the PSD curves from multiple metrology instruments and integrating under the curve.

- **Average Achieved Flare** is:
  2.75% *(spec is 5%)*
  - System Flare is calculated as total integrated scatter (TIS) from the MSFR range surface error.

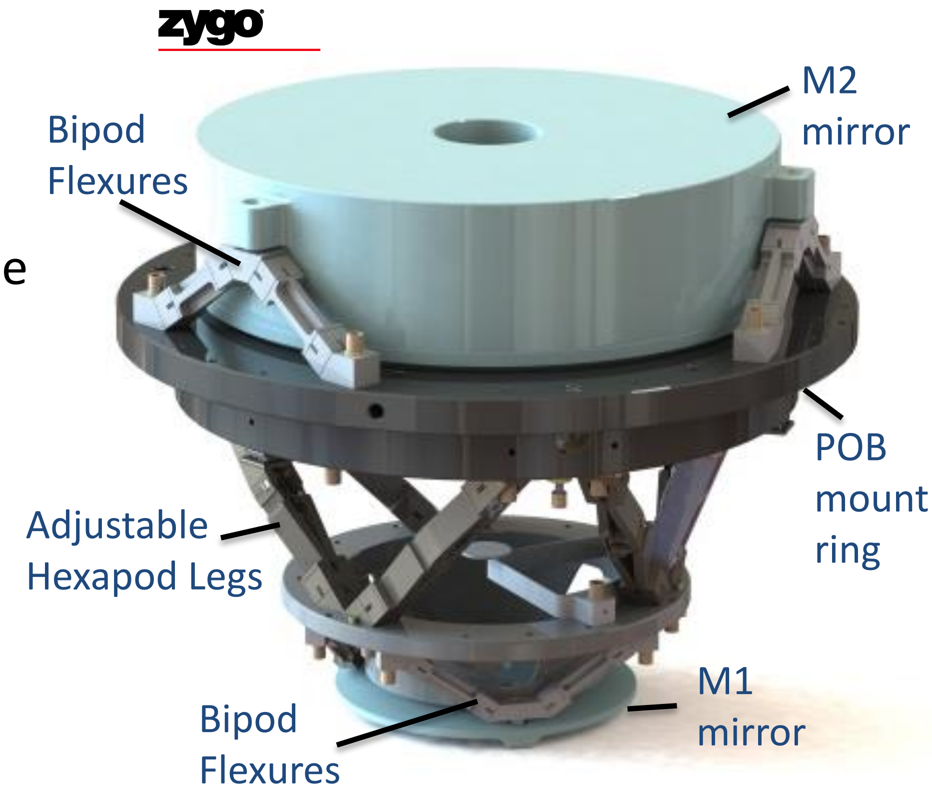
The PSD's of various instruments are combined to get an integrated PSD for the entire surface



MET5 M1 Mirror ID-1 PSD

Opto-Mechanical Assembly and Alignment

- The POB structure is super Invar to match the low expansion material of the mirrors.
- The bipod flexures rigidly constrain the mirror positions, while allowing low force and moments, required to achieve low distortion of the optical surface.
- The POB alignment is performed with the hexapod legs and a software control system.



- Initial POB assembly is done with a Coordinate Measuring Machine (CMM) in order to achieve initial alignment within the range of the hexapod legs.
  - Hexapod legs have super high accuracy (5nm) but limited range (100 microns)
  - CMM process yields wavefront errors <50nm RMS that can be corrected by using less than 30 microns of hexapod leg adjustment.

Opto-Mechanical Assembly and Alignment

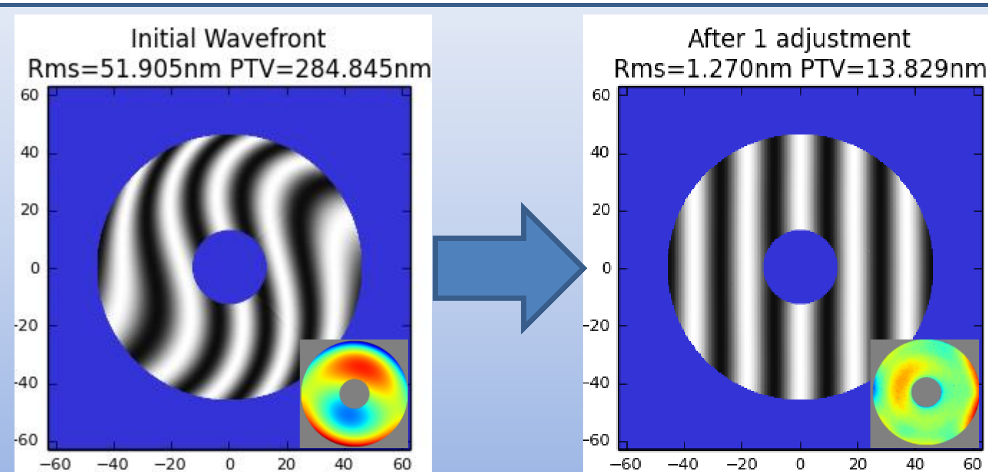
- The *internally developed* Hexapod Control software seamlessly converts wavefront data to mirror adjustments and finally to hexapod leg moves to adjust the wavefront.

Wavefront Error Map → M1 Mirror adjustment → Hexapod leg adjustment → Perform the move

  - **The move executes in approximately 2 minutes with an M1 mirror position accuracy of 10nm laterally and 10nm axially.**
    - *All 6 hexapod legs must move in a coordinated fashion even for the simplest motion of the M1 mirror.*

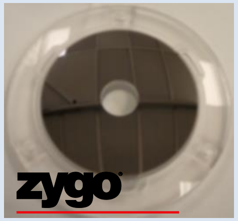
POB initial alignment sequence shows the WFE improving from 52nm RMS to approximately 1 nm RMS in only one adjustment cycle.

- Synthetic fringes shown, with wavefront map shown in lower right frame

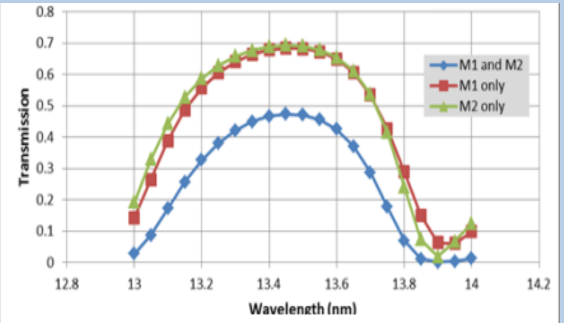


EUV Multilayer Coating

- The mirrors are coated at Lawrence Livermore National Laboratory (LLNL) with a graded EUV multilayer.
- The Mo/Si multilayers are optimized to maximize reflectivity while minimizing resulting coating stress on the optic.
- The Mo/Si coatings were measured at the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory (LBNL).



EUV ML Coated M1 and M2 mirrors



Modeled reflectivity curves for individual mirror and system

Table of Coating Specifications and Achievements

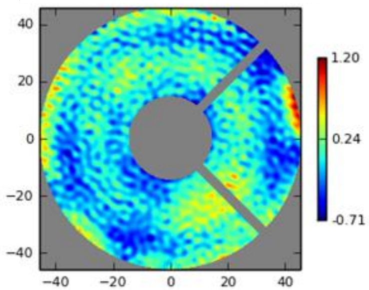
Coating Metric	Spec	Achieved	Method
System Transmission	>= 25%	> 30% ✓	ALS Reflectivity measurement
Centroid wavelength	13.50nm +/- 0.05nm	13.5 ✓	ALS Measurement
Bandwidth	Goal >= 0.5nm	0.59nm FWHM ✓	ALS Measurement
Added Figure Error	Goal < 0.1nm RMS	0.1nm RMS ✓	System Wavefront Test

Final Transmitted Wavefront performance

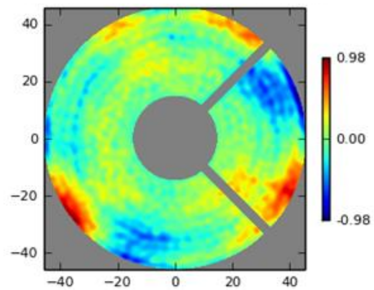
- The measured transmitted wavefront error of the 3 POBs is < 0.25nm RMS.
  - **This is less than half of the specification !!!**

Final Single Pass Transmitted Wavefront Error

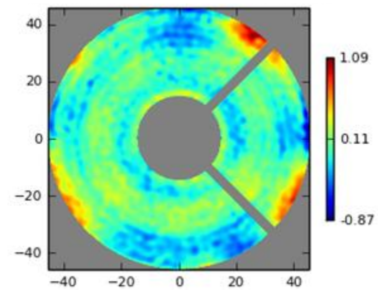
POB 1
0.24nm RMS



POB 2
0.24nm RMS

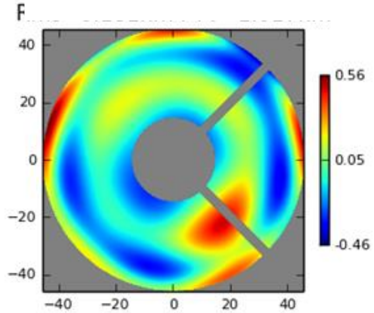


POB 3
0.21nm RMS

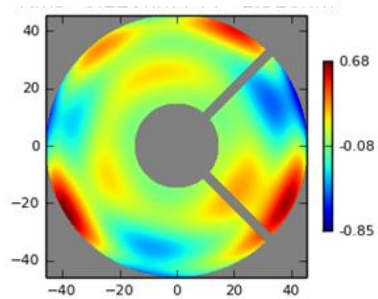


37 Term Zernike Fit of Transmitted Wavefront Error

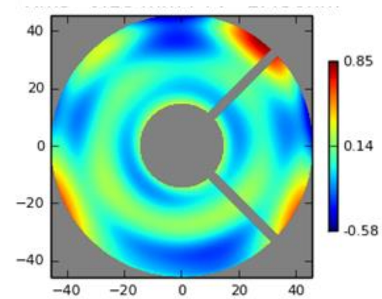
POB 1
0.18nm RMS

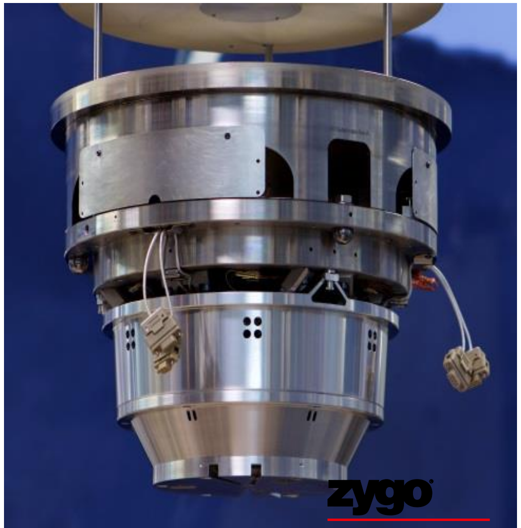


POB 2
0.22nm RMS



POB 3
0.18nm RMS

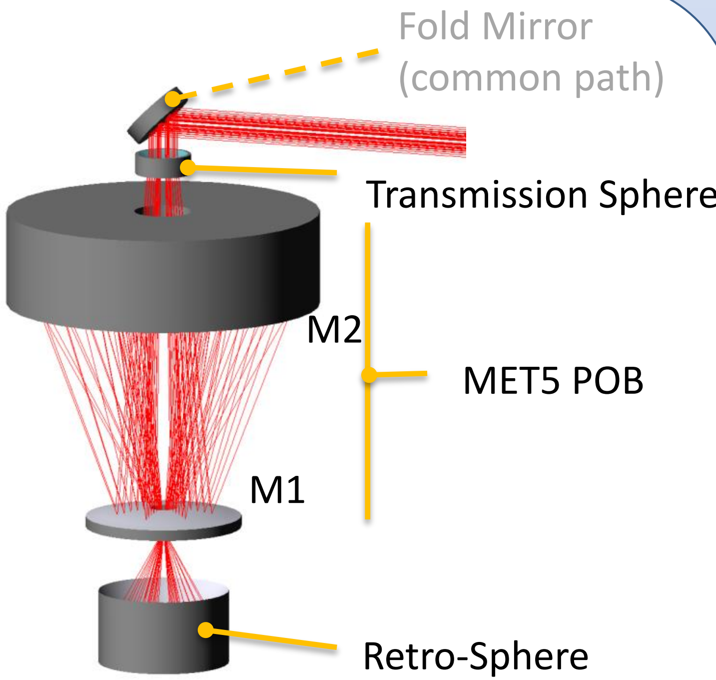




The Final Projection Optics system ready for integration in a vacuum system.

POB System Wavefront Metrology and Reproducibility

The POB system wavefront metrology is performed with a Zygo Verifire™ MST, at visible wavelength.



The measured wavefront RMS has reproducibility of <u>better than 10 picometers.</u>

Test Iteration	*WFE (nm RMS)*
Test 1	*0.212*
Test 2	*0.216*
Test 3	*0.214*
Test 4	*0.212*
Test 5	*0.214*
Test 6	*0.211*
Test 7	*0.212*
Test 8	*0.218*
Average	***0.214***
RMS deviation	***0.002***
P-V deviation	***0.007***

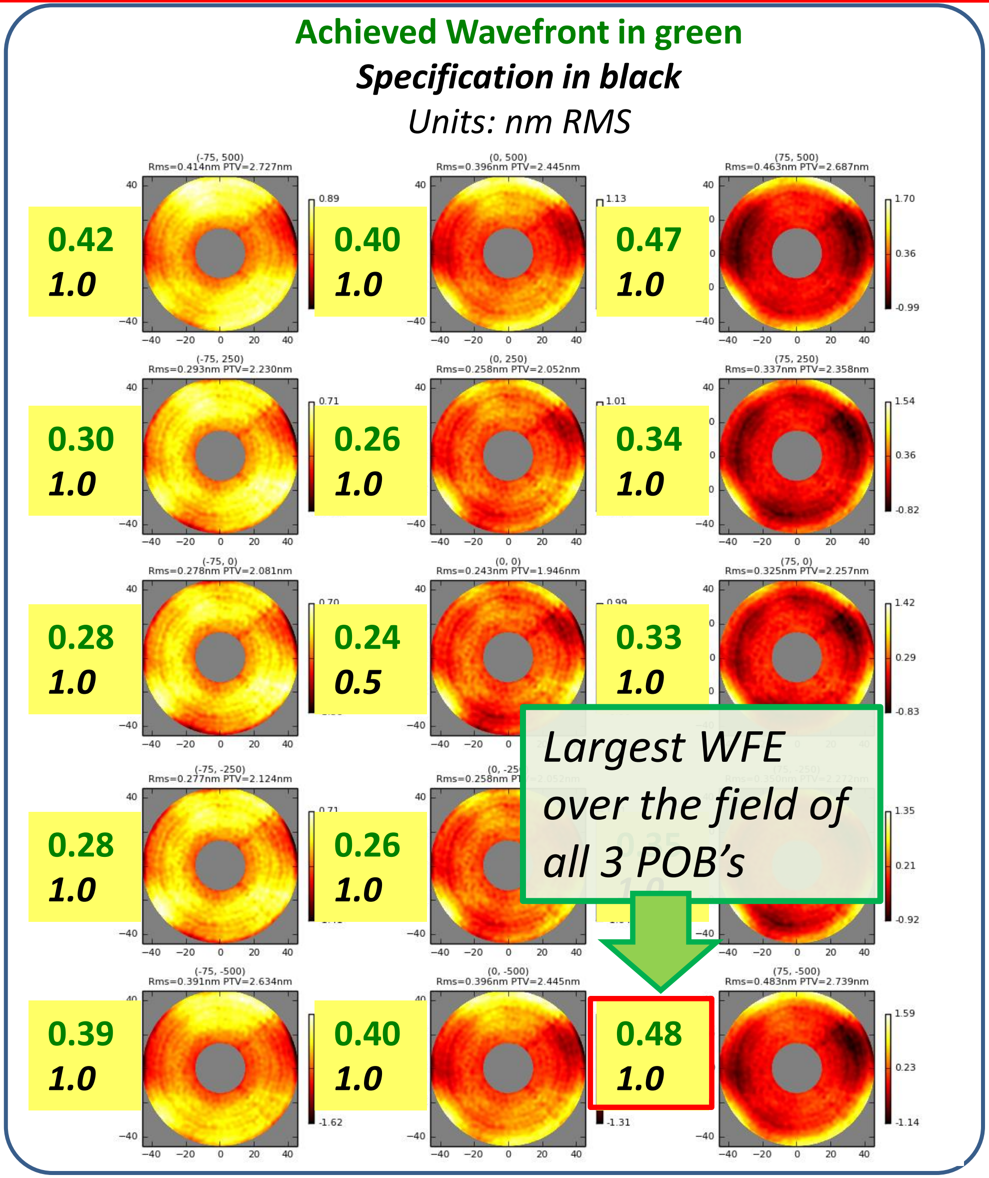
Final Transmitted Wavefront performance

- Wavefront error over the field.
  - 0.15mm x 1.0mm field at the reticle (object side)
    - 30 x 200 microns at wafer

- **Largest Wavefront error over the field is 0.48nm RMS for all 3 POB's.**

  → Less than half of the spec!!!

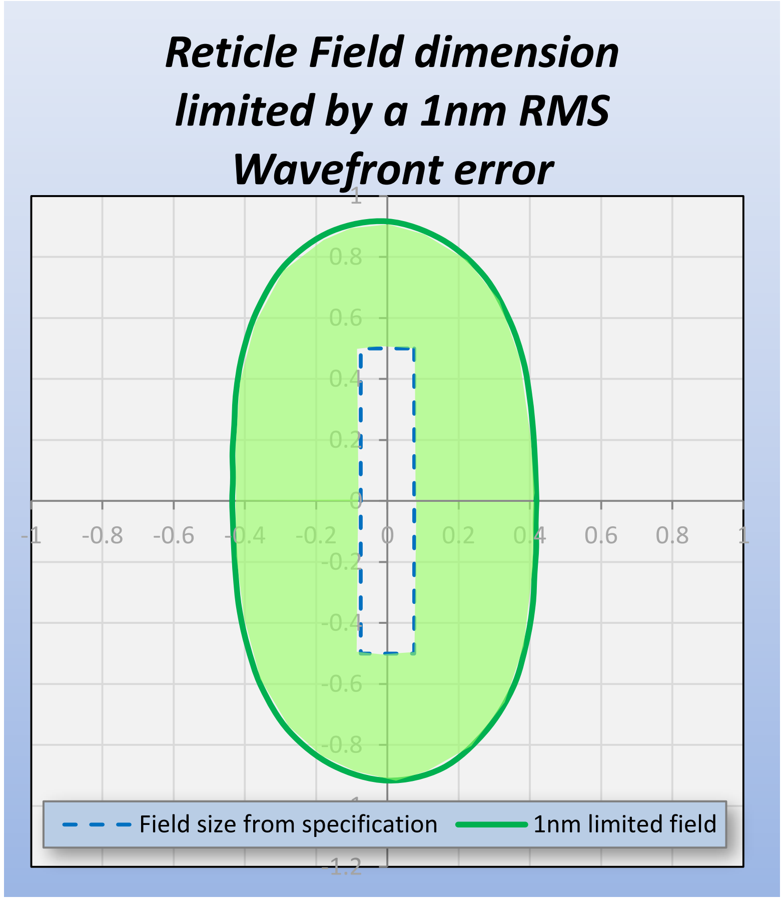
- Field aberrations include: astigmatism, field curvature and spherical aberration.
  - The Field aberrations are prescribed by the nominal optical design



Final Transmitted Wavefront performance

- Due to the excellent wavefront performance achieved, the usable field dimension that meets the specification can be increased.
  - Allows the customer to use a larger area for their printing tests.

- **The increase in the useable area is 8x.**
  - From 0.15mm^2 (0.15mm x 1.0mm)
  - To 1.3mm^2 (0.85mm x 1.8mm)



Summary

The fabrication of three 0.5NA EUV small field micro-exposure tools (MET) is complete. The results of all 3 systems are extremely good:

- The achieved single pass transmitted wavefront of 0.21 to 0.24nm RMS is less than half of the 0.5nm specification at the center of the field.
- The maximum measured single pass transmitted wavefront across the specified field is 0.48nm RMS, less than the 1.0nm specification.
  - This indicates that the dimension of the usable field may be larger than the 0.15mm x 1.00mm specified field dimension by up to 8 times.
- The MSFR and HSFR are well in spec.
- The average achieved flare of 2.75% is close to half of the 5% specification
- The component test accuracy was confirmed by the POB system test measurement of the first assembly.
- The assembly process that was developed produces POBs that are close to final alignment and the resulting POB assemblies have the conjugates near their target positions.
- The POB system test reproducibility is at the picometers level