# Another Missing Piece in China's Pathway to Advanced Lithography

[redacted]

## Introduction

As documented in our previous paper titled "Huawei's Technological Pathway to Advanced Lithography", we strongly believe that China has a viable pathway to filling key gaps in their EUV lithography capabilities. The potential light source we previously described is enabled by [redacted] that China currently has in operation. Following an advanced light source, the most significant remaining gap in known PRC capabilities to pull off such a feat: precision optics.

A widely held assumption is that it will take China many more years to acquire these capabilities, with industry claiming that only ZEISS has the capability to produce the mirrors to the specification required for extreme ultraviolet (EUV) lithography's stringent requirements.

We disagree. A recent presentation documents their stunningly rapid progress in this critical area. The abstract of a recent presentation given at a scientific conference suggests the purpose of researching these optics is for use within synchrotron and free-electron laser (FEL) light sources. This is likely false. These optics are neither commonly found in synchrotrons nor FELs. Unsurprisingly, they are found in EUV lithography systems. We presume this is intentional misdirection to shield the true purpose of the work as being part of China's accelerating EUV efforts as well as prevent scrutiny of the external collaborations enabling their progress.

It is our belief that within two to three years, China will possess the capability to create X-ray optics at the level of precision of ZEISS optics found within today's production EUV systems. This combined with China's accelerating work in precision mechatronics, and Huawei's viable plan for [redacted] will enable China to possess domestic EUV lithography. The combination of technology choices available to the PRC may also enable a higher wafer throughput than current and planned EUV scanners.

While we place China at two to three years away from matching the highest precision levels of ZEISS, the optics they have the ability to produce today are of a quality which would enable China to insert them into an EUV scanner and lithographically pattern features between 20 nm to 30 nm half pitch in a single exposure.

**Presentation of interest**

**Location:**
MEADOW 2023 - Trieste, Italy (September 2023)

**Title:**
Development of stitching interferometry and ion beam figuring methods for high precision X-ray mirrors

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**Abstract:**
Driven by the fast development of the new generation storage ring and free-electron laser facilities, X-ray mirrors with nanometer figure accuracy, complex shape and large size are widely demanded. These optics are being developed in Tongji University using stitching interferometry and ion beam figuring techniques. Stitching interferometry is commonly used for the 2-D figure metrology of X-ray mirrors, while the accumulated angular error among neighboring sub apertures and the systematic error within each subaperture are affecting the stitching accuracy. A method to correct the angular error using low-frequency profiles measured by other instruments is studied, called ‘mixed stitching’ . It directly obtains the stitching angles from the 1-D profile along one direction of the entire tested mirror which further correct the relative angles fitted from the algorithm. The stitching accuracy can be both improved either by a commercial contact profiler or a high-precision slope measurement system and the minimum figure error of below 1 nm RMS can be achieved. The shape error of a single subaperture is studied and reduced by calibration of the reference mirror and lateral resolution of the Fizeau interferometer. Based on these improvements, the measured figure accuracy of the elliptical mirror using simple global stitching algorithm was improved to 1.5 nm RMS. Based on the high precision stitching interferometry, mirrors with maximum length of 500mm and figure height error of 1 nm RMS were manufactured and some of them have been applied in the synchrotron radiation facility. These results will be presented and discussed.

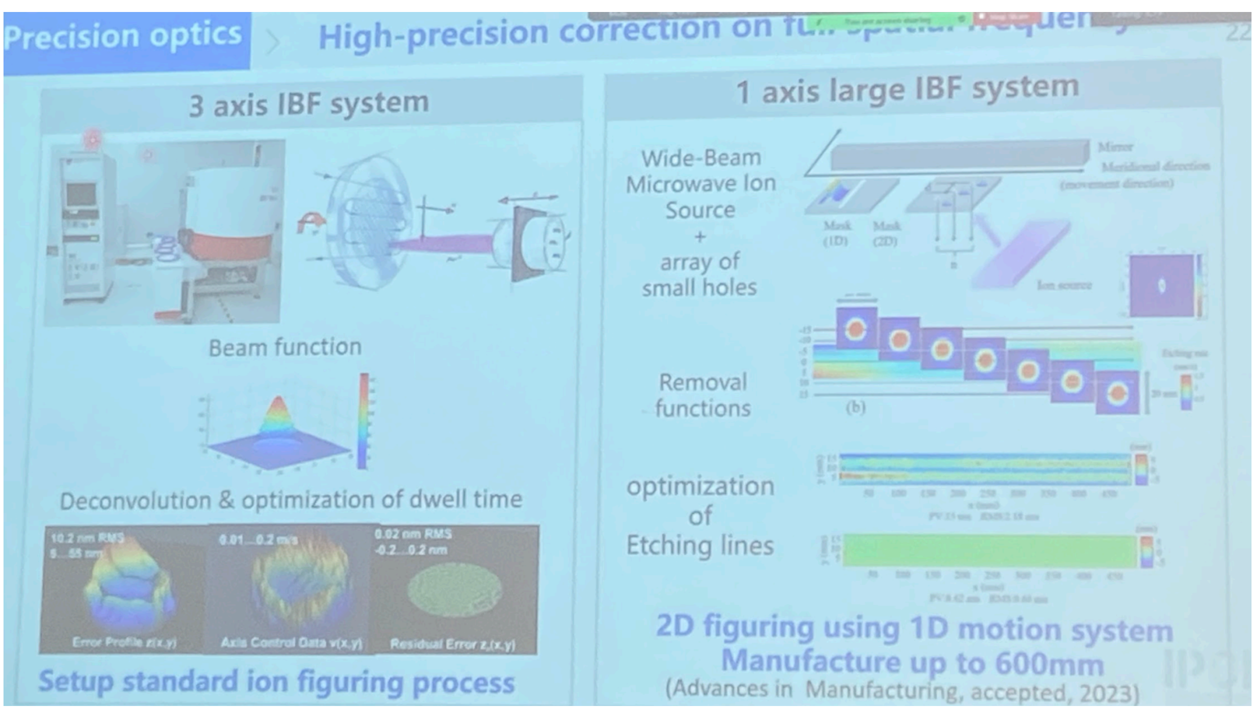
**Analysis**

*Scientific analysis produced by American scientists with:*

- *30+ years of expertise in X-ray optics, metrology, and* [redacted]*. Previously designed key optics and optical infrastructure at U.S.* [redacted]
- *20+ years of expertise as an X-ray* [redacted] *physicist. Previously employed at U.S.* [redacted]

In the presentation, the authors showed they have the capabilities of producing X-ray mirrors with high precision. Also discussed was the procurement of commercial ion beam figuring (IBF) machines (see image below). It is important to note that, contrary to what is commonly needed for standard grazing incidence mirrors, they have also implemented a so-called 3D IBF system that is useful when normal incidence optics are needed. The use of 3D IBF is of interest because in traditional X-ray applications, people rarely care about 3D surfaces as the optics are mostly used in 2D. Whereas in the EUV applications, all of the optics are 3D.

In synchrotrons, you can find normal incidence mirrors (3D optics), but only for very long wavelengths or in the infrared spectrum. Mirrors used in this regime require shape errors on the order of 50 nm, if not 100 nm. It makes no difference if it is 100 or 1 nm. Therefore it makes no sense to develop 1 nm rms normal incidence optics, if not for very specific applications. The only application that requires this level of precision (that we can envisage) is ultra-high resolution EUV imaging with multilayer coatings e.g., EUV lithography.



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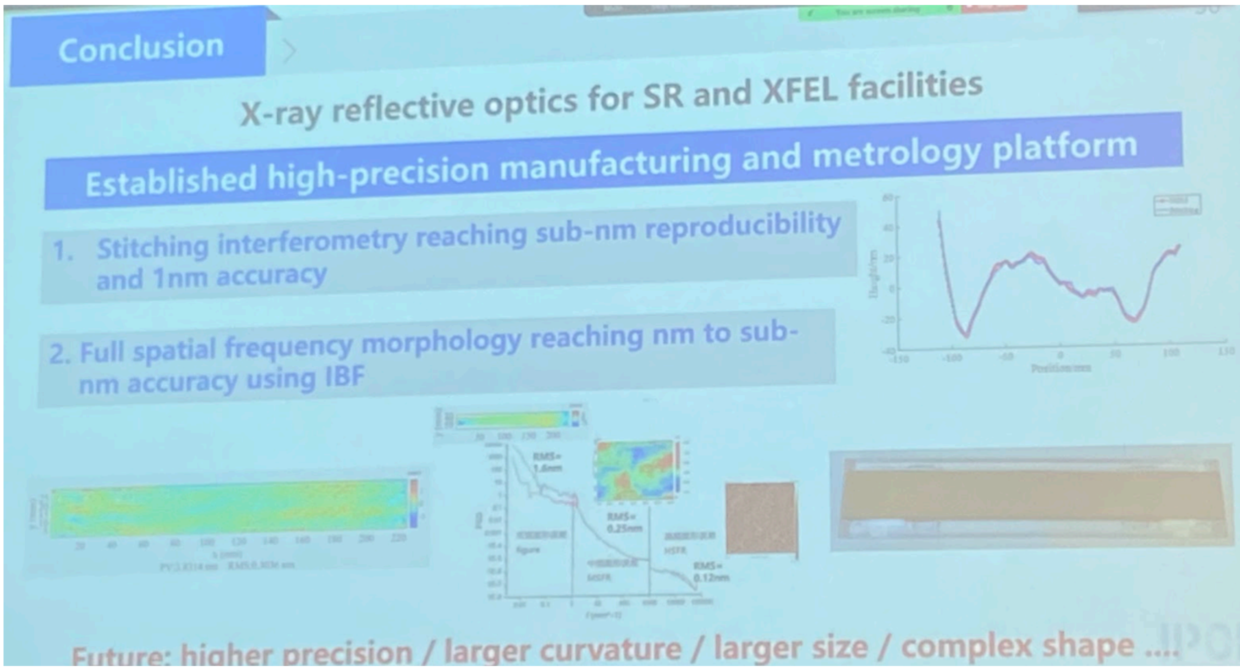
The most important bottleneck for mirror manufacturing is the metrology. Stitching interferometry is by far the most promising technique. They seem to have such capabilities (see image below). Stitching interferometry is something that has been widely developed at European Synchrotron Radiation Facility (ESRF) in France and DIAMOND Light Source (DLS) in the UK, and at SLAC National Accelerator Laboratory in the USA. Full spatial frequency morphology (the other method mentioned in the slide, to cover higher spatial frequency) is likely derived from work conducted in [redacted] (discussed below).




While the capabilities and results shown in this presentation are not yet at ZEISS levels, they are not very far away and are much farther along in competency than the widely held belief of the PRC's capabilities. The PRC is still two or three times away from the precision of ZEISS, but this gap is much smaller than previously believed.

There is a very large team (see image below) working on the two projects (polishing and metrology) in collaboration with two of the most advanced laboratories in Europe, Helmholtz-Zentrum Berlin (HBS) and DLS. HZB has a lot of competencies in standard metrology (not stitching) and calibration. HZB also has direct connection with Physikalisch-Technische Bundesanstalt (PTB), the national metrology institute of Germany, along with ZEISS. DLS is regarded as one of the best groups in the world at stitching metrology, as well as being highly capable at IBF techniques.


With their collaboration with DLS, the Tongji University group has access to two decades of R&D conducted in national laboratories and as a result, they have already produced nm-level mirrors and will likely produce sub-nm mirrors within a couple of years. Once they achieve sub-nm mirrors, they will have reached state-of-the-art quality, enabling an optical system on par with current and future EUV lithography machines.

**[redacted] collaborations of concern**

[redacted]

Below are the most relevant articles showing a collaboration for high quality mirror fabrication and metrology:

- https://opg.optica.org/oe/fulltext.cfm?uri=oe-30-10-16957&id=472452
- https://opg.optica.org/oe/fulltext.cfm?uri=oe-29-9-13388&id=450204
- https://iopscience.iop.org/article/10.1088/2515-7647/abbcd9

- https://www.sciencedirect.com/science/article/abs/pii/S0143816619305020?via%3Dihub
- https://opg.optica.org/oe/fulltext.cfm?uri=oe-29-10-15114&id=450657 [This is the most significant paper.]

The relevant PRC institutions involved [redacted] are:

- School of Mechanical and Automotive Engineering, Xiamen University of Technology, Xiamen
- School of Electronic and Optical Engineering, Nanjing University of Science and Technology, Nanjing
- Jiangsu Key Laboratory of Spectral Imaging & Intelligent Sense, Nanjing University of Science and Technology, Nanjing
- Smart Computational Imaging (SCI) Laboratory, Nanjing University of Science and Technology, Nanjing
- Jiangsu Key Laboratory of Spectral Imaging & Intelligent Sense, Nanjing

**Current applications to EUV lithography**

The current measured polishing capabilities are on the order of 1 nm rms (root mean square). Depending on the spatial frequencies they are able to control, the equivalent slope errors can go from 15 nanoradians (nrad) rms for large error periods, (e.g. affecting the dimensions of features) to 100 nrad for higher frequency errors (the most critical dimension affecting the diffusion of the light).

If we consider a copy of an 0.33 NA EUV scanner with a mirror of 300 mm in diameter positioned 0.6 m away from the wafer, with such a system, the minimum spot size achievable, limited by the optics is: 2 (factor of two due to reflection) x 15 nrad (slope errors) x 0.6m (focal distance) = 20 nm.

This means that a half pitch range of ~ 20 to 30 nm is possible with the mirror quality they have right now, spanning the 7 nanometer and 14 nanometer semiconductor nodes for a single exposure[1,2]. The single patterning half pitch resolution of EUV lithography is 13 nm, multiple-patterning techniques such as litho-etch-litho-etch enable patterning of denser pitches than would otherwise be possible with a single exposure. By employing multi-patterning techniques, a lithography tool with a single exposure half pitch resolution of 20-30 nm would be capable of reaching pitches required for advanced node production.

It is important to note that achieving 1 nm rms on a flat surface is much easier than achieving it on highly curved mirrors. Therefore, it is not necessarily a given that they can produce such curved mirrors with the required tolerances. But they clearly have a high potential of doing so and their progress thus far would indicate that they may soon cross this capability threshold[3].

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[1] https://en.wikichip.org/wiki/7_nm_lithography_process
[2] https://en.wikichip.org/wiki/14_nm_lithography_process
[3] Two recent articles from the author of the presentation:

- https://opg.optica.org/osac/fulltext.cfm?uri=osac-2-10-2783&id=418790
- https://opg.optica.org/oe/fulltext.cfm?uri=oe-31-10-16330&id=530277

In particular, the first paper refers to curved mirrors that are used in nanofocusing on FEL and synchrotrons but also relevant to EUV lithography machines.

**Conclusion**

China continues to make public demonstrable but often obfuscated progress towards EUV lithography independence.

Many visible efforts are underway within the PRC, ranging from developing laser-produced plasma sources to precision mechatronics. It is evident that there is a concerted effort to fill the gaps left by US export restrictions. While there is a lot of noise from these various efforts, it is crucial to differentiate what is succeeding in meaningfully advancing their goals, often against the popular narrative of China's lack of ability in this field.

To that end, we previously highlighted Huawei's highly credible work towards [redacted] capability gap. In this analysis, we have highlighted their rapid progress in mastering the art of creating precision X-ray optics designed for EUV lithography.

Industry estimates on the time required for China to possess advanced EUV lithography capabilities primarily rely on the belief that industrial EUV light sources and the precision X-ray optics required are solely under the ownership and mastery of European companies. The consensus is that replicating these engineering feats will take China well over a decade, if ever.

As of September 2023, the PRC has demonstrated the ability to produce EUV optics capable of being used in the production of advanced semiconductor nodes. China will likely have all the pieces in place by the middle of this decade for high-volume EUV lithography production.