Wavefront correction in the extreme ultraviolet wavelength range using piezoelectric thin films

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Abstract: A new scheme for wavefront correction in the extreme ultraviolet wavelength range is presented. The central feature of the scheme is the successful growth of crystalline piezoelectric thin films with the desired orientation on an amorphous glass substrate. The piezoelectric films show a high piezoelectric coefficient of 250 pm/V. Using wavefront calculations we show that the grown films would enable high-quality wavefront correction, based on a stroke of 25 nm, with voltages that are well below the electrical breakdown limit of the piezoelectric film.

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1. Introduction

Highly reflective multilayer mirrors (MLM) are key optical components for the extreme ultraviolet (EUV) wavelength range [1,2]. However, because all solid materials absorb strongly in the named wavelength range, EUV mirrors are easily subject to a significant heat load when high average powers are required. The associated temperature changes may impose severe distortions (aberrations) of the reflected wavefront which would reduce the optical performance. These distortions are generally non-uniform across the wavefront due to illumination conditions and may have magnitudes that are comparable to the operational wavelength [3–7]. To reach the intended optical performance it is essential to correct the wavefront distortions.

A technique that can perform this task is using adaptive optics based on deformable mirrors. In order to enable correction or shaping of the wavefront with fine resolution, the substrate of the deformable mirror has to be flexible, such as by using a thin membrane substrate with a reflective coating. An array of actuators at the backside adjustably deforms the membrane for removing the wavefront distortions in the reflected light [8–16]. At standard wavelengths, i.e., in the infrared or visible range, this approach has become a key solution to achieve diffraction limited resolution, e.g., in astronomy, vision or microscopy [17–20].

In the EUV range, where wavelengths are about two orders of magnitude shorter, the situation is quite different. Mechanical and thermal stability requirements scale with wavelength and easily reach into the sub-nanometer range. To provide such mechanical stability, the mirror substrates need to be chosen several centimeters thick. For achieving maximum thermal stability, amorphous glass materials with low coefficient of thermal expansion have to be chosen such as Fused Silica, Zerodur or Ultra Low Expansion (ULE) glass. However, choosing a substrate with high mechanical and thermal stability implies severe limitations for wavefront correction because the mirror surface cannot be deformed with fine resolution [21]. Recently, the residual expansion of thick Fused Silica glass substrates, driven by structured back-illumination with a heating light beam, has been utilized for wavefront correction [7]. This method indeed preserves the mechanical substrate stability but actuation becomes slow, about 0.1 nm/min [7], and the transverse resolution of actuation at the mirror surface is limited to several centimeters by heat conduction. Deformable mirrors for grazing incidence EUV optics have been realized based on controlled bending of the
substrate [22–29]. But this method is especially hard to apply to the thick mirror substrates that are used in normal incidence EUV optics, hence a novel approach is desirable. Such approach has to be based on thick and thermally passive glass substrates to preserve mechanical and thermal stability. Nevertheless a sufficient large stroke of at least a quarter of an EUV wavelength (corresponding to 3.4 nm for the application example that will be considered here) has to be provided in combination with sufficiently fine resolution across the reflecting surface [7].

Here we present a piezoelectric thin film approach that provides these features of a high stability, a large stroke and a fine resolution. We demonstrate the basic working of the approach by fabricating single thin film actuator segments, also called pixels (200 × 200 µm² area, and about 2 µm thick) with which we demonstrate a large stroke of 25 nm. The unique manner of achieving such large stroke is based on a crystalline piezoelectric film, lead zirconium titanate PbZrₓTi₁₋ₓO₃ (PZT) at an x = 0.52 composition, is deposited onto an amorphous glass substrate [30]. This choice of an amorphous glass substrate was made to show that our approach is compatible with the substrates normally used for EUV wavelengths that need to be made from amorphous glass. We note that, so far, all attempts to grow piezoelectric films on amorphous glass had resulted only in disordered polycrystalline films, which weakens or disables the piezoelectric response [27,31–37].

The main breakthrough we report here is that we obtain a stroke of 25 nm, which is well above the desired quarter-wavelength stroke of 3.4 nm by achieving, growth of crystalline piezoelectric films with desired (100)-orientation on amorphous glass substrates [30]. We note that the stroke of thin film piezoelectric actuators is not simply given by the intrinsic piezoelectric coefficient of the film material as if it were present in the bulk form. The reason is, as known from previous investigations of piezoelectric thin films [38–50], that the thin film is clamped by the underlying substrate. Qualitatively this leads to a reduction of the stroke if the transverse size of the thin film pixels is smaller than the thickness of the substrate. Predicting quantitative values needs a detailed modeling of the strain distribution. In the context of wavefront correction this raises the question whether a piezoelectric film of given pixel size still yields the required quarter-wavelength stroke and, at the same time, provides sufficient resolution for the corresponding application.

In the following, we first describe the deposition of piezoelectric thin film and its patterning into pixels. We determine the required pixel size for applications at 13.5 nm using the parameters in [7]. The required pixel size is calculated by expressing typical types of wavefront distortion as Zernike polynomials [51] and using the Marechal criterion for the quality of correction in terms of the Strehl ratio [17]. Finally we present measurements at single pixels to determine the absolute piezoelectric response and show that our approach easily fulfills the quantitative requirements for wavefront correction in the EUV wavelengths.

2. Growth of piezoelectric films on glass substrates

The stack of layers we deposited on a glass substrate is comprised of a buffer layer and a piezoelectric layer sandwiched between two electrode layers as schematically shown in Fig. 1(a). We note that PZT grows in polycrystalline form without preferred orientation if directly deposited on the amorphous substrate. In order to induce crystalline growth with the desired (100)-orientation we first cover the glass substrate with a 1.5 nm thick buffer layer consisting of crystalline nanosheets. Such nanosheets have been successfully applied earlier by Nijland et al. for growing films with improved magnetic properties [52], and we have followed their recipe [30]. Next, we have grown a 200 nm thick conductive epitaxial LaNiO₃ (LNO) electrode layer. Besides serving as an electrode, the LNO layer also provides a crystalline template layer for crystalline growth of the piezoelectric layer [33,34,53]. In order to achieve a maximally strong piezoelectric response we selected PZT with PbZr₀.₅₂Ti₀.₄₈O₃ composition. The piezoelectric coefficient is known to increase with thickness and saturate above 1500 nm [54]. A PZT layer of approximately 2000 nm thickness was grown on the
LNO/Nanosheet/Glass structure to demonstrate our wavefront correction approach. An LNO layer with 100 nm thickness was deposited as the top electrode. In order to increase the electrical conductivity and provide a homogeneous electric field across the top electrode, subsequently a 100 nm thick Pt layer was deposited on the LNO electrode. A typical cross-sectional image of the layer stack recorded with a high resolution scanning electrode microscope (HR-SEM, Zeiss, MERLIN) is shown in Fig. 1(b). The SEM image shows well-defined columns as an indication of the successful crystalline growth. On top of the electrode we expect, in a next step, to deposit EUV-reflective MLM layers (which are amorphous) without major problems, because it is relatively easy to deposit amorphous layers on crystalline structures [55]. Finally, using standard UV photolithography the deposited film structure was segmented into single quadratic pixels of 200 × 200 μm² size as schematically shown in Fig. 1(a).

Fig. 1. (a) Schematic view of the film stack structured into a pixel. (b) Cross-sectional scanning electron microscope image of the crystalline piezoelectric actuator film stack deposited on a glass substrate.

3. Calculation of suitable pixel size

Providing crystalline piezoelectric films with (100)-orientation is known to maximize the piezoelectric response as compared to polycrystalline films [30]. But crystallinity is not the only parameter that affects the response. The piezoelectric response obtained with thin films in the direction of the surface normal (longitudinal response) depends also on the transverse, in-plane dimension of the deposited thin film pixel (named pixel size). The reason is that, upon expansion in the longitudinal dimension, the shrinking of the piezoelectric material is limited in the transverse dimension due to clamping to the underlying substrate, which reduces the effective piezoelectric response. The effect becomes more dominant with pixel sizes comparable to the substrate thickness, and a full quantification requires numerical modeling using the detailed mechanical parameters of the structure [38–50]. Clamping may be circumvented by choosing a pixel size that is either much smaller or much larger than the thickness of the substrate. However, small pixels increases the complexity of control and large pixels reduce the spatial resolution with which a wavefront can be corrected. This raises the question as to which size of pixels is required for wavefront correction and whether the stroke measured with a selected pixel size reaches the required value of quarter-wavelength.

In the following we calculate the pixel size that is required to correct a given wavefront distortion with sufficient quality. A standard way to express the strength and type of wavefront distortions is to expand them into Zernike polynomials, \( Z_n \), which yields a set of Zernike coefficients, \( a_n \). The magnitude of the Zernike coefficients indicate the strength of distortion, while the Zernike index, \( n = 1, 2, 3, \ldots \) where Zernike Fringe ordering is used [51], indicates the degree of complexity of the wavefront distortion. For definiteness and in view of its relevance for the considered EUV application at wavelength of \( \lambda_{\text{EUV}} = 13.5 \) nm, here we consider thermally induced wavefront distortions as expected for spatially non-uniform illumination [3–7]. For an exemplary mirror size of 20 cm diameter and 5 cm thickness it was found that the dominant orders of distortion are limited to about \( n = 20 \), while higher orders...
can be neglected. The maximum strength of wavefront distortion found was half a wavelength, i.e., $\lambda_{EUV}/2 = 6.8 \text{ nm}$ \cite{7}. The first four lowest-order coefficients (for tip, tilt and focusing) can be disregarded, i.e., $a_n = 0$ for $n = 1...4$, because correction can be achieved without a deformable mirror, simply by alignment of the optical components. Figure 2(a) shows an example of the lowest order distortion that needs correction with a deformable mirror, $Z_5$, which is an astigmatic deformation, in this case of a wavefront with 20 cm diameter. Since the presented wavefront correction approach is to be obtained in reflection, the stroke needed for compensation of a distortion of half a wavelength is a quarter wavelength ($\lambda_{EUV}/4 \approx 3.4 \text{ nm}$). Next we consider wavefront correction by a deformable mirror which comprises an array of thin film piezoelectric actuators with square shape and size $L$ (area $L^2$). To obtain the best correction, we vary the surface displacement of each pixel until the average wavefront distortion of the reflected light is minimized in each pixel. Figure 2(b) shows as an example the wavefront of Fig. 2(a) after correction for the case that a pixel size of $L = 4 \text{ cm}$ is chosen.

It can be seen that much of the astigmatism is removed in the chosen example. However, the quality of correction needs a quantification, such that it can be judged which pixel size is sufficient for the correction of Zernike distortions with orders of up to $n = 20$. To provide such quantification of correction quality we first take the corrected wavefront and calculate its point spread function (PSF) using numerical wavefront propagation. The PSF is the normalized intensity distribution that is achieved in an image plane when propagating light from a distant point source, here, after first having undergone distortion and then being reflected by the deformable mirror. The obtained PSF is then compared with the maximum achievable quality of a perfectly diffraction-limited wavefront, for which we use the Strehl ratio, $S$, which is defined as the peak ratio of the two PSFs. Finally we apply the Marechal criterion ($S > 0.8$) in order to check whether the distortion can be considered as well-corrected, i.e., whether the wavefront correction is of high quality \cite{17}.

An example of such calculation is shown in Fig. 2(c), which compares the PSF of the astigmatically distorted wavefront of Fig. 2(a) (green curve) and the PSF of the corrected wavefront of Fig. 2(b) (red curve) to that of the ideal diffraction limited PSF (blue curve). We have normalized the latter, ideal PSF to have its peak value at unity, such that the horizontal dashed line corresponds to a Strehl ratio of $S = 0.8$, above which the Marechal quality criterion is fulfilled. It can be seen that an array with 4-cm-sized pixels is able to correct the incident low-quality wavefront ($S = 0.65$) with high quality ($S = 0.93$).
Fig. 2. (a) Example of distorted wavefront, here, a 5th order Zernike-polynomial \( (Z_5, \text{astigmatism}) \) distortion with \( a_5 = \frac{\lambda_{\text{EUV}}}{2} = 6.8 \) nm amplitude and 20 cm diameter (b) The same wavefront corrected by reflection at a deformable mirror comprising an array of \( 4 \times 4 \) cm\(^2 \) square segments (pixels) made of thin film piezoelectric material. (c) Point spread function (PSF) calculated for the distorted wavefront (green, peak height \( S = 0.65 \)), after correction with the array of \( 4 \times 4 \) cm\(^2 \) pixels (red, peak height \( S = 0.93 \)) and the ideally corrected, diffraction limited wavefront (blue line, \( S = 1 \)). The horizontal dashed gray line corresponds to a Strehl ratio of \( S = 0.8 \) above which wavefront correction is generally considered as of high-quality.

As in the shown example for \( Z_5 \), we have calculated the quality of correction for the relevant higher order Zernike distortions, i.e., from the \( Z_6 \) to \( Z_{35} \) using the same initial strength of distortion, \( a_6 = \frac{\lambda_{\text{EUV}}}{2} \), in which we have stepwise varied the size of the square pixels, \( L \). Figure 3 summarizes the results for \( L = 4 \) cm, 2 cm and 1 cm pixel sizes. It can be seen that the Strehl ratio increases with decreasing pixel size, i.e., with finer resolution of the correction, as expected. Starting from values as low as \( S = 0.4 \) for \( Z_9 \) the Strehl ratio reaches the Marechal quality criterion (values above \( S = 0.8 \)) for all the Zernike polynomials up to \( Z_{20} \), when a pixel size of 2 cm and smaller is used.
Fig. 3. The Strehl ratio for aberrations in the shape of Zernike polynomials with a strength of $a_r = \lambda_{\text{EUV}}/2 = 6.8 \text{ nm}$ is shown for four different cases: before the correction and after the correction with a deformable mirror having a pixel size of $L = 4 \text{ cm}$, $2 \text{ cm}$ or $1 \text{ cm}$. The Marechal criterion (Strehl ratio above $S = 0.8$) that proves high correction quality is indicated with dashed gray line.

4. Measurement of piezoelectric response

Having calculated the required size of the thin film piezoelectric pixels with which high-quality EUV wavefront correction is possible, the remaining step is to verify that the fabricated films are capable to provide a stroke of at least the required stroke of 3.4 nm. The stroke is given by the product of the thin film piezoelectric coefficient in longitudinal direction ($d_{33,f}$), which is also named as effective piezoelectric coefficient, and the maximum applicable voltage as limited by electrical breakthrough. As mentioned in Sec. 3, the effective piezoelectric coefficient in thin films depends on the pixel size due to clamping to the substrate. A closer look reveals that the absolute value of the effective piezoelectric coefficient does not depend on the absolute size of the pixel, $L$, but only on the ratio of the pixel size to the substrate thickness, $T$, i.e., on $\eta = L/T$ [42,48,50]. We used finite element modeling [56] to find the value of $\eta$ where the clamping effect is strongest, i.e., at which value of $\eta$ the effective piezoelectric coefficient is smallest. This value corresponds to finding the worst case and guarantees that all other values for $\eta$ will provide at least as good or much better piezoelectric response. Our modeling revealed that the clamping is strongest and the piezoelectric coefficient reaches its minimum around a ratio of $\eta = 0.4$ [48]. We have realized this ratio in our experiments by using samples with $L = 200 \mu\text{m}$ and $T = 500 \mu\text{m}$.

For measuring the longitudinal piezoelectric response of a pixel, an alternating voltage was applied at a frequency of 8 kHz. The surface displacement was recorded with a laser Doppler vibrometer (Polytec, MSA-400, with longitudinal resolution of 20 pm at 8 kHz) [57]. The laser spot size used was approximately 5 μm which defines the transverse spatial resolution. The spot was scanned across the pixel in order to determine the local surface...
displacement. An example of the typical measured piezoelectric response, expressed as piezoelectric coefficient, is shown in Fig. 4. It can be seen that the measured piezoelectric coefficient is very large, around $d_{33,f} = 250 \text{ pm/V}$, to our knowledge a record value for piezoelectric thin films on glass substrates. Typically, the piezoelectric coefficient shows a small variation with the temperature. Considering a realistic scenario in which the temperature varies by few degrees [7], the change in the piezoelectric coefficient is below 1% [58], which can be safely neglected.

![Fig. 4. Measured effective longitudinal piezoelectric coefficient, $d_{33,f}$, of the PZT film for 200 μm pixel size. Gray dashed line is shown as a guide to the eye.](image)

The voltage $V$ required to achieve a stroke of a quarter-wavelength, $\Delta T = 3.4 \text{ nm}$, can be calculated by dividing the stroke by the measured piezoelectric coefficient. This calculation yields a value of $V = \Delta T / d_{33,f} = 13.5 \text{ V}$ for achieving the required wavefront correction.

It is important to note that this value of 13.5 V is, actually, a relatively small value which can be seen as follows. In order to determine the maximum possible stroke that can be achieved with our piezoelectric films, the maximum applicable voltage needs to be determined. We measured the maximum applicable voltage ($V_{\text{max}}$) and found that up to 100 V can be applied, repeatedly without any damage. At voltages higher than 100 V electrical breakdown occurred. This maximum voltage indicates that our film can achieve a high stroke of $\Delta T_{\text{max}} = V_{\text{max}} \times d_{33,f} = 25 \text{ nm}$. With such high stroke, wavefront correction and shaping is certainly feasible for EUV application at 13.5 nm wavelength, and obviously even at longer wavelengths reaching 100 nm.

5. Summary and conclusion

In summary, we have demonstrated the basic feasibility of a novel approach for wavefront correction in the EUV wavelength range based on crystalline piezoelectric thin films grown on amorphous glass substrates. The importance of this particular combination is that a sufficiently large stroke is provided by the film while a high mechanical and thermal stability can be provided by the thick and low thermal expansion glass substrates. Via expressing the typically expected wavefront distortions in terms of Zernike polynomials, we used wavefront calculations to determine the pixel size required for high-quality wavefront correction. The grown crystalline films showed a record-high piezoelectric coefficient, $d_{33,f} = 250 \text{ pm/V}$ measured at a pixel size that is relevant for EUV lithography. With such high piezoelectric coefficient, the quarter-wavelength stroke required for wavefront correction at a wavelength of 13.5 nm can be easily achieved with voltages (13.5 V) that are much lower than the measured voltage limit (100 V) given by electrical breakthrough. These results show that the presented wavefront correction approach using crystalline piezoelectric films on amorphous glass substrates is of high relevance for EUV wavefront correction and shaping. The approach...
can be of interest for other wavelengths and applications such as interferometry or astronomy with appropriate scaling.

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