Nanoscale piezoelectric surface modulation for adaptive XUV and SXR optics

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Extreme ultraviolet and soft X-ray wavelengths have ever-increasing applications in photolithography, imaging, and spectroscopy. Adaptive schemes for wavefront correction at such a short wavelength range have recently gained much attention. In this letter, we report the first demonstration of a functional actuator based on piezoelectric thin films. We introduce a new approach that allows producing a gradually varying surface deformation. White light interferometry is used to show the level of control in generating arbitrary surface profiles at the nanoscale. © 2019 Optical Society of America

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Extreme ultraviolet (XUV) and soft X-ray (SXR) wavelengths are used for a wide range of applications in microscopy [1], spectroscopy [2], space research [3], and photolithography [4]. For this very short wavelengths range (1 to 40 nm [5]) reflective multilayer mirrors (MLM) are key optical elements [6, 7]. An MLM consists of a periodic layer structure, which enables high reflectance by constructive interference of the reflection from different interfaces based on the Bragg law. For instance, the reflectance values are in the range of 70% for the best MLMs in the 13.5nm wavelength range [6]. The remaining radiation is inevitably absorbed in the MLM resulting in heat load and consequently leading to surface temperature gradients and non-uniform surface displacements. These non-uniform and time dependent surface displacements can cause wavefront aberrations on the reflected light, limiting the imaging resolution. Therefore, adaptive MLMs are needed to compensate the aberrations in order to reach the theoretical diffraction limited resolution in the optical systems.

There are two types of adaptive MLM schemes reported in the literature. The first type has the actuator at the back side of the substrate. Examples for this actuator type are thermo-mechanical actuators glued to the rear of the substrate [8], and piezoelectric film coated on the back side of thin substrates [9]. In these approaches the entire substrate deforms. This imposes a limit on the thickness of the substrate and the spatial resolution of the surface deformation. In some applications like photolithography, thick substrates are needed in order to provide

Fig. 1. Schematic cross-section of an adaptive multilayer mirror based on a piezoelectric actuator on the mirror side; the layers and their functions are explained in the text.

a high mechanical stability. Hence, Saathof *et al.* [10] proposed adaptive MLMs based on thermal actuation of a heat absorbing layer coated under the MLM using a spatially extended heat source. However, this scheme and other thermal actuation methods [11] offer low actuation speed.

An approach based on piezoelectric films on the mirror side provides fast and direct actuation of the mirror surface. It also allows surface deformation with very high spatial resolution, and utilizing thick substrates is viable in this approach. The very short wavelength of operation necessitates high degree of control in the adaptive MLMs, which can be achieved by piezoelectric actuators. We have previously introduced an adaptive MLM based on piezoelectric films [12]. In that work, we demonstrated growth of piezoelectric films with sufficiently high piezoelectric coefficient and electrical breakdown strength, enabling their usage in the adaptive MLMs. Yet, the resulted surface deformation was step-like and discrete. Such step-like surface figure requires large number of electrodes to correct for aberrations that are typically smoothly varying, and it limits the wavefront correction quality.

In this letter, we present the first demonstration of a piezoelectric based functional actuator intended for wavefront correction at XUV and SXR wavelengths. First, we show how the actuator is capable of producing gradually varying surface deformation evidenced by the measurements with white light interferometry (WLI). Then, we demonstrate the steering of arbitrary surface

Fig. 2. (a) Schematic drawing of a piezoelectric actuator with continuous bottom electrode and discrete top electrodes/pixels (in red); for simplicity, only three pixels are shown. The density of arrows represent the strength of the electric field when voltage V is applied to the pixel in the center. (b) Schematic drawing of a piezoelectric actuator with a resistive "mediation layer" deposited on the PZT film (in green). When voltage V is applied to the middle pixel, current I flows through the mediation layer, causing a gradually changing electric field strength in the piezoelectric film. (c) Schematic representation of the voltage distribution in (a) and (b) shown by the dashed and solid lines, respectively.

profiles, and we discuss the future potential of the piezoelectric based adaptive MLMs.

The adaptive MLM is consisted of several films deposited on a substrate, and the basic layer structure is shown in Fig. 1. Two main components of the adaptive MLM are the piezoelectric actuator for surface deformation, and the MLM for high reflection at XUV and SXR wavelength. The piezoelectric film is sandwiched between two electrodes. The top electrode is structured into a number of pixels to allow local control of the surface displacement. Additional layers of wiring and isolation are needed to individually power each pixel. The deposition of the MLM requires a sub-nanometer smooth surface. This requirement can be addressed by deposition and polishing of a layer called "smoothing" layer prior to the MLM deposition.

By structuring the top electrode into discrete pixels as shown in Fig. 2(a), the applied voltage and consequently the surface displacement can be controlled independently for each electrode/pixel. This is described as the "structured top electrode" in Fig. 1. The discrete structuring results in abrupt changes of the applied voltage (and displacement) as shown in Fig. 2(c). The dashed line represents the applied voltage to the middle pixel in

Fig. 2(a). As a result, the displacement is zero over the surface, except for that pixel.

Now, we explain how a gradually varying displacement can be produced by introducing a resistive layer between the pixels. We call this layer "mediation layer" and show it on the PZT film with green color in Fig. 2(b). When a voltage (V) is applied to the middle pixel and the neighbouring pixels are grounded, a current passes through the mediation layer, and the voltage on the points between the middle and the neighboring pixels varies continuously. Consequently, the corresponding electric field strength in the piezoelectric film and the resulting displacement varies gradually. The voltage distribution between the pixels can be calculated as follows. In a realistic scenario, each pixel is surrounded by six pixels in a hexagonal grid as shown in Fig. 3(b). We approximate the surrounding pixels as a continuous ring around the middle pixel. In this concentric geometry, where the middle pixel is at voltage V , and the surrounding pixels are at 0 V, the voltage from the middle pixel to the outer ring decreases logarithmically as shown with the solid line in Fig. 2(c). The amount of vertical displacement at each point of the mediation layer depends on the local voltage and the piezoelectric coefficient in the direction of the applied electric field, called d_{33} , which is a function of the applied field.

A desired surface profile can be generated by correctly choosing the shape and the distance of the pixels. Note that the displacement does not depend on the mediation layer sheet resistance assuming a uniform sheet resistance, and no leakage current via the mediation layer and the piezoelectric layer underneath. However, the mediation layer sheet resistance needs to be optimized to the specific application requirements. In this work, we only qualitatively discuss the effect of a mediation layer. Too low sheet resistance can result in a high current within the mediation layer, and therefore, it can cause high parasitic heat loss. On the other hand, too high sheet resistance can result in a low response time of the device. With the resistor-capacitor (RC) circuits in the piezoelectric actuator design, the time constant $\tau = RC$ is higher for high mediation layer sheet resistance.

To demonstrate the capability and surface displacement of the piezoelectric actuator for XUV and SXR wavefront correction, we fabricated devices with the layer structure presented in Fig. 3(a). The electrodes (LaNiO_3 , LNO) and the piezoelectric layer ($\text{PbZr}_{1-x}\text{Ti}_x\text{O}_3$, PZT) were grown by pulsed laser deposition (PLD) using a KrF excimer laser (Lambda Physik, 248 nm, 20 ns) on platinized Si substrate ($\text{Pt}/\text{Ti}/\text{SiO}_2/\text{Si}$). A 4 μm PZT film is used for this study. The growth of the LNO top electrode was optimized in order to reach the sheet resistance values of 500-2500 $\Omega/\square$ needed for the mediation layer in this work. The resistivity of the LNO film was tuned by varying the growth parameters such as the background oxygen pressure and the growth temperature [13]. Hence, the top LNO layer is functioning both as the top electrode and as the mediation layer. Then, twenty-three equidistant Pt pixels were deposited on the mediation layer by DC magnetron sputtering, and structured using photolithography and lift-off technique. The pixels have a diameter of 80 μm and patterned in a hexagonal grid with a 800 μm distance between pixels.

Next, We patterned the mediation layer to a region with a diameter of 5.4 mm at the center of the sample as shown in Fig. 3(b). In order to deposit the wires, first, a 600 nm SiO_2 isolation layer was deposited over the entire area of the sample by Plasma Enhanced Chemical Vapor Deposition (PECVD). The top of the pixels were etched, followed by the deposition of the wires and the contact pads based on the schematic layout shown in

Fig. 3. (a) Schematic layer structure, (b) top-view, and (c) photo of the piezoelectric actuator. The cover layer and the top Pt film are only depicted in the layer structure.

Fig. 3(b). The photo in Fig. 3(b) shows the device after the deposition of wires and contact pads. Note that the peripheral pixels are interconnected to provide the same boundary condition for the 15 inner pixels.

We measured the surface profiles by WLI. To prepare the samples for the measurements, an isolation layer called "cover layer" was deposited on the wires. Then, a thin Pt film was deposited on the cover layer to improve the signal to noise ratio and the optical contrast. Note that the cover layer is not a smoothing layer as depicted in Fig. 1, but it is only needed for the WLI measurement. The contact pads were then connected to a multichannel power supply, i.e. the power supply had independent output channels to each of the pixels. Two contact pads that are not wired to the top pixels were connected to the bottom electrode. The WLI image measured at zero volts is subtracted from the WLI image produced when the desired power is applied to the pixels.

First, we examine the case where all the pixels except one are at 0 V. Fig. 4(a) shows the surface profile around the pixel that is powered with values in the range 0 to 30 V. In the center of the pixel where Pt is directly deposited on LNO, the applied voltage is constant over the area of the pixel; thus, the pixel displacement is nearly constant on the pixel at a value of 7 nm for 30 V. In the surrounding of the pixel, we observe a gradually decreasing displacement that eventually becomes zero at the next nearest pixels with zero potential. This behavior is expected because of the mediation layer effect. The same displacement of 7 nm was also measured for a different sample without the thick isolation and wiring overlays. Therefore, we can expect no drop in the displacement for an adaptive mirror device containing the MLM overlay.

Fig. 4(b) shows the voltage dependency of the average displacement of the top of the powered pixel. Note the small non-linearity in the displacement, which could be due to electrostrictive

Fig. 4. (a) Line profiles of a single pixel powered at different voltages showing that the displacement increases with increasing voltage on the pixel as well as the area around it. The inset shows the three dimensional surface profile of a pixel at 30 V (b) Voltage dependent displacement and a linear fit to the data.

tion and contribution of non-180 degree domains as explained in [14]. A linear fit to the data results in a d_{33} of 219 pm/V for the sample, which is sufficiently high for this work. However, it has been demonstrated that the d_{33} can be enhanced significantly by using nanosheet buffer layer instead of platinized Si substrate [15, 16]. It is also known that by controlling the void fraction in the piezoelectric film the *effective* d_{33} can be enhanced significantly [17].

Next, we examine the generation of different surface profiles by applying various voltages to different pixels. Fig. 5(a-d) shows four different surface profiles as examples of what is possible with the piezoelectric actuator. The color scale represents values from -2 nm to +6 nm. In all the surface profiles, surface displacement is constrained in the mediation layer region with a diameter of 5.4 mm as expected. Outside the active region there is no pixel or mediation layer, and therefore the surface displacement could not be varied and controlled. The four corners of the profiles were outside the optical field of WLI and could not be measured. Note that the imprint of the wires is visible in all of the profiles. The wire imprint is not a real surface displacement but a measurement artifact for two reasons: first, the imprint was observed even in the case where all pixels were powered at 0 V (not shown). Second, the isolation layer was sufficiently isolating the wires from the mediation layer, and the wires were not electrically connected to the mediation layer; only the pixels were powered. The wire imprint was measured as a result of a combination of non-uniform thickness caused by the wire thickness, and an unavoidable sample drift between the main and the baseline measurements. Also note that the noise in Fig. 4(a) was due to the same measurement artifact.

In Fig. 5(a) the voltages were increased radially from 0 V to 21 V with intermediate values of 10 V and 17 V. As can be seen

Fig. 5. (a-d) Generation of surface profiles performed by varying the applied voltages on the pixels: Four surface profiles demonstrating the capability of steering surface profiles. The color scale represents displacement values from -2 nm to +6 nm. (e) Three line profiles for the lines shown in (d).

the result is a radially changing displacement. Another pattern is shown in Fig. 5(b). In this surface profile, all pixels except four were powered at 10 V: the two pixels that are still in blue were at 0 V, and the two red pixels were at 25 V. Fig. 5(c) and (d) were made opposite to each other. In these two profiles, three pixels were powered at 25 V, three pixels were at 0 V, and the rest of the pixels were powered at 10 V.

Further details of the surface profile can be seen from the three line scans shown in Fig. 5(e) that were made from the surface profile in Fig. 5(d). Line 1 passes through the two pixels that were powered at 25 V. These two pixels have a maximum displacement of nearly 6 nm. In between these two pixels, the displacement reaches a lower value of nearly 1.3 nm. This amount is slightly lower than the expected displacement for 10 V (1.7-1.9 nm) just because there is another pixel at 0 V in its vicinity. The second line profile passes through the middle of the sample where the effective applied voltage is nearly the same across the line. Thus, the displacement in the second line profile is nearly constant along the entire diameter. Finally, the third line profile passes through two pixels that are at 0 V, resulting in no displacement on the two pixels. Again, between these two

pixels, the displacement nearly reaches the value for 10 V.

In summary, we have fabricated for the first time a piezoelectric based functional actuator with gradual surface modulation intended for wavefront correction at XUV and SXR wavelengths. The surface manipulation was performed by independently controlling the voltage of a pixels array. We demonstrated the generation of gradually varying surface profiles by including a resistive mediation layer on the piezoelectric film and in-between the pixels. The mediation layer was capable of producing a continuously varying voltage profile between the pixels. We demonstrated nm-scale displacement suitable for nm-scale corrections of optics for XUV and SXR wavelengths. Nevertheless, the method can potentially provide a high level of actuation up to a few tens of nanometer suitable for the vacuum ultraviolet.

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