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# Active multilayer mirrors for reflectance tuning at extreme ultraviolet (EUV) wavelengths

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## Abstract

We propose an active multilayer mirror structure for extreme ultraviolet (EUV) wavelengths, which can be adjusted to compensate for reflectance changes. The multilayer structure tunes the reflectance via an integrated piezoelectric layer that can change its dimension due to an externally applied voltage. Here, we present design and optimization of the mirror structure for maximum reflectance tuning. In addition, we present preliminary results showing that the deposition of piezoelectric thin films with the requisite layer smoothness and crystal structure is possible. Finally piezoelectric coefficient measurement ( $d_{33} = 60 \text{ pm V}^{-1}$ ) of the film is presented.

(Some figures may appear in colour only in the online journal)

## 1. Introduction

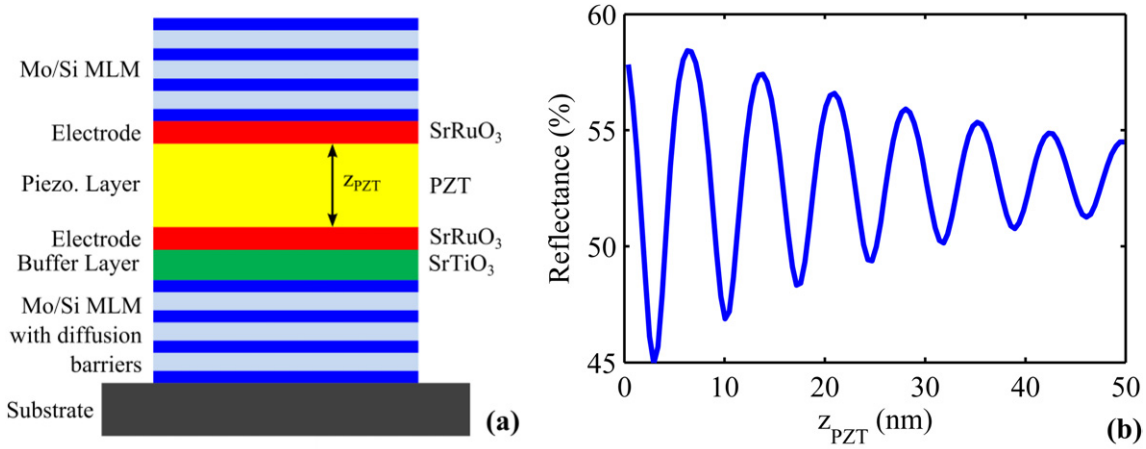
Multilayer mirrors (MLMs) are commonly used at extreme ultraviolet (EUV) and x-ray wavelengths because their high reflectance near normal incidence operation allows high numerical aperture imaging systems. MLMs find applications in astronomy [1, 2], microscopy [3, 4], spectroscopy [5], lasers [6] and next generation EUV lithography (EUVL) systems [7], the latter being the main driving force of the field. MLMs for EUVL systems are fabricated by depositing many pairs of Mo and Si layers such that the Bragg condition is satisfied at normal incidence for a wavelength of 13.5 nm [8]. Maximum reflectance is achieved, typically, when the period of the Mo/Si bilayer is 6.9 nm and the thickness of the Mo is 40% of the bilayer period. For such thin films, roughness, diffusion,

compound formation in the Mo/Si interface and crystallization are the dominant factors affecting the final reflectance of the mirror [9–12].

The reflectance of Mo/Si mirrors are typically 69.5%, which can be increased up to 70.3% by integrating diffusion barriers and reflectivity enhancing layers into the MLM stack [13, 14]. However, even at its best, 30% of the incoming light is absorbed by the mirror, creating significant heat load, which may, under extreme conditions, cause some changes of the bilayer period and degradation of the reflectance with time. Since the mirror is not usually evenly illuminated, the mirror performance does not degrade uniformly. In this paper, we present the design and preliminary experimental results for a new active MLM structure. An integrated piezoelectric layer that can change its dimension via external voltage separates two MLMs. The interference between the waves reflected from the bottom and top stack can, thereby, be adjusted to increase or reduce the reflectance. Small independent regions can be patterned during deposition of the active MLM on



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**Figure 1.** (a) The MLM structure was designed by placing an active piezoelectric layer, along with the necessary electrodes and buffer layer, between two Mo/Si MLMs. (b) Reflectance of the active MLM as a function of piezoelectric layer thickness.

**Table 1.** Parameters used in the simulation. Bulk density and out-of-plane lattice constant values are taken from ICDD database [22].

Parameter	SrTiO <sub>3</sub>	SrRuO <sub>3</sub>	PbZr <sub>0.2</sub> Ti <sub>0.8</sub> O <sub>3</sub>	Top MLM	Base MLM
Density (g cm <sup>-3</sup> )	5.117	7.058	7.376		
Out-of-plane lattice constant (Å)	3.91	3.95	4.19		
Thickness (nm)	19.55	19.75	Variable		
Number of bilayers				24	55
Reflectance (%)				40.4	51.3
Absorption (%)				25.4	33.7

large substrates to make local reflectance adjustments. In section 2, details of the active MLM and the simulation of its reflectance using the IMD software package are explained [15]. In section 3, the reflectance tuning range, the effect of active layer thickness and the absorption are explained. In section 4, the first fabrication results of the active piezoelectric films using pulsed laser deposition (PLD) are presented.

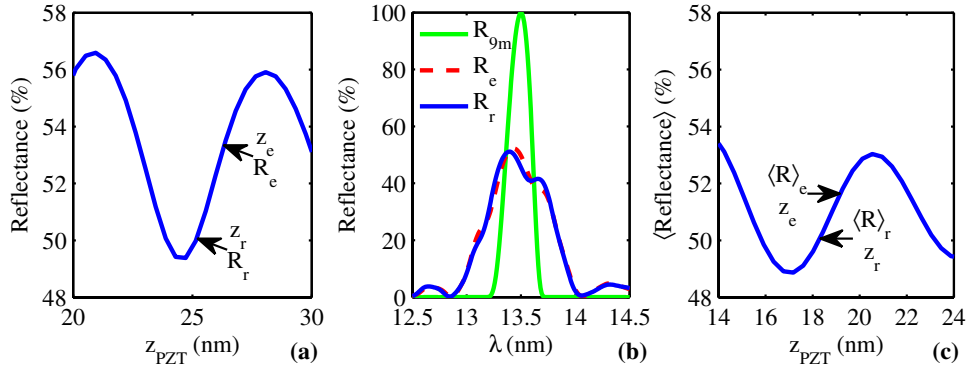
## 2. Active MLM structure

The active MLM structure was designed by integrating an active layer between two Mo/Si MLMs, as shown in figure 1(a). The structure is defined from bottom to top as (a) base Mo/Si MLM stack, (b) buffer layer, (c) electrode/piezoelectric layer/electrode heterostructure and (d) the top Mo/Si MLM stack. The top layer of the base Mo/Si MLM stack is amorphous; therefore, a buffer layer is needed to provide a template for the deposition of the crystalline heterostructure [16, 17]. The buffer layer and the heterostructure are deposited at elevated temperatures (600 °C) to restrict the growth of the amorphous phase. Therefore, more chemically stable MLMs with diffusion barriers replace the standard Mo/Si MLMs as the base MLM stack [18–21]. In the simulation, SrTiO<sub>3</sub> (STO), SrRuO<sub>3</sub> (SRO) and PbZr<sub>0.2</sub>Ti<sub>0.8</sub>O<sub>3</sub> (PZT) were used as the buffer, electrodes, and piezoelectric layers, respectively. The layer thicknesses are limited to integer multiples of the out-of-plane lattice parameters, which are 3.91 Å, 3.95 Å and 4.19 Å for STO, SRO and PZT, respectively. The thickness of the buffer layer and the electrodes are taken as 50 unit cells, which corresponds to

19.55 nm and 19.75 nm, respectively, as listed in table 1. In figure 1(b), the reflectance of the active mirror with respect to the piezoelectric layer thickness is plotted for monochromatic 13.5 nm light at normal incidence for 24 and 55 bilayers at the top and the base MLMs, respectively. The reflectance and the absorption of the top and base MLM stacks are listed in table 1. The reflectance curve is described by the principles of a lossy Fabry–Perot interferometer. When the active mirror is illuminated from the top, light waves are partially absorbed and partially reflected from the top and the base MLMs in which separation between them determines the phase difference between the reflected waves and, therefore, the total reflectance of the mirror for monochromatic light. In this design, the contrast of the interference between reflected waves, shown in figure 1(b), decreases as the piezoelectric layer thickness increases, due to the increasing absorption of the piezoelectric layer.

## 3. Reflectance tuning range

In order to explain the reflectance tuning in more detail, a reflectance value for the relaxed structure is chosen to be  $R_r = 50\%$  corresponding to a layer thickness around  $z_r = z_{PZT} = 25$  nm as shown in figure 2(a) (As can be seen in figure 1(b),  $R_r = 50\%$  occurs for multiple layer thickness values; finding the optimum layer thickness is explained at the end of this section). Denoting the maximum strain of the piezoelectric layer as  $\epsilon$ , the thickness of the layer can be increased up to  $z_e = (1 + \epsilon) z_r$  and the reflectance value at this layer thickness will be the reflectance value of the extended



**Figure 2.** (a) Reflectance tuning for a monochromatic source. Reflectance of the active mirror can be increased from  $R_r$  to  $R_e$  by applying a voltage and increasing the thickness of the piezoelectric layer from  $z_r$  to  $z_e$ . (b) Reflectance curves of an active mirror at its relaxed ( $R_r$ ) and extended state ( $R_e$ ) and the reflectance curve of nine Mo/Si MLMs ( $R_{9m}$ ) when they are illuminated with a broadband source having a power spectrum that has uniform distribution in the range 12.5 and 14.5 nm. The tuning range for the integrated reflectance for a single active mirror is minor, but, when the number of MLMs in the optical system increases, the cascaded mirrors have a filtering effect and only central part of the spectrum around 13.5 nm is reflected, significantly improving the tuning range. (c) Normalized integrated reflectance of the active mirror can be increased from  $\langle R \rangle_r$  to  $\langle R \rangle_e$  by applying a voltage.

mirror  $R_e$ . For the parameters given in table 1, a reflectance tuning close to  $\Delta R = 4\%$  is achieved for a maximum strain of  $\varepsilon = 5\%$ . The change in the reflectance with respect to piezoelectric layer thickness is shown figure 2(a). Here,  $\varepsilon = 5\%$  is taken to clearly show the reflectance tuning, but, reflectance tuning for more realistic  $\varepsilon$  values will be discussed at the end of this section.

Although it is instructive to explain the reflectance tuning process using monochromatic sources, broadband light sources are also used in optical systems. Assuming a light source with a power spectrum that is uniform in the range 12.5 and 14.5 nm, the reflectance spectrum of the mirror in its extended and relaxed states is shown in figure 2(b). The change in the integrated reflectance between the extended and relaxed states is relatively small. On the other hand, assuming an optical system with ten mirrors, in which for instance only one of the mirrors is active, a significant reflectance tuning can be obtained because of the narrow spectrum caused by the reflection from the nine mirrors. The normalized reflectance spectrum after nine mirrors,  $R_{9m}$ , is shown in figure 2(b). In order to see the effect of the broadband source on the reflectance tuning range and to make it comparable to the reflectance tuning range for the monochromatic source, integrated reflectance must be normalized. Here we define normalized integrated reflectance as

$$\langle \text{Reflectance} \rangle = \frac{\int_{\lambda} R(\lambda, z_{PZT}) d\lambda}{\max \left\{ \int_{\lambda} R(\lambda, z_{PZT}) d\lambda \right\}} \times \max \{ R(\lambda_0, z_{PZT}) \}, \quad (1)$$

where  $\lambda_0 = 13.5$  nm. The normalized integrated reflectance is plotted in figure 2(c). The normalized integrated reflectance tuning range for  $\varepsilon = 5\%$  is close to  $\langle \Delta R \rangle = 2\%$ , which is lower than the reflectance tuning range for a monochromatic source.

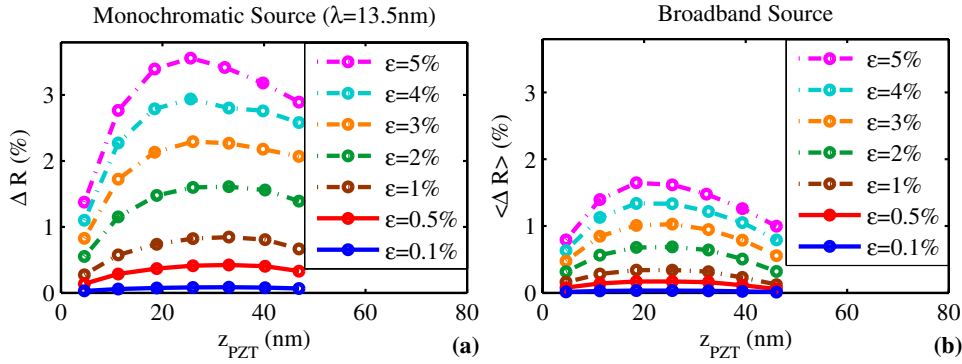
Up to now, the reflectance tuning has been calculated for the layer thickness parameters given in table 1, but, as can be seen from figure 1(b), the relaxed reflectance value ( $R_r$ ), can be satisfied for multiple piezoelectric layer thicknesses. Limiting

ourselves to regions with a positive change in reflectance with respect to increasing thickness, the maximum reflectance tuning has been calculated for multiple piezoelectric layer thicknesses. In figure 3, optimum reflectance tuning ranges ( $\Delta R$ ), for different piezoelectric layer thicknesses ( $z_{PZT}$ ) and different maximum piezoelectric responses ( $\varepsilon$ ), are plotted for monochromatic and broadband sources where the piezoelectric layer thicknesses corresponding to  $R_r$  are shown with markers. For both sources, when the piezoelectric layer thickness is below 15 nm, the dimension change of the piezoelectric layer is not sufficient to cause enough reflectance tuning. On the other hand, when the piezoelectric layer thickness exceeds 30 nm, then the absorption in the piezoelectric layer becomes dominant and the reflectance tuning range decreases. For both sources, the maximum reflectance tuning ranges are obtained for layer thicknesses around 20 nm.

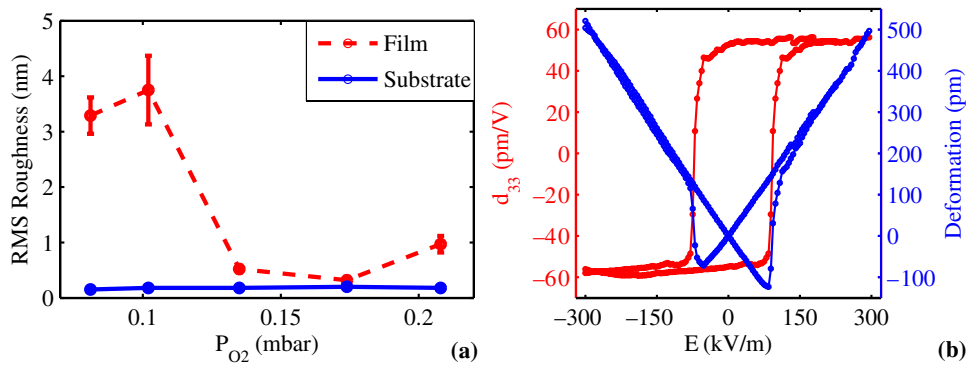
#### 4. Experimental results

In fabricating the active MLM structure, the roughness and the maximum piezoelectric response of the active layer are two important parameters for the maximum reflectance and the reflectance tuning range. We used PLD, which is often preferred for its capability of growing high quality complex piezoelectric oxides, to grow electrode/piezoelectric film/electrode heterostructures to investigate their roughness and piezoelectric response [23]. As with our calculations, we use layer thicknesses that are expected to be relevant to real-world applications. We deposited epitaxial heterostructures consisting of 20 nm SRO, 30 nm PZT and 20 nm SRO on STO substrates with (001) orientation. The STO substrate was chosen because it is one of the candidate buffer layers for the active MLM design, due to its low lattice mismatch with the electrodes and the piezoelectric layer materials. The low lattice mismatch minimizes the in-plane stress and therefore results in optimized smooth growth.

The STO substrate was treated with BHF solution to obtain a  $\text{TiO}_2$  termination layer, followed by annealing at 950 °C for



**Figure 3.** Optimum reflectance tuning ranges for (a) monochromatic, and (b) broadband light sources, for different maximum piezoelectric responses  $\epsilon$ . For each rising region of a reflectance peak (see figure 1(b)), a different reflectance tuning range was calculated, which are shown by markers. Maximum reflectance tuning ranges are obtained for layer thicknesses around 20 nm.



**Figure 4.** (a) RMS roughness of the STO substrate and the SRO/PZT/SRO heterostructure. (b) The piezoelectric coefficient and the deformation measurement for 30 nm thick PZT thin film deposited at 0.175 mbar  $O_2$  partial pressure.

1.5 hours before deposition. A KrF excimer laser (wavelength 248 nm) was used to ablate the target materials with laser fluences of  $2.1 \text{ J cm}^{-2}$  at a 1 Hz repetition rate and  $2.5 \text{ J cm}^{-2}$  at 10 Hz repetition rate for SRO and PZT, respectively. During the deposition, the substrate temperature was kept at  $600^\circ\text{C}$  and the distance to the target was 50 mm. A background pressure of 0.6 mbar was used during SRO deposition with gas ratios of 50% Ar and 50%  $O_2$ , which resulted in atomically smooth growth [24]. PZT was deposited at five different  $O_2$  partial pressures to find the optimum  $O_2$  pressure to grow a smooth PZT film. The surface roughness of the substrates and the heterostructures were measured using a Nanoscope IV (Veeco Instruments, NY, USA) atomic force microscope in tapping mode *ex situ*. The measured root mean square (RMS) surface roughness values as a function of  $O_2$  partial pressure are plotted in figure 4(a). It can be seen that an RMS surface roughness of 0.3 nm was obtained for 0.175 mbar  $O_2$  partial pressure, which is close to the RMS surface roughness of the substrate (0.2 nm). Layer thicknesses were determined by reflectivity measurements and the crystal structure by x-ray diffraction using a Bruker d8 Discover diffractometer (Bruker, Karlsruhe, Germany) (results are not shown). The  $\theta$ - $2\theta$  scans show that the PZT has (001) orientation for the smoothest heterostructures. The local piezoelectric response of a second heterostructure (SRO/PZT), deposited under identical conditions is shown in figure 4(b). The piezoelectric coefficient ( $d_{33}$ ) and the deformation was recorded on the

local ferroelectric domain structure using a Nanoscope III (Veeco Instruments, NY, USA) piezoelectric response force microscope. As can be seen from the figure 4(b), a  $d_{33}$  value of  $60 \text{ pm V}^{-1}$  was measured.

### 5. Conclusions

In conclusion, the design of an active multilayer EUV mirror (MLM) structure has been presented. The active MLM was designed by integrating a piezoelectric layer (with electrodes and buffer layer) between two Mo/Si MLMs to allow reflectance tuning by applying an external voltage. Conditions necessary to optimize the piezoelectric layer thickness for maximum reflectance tuning were calculated. Piezoelectric films with 30 nm thickness have been deposited at different  $O_2$  pressures in order to investigate the RMS surface roughness and the piezoelectric response. RMS roughness of the heterostructure can be decreased down to 0.3 nm, which is comparable to the RMS substrate roughness of 0.2 nm. The piezoelectric coefficient of the film is measured to be  $d_{33} = 60 \text{ pm V}^{-1}$ .

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