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Speed Programmed Shuttering System for Laterally Graded Multilayer Fabrication

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1. Introduction

Multilayers can reflect VUV lights in normal incidence geometry by constructive interference. For imaging application, multilayers should have specific period thickness distributions over the curved mirror substrates as a function of the local ray angles of incidence. Therefore a lateral thickness control is needed in imaging multilayer deposition. For X-ray beamline optics where the lateral gradient of the multilayer thickness is gentle, the source or substrate scan method is usefull [1, 2]. For a short radius of curvature mirror such as normal incidence VUV microscope optics, however, a more powefull thickness control method enabling a steep gradient larger than 3%/mm has been required. It is not easy without a mask technoque. A moving mask method was proposed by a group in Nikon [3]. That idea was developed into our speed programmed shuttering system [4]. An ion beam sputtering (IBS) deposition apparatus equipped with the shuttering system has been constructed and multilayer mirrors of various specifications have been fabricated successfully. A high throughput VUV multilayer microscope has been developed.

2. Design

The side view of the IBS deposition apparatus is illustrated in Fig. 1. Dual ultra high vacuum compatible ion guns of an electron cyclotron resonance type are equipped. Three targets can be mounted and switched during a deposition. The substrate spins at 60 rpm for the rotational thickness uniformity. In front of the spinning substrate the shutter moves along a speed function programmed to obtain a desired radial thickness distribution. The front view of the shutter is illustrated in Fig. 2. The x-axis in the figure is vertical in the actual apparatus. The deposition rate is higher at the center than at the edge while the designed thickness is usually thicker at the edge. That is a reason why the shutter shape is triangular. The angle of vertex is 60° or 90°.

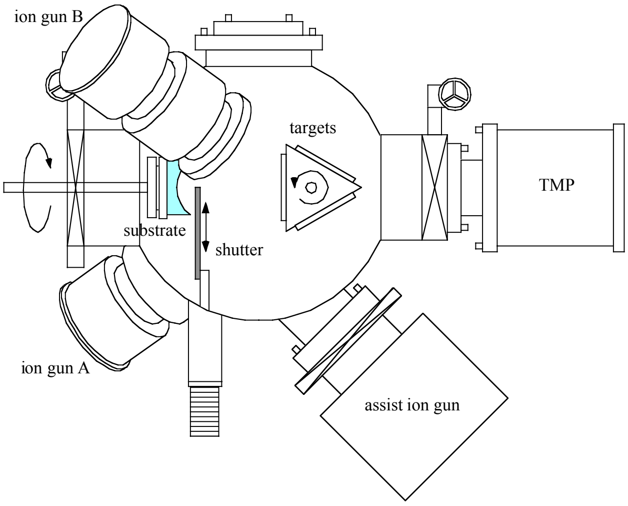

Fig. 1: Schimatic illustration of an IBS deposition apparatus with a speed programmed shuttering system.

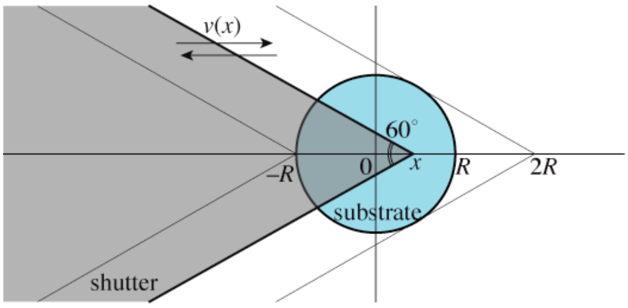

Fig. 2: Schematic illustration of the deposition shutter partially covering the spinning substrate.

The shutter speed programming procedure is briefly described below when the shutter vertex is 60°. The shutter covers the whole substrate at $x = 2R$, where x and R are the position of pointed end of the shutter and the radius of the substrate, respectively. For multilayer fabrication, the sputtering targets are switched at this position. The shutter opens from $x = 2R$ to $x = -R$ along a speed function $v(x)$. The whole substrate is exposed at $x = -R$. The shutter stays here for an interval T, and closes from $x = -R$ to $x = 2R$ along the same speed function. Through that sequence the deposition time has r-dependence, where r is a distance from the center of the substrate. The r-dependent deposition time is written as

$$T(r) = 2\int_{-R}^{2R} \frac{\Theta(x,r)}{2\pi}\frac{dx}{v(x)} + T\,,$$

where $\Theta(x, r)/2\pi$ means the exposed fraction at r when the shutter position is x [4]. Approximating $1/v(x)$ into a finite power series

$$\frac{1}{v(x)} = \sum_{n=0}^{N} c_n x^n\,,$$

the integral can be carried out into the form of

$$T(r) = \sum_{n=0}^{N} T_n r^n\,,$$

and the values of coefficients T_n's are

$$\begin{bmatrix} T_0 \\ T_1 \\ T_2 \\ T_3 \\ \vdots \end{bmatrix} = \begin{bmatrix} 1 & 2R & -R^2 & \frac{2}{3}R^3 & .. \\ 0 & \frac{4\sqrt{3}}{\pi} & 0 & 0 & .. \\ 0 & 0 & 2 & 0 & .. \\ 0 & 0 & 0 & \frac{4\sqrt{3}}{\pi} & .. \\ \vdots & \vdots & \vdots & \vdots & \end{bmatrix} \begin{bmatrix} T \\ c_0 \\ c_1 \\ c_2 \\ \vdots \end{bmatrix}.$$

On the other hand, under the condition that the deposition rate distribution is $S(r)$ the r-dependent deposition time to achieve the designed thickness distribution $D(r)$ should be $D(r)/S(r)$. It determines $T(r)$. From a given $D(r)/S(r)$, T_n's, then c_n's and T are obtained. Only one thing that should be emphasized here is that the shutter speed programming procedure is analytical and clear. When the shutter vertex is 90°, the matrix changes only with diagonal elements.

3. Multilayer Deposition and Evaluation

We fabricated a Mo/Si multilayer on a spherical substrate of 100 mm diameter and 300 mm radius of curvature without the shutter operation. The deposition rates $S(r)$'s of Mo and Si on this sample were measured by the normal incidence VUV reflectometry at BL-12A [5]. To use the multilayer as a high NA condenser mirror of a laser plasma source for 95 eV, we programmed $v(x)$'s and T's to deposit uniform thickness of $D(r)$ = 2.8 nm for Mo and $D(r)$ = 4.1 nm for Si. The shutter speed functions were obtained as shown in Fig. 3. Two curves are close to each other because the thickness to deposition rate ratios of Mo and Si were similar. We fabricated a 30 period multilayer of this design and measured the period thickness distribution by the reflectometry [5]. The results are plotted in Fig. 4. A thickness uniformity of *PV* 1.6% was achieved. With an improvement of the shutter speed program where a continuous function was divided into $x > 0$ and $x < 0$ regions making a jump at $x = 0$, the thickness error decreased to *PV* 0.9%.

A soft X-ray group in Tohoku University designed a transmission VUV microscope based on a laser produced plasma source. It contains four normal incidence multilayer mirrors of radii of curvature of +22.4 mm, –50 mm and –400 mm. We deposited 40 period Mo/Si multilayers on the mirror substrates. The measured thickness error among four mirrors was *PV* 1%, less than the multilayer bandpass $\Delta E/E$ = 4% [6]. The microscope works well with a high throughput at 92.5 eV [7]. It is concluded that a widely applicable multilayer deposition technique for normal incidence imaging optics has been developed using speed programmed shuttering system.

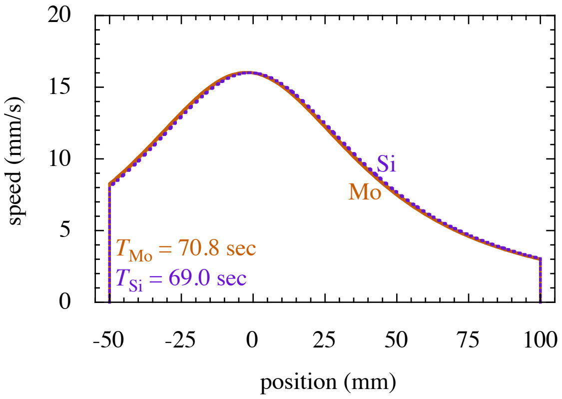

Fig. 3: Shutter speed functions programmed for a Mo/Si multilayer of uniform thickness on a 100 mm^{ϕ}, 300 mm^{r} spherical substrate.

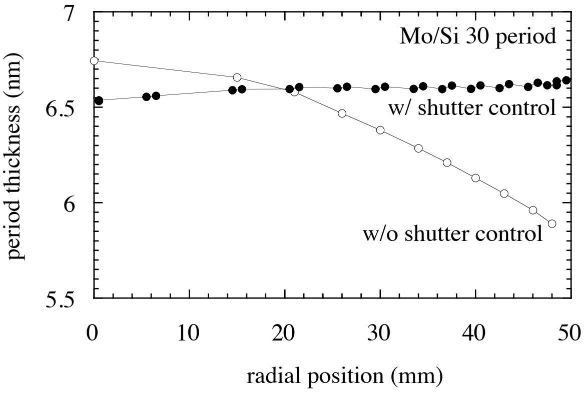

Fig. 4: Period thickness distribution of a Mo/Si multilayer measured by the normal incidence VUV reflectometry.

Acknowledgments

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