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ScienceDirect

Thin Solid Films 515 (2007) 5728 – 5731

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Monochromatization of characteristic X-rays using stepped X-ray waveguide

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Abstract

Depending on the X-ray energy, the structure of an X-ray waveguide needs to be varied for greater efficiency. Therefore, a Si/PMMA (polymethyl methacrylate)/Si thin-film structure, whose top Si layer was steplike, was designed as a planar X-ray waveguide on the basis of calculations, and it was fabricated by spin-coating and sputtering. By irradiating white X-rays on two selected areas of a stepped waveguide, the top-layer thicknesses of which were different, W Lβ and Mo Kα lines were effectively guided and monochromatized.

PACS: 61.10.kw; 68.55.−a; 42.79.Gn
Keywords: X-ray waveguide; X-ray reflectivity; Organic thin film

1. Introduction

Waveguides, such as optical fibers, are materials that can propagate photons without loss. Although waveguides for X-rays exist, they have generally been developed as a tool for focusing to 10–100 nm beam size, and as a band-pass filter of X-rays different from the optical fiber. X-ray waveguide phenomena were first found from multilayers, where a low-density layer was sandwiched between high-density layers [1–3]. In this case, low-density and high-density layers act as the core and the cladding of the optical waveguide, respectively. Total reflections of X-rays at interfaces between the core and the cladding generate standing waves in the guiding layer. The character of the standing wave determines the finite number of guiding modes [4]. Recently, two-dimensional X-ray waveguides have been realized by e-beam lithography, and the possibility of fabricating a focusing tool with nm dimensions has been shown [5,6]. Our group has utilized an X-ray waveguide phenomenon for the precise determination of film densities and thicknesses [7,8].

Bergemann et al. predicted theoretically that an X-ray waveguide could lead to a minimum beam size of the order of 10 nm [9], suggesting that highly coherent X-ray beams can be easily obtained using the X-ray waveguide. Jarre et al. successfully obtained monochromatic X-rays with a 240 eV FWHM from a white beam of synchrotron radiation [10]. Focusing and monochromatization are interesting features of the X-ray waveguide. From the point of view of these two abilities, we designed an efficient X-ray waveguide by computer calculations to guide various characteristic lines from conventional X-ray tubes. In this study, a Si/PMMA(polymethyl methacrylate)/Si thin film, whose top Si layer was steplike, was adopted as the X-ray waveguide. The properties of the designed X-ray waveguide were evaluated from the observed spectra of the guided X-rays of W Lβ and Mo Kα lines.

2. Estimation of waveguide efficiency by the top-layer thickness

When white X-rays are irradiated on a planar X-ray waveguide under a grazing incidence condition, X-rays at the resonant mode energies [7,8,10] can travel through the guiding layer. These resonant modes are called TE0 (transverse electric 0), TE1, TE2 and so on, and are characterized by the number of nodes of the X-ray standing wave in the guiding layer, similar to the case of optical waveguides. The angular distribution of the X-rays emitted from the guiding-layer end face varies depending on the resonant mode. Since the angular distribution of the beam at the TE0 mode is the most simple [4,11], it is appropriate for beam collimation.

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0040-6090/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.tsf.2006.12.017

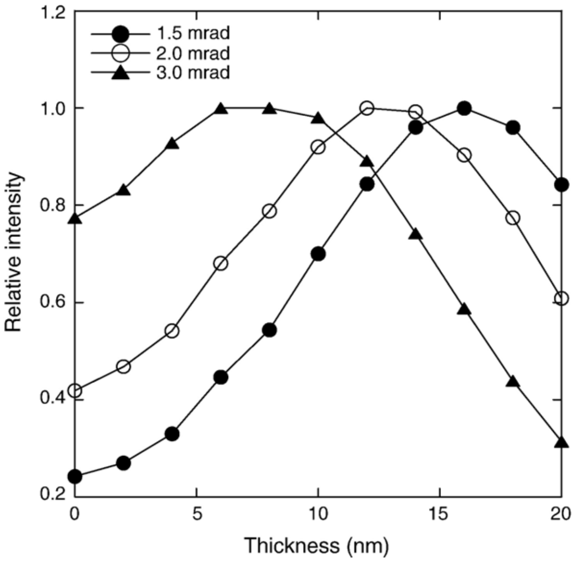

Fig. 1. Calculated intensity maxima of X-rays at TE0 mode in guiding layer as a function of thickness of top Si layer. A Si/PMMA/Si thin-film structure was used for the calculations. The grazing angles ϕ_1 were assumed to be 1.5, 2.0 and 3.0 mrad, and the X-ray energies at the TE0 mode were calculated to be 15.8, 11.8 and 8.5 keV, respectively.

Here, we modeled the Si/PMMA/Si thin-film structure as the planar X-ray waveguide and calculated the intensities of electromagnetic fields at the TE0 mode in the PMMA core layer. [12] The thickness of the core layer in the model was fixed at 100 nm and that of the Si top layer was varied from 0–20 nm with 2 nm steps. Grazing angles ϕ_1 were assumed to be 1.5, 2.0 and 3.0 mrad. The intensity maxima of the electromagnetic fields in the core layer are plotted as a function of the top Si layer thickness, as shown in Fig. 1. The X-ray energies of the TE0 mode at $\phi_1 = 1.5$, 2.0 and 3.0 mrad were about 15.8, 11.8 and 8.5 keV, respectively. These X-ray energies were almost constant even when the thickness of the top Si layer was changed. The maximum intensity of the electromagnetic field corresponds to the efficiency of the waveguide. Thus, the present calculations clarified that the efficiency of the X-ray waveguide for each X-ray energy was affected by the thickness of the top Si layer.

3. Sample and experimental setup

On the basis of the results in the preceding section, we fabricated the Si/PMMA/Si thin film, as shown in Fig. 2 (a). The PMMA and Si layers were grown by spin-coating and sputtering, respectively. The steps of the top Si layer were made by moving the mask during the sputtering.

We carried out an X-ray experiment using the setup shown in Fig. 2 (b). White X-rays from a rotating anode generator with a molybdenum (Mo) target were irradiated on the sample surface under the grazing incidence condition. The spectrum of incident X-rays is shown in Fig. 5 (b). In addition to strong Mo K lines, weak W L lines are observed, which is due to contamination on

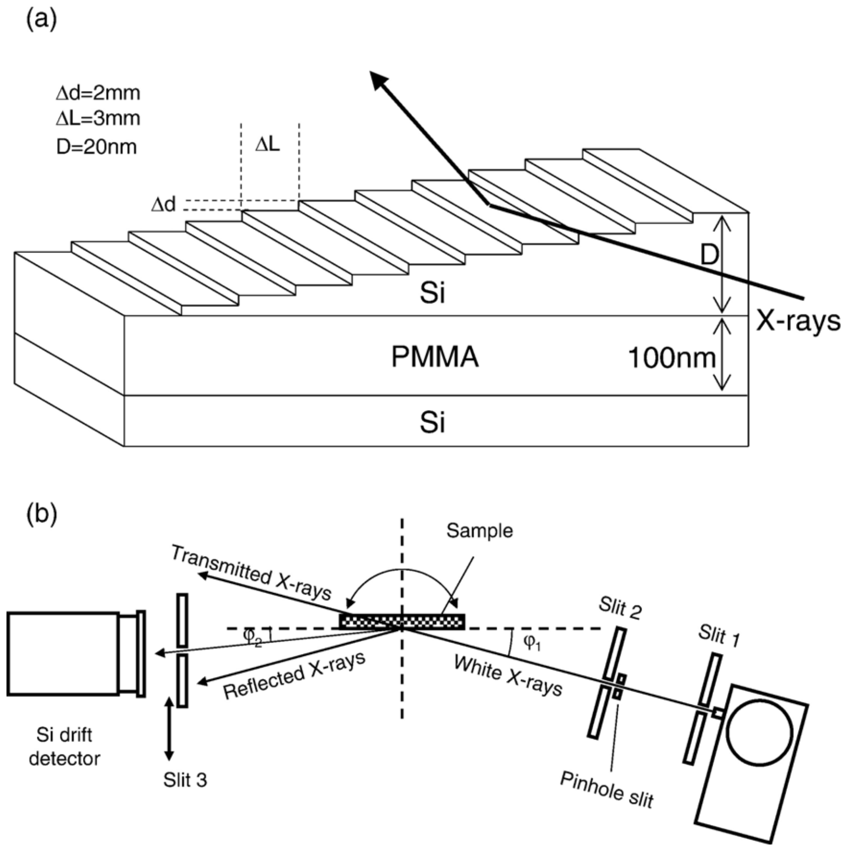

Fig. 2. (a) Designed planar waveguide and (b) experimental setup for measuring guided X-rays.