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Research paper

Fabrication of high aspect ratio nanoscale periodic structures by the soft X-ray interference lithography

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ABSTRACT

Nanoscale periodic structures have been utilized in the scintillator field to obtain enhanced light extraction efficiency. Sufficient structure depth is necessary to achieve better extraction efficiency. Recently, a soft X-ray interference lithography (SXIL) has been developed in the Shanghai Synchrotron Radiation Facility (SSRF). SXIL can be used to fabricate a high aspect ratio pattern due to the uniform distribution of the beam dose at the photoresist depth. A grating mask with a new photon stop layer was attempted, mainly consisting of Perm alloy, and it was optimized for the SXIL to increase the entire service life. Preliminary results suggest that PMMA structure with an aspect ratio of up to 3 has been successfully manufactured using SXIL techniques. Therefore, this technique has been studied to fabricate the artificial nanostructure on the scintillator in the high efficiency radiation detector area.

1. Introduction

With the development of nanoprocessing technology, nanostructures have gained increased interest because of their broad applicability, such as in sensing [1,2], optoelectronics [3], and biological-related applications [4]. Furthermore, some nanostructures performance will be drastically improved if they are arranged in proper ordered array [5]. At present, the main methods of processing nanoscale periodic nanostructures are the direct writing method, nanoimprint and interference lithography. Focused ion beam (FIB) etching and electron beam lithography (EBL) are two direct writing methods by which high resolution nanostructures can be obtained; unfortunately, they are not feasible options for fabricating large area nanostructures because of their high preparation cost. Methods based on nanoimprint could be applied to fabricate large area nanostructures with low cost and high throughput. However, contamination becomes an issue for its contact mode process. As a parallel to the top-down lithography method, extreme ultraviolet interference lithography (EUV-IL) is a welcome method for fabricating large area, high-resolution periodic nanostructures [6–8]. Additionally, the noncontact lithography method has no mechanical stress brought to the substrate. In addition, there is no particular requirement for substrate conductivity within manufacturing [9–11].

Scintillators play an important role in radiation detection systems with various applications in high-energy physics experiments, nuclear medical imaging and homeland security [12]. The efficiency of a scintillator-based detector is strongly dependent on the luminescence conversion efficiency and light extraction efficiency. Currently, nanoscale periodic structures have been promoted to the field of scintillator for the purpose of enhancing light extraction efficiency [13,14]. The mechanism of light extraction with a periodic structure is the diffraction of the evanescent field confined at the surface of the crystal due to total internal reflection [15]. For the scintillator without periodic structures, a large number of photons are restricted in the scintillator because of the total internal reflection, which consequently forms an evanescent field at the interface, Fig. 1(a). Traditionally, the distribution range of the evanescent field is at a similar level of internal wavelength, which is represented by the red line in the graphs. In Fig. 1(b), when the incident light meets the periodic structure of dielectric constant, the wave vector will be split into different harmonics. The harmonics could be radiated into air when they satisfy the following condition:

$$|k_{//} + mG_0| < 2\pi/\lambda_0 \quad (1)$$

where $k_{//} = 2n\pi/\lambda_0 \sin\theta_1$ is the in-plane wave vector, λ_0 is the wavelength in vacuum, m is the diffraction order, and $G_0 = 2\pi/a$ is the reciprocal lattice vectors with the lattice constant a, which is the period of the periodic structure. The light into air has an emergence angle of:

$$\theta_2 = sin^{-1}\left((\lambda_0/2\pi)|k_{//} + mG_0|\right) \quad (2)$$

Therefore, the extraction efficiency varies both depending on the angle θ_1 and the period of the structure, similar to the grating case. The

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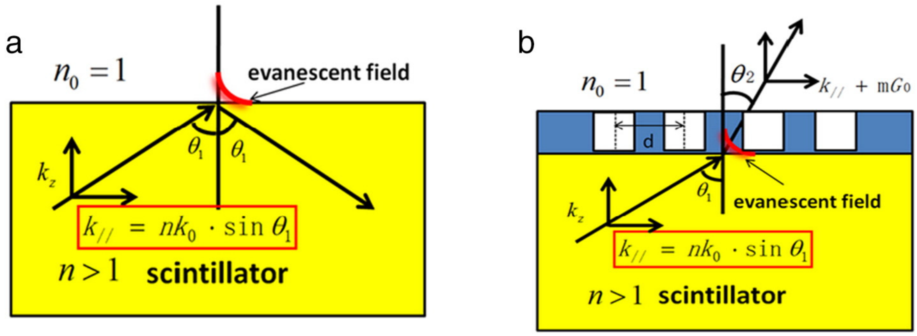

Fig. 1. (a) Scintillator without periodic structure; (b) scintillator with periodic structure.

evanescent field has a certain distribution range at the interface, as the red lines show in Fig. 1. The periodic structure depth would ideally cover the entire evanescent field range, thus achieving the best light extraction efficiency of the scintillator.

The EUV-IL technique is effective for fabrication of large area nanoscale periodic structures on the scintillator. However, at an EUV photon energy of ~92.5 eV the exposure conditions are different between the top surface and the bottom of the photoresist due to the strong absorption of the conventional photoresist and the interference intensity distribution feature [16,17], which could taper the exposure pattern. It is difficult to obtain high aspect ratio exposed patterns. Normally, the aspect ratio of EUV-IL exposed patterns is at most ~2 [18]. As mentioned above, to achieve the best light extraction efficiency of the whole scintillator, the depth of the nanoscale periodic structure should cover the entire evanescent field range (Fig. 1b) to improve the exposure depth for the EUV-IL technique. Surprisingly, soft X-ray is recognized as a better source to achieve high aspect ratio patterns for its higher transmission rate in some photoresists because of its higher photon energy. Soft X-ray with different photon energies, such as 190 eV, 250 eV, and 450 eV, has already been employed in interference lithography as the beam source, and some instructive results have been reported [19,20].

Several factors affect the stable exposure process for high quality and promoted aspect ratio patterns, including the incident photon energy, the efficiency of the optical lithography system and the grating mask quality. Those issues are usually mutually influenced and restricted. A desire for only high photon energy may decrease the whole optical efficiency of the system, resulting in grating mask fabrication problems. To satisfy a high transmission rate in PMMA with balancing consideration of high photon flux in our system, 140 eV photons were selected as our SXIL source. In addition, the grating masks could be easily fabricated and the irradiation damage to the mask grating is not as severe at this photon energy. With the photon energy promoted, normal EUV grating mask is no longer suitable for our SXIL. A thicker gold coating is applied for the photon stop layer [21]. However, our previous work has shown that an exceedingly thick gold photon stop layer has some side effects, such as increased fragility after extensive irradiation. An improved thinner Perm alloy photon stop layer was designed and adopted in this SXIL study. The photon stop layer is more delicate and thinner, but it still can effectively block high energy photons that pass-by. Additionally, it displays good thermal stability behavior. Therefore, the grating mask with this Perm alloy photon stop layer was expected to have a good service life for this experiment. In this paper, we investigate the relationship between the transmission rate of the incident beam in photoresist and the exposure pattern profile during the interference lithography. The grating mask for the SXIL was designed and optimized for 140 eV soft X-ray source. The experiment results demonstrated that this newly designed grating mask can obtain high aspect ratio patterns.

Furthermore, the SXIL method has been adopted by the XIL beamline (beamline BL08U1B) at SSRF [22] for related experiments. It can be applied to solve problems with thin exposure depth to fabricate the artificial nanostructure on a scintillator in the high efficiency radiation detector research field.

2. Theoretical consideration

The photon stop layer in the central area of a grating mask is key to the interference lithography experiment. As shown in Fig. 2, the rest of the substrate area, which contains no grating, is covered by a photon stop layer, which efficiently blocks the beam that penetrates through the gratings. Otherwise, it would decrease the contrast of the interference pattern. Au is usually applied as the photon stop layer material in grating mask fabrication of the EUV-IL. A greater than 600 nm Au layer in the SXIL guaranteed the shading effect. Unfortunately, the grating mask with a thick Au photon stop layer breaks down easily after

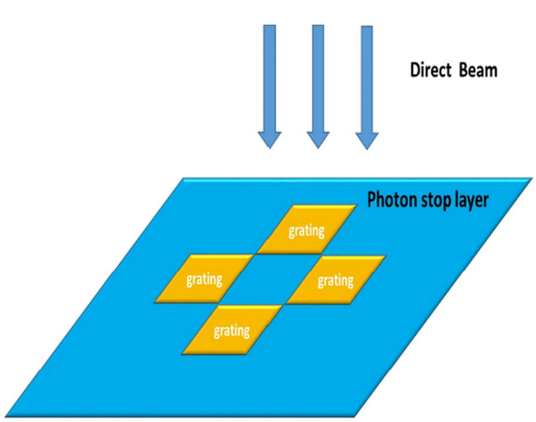

Fig. 2. The layout of the grating mask.

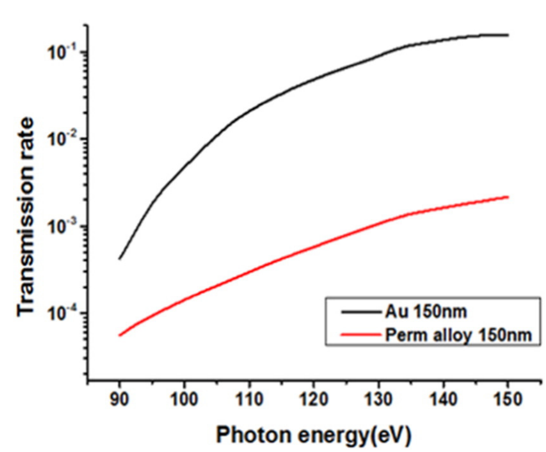

Fig. 3. The transmission rate curve of the EUV beam through the different photon stop layers, where the 150 nm Perm Alloy is supposed to consist of 120 nm thickness Ni and 30 nm thickness Fe.