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Aspherical Lens Design Using Computational Lithography

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ABSTRACT

Optical lithography is often applied to fabricate three-dimensional (3D) patterns because of its capability on the scale of optical wavelengths. An aligner, a laser writer, and a stepper with an optical projection system are used as the exposure tool. The focusing capability must enable exposure of step heights of ≥50 μm, which is normally achieved using an optical projection system with a large focal depth. Recently, a projection lens was developed that can produce a variable step height using an adjustable numerical aperture, which has led to the fabrication of micro-lens arrays (MLAs) with step heights as high as 100 μm. These MLAs are used in various fields but mostly only as condensing lenses. However, wider applications await the realization of optical aberration reduction. The introduction of aspherical lenses would be a major step in this direction; however, aspherical lenses are difficult to produce because of the limitations in processing and polishing the aspherical surfaces of optical elements made of glass. Alternatively, the fabrication of 3D patterns using optical lithography involves a photomask whose optical density distribution corresponds to the 3D profile after exposure and development. A density distribution corresponding to the desired 3D shape can be achieved using a computer to control the dot density of a microdot mask pattern. In this study, we present a design method for low-aberration aspherical MLAs that satisfies the Rayleigh standard using computational lithography.

1. Introduction

The fabrication of fine three-dimensional (3D) patterns in the sub-millimeter range is usually performed using optical lithography, which enables micropatterning on the scale of optical wavelengths. A simple and inexpensive aligner, a laser beam writer for low-volume production, and a stepper equipped with the optical projection system are applied as the exposure tool [1–8]. The limit on the step height in the exposure pattern to be formed is generally 10–20 μm in the aligner and 50 μm in the laser writer [1,5,6]. In the optical projection system treated in this study, the resolving power and depth of focus (*DOF*) of the projection optics are mainly defined by the numerical aperture (*NA*). A large *NA* is effective at high resolution but results in loss of DOF [9]. This trade-off means that the step height of the exposed pattern is limited to several microns for the high *NA* lenses used for semiconductor exposure. However, the recent demand for 3D devices such as MEMS (Micro Electro Mechanical Systems) has resulted in steppers that are equipped with projection lenses with adjustable *NA*s corresponding to a variable step height [8]. By setting the *NA* of the projection lens in the stepper to ∼0.1, fabrication of a micro-lens-array (MLA) with a height of 100 μm has been achieved [8].

High-step MLAs are currently used as optical elements in various fields (e.g., the illumination optics in projectors) but mostly only as simple condensing lenses. However, applications in the near future will likely require imaging that is close to the diffraction limit as well as condensing that is more efficient, which makes it necessary to reduce the degree of aberration [10]. Optical aberration is introduced at both the design and manufacturing stages; however, the former type can be significantly reduced using aspherical lenses [11]. There are many constraints on this type of lens [10,11], including manufacturing facilities for processing and polishing the aspherical surface, all of which reduce the productivity and increase the cost.

In contrast, exposure in optical lithography is generally performed using a photomask whose optical density distribution corresponds to the shape of the required 3D pattern [8,12–14]. A binary-type photomask (optical transmittance: glass portion = 1 (on), Cr-patterned portion = 0 (off)), which is used in the mass production of semiconductors, is applied even for the exposure of 3D patterns, and arbitrary pattern drawing is also possible under com-

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puter control. Microdot patterns are used in the exposure of 3D patterns, and the density of microdots is controlled to obtain a continuous distribution corresponding to the desired 3D shape. In conventional lens fabrication using optical lithography, the glass is etched with the exposed resist pattern as a mask. Recently, high-step applications have led to the development of resin-type resists with excellent optical properties [8]. If the exposed resist pattern is to be used directly as a lens, lithography can be introduced only at the fabrication stage.

In this study, a photomask design corresponding to aspherical lenses was created using computational lithography for the fabrication of high-step MLAs using an optical projection system. By applying this photomask, we analytically demonstrate that it is possible to form a low-aberration MLA that satisfies the Rayleigh standard [11], which is a general performance standard for an aplanatic lens.

2. 3D patterning by exposure technology

2.1. Review of previous literature

To form a high-step 3D pattern of ~100 μm, exposure by an optical projection system that has a high *DOF* is required. Fig. 1 presents a schematic illustration of 3D pattern formation by exposure and development using an optical projection system [8]. A photomask (hereinafter referred to simply as a "mask") with an intensity distribution that corresponds to that of the 3D pattern is irradiated by the illumination optics, and the substrate is exposed through the projector lens. The exposure substrate is a transparent glass plate whose rear side is exposed after adhering a negative-type resist to it. A latent image distribution corresponding to the 3D pattern is formed in the resist, and the cross section of the 3D pattern is finally obtained after the development process. The binary-type mask used in the mass production is applied, and the density of the microdot pattern on the mask is controlled to obtain a continuous transmittance distribution corresponding to the desired 3D shape [26].

The top panels of Fig. 2 show spherical MLA profiles as a 3D pattern with a height of 100 μm, an opening diameter of 346 μm, and a curvature radius of 200 μm after being exposed by the optical projection system [8]. The left-to-right sequence of images in Fig. 2 goes from the best focus to −100 μm defocus and finally to −250 μm defocus. For the formed MLA, the profile errors are defined by *RMS* (root-mean-square) error as the degree of roughness in the lens surface and by Δh as the decrease in the lens height (SAG).

The bottom panels of Fig. 2 show the pattern cross sections obtained by an analytical method for the same conditions as those used in the experiment [15]. An aerial image of the mask pattern after passing through the projection optics was calculated by optical simulation, and the cross section of the pattern was derived by binarizing the latent image distribution. Analytical results that almost correspond to the experimental results were obtained in the region (defocus −250 μm) with small surface roughness that can be used as a micro-lens [15].

The performance of an optical element such as a lens is generally evaluated by its wave aberration, which is expressed in multiples of the wavelength λ used [11]. For the MLA shown in this section, the design aberration is 0.6λ and the manufacturing aberration due to the profile error is 0.4λ; therefore, the total aberration is approximately 1λ [8].

2.2. Theme of this paper

For the aberration amount 1λ of the MLA shown in Section 2.1, the application as an optical element is limited to the light condensing function. In this study, to improve the condensing performance and obtain the imaging function of the MLA in the future, we aim to form a low-aberration MLA that satisfies the Rayleigh standard of wave aberration ≤ 0.25λ [11].

Although the lens surface of the MLA shown in Section 2.1 is a spherical surface, low aberration can be realized by introducing an aspherical shape on the lens surface [11]. However, as described in the Introduction, fabrication of aspherical lenses made of ordinary glass materials is difficult in terms of both cost and technology. In this study, a low-aberration MLA with an aspherical shape is formed using the projection exposure process described in Section 2.1.

In the formation of a fine 3D pattern by exposure, mask design and optimization of exposure conditions are often performed by trial and error, and the development cost is high. Meanwhile, the formation of a pattern using the analytical method shown in Section 2.1 (hereinafter called "computational lithography") has achieved results that almost correspond to the exposure results, which is effective for prediction of optimum mask design and exposure con-

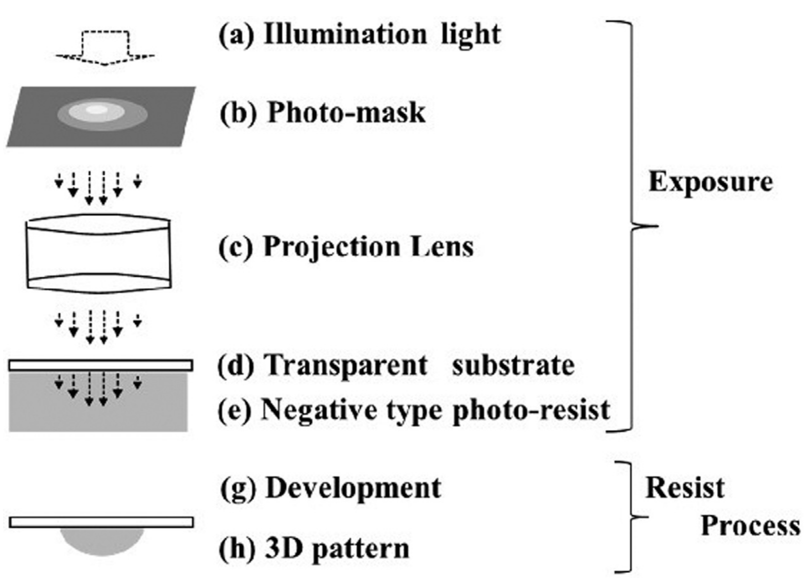

Fig. 1. 3D patterning by a projection lens.