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Depth of focus estimation based on exposure dose distribution

Jiubin Tan, Zhanlei Jin *

Ultra-precision Optical and Electronic Instrument Engineering Center, Harbin Institute of Technology, Harbin, Heilongjiang 150001, China

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Abstract

A defocusing exposure dose distribution model is established with the integral effect of light intensity on time taken into account for laser direct writing on a thin photoresist with total reflection substrate. Exposure dose distribution curves are established using the established model for different photoresist depths. A side slope angle is established for each defocusing amount in accordance with the exposure dose distribution curves, and so depth of focus can be estimated by simply checking to see if the maximum side slope angle with the horizontal is in the range of 80–100°. Simulation results indicate that when laser direct writing is done on a thin photoresist with total reflection substrate using a laser with wavelength equal to 442 nm and a lens with numerical aperture equal to 0.5, the depth of focus estimated using the proposed method is 1 μm, which is just 1/3 of the depth of focus estimated using the method based on intensity distribution. It is therefore concluded that it is the integral effect of light intensity on time that causes the depth of focus estimation error, and the proposed method can be used to achieve a more accurate depth of focus estimation compared to the intensity distribution based method.

Keywords: Exposure dose distribution; Depth of focus estimation; Laser direct writing; Defocusing amount; Intensity distribution

1. Introduction

Laser direct writing (LDW) is one of the nanolithography now in use for micromachining [1–4]. Defocusing writing technology is now widely used for ultra-precision laser machining of complicated optical elements because its light spot is adjustable in size [5–8]. For example, lines of 0.75–200 μm in width were obtained by controlling the laser power and the defocusing amount [5]. Ridging and cracking were eliminated using laser beam shaping and defocusing technique when direct writing grayscale photomask was done on Bi/In composites [6]. The defocusing amount can be adjusted above the photoresist so that a less curved sidewall can be obtained [7]. The main purpose of defocusing writing is to get a wider line in a single pass to improve the writing efficiency. Grating and reticle were fabricated at various defocusing amounts on a four-axis LDW system [9]. A uniform spiral of 3.0 μm linewidth was fabricated in the defocusing mode [10]. Due to the wide use of defocusing writing technology for fabrication of elements with varying linewidth, some researches have been done on the linewidth characteristics of defocusing writing. For example, defocusing LDW linewidth was analyzed using an intensity distribution based method [11]. The intensity distribution in photoresist was assumed to be a Gaussian function and the defocusing LDW linewidth was analyzed with the exposure dose distribution [12]. However, the maximum defocusing amount (namely the depth of focus) within which high quality lines can be obtained has not been specified. It was attempted to define DOF for LDW, and to use the intensity distribution in photoresist to establish a DOF estimation method [13,14]. But the integral effect of light intensity on time was not taken into account. When the defocusing amount is large, the integral effect of light intensity on time causes a large difference between the exposure dose distribution and the intensity distribution. What is the effect of this large difference on the DOF estimation accuracy? To the best of

* Corresponding author.
E-mail address: jinzhanlei@gmail.com (Z. Jin).

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our knowledge, there is no positive response to this question yet so far. It is therefore of great significance to develop a DOF estimation method to establish the range of defocusing amount which can be used to guarantee the line quality of defocusing LDW.

An aluminum coating with reflectivity of more than 90% within the wavelength band of 400–600 nm is applied to the substrate to enhance the adhesion of photoresist to the substrate, and such a substrate is used as a total reflection substrate [13–15]. A defocusing exposure dose distribution model is established with the integral effect of light intensity on time taken into account. Exposure dose distribution curves are established using the established model for different photoresist depths. A side slope angle is established for each defocusing amount in accordance with the exposure dose distribution curves, and so depth of focus can be estimated by simply checking to see if the maximum side slope angle with the horizontal is in the range of 80–100°. Simulation results indicate that when laser direct writing is done on a thin photoresist with total reflection substrate using a laser with wavelength $\lambda = 442$ nm and a lens with numerical aperture NA = 0.5, the depth of focus estimated using the proposed method is 1 μm, which is just 1/3 of the depth of focus estimated using the method based on intensity distribution. It is therefore concluded that it is the integral effect of light intensity on time that causes the depth of focus estimation error, and the proposed method can be used to achieve a more accurate depth of focus estimation compared to the intensity distribution based method.

The general arrangement next in this paper is as follows: (1) Definition of DOF for LDW; (2) Modeling exposure dose distribution in photoresist with total reflection substrate; (3) Comparison between DOFs estimated using intensity distribution based and exposure dose distribution based methods; (4) Conclusion.

2. Definition of DOF for LDW

There is no generally accepted DOF definition under different conditions. The DOF of an imaging system can be defined as the range in which a clear imaging plane can be formed on the other side of a lens. The definition of DOF has nothing to do with light intensity. However, what we are very interested in a LDW system is the magnitude of side slope angle θ as shown in Fig. 1. For a photoresist with an exposure threshold, it is necessary to adjust the output power, the light moving velocity and exposure time in accordance with the defocusing amount to achieve a steep side slope. So DOF in LDW shall be defined as the range within which a side slope angle can be kept in an acceptable range by controlling the laser output power, the light moving velocity and the exposure time.

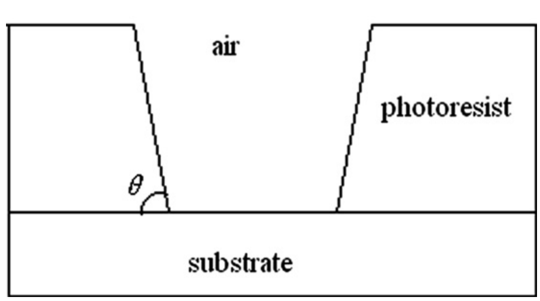

Fig. 1. Definition of side slope angle for LDW.

The different exposure theories of LDW and mask lithography lead to different exposure dose distributions.

Mask lithography is used to transfer patterns to substrate by laser irradiating on mask, as shown in Fig. 2. The laser intensity remains constant during the whole exposure period, and so the exposure dose in the photoresist can be expressed as

$$D = \int_0^{t_0} I \mathrm{d}t = It_0 \tag{1}$$

where I is the laser intensity, and t_0 is the exposure time.

LDW uses a moving focus laser to direct write patterns into photoresist. Because the intensity distribution is not uniform as shown in Fig. 3, the laser intensity varies even when the laser output power is constant while the laser passes through a set point. The exposure process is a dynamic integral of varying laser intensity and exposure time. The exposure dose in the photoresist can be expressed as

$$D = \int_0^{+\infty} I(t)\mathrm{d}t = \frac{1}{v}\int_0^{+\infty} I(t)v\mathrm{d}t = \frac{1}{v}\int_{-\infty}^{+\infty} I(\rho)\mathrm{d}x$$
$$= \frac{2}{v}\int_0^{+\infty} I(\sqrt{x^2+y^2})\mathrm{d}x \tag{2}$$

where v is the moving velocity of light spot, and $I(\rho)$ is the intensity distribution in the photoresist.

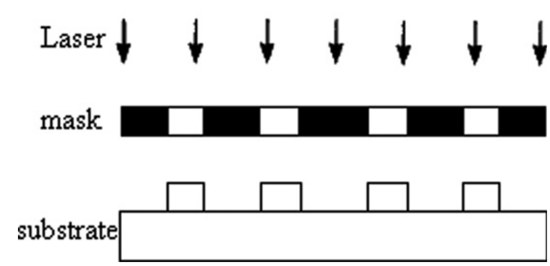

Fig. 2. Schematic diagram of mask lithography.

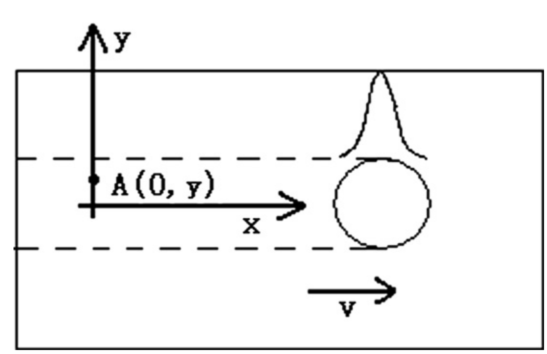

Fig. 3. Schematic diagram of LDW.