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Focused laser lithographic system for efficient and cross-scale fabrication of large-area and 3D micro-patterns

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A B S T R A C T

A novel focused laser lithographic system with a low-power ultraviolet laser, a high-speed galvanometer scanner and a customized *F*-theta lens was constructed and demonstrated for cross-scale, high-efficiency and low-cost fabrication of large-area micro-patterns. In this system, a high-speed galvanometer scanner was used for the first time to greatly improve lithographic efficiency. The optical path was optimized and studied in detail, and the distortions caused by the scanners and *F*-theta lens were explained with mathematical expressions. Then, a method of correction chart was employed to further reduce the distortion and stitching error. The effect of laser parameters on linewidth of the fabricated micro-patterns was investigated and optimized. The significance sequence of these parameters was laser power, scan time, scan speed and defocus, and the optimal line width/space was below 10 µm. After the optimization, a 150 mm × 150 mm gridding with 9.8 µm linewidth and 90 µm line space was fabricated within 300 s, and the stitching error was less than 10%. To demonstrate the ability for arbitrary micro-patterns fabrication, a 150 mm × 120 mm HUST logo with the feature size of about 10 µm was fabricated within 40 s. Array circular holes with the feature size of below 10 µm were also obtained with a scan speed of 2000 mm/s. Using this system, cross-scale and large-area micro-patterns could be fabricated conveniently with high efficiency and less stitching error. With the assistance of *z* stage, the system can also realize three-dimension (3D) micro-fabrication.

1. Introduction

Lithography is a crucial technology in the manufacturing industry of semiconductor integrated circuits (IC), and also plays a very important role in many other areas, such as the fabrications of microelectromechanical systems (MEMS) [1,2], optical waveguides [3,4], microchannel and microfluidic systems [5,6], and solar cells [7]. However, the traditional optical projection lithography usually requires a planar mask with designed micro-patterns, and then transfers the micro-patterns onto a photoresist-coated planar wafer. While this needs expensive masks, which now represents a significant fraction of the total manufacturing cost [8]. Moreover, it is hard to project larger-area micro-patterns because they need larger, more difficultly-fabricated, and more costly masks. Although the step-and-repeat photolithographic system can be used to realize large-area exposure by a small mask [9], it is helpless when the large-area micro-patterns are continuous and non-periodic. Besides, the projection lithography lacks of the fabrication flexibility of complicated and three-dimensional (3D) micro-patterns. Obviously, all above limit its wider applications in larger-area and 3D micro-patterns fabrication.

The focused laser lithographic system had been used to fabricate micro-patterns on substrates for many years [10–14]. It usually utilized a focused laser beam to directly write micro-patterns on a photoresist-coated wafer [15]. In comparison with the projection lithography, it was maskless and more flexible. Thus, this technique had been given many attractions. Two-dimensional (2D) micro-gratings, waveguides or microfluidic channels with 10 µm feature size had been easily fabricated [16–18]. While smaller feature sizes required shorter laser wavelength and larger numerical aperture (NA) [19]. Furthermore, the laser lithographic systems possessed the potential for 3D fabrication. For example, some researchers had fabricated the micro-patterns with the feature size of 10 µm on spherical mirror or concave lens [20,21]. However, all the above laser lithographic systems had a severe disadvantage, i.e., very low fabrication efficiency. In these systems, laser scan entirely depended on a moving mechanical translation stage. It is well known that it is hard to precisely control a heavy stage in a high speed or acceleration. Thus, the laser scan speeds were usually below 100 mm/s, and it would take several hours to fabricate a 150 × 150 mm^2 mesh with 90 µm line space. Obviously, it was very disadvantageous to fabricate cross-scale and large-area micro-patterns. However, few academic literatures have

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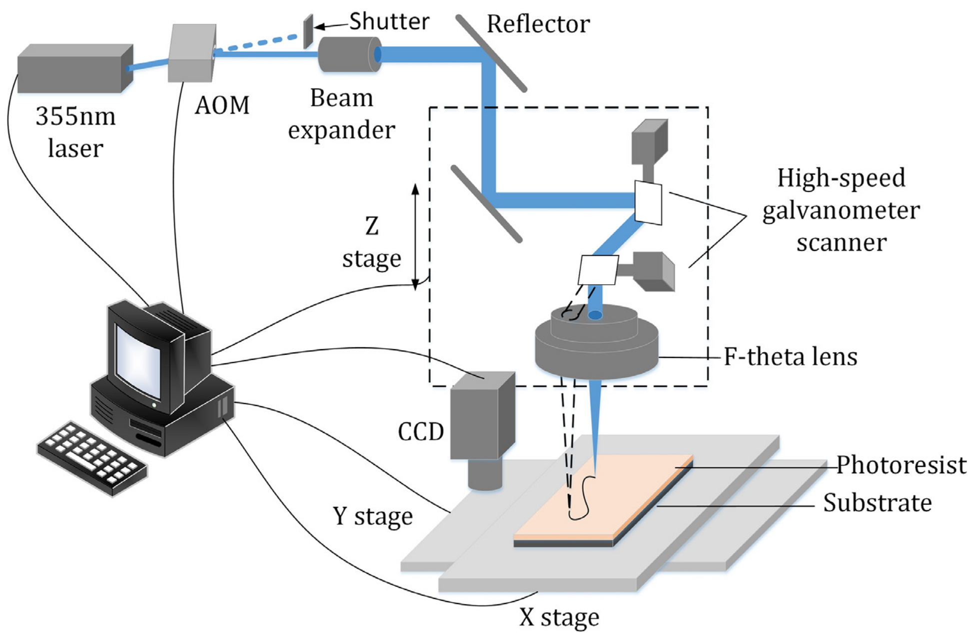

Fig. 1. Schematic diagram of focused laser lithographic system.

been published concerning the high-efficiency fabrication of large-area micro-patterns.

In order to greatly improve the lithographic efficiency, in this paper, a high-speed galvanometer scanner was applied for the first time in a laser lithographic system. Due to the high-speed oscillation motor and ultra-light mirror as a load, the laser beam could scan tens or hundreds of times faster than that of mechanical translation stages. Meanwhile, combining the scanner with an x–y–z mechanical stage, the fabrication of large-area and 3D micro-patterns could be implemented. An F-theta lens was customized for the system, and it was used to focus the laser beam on a plane and reduce the pincushion distortions. The distortions caused by the scanner and the F-theta lens were explored in detail and explained with mathematic expressions. The distortions were finally corrected by a method of correction chart. The effect of laser parameters on lithographic linewidth was investigated and optimized. After correction, the cross-scale fabrication of large-area micro-patterns could be conveniently implemented in a high speed with less stitching error.

2. Materials and methods

2.1. Materials

In the lithography process, commercially available photoresist SUN-110P and developer SUN-238D were purchased from Suntific Materials Co., Ltd. (Weifang, China). The photoresist was a diazonaphthoquinone (DNQ) positive photoresist and the developer was mainly composed of tetramethylammonium hydroxide (TMAH). Glass wafer substrates with the size of 150 mm × 150 mm × 3 mm were purchased from Qinhuangdao Yaodi Glass Co., Ltd. (Qinhuangdao, China).

2.2. Focused laser lithographic system

Fig. 1 depicted the setup of the focused laser lithographic system. It was mainly composed of an all-solid-state pulsed ultraviolet (UV) laser (TEM_{00} mode, Gaussian beam), an optical path unit, a controlling and monitoring unit, and an x–y–z 3D translation stage. The laser was with a wavelength of 355 nm, maximum output power of 0.5 W and a repetition rate of 100 kHz, and used as the exposure light source. In the optical path unit, a beam expander was used to expand and collimate the laser beam, and a high-speed galvanometer scanner (Optical deflection angle: ±20°) was used to rapidly manipulate the laser beam; Besides, an F-theta lens with a focal length of 103 mm and a scan field diagonal of 71 mm was used to focus the laser beam on a plane and reduce the pincushion distortions. In addition, due to the first pulse suppression in Q-switched mode, a little laser energy would leak out when Q-value was low. Although the leaking laser was weak, it still had a significant impact on the photoresist. Thus, an acousto-optic modulator (AOM) was used as a free-space switch to avoid the effect of leaking laser. For safety, a shutter was also used to block the leaking laser. The charge-coupled device (CCD) camera was used to locate the substrate and to assist the distortion correction. Furthermore, the x and y translation stages both had a movement range of 150 mm, and the z stage could carry the scanner and F-theta lens moving up and down in a range of 50 mm. Thus, the system was endowed with the capability of large-area and 3D micro-fabrication.

Table 1
Orthogonal design.

Levels	P (mW)	S (mm/s)	T	D (mm)
1	20	400	1	0
2	40	600	2	0.2
3	60	800	3	0.4
4	80	1000	4	0.6

2.3. Process and characterization

The photoresist was spin-coated on a clean glass wafer under a rotation speed of 3000 rpm to obtain a uniform photoresist film of about 2.5 µm thick. Next, the coated wafer was soft-baked on a 100 °C hotplate for 1 min to dry and improve the adhesion strength between the wafer and photoresist. After that, the wafer was mounted on the X–Y stage, and the laser lithography process (i.e., exposure) was implemented on the photoresist.

During the processing, laser parameters mainly included laser power (P), scan speed (S), scan times (T) and defocus (D). A 4 × 4 orthogonal design was used to optimize the parameters (Table 1). Subsequently, the exposed wafer was developed in the developer solution for 60 s, rinsed in deionized water for 10 s, and hard baked under 120 °C for 5 min.

The fabricated micro-patterns were observed and measured with an optical microscope (Motic China Group Co., Ltd., China).