Computational Lithography for 3-Dimensional Fine Photolithography using Sophisticated Built-in Lens Mask

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Built-in lens mask lithography realizes 3D imaging by a single exposure using a conventional proximity exposure system. 3D structures are divided into seed elements with different depth of focus, and the complex amplitude of the mask is designed by combining the wavefronts that image these elements. However, due to the interference of the seeds, the three-dimensional image may be missing. For this reason, it has been necessary to set the seed pattern based on empirical knowledge. In this paper, we have developed a system to automatically design the seed pattern. The system calculates the light intensity-distribution in space and places seeds with opposite phases to cancel where excessive image remains. On the other hand, additional seeds are placed in space where light intensity is not sufficient. This procedure is repeated step by step until the required image is obtained. Computational lithography will show that this results in the required 3D image.

Keywords: Optical lithography, 3D image, Aerial image, Built-in lens mask

1. Introduction

3-dimensional fabrication has been increasing required for fine micro-scale devices such as advanced microfluidic devices, micro- and nanostructured electromechanical systems, advanced biomimetics systems, and wiring at deep steps in advanced integrated circuits.

Several beam technologies and 3-D printing technology have been proposed for the fabrication of three-dimensional (3D) micro- and nanostructures [1-6].

Si micro machining using sacrificial layers is one of promising approaches [7]. Beam-based processing methods have been proposed, such as focused ion beam deposition techniques [8] or multi-beam exposure methods based on two-photon absorption [9]. Formation of 3D structures has been demonstrated using nanoimprint techniques [10,11] or a multiple exposure technique [12] based on conventional photolithographic processing. Furthermore, microdevice fabrication has also been demonstrated using 3D printer systems [13].

However, these more conventional methods require long production times because they use multiple exposures and step-by-step processing, and they need beam scanning and/or stage movement. As a result, huge processing time is required for integrated 3D structures.

On the other hand, novel 3D photolithography approaches that are based on single-shot exposure without beam scanning or stage movement through a photomask have been proposed, including inverse lithography [14], and holographic lithography [15-17], however, these methods could only be applied to the exposure of two-dimensional or periodic patterns. Also, they need specific optical systems such as lens or millers.

To solve these problems, we previously proposed a novel 3D photolithography method that used the multi-focusing function of built-in lens mask lithography [18] and demonstrated the 3D imaging process capability through computational lithography simulations [19-21].
2. 3-D Photo Lithography by built-in lens mask

The built-in lens mask is an optically transparent mask with complex optical transmittance characteristics (in terms of the amplitude and phase of the optical wave). When coherent light is used to irradiate a built-in lens mask, the complex optical amplitude of the light that is transmitted through the mask is modified. Designing of the complex transmittance, multiple focused imaging could be realized by single mask and single shot. Then, imaging at voluntary focus depth could be realized. Then, 3D imaging could be realized when the 3D structures are divided into seed elements and the complex amplitude of each seed is superposed on a mask. The details of the mask and the associated processes were described theoretically and experimentally in our previous work [19,20]. However, due to the interference of the seeds, a part of three-dimensional image may be missing or unexpected ghost is coming out. For this reason, it has been necessary to set the seed pattern based on empirical knowledge.

To overcome the problem, we have developed a system to automatically design the seed pattern.

3. Automatic seed optimization

Figure 1 shows schematics of automatic seed optimization system. Firstly, the demanded 3D structure is divided into small seeds, which are usually around a quarter of exposure wavelength. Then, the optical intensity in the space is calculated by the seeds. The system calculates the light intensity-distribution in space. Then, the system calculates the light intensity-distribution in space and places seeds with opposite phases to cancel where excessive image remains. On the other hand, additional seeds are placed in space where light intensity is not sufficient. This procedure is repeated step by step until the required image is obtained. As a result, the system automatically relocates the seeds to compensate for the inconveniences.

The procedure of the seed optimization is as follows: Firstly, image intensity profile $I_i(x,y,z)$ in space is calculated for given seed pattern. Then the differential $\delta I$ between the desired profile $I_0(x,y,z)$ and $I_i(x,y,z)$ is evaluated as:

$$\delta I(x,y,z) = I_0(x,y,z) - I_i(x,y,z).$$  \hspace{1cm} (1)

When the expected image intensity is weak or missing, the intensity of the seed $I_{seed}(x,y,z)$ is revised as:

$$I_{seed}(x,y,z)^{n+1} = I_{seed}(x,y,z)^n + \delta I(x,y,z) \times f_1/n,$$

where $n$ is the number of iterations.

On the counterraly, when the image is generated on unexpected area, the intensity of seed pattern is revised as:

$$I_{seed}(x,y,z)^{n+1} = I_{seed}(x,y,z)^n + \delta I(x,y,z) \times f_2/n,$$

where $f_1$ and $f_2$ are feedback coefficients.

Beside intensity revision of the seed, phase inversion of the seed is also performed to prevent interference due to additional seed patterns with the each other.

4. Results and discussion

We demonstrate exposure results of novel 3D structures using the proposed systems by computational study.

Figure 2 shows line pattern on step of 20 $\mu$m in height. The space of each line is 10 $\mu$m. The gap between the mask and substrate is 60 $\mu$m. The exposure wavelength $\lambda$ is 365 nm. Figure 2 (a) shows initial seed pattern. Without optimization, the image intensity profile has missing portion nearby step edges as shown in Fig.2 (b) due to interference. After optimization, the missing parts are recovered and fine line pattern with 2.0 $\mu$m in width is successfully obtained.

The number of iterations for optimization was only once, where convergent parameters were $f_1=0.01$, and $f_2=0.001$, respectively.
Figure 3 shows three-dimensional frame structure. There are three parallel rods of 40 μm in length with 20 μm in spacing, and connecting with each other. The exposure wave length λ is 365 nm. Without optimization of seeds, there are some missing portions due to interference. After optimization, file rod connected structure is successfully obtained as shown in Fig.3 (c), where the rod size is about 3.0 μm. In this case, the number of iterations was 4 times.

5. Conclusion
Smart optimization system of seed patterns for 3-dimensional imaging using the built-in lens mask is newly proposed. We confirmed the optimization methods is effective for elimination of fatal defects such as pattern missing due to interference.

Using the system, we demonstrated automatic optimize of seed arrangement for line pattern along a step and parallel frame structure. As a result, fine 3-dimensional photolithography is successfully confirmed by optimization of the seed using proposed smart system.

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