Optik 124 (2013) 3292–3295

Contents lists available at SciVerse ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Pixel-based partially coherent image method for maskless lithography system

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ARTICLE INFO

Article history:
Received 28 April 2012
Accepted 12 October 2012

Keywords:
Maskless lithography (ML)
Digital micro-mirror device
Pixel
Matrix multiplication

ABSTRACT

Maskless lithography (ML) provides a fast and low-cost method for projecting the images of IC or micro features onto photoresist. However, it needs an efficient simulation method to evaluate the performance of lithography process. In this paper, a pixel-based partially coherent image method for digital micro-mirror device (DMD) based ML is proposed based on the linear invariant theory. In our method, the mask is sampled by DMD pixel (each pixel corresponding to each micro-mirror) and expressed by *rect* function. Using the shift theory of Fourier transform and the stacked pupil operator approach, we build a matrix Φ for system response function of *rect* function. If the DMD pixel state matrix is S, then the aerial image can be calculated with two matrix multiplication $I(x,y)=S\Phi$.

1. Introduction

Maskless lithography (ML) provides a fast and low-cost method for projecting the images of IC or micro features onto photoresist [1,2]. The ML is preferred for the specialized applications of defense and academic research in which the fabrication cost of the masks is relatively high for many of application-specific components that are usually used, while the production volume of each component is small. Resent progress of high-resolution spatial light modulator (SLM) devices has generated the commercialization of compact SLM chips, which contain as much as 1024×768 pixel elements, with a typical size of 13.8–30 μm. These commercial SLM products readily provide a convenient dynamic pattern generator to replace the traditional photomasks. Many papers have reported the application of DMD as an SLM for digital lithography due to its high brightness, high resolution, high contrast and quick response [3,4]. But the technique is still in exploration and research stage. In DMD-based digital lithography system, the mask is sampled with DMD mirror (pixel), and each DMD mirror can be switched between stable positions with the light reflecting "on" and "off" directions.

With the wide application of ML, an efficient simulation method for maskless lithography with consideration of the imaging character of SLM is an urgent need. Limaye established a map relationship between DMD-pixels and resin surface pixels through the ray trace method in 2004 [5], which is the time consumed and improved in 2007 [6]. But in Limaye method, he regards the projection lithography as an aberrations limited system and regardless diffraction. Sun et al. built up DMD-based projection lithography based on diffraction theory [7], he established a point-spread function (PSF) to map DMD-pixels and resin surface pixels, and the image is formed by the linear superposition of flux-density contributions of the light spot that emitted from DMD. While in his method, the partially coherent is neglected. In our previous research, we regarded DMD mask as an integral, and stacked pupil shift method hybrid the imaging characteristics of DMD was used to simulate the image process of lithography system [8], which is high computationally efficient, but not conducive to optical proximity correction (OPC) or mask optimization.

This paper focuses on the development of computationally efficient pixel-based imaging algorithm for SLM-based ML in partially coherent systems. In this paper, DMD is selected as an SLM for mask generator; the system analysis method is adopted in the modeling imaging process. The rest of this paper is organized as follows: The DMD-based digital lithography system is discussed in Section 2. Pixel-based imaging algorithm is developed in Section 3. In Section 4 some simulations are done. And conclusion will be given in Section 5.

2. DMD-based maskless lithography system

The developed DMD-based dynamic projection photolithography system is schematically shown in Fig. 1. It is an integration of five major components: a partially coherent light source, a condenser lens, a DMD as the dynamic mask, a projection lens, and a wafer. The dynamic mask is the core component of the system, which determines the shape of the fabricated microstructure.

As the dynamic mask, the DMD modulates the light by collectively controlling the micro-mirror arrays to switch the light on and off for each individual pixel. The DMD pixel is an integrated

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http://dx.doi.org/10.1016/j.ijleo.2012.10.004

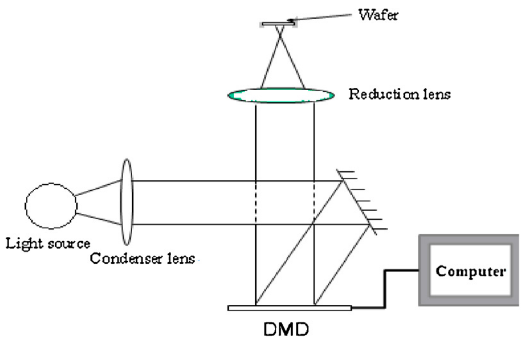

Fig. 1. Schematic diagram of DMD-based digital dynamic projection photolithography.

MEMS structure which is fabricated on a CMOS SRAM cell [3] refers to Fig. 2. The mirror (alumina) is rigidly connected to an underlying yoke. The yoke is connected by two thin, mechanically compliant torsion hinges (also aluminum) which are supported by the posts that are attached to the underlying substrate. The DMD promotes many unique advantages over the conventional LCD spatial light modulator. The DMD has smaller pixel size as well as narrow gaps between pixels, which allow higher display resolution and better intensity uniformity. Furthermore, the fast switching speed in DMD enables more precise control of the exposure time, which is particularly important in achieving gray-tone intensity modulation at pixel level. Thus, the major advantages of DMD enable the development of the high-resolution projection photolithography system. In optical lithography systems, the mask is generally illuminated by partially coherent quasi-monochromatic light. The light originates from an incoherent source and reaches the object plane. The mask patterns can be regarded as inputs to the imaging system.

3. Pixel-based imaging algorithm

3.1. Characteristic of DMD imaging

By toggling the voltage applied to the individual micro-mirror, the DMD mirror can be switched between stable positions with the light reflecting "on" and "off" directions. Two positions are permitted for the mirror to tilt at $+10^0$ (on state) or -10^0 (off state) along its diagonal shown in Fig. 3.

Assume the binary mask in DMD chip coordinate system is

$$M(x,y) = \sum_{m,n} \alpha_{mn} U_{mn}(x,y), \quad m = 1,2,3,\ldots,M, n = 1,2,3,\ldots,N, \tag{1}$$

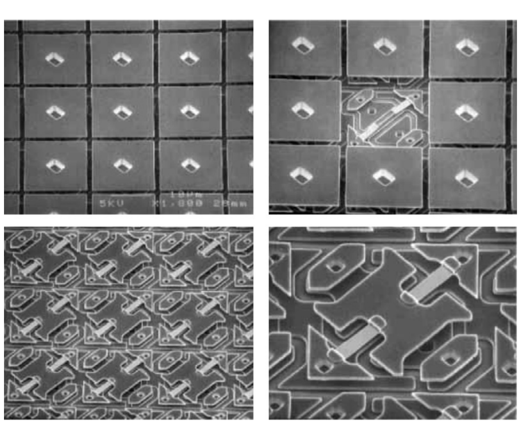

Fig. 2. SEM pictures of DMD mirrors [3].

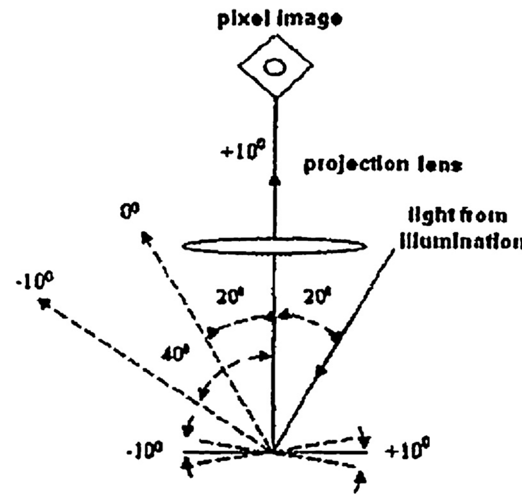

Fig. 3. Schematic diagram of single DMD projection imaging [3].

where

$$U_{mn}(x,y) = rect\left(x - mw_x + \frac{w_x}{2}, y - nw_y + \frac{w_y}{2}\right), \tag{2}$$

where $M \times N$ is the whole number pixels of DMD, $w_x \times w_y$ is the single pixel size of DMD, and

$$\alpha_{mn} = \begin{cases} 1, \text{the DMD pixel is on} \\ 0, \text{the DMD pixel is off.} \end{cases} \tag{3}$$

If we assume the optical system response function for *rect*(*x*,*y*) is $\Phi_r(x,y)$, according to the property of linear system, we obtain the total light intensity:

$$I(x,y) = \sum_{m,n} \alpha_{mn} \Phi_r\left(x - mw_x + \frac{w_x}{2}, y - nw_y + \frac{w_y}{2}\right) \tag{4}$$

then the key problem is using an appropriate method to calculate Φ_r. According to Eq. (4), the intensity of each point in the imaging plane is obtained by superposition of light distributions from all mask points, which is the meaning of diffraction and interference. Furthermore, α_{ij} is a binary variable, it is beneficial to optimization mask using the feature.

3.2. Calculate Φ_r

In DMD-base digital lithography system, the key problem is to compute the Φ_r. In other word, we should find an efficient method to obtain the intensity distribution of *rect* function in the imaging plane with partially coherent illumination. In this paper, we give a pixel-based method to deal with the problem.

According to Abbe's imaging theory [9], the light intensity distribution is obtained by an incoherent superposition of light intensities from all points and thus described by

$$I(x,y) = \sum_{s=1}^{N_s} J_s |H(x,y;f_s,g_s) \times M(x,y)|^2, \tag{5}$$

where J_s is the effective light source, $M(x, y)$ is the mask pattern, $H(x, y)$ is called point spread function. By substituting Eq. (1) into Eq. (5), and noticing the linear property, the