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Multi-step electron beam technology for the fabrication of high performance diffractive optical elements

A. Kowalik [a,*], K. Góra [a], Z. Jaroszewicz [b], A. Kołodziejczyk [c]

[a] Institute of Electronics Materials Technology Wólczyńska 133, 01 919 Warsaw, Poland
[b] Institute of Applied Optics, Kamionkowska 18, 03-805 Warsaw, Poland
[c] Warsaw University of Technology, Faculty of Physics, Koszykowa 75, 00-662 Warsaw, Poland

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Abstract

Optical performance, i.e. the diffraction efficiency, numerical aperture and wave front quality is of great importance for further successful application of diffractive optical elements in a wide range of research and commercial applications. For the fabrication process, simultaneously large numerical aperture and high diffraction efficiency result in a pattern with sub-wavelength resolution and a multi-level phase profile of nanometer accuracy. To fulfill such high requirements, a multi-step fabrication technique is proposed, in which the electron beam is used both for pattern writing and layout alignment. This method enables the fabrication of a structure with the $L = 2^n$ discrete phase levels in n sequential lithographic steps. In each step, the pattern written in a thin, high contrast resist layer is transferred after development into the substrate by reactive ion etching to form the phase profile. In comparison to the multi-mask binary optics technology, the proposed method offers a higher resolution and reduces the alignment errors to insignificant values. On the other hand, in comparison to the direct write analog technique, our approach allows for a much better control of the phase profile and ensures larger process tolerances.

The method has been successfully applied in the fabrication of several types of diffractive elements, including micro-Fresnel lens arrays, phase sampling filters and diffraction gratings on quartz and GaAs wafers. The diffraction efficiencies of these elements were found to be up to 92%. The lens exhibited diffraction-limited focusing characteristics and an insignificant wave front aberration (rms 0.01λ).

Keywords: Micro-optics; Diffractive optical elements; Diffractive microlenses; Electron-beam lithography; Reactive ion etching

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[*] Corresponding author. Tel.: +48 22 835 30 41; fax: +48 22 834 90 03.

E-mail address: akowalik@itme.edu.pl (A. Kowalik).

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1. Introduction

The rapid progress in the development of semiconductor light emitters and the continuous process of miniaturization have made micro-optics one of the fastest developing fields of microtechnology in recent years. Among various kinds of micro-optical elements, diffractive optical elements (DOEs) are especially attractive because of their functional flexibilities in handling wavefront conversion as well as their planar, compact and lightweight nature which makes them suitable for integration with micro-electro-mechanical devices (MEMS, MOEMS) [1]. However, quality and optical performance are of crucial importance for the successful application of DOEs. The most important parameters in their evaluation are diffraction efficiency, numerical aperture (NA), and the quality of diffracted wave front [2]. From the fabrication viewpoint, large NA and high diffraction efficiency will result in a pattern with sub-wavelength resolution and multi-level phase profile that has to be controlled with nanometer accuracy. In spite of the rapid development of DOEs fabrication techniques observed during last years, only a few methods demonstrate the potential to fulfill such high requirements [3,4]. The most advanced of these methods are based on the semiconductor processing technology and can be broadly divided into two major groups:

(1) Multi-mask binary methods, sometimes referred to as 'binary optics' [5,6], in which n sequential photolithographic processes are used to form a structure with $L = 2^n$ discrete phase levels. In each process a standard 'binary' photomask, i.e. the mask consisting of clear and opaque areas only, is used to copy the pattern on the substrate followed by wet or dry etching.
(2) Analog methods [7–13], where variable-dose writing is used to achieve a multi-level or even semi-continuous relief in the resist layer, then transferred into the substrate by proportional dry etching. In order to form a structure with n phase levels, n different doses have to be used.

The electron-beam lithography is still unrivalled in its ability to provide precision pattern of DOEs. The flexibility of pattern generation, high accuracy and submicrometer resolution make the e-beam lithography the most useful technology for direct pattern writing in the application of the analog method and also for the photomasks fabrication while using the binary method. However, constraints in both methods make it impossible to take full advantage of the direct e-beam writing resolution.

The purpose of this paper is to present a multistep fabrication technique, in which the electron beam is used for pattern writing as well as for layout alignment. In our opinion, this technology combines the advantages of both the binary method and the analog one (better profile control, no misalignment errors) and reduces to a significant degree their shortcomings. In Section 2, we begin by outlining the errors arising in both the analog and binary methods and show how they influence DOE efficiency. The potential of our solution is presented in Section 3. The fabricating process of multi-level DOEs is briefly described in Section 4. Finally, in Section 5, the results of measurements taken for the eight-phase-level quartz diffraction gratings and Fresnel microlenses are demonstrated, which confirm well the high resolution and accuracy of the method for both the pattern registration and profile forming.

2. Constraints of analog and multi-mask binary methods

The direct write e-beam analog method seems to be especially attractive due to the possibility of fabricating a complete multi-level structure in a single lithography step. However, a number of obstacles complicate such a method [7]. The most important of them result from the specific requirements of the method, different from those of the standard lithographic processes. It is commonly known that the resolution and accuracy of any lithographic process depend strongly on the resist layer thickness and contrast of the resist – the thinner the layer and higher the contrast, the higher