Microelectronic Engineering 132 (2015) 120–134

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Review Article

High-resolution proximity lithography for nano-optical components

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ARTICLE INFO

Article history:
Received 10 June 2014
Received in revised form 11 October 2014
Accepted 13 October 2014
Available online 19 October 2014

Keywords:
Optical lithography
Proximity exposure
Resolution enhancement techniques
Mask aligner
Nano-optics
Periodic structures

ABSTRACT

Mask aligner lithography, based on shadow printing, is one of the most natural approaches to microfabrication. For high-yield processing, however, contact-free proximity exposures are required, which have stringent resolution limitations. Therefore, resolution enhancement techniques (RETs) for proximity lithography have been a field of extensive research over the past four decades. Refinements like X-ray proximity lithography, near field holography (NFH), phase-shifting masks (PSM), Talbot lithography (TL), holographic lithography, displacement Talbot lithography (D-TL), and rigorously optimized phase-shifting masks (RO-PSM) have been proposed to combine flexible and economical process conditions with high resolution potential. In conjunction with ongoing technical innovations for the mask-to-substrate distance metrology, leveling, illumination optics, and photomask technology, the application potential of proximity lithography has extended significantly compared with the established process of shadow printing. This review provides a comprehensive overview of resolution enhancement techniques and technical innovations in mask aligner lithography, especially the fabrication of periodic structures for nano-optical components. The review concludes with a comparative discussion of the different techniques.

1. Introduction

1.1. Optical nanostructures

Classical optical nanostructures like binary [1–3] and blazed [4–6] diffraction gratings enable the spectral discrimination and angular redistribution of light which was first observed more than 300 years ago [7]. They define a class of optical components which have found versatile applications e.g. in spectrometers [8,9] since the early days of optical instrumentation [10,11] and are essential building blocks for modern optical systems [12–16], light sources [17–21], and optical communication devices [22–24]. Recently, many novel optical nanostructures with unique functionality have appeared: Wire grid polarizers (WGP) [25–27] can achieve polarization discrimination over a broad spectral range and even for deep ultra-violet (DUV) wavelengths. Nano-optical retarders [28–31] can alter the polarization state of light to generate circular, radial or azimuthal polarized beams [32,33]. Both options are e.g. important for state-of-the-art lithography tools [34–36]. Optical nanostructures referred to as resonant waveguide gratings (RWGs) [37,38] can be used as high quality mirrors or filters with a spectral and angular response that can be tuned precisely by structure design. These elements have a unique application potential e.g. in optoelectronics for vertical-cavity surface-emitting lasers (VCSELs) [39], or for reflective cavity couplers [40]. The extensive class of optical nanostructures with two-dimensional geometries like pillar or hole arrays, mainly referred to as two dimensional photonic crystals (PCs) [41] or in more specific applications e.g. as patterned sapphire substrates (PSS) [42,43], can be used to enhance the efficiency of light extraction or in-coupling of (organic) light-emitting diodes (O)LEDs [44–50], detectors [51–54] and solar cells [55–61] as well as the sensitivity of optical bio sensors [62–67]. This class is, accordingly, of very general interest.

The nanostructures described have notable attributes in common: They are composed of high resolution features with critical dimensions (CDs) down to 100 nm and below (e.g. WGP) which are typically extended over large areas with edge lengths in the range of several centimeters. It is also important to emphasize that all geometries described are periodic, which is very typical for optical nanostructures. Elements for applications which require strong dispersion and very high diffraction efficiency like, for example, binary diffraction gratings for chirped pulse amplification (CPA) [17,18] work best with periods in the upper sub-micron range (400 nm . . . 1000 nm). Wire grid polarizers need sub-wavelength periods for a good performance which calls for

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http://dx.doi.org/10.1016/j.mee.2014.10.010

periods in the range of 200–100 nm and below. Blazed spectrometer gratings for broadband applications benefit from a larger period (e.g. 3 μm, accordingly with reduced dispersion) but require a binary [68–70] or continuous sub-structure to concentrate the light in a single diffraction order. Two-dimensional structures again can be useful over the full range from very small periods to several microns where small periods are beneficial for light extraction and in-coupling in the UV and visible. Infra-red (IR) applications and PSS which, in addition to the optical function facilitates the growth of InGaN on sapphire [42,43], can work well with larger periods and e.g. cone shaped profiles. Light management structures for solar cells typically have to work for a broad angular and spectral range and can therefore partly benefit from a larger period and an engineered sub-structure [71,72].

1.2. Fabrication technologies

The fabrication of optical nanostructures requires high resolution lithography on large areas. Especially for applications in which the components fulfill a critical task of the optical system like e.g. pulse compression gratings in an ultra-fast laser or a WGP in the illumination set-up of a lithography tool, superior quality and strict observation of the specified fabrication tolerances is required. This can be addressed by a component fabrication based on electron-beam lithography (EBL) [73,74,70] which allows for a very flexible maskless exposure of high resolution structures. The drawback of the technology is the sequential writing scheme of EBL, which leads to exposure times of several hours per substrate and defines a critical bottleneck for the scalability. Much better throughput-scalability is accessible by optical projection lithography [75] which also offers a very high resolution. Unfortunately, with small exposure fields and limited substrate flexibility, this technology is highly optimized for the semiconductor industry and comes with investment costs which can be even higher than those for EBL. Adaptations for optical applications are probably possible but the lot sizes for optical components are normally not large enough to justify the establishment of projection lithography exclusively dedicated to optical nanostructure fabrication.

1.2.1. Mask aligner lithography

Scalable micro-fabrication with a significantly reduced degree of complexity and financial expense is possible by full-field contact or proximity lithography in a mask aligner [75]. Placement of the resist-coated substrate in contact or at a distance of 20–100 μm in parallel to a photomask allows pattern transfer by simple geometrical shadow printing. This is probably one of the most natural approaches to micro-fabrication and has been utilized since 1872 when Lord Rayleigh used it for copying diffraction gratings [76,77]. The critical point of this approach, however, is a fundamental trade-off between resolution and yield: The depth of focus (DOF) of a light distribution with high-resolution features is strongly limited, no matter whether it has been generated by a demagnifying projection objective or by shadowing of an opaque mask with small apertures. Accordingly, mask aligner lithography in the conventional sense can only offer a high resolution if substrate and mask are brought into close contact, since the mask interface usually defines the plane of best pattern fidelity (Fig. 1). Using DUV (193 nm) illumination, a resolution of 200 nm has been reported [78] for contact lithography, but the severe mechanical stress on substrate and mask results in contamination and potential damage to the mask. The accumulation of contamination reduces the quality of the contact from substrate to substrate within a batch and requires frequent mask cleaning to maintain a good resolution.

Contact-free proximity lithography in contrast allows a convenient and economic large scale production capability with an almost unlimited mask life. However, the separation between mask and substrate implies that not the mask geometry itself but its defocused near field diffraction pattern is recorded (Fig. 1). The similarity between aerial image and mask geometry degrades with increasing separation while the slope of resolution reduction is particularly strong for small gaps. This defines a stringent resolution limitation to critical dimensions larger than 2–3 μm [79], even for the smallest reasonable separations between mask and substrate of 10–25 μm. For many less critical lithography layers e.g. in backend semiconductor lithography and LED manufacturing, this resolution is still sufficient and the technology is extensively used in large-volume production. For optical nanostructure fabrication with resolution demands in the deep sub-micron range, conventional mask aligner lithography cannot be used beneficially.

1.3. Early attempts for resolution enhancement

To make use of the expedient and economic process conditions of proximity lithography for more demanding applications, several attempts for resolution enhancement have been made in the past.

In the 1970s, the use of shorter wavelengths was proposed to enable a higher resolution while maintaining a reasonable separation between mask and substrate. Since the resolution increase for shadow printing is less than linear with the wavelength (c.f. Fig. 1 top right), very short wavelengths in the X-ray region (e.g. 4.5 nm) are necessary to realize a major improvement. Great efforts have been made to establish X-ray proximity lithography (e.g. [80,81]) but the need for X-ray sources which are difficult to collimate or focus, the necessity for a thin membrane mask with thick absorbing layers (e.g. gold), and the necessity for operation under vacuum or Helium conditions caused a significant increase in complexity [82] and finally prevented the breakthrough of the technology.

Back in the UV wavelength range, Levenson et al. proposed in 1982 the use of binary phase-shifting masks (PSMs) to increase contrast and depth of focus of aerial images in lithography [83]. The original publication and many subsequent studies (e.g. [84]) focus on the application of this method for projection lithography, but already in this work the potential for resolution enhancement in proximity lithography was emphasized. In contrast to projection lithography, for which the phase-shifting method was explored in-depth [85], it was not realized for generalized geometries in proximity lithography for over 30 years. Recent works [86,87] have picked up the PSM concept again to achieve better resolution, contrast and depth of focus and will be discussed in detail in Sections 3.3 and 4.3.

1.3.1. Near-field holography

Even though not considered in this context at that time, the special case of ultimate resolution for given illumination wavelength (minimum pitch down to half the wavelength) based on the phase

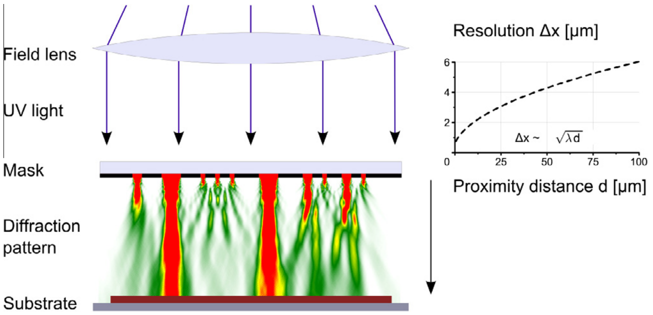

Fig. 1. Trade-off between resolution and yield in conventional shadow printing based mask aligner lithography.