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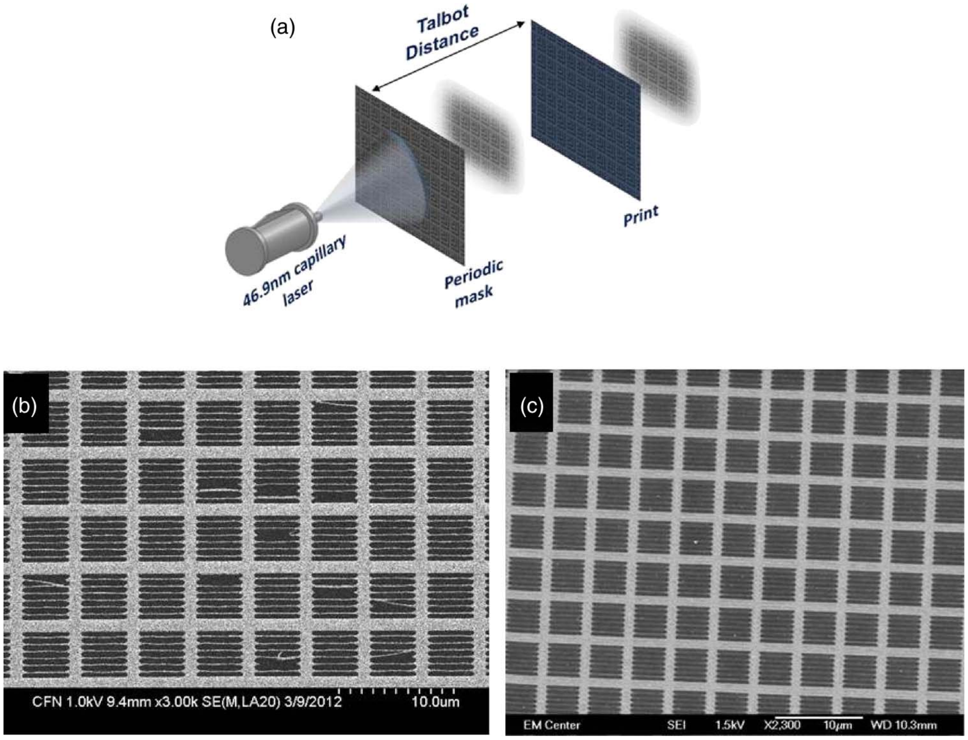

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Breakthroughs in Photonics 2012: Nano-Structuring and Nano-Fabrication Enabled by Extreme Ultraviolet Laser Sources

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Abstract: Two- and three-dimensional structures with submicron dimensions, such as photonic crystals, patterned magnetic media, micro- and nano-electromechanical systems (MEMs/NEMs), microfluidics chips, etc., are becoming ubiquitous in multiple applications across many research fields. The necessity to engineer these devices has inspired the development of novel nanofabrication and nano-patterning methods. This review describes major accomplishments in laser-based nano-patterning and nano-fabrication methods. In particular, it focuses on newly developed nano-patterning techniques based on the use of extreme ultraviolet laser light that contributes to the rapid and efficient fabrication of periodic nano-structures.

Index Terms: Talbot imaging, EUV lasers, coherent lithography.

Rapid advances in nanosciences and nanotechnology are creating the necessity for the implementation of new methods to fabricate and manipulate objects with nanometer dimensions. Nanofabrication is intimately related to the microelectronic industry. This fueled a continuous effort to miniaturize components following the basic concept that smaller means better: higher density packaging, faster response, lower cost, lower power consumption, and overall higher performance. Toward this objective massive amount of resources have been invested in the development of extremely sophisticated lithographic tools that are presently aiming to improve resolution in the 14-nm node [1]. Although these lithographic tools utilize photons for the nanopatterning process, they will not be reviewed in this paper. There are however many applications for which these photolithography tools are not well suited, like low volume production or prototyping in research applications. The implementation of alternative nano-patterning techniques especially adapted to generate periodic structures will be beneficial to the faster development of nano-technology. Examples of devices that require periodic structures and has a low volume nanofabrication needs are UV polarizers, fabricated with dense arrays of metal nanowires [2], plasmonic structures [3], photonic crystals [4], high-density magnetic memories [5], miniaturized RF oscillators [6], among others.

The use of lasers for lithography is well established when coherent illumination is required. Interferometric lithography (IL) has been one of the most widely exploited methods to print periodic structures. The extension of this technique to the nanoscale requires the development of innovative concepts to overcome the diffraction limit One interesting nano-patterning approach that allows overcoming the diffraction limit inherent to optical systems utilizes surface plasmon resonances [7], [8].

IL, also referred as holographic lithography, is ideally suited for low-volume patterning of periodic structures. In IL, the patterning is achieved combining mutually coherent light beams at the surface of a photoresist coated substrate. The intensity distribution produced by interference generates the nanostructure that defines the lithographic mask. This approach allows for a simple way to fabricate periodic structures over large areas [9]. Recently, a novel IL technique that uses up to six exposures with a precise control of the polarization has allowed for the fabrication of 3-D photonic crystals with defined chirality [10]. Multiple-beam IL produced by especially designed diffraction gratings masks has generated 2-D arrays of holes or pillars arranged in rectangular or circular patterns [11]. Subwavelength (22-nm half-pitch) triangular groves were fabricated in Si using a self-aligned technique defined as spatial frequency doubling [12].

One path to print features with nanometer scale dimensions is reducing the wavelength of the illumination. This has led to the demonstration of IL at the extreme ultraviolet and X-ray wavelengths achieving half-pitch resolution of 12.5 nm [13]. A simple interferometer scheme well adapted to EUV wavelengths where high-efficiency optics is not readily available is Lloyd's mirror interferometer. Lloyd's mirror interferometer was used with synchrotron illumination to fabricate gratings in different photoresists with sub-20-nm linewidths utilizing 13.4-nm wavelength illumination [13], [14]. Using the second-order diffracted orders in a two-grating mask, an improvement of 4X reduction in the printed period was demonstrated [15].

The development of EUV and soft X-ray lasers that can easily fit on an optical table facilitated the implementation of different nano-patterning test beds based on IL, coherent imaging, and nano-ablation [16], [17]. The characteristics of compact EUV sources, short wavelength, high flux, and excellent spatial and temporal coherence allows for the demonstration of nano-patterning tools with the capability to print sub-100-nm features. Two schemes of IL were demonstrated with table-top EUV lasers, using a wavefront division interferometer based on Lloyd's mirror configuration and an amplitude division interferometer utilizing a Mach-Zhender configuration. Double exposures and dose control allowed printing cone-shaped nanodots with a full width at half-maximum of 55 nm, arrays of holes or lines over surfaces in excess of 500 μm × 500 μm [17], [18]. However, IL is limited to periodic structures, like gratings, or arrays of pillars and holes. To overcome this limitation, other coherent imaging approaches can be implemented taking advantage of the highly coherent emission of the EUV table-top lasers. Holographic projection lithography is one approach that requires the fabrication of a computer-generated hologram (CGH) that is utilized to print the photoresist [19]. Projecting the CGH onto the photoresist allows for the printing of arbitrary patterns.

Talbot lithography has emerged as an interesting alternative for patterning periodic structures. In this configuration, the coherent illumination is utilized to generate self-images (or Talbot images) of a periodic semitransparent mask. This technique was utilized to fabricate photonic crystals in what was defined as coherent diffraction lithography [20], [21]. A generalization of the Talbot imaging was demonstrated in the EUV utilizing a semitransparent mask. In the generalized Talbot imaging, the mask was composed of an array of tiles or unit cells, each one with an arbitrary design arranged in a square matrix [22]. Although the Talbot imaging is essentially a 1 × replication technique, changing the phase of the illumination beam, it was possible to demonstrate modest demagnification factors maintaining the simplicity of the printing setup [23]. Probably, the most appealing characteristic of the Talbot lithography is its ability to render defect-free images of defective masters. From a heavily damaged master Talbot mask, it is possible to render defect-free images in the photoresist that can be used as a sacrificial mask for processing and fabrication of functional devices. Fig. 1 is an example of this capability. Fig. 1(a) shows the experimental setup of the Talbot lithography scheme. A periodic 2-D semitransparent mask is illuminated by a highly coherent EUV beam from a table-top capillary discharge laser. At the Talbot distance, a photoresist coated substrate is placed to record the self-image of the mask, producing a 1 × replica of the master. Fig. 1(b) and (c) shows the capability of this lithographic method to produce defect-free prints. A heavily damaged periodic mask [see Fig. 1(b)] composed of an array tiles each one formed by a set of 100-nm slits was used to print a photoresist and transfer the structure onto a Au layer. The transferred array [see Fig. 1(c)]

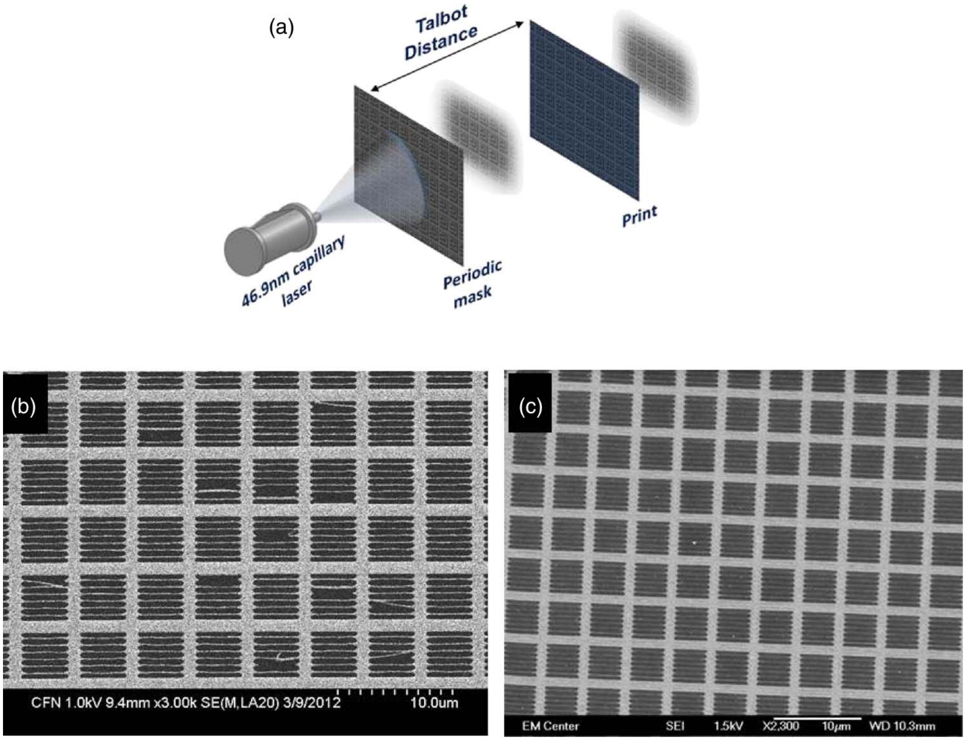

Fig. 1. Demonstration of defect-free fabrication. (a) Experimental setup. (b) A coherent EUV laser renders a defect-free image of a periodic mask at the Talbot distance. (c) Defective Talbot mask utilized to print a defect-free photoresist pattern that was transferred to a Au layer using ion etching to obtain a defect-free metallic structure.

shows no defect. This characteristic would be an asset in a fabrication process because to a certain extend the defects in the Talbot mask are not registered in the print [24], [25].

In summary, the table-top EUV Talbot lithography is a valuable alternative to low volume nanopatterning and is especially adapted to the fabrication of periodic structures. The ultimate resolution of the method is primarily set by the numerical aperture of the Talbot mask. Increasing its size can improve the resolution of the patterning method. Alternatively, the continuous advances in table-top EUV sources at shorter wavelengths (in the vicinity of 13 nm) will further improve this resolution [26]. For example, with illumination around 13 nm, a mask period of 1 μm, and mask overall width of 1 mm, at the fifth Talbot plane, the expected resolution is less than 10 nm. In addition to this direct approach for improvement, as the imaging conditions approach the diffraction limit, it may be possible to resort to the optical pattern corrections typical of optical lithography, thus extending even further the applicability of the technique.

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