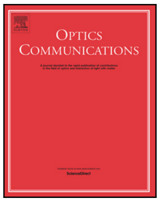
Contents lists available at ScienceDirect

Optics Communications

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



Pushing the plasmonic imaging nanolithography to nano-manufacturing

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A R T I C L E   I N F O

Keywords:
Surface plasmon
Diffraction limit
Subwavelength optics
Super resolution
Nanolithography

A B S T R A C T

Suffering from the so-called diffraction limit, the minimum resolution of conventional photolithography is limited to $\lambda/2$ or $\lambda/4$, where λ is the incident wavelength. The physical mechanism of this limit lies at the fact that the evanescent waves that carry subwavelength information of the object decay exponentially in a medium, and cannot reach the image plane. Surface plasmons (SPs) are non-radiative electromagnetic waves that propagate along the interface between metal and dielectric, which exhibits unique sub-diffraction optical characteristics. In recent years, benefiting from SPs' features, researchers have proposed a variety of plasmonic lithography methods in the manner of interference, imaging and direct writing, and have demonstrated that sub-diffraction resolution could be achieved by theoretical simulations or experiments. Among the various plasmonic lithography modes, plasmonic imaging lithography seems to be of particular importance for applications due to its compatibility with conventional lithography. Recent results show that the half pitch of nanograting can be shrinked down to 22 nm and even 16 nm. This paper will give an overview of research progress, representative achievements of plasmonic imaging lithography, the remained problems and outlook of further developments.

1. Introduction

Optical lithography, a vital stage and fundamental process in integrated circuit (IC) manufacturing [1,2], is a key driver for shrinking the size of transistors [3], to build even smaller, faster and cheaper chips. However, the resolution of conventional photolithography is limited by Rayleigh formula $k \times \lambda/NA$, where k is a process factor, λ is the illumination wavelength, and NA is the numerical aperture of the projection optics. Although by shortening the exposure wavelength and increasing the numerical aperture of the projection lens can achieve a smaller feature size, as demonstrated in 193 nm immersion lithography or extreme ultraviolet (EUV) lithography, the latest 193 nm immersion lithography with single exposure has approached the resolution limit (~38 nm, ~1/5 illumination wavelengths) [4]. Furthermore, the EUV lithography has not yet in full-scale high-volume manufacturing (HVM) stage, which faces enormous challenges in the achievement of the next-generation lithography node.

Various nanofabrication equipments and technologies with high resolutions are available in the current stage, including electron beam lithography (EBL) [5–7], focused ion beam (FIB) [8–11], nanoimprint lithography (NIL) [12–15], thermal scanning probe lithography (t-SPL) [16–18], *etc*. Since EBL and FIB operate in a point-by-point writing manner, they are expensive and inefficient. NIL seems to offer a high-throughput and low-cost method, but it needs further improvement in defect control and alignment [19]. Although t-SPL is an alternative technology for the manufacturing of sub-20 nm nanopatterns and the throughput can achieve the $10^4 - 10^5 \mu m^2 h^{-1}$ range, but it still far from high-volume technique requirement ($>10^{12} \mu m^2 h^{-1}$) [20]. Therefore, it is significant to find an effective way to break the diffraction limit under the conventional optical lithography architecture.

In recent years, many valuable experiments were carried out on how to beat the diffraction limit of optical lithography. These approaches include two-photon photopolymerization [21,22], sub-diffraction lithography based on stimulated emission depletion (STED) [23–25] and absorbance modulation [26]. Unfortunately, these methods do not break the limit at the optical devices level. Some scientists also proposed to improve the resolution by use of two or more quantum entangled photon [27–29], but the implementation is too complex and the efficiency is rather low.

The emergence of surface plasmon subwavelength optics [30] has brought an opportunity to break the diffraction limit of optical lithography. In the 1950s, Ritchie did pioneering work on surface plasmons (SPs) by investigating the plasma losses of fast electrons in thin films [31]. In a general case, SPs are non-radiative electromagnetic waves that

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http://dx.doi.org/10.1016/j.optcom.2017.06.059
Received 22 March 2017; Received in revised form 12 May 2017; Accepted 15 June 2017

Please cite this article in press as: P. Gao, et al., Pushing the plasmonic imaging nanolithography to nano-manufacturing, Optics Communications (2017), http://dx.doi.org/10.1016/j.optcom.2017.06.059.

propagating at the interface between metal and dielectric, and their interaction with free electrons of metal can form surface plasmon polaritons (SPPs) [32,33]. The properties of SPs, including ultrashort wavelength [34] and evanescent field enhancement [35], enable SPs a potential way to break both the far-field [36] and near-field diffraction limit [37].

In 2003, Luo et al. carried out researches on sub-diffraction-limited optical lithography with SPPs [38]. Photoresist nanogratings with 50-nm half-pitch were fabricated by surface plasmon resonant interference nanolithography technique (SPRINT) at g-line (436 nm) illumination [39,40]. The interference pattern was imaged from the top of the mask to the image plane, demonstrating that the metallic mask can be simultaneously used to generated pattern and form super-resolution images. It was predicted that sub-25 nm feature size can be allowed by SPPs [41]. In 2005, the recovery of evanescent waves in an image by the excitation of surface plasmons in superlens was experimentally demonstrated by Fang et al. Sub-diffraction-limited imaging with 60-nm half-pitch resolution can be obtained by using 35 nm silver superlens at a exposure wavelength of 365 nm [42]. After the publication of these representative works, plasmonic lithography has attracted widespread concern. It was thought that plasmonic nanolithography may be an alternative to the complex and costly modern projection lithography techniques [43]. However, developing deep subwavelength plasmonic lithography over large surface remains one of the major challenges of modern plasmonics [44]. In recent years, researchers have proposed a variety of lithography methods in the manner of interference [45–50], imaging and direct writing [51–56] by theoretical simulations or experiments. Among the plasmonic lithography techniques, plasmonic imaging lithography seems to be of particular importance to real applications as its large scale, high throughput, high resolution, high aspect profile and fidelity. Hence, in the following sections, we will comprehensively review the latest achievement on plasmonic lens designs, resolution enhancement techniques, practical applications, and system integrations.

2. Sub-diffraction features of SPPs

2.1. Ultrashort wavelength

By solving Maxwell's equations and matching the boundary conditions, the dispersion relationship of SPPs at the interface between two semi-infinite mediums is given by [34]:

$$k_{SP} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}} \tag{1}$$

where ω is the angular frequency of light, c is the light velocity in vacuum, ε_m and ε_d are the permittivity of metal and dielectric, respectively. Obviously, SPPs are slow waves and their dispersion curve is located at the right side of the light line in the diagram of transverse wave vector k_x and angular frequency ω. Therefore, the wavelength of the excited SPPs can become much shorter compared to the wavelength of the excitation light (Fig. 1(a)); which means the spatial resolution is greatly enhanced (Fig. 1(b)). At proper conditions, the effective wavelength of SPPs can be shrinked to the X-ray range [39].

2.2. Evanescent field enhancement

One of the unique properties of SPPs is the enhancement of evanescent wave, which can be expressed in a closed-form. Considering a thin slab with negative refractive medium of thickness d, dielectric constant ε_2 and magnetic permeability μ_2 sandwiched by medium 1 (ε_1 and μ_1) at object plane and medium 3 (ε_3 and μ_3) at imaging plane. Object plane and imaging plane are all at the distance d from the center of the slab.

For the electrostatic approximation and let p-polarized wave be incident, the transmission coefficient through the slab no longer depends on μ and is only relevant to the dielectric function [58]:

$$T_p\left(k_x\right) = \frac{4\varepsilon_2\varepsilon_3 \exp\left(-k_x d\right)}{\left(\varepsilon_1+\varepsilon_2\right)\left(\varepsilon_2+\varepsilon_3\right)-\left(\varepsilon_2-\varepsilon_1\right)\left(\varepsilon_2-\varepsilon_3\right)\exp\left(-2k_x d\right)} \tag{2}$$

The enhancement of the evanescent wave transmission depends on the condition of the dielectric constant. When $\varepsilon_1 \approx -\varepsilon_2 \approx \varepsilon_3, T_p\left(k_x\right) = \exp\left(k_x d\right)$ show exponential growth of the evanescent field (Fig. 2(a)). This surface-to-surface coupling of this metal slab enables the transmission of enhanced evanescent field through the slab for high resolution imaging, which is called superlensing. Ideally, with optimized design of multilayered superlens, the resolution of the superlens can reach 15 nm at 387.5 nm wavelength illumination (Fig. 2(b)).

3. Lens for plasmonic imaging nanolithography

For conventional projection optical lithography, the evanescent wave that carries the subwavelength information about the object decays exponentially in a medium and cannot reach the far-field image plane, resulting the so-called diffraction limit. By exciting the SPs of metal slab, the evanescent wave can be coupled and amplified, and thus be restored it in the imaging plane. In order to achieve a wider wave vector range and let more evanescent waves participate in super-resolution imaging, SPs should be excited and manipulated effectively. So it is essential to design plasmonic imaging lithography structures properly, which determines the resolution, fidelity, depth, working distance and efficiency.

3.1. Superlens

Superlens, a simplified case of a perfect lens, is first proposed by Pendry in 2000 [35]. The operation principle is as follows: when the permittivity of the metal slab and the surrounding environment meets the matching conditions (equal and of opposite sign), evanescent waves can be generated and the p-polarized wave excite SPs at metal/dielectric interface. The evanescent field is then significantly enhanced and coupled with the other side of the metal layer. Then, the original field of the mask is restored and recorded by photoresist [59].

Early studies of superlens lithography are mainly reported by Zhang's Group and Blaikie's group. The interference patterns experimentally recorded in the photoresist are also the images formed by a silver mask [39]. They experimentally demonstrated the sub-diffraction-limited imaging through silver film. The representative work is reported by Zhang's Group in 2005, where 60-nm half-pitch gratings and "NANO" characters with ~89 nm line width were recorded in photoresist by utilizing a 35 nm Ag film under 365 nm mercury lamp illumination (Fig. 3(a)) [42]. Similar results were obtained by Blaikie's group with a resolution of about 70 nm [61].

To further improve the superlens lithography resolution, researchers optimized the structural parameters and preparation processes. Chaturvedi et al. demonstrated sub-diffraction imaging down to 30-nm half-pitch resolution with 380 nm illumination by a "smooth superlens". They utilized nanoimprint technique to reduce the thickness of the spacer layer down to 6-nm, and 1-nm-thick Ge was used as the wetting layer to fabricate a 15 nm thick "smooth" silver superlens (Fig. 3(b)) [62]. By reducing the PMMA spacer layer to 20 nm, Liu et al. also experimentally achieved 50-nm half-pitch lines with aspect profile of ~45 nm and fidelity ratio of 0.6 through 35 nm thick Ag superlens (Fig. 3(c)) [63].

The performance of superlens based lithography is determined by many factors. N. Fang et al. studied the influence of the metal slab thickness and the parameter mismatches on the resolution by optical transfer functions [64]. On the other hand, researchers paid special attention to the damp losses and surface roughness of metal slabs, and derived some interesting and even seemingly opposite conclusions. Huang et al. demonstrated that small surface roughness can enhance higher spatial wave-vector components, suppress the surface plasmon resonance peaks, and finally improve the resolution [65]. Wang et al. combined surface sinusoidal roughness with the additional loss and achieved flatter transfer function and 86% reduction of beam width compared to the lossless flat superlens [66]. Guo et al. found that

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