A review of interferometric techniques with possible improvement in pattern resolution using near-field patterning

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ABSTRACT

In this paper, we will be initially doing review on the advancement of interference lithography (IL) which is a well-established technique for its facile, efficient, and economical approach to achieve large-scale patterning in a wide variety of substrates at sub-wavelength resolution. Following this, we have configured a two-beam IL patterning system to achieve patterns in a photoresist and verified against the theoretically calculated results. This work will be further extended using near-field patterning techniques to improve the resolution of the pattern as compared to the current conventional IL system. It is envisaged that the obtained initial results can be employed in a graphene substrate for further research and applications in the area of flexible electronics.

Keywords: Near-field, interference lithography, patterning, graphene

1. INTRODUCTION

The semiconductor industry, motivated to keep in pace with Moore's Law, has pushed the development of many alternative fabrication technique to achieve features size down to tens of nanometer. This has enabled the development of the microelectronics applications such as digital televisions, personal computers, the internet, smart phones, wireless communication devices, global positioning satellites, solar cells, etc. [1]. One such approach which has been gaining popularity is multi-beam interference lithography (IL) due to its simple and cost-effective approach to achieve large-scale patterning in various substrate materials such as silicon, glass, etc. [1-3]. IL makes use of the interference of two or more beams from a coherent laser source to generate a standing wave pattern which is then recorded in a photoresist and transferred to the substrate or directly in the substrate material directly [2]. The main benefit of IL over the conventional photolithography process is the non-reliance on costly, high-quality projection masks, thus resulting in a cost-effective approach to nano-fabrication [4]. Additionally, it offers the flexibility to create one-dimensional (1D) grating patterns to two-dimensional (2D) arrays or even three-dimensional (3D) structures with the same set of optical instruments and a rotating sample stage. For example, a simple two-beam IL set-up can only create 1-D line gratings with a single exposure. However, by rotating the sample stage by 90° and exposing a second time, hole/dot arrays with square symmetry can be achieved [2]. Multi-beam IL with at least four beams can achieve 2-D or even 3-D patterning in a single exposure by varying the location of the interference plane. Different patterns have also been reported by employing polarizers to rotate the interference plane or rotating the stage to different angles [5]. The flexibility of IL has enabled the fabrication of complex periodic patterns by simple manipulation of the beam polarization and the number of interfering beams resonate especially well with applications outside of microelectronics industry, such as photonic crystals, metamaterials, field emitter arrays, bio sensing, high-density magnetic data storage, optical trapping and sub-wavelength structures, etc. [5-7].

This paper, in this context, reviews the advances in IL and discuss on their resolution, minimum feature size, relative cost, and flexibility in achieving various type of patterns. The theory behind the achievable 1D and 2D interference patterns will also be compared to a two-beam IL experiment done previously. The experimental results agree well with the theoretically calculated values. Future work employing near-field patterning techniques to enhance the resolution of the patterns. The initial results obtained indicate its potential use for further research in the development of flexible electronics.

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2. MULTI-BEAM INTERFENCE LITHOGRAPHY

IL is simply the interference of two or more waves from the same coherent light source. In a simple two beam IL system, each wave may be defined as a plan wave and are at equal angle from the normal axis from the plane of interference [6]. The resulting periodicity of the interference fringes is given as

$$\Lambda = \frac{\lambda}{2\sin\theta} \tag{1}$$

where θ is the angle between the beams and the normal axis and λ is the wavelength of the laser source as shown in Figure 1.

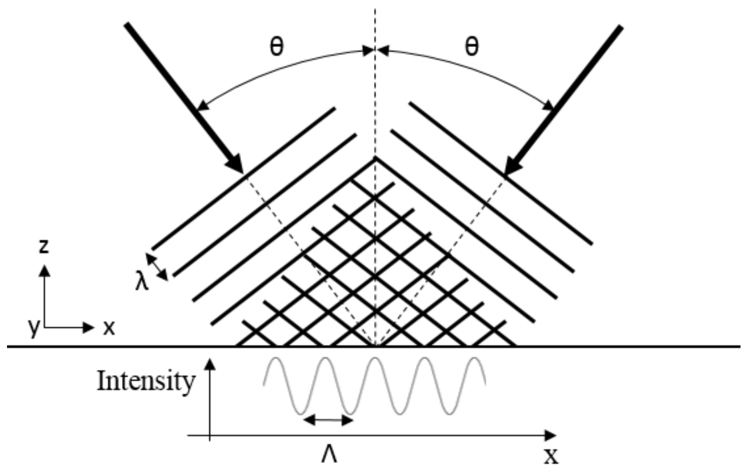

Figure 1. Interference of two linearly-polarized, plane waves at an angle θ to the z-axis with the interference fringes contained in the x-y plane and a periodicity of Λ that runs along the x-direction.

2.1 Beam Polarization

The polarization state of each beam will have an impact on the interference pattern. Sidharthan et al. reported that two pairs of orthogonal p-polarized interfering beams would resulting in a periodic pattern that is arranged in a hexagonal lattice and s-polarized interfering beams would result in a square lattice distribution of periodic patterns. More complex 3D patterns could be realized with an addition of a fifth circularly polarized central beam. Theoretical analysis shown that when the polarization of the two pairs are orthogonal to each other, the resulting 3D pattern is dumb-bell shaped and a body centered tetragonal pattern could also be realized with proper intensity cut off values. S-polarized interfering beams, combined with a circularly polarized central beam would resulting in a woodpile type structure and β-tin type structure [5]. Potential applications for such patterns include photonic crystals where the photonic band gap from such patterning is desired.

2.2 Immersion Interference Lithography

If the interference is contained in a medium besides air, then Eqn. 1 would have an additional term, n which is the refractive index of the surrounding medium and the period will now become as

$$\Lambda = \frac{\lambda}{2n\sin\theta} \tag{2}$$

Comparing Equation 1 and 2, we can see that the period could be reduced by a factor of n, which corresponds to the refractive index of the surrounding medium. Therefore, we can improve the pattern resolution by employing immersion technique [8]. This can be further scaled down by incorporating a prism with high refractive index and adjusting the beam to interfere at the bottom of the prism [9]. Thus, the angle between each beam would be increased (Snell's Law), as shown in Figure 2 and a smaller period could be achieved. An index matching liquid

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could also be introduced at the interface between the prism and photoresist to improve the optical contact for transferring the pattern to the photoresist [10]. However, as the refractive index of the prism is higher than that of the index matching liquid, care must be taken to ensure that the incident angle of the beams is less than the critical angle for total-internal reflection (TIR) which is given as

$$\theta_{critical} = \sin^{-1}\left(\frac{n_{liquid}}{n_{prism}}\right) \quad (3)$$

Hence, an appropriately chosen index matching liquid would increase the critical angle and allows for a larger angle of between the interfering beams. A two-beam immersion based IL set-up using a 364 nm laser source with a high refractive index prism was reportedly able to realize sub-60 nm (<0.2λ) periodic grating feature [11]. Therefore, immersion based IL is highly desired to fabricate high resolution periodic patterns using relative cost effective optical elements and a high refractive index prism.

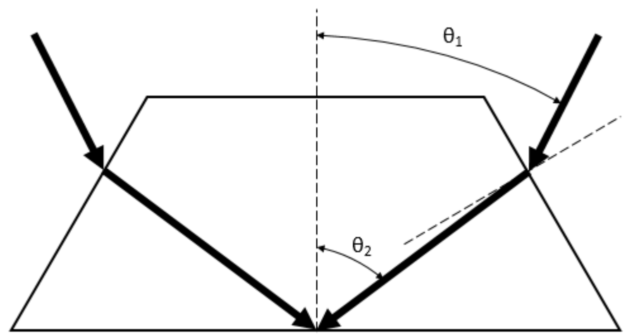

Figure 2. Schematic representation of beams refracted from θ_1 to θ_2 and finally interfering at the bottom surface of the prism

2.3 Near-field Nanopatterning

As the resolution reduces more, it approaches the diffraction limit of photolithography system. Therefore, near-field nanopatterning techniques have be proposed to overcome this barrier. These approaches can be mainly classified into two categories; namely evanescent waves (EW) and surface plasmon (SP) based interference techniques.

EW was first studied for the purpose of holography recording in the early late 1960s by Stetson [12]. When a plane wave is reflected due to the TIR, EW are generated [13]. Multiple EW are made to interfere and the resulting interference patterns could be recorded in a photoresist. A EW based interference technique has been reportedly able to generate 3D surface relief features with minimum feature size smaller than 0.1λ and height-to-width aspect ratio of as high as 10 [14]. It also offers the flexibility to generate periodic patterns with various geometries by simply changing the state of polarization and relative phase difference between the incident plane waves [15]. In recent literature, a multiple EW interference system was demonstrated in an experiment and sub-70 nm 2D features has been realized [16]. Therefore, EW interference concepts could be an alternative approach to achieve high resolution in a photolithography system and have potential applications in nano-field emitters, nano-needles arrays, and nano-wells in biochips.

SP based interference techniques has also been gaining popularity as an alternative approach to realized nanopatterning. When light is incident in a high refractive index dielectric layer above a metal layer, and the attenuated total reflection (ATR) principle is satisfied, surface plasmons would be excited [17]. At a specific angle, the wavelength of the excited SPs could be much shorter as compared to the incident light, and the resulting interference pattern could be at a much small scale [18]. Simulation results using a finite-difference time-domain (FDTD) analytical method also suggests that a SP based interference system could theoretically achieve sub-30 nm (<0.1λ) periodic features [19]. Additional work was done to support this experimentally with good agreement between both simulation and experimental results [20]. SP based interference techniques offers high resolution, good exposure depth, and at a much cheaper cost than conventional photolithography methods. In comparison with EW based interference techniques, it also has better contrast, hence, SP based interference techniques is a promising candidate in the push to achieve an efficient and economical nanopatterning approach.

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3. EXPERIMENT DETAILS AND RESULTS

We have configured an in house developed IL patterning system based on a two-beam approach as shown in Figure 3. The configuration used was a grating based system that has the advantage of flexibility in terms of switching the polarization of the incident laser beams and the incorporation of near-field patterning optics in the future with ease. 2D patterns can also be easily realized using a double exposure with a 90° rotation of the sample stage in between the exposures. The wavelength of the laser used is 364 nm and it passes through a diffraction grating that splits the beam into two second order beams and a central first order beam. The zeroth order beam is not used in this experiment; hence, a hard stop was placed below the central location to filter it out. The first order beams diffract at a 45° from the grating and vertical UV mirrors were used to reflect them at 45° to the sample stage. The incident beams intersect and the resultant interference fringes were then recorded in a negative photoresist that was spin coated on top of a silicon wafer. After developing, it is then imaged under the SEM for further analysis.

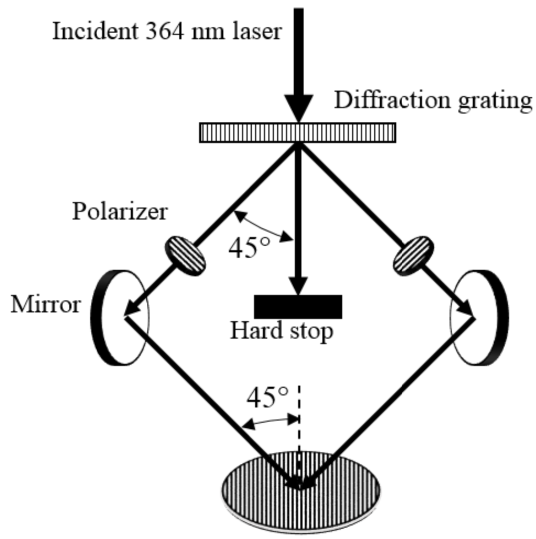

Figure 3. Schematic representation of the experiment setup

The theoretical values can be calculated using Eqn. 1 as the surrounding medium is taken to be air. As the wavelength of the laser source is 364 nm and the angle of incident is 45° for both beams, the periodicity is estimated theoretically to be about 257 nm. Using a similar approach, Chua et al. report the observation of patterns that agrees well with the theoretically calculated values [21]. As shown in Figure 4, a single exposure of a two-beams IL system would result in a 1D line grating pattern. The results support the capability of IL to achieve sub-wavelength nanoscale patterns.

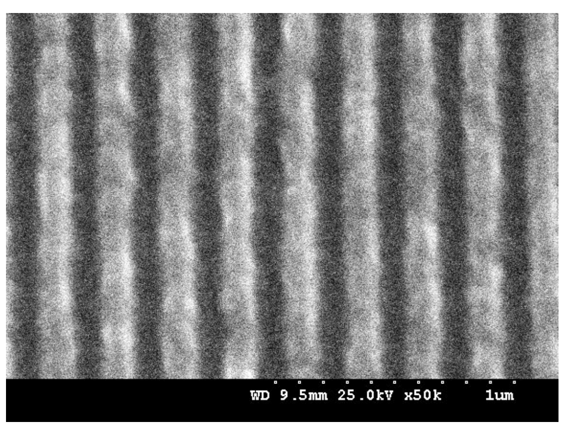

Figure 4. SEM image of line features patterned using single exposure with the two-beam IL system

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4. CONCLUSION

In conclusion, IL is a well-established and efficient tool to achieve sub-wavelength resolution. However, to realize even higher resolution without expensive equipment, near-field techniques can be incorporated. The proposed setup with a grating configuration has the advantage of being flexible by adjusting the state of polarization of each interfering beam to realize a variety of complex patterns. In the future, a normal prism or one that is coated with a metal layer may be achieve better resolution and verify the theoretical limit that near-field techniques could achieve. The fabricated nanopatterns could then be transferred into a graphene substrate by etching for research and development in the area of flexible electronics.

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