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Large area maskless surface plasmon interference for one-and two-dimensional periodic nanoscale feature patterning

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Abstract: A promising maskless surface plasmon interference nano scale lithographic technique is proposed and experimentally demonstrated in this paper. One dimensional (gratings type) and two dimensional (pillar type) nano scale features were patterned on the photoresist layer using 364 nm illumination wavelength source with a single exposure, by employing a custom made prism layer configuration. Large area patterns of grating lines and pillars with feature size ≈ 90 nm were experimentally realized using this configuration.

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1. Introduction

The growing importance of the nanotechnology research leads to the need for patterning technique with the capability to fabricate nanometer scale features and one such technique is optical lithography. High precision photolithography techniques have been used for the fabrication of sub-micron feature size optical elements and devices because of its high throughput and simplicity. Advanced projection optical lithography systems that employs 193 nm wavelength laser sources coupled with wavefront engineering schemes has the capability to achieve sub-50 nm patterns. However, the cost of ownership of these sophisticated systems is exorbitantly high. Also, it is unable to pattern high resolution nanostructures with conventional photolithographic techniques due to optical diffraction limit [1].

Near-field photolithographic techniques such as evanescent wave (EW), surface plasmon (SP) lithography has been proposed recently in this context as an alternate technique to overcome the above mentioned limitations, and offers patterning of high resolution features [2-5]. Plasmonic lithography technique involves the excitation of surface plasmon waves on a metallic mask which is generally put in contact with the photoresist layer in order to expose to the plasmon near field. Such surface plasmons on the metal surface can greatly enhance the light transmission and gives a novel method of near

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field photolithography beyond the diffraction limit. Different configurations have been proposed for this lithography technique to fabricate nanoresolution structures. The surface plasmon interference nanoscale lithography based on Kretschmann-Raether attenuated total reflection (ATIR) geometry has been numerically proposed [6, 7]. Moreover, a near field interference pattern can be formed by using metallic mask configuration that can generate surface plasmon for periodic structure fabrication [8-12]. In all the above mentioned works, surface plasmons can make a certain pattern on the photoresist layer when the incident p-polarized light passes through a prism or thin metallic mask. However, most of these reported techniques demands the fabrication of fine period mask grating and found to be cost effective. The search has thus recently focused on noble metal nanoparticles due to its localization and enhancement of electromagnetic wave at plasmon resonance condition. In this context, it is worth mentioning the recent reported works on direct patterning employing micro or nano-spheres as mask [13, 14]. For high resolution nanopatterning, excitation of gap modes in a metal particle-surface system for plasmonic lithography is also proposed numerically by our group very recently [15]. A direct method for optically exciting and imaging delocalized standing surface plasmons in thin metal film is recently reported by passion et al. [16]. They concluded that surface plasmon interference can be sustained in an arbitrarily large region in comparison to the excitation wavelength.

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In this paper, a maskless single step two- and four-beams surface plasmon interference lithographic configuration is proposed and illustrated experimentally so as to obtain interference pattern with resolution several orders less than the illumination source wavelength. A custom made prism layer configuration is used to pattern both one dimensional and two dimensional periodic nanostructures on the recording medium.

2. Surface plasmon interference

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Surface plasmons (SPs) are a collective charge density oscillation occurring on the surface of metal films [17]. And electromagnetic waves due to such oscillation move along the interface of metal and dielectric. The wavevector of surface plasmon wave becomes significantly larger than that of the incident light wavevector, when the real part of the dielectric constant of metal approaches negative of the dielectric constant of surrounding layer. At this condition, the wavelength of the excited SPs should be shorter compared to the wavelength of illumination light. If ψ_1 and ψ_2 are the two surface plasmon waves, then their superposed interference pattern can be expressed mathematically as [18],

$$|\psi_1 + \psi_2|^2 = 2|\psi_0|^2\left[1 + \cos(\frac{4\pi\sqrt{\varepsilon_d}\sin\theta_{Sp}}{\lambda})x\right] \quad (1)$$

where ψ_0 is the incident wave, ε_d is the dielectric function of photoresist layer, θ_{SP} is the SP resonance angle, λ is the illumination wavelength, and fringe separation (period) is expressed as [18],

$$\Delta x = \frac{\lambda}{2\sqrt{\varepsilon_d}\,\sin\theta_{SP}} \qquad (2)$$

3. Experimental details and discussion

The schematic diagram of the experimental set up of two beams and four beams surface plasmon interference optical lithography is shown in Fig. 1. A test sample of dimension 20 mm X 20 mm is designed for interference lithography at 364 nm wavelength in which the upper layer is a 60^0 triangular prism of refractive index 1.745 (NLAK 8 glass). A silver film of thickness 50 nm is coated at the bottom surface of the prism and they are brought into intimate optical contact (using index matching liquid) with a thin photoresist (AZ7220) layer on silica substrate. AZ7220 is a positive tone UV photoresist of refractive index 1.7 sensitive to illumination wavelength 364nm and photoresist thickness is approximately 100 nm. In order to get thin photoresist thickness, AZ7200 is diluted with EBR solvent (AZ Electronic Material) at 1:4 proportions (1 ml AZ7200 and 4 ml EBR solvent) and spin coated at 1500 rpm. Care has been taken to make the coated resist surface defect free.

In the experimental arrangement, vertically polarized light from a continuous wave UV Argon Ion laser (Spectra Physics, 364 nm wavelength) is

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used as the illumination source. Also an electronic shutter is placed in front of the laser head so as to provide control over the exposure time. The incident light is allowed to incident normal to the axis on a custom made 2-Dimensional diffraction grating to get various diffraction orders. The 2D diffraction grating is designed in such a way that it can suppress the 0th order beam, and generates high diffraction efficiency (17%) four 1st order beams. And when 45^0 linear polarized light incidents on the grating surface the diffracted light is unpolarized. They are then allowed to pass through the polarizer to get p-polarized light. The central beam is blocked with a stop and four counter propagating 1st order beams are made to incident on the test sample placed in a sample holder. The incident angle of the four beams at the prism side is at 45^0 and theoretically calculated incident angle (SP resonance angle) at prism/metal interface is 54^0.

The SP resonance angle is also calculated numerically by Finite Difference Time Domain (FDTD) method. The commercially available FDTD software is used for the numerical study. To find the resonance angle the reflectance of light at the same wavelength to excite the surface plasmon waves, reflectance analysis is carried out as a function of the incidence angle. In the simulation, dielectric constant of silver used at 364 nm illumination wavelength is -2.5575+0.5989i [19] and the remaining parameters are same as mentioned above. The obtained SP resonance angle plot is shown in Fig.2.

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From the figure it is evident that the SP resonance angle is around $53.5^0$and it correlates with the theoretically obtained value.

The p-polarized incident beams at the prism surface has a targeted power density of 334.35 mW/cm^2 and samples are exposed with an exposure time of 1s. The development time is taken as 2 min. After development, the tapping mode atomic force microscope (AFM) with high lateral resolution (5 nm) is used to analysis the topography of the recorded features on the photoresist. AFM image of two beams surface plasmon interference lithographic pattern is shown in Fig.3. In this case two counter propagating 1st order beams out of four 1st order beams are allowed to incident on the prism surface. Large area uniform periodic grating lines were obtained at this exposure dose and exposure time. Figure 4 shows the section analysis of AFM image and it is found that grating lines with fringe separation 172 nm and minimum line width of 89 nm were patterned on the photoresist layer.

Four beams SP interference lithography experiment is also carried out to pattern two dimensional features. Four 1st order beams of 2D diffraction grating are used for this purpose to generate interference of multiple counter propagating surface plasmon waves as a lithographic technique to print periodic two dimensional features. Figure 5 represents obtained AFM images of exposure pattern transferred on the photoresist layer using four beams SP interference lithography and Fig. 6 shows the corresponding three dimensional AFM image. The AFM sectional analysis of the exposed dot array on the

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photoresist film is shown in Fig. 7. It is evident from the Fig.7 that large area periodic dot array with minimum spot size of 93 nm and periodicity around 173 nm was patterned on the photoresist layer. The non uniformity of the exposed dot array patterns presumably attributed to the intensity fluctuation from laser or depends on the development time. We also found that the line width and spot size of the patterns in the exposed area depends on exposure duration. In this context, it should be mentioned that the grating lines and pillars with feature size ≈ 90 nm were obtained with an optimum value of exposure time (1s). The advantage of this configuration is that it can provide large area low cost plasmonic lithographic technique without using any complex mask fabrication techniques. Also this scheme uses a prism instead of metallic grating mask as a coupler, which makes the structure of lithographic system simple and reduces the cost of fabrication.

4. Conclusion

In conclusion, mask less single step two beams and four beams SP interference optical lithography technique has been demonstrated. This technique utilizes a custom made prism layer configuration to pattern both one dimensional and two dimensional high resolution periodic features on the photoresist. Large area grating lines and dot array with feature size of 90 nm were achieved using this configuration at 364 nm illumination wavelength. This technique is expected to provide a convenient route for patterning high

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throughput nanometer structures without employing expensive equipments or complex mask fabrication approaches. The application of this proposed concepts and methodology can find not just silicon-based pathway etchings for semiconductors, but also expects to serve a host of emerging fields that require nano-scale patterns. These include areas involving nano-scale patterning that can find potential photonic crystals, biosensors, field emitter arrays and single nanowire applications.

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Figure Captions

Fig.1. Schematic diagram of the experimental SP interference lithography set up.

Fig.2. SP resonance angle calculation using FDTD method: reflectance vs. incident angle plot.

Fig.3 AFM image of exposure pattern transferred on the photoresist film: large area one dimensional grating lines patterned at exposure time 1 s.

Fig. 4. (a) AFM image of the developed grating lines in 1μm X 1μm exposed area on the photoresist. (b)Sectional analysis along the line drawn in (a): periodic patterns with minimum line width of 89 nm on a 172 nm period are obtained.

Fig. 5 2D AFM images of exposure pattern transferred on the photoresist film: large area dot arrays at exposure time of 1 s.

Fig. 6 3D AFM images of exposure pattern transferred on the photoresist film.

Fig. 7. (a) AFM image of the developed dot array in 3 μm X 3 μm exposed area on the photoresist. (b)Sectional analysis along the line drawn in (a): Periodic dot array with minimum spot size of 93 nm and period 173 nm were realized.

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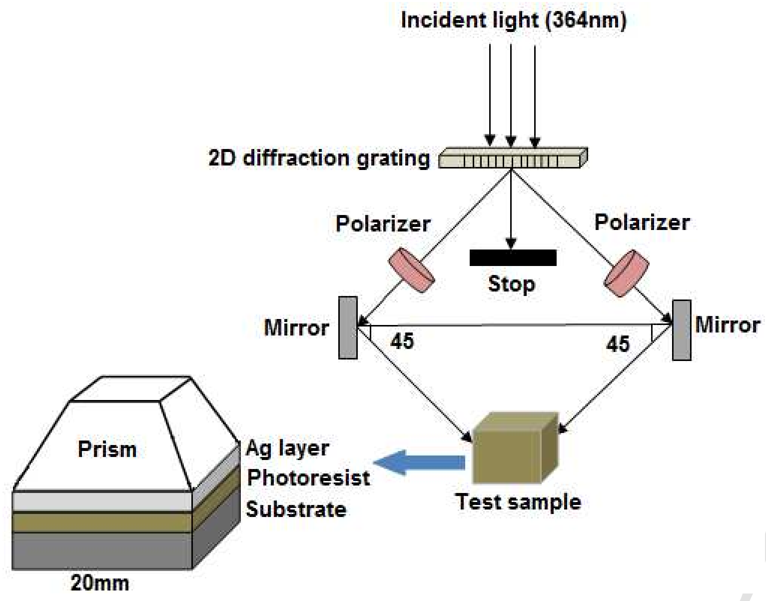

Fig. 1

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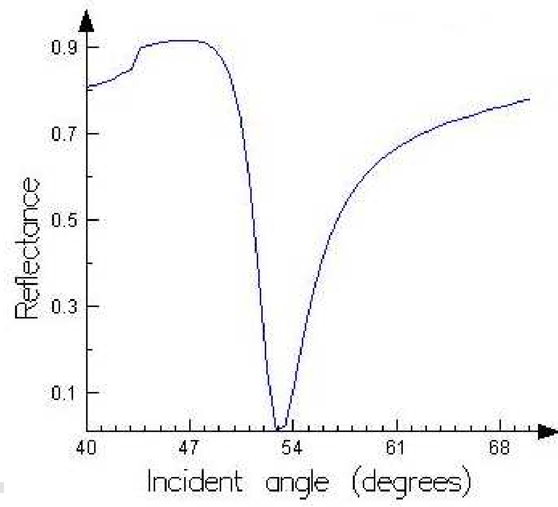

Fig. 2

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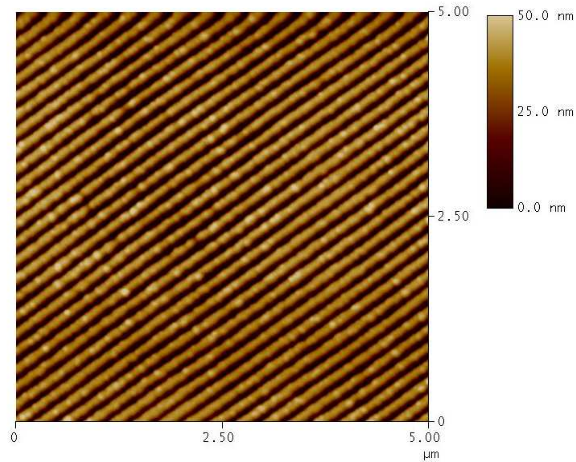

Fig. 3

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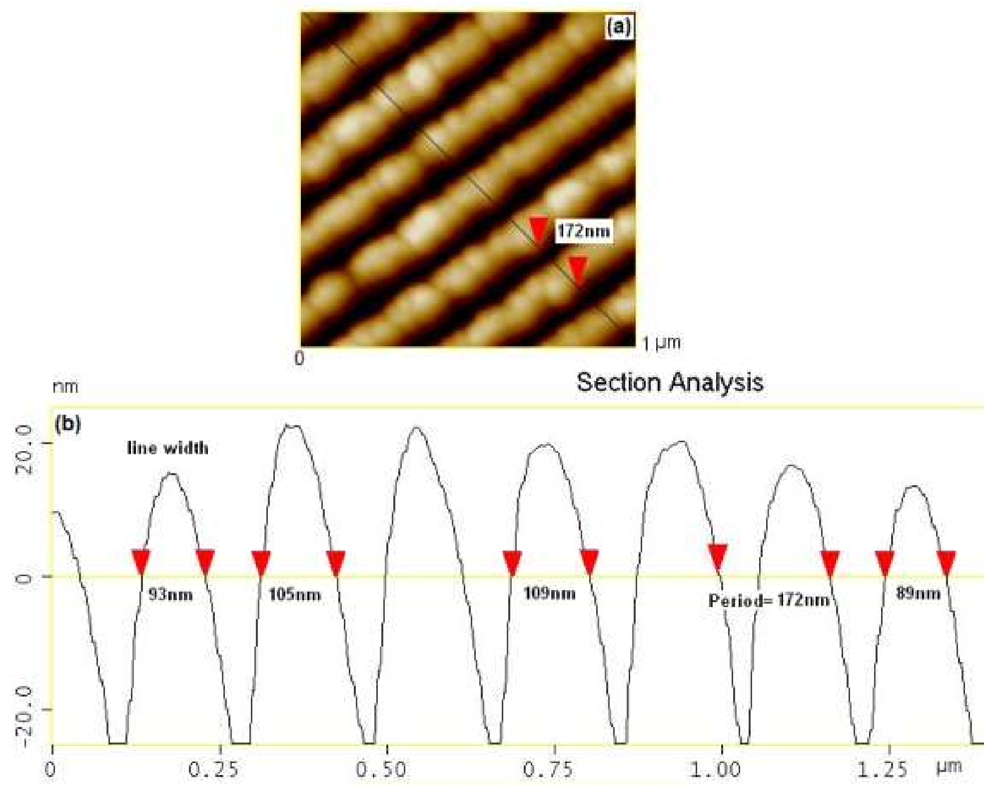

Fig. 4

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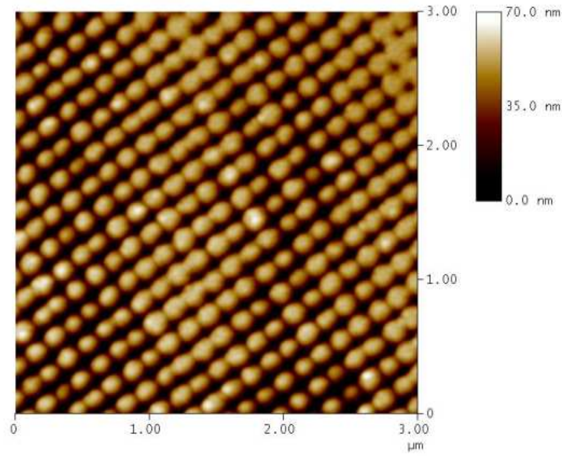

Fig. 5

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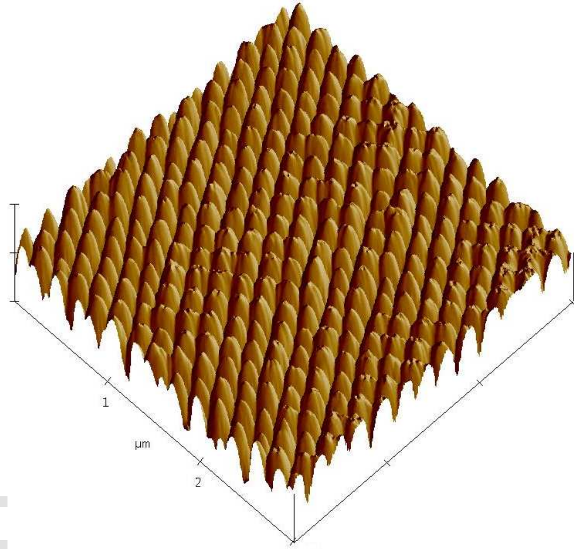

Fig. 6

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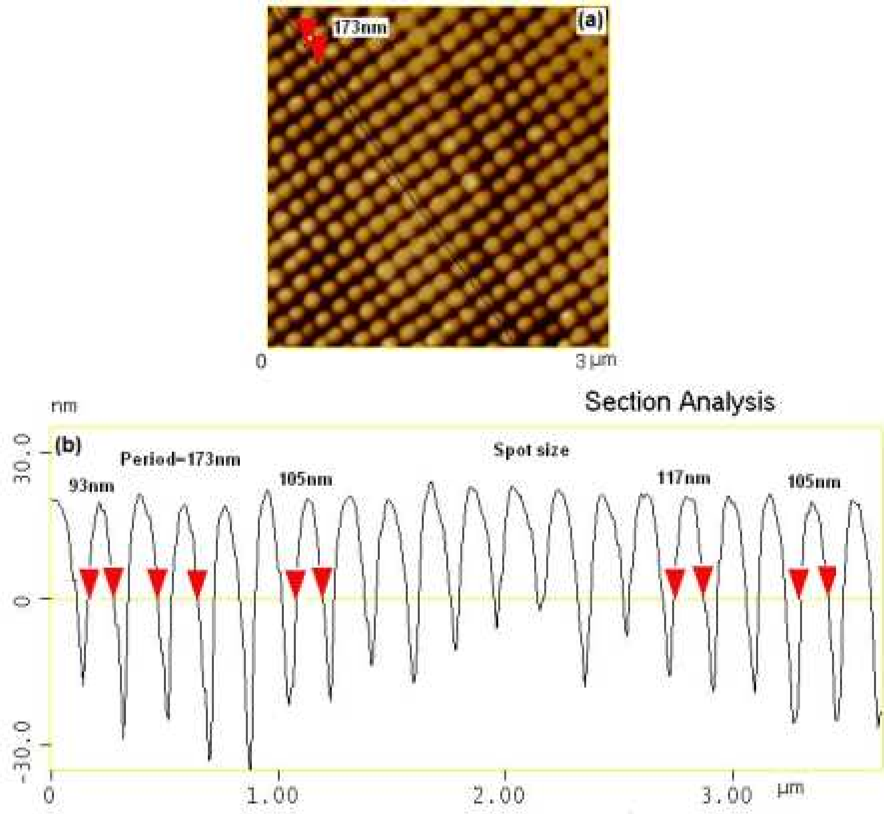

Fig. 7

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