THREE DIMENSIONAL NANOSCALE FABRICATION AND MODELING OF DYNAMIC MODE MULTIDIRECTIONAL UV LITHOGRAPHY

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ABSTRACT

Three dimensional (3-D) nanofabrication using the dynamic mode multidirectional ultraviolet (UV) lithography has been explored, where the size of the photomask pattern is compatible to or smaller than the wavelength of the UV source and therefore the diffraction effect is prominent in photopatterning. Ray trace taking into account the effect of refraction, diffraction, and absorption has been simulated using an optical numerical analysis tool (COMSOL, Inc.). Subwavelength patterning with a pattern diameter of 300nm has been performed on a chromium coated glass substrate using E-beam lithography to form a photomask. A thin layer of SU-8, a negative tone photoresist, with a thickness of 1~10 microns has been coated on the photomask and multidirectional UV lithography is performed through the mask, where the photomask servs as a substrate as well. Nanoscale pillars with a pattern diameter of 300nm have been fabricated with different optical doses and simulation results show good correlation with simulation results in terms of the shape and the height. Various 3-D structures including an inclined pillar array, a vertical triangular slab, a tripod embedded horn, and a triangular slab embedded horn have been successfully fabricated. A vertical triangular slab array has been demonstrated for a terahertz (THz) selective surface application.

KEYWORDS

Dynamic mode multidirectional UV lithography, 3-D nanoscale structure, subwavelength patterning, diffraction, terahertz

INTRODUCTION

3-D nanofabrication technologies have triggered numerous nanoscopic research fields by extending fabrication limits from micron scales to a few nanometer ranges. Several fine fabrication technologies including the two-photon or multi-photon, stereo, e-beam, and X-ray lithography methods have demonstrated their excellent nanoscale 3-D fabrication capabilities [1-4]. However, those technologies require relatively high system cost, limiting its broad usage.

Recently, dynamic mode multidirectional UV lithography (DMUL) has been reported as one of the advanced three dimensional (3-D) fabrication processes for microstructure fabrication [5, 6]. Its advantages include process simplicity for complex 3-D structure fabrication, good repeatability, and cost effectiveness. Early work has focused on 3-D structures with a few tens of micrometers such as a microfluidic filter with a mesh size of 10~50 micrometers [7] and a few millimeters such as a microwave antenna with a height of 4.5 mm for a 12 GHz satellite communication [8]. Meanwhile its capability on submicrometer or nanometer scale 3-D patterning has not been fully explored although its potential impacts on the applications of photonics and terahertz researches are to be great. Since the process uses a UV light source with a wavelength of approximately 300~400nm, patterning nano structures in the size range of the UV wavelength is very challenging in part due to its diffraction limit.

In this work, the 3-D nano patterning capability of the dynamic mode multidirectional UV lithography process has been explored. The 3-D nanopatterning has been simulated using a numerical simulation tool (COMSOL package, COMSOL Inc.), where experimental parameters for optical diffraction, reflection, and absorption are utilized. Diffraction effect in the 3-D nanopatterning through a subwavelength photomask pattern has been described using COMSOL simulation and the results have been compared with fabricated structures. A tilted pillar array and a vertical triangular slab with a subwavelength pattern are demonstrated. As an application of 3-D nanostructures, a vertical triangular slab array is fabricated, metalized, and tested for a THz application.

UV LITHOGRAPHY THROUGH A NANOSCALE PHOTOMASK PATTERN

The resolution of most near UV lithography tools is restricted by their diffraction limit and in most cases is a micrometer or two with its wavelength of 300~400 nm. If

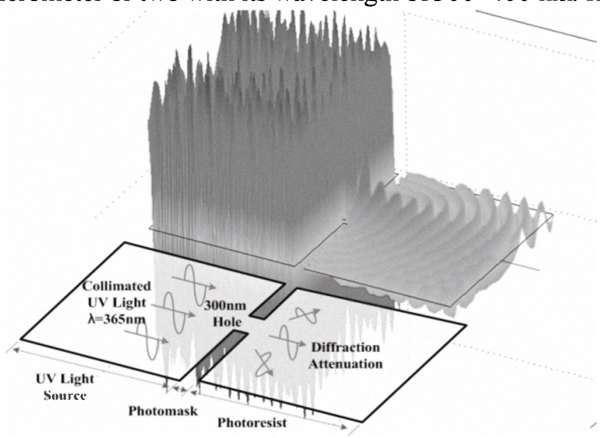

Figure 1: Simulation and schematic diagram of UV wave propagation through a subwavelength single slit

the size of the photomask pattern is near to the wavelength of the UV light source, the light diffraction effect is significant. Figure 1 shows the simulation and the schematic of the wave propagation in UV lithography through a nanoscale photomask pattern when the pattern size is smaller than the UV wavelength. The height of the 3-D plot represents the light intensity. The collimated light with a wavelength of 365nm (*i*-line), which is broadly used in a near UV system, propagates from the left-hand side box and confronts the wall with a 300nm wide slit representing the photomask opening. The wave after the slit diffracts and attenuates in a lossy medium. As a result, the wave trace becomes wider and the energy density becomes weaker as it propagates farther from the slit.

The transient analysis describing the degree of the UV light diffraction effect has been studied. Figure 2 shows fabricated SU-8 pillar structures with different UV doses and the inset shows simulated profiles. For nano pillar fabrication, a circular nano pattern with a diameter of 300nm has been fabricated on a chromium coated glass substrate using E-beam lithography followed by chromium etching. SU-8 2005 (Microchem Inc.) has been spin-coated to a few micrometers thick on the prepared photomask, which in turn serves as a substrate as well upon applying the backside exposure scheme through the mask/substrate. Various optical doses of 60mJ/cm^2, 100mJ/cm^2, 160mJ/cm^2, and 1200mJ/cm^2 have been applied to the prepared samples as shown in Figure 2 (a), (b), (c), and (d), respectively. The larger dose the taller pillar has been formed. The respective simulated profile is shown in the inset. All the fabricated structures have rounded pillar tips attributed to the diffraction effect, which is also illustrated by the simulation. Meantime, the width of the fabricated pillars is slightly narrower than that of simulation in the case of Figure (a), (b), and (c). The surface of the pillars have relatively low optical dose, which does not fully crosslink SU-8. During development the semi crosslinked portion continues to be development, resulting in narrower width. Meantime, Figure 2d shows

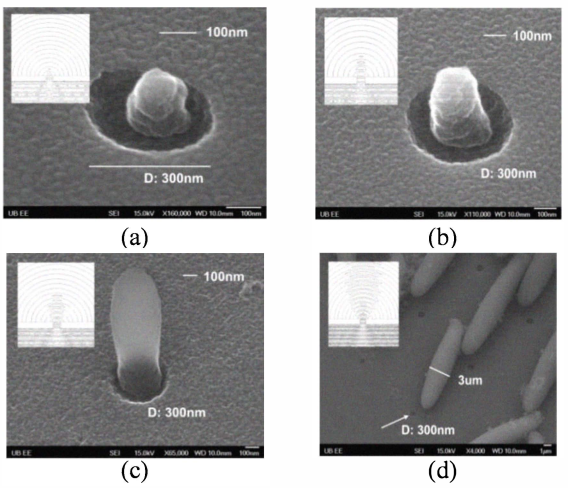

Figure 2: UV lithography through a nano pattern with various optical doses (inset shows associated simulation by COMSOL): (a) 60mJ/cm^2, (b) 100mJ/cm^2, (c) 160mJ/cm^2, (d) 1200mJ/cm^2

the fabricated pillar with the excess of optical dose resulting in much closer resemblance of the diffraction pattern as shown in the inset, where the pillar has a maximum diameter of 3μm from the 300nm circular mask pattern and a height of 10 μm. During development, the pillars have fallen down as shown in Figure 2d. The development time has been kept constant and its effect has not been taken into account in this study. As demonstrated in Figure 2, the fine control of UV dose enables to form 3-D nanoscale pillars by conventional UV lithography.

MULTIDIRECTIONAL UV LIHTOGRAPHY THROUGH A NANOSCALE PHOTOMASK PATTERN

Recently dynamic mode multidirectional UV lithography has been reported as a powerful and cost-effective 3-D microfabrication method [5, 6]. In operation, the arbitrary angle of the substrate to the collimated UV light caused by the movable substrate holder produces various 3-D traces of incident UV light in the photoresist region, resulting in 3-D microstructures after development. To examine the capability of 3-D nanoscale patterning by the dynamic mode multidirectional UV lithography, the wave propagation simulation by COMSOL with a slit size of 300nm has been performed as shown in Figure 3, followed by experiment. The inset shows a SEM image of a fabricated 3-D inclined nano pillar array. In simulation, the incident angle of the collimated UV wave with a wavelength of 365nm has been set at 50° from the photomask substrate. Ray trace in the photoresist area shows the diffraction effect as expected. However, the major UV dose is placed along the tilted trace indicated in the broken line, where the tilting angle follows the refracted angle calculated by the Snell's law [6]. To verify the simulation result of the inclined UV exposure scheme, an experiment has been

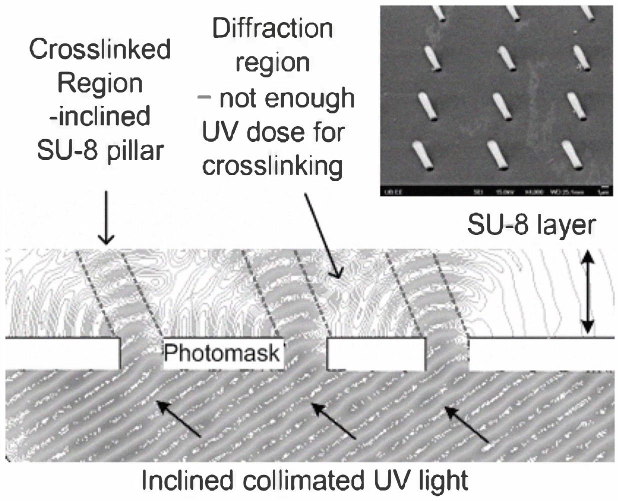

Figure 3: Simulation of 365nm wave propagation through an opening array with each diameter of 300nm for an inclined pillar array (COMSOL), where inset shows a fabricated SU-8 inclined pillar array

performed. SU-8 2005 with a thickness of 5 μm has been spin-coated on a thin chromium layer pre-patterned glass substrate with a circular pattern diameter of 300nm. The spin speed is 3000rpm for 30 seconds and the sample is baked at 95°C for 3 minutes. The substrate has been tilted with a tilting angle of 50° and UV exposure with an optical dose of 240mJ/cm^2 has been performed. After post exposure bake and development, an inclined pillar array with an inclined angle of 27° have been successfully fabricated with a circular base diameter of 300nm ~ 1μm as shown in the inset of Figure 3. Similar to the vertical pillar experiment discussed in the previous section, the contribution to the pillar diameter by the diffraction effect has not been significant with this level of optical dose while all the pillars show rounded tips. The obtained inclined angle agrees very well with the calculated refracted angle.

A nanoscale 3-D triangular slab has been simulated and fabricated by the dynamic mode multidirectional UV lithography as shown in Figure 4. The conceptual system overview of the dynamic mode multidirectional UV lithography is described in Figure 4a. The back side UV exposure scheme has been preferably applied to prevent the secondary diffraction which would be caused from the gap between the photomask and the photoresist upon the front side exposure scheme. The motion of the substrate is programmed using the connected computer and performed by two stepper motors for tilting and rotational motion. SU-8 has been utilized as the photoresist. MathCAD simulation has been used, which enables to predict the 3-D skeletal model of the triangular slab and

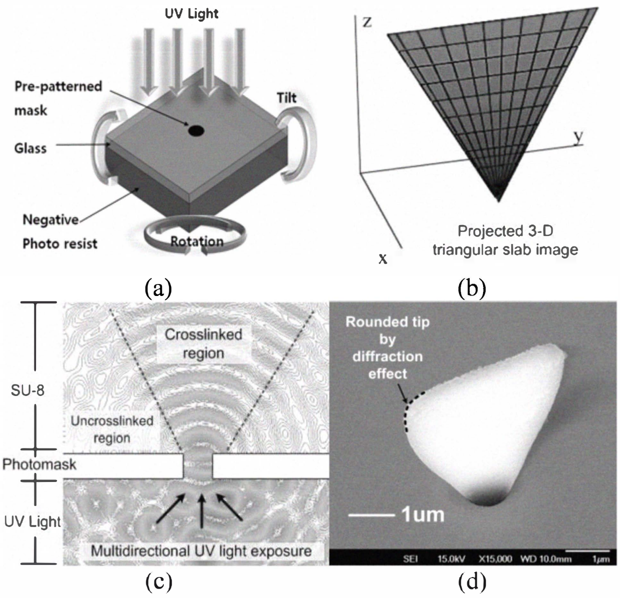

Figure 4: Modeling, simulation, and fabrication of a triangular slab: (a) Schematic diagram of DMUL, (b) 3-D MathCAD skeletal simulation, (c) UV light propagation simulation by COMSOL, (d) SEM of a fabricated 3-D triangular nanoslab (note that the edges are round due to diffraction effects.)

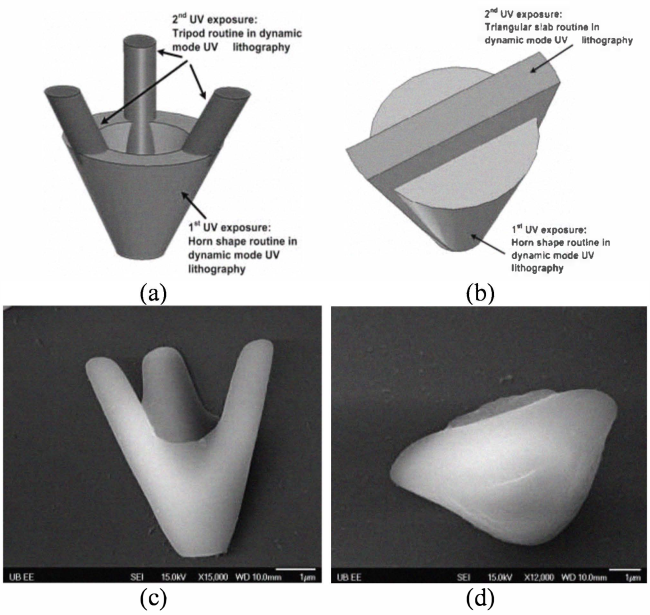

Figure 5: Multiple exposure scheme of dynamic mode multidirectional UV lithography: (a) Schematic of a tripod embedded horn, (b) Schematic of a triangular slab embedded horn, (c) A fabricated tripod embedded horn, (d) A fabricated triangular slab embedded horn

provide the values of the tilting and the rotational angles for the motor control program as shown in Figure 4b. Ray trace simulation of the vertical triangular slab including diffraction, refraction, and attenuation effects has been performed by COMSOL as shown in Figure 4c. The resultant structural shape affected by light refraction, diffraction and attenuation is predictable from the broken line. After simulation, the nanoscale 3-D triangular slab has been fabricated as shown in Figure 4d. The fabricated vertically standing triangular slab has 36° flare angle after refraction and also shows rounded tips at both edges as indicated in Figure 4c and 4d.

The height of a 3-D SU-8 structure is affected by the amount of the incident UV dose as implicated in Figure 2. Incident UV dose through the photomask pattern can control the height of the 3-D structure [9]. UV exposure with multiple optical doses on a single coated photoresist layer allows a 3-D structure with various heights, giving another degree of freedom for 3-D fabrication aside from tilting and rotational angle control in the dynamic mode multidirectional UV lithography. Figure 5 shows a double exposure scheme on single coated photoresist with dynamic mode multidirectional UV lithography. By applying different UV doses, which have been extracted from previous simulation (MathCAD, COMSOL), the 3-D nano structures with multiple heights have been fabricated. The schematic diagrams of a tripod embedded horn and a triangular slab embedded horn with UV exposure procedure have been shown in Figure 5a and 5b, respectively. Two step UV exposures have been made: the first UV exposure to form the 3-D horn shape, and second UV exposure to form the tripod in Figure 5c and the triangular slab in Figure 5d, respectively.

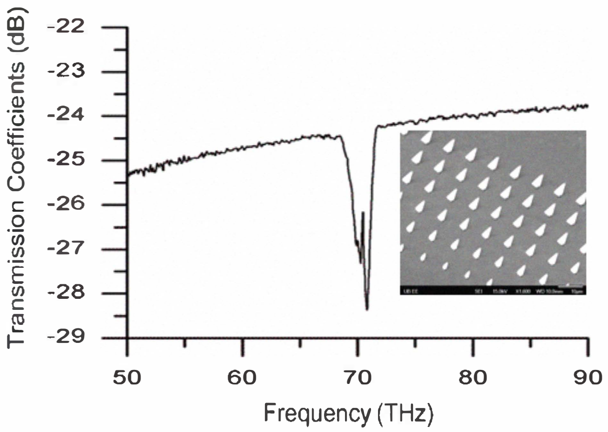

Figure 6: Test results of THz selective surface (inset shows an SEM image of the tested array)

The fabricated 3-D structures shown in Figure 5c and 5d represent the predicted schematic Figure 5a and 5b, respectively, where the tripod and the triangular slab are taller than the horn structure. Also, rounded edges are observed as expected.

THz SELECTIVE SURFACE

The frequency selective surface technique is useful in RF communication. Different from the conventional planar type frequency selective surfaces, which have a relatively narrow flare angle, the selective surface with 3-D structures would have a large flare angle. A THz selective surface has been designed and fabricated using the dynamic mode multidirectional UV lithography in nanoscale. A vertically standing triangular slab array has been designed with a height of 1μm for the resonant frequency of 70 THz. SU-8 has been used as the backbone material of the triangular slab by the dynamic mode multidirectional UV lithography and metalized by copper using sputtering as shown in the SEM image of Figure 6. The frequency response of the fabricated sample has been tested in THz range using the Fourier transform infrared spectroscopy (FTIR, Vertex 70). The test result shows a clear absorption at 70 THz as shown in Figure 6.

CONCLUSION

UV lithography with a wavelength of 365nm has been studied for subwavelength 3-D nanoscale patterning. Although the wave distribution after the subwavelength photomask patterns has been greatly affected by the diffraction effect such as enlarged sidewall dimension, the fine control of the UV dose during UV lithography allows to form overall 3-D nanoscale structures as microscale ones. Meantime, the shape at the edge such as the tip of the pillars or the edges of the vertical triangular slab is much affected by diffraction, resulting in the rounded edges. With such effects known, the dynamic mode multidirectional UV lithography scheme has been applied to fabricate 3-D nanoscale structures with SU-8. The vertically standing triangular slab has been designed using MathCAD for the backbone structure drawing and COMSOL for realistic shape estimation considering various optical parameters including diffraction, refraction, and absorption. The control of UV exposure dose during the dynamic mode multidirectional UV lithography process has been applied to achieve 3-D structures with multiple heights. A tripod embedded horn and a triangular slab embedded horn have been successfully fabricated using the dose control scheme. An array of the triangular slab is fabricated for the THz selective surface application with a resonance absorption frequency of 70 THz successfully.

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