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Double-side Exposure UV-LED CNC Lithography for Fine 3D Microfabrication

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***Abstract*— This paper presents a double-side-exposure scheme based on computer-numerical-controlled (CNC) UV-LED lithography for fine 3-D microfabrication. The CNC UV-LED lithography manipulates the exposure angle of the UV light where the system comprises a switchable, movable UV-LED array as a light source, a motorized tilt-rotational sample holder, and a computer-control unit. The double-sided exposure scheme utilizes an additional photomask on top of the photoresist-bearing photomask/substrate. The CNC UV-LED apparatus programmably introduces tilt-rotational UV light through the two photomasks via sequential exposure of each side by use of a synchronized switchable UV light source. This creates user-definable 3-D light traces, which are transferred into the photosensitive resist. This approach enables the fabrication of new 3-D structures that have previously been impossible to implement using single-side exposure lithography. Sample fabricated 3D microstructures include a micro spear, a micro golf club, a micro folder, and a micro bird. Arrays of micro 'y' and micro mushroom structures are demonstrated as batch fabrications.**

Keywords—UV-LED lithography; Double-side exposure; SU8; 3D microfabrication

I. Introduction

As the recent electronic designs are getting smaller and slimmer e.g. smartphone, and wearable devices, the degree of the miniaturization and its fabrication approach of their associated components become more important. While a UV lithography has knowingly contributed the size reduction by decreasing the footprint area, a method for patterning front and back side of the substrate has provided different aspects of insights into exploiting a dead volume to maximize the space utility [1-6]. However, such schemes have typically required precise alignment and have been limited to two-dimensional (2D) or 2.5D micropatterning.

While three-dimensional (3D) UV lithography has been paid more attention to its flexible design of the microstructures with different approaches [7-9], a CNC UV-LED lithography recently demonstrated the batch formation of fine, complex features, albeit at the expense of the ability to create completely arbitrary patterns. Building on these previous concepts [10-14], we have augmented the CNC-UV-LED-lithography scheme with double-side exposure capability as described in Figure 1, with synchronization between light source energization and position routine of the sample holder. In the previous CNC UV-LED lithography, an automated system for repositioning of a photoresist-bearing substrate together with multiple discrete exposures was used to create 3D microstructures. Subsequently, that process was improved by adding a computer-controlled sample positioning system synchronized with the UV light source. However, there was still a UV-inaccessible shadow zone as described in Figure 2(left), limiting 3D microstructure design. The double-sided exposure scheme utilizes an additional photomask on top of the photoresist-bearing photomask/substrate, and the CNC

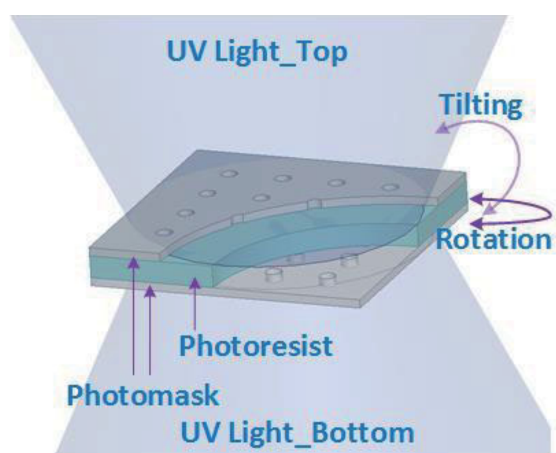


Figure. 1 Concept of the double-sided UV-LED exposure

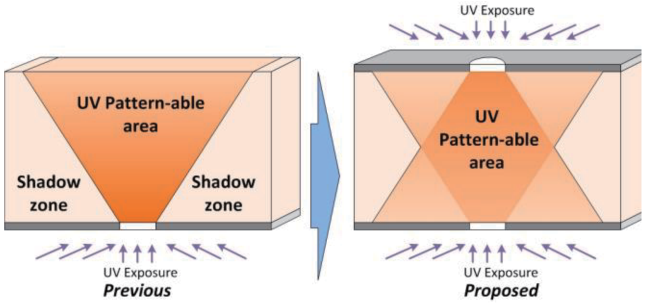


Figure. 2 Comparison between previous and proposed methods

UV-LED introduces the programmed tilt-rotational UV light through the two photomasks via sequential exposure of each side, expanding the region available for UV patterning as described in Figure 2 (right).

This approach enables the fabrication of new 3D structures that have previously been impossible to implement. It also greatly increases ease of fabrication by (a) exploiting a simpler mask alignment scheme, (b) eliminating the multiple manual exposure steps of conventional inclined lithographic approaches, and (c) enables simultaneous double side UV exposure to reduce further processing time.

II. SYSTEM OVERVIEW AND FABRICATION

The integrated CNC lithography system is presented in Figure 3. The system is comprised of a switchable, movable UV-LED array and a motorized tilt-rotational sample holder with a self-alignment frame, all computer-controlled. The UV-LED light source is composed of 10 by 10 5-mm-LED array. A DC motor with gear box rotates the UV-LED light source at 20 rpm. The connector between the DC motor and the UV-LED light source was 3D-printed (fused deposition modeling (FDM) technology) using acrylonitrile butadiene styrene (ABS). 3-mm thick aluminum sheets were milled and assembled for the tilt-rotational sample holder. Two stepper motors were attached to the sample holder for rotation and tilt functions. The motors are capable for micro stepping for

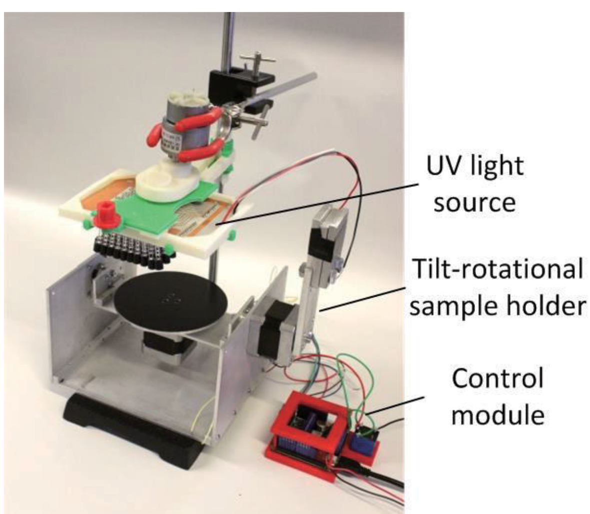


Figure. 3: System overview

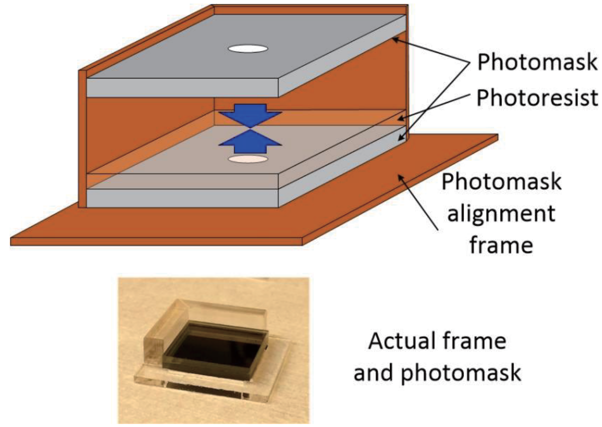


Figure. 4 Self-mask alignment frame

smooth movement. A commercial motor drive used as a control module (EZ4AXIS, Allmotion Inc.) was employed to operate the on-off state of the UV light source and the tilt-rotational sample holder.

Straightforward mask alignment was accomplished by adopting a mask self-alignment frame as shown in Figure 4. A corner wall of the alignment frame guides the edges of the two photomasks for easy alignment. In this experiment, the alignment frame was made of acrylic plater. A 2-inch by 2-inch mask alignment frame was prepared.

A general fabrication process for double-side UV-LED exposure scheme is described as follows. SU-8 was spin-cast on the first photomask and softbaked at 90 °C. For thick SU-8 process (100 µm or thicker), an SU-8 dry film can be directly casted on the photomask to save several hours of the softbake process. The photomask was subsequently fitted on a self-alignment frame, with one edge of the mask tightly positioned at the corner of the frame. The second mask was placed on top of the first mask in the same manner. The mask patterns were registered to their respective corners and therefore rapidly aligned, at the expense of reasonable precision. CNC UV-

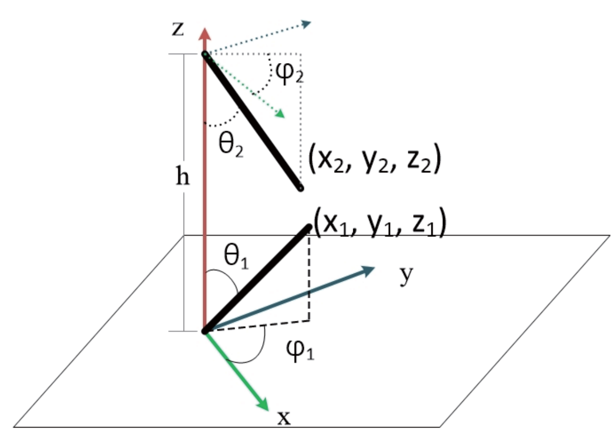


Figure. 5 Coordinate system for UV light trace

LED exposure was conducted as programed where the routine of the tilt-rotational sample holder was synchronized with the on-off control of the UV light including top and bottom side exposures. A standard post-exposure bake at 95°C for an hour, and developing in propylene glycol methyl ether acetate (PGMEA) solution for 40 minutes, completed the process.

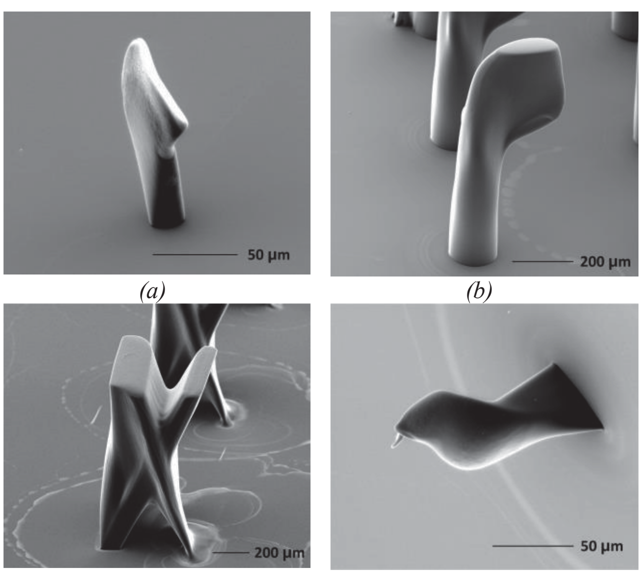
III. Modeling

Since the CNC UV-LED lithography utilizes adjustable inclined UV-exposure with synchronized light illumination state, the optical path through the photomask is varied and, therefore, enables the fabrication of various 3D microstructures. A coordinate system of UV-ray trace as shown in Figure 5 together with dose-exposure curves for SU-8 [10] was found to be an adequate predictor of the final exposed device shape. The coordinate (x_1, y_1, z_1) represents the position of the backside UV exposure light. Since the position of the UV light is determined by the rotation and the tilting, the x_1, y_1, and z_1 can be expressed as the rotational and tilting angle and angular speed as shown in equation (1), (2), and (3). If the x_1, y_1, and z_1 are the expression of the UV light from the bottom-up direction (backside exposure), the reference level of the top-down direction (topside exposure) starts at the thickness of the photoresist which is defined as 'h.' Thus, the top-down direction can be expressed as shown in the equations (4), (5), and (6).

$$x_1=z_1\tan(\theta_1)\cos(\varphi_1) \quad (1)$$

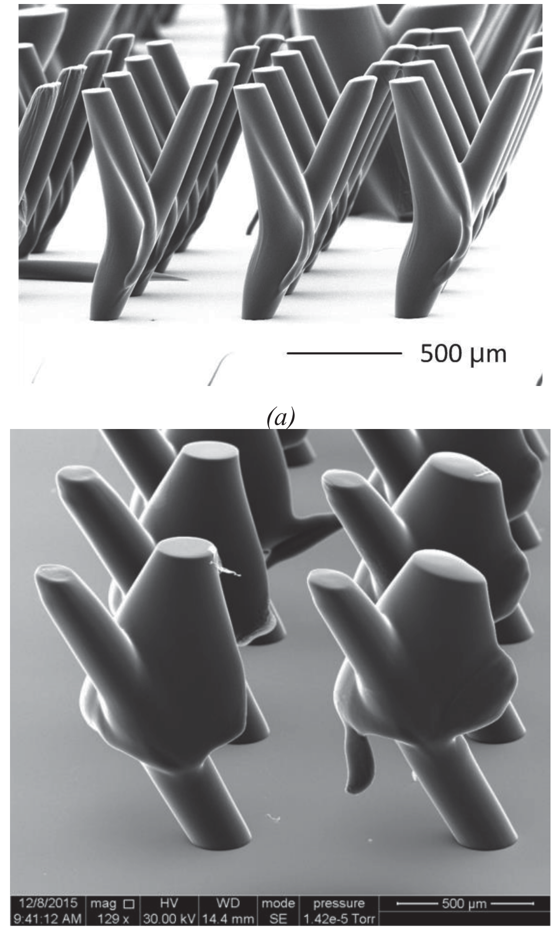
$$y_1=z_1\tan(\theta_1)\sin(\varphi_1) \quad (2)$$

$$z_1=z_1 \quad (3)$$



(a) (b) (c) (d)

Figure 6: Fabrication result: (a) a micro spear, (b)a micro golf club, (c) a micro folder, (d) a micro bird (90° rotated view)



(a) (b)

Figure 7: Batch fabrication of (a) micro letter 'y' and (b) micro mushroom

$$x_2=(h-z_2)\tan(\theta_2)\cos(\varphi_2) \quad (4)$$

$$y_2=(h-z_2)\tan(\theta_2)\sin(\varphi_2) \quad (5)$$

$$z_2=z_2 \quad (6)$$

IV. Results

Various test microstructures have been fabricated including 3D exotic microstructures using the double-side UV exposure scheme as shown in Figure 6.

An exposure scheme of the UV light for micro spear was in a combination of 45° tilt backside exposure and 0-50° tilt top side exposure. Thus backside exposure formed an inclined pillar while the topside exposure made the spearhead as shown in Figure 6(a). In a similar way, a micro golf club structure was fabricated. A 20° tilt backside exposure made a pillar, and the head of the golf club utilized the top side exposure of tilt-rotation angles in synchronous variations ranging of 0-45° and 0-360° respectively as shown in Figure 6(b). A photograph of a micro-folder structure is shown in Figure 6(c). To generate this structure, the UV exposure scheme comprised a lower portion of an inclined panel (tilt angles at 0° and 45° respectively). The upper portion of two panels was fabricated using tilt angles of 0° and 45° respectively. Figure 6(d) demonstrates a micro bird structure. A rectangular photo pattern was utilized to realize the body of the micro bird structure, while a hole pattern was used to realize the head of the micro bird. Note that the tilt and rotational angles in this description were the operation of the sample holder which is different from the angles previously described in 'Modeling' section.

A batch of micro letter 'y' structures and a batch of micro mushroom structures are shown in Figure 7. The long inclined pillar was fabricated from the lower photomask while the branch attached to the inclined structure was patterned from the upper photomask. These unique microstructures show the versatility of the UV-LED double exposure process.

V. Conclusion

Double-side CNC UV-LED lithography has been introduced as a versatile 3D micropatterning process. A simple two photomask alignment method for the double side CNC UV-LED lithography has been demonstrated with a self-mask alignment frame. The ray trace of the double-side UV-LED lithography has been studied, and equations for a predictable model of the fabricated microstructures have been introduced. Using the double-sided UV-LED exposure scheme, exotic 3D microstructures such as new 3D shapes compared to the previous work have been successfully fabricated including a micro spear, a micro golf club, a micro folder, and a micro bird. A batch fabrication of 3D microstructures was also demonstrated including micro letter 'y' and micro mushroom. The 3D structures from the double-sided UV-LED exposure find great potentials for radio frequency (RF)/micorwave applications such as integrated millimeter wave and terahertz antennas and waveguides, 3D photonic bandgap (PBG) structures, 3D metamaterials, as well as power electronic components such as 3D toroidal or solenoid inductors.

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