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CNC-LITHOGRAPHY: COMPUTER-CONTROLLED MULTIDIRECTIONAL LIGHT-MOTION-SYNCHRONIZED LITHOGRAPHY FOR 3-D MICROFABRICATION

Jungkwun 'JK' Kim[1], Yong-Kyu 'YK' Yoon[2], Thomas C. Mier[1], and Mark G. Allen[1]
[1]University of Pennsylvania, Department of Electrical and Systems Engineering
[2]University of Florida, Department of Electrical and Computer Engineering

Abstract

This paper presents a computer-controlled multidirectional UV-LED (ultraviolet light-emitting diode) lithography system for three-dimensional (3-D) microfabrication, introducing the concept of CNC-lithography. The system comprises a switchable, movable UV-LED array as a light source and a motorized tilt-rotational sample holder, in which each system element is computer-controlled. This approach enables a relatively small size and overall portability of the system. The proposed system has two unique features; (1) the movable LED array improves the uniform UV light distribution over the substrate area; and (2) the switchable function of the LEDs is synchronized with the movement of the tilt-rotational sample holder, enabling the creation of 3-D patterns of substantial complexity. Unlike layer-by-layer additive approaches such as stereolithography, the CNC-lithography system can form fine shapes with no layering artifacts in a batch-compatible manner, at the expense of true arbitrariness of formable shape. When compared to conventional inclined lithography, CNC-lithography greatly increases ease of fabrication by eliminating multiple manual exposure steps and also enables the fabrication of new 3-D structures that would have been challenging to implement previously. Demonstration lithographic shapes, including a micro-'pipe,' a micro-'hi,' a micro-'Calla lily,' and a micro-'cyborg', are fabricated to illustrate the range of the process.

KEYWORDS

CNC-lithography, UV-LED, Multidirectional 3-D microfabrication.

INTRODUCTION

Advances in LED technology have resulted in widely-available components possessing simple operation, small size, low power consumption, and low material cost. In particular, LEDs operating at UV wavelengths have been widely utilized in sensor applications including surface acoustic wave generation (SAW) [1], fluorescence detection [2], and ozone sensing [3]. An attractive LED feature exploited by these applications is the single-peak, narrow bandwidth emissive behavior (which results in high selectivity/sensitivity), achievable in a compact package with no additional required optical filters.

Recently, UV-LEDs with emission peaks ranging from 360 – 405 nm have been investigated as light sources for UV lithography, in particular as a comparable photolithography

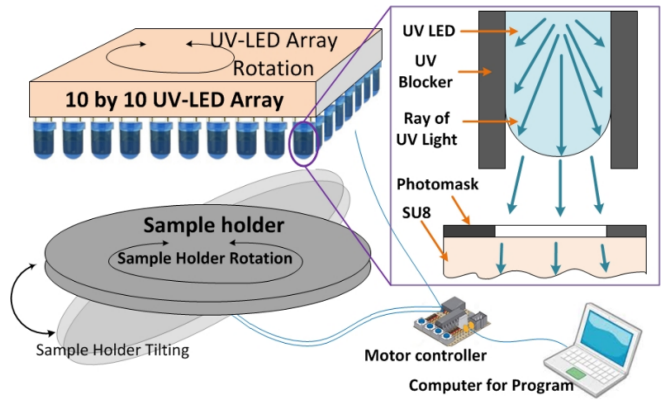


Figure 1. Schematic diagram of CNC-Lithography

system to conventional mercury-lamp-based systems. An array of 200 UV-LEDs with a 405 nm-peak wavelength was introduced as a UV lithography light source and submicron features of 200 nm over 4-in Si wafers were demonstrated [4]. In this system, a diffuser was employed at the UV-LED array to provide the uniform UV light intensity; however, employment of a diffuser sacrifices both light intensity and collimation [5]. This could be problematic for fabricating thick and high-aspect ratio microstructures in thick resist systems. Subsequently, a commercial UV-LED torch was utilized as a UV lithography light source. The UV-LED torch was placed on top of glass-photomask for UV exposure. This method demonstrated a 7-µm pattern feature for SAW device fabrication. However, the method suffered from non-uniform UV-LED illumination, which caused irregular pattern transfer in the fabrication trials [1].

Fabrication of three-dimensional microelectromechanical systems (MEMS) presents additional challenges for lithography; in particular, the creation of arbitrary lithographic constructs using relatively low capital cost equipment. Multidirectional UV lithography has been presented as an approach to overcome these challenges [6,7]. In multidirectional UV lithography, a sample stage supporting a resist-bearing substrate is tilt-rotated with computer control under UV illumination to

Table 1. Comparison between UV-LED and Mercury lamp lithography system

System	UV LED	Mercury lamp
Bulb Life time	~100,000 hrs	~2,000 hrs
Cost (bulb)	~$1/LED	~$300
Intensity	8 – 30 mW/cm^2	5 – 40 mW/cm^2
Light collimation	~15 ° (air) ~7 ° (photoresist)	~7 ° (air) ~3°(photoresist)
System modification	Flexible	Hard

create multi-angle UV-light traces, exposing photoresist along these traces and ultimately resulting in the desired 3-D microstructures. In this system, the optical subsystem for UV exposure tends to be the largest and the most expensive portion of the system due to employment of the Hg-vapor lamp, which also requires multiple optical mirrors, lenses, and high power supplies. Also, from a functionality point of view, the Hg-vapor lamp cannot itself support a rapid change in illumination state; and external mechanical shuttering is also limited in time response. Thus, the UV light source in previous multidirectional UV fabrication method has typically been a constant 'light-on' source while the tilt-rotational sample holder was moving. Accordingly, discrete microstructures such as a multi-branched pillar required manual switching operations.

Bearing these limitations, the use of UV-LEDs as light sources in inclined lithography was previously investigated [8]. In this paper, we extend this work to exploit the rapid switching time of the UV-LEDs to create an exposure system in which the position, rotation angle, and tilt angle of the sample can be synchronized to the 'on-off' state of the LED light source under computer control, thus forming a computer-numerical-controlled (CNC) lithography system. This system allows for the more rapid lithographic fabrication of 3-D microstructures over previous manual exposure approaches, as well as enables the fabrication of new classes of 3-D structures.

SYSTEM CHARACTERIZATION

Figure 2 shows the CNC-Lithography system. The system comprises a UV-LED array as a light source, a tilt-rotation sample holder, and a control unit (not shown in this Figure). The LED array is formed by aligning 100 discrete LEDs in a 10x10 array; the array is electrically driven from the control unit. The housing of the LED array is 3-D printed using acrylonitrile butadiene styrene (ABS) and mounted to the upper rotating motor. The tilt-rotation sample holder is fabricated from 6-mm-thick aluminum sheets, and the tilt and rotation motors are mounted to the sample holder. The circular dish of the sample holder has a diameter of 10.5 cm, which can handle up to a 4-inch wafer size. The control unit includes a computer for programming, and a control board, which includes motor drives, and a solenoid switch for the UV-LED. The overall proposed system has a foot print area of 17 × 15 cm^2 and a height of 35 cm, which is compact and portable. Please note that the sizes of the computer and the power supply have not been included.

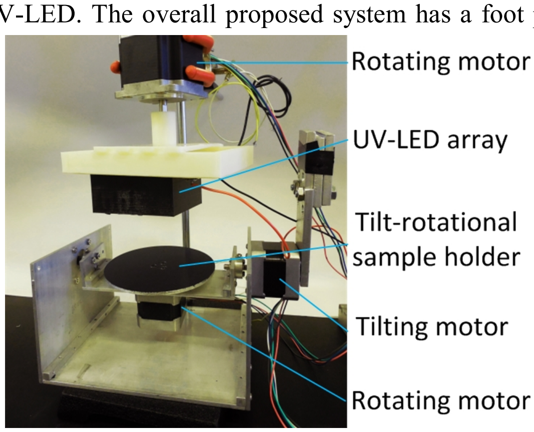


Figure2. CNC-Lithography system

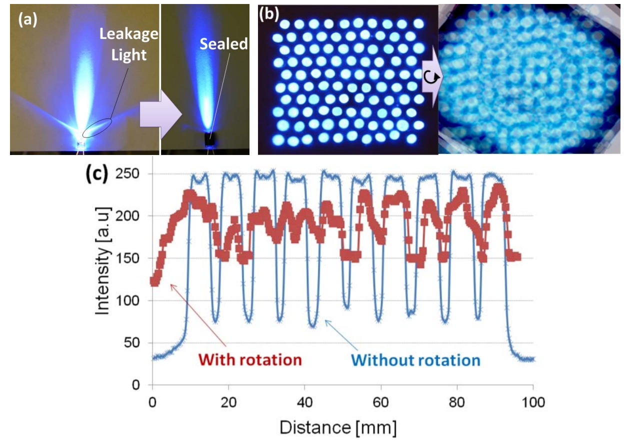


Figure 3. Light intensity distribution: (a) UV-LED sidewall coating and light propagation comparison, (b) optical image of intensity comparison without and with rotation, (c) intensity comparison plot

Figure 3 shows photographs of the UV-LEDs and a plot of the LED intensity distribution. As undesired LED light propagation is observed through the sidewall of the bulb as shown in Figure 3(a)-left, the sidewall of the LED was sealed with a polyolefin tube to improve the light collimation as shown in Figure 3(a)-right. Figure 3b shows a 'light-on' image of the LED array. Since the image clearly shows individual dark and the bright areas, resulting in non-uniform areal light intensity (Figure 3(b)-left), the LED array is made to rotate in an oscillatory fashion during exposure to improve the light intensity distribution without using diffusers (Figure 3(b)-right). This intensity distribution has been plotted using a public domain Java image processing program, ImageJ as shown in Figure 3(c). The data without rotation (the blue plot) show relatively large intensity differences, while the data with rotation (the red plot) show significantly reduced intensity differences.

Figure 4 describes the ray trace of the inclined UV light. The UV light from the LEDs passes through the air with an incident angle of θ_1 and is refracted while passing through the

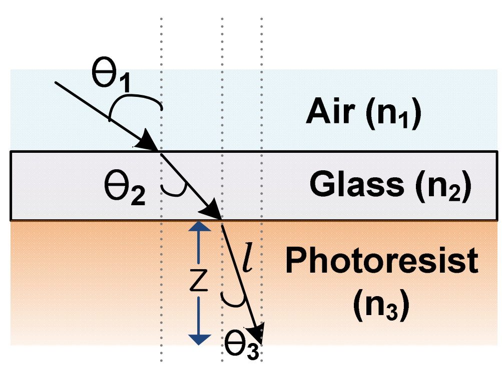


Figure 4. Inclined light propagation in the multidirectional UV lithography

glass with an angle of θ_2 and forms a final inclined angle of θ_3 (the structural angle) at the photoresist, e.g., SU8. This description is converted into a simple equation using Snell's law as shown in Equation (1), which enables prediction of the final inclined angle of the fabricated SU8 structure. The UV intensity at photoresist depth (z) or length (l) can be calculated knowing the incident UV light intensity (I_0) and geometric and material parameters as shown in Equation (2):

$$\theta_3 = \sin^{-1}\left(\frac{n_1}{n_3}\sin\theta_1\right) \tag{1}$$

$$I(l) = I_0 \times e^{-\alpha \times l}, \text{ where } l = \frac{z}{\cos\theta_3} \tag{2}$$

where n_1, n_2, n_3 and α are the refractive indices of air, glass, photoresist, and the absorption coefficient of photoresist, respectively. Equation (2) allows the prediction of additional fabrication parameters such as UV exposure time to fabricate a certain height of SU8 structure. To fabricate, for instance, an inclined pillar in a 500-µm-thick SU8 layer with a structural angle of 30°, the UV intensity at the 500-µm-thick position with 30° inclined angle is calculated as 1.3 mW/cm^2. The absorption coefficient and the UV LED intensity are assumed as 0.0031 [9] and 8 mW/cm^2 [8], respectively. If the SU8 threshold crosslinking dosage is 12 mJ/cm^2 [10], then the minimum exposure time for this structure is approximately 9 seconds. If the ratio of refractive indices of SU8 and air is 1.6, the CNC-lithography inclined angle should be 53°.

FABRICATION

The fabrication process follows the standard procedure recommended by the SU8 manufacturer: spin coating, softbake, UV exposure, post-exposure bake, developing and post cleaning (rinse and dry) [11]. During the exposure step of CNC-lithography, as in traditional multidirectional UV lithography, a backside exposure scheme is typically utilized. In this scheme, the photoresist is coated on a prepatterned Cr mask to eliminate any air gap between the mask and the thick photoresist.

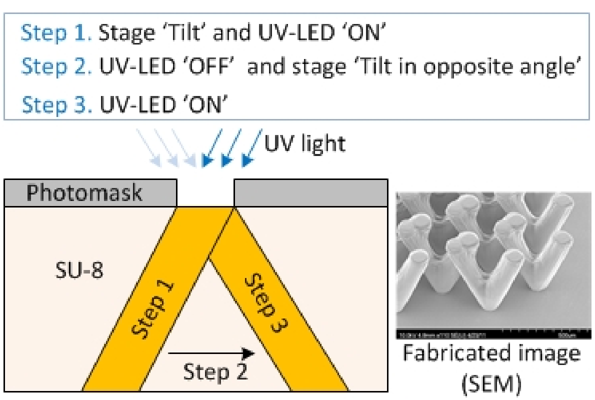
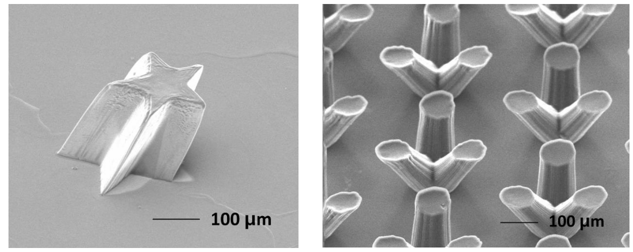


Figure 4. An example of CNC lithography program description for micro-'V' pillars: fabrication steps (left) and an SEM view of fabricated structures (right)



(a) Inclined star shape micropillar *(b) Microtripod*

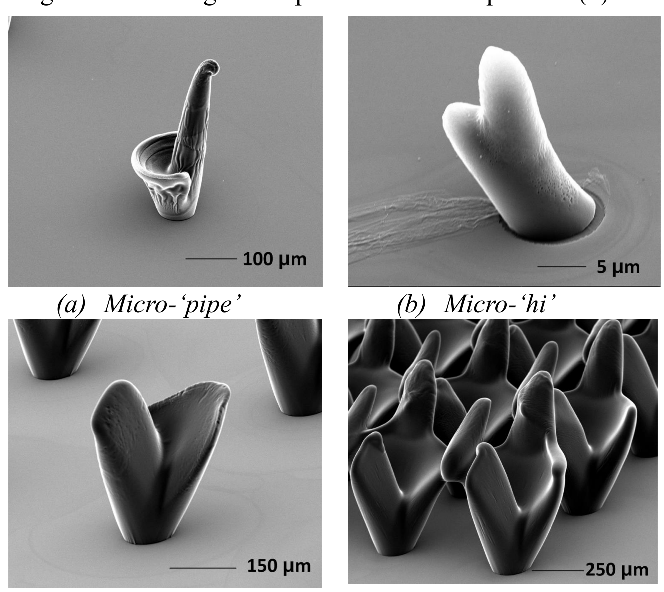
Figure 5. Fabrication result: inclined structures

An example CNC program is illustrated in Figure 4 for fabrication of micro-'V' pillars. A first UV exposure (Step 1) is performed at an inclined angle of 45° without rotation. Then the UV-LED is turned off (Step 2) while the sample holder tilts to an inclined angle of -45°. A second UV exposure (Step 3) follows to complete the process. The corresponding scanning electron microscopy (SEM) image of the fabricated structures is shown in Figure 4-right. Note that the resultant structural angle differs from the inclined angle of 45° in accordance with Equation 1.

RESULT AND DISCUSSION

Figure 5 shows simple inclined test structures using CNC-lithography. An inclined star-shape micropillar is fabricated from 45° inclined UV exposure as shown in Figure 5a. Three discrete UV exposure steps spaced at 120° azimuthal rotation and 45° inclined angle are performed to fabricate microtripod structures as shown in Figure 5b. The LEDs are turned off by computer control while the sample holder moves to the next rotation position; this function has been previously possible only with manual on-off switching.

More exotic 3-D microstructures are demonstrated as shown in Figure 6. In this fabrication, multiple different heights and tilt angles are predicted from Equations (1) and



(a) Micro-'pipe' *(b) Micro-'hi'*

(c) Micro-'Calla lily' *(d) Micro-'cyborg'*

Figure 6. Complex 3-D microstructures using CNC lithography

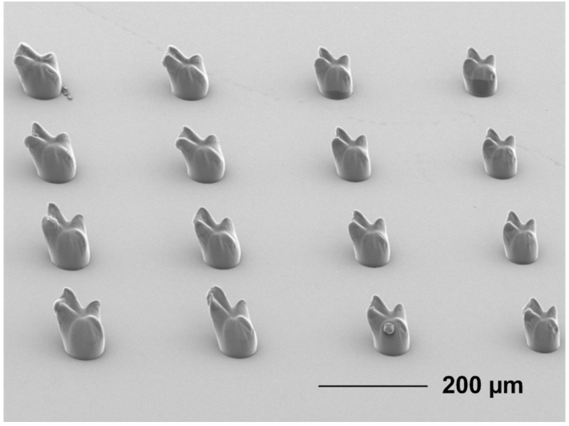


Figure 7. Batch fabrication of micro-cat's-claw

(2). Continuous and discrete UV exposure steps have been programmed as per the height and the tilt angle predictions. An SEM image of a micro-'pipe' structure is shown in Figure 6(a). A hole photopattern with a diameter of 80 µm is used. The heights of the pillar-like structure and the horn-like structure are 310 µm and 100 µm, respectively. Figure 6(b) shows an SEM image of a micro-'hi' structure. A 10-µm-diameter hole mask-pattern is utilized. The fabricated structure has a height of 18 µm with a structural angle of 30°. Figure 6(c) shows a microstructure of micro-'Calla Lily' with a height of 340 µm using a 100-µm-diameter-hole pattern. Figure 6(d) shows further complex 3-D structures, micro-'cyborgs.' A 200-µm-hole pattern is used and the height of the fabricated structure is 930-µm tall. These structures have demonstrated a wide range of microstructures from 18 µm to 930 µm with a powerful 3-D microfabrication capability.

Figure 7 shows an array of hole photopatterns with CNC program to fabricate a micro-cat's-claw array, which shows its batch process capability. Five different claw heights are formed on a cat's paw where multiple discrete UV exposure steps are performed at different tilt-rotation positions with synchronized UV-LED switching. These structures show the versatility of the UV-LEDs and the great potential of advanced UV lithography schemes.

CONCLUSION

CNC-lithography, the synchronized motion and activation of light source and sample holder during lithographic exposure, has been introduced as a versatile 3-D micropattering process. The system comprises 100 UV-LEDs, a tilt-rotational sample holder, and a control unit with an overall dimension of $17\times15\times35$ cm^3. The CNC lithography system can fabricate various 3-D exotic microstructures without manual operation. Various and complex 3-D microstructures have been successfully fabricated including micro-'pipe,' micro-'hi,' micro-'Calla lily' and micro-'cyborg' as well as the batch fabricated array of the micro-cat's-claw. CNC lithography has great potential to create structures in diverse application areas such as microfilters, scaffold structures for cell manipulation, and antenna structures for GHz and THz range applications.

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REFERENCES

[1] C. Y. Bing, A. A. Mohanan, T. Saha, R. N. Ramanan, R. Parthiban, and N. Ramakrishnan, "Microfabrication of surface acoustic wave device using UV LED photolithography technique," *Microelectronic Engineering*, vol. 122, pp. 9–12, (2014).

[2] K. Davitt, Y. K. Song, W. R. Patterson, A. V. Nurmikko, M. Gherasimova, J. Han, Y. L. Pan, and R. K. Chang, "290 and 340 nm UV LED arrays for fluorescence detection from single airborne particles," *Optics Express*, vol. 13, no. 23, pp. 9548-9555, (2005).

[3] M.C. Carotta, A. Cervi, A. Fioravanti, S. Gherardi, A. Giberti,B. Vendemiati, D. Vincenzi, and M. Sacerdoti, "A novel ozone detection at room temperature through UV-LED-assisted ZnO thick film sensors," *Thin Solid Films*, vol. 520, pp. 939–946, (2011).

[4] M. D. Huntington and T. W. Odom, "A Portable, Benchtop Photolithography System Based on a Solid-State Light Source," *Small*, vol. 7, no. 22, pp. 3144–3147, (2011).

[5] D.-H. Kim, J.-H. Lee, H. S. Lee, and J.-B. Yoon, "A trans-scaled nanofabrication using 3D diffuser lithography, metal molding and nano-imprinting," *J. Micromech. Microeng.* vol. 21, 045025, (2011).

[6] Y. Yoon, J. Park, and M. Allen, "Multidirectional UV lithography for complex 3-D MEMS structures," *J. Microelectromech. Syst.*, vol. 15, no. 5, pp. 1121-30, (2005).

[7] J. Kim, M. Allen, Y. Yoon, "Computer controlled dynamic mode multidirectional UV lithography for 3-D microfabrication," *J. Micromechanics and Microengineering*, vol. 21, no.3. pp. 1-14, (2011).

[8] J. Kim, S. Paik, F. Herrault, and M. Allen, "UV-LED Lithography for 3-D high aspect ratio microstructure patterning," *Proc. Hilton Head Workshop* 2014, South Carolina, June 3-7, (2014).

[9] R. Yang, and W. Wang, "A numerical and experimental study on gap compensation and wavelength selection in UV-lithography of ultra-high aspect ratio SU-8 microstructures," *Sensors and Actuators B*, vol. 110, 279–288, (2005).

[10] J. Kim, C. Kim, M. G. Allen and Y.-K. Yoon, "Fabrication of 3D nanostructures by multidirectional UV lithography and predictive structural modeling," *J. Micromech. Microeng.* vol. 25, 025017, (2015).

[11] Microchem Inc. website, [Accessed: 22 March 2015]: http://microchem.com/pdf/SU-82000DataSheet2025thru2075Ver4.pdf.

CONTACT

*J.K. Kim: jungkwun@seas.upenn.edu