Journal of Micromechanics and Microengineering

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To cite this article: Sung Ho Lee *et al* 2016 *J. Micromech. Microeng.* **26** 115008

OPEN ACCESS
IOP Publishing

Journal of Micromechanics and Microengineering

J. Micromech. Microeng. **26** (2016) 115008 (6pp)

doi:10.1088/0960-1317/26/11/115008

Roll-type photolithography for continuous fabrication of narrow bus wires

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Received 23 April 2016, revised 14 September 2016
Accepted for publication 20 September 2016
Published 5 October 2016

Abstract

This paper presents a continuous patterning method to enhance the productivity of metallic microstructure fabrication. The minimum exposure time and the optimum ultraviolet (UV) intensity were determined for the photoresist (PR) to develop micro PR patterns in continuous roll-type photolithography. To confirm the efficiency of continuous roll-type photolithography, wet etching was performed instead of dry etching as a post-lithography process. Parametric study results showed that the minimum exposure time required for sufficient PR reaction during continuous roll-type photolithography was 0.2 s under 1000 mW cm^{-2} of UV intensity. This study demonstrated roll-type photolithography and determined the highest production speed for continuous roll-type photolithography to be 24 mm s^{-1}. Continuous photolithography and wet etching were employed to produce narrow copper bus wires for a bezel-less display panel, indicating the practical applications of continuous roll-type photolithography.

Keywords: continuous process, photolithography, roll-to-roll, bus wire, wet etching

(Some figures may appear in colour only in the online journal)

1. Introduction

Recently invented micro/nanofabrication processes in various fields share a close relationship to continuous production systems, such as roll-based fabrication systems, which enable mass fabrication with high production yields [1–7]. Despite its discontinuity limitation and the recent advancements in novel micro/nanofabrication processes [8–10], photolithography remains the main production method for various micro/nanostructures [11–13] because of its high reproducibility, reliability, and matured pre- and post-processes, such as deposition, aligning, and etching. However, conventional photolithography has not manufactured products for large-area electronic [14] and photonic devices [15] using flexible substrates despite increasing demand. Thus, other continuous techniques, such as roll-to-roll nanoimprint lithography (R2RNIL), have been proposed for large-area and flexible pattern fabrications [1, 16–18]. However, the yields of these techniques are still insufficient to cover the demands on applications of conventional fabrication methods. To solve this issue, continuous photolithography with significantly improved productivity and reduced manufacturing costs is being developed to satisfy scalability and productivity requirements for applications in flexible device production [4]. Recently, conventional photolithography has been extended to a continuous process by utilizing a roll-type photomask for large-area patterning while maintaining reasonable resolutions [3, 4]. Among continuous photolithography processes, photo-roll-lithography (PRL) is based on conventional photolithography [4]. PRL allows a continuous process with a linear UV light source and a flexible photomask with metal patterning. This process can produce various micro/nano patterns with large areas and has a critical resolution of approximately 1 μm, which is limited by the light collimation limit and pattern widening during development [4]. Many applications of conventional photolithography can be realized by PRL because of their shared process details.

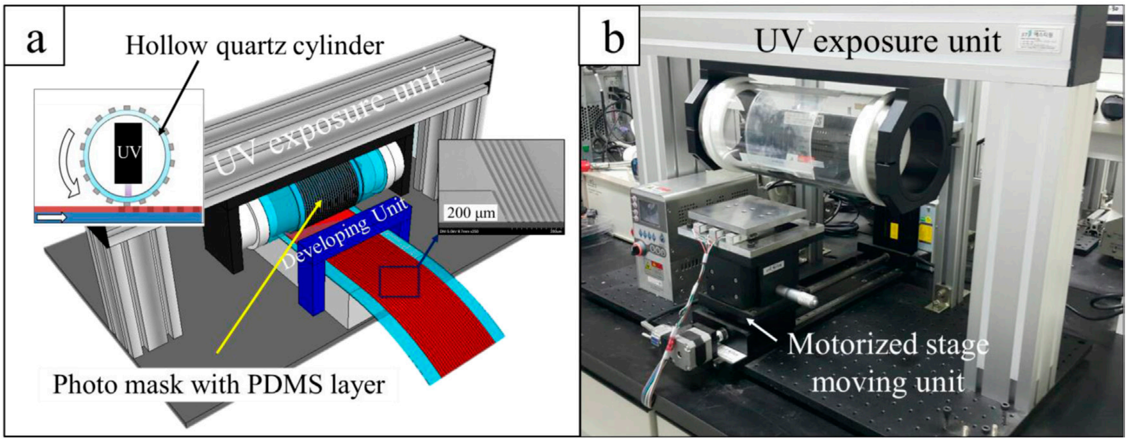

Figure 1. (a) Schematic of the custom-built roll-type photolithography equipment. (b) Image of the custom-built roll-type equipment.

Photolithography entails an appropriate UV dose to define micro/nanostructures in the photoresist (PR). The required UV dose is determined by PR type and coating thickness. In conventional photolithography, PR-coated substrates are usually exposed for several seconds to UV intensities of 10–20 mW cm^{-2}. However, from a production speed perspective, the typical UV intensity is too weak to reach the required UV dose for application in roll-type photolithography processes. The linear-type UV light source used in continuous photolithography has a very low absolute UV dose per unit area because of the narrow exposure width. In the present study, a high-intensity UV light source was used to achieve high-speed roll-type photolithography. Results confirmed that PR structures could be defined in a short time under a high-intensity UV light source. Finally, optimal process parameters were defined to enhance the efficiency and productivity of roll-type photolithography. The proposed method was used to produce narrow copper bus wires for bezel-less displays.

2. Experimental results and discussion

2.1. Setup for roll-type photolithography equipment

The setup for the custom-built roll-type photolithography equipment consists of three parts: a substrate moving unit, a UV light exposure unit, and a developing unit (figure 1). A linear motion guide with a step motor system was constructed to move the PR-coated substrate. The height-adjustable stage was assembled on a motor-driven moving stage to obtain three degrees of freedom. This assembly moved at the speed of 4–24 mm s^{-1} and was controlled by a step motor system. A 110 mm-diameter quartz cylinder with an aluminum profile was installed in the UV light exposure unit. Contact between the stage and the quartz cylinder occurred when the PR-coated substrate passed through the UV light exposure unit. The edge of the quartz cylinder was installed with a ball bearing to enable rolling. The quartz cylinder was constructed with a thickness of 5 mm to prevent breakage. A 365 nm-wavelength linear UV light source (SUV-L, UVSMT) with a UV intensity of 300–1500 mW cm^{-2}, a width of 120 mm, and a slit UV exposure area of 5 mm was installed in the quartz cylinder. A flexible photomask was prepared by a simple fabrication process [4]. A thin adhesive polydimethylsiloxane layer was placed between the photomask and the quartz cylinder for conformal contact when the photomask was attached to the quartz cylinder. Finally, the UV-exposed sample was developed in the developer unit and rinsed with DI water.

2.2. Experiment for high-speed photolithography

An experiment was conducted to observe the formation of PR structures after a short UV exposure time and to determine the feasibility of production with roll-type photolithography. A positive PR (DPR-TR90, DONGJIN SEMICHEM) with 3 μm thickness and a stencil-type metal mask consisting of a square-hole array were used in the experiment. UV dose was set from 80 mJ cm^{-2} to 170 mJ cm^{-2} in accordance with a datasheet recommendation by controlling UV intensity from 300 mWcm^{-2} to 1500 mWcm^{-2} as the target stage moving speed, and developing time was set to 1 min. UV dose is a function of the stage moving speed and UV intensity, as shown in the following equation:

$$D = I \times \frac{w}{v},$$

where D is the UV dose by PRL, I is the UV intensity, and w and v are the slit widths of the UV light source and the stage moving speed, respectively.

Figure 2 shows the results of the PR reactance in response to UV exposure time. UV dose was fixed at 170 mJ cm^{-2} by changing the moving stage speed and UV intensity. PR structures were clearly defined after a short UV exposure time of 0.45–0.2 s, as shown in figures 2(b)–(d). In the samples exposed to UV for 0.15 and 0.10 s (figures 2(e) and (f)), PR reaction to UV light was insufficient to define PR structure although UV dose was the same for the samples in figures 2(b)–(d). These results suggest that a critical exposure time is required to define PR structures regardless if the UV dose is sufficient. To confirm this hypothesis, an additional experiment was conducted. The PR-coated substrate was exposed to two UV doses of 80 and 110 mJ cm^{-2} under two exposure times. As shown in figure 3, PR reactance differed under the same UV dose and showed dependence on UV exposure time. The PR structures in the sample exposed to a low UV dose for 0.37 s

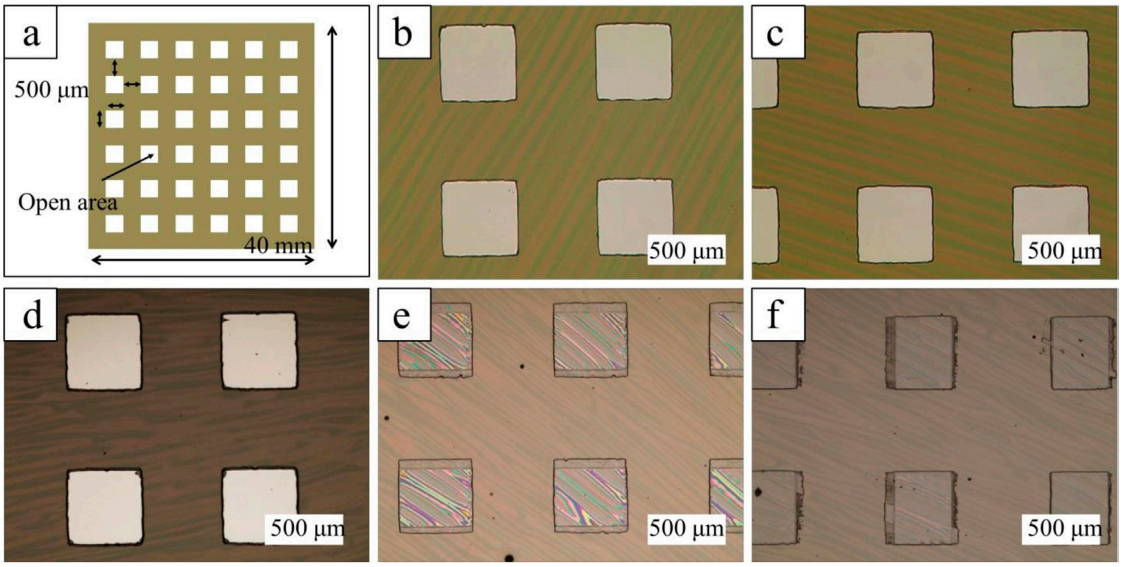

Figure 2. (a) Schematic for stencil-type photomask. Optical microscope images of PR reaction with respect to different UV exposure times: (b) 0.45 s, (c) 0.37 s, (d) 0.20 s, (e) 0.15 s, and (f) 0.10 s.

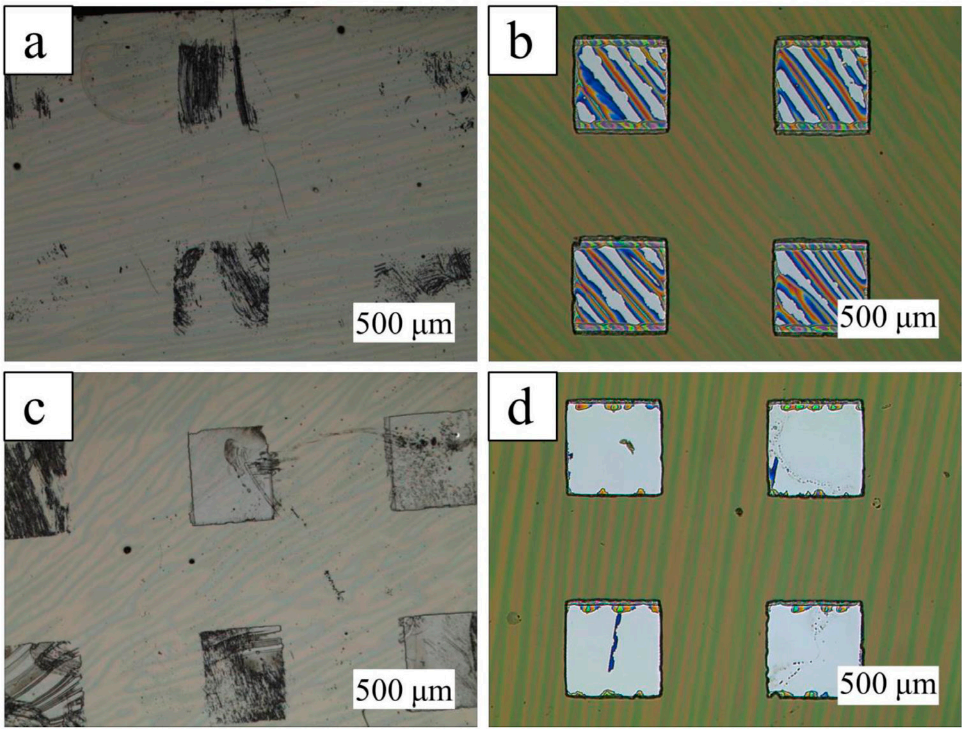

Figure 3. Optical microscope images of PR reaction under different UV doses and exposure times: (a) 80 mJ cm^{-2}, 0.05 s; (b) 80 mJ cm^{-2}, 0.37 s; (c) 110 mJ cm^{-2}, 0.08 s; (d) 110 mJ cm^{-2}, 0.37 s.

developed partially even if the UV dose was insufficient for complete development, whereas those in the samples exposed for 0.05 and 0.08 s did not even show partial development. These results strongly suggest that PR reactions require a critical exposure time to UV light to proceed. These experiments depict that PR structures could be defined in a short time under a high UV intensity and that PR requires a critical exposure time to react to UV light. A previous study reported that the photoreaction of a diazonaphthoquinon-based positive tone PR occurs on the PR surface [19] and that the development rate increases with exposure time. Our experimental result showed that the shortest reaction time to guarantee the stable development of PR structures was 0.2 s.

2.3. Photolithography using roll-type equipment

A linear UV source was installed in the quartz cylinder for the main experiment. Before the experiment, the effective UV intensity of the roll-type equipment was measured with a UV meter (KUHNAST, Germany). To determine the UV dose

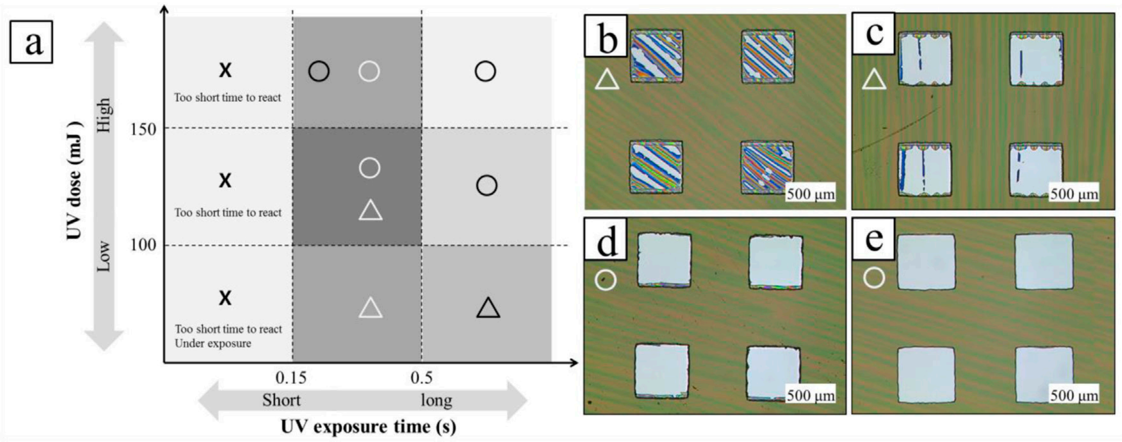

Figure 4. (a) Effective UV dose of the custom-built roll-type equipment. The round symbol represents a good result of patterning and the cross symbol represents poor patterning. The triangle indicates a moderate condition on patterning. Optical micrographs of the PR reaction under various UV doses: (b) 86 mJ cm^{-2}, (c) 104 mJ cm^{-2}, (d) 117 mJ cm^{-2}, (e) 170 mJ cm^{-2}.

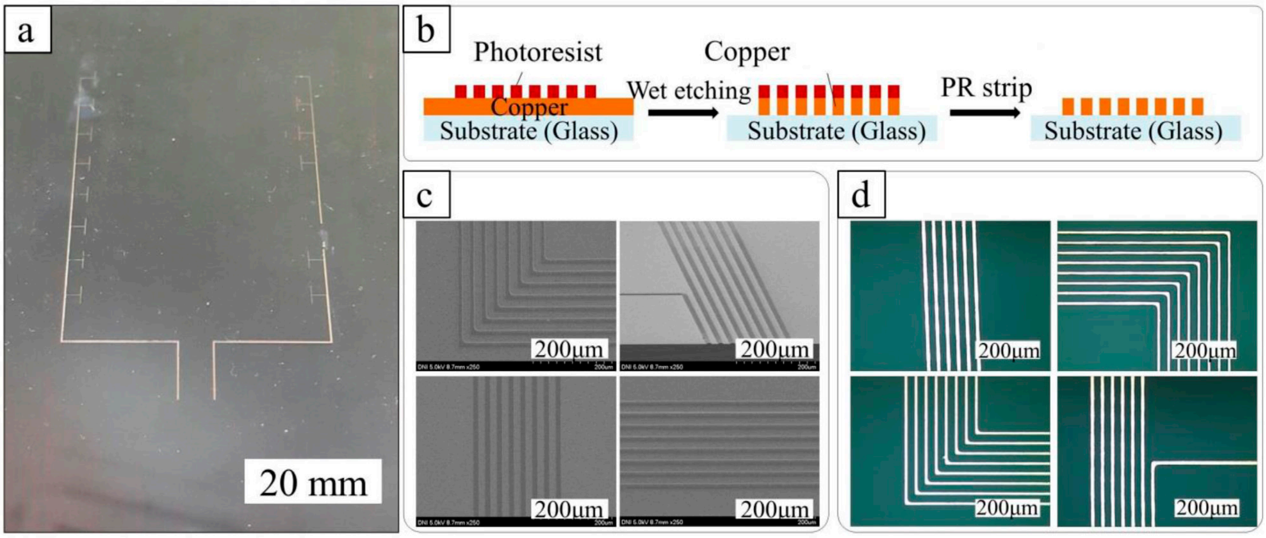

Figure 5. (a) Image of the narrow bus wire sample. (b) Schematic for the fabrication of narrow bus wires. (c) SEM images of narrow bus wires before wet etching. (d) Optical micrographs of the narrow bus wires after wet etching.

required to fabricate PR structures by the roll-type device, PR reaction in response to UV dose was observed (figure 4). The UV exposure time was held constant for 0.37 s, and the UV dose was controlled by a UV intensity controller. The PR sample was clearly fabricated under a UV dose of 170 mJ cm^{-2} (figure 4(e)), showing that high-speed photolithography using roll-type equipment was achieved successfully in this experiment. On the basis of PR responses to UV exposure times, the fabrication speed of photolithography using roll-type equipment was 24 mm s^{-1} and can even reach 50 mm s^{-1} with increased UV intensity, theoretically.

2.4. Fabrication of narrow bus wires by roll-type equipment

Many recent studies have demonstrated the practical application of MEMS in the production of electrical devices [20–25]. Bus wires composed of copper, a material with good electrical conductivity, have been fabricated using the offset printing method; the fabricated bus wires display practical applications in technologies such as smart phones, monitors, and TVs. However, the resolution (up to 10 μm) is limited, and the offset printing method is not suitable for narrow bezel or bezel-less fabrication. In this experiment, narrow bus wires composed of copper were fabricated to demonstrate the practical application of roll-type photolithography. The fabrication parameters of the roll-type photolithography were also characterized for the stable production of narrow bus wires. Narrow bus wires were fabricated on the basis of the results of sections 2.2 and 2.3. First, a photomask with a 15 μm line width and space was designed. A 1 μm-thick copper layer was sputter deposited on a glass substrate. The copper-deposited glass was coated with PR, and PRL was progressed. After photolithography, the sample was immersed in

Table 1. Electrical resistance of narrow bus wires fabricated by roll-type photolithography in Ωs.

Thickness (nm)/Length (mm)	8 mm	18 mm	26 mm
500	4.53	9.13	13
1000	3.07	4.78	7.6

copper etchant (Alfa Aesar). The copper layer was selectively etched except for PR structures (figure 5(b)) [4, 26]. PR structures were visualized by scanning electron microscopy (SEM) (S-4800, Hitachi) and optical microscopy (LV150L, Nikon). Figure 5(c) shows an SEM image of the PR structure before etching, and figure 5(d) shows micrographs of the narrow bus wires on the glass substrate after etching. Figure 5(a) shows the fabrication of narrow bus wires by using our custom-built roll-type device. To determine the electronic properties of the fabricated narrow bus wires (500 nm and 1 μm thick), their resistance values were measured with a multimeter (U1252B, Agilent) (table 1). The sample's resistance was low although the bezel was narrow and long. Resistance could also be improved by controlling the thickness of metal deposition. Curve fitting and simple calculation revealed that the contact resistances of the samples 500 nm and 1 μm in thickness were 0.85 Ω and 0.73 Ω, respectively. Despite their narrow widths compared with conventional bus wires fabricated by offset printing, the narrow bus wires fabricated by roll-type photolithography may be used in display applications.

3. Conclusion

High-speed and continuous photolithography is possible with custom-built roll-type equipment. PR reaction was observed in response to UV dose and exposure time. Results confirmed that the PR required a minimum exposure time to react to UV light even under sufficient UV dose. In addition, PRL could accomplish the large-scale and fast continuous production of micro/nanostructures. To demonstrate the practical application of PRL, prototypes of narrow bus wires were successfully fabricated for use in bezel-less displays. Continuous and high-speed photolithography with roll-type equipment may have practical applications in the large-scale production of electronics and photonics, as well as in various industrial fields.

Acknowledgments

This work was supported by the Fire Fighting Safety & 119 Rescue Technology Research and Development Program funded by the Ministry of Public Safety and Security (2015–73), and the National Research Foundation of Korea (2016R1A2B4007858) funded by the Ministry of Science.

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