A Portable, Benchtop Photolithography System Based on a Solid-State Light Source

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Advances in photolithography have enabled the development of microelectromechanical systems (MEMS)[1] as well as facilitated studies of physical systems at spatial dimensions that mimic natural environments.[2–6] The primary challenge to producing such structures is the high cost of the infrastructure and processing tools necessary for fabrication, such as dedicated cleanroom facilities and mask aligners. Although soft lithography methods have enabled low-cost solutions for the rapid prototyping of micro- and nanometer patterns, mask aligners are still often required to fabricate the masters.[3,4] Here, we describe a compact and portable benchtop photolithography system that can be constructed from an array of UV light-emitting diodes (LEDs) and powered by AA batteries. We demonstrate that this solid-state photolithography (SSP) system, in a single exposure step, can produce patterns as small as 200 nm over 4-in. Si wafers without needing the environmental control of a class 1000 (or lower) cleanroom. By broadening the accessibility of structures with dimensions ranging from 200 nm to over 100 µm, we expect that SSP will expedite the integration of subwavelength patterns, microfluidic devices, and MEMS into a wide range of research areas.

Figure 1 depicts the SSP system when the UV light source is either on or off. We used GaN-based LEDs that emitted 405-nm light (10 nm full width at half-maximum (FWHM)) because of compatibility with g-line photoresists, which have a broad absorption spectrum from 350 to 450 nm.[9] We designed an array-based LED source because of 1) the potential for scalability and 2) the uniformity in exposure conditions. The circular circuit board template was from a 4.75-in. diameter UV flashlight (Guide Gear 200) (Figure S1a, Supporting Information), where each of the 200 white-light LEDs was replaced with a UV LED (RadioShack, average price $0.65). The LEDs were connected in parallel and the entire circuit was powered by 8 AA batteries (6 V, 5000 mA h). Because the UV LED source required 4 A, the batteries could sustain 1.25 h of continuous exposure time. The circuit was built such that if one LED failed, the other diodes would be unaffected.

We converted the array of discrete emitters into a single, homogenous source by placing a ground glass diffuser (Figure S1b, Supporting Information) after the LED array and in front of the substrate to be exposed. We found, however, that the LEDs arranged in this circular circuit configuration produced a 15% spatial gradient in optical intensity from one edge to the opposite edge of the source because of resistive losses in the wires. To remove this gradient, we connected two additional positive electrodes between the LED in the center and on the opposite ends of the array (Figure S2, Supporting Information). In addition, the presence of the diffuser increased the uniformity of the LED source by ±6% such that the spatial intensity did not vary more than ±4% across the 64-cm^2 area light source (Figure S3, Supporting Information). We defined uniformity as the percentage change of dose between the highest and lowest intensity points across the middle section of the light source; ±4% is higher than stand-alone Hg lamps (±50%)[10] and comparable to state-of-the-art Süss MicroTech MA/BA 6 (±5%).[11] The total cost of the 200-LED, SSP system was less than $400 (Table S1, Supporting Information).

The array-based design of the solid-state light source alleviates the need for sophisticated exposure optics used in contact mask aligners and, significantly, allows the exposure area to be easily scaled. There are several other advantages in using an LED array over an Hg-vapor lamp, including the short rise time to maximum optical intensity (<300 ms) and low electrical power consumption (<6 W). For example, in traditional contact mask aligners, the Hg-lamp source requires several minutes to reach full optical power and a mechanical shutter is used to supply a specified dose of UV light. In contrast, our LED array reached full power (5.5 W cm^{-2}) in less than half of a second after the voltage was applied and a digital timer was used to control the exposure dose with an accuracy of 10 ms.[12] In applications where the exposure times were not critical to <0.5 s, we found that a manual electrical switch instead of the timer was sufficient. Another advantage of the SSP system is that the total power consumption of the 200-LED array is less than 0.2% of the power required for Hg-vapor lamps for the same exposure time.[6] This low-power requirement allows the system to run on AA batteries instead of a high-voltage power supply, a feature that contributes to portability. Additionally, GaN-based LEDs have been shown to last more than 50 times longer than Hg-vapor lamps.[7,8]

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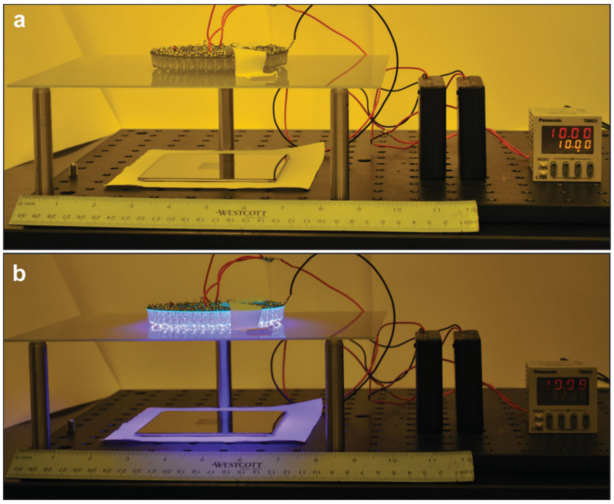

Figure 1. Compact solid-state photolithography (SSP) can be performed on the benchtop. Photographs of the SSP system with the UV LED light source a) off and b) on.

We tested the SSP system using traditional photomasks (fused quartz/Cr windows) as well as unconventional masks (poly(dimethylsiloxane) (PDMS) masks and transparency films) to determine capabilities and to compare against alterative photolithography methods. Typically, photolithography is performed by exposing a photoresist in contact with a hard photomask and minimum feature sizes are around 1 µm.[1] Although vacuum is usually required for uniform contact between the photomask and the resist, our SSP was not designed with this feature so that complexity and cost would be reduced. Thus, we simply pressed the mask into contact with the substrate, which resulted in high quality patterns over ≈70% of the exposed area, which is ≈4 cm^2 for this work. We evaluated the capabilities of SSP with hard photomasks patterned with 1D lines (750-nm wide Cr lines on a 2-µm pitch). Si wafers with a thin (500 nm) layer of Shipley 1805 photoresist were exposed through this mask to form 500-nm tall lines in photoresist (**Figure 2**). Because the sidewalls of the lines were fairly vertical, these patterns can be easily transferred into functional materials. The ridges in the sidewalls are characteristic of thin-film interference between the mask and the substrate, and the standing wave patterns can be removed using antireflective coatings.[13] In addition, we carried out experiments using contact photolithography masks with microscale features (3-µm solid circles on a 4.5-µm pitch). Figure S4 (Supporting Information) indicates that uniform patterns are observed across a 3-in. wafer, which demonstrates how SSP can readily be used with traditional masks.

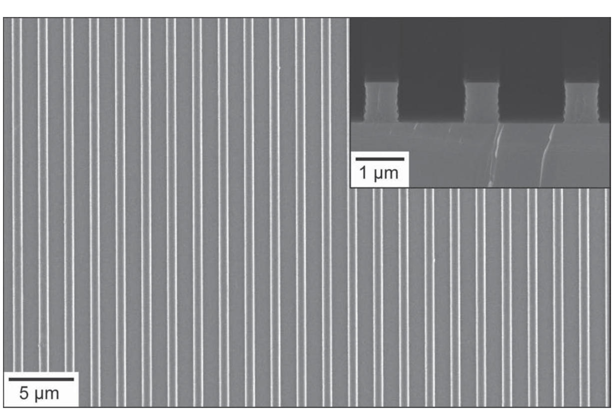

Figure 2. High-quality sub-micrometer photoresist patterns using SSP. Scanning electron microscopy (SEM) images highlight the fidelity of the SSP system using a hard contact photolithography mask (0.75-µm Cr lines on a 2 µm pitch) and without needing a vacuum system.

Recent advances in nanofabrication have resulted in the generation of sub-wavelength features over large areas.[3,6,14–22] In particular, phase-shifting photolithography (PSP) is a soft lithographic technique that uses PDMS phase masks to form photoresist patterns with lateral dimensions as small as 50 nm.[16] PSP takes advantage of differences in refractive index at the air/PDMS interface, which produces nodes in the near-field optical intensity because of destructive interference. Exposure of resist through PDMS masks patterned with microscale features (0.5–50 µm) produces, on average, 200-nm linewidths at the edges of the features in the mask.[14,15] When the recessed features of the mask are decreased to less than 300 nm, however, the masks produce patterns that are the same size laterally as the recessed structures of the PDMS mask.[21] PDMS phase masks are typically prepared by molding PDMS against masters made from photoresist,[15] polyurethane (PU),[16] or Si.[6]

We created composite PDMS phase masks (*h*-PDMS/184 PDMS)[11] from a PU master patterned with a hexagonal array (diameter d = 180 nm, lattice spacing a_0 = 400 nm) of posts (height h = 280 nm) following a similar procedure to that reported previously.[22] Although the total patterned area of the master was ≈80 cm^2, there were some defects, including variations in height from the center of the patterned area to the outer edge (±4 cm) (Figure S5a,b, Supporting Information); therefore, such defects were also transferred into the PDMS phase mask (Figure S5c,d, Supporting Information). Si wafers with a thin (200 nm) layer of Shipley 1805 photoresist were exposed through these masks to form 200-nm tall photoresist posts (**Figure 3**). We found that the exposure times and overall quality of the patterns were similar to those made using the same PDMS mask and state-of-the-art mask aligners.[22] Figure 3a shows that a single exposure from the SSP system can form sub-wavelength patterns that exhibit uniform diffraction across 3-in. wafers. In addition, we patterned hexagonal arrays on larger Si substrates (4-in. wafers). The photoresist patterns were uniform across several centimeters (Figure 3b–d) but not across the entire wafer because of the slight differences in feature sizes across the PU master (Figure S5, Supporting Information). These differences in width were not correlated with intensity variations near the edges of the LED light source.

To demonstrate that this system is compatible with different photoresists, we used SSP to create patterns in SU-8, a negative-tone resist (MicroChem). We used a different type of rudimentary photomask, often referred to as a "transparency mask," which can be produced by using laser printers to print patterns (minimum feature sizes ≈10 µm[28]) on transparent polymer films.[24–28] The most common use of these masks has been to generate masters in SU-8 for PDMS microfluidic channels.[23] Since SU-8 is an i-line photoresist, the 405-nm

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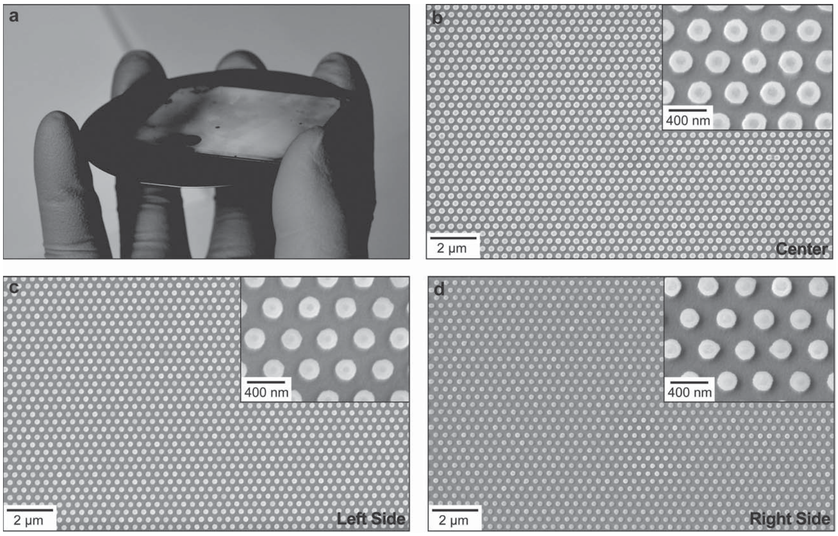

Figure 3. Wafer-scale areas of sub-wavelength patterns using PSP. a) Optical microscopy image of diffraction from a hexagonal array of photoresist posts (*d* = 180 nm, a_0 = 400 nm) across a 3-in. wafer made using a PDMS phase-shifting mask. SEM images of a Si wafer containing a hexagonal array of photoresist posts at different areas of a 4-in. wafer: b) in the center (0 cm), c) on the left (−4 cm from center), and d) on the right (+4 cm from center) side.

light source used previously could not be used as an exposure source; thus, we substituted a commercially available 365-nm flashlight (Nichia) (**Figure 4**a). Similar to the SSP set-up in Figure 1, we used a ground glass diffuser to increase the local homogeneity of the light source.

This modified SSP system was used to expose SU-8 through a transparency mask for the creation of a master with a Y-pattern for a microfluidic device. When the UV light source was the same distance above the resist as in Figure 1 (5.5 cm), however, exposure times exceeded 180 min for SU-8. Therefore, we decreased the distance between the source and the substrate to 1.5 cm. Si wafers with a layer (25 µm) of SU-8-2500 photoresist were exposed through the transparency mask for 40 min to form a Y-channel with channel widths of 50 µm and a height of 25 µm (Figure 4b). We found that because of the lower intensity of the 365-nm light source, the exposure times were much longer than those when a mask aligner was used.[29] PDMS was then molded against the SU-8 master to form a Y-channel system, and then three holes (two inlets and a single outlet) were punched into the channels.[23] The PDMS mold was exposed to an oxygen plasma for 60 s before being sealed against a glass slide. A red dye was introduced in one inlet and a blue dye in the other; laminar flow was observed at the interface of the two fluid streams (Figure 4b). The two streams remained separated throughout the entire 4.5-mm channel until mixing at the outlet (Figure S6, Supporting Information). With the UV flashlight as the light source for i-line resists, the total cost of the SSP system was less than $50.

In summary, we have developed a compact and portable photolithography system based on a solid-state light source that can be used with a wide range of photomasks. This simple SSP system was able to create photoresist patterns with critical feature sizes around 200 nm across 4-in. wafers, and the array design of the UV LED light source allows the exposure area to be readily scaled. SSP is ideal for fabricating patterns that require only a single exposure step. Importantly, we demonstrated that high-quality patterns could be generated without specialized cleanroom equipment such as mask aligners, a vacuum system, and high-voltage power supplies. We anticipate that the ability of SSP to prototype a wide range of structures will accelerate the development of micro- and nanoscale devices and other applications.

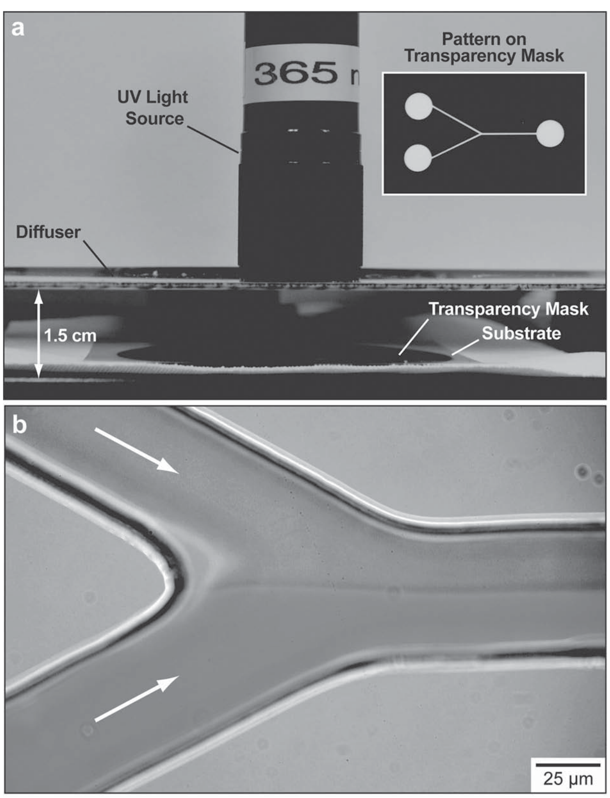

Figure 4. SSP with a UV flashlight source for i-line photoresists. a) Photograph of a SSP system using a 365-nm source for exposing i-line photoresists. b) Optical microscopy image of the inlet of a PDMS Y-channel molded from the SU-8 master made in (a). Laminar flow was demonstrated by flowing red dye in one inlet (upper stream) and a blue dye in the other (lower stream). The white arrows indicate the direction of flow.

Experimental Section

Fabrication of Microscale Lines: Photomasks (fused quartz/Cr windows) with arrays of 750-nm lines spaced by 2 µm were used for contact photolithography. SSP (405-nm source) was carried out by: 1) spin-coating hexamethyldisilazane (HMDS, Sigma Aldrich) primer on Si wafers at 4000 rpm for 40 s; 2) spin-coating Shipley 1805 photoresist on Si wafers at 5000 rpm for 60 s; 3) baking the photoresist at 105 °C for 2 min; 4) exposing the photoresist through the contact photomask for 3.5 s while holding and pressing the mask into contact by hand; and 5) developing the resist in Microposit 351 Developer (Rohm and Haas Electronic Materials LLC, diluted 1:5 in water) for 60 s.

Fabrication of Nanoscale Hexagonal Arrays: Composite PDMS masks patterned with a hexagonal array (d = 180 nm, a_0 = 400 nm) of recessed posts (h = 280 nm) were prepared for phase shifting photolithography (PSP) as reported previously.[15] SSP (405-nm source) was carried out by: 1) spin-coating HMDS on Si wafers at 4000 rpm for 40 s; 2) spin-coating Shipley 1805 diluted 1:2 with PGMEA (propylene glycol monomethyl ether acetate) on Si wafers at 5000 rpm for 60 s; 3) baking the photoresist at 105 °C for 2 min; 4) exposing the photoresist through the PSP mask for 3.5 s; and 5) developing the photoresist in 351 developer (1:5 in water) for ≈5 s.

Fabrication of the Microfluidic Device: Transparency masks (Pageworks) with a Y-channel and channel widths of 50 µm were prepared according to a procedure reported elsewhere.[25,26] SSP (365-nm source) was carried out by: 1) spin-coating SU-8 2025 (Micro Chem) photoresist on Si wafers at 3000 rpm for 30 s; 2) prebaking the SU-8 at 95 °C for 2 min; 3) exposing the SU-8 through the transparency mask for 40 min; 4) postbaking the sample at 95 °C for 1 min; and 5) developing the SU-8 PGMEA (Sigma Aldrich) for 60 s. PDMS was then molded against this master and removed from the substrate to form the top of the channel system. The PDMS was then placed into conformal contact with a glass slide (VWR microscope slides 25 mm × 75 mm, 1 mm thick) that was pretreated in an oxygen plasma for 30 s (Harrick PDC-324).

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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