Maskless photolithography using UV LEDs†‡

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A UV light emitting diode (LED) with a maximum output of 372 nm was collimated using a pinhole and a small plastic tube and focused using a microscope objective onto a substrate for direct lithographic patterning of the photoresist. Movement of the substrate with a motorised linear stage (syringe pump) allowed lines in SU-8 to be pattered with a width down to 35 µm at a linear velocity of 80 µm s^{-1}, while in the dry film resist Ordyl SY 330, features as narrow as 17 µm were made at a linear velocity of 245 µm s^{-1}. At this linear velocity, a 75 mm long feature could be patterned in 5 min. Functional microfluidic devices were made by casting PDMS on a master made by LED lithography. The results show that UV LEDs are a suitable light source for direct writing lithography, offering a budget friendly, and high resolution alternative for rapid prototyping of features smaller than 20 µm.

Introduction

Photolithography is the basis of most microfabrication processes, aiming to selectively remove parts of a thin film using light to transfer a geometric pattern from a photomask to a photoresist.

Light emitting diodes (LEDs) are an inexpensive but powerful light source that have found widespread use around the world as well as having several scientific applications, particularly as alternative light sources for fluorescence and absorption detection in capillaries and microchips.[1,2] For absorbance detection, they have become an attractive alternative to conventional lamps in the visible region due to their high light intensity over a narrow wavelength distribution and their lower noise, which translate to an improvement in LODs by a factor of 10. They have also gained widespread popularity as excitation sources for fluorescence, and while performance is inferior to that achievable with a laser, the cost is substantially less, with LEDs typically costing <\$10, while solid state lasers are at least \$1000, and gas lasers an order of magnitude more again. Additionally, LEDs have a lifetime of approximately 10 000 h, making them a very cost effective alternative to conventional light sources.

Recently, a range of high power near UV-LEDs have become commercially available with an output maximum around 365 nm which makes them suitable for the exposure of SU-8 and other photoresists. The low cost and long lifetime of the LEDs make them an attractive alternative light source for lithography, however the small beam size and low power (<2 mW) makes it impractical to expose a large area through a mask as in conventional lithography. To overcome this limitation we have gone to the other extreme of focusing the output from the LED into a very small spot and using this in a maskless approach to photolithographically pattern photoresist. This is similar to the approach recently employed by Yoshida *et al.* to pattern a gel inside a PDMS microstructure by focusing the light of a Hg lamp onto the microchannel using a fluorescence microscope.[3] In our system, the output of a 365 nm LED was collimated and focused onto the substrate using a microscope objective. The use of readily available components make this a much simpler approach than the matrix addressable micropixellated AlInGaN LED with integrated lenses as presented by Jeon *et al.* to pattern photoresist.[4] The new technique presented here is a rapid prototyping technique, avoiding the investments required for laser ablation or for the fabrication of high resolution moulds by non-lithographic approaches like micro electrode discharge machining (µ-EDM) and milling.[5,6] Other simple and rapid fabrication methods including the use of a photocopier,[7] toner mediated lithography,[8] or etching through a mask made using a cutter plotter[9] are limited to the fabrication of channels that are more than 200 µm wide.

The applicability of UV-LEDs for direct writing lithography is demonstrated using a set-up costing less than US\$6000, with the majority of equipment originating from an optical detection system for use with microchips.

Experimental

Soda glass microscope slides (76 mm × 51 × 1 mm) were rinsed with acetone and methanol, dried using compressed air and spincoated with SU-8 2100 (Microchem, USA) at 4000 rpm for 60 s and were baked according to the SU-8 2100 process guidelines. Substrates were developed in SU-8 developer (Microchem, USA) followed by drying with compressed air.

Soda glass microscope slides (76 mm × 51 mm × 1 mm) were cleaned with damp, lint-free paper with isopropanol, followed by acetone and isopropanol and dried to air. The dry film resist

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† The HTML version of this article has been enhanced with colour images.

‡ Electronic supplementary information (ESI) available: Schematic drawing and photograph of the experimental set-up. Output wavelengths for 5 LEDs. See DOI: 10.1039/b800465j

Ordyl SY 330 (Elga Europe, Milano, Italy) was processed similar to the method described by Vulto *et al*. [10]

LEDs were mounted inside a 50 mm long black polymer tube (i.d. 5 mm) positioned 10 mm from the end which contained a 3 mm pinhole. This was then collected using a microscope objective (Mitutoyo M Plan Apo 50× long working distance, numerical aperture 0.55) and focused on the substrate. For the creation of dots, a silicon wafer was used as a shutter to control exposure times. For direct writing of lines, the substrate was placed on the plunger of a Harvard 22 syringe pump. For the direct writing of lines in the dry film resist, an additional 1 mm pinhole was placed on top of the microscope objective. The linear rate of the stage was controlled by varying the flow rate of the syringe pump. A schematic drawing and photograph and of the experimental set-up are given in the electronic supplementary information.‡

Functional microfluidic devices were made by casting PDMS using standard methods detailed elsewhere.[11,12] Access holes were made at the channel termini using a hole puncher and the channel was sealed using a clean microscope slide.

Results and discussion

Selection of the most appropriate LED must be experimentally determined as it has been previously shown that the wavelength and intensity of LEDs from different manufacturers vary considerably.[13] Five high intensity UV LEDs were selected and the output wavelength for these 5 LEDs is shown in the electronic supplementary information.‡ The best was UV365, which had a wavelength maximum of 372 nm and a width at half the maximum output of 14 nm.

SU-8 is one of the most commonly used photoresists in microfluidics and was therefore chosen for initial studies. Light from the LED was focused onto a microscope slide coated with SU-8 photoresist and exposed for intervals of 5, 10, 20, 40 and 60 s. After development, oval dots were observed on the substrates with the size of the dots increasing with exposure time. Relatively small ovals of 180 μm × 160 μm were obtained with a 5 s exposure (shown in Fig. 1a). A 60 s exposure resulted in features approximately 10 times larger, approaching 2 mm in size, which is highly indicative of over exposure of the photoresist. The reproducibility of the system was excellent, with four dots shown in Fig. 1a.

Having demonstrated that it is possible to expose SU-8 with the UV LED, it was necessary to determine whether it would be possible to 'write' a pattern onto the photoresist using a motorised stage. The recommended exposure for a 100 μm thick film is 250 mJ cm^{-2}.[14] Assuming only 20% of the output of a 1 mW LED is focused in a spot with a diameter of 100 μm, the power in this spot will be 2.5 W cm^{-2}, implying that a 0.1 s exposure should be sufficient. It should therefore be possible to conduct direct writing lithography with linear velocity up to 1 mm s^{-1}. For this purpose, the substrate was placed on top of a motor-controlled stage, the piston of a Harvard 22 syringe pump. The pump was set at flow rates between 100 and 1200 μL min^{-1} for a 250 μL syringe providing a linear velocity between 7 and 80 μm s^{-1}. Inspection of lines exposed at 80 μm s^{-1} revealed that the initial lines were slightly wavy and showed regularly spaced bulges. The bulges were attributed to changes in linear velocity of the piston due to deficiencies in the stepper motor, bulges resulted from low linear velocities and thin lines from higher velocities. The wavy nature of the lines resulted from non-straight movement caused by the actuation on a thread causing the piston to move along a sinusoidal path. Repeating the experiments using a brand new Harvard 22 syringe pump resulted in the writing of straight lines. A smooth and straight moving platform is therefore considered to be crucial for direct writing LED lithography. Fig. 1b shows a representative photograph of a straight line created by direct writing LED lithography at a linear velocity of 80 μm s^{-1}. The width of this line was determined to be 35 μm by SEM. Lines patterned using a linear velocity of 40 μm s^{-1} were found to be approximately twice as wide, with a nominal width of 68 μm.

To demonstrate the ability to fabricate a functional microfluidic device, a cross was made by writing two perpendicular lines on an SU-8 coated substrate. An SEM image of the cross made at a linear velocity of 40 μm s^{-1} is given in Fig. 1c. This SU-8 master was used for casting of PDMS, and an SEM of the cross-section of a microchannel is given in Fig. 1d. It can be seen that the side profiles are not as straight as expected for SU-8 which we believe is due to the limited depth of field (0.9 μm) of the microscope objective. An objective with a smaller numerical aperture and therefore larger depth of field should result in better profiles.

To determine whether it was possible to create sub 20 μm features, studies were conducted with the dry film resist, Ordyl SY330, due to its higher sensitivity to UV light than SU-8. This allowed a smaller and more highly collimated source to be used, which was achieved by using a 1 mm diameter pinhole placed directly on top of the microscope objective. The syringe pump was set at linear velocities between 35 and 245 μm s^{-1}. A linear relationship was found over the range of 35–210 μm s^{-1} corresponding to line widths of 150–25 μm ($r^2 = 0.994$). This has some potential as some automated control on the velocity would allow adjustment of the width of a patterned feature in a very simple manner. The flattening off of the linear relationship at velocities above 210 μm s^{-1} may suggest that the

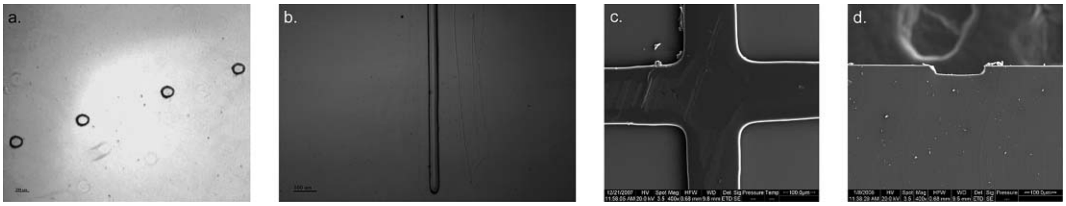

Fig. 1 Direct writing lithography in SU-8 a. Optical microscope image of a dots (160 × 180 μm, 5 s exposure). b. Optical microscope image of a straight line (width 35 μm, linear velocity of 80 μm s^{-1}). c. SEM of a cross pattern at a linear velocity of 40 μm s^{-1}. d. Cross-sectional SEM of the channel cast in PDMS using the SU-8 master in c.

actual spot size of the direct writing light beam is in the order of 17 μm. This corresponds well with the 20 μm expected from the combination of the 1 mm pinhole and the 50× objective. The use of a smaller pinhole should allow for even smaller features to be written. This is a remarkable achievement, for two reasons. First, these lines are thinner than can be obtained by other cheap lithographic methods, particularly transparent films which are limited to >20 μm.[15] Second, dry film resists generally allow for a lower resolution than liquid resists, yet these line widths are the equivalent of those obtained in SU-8.[16]

Finally, to demonstrate the practical potential of this set-up, direct writing lithography was used to create a simple cross template for the construction of a PDMS microchip suitable for electrophoresis. A photograph of the microchip channels filled with green dye is shown in Fig. 2a, an optical image and SEM of the cross of the master are given in Fig. 2b and c, respectively, and an SEM of the cross-section of the channel cast in PDMS is given in Fig. 2d. This template was constructed at a linear velocity of 210 μm s^{-1} and required a little over 10 min to expose. The filling of the channels of this PDMS replicate with an aqueous solution was similar to that of PDMS channels replicated using masters made by conventional techniques. The cross geometry, is suitable for microchip electrophoresis, but the technique is certainly not limited to this.

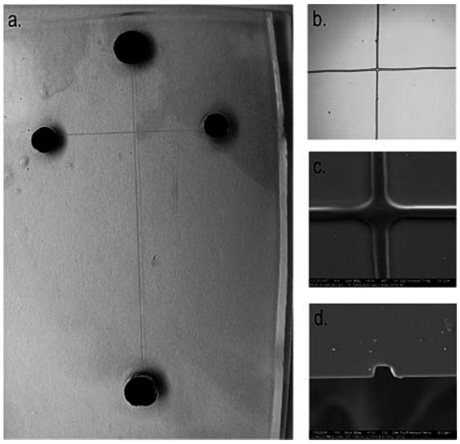

Fig. 2 a. Microfluidic device made by casting PDMS on a dry film master. Channels and reservoirs are filled with a dye solution to aid visualisation b. Optical image of the cross in dry film resist. c. SEM of dry film cross d. Cross-sectional SEM of the PDMS microchannel cast from dry film template.

Conclusions

We have demonstrated that light from a $20 UV-LED can be focused with an objective onto a moving stage and used for direct writing lithography. Line width was observed to be a linear function of the speed and lines with a width of 17 μm were patterned at a linear velocity of 250 μm s^{-1}. At this speed, a 75 mm long line can be patterned within 5 min. While this is longer than can be achieved with a conventional lithographic source, our system can be assembled for a fraction of the cost using components commonly used for microchip fluorescence detection. With the possibility to reproducibly create lines with a width below 30 μm, this system shows great promise for the rapid and cheap high resolution prototyping of photoresist and it provides a low cost exposure system for entry to many researchers around the world into microfluidic research.

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