Grayscale Lithography by a Polymer Photomask Doped with Laser Dye

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We report the development of a novel grayscale photomask which is made of a patterned polymer doped with a laser dye. Using this mask, three-dimensional (3D) microstructures with different heights have been formed in positive photoresist by a single ultra-violet (UV) exposure step. The developed method depends on the differential UV absorption in photo-absorbing material (Figure 1) and uses only a standard UV source, is inexpensive and easy to implement due to its inherent process simplicity. By adjusting the pattern thickness on the photomask and UV exposure dose, a multitude of unique 3D microstructures can be fabricated with desired geometries and dimensions. This method is an alternative to other grayscale lithography techniques involving electron beam methods, direct writing and in some cases, interference lithography.

Polydimethylsiloxane (PDMS) is a moldable polymer which is optically transparent down to 280 nm in its pristine form. When a patterned PDMS layer doped with Coumarin 314 dye (peak absorption around 436 nm) is used as a mask for photolithography, the features on the doped PDMS create areas of different UV absorption or transmission, depending on their individual thicknesses (Figure 2). This causes different intensities of UV light to be delivered to an underlying photoresist, resulting in 3D structures being formed in that photoresist. Coumarin 314 dye, dissolved in toluene (0.025 g/ ml) was mixed with 10 ml PDMS (Sylgard 184) pre-polymer solution in 6:100 volume ratio. The pre-polymer mix was poured over a complimentary silicon mold which was patterned by anisotropic wet etching in potassium hydroxide. The pre-polymer was thermally cured in a convection oven at 60 ^{0}C for two hours. The cured PDMS layer was de-bonded from the mold and attached to a blank glass substrate to function as a grayscale mask when employed in photolithography (Figure 1). Since Coumarin 314 absorbs light down to less than 400nm, we used a standard UV light source with components at wavelengths of 365, 405 and 436 nm respectively to expose positive photoresist (AZ 4620) through the doped PDMS mask in contact mode. 3D patterns with varying heights were obtained from a single exposure step (Figure 3). By selecting alternative dyes with appropriate absorption spectra, this work can be extended to other positive and negative photoresists to realize high aspect ratio microstructures for a wide range of applications in micro-electromechanical systems (MEMS), microfluidics and optics.

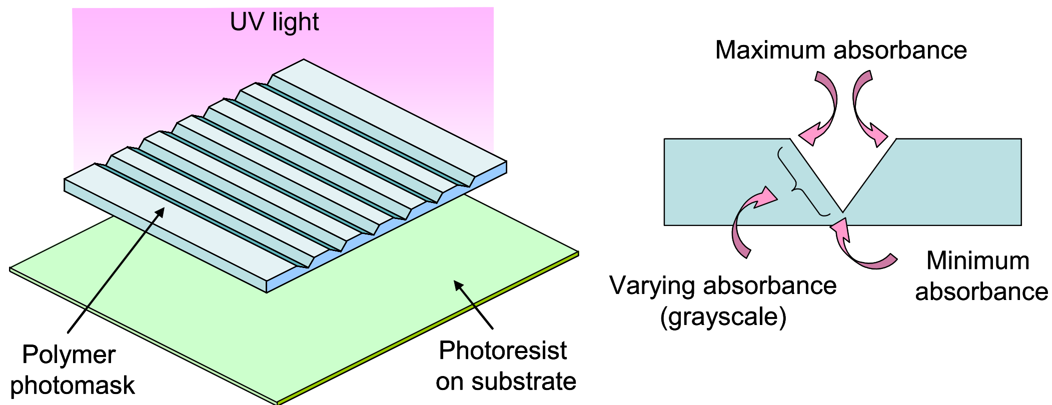

Fig. 1. Schematic of developed polymer photomask for grayscale lithography (not to scale). Thickness variations in the patterns of the doped PDMS mask create corresponding localized changes in UV absorption.

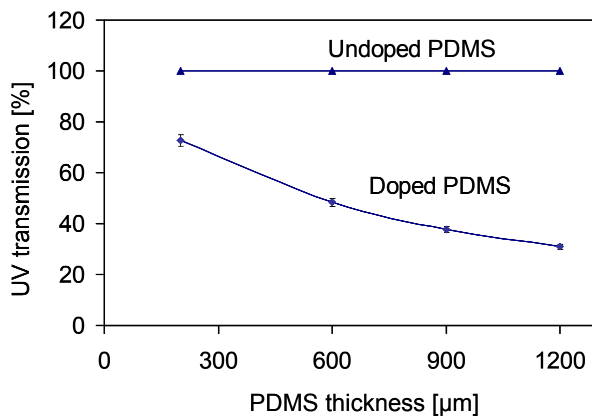

Fig. 2. Dependence of UV transmission on polymer thickness when UV light (λ = 436 nm) is passed through a patterned, doped PDMS photomask. In comparison, there is no transmission loss through an undoped PDMS mask with similar patterns.

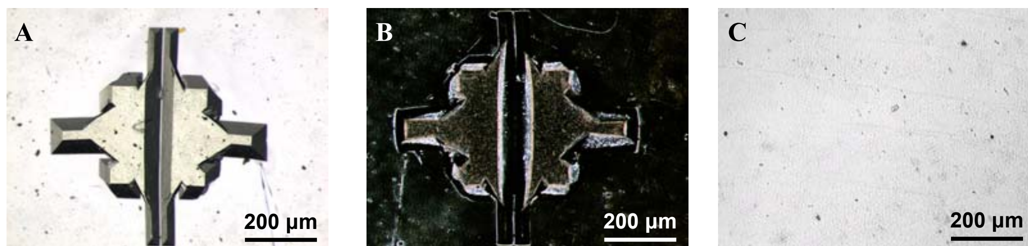

Fig. 3. Stereo microscope images showing (a) test pattern on PDMS photomask, (b) resulting 3D pattern in positive photoresist when doped PDMS mask is used, (c) absence of patterns when undoped PDMS mask with similar patterns is used in photolithography.