Maskless photolithography: Embossed photoresist as its own optical element

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(Received 14 July 1998; accepted for publication 18 September 1998)

This letter demonstrates that features embossed on the surface of a layer of photoresist can direct UV light in the photoresist layer. These topographical features act as optical elements: they focus/disperse and phase shift incident light in the optical near field, inside the resist layer. A number of different surface topographies have been examined, which give 50–250 nm features after exposure and development. This method gives patterns of complex features over large areas, in a parallel process, that can then be transferred into silicon or metal. It provides a method for controlling the intensity of light inside a thin film of photoresist. © 1998 American Institute of Physics.

This letter describes a procedure—combining embossing and photolithography—for the fabrication of features ranging in size from 50 to 250 nm. In this procedure, the topography of the surface of a layer of photoresist patterns UV light in the optical near field inside that layer. This method involves three steps: (i) embossing the surface of a layer of photoresist with features that act as lenses and phase shift elements; (ii) exposing this topographically patterned photoresist layer to flood illumination with incoherent, polychromatic, and uncollimated light ($\lambda = 350–440$ nm); and (iii) developing the exposed photoresist following conventional procedures. In this form of photolithography, there is no mask in the conventional sense; rather, a mold having appropriate surface topography to emboss the photoresist is the source of the pattern, and the embossed surface of the photoresist acts as its own optical element. We refer to this technique as “topographically directed photolithography” and abbreviate the phrase as TOP. We have examined the features derived from flood illumination of several different patterns on the surface of the resist: curved features and square pyramidal structures act as lenses, ray directors, and reflectors; steps in the resist generate small features due to abrupt shifts in phase of the illuminating radiation. We have also combined the embossed structures with conventional amplitude masks during the exposure to generate other patterns.

The elastomeric molds used to transfer the pattern to the photoresist surface were cast in polydimethylsiloxane (PDMS) against a master as described previously. We used solvent-assisted embossing to emboss the surface of the photoresist (1805, 1813; Shipley) that was spun on primed silicon wafers. We exposed the patterned photoresist to flood UV light ($\lambda = 300–460$ nm) in a standard mask aligner (Karl Suss MJ8 UV400); the lamp output was 10 mW/cm$^2$, with exposure times tuned to accommodate fluctuations in this output. A dilute solution of Microposit 351 Concentrate (1.5 in 18 M$\Omega$ water) developed samples in 1 min. A scanning electron microscope (LEO 982 Digital scanning electron microscope) imaged the features. Reactive ion etching (Plasma Sciences, RIE-200) with a combined plasma of SF$_6$ (23 sccm) and O$_2$ (3 sccm) at 30 W for 2 min transferred the photoresist patterns into the silicon. We also transferred patterns into gold by lift-off, using 5 nm of Cr as an adhesion promoter and 50 nm of Au.

Figure 1 summarizes the process by which solvent-assisted embossing formed the topography on the surface of the resist. We applied a small amount (<1 mL) of solvent to an elastomeric mold made of PDMS having an appropriate pattern in bas relief on its surface, and then placed the mold on the surface of a layer of photoresist. The solvent swelled the photoresist and formed a gel that conformed to the to-

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FIG. 1. Scheme illustrating the fabrication of embossed and exposed features in photoresist using a PDMS (polydimethylsiloxane) mold.
The steps at the edges of the embossed rectangular gratings [Fig. 3 (Aembossed); Fig. 3 (Bembossed)] generated patterns that are similar to those generated by near-field phase-shift lithography.7,8 Lines fabricated using rectangular gratings with an embossed periodicity of 4 μm are ~100-nm wide [Fig. 3 (Adeveloped)], and with an embossed periodicity of ~800 nm, the features are ~50-nm wide [Fig. 3 (Bdeveloped)].9 In both cases, the embossed gratings have sloping rather than vertical photoresist sidewalls, and the lines that result from exposure, for reasons we have not clarified in detail, are spaced farther apart than is expected from the edge periodicity. A similar effect occurs with other line patterns: embossed patterns of diamonds [Fig. 4 (Aembossed)] and posts 1.5 μm in diameter [Fig. 4 (Bembossed)] also give ~100-nm lines that appear outside the perimeter of the embossed features [Fig. 4 (Adeveloped); Fig. 4 (Bdeveloped)]. Both patterns were transferred into silicon by RIE [Fig. 4 (ARIE); Fig. 4 (BRIE)] and gold by lift-off [Fig. 4 (Alift-off); Fig. 4 (Blift-off)]. We are currently defining the interactions between the light and resist topography and composition that give rise to different behaviors.

FIG. 2. Features produced by flood exposure (λ=350–440 nm) of an embossed 2400 lines/mm holographic grating. Dashed arrows show where the features originate. (Aembossed): grating embossed on a 0.48-μm thick layer of photoresist; (Adeveloped): exposed for 2.75 s and developed for 1 min. The black arrow at the left of the image indicates the photoresist/substrate interface and the drawings at the right show the exposure process schematically. The photoresist pattern was then transferred into silicon (Arie): by RIE and gold (Alift-off): by lift-off. (Bembossed): an embossed 2400 lines/mm holographic grating was covered with an amplitude mask of 3-μm circles separated by 11 μm and exposed for 1.85 s. (Blift-off): the resulting pattern was transferred into gold by lift-off.

FIG. 3. Features generated using rectangular topographies. All samples were developed for 1 min. The black arrow at the left of the images indicates the photoresist/substrate interface. (Aembossed): lines with 2-μm width and 4-μm periodicity embossed on a 0.50 μm layer of photoresist. (Adeveloped): exposed (Aembossed) (3 s); width of features is ~75 nm. (Bembossed): lines (150-nm wide, with periodicity 800 nm) embossed on a ~200 nm layer of photoresist. (Bdeveloped): exposed (Bembossed) (0.85 s); features are ~50-nm wide.
The importance of the potential limitations—distortion of the patterns on transfer, feature sizes, generation of complex patterns with small spacings—remain to be defined.

This research was supported in part by ONR and DARPA, and in part by the National Science Foundation (PHY-9312572). It also used the MRSEC Shared Facilities supported by the NSF under Award No. DMR-9400396. One of the authors (T. L. B.) gratefully acknowledges the NSERC of Canada for the award of a postdoctoral fellowship. The authors would like to thank Dr. Stephen Shepherd, Adam Cohen, and Dr. Yuanchuang Lu for their technical assistance, Joe Tien for helpful discussions, and Dr. Dragomir Davidovic for assistance with RIE.

9. The mold for the latter sample was prepared by casting PDMS against a master prepared by embossing a 1200 lines/mm holographic grating on a layer of photoresist, exposing it to UV light and reactive ion etching.