Soft-imprint technique for multilevel microstructures using poly(dimethylsiloxane) mold combined with a screen mask

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This letter presents a microfabrication technology of multilevel microstructures via the soft-imprint technique using poly(dimethylsiloxane) (PDMS) mold attached with a screen mask, TEM grid. A prepolymer and monomer mixture, after short UV exposure, rises only up to the open spot of TEM grid, sequentially into the groove of the PDMS mold, then multilevel microstructures are formed in one-step process. The proposed technique is an inexpensive, simple, and reliable method to fabricate multilevel microstructures without expensive and complex lithographic tools. Thus, using this multilevel microfabrication method, various multilevel microstructures of the combination of TEM grid pattern and PDMS mold groove are easily generated with good pattern fidelity. © 2004 American Institute of Physics. [DOI: 10.1063/1.1799230]

Recently, complex microstructures such as multilevel or three-dimensional (3D) structures have been featured in various microsystems, such as micro-optical, electronic, mechanical, and analysis systems. The conventional microlithographic technologies, including electron or ion beam writing, optical nanolithography, and x-ray lithography, are not sufficient to fabricate complex microstructures. Thus, several 3D microfabrication techniques have been developed, such as micro stereo lithography, combined process of deep reactive ion etching and bulk micromachining, inclined deep x-ray lithography, and inclined UV lithography. These techniques are not sufficient to yield a high resolution and throughput, and also require expensive lithographic equipment and time-consuming process. Therefore, the pursuit and development of a low-cost and high throughput lithographic process for multilevel or 3D structures is imperative.

We reported previously the “soft-imprint” technique that is a simple and reliable route to fabricate two-dimensional (2D) submicron scale features using the poly(dimethylsiloxane) (PDMS) elastomeric mold. Since the PDMS mold is applied onto a monomer directly or onto a prepolymer/monomer mixture, followed by UV irradiation, 2D submicron scale features are generated in one-step procedure under room temperature without high pressure. Due to the low surface energy, the use of the PDMS mold enables the fabrication of precise and uniform patterns over a large area without failure or defect problems arising from the resist adhesion to the mold, which is a critical obstacle during the mold detachment step in both nano imprint lithography and step-and-flash imprint lithography. In this letter, we report a multilevel microfabrication method via the soft-imprint technique using a PDMS mold combined with a screen mask. This proposed technique offers rather a simple and inexpensive route for the creation of multilevel microstructures without high cost and complex lithographic equipments.

Figure 1 shows a schematic illustration of the multilevel microfabrication via the soft-imprint technique. A PDMS (Sylgard™ 184, Dow Corning) elastomeric mold having submicron patterns and TEM grid (400 mesh honeycomb and 1000 mesh square type, PELCO) as a screen mask are used here. We first prepare a styrene monomer and UV initiator mixture, which is then spin-coated on the clean substrate. The monomer mixture is then polymerized partially for

![FIG. 1. Schematic diagram of the soft-imprint technique for multilevel microstructures.](image-url)
10 min by exposure to UV light to form a sticky mixture of prepolymer and monomer, but this viscosity increase must be limited in order to retain the possibility of pattern transfer. After the prepolymerization is performed, the PDMS mold coupled with TEM grid is placed onto the prepolymer and monomer mixture. Since the unreacted remaining monomer endows the prepolymer mixture with a proper viscosity, the sticky prepolymer can rise only into the open spot of the grid, and then sequentially into the groove of the PDMS mold. Moreover, a good conformal contact of the PDMS with TEM grid prevents the permeation of prepolymer into the contact interface of TEM grid and the PDMS mold. Full polymerization by further exposure to UV light is then performed for 10 min before the mold is removed from the substrate. Figures 2(a) and 2(b) show scanning electron microscopy (SEM) images of a PDMS mold and of polymer patterns fabricated by the soft-imprint method without TEM grid. A comparison of the mold and the polymer patterns reveals that the original structure of the PDMS mold is successfully transferred to the polymer surface without distortion or defect over a large area. For the case of TEM grid, it tends to stick to the polymer during the detaching step, and the defect or failure of patterns occurs as seen in Fig. 2(c). To overcome this problem, we coated the surface of TEM grid with 0.05 wt % of an amorphous fluoropolymer (Teflon AF, Dupont) in a solvent (FC-77, 3M) as an anti-adhesive layer; this treatment is enabling a clean detachment and a successful fabrication of patterns as shown in Fig. 2(d).

When the PDMS mold attached with TEM grid (1000 mesh, square type) is applied to the soft-imprint, multilevel microstructures from the combination of TEM grid and the PDMS mold are generated, as shown in Figs. 3(a) and 3(b); the surface of 20 μm square patterns is imprinted with 1 μm lines. Also, Figs. 3(c) and 3(d) show that 400 mesh TEM grid (honeycomb type) and the PDMS mold with 1 μm dots array is employed to the same method. Multilevel microstructures of honeycomb imprinted with dots are successfully generated in agreement with the above-mentioned results.

The soft-imprint technique is based on a capillarity effect that forces the sticky prepolymer mixture to penetrate into the grooves of mold. Such penetration is favored by a low prepolymer viscosity, since the time, \( t \), needed for the filling process is proportional to the square of the feature height, \( z \), and to the prepolymer viscosity, \( \eta \):

\[
\gamma = \frac{2 \eta z^2}{\gamma R \cos \Theta},
\]

where \( \gamma \), \( R \), and \( \Theta \) indicate the fluid–air surface tension, the hydraulic radius of the capillary, and the contact angle between the liquid and the surface of the capillary, respectively. Thus, a proper amount of monomer in prepolymer mixture can be exploited to reduce the viscosity of the polymer, consequently allowing the filling to the recessed features of PDMS mold and TEM grid in only a few minutes.

The residual monomer in the prepolymer mixture after the short UV exposure is a critical factor in the proposed technique, since it assigns the flexibility polymer resist to rise into the groove of the mold. When the PDMS mold attached with TEM grid is applied to the prepolymer with excess monomer, the conformal contact between the PDMS mold and TEM grid is ruined due to the permeation of monomer into the interface, and then the PDMS mold and TEM grid are separated. Thus, we choose 10 min of UV exposure for prepolymerization based on experimental observations; this optimal content of residual monomer ensures the fabrication of multilevel microstructures with precise pattern fidelity. Moreover, PDMS molds have a very low interfacial interaction with polymer substrates and their elasticity is sufficient for a clean separation from the patterned polymer without the use of a release agent.

In conclusion, we have demonstrated a microfabrication method for multilevel microstructures via the soft-imprint technique using the PDMS mold attached with a screen mask, TEM grid. The conformal contact of the PDMS mold with TEM grid facilitates fabrication of multilevel microstructures in a one-step processing without expensive and complex lithographic equipment. With this simple technique, we have generated various multilevel microstructures with good pattern fidelity over a large area. This method has the potential to be exploited as a direct and inexpensive method for fabricating multilevel microstructures for use in various applications, especially in micro-electro-mechanical systems and microsensors.
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