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Three-dimensional nanofabrication with a rubber sub-wavelength optical element

Advances in nanoscience and technology rely critically on techniques for fabricating structures with nanometer dimensions. Methods developed by the microelectronics industry—photolithography, electron-beam lithography, and others—are well-suited for patterning two dimensional (2D) structures on ultraflat surfaces. Their limited depth of focus, however, makes it impossible to fabricate directly the types of three-dimensional (3D) nanostructures that are important for many areas of nanotechnology.

An indirect approach to 3D uses the repetitive application of steps for the 2D patterning of sacrificial resists: depositing functional materials, etching or polishing them, removing the sacrificial layers, and so forth. This method requires sophisticated facilities and is difficult to implement for structures that demand more than a few layers. A growing body of research involves developing unusual techniques for 3D nanofabrication, such as those based on colloidal sedimentation, polymer-phase separation, templated growth, fluidic self-assembly, multiple-beam interference lithography, two-photon lithography, and various approaches based on printing, molding, and writing. Each has important limitations, however, in the geometries and sizes of patterns that it can form and in the speed and simplicity of the processing steps.

High-resolution, conformable phase masks have very recently been shown to provide a means for fabricating, in an experimentally simple manner, classes of three-dimensional (3D) nanostructures that are technologically important but difficult to generate in other ways. In this approach, ultraviolet (UV) light passes through a transparent rubber optical element that has features of relief comparable in dimension to the wavelength. This generates a 3D distribution of intensity that exposes a photopolymer film throughout its thickness. Developing away the parts of the polymer that have not been crosslinked by the UV light yields a 3D nanostructure in the geometry of the intensity distribution, with feature sizes as small as 50nm. Figure 1 schematically illustrates the setup.

The rubber optical element forms a perfect, conformal contact with a photopolymer film. General surface forces (i.e. van der Waals type interactions) drive this contact: externally applied pressure is not required. This passive process yields optical alignment of the mask to the polymer with nanometer precision in the normal direction. Exposure of the polymer occurs in the proximity-field region of the mask: for this reason, we refer to the technique as proximity-field nano patterning (PnP). This geometry places requirements on the spatial and temporal coherence of the light source that can be easily met even with low cost setups (a handheld lamp with an interference filter is sufficient). Only the spot diameter of the light

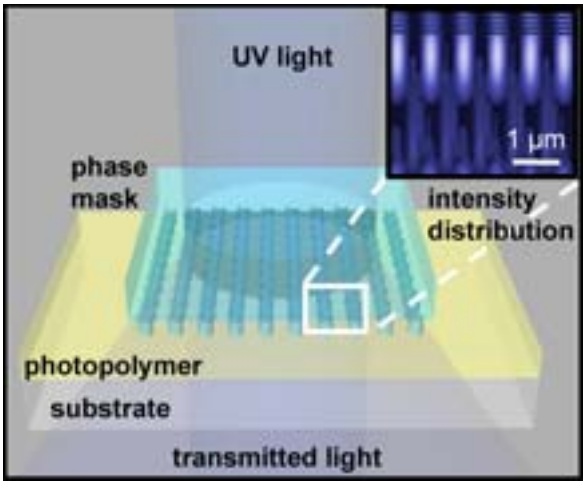

Figure 1. Schematic illustration of optical setup. Right top inset displays a typical computed intensity distribution that exists near the surface of the mask. This pattern induces crosslinking of a photocurable polymer in the bright regions. Developing away the unexposed areas yields a 3D nanostructure in the geometry of the pattern of intensity.

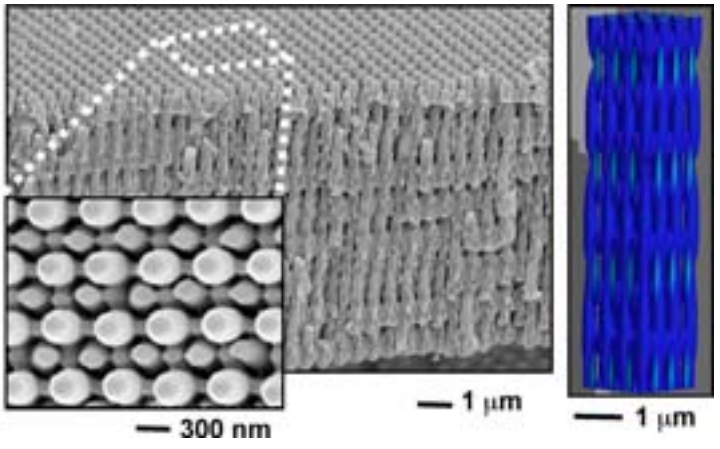

Figure 2. Scanning electron micrographs of a 3D polymeric structure (right), and corresponding simulation (left), based on rigorous coupled-wave analysis. The geometry of the phase mask defines the geometry of the resulting 3D structures.

source and the size of the phase mask limit the dimensions of the patterned areas. Nanostructures with thicknesses up to 100μm, can be achieved: the structural integrity and optical absorption of the polymer itself are the only features that limit this thickness.

Figure 2 shows a scanning electron micrograph (SEM) of a typical 3D structure formed using this technique. Rigorous coupled-wave analysis can model accurately the optics associated with this method. Simulations that quantitatively describe certain of the fabricated structures appear in Figures 1 and 2. The flexibility of the geometries of the structures that can be produced is considerable, since the design of the mask and the wavelength of the light used for exposure determine the intensity distributions.

There are many potential application areas for this technique, including photonics, sensors, catalysis, information storage, and microfluidics. Figure 3 shows a simple example in this last area. Here, PnP has formed a 3D polymer nanostruture integrated directly into a microfluidic channel for filtration, separation, and mixing purposes. The colorized SEM shows the separation of a suspension of 500nm from a flow that moves from left to right through the 3D structure. Our current work examines the use of similar structures for inducing mixing in systems where laminar flow dominates, for chromatographic separations, and for applications in other fields.

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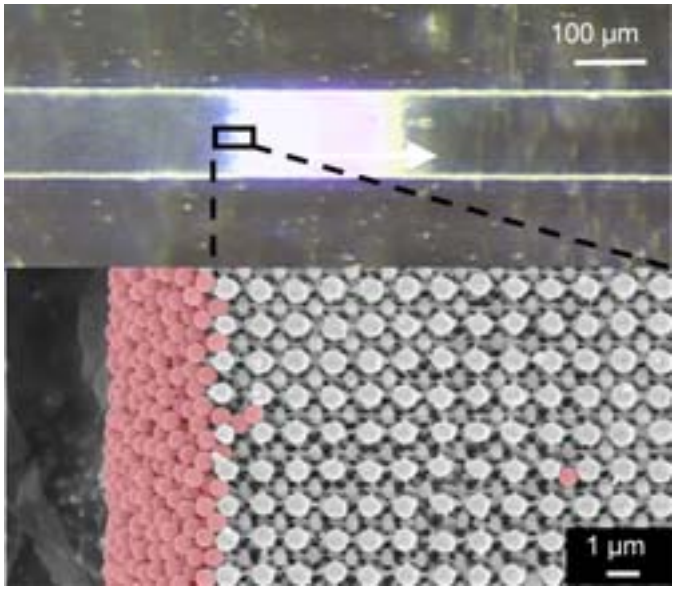

Figure 3. Illustration of the use of 3D nanostructures formed by PnP in microfluidic applications. A structure formed in a microfluidic channel acts as a 3D filter element for separating suspended poly(styrene) beads (500nm diameter) from an aqueous flow: white arrow indicates flow direction.