Large-Area 3D Nanostructures by Proximity-field nanoPatterning (PnP)

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Motivation—Three-dimensional (3D) nanostructures are vital for emerging technologies such as photonics, sensors, fuel cells, catalyst supports, and data storage. Conventional fabrication (repeated cycles of standard photolithography with selective material removal) is costly, time-consuming, and produces limited geometries. Unconventional methods (colloidal self assembly, template-controlled growth, and direct-write or holographic lithography) have uncertain yields, poor defect control, small areas, and/or complicated optical equipment. The Proximity-field nanoPatterning (PnP) method overcomes these limitations by generating complex 3D nanostructures using a simple optic and one lithographic exposure and development cycle. The optic is an elastomeric "rubber phase mask" patterned in x, y, and z with dimensions roughly equal to the exposure wavelength. Exposure through this mask generates a complex 3D light intensity distribution due to diffraction (Abbe theory) and the Talbot effect (self-imaging). The underlying photoresist is thus exposed in certain regions, baked, and developed, producing a 3D network of nanostructures with one lithography cycle. Our goal is to scale this method to 150mm and create full models of the process.

Accomplishment—We have developed a model that generates the phase mask required to generate a specific nanostructure. This "inverse" approach is much more complex than the simplistic modeling of the diffraction pattern produced by passing light through a phase mask. The integrated tool starts with a desired pattern and an initial guess on the PnP mask parameters. Next, the interference pattern is simulated using the mask information and filtered to reveal the expected photoresist burn image, which is then evaluated against the desired pattern. An integrated optimizer makes improvements to the mask parameters and cycles again with a simulation using the new mask parameters. The simulation engine is a high performance, OpenMP (Message Passing) parallelized FDTD (finite difference time domain) simulator optimized to run on SMP (shared memory symmetric multiprocessor) systems. Examples of the unique structural images predicted are shown in Fig 1. We have successfully developed the PnP fabrication process and scaled-up the processed area from $490mm^2$ to $>2000mm^2$. We tested photopolymer additives designed to reduce resist shrinkage and identified those compatible with 3D structure generation. We use atomic layer deposition (ALD) to coat the 3D patterned resist with Al_2O_3, ZnO (Figs. 2a-b), TiO_2, and Pt. We have also generated quasicrystal-patterned phase masks and 3D nanostructures that are interesting for photonics and electronics. We used near-field scanning optical microscopy (NSOM) to characterize the light patterns generated by the quasicrystal phase mask (U. Illinois, NINE) and produced the resist structures here at SNL. An SEM image of the quasicrystal-patterned resist, an image of 532nm light diffracted through this structure, and NSOM images of light intensity at 0.3 µm and 2.4µm above the mask surface are in Figs.2c-f.

Significance—Fabrication of large-area 3D nanostructures within a single lithography cycle is an important capability for future microsystems.

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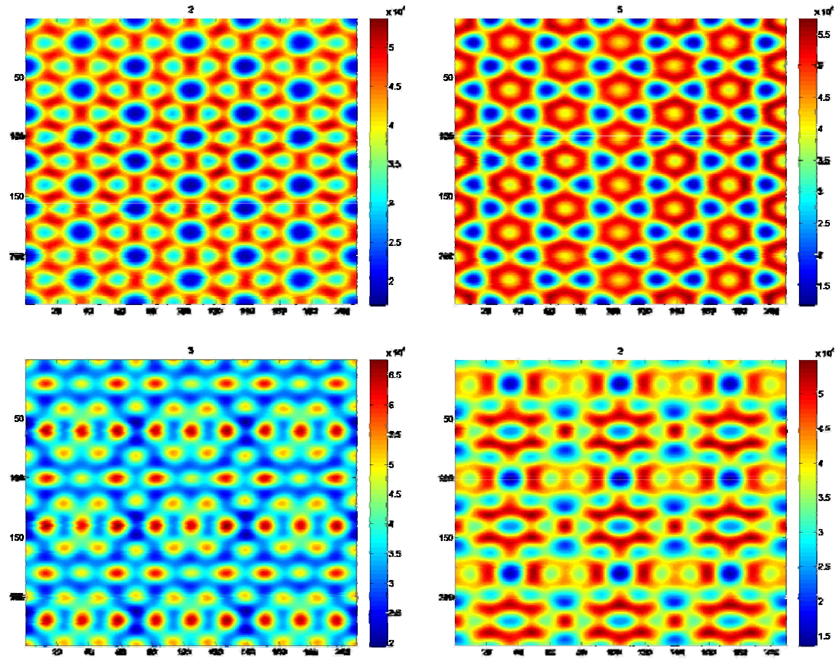

Figure 1. Predicted intensity patterns for an hexagonal array of phase mask features showing the burned resist structures (red) and open (developed away) areas (blue).

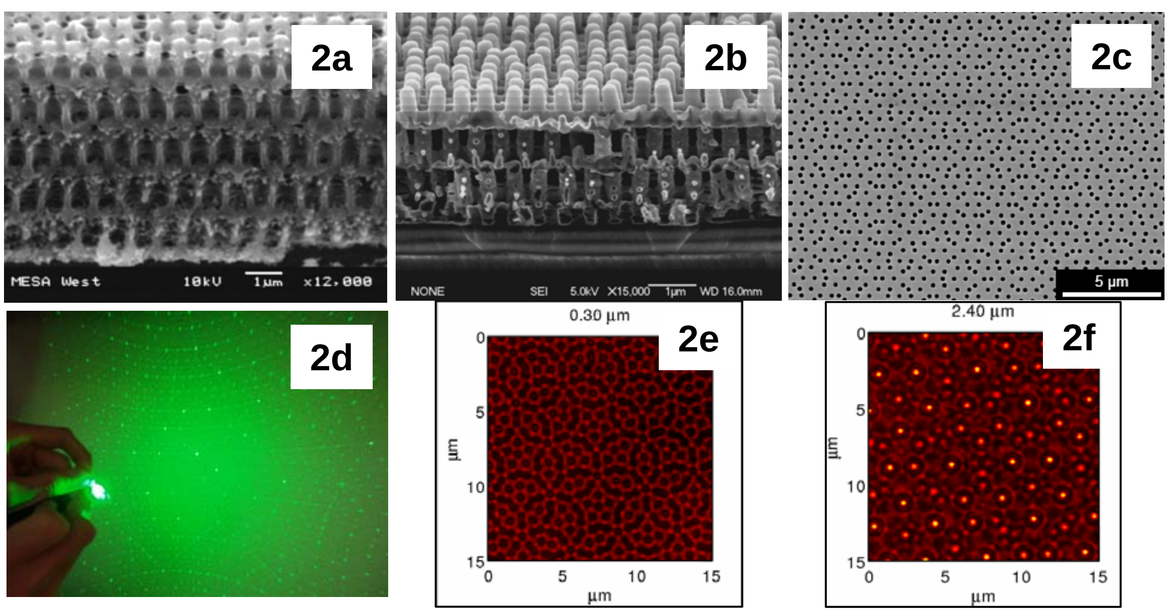

Figure 2. SEM image of PnP 3D resist structure (2a), 3D resist structure fabricated in MESA µFab coated with Al_2O_3 and ZnO by ALD (2b), SEM image of the quasicrystal-patterned resist (2c), image of 532nm light diffracted through the resist quasicrystal (2d), and NSOM images of light intensity 0.3 µm (2e) and 2.4 µm (2f) above the mask surface