8. Zone-Plate-Array Lithography (ZPAL)

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The ZPAL System

Nanolithography is the key technology driving technological progress in electronics, photonics, information technology and biotechnology. The tools and techniques used in the semiconductor industry have become too expensive for applications other than high-volume manufacturing. Masks, which are required for each unique design, can cost tens of thousands of dollars per layer. This economic constraint has made nano-patterning accessible to a select few, namely the major companies of the semiconductor industry, who can absorb these costs with high-volume production. Empowering the next generation of innovators will require making available an inexpensive, yet highly capable optical nanolithography tool.

At the MIT NanoStructures Laboratory, we are pursuing an innovative scheme, which we call Zone-Plate-Array Lithography (ZPAL). ZPAL is an optical maskless technology that operates on the principle of diffraction rather than refraction. Instead of a single massive lens, an array of thousands of nanofabricated Fresnel zone plate lenses is used, each focusing a beam of light onto the substrate. A computer-controlled array of micromechanical spatial-light modulators turns the light to each lens on or off as the substrate is scanned under the array, thereby printing the desired pattern in a "dot-matrix" fashion. A schematic of ZPAL is shown in Figure 1.

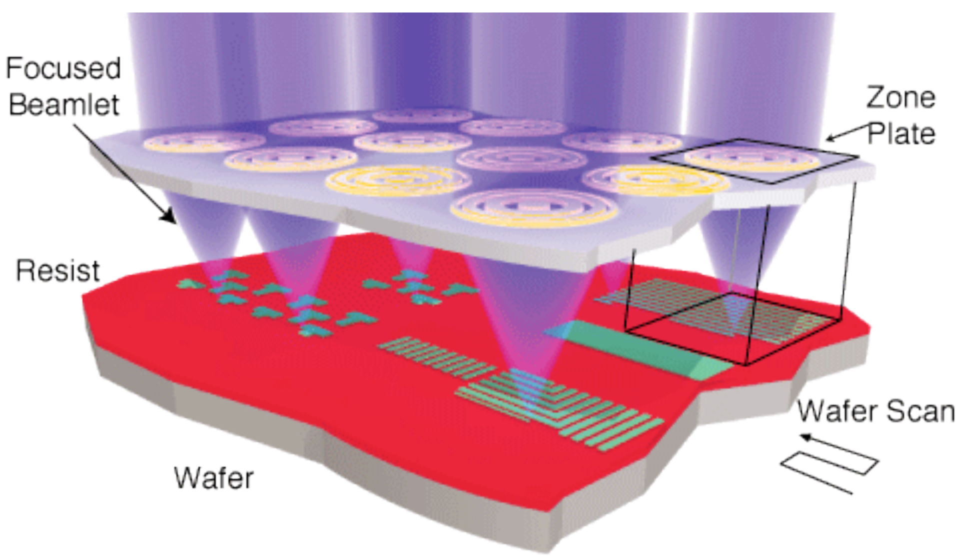

Figure 1: Schematic of Zone-Plate-Array Lithography (ZPAL). An array of Fresnel zone plates focuses radiation beamlets onto a substrate. The individual beamlets are independently turned on and off by upstream micromechanics as the substrate is scanned under the array. In this way, patterns of arbitrary geometries can be created in a "dot-matrix" fashion.

Pushing Lithographic Performance – The iZPAL System

Lithographic resolution is one of the major figures-of-merit in a direct-write system such as ZPAL, and is often expressed with the following equation:

$$W_{\min} = k_1 \frac{\lambda}{NA} \quad \textbf{(1)}$$

where W_{min} represents the minimum linewidth, k_1 is a proportionality factor that takes into account variables such as resist properties, environmental conditions, etc., λ is the wavelength of the radiation reaching the substrate, and NA is the numerical aperture.

Our current ZPAL prototype has already achieved high-resolution patterning (W_{min}=135nm) corresponding to: k_1=0.29, λ=400nm and NA=0.85. To further improve the resolution we have investigated immersion lithography which, scales λ down by a factor of n (where n is the refractive index of the medium between the zone-plate array and the substrate), thus producing a smaller diffraction-limited spot. Figure 2 shows simulated point-spread functions (PSFs) of zone plates operating at λ=400nm under immersion and non-immersion conditions. We see that the immersion zone plate produces a smaller diffraction-limited spot.

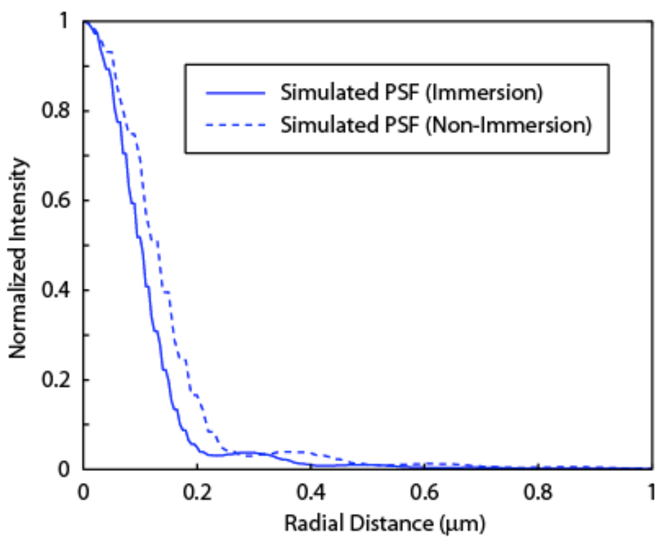

Figure 2: Simulated PSFs of NA=0.85 zone plates operating at λ=400nm under immersion and non-immersion conditions. The simulations were generated using a Finite-Difference-Time-Domain algorithm.

In our initial experiments on immersion Zone-Plate-Array Lithography (iZPAL), the gap between the zone-plate array and the substrate is filled with de-ionized water (n=1.34 at λ=400nm). We can expect a 26% decrease in the minimum feature size (W_{min}=100nm given the values for k_1, λ, and NA listed above). Our iZPAL setup is depicted in Figure 3.

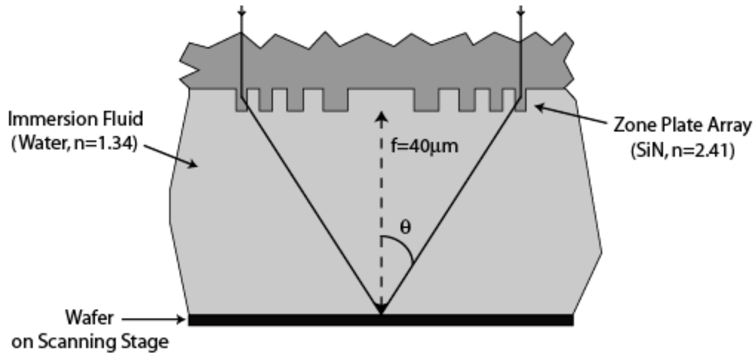

Figure 3: Immersion lithography for ZPAL. We place a droplet of DI water on the substrate, then lower the zone-plate array face down onto the droplet.

We previously demonstrated a robust planar process involving HSQ resist on a fused silica substrate to fabricate zone plates for the non-immersion scheme. The proper functionality of a zone plate is dependent upon introducing a π-phase-shift between adjacent zones. This phase shift becomes difficult to achieve when the refractive indices of HSQ and the immersion liquid (DI water) are almost identical (n_{HSQ} =1.39, $n_{DI\ water}$ =1.34 at λ=400nm). To overcome this, we have developed a new process in which the zones are patterned in Si-rich silicon nitride (n_{SiN}=2.41 at λ=400nm). The immersion zone plates are first patterned on PMMA using e-beam lithography. The pattern is then transferred into a Nickel (Ni) layer through a liftoff process, which is then used as an etch mask for reactive-ion-etching into the underlying SiN layer. Finally, the Fulton-Dolan process is performed to create a chrome (Cr) absorbance layer, which serves to block out all light not incident on the zone plates. Scanning-electron micrographs of a completed immersion zone plate are shown in Figure 4.

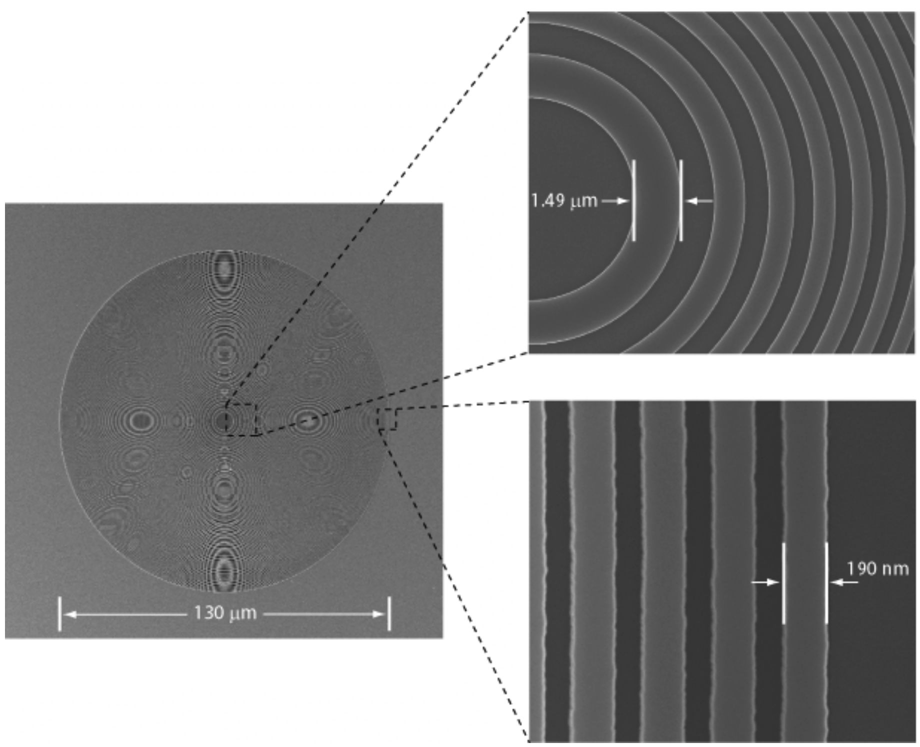

Figure 4: SEMs of an NA=0.85 immersion zone plate, designed for λ=400nm.

The immersion zone-plate array was then integrated into our ZPAL prototype system to test its lithographic performance. Dense lines/spaces were printed using both immersion and non-immersion ZPAL, and compared in Figure 5. To date, we have successfully patterned dense lines/spaces with linewidths as low as 115nm using immersion ZPAL (compared to 135nm using non-immersion ZPAL). In addition, we observe that at the same resolution, the immersion scheme prints with better pattern fidelity compared to the non-immersion scheme.

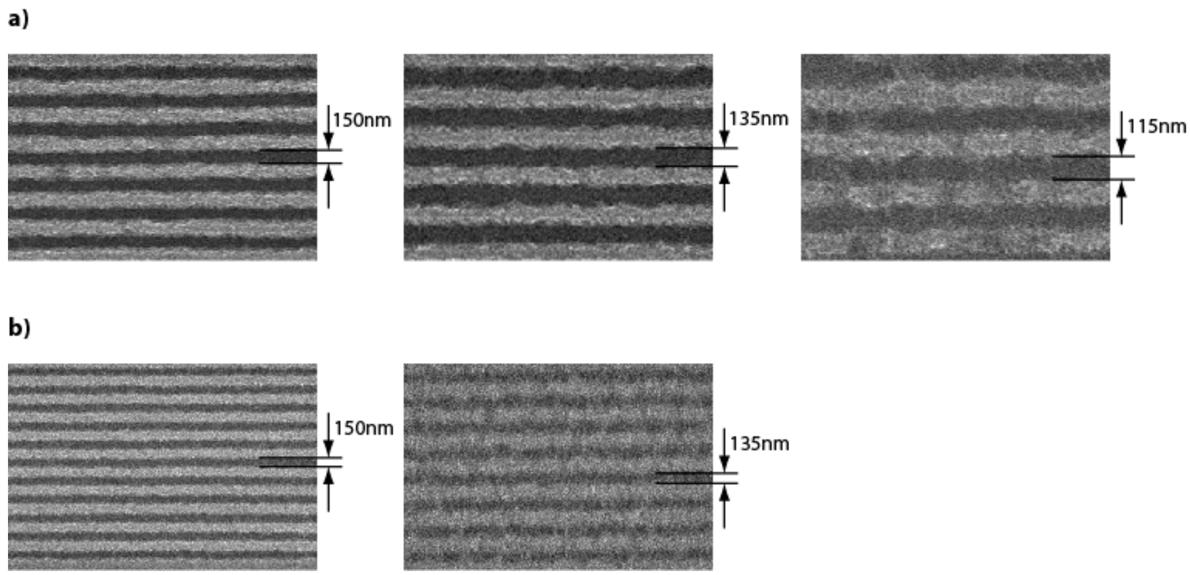

Figure 5: Scanning electron micrographs (SEM's) showing resolution of the immersion and non-immersion ZPAL systems at λ=400nm. (a) The immersion zone plates reliably print dense lines/spaces down to 115nm. (b) The non-immersion zone plates reliably print dense lines/spaces down to 135nm.

SEMs of dense nested-L's and dense arrays of contact holes produced using immersion ZPAL are shown in Figure 6.

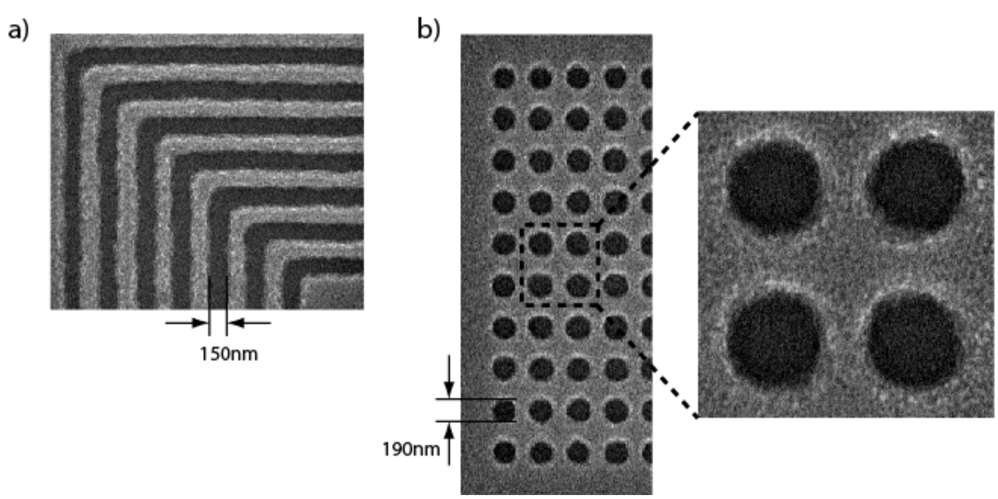

Figure 6: SEMs of (a) nested-L's and (b) arrays of contact holes, demonstrating the performance of the immersion ZPAL system.

In addition to the resolution improvement, the immersion scheme improves ZPAL's exposure latitude and depth-of-focus, as is evidenced by the exposure window plots in Figure 7. The exposure window is quantitatively defined as the range of exposure dose and defocus values which produce linewidths that vary less than ±5% from the nominal linewidth (critical dimension). At focus, the immersion scheme possesses an exposure latitude of ~9.5% compared to ~5.9% for the non-immersion scheme. Furthermore, the exposure window for the immersion system remains fairly constant for defocus values up to ~200nm compared to a more rapid decrease in the exposure window for the non-immersion system.

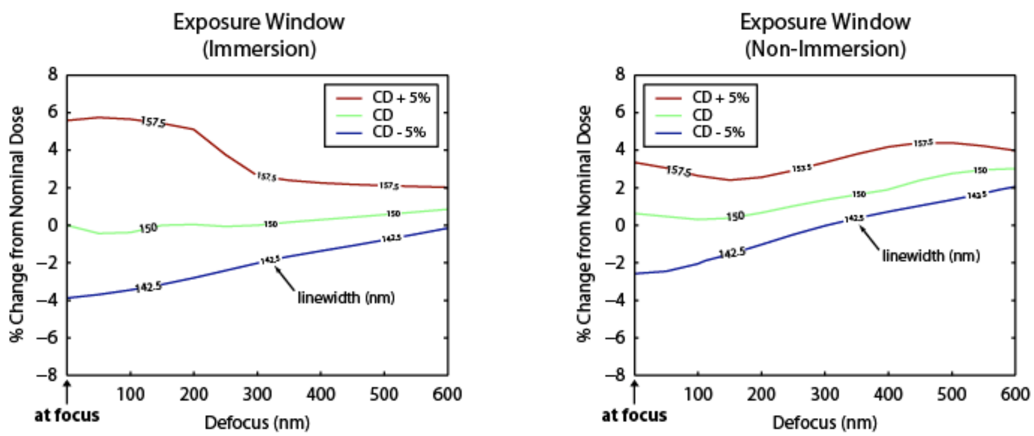

Figure 7: A comparison of the exposure windows for the immersion and non-immersion ZPAL systems. The area between the CD+5% and CD-5% curves defines the exposure window, which is clearly larger for the immersion system.

Fabrication and Replication of Zone-Plate Arrays by NanoImprint Lithography (NIL)

We are investigating the use of nanoimprint lithography for the fabrication of large arrays of high-numerical-aperture diffractive-lens arrays for zone-plate-array lithography (ZPAL). The NanoImprint Lithography (NIL) system in the NSL is capable of 5nm alignment. We intend to use a template consisting of a small array of zone plates with this system to create a much larger array.

The template is fabricated by scanning-electron-beam lithography (SEBL) using the Raith150 SEBL. The patterns are defined in HSQ. Self-aligned apertures are then created by chrome evaporation, followed by a Fulton-Dolan process. These steps are illustrated in Figure 8.

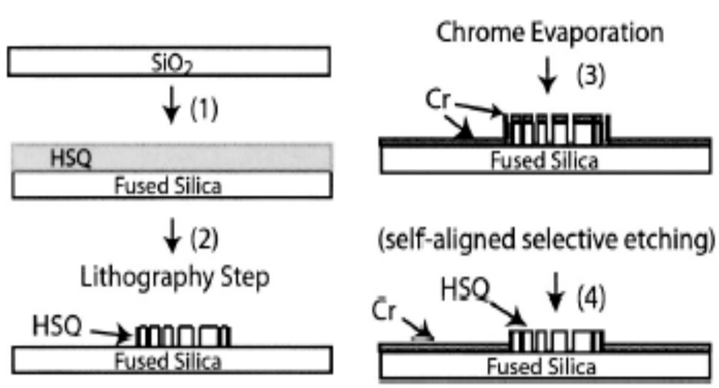

Figure 8: Fabrication of the NIL template.

The template is then pressed into a NIL liquid deposited on top of a glass substrate. Shining UV light through the template cures the liquid, and thus, “fixes” the zone plate patterns in the cured polymer. The template is stepped, and this process is repeated until the required size of the array is obtained. The alignment capability is important to ensure that all the zone plates in the array are aligned to each other.