Zone-Plate-Array Lithography (ZPAL) and Microscopy (ZPAM)

Personnel

D. J. D. Carter, D. Gil, R. Menon, X. Tang, and H. I. Smith

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In semiconductor lithography, glass masks are illuminated with deep UV laser light and their image is reduced through a lens onto the substrate to define circuitry. As feature sizes are pushed toward 100 nm, lithography is becoming increasingly costly and difficult, and may soon limit the industry juggernaut.

At the MIT NanoStructures Laboratory, we are pursuing a radically new scheme. The new scheme, called zone-plate-array lithography (ZPAL) is made possible by inexpensive, high-speed computation and micromechanics. ZPAL replaces the "printing press" of traditional lithography with a technology more akin to that of a laser printer.

Instead of a single, massive lens, an array of hundreds of microfabricated Fresnel-zone-plate lenses is used, each focusing a beam of light onto the substrate. A computer-controlled array of micromechanical mirrors turns the light to each lens on or off as the stage is scanned under the array, thereby printing the desired pattern in a dot-matrix fashion. No mask is required, enabling designers to rapidly change circuit designs. A schematic of ZPAL is shown in Figure 15.

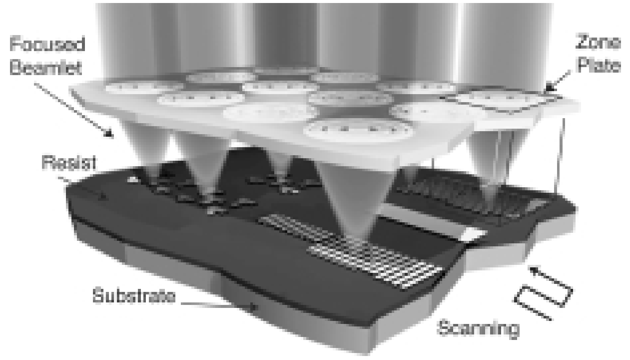

Figure 15: Schematic of zone-plate-array lithography (ZPAL). An array of Fresnel zone plates focuses radiation beamlets onto a substrate. The individual beamlets are turned on and off by upstream micromechanics as the substrate is scanned under the array. In this way, patterns of arbitrary geometry can be created in a dot-matrix fashion. The minimum linewidth is equal to the minimum width of the outermost zone of the zone plates

ZPAL leverages advances in nanofabrication, micromechanics, laser-controlled stages, and high-speed, low-cost computation to create a new form of lithography. We are developing ZPAL at UV, deep UV (DUV), EUV and x-ray wavelengths.

Lithography Results: We have demonstrated ZPAL with a proof-of-concept experimental system that operates at a l=442 nm exposure wavelength. It uses an array of zone plates that was fabricated at MIT, in conjunction with a micromechanical mirror array made by Texas Instruments. Figure 14 shows a scanning electron micrograph of a nested-L pattern exposed with this system. The image quality is very good, showing dense 350 nm lines and spaces.

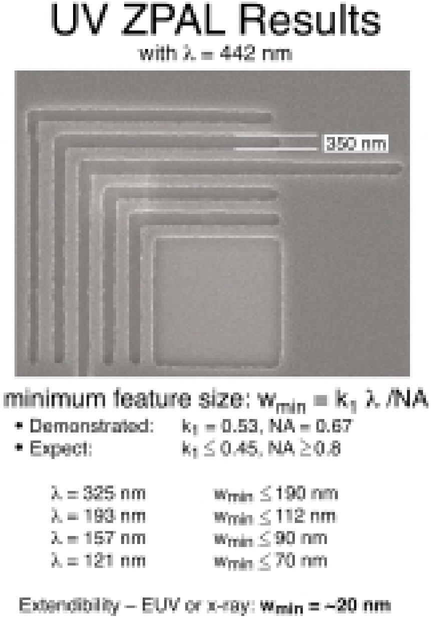

Figure 16: Scanning-electron micrograph of nested-L patterns produced with l=442 nm ZPAL. The minimum feature size of an optical projection system can be described as . In this case the linewidth is 350 nm, the numerical aperture (NA) of the zone plates was 0.67, correspo(l=157nm), we expect to be able to print sub-90 nm features.

The minimum feature size in optical lithography can be written as:

$$w_{\min} = k_1\lambda/NA \tag{1}$$

The above results demonstrate k_1=0.53 at 0.67 NA. Simulation studies indicate that k_1=0.45 at 0.85 NA is a *conservative* estimate for the limits of lithographic patterning with UV/DUV-ZPAL.

For most applications of lithography, it is desirable to control the linewidth to a fraction of the minimum feature size. Figure 17 shows how this is done with grayscaling in ZPAL exposures. In this case, 330 nm-wide pixels were exposed on a 110 nm grid. In the leftmost micrograph, a single column of pixels was exposed. To widen the line, a second column was exposed at increasing doses. A third column was then exposed (as indicated in subsequent micrographs).

Because zone plates are diffractive optical elements, ZPAL can operate at EUV wavelengths (13.4 nm) or even in the soft x-ray regime (l~1-5 nm). EUV or soft X-ray ZPAL should enable us to achieve feature sizes of about 20 nanometers at relatively low cost.

Our main research effort at this time is to build a prototype UV-ZPAL system that will be useful for lithographic patterning at MIT. This system will pattern 210 nm features at a throughput of 0.5 X 0.5 cm in 20 minutes. Such a system will give users a combination of maskless patterning, small feature size and modest throughput not available with any other technology. This prototype system will be a first step towards a commercially viable maskless patterning technology.

This prototype system will operate at l=400 nm exposure wavelength (GaN laser diode source), and will use a micromechanical light modulator made by Silicon Light Machines. The architecture for this system is in place and has been demonstrated to operate 60X faster than the previous proof-of-concept system. Figure 18 shows experimentally demonstrated throughput rates of various components of the system along with the design specification for the throughput described above. The micromechanics and data-delivery subsystems exceed the specification. The current bottleneck is stage speed, which is being optimized with a new control system.

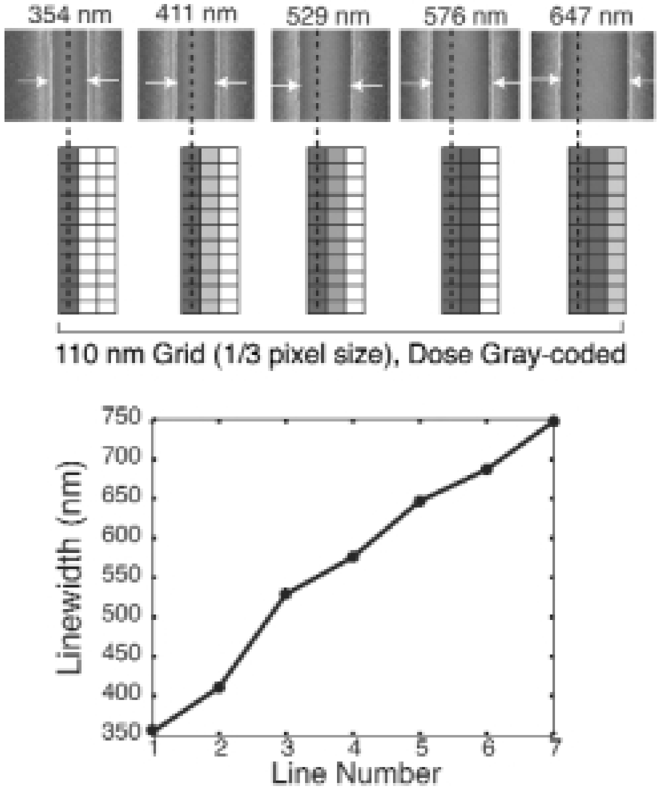

Figure 17: Lines of varying width printed with grayscaling. Pixels (~330 nm in size) were exposed on a 110 nm grid. To widen the lines, a second column of pixels was exposed at increasing doses, then a third line was added. TOP: Scanning-electron micrographs of lines. CENTER: Schematic of exposure conditions for each line. BOTTOM: Plot of linewidth vs. line number.

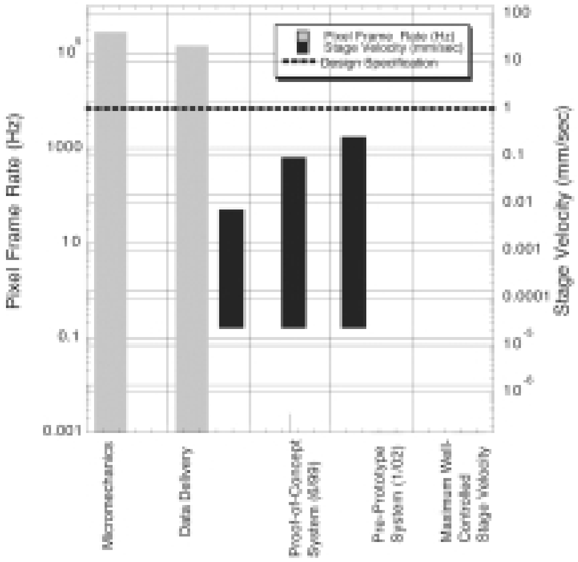

Figure 18: System design specifications for prototype ZPAL system. Left Y-axis, and gray bars, indicate pixel frame rates. Right Y-axis, and black bars, indicate stage speed. Current bottleneck is stage speed, which is being optimized with new control system.

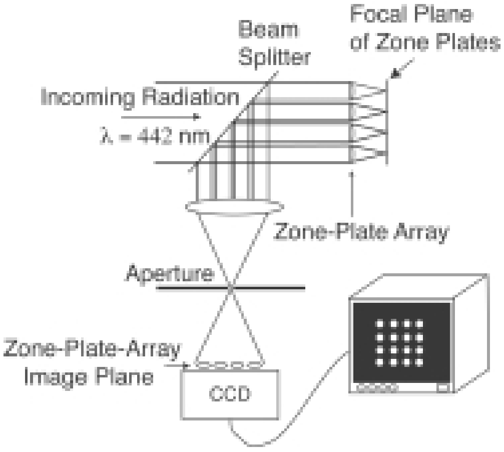

Figure 19: Schematic of Zone-Plate-Array scanning-confocal Microscopy (ZPAM). The zone plates are used as an array of objective lenses. The CCD detector is placed at the image plane of the zone-plate array, after the confocal aperture, allowing the reflected light from each zone plate to be analyzed independently.

Imaging Results: An array of zone plates can also be used as a massively parallel confocal microscope, allowing imaging over a large field of view. In addition, since zone plates can be inexpensively fabricated to work at deep-UV wavelengths, low-cost, high-resolution imaging is possible with Zone-Plate-Array scanning-confocal Microscopy (ZPAM).

ZPAM is similar to conventional Scanning Confocal Microscopy (SCM), but with a few differences, as shown in Figure 19. First, the objective lens in the traditional SCM is replaced by an array of zone-plate objective lenses. Second, a CCD array is placed at the image plane of the zone-plate array, allowing the reflected light from each zone plate to be analyzed independently. In order to accomplish this, the confocal aperture must be somewhat larger than in conventional SCM, to pass enough diffracted orders to properly reconstruct the zone-plate array.

For the smallest feature size in lithography or resolution in microscopy, high-numerical-aperture (NA) zone plates will be required. We have used the prototype system, operating in ZPAM mode at l=442 nm wavelength, to characterize the imaging characteristics of zone plates with NAs up to 0.95, comparable to the highest NA available for a high-resolution microscope objective operating in air.

Given the steep diffraction angle of the outer zones for high-NA zone plates, it was not obvious that the highest-NA zone plates would function as expected. However, imaging experiments indicate that resolution improvement with increasing NA continues for even the 0.95 NA zone plates. Figure 20 shows images of a chirped-grating test object taken with the five-zone-plate sets. Figure 21 plots the minimum resolvable half-pitch of the grating versus zone-plate NA for the images in Figure 20. The minimum resolved half-pitch of 175 nm for 0.95 NA corresponds to a k1 factor of 0.38.

The results of the high-NA imaging experiments, combined with the simulation results, indicate that 210 nm should be readily achievable with the prototype UV-ZPAL system.

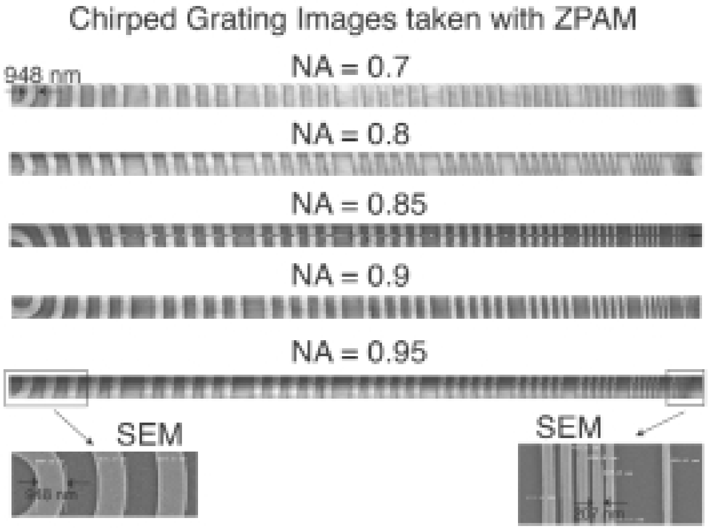

Figure 20: ZPAM micrographs of chirped grating test objects taken using zone-plate sets shown above on the prototype ZPAM system. Clearly the lower-NA zone-plate sets do not resolve the finest-pitched gratings (to the right), where the 0.95 NA set resolves almost all lines.

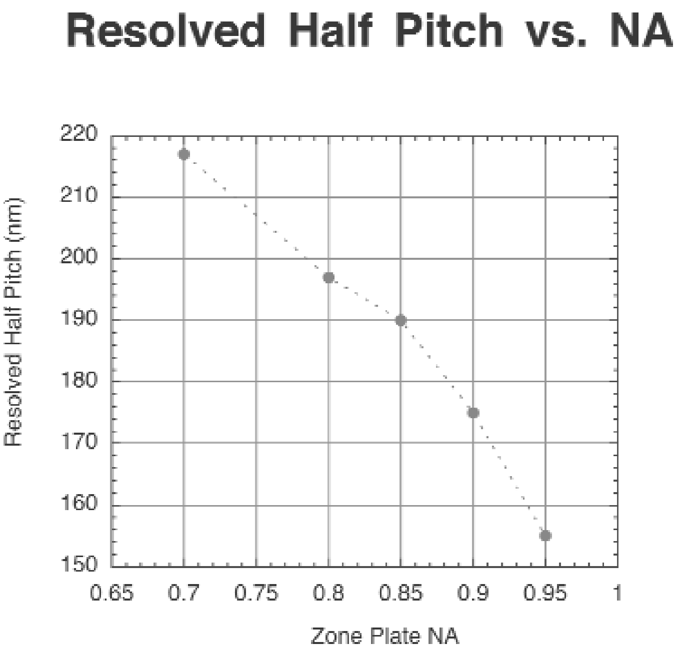

Figure 21: Plot of resolved half-pitch vs. zone-plate NA for the images shown above. The resolution clearly continues to improve up to the highest NA. This data indicates that high-NA zone plates can be used for imaging and should also be suitable for lithography.