Parallel maskless optical lithography for prototyping, low-volume production, and research

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Earlier we reported on a proof-of-concept maskless-lithography system that used an array of Fresnel zone plates to focus multiple beams of 442 nm light onto a substrate, and micromechanics for multiplexing light to the several zone plates, enabling patterns of arbitrary geometry, at 350 nm linewidth, to be written. We referred to the technique as zone-plate-array lithography (ZPAL). We also demonstrated zone-plate-array microscopy. Here, we report on a ''preprototype'' ZPAL system operating at an exposure wavelength of 400 nm, capable of quick-turn-around, maskless lithography. We describe the lithography results with this system as well the development of high-speed data delivery systems, high-numerical-aperture zone plates (up to 0.95), and a multiplexing scheme that will enable us to move to a ''full-prototype'' system capable of 210 nm feature sizes at a moderate but useful throughput of $\sim 0.25\ \mathrm{cm}^2$ in 20 min. [DOI: 10.1116/1.1526353]

I. INTRODUCTION

The ever-increasing demand for finer features, improved alignment, and high throughput is causing a rapid acceleration in the complexity and the cost of lithography tools. Optical projection steppers, although capable of deep submicron and sub-100 nm resolution, suffer from an inherent lack of flexibility that renders them inappropriate for the requirements of a number of disciplines and applications outside of Si semiconductor manufacturing. Furthermore, even within the realm of the Si semiconductor industry, there is a growing awareness that quick turn around in lithography is becoming extremely important both for designers and for special low-volume products. In addition, the cost of low-volume commercial lithography has been growing at an alarming rate, since the high cost of masks cannot be amortized over a large-volume chip production.

The quick creation and delivery to customers of customized chips is becoming important as microprocessors reach performance levels that often exceed the needs of all but a few customers. In the coming years customers will likely be willing to pay extra for a product that is extraordinarily reliable, or one that has been customized to meet *their specific needs*.[1] If flexibility and quick turn around time do indeed become a new element in the Si semiconductor industry, then maskless lithography would appear to be the preferred choice. Because of the cost of modern-day photomasks, and the sometimes long turn-around time, maskless lithography would also be preferred in research and in a large variety of applications, from microphotonics to microelectromechanical systems (MEMS).

For decades, electron-beam lithography (EBL) has provided a maskless approach. However, EBL has its own unique set of problems and limitations[2–4] and has seen few applications outside of research and mask making. There are optical systems available that provide maskless photolithography.[5] However, these also are designed exclusively for mask making and appear to have limited flexibility for general-purpose lithography.

Zone-plate-array lithography (ZPAL) (Refs. 6–8) may provide an optimal approach to maskless lithography. The ZPAL system architecture is fundamentally simple. It takes advantage of recent advances in micromechanics and low-cost computation. Because zone plates are fabricated via planar processing, large-area arrays of such lenses are readily fabricated with identical properties. Because zone plates can focus any type of radiation of interest in lithography, from blue, to deep UV, to x rays, and even neutral atoms,[9] the zone-plate design and the multiplexing can be scaled with the wavelength to meet future needs (as is the case with many other forms of lithography, by using light of shorter wavelengths, higher resolution can be achieved). The ZPAL architecture is also very adaptable to customization. For example, the number of zone plates can be increased to meet requirements for increased throughput; or the focal lengths of the zone plates can be programed to accommodate lithography on curved surfaces.

In this article, we report on a ''preprototype'' ZPAL system operating at an exposure wavelength of 400 nm with a solid-state laser. We describe the lithography results with this system as well as the development of high-speed data delivery systems, high-numerical-aperture (NA) zone plates (up to 0.95), and a multiplexing scheme that will enable us to move to a ''full-prototype'' system capable of 210 nm feature sizes at a moderate but useful throughput of $\sim 0.25\ \mathrm{cm}^2$ in 20 min.

II. ZPAL ARCHITECTURE

Zone-plate-array lithography uses a narrow bandwidth source, an array of Fresnel zone plates, a multiplexing device capable of controlling the illumination to each zone plate in

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the array, and a scanning stage, to print arbitrary patterns on a wafer without a mask. The entire array of zone plates is illuminated and then shuttered by the multiplexing device. The stage is scanned at the same time, enabling the creation of arbitrary patterns. Aside from the necessary beam-shaping optics needed to properly illuminate the pixels of the multiplexing element such that one pixel illuminates one and only one zone plate (ensuring that there is no cross talk between zone plates as well as a uniform phase front across each of them), the optical train of the ZPAL architecture is inherently simple and inexpensive. For the UV and deep UV, the array of zone plates can be fabricated with a planar process on a fused-silica optical flat, requiring only one lithographic step; and the micromechanical elements employed are reliable commercial products of modest cost. The more expensive components are the radiation source and the scanning stage, a cost common to all lithography systems. But, with an architecture that offers a radical departure from a century-old tradition of refractive optics, a high-NA system can be built at a cost no higher than a low-NA one, i.e., fabricating a zone-plate array with NAs of 0.95 is not significantly more difficult than for NAs of 0.6. This is not the case for refractive-optical systems.

A. ZPAL prototype system

With the goal of proving both the technical merit and the potential commercial viability of ZPAL, we are currently building a prototype system that will be used for quick-turnaround, maskless patterning for a number of research applications, from MEMS to microphotonics. The system will have ~200 beams, each operating at a pixel-transfer rate of ~7.5 kHz, a 400 nm exposure wavelength, 0.85 NA zone plates, and $k_1 = 0.45$, with a minimum feature size $w_{\min} = 210$ nm, ($w_{\min} = k_1 \lambda/\mathrm{NA}$). With a pixel size of 105 nm (half the minimum feature size) each zone plate will address an area of 1229×1229 pixels. This prototype system will achieve a moderate but useful throughput of ~0.25 cm^2 in 20 min. A scaled-up version of this system employing 1500 beams operating at 350 kHz would achieve a throughput of one 200 mm wafer per hour.

B. Multiplexing device and data delivery for ZPAL

We have switched from the previously reported method of multiplexing the light for ZPAL, the Texas Instruments DMD™ micromirror array, to the Silicon Light Machines Grating Light Valve™ (GLV™) linear array.[10] Although the GLV™ has a smaller number of pixels (1088) compared to the DMD™ micromirror array (~1 million or more), the higher speed of operation of the GLV™ (20 ns rise time as opposed to 20 μs for the DMD™), the fact that gray scaling is built in, and its diffractive mode of operation (making it compatible with shorter wavelengths, possibly even down to 157 nm) made it a superior choice for ZPAL.

The GLV™ is a micromechanical phase grating consisting of parallel rows of reflective Al ribbons. Alternate rows of ribbons can be pulled down electrostatically in a controlled manner to create diffraction effects on incident light.

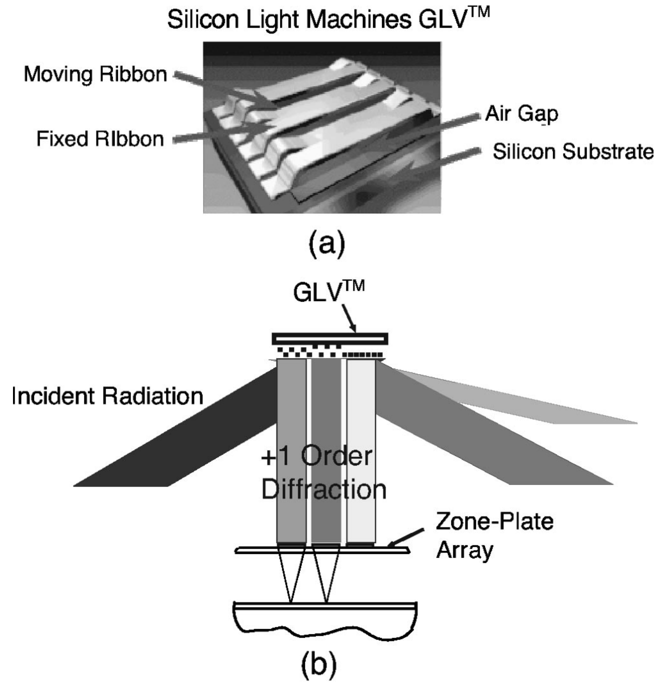

FIG. 1. Silicon Light Machines Grating Light Valve™ (GLV™); (a) one pixel of the GLV™ (each pixel can be thought of as a "minigrating"), and (b) intended implementation of the GLV™ with our linear array of zone plates indicating gray scaling.

When no force is applied, all the ribbons lie in the same plane. If illuminated, incident light will be reflected from their surfaces at the same angle at which it is incident. When alternate ribbons are pulled down, a grating structure is created. In this state diffraction will produce light at an angle different from that of the incident light. By alternating between these two states (i.e., from flat ribbons to a grating structure) the GLV™ can switch light "on" and "off." Furthermore, by tuning the applied electrostatic force, the depth to which the ribbons are pulled down can be controlled, impacting the amount of light diffracted into the first order. Gray scaling of the incident light can be achieved in this manner. Each of the 1088 pixels present in the linear array can accept 8 bits of gray scaling (256 levels). Since the motion involved in switching the pixels of the GLV™ is small (one-quarter wavelength), the GLV™ is capable of very high switching speeds, with a rise time from the on to the off position of only 20 ns.[10] One pixel of the linear array is depicted schematically in Fig. 1, along with the intended implementation in ZPAL.

We have built a custom system to deliver the pattern data from the ZPAL control computer to the 1088 pixels of the GLV™ array at very high speeds. Data are first transferred from the computer through the PCI bus to a National Instruments digital input/output (I/O) board (Model No. 6601). The data are then sent from the I/O board to the GLV™ through a custom-made printed circuit board, which performs the data routing and interpretation as required by the GLV™ electronics. The I/O board, equipped with an 80 MHz clock to enable clocking the data at very high

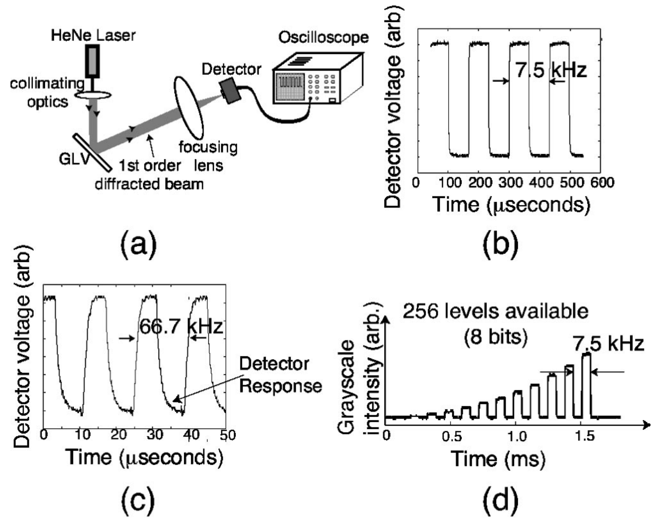

FIG. 2. (a) Schematic of the experimental setup for testing the data delivery system for ZPAL. (b) GLV operating at 7.5 kHz, the required speed for our prototype system. (c) GLV operating at 66.67 kHz, corresponding to a 1 Gbit/s data rate. (d) Gray scaling at 7.5 kHz.

speeds, has the capability of both reading data from the control computer and sending data to the GLV™ simultaneously. In practice, two I/O boards are used in parallel to achieve high data rates. All the software was written in LabView on a Dell windows workstation.

In order to test the data delivery system, we have built an experimental setup as shown in Fig. 2(a). Light from a helium–neon laser is collimated and directed onto the GLV™. A lens is used to focus the first-order diffracted beam onto a detector. We send data to the GLV™ and measure the modulation of the light on the detector. Figure 2(b) shows the detector signal as a function of time when the GLV™ was driven with on–off data at a frequency of 7.5 kHz (the specification required for our prototype system), corresponding to an average data transfer rate of 130 Mbits/s. The vertical axis is the detector voltage, but it was not calibrated, and hence, is not labeled in Fig. 2(b).

Since the GLV™ is capable of operating at much higher frequencies (~500 kHz), we tested our system to determine the limits of the data delivery architecture, even though our requirements had been successfully met. Figure 2(c) shows the GLV™ operating at a frequency of 66.67 kHz, corresponding to a data transfer rate of about 1 Gbit/s. At present, we were limited by the response time of our detector, but data from our logic analyzer indicate that we can successfully send rates in excess of 100 kHz with our current implementation.

Since dose control is an important requirement for good lithographic performance, the ability to gray scale is paramount in any multiplexing device to be employed in a ZPAL system. The GLV™ offers 8 bits of gray scaling (256 levels), 3 bits more than what is needed for our writing strategy, which requires 5 bits.[8] As shown in Fig. 2(d), our data-delivery system is capable of achieving all 8 bits of gray scaling without sacrificing switching speed.

C. Zone plate array

Five linear arrays of phase-zone plates, with NAs ranging from 0.7 to 0.95, were fabricated by scanning-electron-beam lithography and reactive ion etching. Since the ZPAL setup can also operate as a microscope [zone-plate-array microscopy (ZPAM)],[8] the different NA zone plates were characterized by imaging a chirped circular grating resolution standard with linewidths varying from 1 μm to 150 nm. Figure 3 shows five ZPAM images of the resolution standard acquired with the various NA zone plates. Note that as the NA increases, even the finest period gratings can be resolved, demonstrating that very high-NA zone plates (all the way up to 0.95) maintain good focusing properties and can, hence, be

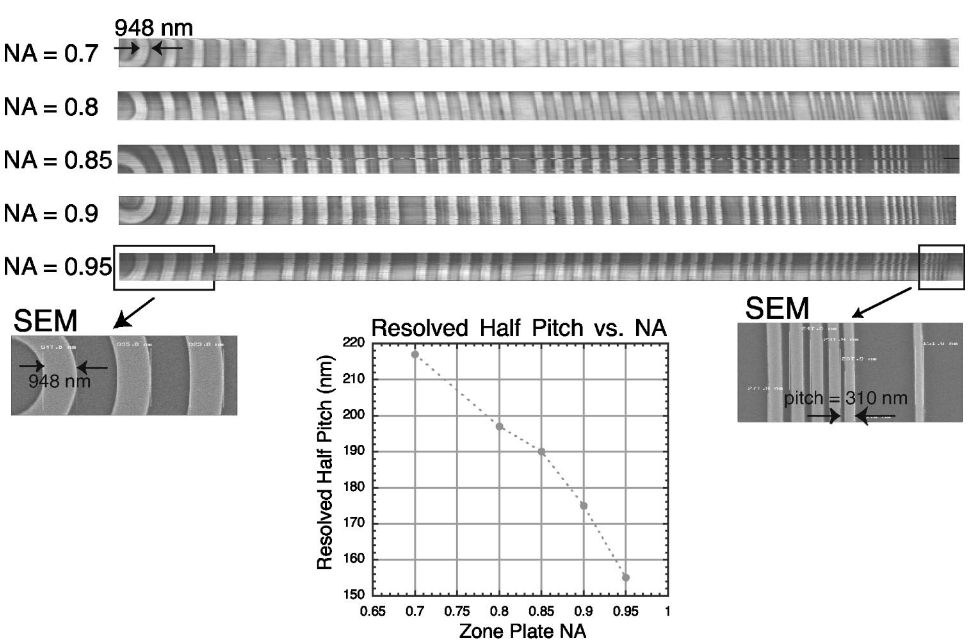

FIG. 3. Top: chirped grating images taken in microscopy mode (ZPAM) with high-NA zone plates operating at $\lambda = 442$ nm. Bottom: plot of the resolved half pitch of the chirped gratings vs the numerical aperture of the zone plate. As the numerical aperture increases, all the way to 0.95, the zone plate is able to resolve finer and finer features, demonstrating that very high-NA zone plates can be utilized for imaging.

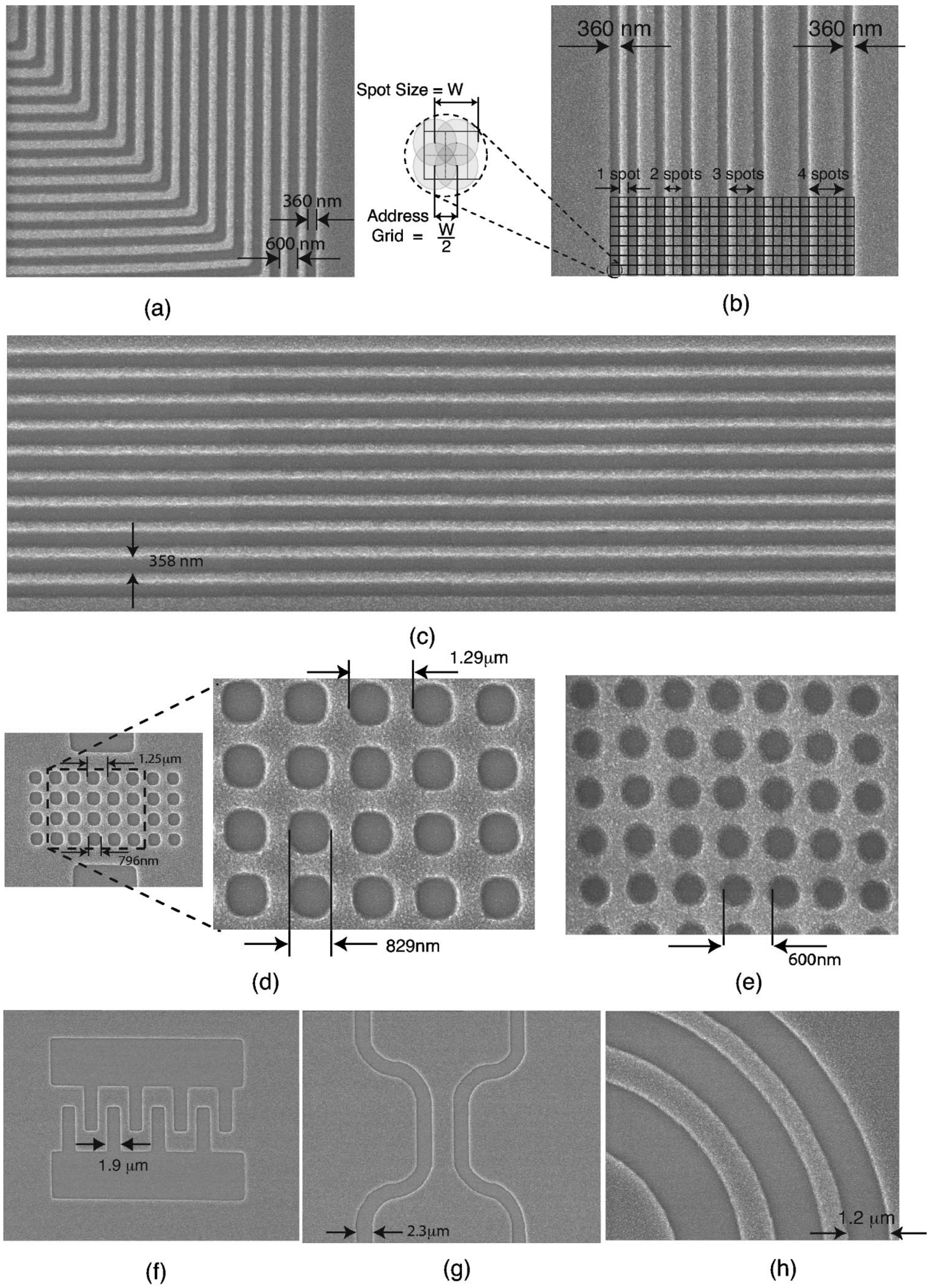

FIG. 4. Scanning electron micrographs of patterns exposed with our continuous-scan UV-ZPAL system. (a) Dense nested Ls; (b) single-pixel lines with different spacing between lines; (c) small section of a 81-μm-long, 600-nm-period grating; (d) 2D photonic band-gap structures with 1.29 μm period; (e) 2D photonic band-gap structures with 600 nm period; (f) microcomb structure for MEMS; (g) curved waveguides; and (h) portion of a zone plate.

utilized for high-resolution imaging. To our knowledge, these results represent the first report of such high-NA optical imaging with zone plates.

D. Scanning stage system (continuous scan ZPAL)

We present here the first lithographic results obtained by continuous scan ZPAL. For our scanning system we use a piezoactuated stage from Physik Instrumente (model P-770). This model offers a scan range of $200\times200\ \mu\text{m}^2$ with a positioning accuracy of less than 10 nm. Capacitive sensors are used for position sensing. Custom-built velocity feedback circuits were implemented to enable continuous-velocity scanning in one dimension. We are in the process of upgrading the scanning stage to incorporate a laser–interferometer-based feedback system for both axes.

The stage scans the substrate in a raster fashion. Custom-built lithographic pattern generation software ensures that any unwritten rows and repeated pixels are discarded from the pattern. In terms of writing strategy, it is important to differentiate the concepts of spot size, determined by $w_{\min} = k_1\lambda/\text{NA}$, and that of pixel size, which refers to the address grid (i.e., the locations on the substrate where spots are flashed at appropriately controlled doses). Based on our simulations and previous work,[8] 5 bits of gray scaling in combination with an address grid of one half the spot size is sufficient to control linewidths to better than 10%. Furthermore, this writing strategy allows all edges of the exposed features to be controlled independently and accurately to a fraction of the spot size.

III. SYSTEM PERFORMANCE: LITHOGRAPHIC RESULTS

The results presented in Fig. 4 are the highest quality lithographic patterns ever produced with ZPAL, showing good fidelity, low edge roughness, and the ability to pattern very dense features down to the minimum spot size. It is worth noting that even though all exposed pixels received the same dose, proximity effects are minimal in the exposures. A large number of patterns were exposed with the system, including two-dimensional (2D) photonic band-gap structures [Figs. 4(d) and 4(e)], microcomb structures [Fig. 4(f)], waveguides [Fig. 4(g)], zone plates [Fig. 4(h)], and a number of lithographic test patterns [Figs. 4(a)–4(c)].

All exposures employed a 25 mW GaN laser diode operating at $\lambda = 400$ nm. For these experiments no multiplexing device was used, i.e., all zone plates in the array wrote the same pattern simultaneously. (Previously, we demonstrated parallel patterning with active multiplexing.[7])

A confocal technique, described in an earlier article,[8] was used to set the substrate at the right gap with respect to the zone-plate array. All exposed substrates were 3 in. silicon wafers spin coated with 200 nm of BarLi ARC (spun at 3000 rpm and baked on a hot plate at 175 °C for 90 s), with 150 nm of thinned Shipley 1813 photoresist on top (spun at 5000 rpm and baked on a hot plate at 90 °C for 60 s). The exposed patterns were developed in a Shipley 351 developer diluted with water in the ratio 1:5 for 45 s.

The address grid for the exposures presented in Fig. 4 was 150 nm [each cleared spot in the pattern is composed 4 subpixels, as depicted in Fig. 4(b)], resulting in an exposure time of 7.5 ms per spot. As the only exception, the smooth curves (zone plates) shown in Fig. 4(h) were written with an address grid of 75 nm and a corresponding exposure time of 1.8 ms/pixel.

IV. CONCLUSION

We have demonstrated high-NA zone-plate microscopy, high-speed data delivery to our GLV multiplexing system, and continuous-scanning zone-plate lithography of high resolution and high fidelity. These combined results imply that when combined into a prototype system comparable lithographic results will be achieved at a throughput of 0.25 cm^2 in 20 min, suitable for research and prototyping. By increasing the number of zone plates from 200 to 1500, and introducing further upgrades of the ZPAL system with commercially available components, we predict a throughput of 1 wafer per hour, suitable for a wide range of applications.

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