APPARATUS AND DEMONSTRATION NOTES

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A maskless photolithographic prototyping system using a low-cost consumer projector and a microscope

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Lithographic processing has been the key technology responsible for the rapid advances in microelectronics, but is typically not accessible to undergraduates. We have developed a maskless photolithographic system that can be assembled from a consumer projector and a trinocular microscope. This system allows students to design and print custom patterns into photoresist in less than 30 min, without using a clean room, a mask facility, or a chrome-etch bath. Students can create and evaluate patterns, make changes to their design, or add additional layers of aligned patterns in a single laboratory session. The rapid turnaround time and low cost of ownership is useful for low-resolution ($\sim 10\ \mu$m) prototyping. Photoresist is spun in a modified food processor and baked on a standard hot plate. Mating pieces were machined from aluminum. Only the digital light processing projector and food processor are modified, so the microscope, camera, and computer need not be dedicated to the system. The entire system can be assembled for less than $5000.

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Photolithography is a key step in the fabrication of the modern integrated circuit. Multiple levels of aligned photolithography, combined with thin-film deposition and etching, allow a three-dimensional circuit to be built up on a two-dimensional surface. Because it is such an important part of the semiconductor manufacturing industry, much research has been performed in this area.[1,2] However, this research is largely directed toward high-volume industrial purposes rather than low-volume academic research needs. Mask costs are a serious issue even in industrial applications, and maskless lithography tools are being developed for next-generation lithography systems such as extreme ultraviolet lithography, where mask costs are expected to be a major problem.[3]

An academic setting requires much more flexibility than is provided using standard methodology. To this end, our goal is to develop a system with which a student or professor can design a pattern on the fly and be able to use it in a photolithography system. The most practical way to do so is to design a system that circumvents the mask fabrication step in the standard process. Performing conventional photolithography with preset masks is economically competitive, but eliminates the flexibility and creativity that makes the process interesting to students. Although some undergraduate laboratories perform lithography experiments with laser printed optical transparencies, these are usually unaligned single layers with poor resolution, poor contrast, and line-edge roughness.

Because commercial maskless photolithography systems already exist,[4,5] our goal is to maximize simplicity and speed, and minimize costs. Our system works by taking a pattern created on a computer, and projecting it through a digital light processing (DLP) projector. The projected image is reduced and sent through the camera port of a trinocular microscope. The optics of the microscope focuses the image on the substrate and allows the image to be reduced, analogous to the reduction in a conventional photolithographic stepper. Our setup can be seen in Fig. 1.

We selected an ultralight projector[6] (~ 2 lbs) so that it could be mounted on top of the microscope, facing downward, leaving the microscope in its intended configuration. The projector image is generated by a DLP chip[7,8] with a resolution of 1024×768 pixels. The projector can be driven by a standard computer video graphics array (VGA) output.

The particular projector used is not critical to the experiment. Our choice combines the attributes of low cost, light weight, high resolution, and high contrast. High resolution is important for generating small-scale images; high contrast is necessary for reasonable process latitude in photolithogra-

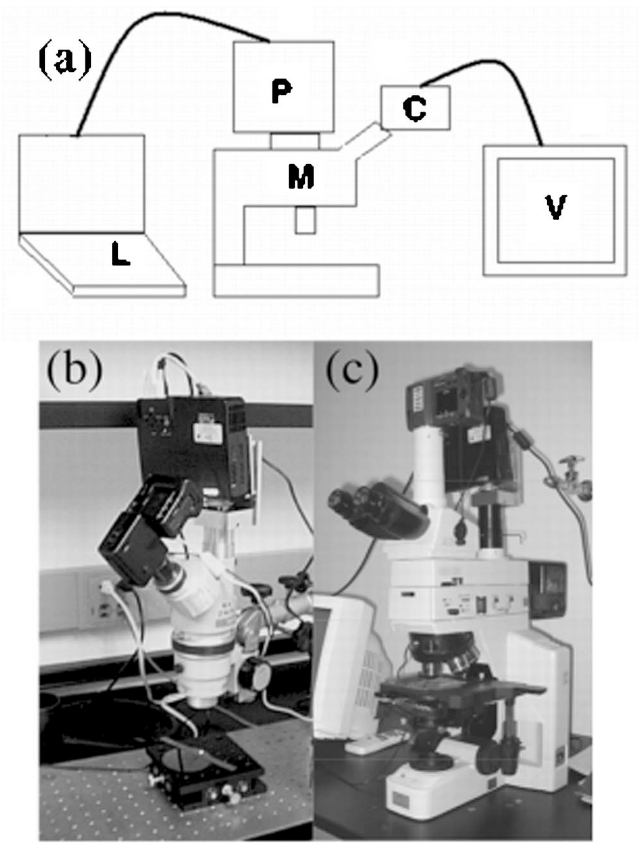

Fig. 1. Experimental setup schematic (a): an image is generated on a laptop computer (L) and projected by a modified consumer DLP projector (P). The image enters the microscope (M) at the camera port. One of the eyepieces is fitted with a digital camera (C) that sends a picture of both the substrate and the projected image to a video monitor (V). Photographs of the system installed on both (b) the stereozoom and (c) an inspection microscopes.

phy. Although the weight restriction is less critical, ultralight models are easier to mount on the camera port of a microscope.

We tested this setup using several microscopes, including a stereoscopic zoom microscope[9] and a semiconductor inspection microscope.[10] The first is a very low cost inspection microscope with a continuous zoom, so that we can change magnifications smoothly; however, it only supports magnifications from 1 to $4\times$, corresponding to an individual pixel on the image plane with linear dimensions between 20 and 5 μm, and a field size ranging from $20\times 15\ \mathrm{mm}^2$ to $5\times 4\ \mathrm{mm}^2$. The inspection microscope uses infinity-corrected objectives at fixed magnifications. We used this microscope with both the 5 and $10\times$ objectives, creating pixels of 1.6 and 0.8 μm in width, respectively, within millimeter-scale fields. At higher magnifications, the theoretical resolution becomes limited by optical diffraction rather than by the size of the mirrors/pixels. Students can calculate the diffraction-limited resolution and depth of focus for our system from the numerical aperture of the objective lenses and the wavelengths of light that we use.

With both microscopes we use a trinocular head with a camera port to which we attach the projector. At the same time that we project the image through the port, we ensure that it is focused and aligned on the surface using the viewing port, where we can also take pictures of the surface and the projected image using a digital camera[11] that is mounted on a standard eyepiece or relay lens.[12]

It is critical to mount the projector rigidly to the microscope. We designed parts specific to our projector, but a similar setup would work with any comparable projector. The bottom of our mounting device mated directly to the trinocular head. Our mounting device was constrained by the vent on the front of the projector and the high throw angle of the projected image. Our mount has a fine tilt-angle adjustment (similar to an optical mirror mount, but more robust and on one axis only), which allows us to align the optical system into the trinocular camera port.

Because we were trying to reduce the image, the built-in short-throw projection lens worked against us by creating light rays that diverged to such a degree that they could not be recaptured by the microscope optics. We removed the lens and inverted it inside our mount to make a real image of the DLP chip outside the projector body (with $\sim 1\times$ magnification) that could be projected fully through the microscope optical train.

To create an image on the substrate, we spun commercial photoresists on standard silicon wafers or glass substrates and exposed the samples using blue light. Commercial polymer spin coaters (spinners) have vacuum chucks that hold down substrates and spin them inside a bowl (to capture the excess polymer) at highly controllable spin speeds (0 to 6000 rpm) and acceleration; unfortunately, these are prohibitively expensive for undergraduate laboratory use. Coated polymer film thickness (typically $\sim 1\ \mu$m) is a function of both the polymer viscosity and the spin speed. Most consumer blenders and food processors have drive shafts that spin inside a container with roughly this same range of speeds as commercial spinners. We purchased a combination blender/food processor, with a variable speed motor base[13] at approximately 1% of the cost of a commercial spinner. We machined an aluminum chuck that mounts in the food processor in place of the cutting blade and has clips that hold down samples while they are spun inside the food processor. As a safety precaution, the lid on the food-processor bowl should always be mounted before spin coating the substrate. The feed tube of the food-processor bowl provides a convenient port for dispensing chemicals onto the substrates.

Most photoresists are polymers dissolved in strong solvents, and should therefore be considered hazardous chemicals in liquid form. It is best to work with the liquid resist in a ventilated hood that holds both the spinner and the hot plate used to bake the spin-coated films. After spin coating and baking, all the hazardous solvents should have been removed, and the samples are harmless. Photoresist films will usually not be exposed by indirect room light, but amber light filters can be added as an extra precaution. These lights also serve to remind students that they are working with light-sensitive materials.

The spinning process is an ideal situation for observing thin-film optical interference in real time. Samples are rinsed in acetone followed by isopropyl alcohol and spun dry. During the drying, multiple full spectral changes occur in the color of the surface of silicon substrates as the solvent layers become thinner as they evaporate. When the polymer resist is spun, a similar process occurs, but the higher viscosity makes the changes slower, and the final remaining film slowly stabilizes rather than clearing. An interesting demonstration or experiment can be made by studying the optical interference patterns observed in polymer films spun at different speeds or with different viscosities (made by diluting the polymers in solvent.) Students can measure the spectral reflectance, $R(\lambda)$, of these films using a low-cost optical-fiber-fed spectrometer[14] with a reflection probe. Students can fit both the local maxima and minima in $R(\lambda)$ and thus determine when even and odd integer multiples of half the wavelength fit in the additional optical path length of the thin film. The relation

$$R(\lambda)=A+B\cos(4\pi nd/\lambda), \tag{1}$$

where n is the refractive index of the polymer film and λ is the wavelength of light, allows students to determine the film thickness, d, just as is in commercial optical film-thickness measurement systems.

We also measured the spin speed of the drive shaft using a strobe light and a function generator. Our food-processor base has a gear assembly to reduce the speed of the drive shaft and increase its torque. We replaced it with rotary vacuum seals mounted in a cylindrical brass bushing to create a stationary vacuum chamber around a portion of the drive shaft. Axial and radial holes were drilled into the drive shaft so that the vacuum pulls on the top of the drive shaft. Aluminum chucks can be mounted on the drive shaft with O-rings to hold standard 4- and 3-in. silicon wafers, as well as smaller pieces. A small vacuum tweezer pump[15] (a diaphragm pump similar to those used for fish tank filters) was used to create a vacuum underneath the samples before turning on the food processor to spin them. It is important to use a bit of vacuum grease to create a good vacuum seal, and to confirm that the samples are held down firmly before starting the drive shaft, because small sharp pieces of silicon or glass can be ejected at high speeds.

We spin coated, baked (~2 min on a 90 or 115 °C hot plate), and exposed a standard novolac resist with the zoom microscope and Shipley 1813 (a general purpose broadband resist) with the inspection microscope. We used our spectrometer to evaluate different computer-generated colors produced by the projector in order to determine which ones should be used with the resists. We found that pure blue had a large peak at 440 nm, which lies in a portion of the spectrum where G-line (436-nm) resists are highly sensitive, whereas pure red did not have this peak. The two spectra are shown in Fig. 2. The resists were developed in aqueous base solutions of either sodium hydroxide or tetra-methyl ammonium hydroxide, rinsed in deionized water, and then blown dry. Students can see the resist development of large features by eye and are always excited to see their first patterns appearing in the films.

Here we present data from both of the microscopes. The semiconductor inspection microscope more than doubles the system cost and does not dramatically improve the lithographic performance, although it is easier to use. With the stereo-zoom microscope, the maskless system can be used to pattern lines larger than 15 μm and spaces larger than 50 μm using positive-tone resists. For the line patterns, the exposure time is highly dependent on feature size, as can be seen in Fig. 3. The inset shows that 100-μm lines can be patterned with a 10-s exposure time.

Initially, a key limitation of the resolution was delamination of the resist films. The application of an adhesion primer (APS 150) before spin coating the resist helps minimize this problem. Although individual pixels of the projected images can be seen with either microscope, the resolution of the lithographic performance has not achieved this level. The lower magnification stereo-zoom microscope has the advantage of providing a larger field size (typically a 4×5 mm^2 field at $4\times$ magnification on the stereo-zoom microscope), although a lower magnification objective could be mounted on the inspection microscope as well. Our inspection microscope is equipped with infinity-corrected bright-field/dark-field objectives, and we actually obtain faster exposures in dark-field than we do in a bright-field configuration, suggesting that there may be better choices for the exposure objective.

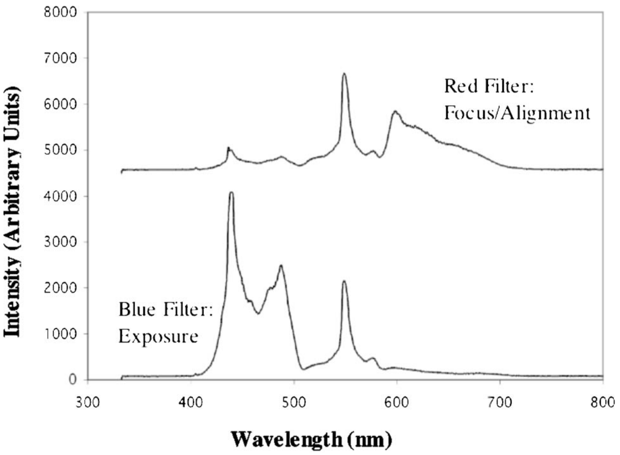

Fig. 2. Spectra from the DLP projector for "exposure" conditions and "safe" conditions used for alignment and focus control. The spectra are offset for clarity.

We also found that our total patternable area was not illuminated uniformly by our system, although the full image from the projector is inside the field of view of the microscopes. The nonuniformity of the illumination comes from both the projector and the optical train of the microscope. The intensity of the light that reached the photoresist initially limited the printable field to about 60% of the full field because some areas were exposed much faster than others.

To expand the printable field we created a semitransparent image on our computer to overlay on the features that we exposed. The overlay is generated in software and is based on inverting the intensities recorded by the digital camera from an open field projection.[16] Applying this overlay to the

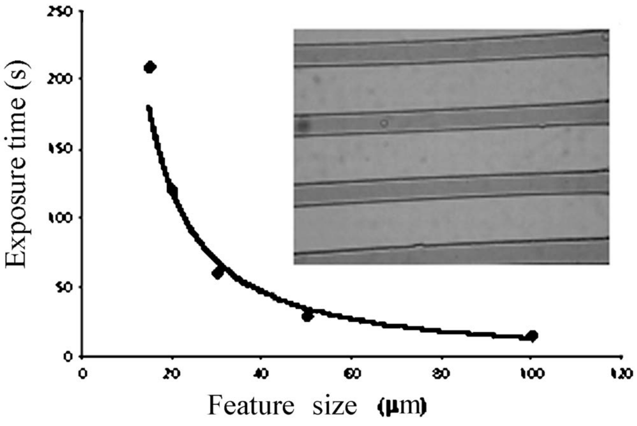

Fig. 3. Graph of exposure times and feature sizes. Inset: Image of 100-μm lines on a 500-μm pitch.

original pattern produced by computer-aided design (CAD) increased the patternable areas from 60% to 95%, with a few unworkable areas in the corners of the field. This overlay technique is easy to implement by placing the overlay in the master-slide mode of presentation software such as PowerPoint. Using the overlay increases exposure times and reduces the contrast between bright and dark pixels. The contrast of the DLP display is one of the principal limitations to the lithographic performance of the system.

The system's components were purchased for about \$4200: \$3000 for the projector; \$500 for a used stereoscopic zoom microscope; \$300 for the digital camera used to capture images; and \$200 for a relay lens to mount the camera in place of an eyepiece. The blender/food processor was \$50, and the vacuum tweezer and seals (which are not required) cost an additional \$150. The largest expense is the projector, but projector prices continue to decrease, and one can now be purchased at significantly lower cost with better performance. For this type of system, a laptop computer works well; it allows the user to simultaneously see the CAD-generated patterns and to project them, yet it need not be dedicated to the system. The camera and relay lens are not required to make a working system, but they do make the training of users much easier, because many people can observe the images at the same time. A dedicated microscope is not necessary, particularly if there is an available camera port on an existing microscope system. Most high-end microscopes can be fitted with an accessory camera port and a beam splitter that allow the projection system to be mounted permanently so as to not interfere with the regular use of the microscope.

By using this system we were able to do custom photolithography in a much shorter time that we could have using masks. The time between the formulation of an idea to a completed project can be less than 20 min. Creation of exposure slides using presentation software is easy. A typical slide show consists of a sequence of slides, with the design projected first in red for alignment and focusing, followed by a blue exposure slide for a controlled time, followed by a new red image to align the next pattern. Figure 4 shows an image of a smiley face that has been exposed, developed, and the returned to the stage of the lithography system. A projection of the exposure pattern has been superimposed on the sample in order to demonstrate the fidelity of the lithographic features as well as the simplicity of multilayer alignment for this system. Exposure dose matrices can be made by repeating the slide sequences with longer exposure times. The spinning and baking of photoresist on the substrate takes less than 5 min, and exposure times have been less than 4 min for all of the features that we have patterned.

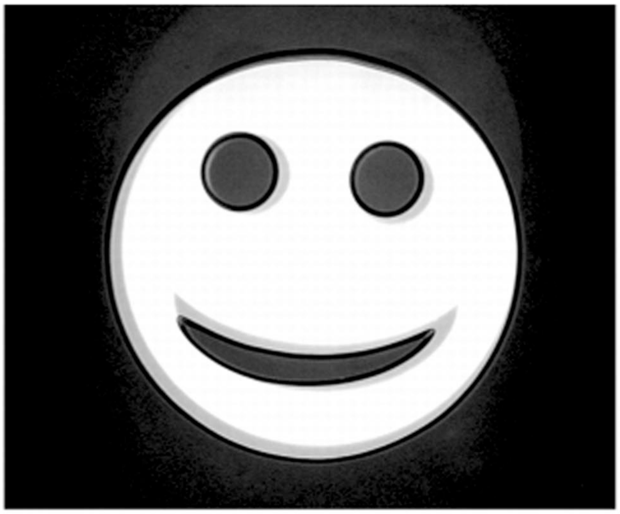

Fig. 4. A 500-μm diam smiley face printed in photoresist with the exposure image superimposed to show the fidelity of the lithography and the simplicity of multilayer alignment.

Students have used this system for a variety of research projects and upper-division laboratory exercises. These have included making optical diffraction patterns, catalyst pads for the growth of carbon nanotubes, and a variety of micron-scale symbols and signs. We have our used our thin-film evaporator in combination with this process to make metal patterns using the liftoff technique, where metal is deposited on the patterns made in the photoresist, and the remaining photoresist is then dissolved, leaving metal patterns stenciled on the substrates. Such films allow millimeter-scale electrical contact pads to be made for micron-scale objects such as thin-film resistors and long carbon nanotubes. Metal patterns on glass substrates should be suitable for creating custom two-dimensional binary diffractive optical elements similar to those used with inexpensive laser pointers. For such purposes, the exposed pattern would need to be the two-dimensional Fourier transform of the desired diffraction pattern. If a metal evaporator is not available, another approach is to electroplate metal films in solution into patterned holes in resist. Glass slides precoated with a transparent conducting oxide[17] can be purchased for less than \$5 each and used as substrates to electrodeposit opaque metal patterns on glass that would be suitable for diffraction experiments.

Although our laboratory does not have the facilities necessary to fabricate an operational transistor, this system has been used to show how multilevel aligned lithography would be used in such important thin-film processes. The patterning of surfaces can be used for a wide range of experiments such as templates for biological growth, microfluidic systems, electrodeposition molds, microcontact printing molds, patterning templates for self-assembled monolayers, and chemical etching studies.

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[1] J. D. Plummer, M. D. Deal, and P. B. Griffin, *Silicon VLSI Technology* (Prentice Hall, Upper Saddle River, NJ, 2000).

[2] *Handbook of Microlithography, Micromachining, and Microfabrication*, edited by Rai Choudhury (SPIE, 1999), Vols. 1 and 2.

[3] N. Choksi, D. S. Pickard, M. McCord, R. F. W. Pease, Y. Shroff, Y. Chen, W. Oldham, and D. Markle, "Maskless extreme ultraviolet lithography," J. Vac. Sci. Technol. B **17**, 3047–3051 (1999).

[4] The Micronic Laser Systems Sigma 7000 series uses a spatial light modulator consisting of over a million (16×16 um) mirrors.

[5] S. Singh-Gasson, R. D. Green, Y. Yuel, C. Nelson, F. Blattner, M. R. Sussman, and F. Cerrina, "Maskless fabrication of light-directed oligonucleotide microarrays using a digital micromirror array," Nat. Biotechnol. **17**, 974–978 (1999).

[6] Plus Vision, model V-1080 (recently discontinued, but similar models exist).