Low-Cost Benchtop Photolithography

Capstone Lab, CHEN 4707

Evan Blanchard, John Peterson, Maxim Balitskiy

Introduction

This project aims to create a fully functional, low-cost, benchtop scale, photolithography stepper modeled after a similar project by the HackerFab at Carnegie Mellon University [1]. Photolithography is an essential step in the semiconductor manufacturing process, the products of which are necessary for modern technology and life. Additionally, recent legislative action has provided significant funding for domestic semiconductor manufacturing. As a result, semiconductor-related employment for chemical engineers is on the rise. Providing the University of Utah Chemical Engineering Department with equipment for hands-on semiconductor education will prepare program graduates for lucrative careers in a growing industry. Finally, the photolithography stepper's micro-milling and micro-manufacturing capabilities can provide valuable utility to a myriad of research projects.

Our Objectives

The first key objective is the successful creation of a functional photolithography stepper. This project plans to fully assemble and test the photolithography tool, making it available for use by the department by March 31st, 2025.

The second objective is to achieve an etch precision of less than 10 microns as measured by scanning electron microscopy (SEM). This level of precision will be useful to the UofU for research projects in need of microscopic manufacturing capabilities. Similar projects have achieved etch precision of approximately 2 microns, so it is physically possible for the device to exceed this precision goal as discussed in accordance with the preliminary data.

This project will also provide training, maintenance, and troubleshooting guides for students to utilize the stepper. So far, this project has created outlines for each of the required materials and collaborated with our sister group HackerFab to improve the documentation provided for the initial construction of the photolithography stepper. Further work will include a detailed manual including troubleshooting and maintenance information and a brief, "crash course" powerpoint meant to bring users up to speed on operation and safety protocols as well as essential theory. These materials will allow the department to use the photolithography tool well into the future. They will also facilitate easier training for seamless integration into the chemical engineering department's curriculum.

Photolithography's Past

In the Early 1820s, Nicéphore Niépce first used Bitumen of Judea, a light-sensitive asphalt that becomes less soluble after exposure to light, to take the first permanent photograph [2]. This made Bitumen of Judea the first known use of a photoresist. The next major step in the development of photolithography would follow just over a century later, in 1940, when Oskar Süß created diazonaphthoquinone, the first positive photoresist [3]. In contrast to Bitumen of

Judea, this synthetic material becomes more soluble after exposure, hence its distinction as a positive photoresist.

Utilizing this technology throughout the 1950s, Jay W. Lathrop and James R. Nall, working at the National Bureau of Standards, would develop a system for the miniaturization of circuitry utilizing photoresist to etch germanium [4]. They would create the first photolithographic transistor and be the ones to coin the term “photolithography.” Finally, building on this work in 1957, Jules Andrus at Bell Laboratories would publish the first patent for photolithographic semiconductor manufacturing [5]. This patent would lay the groundwork for what is today: one of the most precise, complex, and important manufacturing techniques in the world.

Modern Photolithography

Modern photolithography begins with a substrate to etch. Typically, this substrate material is silicon; however, due to the nature of the process, this substrate can be glass, metal, or any material that can be etched into through a photoresist film. Then, a thin layer of photoresist is deposited onto this substrate: this is typically done through spin-coating. Spin-coating begins by adding a small volume of photoresist onto the substrate to be etched. The substrate is then spun at a high rate to thinly spread the photoresist across its surface. This photoresist can be classified as either positive or negative, and the distinction refers to the response of the photoresist to light exposure: positive photoresist depolymerizes in response to light – thereby making it soluble – and negative photoresist acts in opposition, polymerizing instead. Comparing the two, positive photoresists excel at providing high resolution and thermal stability while negative photoresists typically adhere to silicon better, have shorter processing times, and are cheaper [6].

Exposure methods also fall into two broad categories: masked, and maskless photolithography. In the former, a static mask is created and projected onto the photoresist film. The mask shields particular areas from light, leaving those areas soluble or insoluble depending on the selected photoresist type. Masked photolithography is used in industrial applications due to its high precision, repeatability, and throughput rate; however, it requires the assembly of high precision photomasks, which are static, and can only be used for a single pattern. In an environment where patterns change frequently – such as a university lab setting with ongoing research – creating a mask every time a new pattern is desired would be costly. The latter method of maskless photolithography seeks to eliminate the need to produce a physical mask. A common example of a maskless photolithography technique is electron-beam lithography where a precise beam of electrons is scanned over a surface and controlled to only hit areas where exposure is desired. This allows the beam to change the pattern it exposes easily with no need for a physical mask.

Procedures

In order to meet our project objectives, it’s necessary to create the proposed photolithography stepper with the greatest precision we can achieve. This objective is best reached by modeling our photolithography stepper after the photolithography stepper designed by the HackerFab at

Carnegie Mellon University which is discussed further in the theory section below. The HackerFab's stepper gave the project a solid foundation upon which we could build a successful tool.

In addition to building and testing the stepper, we set out to create training and troubleshooting materials for the tool. We have documented the build diligently to provide as much imagery and instructions as will be necessary to maintain the tool. Additionally, we plan to ask inexperienced operators to perform supervised tests using only the provided instructions. In so doing we will find any gaps in scope and remedy them to prepare comprehensive materials.

Theory

The masking method this project will use falls into the maskless photolithography category. Utilizing a technology known as Digital Light Processing (DLP) created by Texas Instruments, a digital mask can be created. DLP relies on a device known as a Digital Micromirror Device (DMD), a MicroOptoElectroMechanical System (MOEMS) which consists of a series of extremely small mirrors that can pivot based on electrical signals as seen in Figure 1a. A light source is projected onto the DMD chip whose array of mirrors are tilted in accordance with the digital signal sent to the DLP device, creating the desired maskless pattern as seen in Figure 1b. This reflects patterned light into the optical train of the DLP device, reflecting the rest of the light away where it is absorbed before emission. This technology serves as a middle ground between some traditional maskless and masked techniques, allowing for digital masking to avoid mask production costs while still preserving the ability to expose an entire area at once – retaining high throughput – without the need for the scan time introduced by techniques such as electron-beam lithography.

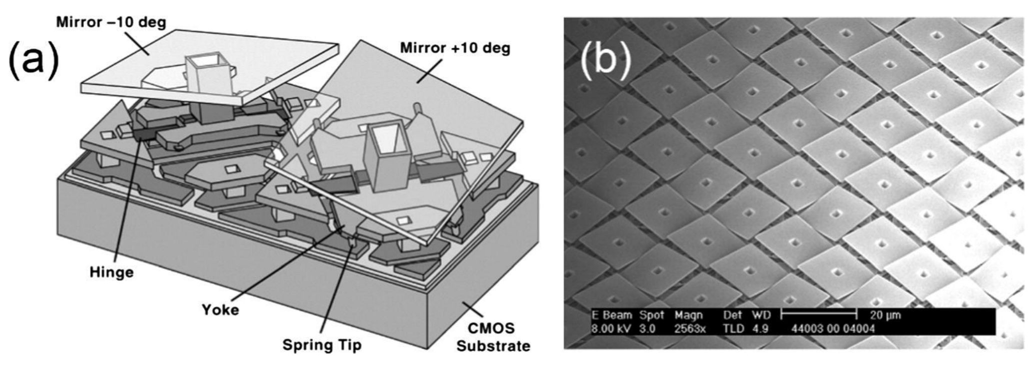

Figure 1. *(a) DMD elements and (b) top-down view of landed DMD mirror array [7].*

Having now masked the light either digitally or physically, the light is directed through an optical train to demagnify it, which is done to achieve the microscale production that is desired in semiconductor manufacturing. This step is what makes photolithography so valuable, being able to take these masks which are produced on a larger scale and utilize them to perform operations at a demagnified scale using light optics to do so giving incredibly precise control of the microscale etching. This demagnified exposure pattern contacts the photoresist and corresponding to the exposure type of the photoresist will either polymerize or depolymerize it allowing for it to be removed selectively. Finally, the removal process is done using a developer – a chemical composition that selectively removes either exposed or unexposed photoresist.

This now completes the photolithography step of the semiconductor production process, having selectively removed only the desired portions of the photoresist. Importantly, this has now created a new kind of mask, one on the surface of the substrate made of the photoresist in use. The value of this is made paramount in what is known as the "wet etch" process. With only desired portions of the substrate exposed, chemicals can be used to etch away the substrate in those areas where the photoresist has been removed. This combination of processes is what enables precision microscale etching, the essential tool used for the production of semiconductor devices which are essential to so many different aspects of modern life.

Apparatus

The design for our photolithography stepper can be summarized as the following. A custom GUI application sends a user-defined pattern to a DLP projector modified to project UV light. The patterned light follows an optical drive through a microscope objective, demagnifying the pattern to its final dimension. A c-mount camera is also mounted on the optical drive, viewing substrate through a dichroic mirror. Finally, the demagnified pattern is imposed upon a UV light sensitive material thereby solidifying or liquifying the pattern on a substrate. The substrate is also held and translated by a precision three dimensional stage. The stage is not strictly necessary for photolithography, but provides additional manufacturing capabilities. Details for the entirety of the apparatus are described below, and key functionality is described in Figure 2.

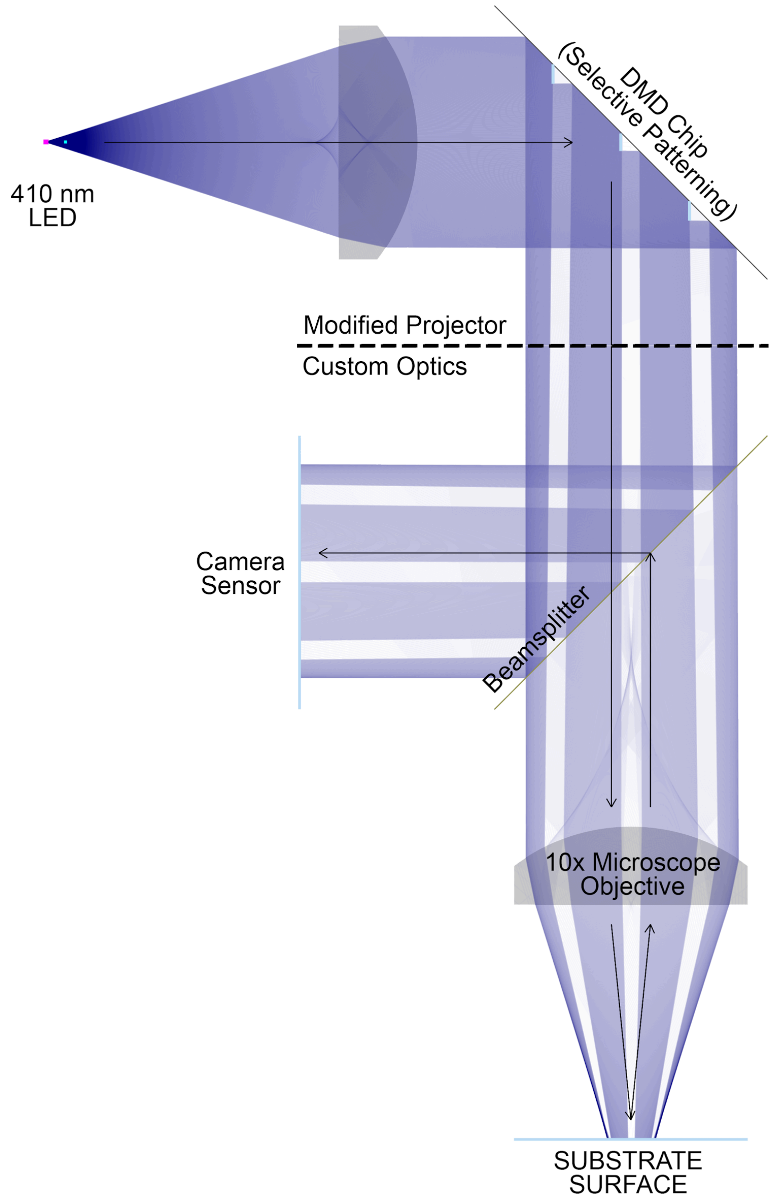

Figure 2. Diagram of photolithography stepper assembly.

The projector in use is the "DLPDLCR471TPEVM" module offered by Texas Instruments. This projector is selected for its DMD chip which has a micromirror size of 1920x1080. This is the most affordable way to get an optical system with an integrated DMD chip. The projector in its whole comprises the light source and the DMD components, both of which are necessary in our final assembly. However, the projector is designed to be a visible light system and as such does not have an LED close enough to the UV range necessary to perform exposure. Instead, this project replaced the blue LED array with a custom LED PCB which we obtained from the HackerFab group[1]. Said LED board is shown in Figure 3.

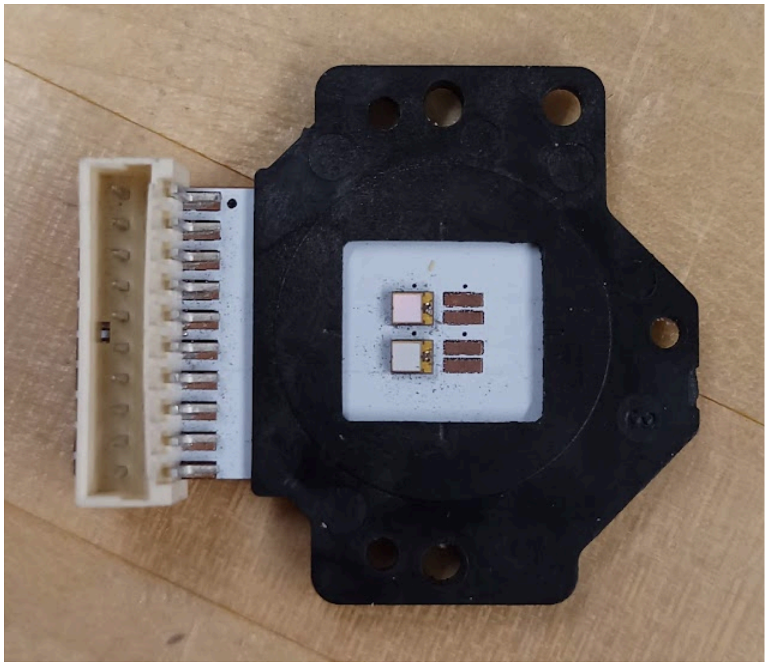

Figure 3. Custom UV LED board for replacement in DLP projector.

This board is designed to serve as an in place swap out for the PCB which is provided in the original projector. It features a copper core designed to transmit heat away from the LEDs into the heatsink. It is paramount that the UV LED be installed with the proper polarity in accordance with the above picture. Additionally, the replacement UV LED board must be bonded to the plastic mounting plate also shown in Figure 3. This mounting plate comes with the projector assembly and was removed from the original LED board with a heat gun. Once removed, the mounting plate was bonded to the replacement UV LED board with Cyanoacrylate glue. After modification, the projector's blue channel projects light at a wavelength of 410 nm, just outside the UV spectrum but close enough for this project's exposure purposes. The fully-modified projector's output is shown in Figure 4.

Figure 4. UV swapped projector showing a “blue” screen with a board.

Having modified the light source system, it is necessary to create an optics system. This project’s optics system consisted of 14 separate optical couplings, each of which was acquired from ThorLabs and a microscope objective acquired from AmScope through Amazon. A complete part list is included in appendix A. The optics assembly and each component’s function is described below. Our completed optics train is shown in Figure 5.

The optics system comprises a microscope objective which will de-magnify our digital light pattern to scale, as well as a beamsplitter and a camera. The light passes from the UV LEDs onto the DMD chip where it is digitally masked, and then into our optics system which replaces the default projector optics. Once in the optics system, the light passes through a beam splitter which is a dichroic mirror. It is then demagnified to where it contacts and exposes the surface of our photoresist-coated substrate. After this, the light bounces back into the optical assembly and now reflects off of the beam splitter into a camera which is mounted to the longest arm of the assembly. This arm length is designed to match the length to the substrate surface so the focal lengths match, ensuring accurate focusing. The c-mount camera provides monitoring, allowing the operator and software to focus the system.

Figure 5. Assembled optical train for photolithography stepper, sealed with parafilm.

The completed optical train is mounted in place of the projector's original optics via a custom 3D printed adaptor included in Appendix B. After completing installation of the optical drive and microscope objective, the photolithography stepper is completely functional. A simple etch can be performed with manual focusing, likely at the sacrifice of precision. Projects with limited budgets/time constraints could successfully etch with this system. However, given this project's goal of 10 μm precision, further assembly is necessary.

To increase photolithography functionality, it's necessary to provide automated focusing and movement. These functions provide the ability to etch larger designs and increase process consistency and repeatability. Given the size of the projector and optical assembly, moving the substrate is significantly simpler. This project uses a precision XYZ stage driven by brushless DC motors each of which are mounted to the XYZ stage's micrometer heads via 3D printed components included in Appendix C. Each of the brushless DC motors are controlled via an Arduino Uno with a CNC shield. The photoresist-coated substrate is secured with a 3D printed vacuum chuck, mounted to the XYZ stage. The vacuum chuck design is included in Appendix D.

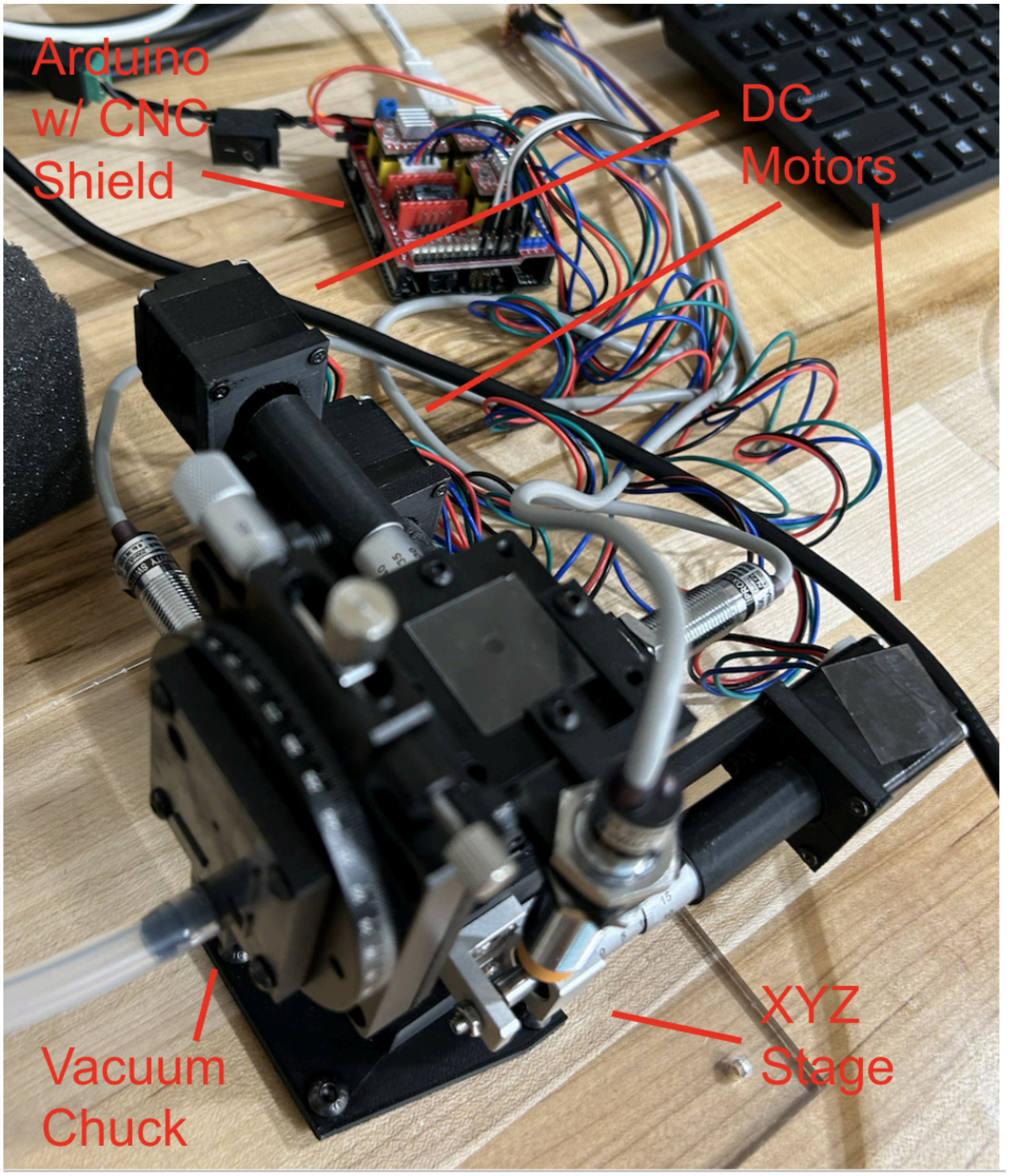

Figure 6. Assembled XYZ stage.

Each of the aforementioned components was mounted on an acrylic plate to provide stable integration. The completed photolithography stepper is shown in Figure 7.

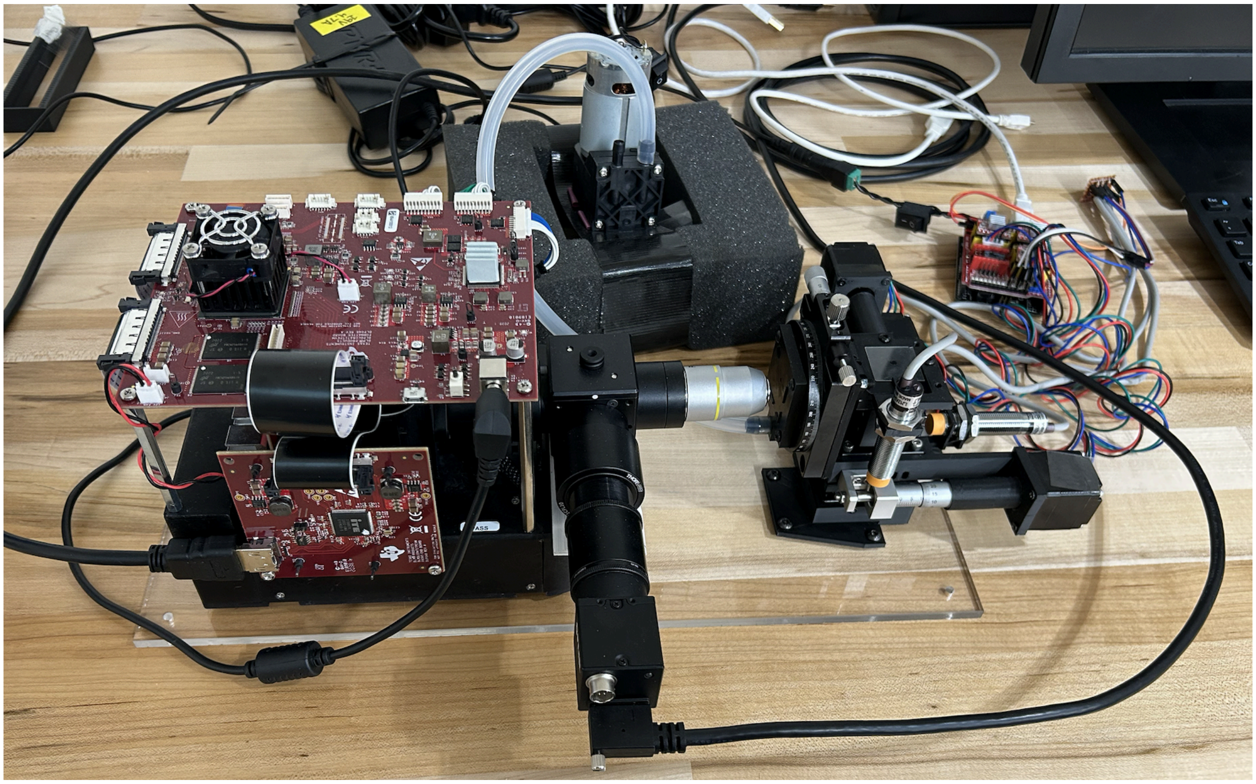

Figure 7. Complete photolithography stepper assembly.

With the physical components of the photolithography stepper assembled, it's necessary to create a custom software to interface with the projector, c-mount camera, and Arduino. The vacuum pump, however, is manually operated via a switch since it is only necessary to ensure proper substrate alignment. Luckily, this project was able to build off of the software already written by the HackerFab team at Carnegie Mellon University[1]. The only necessary components for the software are: interfacing with the c-mount camera and providing a view for focusing, interfacing with and controlling the XYZ stage, thereby allowing consistent and precise focusing and tiling, and finally, interfacing with the projector, allowing users to etch a custom pattern. In addition to the bare-bones software required to operate this device, this project also provided functionality to: automatically focus the camera view using a reference image, invert patterns for quick iterations, tile multiple etches together and view a grid of said in-session etches, automate exposure timing, zoom in on camera view, and various other quality-of-life improvements. A screenshot of the software is shown in Figure 8. Source code for our software can be found in Appendix D.

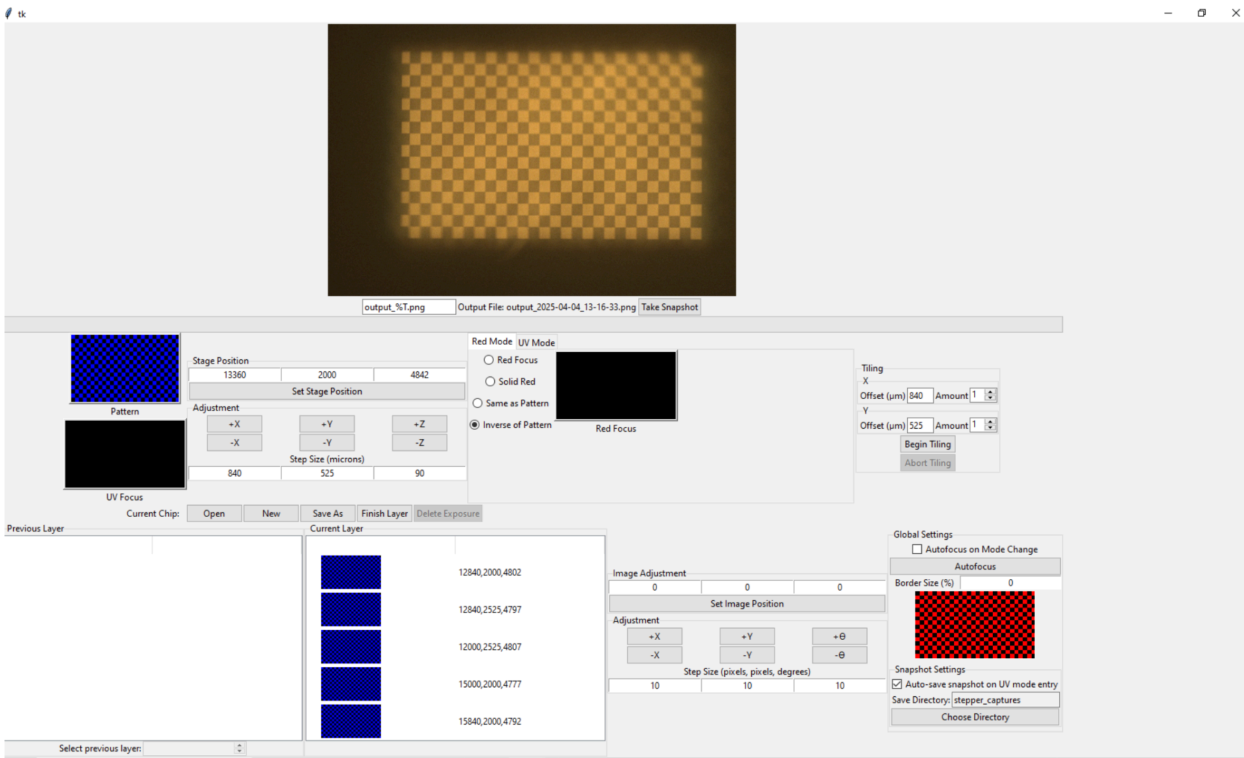

Figure 8. Photolithography stepper software.

The photolithography stepper and software detailed herein is sufficient for some level of precision etching, but utmost process consistency was necessary to reach this project's precision goals. As such, it was necessary to ensure consistent film thickness across etches. This project addressed this goal by building a spin coater. Spinning a photoresist-coated substrate to a consistent speed ensures repeatable film thicknesses. The core functionality of our spin coater utilizes a hard drive with a brushless DC motor and a custom substrate mount, a variable speed controller, an Arduino Mega, and a Hall effect sensor to monitor the RPM of the spin coater. This project's spin coater also included an LCD screen, keypad, potentiometer dial, and 3D printed cover to enhance user experience, although they were not strictly necessary. The completed spin coater is shown in Figure 9.

Figure 9. Spin coater.

The final piece of required apparatus is a PC computer with a keyboard, mouse, HDMI port, and at least two USB ports.

Procedures

This project's goals were to create a photolithography stepper, achieve etch precision of 10 micrometers, and to create training and troubleshooting materials for the photolithography stepper. As such, the experimentation necessary to prove successful completion of each goal is minimal. To prove successful completion of the first goal, creating a photolithography stepper, this project has outlined steps for operation of the photolithography stepper. These instructions also cover the third goal, create training and troubleshooting materials, which will be verified by asking an inexperienced student to follow the instructions and perform a successful etch.

Photolithography Stepper Operation

In ensuring successful operation of the photolithography stepper, this project developed a procedure for its operation. That procedure is detailed below. It is important that the procedure be followed closely. As such, **please read through these instructions before you begin.**

A labeled photo of the completed photolithography stepper is included for reference in Figure 10 below.

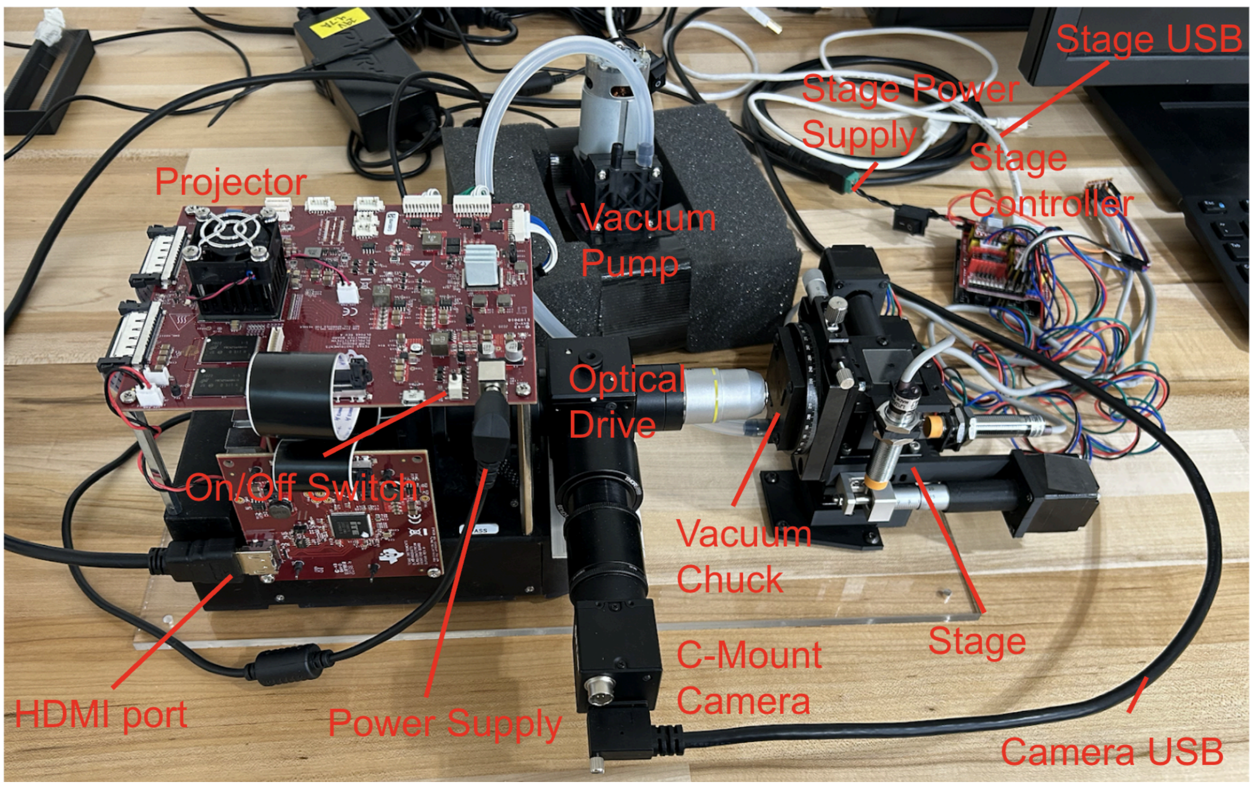

Figure 10. Labeled Photolithography Stepper

1. Start up the projector, stage, camera, and software:
    a. Power on the PC and log in:
        i. Username: "admin"
        ii. Password: "Password"

b. Ensure the projector, stage controller, and vacuum pump power supplies are plugged into the power strip and that the power strip is turned on.
c. Plug the projector's HDMI cord into the computer, but do not yet plug it into the projector.
d. Plug the USBs corresponding to the arduino (stage) and c-mount camera into the computer you intend to run your software on.
e. The projector should be pushed flush against the 3 bolts on the base plate to make sure it is in alignment.
f. Once the software is started, turn the projector on by flipping the switch at the top of the projector as shown in Figure 11 which shows the switch in the, "on" position. A light should appear on the surface of the vacuum chuck.
    i. If the light does not appear, power off the projector, turn off the power strip it is plugged into, then AFTER waiting for the light on the power supply to fade unplug the power supply from the strip and projector. Replug everything in and try again.

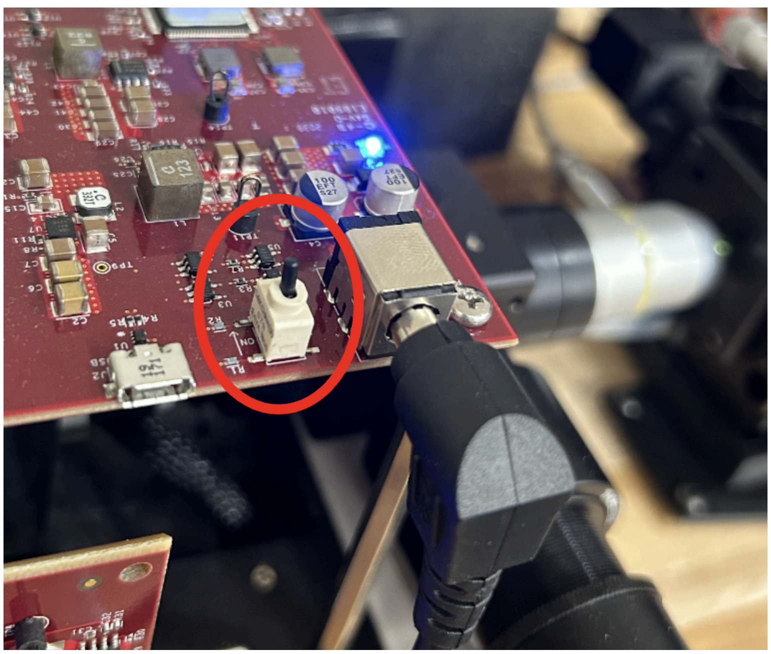

Figure 11. Projector power switch in "on" position

g. Finally, plug the HDMI cord into the projector. The board on the side of the projector has a blue light that should come on. It might blink for a second before going solid blue indicating that the hdmi connection is good. When this happens the light on the surface of the vacuum chuck will dim and the projector will now act like a second monitor of the computer.

i. If this does not happen, follow the above instructions for restarting the projector but unplug the hdmi cord from the computer and projector before plugging everything back in and restarting the procedure.

h. Start the software by double-clicking the “Lithostepper” icon on the PC’s desktop. The running software should look like the screenshot shown in Figure 12.

i. Once the software is started, select the projector window (this may be easier to find if you select the solid red toggle)

ii. With the projector window selected, input: Windows+Shift+Left Arrow to move the red screen to the projector.

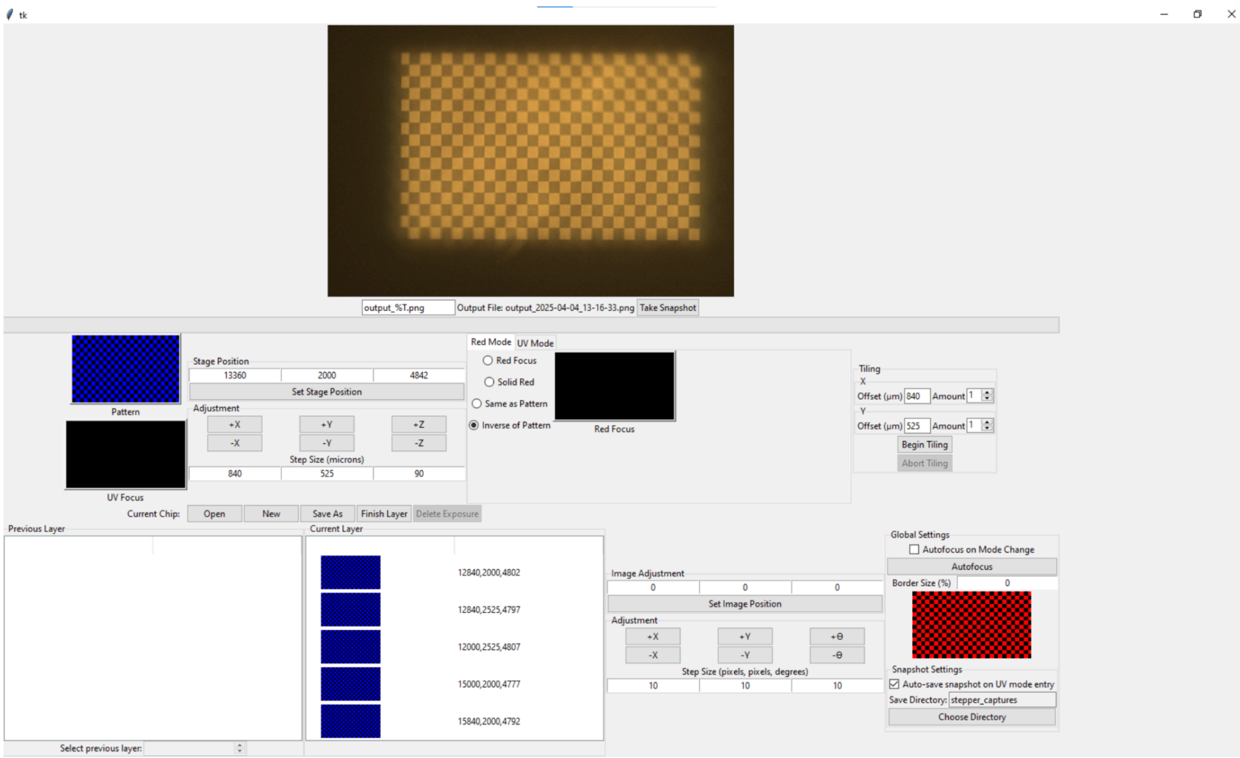

Figure 12: Photolithography Stepper GUI

2. With all components powered up, you can begin preparation of your photoresist coated substrate:

a. Ensure that the spin coater is plugged into the power strip.

b. Double check that the reservoir surrounding the center is not filled with resin. **DO NOT PROCEED IF IT IS FILLED WITH RESIN**

i. If it is filled with resin, please clean with paper towels and isopropyl alcohol or another suitable solvent. Be sure to properly dispose of unwanted materials. The reservoir lifts out although is a tight fit and typically must be rotated as it’s pulled up to free it. When placing it back in, ensure the cutout on the bottom of the reservoir is lined up with the sensor sticking up.

c. After ensuring a clean catch reservoir, place a glass microscope slide cover in the spin coater making sure it is seated down into the holder on all 4 corners.
d. Place 5-7 drops of your photoresist on the substrate using a pipette. This project validated functionality using 3D printable UV-cure resin.
e. Close the spin coater's acrylic lid.

Figure 13. 3D printer UV Resin

f. Bring your spin coater up to the desired spin speed. Higher spin speeds result in thinner film thickness and greater etch precision, but greater risk of an unsuccessful etch. This project uses 2000 rpm for the most consistent results.
    i. Select option A: "Manual Speed" using the "A" button on the spin coater's keypad
    ii. Adjust the dial until the screen displays your desired spin speed.
        1. The spin coater will let you set the rpm below 2000, but it might begin to start and stop. The working range for it is 2000-10000 RPM.
    iii. Press the red button in the bottom right corner of the spin coater labeled, "Touch" to begin the spin coat
g. Once the screen displays that your substrate is spinning at the desired speed, press the keypad button labeled with an asterisk (*) to stop the spin coater.
h. Wait for the spin coater to come to a complete stop before opening the acrylic lid.
i. Remove the photoresist-coated substrate from the spin coater using tweezers.

3. Engage the vacuum pump and place the photoresist-coated substrate onto the vacuum chuck making sure the resist coated side faces away from the vacuum chuck. The corner should be aligned with the guide corner shown below in Figure 14.

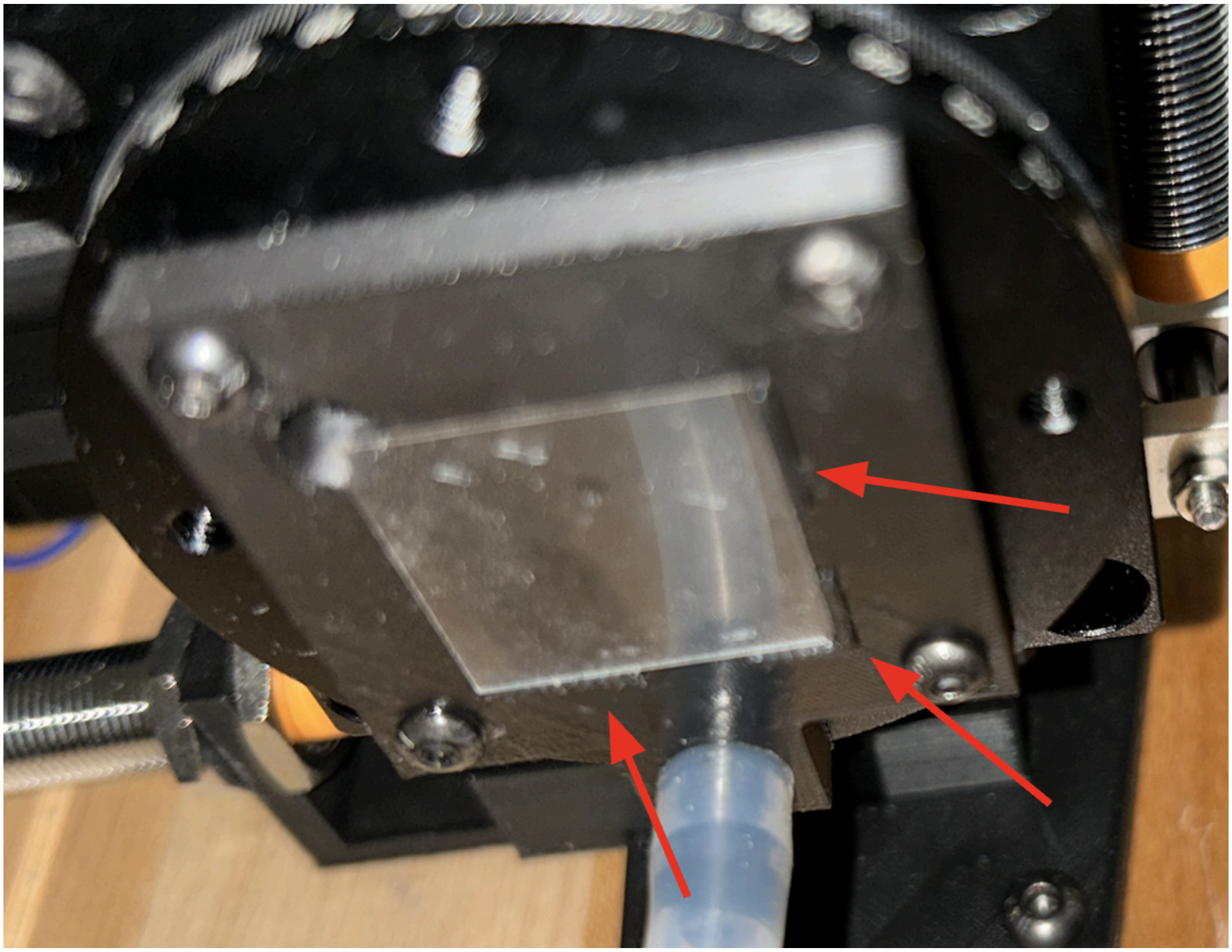

Figure 14. Vacuum chuck guidelines

4. Once seated into the corner, disengage the vacuum pump to reduce outside disturbances.
5. Return to the software and open your desired pattern by clicking the thumbnail image of your pattern shown in Figure 15 and selecting your desired pattern from the file navigator. Ensure that the pattern is in PNG format and only contains black and white or blue and black. Also ensure that you have selected the tab labeled "Red Mode" as shown in Figure 16.

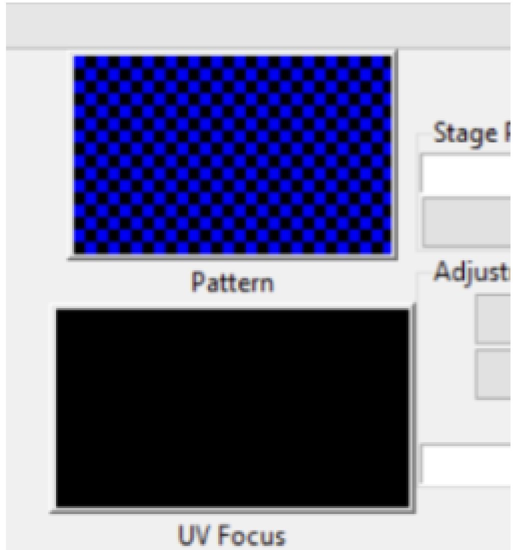

Figure 15. Pattern Thumbnail

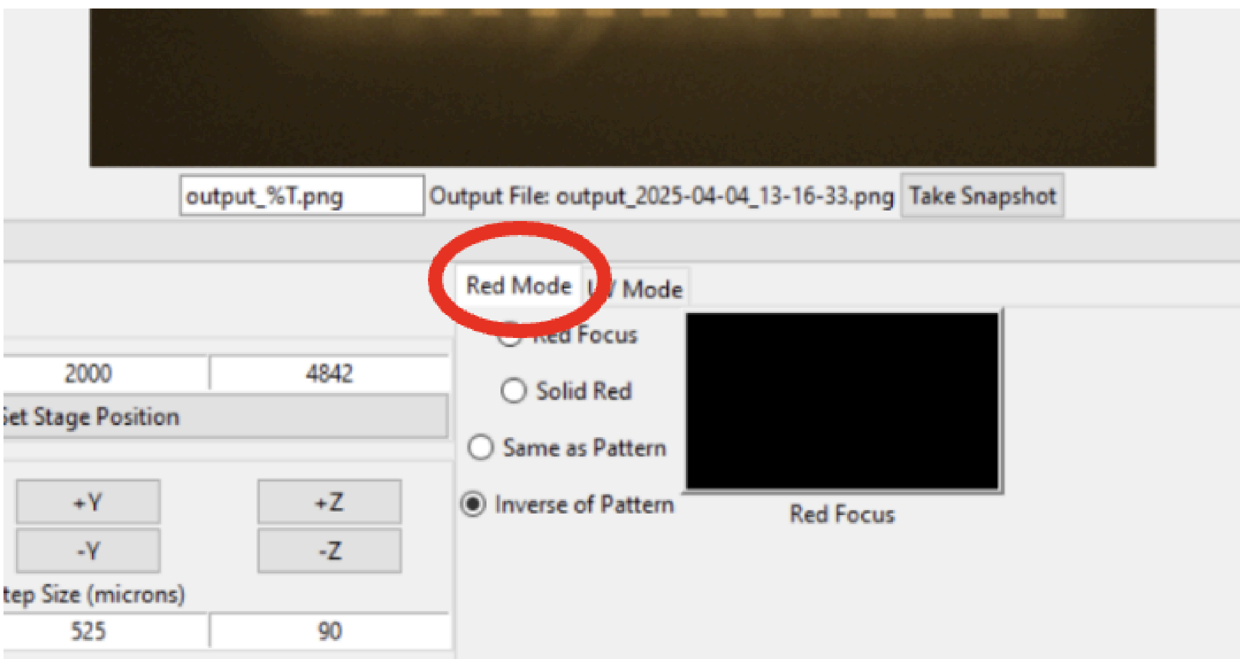

Figure 16. Red mode tab

6. Move the XYZ stage away from the substrate using the controls shown in Figure 17. **Ensure that the substrate is slightly further than the furthest point that the pattern shown on the display is in focus.** Since the substrate and photoresist are near-transparent, it is possible for the display to come into focus at three points: the surface of the photoresist, the surface of the glass slide, and the surface of the vacuum chuck. Beginning beyond the furthest focus point ensures that automatic focusing focuses to the surface of the resin, ensuring maximum etch precision. **Also take this chance to**

double check that the pattern is still being projected where you want it on the substrate.

a. The X direction moves horizontally and perpendicular to the path of the projector.
b. The Y direction moves up and down.
c. The Z direction moves parallel to the path of the projector.

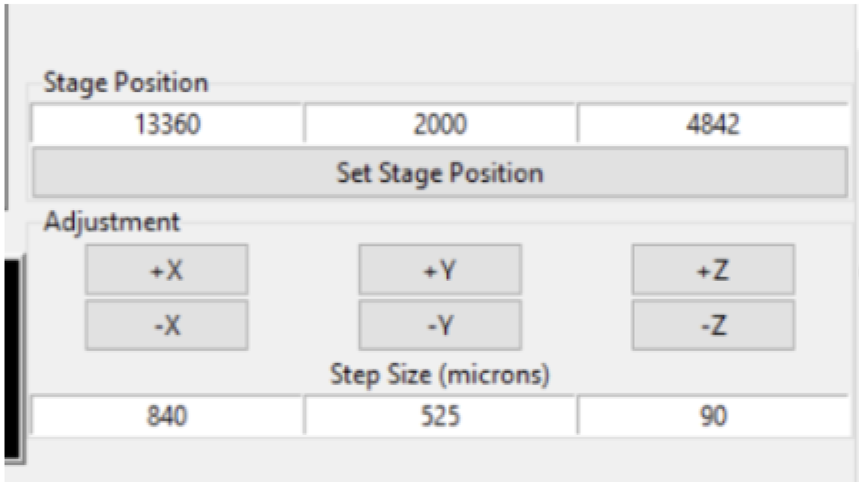

Figure 17. Stage controls

7. With your desired pattern selected, and the display showing just outside of focus, press the "Autofocus" button in the bottom right. The stage will attempt to focus the image on its own. **Please double check that you are happy with the focus as shown in the display before proceeding.** If not, try again until the edges of the projected pattern are crisp.
8. Now that the picture is in focus, you can begin the etching process.
    a. Select the "UV Mode" tab next to the "Red Mode" tab shown in Figure 16. The program is shown in UV mode in Figure 18 below.

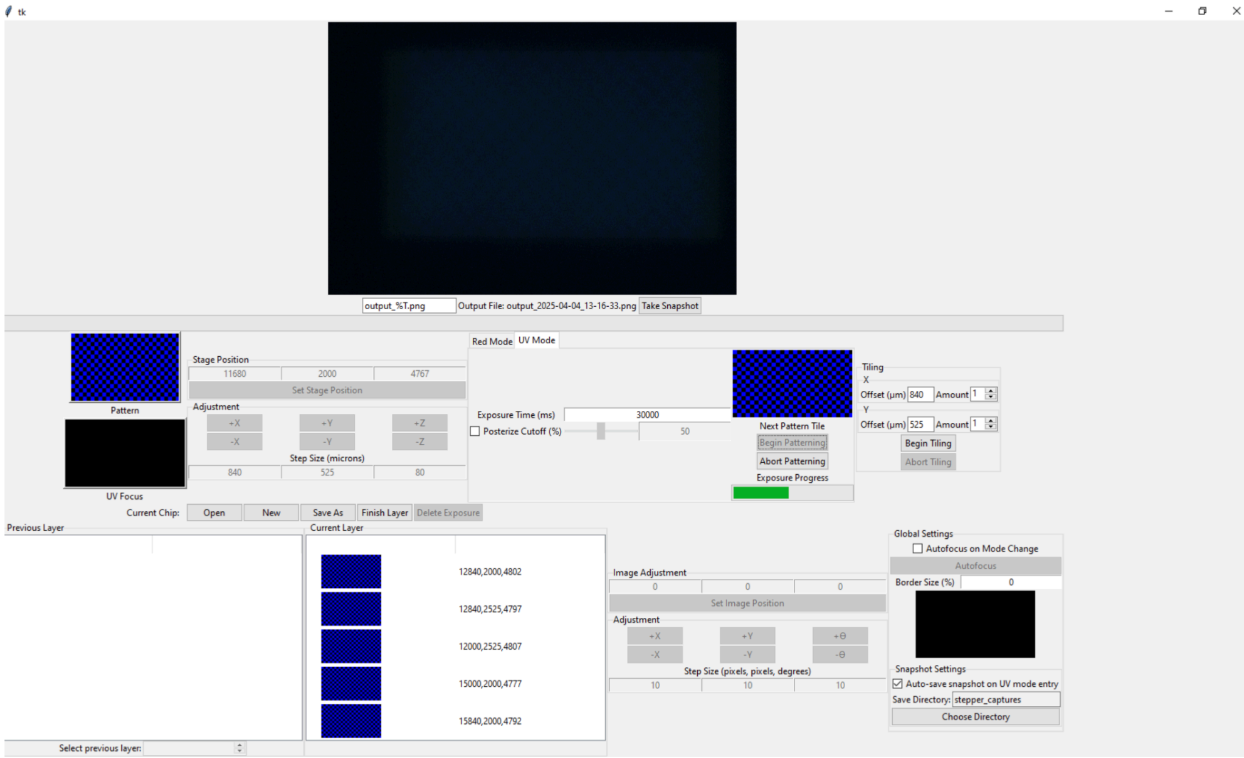

Figure 18. UV Mode

   b. Fill out your desired exposure time in milliseconds. This project routinely uses 30000 ms (30 seconds) for consistent results.
   c. Press the "Begin Patterning" button and follow the exposure progress.
   d. Once the exposure is finished, you can repeat these steps in another location to create a larger pattern or move on to the next steps to clean your etch.

9. Remove your substrate from the vacuum chuck with tweezers and give your substrate a vigorous shower with isopropanol or another suitable solvent until you have removed all of the excess photoresist.
10. Either blow your substrate dry with compressed air, or wait for it to air dry. **Do not attempt to rub, pat, or otherwise disturb the etched resin.**
11. Congratulations! You have successfully patterned! Now you can admire your creation under an optical or scanning electron microscope.

Precision

To ensure that this project's precision goal was met, several etched samples were analyzed under a scanning electron microscope. The scanning electron microscope can effectively measure objects at micron-scale. As with any experiment, multiple trials were performed to ensure process consistency and data validity.

Results & Discussion:

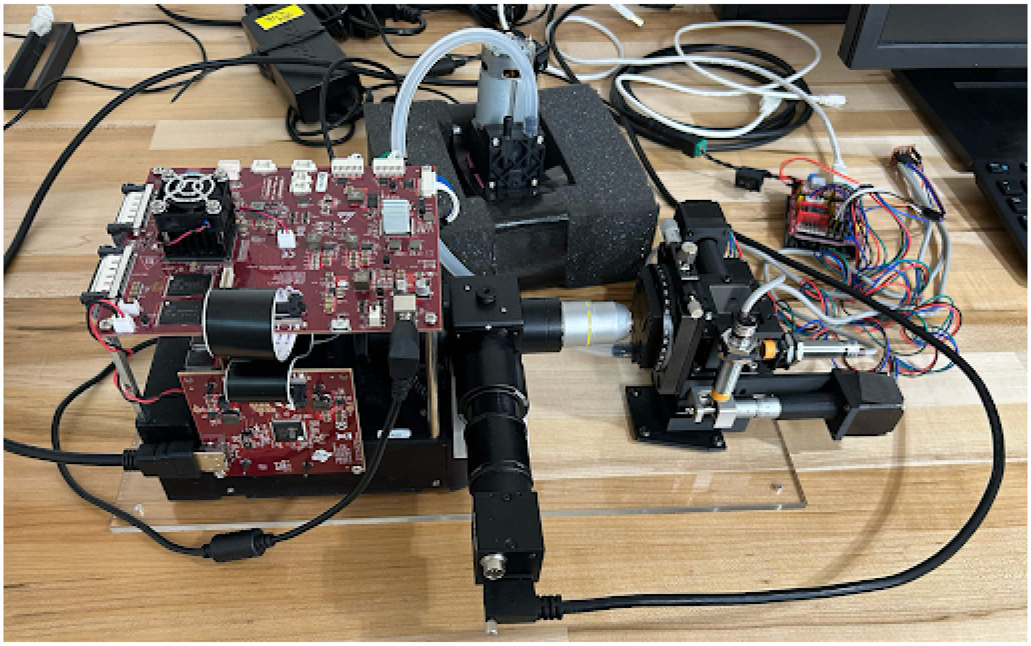

Figure 19. Completed Lithostepper

The work has resulted in the completed stepper shown in Figure 19. Comparing it to Figure 2, the individual parts can be determined from left to right: modified projector, custom beamsplitter / magnifier optics, and XYZ stage. Because of the lab we this work was accomplished in, photoresist would have been a hassle to work with so our group decided to proof the device using a less toxic chemical and turned to UV curable 3D printer resin cured onto glass slides, specifically Anycubic Standard Black Resin V2. This selection was made based on the sensitivity of the resin to the wavelength produced by our device, as well as the ability to work with it outside of a fume hood. Note however, that this selection of resin instead of a traditional photoresist significantly limited our ability to resolve fine details and patterns.

Our procedure resulted from much trial and error and is thus included in discussion of results rather than methods, noting that room remains for improvement. The procedure with this resin involved a 2000 RPM spin coat to get a roughly 50 μm film thickness, followed by a 30 second etch time for each pattern. Finally, once exposed, the uncured resin was washed away using isopropanol leaving behind the pattern we exposed. In essence the resin in this process acts as a negative photoresist.

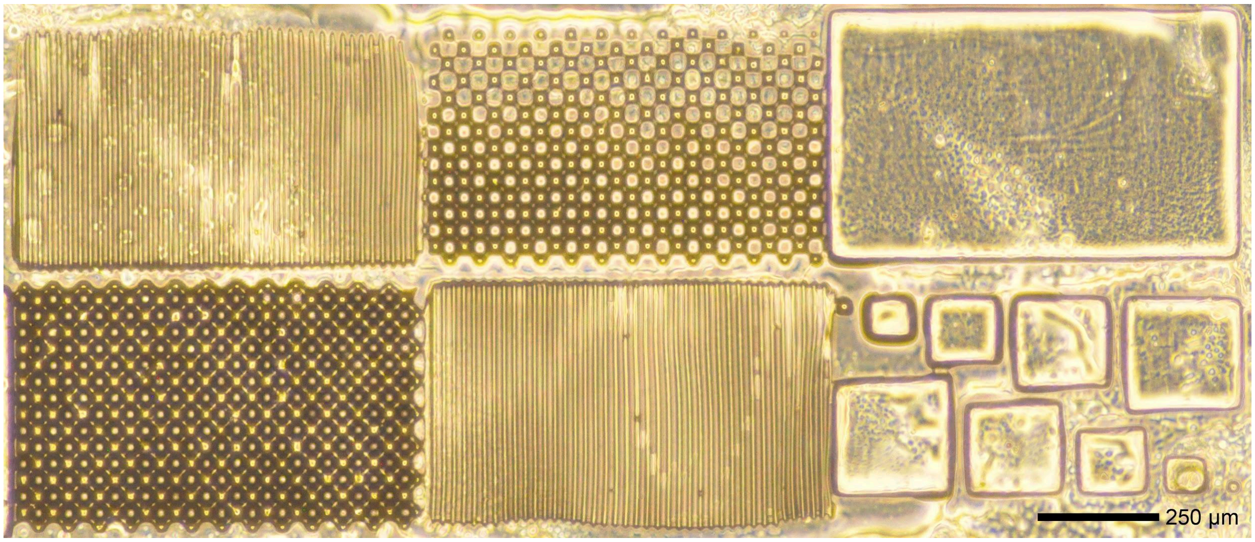

Figure 20. A multi pattern etch showing off the pattern changing and tiling functions

Patterns from a successful etch can be viewed under visual microscopy or scanning electron microscopy (SEM.) An example etch of multiple patterns tiled across the surface can be seen in Figure 20. By using the known distance between etches, the XYZ stage positioning is accurate to a few micrometers. ImageJ software can use this scale and digitally convert from pixels to μm. This yields an exposure size of roughly 840 x 525 μm.

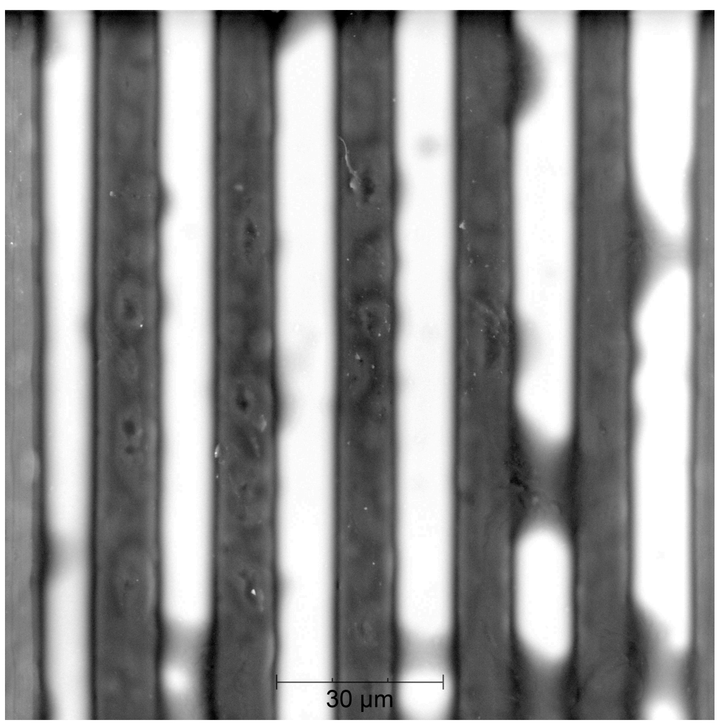

Figure 21. Fine line exposure under BSD SEM

A close up view of the fine line exposure from Figure 20 can be viewed in SEM to determine a better understanding of etch quality. Shown in Figure 21 is the backscattering detection (BSD) mode of the SEM with a scale bar demonstrating somewhat consistent line exposure size as small as 10 μm. Inconsistency arose with the washing or exposure process at some point resulting in the channels between exposed lines not always being clear of uncured resin as can be seen in the channels particularly on the right of this pattern.

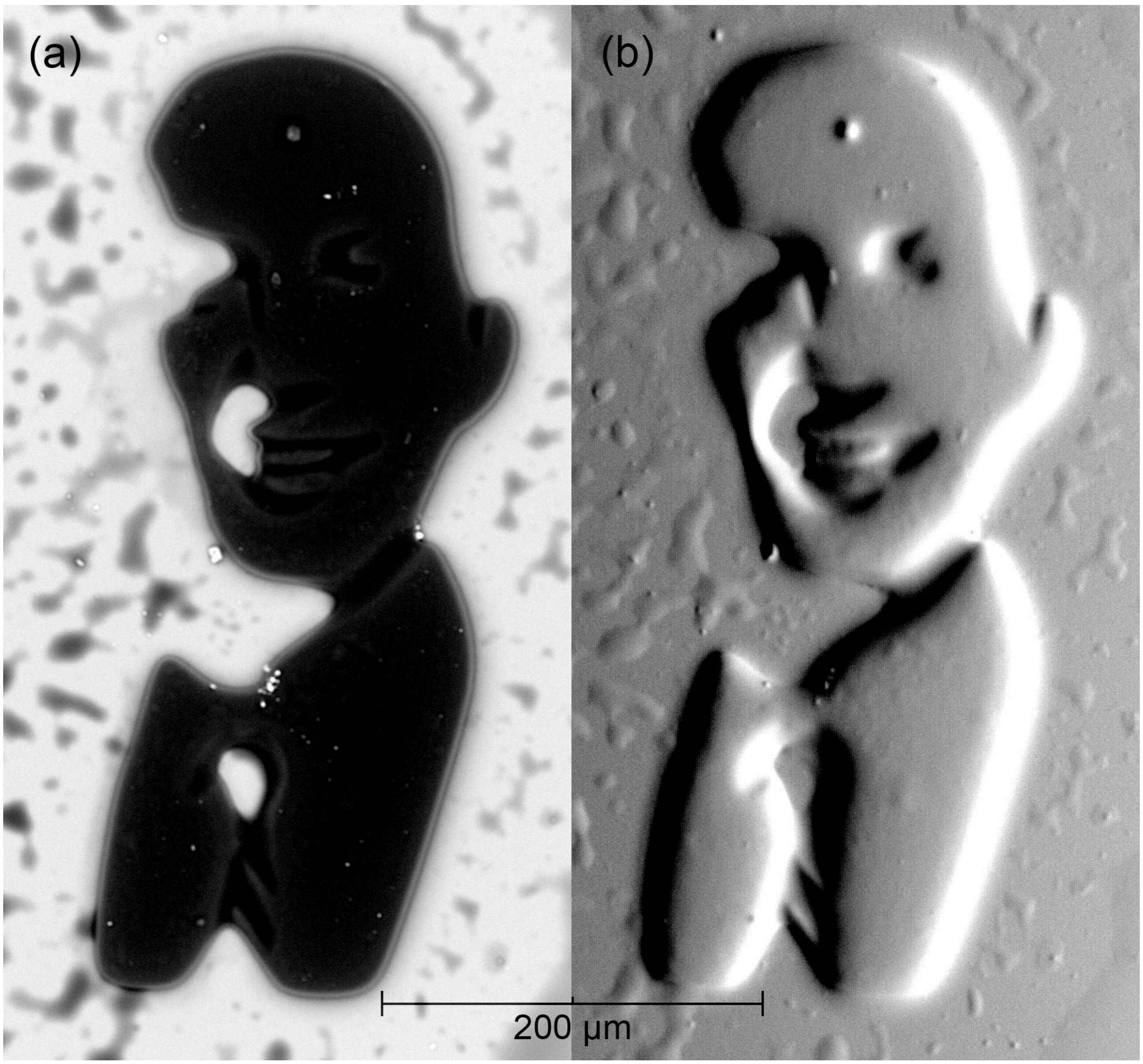

Figure 22. Wide profile of Dr. Tony Butterfield

To further demonstrate the variety of pattern and potential resolution, we etched Figure 22. This etch showcases a profile of one of the advisors for this project, Dr. Anthony Butterfield. Note that the visible stripes on his tie lie just below that 10μm range. The topographical view in Figure

22.b provides a more clear picture of the actual resin shape on the surface with the illumination coming from the right of the image casting shadows to the left.

Conclusion:

The results of this project demonstrate that the developed lithostepper is capable of producing micro-scale features with a practical resolution approaching $10\mu m$. While this falls short of the theoretical diffraction-limited resolution of approximately $1\mu m$ estimated via Rayleigh's criterion as shown in Figure 23, the discrepancy can be attributed to a combination of material, optical, and process limitations inherent in the current system configuration.

$$CD = k_1 \frac{\lambda}{NA}$$

$$CD = 0.61 \frac{410\,nm}{0.25}$$

$$CD = 1000.4\,nm \simeq 1\mu m$$

Figure 23. Rayleigh's Criterion Calculation

Nevertheless, the device successfully demonstrated critical photolithographic functions: dynamic pattern exposure via DMD projection, micron-scale alignment accuracy, and reproducible spin-coated layers. Multi-pattern tiling and recognizable etch structures illustrate the flexibility and creative control afforded by the system. ImageJ and SEM-based analysis confirmed repeatable feature sizes down to $10\mu m$, validating the core design and integration of optics, mechanical stages, and custom software.

The development of this low-cost, maskless photolithography stepper has broader implications that extend well beyond the immediate technical scope of the project. Most notably, it underscores the potential and trend towards democratizing access to microfabrication tools, enabling hands-on experimentation and innovation in environments traditionally excluded from semiconductor research. High-end photolithography tools are often centralized in national laboratories, elite research institutions, or multi-billion-dollar foundries. This consolidation creates a significant accessibility gap, especially for small startups, independent researchers, and educational institutions without cleanroom infrastructure. By contrast, the system developed here offers an alternative: a platform that, while modest in cost, provides a hands-on gateway into the world of optics, lithography, patterning, and MEMS fabrication.

In educational settings, the device offers an opportunity to bridge the divide between theory and practice. Concepts such as diffraction limits, resist chemistry, image alignment, and optical focusing that are often taught abstractly, become tangible and experiment-driven. With its live camera feedback, modular stage control, and visible results under basic microscopy, the stepper facilitates a level of engagement and understanding that is difficult to achieve through textbooks or simulations alone.

Beyond the classroom, the system holds value for early-stage hardware prototyping and interdisciplinary research, especially in fields like microfluidics, MEMS, photonics, and lab-on-a-chip development. The ability to quickly pattern, modify, and re-pattern designs without photomasks significantly reduces iteration time, encouraging exploration of novel structures and process workflows with in-house accessible tools. This kind of agility is essential for applications at the intersection of materials science, chemistry, biology, and electrical engineering—fields increasingly reliant on rapid, micro-scale fabrication.

Overall, the results validate the system as a low-cost, flexible microfabrication tool with adequate capability for education and real-world manufacturing.

Recommendations:

This project recommends the following for improving this photolithography stepper into the sub-5 micron resolution regime.

First, a key factor influencing the practical resolution was the choice of UV-curable 3D printer resin, specifically Anycubic Standard Black Resin V2 as a substitute for traditional photoresist. While this resin offered a safer, fume-hood-free workflow and strong responsiveness to the 410 nm light source, its lower contrast, limited resolution, and development behavior introduced patterning artifacts that reduced feature fidelity and resolution. Similar systems built by other collaborators using the same HackerFab Lithostepper V2 architecture—paired with traditional photoresist on silicon substrates—have demonstrated feature sizes in the 3–4μm range. These results, more closely aligned with Rayleigh's theoretical limit, suggest that the hardware platform is fundamentally capable of finer resolution.

This project also recommends improvement to the mechanical positioning system. While the XYZ stage performed adequately for controlled motion and repeatable tiling, its DIY motorization introduces alignment challenges and stage drift. Backlash, stepper motor vibrations, and thermal expansion effects can affect repeatability and long-term stability, especially during multi-layer alignment. Further precision could be achieved with higher-cost positioning options.

Additionally, several practical limitations emerged in this project's low-cost optical system. The use of off-the-shelf lenses and mounts, though cost-effective, introduces potential for aberrations and misalignment, our device even requiring a shim to ensure alignment. Achieving and maintaining sharp focus across the entire field of view requires meticulous manual adjustment, and the current setup could benefit from improved z-axis focusing and real-time correction. Moreover, the system's current numerical aperture (NA) is limited by the choice of a 10x microscope objective, constraining its theoretical resolution despite the 410 nm light source.

On the software side, limitations arise from the use of proprietary components. The camera integration relies on Teledyne's Spinnaker SDK, which is not open-source and complicates deployment across different platforms or institutions as code written to interface with it cannot be freely distributed. The HackerFab is currently switching to a camera with an open-source API. Additionally, while the current software provides core functionality such as pattern loading, focus scoring, and exposure control, it lacks advanced features like automated overlay registration, adaptive exposure calibration, or real-time image analysis—features that would significantly improve usability for multilayer or high-precision work.

Finally, environmental conditions and lab infrastructure play a non-negligible role. Operating the device in a non-cleanroom setting increases the risk of particulate contamination, inconsistent film deposition, and optical misalignment. These factors, while manageable, introduce noise and variability that must be accounted for in both experimental design and interpretation of results.

Collectively, these limitations highlight areas for improvement in both hardware and process development. However, many of these challenges are not fundamental to the system architecture and can be addressed incrementally through improved materials, mechanical upgrades, and software enhancements, several of which are already underway in parallel HackerFab implementations. While the device has demonstrated substantial promise as a low-cost, maskless photolithography tool, several clear paths exist for future improvements that could dramatically enhance its usability, precision, and overall performance.

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Appendix

A) Complete list of optical components

ThorLabs Part Number:	Description:	Quantity:
SM1A3	Threaded adaptor	1
SM1V10	Adjustable lens tube	1
SM1L10	Lens tube	2
SM1RC/M	Slip ring	2
SM1A9	C-mount adaptor	1
SM1L05	Lens tube	2
CM1-DCH/M	Dichroic filter mount	1
SM1CPL05	Tube coupler	1
SM1L03	Lens tube	3
SM1V05	Adjustable lens tube	1
SM1A53	Nosepiece flange	1
SM1CPL10	Sleeve coupler	1
BSN10R	Beam splitter (dichroic mirror)	1
SM1CP2	End cap	1
AmScope Part Number:	Description:	Quantity:
A10X	Microscope objective	1

B) Complete list of 3D Printed Parts

Part:	Files:
Spin Coater Housing	https://cad.onshape.com/documents/801fa20a4742060c6a7b958b/w/a20a85ffa014883938874be2/e/f83a4cddca90cd46f181cc5a
Spin Coater Gravity Chuck	
Spin Coater Vase	
X/Y/Z Stage Motor Mounts	https://cad.onshape.com/documents/0649d732771a63bcb8e6be1d/w/408d85c155072764ebeaefad/e/301b112b8d29652692865df3
X/Y/Z Stage Sensor Mounts	
X/Y/Z Couplers + Z Key	
90° Theta stage mount	
Vacuum Chuck	https://cad.onshape.com/documents/ef57f8dfa673959417d49ce0/w/63f6ceac85cd7018ae3e2cf6/e/0b4a3cdcf89f0a85155a7992
Optics to Projector Mounting Plate	https://cad.onshape.com/documents/64016e74334e9df7f3829a37/w/da5b11336b83f611c84f6d9f/e/6aae798fd8c31fe1bc320fe1

C) Complete list of laser cut parts

Part:	Files:
Acrylic Base Plate	https://cad.onshape.com/documents/052936cc5219e79ce8b1d191/w/decf2990870bd6e2bca78fa2/e/bd3bd601a477f0977cdc93cc

D) Other Parts

Part:	Description:	Quantity:
TI DLP Evaluation Module	Projector	1
FLIR Blackfly S Camera w/ Sony IMX183	C-Mount Camera	1

Arduino Uno (Elegoo)	Stage Controller	1
CNC Shield for Arduino V3.0	Stage Controller Peripheral	1
Stepper Motor Drivers	Motor drivers for stage control	1
NEMA 28 Steppers	Motors for stage control	4