BIOMEMS Photomask Aligner

Final Report

Biomedical Engineering Design 200/300
Lab 306
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Abstract

Biomedical Microelectromechanical Systems (BioMEMS) are biomedical devices with components generally measuring less than 100 µm. They are often used to study interactions such as cell activity monitoring or biocompatibility testing. These devices are created using photolithography to transfer an image onto a photoresist substrate that can be cross linked with UV light. Consecutive layers of photoresist are added to create a three dimensional structure, and a typical device has three layers. When creating a new layer, the image mask must be precisely aligned with the layer underneath. There are many high fidelity aligners on the market, however these are extremely expensive and impractical for an educational setting. 4 cost efficient designs for alternative aligners have been proposed and evaluated. Based on the evaluations, a final design has been chosen for prototyping and testing.

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Introduction and Background

Motivation

The design project client and his students are having difficulty correctly aligning multiple layers which has inspired the client to request a photomask alignment device. This is an aligner that, theoretically, would be able to accurately align masks within a range of 10 to 100 µm. Currently, manual alignment by the eye through a microscope is accurate in the range of 200 to 300 µm. This difference in accuracy can cause misalignment and discrepancies in the three-dimensional structure created by photolithography. This would then cause the client, or his students, to restart the mask alignment process from the very beginning. A more accurate alignment method/device would minimize material waste and reduce the manufacturing time of the three-layer stack. In the realm of biomedical engineering, the development of low-cost and accessible technologies play a pivotal role in advancing research and applications. The introduction of a low-cost BioMEMS photomask aligner is of paramount importance as it addresses the critical need for affordable tools in the fabrication of microelectromechanical systems (MEMS) for biomedical applications.

Current Devices

There are currently multiple methods of aligning photomasks for BioMEMS purposes. The first method is with the assistance of an electronic aligner. The EVG®610 Mask Alignment System is an example of a compact and multipurpose R&D system that provides an accuracy of around 0.5 µm[1]. Electronic aligners such as this are very accurate, however, they are very costly: a used EVG aligner can cost over $40,000. The benefits of this method include high resolution and accuracy as well as versatility since most digital aligners can accept wafers sizes up to 200 mm. Dr. Justin Williams at The University of Wisconsin–Madison uses a simpler machine as a more cost-efficient alternative. The system used by Dr. Williams utilizes manual alignment techniques such as gears and old microscope parts. The photomasks are taped to a piece of glass that separates the UV light source from the wafer [2]. The UV light is mounted directly to the frame of the aligner. The glass then sits on the microscope stage and can be adjusted with the knobs located on the side of the device. Undesirable gear ratios and poor resolution associated with the microscope eyepieces provide an accuracy of 50-200 µm. The final alignment technique is another manual alignment technique in which everything is aligned by eye. Professor John Puccinelli, also from the University of Wisconsin – Madison designs his photomasks in a CAD program, creating alignment marks on each mask. He then uses a microscope to try to align the marks of each of the masks [3]. As can be expected, accuracy is by far the worst for this method providing around 200-300 µm of accuracy.

Problem Statement

Manual alignment of photomasks provides a layering accuracy of 200-300µm. The current process leads to discrepancies in the three-dimensional structure created by photolithography. This leads to a waste of fabrication material, loss of time, and having to restart the alignment process. A more accurate way to align photomasks is needed for scenarios like these. The design should be easily usable by biomedical engineering students, be significantly lower in cost (<$100), extremely repeatable and easy to construct with minimal tooling, and be precise in accuracy (10-100µm).

BioMEMS

Biomedical/Biological Microelectromechanical Systems (BioMEMS) is the science of nanodevices in the fields of biology and medicine. There have been many new applications of this technology in recent years ranging from new drug delivery techniques as well as implanted devices for medical monitoring [4]. In the scope of this project, the aligner will be used to create a microfluidic photoresist device that is helpful when studying cell cultures, biochemical assays, as well as many other research applications. A process called photolithography, which involves shining UV light through a photocurable epoxy is used when creating the photoresist layers.

Research Required to Build Prototype

1. Photolithography

In the project, photolithography is used to create a multilayer system. The photolithography process starts with spinning a layer of SU-8 photoresist onto a silicon wafer. After this, the wafer must be soft-baked to slightly harden the photoresist. After this, one must align the photomask over the wafer and then shine UV light through the photomask to transfer a pattern on the photoresist. The lab the client envisions this device for uses the OmniCure S1500 to cure the photoresist [5]. Then, one repeats the process of spinning on the photoresist and curing patterns onto the wafer as many times as necessary. In the client's lab, the spin coater is an SCS P-6708 that can spin up to an 8-inch wafer at a range of 100-8000 rpm [6]. For this device, the client requested an aligner that can align up to 4 layers with varying sizes of silicon wafers. After the UV curing process is finished, then one hard bakes the layers and fully hardens the photoresist and cements it onto the wafer. Within the multilayer photolithography process, the alignment of the photomasks on the silicon wafers is a critical step to ensure the accuracy of the device, this is because the patterns must overlap perfectly or with very little error in order for the final product to function correctly.

2. Current Laser Cutting / Printing / Fabrication Techniques

Photomasks are produced using high-resolution printers and are typically outsourced. However, most alignment methods do not specify a standardized technique for cutting the photomask from the transparency. In the context of this project, there is a strong focus on exploring the use of a laser printer/cutter. The UW-Madison BME Department possesses a

40-Watt Epilog industrial printer that offers precise resolution control ranging from 75 to 1200 dpi, equivalent to a maximum resolution of 21 microns [7]. Utilizing this laser cutter to create specific geometries on the photomask transparency allows for precise control over the geometry, which is crucial for the alignment technique. Furthermore, the Maker Space at UW-Madison is a collaborative and creative space that provides access to various tools, equipment, and resources for students and faculty to engage in hands-on projects, prototyping, and experimentation [8]. This area offers 3D printers, laser cutters, woodworking tools, electronics, and other equipment to support a wide range of engineering design projects, which will be of practical use in this design project.

Client information

Dr. John Puccinelli is a faculty member within the department of Biomedical Engineering at the University of Wisconsin-Madison. He leads the BME Design curriculum and is also involved in the Biomedical Engineering teaching lab where he teaches with a hands-on approach in the fields of biomaterials as well as cell/tissue engineering. He is interested in the team creating this photomask aligner for use in the Biomedical Engineering teaching lab.

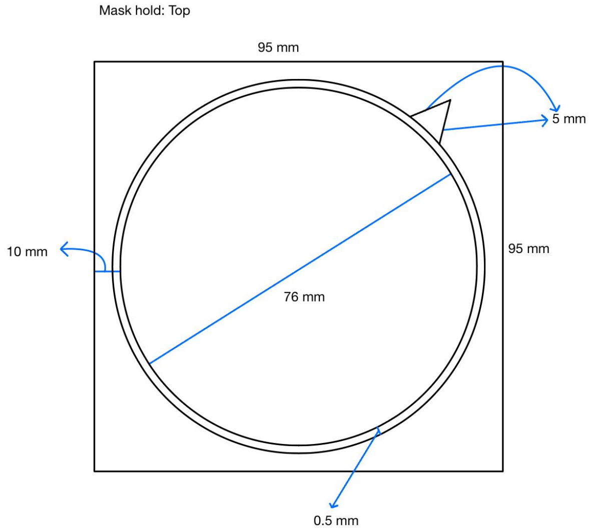
Design Specifications

The client is requesting a budget of less than $100 for the production of the device. The client is looking for accuracy in the range of 10-100 μm when aligning the photomasks and the photomasks should be 10 μm above the photoresist during the UV light step. The design needs to be able to be scaled for wafer sizes of 3”, 4”, and 6”. The device is being created for a teaching lab so it must be easy to use as well as reproducible. There are no critical size or weight concerns but it will likely be used under a fume hood due to the SU-8 photoresist being used in the process [9]. It must fit under the fume hood and function properly in that environment. The product should be designed to last at least 10 years in service, it will be used in a lab environment but it will not need to be stored or used in a sterile environment. The goal is to produce one product as well as a set of instructions outlining how to recreate the process/properly the our device. Additionally, the team will be creating a stamp that allows for a user to accurately and efficiently punch holes into the photomasks to assist with the alignment process.

Preliminary Designs

Rotating Tower

The rotating tower idea is one that works as a swivel with the wafer sitting at the very bottom of this tower. The base has a rod sticking out of it with three platforms connected to it on a hinge. These three platforms would all hold a photomask within them for the three layers of photolithography that need to be completed to the wafer. Each layer of the tower would be 5 millimeters thick. Each layer would have a pin attached to it so the photomask could sit inside of it and be as flat as possible. The layers would also be able to be removed from the tower and their heights would be adjustable as well. The distance because of this between each mask is 5 millimeters. Each platform would be able to swing above the base when needed or be moved out of the way when unnecessary. The rotating tower is illustrated in Figure 1 & 2.



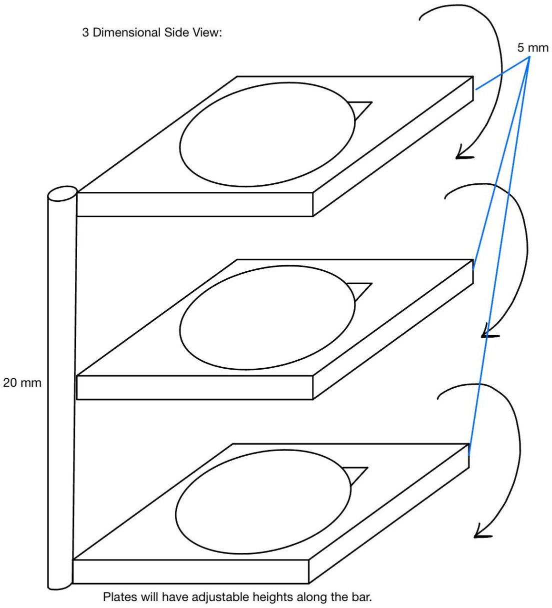


Figure 1. Rotating Tower top view. *Figure 2. Rotating Tower side view.*

Issues arise with this design when it comes to the mask/wafer spacing. The platforms are 5 mm thick, which seems small, but there will be too much space between the masks for the photolithography process to work correctly. This would cause large issues with the accuracy of the aligned masks which would render the device unusable for the client's needs. The accuracy, however, is the only big downfall to the design. The ability to swivel and readjust the height of the masks makes the product very accessible. Its accessibility, combined with its low cost makes it an even more attractive design. The design would also be made with a material that is baking resistant, so the ability to bake it minimizes the need to readjust the device and reinsert the wafer into the device, potentially decreasing the possible error.

Arm-Pin Alignment

The arm pin alignment is a rectangular board with four sections in each of the corners. The four sections consist of: a laser cut divot for 3 inch wafers, a laser cut divot for 6 inch wafers, an arm with a pin measured to insert into the 3 inch wafer's hole, and an arm with a pin measured to insert into the 6 inch wafer's hole. On the laser cut side of the base there is a hole left to cut through the plastic section of the photomask (twice per mask). This design would have to use precise laser cutting techniques to get the most precision out of the holes to line up. Then, one can place the wafer with the spun photoresist in the correct position for either the 3 or 6 inch design. After cutting the photomasks with the laser cutter, the photomasks are inserted on the arm-pins where they will be aligned with the wafer underneath. The process of UV light can then begin. This process of setup is repeated for all the layers. The design is shown below in Figures 3-6.

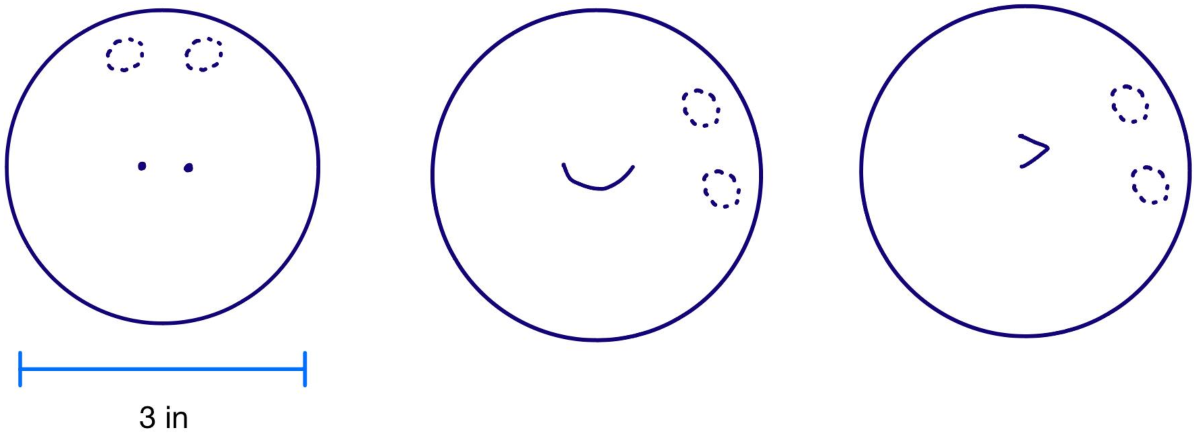


Figure 3. Arm-Pin Alignment design-imprinted wafers.

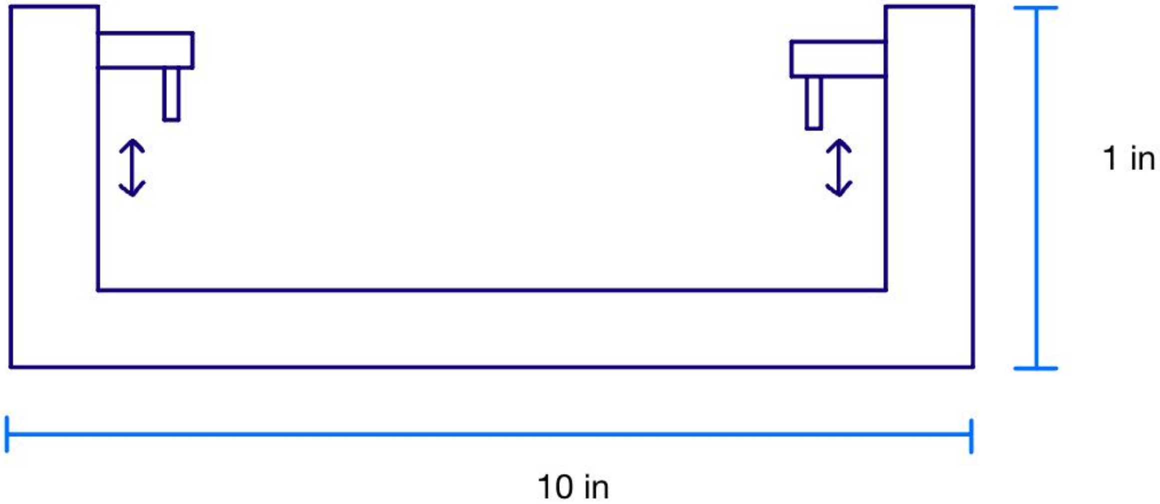


Figure 4. Arm-Pin Alignment base side view.

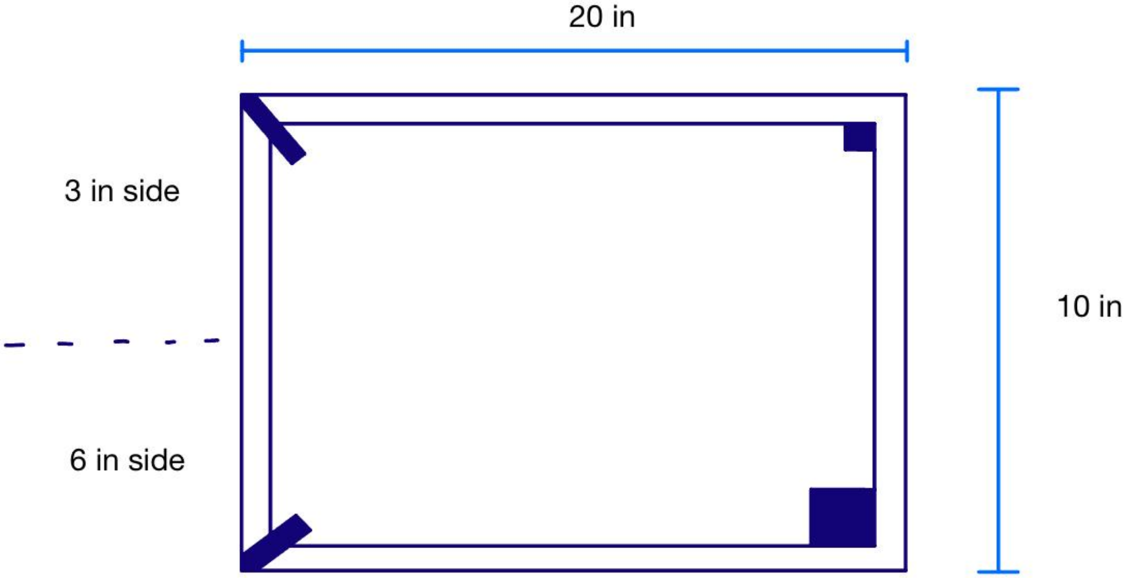


Figure 5. Arm-Pin Alignment base top view.

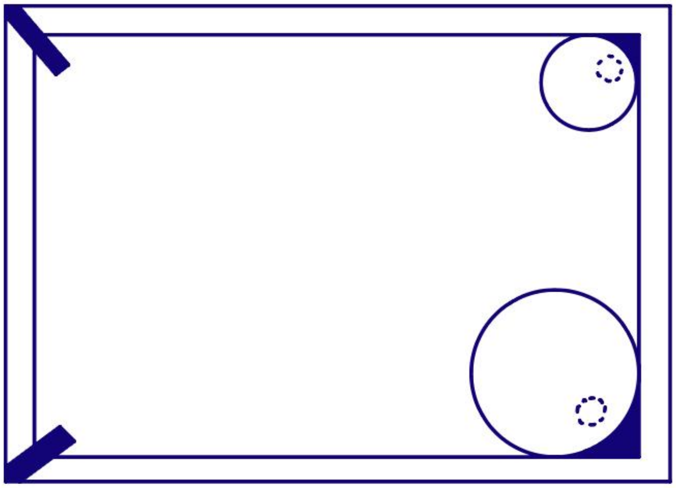
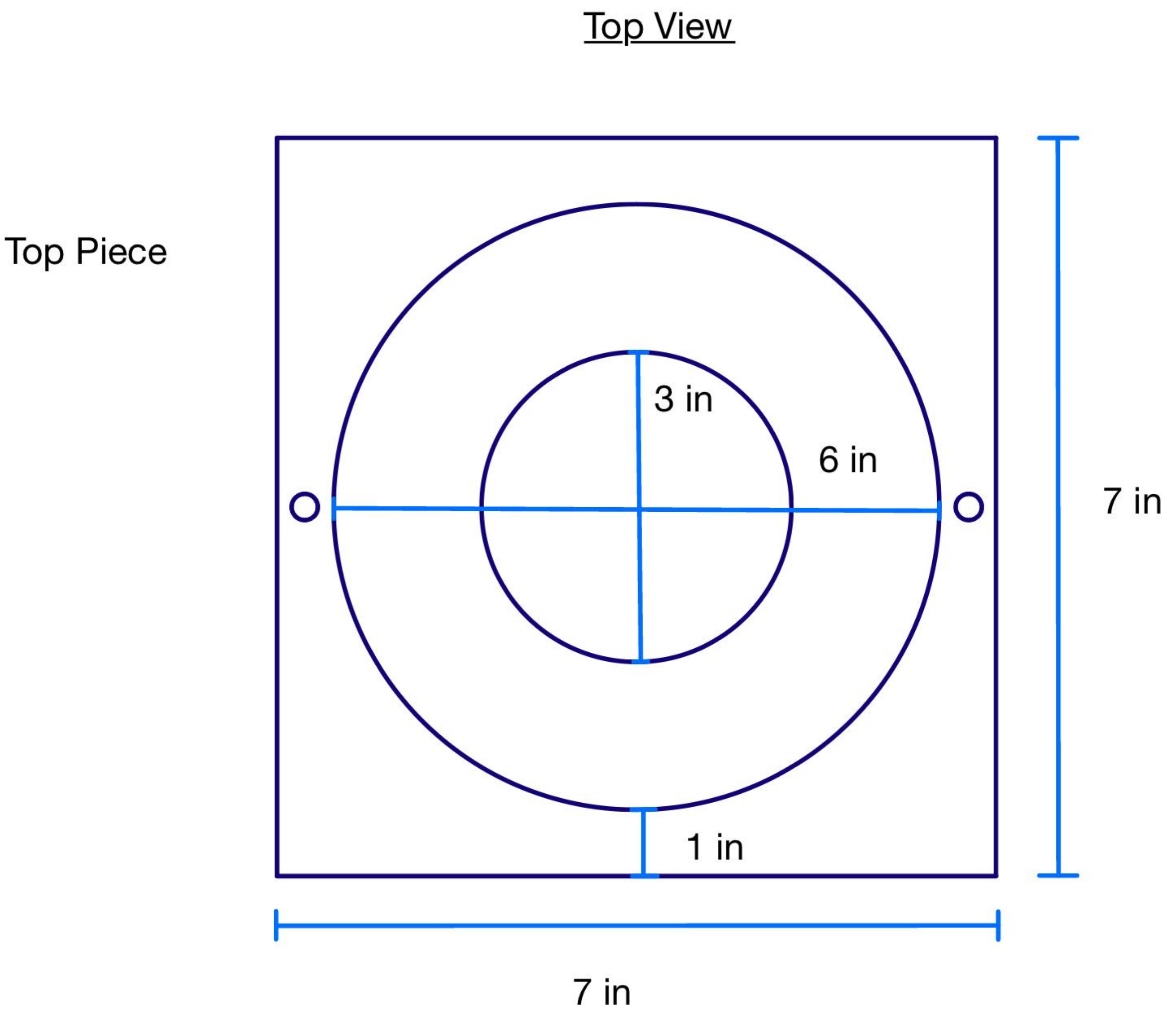


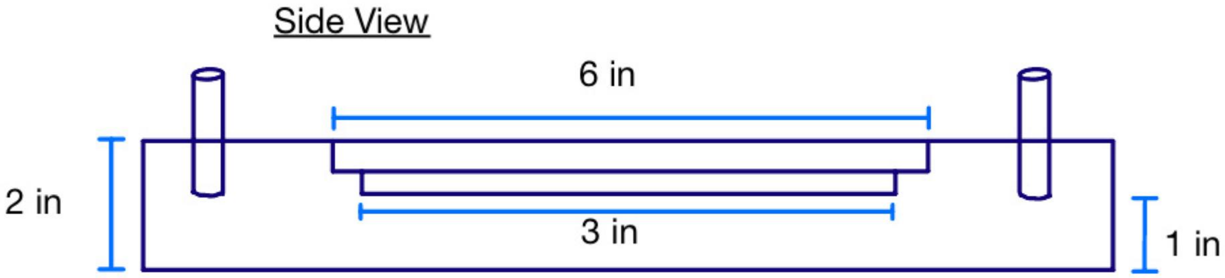
Figure 6. Arm-Pin Alignment base top view with wafers.

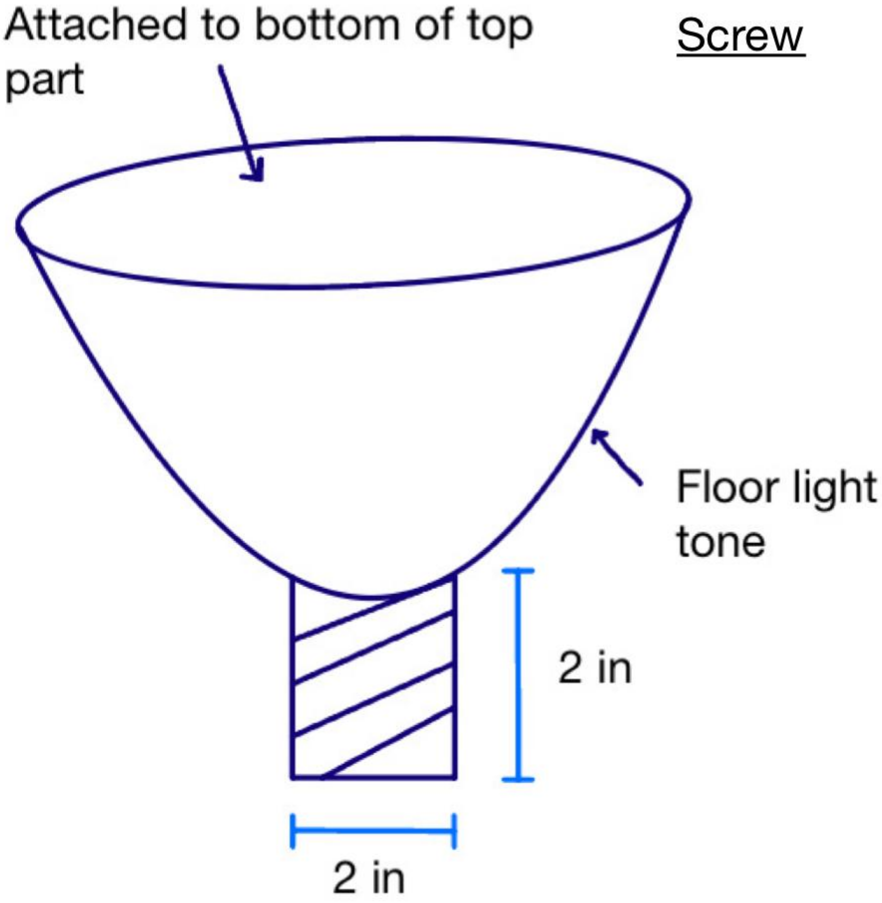
The arm-pin alignment design is good in theory, but difficult to execute. It would have to be bigger than originally asked for to fit the four corners described in the design. The laser cut divot being included would also cause some problems. The laser cutter cannot make precise enough cuts to fit perfectly into the photomask. The laser cutter can be precise to 25 µm, which is not accurate enough as the client wants it to be 10 µm. The cost of this design may also exceed the price limit for the project.

Screw Design

The screw design was a concept from the previous BioMEMS team, but re-designed by this year's group. The basis of the design was a platform with two rings, 3 and 6 inches respectively, that could hold the two different wafers provided by the client. The main platform would be 7 inches wide on each side, with the rings cut into it. This platform would have 2 pegs on each side of the circles cut out, that would allow the photomasks to be put on top of the wafers. The platform would then be attached to an almost “flood light” screw, which would be put into a box to keep it stationary. The screw would provide mobility and the ability to switch between wafers and masks quickly, as well as be able to bake the wafers right in it, as it would be made with acrylic, which is resistant to baking. The design is illustrated in Figure 7, below.







Diameter at top: 4 in

Height: 5 in

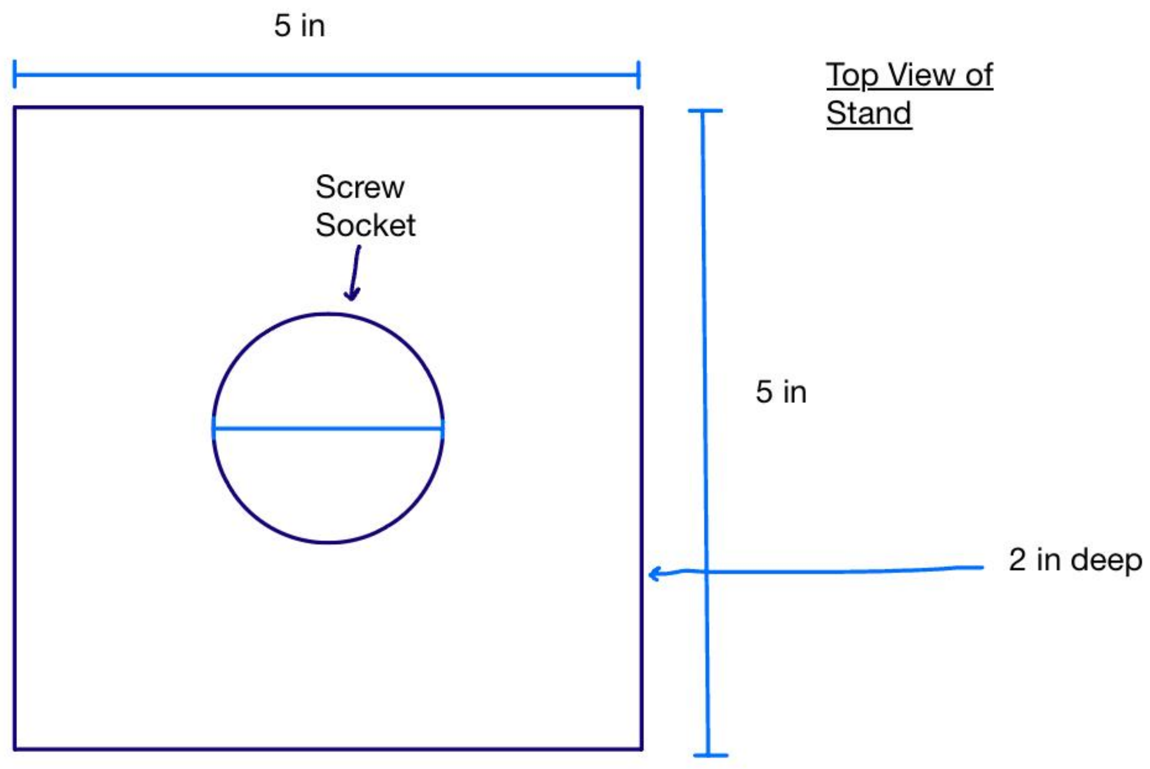
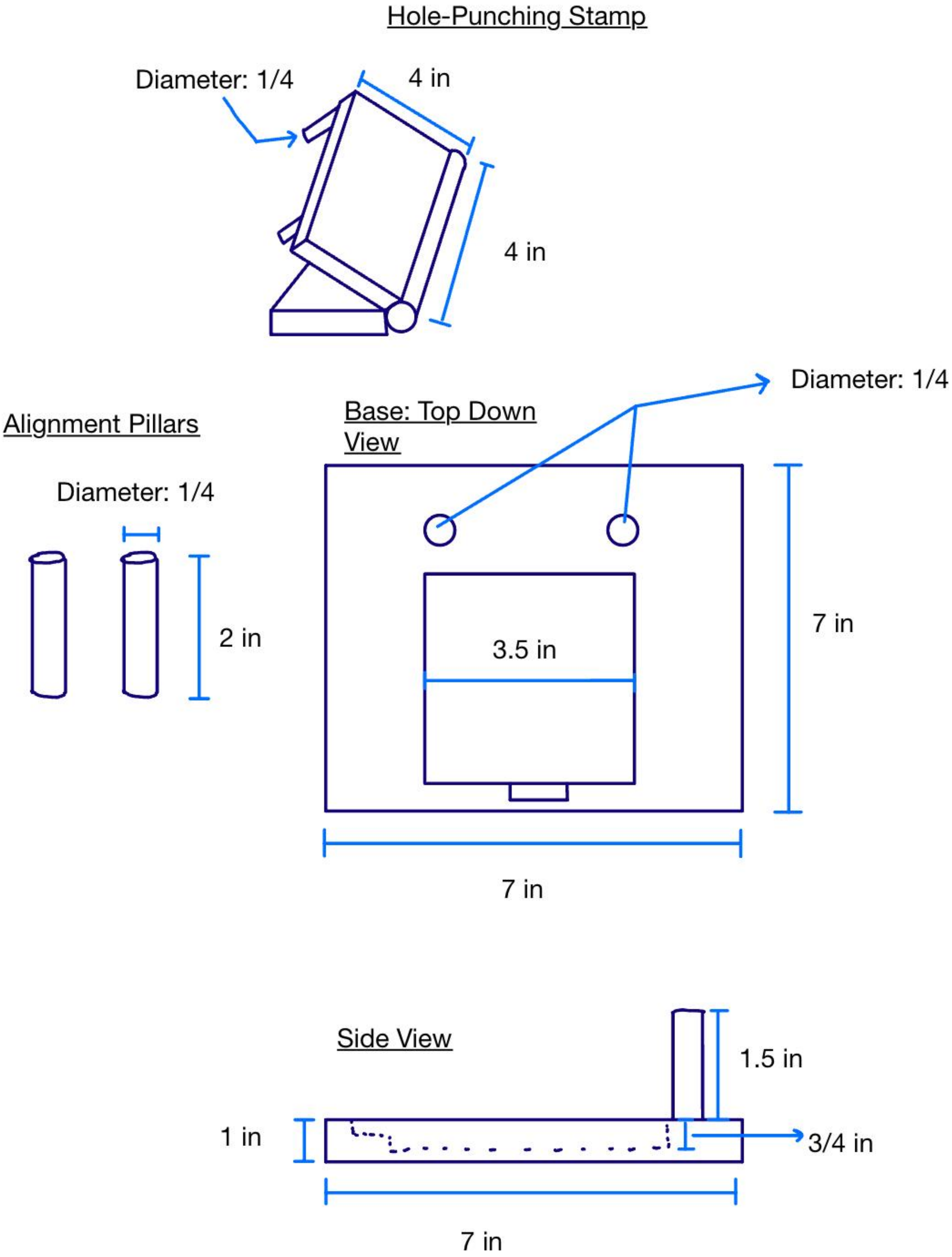


Figure 7. Screw Design top, side and bottom views.

This is a fairly basic design, with some drawbacks. The constant screwing in and out would be tedious and would not be ideal for use in a teaching lab, especially considering that this device will be used only rarely (~2 weeks of the year). Along with that, the effectiveness of this design is not ideal. The client asked us for zero space between the wafer with the photoresist on it, and the mask itself. In the screw design, there would be no space in between as the mask could just rest on top of the photoresist. The ability for the mask and the wafer to touch is a good thing as it leaves room for less error.

Divot Design

The Divot design is a more complicated design than the others. It consists of a base, wafer holders, and alignment pillars. It also has a complimentary hole-punching stamp which is used to punch holes in the masks so that they can be properly aligned on the base using the alignment pillars. The Divot design features two alignment pins that are inserted flush into the base. The masks are then punched with the standardized hole-punching stamp so that they will fit onto the alignment pins exactly. The wafer with the spun photoresist will then be inserted into a wafer holder that corresponds to the space that the user wants. Each wafer will correspond to the different height of the photoresist to ensure that there is no space between the top of the photoresist layer and the mask. Once the user has spun the photoresist they will place the wafer in the correct wafer holder and slot the cut mask onto the alignment pillars. Then, the photoresist will be cured through the mask and then removed from the device for baking. This process will be repeated for each mask. The overall device is shown in Figure 8.



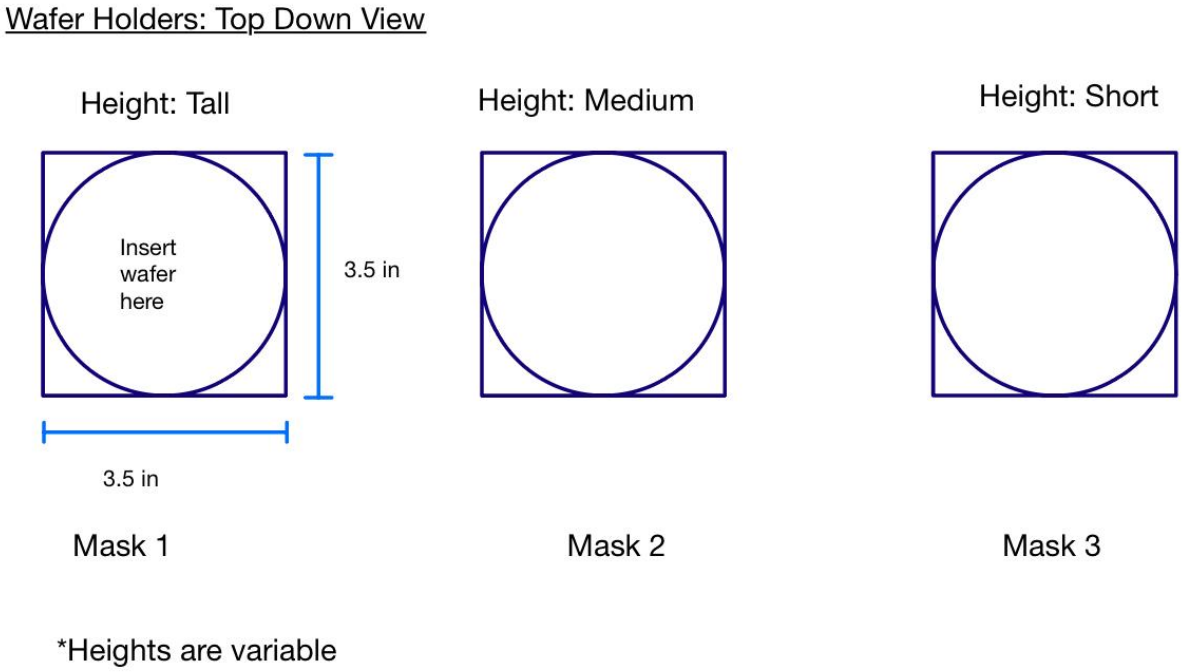


Figure 8. Hole Punch & Divot Design top, side, and bottom views.

The Divot design is innovative although it is more complicated and may require more skill to use. It may also struggle with achieving the accuracy of 10 µm with the current fabrication tools available. However, if done correctly, it will achieve great accuracy and meet the client's requirements.

Design Matrix

In order to compare the four designs from above, the team used a design matrix with different criteria that are weighted based on their importance to meeting the product design specifications. Each category in the design matrix was selected specifically for this project and given a weight deemed by how important it is to this project's success relative to the other categories. Each design was measured against these categories and their scores are depicted numerically below. Each category is also detailed below and a brief description of the rationale used when ranking each design in each category is provided below as well. The design matrix is shown below in Figure 9.

Current Design Matrix		Rotating Tower		Laser Cut Alignment Holes		Screw Idea		Divot Design	
Criteria	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Accuracy	25	3/5	15	4/5	20	3/5	15	4/5	20
Cost	20	4/5	16	3/5	12	5/5	20	5/5	20
Ease of Use	20	5/5	20	3/5	12	3/5	12	3/5	12
Ease of fabrication	15	3/5	9	3/5	9	4/5	12	4/5	12
Size	10	5/5	10	5/5	10	5/5	10	5/5	10
Durability	10	3/5	8	3/5	6	4/5	8	4/5	8
Total		**78**		**69**		**77**		**82**	

Figure 9. Design matrix.

Accuracy (25%): Accuracy in photomask alignment refers to the precision and correctness with which the patterns on two or more layers of a semiconductor or microfabrication process align or match with each other. The goal of this project is to create a mechanism that can align photomasks in successive trials of photolithography with little error. This involves accurately aligning the photomasks such that the mask patterns are as close to 10 µm precision, with a +100 µm tolerance. Accuracy was given the highest weight of 25/100 due to the fact that the main goal of this project is to develop a method of simple alignment that is highly accurate in the alignment of photomasks for a given substrate.

Cost (20%): Cost refers to how much the total expenses in dollars the design will include in this project. Cost was given a weight of 20/100 because of both the history of this project and the real-world struggles with accuracy at far less restrictive budgets. In the past, designers have struggled to create a mechanism that satisfies the client's desired accuracy while complying with a low cost budget. There are some devices that can achieve such desired accuracy, but they cost thousands of dollars usually being either automated, have to utilize built in microscopes, or are some combination of the two. Thus, the budget discrepancy between this project and what is currently produced and manufactured by BioMEMS companies is what ultimately gives the Cost design criteria such a high weight.

Ease of use (20%): Ease of use refers to the ability of the consumer to use the device fully, in a reasonable timeframe, and without unnecessary complexity. A user-friendly system offers increased efficiency, reduced training time, minimized error rates, cost savings, improved productivity, and greater accessibility. Simplified operations make it easier for users to achieve accurate alignment, reduce production downtime, and maintain a skilled workforce, ultimately enhancing the quality and cost-effectiveness of the microfabrication process and therefore earning ease of use a 20/100 on the design matrix. The divot design ranks the highest in this category as it maintains the best balance of the number of steps in the design process, and is fairly easy to use.

Ease of Fabrication (15%): Ease of fabrication refers to how straightforward it is to create or manufacture photomasks used in semiconductor or microfabrication processes. An emphasis on ease of fabrication involves designing photomasks and alignment features in a way that minimizes complexity and reduces the likelihood of errors during the manufacturing process. This can include using well-established manufacturing techniques, clear and intuitive design specifications, and efficient production workflows. Achieving ease of fabrication ensures that photomasks are produced efficiently and accurately, leading to cost savings, reduced production time, and improved overall quality in microfabrication processes. The category ease of fabrication was given a weight of 15/100 as the device needs to also be able to be reproduced for a 6 in. wafer, given that the team is only making this product for a 3 in. wafer.

Size (10%): Size refers to the physical dimensions of the photomasks and alignment features used in microfabrication processes. The size of these components are properly considered as it affects the precision and scale of alignment between different layers or patterns. Smaller features may be used for a 3in wafer alignment, while larger sizes, like for the 6in wafer, may be scaled for different size alignments. The choice of size depends on the specific requirements of the fabrication process and the desired level of precision. Properly managing size in photomask alignment is essential to ensure that the alignment features match the intended patterns and achieve the desired results in the final microfabricated components, thus size earned a relative 10/100 on the design matrix, as it can be scaled and changed accordingly.

Durability (10%): Durability refers to the design's ability to withstand wear, stress, and various environmental conditions over an extended period of time while maintaining its functionality and performance. Just like all the other steps, it is important because it ensures the long-term reliability and consistent performance of the device. Since photomask aligners are used in various biomedical and microfabrication applications where precision and repeatability are essential. These devices need to withstand frequent usage and potentially harsh environmental conditions while maintaining precise alignment for accurate microfabrication processes. A durable aligner ensures stable, high-quality results, reducing the need for frequent maintenance or replacements helping lead to lower cost applications. Thus, the team gave durability a modest 10%, even with this weighted percent, all of the categories in the design matrix are important.

Proposed Final Design

The proposed final design is the Divot design as it scored the highest in cumulative credits. It has good predicted accuracy and cost. However, it is more complicated to use than other designs making it less ideal than the other designs in this department, especially considering that it will be used mainly in a teaching lab. It ties with the Screw design in ease of fabrication, although none of the four design ideas will be particularly easy to fabricate. The Divot design also scores the best in size and durability, making it more fitting for use in a teaching lab than the other designs in these categories.

Fabrication/Development Process

Materials

- ASA (acrylonitrile styrene acrylate) was chosen as the material for the base and wafer holder. Originally, it was planned that Acrylic would be used to fabricate both the base and the wafer holder because Acrylic is known to be resistant to UV light [10]. However, it was determined that 3D printing would be the best method of fabrication for the base and wafer holder due to the available resources and time constraints of the project. Acrylic cannot be 3D printed but a material that has very similar mechanical properties to Acrylic, also being UV light resistant, ASA [11], can. Hence, ASA was chosen to be the material for both the base and the wafer.
- For the alignment pillars, steel rods were ordered because of their smooth and rigid properties. However, they did not arrive in time so wooden replicas were found and substituted so the final material chosen for the alignment pillars was wood.
- The push rectangle was fabricated out of Acrylic because of its ability to be laser cut and its smoothness.
- The cross that was used to align the uncut masks with the hole-punching stamp was fabricated out of wood. Once again, this was due to the time constraints of the project.
- The hole-punching stamp was made of steel and was ordered from a third party source. It also consisted of 2 plastic components.

Methods

Figure 10. Photomask Aligner Complete no Mask.

Figure 11. Photomask Aligner Complete with Mask.

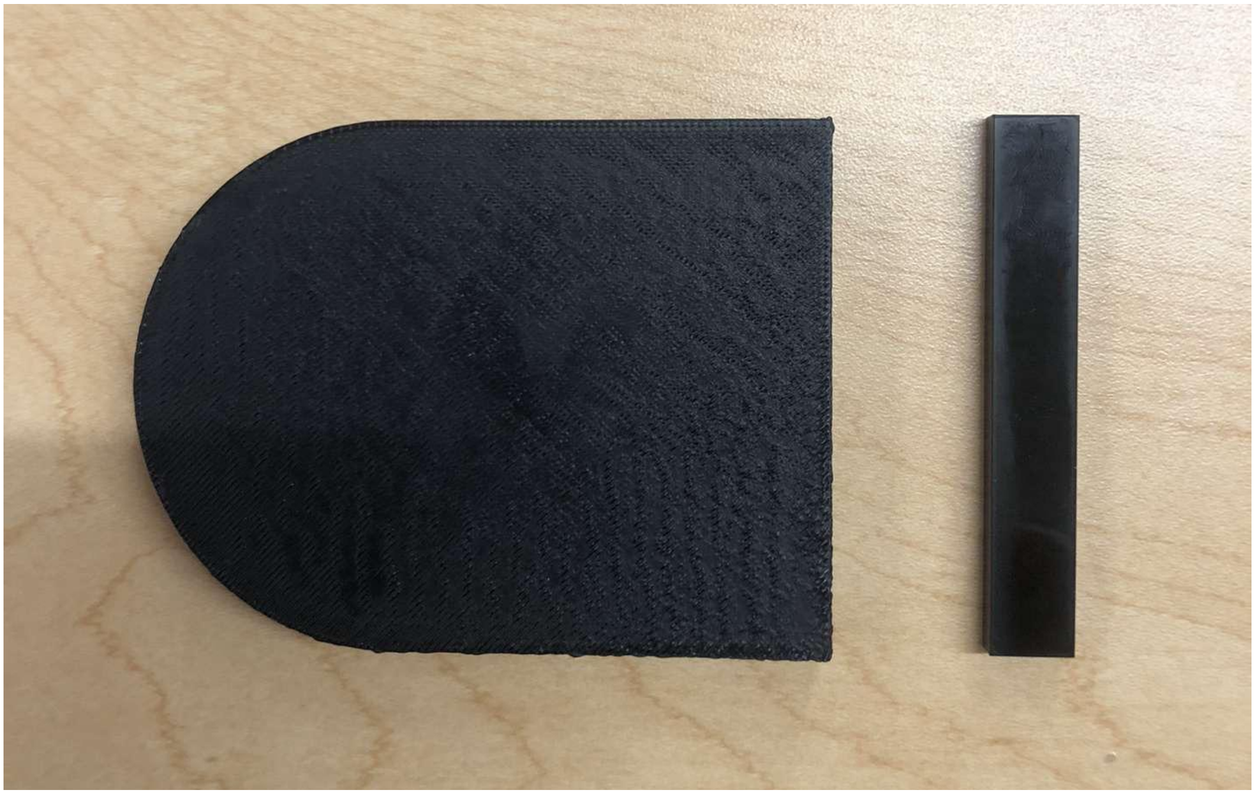


Figure 12. Photomask Aligning Holder and Push Rectangle.

Figure 13. Hole Punch.

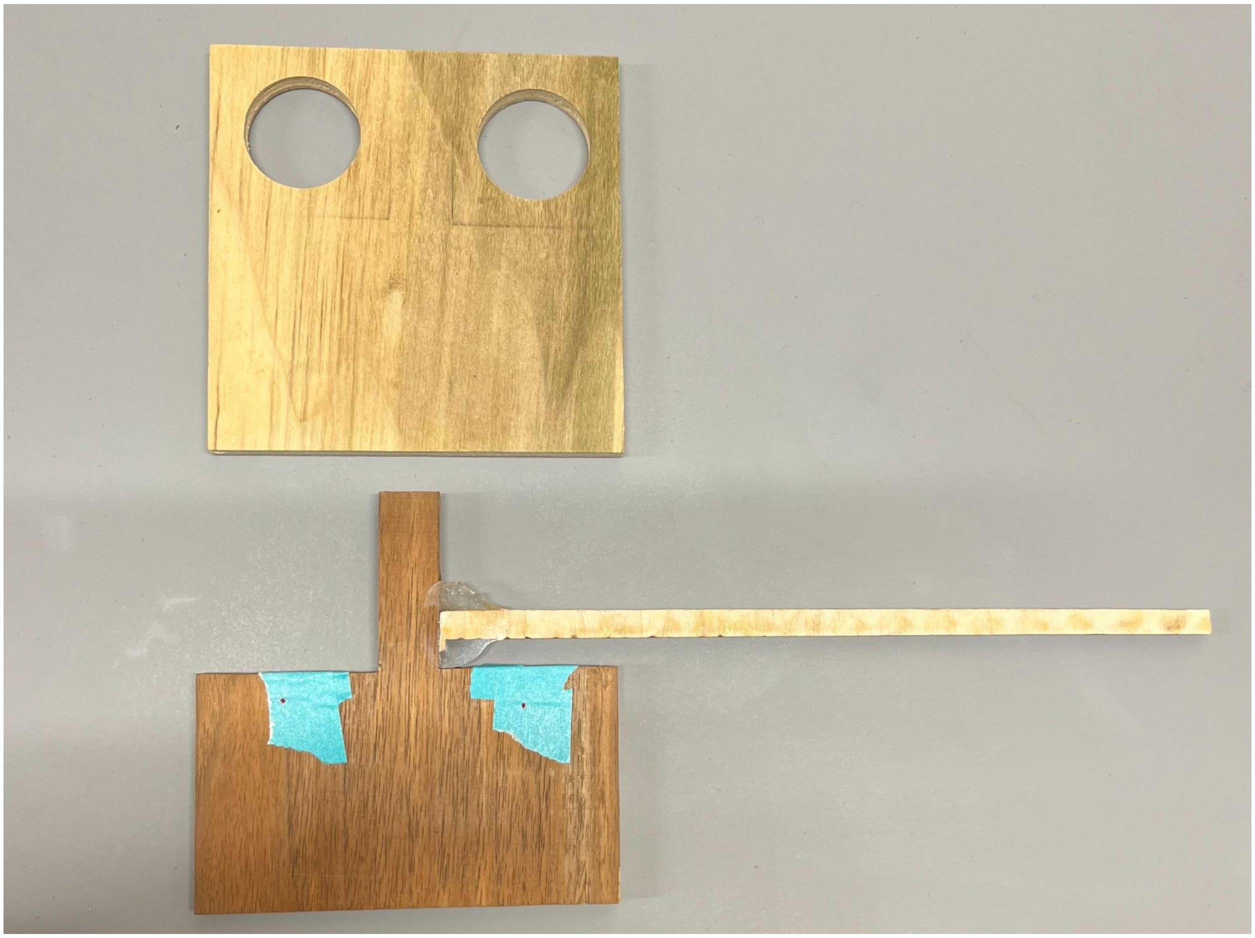


Figure 14. Wooden Alignment Crosses. The bottom one was the one used in the final design.

Base

The base (Figure 11) was fabricated using a Bambu Lab X1 3D printer. A Solidworks file was created in order to print the base. A 50% infill was used for the print. This was done in order to minimize warping in the print after the first print (which used a 20% infill) was not adequate.

Wafer Holder

The wafer holder (Figure 12, left) was also fabricated using a Bambu Lab X1 3D printer. Again, a Solidworks file was created in order to print the wafer holder and a 50% infill was used.

Alignment Pillars

The alignment pillars (Figure 11) were cut using a bandsaw to each be 2 inches in length. The 2 inch pillars were then filed down by hand using sandpaper in order to get them to fit in the holes in the base.

Push Rectangle

The push rectangle (Figure 12, right) was fabricated using the Universal Laser Cutter in the Makerspace. Adobe Illustrator was used to make the file in order to cut the rectangle. The rectangle was cut and was 3.14 inches in length. Scrap acrylic was used, provided by the Makerspace.

Hole-Punching Stamp

The hole-punching stamp (Figure 13) was ordered and not modified at all. The paper aligner was simply pulled out to the A6-S position in order for the wooden cross to function as intended.

Wooden Cross

The wooden cross was fabricated first with a bandsaw, to cut a 4 inch by 4 inch square. Then, the 1.5 inch by 1.5 inch square cutouts on each top corner of the first square were also cut using the bandsaw. The cross was then sanded using a belt sander to remove debris. The cross was finalized by attaching an “alignment stick” to the side of the cross using epoxy to ensure that the masks would only go a certain distance (0.5 inches) into the hole-punching stamp. Then, blue tape was placed where the “alignment dots” would go which would assist the user in lining up the masks correctly on the cross. Then, the correct spot for the alignment dots were determined by visually examining the position of the masks while inserted into the hole-punching stamp and then they were burned into the cross using a soldering iron. Then, they were filled with pink ink using a pink pen. The contrast between the blue tape and the pink alignment dot was done to allow for easier visibility under a microscope.

Final Prototype

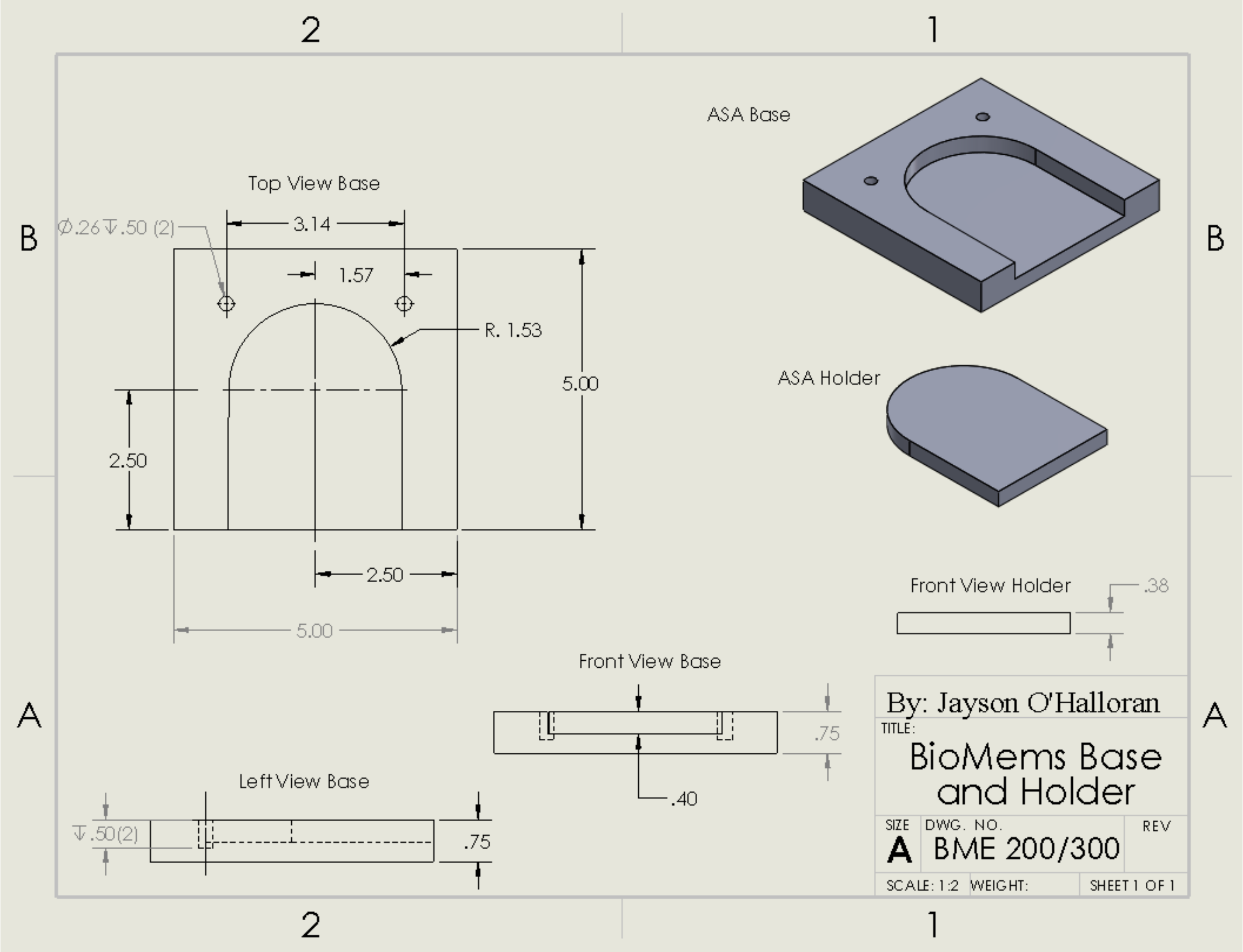


Figure 15. Solidworks Drawing of Base and Holder.

The final prototype first had to be assembled before use. Two separate Solidworks designs were created, one for the base and another for the holder. After each part was 3D printed, they were then able to be assembled to create the photomask aligner. Next, the alignment pillars were inserted into their respective holes and a protocol for use was created. It can be seen in *Appendix C.* The final prototype is a multi-faceted device that requires a process to use. An image of the final prototype is seen in *Figure 15.*

In order for the prototype to accommodate for different wafer sizes, an entirely new base and wafer holder must be printed. However, since this was done using a readily available 3D printer and was not very expensive, this was deemed viable in order to accommodate for differing wafer sizes while still maintaining the specificity of the original prototype. If a prototype that could accommodate different wafer sizes had been created, there would almost certainly be more error introduced into the design which would have been unacceptable. So, it was decided that making different products for different sized wafers was the most preferable option.

Testing

ASA vs. Acrylic Material Properties

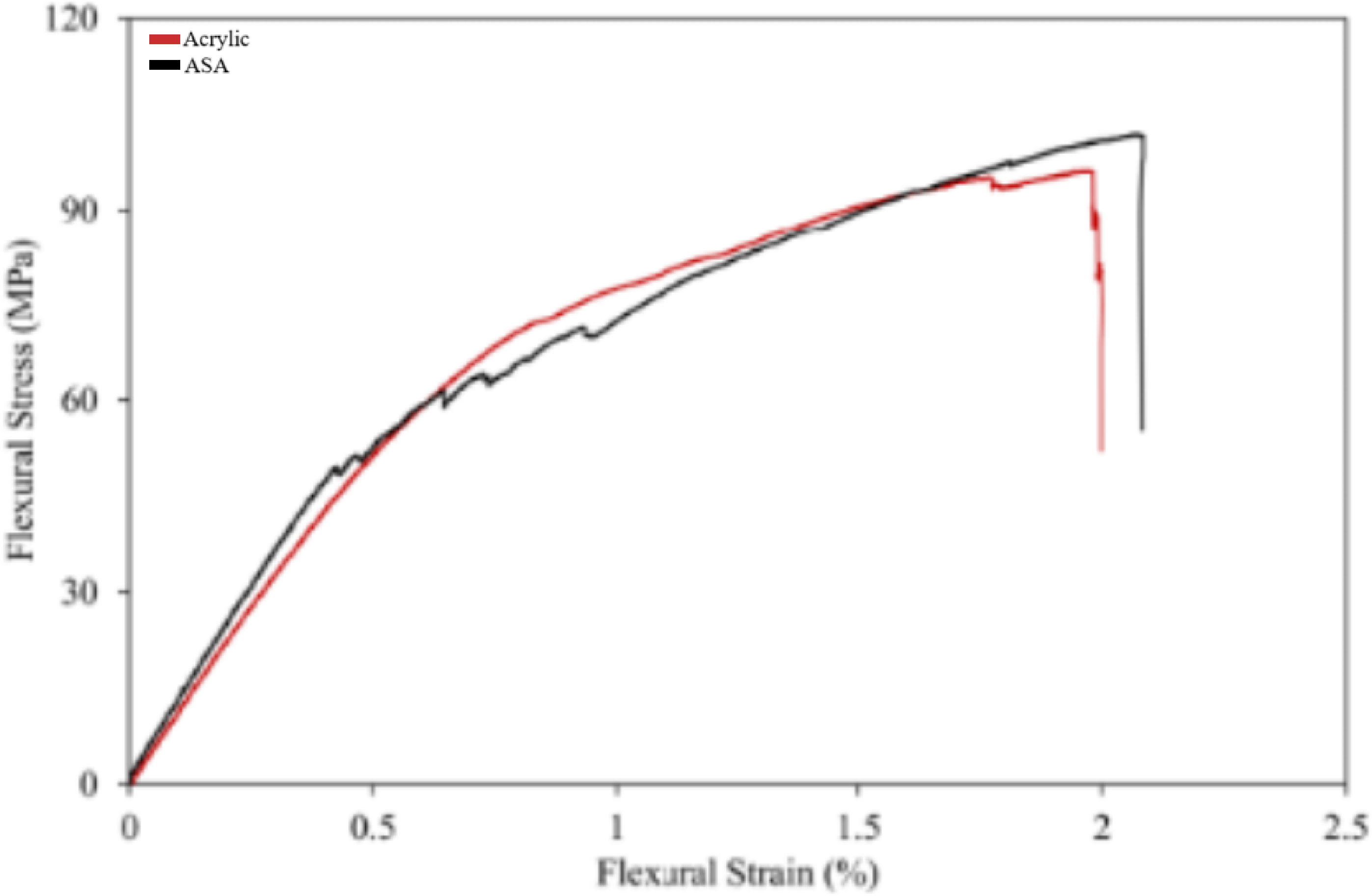


Figure 16. Combined Flexural Stress v Strain graph of Acrylic and ASA

ASA (Acrylonitrile Styrene Acrylate) and Acrylic are two distinct thermoplastic materials with slightly different mechanical properties. In terms of flexural stress, ASA demonstrates a higher maximum flexural stress of 94 MPa compared to Acrylic, which has a maximum flexural stress of 90 MPa. This suggests that ASA exhibits a slightly greater resistance to bending forces before experiencing failure. Additionally, when considering maximum strain, ASA again shows a slightly higher value with a maximum strain of 2.2, while Acrylic has a maximum strain of 2.0. The higher strain capacity of ASA implies that it can undergo more deformation before reaching its breaking point, making it potentially more ductile in certain applications. When considering alternatives to the team's design process, ASA was the only other material that exhibited almost identical mechanical properties to Acrylic. The team was not able to use their first choice of material (Acrylic) later in the semester, and therefore the second choice (ASA) was the only viable option. This tempered ASA is also UV resistant, making it a great choice for a photomask aligner.

Hole-Punching Stamp

The quality of the hole-punching stamp was assessed by aligning the masks on the cross and punching the holes as described in the protocol for use. Then, the masks were realigned under the microscope to each other using their alignment crosses. Then, the stack of masks was moved and the distance between the cuts in the masks was measured using the program ImageJ. It was provided that the diameter of the center circle in each mask's alignment cross (the circle that centers over the pink alignment dot) was 1.25 mm. So, this was used to set the scale of the ratio between pixels/microns in ImageJ. This allowed the actual distance of the error to be measured. This was done to measure the give of the masks under the hole-punching stamp. For example, if the masks were to bend slightly under the pressure of the hole-punching stamp, the holes would be in slightly different places on the masks. This analysis attempted to quantify that. For this test, 3 sets of 3 masks were cut. 3 masks were cut at a time in order to mimic the application of the device. So, in total, 3 trials were done of this analysis. Within each trial, 3 measurements were taken: top to middle, top to bottom, and middle to bottom. These terms correlate to the first (top), second (middle), and bottom (third) masks which were cut. So, for example, top to middle would signify the difference between the hole punches between the first and second masks that were cut. This terminology is consistent throughout all testing performed with both the hole-punching stamp and the base testing. An image of the microscope while aligning a mask to the cross and its pink alignment dots is shown below for reference in Figure 17.

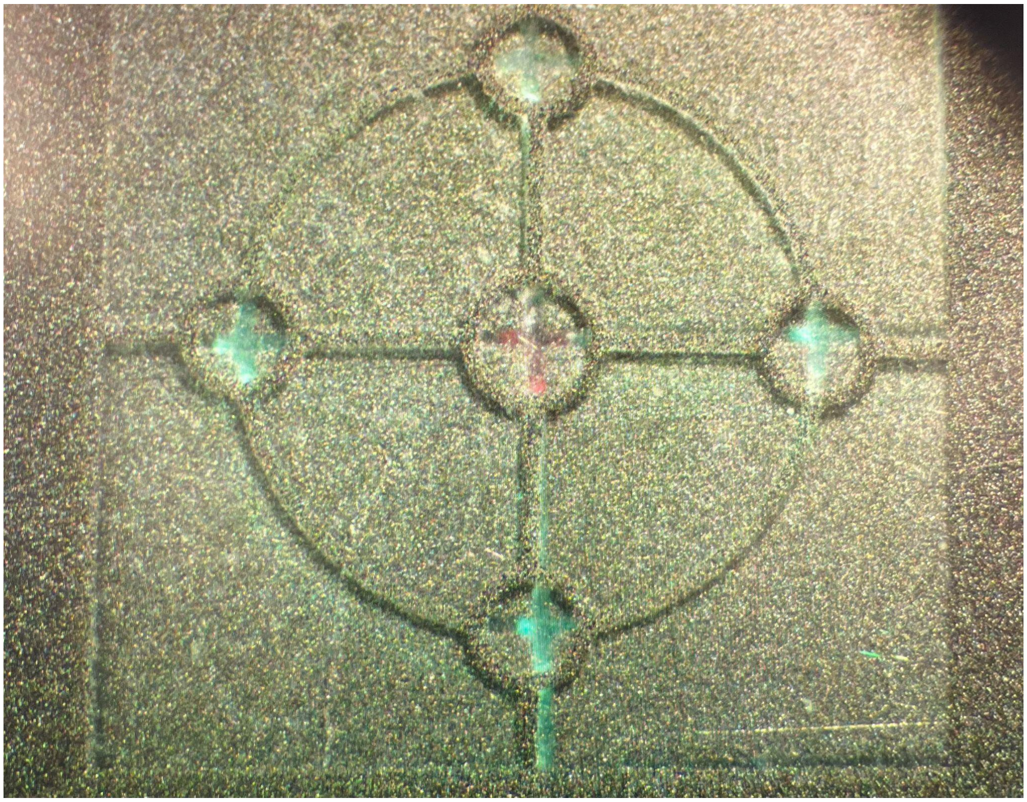


Figure 17. The process of aligning the masks on the cross. The pink spot in the middle is the pink alignment dot. This process was done twice on either side of the cross to ensure that the masks were taped on straight.

Base Alignment Testing

The base was tested using the masks that were cut previously in the hole-punching stamp testing. First, the wafer was aligned using the push rectangle and then a mask was slotted onto the alignment pillars. Then, the entire device was analyzed under a microscope using the same measurement method as in the hole-punching stamp testing. The difference between the edge of the wafer and the edge of the circular portion of the mask was measured. This was to determine how well the cut masks would be able to line up with the wafer and therefore the photoresist during the UV curing process. If the masks were to “miss” the wafer, the design in the photoresist could be offset or in the wrong place. This test aimed to quantify that error. An image showing this process is shown below in Figure 18.

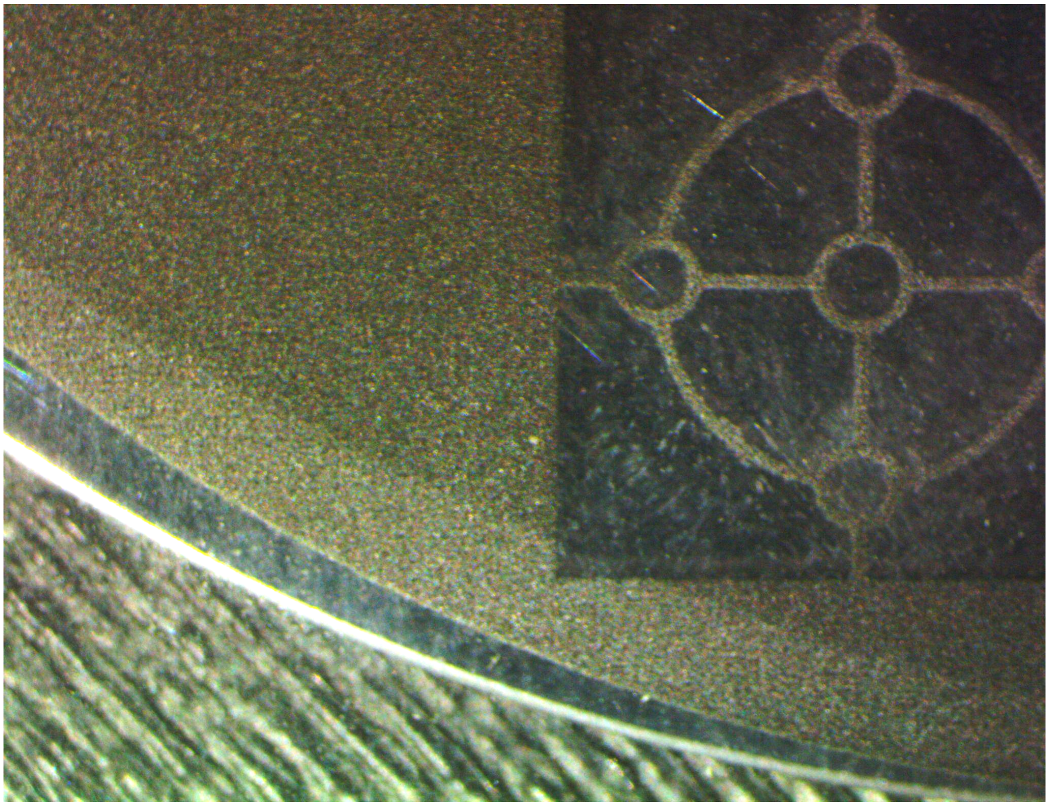


Figure 18. An image of the wafer in the device and the mask laid over it. The edge of the device is the striped or scored looking part near the bottom left corner. The wafer is the thin, black strip through the middle of the image. And, the mask is the large black mass that takes up the majority of the image.

Results

Hole-Punching Testing

The results for the hole-punching testing are shown below in Figure 19. The error bars quantify standard human error. Again, the terms on each point such as “top to middle” would mean that the first mask cut is being compared to the middle mask cut of that trial. This same legend is true for all points seen below.

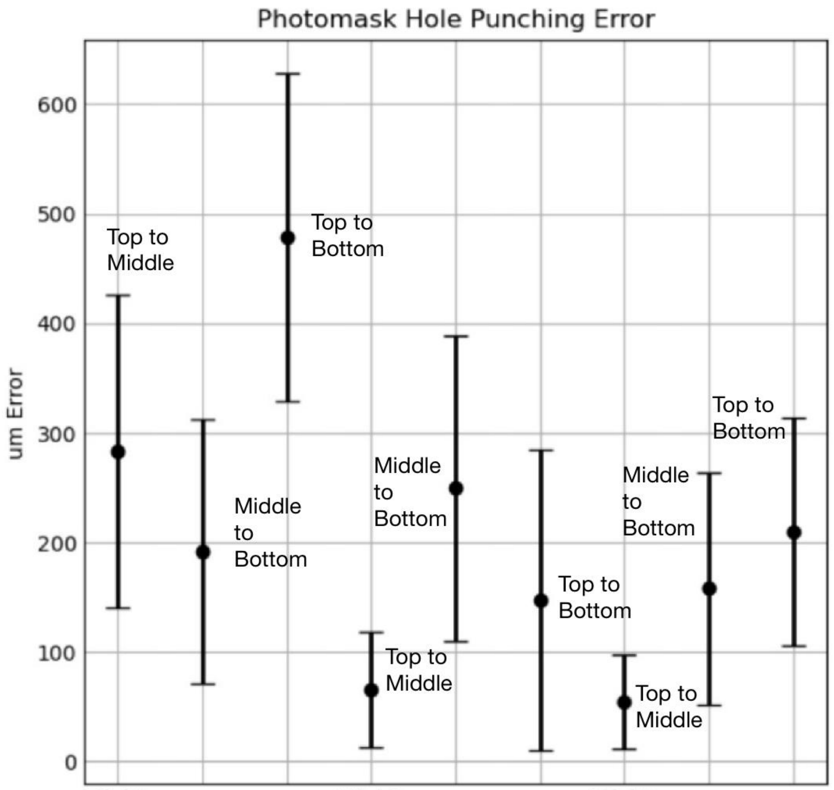


Figure 19. The results for the hole-punching stamp testing. The error bars represent quantified human error.

The device was meant to be with 10-100 µm, however, based on the results, it was not. The average between each subgroup (top to middle, middle to bottom, and top to bottom) for all trials is shown in the following tables.

Top to Middle	Trial	Error (µm)	Average Error (µm)
	Trial 1	282.58	134.08
	Trial 2	65.41	
	Trial 3	54.25	

Table 1. Average error between all top to middle trials.

Middle to Bottom	Trial	Error (µm)	Average Error (µm)
	Trial 1	191.58	199.7266667
	Trial 2	249.63	
	Trial 3	157.97	

Table 2. Average error between all middle to bottom trials.

Top to Bottom	Trial	Error (µm)	Average Error (µm)
	Trial 1	478.46	278.57
	Trial 2	147.41	
	Trial 3	209.84	

Table 3. Average error between all top to bottom trials.

As observed, the error using the device is not always within or under the range of standard human error (200-300 μm) while aligning the photomasks by hand alone. However, the error is not very consistent at all. This means that the device is worse than manual alignment. Also, the team was not able to quantify rotational error (which there was a significant amount of as observed qualitatively) due to a lack of appropriate materials for quantification and time. In short, the team could not devise a way in the remaining time to quantify rotational error, as such it was not analyzed but clearly affected the results. Preferably, this testing protocol will be edited in the future to account for rotational error.

Base Testing

The results for the base testing are shown below in Figure 20. The letter "M" signifies the mask number. For example, "M3" means mask 3. This was important because each mask that was cut was analyzed separately meaning that there were 9 trials in total.

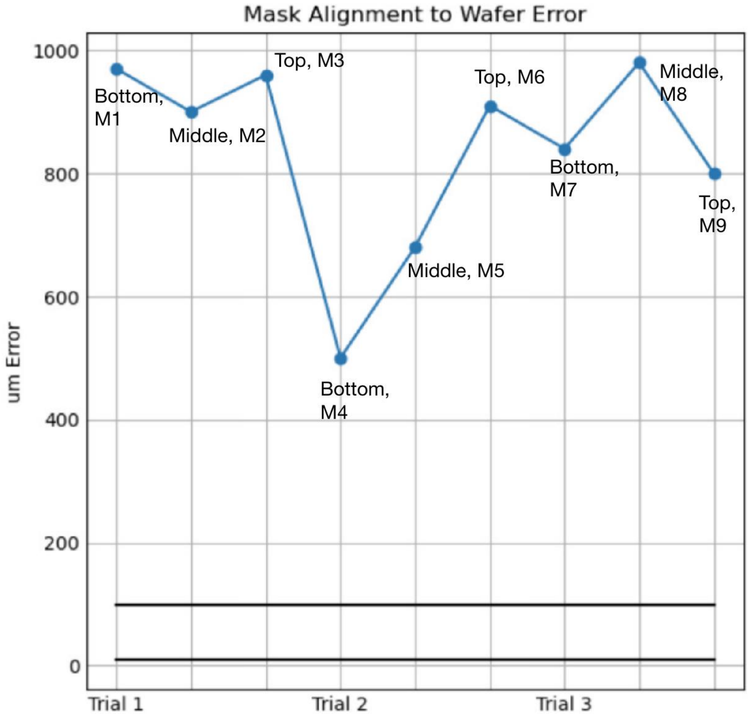


Figure 20. The mask alignment to wafer error. The results of the base testing protocol. The terms "bottom," "middle," and "top" correspond to the same terms in figure x for ease of comparison.

The results for the averages between corresponding masks between different trials is shown in the tables below.

Bottom	Trial	Error (μm)	Average Error (μm)
	Trial 1	970	
	Trial 2	500	
	Trial 3	840	770

Table 4. The average error between the bottom masks (the masks that were cut last) and the wafer.

Middle	Trial	Error (μm)	Average Error (μm)
	Trial 1	900	
	Trial 2	680	
	Trial 3	980	853.3333333

Table 5. The average error between the middle masks and the wafer.

Top	Trial	Error (μm)	Average Error (μm)
	Trial 1	960	
	Trial 2	910	
	Trial 3	800	890

Table 6. The average error between the top masks and the wafer.

As observed, the average error between the masks and the wafer is significantly larger than standard human error. However, the distance from the mean, on average, is shown below in table x.

	Average Error (μm)	Distance from the mean (average, μm)	Difference from the standard deviation
Top	770	67.77777767	6.284026144
Middle	853.333333	-15.55555533	45.9382
Bottom	890	-52.22222233	9.27153

Table 7. The average difference from the mean and difference from the standard deviation.

The difference from the standard deviation is, however, quite good. The standard deviation itself was calculated at 61.49 µm. So, every trial was within one standard deviation of the mean. So, the error was high but was consistent. This means that this design may be able to provide consistent results that fall within the specifications if the design is edited slightly to make it more on target.

Future Work & Discussion

To expand on the future work and discussion of the BioMEMS photomask aligner, the team currently plans on using the design as an IP (independent project) in the future. With that being said, there are going to be some changes in order to make the design more viable. The first notable change comes with the size of the base and holder. The base currently has a height of 0.75 inches, and an LxL dimension of 5x5 inches. Reducing the base height to .5 inches would allow the team to increase the infill thickness to 80%, as the cost of materials would then remain almost the same. Increasing the infill thickness allows for the 3D printer to create less error, as the hollow inside becomes more solid. Moving on to the holder, the size would need to be decreased in order to fit into the new base. The holder would be a better fit at 0.235 inches instead of its current 0.375 inches. Moreover, the reason the holder isn't 0.25 inches is because it has to accommodate for the .015 inch wafer thickness in order to make it flush with the base surface. In addition to the base, the holder will also get an increase in infill thickness, going from 50% to 80% as well. Another addition to the future design would be to add the steel rods for the alignment pillars on the base. This semester the team was only able to use wooden rods due to shipping issues late in the design process. Lastly, the team needs to make a more stable and accurate hole punch. The hole punch errors correlated directly with the errors the masks had on the wafer during the alignment process. These errors arose due to the force required to stamp through three photomasks, as the force generated always slightly moved the hole punch, causing misalignment. Therefore, in the future, the team would need to create a base for the hold punch that allows for more force to be applied without actually moving the hole punch from its original position. This would eliminate most of the hole punching error, which would then allow for a more accurate mask to wafer alignment. Upon completion of the changes made to the BioMEMS project, a "DIY" (do it yourself) manual would be created in order for students and or faculty to be able to scale and make their own low cost BioMEMS photomask aligner. This foresight emphasizes the project's potential broader impact, aligning with ethical considerations, global relevance, and the pursuit of accessible solutions in biomedical contexts. The comprehensive approach aims not only to refine the device but also to empower others to contribute to and benefit from this innovative technology.

Conclusion

The goal of this project is to design a photomask aligner using biological electrical mechanical microsystems (BioMEMS). In conclusion, BioMEMS play a pivotal role in the investigation of biological interactions, particularly in applications such as cell activity monitoring and biocompatibility testing. This project consists of creating an alignment system that can accurately align photomasks within 100 µm. The overall procedure inherently demands precise alignment of image masks for multiple successive layers, a crucial step in BioMEMS fabrication. While high-fidelity aligners are readily available in the market, their exorbitant cost (tens of thousands of dollars), and impracticality for educational settings, have driven the exploration of new cost-efficient alternatives [12]. Consequently, the project consisted of three innovative aligner designs that were proposed and rigorously evaluated, leading to the selection of a final design. A few weeks later, a fourth and more reliable design was proposed, that is both budget-friendly and well-suited for prototyping and testing. The development of these cost-effective aligners not only addresses financial constraints faced by educational institutions but also promotes accessibility and engagement in the field of BioMEMS research, lowering barriers to entry and fostering innovation and progress in the study of biological interactions. These endeavors underscore the collaborative efforts of researchers and educators in driving scientific advancements forward and making cutting-edge technologies more accessible.

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Appendix

A. PDS

October 7th, 2023

Function :

The low cost BioMEMS photomask aligner is a device that is meant to align photomasks relative to each other so that when used in photolithography applications, separately spun photoresist layers are properly aligned for a multitude of uses such as individual cell culture. The photomask aligner must be extremely accurate down to micro-measurements in order to complete this goal.

Client requirements:

- The photomask aligner must be accurate under 100 µm but preferably within 10 µm in accuracy
- The aligner should be able to be held 12 µm above the photoresist layers to ensure the pattern is burned into the photoresist accurately
- The aligner should be resistant to the baking step of the photolithography process

Design requirements:

1. Physical and Operational Characteristics

    a. *Performance requirement*s:

    The photomask aligner should be able to hold the base plate and the subsequent photoresist layers in such a way that the sequence of photomasks are all aligned within 100 µm of each other. Preferably, the photomasks will be aligned within 10 µm of each other, however, 100 µm is the stronger requirement. The aligner should also be able to hold the photomasks about 12 µm above the photoresist layers so that the patterns can be accurately burned into each photoresist layer. Finally, the entire device should be resistant to temperatures of 90-110C [1] to be resistant to the baking step of the photolithography process.

    b. *Safety*:

    The aligner is meant to be used in a teaching lab so it must be extremely safe to use. It must not melt under the aforementioned 90-110C to prevent potential damage to other items in the lab. It also must not conduct heat easily, to prevent burns to the users. It should be able to remain under 52C [2] at all times even during the baking step. Naturally, it should have limited sharp edges or pointy parts to ensure minimized cuts and other physical damage. The aligner should also have a strong center of gravity and be under 2 pounds [3] to prevent potential harm due to falling or dropping.

c. *Accuracy and Reliability*:

The aligner should be accurate to 100 µm but preferably accurate down to 10 µm. The aligner should also be able to hold the photomasks about 12 µm above each layer. The aligner should be able to repeat the layer making process nearly exactly between all uses. This means that the aligner should be accurate down to 5 µm between runs. However, as long as the aligner works as intended for each individual run, it will serve its purpose.

d. *Life in Service*:

The photomask aligner must consistently maintain similar conditions throughout the duration of usage. Since the aligner has to layer masks over each other to a difference of 10 µm, the photomask aligner must be able to accurately layer masks 5 times to complete tests. The time it takes the photomask aligner to align two to three masks (at most four) will take approximately fifteen minutes. The fifteen minutes includes time it takes to align, bake, and run the UV light process.

e. *Shelf Life*:

It is estimated that the product should last more than ten years [4]. Since the photomask aligner will be made out of material similar to Plexiglass, it will be able to withstand temperatures as low as -40C and as high as 200C . However, room temperature storage is ideal.

f. *Operating Environment*:

The aligner is designed to operate within a teaching environment meaning it must be relatively easy to use. It also must be able to withstand 90-110C during the baking stage of the photolithography as stated previously. Sterilization is not a priority for this device and it will not require a clean room to operate. However, this device will likely be used under a fume hood due to the SU-8 solvent that will be applied to the wafers during the photolithography process [5].

g. *Ergonomics*:

The ergonomics of the photomask aligner must allow the photomasks to be placed into the aligner and adjusted relatively easily. It also is critical that the photomasks are able to be aligned extremely accurately. The aligner will have a feature that allows the user to swivel the mask out of the way to allow the user to bake the wafers without them leaving the aligner. Another critical consideration is the ability of the aligner to maintain alignment throughout the photolithography process to ensure a properly aligned product.

h. *Size*:

The photomask aligner is designed to fit varying wafer diameters and thicknesses. The typical sizes are 3, 4, and 6 inches. The thickness of the wafers ranges but this does not affect the alignment of the photomasks. The size of the aligner is not a critical factor. The only requirement is that it will fit under a fume hood. It does not need to be moved.

i. *Weight*:

Acrylic is a lightweight material, which will be used for the aligner. No weight specification was provided, but an estimate of about under 2 pounds for the aligner is a good gauge of what it should be, as it needs to have a strong center of gravity and be able to prevent damage from falls or chips [3].

j. *Materials*:

Both acrylic and polycarbonate were in consideration for the photomask aligner. Both are lightweight materials that will be able to withstand the temperature range it needs to, while staying under 2 pounds as stated before. Acrylic is more likely to shatter while polycarbonate is more likely to get scratches [6]. Acrylic is also cheaper than polycarbonate, which is big considering the budget of $100. Ultimately, acrylic is the final decision, as scratches would not be good to have for a device that needs to be transparent, and acrylic is much cheaper [7].

k. *Aesthetics, Appearance, and Finish*:

The aesthetic and appearance of the photomask aligner, due to the acrylic material, will be a glossy, polished finish. The appearance will be a small device with three circles that are adjustable in height. It will most likely be the same color throughout and whatever color the client.

2. Production Characteristics

a. Quantity:

Only one alignment mechanism needs to be produced. This alignment mechanism will consist of one rod with three attached mask holders.

b. *Target Product Cost:*

The components needed to construct this mask aligner are the mask holders, the rod to which they are attached, and a means of attaching them. Acrylic is resistant to photolithography so acrylic mask holders, an acrylic rod, and acrylic glue will be used. The acrylic mask holders should cost about $5 [8] a piece, giving a total sum of $15. The acrylic rod will cost about $3.63 [9], and the acrylic glue will cost $10 [10]. None of these prices account for tax or shipping costs, so an additional $5 is added for confidence. Additionally, the acrylic rod and acrylic photomask holders will need to be modified, but that should come free of cost at one of the provided labs. Thus, the total cost to construct the photomask aligner should be around $35.

3. Miscellaneous

a. *Standards and Specifications*:

The photomask aligner is not classified by the FDA because it is not a device intended for clinical use or diagnostic purposes, rather it is used in research and laboratory settings. While there are no specific ASTM standards for this project, all individuals interested in using this device should have an understanding of photomask alignment prior to use of the aligner. This is due to the aligner being used for various techniques such as cell cultures, biochemical assays, mask mold alignment, etc.

b. *Customer*:

The customer is requesting the production of a Low-Cost BioMEMS Photomask Aligner that can provide accuracy between 10 and 100 µm during mask alignment, ideally closer to the 10 µm range. Currently the client creates photomasks in a CAD program, creating alignment marks on each mask [11]. The amount, location, and shape of the alignment marks varies based on preference. As expected with photomask alignment by hand and eye coordination, the resolution is to be around 200-300µm of accuracy at the very best, which is three to twenty times the scale than what is done with the traditional photomask aligner device.

c. *Patient-related concerns*:

Currently, there are no patient-related concerns when it comes to the usage of photomask aligners.

d. *Competition*:

There are existing means of aligning photomasks for comparable research and experimental practices. However, many are quite expensive; the cheapest manual mask aligner sells for under, but in the range of, $7,500 [12], and automated mask aligners sell for even more.

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A. *Material Expenses*

Item	Description	Manufacturer	Mft Pt#	Vendor	Vendor Cat#	Date	QTY	Cost Each	Total	Link
Client-Funded Materials										
Hole-Punch Stamp	Punches 2 holes 3.14 inches apart each with a diameter of ¼ inch. We will use this stamp to punch holes in the masks.	YIKANGHENG	n/a	Amazon	B09C7QWW1L	11/19/2023	1	$8.00	$8.00	https://a.co/d/c1Yvp43
1/8 Inch Diameter, 302 Stainless Steel Round Rod	Stainless steel rod of 1/8 in. diameter; 1 ft. long	MSC	87135	MSCdirect	78803822	11/27/2023	1	$1.76	$1.76	1/8 Inch Diameter, 302 Stainless Steel Round Rod - 78803822 - MSC Industrial Supply
Wafer Holder	Made using Bambu Lab 3D printer; made of ASA			UW-Makerspace		11/29/2023	1	$6.86	$6.86	n/a
1/4 Inch Diameter, 302/303 Stainless Steel Round Rod	Stainless steel rod of 1/8 in. diameter; 1 ft. long	MSC	87139	MSCdirect	78803848	12/1/2023	1	$4.37	$4.37	1/4 Inch Diameter, 302/303 Stainless Steel Round Rod - 78803848 - MSC Industrial Supply
Photomask Aligner Base	Made using Bambu Lab 3D printer; made of ASA			UW-Makerspace		11/29/2023	1	$26.31	$26.31	n/a
Photomask Aligner Base	Made using Bambu Lab 3D printer; made of ASA			UW-Makerspace		12/1/2023	1	$15.25	$15.25	n/a
Epoxy	Epoxy used to connect the alignment to cross			UW-Makerspace		12/1/2023	1	$1.00	$1.00	n/a
Sandpaper	Sandpaper used to sand down our prints			UW-Makerspace		12/5/2023	1	$1.00	$1.00	n/a
Non-Client-Funded Materials										
LabArchives Notebook	Notebook for keeping all of our research, progress, and other					9/30/2023	1	$15.00	$15.00	n/a

	team documents organized									
Final Poster	Purchasing the material required for our final poster					12/12/2023	1	$50.00	$50.00	n/a
								TOTAL:	**$129.55**	

B. *Python Code for Mechanics of ASA v Acrylic*

```
import pandas as pd
import matplotlib.pyplot as plt

# Read data
data = pd.read_csv('material_properties.csv')

# Separate data for ASA and Acrylic
asa_data = data[data['Material'] == 'ASA']
acrylic_data = data[data['Material'] == 'Acrylic']

# Plotting
plt.figure(figsize=(10, 6))

# Plot ASA data in black
plt.scatter(asa_data['Flexural Strain (%)'], asa_data['Flexural Stress (MPa)'], label='ASA',
color='black')

# Plot Acrylic data in red
plt.scatter(acrylic_data['Flexural Strain (%)'], acrylic_data['Flexural Stress (MPa)'],
label='Acrylic', color='red')

# Add labels and title
plt.xlabel('Flexural Strain (%)')
plt.ylabel('Flexural Stress (MPa)')
plt.title('Flexural Stress vs Flexural Strain for ASA and Acrylic')
plt.legend()

# Show the plot
plt.show()
```

C. *Python Code for Testing Graphs*

```
import pandas as pd
import matplotlib.pyplot as plt
plt.style.use('_mpl-gallery')

data = pd.read_csv("BME200Data.csv")
data
```

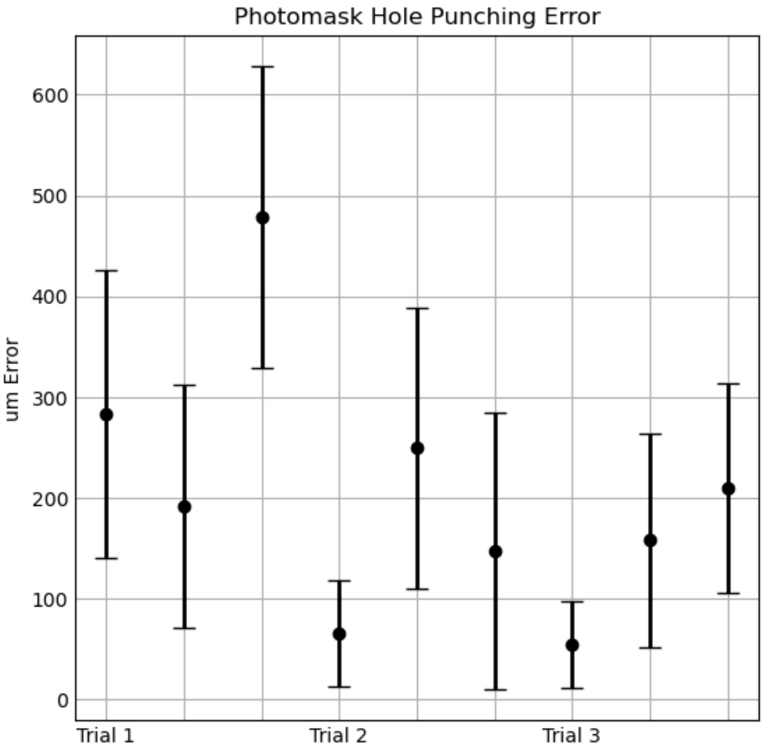
	Trial Number	Hole Alignment	um	Human Error (um)	Mask to Wafer Error
0	Trial 1 Mask 1	Top to Middle	282.58	142.70	0.97
1	Trial 1 Mask 2	Middle to Bottom	191.58	120.70	0.90
2	Trial 1 Mask 3	Top to Bottom	478.46	149.26	0.96
3	Trial 2 Mask 1	Top to Middle	65.41	52.48	0.50
4	Trial 2 Mask 2	Middle to Bottom	249.63	139.18	0.68
5	Trial 2 Mask 3	Top to Bottom	147.41	137.03	0.91
6	Trial 3 Mask 1	Top to Middle	54.25	43.13	0.84
7	Trial 3 Mask 2	Middle to Bottom	157.97	105.60	0.98
8	Trial 3 Mask 3	Top to Bottom	209.84	104.37	0.80

```
x = data["Trial Number"]
y = data["um"]
yerr = data["Human Error (um)"]

x_labels = ["Trial 1","","", "Trial 2","","", "Trial 3","",""]

fig, ax = plt.subplots(figsize=(5, 5))
ax.errorbar(x, y, yerr, fmt='o',color = "black",ecolor = "black", linewidth=2, capsize=6)
```

```
ax.set_ylabel("um Error")
ax.set_xticklabels(x_labels ,rotation = 0)
ax.set_title('Photomask Hole Punching Error')
plt.show()
```



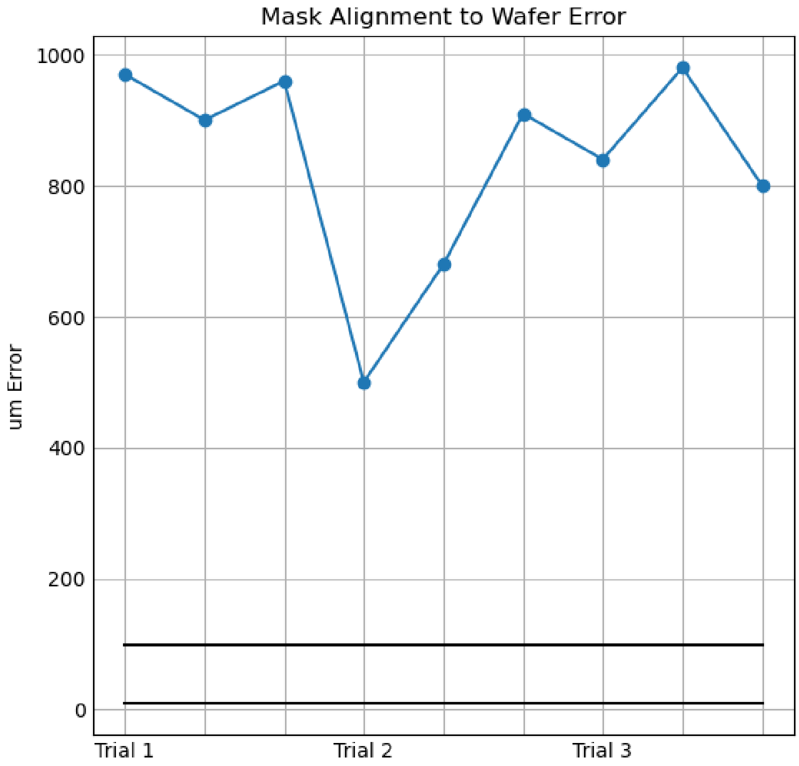
```
data["Desired Mask to Wafer Error Low"] = 10
data["Desired Mask to Wafer Error High"] = 100
data["Mask to Wafer Error(um)"] = data["Mask to Wafer Error"] * 1000
data
```

	Trial Number	Hole Alignment	um	Human Error (um)	Mask to Wafer Error	Desired Mask to Wafer Error Low	Desired Mask to Wafer Error High	Mask to Wafer Error(um)
0	Trial 1 Mask 1	Top to Middle	282.58	142.70	0.97	10	100	970.0
1	Trial 1	Middle to Bottom	191.	120.70	0.90	10	100	900.0

	Mask 2		58					
2	Trial 1 Mask 3	Top to Bottom	478.46	149.26	0.96	10	100	960.0
3	Trial 2 Mask 1	Top to Middle	65.41	52.48	0.50	10	100	500.0
4	Trial 2 Mask 2	Middle to Bottom	249.63	139.18	0.68	10	100	680.0
5	Trial 2 Mask 3	Top to Bottom	147.41	137.03	0.91	10	100	910.0
6	Trial 3 Mask 1	Top to Middle	54.25	43.13	0.84	10	100	840.0
7	Trial 3 Mask 2	Middle to Bottom	157.97	105.60	0.98	10	100	980.0
8	Trial 3 Mask 3	Top to Bottom	209.84	104.37	0.80	10	100	800.0

```
x = data["Trial Number"]
y1 = data["Mask to Wafer Error(um)"]
y2 = data["Desired Mask to Wafer Error Low"]
y3 = data["Desired Mask to Wafer Error High"]
```

```
fig, ax = plt.subplots(figsize=(5, 5))
ax.scatter(x, y1)
ax.plot(x,y1)
ax.plot(x, y2, color = "Black")
ax.plot(x, y3, color = "Black")
ax.set_xticklabels(x_labels ,rotation = 0)
ax.set_ylabel("um Error")
ax.set_title('Mask Alignment to Wafer Error')
#plt.fill_between(x,y2, y3, color = "Black")
```



D. Protocol for Use

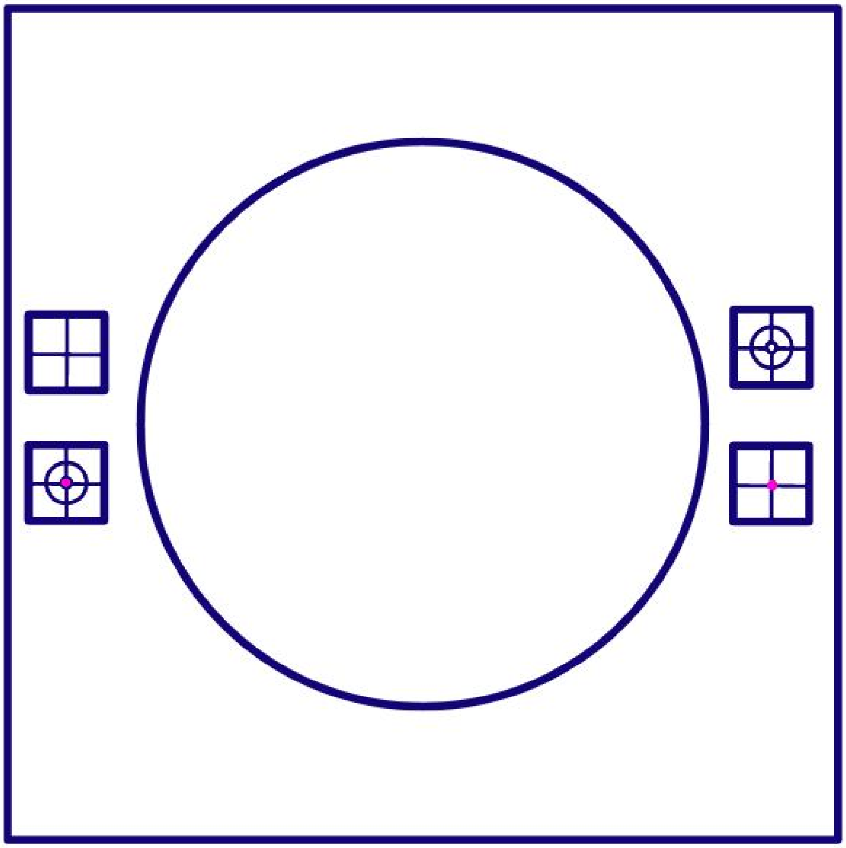
Photoresist Protocol Using BioMEMS Photomask Aligner

Before starting, do the following:

- Locate your desired photoresist
- Locate a wafer
- Locate the air pump and ensure that it is able to seal correctly to the spinner. There should be minimal escaping air from the connection between the air pump and the spinner.

To prepare the pre-cut masks:

- Place the wooden cross with the pink alignment dots facing upwards under a microscope.
- Prepare some pieces of tape so that they will be readily available. At a minimum, you will need 6 pieces of tape.
- Take the first mask and align it using the microscope so that its lower alignment crosses line up with the pink alignment dots. The top of the mask should be placed at the top of the cross, to ensure that the holes are not punched upside down. The pink alignment dots should be in the center of the crosses. It should be as seen below:



-
- After you have aligned the pink alignment dots on both sides of the mask, tape the mask into place.
- Repeat the alignment and taping process for the next two masks. At the end, you should have 3 masks stacked on top of each other which have all been individually taped into place. Do not attempt to hole-punch more than 3 masks.
- Then, take the entire cross-mask complex and flip it upside down so that the masks lay flat on the table and the cross rests on top of them.

- Then, slot the cross-mask complex (still upside down) into the hole-punching stamp. Align the middle of the cross with the triangle that is in the middle of the hole-punching stamp.
- The cross-mask complex should only be able to fit a certain distance into the hole-punching stamp due to the bar that sticks out and stops it.
- Finally, recheck the alignment of the middle triangle to ensure that the masks are centered and then press down firmly on the hole-punch. Try to keep steady so as to make sure that the holes get punched in the correct spots.
- Now, you can remove all three masks from the cross and continue.

To prepare the base:

- If not already assembled, assemble the base by inserting the alignment pillars into the holes of ¼ inch diameter in the base. They should fit snugly but should not need to be forced. If they do not fit snugly and/or need to be forced, you will need new alignment pillars.

To prepare the photoresist:

- Coat
    - Connect the air compressor to the spin coater.
    - Put aluminum foil covering over the spinner so that the excess photoresist does not fly everywhere.
    - Center the wafer on the spinner and put a quarter of a drop (~3 mL) of the correct photoresist on the wafer (The type of photoresist you use will depend on how thick you want the layer to be).
    - Press start and allow it to spin following the spin speeds described in the SU-8 protocol. https://kayakuam.com/products/su-8-photoresists/ For example a 100 um layer with SU-8 100:
        - Spread Cycle: Ramp to 500 rpm at 100 rpm/ second acceleration. Hold at this speed for 5–10 seconds to allow the resist to cover the entire surface.
        - Spin Cycle: Ramp to final spin speed of 3000 rpm at an acceleration of 300 rpm/second and hold for a total of 30 seconds.

- Soft Bake
    - Level the hotplate
    - Follow the directions for the SU-8 being used. For example a 100 um layer with SU-8 100:
        - Slowly ramp (5 °C / min) to 65 °C and hold for 10 minutes
        - Slowly ramp (5 °C / min) to 95 °C and hold for 30 minutes.
    - Turn off hotplate and allow the plate to cool before continuing.

- Exposure
    - Turn on the Omnicure 365 nm UV light and give it 20 minutes to warm up (while the hotplate is cooling).
    - Measure the UV intensity with the radiometer in mW/cm2.
    - Calculate the exposure time based on the directions which specify the energy needed to treat the desired thickness and type of SU-8. For example a 100 um layer with SU-8 100:
        - ~500 mJ/cm2 (generally a few minutes is needed).
        - Seconds = desired mJ/cm2 / measured mW/cm2
    - Place the wafer in the device and slide the alignment rectangle into place. The wafer should now be held steady by the device. Adjust the alignment rectangle so that it lines up snugly with the long, flat edge of the wafer. Be careful not to damage the photoresist in this process.
    - Place a pre-cut mask on the alignment poles and slide down until it rests gently on top of the photoresist. Place the device under the UV light for the appropriate time.

- Post Exposure bake
    - Follow the directions for the SU-8 being used. For example a 100 um layer with SU-8 100:
        - Place the wafer on the hotplate
        - Allow the hot plate to heat to 65 °C and hold for 1 minute.
        - Allow the hot plate to heat to 95 °C and hold for 10 minutes.
        - Turn off the hotplate and allow the plate to cool before continuing.
    - Repeat the process starting at coat for each additional layer. Note additional layers should be baked longer.

- Develop
    - Place the wafer in used SU-8 developer for the time specified in the SU-8 directions. For example a 100 um layer with SU-8 100: 10-20 minutes
    - Finish in new SU-8 developer for 5 minutes

- Repeat the “To prepare the photoresist” 2 times to finish your layered photoresist.

- Rinse and dry
    - When finished, turn off the UV light and all other devices used and clean up.