UNIVERSITY OF WISCONSIN-MADISON
DEPARTMENT OF BIOMEDICAL ENGINEERING
BME 400 DESIGN

BioMEMS Photomask Aligner

Mid-Semester Design Report

Client: Professor John Puccinelli, PhD

Advisor: Professor Willis Tompkins, PhD

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Abstract

Microelectricromechanical Systems (MEMS) are devices with components generally measuring less than 100 µm are often used to study biological 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. Three 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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Background

Biological MicroElectroMechanical Systems (BioMEMS)

The scope of our design project revolves around the field of Biological Microelectromechanical Systems (BioMEMS), which is a subset of the larger field known as Microelectromechanical Systems (MEMS). MEMS processes construct both electrical and mechanical components and can be dated back to 1954, although the majority of inventions and discoveries have come in the last 40 years.[1] BioMEMS can be defined simply as the science of very small biomedical devices. A few reasons why biology is an appropriate field to mix with MEMS are that MEMS deal with cell sized devices, involve sub-cellular interactions, and allow for implantable devices. Typically a BioMEMS device has at least one dimension that is between 100 nm and 200 µm. Additionally, BioMEMS devices can be thought of as new materials that aid our understanding of the microenvironment or biocompatibility. While the field of BioMEMS is relatively new, it is growing quickly and involved in a high number of biomedical and biological devices. Microsensors, stents, cardiac pacemakers, and muscle stimulators are just a few of the many products commonly used today that have BioMEMS components as are those shown in Figure 1.[2] BioMEMS applies to this project through the complementary field of photolithography.

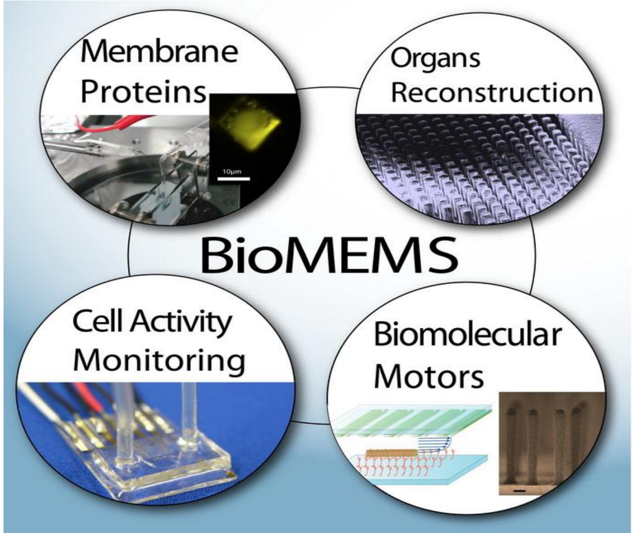

Figure 1: Schematic showing the makeup of BioMEMS. [3]

Photolithography

Photolithography can be defined as an optical means for transferring a pattern onto a substrate. In our case, the pattern is something that will be used to make a PDMS mold for microfluidic or other lab purposes and the substrate used is a silicon wafer. Photolithography that applies to our project can be broken down to seven basic steps. First the wafer must be cleaned chemically to remove all particulate matter that may be on the surface of the wafer. Next an optional barrier layer is formed on top of the silicon wafer. This barrier layer is typically an insulating material such as silicon dioxide (SiO_2). The next step is “coating” the surface of the wafer with a light-sensitive material called photoresist by putting the photoresist on the surface and then using a process called spinning to evenly coat the surface. The speed and length of the spinning can be adjusted to change the thickness of the photoresist applied to the surface. Spinning speeds are determined from manufacturer guidelines for a given photoresist substance. Subsequently the wafer is placed on a hot plate for the step known as “pre-bake” or ”soft-bake.” This step hardens the photoresist slightly as well as causes the evaporation of many of the solvents in the photoresist. The next phase is the aligning of the photomask, which is the most important step in our design process because this is the step that we are attempting to improve. There are various techniques to align the mask, which will be discussed in depth later in this report. Essentially a photomask, in our case a transparency with a high resolution print pattern on it, is placed over the wafer and photoresist. For the initial layer of photoresist, it is only important that the mask line up generally over the wafer. However, it is very common to go through this entire process two or three times for subsequent layers, which creates more problems in alignment as the process is repeated. In our case, the alignment markers are printed on the photomask which aid the user in alignment from one layer to the next. After the photomask has been correctly aligned over the wafer, the photoresist is exposed to ultraviolet (UV) light. The duration and exposure energy that the photoresist should be exposed to the UV light varies based on which photoresist is used. Photolithography is a binary pattern transfer, meaning that either the photoresist is exposed or it is not. This is shown additionally in Figure 2, which depicts how photolithography can use positive or negative photoresists.

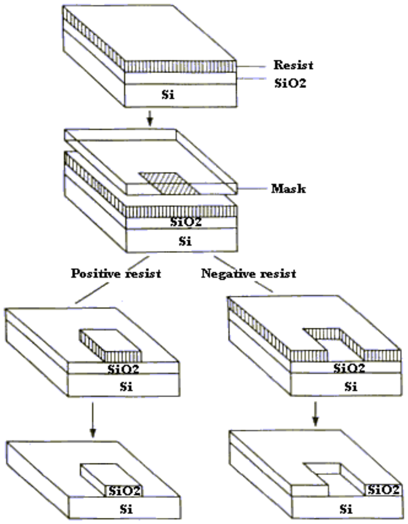

Figure 2: Differences between negative and positive resist are shown. In positive resist, the exposed substrate remains whereas for negative resist, the exposed substrate is eventually removed. [4]

Following the UV exposure, a developer is used to remove non-cross-linked epoxy from the wafer, since our examples use negative photoresist. When completing multiple layers, this step may be skipped in all layers except the final layer. The final step for the wafer and photoresist is a second bake, often called the “hard bake,” which further hardens the photoresist and increases adhesion of the photoresist to the silicon wafer substrate. These basic steps to photolithography will be discussed in further detail where applicable to our design in the remainder of this report.

Current Alignment Techniques

There are currently multiple methods of aligning photomasks for BioMEMS purposes. The first method is with the assistance of an electronic aligner. The Karl Suss MA6 Mask Aligner, shown in Figure 3, is an example of a digital aligner that provides an accuracy of around 0.5 microns. Electronic aligners such as this are very accurate, however are very costly; a used MA6 aligner can run $30,000 and up. Benefits of this method include the high resolution and accuracy as well as versatility since digital aligners can accept wafers of 2, 3, 4, and 6 inch sizes. As a more cost-efficient alternative, Dr. Justin Williams at The University of Wisconsin – Madison uses a simpler machine designed by a UW graduate student for 3D micro-system production.

The system used by Dr. Williams utilizes manual alignment techniques such as gears and old microscope parts. As shown in Figure 4, the eyepieces are positioned directly above the wafer. The photomasks are taped to a piece of glass that separates the UV light source from the wafer. 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.

Figure 3: Karl Suss MA6 mask aligner. This device is designed for high-tech professional applications and includes digital toggles and a visual monitor. [5]

The final alignment technique we are directly trying to improve upon is a manual alignment method in which everything is aligned by eye. Professor John Puccinelli, also from University of Wisconsin – Madison designs his photomasks in a CAD program, creating alignment marks on each mask. The amount, location, and shape of the alignment marks varies based on preference. An example of these photomasks alignment marks can be seen in Figure 5. As can be expected, resolution is the worst for this method being around 200-300µm of accuracy.

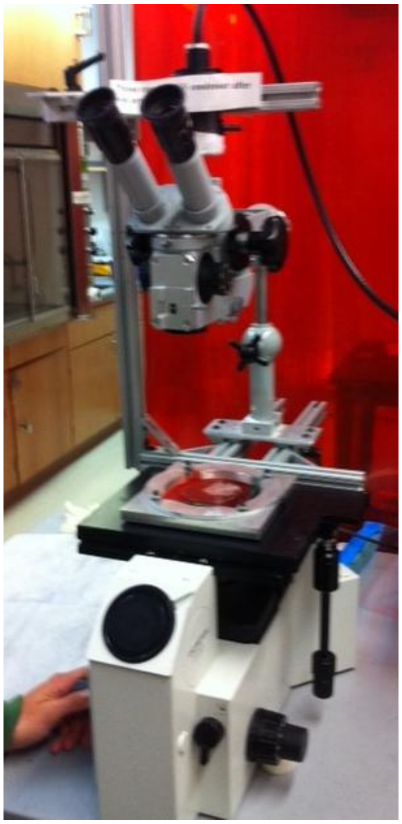

Figure 4: Photomask aligner used in Dr. Justin Williams lab at the University of Wisconsin-Madison. The aligner simply uses an old microscope stage for moving the mask.

Design Statement

Our goal for this semester is to design a photomask aligner that stays under our $200 budget and provides us with accuracy between 10 and 100 µm. We also need our device to be simple to operate with a minimal amount of mechanical parts. Eventually we will want to publish an instructional manual for other labs to use in the creation of their own aligner. We have brainstormed three ideas that will meet all of our needs.

Key Design Factors

Figure 5: Sample alignment marks designed in CAD currently used with the manual alignment technique by Professor Puccinelli. [6]

Wafer Background

When developing methods by which to align photomasks to previously developed layers on the silicon wafer the geometry of wafer itself becomes a controlling factor. The wafers for which this aligner should ideally function with are referred to as 3” and 6” diameter wafers. In the labs at the University of Wisconsin-Madison (the target location for this aligner prototype), all wafers are ordered through WRS Materials. The wafers used in the biotechnology BioMEMS sector are commonly rejected silicon wafers from the electronics industry. Typically when ordering, more demand is placed on cost as compared to specific crystal direction or sizing control of the wafers (specific part number). For the wafers commonly ordered, WRS Materials gives these sizing guarantees [7]:

Wafer Size	Diameter	Flat Angle	Flat Length
3”	76.2 ± 0.3 mm	± 1º	22.22 ± 3.17 mm
6 inch (150 mm)	150 ± 0.2 mm	± 1º	57.5 ± 2.5 mm

Table 1: Wafer specifications as supplied from WRS Materials (current vendor used by UW-Madison BME).

It should be noted however, that there are multiple vendors who sell these wafers; each vendor’s sizing specifications vary from each other slightly. As seen in Table 1, the diameter of WRS Material wafers can vary as much as 600 microns – significantly more than the allotted 10-100 microns allowed in the design constraints.

In addition to the various diameter sizes, silicon wafers used in BioMEMS typically have a certain geometry which is indicative of their underlying crystalline orientation. The wafers are grown from a crystal with a given regular crystal structure. Silicon has a diamond cubic structure with a lattice spacing of 5.43071 Angstroms (0.5430710 nm) [8]. When these silicon wafers are cut into wafers, the silicon surface is arranged in a specific direction (crystal orientation). The orientation is determined by the “Miller index”, which are a set of rules which determine how the crystalline structure is orientated. The common face orientations used with silicon wafers are [100] and [111] [9]. The wafer has flat edges cut into its sides which are indicative of the face orientation of that wafer. Most commonly, there are one or two flats on the 3” and 6” wafers. The tolerances of these flat angles and lengths as supplied by WRS Materials are also shown in Table 1 above.

Laser Cutting

As previously described, all of the photomasks are printed on high-resolution printers and are therefore typically out-vended. Most alignment techniques don't specify a specific method to cut the photomask from the transparency. Typically, the photomask is simply cut in any shape/size with a scissors. One thought heavily pursued in the prospective designs for this project utilize a laser printer/cutter. The UW-Madison BME Department has a 40-Watt Epilog industrial printer with resolution control between 75 and 1200 dpi. This equates to a maximum resolution of 21 microns. By cutting specific geometries from the photomask transparency, the geometry is under heavy control and can be used in the alignment technique.

Design Alternatives

Ejector Well

The ejector well design utilizes the wafer size and shape as an alignment technique. The design essentially is a stock piece of material with the wafer profile milled out to the worst case dimensions of each wafer size (3 inch and 6 inch wafers). After spin-coating the wafer in the photolithography process, the wafer is dropped into the profile well base. The photomask transparency is cut with the laser cutter. All of the layers are printed on the same transparency from the high-resolution printing vendor. Each layer is printed at a specific distance (highly controlled) from each other on the transparency. Then the same spacing distances are used when cutting out the layers with the laser cutter. Beyond simply cutting the mask outline, two holes are also cut; these holes fit over two positioning rods which are tightly controlled in the machining tolerances of the ejector well base. The tight tolerance of the rod positions and the resolution of the holes cut on the photomask by the laser cutter work together to control the repeatable placement of the mask. The tight fit of the wafer into the well control the repeatable accuracy of the wafer position. A sketch of the design concept is shown here in Figure 6. The base also would require an ejection pin (shown at the bottom of the well profile in Figure 6) to pop

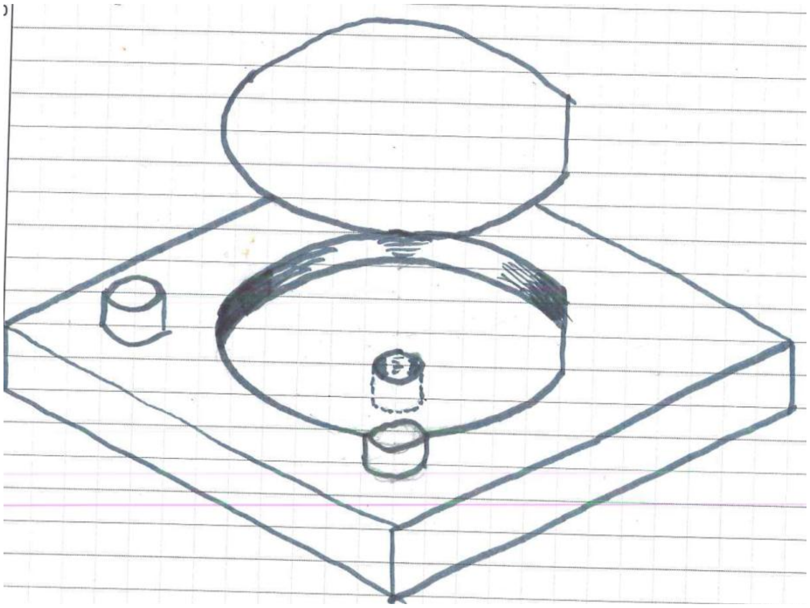

Figure 6: Ejector Well design alternative. The wafer is dropped into a milled out profile and the photomask is aligned by two pins that constrain two holes cut from the photomask.

the wafer out of the well profile.

Despite the requirement to cut out the photomask with extreme accuracy on the laser cutter as opposed to simply cutting it with a scissors, the overall alignment time for this design is significantly reduced. The mask is theoretically perfectly aligned as soon as it is positioned over the alignment rods. This would also contribute to a highly repeatable alignment process. However, the tolerances of the wafers, shown previously in Table 1 already exceed the target resolution. Therefore, just by accounting for the variation in wafer sizing, the desired accuracy cannot be achieved. Furthermore, the machining tolerances would take from the overall accuracy of the device. Although the machining tolerances could be held very tight, this would significantly elevate the production/machining cost of the base. Yet another drawback of the design is that separate devices would be required for the 3-inch diameter and 6-inch diameter wafers.

Wafer Threaded Lock

The wafer threaded lock uses a similar concept in aligning the photomask in that holes are again cut from the transparency with the laser cutter to fit tightly over alignment rods on a base that secures the wafer. However, in this design alternative, the flat of the wafer is placed against an alignment flat on the base. The wafer is then pinned by a locking-alignment bar which rotates about a pin on the wafer holder base. By tightening a threaded screw, the wafer is pinched between the alignment base flat and the locking bar. Repeatability is controlled in this manner since the wafer is in the exact position for each layer. A 3-dimensional CAD rendering of this design alternative is shown in Figure 7.

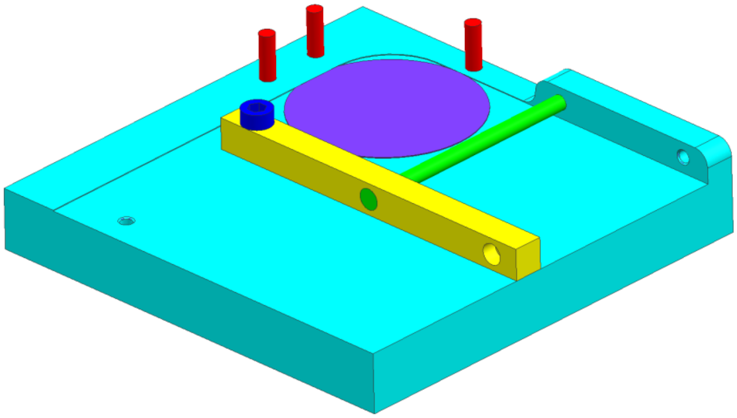

Figure 7: The Wafer threaded lock design alternative utilizes alignment rods which stick through the laser cut holes in the transparency to lie over the wafer, which is held in the same place for each layer by an adjustable locking rod.

The wafer threaded lock design is compatible with both 3-inch and 6-inch wafers. Furthermore, the design is made up of very manufacturable components, with less critical dimensions than the other design alternatives. This would account for a more economical cost of the wafer threaded lock design. However, the repeated exact positioning of the wafer could be a concern since any variation in the alignment locking bar between layers could throw off the accuracy of the device significantly. Extreme care would be required to ensure the positioning of the wafer is consistent between each layer of a particular master. Since the edges of the wafer are used to ensure this consistent alignment and orientation, all edges would need to remain clear of substrate from spin-coating.

Tapered Screws

Similar to the wafer-threaded lock design, the tapered screw design would secure the wafer in a consistent position with an alignment locking rod as seen in Figure 7. However, to accommodate for potential variations in the positions of the wafer when secured, the holes cut in the photomask transparency would be slightly oversized. The alignment pins from the previous design alternatives no longer exist; rather the base has multiple tapped and threaded holes surrounding the wafer location. Each of these holes accommodates a tapered screw. By placing these screws through the corresponding holes in the photomask, the transparency position can be adjusted. As one screw is backed out, it loses contact with the laser-cutout hole in the photomask. An opposing screw can then be tightened to pull the mask in that direction. Figure 8 shows a simple cross-sectional depiction of the design concept.

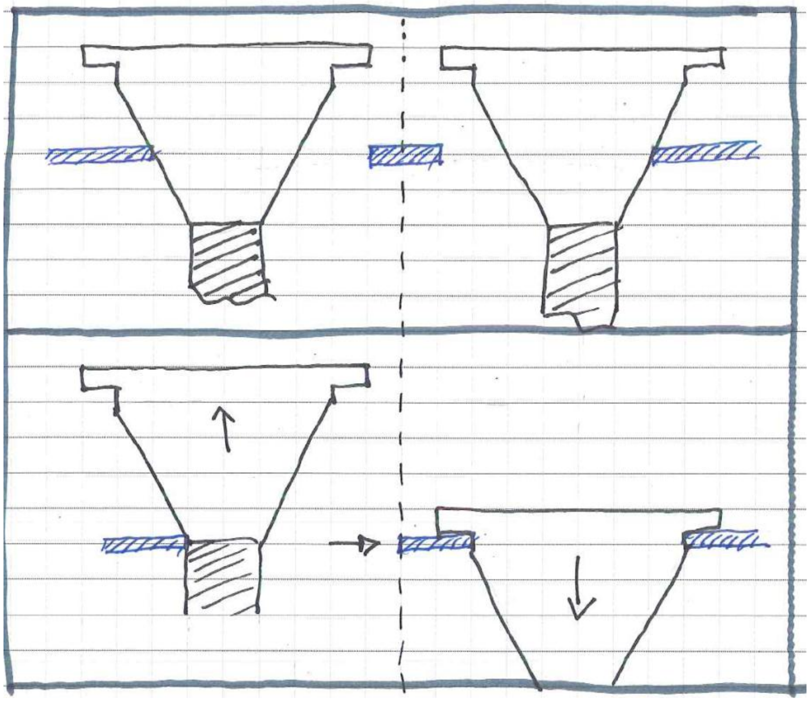

Figure 8: The tapered screw design alternative allows additional adjustment of the photomask by backing-out and tightening-down tapered screws. As shown here in a cross-sectional view, the top diagram has two screws at their middle depth to constrain the photomask. By backing out the left screw and tightening down the right screw (bottom diagram), the photomask is shifted to the right.

The tapered screw design offers increased flexibility for positioning the photomask with the backing out and inserting of the tapered screws. This adjustability can compensate for the inconsitent positioning of the wafer. The solution bolsters a very simple yet robust technique by which to position the photomask. However, the adjustment is very dynamic, since repositioning the mask requires tightening some screws while backing others out.

Design Matrix

A design matrix was constructed to evaluate the three designs and choose which design will continue on to prototyping [Table 2]. Evaluation categories include Accuracy, Cost, Manufacturability, Reproducibility, and Ease of Use. These categories were then given a weight based on importance. Cost received the greatest weight, as the project budget is limited to $200. Accuracy was also highly weighted because it will be our main method to determine the device's success. Reproducibility was given the least weight because the ability for others to recreate our alignment device will not be significantly important until a successful prototype is developed.

Criteria	**Alternative Designs**		
Considerations (Weight Multiplier)	**Ejector Well**	**Wafer Threaded Lock**	**Tapered Screws**
Accuracy/Precision (x7)	2	3	4
Cost (x8)	3	5	4
Manufacturability (x2)	2	4	4
Reproducibility (x1)	4	3	3
Ease of Use (x2)	5	4	3
Total	56	**80**	77

Table 2: Design matrix with three alternative designs scored against a set of weighted criteria regarding the design problem. Each criteria was rated on a 1-5 scale and then multiplied by its weight.

Final Design

Based on the design matrix evaluations we have chosen to continue with the Wafer Threaded Lock design, with the option of adding a Tapered Screw alignment system. Our hope is that the alignment rods will provide a sufficiently accurate registration, however variabilities in the laser cutter or in wafer shape may require the addition of the tapered screws for fine tuning the alignment. Additionally, on this device the swing arm which locks the wafer in place can be moved to allow for both 3” and 6” wafers.

Future Work

Going forward with the wafer threaded lock design, we will further enhance our current 3-D CAD models using NX Unigraphics, specifically focusing on making sure that tolerances are all correct and appropriate to achieve the final tolerances of the design. After completing our design we plan to go forward with fabrication. We will fabricate ourselves the parts that do not require high tolerances and then pay either the University of Wisconsin-Madison College of Engineering shop to manufacture the remaining parts or hire a known, reliable machinist at Tosa Tool (Madison, WI).

After our design has been fabricated we have a series of tests that will verify accuracy and precision as well as improvement over the techniques currently used by Dr. Puccinelli and Dr. Williams in their labs. To begin, we will test the accuracy of the laser cutting printer to make sure that it can indeed cut to 21 µm resolution. An additional test will be to actually go through the entire photolithography process with our design testing the accuracy of the final pattern when using both 2 and 3 layers. Finally, we will compare our design to the current techniques being used by using accuracy, duration of alignment process, ease of use, and repeatability as important factors to analyze. Clearly, the most important factor will be the accuracy that we are able to accomplish.

When we have finished testing we will make any necessary adjustments or improvements to our design and possibly have changes made to the fabrication of the design. One possible addition that could be added to the design at this point would be the tapered screws which were discussed earlier. This addition would be relatively simple to add, and ideally improve the accuracy of the device. When we have a device that meets all of the client requirements we plan to write a “Do-it-yourself” (DIY) report so that other labs and scientific groups may use our design as a cost-efficient, yet accurate alternative to what currently exists for BioMEMS photomask alignment.

Conclusion

In an effort to design a more cost-efficient photomask aligner which can still achieve relatively high-resolution accuracy, the design team created three design alternatives. The alternatives were placed into a matrix with weighted design criteria specific to the potential success of the device. By evaluation of the matrix, the wafer threaded lock design has been chosen as the design to pursue with fabrication and testing. It is also the goal of the team to create a ‘do-it-yourself’ type manual to submit for which other researchers can build their own similar aligner at a much lower cost than the high-tech aligners sold on the market.

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Appendix

Product Design Specifications

BioMEMS Photomask Aligner

Nathan Retzlaff, William Zuleger, Ross Comer, Paul Fossum

Function: An aligner is desired that will hold the master and photomask in place aligning the layers to 10 um resolution. This aligner may or may not utilize a microscope to assist in aligning. Many commercially available aligners are available, however, they are extremely expensive and over complicated. The aligner would be used primarily for teaching purposes. If a successful prototype can be made under specifications, a manual for building and using future aligners could be written and published.

Client requirements:

- Maintain a budget of under $200

Design requirements:

- Aligner must be compatible with both 3 in. and 6 in. sizes of silicon wafers and masks
- Alignment accuracy desired to be 10µm, with a realistic target of 100µm

1. Physical and Operational Characteristics

a. *Performance requirements*:

- Aligner will be used multiple times per week, generally by experienced graduate students and professors
- Could be exposed to UV light on regular basis depending on design solution

b. *Safety*:

- Be aware of UV light exposure and any warnings on epoxies used on silicon wafers

c. *Accuracy and Reliability*:

- Consecutive layers will ideally be positioned within 10-100 microns of accuracy
- Precise alignment must be repeatable every time device is used

d. *Life in Service*:

- 5 years of use in research lab on daily to weekly basis

e. *Operating Environment*:

- Prolonged exposure to UV light, depending upon design
    - Each usage includes exposure to UV light at 350-400nm for 30-60 seconds
- Storage environment is standard room temperature lab

f. *Ergonomics*:

- When using a microscope for alignment, a glare from the light may inhibit ability to align the photomask
- Simple user-product interface

g. *Size*:

- Should be compatible with 3 and 6in disks, therefore not exceeding a 1ft^3 volume
    - 3in wafers ordered from WRS Materials (current vendor) have a diametric tolerance ±300µm with flat location on <110> plane ±1 degree and flat length of 22.22±3.17mm
    - 6in wafers ordered from WRS Materials (current vendor) have a diametric tolerance ±200µm with flat location on <110> plane ±1 degree and flat length of 57.5±2.5mm
- Ideally the device would be portable so as to be used in various labs

h. *Weight*:

- Not to exceed 10 pounds in total weight

i. *Materials*:

- No restrictions to material at this time in design process
- Materials used in procedure include SU-8 100 epoxy (from MicroChem Corp.)

j. *Aesthetics*, *Appearance, and Finish*:

- Aligner should appear professionally finished

2. Production Characteristics

a. *Quantity*:

- One unit with potential future manual for DIY construction

b*. Target Product Cost*:

- Under $200, as current photomask aligners are significantly more expensive

3. Miscellaneous

a. *Standards and Specifications*:

- Not applicable at this time in the design process

b. *User concerns*:

- Easy to train new users on aligner
- Trouble shooting should not require any advanced knowledge of the design

c. *Competition*:

- Current devices do exist and are exceptionally expensive, but we have not performed an extensive literature search