DEVELOPMENT AND FABRICATION OF SILICON V-GROOVES FOR SPATIAL
POSITIONING OF OPTICAL FIBERS

By

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To my wife, Brittany, and my newborn son, Silas
ACKNOWLEDGMENTS

I would like to thank my Lord and Savior Jesus Christ for getting me to this point in my academic career. I know that he has blessed me tremendously. I would also like to thank my adviser, Dr. Tony Schmitz, for the fantastic guidance he has offered me during my tenure in graduate school.
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By

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Chair: Tony Schmitz
Major: Mechanical Engineering

Increased fabrication capabilities for micro-electro-mechanical systems (MEMS) have enabled the development of new microsensors. For example, this work supports the development of an optical shear stress sensor for fluid film measurements. The use of optical fibers as part of the transduction scheme requires that the fibers be positioned accurately with respect to the sensor and each other. To support this requirement, the fabrication of v-groove fiber packages was explored to enable passive alignment of the fibers. The v-grooves were fabricated from bulk silicon with an anisotropic etchant.

Three v-groove geometries were selected and 10 separate packages of each geometry were assembled. These packages were then imaged using a microscope/camera combination and image analysis was performed to identify the final dimensions. For two of the cases, the v-groove was shallow enough that the fiber extended beyond the top of the silicon surface. In the other case, the groove width and depth were selected to exactly capture the fiber (i.e., the top of the fiber was designed to coincide with the silicon surface). Due to uncertainty in the rotation of the wafer flat (which was used for mask alignment during etching) with respect to the crystallographic angle of the silicon, the v-grooves were too wide and deep in all instances. For the
shallow v-groove cases, the fiber still protruded from the top of the v-groove so that a combination of the v-groove and a glass cover constrained the fiber at three points. This yielded accurate lateral placement of the fiber, but a bias in the vertical placement. For the ideal v-groove dimensions, however, the increased width and depth lead to a scenario where the fiber was free to be arbitrarily positioned within the v-groove, even when the glass cover was in place. This caused significant errors in both the lateral and vertical positioning of the fiber center.

The primary conclusion of the work is that rotation of the wafer flat with respect to the crystallographic angle of the silicon is the largest source of uncertainty in the final v-groove geometry. For example, when a 5 mm long groove is rotated just 1 degree, an 87.5 µm error in groove width is obtained. This is a significant error for fiber diameters that are generally on the order of 100-200 µm. For improved accuracy in fiber placement, it was determined that the groove geometry should be selected so that, even with uncertainty in the wafer rotation, the fiber protrudes slightly from the v-groove. This provides two points of constraint by the groove with the third provided by a cover which completes the fiber package.
CHAPTER 1
INTRODUCTION

Continuous increases in micro-electro-mechanical systems (MEMS) fabrication capabilities have resulted in significant interest in the development of new microsensors based on MEMS technology. Many physical properties may be measured with these microsensors, including temperature, pressure, and skin friction, which are important for aerospace applications. Skin friction is used to characterize the flow over the surface of an object; this information can be used to improve the performance of vehicles. Similarly, drag is an important property that can be characterized by measuring pressure differentials.

MEMS pressure sensors may be used for measuring pressure differentials along the surface of a vehicle travelling in a fluid. These sensors offer a small package that typically measures pressure using a diaphragm. The pressure sensor contains a cavity with a small hole for equalization purposes. As the pressure outside the cavity changes, the inside of the sensor remains at a relatively constant pressure. The pressure differential causes a deflection in the diaphragm which may be measured using capacitive or interferometric methods, for example.

Shear stress may be measured using an H-bar sensor [1]. The shear-measuring device described by Horowitz et al. is made of silicon and Pyrex and offers the benefits of a small package and the ability to perform high frequency measurements. The sensor implements a floating element that moves with respect to the sensor body when a force is applied. The element is subjected to the flow and a resultant force causes a displacement of the element. The element is held in place using four tethers that provide resistance to shear. The element is located inside a cavity in silicon which offers
the opportunity for flush mounting. The element displacement may be described using Euler-Bernoulli beam theory as

\[ \delta = \tau_w \frac{L_e W_e}{4E t} \left( \frac{L_t}{w_t} \right)^3 \left( 1 + \frac{L_t}{L_e W_t} \right), \]  

(1-1)

where \( \tau_w \) is the wall shear stress, \( L_e \) is the length of the element, \( w_e \) is the width of the element, \( E \) is the elastic modulus of the material, \( t \) is the thickness of the tethers, \( L_t \) is the length of the tethers, and \( w_t \) is the width of the tethers [2]. The integer value of four in the denominator of the first fractional term represents the four tethers holding the floating element. The measurement of the displacement by Horowitz et al. is accomplished using observation of a Moiré optical pattern on the underside of the floating element and the bottom of the sensor cavity. The fringe pattern provides an amplification of the floating element displacement so that a very small movement may be observed by the camera as a large motion. The pitch of the pattern, \( G \), is given in relation to the minor pitches, \( g_1 \) and \( g_2 \), as [3]

\[ \frac{1}{G} = \frac{1}{g_1} + \frac{1}{g_2} \]  

(1-2)

The observation of this fringe pattern was accomplished using a CCD camera in the Horowitz et al. study. The sensor had the potential to measure shear stress for relatively low temperature due to its materials. Silicon-based sensors are limited to about 200 deg C due to changes in the properties of silicon and a deterioration of p-n junctions between silicon substrates [4]. Additionally, in high-speed applications it is possible that the temperature of the sensor could exceed the melting points of silicon and Pyrex. Finally, the sensor application domain is limited by the selection of a camera as part of the transduction technique.
A potential material for fabrication of high-temperature sensors is sapphire. Sapphire is known for its good thermal properties and stable elastic modulus at very high temperatures. In addition to changing the sensor material, the local CCD camera in the floating element shear stress sensor could also be replaced by optical fibers (which transmit the deflection information to a remote location). Sapphire optical fibers may be placed behind the sensor in a fashion that would enable observation of the sensor in four locations as shown in Figure 1-1.

Figure 1-1. Moiré fringe pattern

A quadrature phase detection technique may be employed to measure the periodic pattern [5] which results from deflection of the floating element. By this technique, light is passed through the fibers and is incident on the Moiré fringe pattern. Much of the light from the fibers passes through the sapphire, while the remaining light is reflected back into the fibers with some losses. The light is then transferred through a 1x2 optical coupler to four photodiodes. The fibers detect differing intensities which depend on the period of the Moiré fringe pattern.
The optical fibers must be in a package that can hold the fibers orthogonal to the sensor over the period of the fringe pattern. V-grooves were proposed as a method for holding these fibers. A fiber positioned in a v-groove ideally contacts the groove at two points when viewing it along its axis. With the addition of a cover over the groove, a third point contact with the fiber is achieved and the fiber is constrained. The use of four side-by-side sapphire v-grooves with spacing that corresponds to a fringe period of 90 deg for the Moiré pattern was proposed as the package design. As an intermediate step, silicon v-grooves were selected as an option for testing this design. The purpose of this research is to investigate: 1) the fabrication of v-grooves in silicon; and 2) the accuracy of the fiber placement in these v-grooves.
CHAPTER 2
LITERATURE REVIEW

Micro-Electrical-Mechanical Systems (MEMS)

A world of increasing technology has caused a surge in demand for smaller, faster, and more economical devices. Originally, silicon was seen primarily as an electrical material. In 1959, however, Robbins demonstrated that silicon could be etched to create mechanical features [6]. This provided a new field where chemical etching of silicon could provide features that traditional manufacturing methods could not produce and provided the basis for a new industry labeled "MEMS".

There are many available MEMS examples. These include sensors and mechanical devices. In 1988 Schmidt produced a microfabricated floating element shear stress sensor using silicon etching techniques [2]. Researchers at the Massachusetts Institute of Technology developed microrotors and microrobots using silicon etching [7]. Kim produced a microgripper that could clasp a 10 µm device [8] and Gianchandani created microgears that were able to transfer mechanical energy [9].

Batch manufacturing in MEMS provides the opportunity for repeatable parallel production of components and devices using the photolithographic process. This style of manufacturing has resulted in reduced costs and increased accuracy and repeatability for MEMS devices. The development of MEMS for optical applications, or micro-opto-electro-mechanical systems (MOEMS), provided an inexpensive alternative to the communications industry for transferring information through optical fibers. The alternative to MEMS optical components is the use of standard, bulky optical components. For this reason there has been growing interest in the use of MOEMS.
Etching of V-Grooves

In the late 1960s, Lee used a mixture of NH$_2$ and water to anisotropically etch v-grooves in <100> silicon [10]. Petersen described silicon as becoming a machinable material rather than just an electrical one [11]. He demonstrated anisotropic etching of silicon to produce inkjets and the optical bench. Petersen also combined anisotropic etching with etch stops to produce more complicated geometries. These stops prevented the anisotropic etchant from penetrating the underlying <100> plane [11].

Shoaf aligned two wafers to their respective crystallographic directions by using fibers as an alignment guide [12]. Orthogonal v-grooves were etched in two wafers where one wafer was inverted and placed on top of the other wafer to create a diamond shape with the fiber residing in the middle. Ideally, the fibers touched each wafer along two line contacts, which constrained the wafers to the crystallographic direction. This precise alignment could be accomplished due to exposure of the <111> planes in the silicon crystallographic structure and the subsequent fiber contact.

Tjerkstra created channels in insulating materials using silicon v-grooves [13]. The method involved the fabrication of v-grooves in silicon followed by a bond of the wafer surface containing the groove to the glass. The interior of the channel, comprised of the glass and silicon groove, was coated and the silicon was removed to leave the channels behind attached to the glass. This method provided for the generation of continuous channels in glass, which had traditionally only been etched isotropically [13]. Wacogne designed a method for joining pyramids to a v-groove channel that would provide a smooth transition between the v-groove and the cavity for microfluidics and biological applications [14].
Alignment of Features to the Crystallographic Direction

The crystallographic nature of silicon is the property that enables anisotropic etching. When the anisotropic etchant comes in contact with the surface of silicon, it preferentially etches the <100> plane in such a way that the <111> planes are left exposed. During v-groove formation, if there is an angular misalignment between the wafer and the mask during the photolithography step, the wafer under the masking material will be etched to generate a larger and deeper v-groove than intended. The flat of the silicon wafer is usually toleranced to within one degree of the silicon structure. For the long narrow structures that make up v-grooves, a large error may therefore be introduced during etching. Prior research has addressed this issue.

In 1996, Ensell developed a method for aligning a mask within 0.1 deg of the crystallographic direction of the silicon wafer [15]. The method was limited in that greater accuracy is generally needed for large thin structures. In the same year, Vangbo created another process for aligning masks to the structure of a silicon wafer [16]. This method could be accurate to within 0.05 deg of the silicon crystallographic direction. In order to obtain accurate measurements with this technique, it incorporated complex features that required a partial etch of the wafer. In 1998, Lai reported a technique for aligning a mask within 0.01 deg of the silicon crystallographic direction [17]. This technique involved etching a series of squares and rectangles in the wafer and measuring the features to decipher the angular rotation of the wafer. In 2005, Chang described an alignment technique that used a smaller pattern on the wafer in order to discover the crystallographic direction [18]. This method yielded an accuracy of 0.0467 deg without requiring as much space on the wafer.
Aligning Optical Fibers Using Silicon V-Grooves

Before the use of passive v-groove alignment, active alignment of fibers provided the best coupling method. In active fiber alignment, a metalized fiber tip is positioned to obtain the most efficient coupling [19,20]. Once this position is realized, the fiber is welded into place.

The use of v-grooves offers the opportunity to place a fiber in a known location to a greater degree of accuracy [19]. Additionally, the use of v-grooves during assembly is a passive method of alignment, lending itself to batch manufacturing of large quantities. For this reason, the communications industry has embraced the use of v-grooves. In 1995, Dautartas developed a method of alignment using microspheres and v-grooves [20]. The microspheres were located in pyramidal structures formed in the silicon on both the bottom and top wafers. These pyramids were formed through an anisotropic etch of the wafers. As the wafers were brought together the spheres engaged the pyramids and aligned the two wafers in the correct position around the fiber to enable coupling to a laser source.

The use of v-grooves requires that the fibers be secured in the grooves. Strandman developed a method to hold the fibers in the grooves using clips [21]. Bostock described a similar method for holding the fibers using silicon nitride clips and introduced wider ends to the grooves to aid in assembly of a groove package [22]. Aoki developed a package array that coupled four fibers at one time without manual manipulation using silicon v-grooves to align the fibers [23].

With the increased use of v-groove arrays, the effects of temperature have become a concern. Zhong performed a finite element analysis of v-groove arrays subjected to high temperatures [24,25]. The exterior fibers in the array had a greater
coupling loss when compared to the interior fibers in the v-groove array. This was the result of fiber displacement due to thermal expansion of the epoxy between the fiber and the silicon base.
CHAPTER 3
FABRICATION

The fabrication of the silicon v-grooves was performed through several photolithographic steps. The process began with a <100> silicon wafer as a base. Subsequent processes were then performed on the wafer.

Chromium Sputter

A <100> polished silicon wafer was sputter coated with a 500 nm thick chrome layer prior to any patterning of the wafer. The sputtering time was calculated by using the pre-defined deposition rate for the plasma gun in the selected sputterer. A sputtering time of 38 minutes was required using the Nanoscale Research Facility gun #2.

Photolithography

The initial stage in the photolithographic process required the application of photoresist (S1813) to the chrome layer on the polished surface of the silicon wafer. The resist was applied while the wafer was spinning on a turntable. The recipe for this spin coating process is provided in Table 3-1.

Table 3-1. Spinner recipe

<table>
<thead>
<tr>
<th>Step</th>
<th>Speed (rpm)</th>
<th>Ramp (rpm/s)</th>
<th>Termination time (s)</th>
</tr>
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<tr>
<td>1</td>
<td>500</td>
<td>1000</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>3000</td>
<td>1000</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1000</td>
<td>0</td>
</tr>
</tbody>
</table>

In step 1 of this recipe, the photoresist was applied to the wafer using a dropper. After 3 ml of photoresist was applied to the wafer, the spinner increased its speed in step 2 to 3000 rpm to evenly spread the resist over the wafer. Step 3 is the end of the spinning process where the wafer is then ready to be removed. The termination time was the time that the wafer was spinning at the constant speed. Since the process was finished after the step 3 ramping time, the termination time is zero. After the resist
application, a “soft” baking of the wafer was necessary to firm the resist so that it did not adhere to the mask during the exposure process. This baking was carried out for 60 seconds on a hot plate at a temperature of 110 deg C. The silicon wafer with the resist was then fully prepared for the mask aligner.

After the bake, the next step was to affix the plastic transparency mask, which included the desired v-groove geometries, to a blank quartz mask that was designed to fit into the mask aligner. The quartz mask was necessary for the photolithographic process because the mask was held above the surface of the silicon wafer with a vacuum. The lamp of the mask aligner was checked for its intensity to calculate the time necessary to expose the resist. A higher intensity would yield a lower exposure time. The necessary dose, D, for the resist was 150 mJ/cm². The lamp intensity, I, was measured to be 7.8 mW/cm² which yielded a calculated exposure time, t, of 19.2 seconds. Equation 3-1 shows this calculation.

\[ t = \frac{D}{I} \] (3-1)

Five resist test areas on a standard single-side polished silicon wafer were exposed to differing amounts of light in increments of 0.1 seconds around a mean value of 19.2 seconds. After development, the test wafers were observed under a microscope and it was determined that 19.2 seconds of exposure was appropriate due to the tight corners of the small features. When the corners were rounded, the exposure time was rejected. Following this observation, the same procedure and exposure time were used for the chromium-sputtered wafer. The wafer and mask were then loaded into the aligner. Once the mask and the wafer were in place, the alignment of the mask to the wafer was initiated. Alignment was achieved by matching the mask’s bottom portion of
the lowest groove to the wafer flat. Once the alignment was achieved, it was necessary
to move the wafer perpendicular to its flat so that the pattern would not be produced at
the flat, but rather more centrally on the wafer. The flat was commonly used to handle
the wafer; therefore, any features produced on this portion of the wafer may have been
lost due to mechanical abrasion of the resist.

With the mask in place, the wafer was then exposed to the ultraviolet radiation
provided by the mask aligner. The radiation did not travel through the opaque portions
of the mask and, therefore, resulted in the exposure of only the desired portions of the
resist. After the wafer exposure, a developing solution (300MIF) was used to dissolve
away the exposed resist. This type of resist is known as a positive resist because the
exposed portion is removed by the developer. Negative resists become resistant to the
developing solution when they are exposed to ultraviolet light so that only the
unexposed resist is removed. After the development of the wafer, the pattern was
observed under a microscope to identify any anomalies that may have occurred during
the photolithographic steps. It was important to observe the smallest features to verify
proper exposure and development. Upon completion of the photolithography, a “hard”
bake of the resist was required for its solidification. This bake was completed at 120 deg
C for one hour.

**Chromium Etch**

After the photolithography, the chromium layer remained underneath the patterned
resist. The resist was intended to shield the chromium around the v-grooves that would
act as the masking material during the potassium hydroxide etch. The chromium mask
etchant had a prescribed etch rate of 80 nm/min. Because the chromium on the surface
of the wafer was approximately 500 nm thick, an etching time of 6.25 minutes was
selected. The wafer was placed in the solution for this time and was clearly not fully etched, so it was left in the solution for three additional minutes and then removed. A black substance was still present in the groove region, so the wafer was submerged three times for two minutes each until the metallic residue was entirely removed.

**Potassium Hydroxide Etch**

The potassium hydroxide etch anisotropically removed the silicon material in the $<100>$ direction, resulting in silicon v-grooves. Before this etch could be performed, a buffered oxide etch was performed on the wafer to remove the natural silicon oxide residing on the surface of the silicon. The oxide forms through a chemical reaction of oxygen in the air. The etchant was a 7:1 hydrofluoric acid solution. This was able to dissolve the oxide and leave the polished silicon surface underneath (which would then be in direct contact with the potassium hydroxide). The oxide that formed during the period of time between the oxide etch and the potassium hydroxide etch (less than 15 minutes) was considered negligible.

The potassium hydroxide solution was obtained by mixing solid pellets of the chemical with water. Specifically, a solution with 500 grams of solid potassium hydroxide and 2 liters of water was used. This base concentration etched the wafer at an average starting rate of 26.7 $\mu$m/hour. After the solution was mixed, it was placed in a constant temperature bath at 60 deg C so that etching would continue at a nominally constant rate.

The wafer was next prepared for submersion into the basic solution by masking the backside of the wafer with a quartz mask and carnauba wax. The quartz mask was placed on a hot plate and heated to 100 deg C which was the melting point of the wax. Small flakes of the wax were placed on the mask and allowed to melt. The wafer was
placed on top of the liquid wax to squeeze the wax to its edges. The edges of the wafer were then coated with wax to protect it from the potassium hydroxide. After all of the virgin silicon surfaces were coated with wax, the quartz mask was removed from the hot plate and allowed to cool to encase the sides and the back of the wafer when it solidified. The mask and the wafer were then placed in the potassium hydroxide solution to begin the anisotropic etch of the v-grooves. The v-grooves were etched for a time commensurate with the groove depth. A narrower groove required less time than a wider groove because of the corresponding etch depth. A program was developed to determine an etch duration based upon the etch rate and observations of the grooves. During the etch, the carrier quartz mask and wafer were removed from the solution after six hours to observe the progress of the etch. The grooves were placed under a microscope, and the bottom of the etched surface was measured to check the required etching duration. It was necessary to check this because, due to a potential rotation of the wafer crystallographic direction with respect to the wafer flat, the duration of the etch was not well known. Equation 3-2 was used to determine the required etch depth, d, required to complete the groove:

\[ d = \frac{w \tan(\alpha)}{2} \quad (3-2) \]

where \( w \) is the measured width of the bottom of the etch, and \( \alpha \) was the crystallographic angle of silicon (ideally equal to 54.74 deg). Since the rate of the etch, \( R \), was known (\( \mu m/hour \)), the remaining etch time in hours could be calculated using Equation 3-3.

\[ t = \frac{d}{R} \quad (3-3) \]
This approach accurately predicted the etch time for small grooves. However, for larger grooves the required etch time was longer than anticipated, likely due to saturation of the solution. Following the potassium hydroxide etch, another chrome etch was performed to remove the remaining chromium. The basic etch steps are described pictorially in Figure 3-1.

The chromium masking material left the polished silicon underneath mostly unaffected by the potassium hydroxide except for small holes that formed in the chromium. The holes resulted in small inverse pyramidal cavities around the grooves. The grooves were then cut into individual dies using a dicing saw. Example v-grooves are shown in Figures 3-2 through 3-8. These images were collected using a scanning electron microscope (SEM).
Figure 3-1. Etching procedure schematic
Figure 3-2. Four diced grooves with identification marks

Figure 3-3. Four diced grooves
Figure 3-4. One diced groove

Figure 3-5. Four grooves with undiced ends
Figure 3-6. Overhead view of two grooves

Figure 3-7. Overhead view of the end of one groove with some debris
Figure 3-8. Overhead view of the diced end of four grooves
CHAPTER 4
ASSEMBLY PROCESS

The final fiber package required the assembly of the silicon v-groove, glass cover, and fibers using an ultraviolet light-sensitive epoxy. Each set of grooves was diced in a 2.6 mm by 3.6 mm rectangle with the ends of the grooves removed to allow fibers to protrude as shown in Figure 4-1. The images in this chapter include the v-groove set with three large grooves to aide with illustration.

![Figure 4-1. Silicon v-groove die](image)

Dualbond 707 (Cyberbond) epoxy was used to bond the assembly due to its ability to be cured under ultraviolet light over a short time period. The volume of epoxy was calculated to be equal to the airspace remaining in the v-grooves after the fibers and glass were in place. This is shown schematically in Figure 4-2, where the grooves were assumed to be an extruded triangle of the package length with volume \( T \), the fibers were assumed to be cylinders of the package length with volume \( F \), and the space between the silicon and the glass lid was a box with a height equal to the amount the fibers were designed to protrude above the surface of the silicon and a length and width equal to the size of the package. The box volume was \( B \). The required volume of epoxy was calculated using Equation 4-1.
The corresponding volume of the epoxy was initially dispensed using a precision epoxy dispenser (EFD Ultimus 2400) at 50 psi. The epoxy was dispensed onto a glass slide in the form of droplets. The volume of the droplet was calculated by measuring its diameter and assuming its shape to be a hemisphere. Once the necessary volume of epoxy was determined, it was applied to the silicon die as shown in Figure 4-3.

After several assemblies, excess epoxy was deemed not to be hazardous to the fiber measurements and, therefore, the epoxy was applied manually using...
approximately the same volume. Once the epoxy was applied, the silica optical fibers were laid in the grooves as shown in Figure 4-4.

Figure 4-4. Silicon v-grooves with fibers

Laying the fibers inside the v-grooves was the most tedious part of the package assembly. The difficulty was primarily due to the small diameter of the fibers (125 µm). The surface tension of the epoxy, as well as the capturing nature of the grooves, aided in this effort, however.

Standard glass microscope cover slips were cut to the same dimension as the silicon v-groove dies to act as the top of the optical fiber package. The glass was placed on the die as shown in Figure 4-5 with the fibers protruding from one end.

Figure 4-5. Silicon v-groove with cover slip
After the lid was bonded, the fibers were no longer visible from the top of the package. If a bubble was present under the glass lid, it was likely that the package needed to be reassembled because a fiber was no longer located in the groove. After the lid was placed on the die, a set of orthogonal gage blocks were brought into contact with the package to align the lid with the silicon die and the fibers. The fibers initially protruded from the package and gage blocks were used to force the fibers to be flush with the edge of the package as shown in Figure 4-6.

![Gage blocks](image)

Figure 4-6. Package alignment

After the alignment was complete, a rod with a flat contact surface was applied to the package to assure even force over the fibers. A more localized force may have deformed the glass lid and resulted in fiber location error. Figure 4-7 shows this setup.

The gage blocks were then removed and a light was placed over the package to cure the epoxy; see Figure 4-8. After 30 minutes the epoxy was considered to be cured and the package was placed in a gel pack for subsequent imaging; see Figure 4-9. Table 4-1 shows the geometries of the assembled packages as well as the number of assembled packages. For the first two sets, the v-grooves were designed so that the
fiber protruded above the silicon surface. However, the final set was designed so that the fiber was exactly capture in the v-grooves.

Figure 4-7. Assembly jig

Figure 4-8. Curing package

Figure 4-9. Assembled packages
<table>
<thead>
<tr>
<th>Set</th>
<th>Width (μm)</th>
<th>Depth (μm)</th>
<th>Grooves</th>
<th>Number assembled</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 μm set</td>
<td>100</td>
<td>71</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>185 μm set</td>
<td>185</td>
<td>131</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>241 μm set</td>
<td>241</td>
<td>170</td>
<td>3</td>
<td>10</td>
</tr>
</tbody>
</table>
CHAPTER 5
RESULTS

Design

When potassium hydroxide (KOH) etches a silicon wafer, it etches the <100> plane of the wafer approximately 400 times faster than it etches the <111> plane [26]. This preferential etch direction was exploited to produce grooves in the wafer; an example cross-section of a groove is shown in Figure 5-1, where \( \alpha \) is the crystallographic angle and \( \beta \) is the groove base angle.

![Figure 5-1. Cross-section of silicon v-groove.](image)

The v-groove’s final dimensions were defined by the crystallographic structure of the silicon and the selected width, \( w \). The angles \( \alpha \) and \( \beta \) in Figure 5-1 were constant due to the anisotropic KOH etch. Therefore, the groove depth, \( d \), was altered by changing \( w \). A number of different groove designs were selected to observe the corresponding effect on fiber placement. A rectangular mask was produced that would allow the KOH to etch the wafer without etching the surrounding area. An example of the photolithographic mask with multiple groove geometries is shown in Figure 5-2.
With respect to the etch, it was important to accurately align the wafer so that the crystallographic direction matched the mask axis. With an angular mismatch, an inaccurate groove would be generated as shown in Figure 5-3.

The uncertainty of the wafer flat angular alignment with respect to the crystallographic direction was 1 deg as stated by the wafer manufacturer. This uncertainty was critical because the wafer flat was the feature used to align the mask to the wafer during the photolithographic process. This uncertainty limited the length of the grooves because longer grooves lead to a greater uncertainty in groove width and, subsequently, depth. Equation 5-1 shows the relationship between the change in width, $2x$, with respect to the rotation angle, $\Theta$, and groove length, $L$. The absolute value in the angle is included because a rotation in either direction leads to an increase in groove width.
Figure 5-4 shows an example of a rotated groove altered by width 2x. Table 5-1 shows the relationship between a potential rotation of the groove mask and the length of the groove.

\[
2x = L \tan(\theta)
\] (5-1)

Table 5-1. Error in groove width with respect to angular misalignment and groove length

<table>
<thead>
<tr>
<th>Length of groove</th>
<th>1 deg rotation</th>
<th>0.1 deg rotation</th>
<th>0.01 deg rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 µm</td>
<td>1.75 µm</td>
<td>0.175</td>
<td>0.0175</td>
</tr>
<tr>
<td>1 mm</td>
<td>17.5</td>
<td>1.75</td>
<td>0.175</td>
</tr>
<tr>
<td>3 mm</td>
<td>52.5</td>
<td>5.25</td>
<td>0.525</td>
</tr>
<tr>
<td>5 mm</td>
<td>87.5</td>
<td>8.75</td>
<td>0.875</td>
</tr>
<tr>
<td>10 mm</td>
<td>175</td>
<td>17.5</td>
<td>0.175</td>
</tr>
</tbody>
</table>

Three separate widths were chosen for the groove etching: 100 µm, 185 µm, and 241 µm. All of the grooves were 5 mm in length. A gap of 180 µm between each groove was selected to account for the potential over-etch of the groove with a factor of safety of just over 2 (87.5 µm×2.06). A total of ten sets of each size were fabricated and assembled as described in Chapter 4.
Following the assembly process, the packages were imaged using a SZX12 Olympus microscope with a Cannon SLR camera. The packages were aligned normal to the microscope using gage blocks which were ideally flat and orthogonal on all edges. A flat plate was used as the base, on which a 3” (76.2 mm) gage block was placed as a stand for the package. The flat plate was placed on the stage of the microscope to ensure that the imaging setup was orthogonal to the camera. The package was affixed to a smaller gage block as shown in Figure 5-5 using a small amount of wax. During mounting of the package to the small block, another gage block was placed in contact with the small gage block and the package to assure an orthogonal placement. The gage block together with the fiber package was placed on top of the 3” block as shown in Figure 5-5. Figures 5-6 and 5-7 show the base plate and the two gage blocks holding the package.

![Image of package imaging setup](image)

Figure 5-5. Package imaging setup
Images were captured for each of the 30 fiber packages. Figure 5-8 is a representative image from this set.
For image acquisition, light was coupled into the fibers so that the fiber center could be identified. Without illumination of the fibers, the fiber core was not as easily located. Illumination was achieved by directing the high intensity lighting conduits below the package and allowing light to rebound off the base-plate and launch into the fiber core.

The images were recorded using the microscope’s CCD camera. It was then necessary to convert from pixels to length units for subsequent image analysis. The calibration factor was established (µm/pixel) by imaging a calibration standard at the same magnification that was used for the package images. The calibration standard had a total length of 1 mm with 10 µm graduations. The calibration image was captured and then distances were calculated in 10 locations as shown in Figure 5-9.
Figure 5-9. Image of calibration artifact and measurement locations

Measurements 1-5 were taken from point O1 and measurements 6-10 were taken from point O2. These measurements in pixels were divided by the artifact distances to yield multiple calibration factors; these factors were averaged to obtain a final value of 0.9022 µm/pixel. The standard deviation of the measurements was 0.0005 µm/pixel. This calibration factor was used in each image to convert from pixels to micrometers.

Since the scale on the images was known, measurements of features were completed using image processing techniques. First, the image was converted from a standard RGB image format to an intensity scale. The intensity scale enables the identification of features in the image via a threshold value in intensity. For example, because the fibers were illuminated, the space around the fibers had a lower intensity. A specific threshold between the low intensity zone and the high intensity interior of the fiber enabled the perimeter of the fiber to be identified. A least-squares circle fit was then completed to identify the fiber center. Figure 5-10 shows an example fit.

Based on the points located on the fiber perimeter, the coordinates of the center of the fiber were identified as the center of the best fit circle. However, the image
coordinates did not identify the fiber center with respect to a local coordinate frame on the silicon wafer containing the grooves.

![Figure 5-10. Circle fit to the perimeter of fiber](image)

Therefore, a local coordinate system was identified on the silicon v-groove die. This local coordinate system enables a comparison of the fiber locations with respect to one another, as well as their location relative to the v-grooves. The bottom of the package was identified using the same threshold technique that identified the center of the fibers. Once the points on the bottom of the package were found with respect to the image coordinate system, a line, B, was fit to these points to define the new x-axis. Next, a line, S, was fit to the side of the package to identify the location of the new y-axis. Because these lines were not necessarily orthogonal, a line, P, perpendicular to the bottom of the package was plotted at the intersection of lines B and S. Figure 5-11 shows the image with the lines B, S, and P plotted on the image; the threshold points are also displayed.
Images of the packages before the assembly were also analyzed to characterize the grooves with respect to their width and angles. This measurement was again completed using the threshold technique. Figure 5-12 shows an example of an image with the geometry of the grooves identified.

From the data provided by Figure 5-12, the groove widths and depths were identified. The thickness of the wafer was found by finding the perpendicular distance between the top and the bottom fit lines. A point from the top line was selected in the center of the selected points and the perpendicular distance to the bottom line was calculated to describe the package thickness.
The average groove width and depths are reported in Table 5-2. Due to the angular misalignment described in Figure 5-4, the actual groove widths deviated from their intended values.

**Table 5-2. Measured groove widths and depths.**

<table>
<thead>
<tr>
<th></th>
<th>100 µm set</th>
<th>185 µm set</th>
<th>241 µm set</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean width</td>
<td>128.0 µm</td>
<td>203.2 µm</td>
<td>269.6 µm</td>
</tr>
<tr>
<td>Mean depth</td>
<td>82.4 µm</td>
<td>137.8 µm</td>
<td>185.1 µm</td>
</tr>
<tr>
<td>Nominal depth</td>
<td>70.7 µm</td>
<td>130.8 µm</td>
<td>170.4 µm</td>
</tr>
</tbody>
</table>

The crystallographic angles were measured for each groove. The average $\alpha$ and $\beta$ angles are reported in Table 5-3. Note that the mean $\alpha$ value differs from the nominal 54.74 deg value.

**Table 5-3. Average measured crystallographic angles for all fabricated grooves**

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>53.6 deg</td>
<td>72.9 deg</td>
</tr>
</tbody>
</table>
The fiber positions were normalized to the rightmost fiber for each package to determine the relative location of the fibers with respect to one another. These measured positions of the fibers were then compared to the commanded positions of the fibers. Figures 5-13 through 5-15 show the differences between the commanded positions and the measured fiber locations, where the (0,0) coordinate represents an exact match between the nominal and actual fiber center location.

<table>
<thead>
<tr>
<th>Table 5-4. Fiber deviations from the commanded locations.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td>X</td>
</tr>
<tr>
<td>Y</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>Standard Deviation</td>
</tr>
</tbody>
</table>

Table 5-4 shows the mean differences and standard deviations for the measured fiber locations. For the 185 µm and 100 µm groove sets, the mean differences between the commanded x-coordinate and the actual fiber x-coordinate were -0.57 µm and -0.83 µm, respectively. Due to the three point constraint of the fiber between the two groove surfaces and the glass cover, both cases resulted in the intended constraint of the fiber and, therefore, accurate horizontal location. The mean differences between the commanded y-coordinate and the actual fiber y-coordinate were 9.89 µm and 17.23 µm, respectively, for these two cases. The 241 µm groove set resulted in a much higher deviation from the commanded fiber locations with an x-coordinate deviation of 20.01µm and a y-coordinate deviation of 19.86µm. In this case, the fibers were free to assume any location within the triangle defined by the two groove sides and the cover. Recall that this set was designed such that the fiber should have been exactly captured within the v-groove.
Figure 5-13. 185 µm groove data
Figure 5-14. 100 µm groove data
Figure 5-15. 241 µm groove data
Analysis

The 241 µm groove set did not constrain the fibers at three points. Figure 5-16 shows an example of one of these sets.

Figure 5-16. Package with partial fiber constraint

This package was designed to ideally constrain the fiber at three points, namely, the groove contacts and contact with the glass lid. However, the fibers were not constrained due to a wider and deeper groove caused by angular misalignment during the etching. Additionally, a bias towards one side of the groove was noticed (see Figure 5-16). This was likely due to the sliding of the gauge block across the front surface of the package during the assembly process. During assembly, the orthogonal gauge blocks were slid to one side of the package to prevent the surface tension from moving the fibers in a direction not constrained by the grooves (i.e., along the axis of the groove and fiber). Since the fibers were not properly constrained by the grooves, it is proposed that they were pulled to one side during this process.
The average crystallographic angle, $\alpha$, was slightly less than the anticipated 54.74 deg. This was likely due to an incomplete etching of the groove. If a portion of the mask were to break off over some of the virgin silicon at the top of the groove, a flat surface propagated down the side of the groove until it reached the bottom. Figures 5-17 and 5-18 show SEM images of this occurrence along the walls of a groove.

![Figure 5-17. A flat propagating down the walls of a groove](image)

This etching error resulted in a smaller angle and, therefore, resulted in grooves with walls slightly less steep than anticipated. A silicon nitride masking material instead of chromium may have reduced this effect.

As noted previously, an inherent bias exists for any misalignment of the mask with respect to the crystallographic orientation of the silicon wafer. This bias was observed in the measurements; all groove width measurements were greater than the intended value. Equation 5-2 shows the angular rotation of the wafer crystallographic direction where $w'$ is the intended groove width and $w$ is the measured groove width. Table 5-5
reports the angular rotation of the silicon crystallographic direction for the three cases calculated from the averages of the measured groove widths.

\[
\theta = \arctan\left(\frac{w-w'}{L}\right)
\]  

(5-2)

Table 5-5. Angular rotations of the wafer determined from width measurements.

<table>
<thead>
<tr>
<th>Angular rotation</th>
<th>185 µm set</th>
<th>100 µm set</th>
<th>241 µm set</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.209 deg</td>
<td>0.321</td>
<td>0.328</td>
</tr>
</tbody>
</table>

The 185 µm set differs from the 100 µm and 241 µm sets because it was fabricated from a different stock wafer. The 100 µm and 241 µm sets were fabricated from the same wafer and, therefore, have nearly identical rotation values. This indicates that the source of angular misalignment was the orientation of the flat on the wafer and not the fabrication process. These values for the angular rotation are within the manufacturer specified uncertainty of 1 deg for the wafer flat orientation.

A Monte Carlo simulation for the 185 µm groove was developed using Equation 5-1 to determine the dominating uncertainty factor in the fabrication process. The
uncertainty in the mask was 5 μm for the width and length of the features; the
uncertainty in the wafer flat angle with respect to the crystallographic orientation was 1
deg. Equations 5-3 and 5-4 describe the actual groove width, w, and depth, d, for given
values of the wafer rotation, Θ, groove length, L, crystallographic angle, α, and
commanded groove width, w_c.

\[ w = w_c + L \cdot \tan(\theta) \]  \hspace{2cm} (5-3)

\[ d = \frac{w_c + L \cdot \tan(\theta) \cdot \tan(\alpha)}{2} \]  \hspace{2cm} (5-4)

In the Monte Carlo simulation, random values of the inputs were selected from
normal distributions with standard deviation equal to two times the uncertainty (to give a
confidence interval of 95%). First, only the uncertainty in wafer rotation was considered.
Figure 5-19 shows the results of the Monte Carlo simulation with an uncertainty of 1
deg. The single-sided distribution is due to the nature of the angular misalignment; any
misalignment caused a wider (and deeper) groove.

The mean and standard deviation of the width were 325 μm and 106 μm,
respectively, for 100000 samples; the mean and standard deviation of the depth were
229 μm and 75 μm, respectively. The fabricated wafers produced grooves with an
average width 203.2 μm, which was smaller than the simulation results. This is
expected since the uncertainty in the Monte Carlo simulation (1 deg) was larger than the
calculated error in the rotation angle (0.209 deg). The larger range in potential angular
effects leads to larger biases in groove width and depth.
A mask uncertainty of 5 μm in the commanded v-groove length and width was then applied in the simulation; see Figure 5-20.
The mean and standard deviation of the width were 185 μm and 10 μm, respectively, and the mean and standard deviation of the depth were 131 μm and 7 μm, respectively. Since the mask uncertainty yielded smaller standard deviations (and no bias) in the groove dimensions, it was determined that the uncertainty in the rotation of the wafer flat dominated this situation.

The Monte Carlo simulation also enabled the allowable level of uncertainty in flat orientation to be determined given the required accuracy in groove widths and depths. The mask uncertainty was not considered. (Note that the mask uncertainty could be reduced by replacing the transparency mask to a glass chromium mask. A chromium mask with features at the size of these grooves has a reduced uncertainty of 1 μm.) Figure 5-21 shows the mean bias in the groove depth determined from the Monte Carlo simulation with uncertainties varying from 0.1 deg to 0.01 deg (5 mm groove length).

![Figure 5-21. Bias in groove depth as a function of the uncertainty in wafer flat orientation.](image)

As the uncertainty in the wafer flat is reduced, the bias in the etched groove depth also decreases. For example, this indicates that if a fiber must be placed with an
accuracy of 5 μm in the y-axis, the uncertainty in the alignment of the mask to the crystallographic direction of the silicon should be less than 0.05 deg.
CHAPTER 6
CONCLUSION

The purpose of this project was to evaluate important design considerations in the
use of silicon v-grooves to position fibers for light-based sensing of MEMS deflections.
Silicon served as an intermediate step in an overall program goal of moving towards
higher-temperature materials such as sapphire. For the introductory silicon v-grooves
fiber packaging option, it was necessary to investigate the fabrication of v-grooves in
silicon and the accuracy of the fiber placement in these v-grooves. Image processing of
data collected using a microscope/camera combination was the primary means of
gathering data for characterizing the grooves. Using a least-squares fit to points on the
perimeter of the fibers, the fiber center locations for assembled packages with various v-
groove geometries were identified. It was observed that the fibers were well-constrained
and the fibers were accurately placed laterally when they were contacted by three
points around their perimeter. For grooves that were so wide such that the fiber could
be entirely capture within the v-groove, this constraint was lost and the accuracy of the
fiber locations was degraded. The primary finding from fabrication of silicon v-grooves
using photolithography was that the wafer flat rotation with respect to the
crystallographic structure of the silicon is critical. Any angular misalignment leads to v-
grooves that are too wide and deep. This, in turn, leads to decreased fiber center
accuracy, particularly when the fiber can be entirely captured within the v-groove.

For the production of more accurate grooves, an alignment using the
crystallographic structure of the wafer should be performed as described in Chapter 2.
Crystallographic accuracy of 0.05 deg could provide a y-coordinate accuracy of 5 µm
(assuming other uncertainties are negligible) for a 5 mm v-groove length. A chromium mask could also be used to provide increased accuracy in the v-groove dimensions.

To generate a more accurate v-groove angle, the observation step during etching may be removed from the fabrication process. Additionally, silicon nitride may be a better masking material since chromium is slowly etched by potassium hydroxide, which caused small pyramidal pits around the grooves. Silicon nitride, however, is more difficult to remove from the silicon after the etch is complete.
clear all
close all
clc

scale=500;
%Pixels on scale
pixel=532;

cf=0.902219649;%um/pixel
A2 = imread('J2.JPG');
F1=A2;
A2=rgb2gray(A2);
F=A2;
H=A2;
A2=double(A2);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Thresh1=10;%bottom threshold
Thresh2=40;%bottom threshold
Thresh3=10;%side threshold
Thresh4=60;%side threshold
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

HS=(H>Thresh3 & H<Thresh4);
H=(H>Thresh1 & H<Thresh2);

A2=H;
[RT,CT]=size(A2);

HH=H;

figure(1)
imshow(A2)

[Kx1,Ky1]=ginput(2);
Kx1 = round(Kx1);
Ky1 = round(Ky1);
H1 = H(Ky1(1):Kx1(1):Kx1(2),Kx1(1):Kx1(2));
H2 = HH(Ky1(1):Kx1(1):Kx1(2),Kx1(1):Kx1(2));
%x2=H1(:,);
%x2=double(x2);
J=H1;

%%
J=A2(Ky1(1):Kx1(1):Kx1(2),Kx1(1):Kx1(2));
%%
imshow(J)
[Kx2,Ky2]=ginput(2);
J1=J;
Kx2 = round(Kx2);
Ky2 = round(Ky2);
J2=J1(Ky2(1):Ky2(2),Kx2(1):Kx2(2));
J1(Ky2(1):Ky2(2),Kx2(1):Kx2(2))=1;
[I2,K2] = find(J1);

H2b=H2;
H2b(Ky2(1):Ky2(2),Kx2(1):Kx2(2))=1;
[R,C]=size(H2b);

for cnt = 1:C
index = find(H2b(:,cnt)==1);
if isempty(index)
    index=H2bb(cnt-10);
end
H2bb(cnt) = index(length(index));
end
H2bb=H2bb+(Ky1(1));

A2=HS;
HH=HS;
figure(1)
imshow(A2)

[Kx4,Ky4]=ginput(2);
Kx4 = round(Kx4);
Ky4 = round(Ky4);

J=H1;

imshow(J)
[J1,K1] = find(J1);

H2c=H2;
H2c(Ky3(1):Ky3(2),Kx3(1):Kx3(2))=1;
[R,C]=size(H2c);
for cnt = 1:R
    index = find(H2c(cnt,:)==1);
    if isempty(index)
        index=H2cb(cnt-10);
    end
    H2cb(cnt) = index(length(index));
end

%H2cb=fliplr(H2cb);
H2cb=H2cb+Kx4(1);

imshow(J)
xbottom = (1:length(H2bb))'+Kx1(1);
ybottom = H2bb';
Xb = xbottom(:); % Make x a column vector
Yb = ybottom(:); % Make y a column vector
Const = ones(size(Xb)); % Vector of ones for constant term
Ab= [Const Xb];
Cbottom=(Ab'*Ab)^-1*Ab'*ybottom;
figure(1);
imshow(F);hold on;
xb=linspace(0,2500,2000);
yb=Cbottom(2)*xb+Cbottom(1);

xside = H2cb';
yside = (1:length(H2cb))'+(Ky4(1));
Xs = xside(:); % Make x a column vector
Ys = yside(:); % Make y a column vector
Const = ones(size(Ys)); % Vector of ones for constant term
As= [Const Ys];
Cside=(As'*As)^-1*As'*xside;
xs=linspace(1500,2500,100);
ys=1/Cside(2)*xs-Cside(1)/Cside(2);
Bottomslope=Cbottom(2);
Bottomintercept=Cbottom(1);
Sideslope=1/Cside(2);
Sideintercept=-Cside(1)/Cside(2);
xintersection=-(Bottomintercept-Sideintercept)/(Bottomslope-Sideslope);
yintersection=xintersection*Bottomslope+Bottomintercept;

%Fiber Fitting

Thresh1=170;
Thresh2=176;
H=F;
I=F1;
coordinates=zeros(4,2);
radius=zeros(4,1);
for i=1:4
  figure(1)
  imshow(H)
  [Kx1,Ky1]=ginput(2);
  Kx1 = round(Kx1);
  Ky1 = round(Ky1);
  H1 = H(Ky1(1):Ky1(2),Kx1(1):Kx1(2));
  x2=H1(:);
  x2=double(x2);
  % hist(x2,40)
  % set(gca,'FontSize',14)
  % xlabel('Light level')
  % ylabel('Freqency')
  J=(H1>Thresh1 & H1<Thresh2);
  [X,Y]=find(J==1);
  one=ones(length(X),1);
  one=one*-0.5;
  A=[X Y one];
  A=-2*A;
  P=[X.^2+Y.^2];
  B=inv(A.'*A)*A.'*(-P);
  B1=B(1);
  B2=B(2);
  B3a=B(3);
  B3=sqrt((B1^2+B2^2)-B3a);
  %circle = rsmak('circle',B3,[B2;B1]);fnplt(circle);
  h=B2; k=B1; r=B3; N=256;
  t=(0:N)*2*pi/N;
figure(4)
plot( r*cos(t)+h, r*sin(t)+k);hold on;contour(J)
axis equal
set(gca,'FontSize',14)
xlabel('Pixels')
ylabel('Pixels')
radius(i)=B3;
Xcoordinate=B2+Kx1(1);
Ycoordinate=B1+Ky1(1);
coordinates(i,1)=Xcoordinate;
coordinates(i,2)=Ycoordinate;
end

%Pixels
D12=sqrt((coordinates(2,1)-coordinates(1,1))^2+(coordinates(2,2)-coordinates(1,2))^2);
D23=sqrt((coordinates(3,1)-coordinates(2,1))^2+(coordinates(3,2)-coordinates(2,2))^2);
D34=sqrt((coordinates(4,1)-coordinates(3,1))^2+(coordinates(4,2)-coordinates(3,2))^2);
N=256;
t=(0:N)*2*pi/N;
%circle1 = rsmak('circle',radius(1),[coordinates(1,1);coordinates(1,2)]);
%circle2 = rsmak('circle',radius(2),[coordinates(2,1);coordinates(2,2)]);
%circle3 = rsmak('circle',radius(3),[coordinates(3,1);coordinates(3,2)]);
%circle4 = rsmak('circle',radius(4),[coordinates(4,1);coordinates(4,2)]);
X=[coordinates(1,1);coordinates(2,1);coordinates(3,1);coordinates(4,1)];
Y=[coordinates(1,2);coordinates(2,2);coordinates(3,2);coordinates(4,2)];

%um
D12=D12*cf*1000;
D23=D23*cf*1000;
D34=D34*cf*1000;
radiusu=radius*cf*1000;
coordinatesu=coordinates*cf*1000;

%Plotting
close all
figure
imshow(I);hold on;
plot( r1*cos(t)+h1, r1*sin(t)+k1);hold on;
plot( r2*cos(t)+h2, r2*sin(t)+k2);hold on;
plot( r3*cos(t)+h3, r3*sin(t)+k3);hold on;
plot( r4*cos(t)+h4, r4*sin(t)+k4);hold on;
plot(X,Y);hold on;
plot(xb,yb);hold on;

Lb = plot(xbottom, ybottom, 'ro');hold on;

plot(xs,ys);hold on;
Lb1 = plot(xside, yside, 'bo');hold on;

Perpslope=1/Bottomslope;
Perpintercept=yintersection-Perpslope*xintersection;

xn=x;
yn=Perpslope*xn+Perpintercept;
plot(xn,yn,'g');

xfiber1dist=abs(-Perpslope*coordinates(1,1)+coordinates(1,2)-Perpintercept)/sqrt(Perpslope^2+1);
yfiber1Dist=abs(-Bottomslope*coordinates(1,1)+coordinates(1,2)-Bottomintercept)/sqrt(Bottomslope^2+1);
xfiber2dist=abs(-Perpslope*coordinates(2,1)+coordinates(2,2)-Perpintercept)/sqrt(Perpslope^2+1);
yfiber2Dist=abs(-Bottomslope*coordinates(2,1)+coordinates(2,2)-Bottomintercept)/sqrt(Bottomslope^2+1);
xfiber3dist=abs(-Perpslope*coordinates(3,1)+coordinates(3,2)-Perpintercept)/sqrt(Perpslope^2+1);
yfiber3Dist=abs(-Bottomslope*coordinates(3,1)+coordinates(3,2)-Bottomintercept)/sqrt(Bottomslope^2+1);
xfiber4dist=abs(-Perpslope*coordinates(4,1)+coordinates(4,2)-Perpintercept)/sqrt(Perpslope^2+1);
yfiber4Dist=abs(-Bottomslope*coordinates(4,1)+coordinates(4,2)-Bottomintercept)/sqrt(Bottomslope^2+1);

PXLS=[xfiber1dist,yfiber1Dist,xfiber2dist,yfiber2Dist,xfiber3dist,yfiber3Dist,xfiber4dist,yfiber4Dist,];

XLS=PXLS*cf
Groove Fitting Code

clear all
close all
cclc

cf=0.902219649;%um/pixel
A2 = imread('J2c.JPG');
F1=A2;
A2=rgb2gray(A2);
F=A2;
H=A2;
A2=double(A2);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Thresh1=180;%bottom threshold
Thresh2=300;%bottom threshold
Thresh3=100;%side threshold
Thresh4=300;%side threshold
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

HS=(H>Thresh3 & H<Thresh4);
H=(H>Thresh1 & H<Thresh2);

A2=H;
[RT,CT]=size(A2);

HH=H;

figure(1)
imshow(A2)

[Kx1,Ky1]=ginput(2);
Kx1 = round(Kx1);
Ky1 = round(Ky1);
H1 = H(Ky1(1):Ky1(2),Kx1(1):Kx1(2));
H2 = HH(Ky1(1):Ky1(2),Kx1(1):Kx1(2));
%x2=H1(:);
%x2=double(x2);
J=H1;

J=A2(Ky1(1):Ky1(2),Kx1(1):Kx1(2));
J1=J;

[I2,K2] = find(J1);
H2b=H2;

[R,C]=size(H2b);

for cnt = 1:C
    index = find(H2b(:,cnt)==1);
    if isempty(index)
        index=H2bb(cnt-10);
    end
    H2bb(cnt) = index(length(index));
end

H2bb=H2bb+(Ky1(1));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
A2=HS;
HH=HS;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Fit the bottom and side
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(1)
imshow(A2)

[Kx4,Ky4]=ginput(2);
Kx4 = round(Kx4);
Ky4 = round(Ky4);

J=H1;
%%

%imshow(J)
J1=J;
% [Kx3,Ky3]=ginput(2);
% Kx3 = round(Kx3);
% Ky3 = round(Ky3);
% J3=J1(Ky3(1):Ky3(2),Kx3(1):Kx3(2));
% J1(Ky3(1):Ky3(2),Kx3(1):Kx3(2))=1;
[I1,K1] = find(J1);

H2c=H2;
%H2c(Ky3(1):Ky3(2),Kx3(1):Kx3(2))=1;
[R,C]=size(H2c);

for cnt = 1:R
    index = find(H2c(cnt,:)==1);
    if isempty(index)
        index=H2cb(cnt-10);
    end
    H2cb(cnt) = index(length(index));
end
%H2cb=fliplr(H2cb);
H2cb=H2cb+Kx4(1);

imshow(J)

xbottom = (1:length(H2bb))'+Kx1(1);
ybottom = H2bb';
Xb = xbottom(:);  % Make x a column vector
Yb = ybottom(:);  % Make y a column vector
Const = ones(size(Xb));  % Vector of ones for constant term
Ab= [Const Xb];
Cbottom=(Ab'*Ab)^-1*Ab'*ybottom;
figure(1);
imshow(F);hold on;
xb=linspace(0,2390,2000);
yb=Cbottom(2)*xb+Cbottom(1);

xside = H2cb';
yside = (1:length(H2cb))'+(Ky4(1));

Xs = xside(:);  % Make x a column vector
Ys = yside(:);  % Make y a column vector
Const = ones(size(Ys));  % Vector of ones for constant term
As= [Const Ys];
Cside=(As'*As)^-1*As'*xside;
xs=linspace(1500,2390,100);
ys=1/Cside(2)*xs-Cside(1)/Cside(2);
Bottomslope=Cbottom(2);
Bottomintercept=Cbottom(1);
Sideslope=1/Cside(2);
Sideintercept=-Cside(1)/Cside(2);
xintersection=-(Bottomintercept-Sideintercept)/(Bottomslope-Sideslope);
yintersection=xintersection*Bottomslope+Bottomintercept;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Fit the top
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
A2=HS;
imshow(A2)
[Kx5,Ky5]=ginput(2);
J1=A2;
Kx5 = round(Kx5);
Ky5 = round(Ky5);

H2t=J2;

[R,C]=size(H2t);

for i=1:C
    for j=1:R
        if H2t(j,i)==1
            H2tb(i)=j-1;
            break;
        end
    end
end

H2tb=H2tb+(Ky5(1));

xtop = (1:length(H2tb))'+Kx5(1);
ytop = H2tb';
Xt = xtop(:,1); % Make x a column vector
Yt = ytop(:,1); % Make y a column vector
Const = ones(size(Xt)); % Vector of ones for constant term
At= [Const Xt];
Ctop=(At'*At)^-1*At'*ytop;
figure(1);
imshow(F);hold on;
xt=linspace(0,2390,2000);
yt=Ctop(2)*xb+Ctop(1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Groove 1 Left (Left to Right)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
A2=HS;
imshow(A2)

[Kx6,Ky6]=ginput(2);
J1=A2;
Kx6 = round(Kx6);
Ky6 = round(Ky6);
J2=J1(Ky6(1):Ky6(2),Kx6(1):Kx6(2));

H26=J2;

[R,C]=size(H26);
for i=1:C
    for j=1:R
        if H26(j,i)==1
            H26b(i)=j-1;
            break;
        end
    end
end

H26b=H26b+(Ky6(1));

x6 = (1:length(H26b))'*Ky6(1);
y6 = H26b';
x6 = x6(:,ones(1,1)); % Make x a column vector
y6 = y6(:,ones(1,1)); % Make y a column vector
Const = ones(size(X6)); % Vector of ones for constant term
A6 = [Const X6];
C6=(A6'*A6)^-1*A6'*y6;
figure(1);
imshow(F);hold on;
x6=linspace(0,2390,2000);
y6=C6(2)*x6+C6(1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Groove 1 Right (Left to Right)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

A2=HS;

imshow(A2)

[Kx7,Ky7]=ginput(2);
J1=J2;
Kx7 = round(Kx7);
Ky7 = round(Ky7);
J2=J1(Ky7(1):Ky7(2),Kx7(1):Kx7(2));
H27=J2;

[R,C]=size(H27);

for i=1:C
    for j=1:R
        if H27(j,i)==1
            H27b(i)=j-1;
            break;
        end
    end
end

H27b=H27b+(Ky7(1));
x7 = (1:length(H27b))'+Kx7(1);
y7 = H27b';
X7 = x7(:); % Make x a column vector
Y7 = y7(:); % Make y a column vector

Const = ones(size(X7)); % Vector of ones for constant term
A7= [Const X7];
C7=(A7'*A7)^-1*A7'*y7;
figure(1);
imshow(F);hold on;
x7=linspace(0,2390,2000);
y7=C7(2)*x7+C7(1);
plot(x7,y7);hold on; %7 Line
Lb = plot(X7, Y7, 'go'); %7 points

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Groove 2 Left (Left to Right)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
A2=HS;
imshow(A2)

[Kx8,Ky8]=ginput(2);
J1=A2;
Kx8 = round(Kx8);
Ky8 = round(Ky8);
J2=J1(Ky8(1):Ky8(2),Kx8(1):Kx8(2));
H28=J2;

[R,C]=size(H28);

for i=1:C
  for j=1:R
    if H28(j,i)==1
      H28b(i)=j-1;
      break;
    end
  end
end

H28b=H28b+(Ky8(1));

x8 = (1:length(H28b))'+Kx8(1);
y8 = H28b';
X8 = x8(:); % Make x a column vector
Y8 = y8(:); % Make y a column vector
Const = ones(size(X8)); % Vector of ones for constant term
A8 = [Const X8];
C8 = (A8'*A8)^(-1)*A8'*y8;
figure(1);
imshow(F); hold on;
x8 = linspace(0, 2390, 2000);
y8 = C8(2)*x8 + C8(1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Groove 2 Right (Left to Right)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

A2 = HS;

imshow(A2)

[Kx9, Ky9] = ginput(2);
J1 = A2;
Kx9 = round(Kx9);
Ky9 = round(Ky9);
J2 = J1(Ky9(1):Ky9(2), Kx9(1):Kx9(2));
H29 = J2;

[R, C] = size(H29);
for i = 1:C
    for j = 1:R
        if H29(j, i) == 1
            H29b(i) = j - 1;
            break;
        end
    end
end
H29b = H29b + (Ky9(1));

x9 = (1:length(H29b))' + Kx9(1);
y9 = H29b;
X9 = x9(:); % Make x a column vector
Y9 = y9(:); % Make y a column vector

Const = ones(size(X9)); % Vector of ones for constant term
A9 = [Const X9];
C9 = (A9'*A9)^(-1)*A9'*y9;
figure(1);
imshow(F); hold on;
x9=linspace(0,2390,2000);
y9=C9(2)*x9+C9(1);

imshow(A2)

[Kx10,Ky10]=ginput(2);
J1=A2;
Kx10 = round(Kx10);
Ky10 = round(Ky10);
J2=J1(Ky10(1):Ky10(2),Kx10(1):Kx10(2));

H210=J2;

for i=1:C
    for j=1:R
        if H210(j,i)==1
            H210b(i)=j-1;
            break;
        end
    end
end

H210b=H210b+(Ky10(1));

x10 = (1:length(H210b))'+Kx10(1);
y10 = H210b';
X10 = x10(:); % Make x a column vector
Y10 = y10(:); % Make y a column vector
Const = ones(size(X10)); % Vector of ones for constant term
A10= [Const X10];
C10=(A10'*A10)^-1*A10'*y10;
figure(1);
imshow(F);hold on;
x10=linspace(0,2390,2000);
y10=C10(2)*x10+C10(1);

imshow(A2)
imshow(A2)

[Kx11,Ky11]=ginput(2);
J1=A2;
Kx11 = round(Kx11);
Ky11 = round(Ky11);
J2=J1(Ky11(1):Ky11(2),Kx11(1):Kx11(2));

H211=J2;

[R,C]=size(H211);

for i=1:C
  for j=1:R
    if H211(j,i)==1
      H211b(i)=j-1;
      break;
    end
  end
end

H211b=H211b+(Ky11(1));

x11 = (1:length(H211b))'+Kx11(1);
y11 = H211b';
X11 = x11(:); % Make x a column vector
Y11 = y11(:); % Make y a column vector

Const = ones(size(X11)); % Vector of ones for constant term
A11 = [Const X11];
C11=(A11'*A11)^-1*A11'*y11;
figure(1);
imshow(F);hold on;
x11=linspace(0,2390,2000);
y11=C11(2)*x11+C11(1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Groove 4 Left (Left to Right)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
A2=HS;
imshow(A2)

[Kx12,Ky12]=ginput(2);
J1=A2;
Kx12 = round(Kx12);
Ky12 = round(Ky12);
J2=J1(Ky12(1):Ky12(2),Kx12(1):Kx12(2));

H212=J2;

[R,C]=size(H212);

for i=1:C
    for j=1:R
        if H212(j,i)==1
            H212b(i)=j-1;
            break;
        end
    end
end

H212b=H212b+(Ky12(1));

x12 = (1:length(H212b))'+Kx12(1);
y12 = H212b;
X12 = x12(:); % Make x a column vector
Y12 = y12(:); % Make y a column vector
Const = ones(size(X12)); % Vector of ones for constant term
A12= [Const X12];
C12=(A12'*A12)^-1*A12'*y12;
figure(1);
imshow(F);hold on;
x12=linspace(0,2390,2000);
y12=C12(2)*x12+C12(1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Groove 4 Right (Left to Right)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

A2=HS;

imshow(A2)

[Kx13,Ky13]=ginput(2);
J1=A2;
Kx13 = round(Kx13);
Ky13 = round(Ky13);
J2=J1(Ky13(1):Ky13(2),Kx13(1):Kx13(2));

H213=J2;

[R,C]=size(H213);

for i=1:C
    for j=1:R
        if H213(j,i)==1
H213b(i)=j-1;
break;
end
end
end

H213b=H213b+(Ky13(1));

x13 = (1:length(H213b))'+Kx13(1);
y13 = H213b';
x13 = x13(:); % Make x a column vector
y13 = y13(:); % Make y a column vector

Const = ones(size(X13)); % Vector of ones for constant term
A13= [Const X13];
C13=(A13'*A13)^-1*A13'*y13;
figure(1);
imshow(F);hold on;
x13=linspace(0,2390,2000);
y13=C13(2)*x13+C13(1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Intersections
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Identify Groove Points
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Topslope=Ctop(2);
Topintercept=Ctop(1);

LGroove1slope=C6(2);
LGroove1intercept=C6(1);
RGroove1slope=C7(2);
RGroove1intercept=C7(1);

LGroove2slope=C8(2);
LGroove2intercept=C8(1);
RGroove2slope=C9(2);
RGroove2intercept=C9(1);

LGroove3slope=C10(2);
LGroove3intercept=C10(1);
\text{RGroove3slope}\text{=}C11(2);
\text{RGroove3intercept}\text{=}C11(1);

\text{LGroove4slope}\text{=}C12(2);
\text{LGroove4intercept}\text{=}C12(1);
\text{RGroove4slope}\text{=}C13(2);
\text{RGroove4intercept}\text{=}C13(1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Intersections at Bottom of Grooves
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

\text{XGroove1}\text{=}-(\text{LGroove1intercept}-\text{RGroove1intercept})/\text{(LGroove1slope-}
\text{RGroove1slope});
\text{YGroove1}\text{=}\text{XGroove1}\text{*LGroove1slope}+\text{LGroove1intercept};

\text{XGroove2}\text{=}-(\text{LGroove2intercept}-\text{RGroove2intercept})/\text{(LGroove2slope-}
\text{RGroove2slope});
\text{YGroove2}\text{=}\text{XGroove2}\text{*LGroove2slope}+\text{LGroove2intercept};

\text{XGroove3}\text{=}-(\text{LGroove3intercept}-\text{RGroove3intercept})/\text{(LGroove3slope-}
\text{RGroove3slope});
\text{YGroove3}\text{=}\text{XGroove3}\text{*LGroove3slope}+\text{LGroove3intercept};

\text{XGroove4}\text{=}-(\text{LGroove4intercept}-\text{RGroove4intercept})/\text{(LGroove4slope-}
\text{RGroove4slope});
\text{YGroove4}\text{=}\text{XGroove4}\text{*LGroove4slope}+\text{LGroove4intercept};

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Intersections at Top of Grooves
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

\text{XGroove1L}\text{=}-(\text{LGroove1intercept}-\text{Topintercept})/\text{(LGroove1slope-Topslope)};
\text{YGroove1L}\text{=}\text{XGroove1L}\text{*LGroove1slope}+\text{LGroove1intercept};
\text{XGroove1R}\text{=}-(\text{RGroove1intercept}-\text{Topintercept})/\text{(RGroove1slope-Topslope)};
\text{YGroove1R}\text{=}\text{XGroove1R}\text{*RGroove1slope}+\text{RGroove1intercept};

\text{XGroove2L}\text{=}-(\text{LGroove2intercept}-\text{Topintercept})/\text{(LGroove2slope-Topslope)};
\text{YGroove2L}\text{=}\text{XGroove2L}\text{*LGroove2slope}+\text{LGroove2intercept};
\text{XGroove2R}\text{=}-(\text{RGroove2intercept}-\text{Topintercept})/\text{(RGroove2slope-Topslope)};
\text{YGroove2R}\text{=}\text{XGroove2R}\text{*RGroove2slope}+\text{RGroove2intercept};

\text{XGroove3L}\text{=}-(\text{LGroove3intercept}-\text{Topintercept})/\text{(LGroove3slope-Topslope)};
\text{YGroove3L}\text{=}\text{XGroove3L}\text{*LGroove3slope}+\text{LGroove3intercept};
\text{XGroove3R}\text{=}-(\text{RGroove3intercept}-\text{Topintercept})/\text{(RGroove3slope-Topslope)};
\text{YGroove3R}\text{=}\text{XGroove3R}\text{*RGroove3slope}+\text{RGroove3intercept};

\text{XGroove4L}\text{=}-(\text{LGroove4intercept}-\text{Topintercept})/\text{(LGroove4slope-Topslope)};
\text{YGroove4L}\text{=}\text{XGroove4L}\text{*LGroove4slope}+\text{LGroove4intercept};
\text{XGroove4R}\text{=}-(\text{RGroove4intercept}-\text{Topintercept})/\text{(RGroove4slope-Topslope)};
\text{YGroove4R}\text{=}\text{XGroove4R}\text{*RGroove4slope}+\text{RGroove4intercept};

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Identify New Axis
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Perpslope=-1/Bottomslope;
Perpintercept=yintersection-Perpslope*xintersection;
xn=xs;
yn=Perpslope*xn+Perpintercept;

%Groove Crux Locations wrt New Axis

Xgroove1dist=abs(-Perpslope*XGroove1+YGroove1-
Perpintercept)/sqrt(Perpslope^2+1);
Ygroove1dist=abs(-Bottomslope*XGroove1+YGroove1-
Bottomintercept)/sqrt(Bottomslope^2+1);

Xgroove2dist=abs(-Perpslope*XGroove2+YGroove2-
Perpintercept)/sqrt(Perpslope^2+1);
Ygroove2dist=abs(-Bottomslope*XGroove2+YGroove2-
Bottomintercept)/sqrt(Bottomslope^2+1);

Xgroove3dist=abs(-Perpslope*XGroove3+YGroove3-
Perpintercept)/sqrt(Perpslope^2+1);
Ygroove3dist=abs(-Bottomslope*XGroove3+YGroove3-
Bottomintercept)/sqrt(Bottomslope^2+1);

Xgroove4dist=abs(-Perpslope*XGroove4+YGroove4-
Perpintercept)/sqrt(Perpslope^2+1);
Ygroove4dist=abs(-Bottomslope*XGroove4+YGroove4-
Bottomintercept)/sqrt(Bottomslope^2+1);

%Groove Top Locations wrt New Axis

Xgroove1distL=abs(-Perpslope*XGroove1L+YGroove1L-
Perpintercept)/sqrt(Perpslope^2+1);
Ygroove1distL=abs(-Bottomslope*XGroove1L+YGroove1L-
Bottomintercept)/sqrt(Bottomslope^2+1);
Xgroove1distR=abs(-Perpslope*XGroove1R+YGroove1R-
Perpintercept)/sqrt(Perpslope^2+1);
Ygroove1distR=abs(-Bottomslope*XGroove1R+YGroove1R-
Bottomintercept)/sqrt(Bottomslope^2+1);

Xgroove2distL=abs(-Perpslope*XGroove2L+YGroove2L-
Perpintercept)/sqrt(Perpslope^2+1);
Ygroove2distL=abs(-Bottomslope*XGroove2L+YGroove2L-
Bottomintercept)/sqrt(Bottomslope^2+1);
Xgroove2distR=abs(-Perpslope*XGroove2R+YGroove2R-
Perpintercept)/sqrt(Perpslope^2+1);
Ygroove2distR=abs(-Bottomslope*XGroove2R+YGroove2R-
Bottomintercept)/sqrt(Bottomslope^2+1);

Xgroove3distL=abs(-Perpslope*XGroove3L+YGroove3L-
Perpintercept)/sqrt(Perpslope^2+1);
Ygroove3distL=abs(-Bottomslope*XGroove3L+YGroove3L-Bottomintercept)/sqrt(Bottomslope^2+1);
Xgroove3distR=abs(-Perpslope*XGroove3R+YGroove3R-Perpintercept)/sqrt(Perpslope^2+1);
Ygroove3distR=abs(-Bottomslope*XGroove3R+YGroove3R-Bottomintercept)/sqrt(Bottomslope^2+1);

Xgroove4distL=abs(-Perpslope*XGroove4L+YGroove4L-Perpintercept)/sqrt(Perpslope^2+1);
Ygroove4distL=abs(-Bottomslope*XGroove4L+YGroove4L-Bottomintercept)/sqrt(Bottomslope^2+1);
Xgroove4distR=abs(-Perpslope*XGroove4R+YGroove4R-Perpintercept)/sqrt(Perpslope^2+1);
Ygroove4distR=abs(-Bottomslope*XGroove4R+YGroove4R-Bottomintercept)/sqrt(Bottomslope^2+1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Groove Widths
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Groove1Width=Xgroove1distL-Xgroove1distR;
Groove2Width=Xgroove2distL-Xgroove2distR;
Groove3Width=Xgroove3distL-Xgroove3distR;
Groove4Width=Xgroove4distL-Xgroove4distR;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Groove Angles
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Groove1Angle=(atan(LGroove1slope)-atan(RGroove1slope))*(180/pi)/2;
Groove2Angle=(atan(LGroove2slope)-atan(RGroove2slope))*(180/pi)/2;
Groove3Angle=(atan(LGroove3slope)-atan(RGroove3slope))*(180/pi)/2;
Groove4Angle=(atan(LGroove4slope)-atan(RGroove4slope))*(180/pi)/2;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Plotting
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
close all
figure
imshow(F1);hold on;
plot(xb,yb);hold on; %Bottom Line
Lb = plot(xbottom, ybottom, 'ro');hold on; %Bottom points
plot(xs,ys);hold on; %Side line
Lb1 = plot(xside, yside, 'bo');hold on; %Side points
plot(xn,yn,'g');hold on; %Perpendicular line
plot(xt,yt);hold on; %Top Line
Lb = plot(xtop, ytop, 'wo'); %Top points
plot(x6,y6);hold on; %6 Line
Lb = plot(X6, Y6, 'go'); %6 points
plot(x7,y7);hold on; %7 Line
Lb = plot(X7, Y7, 'go'); %7 points
plot(x8,y8);hold on; %8 Line
Lb = plot(X8, Y8, 'go'); %8 points
plot(x9,y9);hold on; %9 Line
Lb = plot(X9, Y9, 'go'); %9 points
plot(x10,y10);hold on; %10 Line
Lb = plot(X10, Y10, 'go'); %10 points
plot(x11,y11);hold on; %11 Line
Lb = plot(X11, Y11, 'go'); %11 points
plot(x12,y12);hold on; %12 Line
Lb = plot(X12, Y12, 'go'); %12 points
plot(x13,y13);hold on; %13 Line
Lb = plot(X13, Y13, 'go'); %13 points

PXLS=[Groove1Width,Groove2Width,Groove3Width,Groove4Width,Groove1Angle,...
    Groove2Angle,Groove3Angle,Groove4Angle,...
    Xgroove1dist,Ygroove1dist,Xgroove2dist,Ygroove2dist,...
    ,Xgroove3dist,Ygroove3dist,Xgroove4dist,Ygroove4dist,...
    1/cf,1/cf,1/cf,1/cf,1/cf,1/cf,1/cf,1/cf,...
    Xgroove1distL,Ygroove1distL,Xgroove1distR,Ygroove1distR,...
    Xgroove2distL,Ygroove2distL,Xgroove2distR,Ygroove2distR,...
    Xgroove3distL,Ygroove3distL,Xgroove3distR,Ygroove3distR,...
    Xgroove4distL,Ygroove4distL,Xgroove4distR,Ygroove4distR,...
    Thresh1/cf,Thresh2/cf,Thresh3/cf,Thresh4/cf];

XLS=PXLS*cf
Monte Carlo Simulation Code

clear all
close all
clc

%Units in Microns

%Define Variables

umask=5;                %Microns
utheta=.01;             %Degrees
alphac=54.74;           %Degrees
Lc= 5000;               %Microns
Wc=185;                 %Microns

%Calculations

%Disable Undesired Uncertainties

alphac=alphac*(pi/180);
utheta=utheta*(pi/180);
W=Wc;%+2*umask*randn(1,100000);
L=Lc;%+2*umask*randn(1,100000);
theta=2*utheta*randn(1,100000);
alpha=alphac+0*randn(1,100000);
width=W+abs(L.*tan(theta));
depth=((W+abs(L.*tan(theta))).*tan(alpha))./2;

%Mean and Standard Deviation

%mw=mean(width)
%md=mean(depth)-130.835
%sw=std(width)
%sd=std(depth)

%Plotting

subplot(211)
hist(width,50);
set(gca,'FontSize', 14)
xlabel('Groove width (\mum)')
ylabel('Occurences')
subplot(212)
hist(depth,50);
%plot(depth);
set(gca,'FontSize', 14)
xlabel('Groove depth (\mum)')
ylabel('Occurences')
LIST OF REFERENCES


[18] W. Chang, Y. Huang, A new pre-etching pattern to determine <110> crystallographic orientation on both (100) and (110) silicon wafers, Microsystem Technologies, 11 (2005) 117-128


BIOGRAPHICAL SKETCH

Matthew Rueff was born in Tampa, Florida in 1985. In 1998 he met his future wife Brittany at Carrollwood Baptist Church in Tampa. He earned the International Baccalaureate Diploma at C. Leon King High School in Tampa in 2004. He came to the University of Florida to further his education in mechanical engineering and married Brittany in 2007. Following the completion of his Bachelor of Science degree in mechanical engineering in 2008, he continued to pursue his studies in mechanical engineering under Dr. Tony Schmitz with an emphasis in the fields of manufacturing and biomedical engineering.