Assembly of micro-optical systems with mechanical positioning

Andrew Stockham, Jay A. Hammer, John G. Smith, Luis M. Nelson
MEMS Optical[*], Inc., 205 Import Circle, Huntsville, AL, USA 35806

ABSTRACT

Aligning of multiple micro-optical components is required for many systems composed of arrays of multiple lens elements, apertures, and filters. Methods of aligning two such wafers using mechanical features are discussed here. Alignment features include binary holes and posts, or grooves and ridges. With the circular holes or rectangular grooves etched into the two wafers, the mating pins or ridges are formed on both sides of a separate element to set both the lateral and vertical positioning. Grayscale technology allows for the printing of V-grooves and V-cones onto any substrate material over a wide range of aspect ratios. When integrated with cylindrical (fiber) or spherical (ball lens) mechanical features, this allows for accurate positioning. Some techniques allow for repositioning as well as disassembly and reassembly. The designs are kinematic or nearly kinematic. The paper discusses tolerances on mating components, and the associated precision of the overall alignment.

Keywords: optical alignment, grayscale lithography, positioning, V-grooves, microlenses, kinematic

1. INTRODUCTION

Micro-optical systems often require alignment of multiple components, just as with macro optical systems. Examples include aligning multiple lens arrays and aligning a lens array to an aperture array. For permanent assembles, a variety of techniques exist. Bonding can be done at the wafer level using a mask aligner/bond aligner tool. However, for assemblies that may need to be disassembled, an alternative method of assembly is desirable.

This paper discusses mechanical positioning methods for aligning micro-optics. In general, features are patterned and etched into two or more substrates to be aligned. A set of spacers with features designed to mate with the substrates is used to set the relative position of the two substrates. Typically, all six degrees of freedom need to be controlled. In a macro optical system of radially symmetric components there is no need to control rotation of the components about the optical axis. However, with a part consisting of arrays of such components there is a need to control this rotation to keep all of the individual columns aligned.

In the systems considered here, it desirable to set the height of the second substrate above the first at a required distance uniformly across the substrate, which sets three of the degrees of freedom. The remaining degrees of freedom are lateral displacements, typically x and y translation, and rotation about the center of the optic. From these parameters, the local misalignment at any position on the substrate can be calculated. Often this is the specification for the assembly. However, some systems are more tolerant to a uniform displacement than to a rotation.

In the variations of the alignment methods discussed here, the position is maintained (within some accuracy) at several locations on the wafer. Sufficient points are used to constrain all the degrees of freedom. In the kinematic designs there is no over-constraint. However, several designs have more than the minimum number of constraints. These are generally placed at a precision greater than the alignment requirements, and hence can still be effective.

2. DESIGN OF ALIGNMENT SYSTEMS

2.1 Binary Circular Pins

Two mechanical pieces are often held in alignment using dowel pins. This was the basis for one of the wafer positioning systems used here. Circular holes are etched into both substrates at a number of locations. A separate pin structure is

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[*] info@memsoptical.com; phone 1 256 859-1886; fax 1 256 859-5890; www.memsoptical.com

fabricated, having cylindrical protrusions on both surfaces. By placing the pin in each substrate, the relative position at that location is controlled.

Figure 1 shows a typical pin and hole structure. When in place, the lateral position is constrained in both the x and y directions, to within the undersizing of the pin relative to the hole. For constraining the lateral degrees of freedom, one pin in a circular hole, plus a pin in a slot would be the minimum required. For constraining the longitudinal degrees of freedom, three pins are needed.

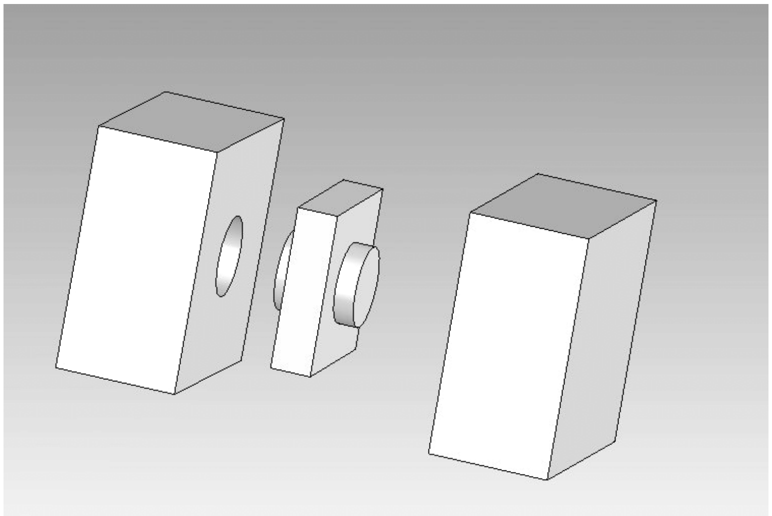

Figure 1. Solid model of pin and mating holes.

In the design employed here, more constraints were applied. Primarily this was done for symmetry in the layout of the device. Figure 2 shows the arrangement of the four pins in corner locations. Arrows indicate the degrees-of-freedom that are constrained at those locations. The alignment accuracy is determined by the amount of undersizing of the pins relative to the holes. Lateral shifts of the top wafer relative to the bottom one are constrained to within the difference between the hold diameter D_h and the pin diameter D_p. The maximum lateral shift is equal to $D_h - D_p$, e.g., with one wafer contacting the left side of the pin, and the other wafer contacting the right side of the pin. The maximum relative rotation about the wafer center, θ, is determined by the radial distance r_p of the pins, and given by $\theta = (D_h - D_p)/ r_p$.

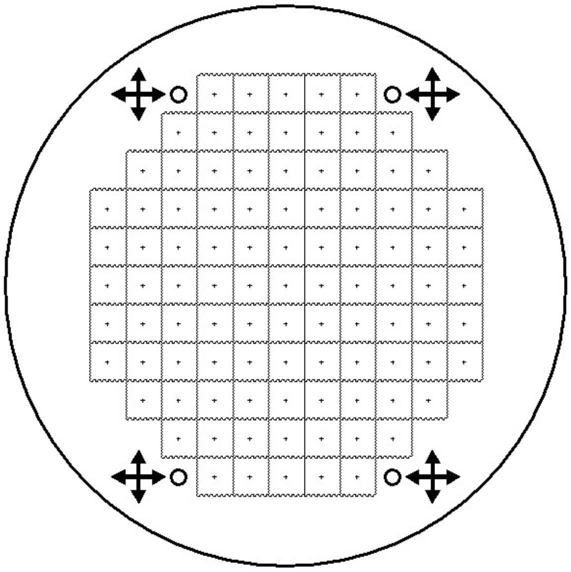

Figure 2. Position of holes for pin alignment.

2.2 Binary Pins in Grooves

Another binary alignment scheme was designed and fabricated. In this design only three pins are used, so there is no over-constraint on the longitudinal positioning (parallelism). Figure 3 shows the concept. For the lateral degrees of freedom, two pins on a line fix the rotation and the horizontal position. The third pin fixes the degree of freedom in the vertical direction.

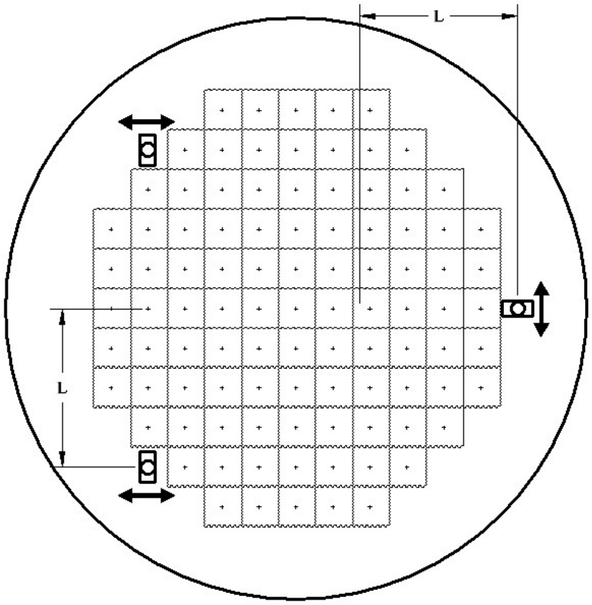

Figure 3. Locations of pins in slots for wafer alignment

The maximum lateral shift in the x or y directions is determined by the oversizing of the slot width W_s, and is given by $\Delta x = \Delta y = W_s - D_p$. The maximum rotation attainable is determined by locating the point on the horizontal centerline where the distance of the vertical slots above and below the centerline is equal to the horizontal distance to the horizontal slot on the right. The rotation is then $\theta = (W_s - D_p) / L$, where L is distance of the upper slot above the centerline.

The parallelism of the two substrates is set by the heights of the flat surfaces of the pins (as in Figure 1). To the extent that these regions are small compared to the separation distance of the pins, this approximates three point contacts, which defines a plane without redundancy. To achieve good planarity, the thicknesses of the pins must be close. This is achieved with wafers having a small total thickness variation (TTV) and further by using pins from nearby locations on the wafer.

In the present design, some differences from that represented in the above figure were employed. First, rather than circular pins, short bars were used. The idea was to avoid relying on a single line of contact, in case damage occurred to that location. The other difference was that three slots were used at each position, again for extra contact area. This is shown in some detail in the fabrication and alignment sections of this paper.

2.3 Grayscale technology background

Additional designs are possible using our gray-scale fabrication method, which can produce structures other than the planar ones described above. Grayscale technology provides a fabrication flexibility that far exceeds that of binary technology. This is particularly apparent in fabricating refractive microlenses, surfaces that are both refractive and diffractive, and V-grooves in any substrate material. Such elements might require several hundred different gray levels and fabricating these with binary chrome masks would be impractical.

The fabrication of such a complex surface relief structure is enabled by the use of grayscale technology. Grayscale photolithography uses a photomask that has a spatially varying transmission. As a result, the amount of energy that is allowed through the mask varies as a function of position as shown in Figure 4. This additional dimension of freedom in the lithography step allows for the realization of complex three-dimensional structures such as cylinder arrays.

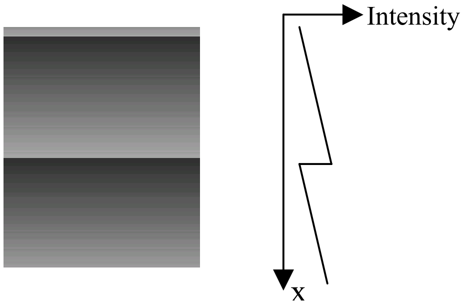

Figure 4. Illustration of the variable transmission of a grayscale photomask.

The grayscale photomask is then used to partially expose photoresist as shown in Figure 5. After photolithography is complete, an etching process is used to transfer the shape into the substrate (the shaded region). The height of the final structure in the substrate is controlled by the ratio of the etch rate of the substrate to the etch rate of the photoresist, defined as the selectivity,

$$S \equiv \frac{R_S}{R_{PR}}. \tag{1}$$

Thus, the final height of the structure is the product of the photoresist height with the selectivity:

$$H_S = S\,H_{PR}. \tag{2}$$

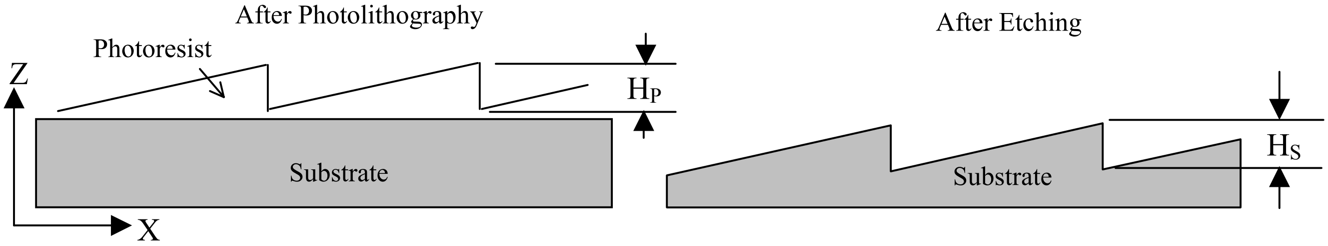

Figure 5. Side profile of the result of a grayscale lithography and etching process.

2.4 Grayscale V-grooves and fibers

By etching mating V-grooves into the substrates and assembling using a cylindrical fiber, one lateral degree of freedom can be constrained. This is sketched in Figure 6. Due to the finite length of the cylinder, there is also some rotational constraint. However, that is neglected in the present analysis.

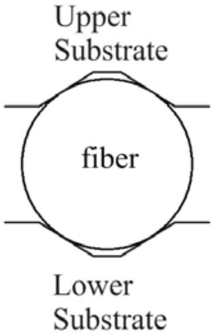

Figure 6. Alignment using cylindrical fiber and corresponding V-grooves.

Similar to the slots and pins, three locations are used to constrain all of the degrees of freedom. Pairs of V-grooves were fabricated for redundancy. One difference of this method from the binary methods discussed above is that the etch depth in the substrates affects their separation distance. Hence, the etch depths should be uniform for good parallelism of the substrates.

2.5 Additional design concepts

Variations on the above concepts were considered, but not implemented. For the V-groove method, it may be difficult to use an available fiber for a desired spacing. To get around this, grayscale pins could be fabricated as shown in Figure 7. Here a pair of protrusions is needed to properly set the relative lateral position of the two components (because the top and bottom arcs generally do not have a common center).

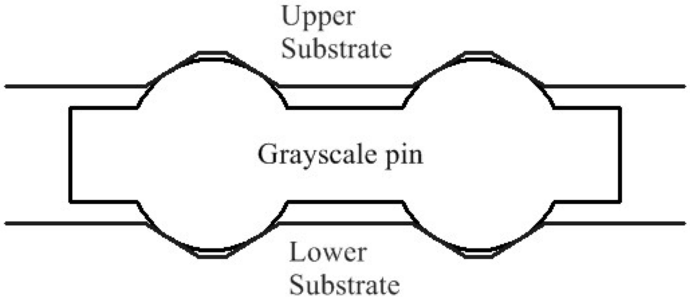

Figure 7. Grayscale pin used to align to pairs of V-grooves.

A variant of the V-groove design (or the slots design) is to have the V-grooves each at 120-degrees apart, rather than having two in line. There is more symmetry in this design. However, it was thought that the alignment procedure might be more difficult.

Also, rather than V-grooves, V-cones can be used, along with glass spheres. Such V-cones were designed into the photomask, and patterned in photoresist. However, we have not yet tried etching or assembling wafers. Three or four locations could be used to position the wafers. Although this would be overconstrained, good lithographic positioning could still render this a useful technique.

3. FABRICATION OF COMPONENTS

Alignment features are patterned into the optical components to be aligned. These may be either the binary or grayscale types, depending on the design as discussed above. Preferably these are etched into the substrate simultaneously with the lenses, to avoid any significant extra effort. By patterning simultaneously with the lenses, good relative alignment can be achieved.

Alignment pins, where used, are fabricated separately. These pins may be either binary or grayscale, and are designed to mate with the features in the optics.

3.1 Circular Pins Alignment

Circular pins were fabricated using a silicon wafer with a relatively tight spec on TTV of 1 micron. Alignment marks were first placed on both sides of the wafer, accurately positioned using an MA6 mask aligner, and verified with an IR microscope. Pins were then patterned using a GCA stepper, accurately aligned to the previously etched marks. These were then etched in an STS Advanced Silicon Etcher using a Bosch process. At the time the etcher was configured for 5-inch wafers, whereas the pins were made on 4-inch wafers, requiring a carrier wafer to be used. The imperfect thermal contact to the carrier wafer presumably caused some roughening of the etched surface, as evident in the photographs. After etching the first side, the process was repeated for the backside. Figure 8 shows an image of the pin under a microscope, along with topography data from a scanning interferometric microscope. A circular protrusion is left un-etched, roughly 15 microns tall. In this design the pins range from 1.990 to 1.993 mm in diameter, and are mated with circular holes 1.996 mm in diameter.

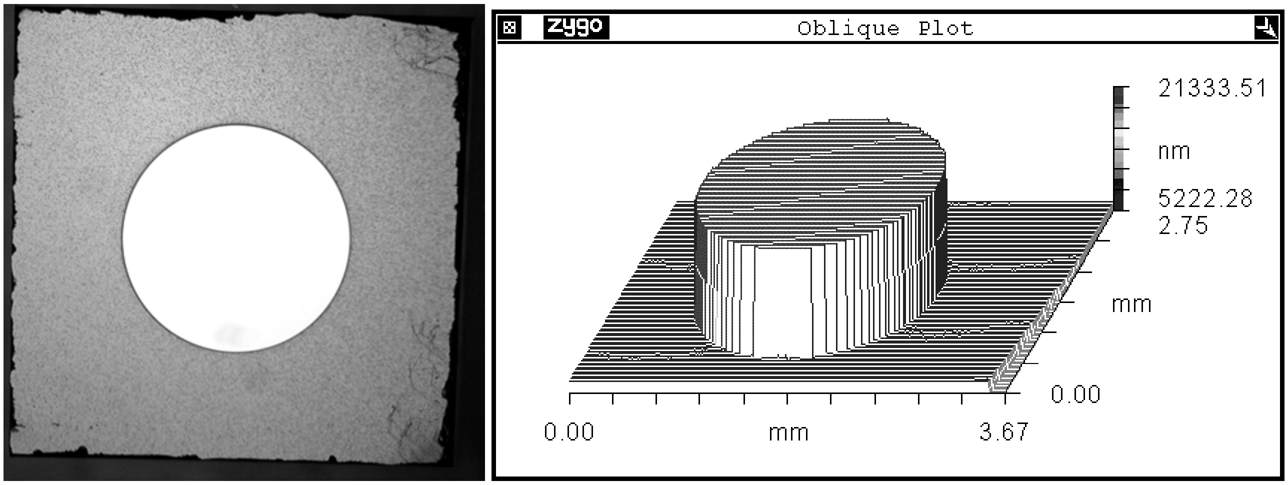

Figure 8. Circular pin, photograph (left) and height data from interferometric microscope (right).

On the glass substrates, circular holes were etched at four locations near the perimeter of the wafer, as described in the design section. The depth was ~ 33 microns, to ensure that the pin did not bottom out in the hole. Figure 9 shows data on the hole profile.

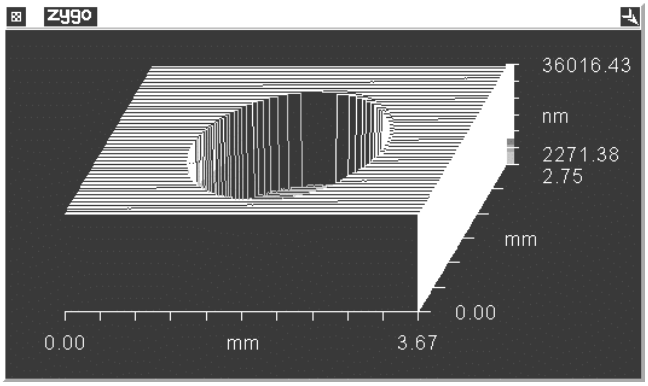

Figure 9. Interferometric height data on the circular holes in the glass substrate.

3.2 Slots and Bars Alignment

The method of aligning to slots was also investigated experimentally. Two silicon wafers were patterned with horizontal and vertical slots. Figure 10 shows these patterns (in photoresist). These were then etched into the wafer 40 microns deep. Each location actually had three parallel slots, for some increase in available surface area for the pins.

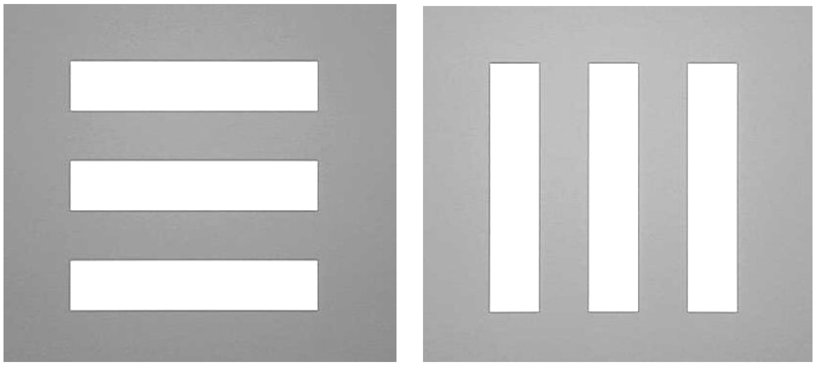

Figure 10. Horizontal and vertical slot patterns in photoresist on silicon wafer.

On the same wafer as the circular pins were fabricated, bar-style pins were also made. These mate with the slots, and are shown in Figure 11. They were undersized by 6 microns relative to the slot width.

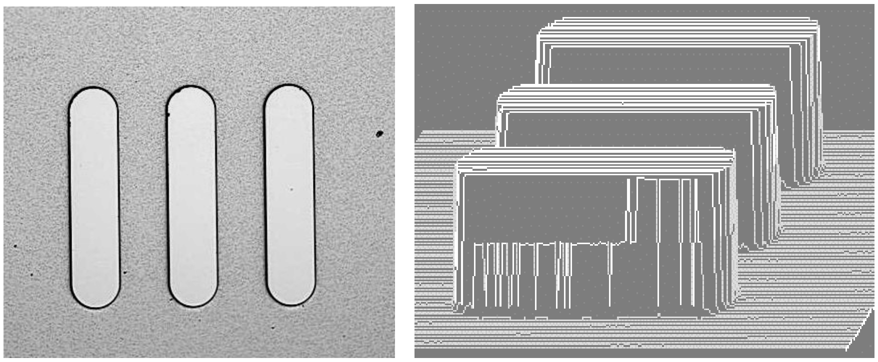

Figure 11. Bar-style pins; photograph (left) and height data (right).

3.3 V-grooves and Fibers

V-grooves were fabricated in the same glass wafers as the circular holes. Figure 12 shows a photograph of the etched features. Two grooves were patterned at each location for redundancy. Also shown is the interferometric data. This shows a depth at the flat region of ~ 30 microns. The sidewall angle was too steep to be measured by our microscope with the available numerical aperture of the objective, hence the data dropout in this region (shown as white regions to either side of the center strip).

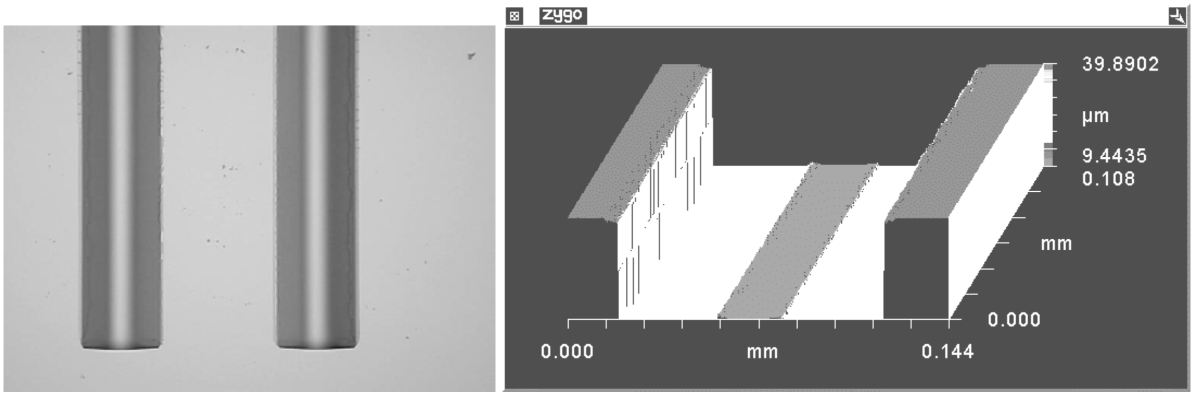

Figure 12. V-grooves etched in glass wafer, photograph and height data (dropout of data occurred on sloped regions).

4. ASSEMBLY

4.1 Circular Pins

Using four circular pins, we have assembled components by hand under a microscope. First the pins are inserted into the lower optic. When the pins are opaque to visible light, an infrared microscope can be helpful in getting the pins into the feature. However, this can also be done without the aid of such a microscope, with a little practice. The ability to rotate the pin without lateral movement generally indicates that the pin is in place. It was, however, difficult to get the pins to sit flat in the holes, as indicated by scanning interferometric microscope data. This might have resulted from particles being knocked off the pins, or an imperfect fit of the pin in the hole.

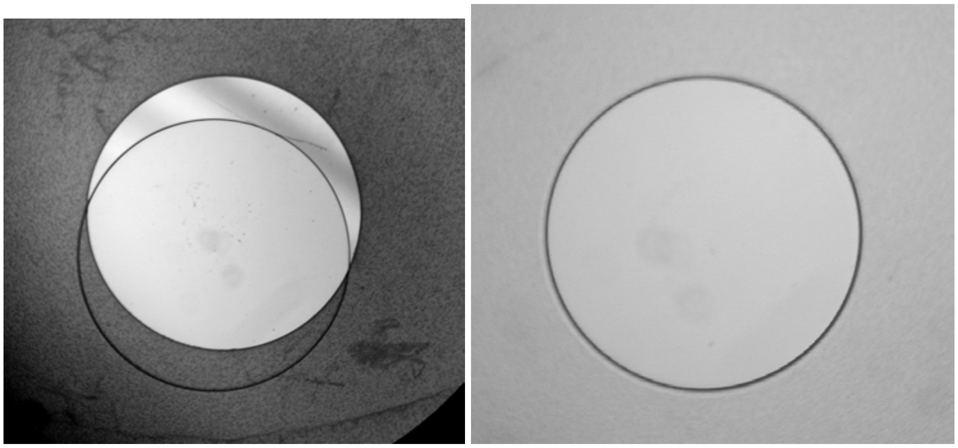

Figure 13. Photographs of glass wafer over circular pin, unaligned (left) and aligned (right).

Once the four pins are in place, the upper substrate is placed on the pins. The top wafer is slid until one pin is in alignment. Figure 13 shows the initially placed wafer, and the wafer once it has been aligned with a pin. After the first pin, the wafer is rotated to get a second pin in alignment. Generally a click can be heard. The remaining two pins are checked, which should also be aligned. Sometimes this step knocks a pin out of place, and the procedure must be repeated (back to the step of checking that each pin is in its hole on the lower wafer). Once the upper wafer is over its pins, the stack can be handled, albeit with some care.

We then checked the alignment under a microscope, first focusing on the upper substrate alignment marks, snapping an image, marking the position, and then focusing on the lower substrate. Figure 14 shows the left and right side alignment marks. Here the alignment is within ~ 3 microns.

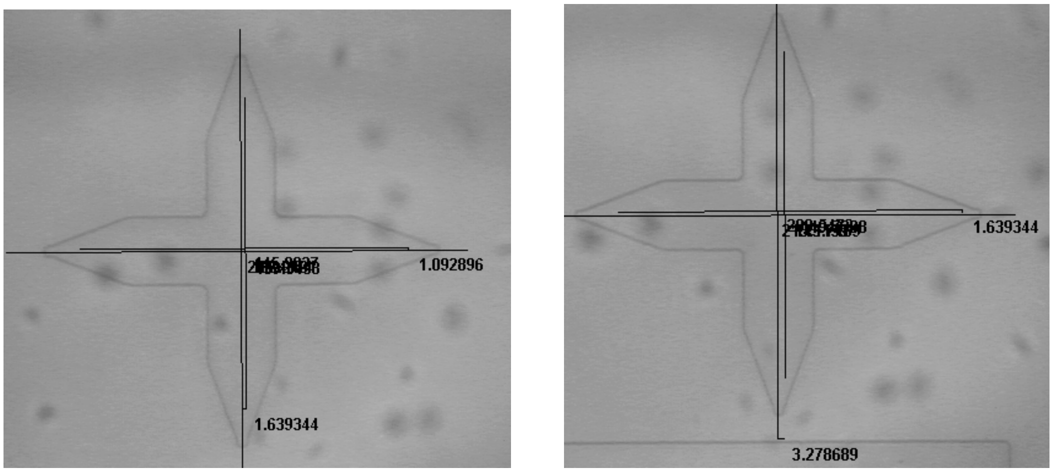

Figure 14. Measurements of alignment error between two wafers using circular pins.

4.2 Pins in slots

Tests were also done with the slots method. Here the two substrates were silicon. To do the alignment, positioning was done under an IR microscope. Figure 15 shows an IR image of the rounded pins in the rectangular slots after placement of the pins in the lower wafer.

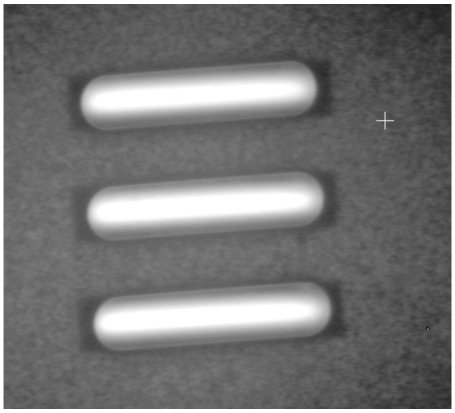

Figure 15. IR photograph of bar-type pins in horizontal slots.

Following placement of the pins, the upper wafer was placed on top and manipulated to get it to fall over the pins. This turned out to be difficult, partly because of the opaque silicon substrates. In this case we have not yet been able to get the wafer aligned to the pins.

4.3 Fibers in V-grooves

The V-grooves on the glass wafers were used, along with an optical fiber, to position the two substrates. Here an SMF-28 fiber with a diameter of 125 microns was used. The sheathing was first stripped from the fiber, and then the fiber was cleaned with methanol. In these tests, the fiber was broken into short lengths with tweezers, rather than cleaving (hence the jagged appearance of the ends in the photographs). A small section of the fiber was placed in each of three grooves, as shown in Figure 16. Next the upper wafer was placed on top, and moved until each of the grooves on the upper wafer was in place, as verified by inspection under a microscope. Having the two grooves close together sometimes caused a problem with the wrong groove settling over the fiber. However, this was easily corrected.

This alignment procedure was generally the easiest alignment to do. Handling the fibers was a bit delicate. However, once the fibers were in place in the lower wafer, positioning the top wafer took only a minute or so.

Once assembled, the stack could be handled, e.g., for carrying to the microscope for inspection of the alignment accuracy. However, if accidentally bumped, it could move out of alignment. It was a little more susceptible to this than were the pins. We believe this was because of the relatively shallow contact angle between the fiber and the V-groove. The fiber diameter and etch depth limited how steep we could make this angle. If smaller diameter fibers are used, or if grayscale pins are used as depicted in Figure 7, then steeper angles can be employed. Grayscale can be used to make steep structures; the primary limit in this is our ability to measure the sloped surfaces, in particular when the shape must be controlled precisely.

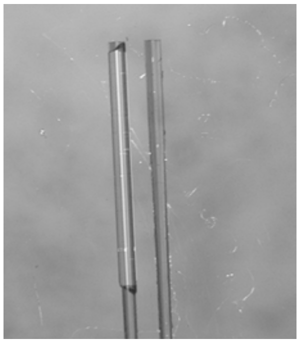

Figure 16. Photograph of fiber laid in V-groove

Alignment accuracy was again checked as shown in Figure 17. Here the alignment accuracy was within a micron, which is about the limit of our ability to measure with the available microscope and camera.

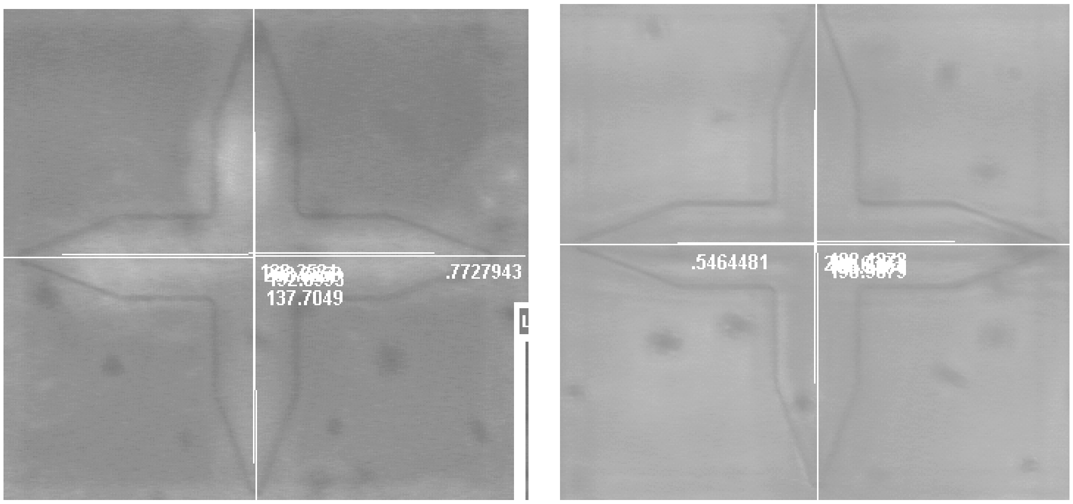

Figure 17. Measurements of alignment accuracy of two wafers using fibers in V-grooves.

5. SUMMARY

Alignment of microoptical components using mechanical methods has been discussed in this paper. Both binary features and grayscale features were used to align two optical components. Circular pins were used successfully, achieving an accuracy of ~ 3 microns. Assembly was reasonably fast and stable enough to handle. The grayscale method used employed V-grooves with 125-micron diameter optical fiber. Alignment accuracy was ~ 1 micron. The assembly was stable enough to handle, but not as stable as with the binary pins. For systems that need to be assembled quickly, and in particular those that must be disassembled, this approach can provide for quick, accurate alignments.

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