Silicon Insert Molded Plastic (SIMP)

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Abstract

As demand for smaller devices continues to increase, current manufacturing processes will find it more challenging to meet cost, quantity, and dimensional requirements. While microfabrication technology processes can create electronic devices in vast quantities with increasingly smaller dimensions, they are challenged to do so for mechanical devices at low cost and in large quantity. More traditional manufacturing processes such as machining or injection molding can more easily meet cost and quantity requirements, but cannot currently match the dimensional abilities of microfabrication processes. By merging microfabrication and traditional injection molding techniques, the benefits of both technologies can be combined to produces parts to meet all three requirements. The objective of this research is to investigate the possibilities of injection molding polymer parts with sub-micron three-dimensional features using a process called Silicon Insert Molded Plastics (SIMP).

Introduction:

Using traditional mold making processes, molds can be manufactured which allow for parts tolerances of approximately ±130μm [1]. State of the art commercial micro-injection molding technology can produce parts typically are in the range of less than 100 mg with critical dimensions of less than 1mm. Micro-injection molds can provide tolerances of less than ±1μm to ±50μm for such parts [2] using manufacturing processes such as electroforming and wire EDM. For applications requiring extremely smooth surfaces, EDM combined with lapping or polishing can create surfaces with 0.1μm - 1μm surface roughness [3]. Precision manufactured molds can be integrated into almost any standard injection molding machine to create reasonably accurate parts. For example, compact discs are micro-injection molded to have features of 3μm by 0.5μm with a spacing of 1.6μm [4]. However, highly accurate parts require additional consideration in the design and control of the machine and process. Most industrial machines can apply large forces onto large mold bases and use large injection screws to supply large quantities of plastic quickly. Newer, small scale machines such as the Sesame Nanomolding machine [5] employ short injection strokes and smaller screws to apply small shot sizes of polymer at higher pressures.

While existing machines and techniques can produce features on the micron scale, they have difficulty extending part capabilities into the nanoscale. Instead, researchers have turned to microfabrication processes such as lithography and etching to investigate new molding techniques. Many of these techniques have been directed towards developing soft lithographic processes, which allow for microfabrication of semiconductor devices on a wide variety of materials without the use of photolithography [6]. These techniques tend to lend themselves to three generic groupings - light based forming, embossing, and the LIGA process.

Light based forming consists of two major forms - laser micromachining similar to the process used to write CDs [4], [7] and photo-molding through light induced reaction injection molding [7]. The photo-molding process requires the use of photo-curable polymers which are injected using a standard injection molding machine. After injection into the mold, the filled cavity is exposed to a high intensity UV source while under pressure to cure the polymer in the molded form. While photo-molding is capable of producing parts with dimensions on the order of 200nm, the molds require complex transparent sections for UV exposure and long curing times.

The next form of molding consists of a variety of embossing, printing, and replication processes for replication of features on a silicon wafer. These processes are used almost exclusively to transfer a pattern from a die to a thin polymer layer on a wafer. Subsequent processes either deposit metal then remove the polymer to create a metal part or use the polymer as a pattern for etching a wafer. The metal nano-replication process is capable of reproducing dimensions of 25nm in both PMMA and aluminum [8]. Investigations into nano-imprint lithography have produced features with 10nm diameter pillars with 60nm spacing after reactive ion etching (RIE) [9] and 40nm features in PMMA layers which transfer to 100nm silicon features after RIE using house-made equipment [10]. While these processes are capable of producing nanoscale features, they typically cannot produce complex three dimensional geometries, but rather produce high aspect ratio planar features in silicon.

The final form of microfabrication techniques applied for injection molding is the LIGA process. LIGA is a German acronym for a process where lithography, electroplating, and injection molding are combined to create plastic parts. The LIGA process uses x-ray lithography to develop a thin layer of photoresist, which is used as a base for electroplating the complex geometry of the part [11], [12]. This metal structure can be removed and used as a part or as a mold for creating additional parts with dimensions of 1µm to 10µm [13]. In experiments using LIGA formed structures as casting molds for PDMS, researchers created high aspect ratio microstructures on the metal mold inserts with surface roughness of 204nm, which yielded roughness of 215nm when replicated into PDMS [14]. The casting process used by the researchers was to spin the PDMS on the LIGA formed structures to obtain a uniform layer, then to vacuum degass and cure the polymer in an oven [15]. In addition to the casting procedure, LIGA molds have found application in injection molds. However, LIGA mold geometries are also restricted to high aspect ratio two dimensional microstructures. Cost restrictions are also a concern with LIGA, primarily due to the high cost of x-ray lithography and multiple steps required to fabricate the mold. A typical LIGA mold produced at Sandia National Labs costs approximately $10,000 for a single 3- or 4-inch diameter wafer, [11].

While these newer polymer processes are currently being developed to create polymer parts with nanoscale resolution and accuracy, they suffer from expensive preprocessing and are generally limited to vertical-wall geometries.

To improve precision molding beyond the current limits, it is proposed that silicon inserts be placed inside the mold cavity. The silicon inserts would be manufactured using microfabrication techniques allowing for tolerances, smoothness, and dimensions at a nanoscale level. For example, anisotropic etching is the process where an etchant preferentially etches certain planes of the crystal lattice at a greater rate. The common etchant potassium hydroxide (KOH) removes the <100> plane of silicon faster than the <111> plane [16]. After etching a <100> wafer, the nanometer smooth <111> plane is exposed at an angle of 54.7 degrees from the plane of the wafer. This angle can be varied by cutting an off-axis wafer from the ingot at an angle other than 90 degrees. Since the silicon inserts have atomically smooth surfaces, dimensions on the micron scale with tolerances in the nanometer to micron range are possible in molded parts. Additional features can be added to the mold using high energy lithography or focused ion beam milling, if necessary. Using these types of basic primitive features, more complex structures can be formed by bonding several sections of silicon together. Based on the capabilities of the microfabrication processes, dimensions on the micron scale and tolerances in the nanometer to micron range should be possible in the molded parts. This structure can then be interfaced to a traditional mold created using traditional machining operations and electro-discharge machining (EDM). By constraining the precise features within the silicon insert, parts can easily transition between highly accurate regions and less precise regions, lowering the costs of manufacturing parts with combined meso and nanoscale features.

Design Application – Precision Edges

To examine the limits of the SIMP process, two applications have been considered as proof-of-concept tests – precision edges and an elastically averaged fiber optic connector. Razor blades, which have an edge radius of curvature on the order of 30-50 nanometers, can serve as an ideal metric for evaluating the capability of nano-molding processes based on edge quality, both in terms of its geometry and its structural integrity. By combining KOH and TMAH etched features with wafer bonding techniques, molds can be created with nanometer smooth surfaces and a nanoscale tip as shown in Figure 1.

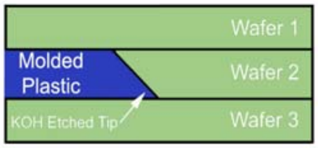

Figure 1 - Basic Schematic of Mold for Blade Design

While the literature is packed with discussion on the use of LIGA and PDMS for replication on the sub-micron level, neither of these processes are suitable for the low cost precision molding that would be required for making parts with tough precision edges such as razor blades [11] - [15]. Preliminary analysis indicates that carbon fiber reinforced plastic can provide sufficient structural integrity to cut hair. Since classical filler materials, such as glass or carbon fiber, are large compared to the required blade edge geometries, carbon nanotubes could be used as a replacement filler. Commercial nanotubes are available in graphite, multi-wall form with minimum diameters on the order of 10 to 15nm [18], which are adequate for the planned edge geometries.

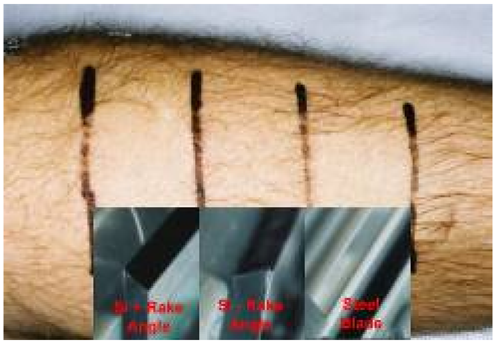

Figure 2 - Proof of Concept Tests for Blade

Proof-of-concept tests were conducted using a silicon edge created by KOH etching. This edge was mounted in a commercially available razor and used to shave a forearm shown in Figure 2. In this test, the positive rake angle mounting compared favorably with a conventional steel blade. After shaving, the silicon and steel razor blades were removed from the razor, and then photographed using a scanning electron microscope. SEM photographs of the edge are shown in Figure 3 and the surface in Figure 4. The steel razor blade demonstrated significant wear to a much larger degree than the silicon on the edge, while the surfaces showed little difference.

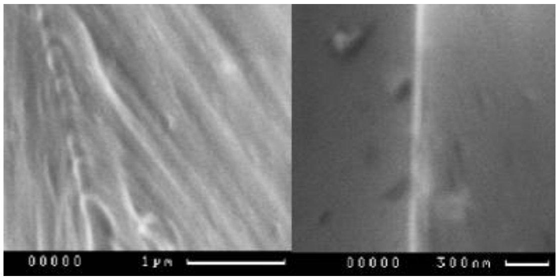

Figure 3 - SEM Images of blade tip in Steel at 1 µm (left) and Silicon at 300 nm (right)

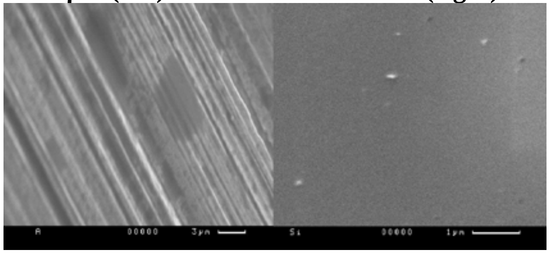

Figure 4 - SEM Images of blade surface texture in steel at 3 µm (left) and Silicon at 1 µm (right)

In addition, the surface texture of the unused blade differs greatly between the two materials, primarily due to the manufacturing process. Since steel blades are normally ground to the desired thickness, the blade shows deep grooves of 3µm. Due to the atomic surface created during etching, the silicon blade has only minimal impurities on the surface at 1µm.

Another topic of investigation is the selection of a method to bond wafers together to make the mold insert. Two processes studied were anodic and fusion bonding. Anodic bonding entails placing wafers, usually a silicon and glass substrate, between two metal electrodes. After heating them to ~400ºC, a DC potential up to 1kV is applied to the top wafer. This electric field makes the glass become highly reactive with the silicon surface and form a solid chemical bond. The fusion bonding process requires that two glass substrates be heated to 600 ºC for 4 – 6 hours. The long heating time creates a fusion bond between the two wafers.

To integrate the etched features into a mold, the silicon features can be bonded to other materials. To thicken the mold, extra glass substrates can be bonded to the silicon. Kovar composite materials can be used to provide extra strength to withstand the mold pressure and thermal support to the mold during cooling cycles. Silicon to Kovar bonding has been experimented with successfully.

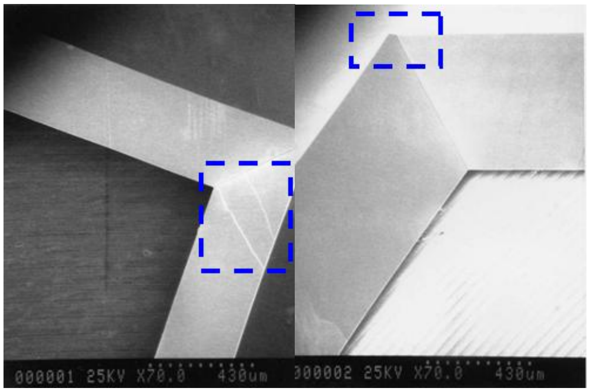

Figure 5 – Crystal plane misalignment

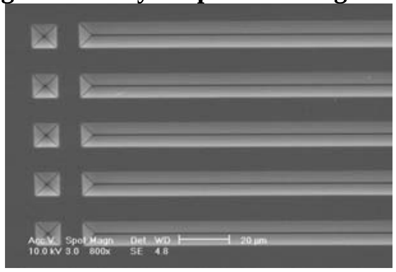

Figure 6 – Wafer alignment features

While etching the silicon, it was discovered that mask misalignment would initiate several incorrect geometric features. These features, shown in Figure 5, included ridges on the etched faces and misalignment of intersecting planes at their corners. It was determined that these features were caused by two errors: systematic errors for a set of wafers due to inaccurate placement of the wafer flat and random errors when aligning a photolithography mask to the flat. The systematic errors can be corrected before photolithography by employing x-ray crystallography to accurately determine the orientations of the crystal planes for that wafer cut [19]. With this error, mask placement for subsequent wafers can be corrected by simply rotating the mask. Better alignment can also be resolved by performing a preliminary etch to determine the orientation of the crystal plane. This preliminary etch will create features in a non-critical area of the wafer similar to the features shown in Figure 6 [20],[21]. When aligning a mask to the wafer, these features can be examined to optically determine the best alignment for photolithography.

In most common photolithography, a polymer material is used as the photoresist to control which areas of the wafer will be exposed to the etchant chemicals. However, for KOH etching, these polymers will etch more quickly than silicon and will not offer any protection. Instead, a protective layer of silicon-rich nitride is grown on the wafer, and then selectively etched to create the masking features. This nitride later etches more slowly than the silicon during KOH processing, allowing for features to be created in the underlying silicon layer. In the case where the etch geometry penetrates completely through the wafer thickness, misaligned features will correct as the etch self-terminates at the nitride layer. During experiments, it was discovered that this process will only work if the nitride protective layer remains flawless. Any flaws in the nitride can allow the chemicals to begin etching the protected silicon. Also, the thin nitride layer can easily break and physically damage the etched surfaces. To protect against these problems with nitride, a case to protect the wafer backside was used as shown in Figure 7.

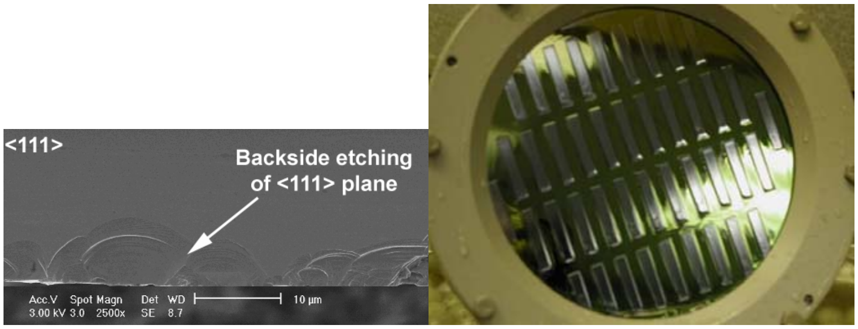

Figure 7 – Backside etching example and Case to protect the backside of the wafer

Proof-of-concept tests were conducted using a silicon edge created by TMAH etching. This edge was mounted in an injection molding press and fidelity parts were molded using optical-grade polycarbonate resin. An edge tip of 14µm was successfully molded as shown in Figure 8, which is capable of cutting through tissue. However, this tip edge is insufficient to act as a razor blade for shaving. Improvements have been made to the microfabricated molds to improve the tip sharpness and new mold trials will be completed before the conference date.

Figure 8: Molded plastic precision blade.

Design Application – Fiber Optic Connector

Another area of research is in the development of a parts design methodology to take advantage of the SIMP process. From a design perspective, designers will now have manufacturing processes available to create precision three dimensional geometries. Using the principles of elastic averaging and exact constraint, parts with high precision can be combined to form assemblies with micron-level precision. Of particular importance to the application of the SIMP process is the development of design philosophies for parts that are to be used in assemblies. In precision assemblies, exact constraint techniques have been used to align removable components in automobile engines, robotics, and many measurement devices. Exact constraint typically requires controlled precision machining to allow an interface to be repeatable and interchangeable. Elastic averaging techniques can be used instead of exact constraint to create slightly less repeatable interfaces with more generous machining requirements. Averaging techniques work by averaging out errors through controlled compliance between precision surfaces. The key to elastic averaging is to control a large number of features spread over a broad region that elastically deform when separate parts are forced into geometric compliance with each other.

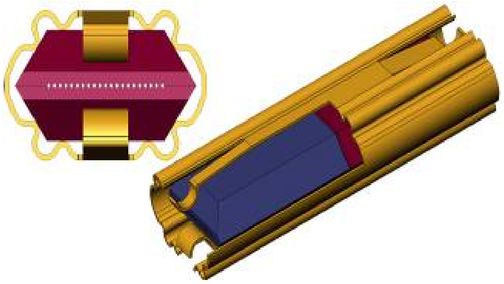

Figure 9 - Two connector elements shown mated inside sleeve – end view (left) and isometric view with cutout showing preload beam (right)

An ideal example application for the SIMP process with wide application is the alignment and mating of optical fibers. Multi-mode fibers have fairly generous alignment tolerances, on the order of three to five microns, while single mode fibers require alignment on the order of a half micron. With the SIMP process, a cost reduction of an order of magnitude should be possible without any reduction in precision. In order to effect this cost reduction, the design philosophy of elastic averaging can be used to reduce the part count to three parts.

Initial large-scale models of the connector were created using approximately 1mm thick waterjet aluminum for the sleeve and a 1-inch wide Delrin hexagonal rod for the connector elements. These models were joined, then measured using a white light profilometer to determine the repeatability of the height difference between the two elements. Results with this fairly basic model show that the standard deviation of the height difference is approximately 5 micrometers and the angular difference is 0.03 degrees. A more complete description of the connector design was presented at the 2004 ASPE Annual Conference [22].

Conclusions:

Preliminary results indicate that the SIMP surfaces can indeed yield nanoscale smoothness and micron scale features. Additional experiments are underway to allow for nanoscale feature size, as well as to transfer SIMP from an experimental tool into an industrially viable process. An SBIR grant with Custom Engineering Plastics of San Diego, CA aims to begin addressing many of these concepts.

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