A New 3D, Direct-Write, Sub-Micron Microfabrication Process that Achieves True Optical, Mechatronic and Packaging Integration on Glass-Ceramic Substrates

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Abstract
The 2D MEMS processes today provide limited capability to achieve true 3D functionality. In addition, integration of the MEMS into functioning systems is difficult and often represents over 80% of the cost of the final packaged solution. Finally, the batch nature of the process, while efficient from a production efficiency standpoint, introduces significant time and tooling investment to get functioning product. In this paper we describe a true sub-micron, 3D micro-fabrication process that represents a paradigm shift toward "rapid production" of integrated solutions for a broad range of applications including micro-replication, micro-robotics, MOEMS and microfluidics.

1 Introduction

Three different manufacturing processes have been traditionally used in the fabrication of Micro-Electro-Mechanical Systems (MEMS):

1. **Bulk Micromachining** of silicon or other crystalline materials
2. **Surface Micromachining** of silicon or other silicon derivatives
3. **LIGA—**a lithographic process employing electroforming and micromolding used for creation of high-aspect ratio, 2D metal and ceramic structures.

Leveraging the use of commercially available semiconductor process equipment, these planar manufacturing processes have achieved commercial success in the industrial sensor (eg. Pressure sensors), inertial sensor (eg. Accelerometers, rate gyros), and telecommunications (eg. Variable optical attenuators, cross-connect switches, compliant structures for fiber-waveguide alignment) applications, to name a few. [1]

Despite these technical and commercial successes, the planar manufacturing processes employed in these have fundamental limitations that have slowed the adoption and growth of MEMS-based systems:

1. **The structures created by these processes are inherently limited** to 2D (eg. Inch-worm, comb-drive) or to "2.5D" (eg. self-erecting mirrors) structures that can be erected from 2-D structures. True 3D mechatronics implemented this way requires, often tricky, assembly of multiple 2D MEMS components.
2. **The non-recurring engineering costs, including mask generation, are high**—typically \$50-\$100,000 on a multi-layer process—making it difficult for emerging companies with comparatively small volumes to deploy the technology.
3. **The delivery times are long**—often 12-15 weeks—extending the "time-to-money" by stretching design, verification, and validation cycles.
4. **The manufacturing processes are not truly scaleable.** Extending the number of layers, say, in a surface micro-machining process from four to five layers (extending the height of the machine from 10 μ to 12 μ!) could take months or years due to the impact of thermal cycles during deposition of the fifth layer on the residual stresses in Layers 1-4, and the corresponding effect of these residual stresses on Layer 5.
5. **The "Cost-of-Packaging" these components is high.** Integration of planar MEMS with optical components (fiber, array wave-guides, etc) and housing often represents 80% of the manufacturing cost of a microsystem.
6. **There is a lack of microsystem packaging standards.** As a result, custom tooling and significant process development is required to assemble integrated microsystems employing MEMS.

To mitigate the impact of 2) and 3) above for emerging companies, "multi-user" processes have been created by MCNC and the Sandia National Labs whereby users with small volume requirements can "share a wafer" with other companies thereby sharing the NRE costs and leveraging a proven micro-fabrication process. Such measures do not shorten the development and manufacturing cycles. In fact these cycles are often lengthened unless these are somehow synchronized with the wafer starts.

This paper presents a new micro-fabrication process— a non-ablative, laser-patterning process performed on photo-structurable, aluminosilicate, glass-ceramic substrates (PSGC). The new process leverages the work of researchers led by Dr. Henry Helvajian at the Aerospace Corporation (Aerospace), who developed the technology for use in the fabrication of pico-satellites. **[2][3][4][5]**

This true 3D, "direct-write" process, which is now being commercialized, naturally integrates optical, mechatronic, and housing functionality into the substrates, thereby eliminating the costly and time-consuming mask generation, wafer processing, and assembly process development **AND** shortening the delivery cycle for prototype and production components from months to days. Introduction of this true 3D direct-write process represents a paradigm shift away from the traditional approaches based upon the lithographic techniques noted above. The paper

- Describes the laser patterning process and how it is being deployed in the creation of true 3D structures, masks, sensors, and machines;
- Reviews experimental results;
- Reviews the range of applications that can benefit from the direct-write, laser patterning process

2 Description of the New Process

A contract manufacturing facility is being constructed to build 3D MEMS and microsystems that employ the direct-write laser patterning process. The theory of operation of the laser-patterning process employed in this facility is described in Section 2.1. Section 2.2 outlines the overall design and the direct-write "rapid production" manufacturing process employed within the facility to create functional microsystems that employ the laser-patterned substrates.

2.1 Theory of the Direct-Write Laser Patterning Process

The term "direct write" refers to "any technique or process capable of depositing, dispensing, or processing different types of materials over various surfaces following a preset pattern or layout."**[6]**

The laser patterning process leverages the unique characteristics of photo-structurable glass-ceramics. When such glasses are exposed to modest levels of pulsed UV laser energy density (fluence) in excess of the critical fluence, F_c, a photo-chemical reaction creates a density of nanocrystals within the critically-exposed volume as shown in Figure 1.

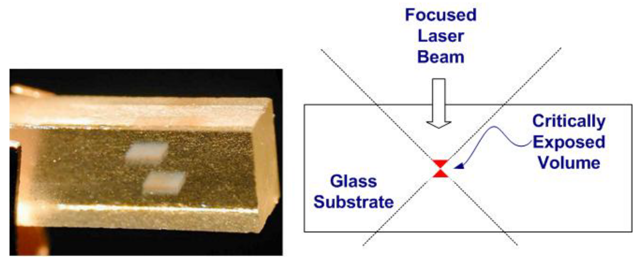

Figure 1. UV Exposure of the Photo-Structurable Glass

The density of nanocrystals is directly proportional to the fluence within the critically exposed volume. By controlling the depth of focus and numerical aperture of the UV laser optics, sub-micron features can be easily created. Or, when larger critically exposed volumes are desired, say, for large diameter holes, optics with a larger depth of focus can be employed.

The critically-exposed volume can be extended by employing successive pulses of laser energy along a specified path—defined by a computer-controlled multi-axis positioning system as shown in Figure 2.

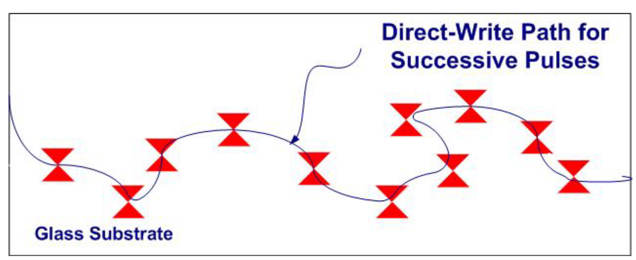

Figure 2. Extending the Exposed Volume via pulsing the laser on prescribed, computer-controlled paths

By linking such paths, complex, 3D volumes of critically exposed material can be created.

By applying a thermal treatment protocol, the nanocrystals grow to form large crystalline structures (ceramic) as shown in Figure 3.

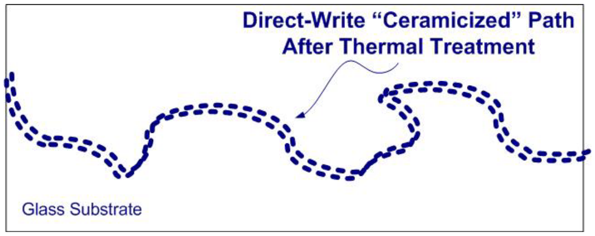

Figure 3. Critically-Exposed Volume after Thermal Treatment

Depending on the thermal treatment protocol and the fluence levels applied, the "ceramicized" material changes color—transitioning from transparent to black (through yellow, orange, red, and brown) as shown in Figure 4.**[7]** It is this behavior that enables the creation of embedded masks with sub-micron features.

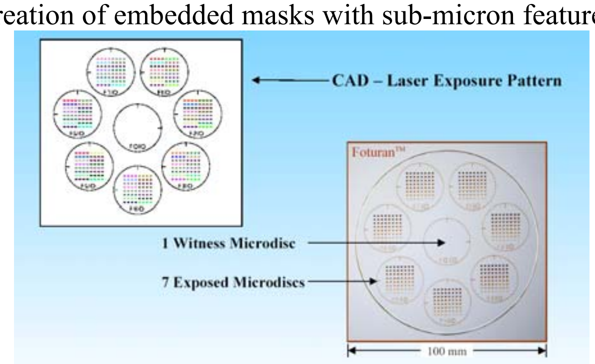

Figure 4. Variation in Color as a Function of Exposure and Thermal Treatment Protocol

It has been shown in the research work at Aerospace that the critically exposed volume will, when subjected to a mild etchant, etch faster than the unexposed material by an "etch contrast ratio" that is defined by an "s-shaped" non-linear function of the exposure. Etch-rate contrasts in excess of 25:1 have been achieved as shown in Figure 5. **[8]**

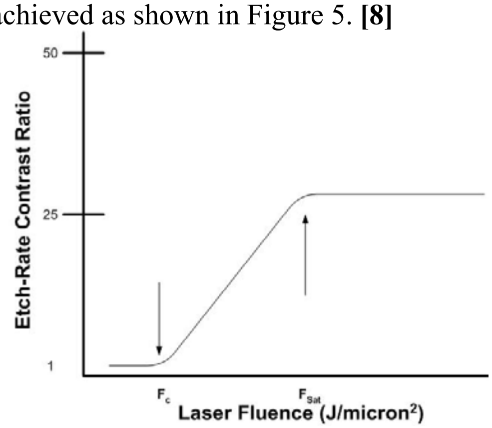

Figure 5. Etch-Rate Contrast as a Function of Exposure

After etching, the critically exposed volume is removed, along with small amounts of the non-exposed volume at the exposure boundary transition as shown in Figure 6. The result is a true-3D structure with sub-micron features.

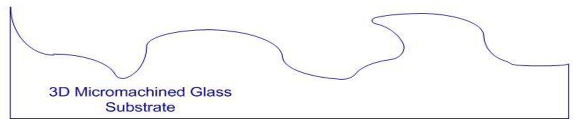

Figure 6. Final Micromachined Part

The etch process can be followed by a second UV exposure and baking step. This additional UV process and thermal treatment is used to convert the glass to the full ceramic state or, if desired, to an intermediate transition state. Table 1 summarizes the material properties of the glass-ceramic material as this ranges from the amorphous glass to the fully ceramicized state. Through the use of this optional expose-thermal treatment step, the material properties can be "dialed in" to a value between these two extremes.

Material Parameter	Units	State	
		Glass	Ceramic
Density	g/cm^3	2.37	2.41
Elastic Modulus	Gpa	78	88
Rupture Modulus	Mpa	60	150
Hardness, Knoop	Mpa	4600	5200
Dielectric Constant		6.5	5.7
Loss Factor ($\tan\delta$)		65	25
Resistivity	Ω-cm	$8.1x10^{12}$	$5.6x10^{16}$
Index of Refraction[1]	n_E	1.51445	1.418
Abbe Number[1]	v_E	60.93	60.93
Transformation Temp	°C	465	
Maximum Safe Temperature	°C		750
Thermal Expansion	$10^{-6}K^{-1}$	8.6	10.5
Thermal Conductivity	$Wm^{-1}K^{-1}$	1.35	2.73

Table 1. Key Material Parameters for the Amorphous Glass and Ceramic (Crystalline) States

2.2 Manufacturing Process and Facility Details

The manufacturing process employed in the proposed contract manufacturing facility (Facility) is outlined in Figure 7.

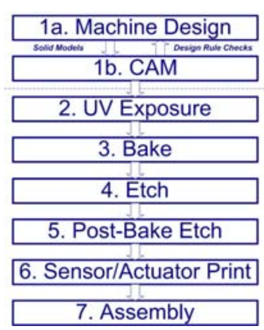

Figure 7. Manufacturing Process

A block diagram describing the key elements of the proposed flexible manufacturing cell employed in the manufacturing facility is shown in Figure 8.

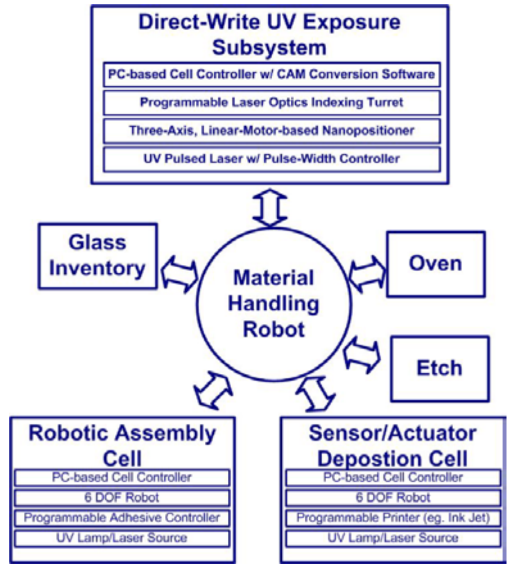

Figure 8. Block Diagram of Flexible Manufacturing Cell

The proposed flexible manufacturing cell will be built within a Class 10 environment. The ensuing subsections describe the process steps and the flexible manufacturing cell in detail.

2.2.1 Step 1: Design

In the current process, solid models in a parasolid format compatible with SolidWorks™ are processed by proprietary computer-aided manufacturing (CAM) software. This software performs design rule checking and generates trajectories and process vectors—laser pulse width, frequency, and intensity—for each of the laser optic configurations ("laser tools") carried by the optics indexing turret and a high speed (1kHz) proprietary nanometer resolution scanner. As shown in Figures 9, the "laser tools" control the size and shape of the critically exposed volume created by each laser pulse on a particular path. Depending on the type of part being created, laser tools ranging from sub-micron to several hundred microns in size are used, as shown superimposed on the desired micromachined surfaces in Figure 9. The CAM software automatically selects the proper laser tool to maximize the throughput of the exposure process.

[1] n_E, v_E are measured at a wavelength of 587.56nm.

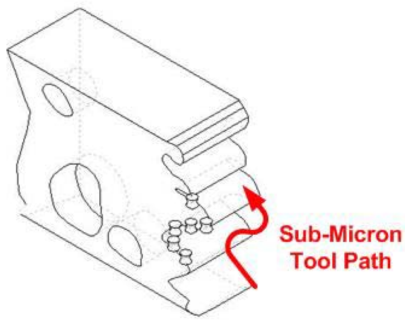

Figure 9a. Use of Small (<1μ) Exposure Tool to Micromachine Sub-micron Features (Superimposed on final micromachined component)

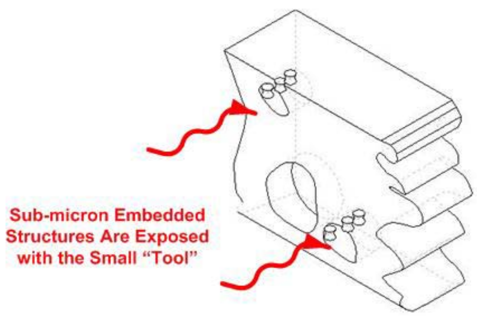

Figure 9b. Use of Small (<1μ) Exposure Tool to Micromachine Embedded Features (Superimposed on final micromachined component)

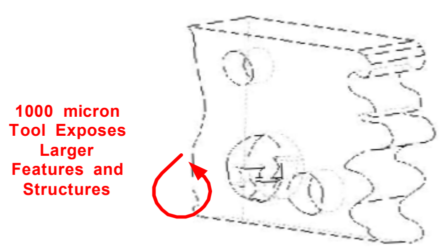

Figure 9c. Use of Medium (10μ) Exposure Tool to Micromachine Larger Features (Superimposed on final micromachined component)

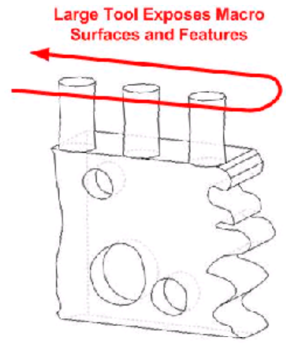

Figure 9d. Use of Blanket Exposure Tool to Micromachine Macro Features

2.2.2 Step 2: Direct-Write UV Exposure

In this step, glass is loaded onto the wafer chuck and exposed per the CAM profiles and process vectors generated in the previous step. Square "wafers" of four different (Length, thickness) configurations—200 mm by 2mm, 200mm by 4 mm, 400mm by 6mm, and 600mm by 10mm— are employed within the Facility to support a wide range of laser-patterned microsystem components and systems. For 200mm wafers, typical exposure times range from 15 minutes to 1 hour.

2.2.3 Step 3: Thermal treatment

In this step, the exposed glass is loaded into an oven. Typical process times within the oven range from three to five hours.

2.2.4 Step 4: Etch

In this step, the exposed and thermally treated glass is loaded into the mild etchant. Etch times range from 15 minutes to 2 hours depending on the glass thickness, etch-rate contrast, and total depth of cut.

2.2.5 Step 5: Post Etch Expose-Thermal

In this optional step, the etched wafer is reloaded into the Direct-Write UV Exposure Cell where it is again exposed to UV radiation—specifically in those structures or volumes for which transition or fully ceramicized material properties are desired. Following this exposure, the wafer is reloaded into the oven for final thermal treatment. Typical times range from one to four hours depending on the initial thermal treatment protocol.

2.2.6 Step 6: Sensor/Actuator Printing

In this step, the wafer is loaded into a direct-write sensor/actuator printer. This 3D printer applies inks or pastes as required to draw electrical traces, sensors, and/or actuators onto the glass-ceramic substrate. Through direct-write UV exposure, these materials—typically metals, shape memory alloys, or piezo-electrics—are fixed to the substrate. Unexposed material is washed away in a separate step. Depending on the ink or paste used, a thermal treatment step is often employed to complete the deposition process. Where piezo-electric actuators are employed, poling may be required—through application of an electric field—to functionalize the material for use as an actuator.

2.2.7 Step 7: Assembly and Lockdown

In some complex microsystems, assembly and integration of the finished glass-ceramic substrates may be required. This capability is useful when integration, including alignment, with external optical components (fiber, for instance) is required or when embedded actuators are employed that would otherwise not be accessible by the sensor/actuator printer. In these applications, the components that comprise the microsystem will be patterned into a common wafer. In this final step, a six degree-of-freedom, force-controlled robotic nanopositioner breaks off the component assemblies from the wafer and integrates these in succession into the base assembly. A variety of methods are being employed to lockdown/bond the components. In the most common method, nanoliter quantities of UV-curable adhesive are applied to the mating surfaces under robotic control. A UV laser carried by the nanopositioner pulses energy onto the surfaces to be bonded after the parts are mated. Where necessary the laser is scanned across the surfaces at very high rates to ensure that the parts cure evenly.

3 Experimental Results

In this section we review sample test structures built using the process outlined in Section 2 above.

The process work to date has primarily focused on the development and commercialization of micromachining of static structures and mask components. Figures 10, a-f are illustrative examples, supplied courtesy of Aerospace, that demonstrate the capability of the process to micromachinining of complex 3D structures.

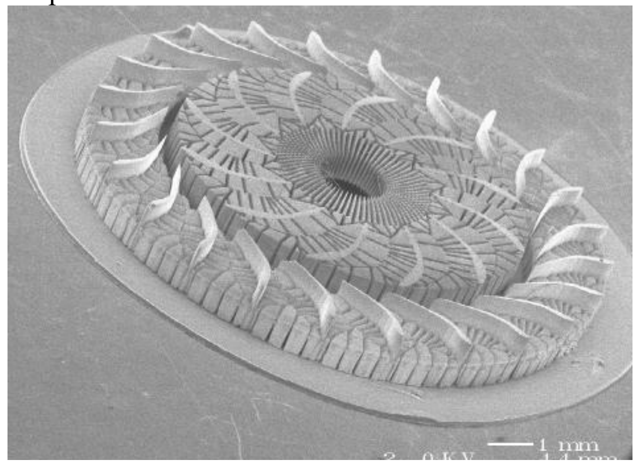

Figure 10a. High-Speed Turbine (Tested at 100 kRPM)

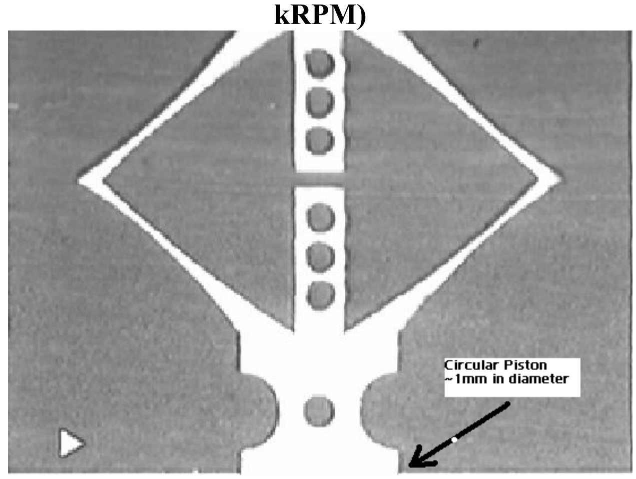

Figure 10b. Flexure-Driven Piston (Note: Piston has a rectangular cross-section)

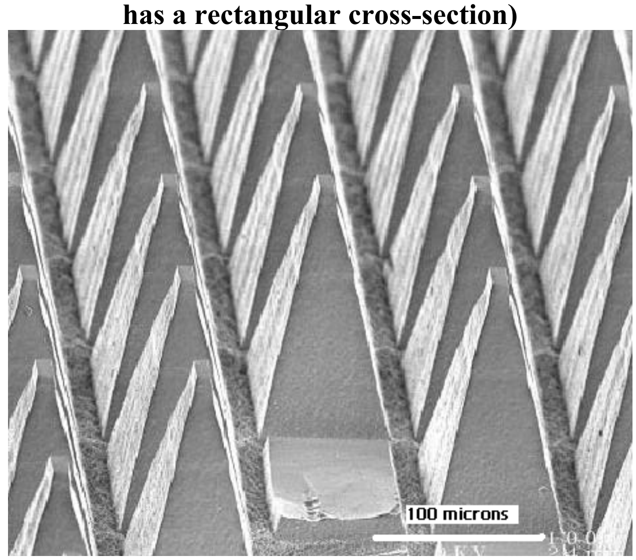

Figure 10c. High Aspect Ratio Periodic Structure for use as a Microreplication Mold

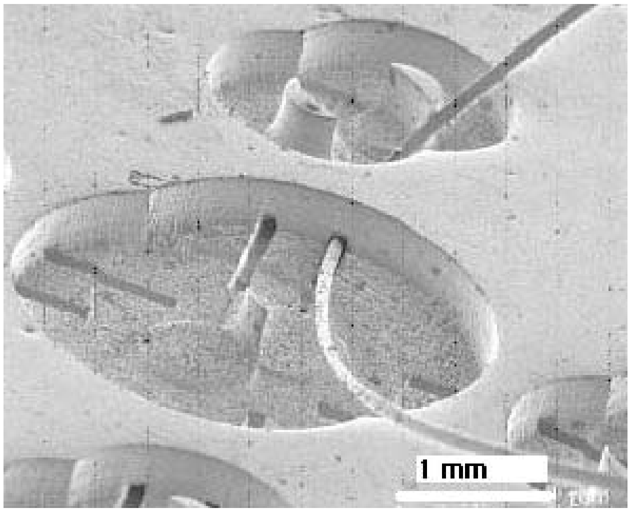

Figure 10d. Embedded Channels for use in 3D Microfluidic Applications

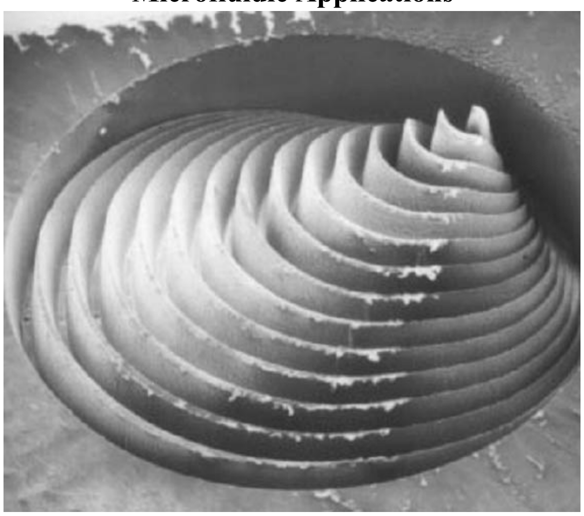

Figure 10e. High Aspect Ratio Structure (75µ kerfs, 2mmX2mm)

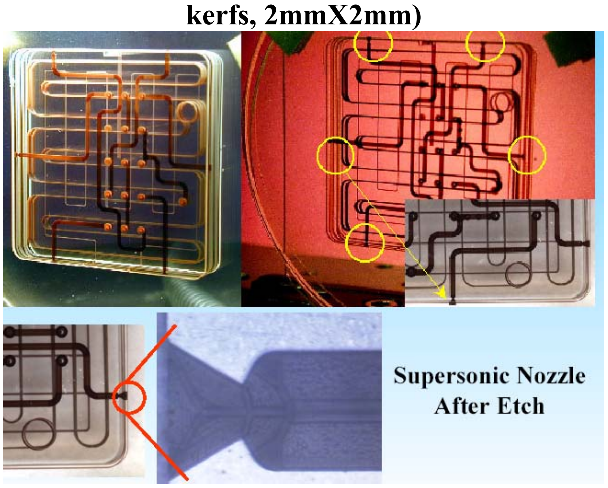

Figure 10f. One of six layers employed in picosatellite (Shows integration of fuel tank, fuel lines, and rocket nozzles)

4 Potential Applications

The new MEMS process outlined in the above sections can be applied across a broad range of microsystem applications. These could include both passive and active microsystem and microsystem components in the following applications:

- **Optical Masks and Gratings**
  - Incremental and Absolute Position Transducers
  - Low-resolution masks for photolithographic applications
  - Computer Art
  - Holograms
- **Micromolds**
  - Microreplication via imprint methods
  - Micro-injection molding
- **Microfluidic Applications**
  - 3D "Lab-on-a-Chip"
  - Industrial Ink Jet Printing
  - Microreactors
- **Adaptive Optics**
  - High-bandwidth laser pointing systems for space communications
  - 3D Deformable Mirrors
- **Microrobotic Applications**
  - µ aerial vehicles
  - µ submersibles

These new applications leverage the 3D micromachining capabilities; the direct-write capabilities of the laser patterning and sensor/actuator deposition processes; and the capability to tightly integrate optic, mechatronic, and packaging functionality.

5 Summary

The conventional planar (2D) processes employed by the MEMS industry today make it difficult to produce integrated microsystems with 3D machine functionality. In addition, the NRE and tooling costs associated with these processes are often not easily amortized by the low-to-medium production volumes that are common in emerging markets. Further, the batch production methodology embodied within these processes can sometimes extend development and production delivery cycles.

The new direct-write manufacturing process described in this paper—a process that employs non-ablative, 3D laser patterning of photo-structurable glass-ceramic substrates—can provide:

1. Scaleable, 3D Micromachining;

2. Lower NRE and Tooling costs;
3. Shortened development manufacturing cycle time—well-suited to prototype development, design verification/validation, and low-to-medium volume production processes; and
4. Lower recurring costs—owing to the integration of optical, mechatronic, and packaging functionality onto a single substrate.

This direct-write process can be applied to the production of embedded optical masks and gratings and to the manufacture of microsystems and components found in new microreplication, micro-robotic, MOEMS and microfluidic applications.

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