

Laser Material Processing for Microengineering Applications

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Abstract

The processing of materials via laser irradiation is presented in a brief survey. Various techniques currently used in laser processing are outlined and the significance to the development of space qualified microinstruments are identified. In general the laser processing technique permits the transferring of patterns (i.e. lithography), machining (i.e. with nanometer precision), material deposition (e.g. metals, dielectrics), the removal of contaminants/debris/passivation layers and the ability for providing process control through spectroscopy.

Introduction

The microelectronics processing technique has been successfully used to cofabricate microstructures (i.e. transducers) alongside electronics (i.e. "intelligence"). The result is a "smart" microinstrument comprising of materials compatible with microelectronics processing. The use of materials outside the fabrication recipe list is typically not recommended as it may jeopardize the product yield or contaminate a process line. As a consequence, a limited set of materials are available for most microinstrument development. This limitation is dictated by the processing approach and would be less restrictive for a processing tool which could alter materials with "site-specific" precision and without the need for raising the sample bulk temperature. Laser processing is one such technique which complements the microelectronics processing technique and permits the site-selective processing of materials at low bulk temperatures. For example, the laser based technique has been used as a "direct-write" processing tool for circuit repair operations. Still, more is possible if the knowledge in laser material interaction physics/chemistry is used to advantage. A laser "tool" can provide capabilities which are beyond the post-assembly simple-repair operations. First, as a processing tool the laser is non intrusive and can easily be integrated into a microelectronics fabrication assembly line. Second, the laser tool is amenable to automation. Third, a laser tool can be configured for multitasking in situ operations (i.e. it can put down and/or remove material, serve as process diagnostic). Finally, a laser based tool offers new capabilities, such as processing at an imbedded interface. A technique currently unavailable in the microelectronics processing tool chest. There is sufficient experimental evidence that a laser based material processing tool will serve to accelerate the development of microinstruments by allowing materials with unique chemical and physical properties (e.g. ceramics, diamond, polymers) to be processed. This capability will be specially important for space applications where materials are designed to meet stringent standards.

Space qualified hardware must meet a diverse set of environmental conditions. Prior to launch, space qualified hardware is typically placed in storage, sometimes for years. The storage environment may include both high temperature and humidity. During the launch the hardware must survive the high acoustic and acceleration forces and subsequent to the launch, they must operate in vacuum, without the benefit of cooling air. Furthermore, the hardware is exposed to cosmic radiation and must survive thousands of heating-cooling cycles. Therefore,

materials are specifically chosen or "engineered" to withstand both the launch and the space environments. Likewise, component packaging for space applications is also non trivial. The package or an enclosure may serve two purposes. First, to mitigate the effects of the space environment and second, to provide an exit pathway for outgassing of materials contained. Consequently, some components may have to be locally sealed while others may require pathways for outgassing.

Microinstruments designed for space applications must also meet the diverse set of environmental conditions a described. As a consequence space qualified microinstruments (and application specific integrated microinstruments- ASIMs) may incorporate materials not commonly used in terrestrial applications. Likewise, the integrated packaging approaches used must employ localized hermetic seals to protect contaminant sensitive components. A hypothetical example of such a package is given in Figure 1 where various devices and components, comprising of a variety of materials, are assembled on a common substrate. To fabricate, test and repair such a module requires a material processing tool with "direct-write" capability. The laser is a "direct-write" processing tool which does not require vacuum, can deposit, remove or alter materials with both site and material specificity and can deposit energy at an imbedded interface. The result is the ability for localized material processing without raising the temperature of adjoining structures or components. Figure 1 shows a few of the viable laser processing tasks for the hypothetical package example and Table 1 lists a few of the current laser applications in material processing.

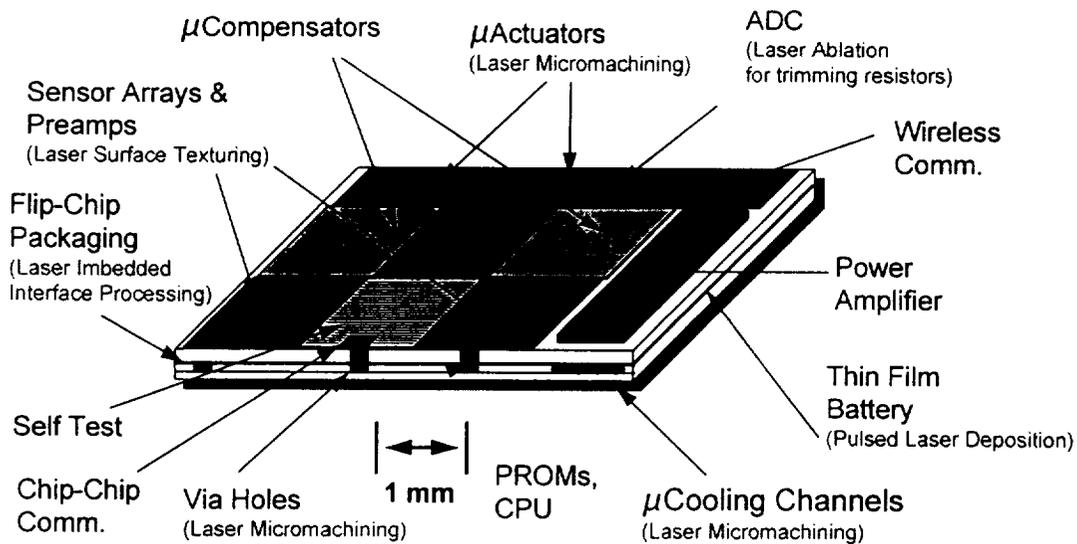


Figure 1: Hypothetical ASIM in a hybrid multichip module (MCM) package employing flip-chip technology.

Table 1: Examples of Laser Applications in Material Processing

1	Pulsed Laser Deposition (via Ablation) - scale-up to 200mm wafers shown. Bibliography of deposited thin films ¹ Bandgap Engineering ² Biocompatible Materials ³	8	Micrometer scale "Machining" Etching: Metals, Insulators, Semiconductors Soft Ablation: Polymers Scribing and Contouring
2	Nanometer Scale "Machining" (via nonthermal ablation) --- Crystals	9	Spectroscopy Surface, Above surface, Process Control
3	Photochemical Deposition	10	Photolithography
4	Surface Annealing	11	Localized Oxidation
5	Annealing	12	Surface texturing/contouring
6	Semiconductor Doping and Drive-in.	13	Surface Debris Removal (i.e. cleaning)
7	Laser-LIGA	14	Embedded Interface Diffusion

Fundamentals and Selected Application Examples

To refine the laser material processing technique requires understanding the laser material interaction phenomenon. Many textbooks and articles cover this material at depth⁴. This report only summarizes the salient features and without the benefit of supporting equations. Under most laser processing conditions the criteria for optimum laser material interaction is described by a handful of equations⁵. These equations describe the propagation of the laser beam energy through the beam delivery optics, the photophysical interaction with the surface (i.e. absorption, surface chemical interactions) and the subsequent surface modification. The equations are simplified for a Gaussian laser beam propagating in a diffraction-limited optical system, though for most material processing a top-hat or flat top homogenized beam is used⁶. In general, the fundamental physics is driven by the incident laser fluence (J/cm^2), the responsivity of the material and the photochemistry of the ablated material. In vacuum and for very low laser fluences the particle or "processing" yield is governed via non thermal photoactivated mechanisms. In this processing regime the yield is non linear with the laser fluence and the surface is "processed" with nanometer precision. At somewhat higher laser fluences the irradiated surface is abruptly heated and material processing is via thermal initiated mechanisms. In this regime, processing yield is typically linear and the processing precision is micrometers. At much higher laser fluences, where an above surface plasma is ignited, the interaction of the laser with the surface is reduced as a result of absorption in the plasma. In this regime, the surface morphology is altered not by the laser but by the above surface plasma. The processing precision is not easily controllable but is nominally on the millimeter scale. Table 2 shows the process criteria and related parameters for laser "direct-write" processing and Table 3 gives a summary of common laser parameters that can be controlled and the induced effect in processing. Application examples of processing materials in these different regimes are also given below.

Table 2: Process considerations in direct write processing (from Ref 7)

Process Considerations	Related Mechanisms
Resolution	Wavelength Beam spot size Thermal diffusivity Nonreciprocity
Writing Speed	Beam size Film growth rates
Resistivity	Composition Impurity Physical structures
Morphology	Coherence effects Nonuniform heating Instabilities
Adhesion	Interfaces Thermal mismatch

Table 3: Laser parameters and related processing parameters (from Ref 8)

Laser Parameters	Effect on Material Processing
Power (average) (W)	Temperature (steady state) Process throughput
Wavelength (μm)	Optical absorption, reflection, and Transmission, Resolution Photochemical effects
Spectral linewidth (nm)	Temporal coherence Chromatic aberration
Beam size (mm)	Focal spot size, Depth of focus Beam transformation characteristics Intensity
Lasing modes	Intensity distribution Spatial uniformity Speckle, Spatial coherence Modulation transfer function
Peak power (W)	Peak temperature Damage/induced stress Nonlinear effects
Pulsewidth (sec)	Interaction time Transient processes
Stability (%)	Process latitude
Efficiency (%)	Cost
Reliability	Cost

For some materials, with UV laser irradiation and at very low laser fluences ($<100\text{mJ/cm}^2$) the laser material interaction is driven by electronic rather than thermal excitation. Under these circumstances nanometer scale precision surface processing becomes possible. By controlling the laser fluence during the irradiation, a surface can be "peeled" atomic layer-by-layer. Furthermore, by tuning the laser wavelength selective removal of species from the surface is possible. Figures 2 and 3 present both of these phenomenon for the perovskite ceramic $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$. Figure 2 shows the calcium atom photodesorption yield as a function of laser shot number. The oscillation in the calcium signal as measured by the mass spectrometer corroborates with the layer-by-layer removal concept. Figure 3 shows two mass spectra of the photoejected species for two laser irradiation wavelengths. For 351 nm irradiation the mass spectrum is representative of the all the species while for 248 nm irradiation a single mass peak is measured. Most laser material processing is conducted at higher laser fluences than that used in acquiring the data shown in Figures 2 and 3. Laser material processing via non thermal excitation becomes economical for laser repetition rates greater than 1 MHz. At the higher fluences, microscribing or surface texturing become economically feasible for most laser systems commercially available. Laser microscribing is a value added process because laser scribing is generally faster than most techniques and leaves the surface with less overall damage. Even in comparison diamond scribed surfaces. An example is in the development of large area (1m x 1m) photovoltaics where laser scribed surfaces result in cleaner cuts. Microscribed surfaces also have properties which may be important in space applications. Surfaces with complex topologies are known to enhance chemical reactivity (e.g. catalysis), optical reflectivity (e.g. light trapping), mechanical action (e.g. microVelcro, precision abrasion) and load-handling capability in lubricated journal bearing systems. Surfaces can be laser microscribed either via a "direct-write" method, through the formation of an interference pattern in a chemical etching environment or via a rapid heating and recrystallization process (temperature rise rate $>10^7$ K). Figure 4 shows a scanning electron micrograph of a microtextured crystalline aluminum surface prepared in vacuum at The Aerospace Corporation using the latter method. The inset shows the scale where the measured corrugation period is approximately $0.15\ \mu\text{m}$. Most surface texturing or scribing by laser is typically done by the two other methods using an etching solution. Table 4 lists typical etching/ablation rates for a laser based material processing system. For the etching of Si and SiO_2 the table also includes, for comparison, the predicted etching rates used in microelectronics processing ---- for etching without a laser and using a relatively vigorous KOH/water recipe.

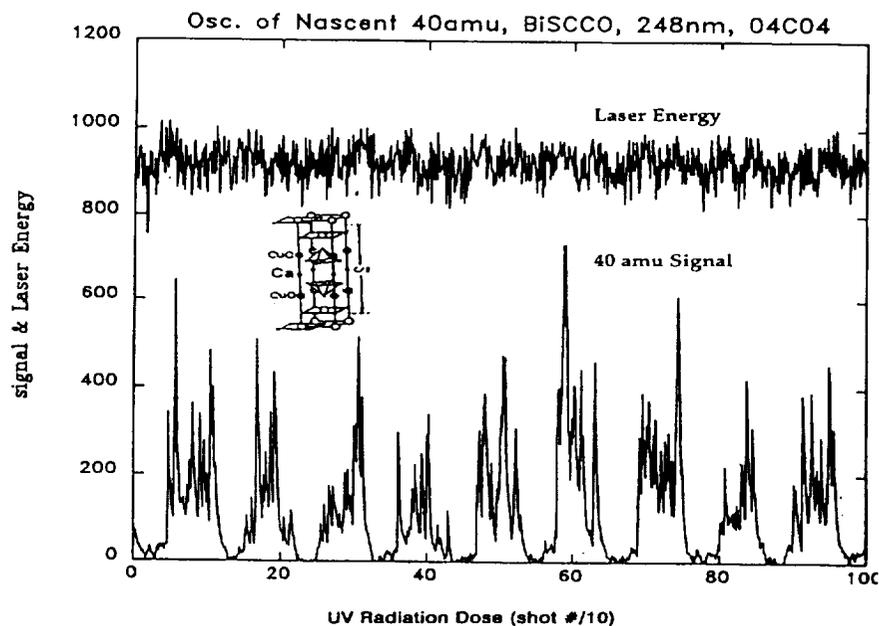


Figure 2: Measurement of the photoejected atomic calcium yield as a function of laser pulse number. The irradiation is via a UV laser nonthermal photosputtering from an aligned single crystal, high T_c perovskite ceramic ($\text{Bi}_2\text{Sr}_2\text{Cu}_2\text{CaO}_8$)⁹.

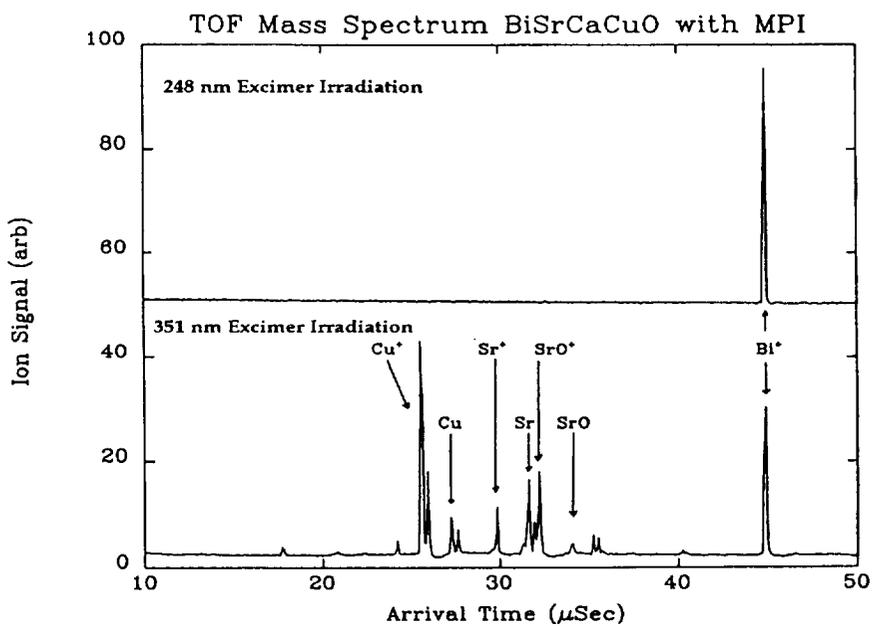


Figure 3: Time-of-flight mass spectrum of photoejected species following pulsed UV laser irradiation of $\text{Bi}_2\text{Sr}_2\text{Cu}_2\text{CaO}_8$ ¹⁰.

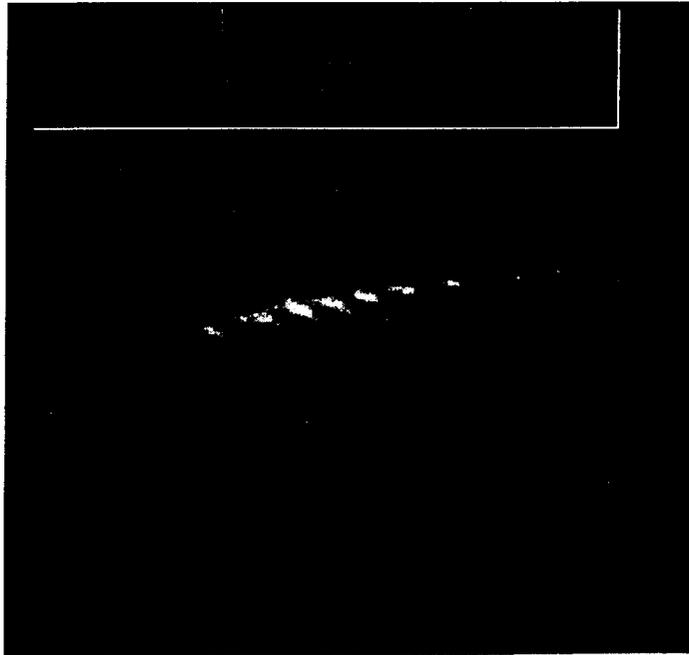


Figure 4: UV laser microtexturing of an aluminum (111) surface prepared in UHV.

Table 4: Etching/ablation rates for typical materials used in semiconductor processing (data from tables in Ref.¹¹)

Si:: ~ 7-15 μ /sec (KOH etch rate Si<100>, 35%, 100C is 55 nm/sec)	SiO ₂ :: ~ 0.5 -3 nm/sec (KOH etch rate 40%, 100C is 0.5 nm/sec)
- α Si:: ~ 50 nm/pulse	Ge:: ~ 36 μ /sec
GaAs:: ~ 0.5 - 2 μ /sec	InP:: ~ 140 μ /sec
GaP:: ~ 60 nm/sec	Diamond:: ~ 140 nm/pulse
Polimide:: ~ 0.1 - 1.0 μ /pulse	PET:: ~ 0.1-1.0 μ /pulse
PMMA:: ~ 0.3 μ /pulse	Ag: ~ 0.1 μ /pulse
Al:: ~ 0.1 - 1.0 μ /sec	Au:: ~ 50-80 nm/pulse
Cr:: ~ 80 nm/pulse	Cu:: ~ 0.1 μ /pulse
Mo:: ~ 20 μ /pulse	W:: ~ 3 nm/sec

Recent interest has focused on the ability of UV lasers to micromachine diamond. Diamond is a material which offers significant advantages in applications for space systems. It is both a good electrical insulator and a chemically inert material. Moreover, it has low thermal expansion when compared to silicon, aluminum nitride, Kovar and alumina. It could serve as an ideal material for packaging. Lasers can not only machine diamond but can also grow a variant of true natural diamond. Amorphous diamond (~75% true diamond by volume) is one form which is similar to natural diamond in hardness (~78GPa) and has a low coefficient of friction (~0.1).

Using high intensity ablation, amorphous diamond can be deposited without catalysts¹². Various steels have been coated (304, 316L, 440C)¹³ along with silicon, titanium and IR optics (Ge, ZnS)¹⁴. Growth rates of 0.5 $\mu\text{m/hr}$ over 100 cm^2 have been realized. Figure 5 shows a free standing laser micromachined diamond microgear while Figure 6 shows a laser micromachined valve in a diamond substrate.



(a)



Figure 5: a) Freestanding laser micromachined diamond microgear. b) Engraved laser micromachined gear in type 1b diamond substrate (Courtesy of Potomac Corp.¹⁵)

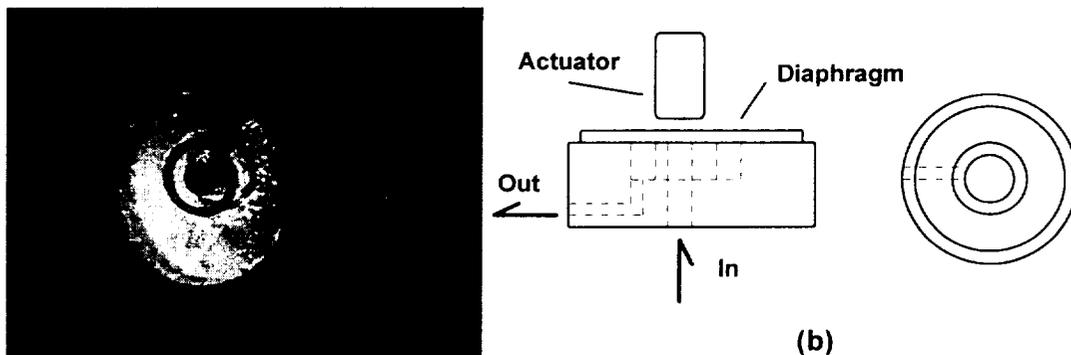


Figure 6: a) Laser micromachined valve in diamond substrate without the actuator b) Schematic of the valve design. (Courtesy of Potomac Corp.)

Experiments now in preparation at The Aerospace Corporation will utilize the laser processing techniques as described to develop microthrusters for space applications. The intent is to develop a miniature (15 cm diameter) space micropropulsion platform. Several concepts are under consideration, they include the traditional monopropellant thrusters and a miniaturized ion propulsion thruster. Key to developing this subsystem is the fabrication of a very low-leak rate microvalve which is resistant to caustic gases (e.g. hydrazine) and the integrating of the valving, propellant tank and the thruster nozzles.

A general survey of current space systems finds that there are applications where the laser material processing technique would be of value. A few examples are given. Under the general area of fabrication, laser processing could be used to machine microchannels in sensor arrays for integrated cooling systems, lasers could also be used to machine vias for multilevel interconnects and for developing media for permanent high density information storage (WORM). Laser processing tools are certainly needed in the development of large area photovoltaics, diamond coating of surfaces and in advanced packaging schemes where localized hermetic seals are required. In the area of repair or modification, laser tools can be used to trim resistor and capacitor values, can be used for fixing interconnects in DRAM chips and the alloying of metals for increased corrosion resistance. Laser processing tools have the greatest impact in the area of prototyping. Whether for prototyping complex multitiered microoptics in various materials or in fabricating microstructures in diamond or ceramics --- the laser tool is unsurpassed in its versatility. The only barrier to implementing laser processing in microengineering is the lack of prototyping service-centers and in the lack of process development.

Acknowledgments

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