Development of Laser-based Tools for MEMS Rapid Prototyping

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Abstract: In this paper (progress report), results and recommendations are discussed in the area of laser-based tools development for rapid prototyping of micro-electro-mechanical (MEMS) features. The undertaken research work was motivated by a trend towards the development of desktop fabrication (tele-manufacturing) consumer electronics as well as current needs for the development of rapid prototyping (non-batch, maskless, direct-write, restructuring) tools for the electronic/semiconductor and emerging MEMS industries. The research program claims contributions in new laser-based tools development and in specific in their calibration, scaling and automation.

Introduction: During the course of the last two years, the Arizona State University (ASU) Laser Fabrication Lab (LFL) research program has focused resources on:

- Defining the operational space (process window) of an in-house laser-based experimental set-up
- Evaluating four distinct industrial laser-based systems through a comparative study
- Developing and automated a Laser-CAD calibration process
- Fabricating preliminary structures and components for MEMS devices on thinned and unthinned silicon and on metallic foils and thick films (copper and permalloy on silicon).

Methodology: The underlying philosophy of our Laser-based Tools Development Program begins with the premise that advanced machine tools development is a continuous and concurrent engineering D&M process, which in an effort to create simpler products, it results in more complex tools. Thus, the tools development task is seen as a compromising/optimization task between the consumer requirements/specs promoted by the product engineer and the tool D&M capabilities of the tools manufacturer engineer. Specializing this philosophy to the development of laser-based tools for rapid prototyping of MEMS, it is imperative to keep both perspectives in tools development:

- Top-down or tool-centered (i.e. What is the basic laser-material interaction principles behind each tool/material system and what are the attainable feature sizes, limits and range of a given microfabrication tool) and
- Bottom-up or product-centered (i.e. What are the requirements in terms of minimum feature sizes, uniformity and leadtimes for typical MEMS fabricated microstructures).

These two perspectives will be evident during the complete research process and conclusions, as seen in the sections that follow.

Experimental Apparatus & Industrial Tools Gap Analysis & Evaluation: During the last three years of the ASU Laser Fabrication Research Program, an Nd:YAG laser-based direct-write XYZ fabrication system (Fig. 1) was set-up, calibrated and used for prototype fabrication of MEMS features on a wide range of materials.

The in-house system was compared with three industrial systems (see Tables 1 and 2). The industrial systems were selected based on criteria for distinct operating principles (laser-material physics) and covering a wide range of power output, pulse duration and pulse repetition rate. Tool availability was also an issue that had to be taken into consideration, although retrospectively, this was not manifested as a problem.

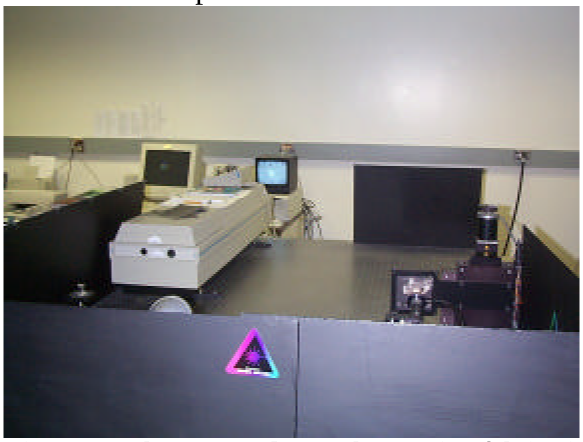

Figure 1: The ASU Nd:YAG laser microfabrication experimental set-up: laser, focusing optics, precision-motorized XYZ-stage, imaging system, computer and LabVIEW controls.

For example, in terms of the first criterion, the four laser systems span distinct laser-material interaction phenomena. For completeness, this criterion is further summarized in Table 1, which follows.

Table 1: A comparative matrix of the fabrication tools investigated according to their distinct, operative laser-material interaction physics

Fabrication Tool	**Operating (machining) principle**
ASU experimental set-up (Class IV, low-PRF)	Thermal machining (material melting, vaporization and/or sublimation)
Coherent Quicklaze laser marking system (Class IIIb, high-PRF)	-same as above-
Revise LACE (LCE) laser chemical etcher	Thermally-assisted chemical etching (material melting and reaction-driven ablation)
Femtosecond laser system	Material ablation by multi-photon absorption and ionization

Three metrics were developed and used for comparison of laser-based microfabrication experimental apparatus as well as commercially available industrial tools. These metrics are:

- The attainable maximum power (and consequently laser fluence and heat flux)
- The minimum fabricated feature size and
- A qualitative measure of collateral (thermal and microhardness) damage.

Table 2: Laser-based experimental set-up and current industrial tools: A comparative matrix

Fabrication Tool	**Characteristics/Metrics**		
	Max. Power, Fluence, Heatflux	**Min. Feature size**	**Collateral damage**
ASU Nd:YAG ns/µs experimental set-up	P_{avg}=2W P_{peak}=2.5e7W E_{pulse}=200mJ F_{pulse}=2e9J/m^2 q_{peak}=3e17W/m^2	5-100 µm	Medium (µs pulses) High (ns pulses)
Coherent Quicklaze laser marking station	P_{avg}=0.6W P_{peak}=1e5W E_{pulse}=0.6mJ F_{pulse}=6e6J/m^2 q_{peak}=1e15W/m^2	50-1000 µm	Medium (ns pulses)
Revise LACE(LCE) laser chem. etcher	P_{avg}=10W q_{ave}=1e11W/m^2	1-500 µm	Low (CW)
SP Femto-second laser	P_{avg}=0.2W P_{peak}=6e11W E_{pulse}=0.2mJ F_{pulse}=2.5e6J/m^2 q_{peak}=2e19W/m^2	5-100 µm	Low (fs pulses)

The purpose of this comparison was to provide a qualitative matrix that could aid in obtaining insight for a subsequent gap analysis. The purpose was not to construct a revised performance rating of the various available tools as of yet. The gap analysis focused on the following questions:

1. What are the limits and range of currently commercially available laser-based micromachining tools in terms of minimum feature attainable and design scaling with respect to physical dimension and material?

2. Which single tool (or process) parameter is mostly responsible for augmenting the observable and useful laser-material physical phenomena during a laser micromachining process?

3. Which single tool (or process) parameter is both widely responsible for spanning a variety of laser-material interaction phenomena and can be most economically controlled in the development of a new tool.

Results of this gap analysis reinforced by experimental verification from preliminary fabrication results are presented in the sections that follow.

Laser-CAD/CAM issues: Tool /Process Calibration & Automation: In order to test the capabilities of a given tool across materials (metals, ceramics and organics) in a reasonable amount of time, a minimum level of process control automation was essential and was thus implemented. The LabVIEW control software, which was documented elsewhere [2], is EPROM-, cross platform- and internet- portable, thus presenting itself as a potential tele-manufacturing software solution for futuristic laser-based desktop fabrication consumer electronics. The three components of the experimental set-up are simultaneously controlled by an in-house developed LabVIEW interface are:

- The laser (on/off)
- The motorized XYZ precision stage (speed and direction thus resulting in variable laser fluence deposition on the irradiated targets) and
- The CCD-camera imaging, monitoring subsystem for image grabbing, measurement and evaluation.

Primitive continuous and perforated CAD designs (see Fig. 2, 3a, 3b) were programmed using the AT6400 Parker Compumotor proprietary motion control code by specifying a relation between the pulse repetition frequency (PRF) and the scanning (laser-XYZ) speed.

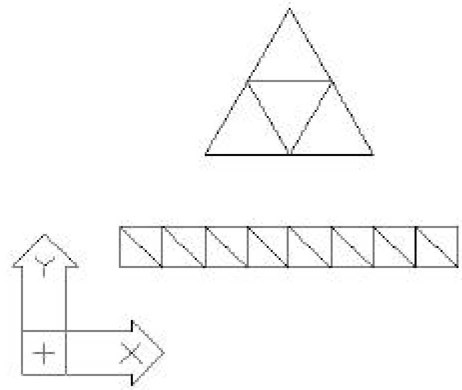

Figure 2: A number of continuous (Euler paths) and perforated CAD designs were prototyped and programmed. Patterns include: serpentines, hexagonal-cell (repeating-feature) geometries and text (see Fig. 3)

Typical process parameters for the ASU microfabrication apparatus are shown below.

Table 3: ASU Laser apparatus process parameters for the two distinct laser pulse durations available

Nd:YAG LASER PARAMETERS (GWC589, ASU)					
Process parameters for:	Q-switched (8ns) pulse			Long (100µs) pulse	
wavelength	5.32E-07	m			
repetition rate	10.0	s-1			
pulseDuration	**6.5E-09**	**s**		**1.250E-04**	**s**
Energy per pulse	0.16	J		0.16	J
average power	1.60	W (80% of max.)		0.00	W
peak power	**2.5E+07**	**W**		**1.28E+03**	**W**
laser spot size	1.0E-05	m		1.0E-04	m
laser spot area	7.9E-11	m2		7.9E-09	m2
fluence	2.0E+09	J/m2		2.0E+07	J/m2
tmaxI	1.6E-09	s			
heat flux (power density)	**3.1E+17**	**W/m2**		**1.6E+11**	**W/m2**

Process Analysis: A theoretical macro/micro ablation model was developed from first principles and was used in conjunction with the calibration software to predict a process window for laser processing of a certain material. Figure 3 presents an example of such a calculation of laser fluences for laser processing of ferromagnetic films sputtered on silicon wafers.

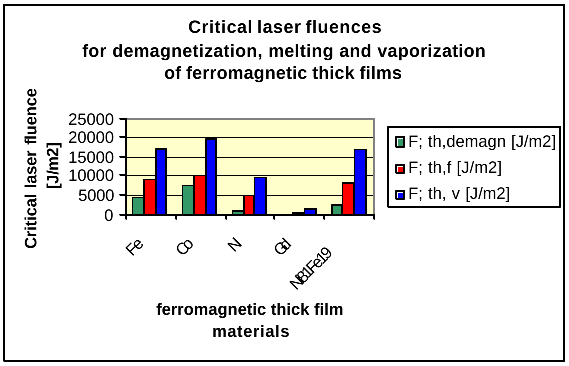

Figure 3: Critical laser fluences (for demagnetization, melting and vaporization) of representative ferromagnetic films (Iron, Cobalt, Nickel, Gadolinium, permalloy)

Further such theoretical results relating, among others, the radiation absorption length with the thermal diffusion length and the resulting observable ablation depth have been obtained and documented elsewhere. As outlined in the Methodology section (page 1), in the process of defining the microfabrication tools requirements, such results follow the top-down (tool/process –centered perspective). These results will be coupled with the bottom-up (product-oriented) perspective of the following section.

Development of Requirements for Primitive and Derivative Features for Rapid Prototyping of MEMS: Given the complexity, cost, lead-times and batch processing of MEMS foundry services today, the need for direct-write tools for low-volume, low lead-time (thus rapid) prototyping and manufacturing of microscale and mesoscale structures (10µm-1mm) is real. Thus, as outlined in the Methodology section (page 1) a second perspective (bottom-up and product-oriented) was adopted in order to identify MEMS primitive and derivative features that can be directly integrated to form functional MEMS and mesoscale devices. With the mere capability of machining crater-shaped blind holes with a typical diffraction-limited laser spot size of ~5µm as primitive features, derivative features such as perforated and continuous lines, serpentines and closed polygon repeating and non-repeating geometries can be achieved. It only takes human design creativity then to turn these derivative features into building blocks for prototype MEMS and mesoscale devices. Such device examples conceptualized and are developed include:

- Active fluidic MEMS for electronic cooling on the back side of functional silicon die
- Passive, two-phase flow fluidic MEMS as micro heat pipe arrays on the back side of functional silicon die
- Electrokinetic (EK) and Magnetohydrodynamic (MHD) MEMS pump s

A rule of thumb was developed in order to fix requirements for derivative features based on a ~5µm diffraction-limited laser spot size. For surface roughness, a one order of magnitude allowance based on the worst-case scenario of recast dynamics requires roughness for mesoscale structures of the order of 0.5 µm. For overall size feature, a two order of magnitude allowance, defined by an overall lead-time ceiling, was defined as 500µm.

Design of Experiments: Experiments were carried out in order to:

- Investigate the effect of peak and average power and laser fluence (heat deposition) on a variety of materials (metallic foils, silicon wafers and thick films on silicon)
- Investigate the effect of the pulse duration to the minimum feature size attainable
- Characterize the vibration induced during the micromachining process by environmental as well as process-line components
- Calibrate mesoscale laser-CAD patterns & repeating geometries [5]
- Fabricate and characterize fluidic MEMS and mesoscale structures (10µm-1mm), on the backside of functional silicon die. Such applications are presented elsewhere [3, 4]

Fabrication results: Prototypes were fabricated on 0.1mm thick metallic foils

(Al6061, Cu110an, S304) on 100μm-thick silicon wafers and functional unpackaged die and on 5-10μm-thick copper and permalloy films on silicon. A thorough cross-material study is still in progress. Preliminary fabrication results are presented in the figures that follow.

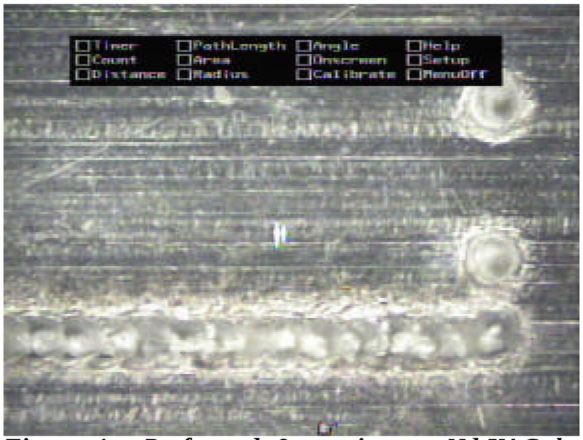

Figure 4a: Perforated & continuous Nd:YAG laser micromachining on Aluminum 6061. Average Power: 1.6W (80% of max), ~8 ns pulse, melt zone ~ 30mm

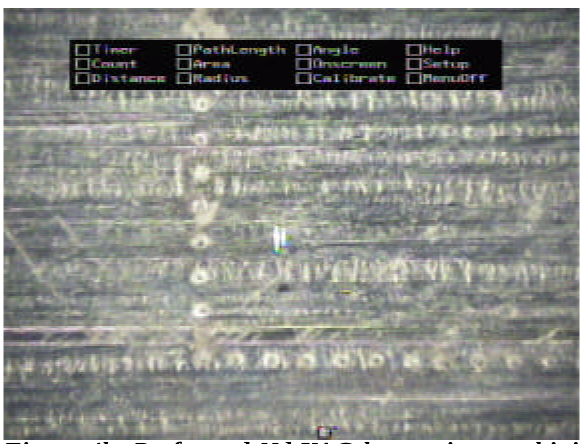

Figure 4b: Perforated Nd:YAG laser micromachining on Aluminum 6061. Average power: 1.6W (same as in Fig. 1a), pulse duration: 100ms = 0.1ms, normally used for alignment. Note: smaller feature size attained w.r.t. Figure 4a.

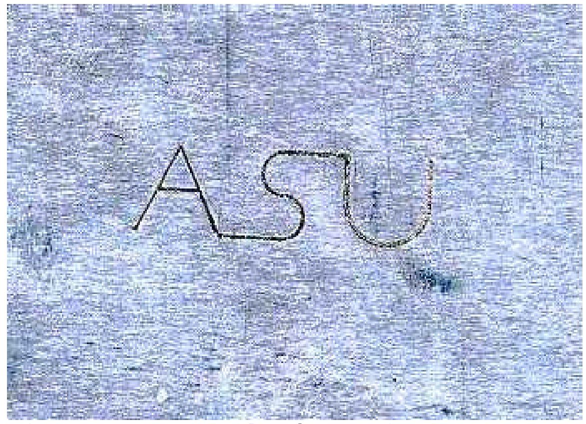

Figure 5: An example of a continuous text pattern (ASU) programmed and scribed on Al6061

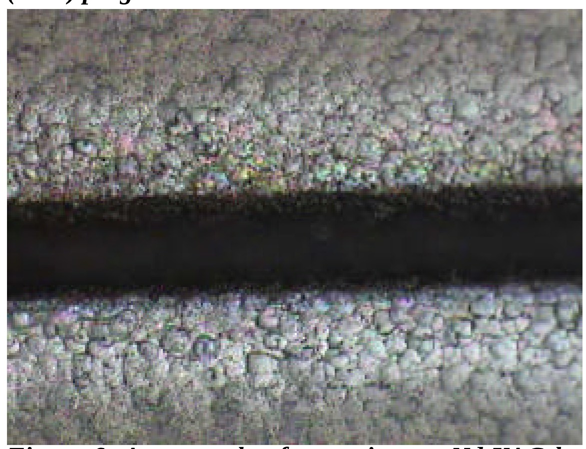

Figure 6: An example of a continuous Nd:YAG laser micromachining on 100mm-thick n-Silicon wafer. Average power: 1.6W, pulse duration: 8ns, melt zone= linewidth~30mm

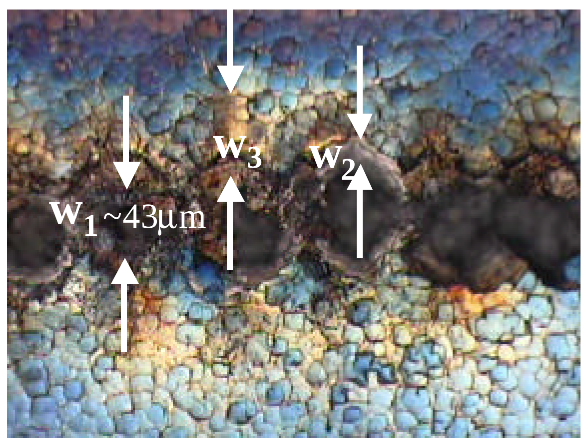

Figure 7: An example of perforated Nd:YAG laser micromachining; with process parameters as in Fig. 6. The three measures used for the quality evaluation of the machined features: melt zone (w_1), recast corona (w_2) and heat-affected zone (w_3) are identified.

Conclusions: Short-term and long-term impact of the research program are identified in the technical, management and training areas. A list of significant results follows:

1. A laser-CAD calibration technique based on repeating geometrical features (e.g. hexagonal) was verified for silicon and copper as per Nikumb and Islam [6]. Whenever the laser-material interaction is based on melting and vaporization, the resulting mesoscale patterns in copper appear greater due to the smaller crater size (melt zone) of copper w.r.t. silicon. The importance of the laser-CAD calibration technique cannot be over-emphasized as it extends the agility of the tool with respect to a change of material and development of new process windows.

2. A thermal (heat-conduction) ablation model was developed and can predict calibration process parameters for pure metallic foil targets and ferromagnetic thick films (Fig. 5). In specific, a laser process window with a fluence in the range of 5-10 kJ/m^2 that encompasses the demagnetization fluence thresholds for common elemental ferromagnets (i.e. Ni, Fe, Co, Gd) was theoretically predicted and experimentally verified [3]. However, the model is limited to pure (elemental) target materials, power densities below the ionization threshold (~ 1e17W/m2) and pulse durations larger than the tens-of-picosecond range.

3. The minimum feature size (melt zone) resulting from irradiation by a diffraction-limited laser spot is a function of the peak and average power fluxes which are in turn a function of the power input, pulse duration, laser spot and laser pulse repetition rate. Results for Al6061 (Fig. 4a, b) show that the minimum feature size was obtained using long pulse durations (100μs) rather than Q-switched (8ns) pulses. Longer pulses result in longer thermal diffusion length and therefore less heat deposition for ablation by melting and vaporization.

4. In developing new laser-based microfabrication tools with distinct material interaction dynamics, closer attention and investment should be dedicated to the incorporation of variable pulse duration and wavelength (frequency chopping) capabilities along with the current trend of expanding the power range. A wide range of laser fluences (deposited energy) can be simulated by controlling the scanning speed of the tool rather than by varying the input power.

5. Concurrent chemical etching alongside the laser process can greatly enhance attainable MEMS features in silicon where etching chemistries (e.g. chlorine atmosphere for silicon) are already well known and practiced [8]. For the rest of the materials other techniques for enhancing the resulting surface roughness are sought. These could be: material-specific etching chemistry, fundamentally distinct interaction phenomena (e.g. ultrafast laser irradiation) or process modification (e.g. simultaneous blowing or suction gas dynamics during the laser process).

6. Innovative mesoscale and MEMS structures, components and devices can be the result of a synthesis of primitive (simple and elementary) laser-micromachined features. The examples of microfluidic devices where

continuous line features are utilized as functional microchannels for such devices as EK and MHD pumps, microheat pipe arrays and DNA chips, should suffice to demonstrate this point!

7. In order to improve on an existing laser-based microfabrication tool or develop a new Rapid Prototyping tool or process, a concurrent bi-directional interaction of a top-down (tool-centered) and bottom-up (product-centered) design process appears more beneficial in optimizing the tool, process and prototyping cycle.

Recommendations for Future Work: What follows is a list of future directions of our on-going ASU Research Program as well as recommendations for extending the impact of this work in research and education.

1. Expand the materials design space by replicating preliminary fabrication results on materials of interest to the semiconductor industry such as: polymers (kapton= polyimide), composites, and organics.
2. Identify and prioritize of the sources of error (e.g. relative impact of induced vibration versus optical aberrations) and their influence on the final micromachined features
3. Compile a list of recommendations (in the form of tools re-design and manufacturing specs) for opening up the operational space of a laser micromachining tool
4. Compile a list of primitive and derivate machining features attained by the laser micromachining tools and comparison with MEMS rapid prototyping requirements.
5. Design and implement of laboratory teaching modules and lesson plans derived from research experience in support of the undergraduate and graduate manufacturing processes classes (MAE351, MAE591) at Arizona State University.

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