LiGA Research and Service at CAMD

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Abstract. Since 1995 CAMD has been offering exposure services, so called print shop for a variety of users interested in making precision High-Aspect-Ratio Microstructures (HARMST) for various application. Services have been expanded beyond only the print shop service in recent years and now include x-ray mask fabrication, substrate preparation for PMMA and SU-8 resists, electroplating, finishing and molding. Metallic and polymeric parts are now routinely fabricated for precision engineering, micro-fluidic and micro-optic applications. This paper presents a brief overview of the actual status of LiGA services provided at CAMD including ongoing research efforts and examples of LiGA components for different applications.

1. Introduction

The recently held HARMST 2005[1] Conference in Geongju, South Korea, presented many technical papers from groups worldwide related to LiGA based research efforts, new processing capabilities and applications. These contributions also included details on new equipment and fabrication capabilities demonstrating a strong interest from industrial users to consider LiGA technology for their applications and products.

In the past years efforts at CAMD have been focused on providing new process capabilities including making taller (millimeter and higher) structures, structures with sub-micrometer features, 3D patterning, better X-ray masks, and use of advanced materials. Besides R&D efforts in these areas the group has also established a LiGA service offering their skills to external customers and satisfying their needs for precision engineering parts and innovative high-tech products. CAMD collaborates with a number of small start-up companies[2,3,4], who cannot afford to make multi-million dollar investments into infrastructure yet have a strong need for LiGA ‘service’ and ‘partnership’.

Since its inception, the LiGA process has impressed potential users with the outstanding precision, tight tolerance, high aspect ratio, flexible 2.5 dimensional design, sub-micrometer feature size, smooth and vertical sidewalls, and wide material choices. These unique characteristics of LiGA structures provide component and system designers with a wide selection of material properties and flexible geometry for their applications. Aspect ratios (defined as the ratio of structure height to smallest lateral dimensions) of 20-30 are typically patterned for ‘free-standing’ microstructures and sub-micrometer features are successfully patterned when being part of a larger structure. It should also be noted that even millimeter tall structures demonstrate extremely high precision with typical surface roughness of 20-50 nm Rv value and deviation from a perfectly straight sidewall of approximately 1 µm per 1 mm structure height[5]. Besides fabrication of simple, cylindrical structures more complex shapes including multi-level[6] and “quasi 3D” pattern as well as taller(7) (millimeter and higher) and
smaller\(^\text{\textregistered}\) (sub-micrometer) HARM structures are also patterned routinely as shown in Figs. 1a-e. In this paper, we will briefly describe the LiGA service capabilities available at CAMD and show some examples of internal and external applications.

Fig. 1a: \(~2.5\ \text{mm tall gear patterned into PMMA resist}\)\(^5\).

Fig. 1b: \(3\ \text{mm tall SU-8 posts with } ~300\ \mu\text{m gaps}\)\(^7\).

Fig. 1c: \(50\ \mu\text{m tall fluidic channels with } ~5\ \mu\text{m wide post arrays}\).

Fig. 1d: Conical posts in SU-8, made by 6x tilted and rotated exposures in 1 mm thick SU-8\(^9\).

Fig. 1e: 3-level processed, 1.5mm tall SU-8 micro-engine housing fabricated by combined optical and x-ray lithography\(^6\).

2. X-ray Lithography Service and New Process Capabilities at CAMD

CAMD operates four micromachining beamlines equipped with different scanners providing patterning solutions including aligned, tilted and rotated exposures as well as multiple- and/or large substrate formats needed for high throughput exposures. Light is provided from bending magnets to three of the beamlines (critical energy = 1.6 keV) while a 7-Tesla wiggler provides hard x-rays (critical energy = 7.95 keV) for UDXRL exposures at one port\(^\text{[10]}\). Over the last years CAMD has exposed more than 650 substrates per year for a number of users. Approximately 1/3 of these substrates are from industrial users indicating a strong interest in the exposure capabilities offered\(^\text{[11]}\). In the past year (2005) the number of industry user substrates increased to 40 \% demonstrating a growing interest. There was also a significant increase (> 50 \%) of accumulated exposure dose from 1.34 \times 10^7 \text{mA-min} in 2004 to 2.105 \times 10^7 \text{mA-min} in 2005 showing the need for exposing thick resist layers as well as larger areas. This accumulated exposure dose and thus fabrication costs could be significantly reduced if the primarily used PMMA resist could be replaced with SU-8, which still suffers from a lack of process stability and repeatability.

New process capabilities are shown in Figs. 2a-c. A ‘higher throughput’ scanner (DEX 03 from Jenoptik GmbH\(^\text{[12]}\), Germany) financially supported through a DARPA grant (grant # N66001–00–8968) and designed and engineered by Jenoptik GmbH, Germany according to specifications from CAMD researchers. Figure 2b shows the open flap of the DEX 03 scanner. The mask is mounted to a mask holder sitting on the Y-scanning stage. Up to five 4” wafer substrates are pressed sequentially
against the mask ring separated by shims which define a proximity gap of typically a few 100 \(\mu\)m. The backside of the substrate fixture, as well as the mask holder, is water-cooled to minimize thermal load. The high-throughput is achieved by loading five substrates onto the substrate holder and expose them sequentially without venting the chamber. This aspect is especially important for SU-8 exposures with exposure times of several minutes and thus comparable to the venting/pumping time of the scanner chamber. Instead of multiple substrates one large substrate up to 10”x 10” can be loaded onto the substrate holder and be exposed in a step-and-repeat mode with ~10-15 \(\mu\)m stitching accuracy.

Another improvement towards reproducible production of metal structures has been achieved using a commercial plating station for the CD/DVD industry modified for the needs of LiGA MEMS. Figure 2c shows the electroplating station installed at CAMD made by Technotrans America, Inc. with nickel DC as well as pulse and nickel-iron plating capability. The rotating cathode technology shown in Fig. 2c ensure high plating uniformity thus reducing polishing and finishing efforts typically following the plating process.

Critical for LiGA services is the ability to fabricate X-ray masks. CAMD offers several choices with different performance properties and costs and advices its customers for the ‘best solution’ while discussing the design. A low cost version uses optical lithography in thick photo resist like SU-8 to pattern resist templates ranging from 10 \(\mu\)m to 70 \(\mu\)m in height followed by Au electroplating on various substrates including graphite, Kapton®, beryllium and silicon-nitride (SiN). Depending upon the resist height feature sizes of approximately 5 \(\mu\)m for a 15 \(\mu\)m-thick resist are possible but increase with thicker resist layers. While this ‘rapid’ prototyping approach (typical turnaround time is 2 weeks) offers moderate quality at reasonable costs (depending upon the substrate approx. $ 2,000 – $ 3,500) high resolution e-beam written intermediate masks will allow patterning of sub-micrometer structures but at significantly higher costs (this service is provided by the Institut für Mikrostrukturtechnik at the FZK Karlsruhe). This intermediate mask will then be copied onto a working x-ray mask using soft X-rays from the CAMD mirror beamline (XRLM 1). Even though a variety of fabrication and material options for fabricating X-ray masks exists, it is a fairly mature process with acceptable yield (50 % and more) and routinely provided as a service to our customers.

Critical for any LiGA service is the in-house capability to turn a design into a part within a reasonable time and with controlled quality. The following list briefly summarizes our key capabilities available to external customers.

**Design rule:** while there is no complete LiGA process database CAMD service staff has accumulated great expertise used to advise customers on doable specifications for their application.

**X-ray masks:** a variety of choices are offered including low performance X-ray masks using Kapton® and graphite mask substrates, and high end X-ray masks made on SiN membranes and beryllium substrates. Large area X-ray masks covering a patterned area of up to 85 mm in diameter on a 4” substrate are also possible.

**Resists:** polymethylmethacrylate (PMMA) is still the resist of choice for many applications and can be patterned into heights ranging from a few 10 micrometers to several millimeters. SU-8 is a very
attractive resist alternative but still lacks stable process parameters especially for thicker layers (500 µm and higher). CAMD also provides resist coated substrates as a service.

**Exposure Service:** LiGA print-shop services allow customers to submit exposure requests with CAMD experts performing the service. Special customer mask and substrate format can be accommodated even though the CAMD standard formats are preferred.

**Sample developing:** CAMD provides developing services using beaker-type setups with magnetic stirring and cyclic development for minimum exposure of the resist to the developer solution.

**Electroplating:** a variety of plating baths including nickel, nickel-iron alloy, copper and gold are available for plating into LiGA substrates or other customer-provided resist templates.

**Polishing and finishing:** surface finishing of metal structures is achieved by lapping and polishing with typical roughness of less than 1 µm Rₐ value and height control of +/- 5 µm.

**Molding:** CAMD offers molding services including mold insert fabrication and small scale replication in commonly used polymers like PMMA, PC, and COC. Molding of new materials will be provided as development service.

3. Examples of Research and Applications

3.1. Materials Research

Polymer nano-composites (PNCs) have, in the past decade, emerged as a new class of materials due to much improved mechanical, thermal, electrical and optical properties as compared to their macro- and micro-composites [15,16]. However, there is the challenge in the integration of multi-functional PNC components into micro-electro-mechanical systems (MEMS). CAMD researchers use epoxy resist (SU-8 5) with carbon black powder filler (2-15 wt%) in combination with x-ray lithography to pattern conductive resist materials. Figure 3a and b show some first structures patterned with a bottom dose of 10 mJ/cm³ using a graphite X-ray mask. A high load of 15 wt% of carbon black in the resist material yielded an average elastic modulus of 15 GPa, nearly five times that of pure SU-8.

Ni-Fe alloy is a potential material to replace Ni for specific applications such as high strength microstructures, high temperature mold insert, or microstructures with magnetic property based applications. Figure 3c illustrates the current capabilities in Ni-Fe alloy electroplating of the CAMD/LSU service group. Electroplating was performed using a plating bath prepared by mixing nickel sulfate and iron sulfate. Ni-Fe alloy with Fe content of 15% producing a hardness of 690 HK₉₀₀N with a high wear resistance, can be plated with a plating rate >20 µm/hr. The high material uniformity across a 1mm tall structure has been measured using the EDS feature of the SEM. The SEM picture illustrates that the quality of deposition is comparable to Ni electroplated structures.

![Fig. 3a,b: Preliminary PNC structures (SU-8 resist with carbon black) patterned by x-ray lithography.](image1)

![Fig. 3c: SEM image of microgear with EDS results of NiFe alloy with 15% Fe.](image2)
3.2. Polymer chips for BioMEMS applications
CAMD offers molding services including mold insert fabrication and small scale replication in commonly used polymers like PMMA, PC and COC. Molding is one of the paths to mass production of high aspect ratio microstructures. Mold inserts are fabricated using X-ray LiGA, SU-8 LiGA and direct micromilling of brass. Brass mold inserts do not possess the surface and sidewall roughness or the aspect ratios that can be achieved using a LiGA mold insert, but they are useful as a rapid prototyping tool. In collaboration with LSU’s Center for BioModular Multi-scale Systems (CBM²) a number of fluidic chips for BioMEMS applications are routinely fabricated and combined to perform complex analytical protocols. Some examples of inserts and molded chips are shown in Figs 4a-4d.

Fig. 4a,b: Brass (left) and LiGA Ni (right) mold inserts.
Fig. 4c,d: Examples of fluidic chips; left shows a set of 1”x3” chips to be combined for a fluidic stack, right shows a fluidic chip with integrated waveguide.

3.3. Examples of Applications from HT Micro
Commercial applications for deep X-ray lithography based processing include several broad categories where the ability to batch fabricate precision high aspect-ratio geometry offers unique solutions.

For many milliscale components the challenge that presents itself is how to maintain dimensional tolerances as well as minimum dimensions at reduced component size with materials suited for and compatible with a given application. As an example, biofluidic interfaces many times share these requirements. Figure 5a shows a 4-layer plastic component comprised entirely of PMMA and fabricated with deep X-ray lithography. Within this component are 12 channels that feed 12 reservoirs “caged” in by PMMA pillars as shown in the detail photographs in Fig. 5b. The PMMA cage structures consist of rows of 30 µm diameter cylindrical pillars with 300 µm height that reside on 33 µm centers resulting in rows of 3 x 300 µm gaps. Another similar millimeter size bio interface structure with micron precision features is exhibited in Fig. 5c. This particular component, also constructed with multi-layer PMMA contains features interfacing with three optical fibers. This optical biosensor component consists of plastic layers that form a press-fit with the optical fiber.

Another set of components, springs, combines precision patterning using deep X-ray lithography and electroplating of high yield strength materials such as NiFe alloys. By precisely controlling the structure features a simple spring-mass acceleration switch may be realized as shown in Fig. 5d. The spiral spring supports a ring which when accelerated will contact the outer rim or top (not shown) and bottom shoulder at a predefined acceleration threshold.

Fig. 5a,b: PMMA Fluidic chips with integrated flow filter structures.
Fig. 5c: Optical biosensor with fibers.
Fig. 5d: NiFe acceleration switch.

The ability to maintain tolerances between high aspect ratio structures also aids considerably in the ability to batch fabricate microactuators where a small (micron) working gap can be maintained...
through relatively much larger thickness and overlap stroke dimensions of several hundred microns. Coupled with compliant springs, low frequency (20 Hz) resonators with several hundred micron amplitudes may be fabricated. Such resonant actuators have been applied to generate structured light sources for use in miniature con-focal microscopes. Figure 6a shows a microscope developed at the University of Arizona which uses a deep X-ray lithography defined “optical bench” for alignment and support of miniature optics as well as a resonant amplitude grating that provides structured light into the microscope when illuminated from a dc source. The amplitude grating is shown supported by the center of the resonant actuator in Fig. 6b which also shows the electrostatic comb drive which is capable of resonating the grating at +/- 100 µm amplitude with 10 Volts with quality factors at atmosphere of over 50. Figure 6c reveals a view of the left side of the microscope in Fig. 6a where a conventional 1mm diameter glass objective lens is supported and clamped to the optical bench.

Fig. 6a-c: Example of a micro-optical bench with integrated electrostatic actuator (see text for details).

4. Conclusions
This paper briefly described the ongoing activities in LiGA research and service at CAMD. The examples of applications in microfluidic, micro-optic and precision engineering are mainly made possible by the unique patterning capabilities of the x-ray lithography process and the choices of materials in the electroplating and molding steps. While ‘manufacturing’ service with many hundreds or even thousands of parts remains a major challenge for the CAMD service group, ‘prototype production’ of several ten prototypes with good yield and reasonable turnaround time is routinely provided and in growing demand also from industrial users.

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