Cost Effective Fabrication of High Precision Microstructures Using a Direct-LIGA Approach

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Abstract
Direct and cost-effective mass fabrication of LIGA metal structures has been first proposed as a commercially viable production method in 1991[1]. But it is only due to recent improvements in resist technology resulting in a decrease in exposure time of 10-15 min per wafer, the concrete market needs for a x-ray micro-machined part, and the available LIGA process infrastructure and service capability that has brought this concept closer to reality. This paper will report on the joint efforts from the four partners Micromotion[2], micro resist technology[3], BESSY[4], and CAMD[5] to establish a direct LIGA fabrication to build Micro Harmonic Drive® gear[6] assemblies as well as will highlight some of the accomplishments and also obstacles on the way to mass production.

Introduction

The use of very small electronic components in a variety of consumer goods makes necessary the use of small-scaled servo actuators for positioning applications in production equipment and robotics[7]. The Micro Harmonic Drive® gear was introduced into the market in 2001 as the world's smallest backlash-free micro gear. In the meantime this gear has been implemented in a new range of miniaturized servo actuators, which provide zero backlash, excellent repeatability and long operating life. The requirements for the gears including heights in excess of 1mm, smallest structure details of approximately 20µm, freely shaped gear teeth structures for optimized motion, and high quality NiFe alloy material for reduced wear has led to a mass fabrication concept based on a direct LIGA fabrication process. The main fabrication steps consist of deep x-ray lithography in SU-8 resist, electroplating of NiFe alloy, polishing, release of metal structure from the SU-8 mold, and assembly of the gear train.

The Micro Harmonic Drive® - Principle of operation

The Micro Harmonic Drive® offers a number of advantages like zero backlash, excellent repeatability, high torque capacity, consists of only six components resulting in high reliability and minimum assembly effort, high efficiency, extremely flat design, low weight, and overall compact dimensions. Furthermore, the high reduction ratio necessary for micro motors can be reached in a single gear stage. The basic elements of the Micro Harmonic Drive® gear system are the Wave Generator consisting of two planetary wheels, a sun gear wheel and the three gear wheels, Flexspline, Circular Spline, and Dynamic Spline. The Wave Generator deflects the elastically deformable Flexspline elliptically across the major axis. Due to that the teeth of the Flexspline engage simultaneously with the two ring gears - Circular Spline and Dynamic Spline - in two zones at either end of the major elliptical axis. **Fig. 1** illustrates the schematic of the operation, **Fig. 2** shows an assembled gear set from LIGA parts. Excluding the input and output bearing arrangements the outer dimensions of the Micro Harmonic Drive® are 1 mm axial length and 8 mm in diameter.

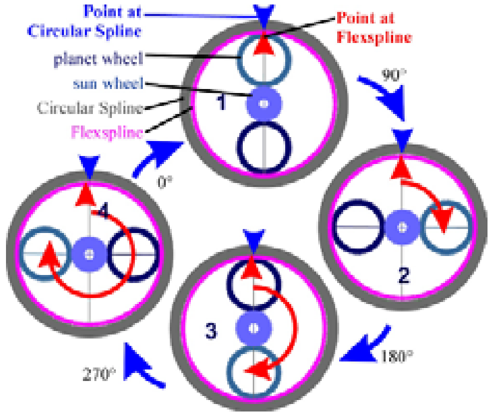

Fig. 1: Operating principle of the Micro Harmonic Drive® gear.

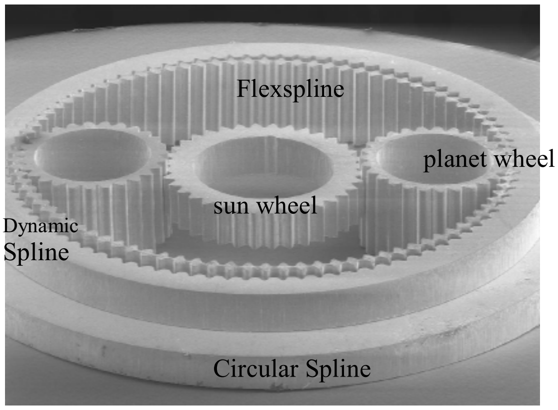

Fig. 2: Components of the Micro Harmonic Drive® Gear made by direct LIGA fabrication.

Direct LIGA Fabrication

In order to build high precision gear sets the individual parts have to be fabricated with very high precision, low tolerances, and from advanced materials. A direct LIGA approach utilizing x-ray lithography, electroplating, and assembly as main process steps has been proposed, demonstrated, and first motor prototypes using Micro Harmonic Drive® gear sets are currently tested.

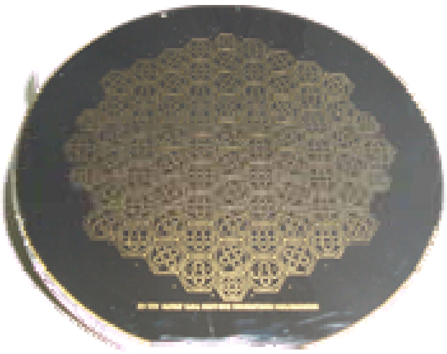

Fig. 3: 4" graphite mask with approx. 20 μm thick Au absorber; the patterned area covers a circle of 80mm in diameter

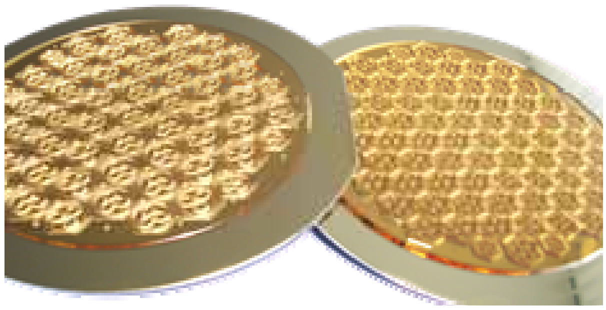

Fig. 4: Si wafer with 500μm and 1mm thick SU-8 layers fabricated by MRT and patterned at BESSY.

Utilizing the existing LIGA infrastructure, expertise, and service capability provided by CAMD[8] and BESSY has enabled the fast turnaround from design to fabricated microstructure, typically within 2-3 weeks. One of the important aspects for a fast turnaround time is CAMD's expertise in making graphite x-ray mask (**see Fig. 3**). This technology is now also available at BESSY and both partners are continuously improving their mask making capability with respect to larger formats, taller absorbers, and less defects. Furthermore, alternative mask substrates such as Si_3N_4 or thin glass membranes are also tested that may offer solutions to some of the graphite mask problems[9]. One of the key factors to improved process stability and yield is the active engagement of micro resist technology[10,11,12] in further optimizing the application and patterning of thick SU-8 layers onto silicon substrates (**see Fig. 4**). Typical problems such as uniformity, stress, and poor adhesion have been solved and pre-coated wafers in thickness ranging from 500 μm to 1000 μm are now commercially available from micro resist technology together with optimized processing instructions. Nevertheless, continuous efforts to make uniform and thicker resist layers (up to 1.5mm) and establish a 100% quality control program is needed to meet future technical and production requirements. X-ray lithography is performed with a low bottom dose of 10 J/cm^3 resulting in typical exposure times of 10-15 minutes for a scan distance of 80 mm. Current process parameters accept a fairly high top to bottom dose ratio of up to 10 to achieve best structure properties. The extremely high resist sensitivity requires a minimum Au absorber thickness on the mask of 22 µm for a 1000 µm thick resist making sure that a maximum dose of only 0.05 J/cm^3 in the shaded area is not exceeded. The structure development has been optimized utilizing ultra- and megasonic enhanced development procedures. As an example the SU-8 structure of a 500 µm tall gear is presented in Fig. 5.

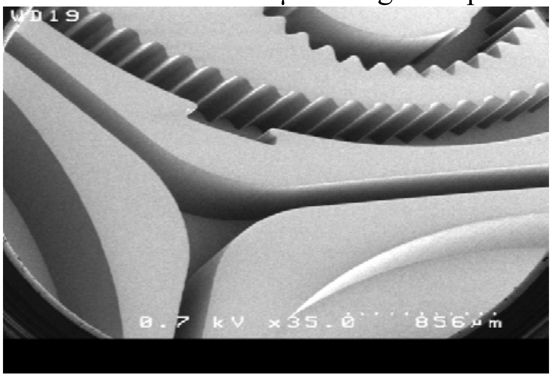

Fig. 5: Negative pattern of the Flexspline gear patterned into a 500 µm thick SU-8 resist. The sidewalls are nearly perfectly straight and no defects are seen in this area.

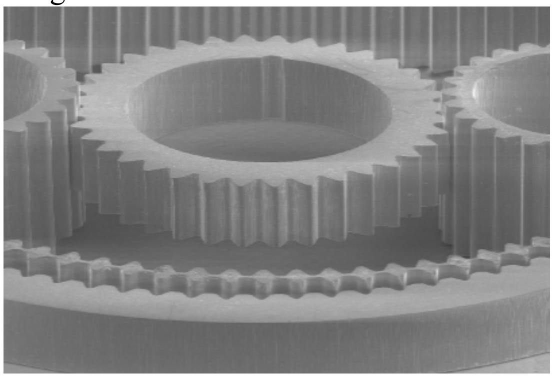

Fig. 6: Close up view of a metal sun gear assembled with planetary gears, The central bore in the sun gear enables mounting of a hollow shaft.

Electroplating is performed in a commercial bath (supplier M.O.T., Mainz, Germany) using a NiFe electrolyte. Parameters have been optimized and NiFe micro gears with nearly uniform Fe distribution across the structure height are fabricated routinely (see Fig. 6). After electroplating the SU-8 resist including the electroplated and surface polished metal gears is released from the silicon substrate. Assembly of the Micro Harmonic Drive® gear takes advantage of the pre-alignment within the SU-8 matrix. First gear systems have been successfully assembled and combined with actuator units to build tiny motors. Results of the first tests have been presented and fully meet the expectations[6].

Micro drive systems and their applications

The Micro Harmonic Drive® can be combined with all currently available micro motors, e.g. stepping motors, AC or DC motors and pancake motors.

Fig. 7: Ultra flat micro drive system.

Fig. 8: *Comparison between the w*orld's smallest backlash-free servo actuator *and an optical fiber connector*

The combination of the Micro Harmonic Drive® with the Penny motor (mymotor GmbH), represents a powerful and 4.2 mm flat micro drive system (see Fig. 7). The world's smallest backlash-free servo actuator is the result of close cooperation between the gear manufacturer Micromotion GmbH and the leading motor manufacturer Maxon Motor AG. The main objective is to provide a relaible and robust actuator for precise industrial positioning applications. The servo actuator comprises a Maxon EC6 motor, an MR Encoder and the MHD 8-160-SP micro-gearbox with hollow shaft. Additionally to their small dimensions micro actuators incorporating the Micro Harmonic Drive® gear offer new advantages due to their low mass, low inertia and low power consumption combined with their excellent positioning accuracy and highly dynamic performance. The precision micro gears and micro actuators from Micromotion GmbH are a key enabling technology for a new generation of miniaturized devices in a wide range of application areas. The Micro Harmonic Drive® is ideally suited to precise positioning applications in the following fields:

- optics, e.g. to adjust lenses and mirrors,
- medical equipment, e.g. to dose drugs or to drive surgical instruments,
- optical communication, e.g. to switch or adjust fibers,
- semicon, e.g. to assemble, handle and adjust semi-conductor components,
- robotics, e.g. to drive axes of micro robots with high accuracy,
- laser technology, e.g. to adjust the beam by means of mirrors or lenses,
- biotechnology, e.g. to dose expensive materials and to adjust pipette probes,
- measuring machines, e.g. to adjust non-contacting sensors
- aircraft and spacecraft, e.g. to control nozzles or valves in nanosatellites.

Summary and Outlook

A direct LIGA process has been successfully used for the fabrication of Micro Harmonic Drive® gears. Key infrastructure and production steps are implemented and a strong collaborative effort is established to further improve the production capability with respect to reproducibility, yield, and optimized structure and material properties. Furthermore, assembly with actuators has been successfully demonstrated and first micro motors are currently undergoing extensive tests. In the next year production of hundreds of motors for concrete customer applications is already planned bringing up the challenge for the partners to optimize process yield and establish a quality control program enabling the cost-effective, high –volume production.

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