APPLICATIONS OF LIGA TECHNOLOGY FOR THE DEVELOPMENT OF MICROMECHANICAL SYSTEMS

Cristinel ILIE[1], Marius POPA[2], Paula PRIOTEASA[3], Ionel CHIRIȚĂ[4], Nicolae TĂNASE[5]

In acest articol este prezentat procesul de fabricatie pentru realizarea de repere micromecanice prin tehnologie LIGA. In procesul de fabricatie au fost realizate roti dintate miniaturale cu diametrul exterior de 0,9mm, depuse galvanic din Ni pe suport de Si acoperit cu fotorezist SU8 de 100 µm grosime. Au fost optimizati toti parametrii de proces pentru expunere, developare, depunere galvaanica si indepartare SU8 expus. S-au facut masurari dimensionale pentru piesele finite, comparandu-le cu datele de proiectare. Această cercetare implică faptul că pot fi dezvoltate la preturi scazute si cu mare flexibilitate de proiectare diferite tipuri de dispozitive MEMS

In this paper, it is presented the fabrication technology of mechanical structures using LIGA technology. In the manufacturing process there have been processed miniature gears with outside diameter of 0.9mm, electroplated from Ni on a silicon wafer coated with 100µm thick SU8 photoresist. All process parameters for the exposure, development, electroforming and removal of the exposed SU8 were optimized. Dimensional measurements were made for the finished parts, comparing them with designed data. This research implies that various types of MEMS devices can be developed at a low-cost with design flexibility.

Keywords: Microfabrication technologies, Micromachining, Direct writing lithography, UV-LIGA, SU8.

1. Introduction

This article shows how to implement the LIGA technology in ICPE-CA, using the existing equipments, to process micromechanical parts used in the manufacture of micro-electro-mechanical-systems (MEMS). Fabrication of these

[1] Eng., National Institute for Research and Development in Electrical Engineering, ICPE-CA, Romania, e-mail: cristinel_ilie@icpe-ca.ro;
[2] Eng., National Institute for Research and Development in Electrical Engineering, ICPE-CA, Romani
[3] Eng., National Institute for Research and Development in Electrical Engineering, ICPE-CA, Romania
[4] PhD Eng., National Institute for Research and Development in Electrical Engineering, ICPE-CA, Romania
[5] Eng., National Institute for Research and Development in Electrical Engineering, ICPE-CA, Romania, e-mail: cristinel_ilie@icpe-ca.ro

small sized devices is clearly beyond traditional mechanical means such as: turning, drilling, milling, casting, welding, etc. For this reason they were developed and imposed on the market a number of new manufacturing technologies and machines that meet new requirements in terms of reduced size and dimensional accuracy. The technologies used to produce these small sized components are known generically as microfabrication technologies or micromashining.

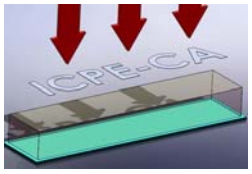
For example, one can obtain three-dimensional microstructures, removing some of the material by chemical or mechanical etching (Bulk Micromachining) or by depositing thin films on a solid material basis (Surface Micromachining). These techniques have several disadvantages, such as a large stress of the mechanical structure for "Bulk Micromachining" and a limit to the thickness of deposited structure for "Surface Micromachining". To remove the above technology drawbacks it has developed the LIGA technology, which creates small devices, but with a relative high aspect ratio, using X-ray lithography. Recent advances in resist chemistry have allowed the development of a UV-LIGA process. The UV-LIGA technique uses either a positive or negative photoresist sensitive to ultraviolet light.The process starts generally from a rigid wafer coated with a thick photoresist film, in which the future piece's configuration is "digged" and this way a pattern is being made.

The wafer is then introduced in a galvanic bath, where the empty spaces are filled by electro-deposition. After deposal, the remained photoresist is removed, resulting extremly precise metallic microscopical elements. These pieces can be used as finished pieces in different devices or as tools for future operations of punching in a softer material. The structures manufactured by LIGA technology are characterized by the following properties:

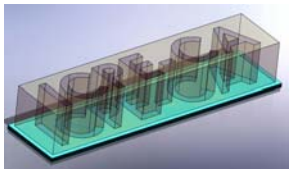
- parallel, almost vertical side walls,
- lateral dimensional stability in the range of some micrometers over distances of some centimeters,
- structural details down into the range of 1μm are feasible,
- low cost compared with other microfabrication technologies.

2. Manufacturing process and required equipment

The main steps of the manufacturing process are shown in Figure 1 [1]. For our concrete application they have been processed freestanding micro mechanical structures, which can be included in various microdevices.

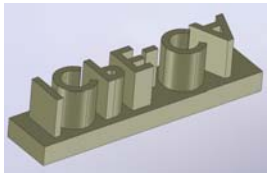


1 Lithographie (exposure)



2 Development

3 Galvanic deposition



4 Photorezist removal

Fig .1. The main steps to obtain parts by LIGA technology

2.1 Direct writing lithography

An important limitation, given by X-ray lithography, which is complex and generates high costs, has been avoided by choosing a simpler solution, based on UV laser lithography. The system we used was the DWL66FS. With this equipment the first step was done: the drawings of the parts we intended to process were transfered from the computer on a rigid wafer, coated with SU8 photoresist – the SU8 photoresist is the most used polimer in LIGA technology. We used direct laser writing. The direct writing system removes the masks shortcomings, mainly regarding the fabrication time of the mask and the possibility of an uneven gap between mask and photoresist [1](Schulz, J., 2008). Also no disturbances occure on mask gaps, due to light diffraction. The direct writing system uses a raster scan technology to expose the substrates. The writing time of a specific design does not depend on the fill factor of the structures, as in a vector scan technology, but only on the overall area of the design [2]. The system we used is equipped with a diode laser with 18mW average power and a 375nm wavelength (UV). The laser wavelength was chosen to work with SU8 photoresist, allowing a layer thickness of hundreds of micrometers, specific for the production of micromechanical parts. The 4 mm writing head is a good compromise between accuracy and speed of writing (precision 1μm and 5.7 [mm² / min] write speed) [3].

2.2 Development

The development requires no special equipment. It is only necessary a glass tank measuring 12 cm diameter.

2.3 Galvanic Deposition

In this step, after development, the empty spaces of the wafer are filled by galvanic deposition. For micromechanical parts, the most used elements are: Ni, Cu, Ag, Au and alloys.

Among the electrochemical processes with a considerable impact in the area of microelements / microsystems, are included electrodeposition and electroforming (cathodic processes). Electroforming is a process for creating 3-dimensional metal parts by using a carefully controlled long-duration electroplating process.

Because the electrochemical deposition is an atomic / molecular process, the formed metal layer assumes all of the three-dimensional shape pattern, with a very good micron or submicron accuracy. Metal layers deposition is an important part of the manufacturing process of the parts, because the quality of the galvanic and/or chemical deposition influences the quality of the finished product. After an electroforming process, the thickness of the metallic deposited layer for mechanical microstructures is generally in the ranges of 10… 1000 μm.

Due to internal stresses that occur during the galvanic deposition, there are a limited number of metals and alloys which can be electroformed in order to form mechanical microstructures, Ni being among them.

2.4 Selective removal of exposed SU8 photoresist

After galvanic deposition, the exposed SU8 photoresist layer must be removed, in order to extract the micromechanical parts from the wafer.

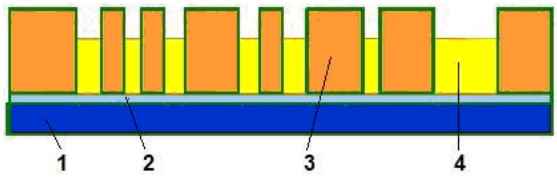


Fig. 2. A wafer with SU8 photoresist and a galvanically deposited Ni layer

To obtain the micromechanical parts (4), it is necessary to remove the exposed photoresist (3) and separate the parts from the metalized wafer (1 + 2). SU8 is a high contrast, epoxi based photoresist, designed for micromachining and other microelectronic aplications, were it is desired a thick layer, with a high chemical and thermal stability [4]. Dissolving the exposed SU8 layer is not possible by wet chemical processes; it has not been found a way to attack the resist with a reasonable speed without affecting the electroplated metals. They have been tried plasmas with different types of gas, but the plasma nature (high-

energy ions) heats the whole wafer with the exposed SU8 and the microstructures, leading to degradation of the structures. The solution found by the R3T company was to use free radicals instead ions, radicals which corrode C and N of the SU8 epoxy network by forming N2O and CO/CO2. The plasma is used to generate radicals. For separation of the charged ions from the neutral radicals it is used a specially designed enclosure [5]. The whole process is controlled in order not to overheat the structures. The SU8 photoresist removal equipment, type STP2020, was provided by the R3T company and it is composed of a vacuum chamber (with an external vacuum pump), a microwave source, a temperature control system and software programs for processes and data tracking. Dry chemical etching without agressing the sample with the ions, performes a gentle and controlled removal with high selectivity (typically 500:1). The metals (Ni, Ni / Fe, Au, Cu, etc..) don't react with these radicals and therefore they are not attacked. The used types of gas are O_2, N_2 and CF_4. The equipment uses an external molecular vacuum pump type Adixen A 300, which provides a pumping speed up to 320 m3 / h and can ensure a minimum pressure of 120 mbar, requiring a cooling water consumption of min. 100 l / h.

3. Designing and realizing micromechanical parts. Experimental results

It is proposed to process a range of Ni gears with 10 teeth and another with 5 teeth.

All micromechanical parts and test structures were processed on silicon wafers, Si(100), doped n-type, 4 inch diameter, oxidized on 500nm thermal SiO2, one side coated with a Cr/Au layer and a 100 μm SU8 photoresist layer on top of the Cr/Au layer, with constant thickness.

Manufacturing micromechanical structures involved the following, in accordance with steps 1 to 4 of the technological process, presented in Fig. 1:

Step 1 - Lithographie

a) achieving the drawing of the part in an accepted format by the laser lithographie system, DWL66 FS, (DXF, CIF, Gerber, GDSII),

b) conversion of the drawing (which is a DXF, CIF, Gerber or GDSII- format) into a dot matrix (LIC) and positioning each part on the support (MAP file), in a matrix format,

c) establishing the exposure parameters (to make JOB file),

d) exposure using the laser lithographie system, DWL66 FS,

e) time and temperature for post-exposure baking – establishing the value of PE1 and PE2 [6]

Step 2- Development

a) unexposed SU8 photoresist development

b) rinsing and drying [7]
Step 3- Galvanic deposition
Ni electroformed layer.
Step 4 - Photorezist removal
a) selective removal of the exposed SU8 photoresist,
b) extracting parts from the wafer.

For all technological process operations it was necessary the testing and optimization of all process parameters, in real conditions and with existing equipment, to achieve the design objectives. The approach has followed a logical course, each time varying a single process parameter. After determining the optimal value for tested parameter, the following parameter has been optimized, the process continues until all controllable variables have been exhausted. The exposure, baking and development processes, took place in a room with yellow light, to avoid unwanted exposure to light of SU8 photoresist.

3.1 Optimization of the process parameters described by step 1: lithography

The knowledge of the software and of the equipment was enough to run in good conditions the technological operation process described by step 1-a), b) and d). The other technological process operations, 1-c) and e), were optimized.

Optimal values mean the best structure images we obtained.

The following parameters were optimized:
1. Optical gray filter. During the exposure we used different types of optical filter : Without Filter, 50% filter and 25% filter.
Optimal value: 50% filter.
2. Software filter. We also used different values for the software filter (percentage of maximum exposure energy): 40, 50, 60, 70, 80, 90, 100. Optimal value: 80%.
3. Software parameter DEFOC. During the exposures we used also different values of the software parameter DEFOC (fine adjustment of the distance between the writing head and substrate). We used values from 2000 to 4000 in increments of 50.
Optimal value: 3450.
4. First baking temperature and time (PE1):
The baking temperature was from 60 °C to 65 °C. The baking time was from 1 min. to 5 min [8].
Optimal values: 65 °C, 3 min.
5. The time for raising the temperature between PE1 and PE2 was between 0 and 3 min.[9].
Optimal value: 90 sec.

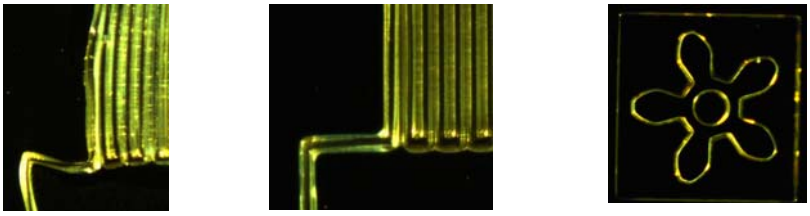
6. Second baking temperature and time (PE2):
The baking temperature was from 90°C to 95°C.
The baking time was from 7 to 25min [8].
Optimal value: 95°C , 10 min.
7. Cooling time and cooling type until reaching the ambient temperature.
We tried some different cooling types, such as: cooling in the convection oven, cooling in a free space and accelerated cooling with light air-jet.
Optimal value: in the convection oven: 30 min.
8. Structures relaxation time: 0-48 hours. We tested the samples every hour.
Optimal value was obtained after 3 hours.
The baking was done as follows:
- PE1: on a thermostated hob, type FALC MOD F 70.
- The increasing ramp of the temperature was from 65ºC to 95ºC on a thermostated hob, type FALC MOD F 70.
- PE2: in the convection oven type Binder FD70, placed on a metal substrate with high thermal inertia.
- Cooling: at room temperature or in a forced convection oven type Binder FD70.

3.2 Optimization of the process parameters described by step 2: development

The following parameters were optimized:
a. Time and type of development:
The samples were maintained in the developer from 7min to75min, with and without shaking them [10]. Optimal values:14 min. with mild shaking.
b. Drying type: natural or forced convection (air jet). Optimal value: natural.

The development of the unexposed SU8 photoresist was achieved by immersion in mr-Dev 600 solvent type. They have been made experiments, ranging the immersion time of the microstructure in the solvent, and experiments with the intercalation of rinses in 2-propanol (ICAO: isopropanol), to remove the resist from the small-sized channels. The developing temperature was the room temperature (21-25° C), and there were made developments without shaking, with vigorous stirring and intermediate variants. The developing was executed immediately after the sample reached the room temperature, or after expiring a structures relaxation time between 3-48 hours. The final rinse was done with 2-propanol and the drying was realized with compressed air or natural convection.
Conclusive structure images during the optimization of exposure and development technological process are presented in Fig.3.

a. Detail of a deformed route due to too low energy level
b. Detail of an apparently correctly done structure, but with increased sized whirls, due to overexposures. Structure obtained by vigorous shaking of the developer and a relaxation time of 6 hours.
c. Detail of properly exposed, baked and developed structures.
Following these practical experiments there have been made patterns for bidimensional microstructures of SU8 photoresist (negative) that will be used for electrodeposition.



a b c

Fig. 3 Microscope images by ZEISS Stemi 2000C -50X, representing structures obtained during the process parameters optimization for postexposure baking and developing.

3.3 Optimization of the process parameters described by step 3 - electrodeposition

Ni was deposited in the SU8 template with a thickness of 100 μm, using Watts baths and also sulphamate ones.
Parameters that have been controlled and that contribute to realize deposits are divided into two categories [11]:

- parameters which are contributing to the deposition: the concentrations of salts and buffer substance, the presence of additives, pH and temperature of the bath;
- parameters which are affecting the uniformity and quality of submission: electric power density and the application method, the geometry and configuration of the bath and the bath stirring rate.

For the sulphamate baths we used an electrolyte having the following composition:

Nickel sulphamate 300g / L
NiCl2.6H2O 30g / L
H3BO3 30g / L
Naftalentrisulfonic Acid 7.5g / L
Sodium lauryl sulfate 0.05 to 0.1 g / l
Working conditions:
Temperature 50-55 ° C

Current density 2-6 A/dm2
pH value = 3.5-4.2 electrometric ,
Terminals voltage: 2-5V;

To limit diffusion and increase the electric power density the electrolyte convection was performed by shaking it with a magnetic stirrer. The pH value was adjusted with amidosulfonic acid. The substrate surface was prepared in advance through the following sequence:

- degreasing in organic solvents (acetone, ethyl alcohol),

T = 25-30ºC, immersion time for about 120 seconds.

- etching / chemical deoxidation in HNO3 1:1 (vol),

T = 25-30ºC, immersion time for about 30-60 s.

- between the two sequences the sample was rinsed and dried.
- deposits were made with a thickness of about: 30µm, 80µm, 100µm, at electric power densities between 2.5 and 5 A/dm² and time periods between 1 and 5:00 hours.

The results were summarized in Table 1.

Below are the images obtained by optical microscopy on samples of Ni deposition.

Table 1

The obtained results

No.	Temp ºC	Current densityA/ dm²	Time min.	Thick µm	Characteristics
1	52-55	3.5	60	30-40	Shiny deposit, with well defined edges
2	52-55	2.6	180	79-80	Glossy and in the middle uniform deposit, matted and with dendrites on the edges
3	52-55	5	180	90-100	Uniform and sharp deposit inside but with dendrites at the edges

Fig. 4 presents images of Ni deposits with thicknesses about 90-100 µm in the photoresist pattern (miniature gear wheel). There is a well defined and uniform deposition in the profile, but dendrite edges.

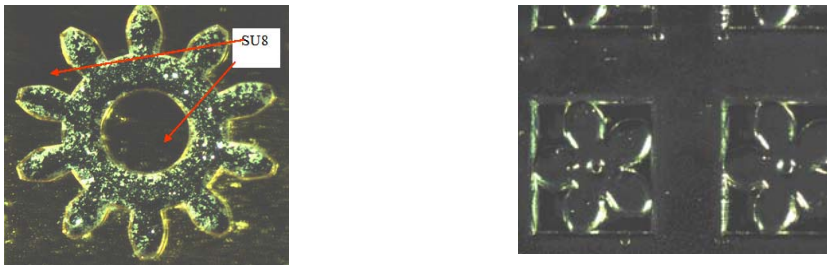


Fig. 4 Optical image of a deposition depth of 90-100µm Ni in a SU8 photoresist pattern: 10 teeth gear wheel (left) and five teeth gear wheel (right)- Optical microscopy, 50x

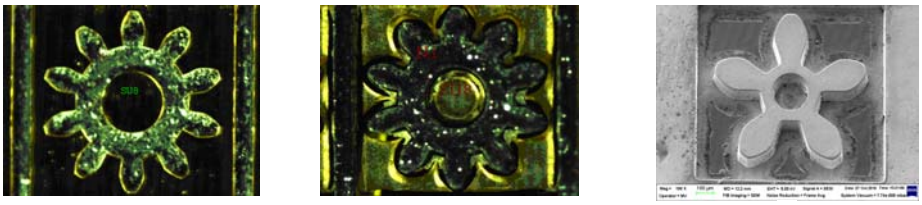
3.4 Optimization of the process parameters described by step 4 - exposed photorezist removal. Practical results for the removal of exposed photoresist.

To determine the working parameters, we used standard samples with photoresist thickness of 6.22µm and an area of 300mm^2, with the whole photoresist surface exposed and samples with various sizes, having structures with nickel and a photoresist thickness of 100µm. The STP2020 equipment operates manually or semi-automatically. In manual mode all operations are controlled by the operator. For the test wafer with SU8 exposed over the whole surface of 300mm^2, it was found that this approach is suitable because the reactions between the free radicals and the photoresist are visible as a bright area on the wafer surface, the time the plasma has to be maintained can be established through visualization.

For electrochemically deposited structures was found that manual mode can not be used effectively, because after partial removal of the photoresist the characteristic light in the area where reactions take place is sinking in the cavity and can not be observed by the operator. There has been used the automatically mode.

We used three levels of magnetron power: 800W, 1000W and 1200W. Substrate temperatures were tested in the range from 50 to 65°C. The O2 flow was 800sccm, 1000sccm and 1200sccm (in correspondence with the magnetron power).

Experiments were made with one plate and five plates placed simultaneously in the plant. There were not available five plates with identical structures in order to optimize a process of mass production, but the differences between the different plates structures (fill-grade of the plate, the largest area with SU8, the minimum size of a structure) can not influence the trend and typical values of working parameters.



a) b) c)

Fig. 5 Gear wheel before, during and after removal of photoresist SU8

a. Structure with gear wheel embedded in SU8 photoresist.
Optical microscopy, 50x.
b. Structure with gear wheel partial extracted. Optical microscopy, 50x.
c. Gear wheel without photoresist SU8, separated from the Si substrate. SEM microscopy, 198x.

An important observation in removing photoresist SU8 is the place where reactions take place: at the free surface and near the nickel structures. This means a more rapid removal of the photoresist in the narrower channels than in areas with large area of photoresist. A reliable method for determining the moment when the photoresist is completely removed, appliable for plates of different sizes and with different degrees of filling, is monitorizing the plate temperature. Reactions occurring in the photoresist SU8 lead to a slight temperature increase and the end of the reactions are leading to a slight decrease of the temperature. These variations of the temperature (0.2°C ... 0.4°C) indicate the fact that the process has ended. The substrate temperature is a parameter with major influence on the rate of removal of SU8. The predominant mechanism in the transmission of heat from the thermostatically table to the substrate with fine structures is thermic conduction (convection is limited due to the very low pressure in the chamber during the process). Substrate flatness has a major influence over the removal rate.

Experiments have shown the following results:
- optimum substrate temperature was 60°C (temperatures below 60°C lead to reduced rates of removal, and at about 65 °C a slight softening of the resist takes place, softening which can lead to migration or destruction of fine structures of nickel),
- for a single wafer we used a magnetron power of 800W, for 5 wafers the magnetron power was 1200W,
- for the magnetron power of 800 W the working gas flow for CF4 and N2 was 70sccm and for O2 the gas flow was 1000sccm,
- for the magnetron power of 1200 W the working gas flow for CF4 and N2 was 80sccm and for O2 the gas flow was 1200sccm

- the SU8 photoresist removal rate was 3.1 µm/min. at wafers with thin layer of photoresist (without structure) and 2µm/min for 5 wafers with structures and thicknesses up to 100µm simultaneously loaded into the machine

4. Determination of dimensional accuracy of parts

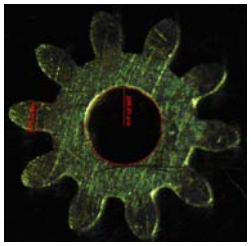
For determining the precision of the execution of mechanical parts for systems it was used optical microscopy and SEM for finished and semi-finished parts (with parts attached to the substrate, with the SU8 photoresist not being totally removed).

All measurements were performed on parts realized after the whole technological process was optimized.

The quality of the produced parts was determined by:

- the exposure process of the structures,
- the SU8 photoresist baking process,
- the SU8 photoresist developing process,
- the galvanic process of growing (thickening) of the metal layer

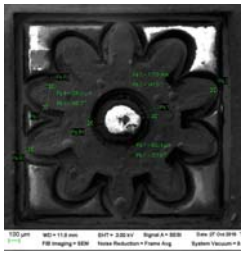
The following examples are items with measured values and planned values.



Gear wheel,
-projected inner diameter: 600 µm,
-measured inner diameter: 597.66 µm.
-designed tooth width: 210 µm,
-measured tooth width: 210.33 µm

Fig. 6. Image representing measurements of a nickel structure - Optical microscopy, 50x.

To obtain results with high precision, measurements were performed on a SEM ZEISS microscope, some results are presented in Fig. 7.



Designed inner diameter 600 µm,
Measured inner diameter 600.4 µm

Fig. 7. Images obtained by SEM microscopy- 200x (measurements on the Ni- structure)

There have been made measurements on a set of 50 gears. The standard deviation was 1.15 μm.

The accuracy of parts is strongly influenced by the aspect ratio (the ratio between the width of the narrow channel and the photoresist layer height). For rates below 3:1 it is a very good precision, about 1 μm. For aspect ratio over 5:1 the accuracy and repeatability of processes are affected and the quality of the results is decreasing. It can be concluded that up to a 4:1 ratio results are good, processes are well characterized and repeatable, projects based on this rate achieve the required tolerances.

There have been made experiments for establishing the elements of electroplated elements, the crystalline phase and the crystallographic plane, also determination of Vickers hardness. The determination of qualitative phase was done by X-ray-diffraction, with a Brukner-AXS D8 ADVANCE X-ray diffractometer. Hardness measurement was made on an FM hardness measurer Vickers XMO series 195. The measured hardness value was 334 HB units. All measured values recommend using without problems the processed microparts [12].

5. Conclusions

- For establishing of optimal technologies to obtain microsystems, the authors recommend to optimize the exposure, baking and developing processes, the galvanic depositon and the retrieving of the parts out of the photoresist
and propose solutions that can provide high accuracy, the differences between designed data and the measured ones being of μm size.
- The proposed technology - optimizing process parameters and verified by the freestanding microsystems - allows the development of micro gear wheels in sizes below 1 mm, made of galvanically deposited Ni, with a thickness of 100 μm, with variable number of teeth (5 and 10). The difference between designed and measured data remains in the required tolerances.
All this results recommend to increase and to diversify the number of applications.
- The technology being verified by a large number of tests, we can go in carrying out various configurations of components for transducers, sensors and micro actuators, using different thicknesses (max. 400μm) and different materials that can be deposited by electroplating processes (Cu, Au, Ni, etc.).
- The first application of LIGA technology in Romania, for making microelectromechanical systems, the existence of high-precision equipment in the ICPE-CA and a team which was trained in Romania and abroad, are an invitation for research and industry specialists to associate this new technology to achieve electromechanical components with high precision and low cost.

R E F E R E N C E S

[1]. *J. Schulz, ,* Study concerning metal microstructure processing using LIGA technology, 2008
[2]. ***, DWL 66FS Product Description, 2007, Heidelberg Instruments
[3]. ***, DWL 66FS Reference Manual, 2007, Heidelberg Instruments
[4]. ***, NANO SU8 – Negative Tone Photoresist, 2002, MicroChem
[5]. *J. Mathuni, ,* Fast and reliable removal of SU8 resist, 2009, R3T
[6]. *C.Koch, , T. J. Rinke,* Lithography – Theory and Application of Photoresists, Developers, Solvent and Etchants, 2008, MicroChemicals
[7]. *G. Ionascu, N. Alexandrescu, L. Bogatu, E. Manea, , I. Cernica, T. Ciulacu,* Advanced SU-8 Photoresist Technology for MEMS, 2007, Journal of Mecatronics no.2 ISSN 1583-7653
[8]. *A.Campo, C. Greiner,* SU-8: a photoresist for high- aspect-ratio, 2007, Journal of Micromecanics and Microengineering
[9]. *J. D. Williams, ,* Design and Fabrication of Electromagnetic Micro-relays using the UV-LIGA Technique, 2004, Louisiana State University
[10]. *A. Saghiri, M. Kaden,* SU8 multiple layer structuring by means of maskless photolithography, 2005
[11]. *C. Kollia, N. Spyrellis, J. Amblard, M. Froment, G. J. Maurin,* Appl. Electrochem. 20 (1990) 1025
[12]. *V. Vasilache,* Studies of Hardness for the Electrodepozited Nickel from Watts Baths with addition of Polyvinyl Pyrrolidone (PVP), 2009, Revue Roumaine de Chemie.