SANDIA REPORT

SAND99–8228
Unlimited Release
Printed February 1999

LIGA Micromachining: Infrastructure Establishment

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ABSTRACT

LIGA is a micromachining technology that uses high energy x-rays from a synchrotron to create patterns with small lateral dimensions in a deep, non-conducting polymeric resist. Typical dimensions for LIGA parts are microns to tens of microns in lateral size, and hundreds of microns to millimeters in depth. Once the resist is patterned, metal is electrodeposited in the features to create metal microparts, or to create a metal mold for subsequent replication. The acronym LIGA comes from the German words for lithography, electroforming, and molding, and the technology has been under worldwide development for more than a decade. Over the last five years, a full-service capability to produce metal microparts using the LIGA process has been established at Sandia National Laboratories, California. This report describes the accomplishments made during the past two years in infrastructure establishment funded by a Laboratory Directed Research and Development (LDRD) project entitled "LIGA Micromachining". Specific topics include photoresist processing for LIGA mask making, x-ray scanning equipment, plating bath instrumentation, plating uniformity, and software architecture.

LIGA MICROMACHINING: INFRASTRUCTURE ESTABLISHMENT

INTRODUCTION

LIGA, an acronym from the German words for lithography, electroforming and molding, is a promising new process for producing high aspect-ratio metal microdevices having micron to millimeter features [1,2,3]. In LIGA, high-energy x-ray lithography is used to produce a deep non-conducting mold [4,5,6] that is subsequently filled by means of electrodeposition to produce metal parts. The overall process is illustrated in Figure 1. The final step in the process as originally conceived by the inventors, is injection molding for mass production using the electroformed metal part as a mold. Currently under worldwide development, this process offers a means to manufacture high resolution, high aspect-ratio devices including microscale valves, motors, solenoid actuators, and gear trains. Such devices cannot be fabricated either by silicon micromachining or by precision machine tool operations.

The LIGA fabrication process involves a number of distinct process steps. These steps include mask layout, chrome mask generation, LIGA mask fabrication, substrate preparation, x-ray exposure, chemical development, electroplating, lapping, and replication. Each of these process steps requires specialized equipment and expertise. Over the past five years or so, Sandia National Laboratories, California has been establishing the infrastructure to conduct all the LIGA process steps, except generation of the chrome mask. During the past two years, the LIGA process team obtained Laboratory Directed Research and Development (LDRD) funding to advance the infrastructure development for LIGA at Sandia National Laboratories, California. This report summarizes the progress on infrastructure development funded by that LDRD.

At the present time, all the LIGA process steps are conducted in our on-site laboratories with the exception of chrome mask generation and x-ray synchrotron exposure. The exposures are performed at one of several DOE-owned and -operated facilities. The three synchrotron light sources used by the Sandia National Laboratories, California LIGA team are the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory, Stanford Synchrotron Radiation Laboratory (SSRL), and the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory.

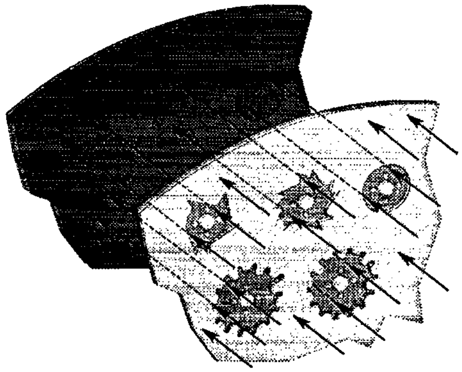
The specific accomplishments from this LDRD that enabled us to improve our LIGA infrastructure for metal parts include:

- establishment of the photoresist processing for LIGA mask fabrication
- design and procurement of a scanning station for use at the synchrotron(s)
- instrumentation of a dedicated LIGA plating line for process monitoring
- design and fabrication of a LIGA plating apparatus for uniform deposition
- creation of a software architecture to allow routine LIGA business to be conducted on the world wide web

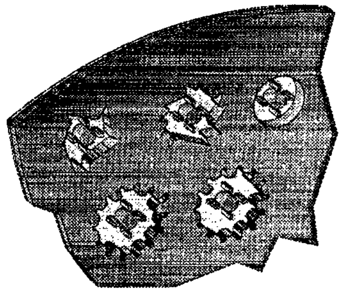
This report contains detailed discussion of the work conducted under the LDRD entitled "LIGA Micromachining". It is not intended to be a description of the complete LIGA capability at Sandia National Laboratories, California.

Figure 1. Illustration of the LIGA process steps

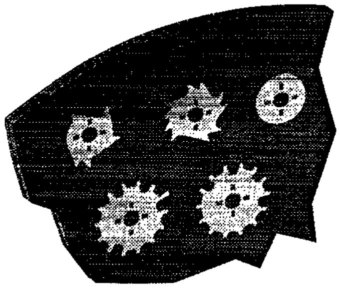
1. X-rays from a synchrotron are incident on a mask patterned with high Z absorbers. X-ray are used to expose a pattern in PMMA, normally supported on a metallized substrate.



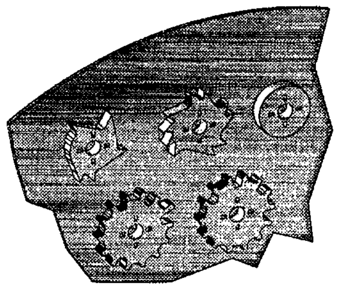
2. The PMMA is chemically developed to create a high aspect ratio, parallel-wall mold.



3. A metal or alloy is electroplated in the PMMA mold to create a metal micropart.



4. The PMMA is dissolved leaving metal microparts. These microparts can be separated from the base plate if desired.



LIGA X-RAY MASK FABRICATION

LIGA utilizes short wavelength x-rays generated by a synchrotron to expose thick polymethylmethacrylate (PMMA) resist through a patterned absorber mask [7]. In order to obtain the faithful transfer of micron size features into PMMA hundreds of micron thick, LIGA x-ray masks must meet the following requirements [8]:

1. The mask absorber material must have a high x-ray absorption coefficient. High Z (atomic number) elements such as gold, tungsten, or tantalum satisfy this requirement, with gold being the preferred absorber material (and our material of choice) because of its ease of electrodeposition.
2. The absorber must be thick enough to minimize dark erosion of the PMMA. This translates into an absorber thickness of at least 6 microns with the thickness increasing as the thickness of the PMMA increases and as the x-ray spectrum energy increases.
3. The substrate must be made of a material that minimizes the loss of x-rays through absorption. This requirement leads to low Z materials such as Si, Be, diamond, and others, typically as thin membranes (<5 micron thick) [9]. However, since it is also desirable that the substrate be mechanically robust to ensure high fabrication yields and to survive frequent handling during plating and exposure, and since the synchrotrons we typically use are too energetic to be used with thin membranes, our group has decided to use 100 micron thick silicon wafers as substrates instead of the usual 2 micron thick membranes.
4. In our particular case, the LIGA mask should be usable at any of the three synchrotrons where we currently conduct exposures.

Given the above requirements, we selected a gold thickness of 35 microns for the baseline case of a 100 micron thick silicon wafer substrate, lateral feature sizes greater than ten microns, and tight tolerance control. While the gold thickness can be considerably less, the 35 micron thick gold allows tight tolerance control if lateral feature sizes stay in the range of ten microns or higher. The need for this rather thick absorber places strict dimensional requirements on the photoresist sidewall profile as discussed below.

Mask fabrication

From the requirements described in the preceding section, our standard mask is fabricated in the following way:

1. A 100 micron thick, three inch diameter silicon wafer is metallized with 60 angstroms of chrome, followed by 300 angstroms of gold.
2. A UV photoresist is spun on the metallized silicon wafer to a total thickness of about 50 microns.
3. The resist is patterned using a chrome mask in a UV exposure station. The exposed pattern is then developed.
4. Gold is electrodeposited in the resist to a total average thickness of approximately 35 microns.

In this section, the photoresist and photoresist exposure steps will be discussed in detail since these were the process steps that were developed as a result of this LDRD funding.

Photoresist.

For our process, we employ SJR5740, a viscous, novolac-based thick photoresist from Shipley [11]. This photoresist is used by industry for applications such as thin film heads, MEMs, and bumps and wire bond pads. Even a 30 second spin at 4500 rpm (standard spinning conditions) yields a 7.4 micron coat, a rather thick coat compared to the 1 to 2 micron coat normally used in integrated circuit manufacturing. We usually obtain a 25 micron thick coat by spinning at 1200 rpm for 10 seconds and typically spin two coats for a final thickness of 50 microns.

Since the silicon substrate is only 100 microns thick, coating with 50 microns of photoresist introduces significant stress that bends the substrate. In order to minimize the stress, the photoresist is cured by heating and cooling slowly.

Finally, the photoresist must be spun on a silicon wafer metallized with chrome and gold. The adhesion of SJR 5740 on the as deposited gold is rather poor. Thus, after metallization, the gold covered substrates are rinsed in trichloroethane, isopropyl alcohol, and acetone.

Exposure Optimization

The goal of the lithography step in the mask fabrication process is to faithfully replicate a pattern with lateral features as small as 10 microns in a 50 micron thick photoresist. Unlike traditional integrated circuit lithography, where the UV light is stopped by even a thin absorber in the line of sight, LIGA x-rays need thick absorber to effectively stop the x-rays [8]. Thus, it is important that every feature from the chrome mask maintain the same lateral dimensions through the entire resist thickness for the LIGA mask. Relatively small angle deviations from a perfect 90° in the mask sidewall cause significant dimensional distortion in the PMMA as illustrated in Figure 2.

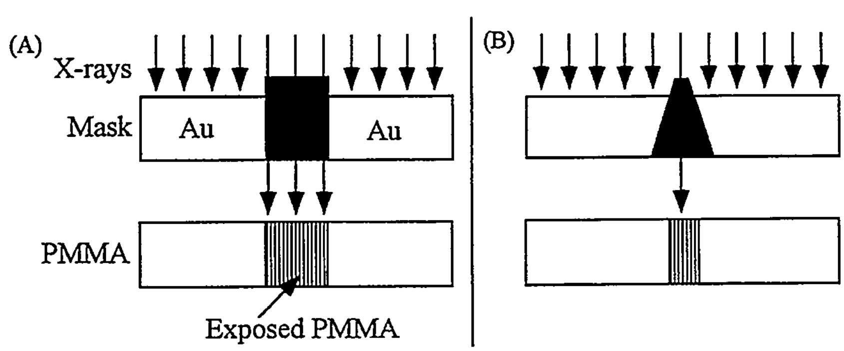


Figure 2. (A) A mask with ideal 90° photoresist sidewall faithfully replicates features in the PMMA. (B) When the photoresist sidewall is angled, the dimensions of the exposed PMMA differ from the intended dimensions.

Although our typical photoresist thickness is 50 microns, the plated gold is generally about 35 microns. An 86° sidewall angle, quite acceptable for traditional integrated circuit lithography, causes a 4.9 micron lateral variance in the photoresist (2.45 microns variation at each side) at a thickness of 35 microns. As shown in Figure 3, this variation severely limits the achievable lateral resolution in LIGA x-ray masks, and therefore in the LIGA-produced PMMA mold.

Figure 3. Total lateral resist variance as a function of resist thickness for an angle of 86°.

There are several mechanisms that limit the ability to obtain 90° sidewalls with thick photoresists. From the purely physical (diffraction effects) point of view, consider the intensity distribution of light on the surface of a photoresist coating after the light has passed through a mask containing a periodic grating consisting of opaque and transparent lines of equal width b [12]. This is illustrated in Figure 4.

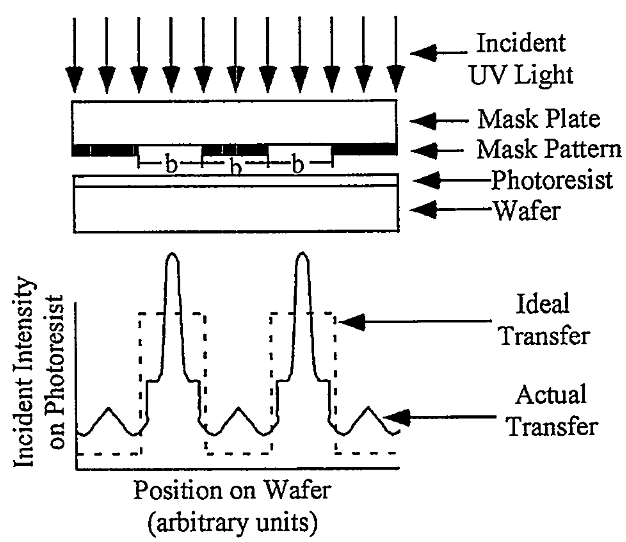


Figure 4. Light intensity profile at the surface of the photoresist after diffraction at the edges of the mask pattern.

The actual intensity pattern (solid line) differs considerably from the ideal square-wave pattern (dashed line) because diffraction blurs the edges of features. In general, the minimum spacing b is given by [12],

$$b = \frac{3}{2}\sqrt{\lambda\left(s + \left(\frac{z}{2}\right)\right)}$$

where λ is the wavelength of light, s is the separation between the mask pattern and the photoresist, and z is the thickness of the photoresist. In our case, we utilize contact printing so that $s = 0$. Similarly, λ can be approximated by 365 nm (so called I-line radiation). The expected resolution is shown in Figure 5 as a function of photoresist thickness. Thus, if only diffraction is considered, a 50 micron thick photoresist should have a resolution of about 4.2 microns.

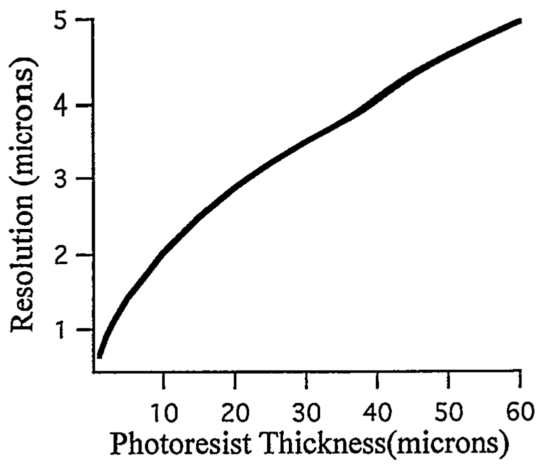


Figure 5. Lateral resolution as a function of photoresist thickness due to diffraction limits.

In practice, however, in addition to diffraction effects, one must also take into account nonlinearities in the photoresist response to light, contributions from wavelengths other than I-line radiation, light reflection from the substrate, imperfect contact between the mask and the photoresist, chemical variations in the photoresist, and imperfect development. Unlike diffraction, these additional factors are difficult to quantify and model. Thus, in order to optimize the sidewall profile, SEM studies must be conducted to determine optimal exposure and development conditions.

In agreement with documented photoresist behavior [13], the SJR5740 photoresist features follow well known geometric trends with extent of exposure, see Figure 6. When underexposed, the developer takes a relatively long time to dissolve the underexposed photoresist near the substrate. By the time the bottom underexposed photoresist has been dissolved, the top of the unexposed photoresist is eroded. At the optimal dose, the developer has no trouble dissolving the bottom exposed photoresist, and the developed pattern faithfully reproduces the mask. If the photoresist receives more than the optimal dose, the backscatter from the substrate causes an effectively higher dose at the bottom, resulting in an inverted pyramid profile and eventually adhesion failure between the substrate and the photoresist occurs.

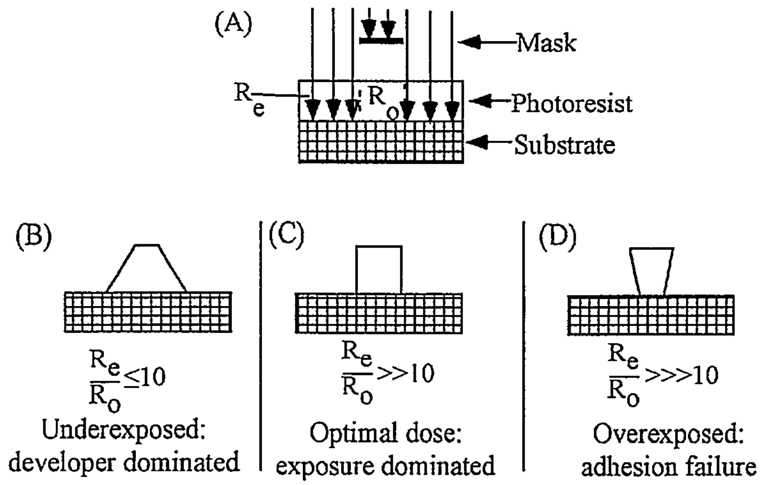


Figure 6. (A) Photoresist exposure. R_e is the development rate of the exposed area, R_o is the development rate of the unexposed area. (B) Underexposure causes a pyramidal shape because of dark erosion at the top. (C) With optimal dose the features are faithfully replicated. (D) Overexposure causes an adhesion failure.

Figures 7 and 8 show examples of the underexposed and optimized SJR5740 photoresist respectively. The optimized dose value we obtained was 2.2 J/cm^2 for a 50 micron thick SJR 5740 coating.

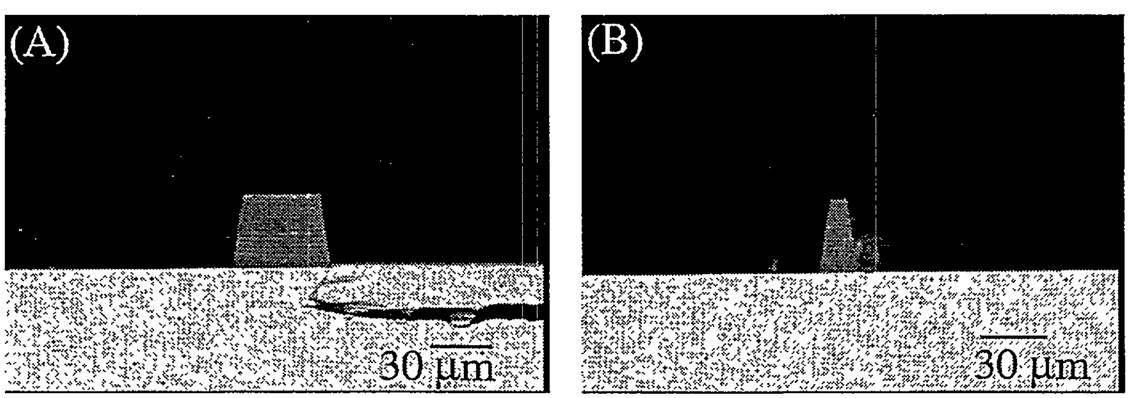


Figure 7. Optical microscopy of, nominally, (A) 50 micron and (B) 15 micron wide features in underexposed 50 micron thick SJR5740 photoresist.

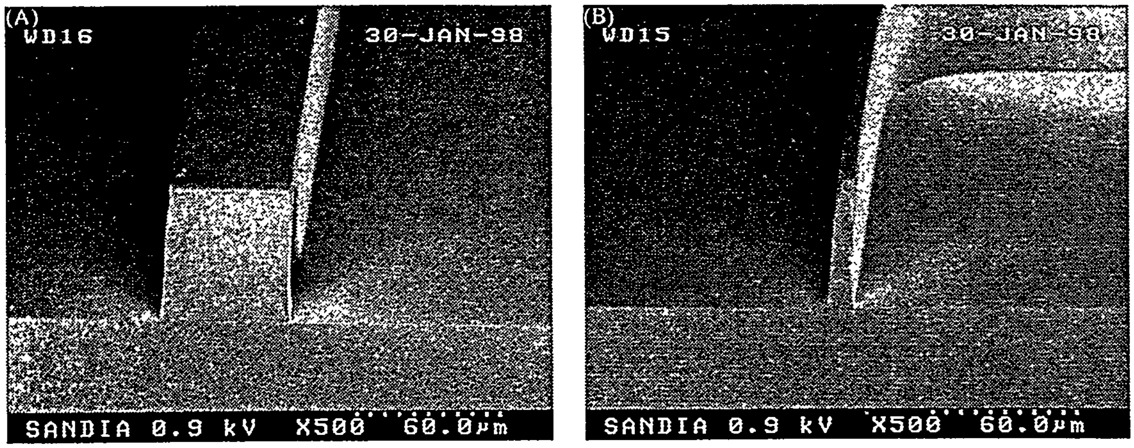


Figure 8. Scanning electron micrographs of optimized exposure for, nominally, (A) 50 micron and (B) 10 micron wide features in 50 micron thick SJR5740 photoresist.

Equipment Required

We currently fabricate our LIGA x-ray masks at Sandia and the UC Berkeley Microlab (cleanroom facilities at the Electrical Engineering and Computer Science Department). Table 1 lists the equipment needed for fabricating LIGA x-ray masks, the function of the equipment, and the current capabilities.

Table 1: Equipment required for the fabrication of LIGA x-ray masks and current capabilities.

Function	Equipment	Current Capabilities
Silicon substrate cleaning	Chemical hood	UCB and SNL: chemical hood with piranha bath, DI water, buffer HF etch.
Substrate metallization	Thermal evaporator	SNL: Thermal evaporator in LIGA lab.
Metallized wafer cleaning	Chemical hood	UCB and SNL: chemical hood.
Photoresist application	Spinner	UCB and SNL: Computer controlled spinner (Cee Model 100).
Photoresist curing	Heating plate	UCB and SNL: Vented heating plates.
Exposure	Contact aligner	UCB: Quintel, a broad band contact aligner. SNL: Karl Suss MA6.
Development	Chemical hood	UCB and SNL: Chemical hood.

Fabrication Steps

Typical fabrication steps to prepare a LIGA mask for the electroplating step are:
1) Cleaning of the silicon substrates in a Piranha (10 parts concentrated H_3SO_4 and one part 30% H_2O_2) bath.
2) Metallization of the substrate by thermal evaporation. An adhesion layer consisting of 60 Å of chrome is deposited first followed by 300 Å of gold.
3) Just prior to spinning photoresist, the substrate is rinsed with trichloroethane, isopropyl alcohol, and acetone. The substrate is then dried in an oven at 120°C.
4) SJR5740 photoresist is spun onto the metallized substrate at 1200 rpm for 10 seconds. After curing, this single layer is approximately 25 microns thick.
5) The photoresist is allowed to relax for at least five minutes before curing. To avoid the build up of stress, the substrate/photoresist is heated and cooled in steps:
2 minutes at 70°C.
2 minutes at 90°C.
10 minutes at 110°C.
2 minutes at 90°C.
2 minutes at 70°C.
2 minutes at 30°C.
Ramped down to 19°C at 3 C/ minute.
6) Another 25 micron thick photoresist layer is applied following steps 4 and 5.
7) The edge bead is removed by spinning the wafer at 2200 rpm and carefully squirting acetone at the edge of the photoresist with a syringe and a hypodermic needle.
8) The photoresist is patterned in the mask aligner (hard vacuum contact) by exposing it to a total dose of 2.2 J/cm^2.
9) The exposed photoresist is developed by immersion in Microposit Developer Concentrate. The photoresist quickly saturates the developer so that every 4 to 5 minutes the sample must be rinsed with DI water and reimmersed in fresh developer. Total development time is about 15 minutes.

SNL/CA Cleanroom

Much of the mask fabrication work for this LDRD was performed at University of California, Berkeley. In parallel, we redesigned and modified an on-site cleanroom in building 968, room 120. This LDRD project funded the facilities modification work necessary for the cleanroom to support LIGA mask fabrication. The newly configured cleanroom is shown in Figure 9.

The cleanroom, named the Microstructures Lab, is divided into three main areas with the following equipment:
1) Thin film area: thermal evaporator, sputter, e-beam evaporator, paralene coater, wire bonder, electronic testing station.
2) Photolithography and chemical bay: Karl Suss MA6 mask aligner (for up to 6" diameter wafers, equipped with optical back side alignment capabilities), Karl Suss MJB-3 mask aligner (for up to 2" diameter wafer), optical microscope, ovens, spinner, developer station, chemical hood.
3) Etching bay: Plasma etcher, plasma asher, chemical mechanical polishing stations.

The cleanroom came partially on line in November, 1998.

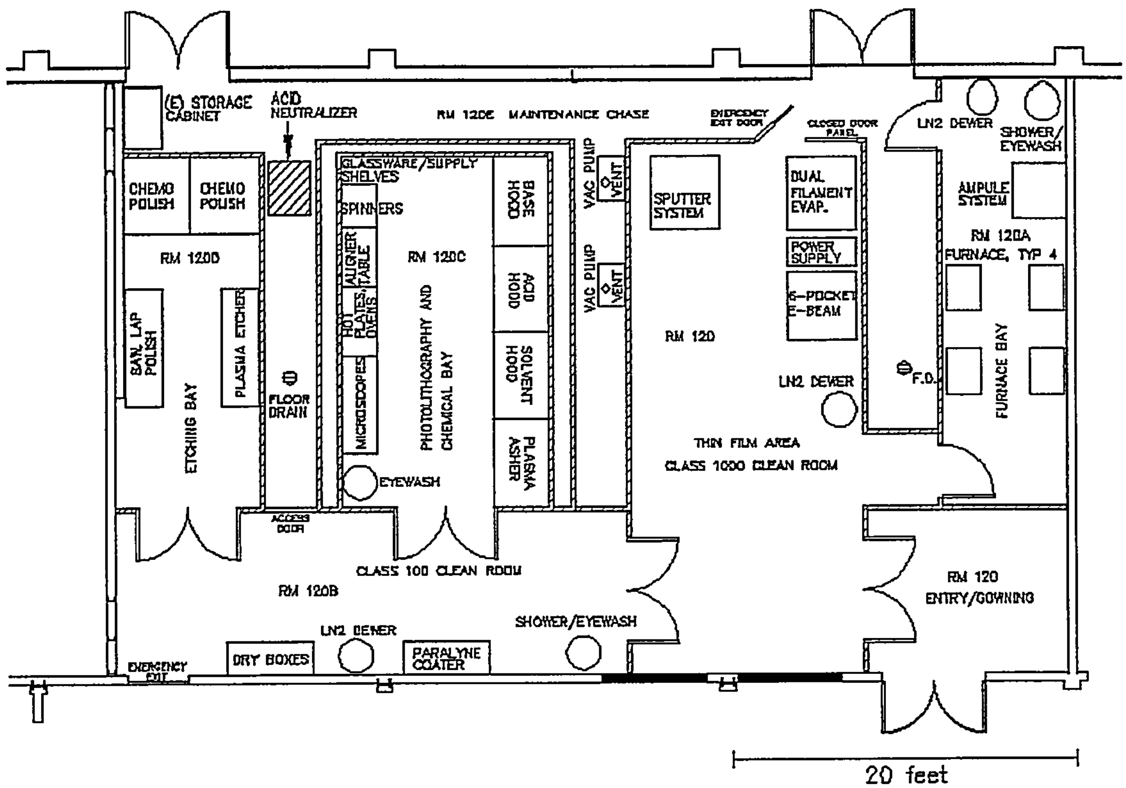


Figure 9. Microstructures Lab located in Building 968, Room 120 at Sandia National Laboratories, California.

Alternative Mask Technologies

Using 50 micron thick SJR 5740 we have been able to resolve 10 micron features. We are at the limit of resolution set by diffraction and other processing factors. We expect that future customers will request lateral features smaller than 10 microns. Thus, we have been exploring alternative resist technologies. We have chosen not to report these alternative technologies here due to potential intellectual property protection issues.

LIGA X-RAY SCANNING SYSTEM

X-rays from a synchrotron arrive at an end station with a geometry that is slit-like. At ALS and SSRL the beam footprint is about 10 cm wide by about 1 cm high. X-ray synchrotron exposures for LIGA therefore require scanning of the LIGA mask and PMMA resist through a stationary x-ray beam to provide an evenly distributed x-ray exposure over the three inch diameter wafer. All the synchrotrons we currently use employ different scanner technologies for LIGA x-ray exposure. The ALS and SSRL use electrical-mechanical scanners, while the NSLS uses a pneumatically operated system to scan an x-ray mask and PMMA through the synchrotron beam.

The ALS scanner consists of an 8-sample position turret that employs a counter-weighted belt drive system. The entire instrument operates in a non-hutch, closed box, x-ray safety enclosure using an inter-locked door for sample placement and is dedicated for LIGA at Beamline 3.3.2. The SSRL system consists of an electrically driven screw drive stage mounted to two machine tool rotational stages for alignment to the x-ray beam. This system has been used at Beamline 2-2 in an x-ray safety enclosed hutch. This scanner has been in operation for over five years. NSLS operates two pneumatic systems that are dedicated to performing deep etch x-ray lithography for LIGA. A single mask scanning system is located in the hutch at Beamline X27B and a second system, just coming on line, has been designed for mounting multiple masks and substrates.

All the scanning systems mentioned use National Instrument's Labview software for controlling the scanning operation and sample manipulation, however, each is a stand-alone system and individually unique in its programming and operation. None of the above mentioned systems provide for rotation of the mask and sample to perform transverse x-ray exposures.

Sandia and the Jet Propulsion Laboratory (JPL) are building a new branch line on Beamline 3 at SSRL dedicated to LIGA. This beamline is expected to be in operation in the first quarter of CY99. Sandia decided to construct a new scanner with enhanced capability for use in this new facility. This LDRD project funded the design and fabrication of the new scanner for use primarily at SSRL.

Characteristics & Configuration

As mentioned earlier, synchrotron beam profiles at SSRL and ALS consist of a rectangular footprint approximately 10 cm wide by 1 cm high. The NSLS configuration at X27B is somewhat smaller, providing a beam width at the sample of approximately 6 cm. X-ray masks used to date are primarily three-inch diameter formats. Since the beam is nominally four inches in width, the x-ray mask needs only to be scanned in a vertical fashion through the beam to provide a successful exposure. (At NSLS only a fraction of the full mask is exposed.) With the increasing demand for larger and more complex structures, the capability to provide exposures on four-inch diameter or larger masks becomes necessary. The new scanning system has been designed to meet anticipated needs and will be in place at SSRL in the first quarter of CY99.

Our new scanner has been designed to provide the following new capabilities:

1. Scan masks larger than three inches in diameter, preferably at least four inches.
2. Mount multiple masks simultaneously to ease demands on time required by the operator.
3. Rotate mask and PMMA substrates to perform exposures that have a non-parallel sidewall (three-dimensional).
4. Operate the system with a user-friendly control system.

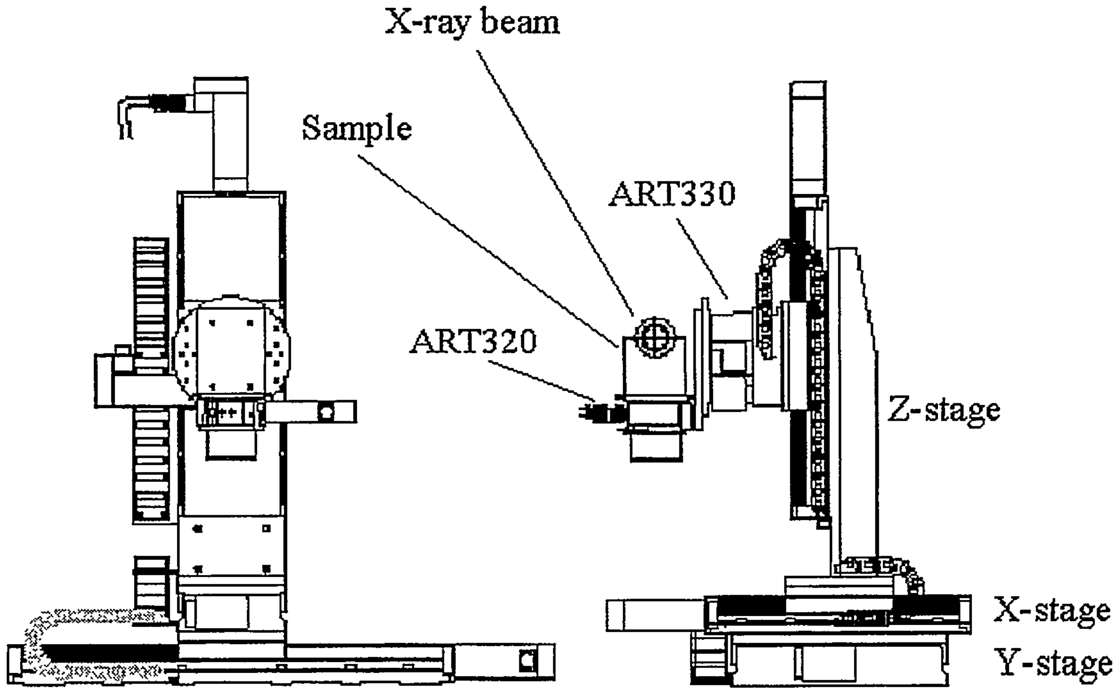
In designing for the ability to mount multiple masks and scan large samples, the combination of sample weight and travel distance became critical features that eliminated most equipment manufacturers. In addition, the added requirements of precise positioning and high scanning speeds for the positioning stages (up to 200 mm/sec) further limited the number of manufacturers that could provide such a system. Aerotech Inc, Pittsburg, PA was chosen to build the scanning system based on their product performance and history of providing instrumentation for the laser machining industry.

The scanner design consists of 3 linear stages and 2 rotational stages configured as shown in Figure 10. The naming convention and characteristics of each stage are as follows. The Z-stage is a linear motion stage providing an 18 inch scanning range of vertical motion through the x-ray beam; the scanning velocity is variable from 30 mm/sec to 50 mm/sec and has a positioning resolution of 0.1 micron. The two rotational stages are mounted to the Z-axis and the weight capacity still provides for a sample of up to 10 kg. The X-stage is another linear stage providing positioning and scanning horizontal to the x-ray beam; the scanning velocity is variable from 30 mm/sec up to 50 mm/sec with a positioning resolution of 0.1 micron. The Y-stage is a third linear stage providing positioning within the x-ray beam. This wide body stage is the base stage for the system to which all other stages are mounted. It provides positioning of the entire system parallel to the x-ray beam. The positioning velocity is 30 mm/sec with 0.1 micron resolution and 30 inches of linear travel. There are two rotational stages, the ART320 and the ART330. The ART320 is mounted to the ART330 stage to provide for mask and sample horizontal rotation relative to the x-ray beam with an operational speed of 5-10 rpm and 360 degrees of motion. The ART330 is mounted to the Z-axis stage to provide for mask and sample vertical rotation relative to the x-ray beam with an operating speed of 5-10 rpm and 360 degrees of motion.

The Z-stage is the workhorse of the scanning system providing vertical rastering of the mask through the x-ray beam. The four other stages provide positioning of the mask relative to the x-ray beam with the exception of the X-stage, which in addition to positioning, can provide for raster motion of the mask in a horizontal motion in conjunction with the vertical direction of the Z-stage. This permits the exposure of large areas beyond a typical 4 inch mask diameter. Individual samples up to approximately 5.5 inches in width and 8.5 inches in length could be evenly exposed in the x-ray beam by using a combination of Z-stage and X-stage motion.

Status

The scanner is currently at Sandia National Laboratories, California and Labview control software is being developed. The scanner should be in place at the new SSRL beamline in about March 1999. A technical disclosure for the scanner design is being prepared to eventually allow for licensing.



Side View: Perpendicular to x-ray beam FrontView: Parallel to X-ray beam

Figure 10. X-ray scanning system configuration. The height of the system as shown is approximately four feet.

PLATING BATH INSTRUMENTATION

Plating into the high aspect ratios used in LIGA is generally accomplished using low currents and long times. The need for accurate current control over long times has led to the development of a computer based diagnostic and control system for our LIGA plating line. This development effort is being carried out in two phases. The first, which this funding covered, was design, acquisition, fabrication and start-up.

Computer Based Diagnostics

In order to evaluate and characterize long-term plating processes, a diagnostic computer based system was developed. The system includes a Pentium II PC, 1.25 MHz - 8 channel data acquisition card, and the necessary shunt resistors for measuring currents in the milliampere range. Plating bath characterization can be difficult due to the complexity of electroplating solutions and the electrically noisy environment. Low current monitoring can be influenced by stirring motors, heating elements, filter pumps, agitators, and line noise. However, if suitable characterization of current and voltage can be achieved, the plating process can be characterized to both enhance the quality of the deposition and decrease the time required to successfully plate a LIGA wafer.

The diagnostic system is comprised of four separate components: data logger; dynamic frequency analyzer (DSA); waveform/function generator; and alarm status menu with e-mail notification. The data logger is used in long-term compiling and storing of electroplating data. The data are acquired at rates between five seconds to several hours and stored to disk in real time within a share folder. Users can access the data periodically or view the GUI over the network using TCP/IP connections and a web browser.

Presently, four channels of voltage and current are measured at the cathode by shielded coaxial cable and terminated at a differential-ended input on a high-speed data acquisition card. The operator determines a suitable acquisition rate to render historical trending data without over sampling. Figure 11 is a typical plot of voltage and current during a 50 hour plating cycle. Note the slow increase in voltage, which could be attributed to the depletion of ionic solution reaching the substrate through a deep cavity. It is believed that interfacial resistance has increased, which requires a higher voltage to maintain a constant current. Other devices, such as stress monitors, pH sensors and ion detectors can be added for real time monitoring. The logger can run independently, allowing other diagnostic components to operate such as the dynamic signal analyzer.

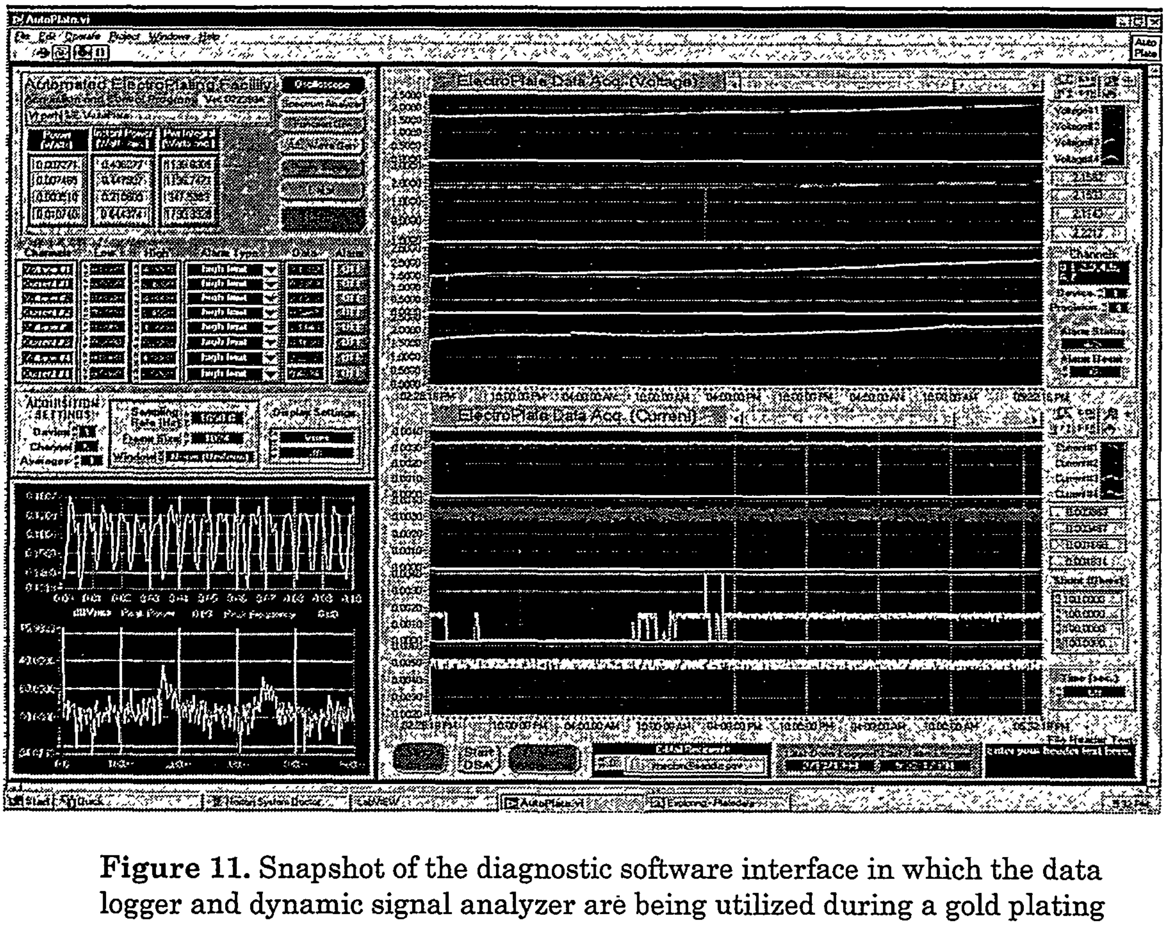


Figure 11. Snapshot of the diagnostic software interface in which the data logger and dynamic signal analyzer are being utilized during a gold plating process.

The dynamic signal analyzer is used to identify source signal anomalies that can influence the plating process. By recognizing these harmful signal attributes as a function of time history or frequency domain, events such as ion depletion or hydrogen generation can be identified. The DSA is a high-speed digital oscilloscope with a spectrum analyzer that plots the intensity as a function of frequency using an FFT algorithm. Most plating source signals have a response frequency under 1 KHz with typical intensity spikes between .01 and 200 Hz. These spikes are artifacts of AC signals or motors operating near or in the plating solution. By identifying these noisy signals, steps can be taken to minimize their effect on the cathode current source.

Figure 12 shows the dynamic signal analyzer interface operating in a typical nickel plating solution. Although the RMS current is at the desired level, the lower graph indicates strong intensities at common line frequency components, i.e. 60, 120, 240, 300 Hz. These spikes are recognized as potential shorts, grounding loop circuits or EMF from neighboring motors and heaters. Correcting an electrically noisy environment may require using pneumatic mixers or remote heating sources. Regardless, the DSA is an excellent tool for diagnosing complex signals from a known voltage/current source signal.

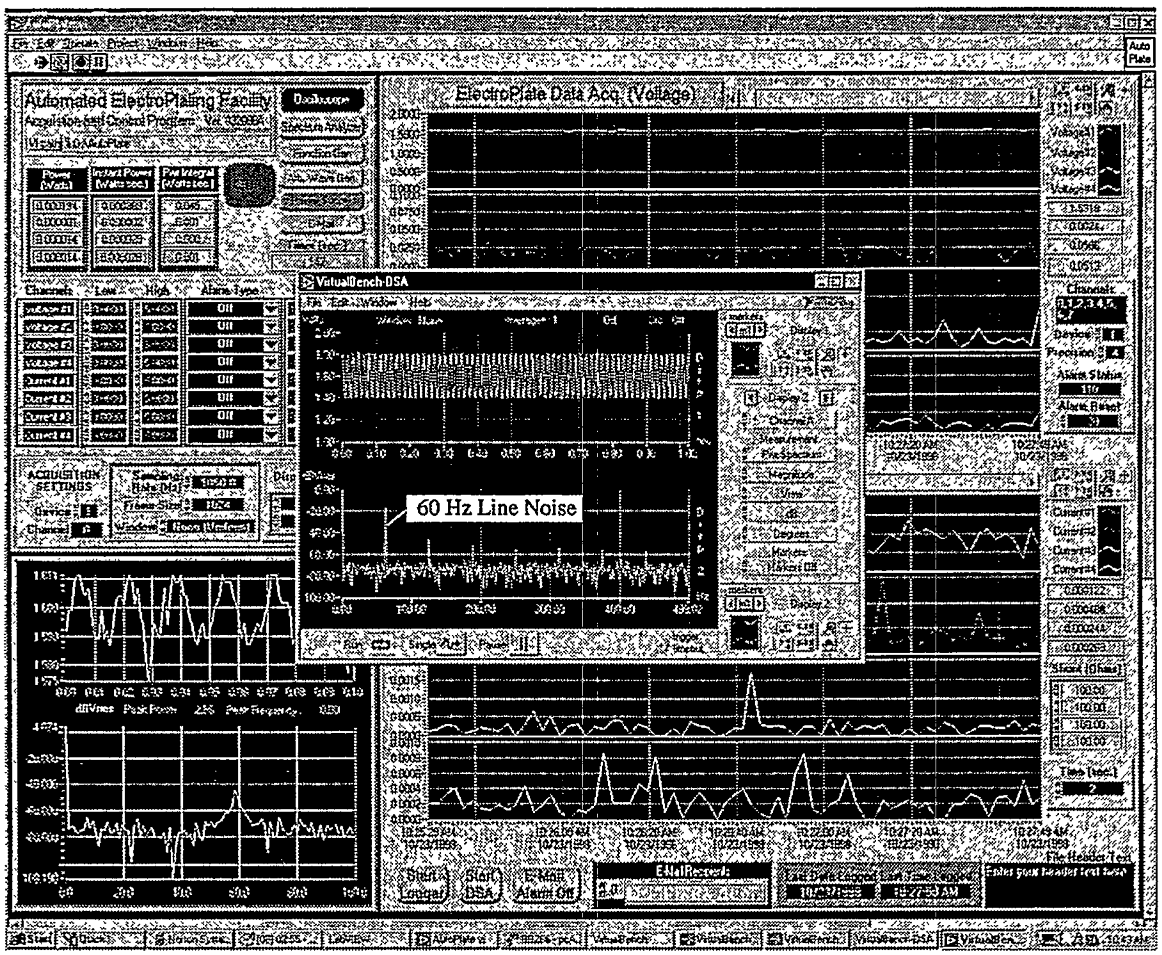


Figure 12. Snapshot of the dynamic signal analyzer used to diagnose line noise in a plating solution. Note: the noise represents typical stirring motor EMF with intensities at 60 Hz components.

A waveform/function generator is available for defining plating signals. The function generator has tunable standard waveforms such as sine, triangle or square waves. If desired, arbitrary waveforms can be developed using the waveform editor and stored on hard disks. Computer waveforms are generated in a buffer on an analog output card in the PC which is connected to a potentiostat for plating in constant current or voltage. The computer manages the waveform generation and output, while simultaneously running the data logger and DSA. This technique for signal generation has been a useful diagnostic tool during a plating cycle. By superimposing sine or arbitrary waves on a primary plating signal, the resultant waveform can help researchers using the DSA to identify changes in the chemistry, process or environment.

Alarm status controls were developed to notify the plater of critical limits. Due to the long plating cycles, a plater may want to be notified remotely of any deviation from process control. Notification is accomplished through e-mail from an address file and sent automatically during the event. These status controls can save valuable hours during a production process problem when human intervention is required. In special cases, a pager service can be notified, which in turn would page the client with vital information. Tracking limits in current, voltage, sensors or noise can help to recognize and rectify problems quickly and efficiently.

Status

During start-up the first anomaly seen by the system was a large amount of signal noise generated by both incoming line voltage, and the motors on pumps, agitators and associated equipment used in the plating process. Our first step in minimizing this problem was the installation of an isolation transformer on the incoming power.

The next phase of the project will be the characterization of the plating process. Our initial testing, using a small bench-top setup, demonstrated the ability of the system to track the plating process. Under controlled conditions both current and voltage signals responded to changes in ion concentrations and decreasing aspect ratio. The next phase will start with profiling each tank and the noise associated with the hardware used in the tank and any capacitance effect generated from the noise. Once characterized, we will take further steps in reducing signal anomalies produced during the plating process, thus increasing the signal-to-noise ratio and dynamic range, which can lead to better product.

UNIFORM PLATING IN LIGA MOLDS

One difficult problem in the LIGA process is nonuniform deposition of metal within the mold. In all electroplating processes, geometric irregularities give rise to nonuniform electric current densities. Since electric currents drive the electrodeposition process, nonuniform currents give rise to nonuniform metal deposition rates. For example, the corners of a rectangular region will always have a local current density that exceeds the mean value for the surface by a significant factor. As a result, deposition rates at these corners will be greater than the average rate. Similarly, a hole in an otherwise uniform surface, sharp bends in a linear feature, or parallel linear features of irregular spacing will also give rise to nonuniform deposition rates near the geometric irregularity.

In conventional electroplating practice, robbers and shields are employed to improve metal deposition uniformity on surfaces of irregular geometries. Robbers are electrically conducting elements placed near the deposition surface with the intent of locally altering the electric potential to produce a more uniform current flux over the surface. The shape, position and electric potential of the robber must be carefully selected to produce the desired effect. In contrast, shields are electrically insulating elements usually placed between the bath electrode and the deposition surface. Their purpose, however, is the same as that of a robber -- to locally alter the current density to obtain a more uniform deposition rate. Like robbers, shields must be carefully designed and placed to illicit the desired benefit.

Because of the very small feature sizes of LIGA molds, shields and robbers are not practical. In principle robbers could be designed as part of the LIGA mold, but this would require many iterations of the robber design to effectively achieve uniform deposition over the many features present in a typical LIGA part. Further, such integral robbers would likely limit the range of possible designs for the LIGA device. Special shields also could be fabricated using lithographic methods, but again these would require many trial-and-error iterations to be highly effective. Since shields and robbers are not very practical for the LIGA process, we have chosen to pursue other techniques to ensure uniform deposition in the LIGA mold.

Current practice in LIGA manufacturing is largely to tolerate nonuniform deposition or to attempt to correct it in an iterative fashion. The mold is periodically removed from the plating bath and inspected. Areas experiencing excessive deposition rates are coated with an insulating paint to inhibit further deposition in those areas, and the mold is then returned to the bath for an additional period of plating. This cycle is repeated until all features in the mold are filled. This is a costly and time-consuming practice that is not well suited to the mass production of LIGA parts. To successfully develop the LIGA process as a flexible and cost-effective manufacturing method, the problem of nonuniform deposition in the mold must be solved.

As part of this LDRD, an apparatus was designed and fabricated that can potentially eliminate non-uniformities in the plating process. The details of the apparatus are not discussed here due to its potential as a source of intellectual property.

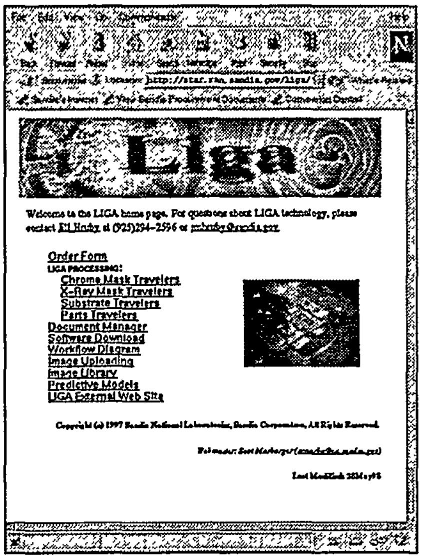
LIGA SOFTWARE ARCHITECTURE

The LIGA Software Architecture Project had three deliverables designed to give the LIGA team members single point access to distributed information and resouces. The three deliverables included:

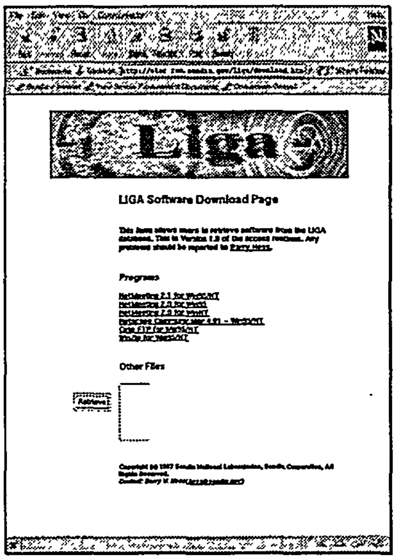
1. Web site design and installation.
2. Image library with remote upload and download capability.
3. Remote web browser version of LEX modeling codes.

Web Site Design and Installation

A web site was designed and installed on "star.ran.sandia.gov" to give the LIGA team single point access to their project information and resources. The full URL is http://star.ran.sandia.gov/liga. This machine is a Sun Microsystems Ultra 170E. Design of site and graphics have been completed and maintenance responsibilities established.



Home Page



Software Download Page

Figure 13. Thumbnail images of the home page and the software download page from the LIGA web site.

The web site includes a software distribution page, which gives users the option of downloading software for installation on their machine. It also has links to the PRIME software environment [14]. Shown in Figure 13 are thumbnail images of the home page and the software download page from the LIGA web site.

Image Library with Remote Upload and Download Capability

The image library was designed to allow images and photographs to be easily uploaded to a storage area that can be easily accessed by any of the team members or other personnel that need access to the images. When images are uploaded, a thumbnail image is produced and installed in a search directory to be viewed by users. Currently TIFF, JPEG, GIF and PostScript files are supported. The software is designed to easily add new image or data formats. Examples of downloading and uploading pages are shown in Figure 14.

When selecting an image for downloading, the user is presented with tiles of these thumbnails, allowing them to see what each image looks like. They can then download the image in the original format by selecting the image. Image uploading is controlled by password access and allows images to be uploaded from any machine on the RAN or IRN network within Sandia.

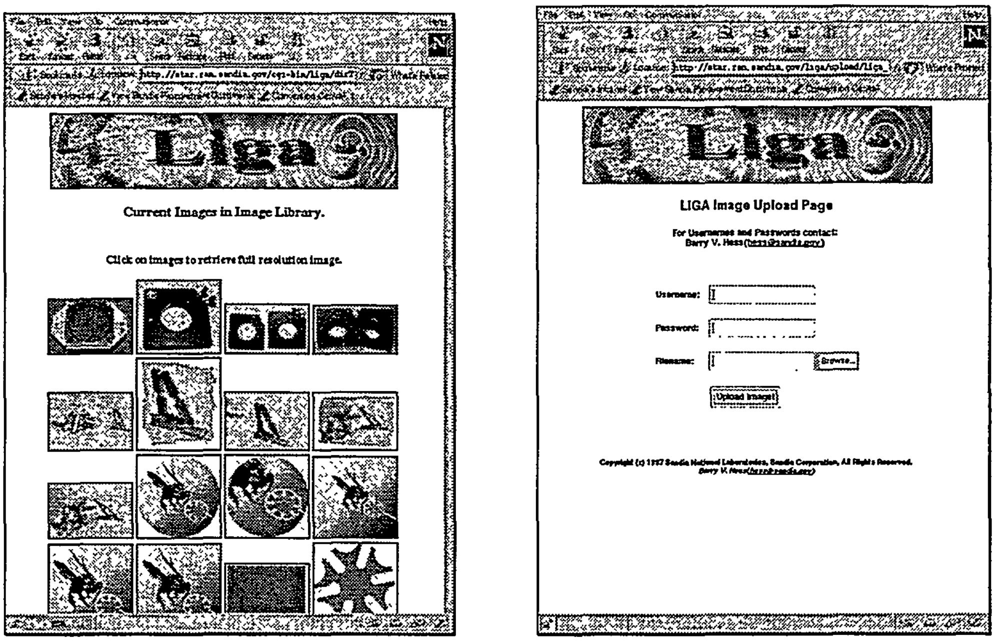


Image Download Page **Image Upload Page**

Figure 14. Examples of image download and image upload pages from the LIGA web site.

Remote Web Browser Version of LEX Modeling Codes
The LEX code is an interactive code used to model LIGA exposure and development processes [10]. The original code was written in Digital FORTRAN for VMS. The objective was to allow users sitting at their desks to run the code at a remote computer, without the need to install client software on each user's desktop.

The solution was to install a network daemon on a SUN Workstation to act as the multi-user server, and then design a Java client that could run as an applet in a web page at the user's desktop. This means that when the LEX web page is downloaded from the web server, the latest version of the Java client is also downloaded to the user's desktop. This client then starts to execute on the user's machine and connects back to the server to request a LEX session. Implementation included porting the LEX code to a Sun Microsystems SPARCstation workstation. This allows the code to be run as a multi-user, background process on the web server. The LEX server uses the architecture shown in Figure 15 to create a new process for every new user that tries to connect to the system. The system has been tested with up to 50 concurrent users.

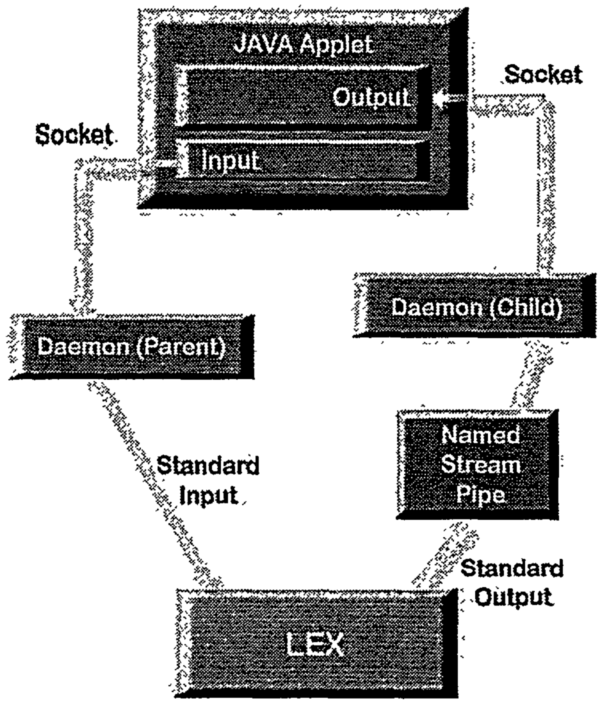


Figure 15. LEX Modeling Architecture

The LEX server is started on the server machine at boot time and listens for connections continuously. Each user runs their own LEX process, which maintains its own state information and resources until the user releases the process. Each process then collects garbage and exits. Each process handles closing all the sockets and pipes under its control to prevent resource leaks. The Java Applet client is stateless and runs input and output asynchronously. This means that the client's behavior is very close to that of a terminal connected to a server, including the ability to type ahead without race conditions. A snapshot of the LEX page is shown in Figure 16.

The software is designed to allow multiple versions of LEX code to be run at the same time. This allows installation of new versions of LEX, without disturbing current users. The current implementation is version number three. No password is required at this time to access the LEX server, but the hooks have been added to the code to enable this feature, if required at a later time. The LEX Server supports full access and process logging. Since the first server was installed on November 24, 1997 and through September 15, 1998, the LEX code has been accessed 329 times. The LEX server has been running for 6 months without an error.

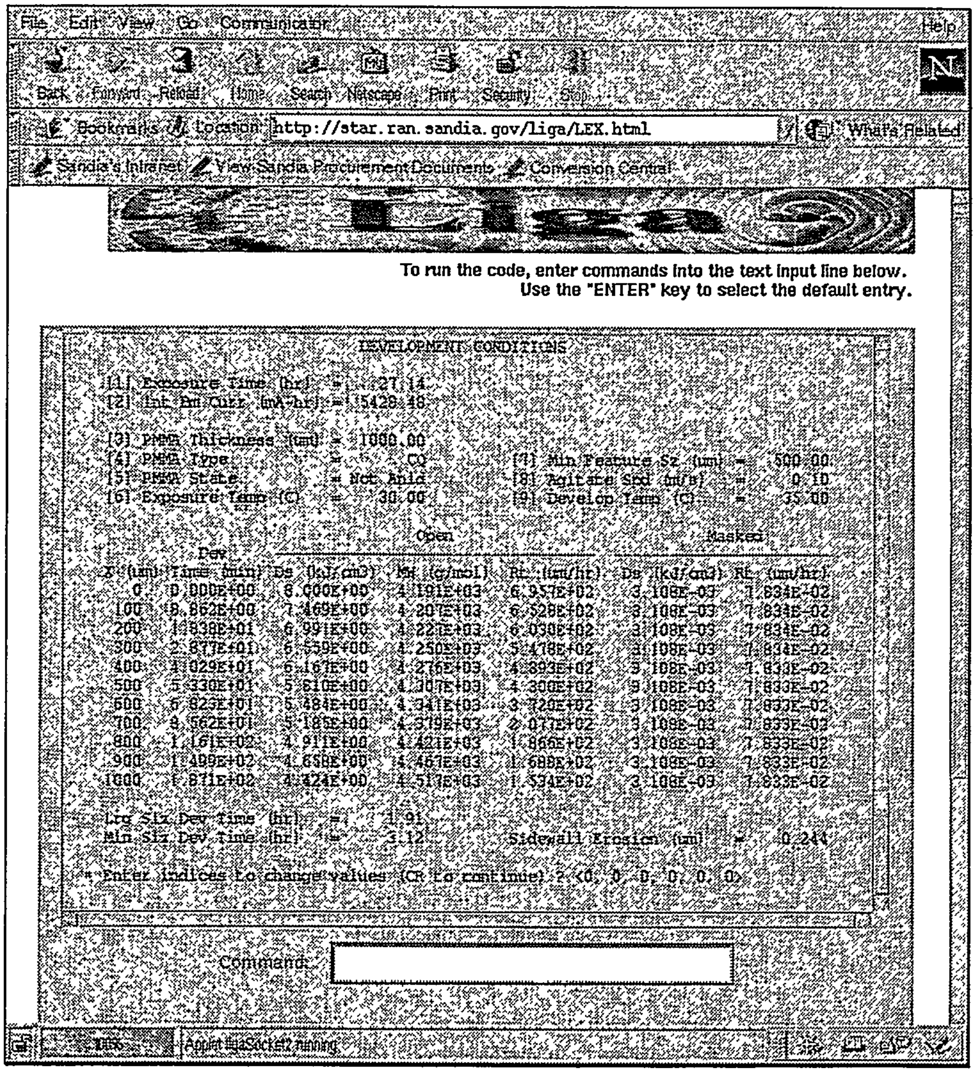


Figure 16. LEX Modeling Code Page

SUMMARY

This LDRD funded establishment of important aspects of the LIGA infrastructure needed to create metal microparts. Specifically, an optimized mask making process and associated facilities were established; a LIGA x-ray scanning system was designed and built; instrumentation for the dedicated LIGA plating line was specified, procured, and installed; an apparatus for uniform metal deposition was designed and built; and web-based software was written and deployed for daily use by the LIGA team.

The emphasis in the LIGA mask making portion of this work was optimizing the thick photoresist application and exposure. A process for applying two 25 micron thick layers of SJR5740 photoresist was established. Optimized exposure conditions of 2.2 J/m^2 for this thick resist were established to provide minimum sidewall taper in the resist. The detailed process steps for the fabrication of this standard LIGA mask are presented in this report.

A scanner with new capabilities to be used primarily at the Stanford Synchrotron Radiation Laboratory was designed and built. This scanner offers the capability to scan 8.5 inches in the vertical direction and 5.5 inches in the horizontal direction allowing very large area LIGA exposures. It also provides the capability for off-axis exposure. We believe this scanner will provide unique capabilities at a relatively low price compared to other scanners that have been designed for LIGA exposures.

Instrumentation for the dedicated LIGA plating baths has been installed to control the electrical input and generate waveforms, as well as record output from sensors in the bath. This instrumentation additionally allows for email or paging when conditions go off-normal. The computer controlled system will allow accurate input, monitoring, and recording of the conditions of plating in the high value LIGA molds.

An apparatus was designed and built that should eliminate non-uniformities in electroplating LIGA molds. The non-uniformities result from non-uniform electric fields, as well as from local variations in ion transport rates. Both of these effects make plating in LIGA molds in a production environment problematic. We believe our apparatus overcomes these problems and is suitable for a production environment. Details of this apparatus are not described due to potential intellectual property concerns.

A web-based software architecture for LIGA was brought on-line. This architecture allows the ordering, tracking, archiving, and real-time code operation to be accessed through a common web-page. The members of the LIGA team have been routinely using this architecture for conducting LIGA processing.

While the work in this report does not represent the complete infrastructure for LIGA, it describes the work supported by an LDRD that contributed significantly to the infrastructure development. Other details on the infrastructure for LIGA can be found at http://daytona.ca.sandia.gov/LIGA.

ACKNOWLEDGEMENT

Much of the research conducted on photoresist processing for LIGA masks was conducted in the University of California, Berkeley Microlab.

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