High-Aspect-Ratio Micromachining Via Deep X-Ray Lithography

H. GUCKEL

Invited Paper

High-aspect-ratio microsystems technology (HARMST) can be implemented by using thick photoresist technology, which requires X-ray photons for exposure. This was first realized in Germany via the so-called LIGA process. To make this process cost effective, exposures with high-energy photons were introduced in 1993 via a University of Wisconsin–Brookhaven National Laboratory cooperation. The addition of a solvent bonded resist technology and replanarization after electroplating and X-ray mask aligning yield a HARMST processing sequence that uses large-area, sequential X-ray masks without diaphragms.

This technology may be applied to precision engineered parts which do not involve electronics. The processing sequence is also used for high performance linear and rotational, magnetic and electrostatic actuators. System applications in optics involve spectrometers and other devices. A discussion of US and world wide efforts in HARMST points at increasing demands for this type of processing tool.

Keywords— *LIGA, microelectromechanical devices, micromachining, precision engineering, X-ray lithography.*

I. Introduction

Micromechanics is a word identified with sensors and actuators. The tool or processing sequence used to fabricate micromechanical sensors is normally a modified microelectronic procedure. The reason for this is found in the fact that sensors are ideally noninvasive devices, an attribute that profits from size reductions. The same comment applies to integrated circuits (IC's), which leads to the process compatibility.

Actuators are devices that modify their environment. They are fundamentally three-dimensional devices. The fabrication process must address this fact and must be applicable to a large material base. For microactuator fabrication, tolerance issues arise that allow the construction process to be used in nonelectronic, precision engineering applications.

A useful actuator, one that fills a need in a cost-effective manner, is ideally designed with a set of *a priori* defined performance specifications. These specifications must include packaging since this device aspect can have a major impact on cost. There are many possible processing techniques. Stamping followed by assembly is the mainstay of the watch industry. The technique is very effective but runs into tolerance problems for very small parts. Microelectrodischarge machining (EDM), as practiced by Panasonic [1], has the ability to produce precision three-dimensional parts from virtually any conductor. EDM does have a drawback: it is a serial manufacturing tool. This situation would change if the EDM electrodes could be manufactured to produce several parts in a single cycle [2].

Processing sequences that fall under the category of IC-like processing for actuators involve plasma etching with high aspect ratios and thick photoresist procedures. Both processes use integrated circuit masks to define geometric shapes in the x-y plane. In the early attempts to use plasma etching for high-aspect-ratio structures [3], [4], polyimide was applied to a planar substrate, typically a silicon wafer. The polymer was imidized and covered with a metal such as aluminum or nickel. The metal was patterned via standard photoresist patterning. The metal is used as a mask against reactive ion etching. All unprotected polyimide is removed. Practical heights of up to 100 μm with good aspect ratios were obtained. Since imidized polyimide is mechanically and chemically stable, the regions on the wafer without polyimide can be filled with metals via electroplating. Recently, reactive ion etching has been used to etch silicon to 300 μm thickness with better than 20 : 1 aspect ratios [5]. In this procedure, the mask against etching simplifies to a patterned oxide layer and/or a patterned photoresist layer. The process does have a problem: the etch rate is geometry dependent, and small features etch slower than large features.

Thick photoresist processing for actuator fabrication falls into three categories. Light-sensitive polyimide was applied to planar substrates, exposed and developed, but not imidized to avoid polymer shrinkage during imidization [6]. The polyimide was next used as a mask against

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The author is with the Department of Electrical and Computer Engineering, University of Wisconsin–Madison, Madison, WI 53706 USA.
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electroplating. Obtained aspect ratios and heights were modest. Recent advances in photoresists, both positive and negative, have produced results in the up to 50 μm range, which are encouraging.

A radically different approach to thick photoresist work is based on the use of polymethylmethacrylate (PMMA) as a photoresist. This plexiglas-like material is sensitive to X-rays and can be exposed to a set of processes that will be discussed in some detail in the later sections of this paper. Here, it is important to note that the selection of a photoresist-based process sequence for actuator construction enhances the possibility of cost effectiveness via parallel rather than serial processing. However, this choice also restricts geometric shapes to the prismatic variety. This would suggest that energy storage in an actuator can be written as

$$U = \rho_E H A_{ST} \tag{1}$$

where ρ_E is an energy density of the form $\frac{1}{2}\vec{D} \bullet \vec{E}$ or $\frac{1}{2}\vec{B} \bullet \vec{H}$, H is the structural height, and A_{ST} is the area of the volume $H \cdot A_{ST}$ in which the energy is stored. The storage area can be written as

$$A_{ST} = \eta A \tag{2}$$

where η is the filling fraction and A the chip area for the actuator. Equations (1) and (2) are combined to yield

$$\frac{U}{A} = \rho_E \eta H. \tag{3}$$

Equation (3) may be viewed as a figure of merit for prismatic actuators. It is directly proportional to structural height, which is set by the photoresist process. A large filling fraction requires high-resolution lithography, and the energy density hints at the fact that things get better as one moves from electrostatics to magnetics to pneumatics to hydraulics [7]. Unfortunately, the need to become more three dimensional obeys the same order. That makes process selection and development for actuators a difficult task.

1) The Basic LIGA Process: A photoresist-based possible fabrication procedure for actuators is the so-called LIGA process. This construction procedure originated in Germany [8]. The acronym LIGA stands for lithography and galvo or electroplating. Later publications associate the "A" with the German word *Abformung,* which translates as injection molding. LIGA is based on PMMA, which is used as a photo polymer. Photoresist thicknesses of up to 500 μm were claimed in the original publications [9], [10]. The photoresist application procedure did not rely on the customary spin-on techniques but resorted to *in situ* polymerization. The resultant PMMA layer is badly strained because the polymerization process involves a shrinkage of roughly 20% and a surface to which the PMMA is to adhere. This compromises the mechanical properties of the resist even though strain-free PMMA has very acceptable mechanical properties for a thick photoresist.

The applied PMMA is exposed through an X-ray mask. The required dose for PMMA exposure is near 3000 J/cm^3. For a 1-μm-thick layer and uniform absorption, this translates to 300 mJ/cm^2. Photoresists for microelectronics are typically at least five times more sensitive. This difficulty is overcome by using synchrotron radiation for the X-ray exposure. Very high X-ray flux densities with excellent collimation produce exposures for which diffraction effects are negligible and standing wave problems are absent. The result is a vertical exposure. The exposed region is removed via highly selective developers [11]. Measured PMMA features exhibit flanks with runouts of less than 0.1 μm per 100 μm of structural height.

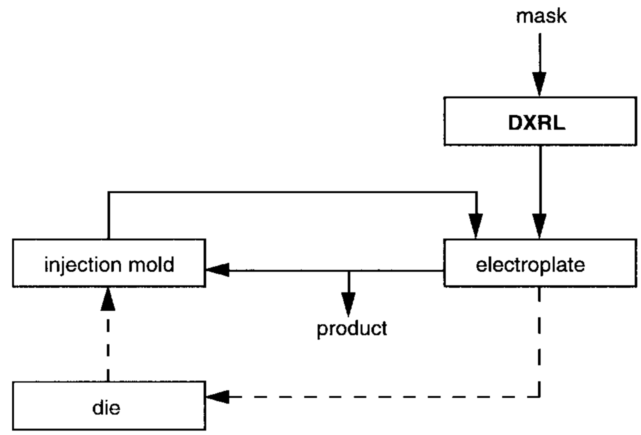

Fig. 1. Process flow for early LIGA.

The penetration depth for X-ray photons depends on the photon energy and the nature of the absorbing material. Higher energies produce more penetration, i.e., have a larger absorption length, and low atomic number material are more transparent than high Z substances. These observations have major implications on X-ray masks for LIGA. Thus, the transparent mask blank must be made of low Z material that is as thin as possible. Beryllium, titanium, silicon, and silicon nitride films with thicknesses in the few micrometer range are acceptable for photon energies of 2000–3000 eV. The mask blank must support the absorber, a high Z material such as gold or tungsten. Thus, the X-ray mask for low-energy exposures becomes a decorated membrane with many mechanical problems that restrict its useful exposure area. This has two effects: throughput is very small and cost is very large.

The German LIGA solution to this problem was that of minimizing X-ray exposures and utilizing the inherent precision of deep X-ray lithography to fabricate injection-molding dies for molding equipment, which would remove cost and throughput constraints. The resulting process flow is shown in Fig. 1.

The diagram indicates that PMMA X-ray exposure and developing is followed by electroplating. The very low runout can therefore produce nearly perfect prismatic metal structures. However, there is the problem of height control [12] for electroplating situations with geometrically varying deposition areas. Additional questions concern tolerances that are set by mask dimensions and process conditions. Restrictions to single-level processing are troublesome. But the most important problem is clearly evident from

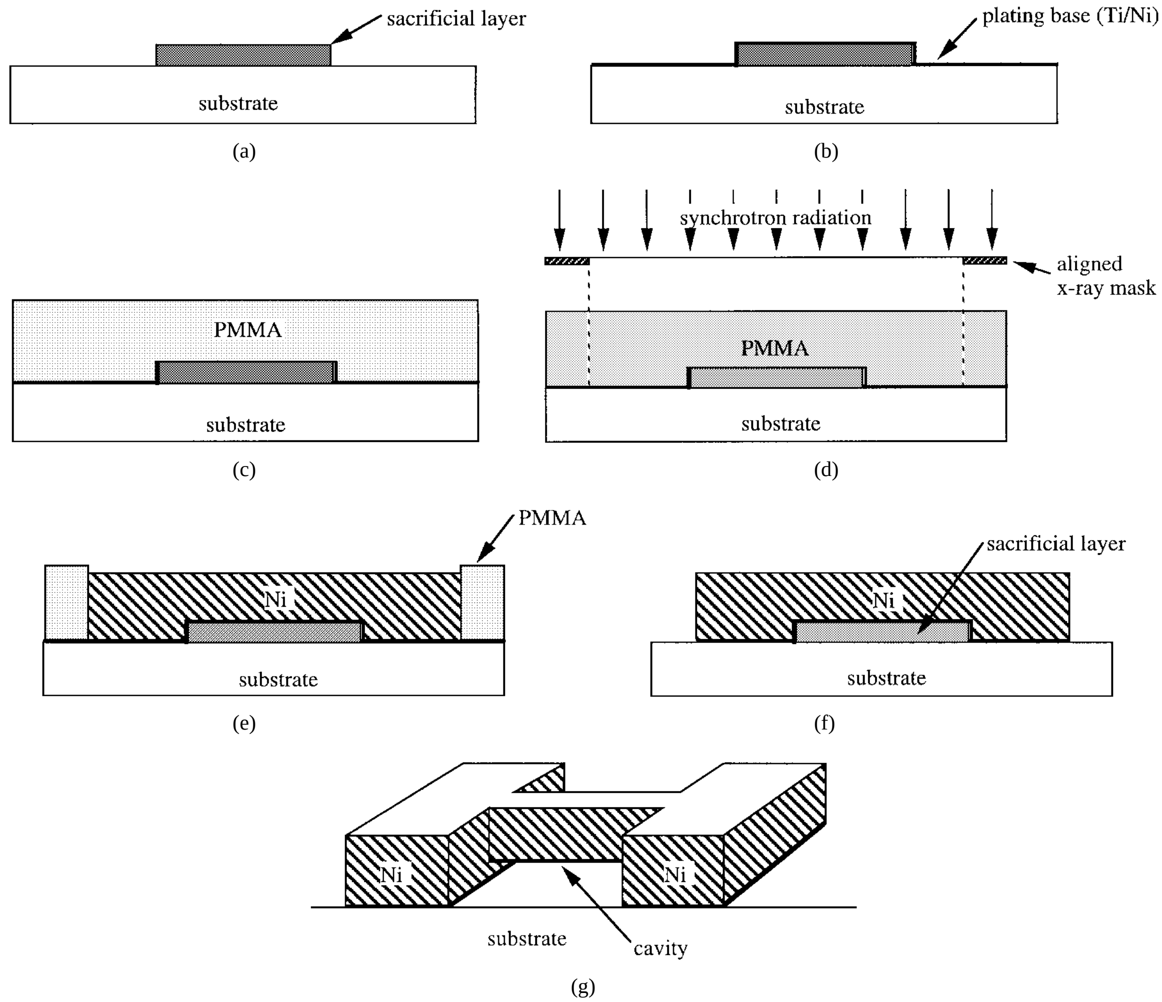

Fig. 2. Cross-sectional view of LIGA with sacrificial layers: SLIGA. (a) Pattern sacrificial (removable) layer. (b) Sputter plating base. (c) Cast and anneal PMMA. (d) Align X-ray mask and expose PMMA. (e) Develop PMMA and electroplate Ni. (f) Remove PMMA and plating base to clear access to the sacrificial layer. (g) Etch sacrificial layer, thereby undercutting and freeing Ni structure.

Fig. 1: there are alternative procedures for the fabrication of injection-molding dies.

2) Surface Micromachining and LIGA (SLIGA): LIGA, as introduced in the previous section, is a single-level process that produces fixed, prismatic parts. The addition of a sacrificial layer would remove the fixed-part-only restriction. Thus, free, partially attached, and fixed parts result from this type of processing. Fig. 2 illustrates the processing sequence. This fabrication procedure very naturally leads to assembled structures, as shown in Fig. 3 [13].

The advantage of assembly involves tolerances. In all mask making, there is the concept of critical dimensions. Thus, above some minimum line width, a dimension in micrometers may be specified to one or more decimal points. For example, for a single decimal point, 100.0 and 100.1 μm are legal and distinct dimensions. This would suggest that a gear with a hole diameter of 100.5 μm could be assembled on a shaft of 100.0 μm diameter if the runout is 0.1 μm per 100 μm height and the gear height is less than 500 μm. The alternative, a photoresist shape of 0.25 μm thickness and 500 μm height, is not feasible because such a PMMA structure would be mechanically unstable. The tolerance issue is demonstrated in Fig. 4. Assembly is evidently an enabling technology.

3) Improvements in SLIGA via High-Energy Exposures: The basic SLIGA or LIGA processes produce very precise, prismatic metal structures that have a reasonably high technical application potential. The envisioned applications become practical if throughput can be increased and cost can be decreased. In Germany, this resulted in a major research effort at the Forschungs Zentrum Karlsruhe (FZK) and the Institut für Mikromechaniks in Mainz (IMM) in injection molding and embossing of microparts [14]. In the United States—where LIGA-like processing was started in 1988 at the University of Wisconsin (UW)–Madison with National Science Foundation financing via an emerging technology program administered by G. Hazelrigg—the throughput and cost problem is being investigated differently. The present U.S. approach nearly ignores injection molding and concentrates on high-energy X-ray exposures, which lead to low cost and high throughput.

Fig. 3. Assembled nickel structures for friction and magnetic properties testing.

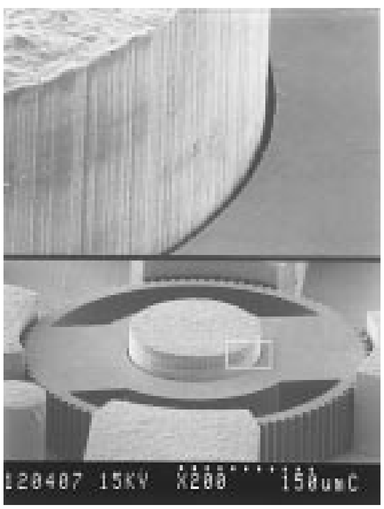

Fig. 4. Assembled shaft-gear combination. The material is nickel with a height of 150 μm. The bushing tolerance is 0.25 μm.

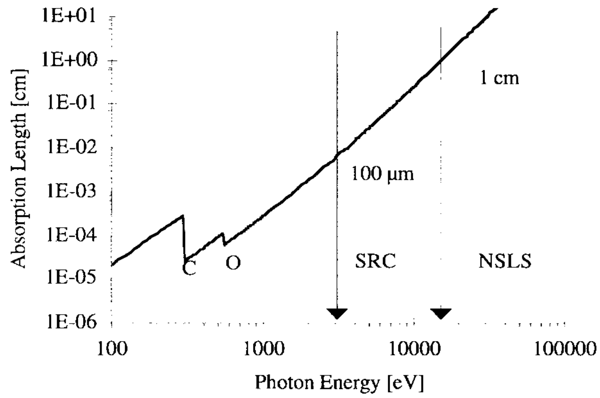

Fig. 5. PMMA absorption length versus photon energy.

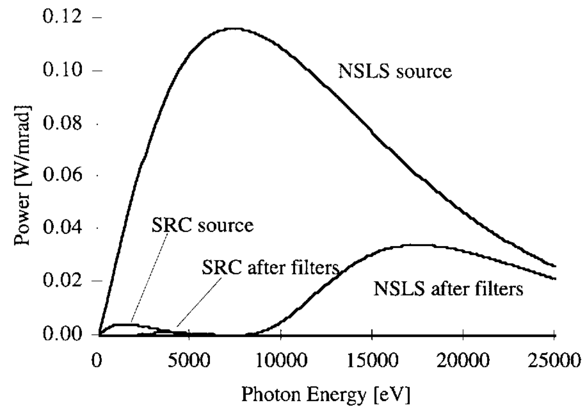

Fig. 6. Emission spectra for Aladdin and NSLS.

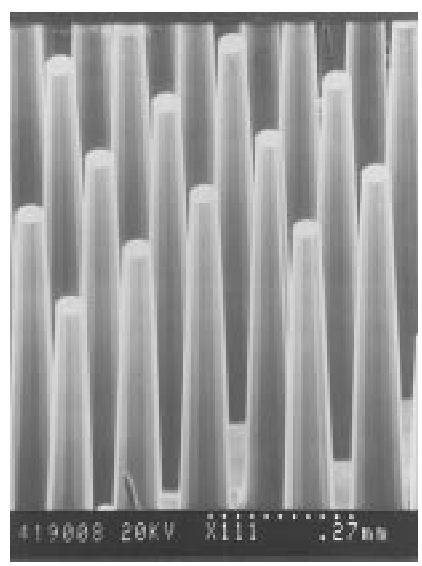

Fig. 7. Posts, 3200 μm tall, of partially exposed PMMA after high-contrast developing.

The scientific argument for high-energy exposures is supported by the absorption behavior of PMMA, which is shown in Fig. 5. Since reasonable exposure times can only be obtained if the PMMA thickness is less than three absorption lengths, exposures with, on the average, 3000 eV photons are restricted to 300 μm, whereas PMMA exposures at 20 000 eV can expose 60 000 μm of PMMA. A suitable source for this type of X-ray photon flux is the 2.6 GeV X-ray ring at Brookhaven National Laboratory (BNL) in Upton, NY. Aladdin, a 1 GeV machine operated by the Synchrotron Radiation Center at the University of Wisconsin–Madison, on the average provides 3000 eV photons and is therefore restricted to at most 500-μm-thick PMMA layers. Fig. 6 illustrates the spectra for Aladdin at 1 GeV and the National Synchrotron Light Source (NSLS) at BNL at 2.6 GeV. There are other sources available in the United States. The Center for Advanced Micro Devices (CAMD) at Baton Rouge, LA, can produce high-energy exposures. The same is true for the Advanced Light Source at Lawrence Berkeley Laboratory (LBL) and the machine at the Stanford Synchrotron Radiation Laboratory. A very-high-energy synchrotron, the Advanced Photon Source, at Argonne National Laboratory near Chicago, IL, can also provide high-energy photons.

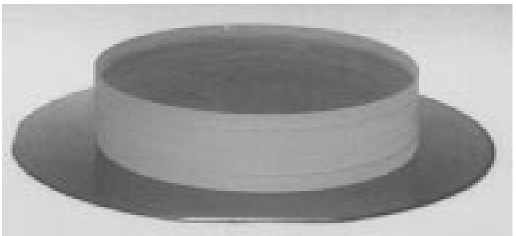

Fig. 8. PMMA bonded to 3-in silicon wafer. The total PMMA height is 1.6 cm.

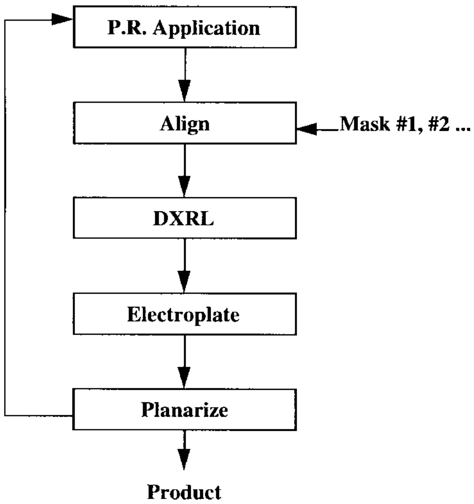

Fig. 9. Process flow for multiple X-ray mask LIGA.

High-energy exposures do have two additional problems. If the photon flux is delivered at too high a rate, the PMMA will experience thermal and chemistry problems. This can be avoided by the proper use of filters. Thus, at BNL, a filter of 500 μm of Be followed by 50 μm of Al and 650 μm of Si results in 100 mW/cm^2 of photon power, which is acceptable for PMMA. There is very little dependence of exposure time on photoresist thickness as long as the PMMA thickness is less than one absorption length.

The second problem involves the X-ray mask. High-energy photons penetrate low Z material easier than do low-energy photons. The absorption length for silicon at 20 000 eV is 1000 μm. This and the previous filter requirement make the use of a silicon wafer without a diaphragm or an aluminum sheet for a large-area mask blank feasible. The absorber thickness must increase in order to maintain the contrast ratio. This can be achieved by printing a small-area, low-energy mask via step and repeat into thicker PMMA on the mask blank and then plating the absorber. This technique results in masks without diaphragms with exposure fields of 15 $\times$ 15 cm.

The feasibility of high-energy exposures was established in a series of UW-BNL experiments in 1993 [15], [16]. In these experiments, E. Johnson of BNL demonstrated that interior sections of PMMA could be exposed in a lathe-like experiment, the so-called wine-glass procedure [17]. The 1993 experiments also led to the conclusion that a

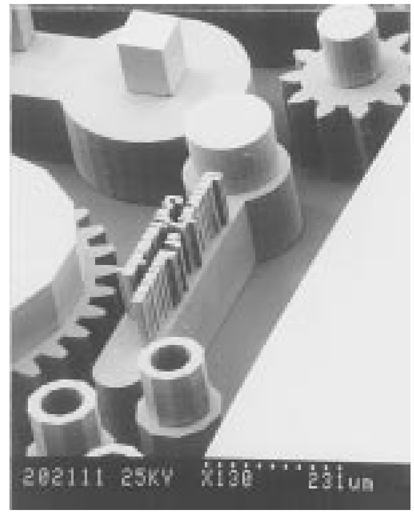

Fig. 10. Double nickel layers of 150 μm height each.

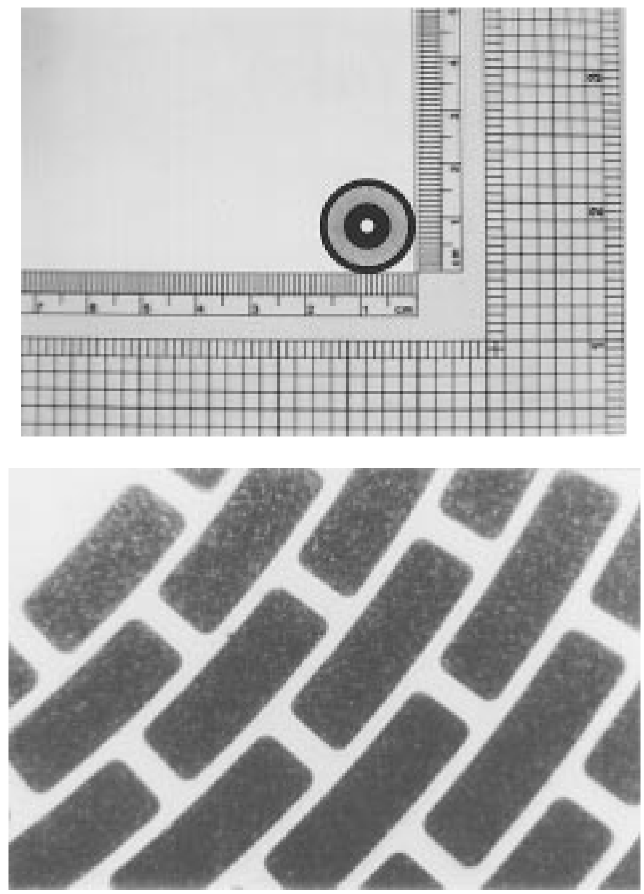

Fig. 11. Precision permalloy screen and close-up.

low-contrast X-ray mask can be used to produce designable flanks on PMMA, as indicated in Fig. 7. However, the most important conclusion from 1993 involved the concept of large-area exposures of 40 stacked, 300-μm-thick PMMA sheets at the same time with the same mask, which produces 9000 cm^2 exposed PMMA in one eight-hour shift [16]. To implement this, BNL via C. Milne, Johnson, and P. Siddon designed and are constructing a new exposure station with

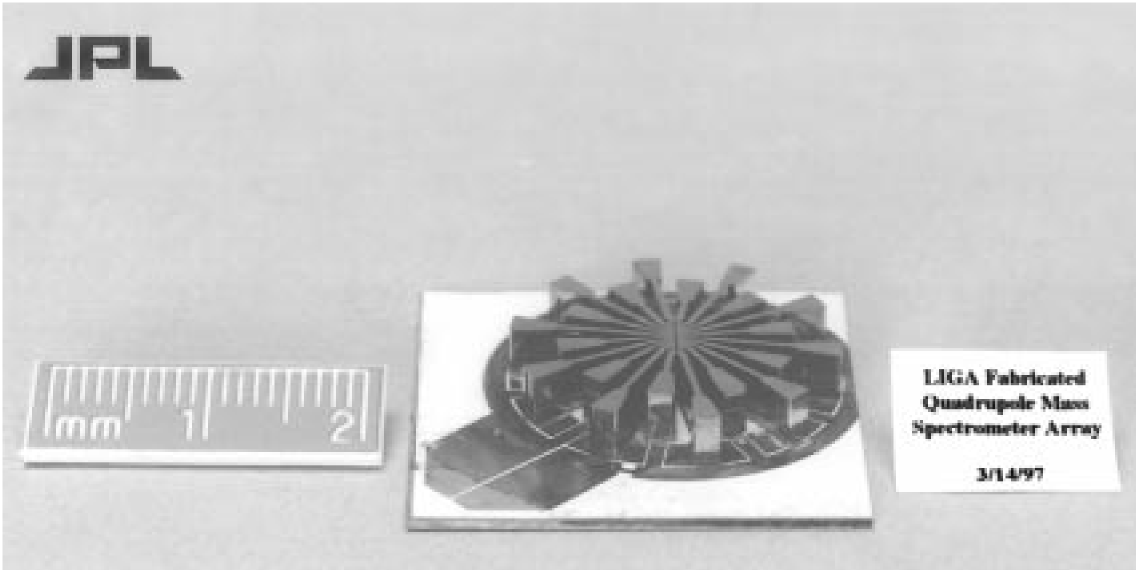

Fig. 12. A LIGA fabricated linear quadruple array for mass spectroscopy consisting of 20 individual hyperbolic poles configured to form nine quadrupoles. The device was electroformed to a lapped thickness of 3.4 mm in nickel with minimum feature aspect ratio of 75 : 1. This work was performed at the Center for Space Microelectronics Technology at the Jet Propulsion Laboratory in conjunction with the West Coast LIGA Consortium, which consists of the Jet Propulsion Laboratory, Sandia National Laboratory at Livermore, CA, and Lawrence Berkeley National Laboratory.

a beam width of 12.5 cm and a height of a few millimeters. The mask-PMMA combination is attached to a scanner, which moves the assembly past the stationary beam. The total scanned area is roughly 20×4 in or 516 cm^2. At 300 μm thickness, this instrument can produce 20 000 cm^2 of exposed PMMA in 24 hours.

The BNL effort is complemented by three enabling technologies. The first of these involves the fabrication of 300-μm-thick sheets and the attachment of the exposed PMMA to substrates with plating bases [18]. This has been accomplished by using commercially available PMMA sheets, cutting them to size via water jet machining, and thinning them to 300 μm with a precision fly cutter. The substrate to be plated is spin coated with PMMA to a thickness of 1 μm. This layer and the PMMA surface to be bonded are solvated with the monomer MMA to form a bond. Fig. 8 illustrates the result.

The second enabling technology involves replanarization after electroplating in the presence of and without damage to the PMMA that formed the plating mold. Availability of this process provides height control and enables multiple, sequential X-ray mask processing. This process, multiple X-ray mask SLIGA, also requires a mask-aligning procedure that is suitable for thick photoresist work. Fig. 9 summarizes microelectromechanical systems LIGA, and Fig. 10 illustrates the results.

4) Application of High-Aspect-Ratio Microsystem Technology (HARMST): Application of the previously described technology falls into two broad categories: precision engineering and electronic devices. Fig. 11 illustrates a precision screen formed from 78% Ni and 22% Fe, i.e., permalloy. The device was designed by T. R. Christenson of Sandia National Laboratory in Albuquerque, NM. The structure is 150 ± 1 μm tall and has been lapped and polished on one side. The diameter is 2 cm. Wall thicknesses are 5 ± 0.1 μm with runouts of less than 0.1 μm.

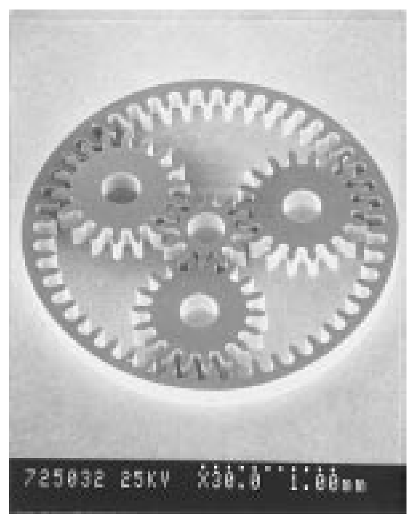

Fig. 13. Precision reduction gear box.

A second example is found in Fig. 12 [19]. The structure is formed from nickel and has been lapped. The device is part of a quadruple mass spectrometer that was designed at the Jet Propulsion Laboratory (JPL) and fabricated by the West Coast LIGA Consortium.

A third precision engineering example is shown in Fig. 13. It is a reduction gear box that was fabricated for the RMB Corporation, A. Birkicht, in Biel, Switzerland, by UW–Madison, by the Microelectronics Center of North Carolina (MCNC), and also by an American company that did contract work in this type of HARMST.

Fig. 14. Linear magnetic actuator with assembled coil. The material is 78-22 permalloy, a soft, very-high-permeability magnetic material that is also used for the coil mandrel.

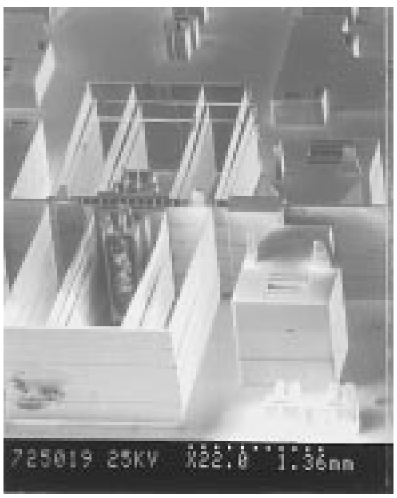

Fig. 15. Linear actuator with 1-mm structural height.

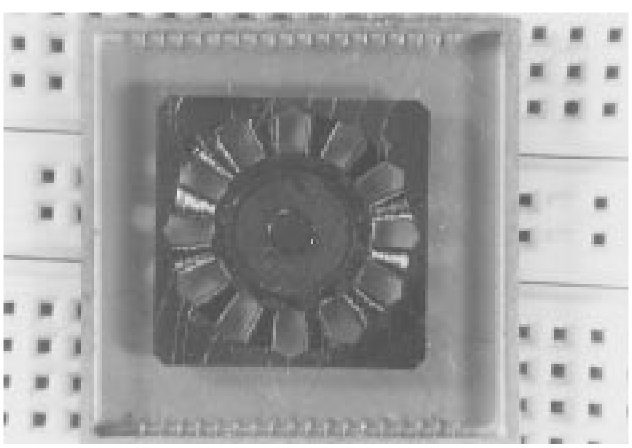

Fig. 16. Twelve-pole induction motor.

Electronic devices that become economically viable because of this type of processing are mostly in the actuator area. Linear motors for precision positioning systems, both open and closed loop, with output forces of up to 100 $\times\ 10^{-3}$ newton and throws to 2 mm have been reported in [20] and [21]. They are exemplified by the magnetic actuator shown in Fig. 14.

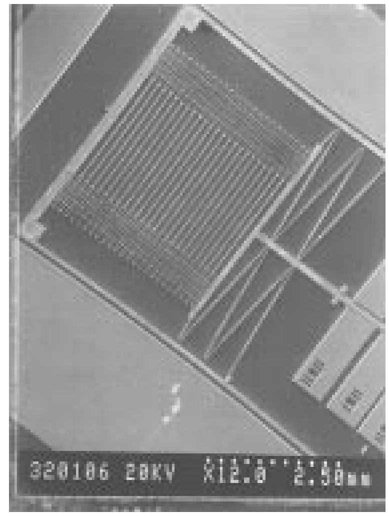

Fig. 17. Infrared spectrometer. The device uses three coils for three-phase excitation. The coils are not shown. The grating when closed involves 4 μm beams with 4 μm spacings with a length of up to 2 mm. The number of spacings is typically 125. The actuator step size is 12.5 μm. The total displacement is 1.25 mm or 100 steps.

Fig. 15 is another version of a linear motor with a structural height of 1 mm. This height is obtained by stacking five 200-μm-thick layers. The material again is 78-22 permalloy [22].

The progress in rotational micromotors is somewhat slower. Fig. 16 illustrates a 12-pole experimental induction motor [23]. It is to be used in applications for which synchronous motors such as reluctance motors will not work. This type of a machine also has applications as a sensor.

HARMST as reported here lends itself to optical applications. Very nice results in spectrometers and other optical devices have been reported by J. Mohr from FZK [24]. Waveguide and Y-coupler work has been described by Bauer of IMM [25]. An entire system, a spectrometer for the infrared region, is in the prototype stage at Honeywell, Inc. [26]. The instrument is tunable because the grating acts like a distributed spring with a linear motor-controlled grating spacing. Fig. 17 illustrates a prototype version of the device.

II. Closing Remarks

In a paper of this type, it is very difficult to cover all related work. The U.S. synchrotron sources have already been mentioned. There are HARMST activities at all of them. The same is true for sources in mainland China, Taiwan, Korea, and Japan. In Europe, large activities are found at FZK and IMM. There are some activities in France and Italy, and in England, a LIGA club has been formed that uses the synchrotron at Daresbury.

There are several groups in the United States. The University of Wisconsin–Madison works with BNL and several commercial companies. JPL, LBL, and Sandia at Livermore, CA, cooperate via the West Coast LIGA effort. The MCNC was instrumental in an attempt to commercialize HARMST. This was done with a consortium that included, among others, IBM, MCNC, Oak Ridge National Laboratory, UW-Madison, and photons that were supplied by CAMD. The program included multiuser LIGA services. MCNC has continued some of the efforts. CAMD provides X-ray exposures for Sandia National Laboratory in New Mexico, where a potentially large HARMST effort is taking shape. A commercial American company also has used the exposure services of CAMD and has produced HARMST devices for third parties. A second American company, Quantum Devices, Inc., is starting to produce HARMST devices via exposures at Brookhaven and at the University of Wisconsin.

The second international meeting, HARMST'97, was held in June 1997 in Madison, WI. It attracted nearly 200 people. The third meeting, HARMST'99, will be held in Japan immediately after the Transducer'99 conference.

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H. Guckel received the Ph.D. degree in electrical engineering from the University of Illinois–Urbana in 1963.

During his graduate studies he contributed to the hardware phase of Illiac II, an early high-speed computer. He joined IBM Research in Yorktown Heights, NY, in 1963 and worked on high-speed digital circuits and slow mode effects in lossy microstrip transmission lines. He joined the Department of Electrical Engineering of the University of Wisconsin, Madison, in 1970. He currently is a Full Professor in that department and holds the IBM-endowed chair of Bascom Professor in Engineering. He is responsible for the silicon program at the university and is the founder of the Wisconsin Center for Applied Microelectronics, a functional integrated circuit facility. He contributed significantly to the original effort in X-ray lithography at the university and was a member of the Sematech Center of Excellence in X-ray lithography. His interests in micromechanics involve two research areas: surface micromachining and deep X-ray lithography. His contributions in surface micromachining include pressure transducers and resonating force transducers as well as material science and measurement procedures for the mechanical properties of thin films. His efforts in deep X-ray lithography and electroplating are contributing significantly to three-dimensional micromechanisms. His current research activities include high-performance sensors and electronics interfaces as well as assembled micromechanical systems that are produced by synchrotron-based X-ray lithography. He has published more than 180 papers in microelectronics and micromechanics and has received more than 70 patents.

Dr. Guckel is a member of many technical societies.