Electroforming of Electronic Devices

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Dr. Lubomyr Romankiw, who was the AESF Scientific Achievement Award recipient in 1991, was judged by the attendees at the March 1996 AESF Electroforming Symposium as being the "excellence in presentation" winner among the individuals who presented papers at that event.

This is an edited version of his informative discussion of plating through mask technology (one of the names electroforming in electronics is known by). In traditional electroforming, the object is an entity by itself and is expected to part readily from the substrate after plating. In plating through mask technology in electronics, the electroformed metal has to adhere very strongly to the substrate, and it usually represents only one layer of a multilayer structure. Dr. Romankiw's paper covers a history of the development of plating-through-mask technology in electronics, patterning and pattern transfer, plating through lithographic masks as used in thin film heads, thin film chip carrier manufacture and in fabrication of a prototype of an integrated magnetic minimotor.

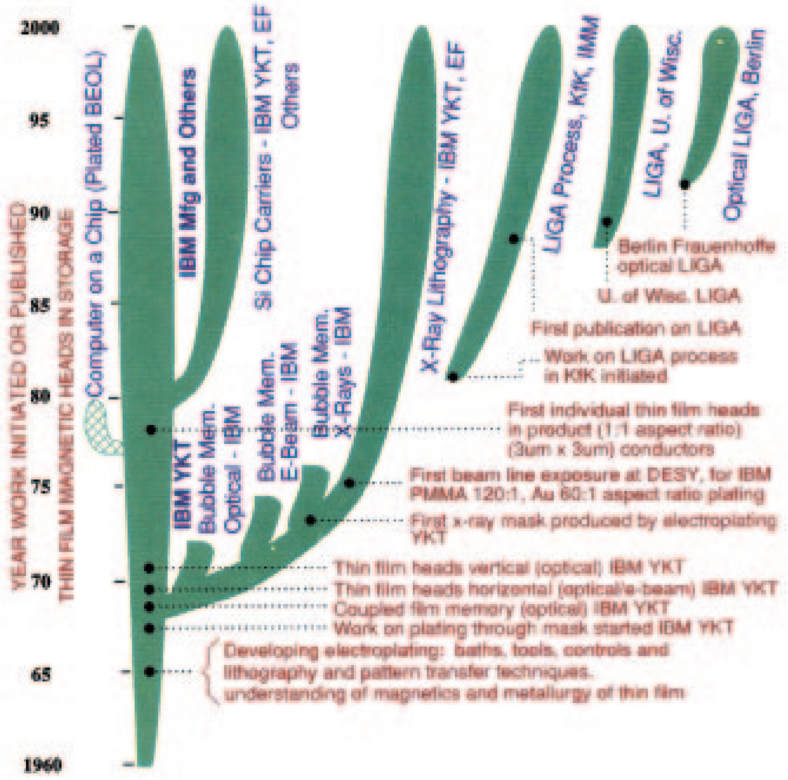

Fig. 1—Historical developments in the evolution of through lithographic masks plating technology.

Electroforming is an old art that has been practiced by electroplaters for many years. In this process, the metal is deposited onto a cathode mandrel or into a mold. Upon completion of the plating, the mandrel/mold and the plated metal are separated. The plated metal represents an entity by itself—a finished part.

To electroform parts, plating is usually done onto a suitably pretreated cathode for easy parting, such as a dielectric coated with a thin film of Ag that has limited adhesion, onto an austenitic stainless steel mandrel or onto copper overcoated with a thin flash of chromium. Because of the thin native oxide on both stainless steel and chromium, an electroformed part is easily removed from them. The adhesion has to be sufficient for the electroformed metal not to separate before the electroforming process is completed. In some cases, the plating is done onto a substrate that has features formed in it (LP records or CD disks, for example). The objective is to replicate the features present in the polymer substrate into the metal that will subsequently be used as a stamping die. In other cases, plating is done through a resist mask onto a metal mandrel (in the fabrication of screens, masks, etc.). Many examples of traditional electroforming are included in the proceedings of the 1996 symposium.[1]

How Electroforming For Electronics Contrasts With Traditional Approach

By contrast, when electroforming metal patterns for electronic applications, the electrodeposit that is made through a resist mask usually does not represent a finished product by itself. It also is rarely removed off the substrate. Instead, it remains on it and becomes an integral part of the electronic or magnetic device being built. Indeed, the device may contain several such through-mask electroformed layers, each having a different pattern and each being separated from the previous one by a dielectric. Because good adhesion of the plated pattern is of critical importance most of the time, a special adhesion layer is deposited on the dielectric to ensure excellent adhesion of the plated features to the substrate. The adhesion layer consists of an evaporated or sputtered refractory metal (such as Cr, Ti, Ta, etc.) In the same vacuum step, it is overcoated by a conducting metal, such as Cu, Ag, Au or Ni to form a cathode. Refractory metals usually provide very good adhesion to oxides and other dielectrics. Metals such as Cu, Au, Ag, Ni and others adhere well to the top side of the refractory metal. The refractory metal, therefore, serves as a bridge between the dielectric and the metal.

Electroforming in Electronics Is Known By Many Names

The application of electroforming in electronics is known under several different names: Plating through lithographic masks;[2] plating through masks; pattern plating; plate-up; and additive

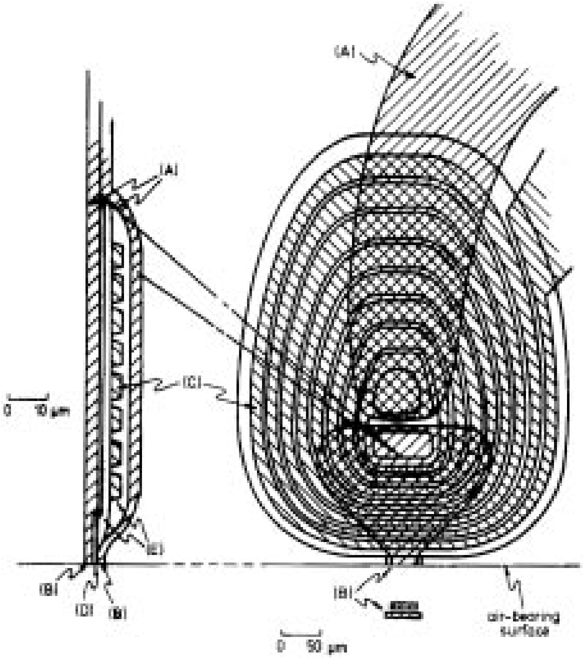

Fig. 2—Schematic view of the thin film head of a vertical configuration cross-sectional view, with level of coils and the top view of pancake-wound coil.

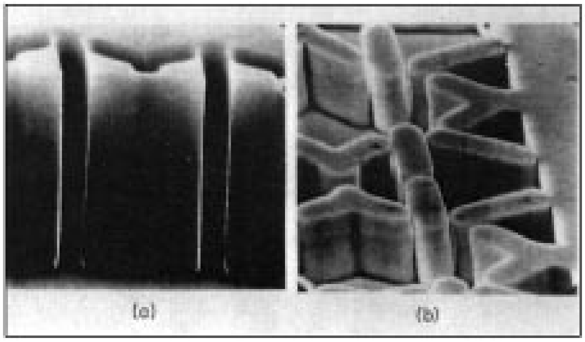

Fig. 3—X-ray lithography exposed patterns in 12 µm of PMMA at DESY accelerator in Hamburg, Germany. (a) X-ray resist, 12 µm thick; 1 µm wide pattern; narrowest space 1000 Å. (b) Plated with 6 µm of gold. High aspect ratio; high resolution electroplating.

plating. Recently, the acronym *LIGA* has been appearing in the field of micro-electro-mechanical systems (MEMS). LIGA is an abbreviation of the German Lithographie, Galvanoformung and Abformung (lithography, electroforming and replication)[3], and was coined by Kernforschungszeutrum Karlsruhe (KfK) in Germany.[3]

Through-Mask Technology

In electronics, the plating through lithographic polymeric mask technology or electroforming had its beginning in the late 1960s. Inventions and breakthroughs (Fig. 1) led to the current extensive use and popularity of the electroforming process in electronics.[2] The electroforming through masks was first tried in connection with fabrication of magnetic storage devices. In order to build thin film inductive read-write heads, it was necessary to produce µm-size copper conductor coils nearly square in cross section, with as many conductor turns crowded around the magnetic yoke as possible.[4,5,6] The yoke was only 100 µm high, with a separation between the yoke legs of only 15–20 µm (Fig. 2)

The electroforming (or plating through mask technology) for electronic thin film head fabrication was first introduced at the T.J. Watson Research Center. We have decided to exploit, for this purpose, the combination of lithography and plating processes, similar to those used in electroforming, with the key differences being as outlined earlier. Each electroformed layer was only part of a completed multilayer structure. After introducing the electroforming through resist mask in thin film heads, we have introduced this technology also in the fabrication of bubble memory.

Because bubble memory required submicron dimensions in addition to the optical lithography, we have also explored and extended the plating-through-mask technology to e-beam and X-ray lithographically formed patterns. [7,8] Having demonstrated in 1974 an unparalleled fidelity of pattern replication of the plating through mask technology, the gold electroforming was adopted as the only successful process for fabrication of X-ray lithography masks (which requires pattern replication nearly on atomic level). In 1976, we made public the fact that X-ray masks produced by plating can be inverted several times with almost no loss of fidelity.[8] Several mother-daughter replicas were produced using electroplated gold. In each replication, the height-to-width aspect ratio of the plated pattern was increased without loss of fidelity in the subsequent replicas. Figure 3 shows a structure with 60:1 aspect ratio, with six µm thick, 1 µm wide patterns separated by 1000 Å spaces produced by X-ray lithography followed by gold plating.

As the understanding of the plating through resist masks grew, precision tools, processes and process controls were developed, and through-mask plating technology became a critical technology in magnetic thin film head manufacturing. Today, several hundred millions of heads per year are manufactured by electronic companies around the world, using the plating through mask technology, representing a $2–3 billion market. There is currently no deposition method that can compete cost-wise with electroforming for thin film head manufacturing. Plating through masks has also become the exclusive fabrication process for very high fidelity X-ray masks and has been adopted in manufacturing as low-cost, high-precision thin film chip carriers. High aspect ratio structures with up to 12:1 were produced, not only using X-ray lithography, but also using optical lithography and through-mask plating (Fig. 4) [2].

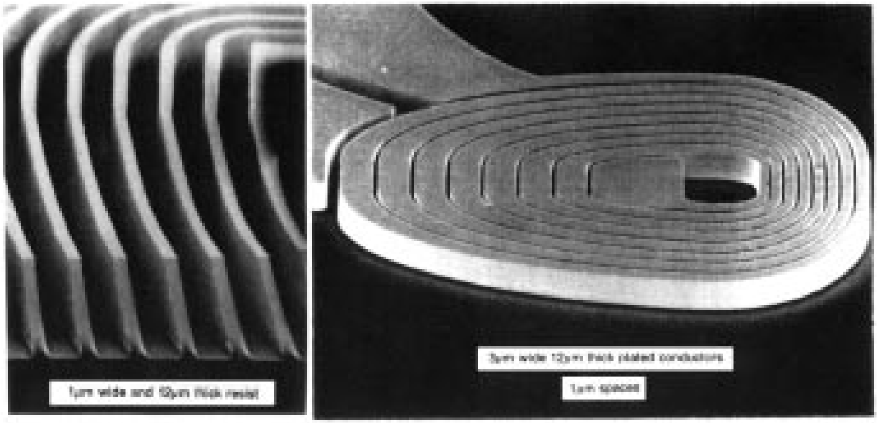

Fig. 4—Optically exposed and developed structure (produced in 1977) in Novolac-type positive working resist showing one micron space between 3 µm-wide conductors that are 12 µm tall. The insert shows lithography before plating.

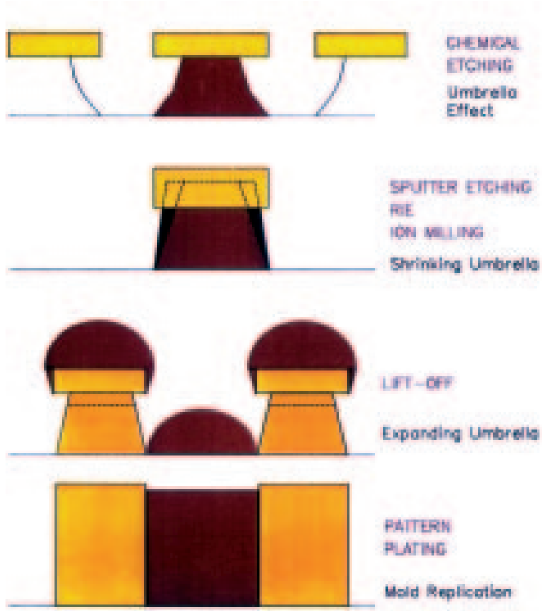

Fig. 5—Schematic summary comparing four pattern transfer techniques—chemical etching, sputter etching & RIE, lift-off & pattern plating, and plating through mask technology using UV lithography— using the same width mask and the same spaces. Because of the nature of the plating process, even the smallest features that can be wetted will plate. The height-to-width aspect ratio of pattern depends only on how tall the lithographic mask can be made.

Electronic parts require very tight thickness tolerances, exceptionally uniform current distribution and mass transport, very rapid real-time on-line process control and good understanding of the relation between solution chemistry, nucleation, film growth and other parameters that define the material, magnetic, electrical and other properties. Most of these requirements are affected by uniformity of agitation, pattern distribution and current distribution. A unique paddle plating cell design has been developed that provides extremely reproducible agitation, and permits plating—very reproducibly—films with excellent current and thickness distribution on a wafer.[9,10] It is known that agitation in a plating tank is hard to reproduce, and that scaling up of the plating environment is very difficult. In the paddle cell, because of the method of agitation used, agitation is easy to reproduce and the paddle plating tanks are easy to scale up from a small laboratory size tank to a full-scale manufacturing tank. The agitation is accomplished by a windshield-wiper-like device (arm) moving only a millimeter away from the cathode. We have investigated these relationships and have come up with a model that permits us to approach the electrochemical process with a considerable amount of understanding.[11–14]

Patterning & Pattern Transfer

For a long time, the most popular technique for pattern transfer in electronics was wet chemical etching. This process runs into limitations because as device density increases, it becomes necessary to place conductors closer and closer together, and at the same time to maintain the largest possible cross-sectional area of the conductors.

A considerable amount of work has been and is still being done on dry processes of pattern transfer, such as: Sputter etching, reactive ion etching and lift-off. The advantages and limitations of various pattern transfer techniques have been studied and compared with the electroplating through mask technology.[15] A comparison of the various techniques is shown in Fig. 5. It is easy to conclude that the plating through masks is the only technique that permits the highest packing density, the highest cross-sectional area and the tallest structures. This technology has been clearly demonstrated in electronics to be the only one that is capable of producing truly three-dimensional, micron-size structures with nearly atomic resolution and vertical walls, as it is known to do in electroforming of much larger articles for automotive, aerospace, jewelry and other applications.

Plating Through Lithographic Masks

The typical process steps used in fabrication of patterns using the plating through mask technology are demonstrated in Fig. 6. The substrate is usually a dielectric that is typically metallized first with an adhesion layer of 50 to 500Å of refractory metal (such as Cr, Ti, Ta, etc.) followed immediately in the same vacuum pump down, by a 400 to 5000Å of Ni, Au, Co or NiFe as a cathode plating surface. In the case of Ni or NiFe, occasionally the adhesion layer is omitted, but then the Ni or NiFe is deposited at 200 to 300 C to form the Ni-oxide and Fe-oxide bond between the oxygen in the dielectric and the metal.

The seed layer is coated with an organic polymer, an optical, e-beam, or X-ray resist that when exposed through a mask will leave certain areas depolymerized and ready to be dissolved by the developing solution. After development and upon water rinsing and drying, any remaining organic residue of the resist is removed by plasma ashing with oxygen containing plasma. The open areas are then electroplated through.

If a Novolac-type positive working resist is used, the plating solution usually readily wets and fills even a very high-resolution pattern. Upon completion of the plating, the remaining resist is removed by second exposure and development. The seed layer and adhesion layer are then removed by chemical etching or by sputter etching or RIE. This leaves the plated features isolated on top of the dielectric substrate. These features are then overcoated with a new dielectric. If necessary, the structure is planarized and the process is repeated as many more times as is required to complete the device.[16]

The fidelity of electroformed pattern is extremely high, and if a high resolution resist is used, the pattern can be extremely densely packed. When opti-

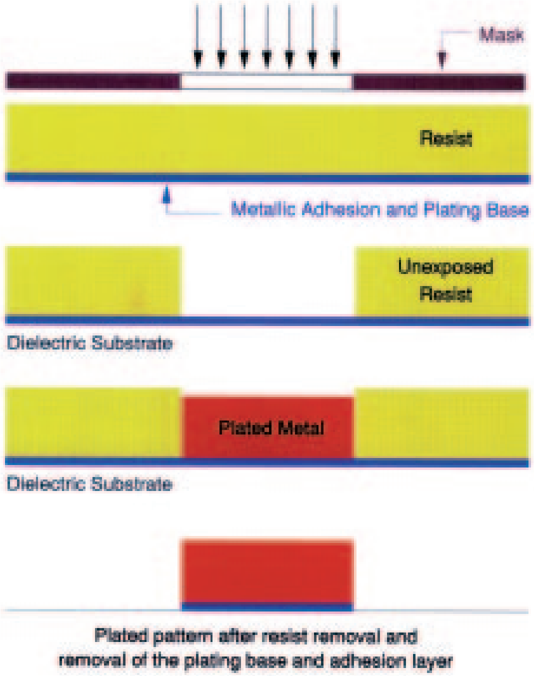

Fig. 6—A schematic of plating through mask technology. This fundamental process is repeated as many times as necessary to build an electronic structure.

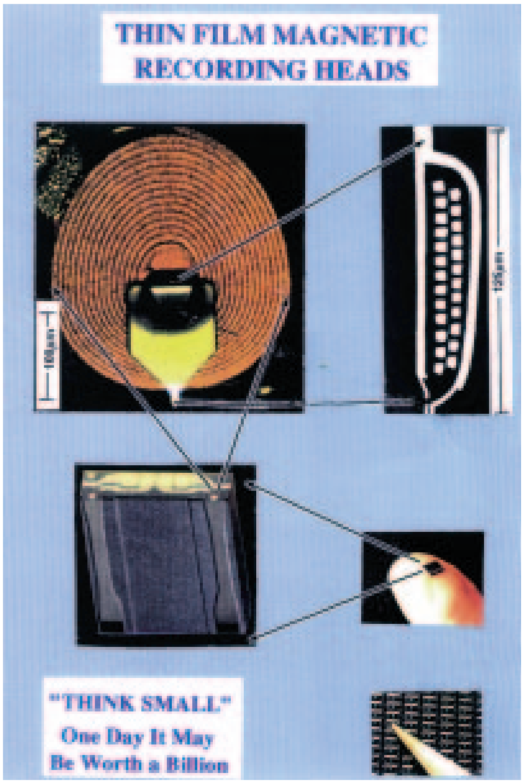

Fig. 7—A top and cross-sectional view of a popular inductive head with 31 Cu coil turns. In the lower part of the figure is a section of wafer showing heads arranged in rows and columns. The central part of the figure shows a magnetic slider (on top of a fingertip) and an enlarged version of the slider showing the location of the head at the end of the slider.

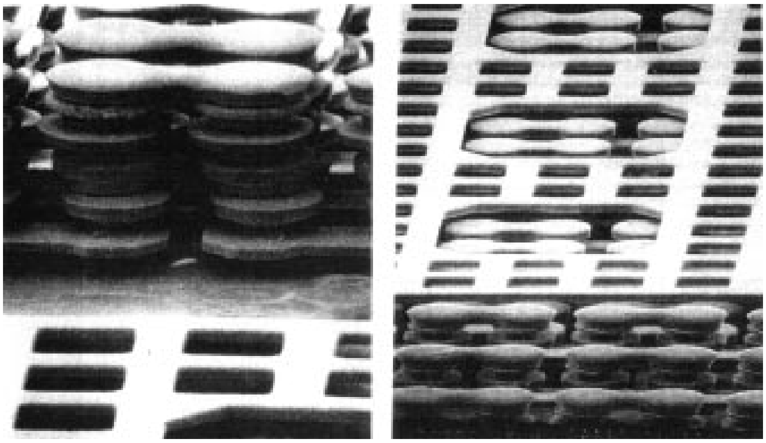

Fig. 8—An example of a thin film package or chip carrier, showing 11 layers of metallurgy. The Cu conductors and vias are alternating. The conductors are plated through Novolac positive working resist. Note the sharpness of the edges of the pattern and the high packing density of conductors.

cal lithography is replaced by e-beam and by the X-ray lithography, pattern dimesnions as small as 0.1 µm have been achieved.[8] Additionally, an important feature of X-ray lithography is that, because of the extremely short wavelength, it is capable of producing nearly vertical walls in very thick PMMA resist (Fig. 3). Because of this, three-dimensional structures with completely vertical walls can be fabricated.

Thin Film Heads

Shown in Fig. 7 are a top view and a cross-sectional view of a magnetic thin head typical of the heads that have been in use since 1979 in most of the magnetic storage devices using hard disks. This is an inductive read-write head with 31 electroplated copper conductor turns and an electroplated horseshoe magnet. (A typical fabrication process of such a head is described in Ref. 10.) The substrate is Al_2O_3• TiC ceramic overcoated with sputtered Al_2O_3. The structure contains four separately electroplated through mask permalloy layers (81% Ni; 19% Fe alloy) and two copper conductor layers that are also electroplated through lithographic masks.

Several hundred—or even thousands—heads are fabricated on each substrate. The heads are arranged in rows and columns, with each head lithographically defined by several lithographic masks used sequentially in the process. For each metal and dielectric layer, a different mask is used. When the sequential process is completed, the wafer is cut into sliders, with one head per slider. The overall sequence is:

- Sputtering of thin seed layer of NiFe alloy, which will serve as a cathode for plating of the first leg of the horseshoe magnet through a photoresist mask, and then plating of permalloy and etching away of the seed layer.
- Sputtering and defining into shape, by etching, 0.3 to 0.5 µm of Al_2O_3, which will define the magnetic gap in the finished horseshoe magnet (the head).
- Sputtering a seed layer that consists of Cr and Cu, applying resist, exposing and developing the outline of the first pancake-shaped copper conductor coil and then plating the first copper conductor coil through the mask. After plating approximately three µm of the Cu, removing the resist mask and sputter etching the thin Cu seed and Cr adhesion layers.
- Forming the dielectric that will separate the first level of Cu conductors from the second by applying a Novolac photosensitive resin, defining it by the photo processing, and then hard-baking it to serve as insulation between the coils.
- Sputtering a new Cr and Cu seed layer and electroforming through resist mask the seed layer of the Cu conductors in the same way as the first layer was formed.
- Forming a second hard-baked Novolac dielectric layer on top of the second level Cu coil in the same way as the first hard-baked dielectric layer was formed.
- Forming the second leg of the horseshoe magnet by sputtering the thin permalloy seed layer and then electroforming the thicker permalloy by electroplating through resist mask and then etching the excess permalloy and the seed layer.

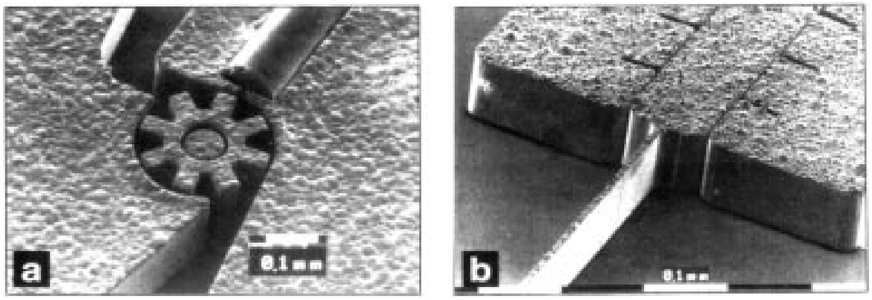

Fig. 9—Some selected plated structures produced by using X-ray lithography and plating of Ni by Kernforschungszentrum Karlsruhe, Germany. (a) Micro turbine; (b) accelerometer. These structures were fabricated using PMMA and X-ray lithography.

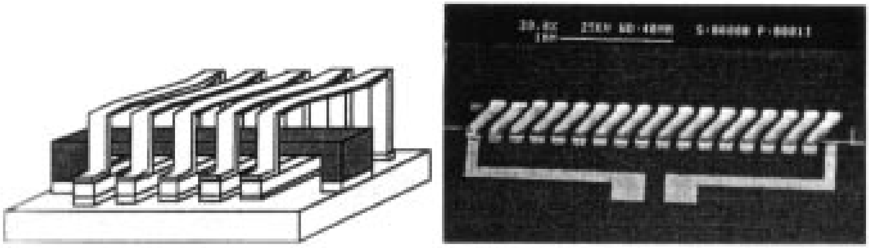

Fig. 10—A gold micro solenoid (linear actuator) that was produced by Frauenhofer Institute für Siliziumtechnologies, Dillingburg, Germany, using AZ 4620 resist and optical lithography. In the last two years, there has been a trend to utilize a Novolac-type resist in connection with UV exposure to build such devices. Such structures were built by Berlin Frauenhoff Institute,[18] and by IBM' s T.J. Watson Research Center.[19]

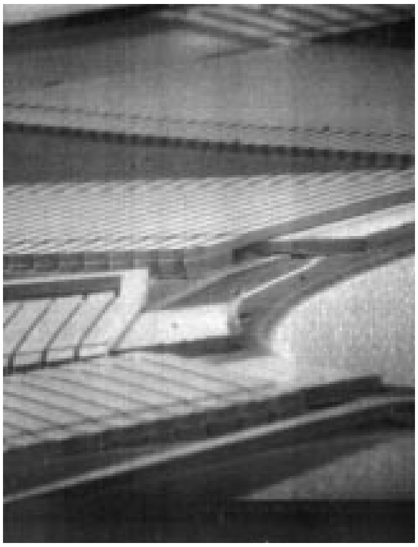

Fig. 11—Part of a stator of a variable reluctance minimotor built at IBM's Watson Research Center. For the purpose of showing the metallurgical structure, the epoxy dielectric was removed by O_2 plasma ashing. The Cu conductors in this structure are 60 µm-wide and 30 µm tall, with 20 µm separation between them. The permalloy yoke is 60 microns thick and is separated by 7 µm of an epoxy dielectric from the coils.

The completed head (Fig. 7) has about a 100-µm-wide yoke (approximately the width of a human hair); the pole tip is only about 5 µm wide. The Cu conductors are 3.8 µm tall, 3µm wide, and the spaces between them are 2 µm wide. All the metal layers were plated through optically exposed Novolac-type-positive working resist. Each layer was produced as described in Fig. 3. Because of the need to have very precise permalloy composition and very uniform thickness distribution, the wafers are plated in a paddle cell.[9] The paddle cell design and the mode of agitation make this tool particularly useful in plating parts through resist masks that require very precise alloy compositon, and very reproducible thickness uniformity.

Thin Film Chip Carriers

The thin film chip carriers are used in nearly all computers. They are the substrates to which semiconductor chips are attached. They provide connection and electrical communication paths between the chips and the other parts of the computer. The chip carrier shown in Fig. 8 consists of a ceramic module with several layers of paste metallurgy on which 11 layers of Cu conductors were formed by plating of Cu through Novolac-type-positive working resist. Each layer is produced using the process described in Fig. 6. The conductors are 15 µm wide and 5 µm thick. Each time after the seed layer was removed, polyimide was applied. The polyimide is the dielectric separating and insulating the conductors from each other. For the purpose of illustration, the figure shows a section of the thin film chip carrier from which the polyimide was removed by oxygen plasma treatment. The 11 layers of Cu metallurgy, formed by plating through photoresist masks, can be clearly observed. The edges of each conductor and of each via are clearly defined. Such high conductor density, small spaces between the conductors, excellent electrical conductivity and sharp edge definition would be very difficult to achieve by other patterning techniques.

Integrated Magnetic Minimotor

The minimotor discussed in this article belongs to a class of devices known as MEMS (micro-electro-mechanical systems). This very rapidly developing field

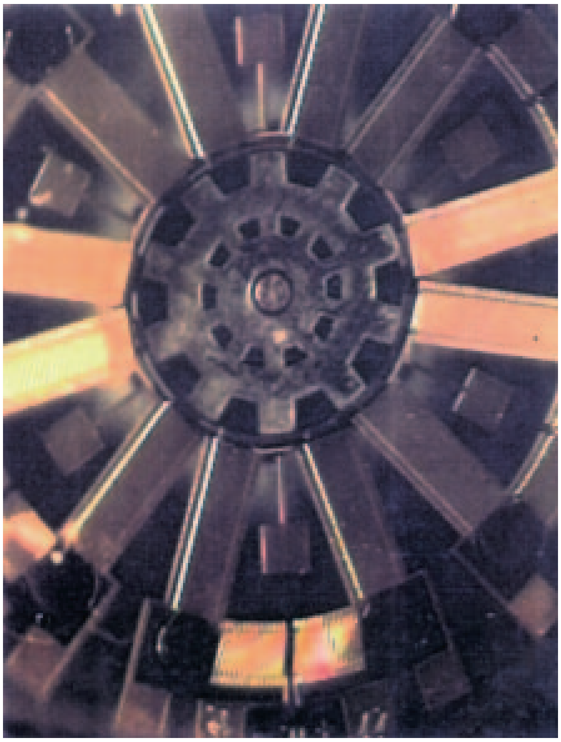

Fig. 12—The assembled motor with a 6-mm diameter rotor in place, surrounded by 6 horseshoe magnets.

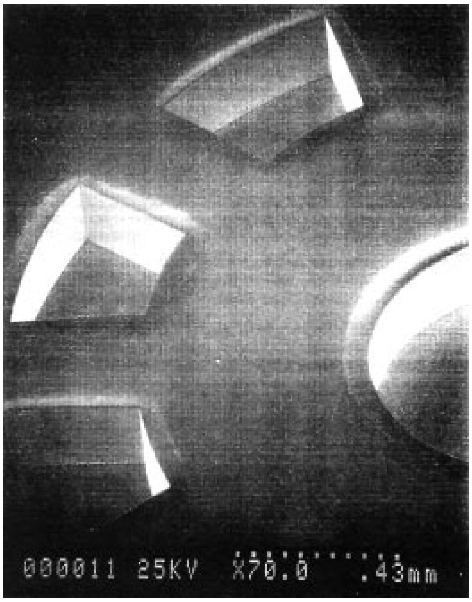

Fig. 13—Part of the rotor for which lithography was produced by X-ray radiation at Louisiana Tech. The X-ray lithography masks were produced by MCNC in Raleigh, NC. The plating of permalloy, 250 µm thick, was done at the Watson Research Center. Note the perfectly vertical and nearly atomically smooth wall of the permalloy, which was defined by X-ray exposed and developed PMMA. The project was done with the partical support of ARPA, under the name of ARPA HI-MEMS Alliance. These structures clearly demonstrate the power of the electroforming or LIGA technology, particularly when combined with X-ray lithography to build a variety of micrometer-size devices for MEMS.

is making very effective use of the electroforming or plating through mask technology. In micromechanics, linear actuators, rotary motors and a variety of sensors and instruments are shrunken by orders of magnitude from the well-known, smaller mechanically machined and assembled dimensions. The plating through mask technology, particularly when the patterns are defined by X-ray lithography, provide entirely new capabilities to this field because it is capable of extremely large depth of focus. The plating through patterned resist made possible a variety of magnetic devices, some of which require very tall, extremely closely spaced structures with very tight dimensional tolerances. The plating approach opened up many new possibilities in the field of micromechanics and in micromechanical systems (MEMS). As discussed, in this particular field, electroforming or plating through lithographic masks is known under the acronym “LIGA.” There are only a few MEMS devices in manufacturing today that utilize electroforming. It is predicted that many MEMS devices based on plating processes will be in use by the year 2000 and that plating will be widely used in MEMS device fabrication thereafter.

There are a variety of experimental devices that have been built and demonstrated, including accelerators, gyroscopes, motors, linear calculators and more (see Figs. 9–13).

Electroforming Technology Has Huge Impact On Several Areas

The introduction of plating through mask technology as a process has had an unprecedented impact on magnetic storage density capability. Storage density per square inch has increased from two million in 1976 to 1000 million bits/in.^{2} in 1996, and the density storage race still continues. The information that once required several 14-in.-diameter disks when using ferrite heads, with the invention of thin film heads and thin film disks can now be stored on two or three of $3^{1}/_{4}$- or even $2^{1}/_{2}$-in.-diameter disks. It is anticipated that electroplating through lithographic masks processes will carry us through year 2010, all the way to the theoretical limit of the magnetic recording.

Another important impact of the capability of high density magnetic storage—with its electroformed through resist mask heads—was the development of the Internet, with the servers capable of storing very large amounts of data and being capable of readily transmitting, in fractions of seconds, extremely large volumes of data from servers to the personal computers connected to the Internet.

In the electronics industry, since the first introduction of plating through masks to electroform thin film heads in 1979, this technology has been introduced in fabrication of conductors in thin film silicon chip carriers, in high resolution printed circuit boards, and was explored as a potentially important technique for circuitization of the silicon chips.

The application of the electroforming approach through resist mask is making possible what was once the impossible: Micromotors, accelerators, micro-valves, electro-optical devices and many other three-dimensional structures. Micromechanics is on the verge of nearly explosive growth. Its application is being considered in a variety of areas: Automotive, magnetic storage, medical instruments, aerospace, and military and civilian applications in which it is expected to replace very mechanically fabricated and assembled complex mechanically fabricated and assembled instruments.

While plating through mask technology has found many uses in electronics, made possible thin film magnetic heads and a variety of other devices, and represents several billion dollars in business per year in electronics, there are still many reluctant engineers and skeptics among the physicists and electrical engineers. They look on the field of electroplating as an art rather than a controllable and reproducible science. For suggestions on how to change these views, the reader is referred to a paper written in 1984.[20]

Electroplating through mask technology has found its way into fabrication of almost all components of a modern computer, and has enabled manufacture of personal computers and laptops. Because of its very high precision, faithful replication of masks and ability to form very high aspect ratio structures, it now commands a multi-billion-dollar market per year in electronics alone. It has still yet an exciting future with its latest application in MEMS. Who can foresee its next application?***P&SF***

Acknowledgment

Dr. Romankiw extends his sincere thanks to his co-workers who have worked with him for more than 25 years to change the perception of plating from an art to a science by demonstrating its usefulness in many areas of electronics and in MEMS. He acknowledges that part of the motor project was done under ARPA sponsorship.

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About the Author

Dr. Lubomyr T. Romankiw is an IBM Fellow in IBM's T.J. Watson Research Center, Yorktown Heights, NY (10598), where he has been affiliated since 1962. He holds a BSc in chemical engineering from the University of Alberta and MSc and PhD degrees in metallurgy from MIT. The holder of 47 patents and 119 published inventions, Dr. Romankiw has also published more than 120 scientific papers and reports. His research has dealt with nearly all aspects of plating and etching technology as used in the electronics industry. He is a co-inventor of laser-enhanced plating and etching. His work—particularly in electrochemistry and electrochemical technology in the electronics and electrochemical fabrication of thin film heads for high-performance magnetic storage—has had immense impact on the industry.

Dr. Romankiw's perspective in research has always been to find and give a scientifically sound explanation to observed phenomena and to relate plating conditions, solution chemistry, electrode kinetics and processing parameters to structure and properties of the deposits and device performance. As a result, with his co-workers, he has made a substantial contribution toward making plating technology a science. He organized eight major electroplating symposia in connection with the Electrochemical Society (ECS) and the International Society of Electrochemists on plating for magnetic and electronic applications, and was co-editor of seven volumes of symposia proceedings. His work on the development of thin film inductive and MR recording head processes, X-ray mask lithography, laser-enhanced plating, electro-etching and other aspects of application of electrochemical technology in electronic device fabrication has earned him 12 IBM Outstanding Invention and Outstanding Contribution Awards, along with 24 IBM Invention Achievement Awards.

In 1991, Dr. Romankiw was named as the AESF Scientific Achievement Award recipient. He has also received other prestigious awards and recognition: In 1990, elected a Fellow of ECS, Inc.; a charter member of IBM's Academy of Technology in 1987; and a member of the Academy of Engineering Sciences of Ukraines in 1992. He was awarded the Vittoria de Nore Medal of ECS in 1994; the IEEE Morris A. Lieberman Award in 1994; and was awarded thePerkin Medal in 1993 by the Society of Chemical Industries of the U.S., the highest honor of the chemical industry, for his inventions and development of thin film head technologies.