Modulation Collimator Fine Grids for HESP

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ABSTRACT

The proposed High Energy. Solar Physics (HESP) mission will require fine, precise, high 'aspect ratio modulation collimators for the High Energy Imaging Spectrometer (HEISPEC). The fabrication approach described here rests on the proven precision of semiconductor lithography - the ability to replicate extremely accurate patterns onto different planar substrates. Techniques are described for converting these patterns into high aspect ratio molds and then metalforming the molds to create the final grid structure. Use of a recently developed technique known as LIGA is proposed to form the finest, 34 μm pitch structures. LIGA utilizes synchrotrons radiation to pattern a thick acrylic resist on a conducting substrate. The exposed pattern is then converted to metal through an electroforming process.

INTRODUCTION

The High Energy Solar Physics (HESP) mission is proposed to perform imaging spectroscopy of hard solar x-rays and gamma rays from Earth orbit. Imaging will be accomplished by a telescope consisting of matched pairs of rotating modulation collimators preceding a set of cooled germanium detectors. [1] These collimators must be 9 cm in diameter and must be fabricated from a high atomic number material (W, Au, Rh, etc.). Each collimator, or grid, must consist of precisely periodic and parallel slats with aspect ratios ideally 55:1. The slit/slat ratio is approximately 1:1, and the pitches will be between 34μm and 2 mm. Microfabrication is required for pitches up to approximately 0.5 mm.

Manufacture of these grids will require microfabrication of a unique kind. Particularly challenging is the combination of three requirements which, by themselves, are routinely achieved - high aspect ratio, high atomic weight elements or alloys, and the need for perfection over a 9 cm diameter disk. High aspect ratios are commonly obtained through extrusion or stacking techniques which, however, lack precision across large arrays. Tungsten is commonly formed as a coating through deposition techniques, but not as a free-standing structure. Gold, while easily formed, is extremely expensive and lacks the required mechanical strength. Finally, while microfabrication of arrays of independent components is common, there is little experience with extended microstructure which demand large scale registration and uniformity.

The underlying principle of our approach is to cast the grids in accurately machined molds rather than assembling them out of individual tungsten components. In this way the final product will have the mechanical integrity of single-piece construction, and the precision machining can be performed on the optimal materials. The specific process involves metalforming of micromachined molds precisely formed using semiconductor lithography techniques. The following sections review different aspects of mold formation and metalforming.

Fabrication of ultrafine grids presents a fundamental challenge in that the mechanical strength of even a refractory metal structure is severely compromised when the thickness of the slats is only tens of microns. In this regard it is worth considering "Z-Contrast" structures consisting of alternating stripes of low-Z and high-Z material. This is acceptable since diffraction imposes an effective upper limit to the x-ray wavelength which may be imaged with modulation collimators. Au-filled silicon molds, for example, will work in the range of silicon transparency above 20 keV. Au-filled acrylic molds (as proposed for the fine grids) will work well above 10 keV.

Silicon Micromachining

Several different methods have been developed for precision machining of fine structures in silicon. One approach used extensively in this work utilizes the simple "dicing" saw, a precision rotary saw with a fine, diamond-coated blade. Since these saws are used primarily to separate integrated circuits fabricated on silicon wafers, they are built with highly precise sample stages which can position the part with an accuracy of - 1 μm anywhere on the sample. They can also be preprogrammed to cut simple structures such as grids automatically, and crystal orientation is not a relevant consideration. A complete grid can, in fact, be cut within a few hours.

The principle limitation of the dicing saw for this application is the achievable depth of cut, which we have found to limit the aspect ratios to no more than 20:1. This is probably not intrinsic to the technology, but rather a design issue - In normal use a dicing saw would not be called on to cut anything thicker than 1 mm. In addition, it is not feasible to make cuts finer than ~35 μm due to the fragility of the fine saw blades. The figure of the trench cut by a dicing saw is not ideal - it has micron-scale roughness and is prone to taper as the blades wear - but is probably adequate for this application.. A schematic of this process is shown in figure 1. Not shown are the support structures which have been successfully cut orthogonal to the trenches with the same saw.

Higher aspect ratios can be achieved by sawing with a gang saw rather than a dicing saw. Gang saws are fabricated out of thin steel blades which are separated by precision spacers and tensioned to maintain alignment- The gang saw is used to slice boules of silicon or other semiconductor material into wafer stock. As with the dicing saw, uniformity in wafer thickness and smoothness of finish are demanded by the application. Custom gang saw assemblies can be fabricated to correspond to the various grid pitches, but it is unlikely that grids finer than 200 μm can be made with this approach.

The most conventional method for forming microstructure in silicon is a technique which is generically known as "bulk micromachining[2]", but which is referred to here as chemical (micro) machining to distinguish it from the methods discussed above. It has long been known that certain solvents (KOH, EDP) can be used to etch silicon with anisotropy of several hundred to onc along the (11 1) crystal plane[2]. By depositing **a silicon** nitride mask on [110]-oriented silicon wafers, and exposing openings sufficiently well aligned to this plane, deep trenches normal to the surface can be formed. Since only one crystalline direction can be deep etched in this manner, the technique is ideal for the proposed grid structure which consists of an army of parallel trenches.

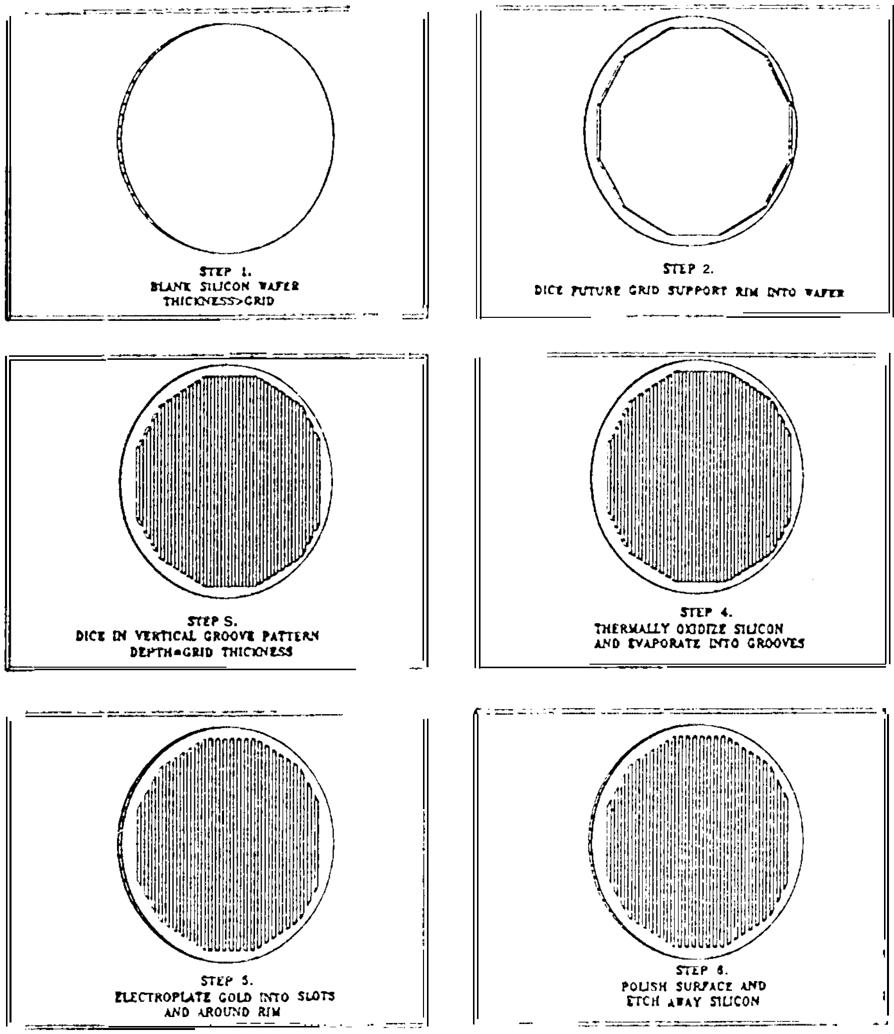

Figure 1. Schematic of one process for mold formation and metalforming, utilizing a dicing saw. Not shown are the horizontal support bars.

The chemical micromachining approach has the advantage that it is based on the same lithographic process which is used to fabricate integrated circuits. The lithography mask itself can easily have an accuracy of better than 0.1 μm across the entire wafer. Similarly, the processes used to deposit and pattern the mask, and even the process used to etch the nitride and the silicon, derive from well established integrated circuit methodology. 'Tie sidewalls of the trenches are defined by the crystal planes, and should be extraordinarily smooth and parallel.

While this procedure works well in principle, certain obstacles were discovered in attempts to make 55:1 aspect ratio structures. To begin with, consider the degree of selectivity required under most favorable circumstances. The finite etch rate transverse to the [111] direction results in undercutting of the structure defined by the mask. Hence, for example, a 100:1 selectivity will result in 1 μm undercutting on *each side* of a 100 μm deep trench. As shown in figure 2, selectivity of at least 110:1 is required to achieve a 55:1 aspect ratio with a negligibly small window in the mask. For the best reported selectivity, 400:1, the lithographically defined opening would have to be 72.59'io of the desired width. If the selectivity drops substantially, the window width becomes correspondingly smaller.

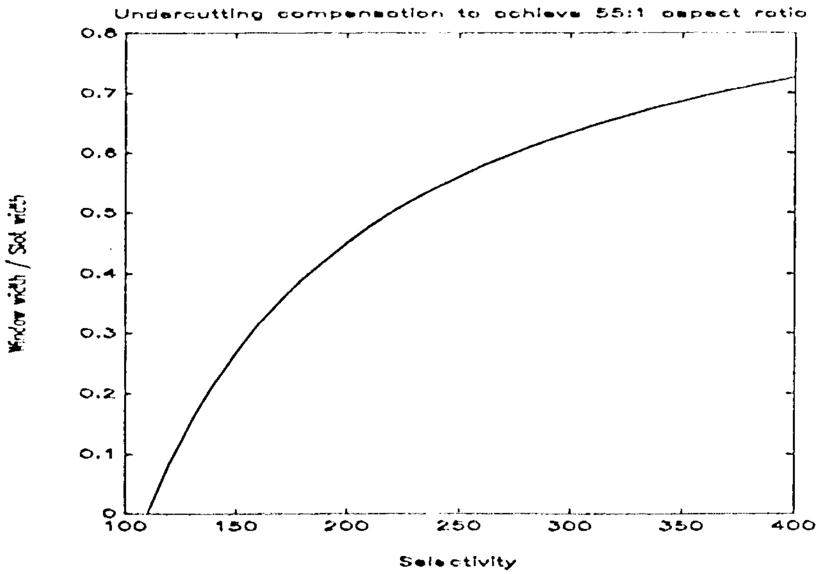

Figure 2. The finite selectivity of the etch causes undercutting on each side of a lithographically defined trench. As a result, for the target aspect ratio of 55:1, it is necessary to make the mask window narrower- than the desired feature width by the amount shown in the graph. Selectivity up to 400."1 has been reported in the literature

To achieve even the minimum 110:1 selectivity, etch conditions need to be optimized. As the trenches are formed, the etch rate at the bottom becomes limited by the transport of fresh etchant. We compensate for this by lowering the etchant temperature to less than 40°C and, therefore, the etch rate. In practice, etch rates approaching even 1 mm per week were difficult to achieve. Wafer quality must be high, strain must be low, and conditions must be carefully controlled. A particularly crucial requirement is the need to accurately align the mask openings to the (11 1) planes. To maintain 110:1 selectivity, rotational accuracy of 9 mrad is required. For 400:1, 2.5 mrad accuracy is required. Rotational alignment can only be achieved by etching a fan-shaped test structure and identifying the narrowest slots. To achieve 1 mrad resolution, for example, a pair of 1 cm long lines differ from parallelism by only 10 μm over their length. The test pattern thus requires at least micron scale accuracy, In practice, alignment accuracy substantially better than 10 rnrad is difficult, and 1 mrad should be considered a practical limit.

Another frequently encountered difficulty in the silicon micromachining of structures which occupy such large areas is the presence of defects either in the etch masks or in the bulk silicon. These can cause large areas of silicon to be completely removed, which can in turn cause substantial nonuniformities in the electrodeposition rates.

Despite the pitfalls described above, silicon rnicrornachining remains a feasible approach to mold formation, particularly if the aspect ratio requirements are relaxed (e.g. by stacking two or three parts back-to-back to achieve 55:1 ratio structures). For the finer grids, however, the requirement for extensive structural support in the form of cross-members is not easily achieved with the micromachining process. These grids contain structures less than 20 μm wide, thinner than, for example, commercial aluminum foils. It is likely that a free-standing structure will not have the mechanical stability to survive post-metalforming handling and processing unless substantial cross-support is provided. Unfortunately, it is not possible to anisotropically etch orthogonal or even intersecting vertical planes in silicon. The support structure, therefore, must either be out of the plane of the grid (above or below), or it must be imposed by a separate process, such as with a dicing saw.

Micromachining of Acrylic Sheet by LIGA

A new technique, LIGA, has recently been demonstrated to be effective for forming complex high aspect ratio *polymer* structures. The acronym LIGA (Lithographic, Galvanoformung, Abformung) refers to a complete process for producing and replicating high aspect ratio microstructures. The LIGA process, as developed at the Karlsruhe Nuclear Research Center in Germany, incorporates deep-etch x-ray lithography of acrylic resists, electroforming, and replication (specifically, injection molding). The process is outlined schematically in figure 3. The poly methyl methacrylate (PMMA) resist is cast on a metal substrate and aligned to an x-ray mask. The mask typically consists of a gold pattern several microns thick deposited on an x-ray transparent membrane such as silicon nitride or a polyimide. The structure is then exposed to collimated x-rays, several keV in energy, typically produced by a synchrotrons radiation source. This exposure depolymerizes the acrylic, allowing it to be dissolved by a suitable solvent. The resulting structure is then put in an electroplating bath, and the removed PMMA is replaced by Ni, Cu, or another suitable metal. The metal substrate forms the electrode for the electrodeposition, resulting in uniform growth of the metal structure starting at the bottom of the developed features. This avoids formation of voids that typically result when deep features are filled from the top. The rest of the PMMA is then removed, leaving the free-standing metal structure. This structure can in principle be replicated in plastic, metal, or ceramic by techniques similar to macroscopic injection molding.

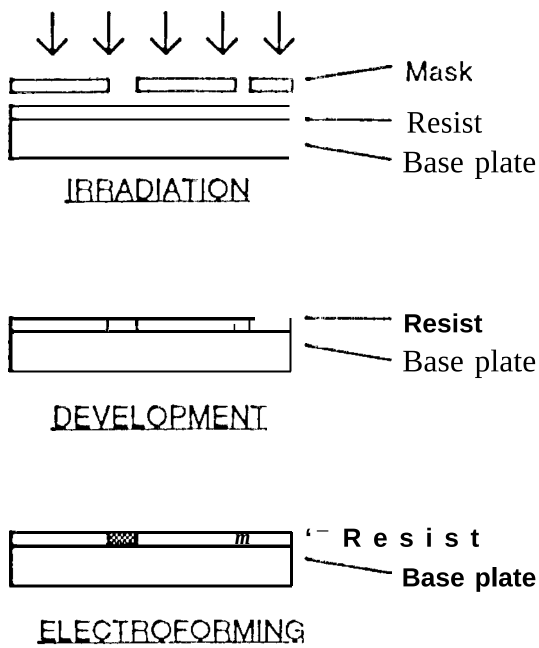

Figure 3: The LIGA process

A typical LIGA structure is from 100 μm to 300 μm in thickness, with feature sizes ranging from less than 1 pm to greater than 1 μm. Structures have. been successfully replicated in both metals and ceramics, although many of the replication processes are still proprietary.

Particularly noteworthy in the LIGA process is the deep etch lithography step, not necessarily because it represents the greatest difficulty, but because a synchrotrons radiation facility is conventionally used as the source of collimated x-rays. While several such facilities are available in the United States alone, their use as microfabrication foundries is a novelty, and has received considerable attention. The ultimate limitation on the size and thickness of a LIGA structure is determined by the characteristics of the synchrotrons radiation source. More specifically, the depth of the exposure is a function of the x-ray beam (photon) energy, which is determined by the energy of the electrons in the storage ring and the radius of curvature of the electron beam as it passes through the bending magnet. The area of exposure is limited by the total x-ray flux, which is in turn limited by the electron current in the ring, the solid angle accepted by the optics, and absorption by beam line windows and filters.

Until the present work, no LIGA structures had been reported for thicknesses greater than 500 pm. The requirement of this project to produce grids with thicknesses greater than 1 mm appeared to present a significant obstacle to the use of LIGA. However, the development of thicker than conventional LIGA structures only requires either more energetic x-rays or multiple exposures and development of the same areas. The former condition is met by the more powerful synchrotrons radiation sources to be utilized for this project, those at the Berkeley Advanced Light Source (ALS) and the Stanford Synchrotrons Radiation Laboratory (SSRL). However, if high energy x-rays arc used, new mask technologies must be developed to provide adequate contrast, and new methods must be found for forming the resist blanks. The conventional LIGA process is derivative of semiconductor processing - photoresist material is spun onto a substrate and cured, leading to thin and highly strained films. Masks are formed by electrodeposition on free-standing membranes. It is difficult to form more than 5-10 µm of masking material in this way, which is unacceptably transparent to 10 keV x-rays. High energy x-rays may also result in greater proximity damage, as secondary electrons scatter through adjoining m ateri al.

To test the feasibility of forming millimeter-scale structures with LIGA, a simple experiment was performed using an SSRL bending magnet line which provided plentiful x-rays in the 10-15 keV range as compared to the 3-5 keV x-rays typically used for LIGA. The light was unmonochromatized except for a beryllium window separating the vacuum from the exposure station. The two problems discussed above were addressed using radically different approaches from conventional LIGA. Instead of forming and curing the resist from solution, commercial acrylic sheet (Plexiglas manufactured by Rohm and Haas) was used. For masks, test patterns chemicall y milled in 50-100 µm thick stainless steel were obtained from Buckbee Meers, Inc. These patterns were free-standing, so no supporting membrane was required. The masks were clamped to the acrylic sheet, which had an added advantage over the conventional projection approach in that the mask provides a good heat sink for the substantial thermal load deposited by the. x-ray beam. After developing in methyl isobutyl ketone, high quality millimeter-scale structures were obtained.

LIGA efforts will continue at Berkeley's ALS in the near future. In addition, alternative methods are being explored for fabricating polymer molds which do not require synchrotrons radiation sources. This includes the use of resist materials which are reported to be effective with ultraviolet radiation from conventional lamps. Laser machining of plastics may also bear investigation in this regard. It has been reported that laser-machined plastics suffer from far less taper than is characteristic of laser machining of other materials.

Metalforming

Several different approaches to metalforming of micromachined molds have been investigated. All arc well established methods which are being adapted for use in high aspect structures. The most intensive effort is concentrated on electrodeposition and chemical vapor deposition. In addition, collaborators at TRW are pursuing an approach of inserting chemically cut tungsten foils directly into a micromachined mold, avoiding the metalforming step entirely.

Electrodeposition into high aspect ratio structures requires specialized techniques which are, however, relatively well understood. Working with Metal Surfaces, Inc. we used a continuous plating approach, with agitation provided by a laminar flow cell or local heating using a laser. Deposition rates approaching 1 µm per minute can be achieved with this method.

The simplest metals to be electrodeposited, and the most common metals used in LIGA, are copper and nickel. While these materials do not satisfy the requirement for high atomic weight and density, a first electroforming in nickel or copper can produce a robust mold for higher temperature processing, such as powder metallurgy or chemical vapor deposition (see below). Gold grids do satisfy the density and atomic weight requirements, and gold can be adequately electrodeposited. Certain gold alloys can be deposited for added hardness. Tungsten alloys can also be electrodeposited from aqueous solutions (by, e.g., Amorphous Technologies International), but the fraction of tungsten is no more than 60% *by weight*, which is probably inadequate for this application.

Preparation for electroforming and final polishing poses a challenge equal to the actual deposition process. In the case of silicon molds, the sidewalls must first be passivated by formation of a thick oxide (> 1 pm) in an oxidation furnace. A conducting electrode must then be formed at the base of the slots. In order to provide adequate structural integrity, we have determined that the silicon molds can not be freestanding, i.e. they must consist of trenches in a thick silicon "puck" rather than through slots (figure 1).

The electrode can be formed at the bottom of the trenches by evaporation from a highly collimated source. Typically a minimum of 100 nm of material is required due to the poor wetting of the oxide. While this process has been demonstrated successfully, it consumes a great deal of raw material and time in the evaporator. Consequently, two other techniques have been developed to address this problem. In the first, a two dimensional model of the grid structure is formed out of metal using chemical milling or laser machining. This template is then dropped into the silicon structure as an electroforming base. In the second approach (the conventional LIGA method) the mold material is bonded to a thick metal base plate prior to the lithography step. The mold material is then etched all the way through to the metal, which serves both as a structural support and as an electrode.

For refractory metal grids, techniques are being developed for metalforming by chemical vapor deposition (CVD) of tungsten or tungsten/rhenium alloy which has greater ductility. CVD has the advantage that the growth rate is so uniform it is possible to fill from the outside of the slots inward rather than from the bottom up. This reduces the thickness of the deposited film, and hence the deposition time, by up to a factor of 100. Several approaches have been proposed to accomplish void-free, high density growth. One approach is to maintain a thermal gradient across the mold, thereby maintaining a slightly greater growth rate near the bottom of the slots. This will result in a "zipping up" of the tungsten plug. Preliminary efforts using silicon molds have been carried out by Ultramet, Inc., of Sylmar, CA. Filling has been adequate, and the major problem has been erosion of the silicon mold by evolved hydrofluoric acid. This will be addressed by using lower deposition temperatures or thicker oxide barriers.

conclusions

An effort has been described to fabricate prototype fine modulation collimator grids for HESP. Work to date has encompassed formation of silicon molds by various micromachining techniques, followed by passivation, electrode formation, and electroforming. For full-scale grid fabrication the LIGA process will be used to produce an acrylic mold which will replace the silicon mold. The acrylic mold will either be electroformed with gold to form a Z-contrast structure, or electroformed with nickel to form a first casting for the chemical vapor deposition of tungsten.

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