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Photoresist application for the LIGA process

B. Chaudhuri, H. Guckel, J. Klein, K. Fischer

Abstract Fabrication of high aspect ratio structures requires the use of a photoresist able to form a mold with vertical sidewalls. Thus the photoresist should have a high selectivity between the exposed and the unexposed area in the developer. It should be relatively free from stress when applied in thick layers necessary to make high aspect ratio structures. PMMA (Poly Methyl Methacrylate) is the photoresist of choice in the LIGA process, mainly for its ability to hold vertical sidewalls for tall structures. It is applied to the substrate by a glue-down process in which a pre-cast, high molecular weight, sheet of PMMA is attached to the plating base on a substrate. The applied photoresist is then milled down to the precise height by a fly-cutter prior to pattern transfer by x-ray exposure. The requirement that the applied layer be relatively free from stress dictates the choice of glue-down over casting. The substrate preparation steps, as well as the conditioning of the PMMA sheet prior to the glue-down, are done, in part, to reduce the stress in the glued down sheet of photoresist. The cutting of the PMMA sheet in the fly-cutter requires specific operating conditions as well as particular cutting tools to avoid introducing any stress and the resultant crazing of the photoresist.

1 Introduction

Some of the initial work in the area of LIGA processing was done by Dr Becker et al. who was able to get patterned structures up to 500 microns tall [Becker et al. (1986)]. PMMA was used as a photoresist, which was applied by casting, a process that introduces high levels of internal stress during the curing step. To circumvent this problem, Guckel et al. (1995) developed the glue-down process, whereby a pre-made, stress-free, sheet of photoresist is bonded to the wafer and then subjected to exposure and patterning [Guckel et al. (1995)]. This process has been used with great success. Structures in excess of a millimeter in height have been fabricated [Guckel et al. (1993)].

As a result of the greater demands placed on the performance of the photoresist as a mold for high aspect ratio structures, more care and effort has being expended on the photoresist application process. This has resulted not only in an increase in yield, (that is, a large reduction in the failure of the photoresist), but has also extended the capabilities of PMMA as a photoresist.

2 Substrate and photoresist preparation

Prior to the glue-down step, one must ensure that the two surfaces to be bonded are free of any contaminants. The wafer itself undergoes a stringent cleaning process to ensure that the plating base sputtered onto it has excellent adhesion. A layer of PMMA is spun onto the wafer next. This spun-on layer bonds to the plating base, and the thick PMMA sheet is later glued to this spun-on layer. The spun-on layer of PMMA is necessary since the glue-down is achieved by bonding two surfaces of PMMA together. One has to minimize the exposure of the freshly sputtered surface to the ambient, so that the surface remains free of moisture and oxides, to ensure a good bond between the plating base and the spun-on layer of PMMA. The photoresist used for the spun-on layer is a commercially available, 9% solution of 950 K molecular weight PMMA in chlorobenzene. Other molecular weights for the PMMA can also be used for the spun-on layer, but a higher molecular weight PMMA has better selectivity during the development step. The spun-on PMMA, which is about 1.6 μm thick, is annealed at 180°C to relieve the stress introduced during the application of the photoresist, as well as to cure it. One must make sure that the chlorobenzene is adequately removed since the presence of any chlorobenzene can cause crazing of the spun-on layer of PMMA.

The thick PMMA sheet used is a high molecular weight, pre-cast, commercially available sheet with minimal stress. Its molecular weight is in the range of millions of grams per mole. The sheet is stored in nitrogen ambient since PMMA has a tendency to absorb moisture, which could cause an increase in its volume by about 3%. Since some residual stress may still be present from the manufacturing process, it is annealed at 100°C for an hour, with a gradual ramp-up and a ramp-down. After the sheet is cut to the desired size, the individual

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B. Chaudhuri
Material Science Program

K. Fischer, H. Guckel, J. Klein
Department of Electrical and Computer Engineering
University of Wisconsin, Madison, WI, 53706, USA

Correspondence to: B. Chaudhuri

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pieces are cleaned to obtain a contaminant-free, moisture-free surface. Isopropanol alcohol is used to clean the surface of any residual organic contaminants introduced during the manufacturing process.

3
Glue-down process

Once completely cleaned, the sheet of PMMA is placed on the wafer, ready to be bonded. The edges of the PMMA sheet need to be deburred for it to lie flat on the wafer. It is necessary that the PMMA sheet itself be completely flat. One can observe that the sheet, once it is placed on the wafer, forms circular interference patterns if it is not completely flat. The chances of obtaining a stress-free glue-down are much reduced if the piece of PMMA sheet is not completely flat.

The thickness of the sheet of PMMA used for the glue-down is in excess of a millimeter thick. A thick PMMA sheet allows one to handle the sheet without introducing any stress due to bending of the sheet. A thicker sheet is also better able to resist any deformation due to the capillary forces present during the glue-down step. The earlier practice of milling the sheet of PMMA down to the desired height before the glue-down step had often led to excessive stress being introduced in the PMMA sheet. Non-uniformity in PMMA height would be introduced during the fly-cutting step. As the sheet was thinned, it would flex under the forces of the vacuum chuck used to hold it down during milling. Later, as the milled sheet of PMMA was being glued down to the wafer, the capillary forces that developed, could easily flex the thinned sheet of PMMA, which lead to pockets of air and monomer being trapped under the PMMA sheet. The use of a thick sheet of PMMA for the glue-down step, followed by fly-cutting down to the desired height, has alleviated the problems associated with the glue-down of a thin sheet of PMMA. Sheets ranging in thickness of 1 mm to 3 mm have been used with success.

A monomer, MMA (Methyl Methacrylate), is used to bond the two PMMA surfaces together. About 10 µl of MMA is applied per square inch of PMMA sheet area to be bonded. A micropipette is used to dispense the monomer to the edge of the sheet. The monomer is then drawn to the interface by capillary action. If either of the surfaces the sheet or the spun-on PMMA on the wafer were not clean, the capillary action would fail to draw the MMA to completely cover the entire interface, leading to voids and other defects. Also, if the sheet were not quite flat, then the surface of the sheet in contact with the wafer would receive only a thin layer of MMA, insufficient to form a good bond with the lower layer of the spun-on PMMA. The capillary action that pulls the PMMA sheet down along the edges, as the MMA evaporates or gets absorbed, introduces a stress in the sheet. This stress is later relieved by the crazing of the sheet (Fig. 2a), which makes it unusable for further processing. The capillary force, which draws the MMA into the interface, also depletes the corners of the sheet of monomer. It leads to the corners being poorly bonded to the wafer, and they often lose adhesion during subsequent processing steps. To minimize this effect the corners of the PMMA sheets are rounded, the ideal shape of the PMMA sheet being circular (Fig. 1).

The excess monomer that was applied to the interface is removed by evaporation and by absorption. As the monomer is removed, a non-uniform distribution of monomer exists at the interface. The edges are depleted of monomer much faster than the center. This often causes the edges to lose adhesion. To counter this effect, the sheet is kept pressed flat with a uniform loading, and the wafer is kept enclosed to minimize the evaporation loss. However, the above counter-measure has a drawback. The loading introduces a stress, and the presence of the excess monomer enhances the breaking of bonds, which causes the PMMA sheet to craze. As a result, the loading is applied for a short time only, about a one half-hour, just sufficient to effect the bonding of the two surfaces, after which it is removed and the wafer is kept open under nitrogen so that the excess monomer can be removed by evaporation. To further speed the removal of the excess monomer, the PMMA sheet is fly-cut to the desired final height within an hour after glue-down, so that it is easier for the MMA to diffuse out.

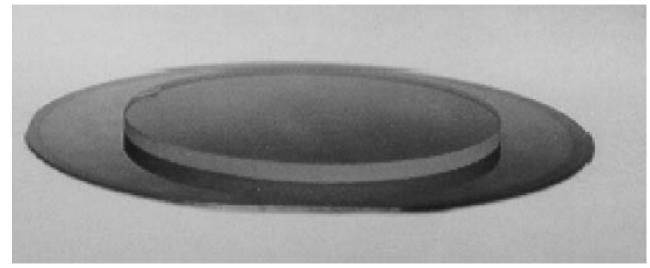

Fig. 1. PMMA Sheet on Wafer

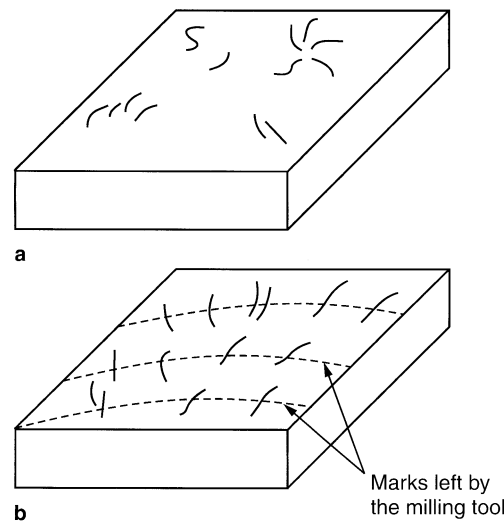

Fig. 2a, b. Crazing due to stress. **a** During glue down; **b** during fly-cutting

4
Fly-cutting

The bonded sheet of PMMA is now ready to be fly-cut to achieve the desired height of the PMMA sheet. A well-bonded sheet of PMMA should be free of any residual stress, and any stress would now be evident from the curvature of the wafer. A stressed sheet of PMMA will lead to the wafer being bent.

Fly-cutting is achieved using a commercially available precision milling machine. The tool used is a diamond tip, or an edge, with a negative rake angle. During fly-cutting one must ensure that the shear stress is kept to a minimum. Removing material by cutting with a negative rake angle introduces a much lower shear stress than cutting with a positive rake angle, which removes material by pushing it along, rather than cutting. The later process introduces a much higher shear stress, and it also smears the top surface of the PMMA sheet. This results in a rather rough non-transparent surface finish, and it has a high incidence of the surface crazing (Fig. 2b).

The initial cuts into the PMMA, done with a diamond tip, are made primarily to remove material. The depths of the cuts are large. This introduces a lot of shear stress and leaves the upper surface of the PMMA rough, with a rms$\hat{Z}$ of about 1.2 μm. The strained surface of the PMMA sheet tends to craze and the milling marks left on the surface of the PMMA sheet allow the initiation of cracks. Thus the top layer of the PMMA has to be removed to prevent crazing. A finishing cut, done with a diamond edge, leaves the surface of the PMMA sheet smooth, with a rms_Z of about 35 nm. The finishing pass, being made at a low feed rate and only a thin layer being removed, minimizes the stress introduced to the surface. This last step is particularly critical in the fabrication of long, thin, very delicate structures of PMMA (as in a fine grating). Any stress on the surface of the PMMA will cause these structures to bend and collapse upon developing the pattern (Fig. 3).

Fig. 4. A 350micron tall metal structure, with the thinnest line being 3 micron in width, producing an aspect ratio of approximately 110:1

Table 1. Fly-cutting parameters

Cut type	initial	final
Tool type	tip	edge
RPM	3000	3000
Feed rate	3.0 mm/sec	1.0 mm/sec
Depth	50 μm	10 μm
rms$\hat{Z}$	1.2 μm	35 nm

(rms_z is the root-mean-square roughness)

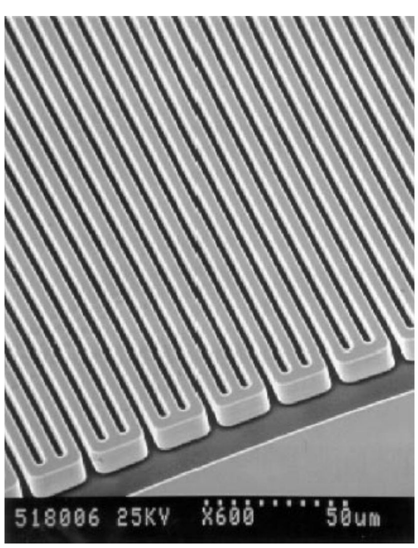

Fig. 3. The fine, metallized gratings, which involve thin PMMA structures several millimeters long, were possible only by having the PMMA completely free of stress. The PMMA structures for the mold of this pattern were unsupported at both ends and 3 microns in width, 6 millimeters in length and 50 microns in height

A good test to determine if the procedure followed for the preparation of photoresist for the LIGA process allows for a stress-free mold for the pattern is the fabrication of weak structures, such as thin, long lines. The pattern used for testing should include delicate structures of the photoresist itself. Figure 3 shows a metal grating made from a PMMA mold. The pattern in the PMMA mold included thin, long lines, the thinnest of which were 3 microns wide, about 6 mm long and 50 microns tall. Such structures were very weak and any stress in the PMMA would have caused it to flex. For example, if some stress were introduced in the upper surface of the PMMA during the fly-cutting step, the top layer of the thin PMMA structure would tend to deform, the lower surface being constrained by the wafer. This would give the thin structure a wavy pattern.

5 Conclusion

A good, repeatable glue-down process is crucial to the success of the whole process of LIGA in general. The improvements just described in the previous sections have increased the confidence in the repeatability of the photoresist application process. It has also allowed the extension of the capabilities of the LIGA process. In conjunction with an improved developing process, one can now, using the LIGA process, fabricate structures previously deemed difficult to make. Shown in Fig. 4 is a metal structure, fabricated using the LIGA process, with an aspect ratio in excess of a 100:1. The width of the thinnest beam is 3 microns and its height is about 350 microns. Such structures can now be repeatedly made, following the procedure described above.

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