Optimizing Fabrication of Electrodeposited 3D Surface Features

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July 1998

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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Summary

Selective electrodeposition onto specially masked surfaces (producing blind holes with non-conductive side walls) has been investigated. The thick masks are low cost polymer sheet into which holes and other patterns are machined. Plating with this type of masking system is one method of fabricating medium aspect ratio metallic structures (structures whose width to length ratio is greater than 10/1). The experiment was conducted with deposits of OFC copper from an acid sulfate solution, but similar results are expected with other metals. Structure diameter varied from 0.25 mm to 3.8 mm (0.01" to 0.150"). The effect of current density, electrolyte concentration, solution temperature, and agitation on deposition rate were investigated. Deposit quality, deposition rate, and optimal plating parameters were evaluated.

Introduction

The typical method of producing 3 dimensional profiles on flat surfaces is by machining. The machining process can be either mechanical (milling), electrical (EDM), or chemical (etching). As the features become smaller the use of these techniques becomes limited. Another method that is available for forming these structures is electrodeposition. This approach requires a non-conductive mask to be applied to the surface of the part. The features are then grown perpendicularly from the surface to their desired dimension. The size of the features are only limited by the mask geometry. Another benefit of electrodeposition is that alloys & composite coatings of various materials can be produced^{1,2,3}, providing properties unavailable by other methods, such as high strength/weight ratios, and unique thermal and electrical properties.

Electrodeposition as a manufacturing technique for high aspect ratio structures has been utilized for several years⁴. For the extreme precision and parallel side walls, ultra-violet light or X-ray lithography is used to pattern special resist layers which are used as masks⁵. This technique has produced parts approaching sub micron size, and aspect ratios greater than 200-1. However much of this work requires expensive equipment to apply the maskant layer and involves resist application, image development, and then carefully controlled electrodeposition. Because many structures do not require the precision of x-ray lithography, a simple approach using conventionally machined plastic masks was investigated.

Experimental procedure

Three masks were produced from different thicknesses of CPVC. Two different hole diameters were drilled into each mask by conventional drilling. The drilled bore was then hand reamed and polished to insure smooth, parallel side walls. This produced 6 resist structures with depth to width ratios from 40/1 to 7.5/1. The diameters and mask thicknesses (depth) are listed in table 1.

Depth mm (inches)	Width mm (inches)	D/W ratio
10.1 (0.40)	0.25 (0.01)	40
6.3 (0.25)	0.25 (0.01)	25
10.1 (0.40)	0.50 (0.02)	20
3.8 (0.15)	0.25 (0.01)	15
6.3 (0.25)	0.50 (0.02)	13
3.8 (0.15)	0.50 (0.02)	7.5

Table 1

A copper sample substrate was chosen for the initial work to reduce the amount of surface pre-treatment required. Substrates were cleaned with detergent and washed with a 10 vol. % sulfuric acid solution. A fixture supporting the substrate and the mask was attached (Fig 1), and then the assembly was immersed into the electrolyte. The normal electrolyte was composed of 175 gm/l $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ + 75 gm/l H_2SO_4 . Current was applied for 24 hours. Using the published electrochemical value for copper (19.75 mg/amp-minute)⁶ the 100% efficiency of copper reduction was obtained

Fig. 1

The first test investigated was the effect of current density. Several different current densities were selected with thickness and mass measurements used to determine plating efficiency. The results are shown in Fig. 2.

Fig. 2

As is expected the current efficiency was reduced as the depth of the mask recess increased. This occurs primarily due to the reduced agitation, and hence reduced copper ion replenishment at the electrolyte/cathode

boundary. Several methods were tested to increase the agitation into the recess; frontal agitation (perpendicular to mask), cross agitation (parallel from side of mask), and bottom agitation (parallel from bottom).

A polyvinyl chloride (PVC) impeller type pump fitted with a 1 micron polypropylene filter cartridge was used for agitation. The flow rate remained constant at 80 liters/minute, but the velocity was varied by reducing the outlet orifice diameter. The velocity value was calculated by using an electronic paddle wheel meter on the pump discharge. By dividing the outlet area (m^2) by the flow (liters/minute). To determine the agitation effect on efficiency the samples with the lowest efficiency (the highest depth to width ratio, and maximum current density) were chosen. As can be seen in Fig. 3, the agitation increase is the greatest when flow is directed across the recess opening. This continuously forces new solution into the mask cavity, replenishing the copper ions, and removing any hydrogen gas bubbles.

Fig. 3

Because the effect of ion replenishment was so important on the efficiency and speed of deposition, a solution that is high in copper and at elevated

temperature should plate faster and more efficiently. To determine an optimum chemistry and operating temperature, four different electrolyte concentrations, and three different temperatures, were investigated. The electrolyte consists of copper sulfate and sulfuric acid. Because the ratio of these materials can be infinitely varied, the choice of concentrations was arbitrarily selected from a defined range; High acid/low copper, low acid/high copper, high acid/high copper, low acid/low copper. Low acid being 50 gm/l, high acid being 150 gm/L, low copper being 25 gm/l, high copper being 200 gm/l. The mask and current selected was 10.1 mm depth (40-1 D/W ratio) and 4.31 amp/dm². Again the substrate was a cleaned copper sheet, to which the mask was attached. The masked sheet was placed into the plating solution and current was applied for 24 hours. The results are listed in Figure 4.

Fig. 4

As can be seen in Figure 4, the LA/HC, high temperature chemistry achieved the best efficiency. This is quite different from plating into conductive recesses where a low metal ion concentration is preferred. This is due to the fact that the surrounding area is also conductive and the primary current distribution is the controlling factor. In the case of non conductive side walls, it is ion replenishment and boundary layer kinetics that limit deposition, and high metal ion concentrations increase deposition efficiency. Although in both cases an increased electrolyte temperature enhances ion mobility and increases maximum current efficiency.

Conclusions

Copper features 0.25 mm (0.01") wide, with depth to width ratios of at least 40/1 can be preferentially deposited onto conductive substrates using low cost non conductive masks. The use of a 200 gm/l $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ + 50 gm/l H_2SO_4 chemistry, a current density of 4.3 A/dm² (40 A/ft²), a temperature of 43 C (110 F), and cross flow agitation, efficiencies can be as high as 83%, resulting in plating rates of 47 $\mu\text{m/hr}$ (0.0018"/hr).

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