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Microelectronic Engineering 61–62 (2002) 1001–1007

MICROELECTRONIC ENGINEERING

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High aspect ratio patterning with a proximity ultraviolet source

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Abstract

A considerably less expensive option to synchrotron exposures of thick film photoresists is to use a proximity UV exposure tool. The use of UV radiation, however, is potentially limited by aerial image degradation as the image propagates through the thick photoresist layer. In addition to diffraction, run-out from uncollimated light or absorption in the resist easily dominate the aerial image problems for thick films. Alternatively, thick film lithography may be limited by the ability of present photoresists to print the aerial image. With some formulations, calculated line-and-space theoretical limits can be printed for 150-μm thick films. Typical aspect ratios for films greater than 200-μm thick exceed 20:1 with good process linearity and sidewall profiles and extension to 700-μm thick films is shown. We show that present commercial formulations of photoresists and not aerial image are likely the limiting factor in the practical resolution of final features from proximity UV printing. In particular, the redeposition of partially dissolved resist during drying after development leads to feature degradation. Released electrodeposited metal parts are also produced and demonstrated. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: SU-8; Photoresist; LIGA; Proximity printing

1. Introduction

One type of microfabrication process that has shown considerable promise is the LIGA process [1], where metallic parts are made via electrodeposition within synchrotron radiation-patterned photomasks. However, synchrotron sources are limited and throughput is low, so inexpensive exposures that lead to metallic parts would be particularly useful. One such inexpensive source is an UV contact/proximity aligner.

A UV contact aligner uses photons in the range of 400 nm vs. synchrotron-based LIGA which utilizes an X-ray distribution of several nanometers critical wavelengths. From the aerial image perspective, the use of longer wavelength photons for lithography typically induces the question of

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PII: S0167-9317(02)00491-4

diffraction. From the material perspective, however, it is critical that a resist be able to accurately print or improve the theoretical resolution of the exposure tool. With any lithographic technology, therefore, the question arises as to whether the printed features are representative of shortcomings in the aerial image or whether they are representative of shortcomings in the photoresist. It is important to the progress of the technology to clarify this issue.

Theoretical diffraction limits for UV exposure are considerably superior to tolerances attainable in traditional machining techniques. Therefore, even nondiffraction limited printing can produce useful parts. In addition to resolution, however, photolithography has several other strengths such as accurate and repeatable placement of features relative to each other. In this regard, some applications can take advantage of the low cost exposure method as long as an end-to-end process exists for making parts.

Producing electrodeposition molds with a UV source requires a different photomask material. There has been some work in diazonapthoquinone (DNQ)/Novolac-based resist chemistries to create films up to and greater than 100-μm film thicknesses [2,3]. However, low thermal stability of the photoactive DNQ makes it difficult to remove the solvent from spun cast thick films without using radiative driers. In addition, the DNQ produces nitrogen with exposure which tends to produce bubbles in thick films and has high absorbance due to the direct photolysis mechanism. Finally, the DNQ requires water for the reaction, so long rehydration times may be necessary after post-apply bake (PAB) and the novolac-based materials tend to crack. Because of these drawbacks, much attention has been focused elsewhere.

SU-8 photoresist was developed by Gelorme et al. [4] for printed circuit board fabrication, and has been consistently reported to print the highest resolution features from UV sources as well as superior sidewall fidelity [5]. SU-8 polymer used as a resist is negative tone which apparently crosslinks sufficiently to repel swelling in an organic developer. This high crosslink density produces the undesired side-effect of making it difficult to remove, and removal is the subject of a companion paper [6]. In this paper we show the resolution capability of SU-8 exposed with a standard proximity aligner and show that many improvements to printed feature fidelity can be made by varying only the resist. In addition, we show electrodeposited parts made from this process.

2. Experimental

A typical process for a 150-μm thick film of photoresist based on SU-8 polymer (69% polymer, MicroChem, Newton, MA, USA) is to spin at approximately 1000 rpm for 15 s, and bake 5 min at 85 °C. The wafer is cooled and returned to the spin chuck and the edge bead is removed under flowing acetone at a lower spin speed. The post-apply bake (PAB) is ramped from room temperature to 95 °C at 2 °C/min, held for 15 min before it is ramped down to room temperature at 1 °C/min. Exposure was done on a Karl Suss MA/BA6 aligner typically under soft contact. A postexposure bake (PEB) was ramped from room temperature to 85 °C at 2 °C/min, held typically for 15 min, and ramped to room temperature at 1 °C/min. Development was done in crystallization dish with SU-8 Developer (MicroChem) for approximately three times the clearing time for a large, unexposed area. After development, the wafer was baked in a convection oven, ramping from room temperature to 110 °C at 1 °C/min, held at 60 min and returned to room temperature at 1 °C/min to harden the material for postplating lapping operations. Ni and Ni–Fe electrodeposition was performed using sulfamate and/or sulfate aqueous electrolytes at pH 3–4 a plating temperature of 50 °C, 0.5 M boric acid, 0.2 g/l

surfactant, and a nominal metal ion concentration of 1 M. Removal of the SU-8 mold after electrodeposition is detailed in a companion publication [6].

3. Results and discussion

3.1. Resolution of SU-8 with proximity aligner

In an attempt to quantify lithographic capability of SU-8 under exposure to UV radiation, Flack et al. addressed process latitude and linearity [7]. They showed that SU-8 printed with good linearity though tended to print with a process bias. Fig. 1 shows that SU-8 materials can be printed with excellent linearity and little or no process bias at 150-μm thick films. The linearity measurement indicated that no egregious aerial image or materials issues resulted from UV printing down to 12.5 μm line-and-space (L/S) for these geometries. In addition to linearity, however, it was desired to determine whether the actual diffraction-limited imaging could be attained or whether some other degradation mechanism was occurring. Cullman et al. [8] showed aerial image resolution in proximity printing of line/space patterns to be governed by $2b_{\min} = 3\sqrt{[\lambda(s + d/2)]}$, where $2b$ is the grating, λ is the exposure wavelength, s is the gap and d is the resist thickness. If we assume good contact so that $s = 0$, the period resolved for 365 nm incident light can be 15.8 μm for a 150-μm thick film and 41 μm for 1-mm thick films. Thus, a 20.5-μm line within a L/S pattern should be possible for a 1-mm film or a 49:1 aspect ratio. In order to determine whether the calculated aerial image was possible, the 150-μm film thickness was optimized. Fig. 2 shows a cross-section SEM of a 150-μm thick film L/S pattern that was 10 μm on the mask. The actual lines measure approximately 8 μm in this image, but two things are clear. First, the calculated aerial image can be resolved, though the

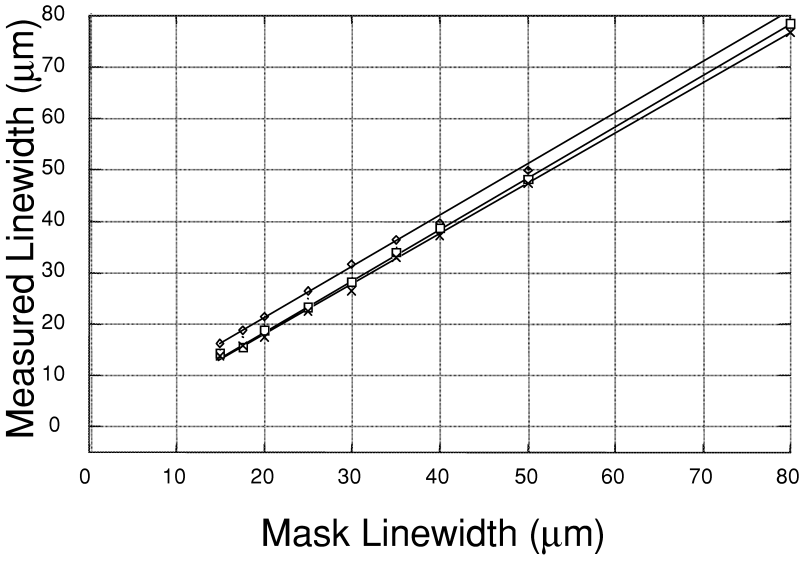

Fig. 1. Linearity measurements for 150-μm thick SU-8 films. There appears to be excellent linearity through 12.5 μm L/S patterns with little process bias.

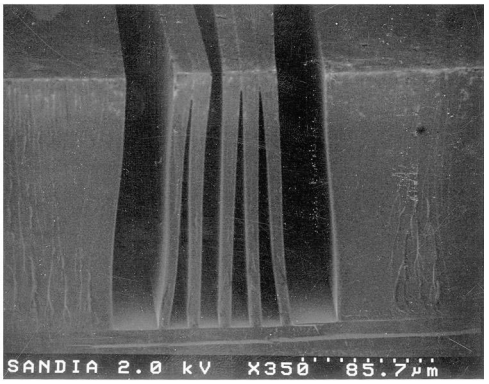

Fig. 2. Cross-section SEM of L/S patterns printed with UV broad band exposure. The mask pattern was 10 μm L/S and the features measure 8 μm.

patterns measure less than the mask features, indicating that some aerial image/resist problems are occurring. Second, limitations of printing the feature are clearly due to resist. This figure illustrates two common limitations. The first is pattern collapse and the second is that the sidewall of bulk features is bowed presumably due to shrinkage and will be discussed below.

The prior results focused mainly on line-and-space (L/S) patterns. However, another perceived fundamental problem with UV printing is sidewall slope. This at least can be due either to uncollimated light or to absorption in the resist material. Because SU-8 does not use direct photolysis for the solubility mechanism, but instead relies on the photolysis of a catalyst-producing compound which crosslinks the network during the PEB, it is a particularly transparent resist. Nonetheless, some resin and initiator absorption can potentially produce absorption-degraded images. Fig. 3 shows a variety of images that address the sidewall angle. Fig. 3a shows a 105-μm thick film with a 6.5-μm trench in cross-section. The sidewall slope produces less than 1 μm of image distortion throughout the 105-μm thickness. Fig. 3b shows some lower resolution patterns that are 350 μm thick. Fig. 3c shows a 700-μm thick isolated line in cross-sectional SEM. Because the line would fall over, a zig-zag pattern is printed and cleaved. The top of this feature measures 12 μm while the bottom measures 10 μm, for an average aspect ratio of 66:1 and a line variation of approximately 2 μm over 700 μm.

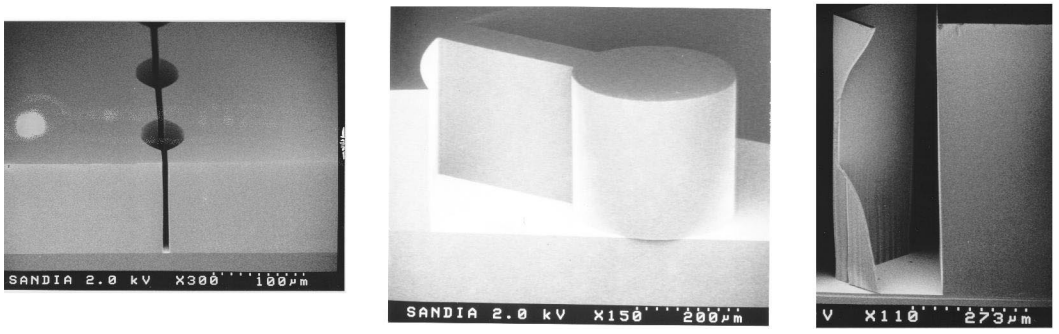

Fig. 3. (a) A 6.5-μm trench in 105-μm thick film in cross-section. (b) Large parts in 350-μm thick mold. (c) Average 11-μm wide line in 700-μm thick film. The line is a cross-section of a zig-zag pattern.

Some undulations are observed in the pattern near the bottom of the 700-μm thick image. As this time, it is not clear if this is a result of shrinkage/mechanical instability in the resist or some product of the aerial image. It is clear from these images that sidewall slope can be minimized to provide greater than 89° if necessary.

3.2. Resolution limitations

The prior section indicated that the theoretical resolution limit of proximity printing is possible with the present system, and that sidewall run-out can be minimal for SU-8 based patterning. However, other feature degradation mechanisms persist. In particular, we have found that the largest contributor to feature degradation is the redeposition of partially dissolved resist material during the drying process after development. Fig. 4a shows L/S patterns in cross-section that indicate this phenomena. When viewed in cross-section, it is clear that the space has been developed throughout the trench, while top-down microscopy would indicate that the features were not resolved. Indeed, the resist was able to record the aerial image, but surface tension/redeposition processes did not allow the feature to withstand the development. Proper control over the molecular weight distribution of the resist may help alleviate this problem [9]. Fig. 4b shows a similar issue with a grating-type pattern. In this case, the feature has been cleared out underneath and the surface webbing can be cleared out with an etch step. However, this indicates that pattern-specific issues with SU-8 can be dominant, even if the aerial image considerations are quite favorable. Finally, Fig. 4c shows an isolated feature in cross-section. Isolated patterns tend to appear most favorable by top down microscopy because they do not stick via redeposition to neighboring features and are less susceptible to shrinkage. However, close inspection of the top indicates that there is a several μm thick layer on top of the feature. Redeposited species is still present in this feature, but the detrimental effects are not realized. Some degree of agitation during development may mitigate this issue as well as some additive species, but for commercial formulations, this process significantly degrades the observed resolution capabilities.

Finally, another major pattern degradation mechanism was expected to be film shrinkage. On occasion, large bulk pads show bowing in cross-section that indicate shrinkage such as in Fig. 2. However, this can be alleviated with proximity features near the desired printed geometries as isolated lines rarely indicated detrimental shrinkage effects and features of several hundred microns in dimension (Fig. 3c) typically do not indicate similar effects from shrinkage. Film shrinkage due to

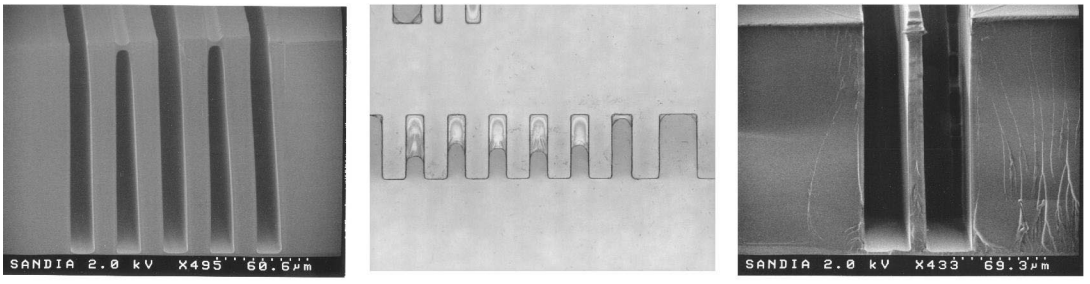

Fig. 4. Examples of resolution limitations of SU-8. (Left) SEM cross-section of L/S patterns. Redeposition causing pattern collapse. (Middle) Top-down optical microscopy. Top-layer webbing on grating structure. (Right) Cross-section SEM of isolated line. Top of isolated line clearly shows 1–2 μm thick scum layer.

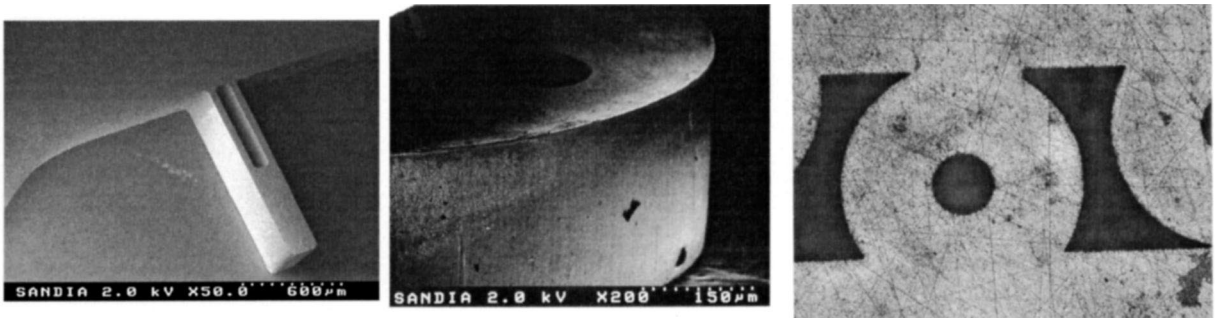

Fig. 5. Metallic parts made from SU-8 molds. (a) 250-μm thick mold in NiFe. (b) Sidewall angle of 250 μm thick gear in Ni. (c) Top down microscopy of 630 μm thick Ni structure. The scratches are due to lapping.

crosslinking appears to be less problematic for feature fidelity than originally expected and appears to be easily mitigated with proximity features, though its affect on wafer bowing has been reported [5].

3.3. Parts

It is clear from the preceding sections that photoresist SU-8 can realize the theoretical resolution of proximity printing, but that other feature degradation mechanisms can make process implication difficult. While it may be possible to circumvent the redeposition problem with the use of photoresist additives [9], it is also clear that larger features, and some with geometrically favorable patterns are readily obtained using SU-8. To show the complete utility, then, electrodeposited parts are shown. Fig. 5 shows three different parts made from SU-8 molds. Fig. 5a shows NiFe part of 250-μm thick. The thinnest ligament is 12.5-μm thick and the SU-8 mold was removed by molten salt bath as discussed in a companion article [6]. Fig. 5b. shows a 250-μm thick gear pattern from the side indicating the straight sidewalls. Removal of the SU-8 was done with downstream chemical etching[1]. Finally, Fig. 5c shows a top-down optical micrograph of a 630-μm thick Ni base plate. The holes in the picture are large by microlithography standards, but the precise and repeatable registration of the holes makes the use of this inexpensive method practicable. The SU-8 mold was removed using a molten salt bath.

4. Conclusions

Proximity printing of electrodeposition molds using a UV source is an inexpensive alternative for microfabrication of metallic parts. We have shown that calculated L/S pattern resolution limits can be achieved, 66:1 aspect ratio features of in 700-μm thick are possible for favorable feature geometries, and sidewall run-out of $<1\%$ can be achieved. However, present resolution is largely limited by the redeposition of partially dissolved resist and mechanical instabilities in the features. Electrodeposited parts can be produced with this process which take advantage of some of the strengths of

[1]CA. Downstream chemical etching was performed at matrix integrated systems in Richmond.

microlithographic based microfabrication such as registration of parts and superior resolution to other metal fabrication techniques.

Acknowledgements

The authors would like to thank Steven Leith for electrodeposition. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the US Department of Energy under contract DE-AC04-94-AL85000.

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