LOW-COST MASKLESS GRAYSCALE LITHOGRAPHY USING A NEW PHOTO-DEFINABLE POLYIMIDE FOR POLYMER MEMS APPLICATIONS

Joseph H. Lake, Kevin M. Walsh and Shamus McNamara
Dept. of Electrical and Computer Engineering, University of Louisville, Louisville, KY, USA

ABSTRACT

We present the novel use of a positive-tone photosensitive polyimide for the rapid production of grayscale features using a maskless lithography system including several sample geometries to illustrate the general capabilities of this method. Commonly used in the fabrication of MEMS and other micro-scale devices, polyimide films are known for their extreme mechanical and thermal stability [1,2,3]. Unfortunately, photo-definable polyimides historically have possessed significantly limiting critical properties, i.e. decreased elongation, low tensile strength and high film stresses. The use of a new polyimide, HD-8820, overcomes these limitations and allows direct patterning of polyimide into complex geometries without the need for imprinting, plasma etching or other secondary processing steps [4]. The entire fabrication sequence, from CAD file to cured structure, can take only 4 hours making this a fast, low-cost method of producing polymer MEMS devices with excellent mechanical properties.

INTRODUCTION

Historically, *non*-photo-definable polyimides have excellent mechanical properties, negative-tone polyimides have moderate and positive-tone polyimides poor mechanical properties. Because development occurs first at the surface of the exposed film, a positive-tone is preferred over a negative-tone for grayscale lithography. HD Microsystems HD-8820 is an ideal candidate for this type of fabrication in that it is a positive-tone polymer exhibiting improved mechanical properties [4].

S. Akbar, et. al. presented the use of pyrolyzed grayscale features made from HD-8820 as an implantation barrier. In this investigation, an electron beam exposure of silver doped HEBS glass was used to produce the requisite grayscale mask [5]. This non-MEMS application used the traditional, mask-based approach to grayscale lithography. HEBS masks are very expensive and time consuming to generate, require the use of e-beam lithography, and reduce the ability to quickly move through multiple design iterations.

This work presents the use of HD-8820 as a structural device layer using a direct write exposure system. The use of direct write lithography, especially during early prototyping phases, has the ability to reduce cost and shorten the time needed for a design iteration, even if a traditional grayscale mask is used for final device production.

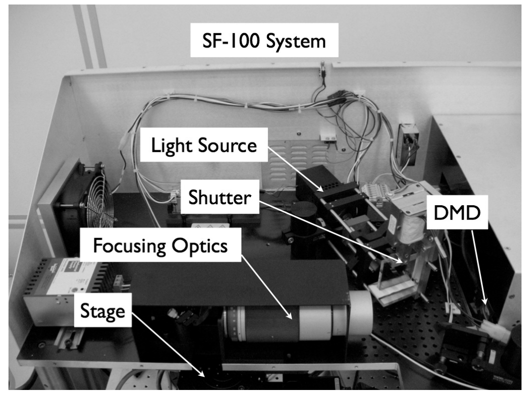

Figure 1: Layout of SF-100, DMD-based maskless lithography system used for grayscale exposures.

FEATURE GENERATION

The SF-100 DMD-based (Deformable Mirror Device) maskless lithography system from Intelligent Micro Patterning Systems was used for this research (Fig. 1). This system accepts standard 32-bit bitmap files as input

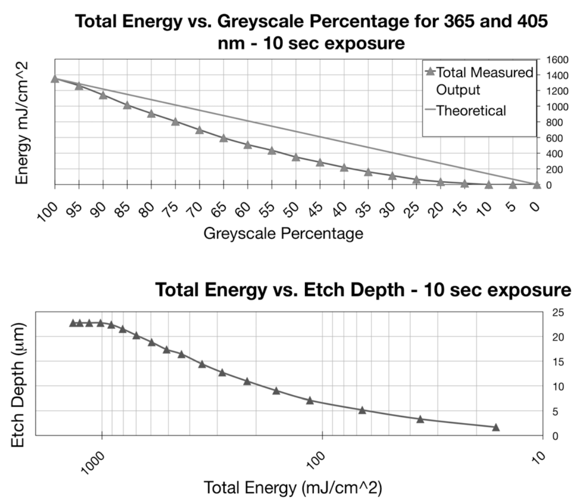

Figure 2: (Top) Combined h and i-line energy output from SF-100 compared to expected theoretical energy for a 10 second exposure for grayscale range 100 (white) - 0% (black). (Bottom) Etch depth vs. dose over same grayscale range. 100 - 85% resulted in complete development for 10 second exposure.

allowing designs to be generated in many standard graphics, desktop publishing or CAD packages. The designs presented in this work were generated using Omnigraffle running under Mac OS 10.5.5 using a 15 mm x 13 mm canvas. This canvas size corresponds to the frame size of the SF-100. Multiple frames can be used and stitched together to form larger structures. The design was then exported as a 1680 dpi TIFF file, at this resolution there is a 1:1 correlation between drawn pixels and mirrors in the DMD array. This direct match between drawn and physical pixels reduces the likelihood of conversion errors. AutoVue was then used to convert the design to the final BMP file required by the lithography system.

GRAYSCALE CHARACTERIZATION

The DMD system was characterized by measuring the energy output as a function of the input percentage. Figure 2 (top) shows the total energy for h and i-line wavelengths measured at 5% increments with 100% being white and 0% representing black. These data, along with profilometry measurements, allow etch depth to be correlated to dose (Fig 2 – bottom, Fig 3). This relatively broad contrast curve makes this polyimide an ideal candidate for the production of grayscale structures. Further investigation of this data will open the possibility of process simulation in the future.

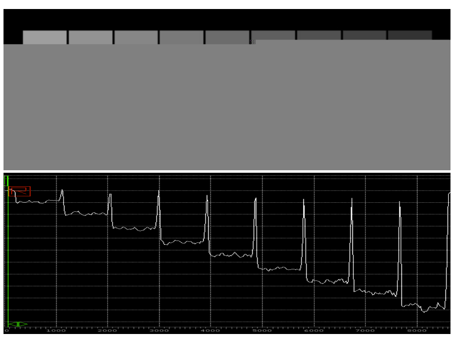

Figure 3: Example grayscale pattern generated using OmniGraffle (top). Contact profile of as developed HD-8820 film, before cure surface roughness is visible (bottom).

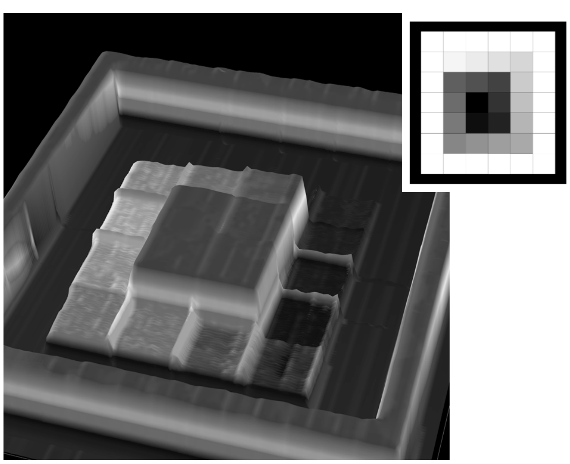

Figure 4: 3-D profile of as developed HD-8820 structure measured with Dektak Profilometer. Grayscale pattern (inset) composed of 300 µm squares spiraling from 0% (black) in the center to 100% in 5% steps produced in OmniGraffle. Overall film thickness for this sample is 22.5 µm.

Table 1: Spin Development recipe used for grayscale exposed HD-8820 films. This recipe was repeated 4 times for a 20 µm nominal thickness.

Development Cycle

Speed (RPM)	Time (sec)	Chemical Spray
1000	3	MF-319
50	3	MF-319
0	40	NA

A range of nominal film thicknesses, approximately 4 to 20 µm, is possible by varying spin parameters [4]. After spinning, the films were soft baked on a hot plate in an air atmosphere at 123° C for 3 minutes. These films were then exposed using the IMP system using a 10 second exposure. Initial attempts at pan development resulted in damage to unexposed areas of the polyimide film. A spin development recipe was developed as shown in Table 1. This spray development was followed by a DI rinse and spin dry. After development the film was cured using a hot plate with controllable ramp and N_2 blanket to reduce oxidation during the high temperature cure. This final cure is performed in two stages, ramping from room temperature to 200°C at 4°C/min with a 30 minute soak and from 200°C to 350°C @ 2.5°C with a 60 minute soak. The hot plate was then allowed to cool to room temperature while maintaining the N_2 blanket.

Figures 3 and 4 show the ability of this method of grayscale lithography to reproduce completely arbitrary patterns. The pixel size used to produce the structures shown in figures 3 & 4 is 15 microns. Although this is not the smallest pixel size available using this system, decreases in feature size lead to a reduction in the size of the exposed area.

Surface roughness was measured after development (Fig. 5) and after final cure (Fig. 6). The peaks shown in figure 5, correspond to the individual micro mirrors in the DMD's array. The peak-to-peak distance of 15 µm matches the pixel size of the exposure system. Ra was measured to be 11.2 nm immediately after development. This roughness improved greatly after the final cure of the polyimide (Fig. 6). The fully cured polyimide film had a Ra of 4.4 nm. This final surface roughness makes this

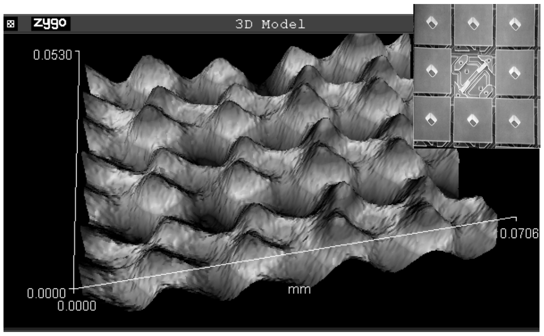

Figure 5: 3-d profile of surface roughness prior to final cure measured with Zygo interferometric system. 15 μm peak to peak distance (red) corresponds to the individual micro-mirrors in DMD array. Ra = 11.2 nm. (Inset) SEM image of DMD array (Texas Instruments).

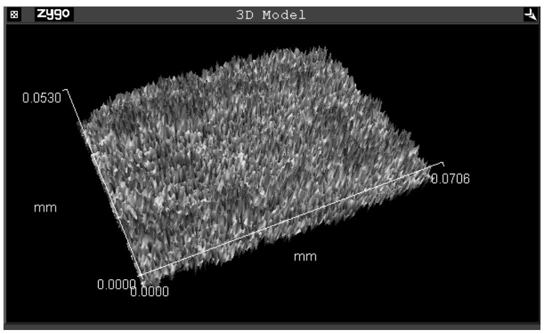

Figure 6: 3-d profile of surface roughness after final cure measured with Zygo interferometric system. Corners of mirrors are still visible, but Ra reduced to 4.4 nm.

polymer more than acceptable for most MEMS applications, including many optical device applications.

CONCLUSIONS

This initial study of the use of grayscale exposed HD-8820 shows that this polymer has great potential in this area. The ability to use direct write lithography to produce arbitrary features in polyimide presented here, removing the need for the costly production of grayscale masks, opens new fabrication sequence possibilities especially in the area of device prototyping. The ability to quickly move through design iterations without the time and expense of generating a grayscale mask for each cycle should help move this lithography method into more mainstream use. Additionally, given that dry etching can be a very costly and time consuming processing step during production, the ability to replace this process, while maintaining good electrical and mechanical properties, makes the use of HD-8820 combined with grayscale lithography an especially attractive option for the large scale production of MEMS and microelectronic devices and systems.

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Contact: Joseph H. Lake
joseph.lake@louisville.edu
Dept. of Elect. and Computer Engineering
University of Louisville