Improved Grayscale Lithography

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***Abstract*— Commercially available laser lithography systems have been available for several years. One such system manufactured by Heidelberg Instruments can be used to produce masks for lithography or to directly pattern photoresist using either a 3 micron or 1 micron beam. These systems are designed to operate using computer aided design (CAD) mask files, but also have the capability of using images. In image mode, the power of the exposure is based on the intensity of each pixel in the image. This results in individual pixels that are the size of the beam, which establishes the smallest feature that can be patterned. When developed, this produces a range of heights within the photoresist which can then be transferred to the material beneath and used for a variety of applications. Previous research efforts have demonstrated that this process works well overall, but is limited in resolution and feature size due to the pixel approach of the exposure. However, if we modify the method used, much smaller features can be resolved, without the pixilation. This is achieved by utilizing multiple exposures of slightly different CAD type files in sequence. While the smallest beam width is approximately 1 micron, the beam positioning accuracy is much smaller, with 40 nm step changes in beam position based on the machine's servo gearing and optical design. When exposing in CAD mode, the beam travels along lines at constant power, so by automating multiple files in succession, and employing multiple smaller exposures of lower intensity, a similar result can be achieved. With this line exposure approach, pixilation can be greatly reduced. Due to the beam positioning accuracy of this mode, the effective resolution between lines is on the order of 40 nm steps, resulting in unexposed features of much smaller size and higher resolution.**

Keywords—Grayscale Lithography, Laser Lithograph, Surface Engineering

I. Introduction

One particular method of writing lithography masks involves the use of laser lithography systems, such as the Heidelberg µPG-101[1][2]. The system uses a small diameter UV laser along with a precise positioning system. As built, the device is provided from the manufacturer with a guaranteed beam diameter not to exceed 1 µm, and with a positioning step size of 400 nm in both the X and Y dimensions. Because other models are available from the same manufacturer with more precise positioning capabilities, parts and software commonality suggests that higher accuracy can be achieved on this model, but cannot be guaranteed with this particular machine design as most manufacturers save significant cost in carrying commonality between product lines. Also, the exact diameter of the beam may be slightly smaller than 1 µm. Both of these characteristics are critical in defining the smallest feature which can be realized.

The system as supplied operates with software which provides two different modes. The first is image based and provides the ability to perform basic grayscale lithography. The second is line-scan based which operates at much higher precision but uses a single power and duty cycle, offering only one level of exposure. It is possible to create a hybrid approach which combines these two methods. This technique is similar to methods that have been proposed for some time, but lacked the technology to conduct the process[3][4].

In this paper, the process will be demonstrated with a specific application in mind: the fabrication of a micro-contact surface, but the technique is more widely applicable. The objective is to produce extremely small, controllable areas in a pattern well beyond the capability of the system using the default tools provided. This requires the addition of third party emulation software [5], which offers a great deal of flexibility for a variety of applications.

II. Background

The system as supplied includes software which allows for two modes of operation: grayscale image exposure or direct writing using computer aided design (CAD) files.

A. Grayscale Image Exposure

The first mode utilizes images instead of CAD files, and doesn't produce a binary mask, but rather a contoured, 3D surface. In this mode, each pixel within the image is scaled down to the size of the beam (1 µm) as illustrated in Fig. 1. The system then positions the beam at each pixel location and scales the amount of power delivered based on the shade of gray of that particular pixel. When the photoresist is developed, these regions of partial exposure only result in partial removal. The final result is photoresist with a three dimensional topology.

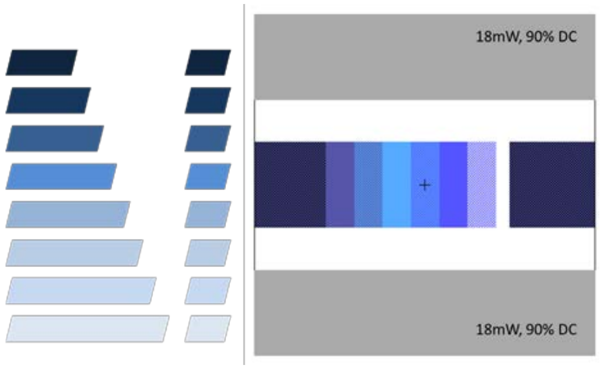

Fig. 4.. Illustration of seven step exposure test files used to evaluate various power and duty cycle settings for determining optimal recipe for multiple exposure processes.

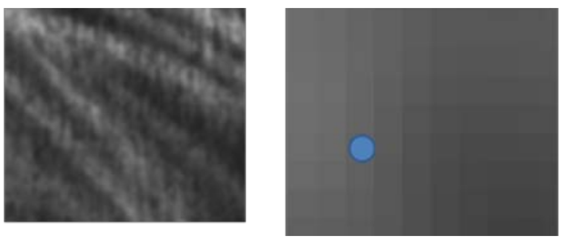

Fig. 1. Illustration of bitmap image based grayscale lithography in which individual pixels are scaled to the size of the beam and exposure is determined by overall grayscale of each pixel.

B. Line Scan Exposure

The second mode of operation utilizes files designed in CAD software which establish basic geometric shapes. To print the shapes, the software determines the number of lines which need to be written to be able to fully expose these regions such as that shown in Fig. 2. Before printing, both the power and the duty cycle of the laser is set by the user, and everything within these regions is exposed to the laser at those settings. Typically this method is used by setting these parameters high enough to fully expose these regions, which completely removes photoresist in these selected areas. The beam positioning is calculated using the full resolution capability of the system, and because continual lines of exposure are used this allows for the highest resolution of the machine's capability to be realized.

C. Hybrid Exposure

Consider Fig. 3 below, which illustrates the hybrid grayscale concept. Instead of the standard method of grayscale exposure, this approach uses several different CAD designs along with repeated, low-dose exposures to achieve the same effect as the bitmap approach, but with the resolution of the CAD approach. This does however require characterization of how much power must be used in each step to achieve repeatable depths of exposure, as well as the ability to run several repetitive runs, but offers the potential of superior results.

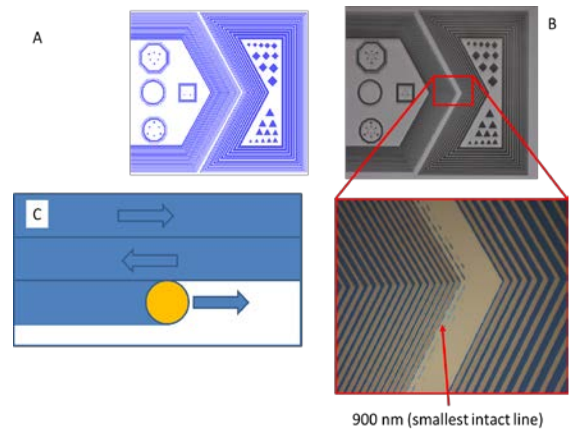

Fig. 2. Conceptual illustration of lithographic printing from a CAD-based file (A), resulting in fully exposed or unexposed areas (B). To accomplish this, the beam used to print is swept horizontally along pre-calculated lines (C), and beam is activated and deactivated to expose only the geometric shapes provided.

III. METHODOLOGY

The first step was to characterize what power levels and duty cycles achieved the desired results. Various combinations of power and duty cycle were characterized using a combination of simple rectangular shapes which partially overlapped. The results were used to determine which recipes provided optimal exposure as shown in Fig. 4 below. Characterization was performed using a seven step process, which was intended to yield recipes more suited for two, four, and six step designs.

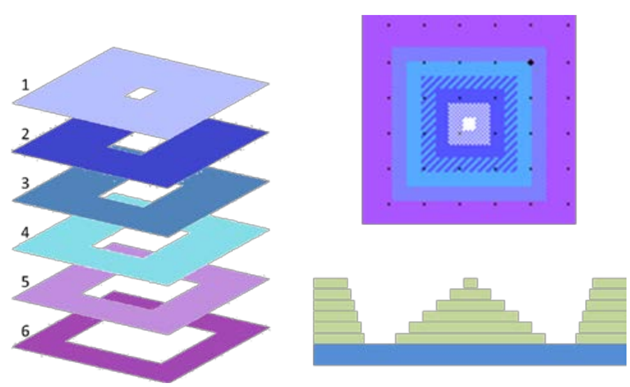

Fig. 3. Improved grayscale method in which multiple CAD exposures are used repeatedly over the same section of photoresist resulting in similar three-dimensional featuring as the image-based grayscale method, but with the resolution capability of CAD-based printing.

One approach was to manually execute the required exposures at multiple locations and at multiple settings, but this repetition would have quickly become a daunting task for a full wafer of devices. Consider a single 3 inch wafer which contains approximately 250 reticles. Each reticle contains up to 16 micro-contacts, and each contact may require up to six steps. This would have required 24,000 repetitive runs on this laser lithography system. While each run required only a few seconds, the process of loading and positioning this number of files would have become overwhelming. To address this, an additional level of automation was applied using keyboard and mouse emulation.

Once the CAD files were created for the various layers used in the contacts, these were stored on the Heidelberg system. Next, the exact position of each of the reticles was stored in a text file, along with the position of each device within the reticle, as well as the desired power and duty cycle for each step of the process. This file was run through a second program which translated this information along with the names of the design files into a script file which was loaded directly by the emulation software. A segment of the text file, and screenshot of the script writing software is shown in Fig. 5.

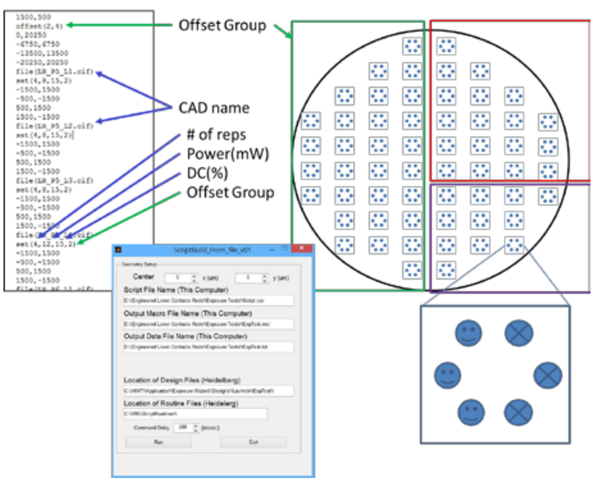

Fig. 5. A segment of code used to define offset groups, files to be printed, and locations within each reticle. This file contains the exact list of files to be printed, location of each printing, the order, power, and duty cycle for each exposure. This text file is fed into script generating software and the resulting file is then run using a 3rd party emulator for autonomous zone-based printing across an entire wafer utilizing any number of patterns and print locations.

When the script file was saved to the Heidelberg system and executed, it performed all the necessary file loading, offset positioning, parameter setting, and exposure triggering for each layer of the process. The software then waited for confirmation at each step, which came in the form of observing the expected change in the images on the screen. If each step was executed correctly, then the system behaved as expected and the emulator was able to continue. However, if anything unexpected occurred, the emulator waited for a conformation screen which never appeared, and it did not proceed. Thus, this process was run safely and autonomously without the need for constant oversight.

This particular system was manufactured with a guarantee of 400 nm beam positioning accuracy, but the manufacturer produces other models with much higher resolution. These high-resolution systems were much larger and heavier, which is presumably a requirement to hold these higher tolerances through vibration resistance. This does not mean however that they do not use similar control hardware and motors, and therefore the actual resolution of this system may be better than the guaranteed 400 nm. If this was true, then we should have expected to see at higher resolutions more variability in the shapes of identical repeated features. Testing this characteristic of the system was accomplished with two sets of design files designed for the task. The first set was with low-resolution files built under the assumption that 400 nm was the smallest step size available. A second set was built with 80 nm step sizes, which was considerably better but not the highest theoretical resolution. A sample of these two cases in Fig. 6 shows the impact of both the step size resolution and beam width on the overall designs desired for this application. Note that the two sample lower contact pads were sized for a 6 µm radius upper hemispherical contact bump.

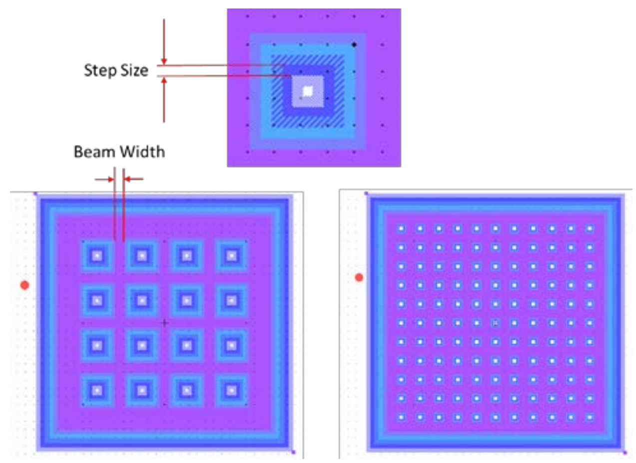

Fig. 6. Impact of beam size and positioning error on a repetitive pattern. Step size dictates the smallest change in features between layers and beam width dictates pitch based on clearance between the largest patterns. The red dot to the left of the lower figures indicates the relative size of a 1 µm diameter beam, and the resulting patterns permitted for a six step process. The left shows the smallest features and pitch spacing for 400 nm step size accuracy and on the right the smallest feature and pitch spacing for 80 nm step size accuracy.

This step size was important not only because it defined the size of the smallest feature, but along with the beam width, established the minimum possible pitch between features. As shown in Fig. 6, the beam must pass between the outermost patterns, which ultimately determined the pitch. Patterns which utilize only two steps however were placed much closer than those with six steps, which is also explained in this figure.

With this automated run capability in hand, the characterization of the system was addressed in order to produce our 3D structures using the rectangular patterns shown in Fig. 3. With these CAD files, we devised a series of test exposures at various combinations of powers and duty cycles, which are shown as a matrix in Fig. 7.

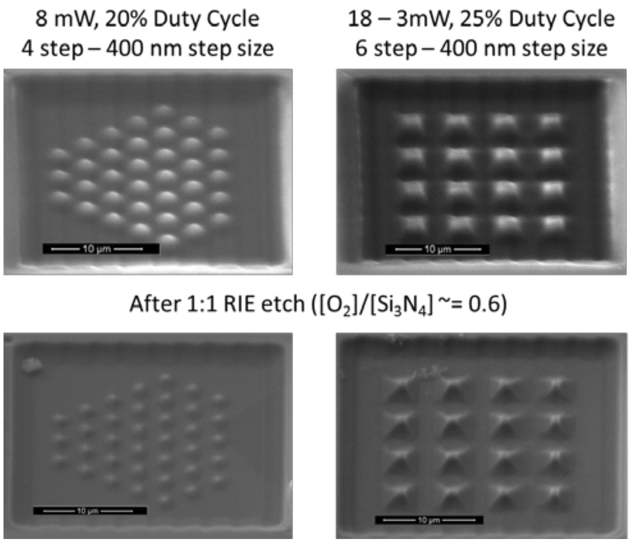

Fig. 10. SEM imagery showing grayscale patterned photoresist (top figures) and patterned silicon nitride (bottom figures) after 1.0 selectivity RIE etch for circular close packed formation (left), and rectangular 3-D pyramid formation (right).

In this figure, power was either held constant for all seven layers, incrementally decreased, or incrementally increased. For the powers ranging from 1-7 mW, the step size was 1 mW per layer, and for the 3-18 mW the step size was 3 mW. Similarly, the duty cycle was either held constant, incrementally increased or decreased. For the 20-80% ranges, the step size was 10% per layer, and for the 3-21% ranges the step size was 3%. The positioning of each run was arranged in a similar matrix on the test wafer. Each successful pattern resulted in a staircase which was measured by a profilometer to determine the incremental change for that particular recipe.

IV. Results

Fig. 8 shows the results from measuring a single power and duty cycle setting. The top shows a microscope image of the staircase pattern measured and the bottom shows the resulting profilometer depths for each step. Note that the bottom of the scale was from the upper and lower wells which were patterned separately at 18 mW and 90% duty cycle, in order to identify the true thickness of the photoresist.

The automation capability discussed earlier was applied to this approach, resulting in all 42 test cases shown. The resulting cross sections were then plotted against the images for each case. This was used to identify several recipe settings which were suitable for our purposes as shown in Fig. 9. To test two, four, and six layer patterning capabilities, the cases circled were all potential solutions after some minor adjustments.

Using this information, patterning lower contact surfaces was performed in photoresist, then etched into the nitride substrate, and the results were evaluated. Two wafers were run, the first used patterns designed to test the 400nm

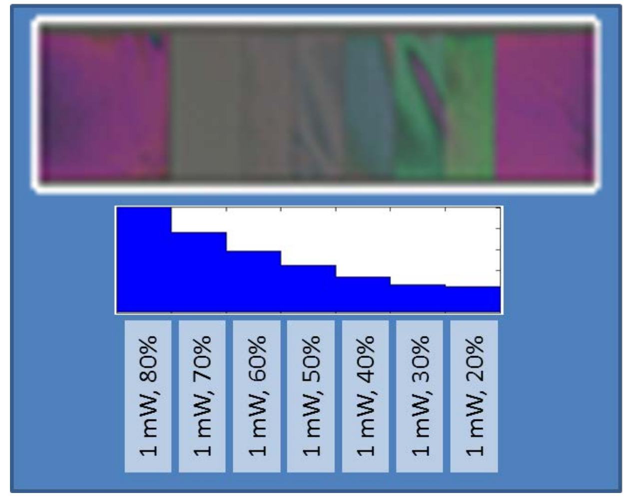

Fig. 8. Image showing one resulting pattern from exposure study and corresponding profilometer data below illustrating the resulting cross-section, step change resulting from multiple exposures at the power and duty cycle indicated for each step.

positioning limit discussed earlier. The second attempted to push this limitation and used patterns with only 80nm of spacing to see if usable features resulted.

These results were imaged using an SEM, then exposed to an RIE etch with a selectivity of ~1.0, and re-imaged. Fig. 10 shows two sets of results from this low resolution test. The upper two images show the photoresist, and the lower are the results obtained from imaging the silicon nitride. The left pattern was a simple, close-packed configuration using a 4 step design and the right was a six step repeating pyramid structure. The images of the resulting silicon nitride illustrated that the features did transfer, however they seemed to be much shallower than the photoresist versions, indicating a selectivity which favors the photoresist to the nitride.

A second wafer was run with designs which assumed an

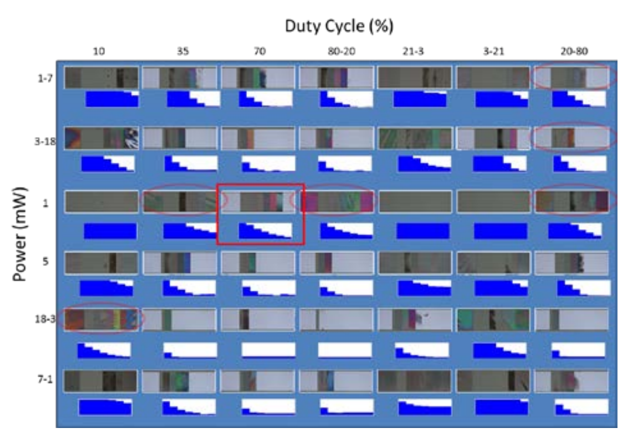

Fig. 9. Matrix showing the resulting images from various combinations of power and duty cycle using the seven step process with corresponding profilometer data cross-section profiles below each run showing relative depths of each step. Circled cases represent candidate recipes for use in 2, 4, or 6 step processes with uniform depth change per step.

80nm horizontal tolerance could be held. A comparison of a 400nm 2-D pyramid ridge structure to an 80nm 2-D structure is shown in Fig. 11. While the height of the features using this much finer resolution was noticeably reduced, it performed well considering it was using designs which were 1/5 the resolution which should have been possible.

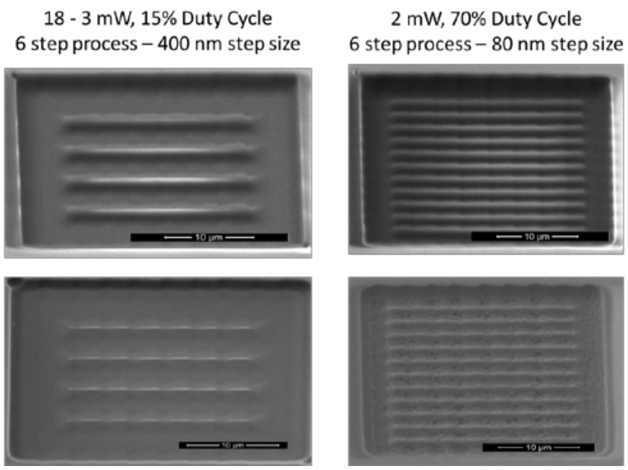

Fig. 11. SEM imagery showing comparison of six step designs for horizontal 2-D pyramid structures for both the 400 nm step size (left), and 80 nm step size (right). The top images show the patterned 1800 photoresist and bottom shows the resulting pattern after an RIE etch with selectivity of 1.0.

Finally, one last pair of images is provided from another pattern fabricated at this higher resolution and is shown in Fig. 12. In these images, it is clear that the repeatability was greatly reduced when exposure at this resolution is performed. For the purposes of creating repeated structures for a micro-contact surface this variability severely limited the reliability of any results. However, these results are encouraging enough however to indicate that features finer than 400nm can be fabricated with this system, and should be further explored.

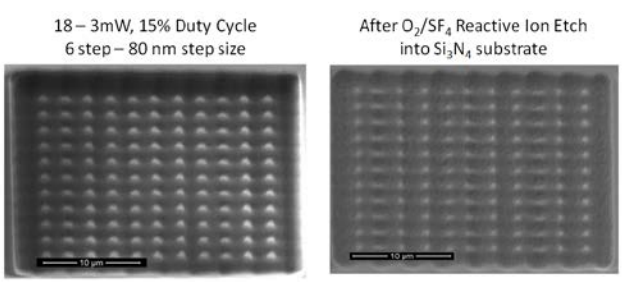

Fig. 12. SEM imagery showing patterned photoresist (left) and resulting post etch nitride (right) for the six step, 80 nm step size design.

V. Conclusions

A new method of grayscale lithography was attempted. This method utilized the high resolution capabilities of operating the Heidelberg µPG-101 system with CAD files in line scan mode. To achieve 3-D features, multiple CAD files were used in succession. This resulted in final products which were superior to what could be achieved using an image patterning approach.

Due to the repetitive nature of the process, software was implemented to automate the repeated exposures. This resulted in a reliable, safe method to operate the system in this manner without requiring human supervision. Additionally, this prevented the possibility of errors which would likely result from attempting to perform this sort of process manually.

Two feature resolutions were attempted, one which assumed the 400nm horizontal accuracy advertised by the manufacturer was the best that could be achieved, and another which pushed this by a factor of 5 and attempted 80nm accuracy. While many of the features at this higher resolution were still realized, repeatability for this application was an issue and the best resolution is likely somewhere between these two resolutions.

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