Repair of step and flash imprint lithography templates

W. J. Dauksher,[a] K. J. Nordquist, N. V. Le, K. A. Gehoski, D. P. Mancini, and D. J. Resnick
Motorola Labs, Microelectronics and Physical Sciences Laboratory, Tempe, Arizona 85284

L. Casoose
Freescale Semiconductor, Tempe, Arizona 85284

R. Bozak, R. White, J. Csuy, and D. Lee
RAVE LLC, Delray Beach, Florida 33445

(Received 2 June 2004; accepted 21 September 2004; published 13 December 2004)

In order for step and flash imprint lithography (S-FIL) to become a truly viable manufacturing technology, infrastructure including template repair must be commercially available. Extensive template repair studies were undertaken using RAVE's nm 650 tool which is predicated on an AFM platform and relies upon a nanomachining technique for opaque defect removal. On S-FIL templates, the standard deviation for depth repairs in quartz from the target depth was found to be 3.1 nm (1σ). At 21.5 nm (1σ), the analogous spread in edge placement data for opaque line protrusions was somewhat higher. Trench cuts through lines were successfully created with a minimum size of about 55 nm. The effectiveness of the repairs on the template was verified by imprinting experiments. The range of depth offsets studied $(-15 \text{ to } +15 \text{ nm})$ had no bearing on the imprinting process. The edge placement on wafers virtually mirrored the edge placement of the repaired templates. Connections between features which were created by trench cuts on the template were filled with the imprint monomer and measured slightly larger than the minimum gap size. Finally, imprinted wafers were used to pattern transfer features into 100 nm of oxide. © *2004 American Vacuum Society.* [DOI: 10.1116/1.1815300]

I. INTRODUCTION

Imprint lithography continues to be a budding technology that is attracting significant attention, both from the perspective of semiconductor manufacturers and from tool manufacturers. In fact, this interest has been mirrored by International Sematech, which recently responded by placing imprint lithography on the ITRS roadmap as a potential candidate for 32 and 22 nm fabrication. Within the arena of imprint lithography, one form of the art that is particularly appealing is step and flash imprint lithography (S-FIL). In short, S-FIL employs a transparent template which is pressed with low force into a low viscosity, photosensitive material.[1,2] After a through-the-template exposure step, the cured image on the wafer can be used as a high resolution masking layer for subsequent pattern transfer of a film on the substrate. Prospective applications for S-FIL include fabrication of filters, waveguides, and photonic crystals.

In order for S-FIL technology to successfully make the transition from a research and development technique to a viable manufacturing processing technique, 1× template infrastructure needs to be both defined and supported. In particular, this dictates the requirement for fast e-beam tools with appropriate resolution and image placement,[3] inspection,[4] and repair capabilities, all of which must be commercially available. In the present article, the first attempts at repair of S-FIL templates will be discussed at length.

For the purpose of studying repair capabilities, S-FIL templates were e-beam written on 6 in. × 6 in. × 0.25 in. (6025) plates with a special programmed defect pattern. This pattern was comprised of subsections which contained line edge defects, point defects, dual defects (adjacent line edge and point defects), line-end bridging defects, and line edge bridging defects. In turn, each of these defects existed in both tones and in a variety of sizes down to 50 nm.

RAVE manufactures a commercially available repair tool, the nm650, predicated on nanomachining with an atomic force microscope-based (AFM) platform. Extensive repair studies were conducted on the nm650 to evaluate the viability of such a technique for S-FIL template repair. For example, removal of simulated opaque defects will be outlined in the context of edge placement and the impact of repair depth. Further repairs were enacted using "mouse bites" in lines as a starting point for milling through the lines. Extendibility of the RAVE nm650 tool will also be covered.

We have previously observed that even small template imperfections such as regions of ion trenching at the base of the quartz features replicate faithfully when imprints are made. Given this perspective, imprinting with the repaired S-FIL templates was conducted, and scanning electron microscope (SEM) data collected. Finally, ultimate confirmation of the effectiveness of the repairs was determined via pattern transfer into an underlying oxide layer.

II. EXPERIMENTAL METHODS

The S-FIL templates were fabricated by first depositing 15 nm of Cr on standard 6025 quartz mask blanks. A Leica

---

[a] Electronic mail: axyx50@motorola.com

VB-6 HR electron beam exposure system operating at 100 kV was used to image ZEP520A resist spun on top of the Cr.

The actual pattern was written in four 25×25 mm areas centered in each of four quadrants on a 6025 plate. In turn, each template quadrant had a 2×2 matrix consisting of two positive and two negative tone die, and two die with and without extra defects that could be used for die-to-die inspection. Various types of defects were present down to a feature size of 50 nm.

Following a descum step, pattern transfer of the Cr was accomplished using a Cl_2/O_2-based process in an Unaxis VLR dry etch tool. The remaining resist was then stripped in a 5 H_2SO_4:1 H_2O_2 piranha solution. Subsequently, the Cr was used as a hardmask during a CF_4 ICP dry etch process to define relief in the quartz to a target depth of 100 nm. All of the dry etch processes used to create S-FIL templates have been previously described in the literature.[5]

After stripping the Cr hardmask in a wet etch solution, representative top-down images were collected on a Hitachi S-7800 critical dimension (CD) SEM. Defect studies were conducted at RAVE using their nm650 nanomachining tool. Comprehensive data was collected on the 6025 plate prior to dicing. Individual 1 in. templates were then cut from the 6025 plate with a diamond saw.

Double-side polished 200 mm wafers were employed for imprinting studies. An oxide layer of 100 nm thickness was deposited via plasma enhanced chemical vapor deposition (PECVD). The wafers were then coated with 200 nm of DUV30J antireflective coating (ARC), manufactured by Brewer Science. A photosensitive imaging layer of 9 wt.% Si was imprinted with the template patterns in an Imprio 100 tool manufactured by Molecular Imprints Inc. Once again, the repaired defect sides were imaged via SEM. The bilayer imprint stack was then used to pattern transfer the underlying oxide film. Finally, after stripping the residual imprint bilayer, the oxide features were imaged.

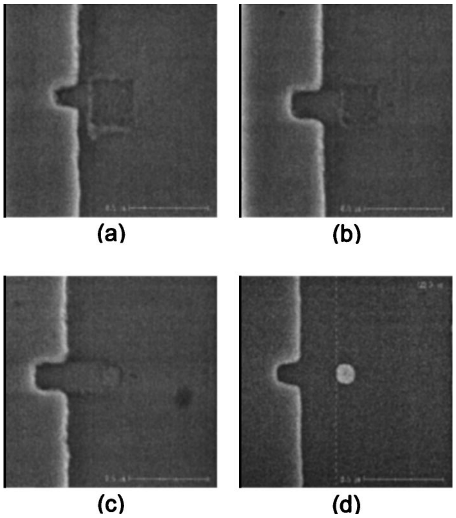
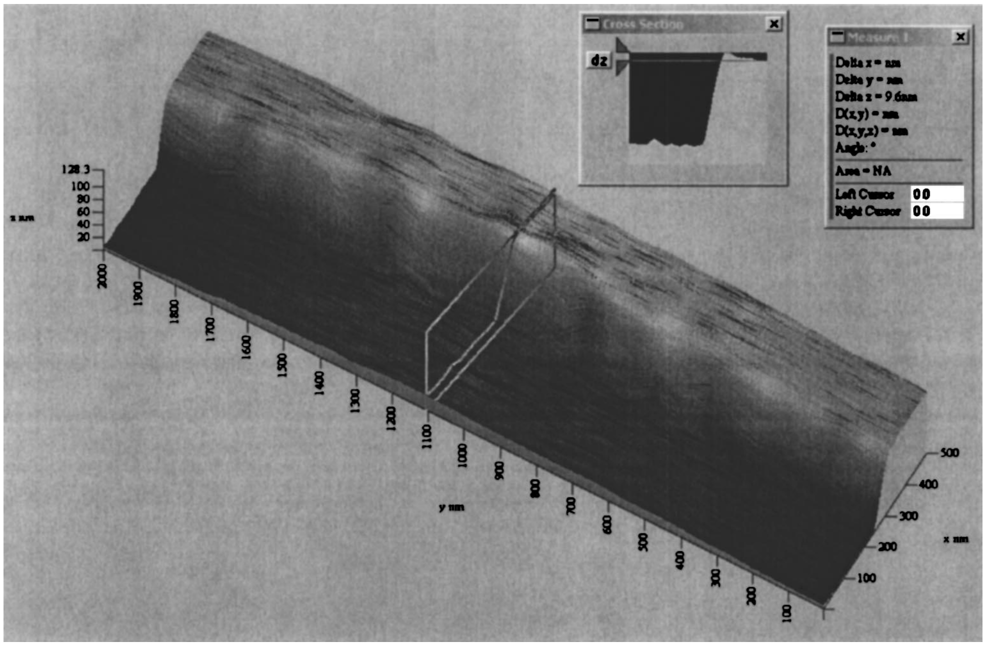


FIG. 1. SEM images of repaired regions on a template after nanomachining to remove pillars. Three different target depths were chosen: (a) deep or positive depth; (b) zero offset; and (c) negative depth. An unrepaired pillar (d) is also shown.

III. REPAIR TOOL

Very briefly, the RAVE nm650 nanomachining system is based upon coupling a proprietary nanomachining head to an AFM platform.[6] After loading and aligning a template, coordinates imported from an inspection tool or equivalent can be used to drive the stage to a defect of interest. High NA optics are utilized to image the region in which the defect resides.



Delta x = nm
Delta y = nm
Delta z = 9.6nm
D(x,y) = nm
D(x,y,z) = nm
Angle: °
Area = NA
Left Cursor 0.0
Right Cursor 0.0

FIG. 2. AFM image of a template section nanomachined to remove a protrusion. The sectional analysis indicates a slightly negative repair.

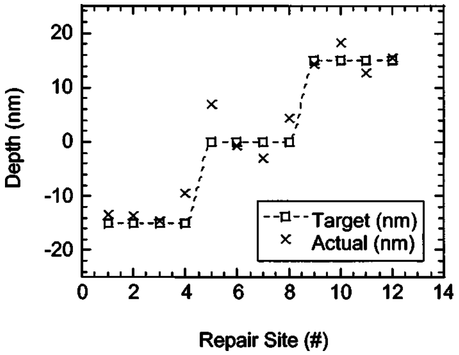


FIG. 3. AFM data indicating the actual repair depth on a template for three different target depths of −15, 0, and +15 nm. Close agreement is observed.

Next, the subnanometer resolution of the AFM is exploited to image the defect precisely and then repair it. In this manner, the nm650 system can be applied to remove opaque defects on S-FIL templates. By virtue of the technology employed, the nm650 is only applicable for subtractive repairs; additive repairs could, for example, be enacted using ion beam induced deposition or the analogous e-beam method. After all defects have been repaired, the mask is unloaded and a cryogenic cleaner is employed to remove any debris generated by the repair process.

Repairs conducted on S-FIL templates with the nm650 targeted three types of studies: depth of the repair, edge placement, and extendibility. Each of these repair types will be detailed in the next section.

IV. TEMPLATE REPAIR RESULTS

A. Depth effects

Using RAVE's vernacular, the Z offset is defined to be the depth of the machined repair relative to, in this case, the relief surface of the S-FIL template. A positive Z offset implies trenching into the template, whereas a negative Z offset means a residual quartz protrusion exists where the defect was not completely removed to the relief surface.

Shown in Fig. 1 are SEM images of a deep, a shallow, and a negative repair after nanomachining pillars in the field regions. Note that the box sizes are expected to be different, as the cut boxes were drawn by freehand. For the sake of reference, an unrepaired pillar with a CD of approximately 120 nm is also pictured in the lower right-hand corner of Fig. 1. AFM data collected on the nm650 tool suggests the depths of the respective cuts are 15.5, 4.3, and −9.4 nm, as compared to targets of +15, 0, and −15 nm. To a first approximation, it is not anticipated that these relatively small Z offsets will impact the S-FIL pattern transfer process. As long as the substrate is not deeply gouged, small positive Z offsets will translate into slightly thicker regions of etch barrier. An AFM image of a depth cut with a negative Z offset of about 15 nm may be found in Fig. 2.

For the purpose of understanding control and repeatability of the Z offset, a series of pillars was removed from a S-FIL template. The data, as plotted in Fig. 3 for 12 such sites, records both target depth for a given repair and actual depth as measured via AFM. Collectively, the standard deviation for delta from target is very good: 3.1 nm (1σ).

B. Line edge defects

The ability of the repair tool to precisely remove extra material such as protrusions up to a line edge is referred to as edge placement. Similar to the Z offset, a positive edge placement is defined by removal of extra material, and a negative edge placement means an amount of material that should have been removed is left behind. For S-FIL templates, edge placement has more significance than Z offset because the edge placement manifests itself directly as a CD error.

Figure 4 contains AFM images of a line edge defect be-

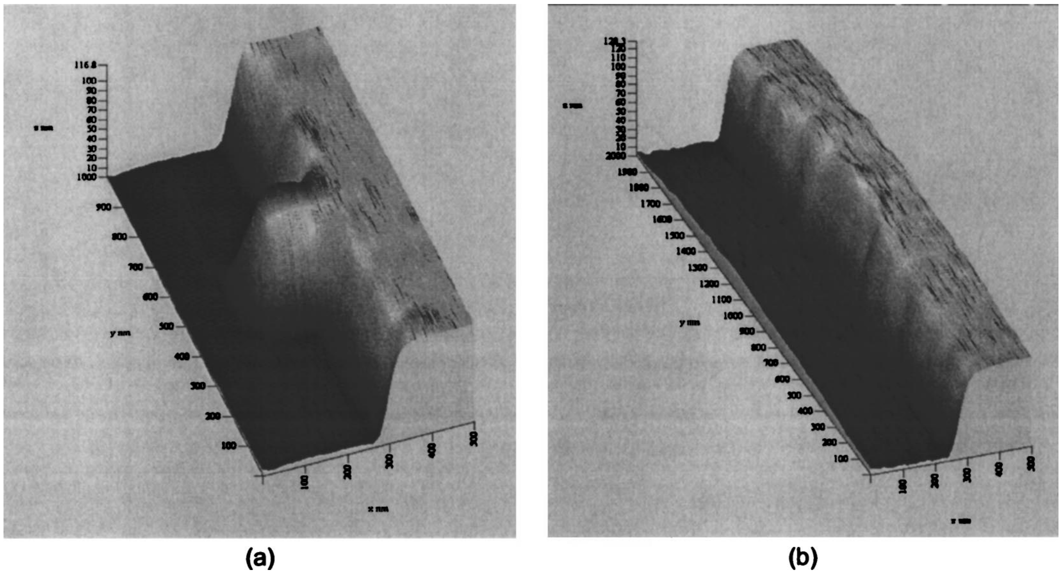


FIG. 4. AFM images of a line edge defect (a) before and (b) after nanomachining a template. The edge placement for this site was found to be about 22 nm.

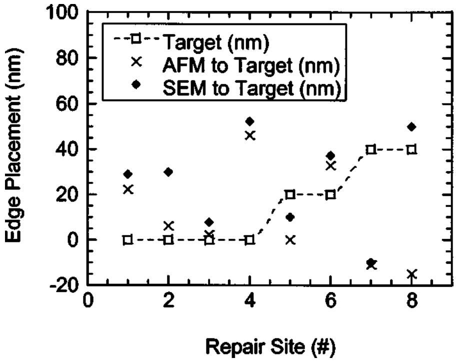


FIG. 5. Plot of edge placement as a function of target for eight template repair sites. Target edge placements of 0, 20, and 40 nm were selected. Deviations from target are shown, as measured both by AFM and SEM.

fore and after nanomachining operations. As defined by the *in situ* AFM, the edge placement is 22 nm. The line edge defect repairs enacted attempted to hit three edge placement targets: 0, 20, and 40 nm. Plotted in Fig. 5 is repair data listing edge placement as determined by both AFM and SEM as a function of the edge placement target. It can be seen that, with the exception of site 8, the AFM and SEM data track fairly well. Regardless of which measurement technique is used, the spread in the edge placement data is on the order of 21.5 nm (1σ). RAVE typically observes edge placement on the order of 10 nm. Since the S-FIL substrate is similar to standard reticle materials, the reason for this disparity is not currently known.

C. Trench cuts

Using a programmed defect "mouse bite" in a line as a starting point, nanomachining cuts were made to mill through a line in a direction perpendicular to the long axis. An exemplary cut is shown in Fig. 6. The gap created in the line using this technique is informative inasmuch as it provides information on both repair resolution and profile. As measured by SEM, the average gap at the bottom of the trench was found to be 55.0 nm ± 6.4 nm (1σ) on the 6 sites repaired in such a manner. Further, the SEM image indicates that a taper is present in the sidewalls of the gap as created by the tip geometry. In all but one case, this taper appears to be very smooth and uniform. Solely on the basis of measuring the CD at the bottom of the trench versus at the top of the trench, an approximation of the sidewall angle was determined to be about 117.5°.

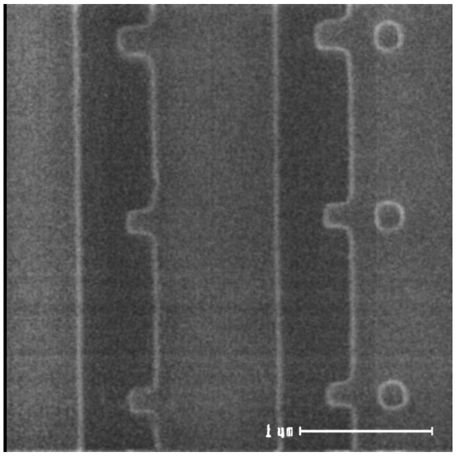


FIG. 7. SEM images of an imprinted etch barrier film. The three holes missing from the left-hand side of the image correspond to pillars on the template that were repaired. A barely discernable shadow where the bottom hole should be is the only evidence that a repair was enacted.

V. IMPRINT DATA

In order to verify the effectiveness of the repairs on the template, actual imprints were made, and the repaired sites were then imaged. In the SEM micrographs referred to in this section, the brighter regions define areas in which approximately 100 nm of etch barrier is present. Similarly, the darker regions represent areas where only a residual layer is present due to quartz features on the template during the imprint process.

As suspected, the depth defects created by nanomachining pillars to different depths did not measurably affect the imprinted features. A picture of an imprinted wafer is shown in Fig. 7. In this picture, the three missing holes represent regions in which pillars were nanomachined away on the template used for the imprinting process. In fact, the three repaired defects shown in Figs. 1(a)–1(c) are actually images of the template that was used to create the repaired imprint of

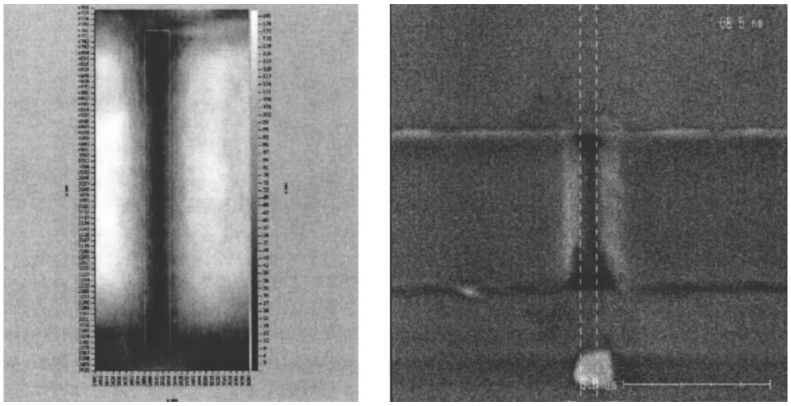


FIG. 6. AFM image (left) from the RAVE nm650 repair tool showing a line that was cut on a template using a mouse bite as a starting point. SEM inspection (right) suggests a tapered sidewall with a gap of 58.5 nm.

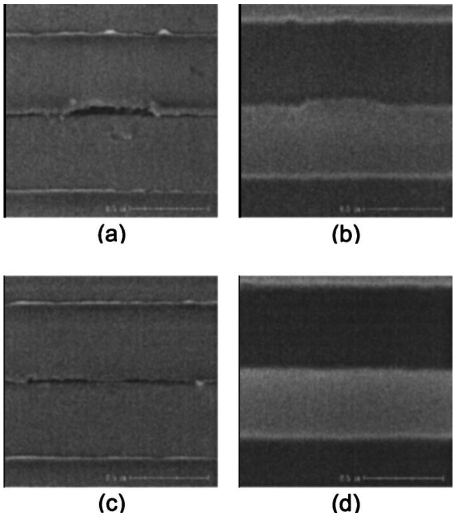


FIG. 8. SEM images of (a, c) repaired template regions and (b, d) the corresponding imprinted areas on wafers. See the text for details.

Fig. 7. The faintest trace of a shadow where the bottom hole would be is the only indication that a repair was even made. It is possible that vertical shrinkage of the etch barrier partially tempers any subtle relief that might have been observed due to Z offsets in the repair process. At any rate, the range of Z offsets studied in the present work do not seem to have an impact on the S-FIL imprint process.

Edge placement on imprinted wafers was found to be virtually identical to the edge placement on the templates. In Fig. 8(a) is a SEM image of a line edge defect repaired with a positive edge placement. The defect encroaches into the quartz line on the template by 51.7 nm. The corresponding imprinted region on the wafer [Fig. 8(b)] is mirrored by the imprinting process but otherwise replicates the edge placement of the template precisely. On the wafer, the edge placement measures 46.5 nm. Analogously, SEM images of a line edge defect repaired with a targeted zero edge placement are also shown for the template [Fig. 8(c)] and the imprinted wafer [Fig. 8(d)]. In this case, the edge placement of the template is near the noise of the SEM, and the imprinted line is of very good quality. As mentioned above, very good correlation was generally observed between edge placement on the templates and imprinted dies. As measured by SEM, the standard deviation of the delta CD measurement between template and imprinted die was found to be 8.6 nm (1σ). Therefore, the ability to control edge placement very tightly will be required by any technique used to repair S-FIL templates.

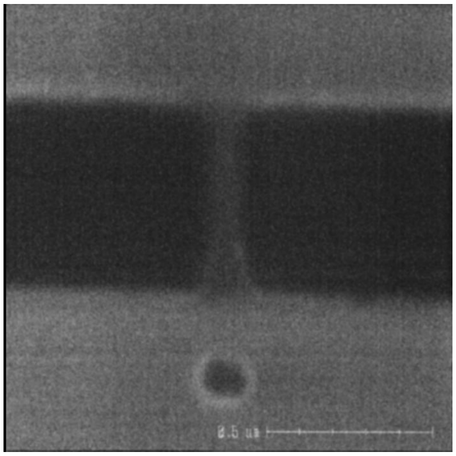


FIG. 9. As imaged by SEM, a trench defect after imprinting into the etch barrier. The area of the original mouse bite can be clearly seen.

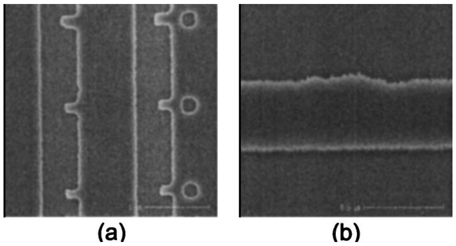


FIG. 10. Representative SEM images showing pattern transfer into a 100 nm oxide film. Regions that correspond to (a) nanomachined pillars and (b) an edge placement study on the imprinting template are shown.

Trench defects were also imaged after imprinting, as shown in Fig. 9. The etch barrier now connects adjacent features in trench areas that were nanomachined away. CD measurements of the etch barrier connections were found to measure larger than data collected on the templates. However, this is not surprising since a slope in the etch barrier is present and no attempt was made to force the SEM algorithm to measure either the top or the bottom of the etch barrier connection. The connection in Fig. 9, for example, measured 69.5 nm.

VI. PATTERN TRANSFER DATA

The imprinted films were used, in turn, as a mask to pattern transfer features into a 100 nm oxide film. Representative SEM images are shown in Fig. 10. Note that now the darker regions indicate the presence of an oxide film, and the lighter regions are underlying silicon where the oxide has been etched away. Figure 10(a) is the oxide-etched complement to Fig. 7, and Fig. 10(b) continues the sequence in Figs. 8(a) and 8(b). Details of the pattern transfer process are beyond the scope of this article and will be presented in another forum. What can be said, though, is that the etch process faithfully replicates the imprinted layers. Therefore, ever-increasing control of the repair process will be necessary as S-FIL technology evolves to smaller and smaller critical dimensions.

VII. CONCLUSION

As infrastructure requirements such as e-beam imaging, inspection, and now repair become available to support the requirements of S-FIL, the technology becomes more and more attractive from a manufacturing perspective. For the first time, a demonstration of repair of S-FIL templates was conducted using RAVE's nm650 tool which relies on nanomachining via an AFM head. Control of the repair of template defects was found to be 3.1 nm (1σ) for depth and 21.5 nm (1σ) for edge placement. Extendibility of the technique to mill trenches as small as 55.0 nm through lines was also demonstrated. Repair efficiency was demonstrated by imprinting with a repaired template. Finally, the imprinted layers were used to successfully pattern transfer an oxide film 100 nm thick.

ACKNOWLEDGMENTS

The authors are particularly appreciative of the efforts of Motorola Lab's Microelectronics and Physical Sciences Laboratory for fabrication of the S-FIL templates. Additionally, this work was funded in part by DARPA (N66001-02-C-8011).

[1] M. Colburn, S. Johnson, M. Stewart, S. Damle, T. Bailey, B. Choi, M. Wedlake, T. Michaelson, S. V. Sreenivasan, J. Ekerdt, and C. G. Willson, Proc. SPIE **3676**, 171 (1999).

[2] T. C. Bailey, D. J. Resnick, D. Mancini, K. J. Nordquist, W. J. Dauksher, E. Ainley, A. Talin, K. Gehoski, J. H. Baker, B. J. Choi, S. Johnson, M. Colburn, M. Meissl, S. V. Sreenivasan, J. G. Ekerdt, and C. G. Willson, Microelectron. Eng. **61**/**62**, 461 (2002).

[3] W. J. Dauksher, D. Mancini, K. J. Nordquist, D. J. Resnick, P. Hudek, D. Beyer, and O. Fortagne, Microelectron. Eng. **75**, 345 (2003).

[4] H. F. Hess, D. Pettibone, D. Adler, K. Bertsche, K. J. Nordquist, D. P. Mancini, W. J. Dauksher, and D. J. Resnick, J. Vac. Sci. Technol. B, these proceedings.

[5] W. J. Dauksher, D. P. Mancini, K. J. Nordquist, D. J. Resnick, D. L. Standfast, D. Convey, and Y. Wei, J. Vac. Sci. Technol. B **21**, 2771 (2003).

[6] R. White, M. Verbeek, R. Bozak, and M. Klos, Proc. SPIE **4562**, 213 (2002).