

Self-limited self-perfection by liquefaction for sub-20 nm trench/line fabrication

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2009 Nanotechnology 20 465305

(<http://iopscience.iop.org/0957-4484/20/46/465305>)

[The Table of Contents](#) and [more related content](#) is available

Download details:

IP Address: 128.112.48.116

The article was downloaded on 26/03/2010 at 15:52

Please note that [terms and conditions apply](#).

Self-limited self-perfection by liquefaction for sub-20 nm trench/line fabrication

Yixing Liang, Patrick Murphy, Wen-Di Li and Stephen Y Chou¹

NanoStructure Laboratory, Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA

E-mail: chou@princeton.edu

Received 29 July 2009, in final form 28 September 2009

Published 22 October 2009

Online at stacks.iop.org/Nano/20/465305

Abstract

We proposed and demonstrated a new approach to pressed self-perfection by liquefaction (P-SPEL), where a layer of SiO₂ is used as a stopper on one sidewall of gratings, to self-limit the final trench width in P-SPEL to a preset stopper layer thickness, allowing a precise control of the final trench width without the need to control any pressing parameters such as pressure, temperature and the gap between the pressing plate and the substrate. We achieved 20 nm wide trenches from a 90 nm original width, reducing the original trench by 450%. We also observed improvement in the trench width uniformity. Using the fabricated resist trenches as templates, 20 nm metal lines were achieved by lift-off.

(Some figures in this article are in colour only in the electronic version)

As conventional lithography techniques are approaching their limits, either in resolution or in cost, the development of a path-changing method that improves a nanostructure pattern after its fabrication becomes increasingly significant. Recently, one of such methods, self-perfection by liquefaction (SPEL), has been developed [1, 2]. One form of the SPEL is pressed-SPEL (P-SPEL), where the width of a trench or the diameter of a hole in a material layer (e.g. resist) on a substrate gets reduced to sub-10 nm while the line edge roughness being smoothed out significantly (>200% improvement) and the shape of the hole being perfected into round shape [2].

But P-SPEL, although offering post-fabrication improvements that cannot be obtained directly in conventional nanofabrication, needs a precise control of the gap between the top pressing plate and the substrate, which in turn determines the final trench width, and needs being well controlled over entire wafer,—all are very challenging. Here, we propose and demonstrate a self-limiting process to P-SPEL, which eliminates the need of such controls. Using the self-limited P-SPEL (SP-SPEL), we achieved 20 nm trenches and lines from initial 90 nm trenches with 3σ line width variation less than 4 nm.

In a SP-SPEL process (figure 1), a stopper layer is first deposited on one of the sidewall of a trench, and followed by pressing at a temperature where the trench material become

soften and can flow (e.g. above the glass transition temperature if a polymer resist). After the pressing, the top of stopper is removed by RIE (reactive ion etching) first and the remaining part is then by HF wet etched. After the removal of the stopper, double sided shadow evaporation of 2 nm thick Cr film was used to cover part of both sidewalls and the top of the grating, followed by removal of the residual resist in the narrow trench using RIE.

Figure 2 shows the results of SP-SPEL. In the experiments of testing SP-SPEL, the initial resist on a silicon substrate is NXR-1025 whose glass transition temperature is 55 °C and was patterned into a grating of 200 nm period, 90 nm spacing (trench), and 220 nm height by thermal nanoimprint [3, 4] (Nanonex NX-2000 imprinter, followed by O₂ RIE to remove the residual resist layer). During SP-SPEL, a 20 nm thick SiO₂ stopper layer was evaporated at an oblique angle (shadow evaporation) onto the top and one sidewall of the grating (figure 2(c)). The thickness of the stopper determines the final trench width and can be accurately controlled by the crystal sensor (Inficon deposition controller) in the e-beam evaporator (Temescal BJD-1800) used in this experiment, and the control of the evaporation angle. There are two reasons for choosing SiO₂ as the material of the stopper. (a) SiO₂ has the strong enough mechanical strength to maintain the trench width during the pressing process; (b) SiO₂ can also be easily removed by HF wet etching without affecting the polymer pattern.

¹ Author to whom any correspondence should be addressed.

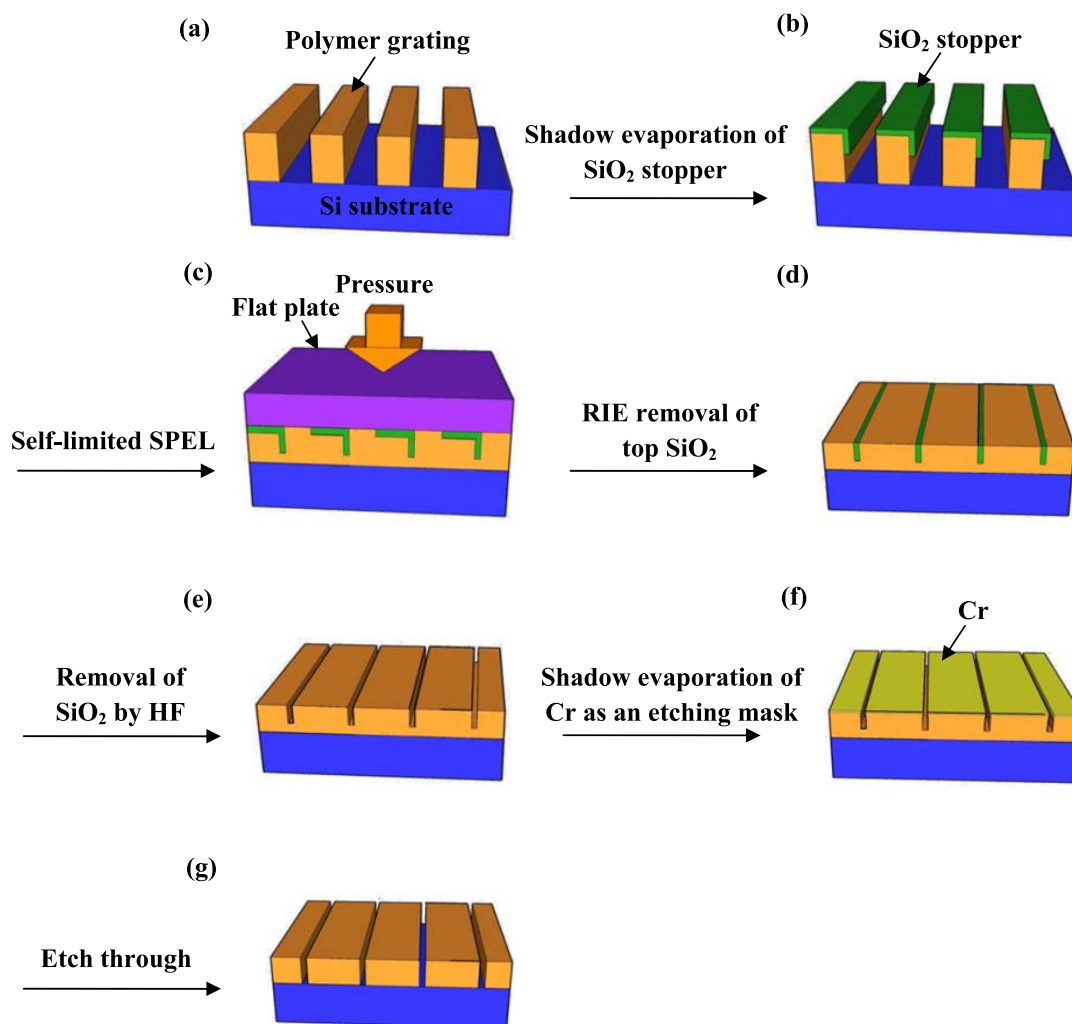


Figure 1. Schematic of self-limited self-perfection by liquefaction (SP-SPEL) process.

After the deposition of SiO₂ stopper, the sample underwent P-SPEL, where a top flat plate was pressed on the sample while being heated to 150 °C which is higher than the glass transition temperature of the thermoplastic polymer. Before use, the top plate was RCA cleaned and chemically treated with Nanonex NXT-100 surfactant to avoid adhesion of the polymers to the top plate. The top plate is a 500 μm thick silicon wafer. Since the final trench width is self-limited by the SiO₂ stopper layer thickness, there is no need to precisely control any of pressing parameters, such as the gap between the top plate and the substrate, pressing pressure, temperature and time. In pressing, we used a relative flexible top plate and air cushion press [5], which makes the pressing conformable to surface and ensures a good pressing over a wafer scale.

After the SP-SPEL, CHF₃/O₂ based RIE was used to etch away both the SiO₂ and a thin polymer top at an equal rate, the equal rate was achieved by adjusting the composition and flow rate of CHF₃ and O₂. In this RIE step, there is no etch stop and the RIE etching depth is controlled by controlling the etching time. However, in future a RIE etching end point detection can be used. Furthermore, the exact resist thickness is not very critical in many applications (particularly in the case of a Cr

etching layer will be deposited as discussed later). Then HF wet etching was used to remove the remaining vertical SiO₂ stopper, followed by another O₂ RIE to remove the residual resist layer in the reduced trench, exposing the substrate and completing the trench narrowing process.

Furthermore, the patterns in polymers created by SP-SPEL can be transferred into metal lines on a silicon substrate by a lift-off. For the pattern transfer process, double sided shadow evaporation (the shadow angle is 30°) was used to deposit a layer of Cr (several nanometers thick) on the top and part of both sidewalls of the polymer trenches to act as a RIE etching mask. Then O₂ RIE was used to etch away the residual resist layer between the two neighboring grating walls (figure 2(e)). Because of the protection of the Cr mask during the RIE etching, the sidewalls of grating after RIE remain very vertical. For the pattern transfer of metal lines, a 10 nm thick layer of Cr was evaporated by an angle that was normal to the silicon substrate, followed by a lift-off process to remove the polymer and the metal, leaving only the Cr lines on the silicon substrate (figure 2(f)).

For the duplication of the patterns fabricated with SP-SPEL, we fabricated a thermal imprint mold. The Cr

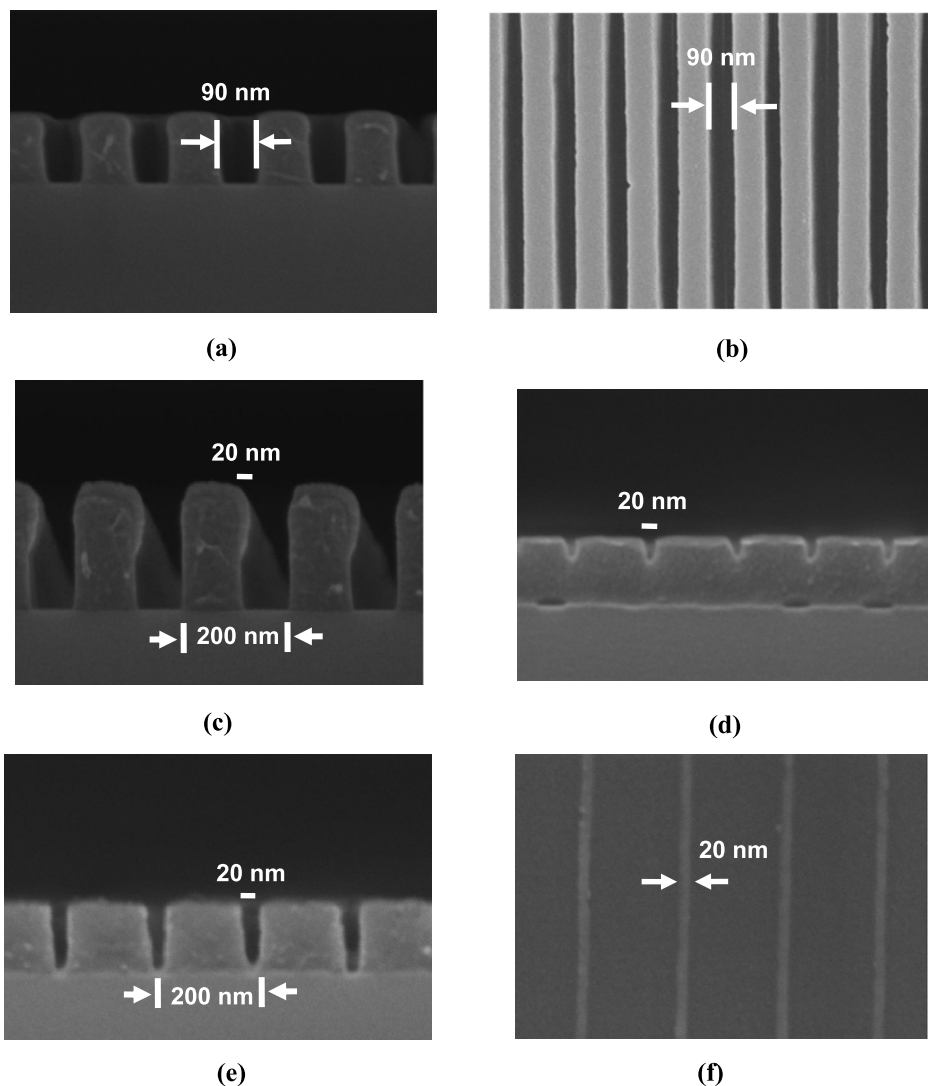


Figure 2. SEM images of various steps before and after SP-SPEL using 20 nm thick stopper. (a) Cross-section view of original grating lines. (b) Top view of original grating lines. (c) One-side e-beam shadow evaporation of 20 nm SiO_2 which acts as a stopper. (d) Cross-section view after SP-SPEL and removal of the vertical of SiO_2 stopper. (e) Polymer gratings by SP-SPEL with a trench width of 20 nm. (f) 20 nm Cr lines after a Cr lift-off.

lines on the silicon substrate, made by SP-SPEL, deposition and lift-off, were used as a RIE etching mask for the fabrication of the Si mold. A $\text{CF}_4/\text{O}_2/\text{Ar}/\text{SF}_6$ based RIE was used to etch 70 nm deep trenches into Si substrate, followed by a CR-7 wet etching to remove the Cr. After fabrication, the Si mold surface was chemically treated with Nanonex NXT-100 surfactant to avoid adhesion in later nanoimprinting [3, 4].

By varying the thickness of the SiO_2 stopper, nano-trenches and nano-lines with different width can be fabricated by SP-SPEL on the silicon substrate; we also fabricated 27 nm wide polymer trenches by SP-SPEL and 27 nm wide Cr lines on Si substrate after a lift-off.

Both 20 and 27 nm Cr lines fabricated were used to fabricate Si molds, which were then used to imprint into a thermoplastic resist with good large area uniformity (figure 3). The thermoplastic polymer resist for the thermal nanoimprint was NXR-1025 and the thermal nanoimprint process was

operated in Nanonex NX-2000 imprinter at a temperature of 135 °C and a pressure of 250 psi.

One major difference between SP-SPEL and other types of SPEL technology is that the SiO_2 spacer is conformally deposited on one sidewall of the trenches in SP-SPEL, which could lead to the same line edge roughness (LER) before and after SP-SPEL. However, surprisingly, we observed that although it indeed cannot improve the high frequency LER of original grating pattern, SP-SPEL can improve the low frequency LER.

For the line edge roughness analysis, we used fractal analysis [6] to analyze the SEM pictures. We also used the method described by Winkelmeier *et al* [7], which states that the 3σ for low frequency noise should be operated on longer distance along the line edge than high frequency noise. In our method, using the correlation length ξ [6], we define 3σ for low frequency noise as for analysis on line edge longer than 6ξ and 3σ for high frequency noise as for short line length

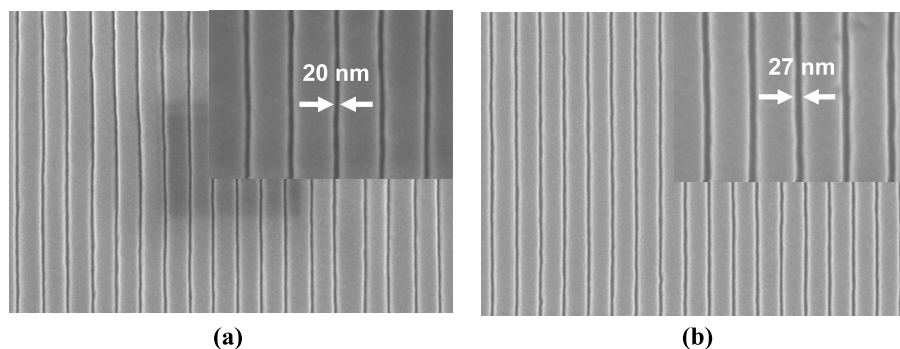


Figure 3. SEM images of gratings imprinted by the mold fabricated by SP-SPEL. (a) Gratings with 20 nm wide trench. (b) Gratings with 27 nm wide trench. The images show good uniformity of SP-SPEL over large area.

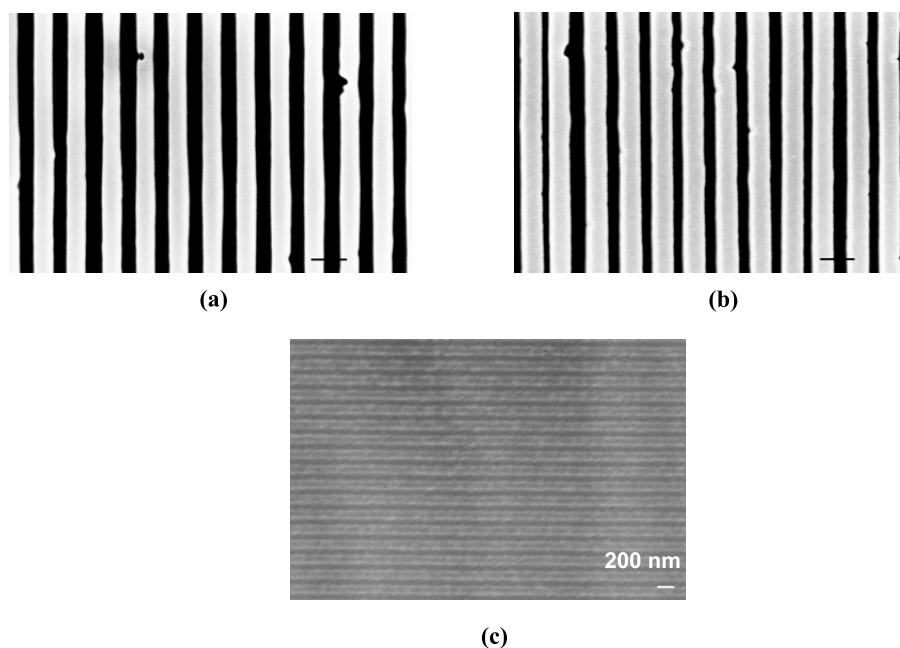


Figure 4. SEM images for line edge roughness analysis in three different situations. (a) Top view of original grating lines. (b) Top view of grating lines as evaporated SiO₂ stopper and before SP-SPEL pressing. (c) Top view of patterns after SP-SPEL pressing. All the scale bars are 200 nm.

which is within ξ . Figure 4 shows the SEM pictures for 3σ LER analysis in three situations: the trench sidewall profile of original lines, just after SiO₂ deposition and before SP-SPEL, and after SP-SPEL. The correlation length ξ for original lines (figure 4(a)) is 150 nm and our comparison for two cases was each based on the same length, 150 nm for high frequency noise and 1400 nm for low frequency noise.

Figure 5 shows the high frequency 3σ -LER for the original lines, just after SiO₂ deposition and before SP-SPEL, and after SP-SPEL is 4.2 nm, 3.1 nm and 6.0 nm respectively. The high frequency 3σ -LER for original lines and the lines before SP-SPEL and after SP-SPEL are identical within the measurement noise. Moreover, it should be pointed out that the high frequency LER problem in SP-SPEL can be solved by using capped SPEL before a SP-SPEL, especially when there is a need to reduce the high frequency LER. Therefore, to optimize a perfection of nanostructure post-fabrication,

different types of SPEL technology should be combined to achieve intended goals.

Figure 6 illustrates that the low frequency 3σ -LER for the same three situations is 13.0 nm, 18.6 nm, and 7.2 nm respectively. Therefore, surprisingly, the low frequency 3σ -LER did get improved by $\sim 181\%$ after SP-SPEL. We think such improvement is due to (a) the SiO₂ stopper is flexible due to its thin thickness (<20 nm), and (b) the flow of a pressured polymer melt may smooth out the low frequency LER.

SP-SPEL can achieve very uniform grating lines over large area. In figure 7, the trench width was averaged for each single trench and the analytical result was based on 15 trenches from figures 2(b), 3(a) and (b) respectively. The root mean square value of trench width over the 15 samples is 9.9 nm for original gratings. For the gratings imprinted by the mold by SP-SPEL with 20 nm stopper, the value reduces down to 1.3 nm. And for the 27 nm stopper

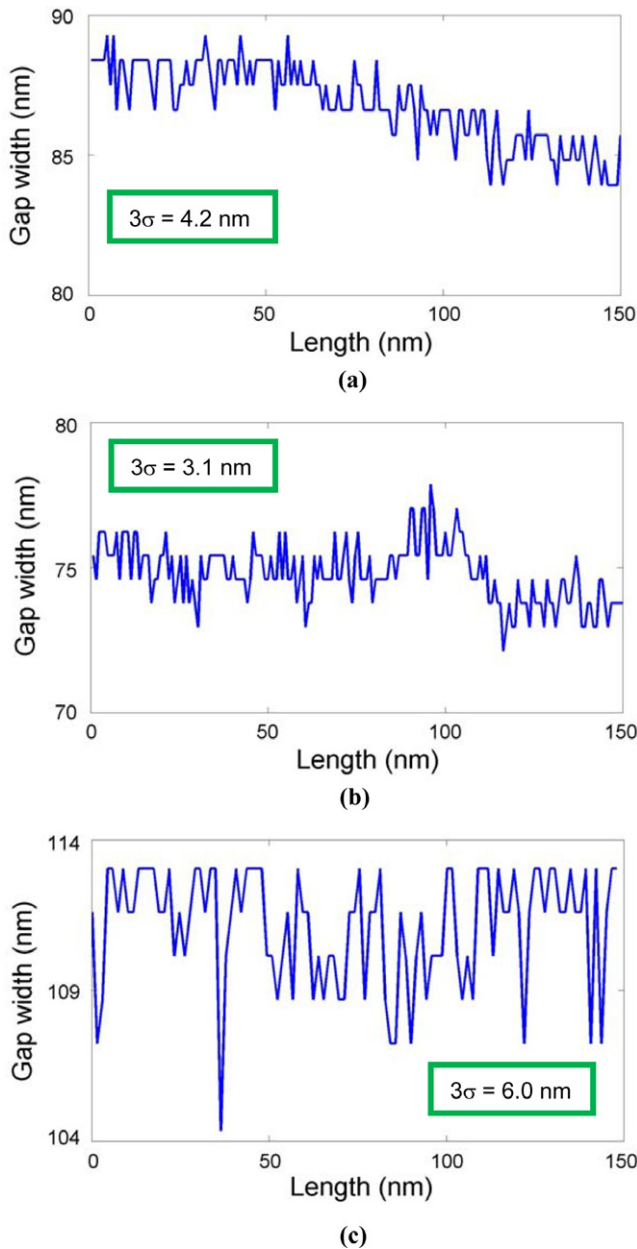


Figure 5. High frequency 3σ -LER analysis for (a) original grating lines, (b) gratings as evaporated SiO_2 stopper and before SP-SPEL and (c) gratings after SP-SPEL. Unlike other SPEL technology, SP-SPEL cannot improve high frequency noise.

case, the value reduces down to 1.2 nm. We think this improvement in trench width uniformity over large area is due to (a) improvement in low frequency LER of original grating lines and (b) independence on many experimental conditions in SP-SPEL (such as pressing temperature, time and pressure).

Previous fabrication techniques for sub-20 nm trenches and lines include electron beam lithography [8–11], extreme ultraviolet interferometry [12], focused ion beam lithography [13] as well as diblock copolymer lithography [14, 15]. However these methods have limits on cost, throughput, large area uniformity and line edge roughness. SP-SPEL starts from large feature size patterns and hence is a cheaper,

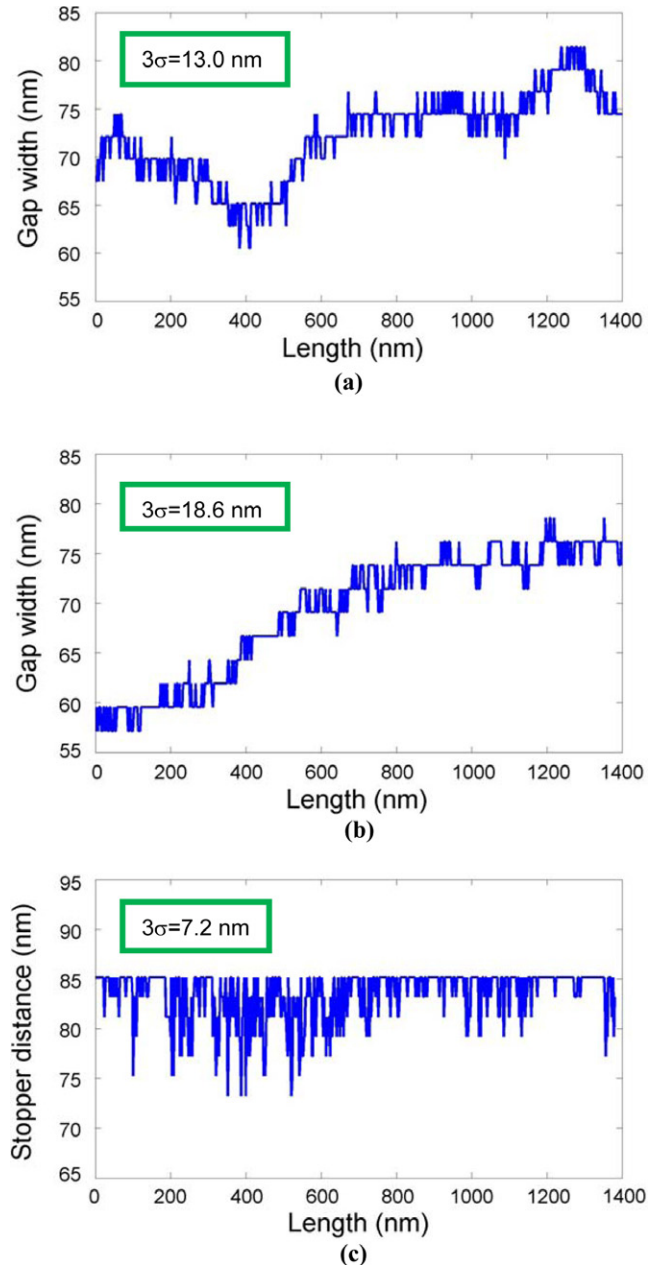


Figure 6. Low frequency 3σ -LER analysis for (a) original grating lines, (b) gratings as evaporated SiO_2 stopper and before SP-SPEL and (c) gratings after SP-SPEL. SP-SPEL can improve the low frequency noise by $\sim 181\%$.

faster and larger area lithography tool. In addition, SP-SPEL can improve the low frequency LER. Furthermore, unlike other size reduction lithography methods [16–18], the array of polymer trenches and metal lines after SP-SPEL has small line width variation over large area and has the same periodicity as the initial grating. Figures 2(c) and (e) illustrate the maintenance of periodicity before and after SP-SPEL. The period of initial grating is 200 nm (figure 2(c)), and remains the same after SP-SPEL (figure 2(e)).

In conclusion, SP-SPEL eliminates the need to precisely and uniformly control the gap between the top plate and the

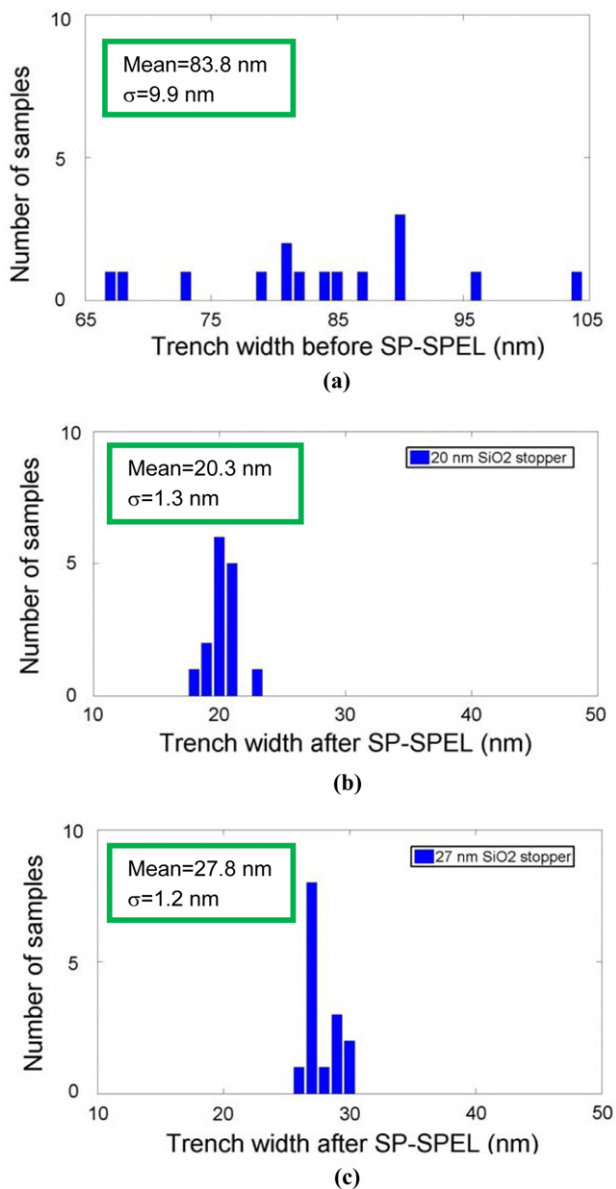


Figure 7. Analysis of large area uniformity of trenches imprinted by the mold operated by SP-SPEL. (a) Original gratings. (b) Gratings imprinted by the mold with 20 nm wide trench. (c) Gratings imprinted by the mold with 27 nm wide trench. SP-SPEL can yield uniform grating lines with trench width reduced by 450% over large area.

substrate over the entire wafer, as well as the processing time, pressure and temperature during the P-SPEL process. Using SP-SPEL, we achieved sub-20 nm wide polymer trenches

and chromium lines with small line width variation ($3\sigma < 4$ nm).

SP-SPEL, which can significantly reduce the trench width beyond what is permitted by conventional methods with an excellent precision and accuracy, has a broad range of applications in semiconductor ICs, nanophotonics, nanobiotech and other disciplines.

Acknowledgments

This work was supported in part by ONR, DARPA and NSF. We thank Dr Zengli Fu for preparing the polymers used in the experiments and Chao Wang for providing the RIE recipe for etching Si.

References

- [1] Chou S Y and Xia Q F 2008 *Nat. Nanotechnol.* **3** 295–300
- [2] Wang Y, Liang X, Liang Y and Chou S Y 2008 *Nano Lett.* **8** 1986–90
- [3] Chou S Y, Krauss P R and Renstrom P J 1996 *Science* **272** 85–7
- [4] Chou S Y, Krauss P R and Renstrom P J 1995 *Appl. Phys. Lett.* **67** 3114–6
- [5] Gao H, Hua T, Zhang W, Morton K and Chou S Y 2006 *Nano Lett.* **6** 2438–41
- [6] Constantoudis V, Patsis G P, Tserepi A and Gogolides E 2003 *J. Vac. Sci. Technol. B* **21** 1019–26
- [7] Windelmeier S, Sarstedt M, Erekem M, Goethals M and Ronse K 2001 *Microelectron. Eng.* **57/58** 665–72
- [8] Dobisz E A, Brandow S L, Bass R and Shirey L M 1998 *J. Vac. Sci. Technol. B* **16** 3695–70
- [9] Dial O, Cheng C and Scherer A 1998 *J. Vac. Sci. Technol. B* **16** 3887–90
- [10] Vieu C, Carcenac F, Pepin A, Chen Y, Mejjias M, Lebib A, Manin-Ferlazzo L, Couraud L and Launois H 2000 *Appl. Surf. Sci.* **164** 111–7
- [11] Austin M D, Zhang W, Ge H, Wasserman D, Lyon S A and Chou S Y 2005 *Nanotechnology* **16** 1058–61
- [12] Solak H H, He D, Li W, Gasson S S, Cerrina S S, Sohn B H, Yang X M and Nealey P F 1999 *Appl. Phys. Lett.* **75** 2328–30
- [13] Kubena R L, Stratton F P, Ward J W, Atkinson G M and Joyce R J 1989 *J. Vac. Sci. Technol. B* **7** 1798–801
- [14] Kim S O, Solak H H, Stoykovich M P, Ferrier N J, de Pablo J J and Nealey P F 2003 *Nature* **424** 411–4
- [15] Park C, Yoon J and Thomas E L 2003 *Polymer* **44** 6725–60
- [16] Cao H, Yu Z, Wang J, Tegenfeldt J O, Austin R H, Chen E, Wu W and Chou S Y 2002 *Appl. Phys. Lett.* **81** 174–6
- [17] Yan X M, Kwon S, Contreras A M, Bokor J and Somorjal G A 2005 *Nano Lett.* **5** 745–8
- [18] Srinivasan C, Hohman J N, Anderson M E, Weiss P S and Horn M W 2008 *Appl. Phys. Lett.* **93** 083123