Multi-silicon ridge nanofabrication by repeated edge lithography

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

2009 Nanotechnology 20 315305

(<http://iopscience.iop.org/0957-4484/20/31/315305>)

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

Download details:

IP Address: 130.89.19.74

The article was downloaded on 14/07/2009 at 06:58

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

Multi-silicon ridge nanofabrication by repeated edge lithography

Yiping Zhao^{1,2}, Erwin Berenschot¹, Henri Jansen¹, Niels Tas¹,
Jurriaan Huskens² and Miko Elwenspoeck^{1,3}

¹ Transducers Science and Technology, MESA+ Institute for Nanotechnology,
University of Twente, Enschede, The Netherlands

² Molecular Nanofabrication, MESA+ Institute for Nanotechnology, University of Twente,
Enschede, The Netherlands

³ FRIAS, Albert-Ludwigs University, Albertstr. 19, 79104, Freiburg, Germany

E-mail: y.zhao@ewi.utwente.nl

Received 25 February 2009, in final form 15 May 2009

Published 13 July 2009

Online at stacks.iop.org/Nano/20/315305

Abstract

We present a multi-Si nanoridge fabrication scheme and its application in nanoimprint lithography (NIL). Triple Si nanoridges approximately 120 nm high and 40 nm wide separated by 40 nm spacing are fabricated and successfully applied as a stamp in nanoimprint lithography. The fabrication scheme, using a full-wet etching procedure in combination with repeated edge lithography, consists of hot H₃PO₄ acid SiN_x retraction etching, 20% KOH Si etching, 50% HF SiN_x retraction etching and Local Oxidation of Silicon (LOCOS). Si nanoridges with smooth vertical sidewalls are fabricated by using Si <110> substrates and KOH etching. The presented technology utilizes a conventional photolithography technique, and the fabrication of multi-Si nanoridges on a full wafer scale has been demonstrated.

1. Introduction

Beam writing techniques, such as electron beam lithography (EBL) and focused ion beam lithography (FIB), have become the conventional and standard means of nanofabrication. To reduce the high cost and low throughput of nanofabrication using beam writing techniques, the fabrication of nano-structures employing unconventional methods has been an attractive research topic in nanotechnology [1]. Researchers have explored the possibilities of integration of micro-machining technologies, for example conventional photolithography, chemical vapor deposition of materials and micro-machining etching methods, into nanofabrication. Amongst all the unconventional methods, edge lithography is widely used and has proven to be a competent means of nanofabrication in combination with micro-machining technologies [2]. In edge lithography, the edges of the original pattern become the features of the final pattern.

Developed in a similar way to edge lithography, the spacer patterning technique (SPT) generally comprises: (1) sacrificial structures with vertical sidewalls patterned by photolithography and directional etching; (2) conformal deposition of another layer; (3) maskless directional etching of this layer; and (4) final selective etching of the sacrificial

layer [3]. Several publications have demonstrated the fabrication of spacer-like structures employing similar working principles to SPT. Choi *et al* demonstrated the fabrication of nanoscale phosphosilicate glass (PSG) complementary metal oxide semiconductor (CMOS) by conformal deposition of PSG over an SiGe block pattern defined by photolithography, reactive ion etching of this PSG and removal of the SiGe sacrificial pattern [4]. Degroote used a SPT in combination with resist based patterning to define a Si-fin with a critical dimension below 20 nm [5]. Based on SPT, multi-SPT was developed by repeating a series of conformal deposition and anisotropic etching steps; it was shown to have potential in nanoelectronics applications [6, 7].

The multi-spacer patterns can also be created by a so-called planar edge defined alternate layer (PEDAL) process [8, 9]. The PEDAL process consists of: (1) fabrication of trench-like structures with vertical sidewalls; (2) alternating deposition of materials upon the trench-like structure, e.g. silicon nitride and polysilicon; (3) substrate planarization by a spin-coated polymer; (4) etch-back of the polymer, silicon nitride and polysilicon by RIE etching; and finally (5) selective polysilicon etching to obtain spacers made of silicon nitride. Hussain *et al* employed a similar process flow to fabricate a template with Si nanowires for nanoimprint applications [10].

Figure 1. Multi-Si nanoridge fabrication scheme: (A)–(C) substrate preparation, grating pattern definition by photolithography and transfer into the top layers; (D) Si etching using 20% KOH; (E) SiNx retraction etching using 50% HF; (F) LOCOS; (G)–(J) and (K)–(M) repeated edge lithography consisting of SiNx retraction etching by hot H₃PO₄ acid, Si etching using 20% KOH, SiNx retraction etching by 50% HF and LOCOS. The fabrication sequence can be stopped by SiNx total removal using hot H₃PO₄ acid, Si etching in 20% KOH and final removal of SiO₂ in 50% HF.

(This figure is in colour only in the electronic version)

Generally, the critical dimensions of the spacers fabricated by either SPT or PEDAL are defined by the conformal layer deposition. The initial pattern with vertical sidewalls determines the verticality of the spacers. Both smoothness of the initial pattern sidewalls and selective dry etching influence the smoothness and the shape of the spacer sidewalls. In a previous publication, we introduced a related but different technique—the fabrication of monocrystalline Si nanoridges by using a full-wet etch procedure including local oxidation of silicon (LOCOS) and an adapted edge lithography technique on top of conventional photolithography [2]. Here, we present the fabrication of multi-monocrystalline Si nanoridges using repeated edge lithography, which consists of sequentially performed SiNx retraction etching in hot H₃PO₄ acid, Si etching in KOH, SiNx retraction etching in 50% HF and LOCOS.

2. Fabrication

The fabrication scheme for multi-Si nanoridges is shown in figure 1: (A) 100 mm, double side polished, p-type Si <110>

substrates are used. The substrate is prepared with 200 nm low pressure vapor deposition (LPCVD) silicon-rich nitride (SiNx) and 50 nm LPCVD tetraethylorthosilicate (TEOS) annealed in a furnace with a N₂ atmosphere at 1050 °C for 1 h. (B) The substrate is patterned by conventional photolithography using a resist mask (Olin 907-12) containing 4 μm gratings covering the whole wafer surface. The substrate is treated in UV/ozone for 300 s to increase the hydrophilicity of the photoresist to improve TEOS wet etching. Then the TEOS is patterned by buffered HF (NH₄F:HF = 1:7) for 45 s. Since the SiNx surface shows hydrophilic behavior, like TEOS, about 10% over-etch is performed here to ensure complete pattern transfer. A dummy wafer with only a TEOS layer is used to test the etch rate. The completion of etching can be observed when the wafer surface turns from hydrophilic to hydrophobic. The etch rate of TEOS annealed at 1050 °C in buffered HF is approximately 80 nm min^{−1}. (C) After stripping the photoresist in 100% HNO₃ for 20 min, the SiNx is patterned in 85% H₃PO₄ heated up to 180 °C (referred to as hot H₃PO₄ acid in the remainder of the paper) using TEOS as the mask for 55 min. The completion of etching can be observed when water runs along the patterned surface, since

Figure 2. SEM image showing the etch result after step (D) of figure 1: Si etching in 20% KOH for 5 min.

Figure 3. SEM image showing the result after step (E) of figure 1: SiN_x etching in 50% HF for 25 min.

Figure 4. SEM image showing the result after step (F) of figure 1: LOCOS at 950 °C for 15 min.

Figure 5. SEM image showing the result after step (G) of figure 1: SiN_x etching in hot H₃PO₄ acid for 8 min.

the Si surface shows hydrophobic characteristics. The etch rate of 1050 °C annealed SiN_x and TEOS in hot H₃PO₄ acid is 3.9 nm min⁻¹ and 0.29 nm min⁻¹, respectively [11]. The SiN_x etching is carried out with about 10% over-etch to ensure complete pattern transfer. (D) Before Si etching, TEOS is stripped in 1% HF for 20 min. Anisotropic Si etching is performed in 20% KOH used at room temperature (referred to as 20% KOH in the remainder of the paper) for 5 min and followed by RCA-2 cleaning (a mixture of HCl:H₂O₂:H₂O of 5:1:1 at 80 °C) for 10–15 min to remove contaminants harmful to the oxidation furnace in step F. The etch rate of Si (110) in 20% KOH solution is 25 nm min⁻¹. (E) Then SiN_x retraction etching is carried out in 50% HF for 25 min to obtain an opening on the Si surface. The etch rate of SiN_x in 50% HF dropped from 2.7 nm min⁻¹ before annealing to 1.7 nm min⁻¹ after annealing at 1050 °C. (F) Subsequently the exposed Si part is dry oxidized at 950 °C for 15 min using SiN_x as the mask (the so-called LOCOS process). (G) SiN_x retraction etching is performed in hot H₃PO₄ acid for 8 min to make an

opening in the Si surface. (H) Si etching in 20% KOH for 10 min. Figures 2–6 show the fabrication results in accordance with steps (D)–(H).

This edge lithography scheme, which consists of hot H₃PO₄ acid SiN_x retraction etching (G, K), 20% KOH Si etching (D, H, L), 50% HF SiN_x retraction etching (E, I, M) and LOCOS (F, J, N), is repeated to fabricate multi-Si nanoridges. By iterating the repeated lithography steps results in the second fabricated Si nanoridge illustrated in figures 7 and 8. By terminating the fabrication scheme, for example after step (F), (J) or (N), single, double or triple Si nanoridges can be obtained by complete removal of SiN_x in hot H₃PO₄ acid, Si etching in 20% KOH and then complete removal of SiO₂ in 50% HF. Stopped at step (N), figures 9 and 10 show examples of triple Si nanoridges by complete removal of SiN_x in hot H₃PO₄ acid, Si etching in 20% KOH for 5 min and complete SiO₂ removal in 50% HF.

Figure 6. SEM image showing the result after step (H) of figure 1: the first Si ridge is finished by anisotropic etching of Si in 20% KOH for 10 min.

Figure 7. Continuation of Si nanoridge fabrication after figure 6 by repeating 50% HF SiN_x retraction etching for 25 min, LOCOS at 950 °C for 15 min, hot H₃PO₄ acid SiN_x retraction etching for 8 min and 20% KOH Si etching for 10 min.

3. Discussion

3.1. Substrate preparation and layer patterning

To illustrate the feasibility of the multi-Si nanoridge fabrication scheme, we chose to deposit 200 nm SiN_x and then 50 nm TEOS. The 1050 °C annealing step is introduced to increase the etch selectivity of SiN_x to TEOS in hot H₃PO₄ acid from 1.4 (4.2 to 2.9 nm min⁻¹) to 15 (3.9 to 0.29 nm min⁻¹) [11]. Therefore, 50 nm TEOS is sufficient for pattern transfer into 200 nm SiN_x in 52 min. Normally 10% over-etch is performed to ensure complete etching. As shown in figure 2, SiN_x displays an isotropically etched profile after etching in hot H₃PO₄ acid using TEOS as the mask.

Figure 8. Magnification of figure 7 showing the non-uniform LOCOS inside the narrow trench.

Figure 9. SEM image of triple Si nanoridges after complete removal of SiN_x, 20% KOH etching and final removal of SiO₂ in 50% HF.

3.2. Si etching in 20% KOH at room temperature (step D, H, L)

In figure 2, the vertical smooth Si sidewalls are achieved by 20% KOH etching of Si <110> substrate, which automatically stops etching at Si <111> planes. For the purpose of this fabrication scheme, 20% KOH is used instead of other standard wet chemicals for Si etching, which include OPD 4262, 5% tetramethylammonium hydroxide (TMAH) used at 70 °C and 25% KOH used at 75 °C. Table 1 lists the etch rates of <110> Si and selectivities between Si <111> and Si <110> planes in these wet chemicals. The etch rates of Si <110> in 5% TMAH used at 70 °C and 25% KOH used at 75 °C are too fast to be useful. Although the slow etch rate of OPD 4262 is favorable, the etch selectivity between the Si <111> and <110> planes makes the etching of Si <111> planes non-negligible while making Si nanoridges 100–200 nm deep and a few tens of nanometers wide. Therefore the use of OPD 4262 in this scheme can lead to reduced control of the lateral dimensions of multi-Si

Table 1. Etch rates of Si $\langle 110 \rangle$ planes and selectivity between Si $\langle 110 \rangle$ and $\langle 111 \rangle$ planes in different etch solutions.

	OPD 4262 @20 °C (nm min ⁻¹)	5% TMAH @70 °C (nm min ⁻¹)	20% KOH @20 °C (nm min ⁻¹)	25% KOH @75 °C (nm min ⁻¹)
$\langle 110 \rangle$	3.5	750	25	1800
Selectivity $\langle 111 \rangle : \langle 110 \rangle$	1:5	1:100	1:400 [12]	1:400

Figure 10. SEM image of an overview of groups of triple Si nanoridges. **Figure 11.** SEM image of a Si nanoridge with a cleavage at its side.

nanoridges, and consequently making the control of spacing dimension more difficult. Therefore, 20% KOH is selected, considering the relatively low etch rate on Si $\langle 110 \rangle$ planes and high selectivity between Si $\langle 111 \rangle$ and $\langle 110 \rangle$ planes [12]. Moreover, the effect of line edge roughness brought by the use of conventional photolithography is avoided by self-alignment to Si $\langle 111 \rangle$ planes in KOH etching [13].

To obtain a relatively even level of the Si surface surrounding the Si nanoridges, the first KOH etching shown in figure 2 is executed for 5 min while the following 20% KOH Si etching shown in figures 6 and 7 is performed for 10 min. It is estimated that the large difference in the trench aspect ratio is the reason for the difference in etching time. In figures 6 and 7, the trench aspect ratio (depth to width) is approximately 3:1 (120 nm:40 nm), while the trench aspect ratio is about 0.03:1 (120 nm:4000 nm) in figure 2. In this specific case, to obtain an even trench depth, etching the nano-sized opening takes roughly twice as long as the time needed for the 4 μ m opening. This effect can be called KOH lag and closely resembles RIE lag [14]. At present, we assume the reason behind the KOH lag is the depletion of active species into deep and narrow trenches.

3.3. SiN_x retraction etching using a 50% HF (step E, I, M)

After Si patterning in 20% KOH and RCA-2 cleaning, SiN_x is etched in both lateral and vertical directions using 50% HF for 25 min to receive an approximately 40 nm opening on the Si surface, as shown in figure 3. As the Si edge is exposed to the etchant, 50% HF is used instead of hot H₃PO₄ to avoid Si surface attack [2].

3.4. LOCOS (step F, J, N)

The LOCOS step is executed to form a thermal SiO₂ layer on the fabricated Si edges to protect them from being deteriorated in the following hot H₃PO₄ acid SiN_x retraction etching and 20% KOH Si etching steps. Except for the purpose of serving as the protective layer, this SiO₂ layer influences the dimensions of the fabricated Si ridges and spacing between them. Since Si is consumed during oxidation, the LOCOS step leads to shrinkage in Si nanoridge height and width and widening of the spacing. Therefore we tried decreasing the oxidation time to minimize the influence of LOCOS. A thickness of 2 nm SiO₂ proved to be sufficient to withstand 20% KOH etching Si $\langle 110 \rangle$ for 400 nm at room temperature [12]. Figure 11 shows a Si ridge with a cleavage at the side. In this case, the protective SiO₂ was obtained by 5 min LOCOS (about 10 nm SiO₂ obtained), which proved to be insufficient due to the non-uniform SiO₂ thickness at shaped Si surfaces as discussed by Marcus *et al* [15]. The drawings shown in figure 12 illustrate the shaped Si surface after LOCOS for 5 min followed by etching in hot H₃PO₄ acid for 15 min [16]. Since the SiO₂ at the top corner is thinner, it can first be etched away during SiN_x retraction etching in hot H₃PO₄ acid. The cleavage is then made during the next 20% KOH Si etching step as a result of opening at the protective SiO₂ layer. It is reported that the non-uniform SiO₂ thickness can be suppressed by: (1) increasing the oxidation temperature, (2) adding NH₃ gas during dry oxidation; or (3) decreasing the oxidation rate by inert gas addition [15, 17, 18]. All of these solutions are based on the fact that the oxide stress is reduced by viscous relaxation. Concerning this multi-Si nanoridge fabrication scheme, the LOCOS temperature cannot

Figure 12. Illustrations of oxidation of a shaped Si surface. Top: oxidation of shaped Si surface [16]. Bottom: SiO₂ etched in hot H₃PO₄ acid.

go beyond 1100 °C so as to keep the intrinsic characteristics of SiN_x [19]. Besides improving the uniformity of oxide growth, the selectivity between the SiN_x and SiO₂ layers might be increased as found by Vos [20]. The improvement of the SiO₂ growth or SiN_x selectivity needs further investigation but this is beyond the scope of this paper.

The result of LOCOS inside a narrow trench after dry oxidation can be observed in figure 8 with the help of the illustration in figure 12. Clearly, the thickness of the grown oxide layer depends on the position along the wall. At the convex and concave corners it is less than on the other positions as observed by Marcus [15]. Moreover, the thickness depends on the orientation of the underlying silicon surface [21]. Depletion of the oxidizing agent seems to be unlikely because both the narrow (40 nm) as well as the wide open trenches (4 μm) have an almost identical oxide layer at their surface. Further research is needed to fully understand the oxidation behavior in narrow high aspect ratio trenches.

3.5. SiN_x retraction etching using hot H₃PO₄ acid (steps G, K)

After LOCOS, hot H₃PO₄ acid is used for SiN_x retraction etching taking advantage of the selectivity between SiN_x and SiO₂ (3.9 to 0.25 nm min⁻¹). An opening of 20 nm on the Si surface is obtained by etching SiN_x in hot H₃PO₄ acid for 8 min, as shown in figure 5. Because the SiN_x etch rate is 3.9 nm min⁻¹, we should have observed 31 nm of retraction. However, SiN_x is partly oxidized during the LOCOS [22]. Due to this oxide, we have a delay of approximately 2 min before SiN_x starts etching. Finally, we find that the etching of SiN_x in hot H₃PO₄ acid plays an important role in influencing the uniformity of etching over the whole wafer. Therefore, a stirrer is used to maintain a uniform temperature within the heated acid.

3.6. The determination of multi-Si nanoridge dimensions

As can be concluded from the previous discussions, the height of the Si nanoridges is predominantly determined by 20% KOH Si etching while the width of each Si nanoridge and the opening between the Si nanoridges are largely determined by 50% HF SiN_x retraction etching and hot H₃PO₄ acid SiN_x retraction etching, respectively. Moreover, the LOCOS step influences the dimensions of the multi-Si nanoridges by reducing the width and height of the Si nanoridges and consequently widening the spacing between them. In other words, the width and height of the fabricated Si nanoridges are decreased in the subsequent fabrication steps due to the consumption of Si in LOCOS. Also the proposed multi-Si ridge nanofabrication scheme is performed with uniform results on a full 100 mm wafer scale. By knowing these factors, each Si nanoridge and spacing can be tuned according to specific requirements after calculation and careful experimental handling. Furthermore, the Si substrate is prepared with 200 nm SiN_x and 50 nm TEOS to show the feasibility of our fabrication scheme. The substrate can be prepared with different SiN_x layer thicknesses considering the dimensions and number of Si nanoridges required. Accordingly, the TEOS layer thickness can also be tuned as needed. Since the multi-Si nanoridge process steps can be well controlled, we assume that the fabrication of Si nanoridges down to 10 nm is attainable, as we have already demonstrated the successful wafer-scale fabrication of single Si nanoridges down to 10 nm by edge lithography in our previous publication [2].

4. Application in nanoimprint lithography

The fabricated triple Si nanoridge sample, as shown in figures 9 and 10, is used in thermal nanoimprinting [23]. Before imprinting, the wafer template is cleaned in Piranha (H₂SO₄:H₂O₂ = 3:1, around 100 °C) for 30 min, rinsed with deionized (DI) water and blown dry with N₂. Then, a monolayer of 1H,1H,2H,2H-perfluorodecyltrichlorosilane is deposited from the gas phase under vacuum condition in a desiccator. This layer acts as the anti-adhesion layer on the mold to facilitate demolding. The imprint process is performed on a wafer coated with PMMA (MW 38 kDa, 4 wt% as to receive 200 nm layer thickness at 3000 rpm spin rate) using an Obducat thermal nanoimprint machine. The imprint is carried out at 180 °C and 40 bar for 10 min and the demold temperature is 90 °C. The imprint result is shown in figure 13. We observed polymer filling problems inside Si narrow trenches of the imprint sample, as can be seen in the image. We did not try to solve the problem since polymer filling is a typical issue in thermal nanoimprinting and goes beyond the focus of this paper.

5. Conclusions

A multi-Si ridge nanofabrication scheme has been successfully used in producing multi-Si nanoridges. The use of 20% KOH and a Si (110) substrate promises to obtain smooth and vertical

Figure 13. SEM image of thermal nanoimprint in PMMA (38 kDa) using the triple Si ridge template as shown in figure 9.

Si sidewalls, which automatically stops at the Si $\langle 111 \rangle$ planes. Different from spacer patterning technology, the incorporation of LOCOS improves the dimension and shape of the silicon ridges. Without relying on the resolution of beam writing technologies, the width of an individual Si nanoridge and spacing can be well controlled by SiN_x retraction etching in 50% HF and hot H_3PO_4 acid, respectively. We have demonstrated ridges 120 nm high, 40 nm wide and 40 nm apart but are confident of reaching sub-10 nm resolution without complicating the process scheme. We can fabricate these multi-Si nanoridges with uniform dimensions within the 100 mm wafer scale by using photolithography and the full-wet etching scheme. Multi-Si nanoridges with specific dimensions can be produced by modifying the fabrication parameters as required, such as the layer thickness of SiN_x and TEOS, etching time of SiN_x and Si and oxidation time.

Acknowledgments

Mark Smithers is acknowledged for his help in taking the SEM pictures. The project is financed by Nanoned through Strategic Research Orientation (SRO) program Nanofabrication at MESA+ Institute for Nanotechnology at the University of Twente.

References

- [1] Gates B D, Xu Q, Stewart M, Ryan D, Willson C G and Whitesides G M 2005 New approaches to nanofabrication: molding, printing, and other techniques *Chem. Rev.* **105** 1171–96
- [2] Zhao Y, Berenschot E, Jansen H, Tas N, Huskens J and Elwenspoek M 2009 Sub-10 nm silicon ridge nanofabrication by advanced edge lithography for NIL applications *Microelectron. Eng.* **86** 832–5
- [3] Hunter W R, Holloway T C, Chatterjee P K and Tasch A F Jr 1981 A new edge-defined approach for submicrometer MOSFET fabrication *IEEE Electron Device Lett.* **2** 4–6
- [4] Choi Y-K, King T-J and Hu C 2002 A spacer patterning technology for nanoscale CMOS *IEEE Trans. Electron Devices* **49** 436–41
- [5] Degroote B *et al* 2007 Spacer defined FinFET: active area patterning of sub-20 nm fins with high density *Microelectron. Eng.* **84** 609–18
- [6] Cerofolini G F, Arena G, Camalleri C M, Galati C, Reina S, Renna L and Mascolo D 2005 A hybrid approach to nanoelectronics *Nanotechnology* **16** 1040
- [7] Cerofolini G F, Amato P and Romano E 2008 The multi-spacer patterning technique: a non-lithographic technique for terascale integration *Semicond. Sci. Technol.* **23** 075020
- [8] Sonkusale S R, Amsinck C J, Nackashi D P, Di Spigna N H, Barlage D, Johnson M and Franzon P D 2005 Fabrication of wafer scale, aligned sub-25 nm nanowire and nanowire templates using planar edge defined alternate layer process *Physica E* **28** 107–14
- [9] Sonkusale S R, Di Spigna N H and Franzon P D 2007 Uniformity analysis of wafer scale sub-25 nm wide nanowire array nanoimprint mold fabricated by PEDAL process *Microelectron. Eng.* **84** 1523–7
- [10] Hussain M M, Labelle E, Sassman B, Gebara G, Lanee S, Moumen N and Larson L 2007 Deposition thickness based high-throughput nano-imprint template *Microelectron. Eng.* **84** 594–8
- [11] Bruinink C M, Burresi M, de Boer M J, Segerink F B, Jansen H V, Berenschot E, Reinhoudt D N, Huskens J and Kuipers L 2008 Nanoimprint lithography for nanophotonics in silicon *Nano Lett.* **8** 2872–7
- [12] Namatsu H, Nagase M, Kurihara K, Iwada K, Furuta T and Murase K 1995 Fabrication of sub-10-nm silicon lines with minimum fluctuation *J. Vac. Sci. Technol. B* **13** 1473–6
- [13] Kendall D L 1975 On etching very narrow grooves in silicon *Appl. Phys. Lett.* **26** 195–8
- [14] Jansen H V, Boer M J d, Unnikrishnan S, Louwerse M C and Elwenspoek M C 2009 Black silicon method X: a review on high speed and selective plasma etching of silicon with profile control: an in-depth comparison between Bosch and cryostat DRIE processes as a roadmap to next generation equipment *J. Micromech. Microeng.* **19** 033001
- [15] Marcus R B and Sheng T T 1982 The oxidation of shaped silicon surfaces *J. Electrochem. Soc.* **129** 1278–82
- [16] Minh P N, Ono T and Esashi M 1999 Nonuniform silicon oxidation and application for the fabrication of aperture for near-field scanning optical microscopy *Appl. Phys. Lett.* **75** 4076–8
- [17] Imai K and Yamabe K 1990 Nonplanar silicon oxidation in dry $\text{O}_2 + \text{NF}_3$ *Appl. Phys. Lett.* **56** 280–2
- [18] Yamabe K and Imai K 1987 Nonplanar oxidation and reduction of oxide leakage currents at silicon corners by rounding-off oxidation *IEEE Trans. Electron Devices* **34** 1681–7
- [19] Zhao Y, Berenschot E, Boer M d, Jansen H, Tas N, Huskens J and Elwenspoek M 2008 Fabrication of a silicon oxide stamp by edge lithography reinforced with silicon nitride for nanoimprint lithography *J. Micromech. Microeng.* **18** 064013
- [20] Vos R, Lux M, Conard T, De Witte H, Mertens P, Heyns M and Hatcher Z 2000 Improved phosphoric acid mixtures for nitride strip *Diffus. Defect Data B* **76/77** 43–6
- [21] Lewis E A and Irene E A 1987 The effect of surface orientation on silicon oxidation kinetics *J. Electrochem. Soc.* **134** 2332–9
- [22] Fränz I and Langheinrich W 1971 Conversion of silicon nitride into silicon dioxide through the influence of oxygen *Solid-State Electron.* **14** 499–505
- [23] Guo L J 2007 Nanoimprint lithography: methods and material requirements *Adv. Mater.* **19** 495–513