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Wafer-scale fabrication of nanoapertures using corner lithography

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Abstract

Several submicron probe technologies require the use of apertures to serve as electrical, optical or fluidic probes; for example, writing precisely using an atomic force microscope or near-field sensing of light reflecting from a biological surface. Controlling the size of such apertures below 100 nm is a challenge in fabrication. One way to accomplish this scale is to use high resolution tools such as deep UV or e-beam. However, these tools are wafer-scale and expensive, or only provide series fabrication. For this reason, in this study a versatile method adapted from conventional micromachining is investigated to fabricate protruding apertures on wafer-scale. This approach is called corner lithography and offers control of the size of the aperture with diameter less than 50 nm using a low-budget lithography tool. For example, by tuning the process parameters, an estimated mean size of 44.5 nm and an estimated standard deviation of 2.3 nm are found. The technique is demonstrated—based on a theoretical foundation including a statistical analysis—with the nanofabrication of apertures at the apexes of micromachined pyramids. Besides apertures, the technique enables the construction of wires, slits and dots into versatile three-dimensional structures.

(Some figures may appear in colour only in the online journal)

1. Introduction

Micromanipulators with integrated tiny apertures for sub-micron modification or sensing of surfaces are essential components in the state-of-the-art and emerging nanotechnology. Application fields of apertures include near-field scanning optical microscopy (NSOM) to study molecules in their native environment [1–4], and fluidic probes, e.g. to study the electrophysiology of single cells such as in scanning ion-conductance microscopy (SICM) [5–7] or to shape surfaces at the nanoscale using electrochemical deposition [8–10]. Apertures are also useful in DNA and single cell devices for screening or sequencing purposes [11–13], and next generation lithography equipment to further extend the resolution limit of optical exposure tools [14, 15]. Furthermore, the use of submicron apertures for fluid delivery can overcome the limitation of dip pen lithography (DPL) [16, 17], i.e. the necessity of fluid replenishment and inevitable realignment procedures during a patterning process.

In particular, fountain pen lithography (FPL), which might replace DPL, is of interest here [18–22].

Even though the art of aperture engineering has a long history of development¹, it has passed a few turbulent decades of innovation with the introduction of nanofabrication. In the early days, before 1990, aperture probes were mainly hollow glass pipettes. However, ongoing developments have led to silicon micro- or nanofabricated counterparts that greatly improve the performance: besides ultra-small apertures [23–28], nanofabrication allows for device integration, such as combining them with micro-channels and micro-reservoirs to deliver fluids [29–36]. Furthermore, it enables arrays of probes for parallel operation and batch processing [37]. Moreover, arrays of tiny apertures are useful in supporting extremely thin membranes. This facilitates fast and selective molecular transport via diffusive

¹ In this context, an aperture is an opening through which molecules may pass. The fabrication of transparent solid apertures, e.g. metal-coated glass fibers for NSOM to guide photons, is excluded from this study.

Figure 1. Various aperture microfabrication schemes: tip-approach by (A) Prater *et al* [61] (reprinted with permission, copyright American Institute of Physics 1991) and (B) Davis *et al* [62] (reprinted with permission, copyright American Institute of Physics 1995), and pit-approach by (C) Milhalcea *et al* [63] (reprinted with permission, copyright American Institute of Physics 1996) and (D) Minh *et al* [67] (reprinted with permission, copyright American Institute of Physics 1999).

or free molecular mechanisms [38–42]. Nanofabrication relies on planar photo-lithography—which is the main driving force behind the ever decreasing size of the devices—to fulfil automated mass production that achieves astonishing low per-device costs. The construction of wafer-scale full three-dimensional (3D) nanofeatures, though, is challenging. For instance, the creation of a sub-100 nm aperture at the apex of a tip is not at all straightforward in planar lithography due to alignment and step coverage issues. Self-aligned schemes have the ability to overcome this problem [43–47]. The corner lithography method [48–54], which is applied in this paper, is an example of such a self-aligned technique.

In the established micro-system technology, two complementary wafer-scale approaches to create self-aligned submicron apertures can be distinguished (figure 1). In the oldest technique, the aperture is formed at the tip-end of a previously fabricated sharp tip [55–58]. The ‘inverse’ technique forms the aperture inside the sharp concave corner of a previously fabricated etch pit, also with a tiny radius [59, 60]. An example of the ‘tip-approach’ was presented in 1991 by Prater [61], figure 1(A), who used isotropic undercutting of a micron-sized oxide mask to form a silicon tip and additional boron doping and back-side etching to create a hollow needle. Davis [62] came up with an improved scheme in 1995

by sharpening the tip using wet oxidation (figure 1(B)). Subsequently, the tip-end was opened from the front-side using the incomplete coverage of resist due to de-wetting at the sharp tip-end. However, this procedure resulted in a rather unpredictable aperture size.

This issue improved after the introduction of the pit-approach in 1996 by Milhalcea [63], figure 1(C), in which a sharp etch pit was used as a template to construct the aperture. The pit typically forms following the anisotropic etch characteristics of crystalline silicon in hydroxide-based solutions [64, 65]. Even though submicron apertures were achieved, they improved the technique in 2000 to sub-200 nm resolution by the effect of oxidation retardation at the concave corner of the etch pit [66]. The effect is essentially identical to the previously mentioned oxidation-based sharpening technique. A disadvantage, though, of this concave etch technique is that resolution is limited due to oxide thinning near, but not at, the tip-end (figure 2 top and bottom-left). It results in apertures having difficulties in achieving sub-100 nm resolution. However, meanwhile a further improvement of the aperture size was presented in 1999 by Minh [67] who thinned down the oxide using an isotropic etch from the convex side (figures 1(D) and 2 bottom-right). In this way sub-25 nm apertures were created successfully.

Figure 2. Isotropic etch-back of oxide in etch pits. Top: Milhalcea *et al* [66] (reprinted with permission, copyright The Electrochemical Society 2000) showing a four-fold aperture. Left: concave side etch resulting in tip broadening [66] (reprinted with permission, copyright The Electrochemical Society 2000). Right: convex side etch forming a sharp single aperture [67] (reprinted with permission, copyright American Institute of Physics 1999).

In this paper, an alternative technique to create 3D nanostructures and apertures (and tips) at sharp corners (in fact the apexes of micromachined pyramidal shapes) is presented with the general aim of achieving high resolution throughout the wafer, while allowing freedom to create apertures with characteristic dimensions up to a few hundreds of nanometers. It has the advantage, with respect to the established techniques shown in figure 1, that the apertures are formed prior to the aperture release (like the tip-approach) but still have the ability to reach sub-50 nm apertures (like the pit-approach). Furthermore, in the current approach additional freedom in aperture size is achieved, as compared with Minh's approach, mainly because the latter has to rely on the effect of oxidation retardation caused by the angle of the concave corner and the surface orientation. The advantage of the presented technique with respect to Milhalcea's approach (of using the deposition of nitride instead of the growth of oxide) is that multiple aperture 'ghost' holes are prevented and, therefore, an increased resolution is possible. Like the other techniques, this technique is fully compatible with standard micromachining methods and, as such, it does not rely on mainstream sub-100 nm nanolithography tools. It is based on the so-called corner lithography technique, as will be explained in detail in section 2.

Corner lithography was introduced by Sarajlic [48] in 2005 and was used to create a nanowire frame (figure 3), and a brief theoretical foundation for a simplistic two-dimensional shape (V-groove) was formulated. In 2008,

Figure 3. Pyramidal wire frame [48]. The wires are roughly 100 nm in width.

Berenschot [49] extended this work with a few other 3D structures, such as a pyramid with a metal nanotip. In 2010, Yagubizade [50] presented corner lithography as a tool to construct silicon nanowires and in 2012 Berenschot [53] used corner lithography to construct wire frames able to catch living cells. Most recently, Berenschot presented a new class of structures—octahedral fractals—having the potential to fabricate extremely porous or large area membrane devices [54]. The fractals were fabricated with the aid of anisotropic etching of silicon in combination with the self-aligned three-dimensional corner lithographic technique. The fractals demonstrated were dense and porous, as well as a wire frame. However, in neither case were details on the 3D size of these nanostructures given.

To summarize, the objective of this paper is to demonstrate the main concept of corner lithography and to present some fundamental issues controlling the aperture shape and size. Results from statistical data on the wafer-scale uniformity support this study.

2. Corner lithography concept and theory

Figure 4 illustrates the basic corner lithography scheme, which is compatible with conventional micromachining techniques. (I) It starts with the definition of micron-sized patterns using print lithography. For example, a $\langle 100 \rangle$ silicon wafer is oxidized and patterned with a resist mask having a micron-sized grating pattern. After pattern transfer using BHF and resist stripping, the oxide is used as a mask to etch the silicon anisotropically using a hydroxide-solution and form V-grooves bounded by slowly etching $\langle 111 \rangle$ planes [64, 65]. For silicon, the concave angle α between these planes will be ca. 70.53° . (II) Next, a thin conformal layer of silicon nitride is deposited in this silicon template by low-pressure chemical vapor deposition (LPCVD). (III) Subsequently, the nitride is partly removed (time-stop), leaving a nitride residue in the concave corners. The process results in well-defined nanometer-scale structures controlled by the template. The remaining material in the corners directly forms the structural material of tips and wire structures or is used as an inversion mask in subsequent fabrication steps to form apertures or slits.

The theoretical analysis of the final width a after etch-back of a filled V-groove is straightforward by solving

Figure 4. Corner lithography concept (cross-sectional view): (I) V-groove template preparation, (II) deposition of conformal material and (III) time controlled selective isotropic thinning leaving a nanofeature of size a . The concave corner angle is defined as α , which is between 0 and π . A different concave angle, layer thickness or etch-back will result in a different feature size and shape.

Figure 5. Feature size relative to the deposited layer of thickness t , as a function of the relative isotropic etch distance. a is the minimum size of the dot in the apex, b is the maximum size of the dot in the apex and c is the minimum width of the wires remaining in the ribs of the pyramid.

for the intersection of a circle ($x^2 + y^2 = r^2$) with a triangle ($y = c_1 + c_2|x|$) and with the center of the circle as indicated in figure 4(III),

$$\frac{a}{t} = 2 \cos\left(\frac{\alpha}{2}\right) - 2 \sin\left(\frac{\alpha}{2}\right) \sqrt{\left(\frac{r}{t}\right)^2 - 1}. \quad (1)$$

The analysis for the 3D case is identical except that we have to equate a sphere with a pyramid, which results in a hyperbolic square. Figure 5 and table 1 show how the aperture changes size and shape with the relative amount of material removed.

3. Aperture fabrication

The nanoaperture fabrication (figure 6) starts with a $\langle 100 \rangle$ silicon wafer coated with 76 nm of thermal oxide, which is patterned by conventional resist lithography using a periodic hole pattern (circles of 5 μm). The mask is fabricated with the Heidelberg DWL 2000 laser-beam pattern generator (minimum structure size of 0.8 μm , 25 nm address grid, edge roughness $3\sigma = 80$ nm, CD uniformity $3\sigma = 90$ nm and

Table 1. Feature size for different corner angles.

Corner angle α (deg)	Relative feature size
70.53	$a/t = 2/3\sqrt{6} - 2/3\sqrt{3}\sqrt{[(r/t)^2 - 1]}$
90.00	$b/t = 1/2\sqrt{6} - 1/2\sqrt{6}\sqrt{[2/3(r/t)^2 - 1]}$
109.47	$c/t = 2/3\sqrt{3} - 2/3\sqrt{6}\sqrt{[(r/t)^2 - 1]}$

alignment accuracy $3\sigma = 100$ nm). The oxide is etched in BHF and subsequently the silicon is anisotropically etched for 6 min in 25% w/w KOH/H₂O at 75 °C. RCA cleaning is performed to remove residual potassium ions and the remaining oxide is stripped for 1 min in 50% HF. This forms a silicon template with many inverted pyramids—the etch pits—having sharp concave corners (6(A)). The silicon template receives a conformal layer of $t = 61$ nm LPCVD silicon-rich nitride (SiN_x) (6(B)). Based on the angle of the corners, this will result in a thickness of $t\sqrt{3} \approx 1.73t$ in the apex ($\alpha = 70.5^\circ$) of the pyramid and $1/2t\sqrt{6} \approx 1.22t$ in the ribs ($\alpha = 109.5^\circ$). An etch in 85% phosphoric acid heated up to 160 °C (hot H₃PO₄) between 1.00t and 1.22t results in a nanowire pyramid [48] (6(C), 1.15t) and for the fabrication of a nanodot this is between 1.22t and 1.73t (6(D), 1.35t). To have a safe margin with respect to possible non-uniformity, a relative layer of around 1.35t is removed and a residual nitride dot of around 40 nm is left (figure 5: b -side $\approx 0.65t$). The wafers are HNO₃ cleaned and 54 nm of oxide ((111) surface) is grown by dry oxidation for 20 min at 1050 °C in which the nitride dot serves as an inversion mask, i.e. the local oxidation of silicon (LOCOS, 6(E)). After removing the oxidized nitride for 30 s in 1% HF, the nitride is stripped in hot H₃PO₄ with 35% extra time (6(F)). A thin oxy-nitride transition layer of ca. 3 nm, grown during loading the wafers in the LPCVD furnace [68], is stripped for 45 s in 1% HF. Finally, the wafer is bonded to a second patterned wafer and stripped from the silicon to reveal apertures with fluid access holes through the second wafer or it is bonded to a glass tube and then the silicon is stripped (6(G)) [35, 36]. The aperture is drawn not to scale with respect to the glass tube.

4. Results and discussion

The fundamental assumption of corner lithography is that the isotropic etch rate is the same for a flat surface and a concave corner, whether it is a V-groove (figure 4) or an inverted pyramid (figure 6). More importantly, in order to predict the aperture size at the apex of the pyramid (figure 6(F)), the isotropic etch of the nitride inversion mask has to be controlled. Two etchants have been studied: hot phosphoric acid (H₃PO₄) and 50% hydrofluoric acid (HF) at room temperature. In silicon micromachining, typically a hot H₃PO₄ solution is used as it has a reasonable selectivity with respect to silicon and silicon dioxide, which are common materials present during silicon-based etching. However, when the presence of oxide is not important, 50% HF is favored because silicon is virtually undisturbed in pure HF solutions [34]. An important issue addressed in this paper

Figure 6. Fabrication process of a 3D aperture. Left panel top view and right panel bird's eye view: (A) pit formation using a patterned SiO₂ mask and KOH, (B) conformal deposition of SiN_x of thickness t , (C) etch-back of $1.15t$ with HF or H₃PO₄, (D) etch-back of $1.35t$, (E) LOCOS using nitride dot, (F) nitride strip, (G) bonding with a second wafer patterned with access holes and aperture release (not to scale).

is to find the characteristics for both etchants. For this, the wafer-scale thickness uniformities (mean value and standard deviation) of the initial nitride layer, the remaining layer after the isotropic etch and the final aperture size are estimated in the coming sections. Non-patterned (dummy) wafers and ellipsometry are employed to subtract the global etch rate and wafer uniformity. Processed wafers with V-grooves, which received an identical treatment, are used to check these values. Finally, the shape and size of the apex aperture are examined with high resolution scanning electron microscopy (HRSEM).

4.1. Uniformity of non-patterned wafers

Native oxide was stripped from (100) silicon wafers in 50% HF. Subsequently, the wafers were coated with 250 nm of nitride. The nitride was isotropically etched by hot H₃PO₄ and the remaining thickness was measured every 10 min using ellipsometry at 25 uniformly distributed spots across the wafer. The experiment was repeated with 50% HF. Figure 7 shows for both etchants the thickness t of the remaining nitride layer and the estimated standard deviation S_t as derived from the measured $n = 25$ spots against time and defined as

$$S_t = \sqrt{\frac{\sum_{i=1}^n (t_i - \bar{t})^2}{n-1}}, \quad (2)$$

in which t_i is the value of each individual measured spot and $\bar{t}$ is the average of these values. Before etching, the deposited nitride is quite uniform ($3S_t \approx 6$ nm out of 250 nm, i.e. better than 3%), but during etching the estimated standard deviation in the thickness of the remaining layer increases due to local variations in the etch rate. This local variation can be due to differences in the nitride film density (or another property), or can come from fluctuations in the concentration and temperature of the wet etchant. Furthermore, the etch rate for 50% HF is around 4.4 nm min^{-1} and that of hot H₃PO₄ is roughly 3.8 nm min^{-1} . The observed variation in the local etch rate causes a $3S_t$ error in the remaining layer of $0.04t$ after etching a layer of $1.35t$ (in order to create a nanoaperture), so it is possible to etch accurately enough to be well within the required range of $1.22 \leq 1.35 \pm 0.04 \leq 1.73$ for the nanodots to exist. Furthermore, the control of the size of the final aperture becomes better, the closer the required aperture size is to the nitride thickness deposited initially. Creation of a small aperture by starting with a relatively thick layer and etching for a bit longer in the corner lithography (e.g. for $1.60t$) will result in a larger spread of the aperture size due to the increase of the relative non-uniformity with etching time. However, it is recommended not to restrict the over etch time too much below 35%. The reason is that inaccuracy of the etch rate (the slopes of the curves found in figure 5 get steeper at less relative etch-back time) and depletion in small confined structures may even cause the wires to not disappear, which excludes apertures from forming correctly.

4.2. V-grooves

Wafers with V-grooves (like figure 4) and flat dummy wafers were coated with 250 nm of SiN_x and etched in the same

Figure 7. Global SiNx etching in 50% HF and hot H₃PO₄.

Figure 8. Nanofeatures in a corner ($\alpha = 70.5^\circ$) after time-stopped etching (0.00t, 0.40t, 0.60t, 1.00t, 1.23t, 1.35t and 1.50t) with 50% HF (left) and hot H₃PO₄ (right). The bar in the picture represents 250 nm.

bath to remove 0, 100, 150, 250, 308, 338 and 375 nm (0.0, 0.4, 0.6, 1.0, 1.23, 1.35 and 1.50t respectively). Subsequently, the remaining nitride shape and etch uniformity at the apex were observed by HRSEM (figure 8). The same etch rate was found at the inclined wall of the V-groove, compared with that of the flat surface of the dummies. This indicates that the size of the remaining nitride in the concave corners can be predicted accurately. Also, the shape of the material left is as

Figure 9. A nitride nanowire after hot H_3PO_4 etch (1.23t) in a V-groove prior to LOCOS inversion. The silicon is partly etched anisotropically to observe the shape better.

Figure 10. A nitride nanodot at the apex of an inverted pyramid prior to LOCOS inversion. The silicon is partly etched anisotropically to observe the shape.

expected for etching in hot H_3PO_4 , but it shows a deviation for etching in 50% HF. As indicated in figure 8 with the arrows, the etch-front follows a kind of cosine shape. A possible explanation is that a thin oxide is grown unintentionally during loading of the wafers into the hot LPCVD tube [68]. Delayed deposition (causing oxide to grow) as well as flushing with ammonia gas (causing oxide to convert into nitride) both influence the final native oxide thickness. This oxide or oxy-nitride transition layer is eroded faster in 50% HF than the intended nitride layer.

In figure 9, a nitride nanowire situated in the corner of the V-groove is shown. The silicon surrounding the wire is partly etched anisotropically to have a better view with respect to the shape of the wire. It is worthwhile to mention that this extra silicon retraction etch causes two nanometer-sized V-grooves to appear adjacent to the original V-groove. Oxidizing this structure or performing once again nitride deposition and partial etch-back might show even more exciting nanostructures with sub-100 nm resolution. The reader is encouraged to explore this possibility further, but in this work we go back to the basic aperture process flow.

4.3. Apertures

Series of inverted pyramids are defined as discussed in section 3. The nitride layer is etched with a 135% etch time in hot H_3PO_4 , leaving nitride dots in the apexes. The over etch is controlled by separate dummies. Figure 10 shows a dot after an additional anisotropic silicon etch but, like the V-grooves, starting with a rather thick 250 nm nitride. The hyperbolically sharpened 200 nm features are as expected for corner lithography. For the sub-50 nm apertures, a thinner layer of 61 nm nitride has been selected. After LOCOS and nitride strip, including the 3 nm oxy-nitride transition layer, the silicon is etched in TMAH solution. This leaves an aperture at the apex of the pyramid as can be seen in figure 11. The opening measures 44 nm $\times$ 55 nm and it is not truly a (hyperbolic) square as one might expect. This issue is addressed by Moldovan [69]: ‘Optical lithography can control the equality of adjacent sides of squares or circle eccentricities only down to 20–50 nm, due to factors such as

Figure 11. An aperture of 44 nm $\times$ 55 nm inside an oxide frame (bird's eye and side views) after corner lithography in a pyramidal etch pit. The aperture is not a perfect square but has a hyperbolic rectangular shape [58]. The lips along the sides are a consequence of the corner lithography, as found in figure 5.

illumination non-uniformities, mask imperfection, proximity effects in the aerial image, and concentration gradients in the developer.... Thus, the wedge size on four-faceted pyramidal molds can be controlled only to the limit of tens of nanometers. Figure 12 shows a top view of the inverted pyramid just before removing the 76 nm thermal oxide mask. It can be seen that the circular distortion matches the wedge length.

To prove the wafer-scale ability of corner lithography, a detailed statistical analysis has been made for a total

Figure 12. Imperfection of the mask shape causing a wedge to develop. The dashed line is a perfect circle.

population of 50 million apertures. For this, five spots were quasi-randomly selected to investigate the 100 mm wafer uniformity. One in the center of the wafer, one north and 1 cm away from the periphery, the other three east, south and west, also 1 cm from the wafer edge. HRSEM pictures were taken at a fixed magnification of 5000 times, which resembles an area of $60 \mu\text{m} \times 40 \mu\text{m}$ and containing 20 oxide pyramids with apertures. From each spot, six apertures were randomly selected for a high resolution picture at a fixed magnification of 800,000 times and the aperture size was measured within seconds to minimize carbon deposition while scanning. Figure 13 shows the size variation of some apertures

Table 2. Aperture size (length l and width w in nm) at different wafer positions (north, west, center, east and south). The value of the longest b -side is taken negative in the statistical analysis when the ridge is 90° rotated with respect to the most frequently found direction.

N	l	42.9	41.4	43.6	40.0	−119.3	40.0
	w	66.2	102.4	85.5	221.0	42.1	140.2
W	l	44.3	−79.0	42.9	−85.2	45.7	−100.0
	w	159.3	46.0	107.6	44.8	143.3	46.2
C	l	41.9	45.5	43.8	43.3	43.8	−58.6
	w	97.9	64.3	106.7	94.3	124.5	44.3
E	l	−79.0	44.3	45.5	45.2	43.1	45.7
	w	45.2	104.8	64.0	53.3	238.6	138.6
S	l	49.0	47.9	49.3	47.9	45.0	44.5
	w	66.9	115.0	100.7	138.3	66.2	63.6

situated close together on the wafer. Table 2 presents the data on wafer-scale.

Taking only the center spot, the size of the smallest b -side is found to be 43.8 nm with an estimated standard deviation (s_{n-1}) of 1.2 nm. The longest b -side is 71.5 ± 66.7 nm. The latter means that pattern imperfections have created knives (or wedges) of 27.7 ± 67.1 nm. This number corresponds well with the given CD uniformity of the pattern generator to create the mask: $\sigma = 30$ nm.

Taking the average size of all the $n = 30$ samples across the wafer, the smallest side is calculated to be 44.5 ± 2.3 nm and the longest side to be 71.4 ± 91.3 nm. The precision uncertainty of the smallest b -side is therefore (in Excel) $P_b = \text{TINV}(0, 05; 29) \times S_{n-1} = 2.045 \times 2.3 = 4.6$ nm, where TINV is the Student t -distribution variable at the 95% confidence

Figure 13. Variation of the size of four apertures (exact top view) taken at the east position of the wafer. The apertures are situated close together in an area of $40 \mu\text{m} \times 60 \mu\text{m}$. The white dashed rectangular shape is enclosing exactly the limits of the aperture, i.e. the b -sides. The smallest side is always around 44 nm whereas the longest side has a large variation.

level with $n - 1 = 29$ degrees of freedom [70]. Indeed, taking a closer look at values for the smallest b -sides in table 2, only one value does not fit within the range between 39.9 (44.5 – 4.6) and 49.1 (44.5 + 4.6) nm. Therefore, it can be concluded that the smallest side is highly reproducible on the wafer-scale and that corner lithography is sufficiently accurate. This is a direct result of the ability of anisotropic etching to create very sharp edges where $\langle 111 \rangle$ -planes meet. However, the longer side of the apertures is very inaccurate (large standard deviation). The reason is most probably the lack of sufficient symmetry control of the original mask (the predefined circles are always distorted as previously shown in figure 12).

Finally, having a closer look at table 2, the mean value of the smallest b -sides of the north position (41.7 nm) is less than that of the south position (47.3 nm). We believe that this is caused by a temperature gradient in the H_3PO_4 bath. Furthermore, the ‘predicted’ minimum size of 40 nm is approximately 4 nm less than observed. We believe that the 6 nm oxy-nitride layer has caused this offset.

5. Conclusions

We have investigated a wafer-scale method to obtain three-dimensional nanostructures, called corner lithography. The technique explores the conformal deposition and subsequent timed isotropic etching of a thin nitride film into a very sharp etch pit, the latter serving as a template. This leaves a small nitride residue in the pit’s corner, which is used as a self-aligned mask with high resolution ability to oxidize the freely-accessible silicon. This residual nitride dot is selectively removed to create the nanoaperture at the tip apex. A size of below 50 nm is demonstrated, but potentially it allows even smaller openings. The advantage of this method in aperture fabrication over existing wafer-scale methods is the large possible range of sizes of the aperture while the structure is still in the mold. This gives flexibility in further machining steps.

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