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Polymer as the protecting passivaton layer in fabricating suspended SCS structures in both anisotropic and isotropic etching

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Abstract

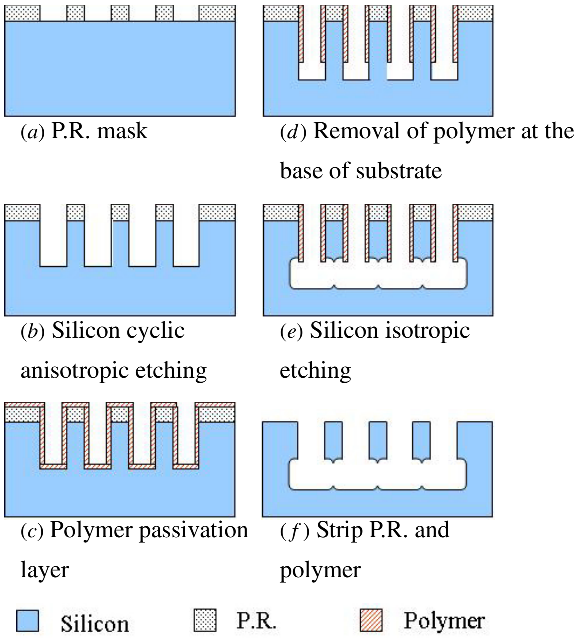
This paper presents a rapid bulk micromachining process named polymer passivation layer for suspended structures etching by using a polymer as a protecting passivation layer at both anisotropic and isotropic etching steps. Without using silicon-dioxide (SiO_2) deposition or boron doping as a protection layer at the releasing step, the proposed method can fabricate suspended single-crystal silicon structures in an inductively coupled plasma reactive ion etching chamber directly, which would simplify the fabrication process and save fabrication time. The current study systematically investigates critical fabrication parameters to verify the feasibility of the proposed method, and discusses the polymer passivation time and removal time of a polymer at the base of a substrate at four different opening gaps of 5, 10, 30 and 50 μm with the 30 μm deep trench to establish suitable recipes for fabricating suspended microstructures. It is also shown that the proposed method can fabricate not only the suspended microstructures with the same thickness, but also suspended microstructures with different thicknesses, as well as in sub-micro scale.

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

1. Introduction

Due to excellent material properties of the single-crystal silicon (SCS), researchers have developed different methods to fabricate suspended SCS structures [1–6]. In the deep reactive ion etching technique, protecting the silicon sidewall during the releasing process is a critical step to form a suspended SCS structure. Inductively coupled plasma reactive ion etching (ICP-RIE) has used the polymer in the standard Bosch recipe as the protecting passivation layer to fabricate high-aspect-ratio structures at the anisotropic etching step. However, the polymer is a soft material, which is considered to be difficult to protect silicon during long isotropic etching period at the releasing step. Therefore, previous literatures have proposed silicon-dioxide (SiO_2) deposition [1–4] and boron doping [5, 6] to protect the silicon sidewall during the isotropic etching step to release suspended SCS structures. However, SiO_2 deposition or boron doping needs additional equipment besides ICP-RIE.

In this work, we try to show the possibility of using the polymer as the protecting passivation layer not only at the anisotropic etching step, but also at the isotropic etching step. This rapid bulk micromachining method is called the polymer passivation layer for the suspended structure etching (PoPLSE) method, which uses only ICP-RIE, beside lithography systems, to fabricate suspended SCS structures. This study experimentally investigates key parameters, such as polymer passivation time, removal time of polymer at the base of substrate and isotropic etching time at different opening gaps, and then establishes a suitable recipe to successfully fabricate suspended microstructures.


(*a*) P.R. mask

(*d*) Removal of polymer at the base of substrate

(*b*) Silicon cyclic anisotropic etching

(*e*) Silicon isotropic etching

(*c*) Polymer passivation layer

(*f*) Strip P.R. and polymer

Figure 1. Fabrication flowchart of a suspended SCS structure using the polymer as the protecting passivation layer.

2. Fabrication process design

In the proposed PoPLSE method, not only anisotropic etching but also isotropic etching are all performed in the STS Multiplex ICP-RIE. This tool generates the source plasma by an inductively coupled coil with the 1 kW 13.56 MHz RF generator and uses another 13.56 MHz generator as a platen power to independently control the bias potential of the wafer relative to the source plasma. The anisotropic etching or isotropic etching can be controlled by turning platen power on or off. The fabrication process is maintained at low temperature using helium as cooling gas supplied to the backside of the wafer. Sulfur hexafluoride (SF_6) and octafluorocyclobutane (C_4F_8) are used as the main etch and passivation gases, respectively. The current process uses the polymer produced by C_4F_8 gas as a protecting passivation layer covering the silicon to replace the conventional SiO_2 or boron doping in isotropic etching. In anisotropic silicon etching, under the Bosch patent, sequentially alternating etch and passivation cycles can easily achieve high-aspect-ratio silicon structures [7]. Many fabrication parameters in ICP-RIE have been investigated to obtain high-aspect-ratio structures [8–14].

Figure 1 schematically shows the fabrication flowchart using a polymer as the protecting passivation layer in fabricating suspended SCS structures. First, the positive photoresist (AZ4620) is spun and patterned as an etch mask on a standard wafer, as shown in figure 1(*a*). Besides the lithography process, all other steps are conducted in the ICP-RIE chamber, as shown in figures 1(*b*)–(*f*). After forming high-aspect-ratio trenches by Bosch silicon-cyclic anisotropic etching, as shown in figure 1(*b*), the main steps to fabricate suspended structures are deposition of the polymer passivation layer, removal of polymer at the base of the substrate and silicon isotropic etching. The critical step is the proper deposition of the polymer passivation layer, as shown in figure 1(*c*), which needs to provide sufficient protection to the sidewall during the removal step of polymer at the base of the substrate (figure 1(*d*)) and the silicon isotropic etching step (figure 1(*e*)). Finally, the photoresist and polymer film can be removed using the oxygen plasma, as shown in figure 1(*f*).

3. Experimental results and discussions

Protection of the structure sidewall is vital to the success of the fabrication process. The effective coverage of the sidewall protective layer is influenced by the depth of the structure, the size of the structural opening and the roughness of the sidewall. This section uses a microstructure with the same trench depth to examine the effects of the polymer passivation layer and removal of the polymer at the base of the substrate under four structural opening sizes of 5, 10, 30 and 50 μm. A comb-drive microstructure is fabricated to test the protecting effects of the polymer passivation layer under isotropic etching. The silicon-cyclic anisotropic etching recipes used in this study, which is based on the standard Bosch anisotropic etching method, are the source power of 800 W, bias power of 12 W, SF_6 gas flow rate of 130 sccm (standard cubic centimeter per minute), O_2 gas flow rate of 13 sccm, time of 12 s in the etching step, and the source power of 800 W, bias power of 0 W, C_4F_8 gas flow rate of 85 sccm, time of 8 s in the passivation step. The etch rate is about 2.3 μm min^{-1}.

3.1. Polymer passivation layer and removal of polymer at the base of the substrate

In the standard Bosch etching process, the polymer is made up of the C_4F_8 gas ionized into plasma, which is then formed into a thin film through a deposition process [8]. The composition of a polymer includes the compounds CF_x^{+}, $CF_x^{\bullet}$, and $F^{\bullet}$. The compound $CF_x^{\bullet}$, due to its adsorptive function, forms the CF_2 thin film on the surface of the silicon structure. This CF_2 thin film acts as a protecting passivation layer to obstruct Fluorine ($F^{\bullet}$) ion etching silicon.

In our chemical composition measurement of the polymer passivation layer with the energy dispersive spectrometer (EDS) method, a polymer passivation layer about 500 nm in thickness is deposited on the surface of a silicon wafer as the test sample. The recipe for the polymer passivation layer deposition is the source power of 800 W, bias power of 0 W, C_4F_8 gas flow rate of 130 sccm and time of 5 min. EDS is performed in a Hitachi S-4300 Field emission scanning electron microscope with the accelerating voltage of 15 kV, where the vacuum in the chamber is 1×10^{-5} Pa to avoid the air contamination. The deposited polymer passivation layer is found to have 45% of carbon and 55% of fluorine in atomic percentages. The quality of the polymer passivation layer is influenced by the dimensions of the structural opening. Therefore, this study examines the conditions of the polymer passivation layer under various structural openings. The roughness of the microstructure sidewall also influences the deposition results of the polymer passivation layer. In reactive ion etching, the cyclic process of alternating Bosch

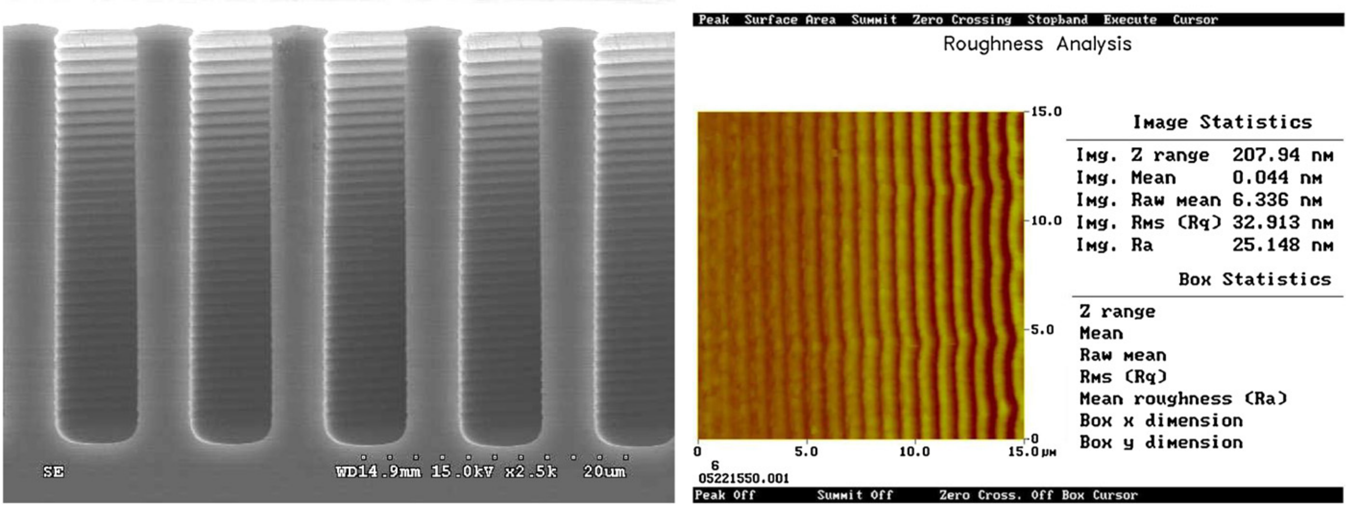


Image Statistics

Img. Z range 207.94 nm
Img. Mean 0.044 nm
Img. Raw mean 6.336 nm
Img. Rms (Rq) 32.913 nm
Img. Ra 25.148 nm

Box Statistics

Z range
Mean
Raw mean
Rms (Rq)
Mean roughness (Ra)
Box x dimension
Box y dimension

(*a*) (*b*)

Figure 2. (*a*) The SEM micrograph showing the trench microstructure with a 5 μm gap and a 30 μm depth by standard Bosch anisotropic etching. (*b*) The roughness measurement at the sidewall ripple structure by AFM, PV value is about 200 nm.

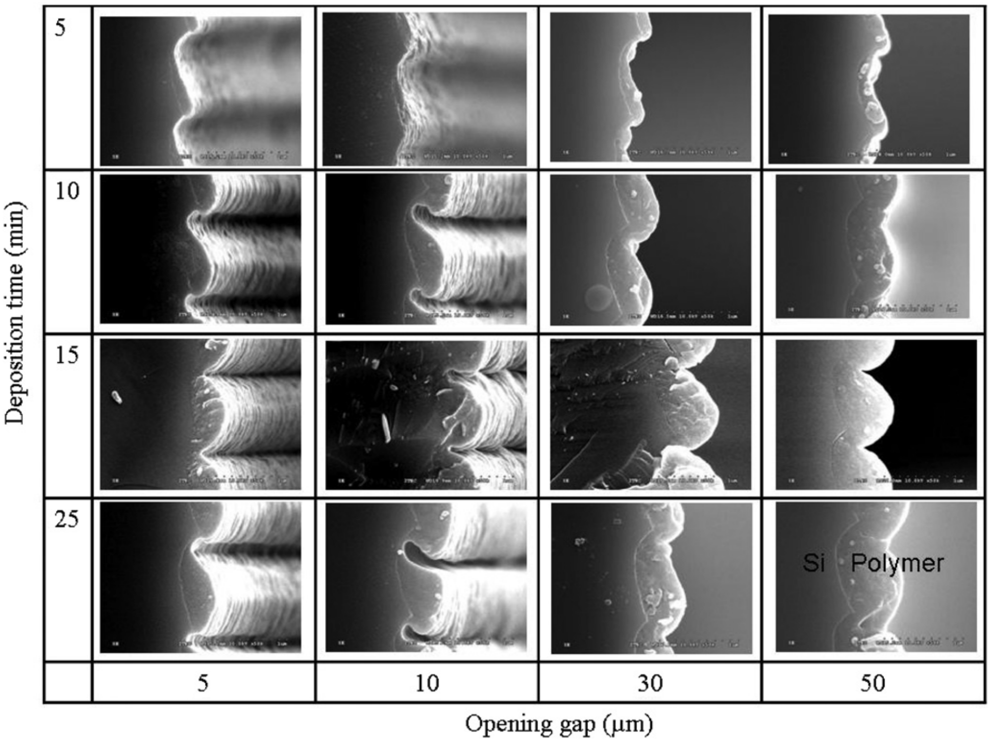


Figure 3. SEM micrographs show coverage conditions of the polymer at the sidewall of 30 μm deep trench structures under four different opening gaps and four different polymer deposition time.

etching and the passivation can produce a structure with an extremely high aspect ratio. However, this etching mechanism also causes ripple-like periodic structures on the sidewall, as shown in figure 2(*a*) with the SEM photograph of the trench microstructure after the anisotropic etching step. The line width and structural opening size of the trenches are both 5 μm, and the etched trench depth is 30 μm. The roughness of the sidewall is measured by atomic force microscopy (AFM), and the average roughness of the ripple structures is found to be 25 nm. The peak to valley values of the roughness of the ripple structures is ∼200 nm, as shown in figure 2(*b*). The ripple structures have a shading effect on the polymer passivation layer. This would make depositing polymer in the area below the ripple structures difficult, leading to a poor polymer passivation layer. While fabricating the suspended SCS structure, this means that the polymer passivation layer may not be able to sufficiently protect the structure in the isotropic etching step. Therefore, the effectiveness of the polymer passivation layer due to sidewall ripples after the anisotropic etching step needs to be examined first.

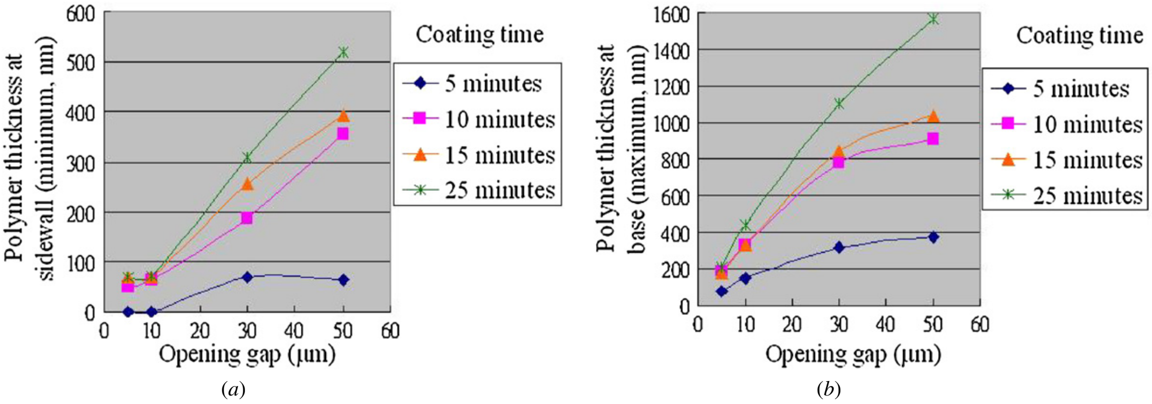


Figure 4. Measured polymer thickness. (*a*) Minimum thickness on the sidewall and (*b*) the maximum thickness on the base at four different opening sizes in the 30 μm deep trench.

A trench microstructure is fabricated to have 30 μm depth with four different structural openings (5, 10, 30 and 50 μm) by the standard Bosch anisotropic etching recipe first. Then various polymer passivation time (5, 10, 15 25 min) and removal time of polymer at the base of the substrate are performed to investigate the conditions of the polymer passivation layer. In the ICP-RIE processing chamber, shutting off platen generator power can allow isotropic polymers to cover the surface of the structure. Here, the recipe for the polymer passivation layer is the source power of 800 W, bias power of 0 W and C_4F_8 gas flow rate of 130 sccm.

The SEM photographs of the polymer passivation layer deposited on the trench microstructure sidewall at four different openings and deposition time are shown in figure 3. It is shown that the polymer thickness at the sidewall is not uniform. The polymer thicknesses under different deposition conditions are also measured and shown in figure 4. The deposited polymer passivation layer at the sidewall must be thick enough to protect the silicon sidewall during the etching process. Therefore, the region with the lowest thickness of the polymer passivation layer becomes the weakest area for the passivation layer to be etched away. Figure 4(*a*) shows the measured minimum thickness of the deposited polymer on the trench sidewall. It is observed that the thickness of the deposited polymer in the narrow opening is much less than that of the deposited polymer in the wide opening under the same polymer passivation time. It is also found that the polymer passivation layer at the sidewall becomes thinner at the deeper region even at the same trench because of the lower plasma density at the deeper region. The locations with minimum polymer thickness on the trench side wall are all observed near the bottom of the trenches.

For structural opening sizes of 5 and 10 μm, due to the shading effect produced by ripple structures, only a very thin polymer film can be deposited in areas beneath the ripple structures. With a short polymer passivation time of 5 min, no polymer can be deposited at areas beneath ripple structures. Even when the coating time is increased from 5 min to 25 min, which generally would increase the thickness of the deposited polymer, the thickness of the polymer film in areas beneath ripple structures is still much thinner than that of the polymer film in other areas. To improve the insufficient polymer passivation layer resulting from the shading effect of ripple structures, especially at narrow opening gaps, other anisotropic etching recipes to minimize the microstructure sidewall ripples [15, 16] might be helpful. When structural opening sizes are 30 and 50 μm, the shading effect of ripple structures on the polymer deposition is significantly reduced, facilitating the formation of a complete polymer protective film.

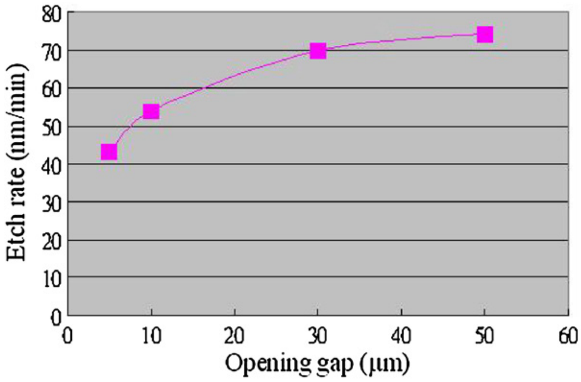
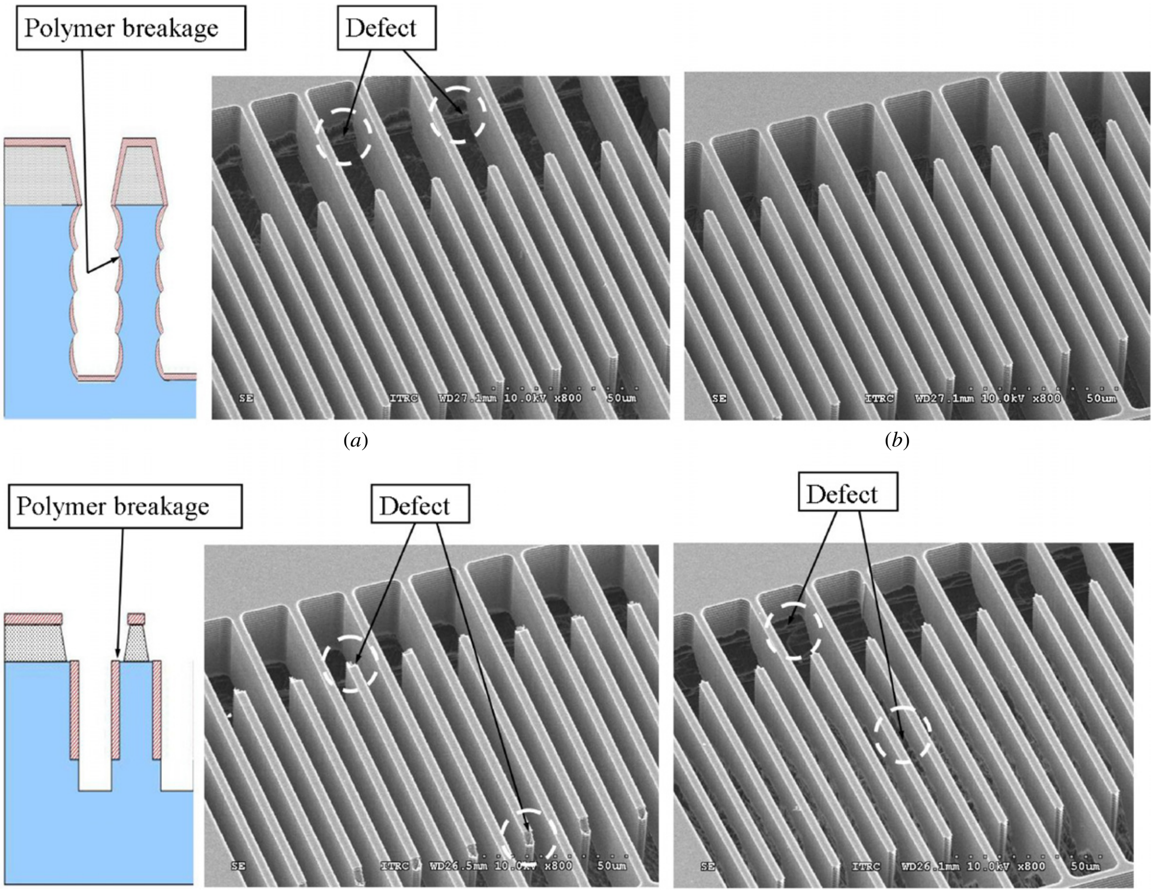


Figure 5. Removing rates of the polymer at the base of the substrate in the 30 μm deep trench at four different opening gaps.

During the fabrication process of suspended structures, polymer at the base of the substrate must be completely removed in order to conduct subsequent isotropic etching. Therefore, the maximum thickness of the polymer at the base of the substrate under various deposition conditions are measured and shown in figure 4(*b*). It is found that the polymer thickness increases with the structural opening size and deposition time as expected.

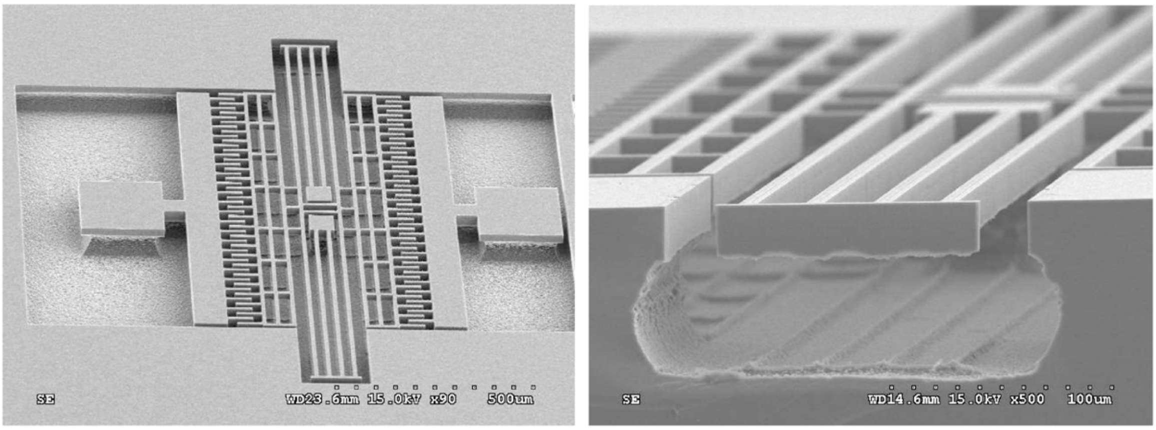
The recipe for the removal of the polymer at the base of the substrate is the source power of 800 W, bias power of 12 W, SF_6 gas flow rate of 130 sccm and O_2 gas flow rate of 13 sccm. Figure 5 shows the removal rates of the polymer at the base of the substrate in the 30 μm deep trench with the four opening gaps. It indicates that a wider opening gap will lead to a faster removal rate.



(*a*) (*b*)

(*c*) (*d*)

Figure 6. The fabricated suspended comb-drive microstructures with 5 μm line width/opening and 30 μm depth. (*a*) Defects due to an insufficient polymer passivation layer (5 min polymer passivation, 4 min removal of polymer at the base of substrate, 6 min isotropic etching). (*b*) Successful case (10 min polymer passivation, 8 min removal of the polymer at the base of the substrate, 6 min isotropic etching). (*c*) Defect due to excessive ion bombardment after the removal step of the polymer at the base of the substrate (10 min polymer passivation, 10 min removal of the polymer at the base of the substrate, 6 min isotropic etching). (*d*) Defect due to excessive isotropic etching (10 min polymer passivation, 8 min removal of the polymer at the base of the substrate, 9 min isotropic etching).

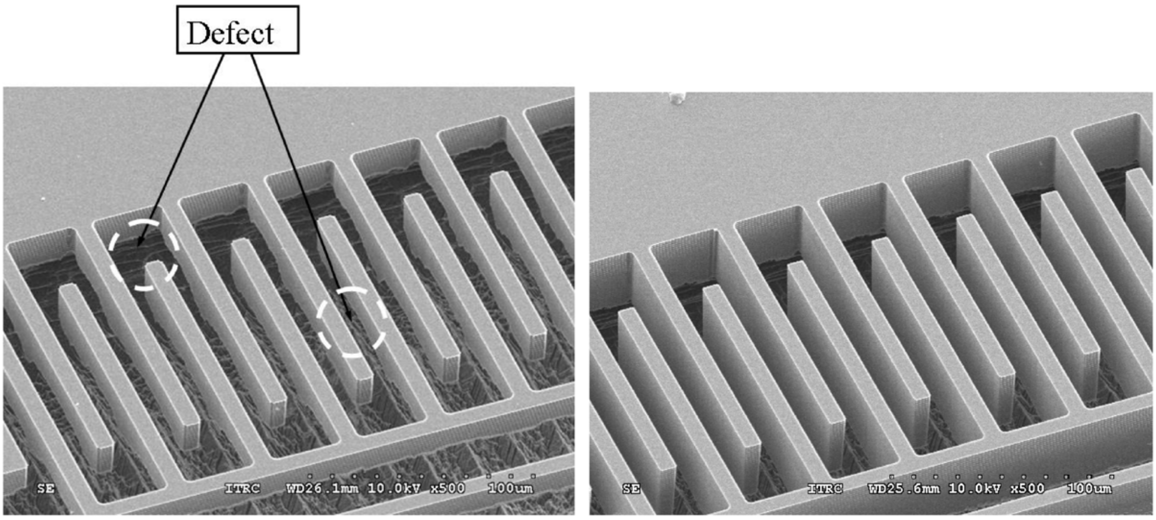


(*a*) (*b*)

Figure 7. SEM photographs of (*a*) suspended comb-drive microstructures and (*b*) a close view of the spring segment.

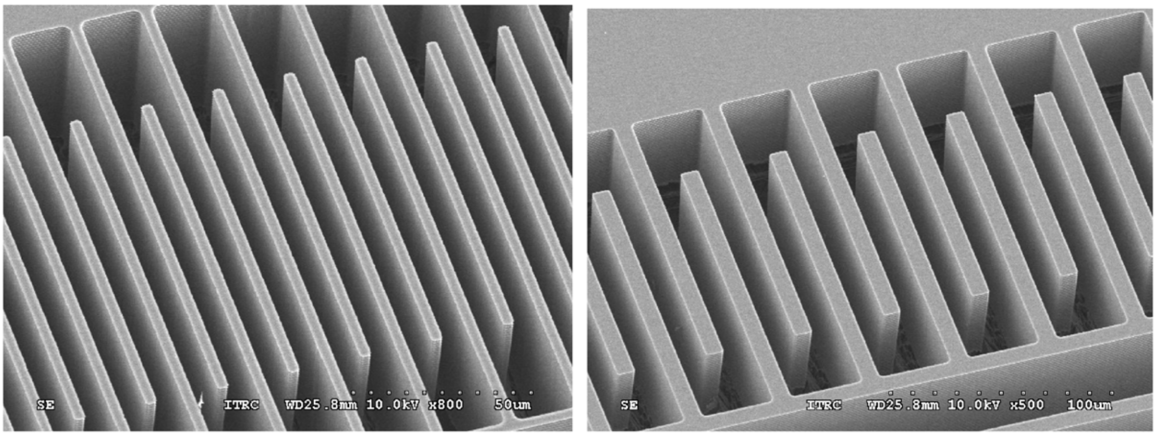
3.2. Polymer protecting effect in isotropic etching

In the fabrication process of suspended SCS structures, isotropic etching can be divided into wet etching and dry etching. Dry etching is more popular because it can prevent the suspended structure from sticking to the substrate. Xenon difluoride (XeF_2) gas is often used for dry isotropic etching [17, 18]. The gas XeF_2 has a spontaneous etching reaction with silicon to provide good isotropic etching effects. However, XeF_2 is highly toxic and costly.



(*a*) (*b*)

Figure 8. Suspended comb-drive microstructures with 10 μm gap and 30 μm depth. (*a*) Defect due to insufficient polymer protection (10 min polymer passivation, 8 min removal of the polymer at the base of the substrate, and 9 min and isotropic etching). (*b*) Result with the proper recipe (15 min polymer passivation, 10 min removal of the polymer at the base of the substrate and 9 min isotropic etching time).



(*a*) (*b*)

Figure 9. Suspended com-drive microstructures with 60 μm depth at the line width/opening of (*a*) 5 μm and (*b*) 10 μm.

This study uses SF_6 as the gas for isotropic dry etching [19, 20]. Although the isotropic etching effects with SF_6 are inferior to those resulting from XeF_2, SF_6 is cheaper and safer than XeF_2. Using SF_6 isotropic etching while shutting off platen generator power in the ICP machine causes SF_6 gas to ionize a large amount of Fluorine $F^\bullet$ ions. These $F^\bullet$ ions have spontaneous etching reactions with silicon material, forming an isotropic etching mechanism. The silicon material at the base of the microstructure spontaneously combines with the $F^\bullet$ ions to form SiF_x gaseous molecules, which are then removed due to vacuum.

In the standard Bosch anisotropic process, the polymer film produced is extremely thin and cannot tolerate long isotropic etching time. This polymer is a soft material that is easily deposited and removed but not as effective in resisting $F^\bullet$ ions as SiO_2 or boron doping. During the etching process, a large amount of $F^\bullet$ ions react with the polymer to form gaseous CF_x to cause the removal of the polymer.

As shown in figure 1(*e*), a thicker polymer film on the trench sidewall can provide better protection on the silicon sidewall in the isotropic etching process. However, a thicker polymer film on the trench base will take longer time to be removed, as shown in figure 1(*d*), which may cause damage to the polymer on the sidewall to expose silicon. Therefore, appropriate recipes must be established for the polymer to successfully protect the structure without causing long polymer removing time. Here the comb-drive microstructures with line width/structural opening sizes of 5 and 10 μm are used to test different recipes on polymer film deposition and removal. The recipe for isotropic etching is the source power of 800 W, bias power of 0 W, SF_6 gas flow rate of 130 sccm and O_2 gas flow rate of 13 sccm.

First, a comb-drive microstructure of 30 μm in depth with the line width/opening size of 5 μm is used to test recipes. Figure 6(*a*) shows the SEM photograph with the following conditions: 5 min polymer passivation time, 4 min removal time of polymer at the base of the substrate and 6 min isotropic etching time. It is found that the silicon beams with 5 μm width can be suspended. It indicates that 6 min isotropic etching time is sufficient for the silicon under the microstructure with a line width of 5 μm to be completely removed. However, some defects are formed near the base of the silicon sidewall, and it means that the polymer fails to protect the microstructure completely from isotropic etching. The reason could be either insufficient polymer passivation time or the shading effect of sidewall ripple structures. From our tested data in figure 4(*a*), for 5 min polymer passivation time, the minimum thickness of the polymer film on the trench sidewall with an opening size of 5 μm is all found to be around the bottom of the trench and could be zero, which can explain the defects in figure 6(*a*) due to the poor polymer passivation layer.

Figure 6(*b*) shows the results for polymer passivation time increased to 10 min. When polymer passivation time is increased, the thickness of the polymer at the base of the substrate is also increased, which would need longer removing time for the polymer at the base of the substrate to 8 min. The isotropic etching time remains to be 6 min. Under these conditions, a suspended comb-drive microstructure is successfully fabricated.

In figure 6(*c*), polymer passivation time is remained at 10 min, removal time of the polymer at the base of the substrate is increased to 10 min, and isotropic etching time is still 6 min. Some defects can be observed at the upper corner of the suspended silicon beams. The removal of the polymer at the base of the substrate mainly depends on the ion bombardment. In this case, the ion bombardment removes not only the polymer at the base of the substrate but also the masking material on the upper region of the structure. The removal rate of corner material is faster than that of material in other areas. When the removal time for the polymer at the base of the substrate is too long, damage to the polymer on the upper corner edge would happen to expose the silicon under the polymer. After isotropic etching, the exposed silicon will be etched away to cause defects. Therefore, the time to remove the polymer at the base of the substrate must not exceed the limit.

In figure 6(*d*), time for polymer passivation and removal of the polymer at the base of the substrate are 10 and 8 min, respectively. The isotropic etching time is increased from 6 to 9 min. Defects are all observed to be around the bottom of the trench. This indicates that the thickness of the polymer film deposited for 10 min is unable to resist 9 min isotropic etching, because the polymer thickness near the trench bottom is thinner. Therefore, the period of isotropic etching must not be too long. If isotropic etching must be increased to fabricate a suspended SCS microstructure with larger line width, polymer passivation time must also be increased.

The etching rate of the polymer passivation layer at the sidewall during the isotropic etching is very important. For the structural opening size of 5 μm and the depth of 30 μm, the minimum polymer thickness at the sidewall is about 50 nm with the 10 min deposition of the polymer passivation layer, as shown in figure 4(*a*). Figures 6(*b*) and (*c*) indicate that the 50 nm thickness of the polymer can resist 6 min of isotropic etching, but cannot resist 9 min of isotropic etching. Therefore, the etching rate of the polymer passivation layer at the sidewall should be within 5.6–8.3 nm min^{-1}.

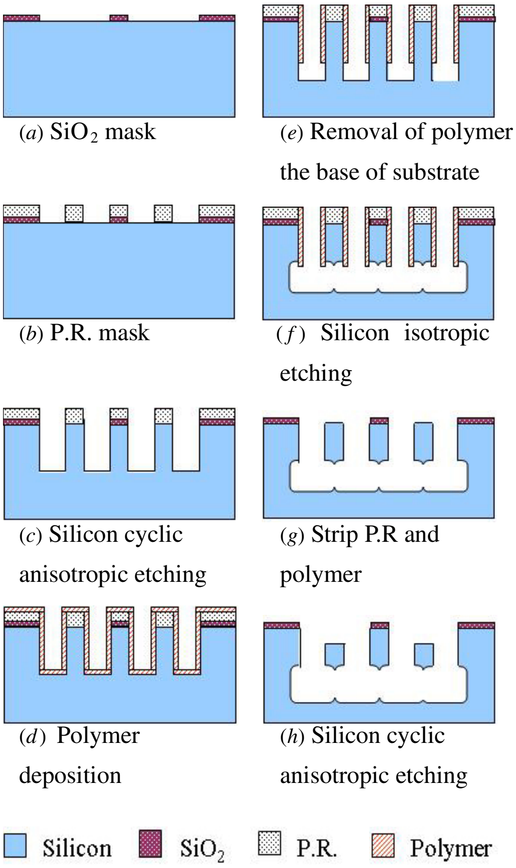
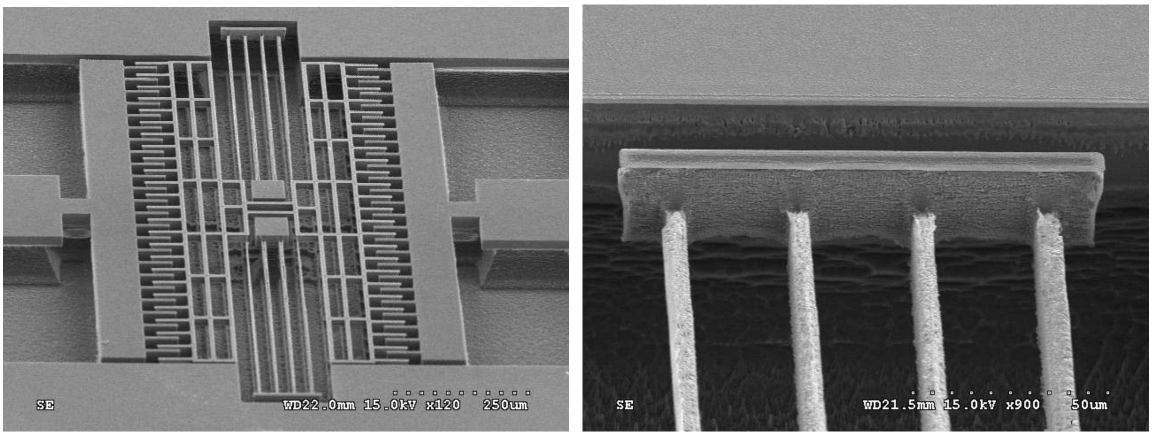

(*a*) SiO_2 mask
(*e*) Removal of polymer at the base of substrate
(*b*) P.R. mask
(*f*) Silicon isotropic etching
(*c*) Silicon cyclic anisotropic etching
(*g*) Strip P.R and polymer
(*d*) Polymer deposition
(*h*) Silicon cyclic anisotropic etching

Figure 10. Fabrication flowchart of bi-level suspended microstructures based on the PoPLSE method.

Based on the above experimental investigations, a suspended comb-drive SCS microstructure with 30 μm in depth and the line width/structural opening size of 5 μm can be successfully fabricated by 10 min polymer passivation time, 8 min removal time of polymer at the base of the substrate and 6 min isotropic etching time, as shown in figure 7(*a*). Figure 7(*b*) shows a close view of the suspended microstructure to verify the feasibility of the proposed PoPLSE method.

For the suspended microstructure with larger line width, longer isotropic etching time is needed. The parameters on the deposition of the polymer passivation layer and the removal of the polymer at the base of the substrate must be adjusted accordingly. Using a comb-drive microstructure with 30 μm in depth and 10 μm in line width/opening size as an example, figure 8(*a*) shows that with 10 min polymer passivation time, 8 min removal time of the polymer at the base of the substrate and 9 min isotropic etching time, the fabricated microstructure still exhibits defects near the bottom of the beams due to insufficient polymer protection. When the polymer passivation time and removal time of polymer at the base of the substrate are increased to 15 and 10 min, respectively, while keeping the isotropic etching period at 9 min, a suspended comb-drive microstructure with the depth of 30 μm and the line width of 10 μm is successfully fabricated, as shown in figure 8(*b*).



(*a*) (*b*)

Figure 11. SEM photographs of (*a*) bi-level suspended com-drive microstructures and (*b*) a close view of the spring segment.

For a structural opening size of 10 μm and depth of 30 μm, with 10 and 15 min deposition of a polymer passivation layer, as shown in figure 4(*a*), the minimum polymer thickness at the sidewall is about 60 and 70 nm, respectively. Figures 8(*a*) and (*b*) show that the 60 nm thickness of polymer cannot resist 9 min isotropic etching, but the 70 nm thickness of the polymer can resist 9 min isotropic etching. Therefore, the etching rate of the polymer passivation layer at the sidewall can be estimated to be around 6.67–7.78 nm min^{-1}.

When the depth of the microstructure is increased, polymer passivation time needs to be longer. The removal time for the polymer at the base of the substrate and the isotropic etching period must also be adjusted accordingly. Figure 9 shows other successfully fabricated comb-drive microstructures using the proposed PoPLSE method. The comb-drive structures have the depth of 60 μm and the line width/structural opening size of 5 and 10 μm, respectively. The recipe used in the fabrication process is 25 min polymer passivation period, 14 min removal time of the polymer at the base of the substrate and 9 min isotropic etching period.

4. PoPLSE method extension

4.1. Bi-level suspended microstructures

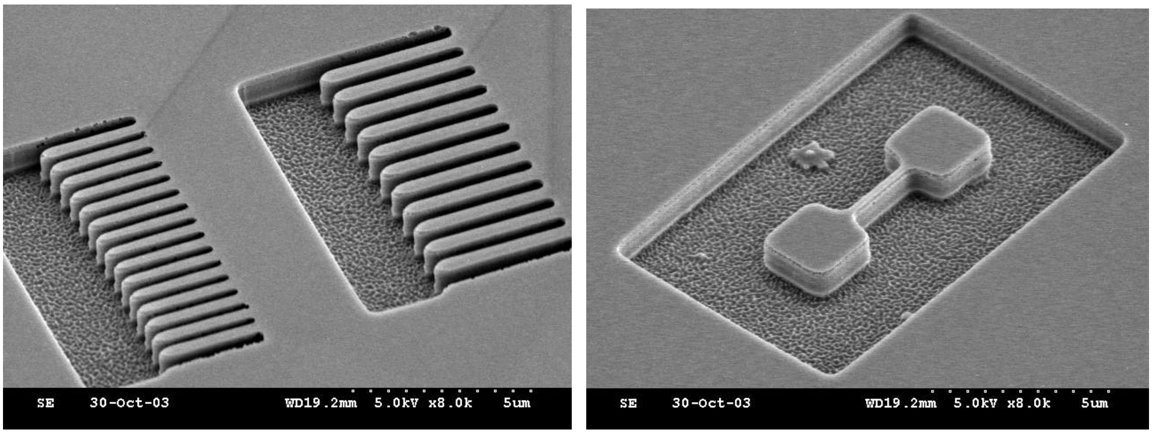
In the previous section, single-level suspended SCS microstructures, i.e. suspended microstructures with the same thickness, are demonstrated by the proposed PoPLSE method. The proposed method can be further extended to fabricate not only single-level, but bi-level suspended microstructures. Still using the comb-drive structure as an example, if the thicknesses of spring and finger can be trimmed separately, the thinner spring can reduces structure stiffness and then lead to a lower driving voltage. Different thicknesses of the fingers can be used to fabricate torsional or vertical comb drives to have out-of-plane motion.

Figure 10 shows the fabrication flowchart of the bi-level suspended structures. The mask processes are shown in figures 10(*a*) and (*b*). The current study chooses the hard mask like silicon-oxide or silicon-nitride and the soft mask like photoresist. The thermal oxide with 1 μm thickness is deposited using the oxidation furnace on a standard silicon wafer. Then, the first etching mask is patterned with photoresist and transferred to thermal oxide using lithography and RIE, respectively, as shown in figure 10(*a*). The second etching mask is the soft photoresist patterned on the first oxide etch mask, as shown in figure 10(*b*). After these two mask processes, other fabrication steps are all conducted in the ICP-RIE chamber, as shown in figures 10(*c*)–(*h*). First, the single-level suspended structures are fabricated, shown in figures 10(*c*)–(*g*), which are the same steps as those in figures 1(*b*)–(*f*). It should be noted that there are still some regions with a hard mask on top after the step taken as shown in figure 10(*g*). Finally, the silicon-cyclic anisotropic etching is applied again to etch the suspended SCS microstructure without the hard mask on top to achieve various thicknesses of suspended microstructures, as shown in figure 10(*h*). A comb-drive microstructure with the thinner spring segment is shown in figure 11 to demonstrate this process.

4.2. Sub-micro suspended structure

Researchers have already fabricated sub-micro suspended SCS microstructures previously [21]. However, the fabrication process needs many micromachining instruments. Here the PoPLSE method is shown to have the capability of fabricating sub-micro or nano-scale suspended structures with fewer capital requirements.

First, the sub-micro or nano-scale PMMA resist etch mask is spun and patterned using 30 kV Raith50 electro-beam lithography systems. The sub-micro cantilever beam and bridge structures successfully fabricated by the polymer protecting method are shown in figures 12(*a*) and (*b*), respectively. The width of the cantilever beam is 400 nm, and the thickness is 1 μm. The width of the bridge is 200 nm, and the thickness is 1 μm. The cyclic anisotropic etching recipe for sub-micro silicon has been provided as follows. In the etching step, source power = 100 W, bias power = 12 W, SF_6 gas



(*a*) (*b*)

Figure 12. SEM photographs of fabricated sub-micro suspended structures based on the PoPLSE method. (*a*) Cantilever beam with 400 nm width and 1 μm thickness. (*b*) The bridge structure with 200 nm width and 1 μm thickness.

flow rate = 20 sccm, O_2 gas flow rate = 13 sccm, etching time = 4 s, and in the passivation step, source power = 100 W, bias power = 0 W, C_4F_8 gas flow rate = 15 sccm, passivation time = 4 s, where process time = 200 s. The recipe for polymer passivation before isotropic etching is source power = 100 W, bias power = 0 W, C_4F_8 gas flow rate = 85 sccm and time = 180 s. The recipe for the removal of the polymer at the base of the substrate is source power = 100 W, bias power = 12 W, SF_6 gas flow rate = 20 sccm, O_2 gas flow rate = 13 sccm and time = 80 s. The recipe for isotropic etching is source power = 100 W, bias = 0 W, SF_6 gas flow rate = 130 sccm, O_2 gas flow rate = 13 sccm and time = 60 s.

5. Conclusion

This study successfully verifies the feasibility of the proposed PoPLSE method by using the polymer as a protection layer to fabricate suspended SCS microstructures. Without using SiO_2 deposition or boron doping as the protection layer in the isotropic etching to release the microstructure, the anisotropic and isotropic etching steps can all be performed in the ICP-RIE chamber, which simplifies the fabrication process and saves fabrication time. The suitable recipes between polymer passivation time, removal time of polymer at the base of substrate, and isotropic etching time for comb-drive microstructures with 30 or 60 μm in depth and 5 μm line width at different opening sizes are experimentally identified. The proposed PoPLSE method is also shown to be capable of fabricating bi-level or sub-micro suspended structures, which may act as an alternative method to fabricate suspended micro devices with less capital requirement.

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