High aspect ratio polystyrene structure fabrication using electron beam lithography

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Fabrication of high aspect ratio protruded nano-structures[1] plays a very important role in various applications such as MEMS/NEMS and especially BioMEMS. Such high aspect ratio structure can be patterned using conventional electron beam lithography followed by etching the substrate/sub-layer, ideally using a negative resist such as polystyrene to form the etching mask. However, the tall resist structure defined in negative resist is often unstable, suffering from collapse and detachment after the development because of capillary force; and critical point drying is not effective for releasing the soft polymer structures.

In this study we report an alternative approach to tackle this issue to a certain degree. We form an array of thin “ceiling” on top of the tall resist structures (here an array of pillar) to “hold” them together and thus reduce the structure collapse. Meanwhile, development can still be completed by optimizing the size of the ceiling patches such that developer has enough time to enter and dissolve the unexposed negative resist under the ceiling. The “ceiling” can be formed by low-energy (<5 keV) electron beam exposure that will cross-link only the upper portion of the thick resist; whereas the tall resist structure is exposed at high energy (20 keV) having deep penetration depth.

In the experiment (Figure 1), we coated 2 µm polystyrene (Mw 700 kg/mol, negative resist) on silicon wafer. Such a thick resist is required for etching very tall structures for subsequent pattern transfer. Next, electron beam exposure at 20 keV and 800 $\mu C/cm^2$ area dose was performed to define the tall pillar structure. Subsequently, the ceiling pattern was exposed at low energy of 4 keV at 40 $\mu C/cm^2$ that cross-linked only the upper film (top ~300-400 nm, see Ref. [2] for exposure depth simulation). Finally oxygen plasma etching was performed to remove the ceiling patches. For the area without the ceiling, the pillars were often collapsed or detached; and in both cases, there would be no pillar left after this etching step.

Figure 2a shows polystyrene pillar arrays over the area originally without “ceiling” and with ceiling, showing that the pillars were all detached for the area without ceiling. Whereas the pillars all remained over the area with ceiling, though some pillars were distorted. Large microscale pillars were designed near the corners of each ceiling patch to help hold them stronger. Even so, because the capillary force is really strong for the soft polymer ceiling, some ceilings were greatly deformed and displaced as shown in Figure 2b. Figure 2c shows a 3 by 3 nano-pillar array that well survived the fabrication process under the protection of the ceiling structure.

[1] A. Zeniou, K. Ellinas, A. Olziersky and E. Gogolides, "Ultra-high aspect ratio Si nanowires fabricated with plasma etching: plasma processing, mechanical stability analysis against adhesion and capillary forces and oleophobicity", Nanotechnology, 25(3), 035302 (2014).

[2] R. K. Dey and B. Cui, "Lift-off with solvent for negative resist using low energy electron beam exposure", J. Vac. Sci. Technol. B, 32, 06F507 (2014).

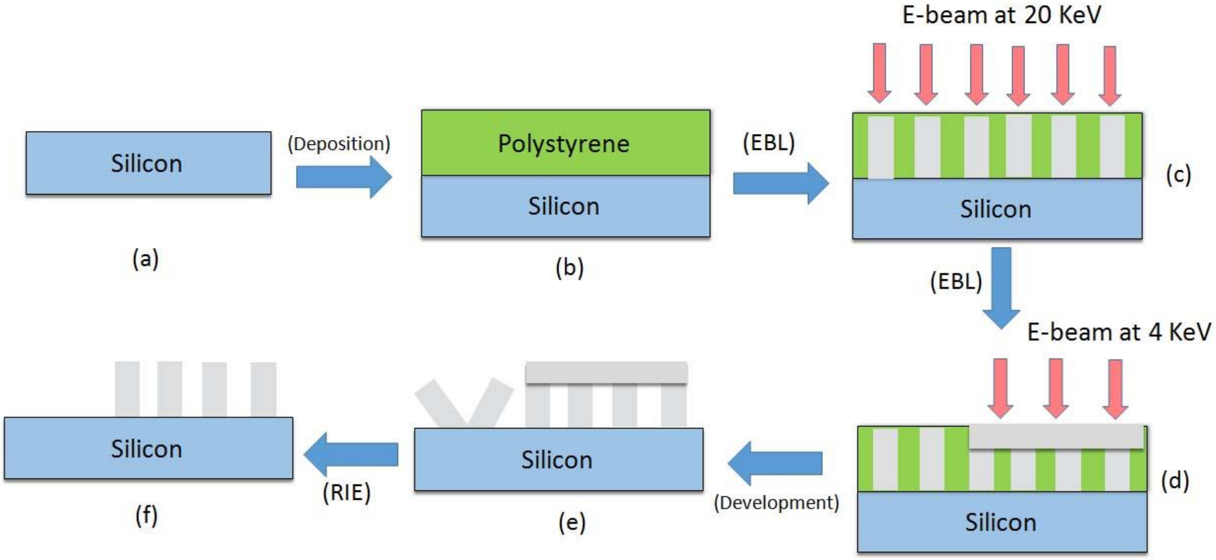

Figure 1 Process steps for the fabrication of high aspect ratio polystyrene nano-structures (array of pillars) by electron beam lithography, with or without ceiling patches defined by low energy (4 keV) exposure.

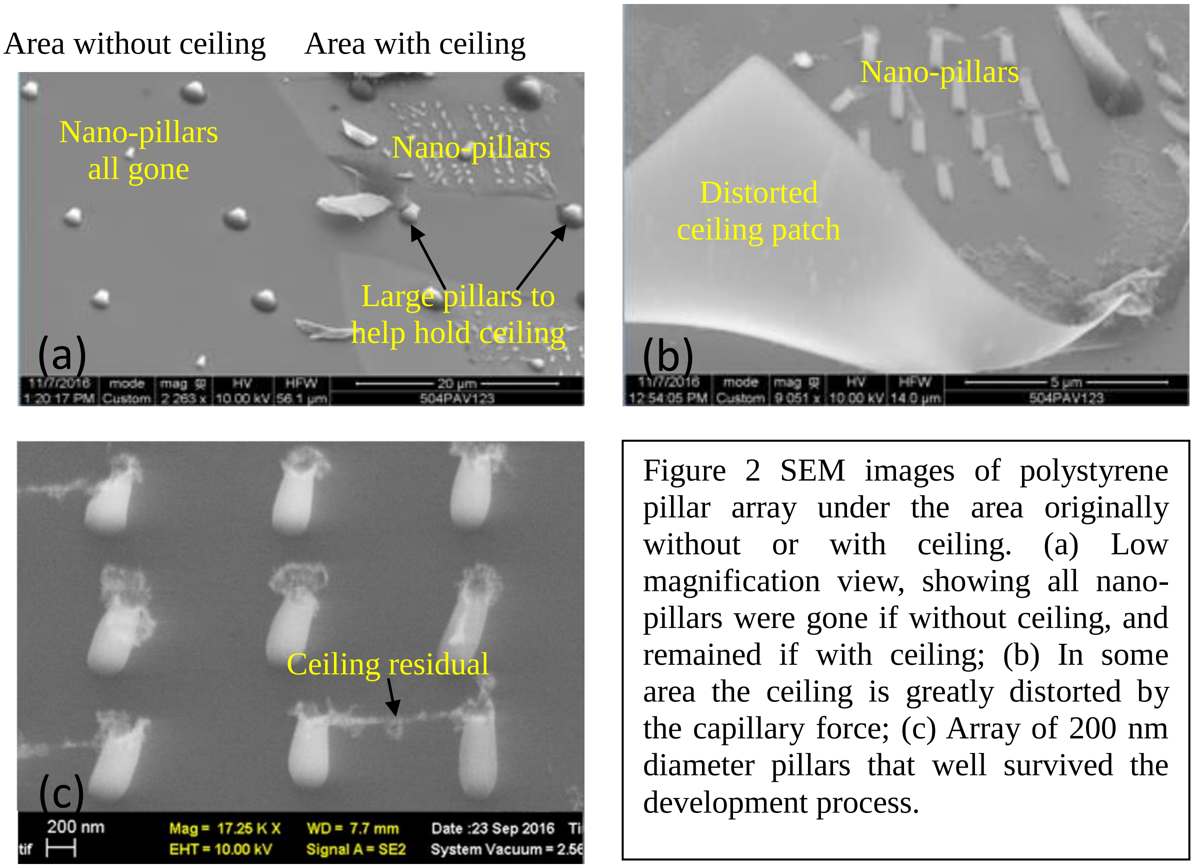

Figure 2 SEM images of polystyrene pillar array under the area originally without or with ceiling. (a) Low magnification view, showing all nano-pillars were gone if without ceiling, and remained if with ceiling; (b) In some area the ceiling is greatly distorted by the capillary force; (c) Array of 200 nm diameter pillars that well survived the development process.