Wafer-Scale Patterning of High-Aspect-Ratio (50:1) Silicon Nanostructures (<50 nm) by Nanoimprinting and Deep Reactive Ion Etching

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High-aspect-ratio nanostructures over a large area have many applications in electronics, optics, optoelectronics, chemical detection and biotechnology. Here we present direct, high-aspect-ratio (50:1) nanostructuring of bulk crystalline silicon with vertical sidewalls. Combining nanoimprint lithography (NIL) and an optimized deep reactive ion etch (DRIE) we demonstrate wafer scale fabrication of vertical silicon nanopillars (50 nm dia. x 2.4 um tall) and high-aspect ratio gratings (140 nm wide and 6 um tall.) Using these arrays we also demonstrate continuous flow bifurcation of suspended nanoparticles using a large-area, high-aspect-ratio pillar array.

Previously, submicron features have been etched by standard RIE to aspect ratios as high as (23:1, 120 nm pillars), but achieving vertical sidewalls is difficult [1]. Highly anisotropic etching of 400nm features has been demonstrated using cryogenic inductively couple plasma etching (30:1) [2]. Aspect ratios can be dramatically increased from the as-etched value by subsequent reduction of structure diameter or width by wet chemical etching or by oxidation and etch back [1,3]. Anodization of silicon to create deep macropores combined with wet etching to invert the structure to submicron pillars has resulted in aspect ratios of (50:1) [4]. All of them need additional steps, that could reduce the yield and increase the cost. Here, we demonstrate simple nanopatterning of nanostructures with substantially smaller feature sizes and larger aspect ratios than previous work by nanoimprint and direct etching.

In fabrication, we first patterned the etching mask: thermal-silicon-dioxide nanostructures of ~100nm height, by thermal nanoimprint lithography (Nanonex NX-2000 Imprintor and NX1020 resist) and standard RIE (PlasmaTherm SLR). Wafer scale (4” dia.) master imprint molds (200nm-300nm pitch) were made using interference lithography and mold-to-mold cross imprinting [5,6]. After SiO2 etch mask patterning, DRIE with the Bosch Process™ , which alternates isotropic plasma etching with plasma assisted sidewall passivation, was used to etch the silicon. Generally, the ratio of etching to passivation determines the etching anisotropy, and was optimized to achieve vertical sidewalls. However, the characteristic *scalloping* of the sidewalls from the two step process (normally more than 100nm peak to peak) can quickly destroy sub-micron features. To avoid such large scalloping, we shortened the etching and passivation cycle times to ~5 seconds to reduce the scalloping below 10 nm, resulting in precise high aspect ratio etching of dense nanostructures (Figures 1-3).

Applications for dense, high-aspect ratio nanostructures include vertical nanowires, subwavelength optical devices and lab-on-a-chip devices[6]. For example, we explored the laminar fluid flow through a deep-etched nanopillar array to separate particles by size (Fig. 4.)

References:
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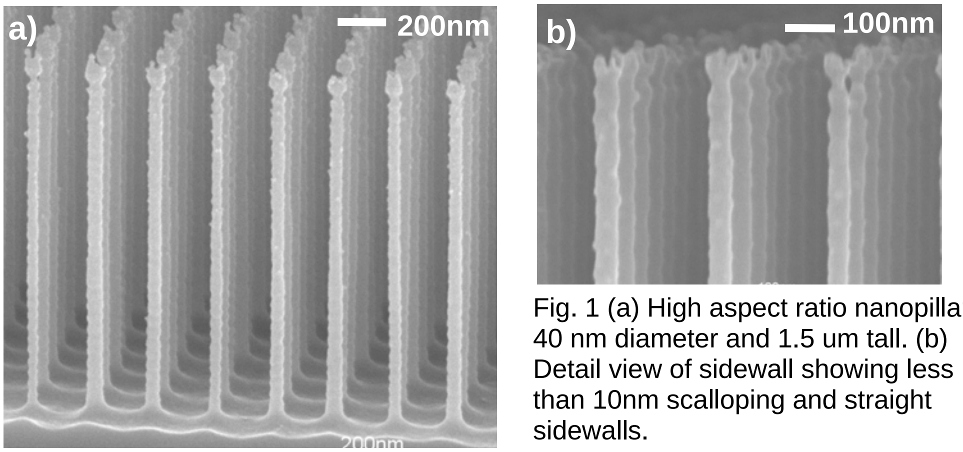
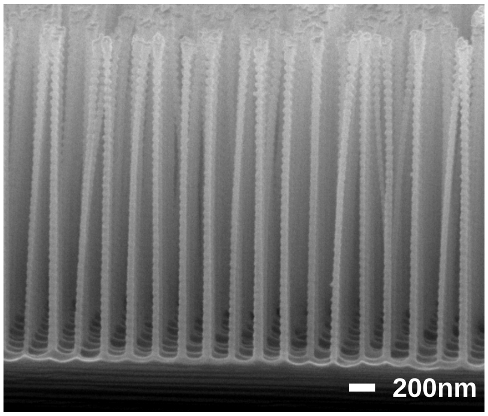


Fig. 1 (a) High aspect ratio nanopillars: 40 nm diameter and 1.5 um tall. (b) Detail view of sidewall showing less than 10nm scalloping and straight sidewalls.



Fi. 2 (a) High aspect ratio nanopillars: 50 nm diameter and 2.4 um tall. (aspect ratio of ~ 50:1)

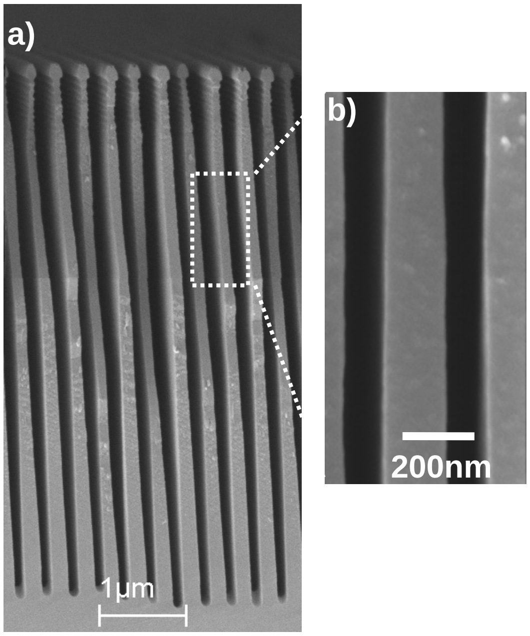


Fig. 3 (a) High aspect ratio gratings: 140 nm wide and 6 um tall. (b) Detail of sidewall etching with little appreciable scalloping.

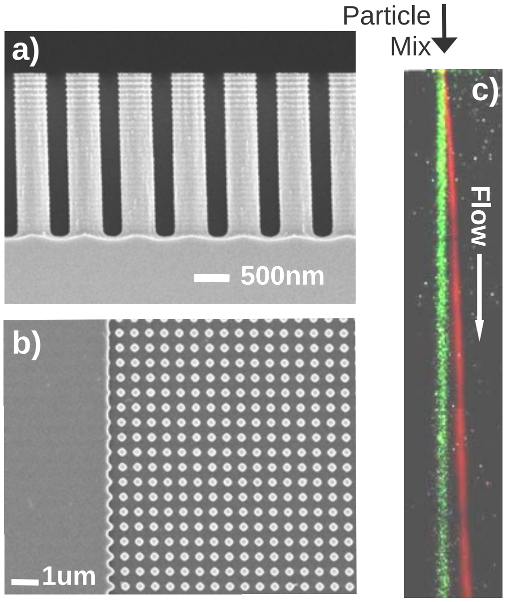


Fig. 4. (a) Profile of deep etched nanopillar array used for sized based fluidic separation. (b) Top view of pillar array c) Continuous flow separation of 200nm (red) and 100nm (green fluorescent beads in nanopillar array.