Electron-Beam Templating of Capillary-Force-Induced Nanocollapse

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Capillary force is a dominant force at meso-, micro-, and nanometer- scale structures due to the relatively large surface-to-volume ratios at nanoscale dimensions. This force can be used to assemble small objects [1-5]. Here, we demonstrate a directed-assembly process based on controllable capillary-force-induced collapse that can precisely assemble individual high-aspect-ratio nanostructures at 10-nm-length-scales into complex two- and three-dimensional structures.

High-aspect-ratio lines can collapse due to capillary forces in the drying process to form rectangular areas and dots can collapse to form lines. Fig. 1 shows that by controlling the initial pattern geometry and nanostructure shape, a deterministic collapse direction was achieved. This technique enabled the fabrication of different kinds of nanostructures by using electron-beam-lithography to define high-aspect-ratio hydrogen silsesquioxane (HSQ) or negative polymethyl-methacrylate PMMA nanostructures. These nanostructures then self-assembled during drying to form 3D nanostructures, nanoconnects, nanogaps, or line and area arrays. By locally adjusting the pillar spacing, we were also able to fabricate complex hierarchical networks from isolated nanopillars, as shown in Fig. 2.

To further understand this process, we systematically studied how electron-beam dose, resist thickness, feature dimension, pattern pitch, and pattern positioning determined the resulting nanocollapse-induced self-assembly.

This technique suggests a number of potential applications, including: (1) increasing the throughput of electron-beam lithography by permitting patterning of only a portion of the final structure; (2) reducing proximity effect by reducing the total dose needed to make linear patterns in a given area; and (3) reducing electron exposure in radiation-sensitive devices by using induced collapse over the device material to define a device feature.

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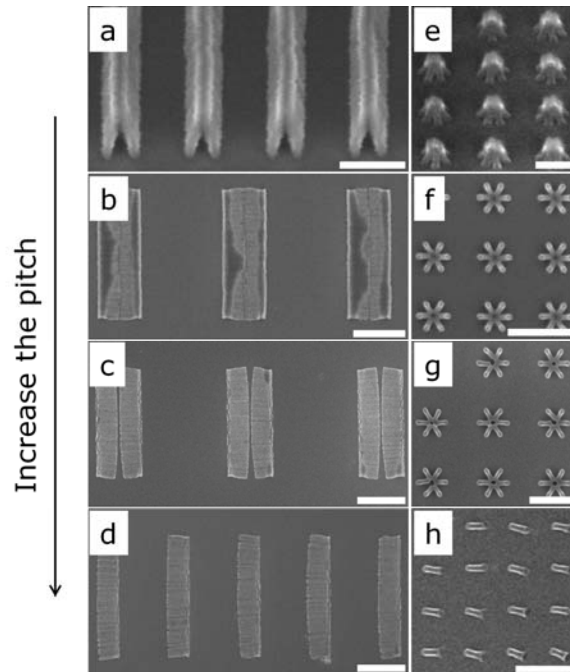

Figure 1. Scanning-electron-microscopy (SEM) images of simple self-assembly induced by designed capillary force. (a-d) self-assembly of 100-nm-tall HSQ lines into rectangular array with increasing pitch; (e-h) self-assembly of 80-nm-tall negative PMMA nanopillars into: 3D nanostructures (e), connected structures (f), nanoholes (g), and linear arrays (h). The scale bars for (a, e) are 100 nm; and for (b-d) and (f-h) are 200 nm.

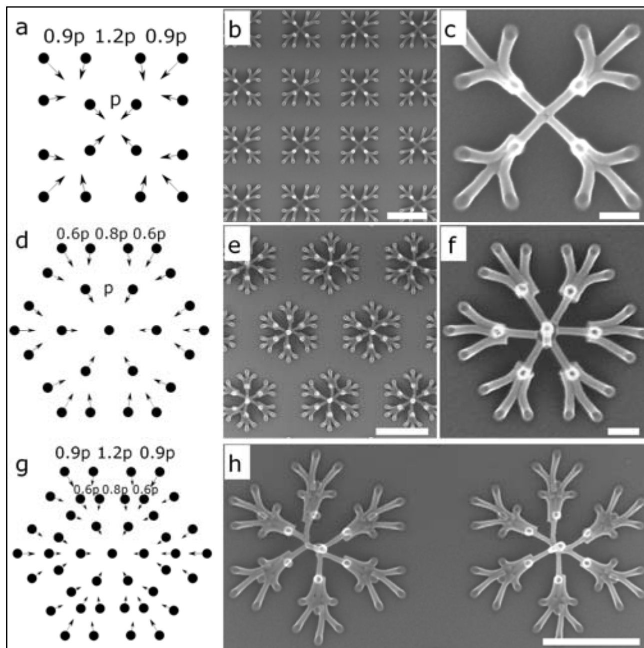

Figure 2. Demonstration of complex hierarchical networks fabricated by designed capillary-force-induced nano-collapse. (a, d, g) are schematics of sparsely-distributed nanopillar designs. (b, c) are SEM images of network self-assembled from (a); (e, f) are SEM images of hexagonal networks self-assembled from (d); (h) is an SEM image of hexagonal networks self-assembled from (g). The height of negative PMMA nanopillars was about 220 nm, and the designed pitch p was 150 nm. The scale bars for (b, e, h) are 500 nm, and for (c, f) are 100 nm. SEM images were performed with accelerating voltage of 10 kV and working distance of ~ 6 mm.