

Nanohybrids and Nanobiohybrids: bottom-up approach to nanopatterned surface arrays and applications

NSF NIRT Grant 0404195

PI's: Barbara A. Baird, Sol M. Gruner, David A. Muller, Michael O. Thompson,
and Ulrich B. Wiesner; Collaborator: Christopher K. Ober

Cornell University

Despite enormous scientific and technological promise the routine formation of nanometer size structures remains a challenge that limits advances in *many* fields of nanotechnology, ranging from microelectronics to biomolecular detection. The smallest lateral spacing on a commercially available microprocessor is currently about 100 nm. In contrast, the distance between binding sites on a human antibody, a biomolecule within our immune system, is 10 nm. Nanofabrication at the 10 nm length scale is expected to remain beyond the grasp of commercial lithographic processes for the foreseeable future. Although matter can be manipulated at the atomic length scale using, e.g., a scanning tunneling microscope, such serial technologies are very slow and thus very costly. Presumably, the commercialization of nanometer-scale devices will require a parallel process capable of producing millions of devices at a time.

The goal of the present program is to develop and understand inexpensive and reliable parallel fabrication methods of periodic surface structures in silicon and related materials with spacings down to 10 nm, based on a novel "bottom-up" approach developed at Cornell. The process relies on the co-assembly of a particular class of macromolecules known as block copolymers with inorganic silica-type materials leading to nanostructured porous thin films. These films subsequently serve as a template for a laser induced melting and capillary-driven filling process to form two-dimensionally periodic surface pillar arrays with spacings down to 10 nm. Achieving this goal will have a profound impact in a broad range of areas including advanced microelectronics, photonics, microfluidics, and biotechnology.

As a first application we propose the use of the periodic surface pillar arrays for binding of specific molecules and biomolecular recognition (see Figure 1). The ability to engineer synthetic materials towards the length scales and architecture of natural, biological molecules and assemblies is a fundamental goal of nanobiotechnology. Emerging from this goal is a vision that nanobiotechnology will be the genesis of substantial new insights into the function of biological systems, and conversely, that nanobiotechnology will lead to the design of entirely new classes of micro- and nanofabricated devices and machines. Regularly patterned surfaces for recognition and regulatory purposes combined with "multivalent binding" events, i.e., the interaction between two biological entities through simultaneous, specific association of two or more ligands and receptors, are of central importance in biological systems. One key challenge for nanobiotechnology is thus reliable production of controlled arrays of molecules on a nanometer scale for surface presentation and recognition.

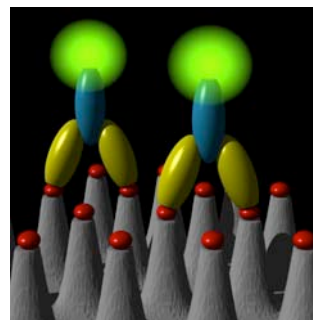


Figure 1. Schematic of a nanopillar surface array engineered towards the molecular architecture of a Y shaped antibody. The red dots represent surface functionalization of the pillars for specific antibody conjugation. Fluorescent nanoparticles for detection are also shown

The first step to these periodic surface arrays is the fabrication of nanostructured polymer-inorganic hybrid thin films through the use of a block copolymer as a structure directing agent for sol-gel silica precursors. Films are generated from several block copolymers with varying molecular weights and block fractions, different amounts of inorganic loading, and varied from monolayer to multilayer assemblies². Local (micron-scale) inspection of sample topography is performed with atomic force microscopy and scanning electron microscopy and provides insight into the quality of the mesoporous samples as they evolve through optimization of processing and compositional parameters. A quantitative IDL image analysis package extracts relevant statistical data for pore density, nearest neighbor distribution, and angular distribution. Voronoi analysis creates easy-to-read diagrams to identify grain size and defect density and location (see Figure 2). Radial and bond orientation distribution analysis differentiates between different regimes of ordering, namely crystalline, hexatic, and liquid-like disorder. Global characterization (centimeter-scale) is accomplished with grazing incidence small angle x-ray scattering (GISAXS) showing good agreement with local data, such as pore-pore spacing, correlation length, and aspect ratio, thereby confirming that AFM and SEM analysis is representative of the entire film³.

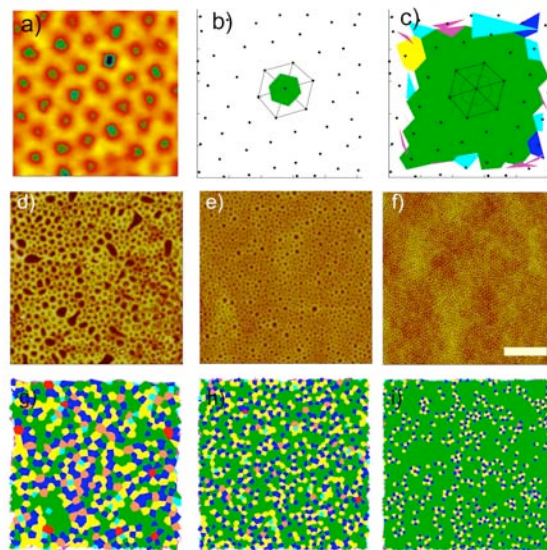


Figure 2. (a) raw AFM image for input into an IDL program; (b & c) construction of Voronoi diagram. (d-f) AFM data of films depicting improvements in quality; (g-i) respective Voronoi diagrams showing the grain growth (green) and decrease in defect density (non-green). Scale bar = 500 nm.

These thin film assemblies are then used as a template for the generation of silicon surface arrays on the sub-50 nm regime through a simple laser processing technique. A transient excimer laser exposure (<50 ns) deposits sufficient energy to convert the substrate to molten silicon which fills the pores through capillary action. The nanopillars are then exposed through removal of the aluminosilicate template via a simple HF etch. AFM imaging of the subsequent nanopillar array shows an inverse replicate of the template. Voronoi and angular distribution analyses on the template and nanopillar array show remarkable congruence, especially the retention of 6-fold symmetry and efficiency of pattern transfer. Auger electron spectroscopy measurements confirm the complete removal of the template and that the nanopillar array is indeed composed of silicon.

Next, efforts were concentrated on increasing the aspect ratio of these pillars. Different amounts of amorphous silicon are deposited on the template, both on top of the walls and inside of the pores, through a variety of techniques such as thermal evaporation, sputtering, and plasma enhanced chemical vapor deposition. The sample is then subjected to laser processing to melt the deposited silicon and solidify it to the crystalline substrate. The deposited amorphous silicon modifies the absorptive properties of the sample such that the crystalline substrate transitions into the molten state at lower laser fluences and persists for longer times. We developed new laser processing protocols to account for, and take advantage of, this change in behavior. After laser exposure, HF etching removes the aluminosilicate template which also carries away any surface debris. AFM imaging and analysis show a significant increase in the height of the

pillars, from the initial 1-2 nm to over 15 nm (see Figure 3). Current efforts are underway to improve the spatial correlation of these pillars and to develop a narrower height distribution.

In parallel to efforts generating high aspect ratio nanopillars, we also use low-energy electron beam lithography to pattern model molecular templates for the immobilization of antibodies through ligand recognition⁴. The templates are patterned using poly(ethylene glycol) (PEG) modified silicon oxide (SiO_x) surfaces. These substrates are exposed to a low voltage (1-2 keV) electron beam to selectively remove PEG from exposed regions. Exposed regions are functionalized with a dinitrophenyl (DNP) ligand and tested for the specific binding of fluorescently labeled anti-DNP antibodies. Using PEG containing regions in conjunction with ligand-presenting regions in the patterned arrays help reduce the non-specific adsorption of proteins, yielding a specific/nonspecific ratio of 9-10⁵. The surface coverage of the biologically active DNP groups on SiO_x and the amount of immobilized antibody on DNP is determined using a fluorescence based enzyme linked immunosorbent assay. The specificity of the interaction between DNP ligand and fluorescently labeled anti-DNP antibodies is evaluated with fluorescence microscopy. We showed that the patterning of these molecular templates and the development of assays for quantification are generally applicable to immobilization of any ligand-receptor pair on a wide range of substrates.

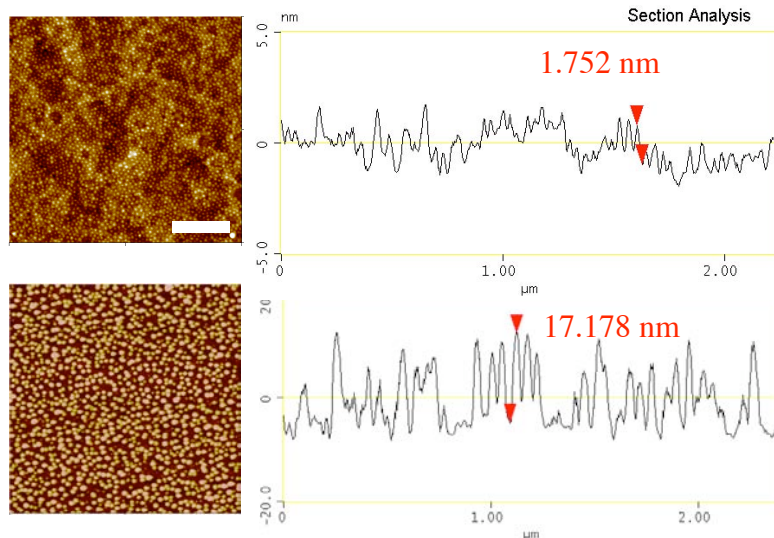


Figure 3. AFM image and cross section analysis after HF etch on samples made with only template (top) and with template and deposited amorphous silicon (bottom). Section analysis depicts the heights of these nanopillars to be ca. 2 nm with the original protocol and ca. 17 nm with the new method. Decreased spatial ordering, due to a poorly ordered template, and scatter in height distribution in the bottom sample are evident. Scale bar = 500 nm.

References

- [1] For further information about this project email the PIs Barbara A. Baird bab13@cornell.edu, Sol M. Gruner smg26@cornell.edu, David A. Muller dm24@cornell.edu, Christopher K. Ober cober@ccmr.cornell.edu, Michael O. Thompson mot1@cornell.edu, or Ulrich Wiesner ubw1@cornell.edu.
- [2] P. Du, M. Li, K. Douki, X. F. Li, C. R. W. Garcia, A. Jain, D. M. Smilgies, L. J. Fetters, S. M. Gruner, U. Wiesner, C. K. Ober; "Additive-driven phase selective chemistry in block copolymer thin films: the convergence of top-down and bottom-up approaches." *Advanced Materials*, **16(12)**, 953 (2004)
- [3] P. Du, J. S. Gutmann, S. M. Gruner, U. Wiesner; "Block copolymer derived hybrid organic-inorganic thin films: complementary local and global ordering analysis" *Macromolecules*, submitted
- [4] W. Senaratne, C. Harnett, P. Sengupta, B. Baird, H. Craighead, C. K. Ober; "Molecular Templates for Bio-specific Recognition by Low-Energy Electron Beam Lithography", *Nanobiotechnology*, **1**, 23, (2005).
- [5] W. Senaratne, K. Takada, R. Das, J. Cohen, B. Baird, H. D. Abruna and C. K. Ober, "Dinitrophenyl Ligand Substrates and their Application to Immunosensors", *Biosensors and Biotechnology*, under revision