# Optimal nanofabrication of complex nanofluidics for interfacial characterization of colloidal nanoparticles

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Dimensional, optical, and interfacial properties of colloidal nanoparticles are essential in applications ranging from material assembly to cancer therapeutics. Surface functionalization is an interfacial property of increasing interest that is critically important but currently impossible to measure in a practical context.[1] The combination of nanofluidic size exclusion and widefield optical microscopy is emerging to meet this challenge. Complex nanofluidic devices enable size exclusion of nanoparticles by decreasing in depth from hundreds to tens of nanometers, functioning as separation matrices and reference materials under optical microscopy.[2] Control of numerous critical dimensions is fundamental to the method, motivating optimization of the enabling nanofabrication process.

Focused-ion-beam (FIB) milling is the most advanced process for fabricating complex nanofluidic devices.[2] To allow real-time optimization of this process, for the first time, we perform beam-burn diagnostics in a dielectric film with a submicrometer thickness and characterize the results by scanning electron microscopy (SEM) and atomic force microscopy (AFM) (Figure 1, a–c). Quantitative correlation allows for SEM to serve as a rapid diagnostic of beam focus immediately before fabrication with a dual-beam SEM/FIB system, ensuring process control and reproducibility. We then demonstrate the vertical range and resolution of the FIB process by patterning and characterizing by AFM test structures in silica with 256 features in depth increments of 1.0 nm ± 0.3 nm for a range of beam currents (Figure 2, a–c), achieving record control of vertical dimensions. We report uncertainties as standard deviations. In this way, we extend atomic resolution of vertical dimensions into the submicrometer range.

To assess the utility of complex nanofluidics for novel measurements of the surface functionalization of colloidal nanoparticles, we input these device dimensions into simulations of the nanofluidic size exclusion of nanoparticles without and with steric shells of fluorescent ligands (Figure 3, a–b). The results indicate the potential of the method to simultaneously measure statistical distributions of dimensional, optical, and interfacial properties of nanoparticles such as ligand shell thickness and ligand areal density (Figure 3, c–f).

[1] A. M. Smith, et al., *Analyst* 142, 11-29, 2017.
[2] K.-T. Liao, et al., *Lab on a Chip* 18, 139-152, 2018.

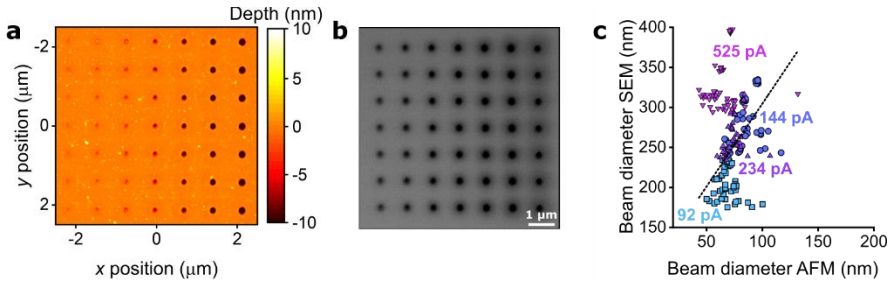


Figure 1. Beam-burn diagnostics. (a) Atomic force and (b) scanning electron micrograph showing the same burn pattern in a silica film with a thickness of approximately 500 nm. Dwell time increases by column with replicate rows. (c) Plot correlating the results of the two microscopy methods to allow SEM as a real-time diagnostic prior to fabrication.

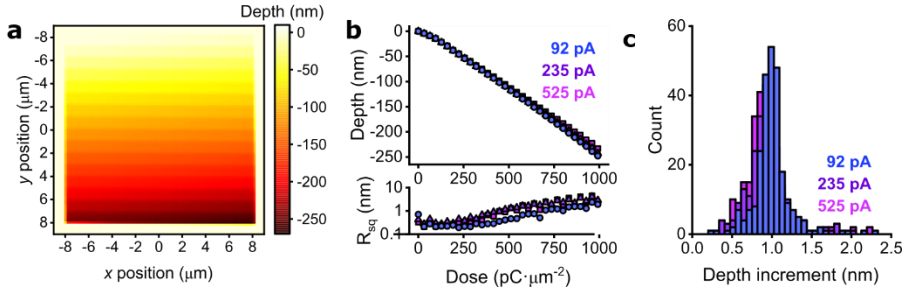


Figure 2. Vertical dimensional control. (a) Atomic force micrograph showing a test structure with 256 features in the silica film. (b) Plots showing consistent depth profiles below the zero plane and surface roughness over a wide range of beam currents for three test structures. (c) Histograms showing depth increments for the test structures.

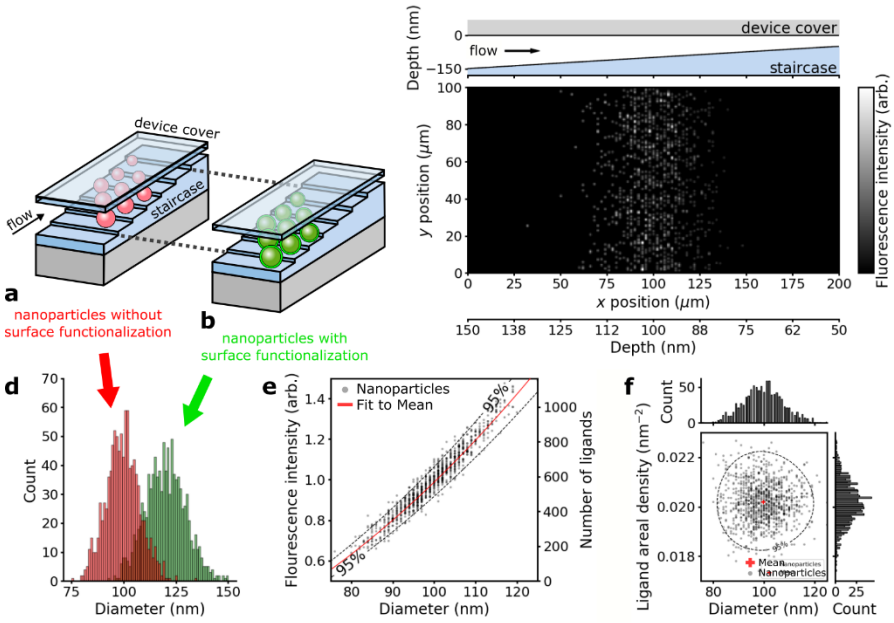


Figure 3. Surface functionalization characterization. Simulations of the nanofluidic size exclusion of nanoparticles (a) without and (b) with surface functionalization by steric shells of fluorescent ligands. (c) Synthetic fluorescence micrograph showing the size exclusion of nanoparticles in a nanofluidic staircase with depth increments of 1 nm ranging from 50 nm to 150 nm (top). (d) Histograms showing nanoparticle diameters. (e) Plot showing fluorescence intensity variation with nanoparticle diameter. (f) Plot and histograms showing nanoparticle diameter and ligand areal density distributions.