# Fabrication of Sub-5 nm Nanoscale Arrays by Nanoimprint Lithography Combined with an Angle-Evaporated Hard Mask and Lift-off

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High throughput fabrication of regular arrays of ultra-small structures covering relatively large areas is required today in various applications, including (but not restricted to) electronic and magnetic storage, photonics and biology and medicine. In our work, we fabricate arrays of nanoscale features for the purpose of studying cytoskeletal protein binding interactions.[1] These interactions are critical to the formation of focal adhesions, and our work should shed light on the importance of external mechanical factors (e.g., force, rigidity and geometry) on cell function and behavior. The metal features, ~ 5 – 10 nm in diameter, are used as “anchors” to which extracellular matrix ligands (or, alternatively, integrin fragments) are selectively bound by a biotin/avidin linkage. These can then be used to study protein binding by cell spreading assays or by single-molecule fluorescence microscopy.[1, 2]

Using a process that combines nanoimprint lithography (NIL) with an angle-evaporated hard mask, we previously reported the fabrication of sub-10 nm circular dots.[2] The process, shown schematically in Fig. 1. This process is particularly effective, as it alleviates several challenging factors frequently encountered when attempting to lift off metal using a thin imprint resist: (1) The resist thickness is limited by the thickness of metal to be deposited. (2) No negative side walls can be formed by NIL. (3) Removal of the residual resist layer after NIL further constrains the achievable aspect ratio.

Use of a metal hard mask on top of the imprinted resist affords a very wide process window for the residual layer etch, allowing for significant lateral etching, which effectively creates an undercut profile, as in Fig. 1c. In order to form this hard mask after the imprint step, the metal must be evaporated at an angle (Fig. 1b), leaving the imprinted features essentially open. (Of course, this restricts the size and geometry of the features that can take advantage of this approach.) The subsequent lift-off (Fig. 1d) is simple and robust. An added benefit of this process is a slight reduction of the feature dimensions due to deposition of the metal hard mask material on the sidewalls of the resist (Fig. 1b).

In order to study the limits of this process, we fabricated arrays of dots with 100 nm horizontal spacing and 200 nm vertical spacing over an areas ranging from 5 μm x 5 μm to 200 μm x 200 μm. The pattern was formed in 60 nm-thick PMMA by thermal NIL. The dot size was varied from 10 nm to 35 nm. We also varied the thickness of the angle-evaporated Ti hard mask from 10 – 40 nm. (The substrate was continuously rotated during deposition in order to allow an uniform metal deposition on the side walls.) Reduction of the dot diameter after liftoff - due to the sidewall deposition is shown in Fig. 2. Further reduction in dot size was achieved by thermal annealing at $450^{o}$ C, with dot diameters as small as ~3.5 nm obtained (Fig 3). The annealing also improved the uniformity of the dots.

This process is not restricted to circular dots. We applied it as well to a pattern of orthogonal lines forming a grid with linewidths ~ 20 – 50 nm. The grids were designed with small openings at the vertices ranging from 0 – 200 nm. For this type of pattern, the substrate could not be rotated during hard mask deposition. Rather, the substrate was tilted relatively to the metal flux direction by $30^{o}$ fixed at $45^{o}$ angle relative to the grid axes (Fig 4a). A 15 nm Ti mask was deposited. Following descum, Ti/AuPd (1nm/5nm) evaporation and lift-off resulted in high quality metal grids (Fig 4b and 4c).

This presentation will describe the concept, the technical details and the characterization results of the developed process, which allows enables the patterning of large area arrays of sub-5 nm metal features with high throughput.

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1. O. C. Cherniavskaya, C. J. Chen, E. Heller, J. Provenzano, E. Sun, J. Hone, L. Kam, M. P. Sheetz and S. J. Wind, JVST B **23**, 2972 (2005).
2. M. Schvartzman, K. Nguyen, M. Palma, J. Abramson, J. Sable, J. Hone, M. P. Sheetz and S. J. Wind, JVST B (in press).

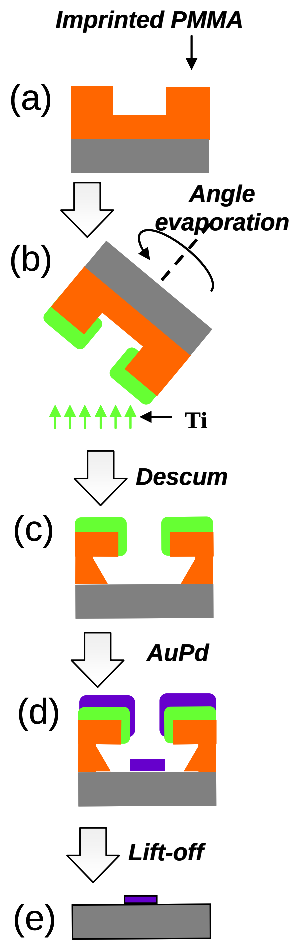


**Figure 1.** Schematic of the process flow which includes angle evaporation of a metal mask (Ti) on the imprinted substrate, descum, AuPd evaporation through the formed Ti mask and lift-off.

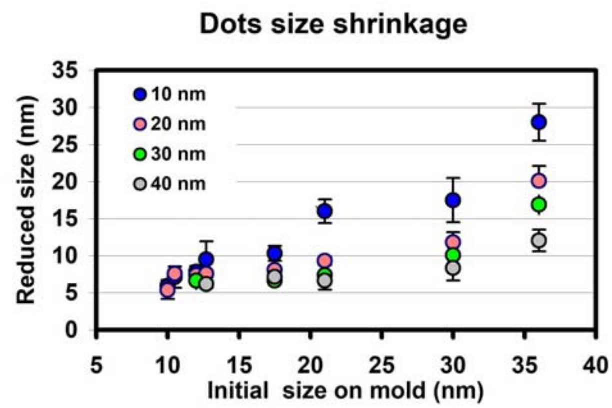


**Figure 2.** Shrinkage in the dots size due the Ti mask deposition on side-walls. The showed thickness is the nominal thickness as measured by the evaporator thickness monitor.

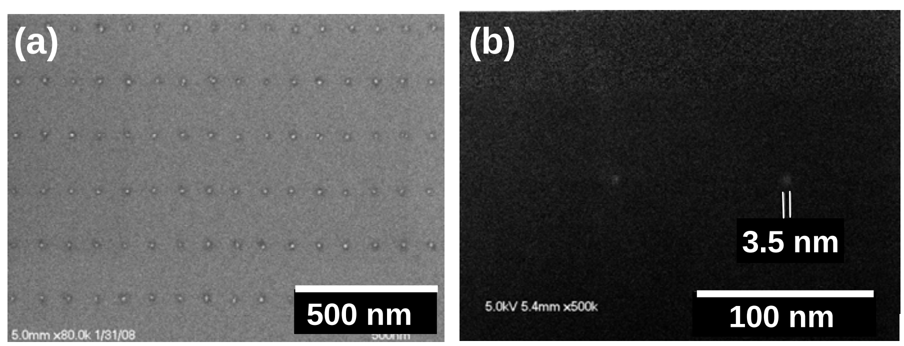


**Figure 3.** Arrays of AuPd dots after annealing. (a)Array of dots with the dot size of about ~ 8-10 nm. (b) Array of smallest dots, obtained by imprint with the NIL template with 10 nm features in combination with the deposition of 10nm of Ti (hard mask).

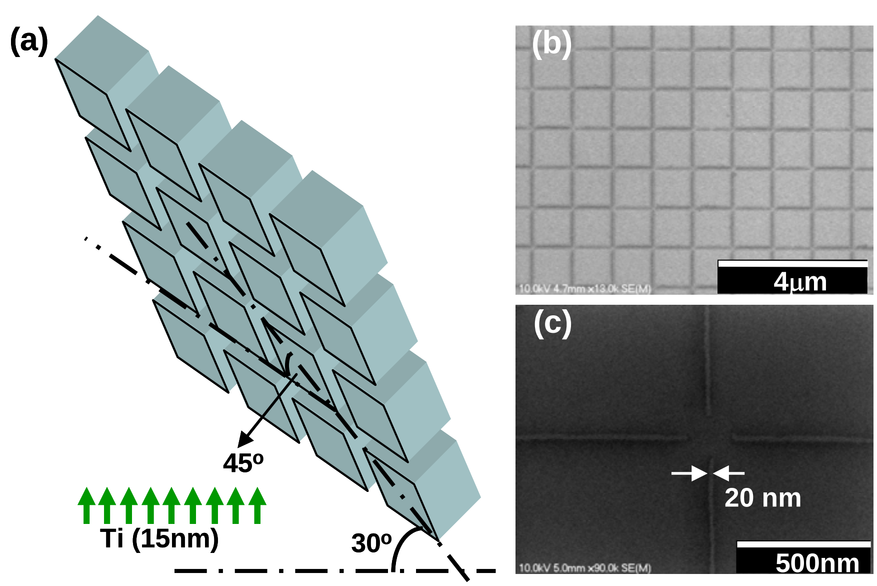


**Figure 4.** (a) Imprinted grid position during Ti mask evaporation. (b), (c) AuPd grid after lift-off.