



Understanding and Eliminating Sidewall Roughness in 3D Nanoprinting via Focused Ion Beam Induced Deposition

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Focused Ion Beam Induced Deposition (FIBID) combines maskless direct-write fabrication with high deposition efficiency and access to material compositions that can be difficult to obtain by Focused Electron Beam Induced Deposition (FEBID). Despite these advantages, its application to complex three-dimensional nanomanufacturing remains limited by the narrow balance between precursor-driven deposition and simultaneous ion-induced sputtering [1]. A particularly persistent and poorly understood limitation is the formation of platelet-like protrusions along the sidewalls of vertically grown structures, which strongly compromises morphological fidelity and prevents the predictable fabrication of smooth three-dimensional nanoarchitectures as achievable with its sister technology FEBID [2].

Here, we systematically investigate Ga⁺-FIBID using a MeCpPtMe₃ precursor across increasing levels of structural complexity, ranging from planar deposits and free-standing walls to pillars, tilted elements, and advanced three-dimensional architectures. Ion beam current, dwell time, point pitch, total exposure time, refresh time, beam defocus, and growth direction are varied to identify stable process windows and gradually isolate the mechanisms responsible for sidewall roughening. Morphological evolution is quantified by lateral root-mean-square and roughness analyses, while scanning and transmission electron microscopy, energy-dispersive X-ray spectroscopy, and electron energy-loss spectroscopy provide structural and compositional insight.

The study reveals that low ion currents are essential for maintaining a robust additive regime, whereas increasing current rapidly narrows the accessible parameter space through precursor depletion and sputtering. Vertical pillars with heights exceeding 25 µm can be fabricated, but develop pronounced sidewall platelets whose growth is strongest near the substrate. Time-resolved experiments reveal a rapid initial increase in roughness followed by saturation. Neither extended refresh times nor deliberate beam defocusing suppresses this behavior, indicating that beam-induced heating alone cannot explain the observed morphology. Instead, the combined results support a beam-tail-mediated growth model: low-intensity ions outside the nominal beam center initiate precursor dissociation at stochastic sidewall imperfections, while edge-enhanced secondary-electron emission is suggested to promote preferential lateral growth. Elemental mapping reinforces this interpretation, revealing Pt- and C-containing platelets that are strongly depleted in Ga compared with the central pillar body, consistent with increasingly electron-assisted deposition contribution at the periphery.

A decisive test is provided by controlling the orientation between the ion beam and the growth direction. Tilting the substrate alone leaves the growth axis aligned with the beam and does not suppress platelet formation. In contrast, parameter-controlled growth at an angle to the primary beam progressively reduces sidewall roughness, yielding essentially smooth surfaces at deviations of approximately 10° from vertical growth. Combining this principle with a compensating stage tilt ultimately enables vertically oriented structures with smooth sidewalls, in striking contrast to conventionally grown pillars. The same process knowledge is transferable to complex architectures, including tetrapods and specific nanoheater-like geometries.

These findings transform sidewall roughening from an intrinsic limitation into a geometrically controllable process phenomenon. By linking beam profile, secondary-electron-assisted peripheral growth, and beam-growth-axis orientation, this work establishes a mechanistic and practical framework for high-fidelity 3D FIBID and expands its potential as a complementary platform for functional three-dimensional nanomanufacturing.

References

- [1] Katja Höflich et al., *Applied Physics Reviews* (2023), 10, 041311.
- [2] Verena Reisecker et al., *Advanced Functional Materials* (2024), 34, 46, 2407567.