SEM as a Surface-Engineering Platform for Nanoprototyping: In Situ FEBID/FEBIE, Scripted Workflows, and Digital-Twin Process Control

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Surface-sensitive microscopy is increasingly used for both imaging and engineering near-surface regions with nm-scale registration. Scanning electron microscopy (SEM), long associated with inspection and electron-beam lithography, is now evolving into a nanoprototyping platform that combines in situ characterization with direct surface manipulation. Here we focus on focused electron beam induced processing (FEBIP) as a route to fabricate and iteratively refine functional nanoscale structures, especially where 3D geometry and local composition are critical.

SEM-based nanoprototyping now extends beyond electron-beam lithography to focused electron beam induced deposition (FEBID) and focused electron beam induced etching (FEBIE). FEBID enables direct additive growth of complex 3D nano-architectures, while FEBIE supports local subtractive editing such as trimming, isolation, and gap formation. Together, these modes enable imaging-coupled surface engineering with in situ feedback.

A central challenge is the predictability and reproducibility of 3D growth and etching. Recent modelling introduces a multiscale FEBID description based on stochastic dynamics with parameters informed by molecular dynamics, enabling more realistic process prediction [2]. Building on this, INDICO is developing a digital-twin approach that links scripted fabrication with process simulation (Figure 1) to accelerate parameter exploration and improve transferability across geometries. The broader multiscale context for radiation-driven condensed-matter processes has recently been reviewed [1].

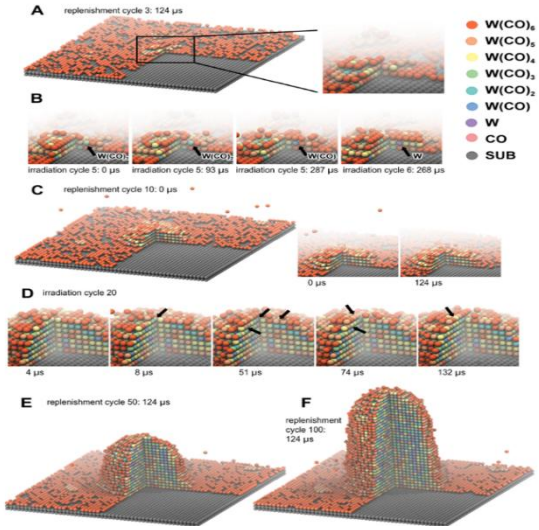

Figure 1: Simulation snapshots of FEBID growth on SiO2, showing evolution during repeated irradiation/replenishment cycles.

We also emphasize reproducible scripting toolchains for FEBIP. The open-source program f3ast supports slicing, calibration, and simulation by converting 3D designs into layer-wise exposure patterns and enabling simulation-guided iteration before fabrication (Figure 2) [3]. Overall, SEM-based nanoprototyping is moving toward a programmable workflow that combines additive/subtractive engineering, in situ feedback, simulation-guided control, and reproducible scripting.

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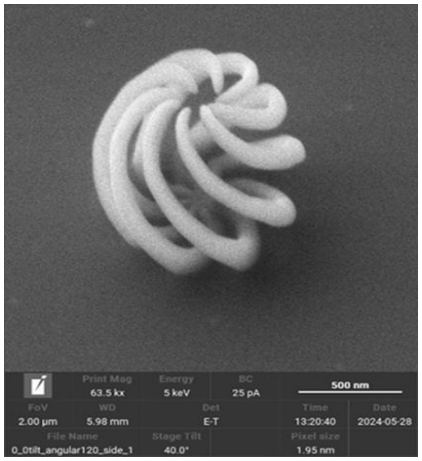

Figure 2: 3D FEBID spiral-ball fabricated using a calibration-driven workflow with the open-source f3ast toolchain.

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[1] Solov'yov, A. V.; Verkhovtsev, A. V.; Mason, N. J.; Amos, R. A.; Bald, I.; Baldacchino, G.; et al. Condensed Matter Systems Exposed to Radiation: Multiscale Theory, Simulations, and Experiment. Chemical Reviews 2024, 124, 8014–8129. https://doi.org/10.1021/acs.chemrev.3c00902
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[2] Solov'yov, I. (arXiv) Stochastic dynamics simulation of the focused electron beam induced deposition process. arXiv:2506.18163 (2025). https://doi.org/10.48550/arXiv.2506.18163
[3] Skoric, L.; Sanz-Hernández, D.; Meng, F.; Donnelly, C.; Merino-Aceituno, S.; Fernández-Pacheco, A. F3AST (FEBID 3D Algorithm for Stream File generation), open-source software (GitHub repository)