AI-assisted FIB nanofabrication

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Abstract: Deep learning can be used to predict the post-fabrication appearance of structures manufactured by focused ion beam (FIB) milling, accounting for variations in beam focusing/scanning parameters and target medium characteristics with nanoscale accuracy. With predictions generated in milliseconds, the approach can expedite process optimization and enhance precision/reproducibility in FIB nanofabrication.

Focused Ion Beam (FIB) milling is a vitally important direct-write process for rapid prototyping and materials/device characterisation in both fundamental research and industrial manufacturing of nano-/microtechnologies. It provides for etching of arbitrary features with nanometric resolution into a wide variety of target media. However, establishing process parameters for any specific task is a multi-dimensional optimization challenge, typically undertaken by iterative (i.e. time-consuming) trial-and-error. We show here that deep learning – a neural network trained on the basis of prior manufacturing experience – can predict the outcome of FIB milling processes with high accuracy: >96% over a range of ion beam current and dosage parameters, taking account of instrumental and target-specific artefacts. Predictions are generated within a few milliseconds, so the methodology may be deployed in near real-time to expedite optimization and improve reproducibility in FIB processing.

We demonstrate that a deep learning network can simulate the FIB milling process for arbitrary 2D binary patterns etched into gold thin films, i.e. structures common to a range of nanophotonic/plasmonic applications, from metamaterial devices to spectroscopy (esp. surface-enhanced Raman) and seeded nano-materials growth. Simulations are performed by a conditional generative adversarial network trained on a set of binary designs and corresponding scanning electron microscope (SEM) images of samples fabricated with a range of FIB process parameters (Fig.1a). The trained network is then able to accurately predict process outcomes for previously unseen designs - specifically their appearance in SEM imaging, as a strong gauge of process accuracy and quality (Fig.1b).

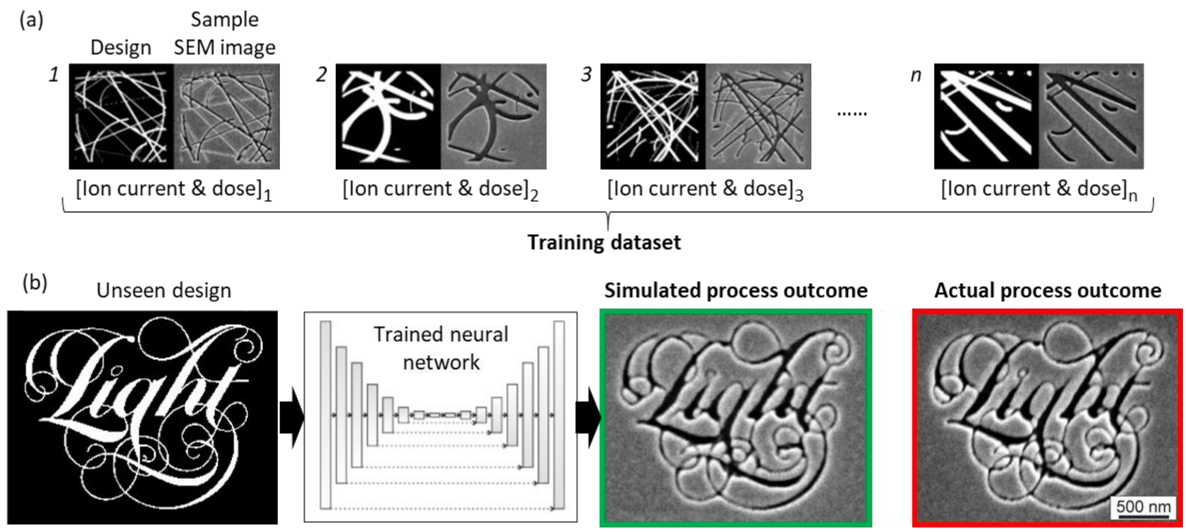

Fig. 1 Deep learning simulation of FIB nanofabrication. (a) The neural network is trained on a set of randomly generated binary designs, SEM images of samples manufactured to those designs by FIB milling in a 50 nm thick gold film, and detail of the ion beam parameters used in their production. (b) The trained network predicts the outcome of FIB milling processes – the expected appearance of a sample in SEM imaging [outlined in green] – for previously unseen designs. For comparison, the actual outcome – an SEM image of a sample fabricated to the design on the left – is shown outlined in red on the right.

This artificial intelligence-enabled capability can markedly reduce the number of experimental dose-test iterations required for, and therefore time and cost of, developing and optimizing new FIB nanofabrication processes. With predictions being sufficiently accurate to encompass systematic artefacts that are imperceptible to the human eye in training samples, which may manifest as random defects in isolated test samples, the methodology may also be deployed for early fault (e.g. beam alignment, aperture damage) detection, and to maintain performance (i.e. consistency of outcomes from established processes) against ageing of the ion source and beam apertures.