High Precision 3D Nanoprinting of Sheet-like Structures and their Controlled Spatial Bending via Electron Beam Curing

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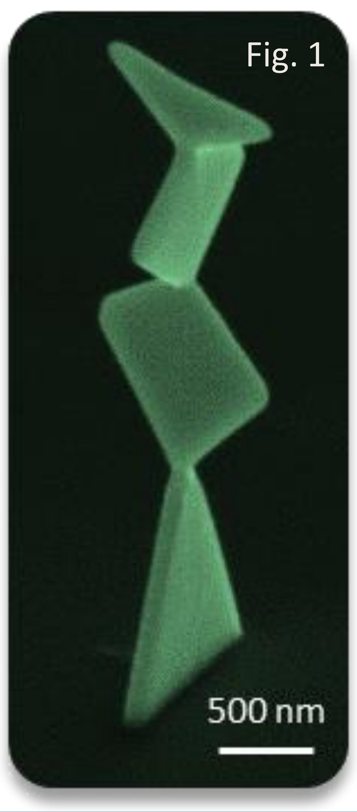


Introduction

3D nanoprinting via **Focused Electron Beam Induced Deposition (3D-FEBID)** is one of the few additive, direct-write methods capable of producing real 3D objects on the nanoscale. In the past, it was mainly used for building mesh-like structures [1]. This project focuses on the expansion towards closed/sheet-like structures, where additional growth affecting factors, such as edge effects and more advanced temperature distributions apply (Fig. 1). We approach the situation with a combination of experiments and simulations to develop a compensation tool for arising challenges, which forms the basis of next-generation 3D nanoprinting via electrons [2, 3].

We further explore post-growth **Electron Beam Curing (EBC)** [4] without precursor gas for **closed, Pt-based FEBID structures** [5]. While EBC was mostly used for full area curing in the past, we here explore the possibilities of selected area EBC on freestanding 3D objects. This process impacts the inner structure and the volume of exposed regions, which enables controlled deformation. We therefore performed systematic experimental series complemented by Monte Carlo Simulations to identify ideal parameters for smooth, stable, reproducible and controlled morphological bending.

Improving 3D-FEBID for Sheet-like Structures Experimentally and Via Simulations

Height Correction

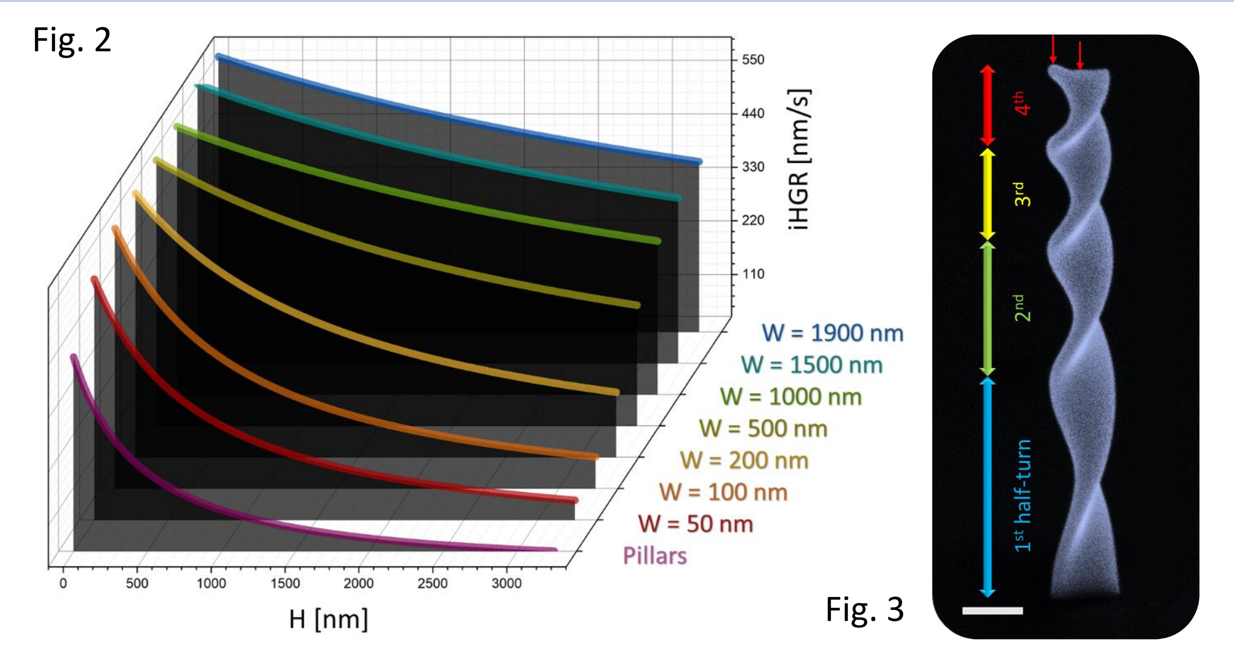
The main challenge in working with closed structures are the different growth rates depending on the element dimensions. Fig. 2 illustrates the varying incremental height growth rates (**iHGR**). They depend on the width and the height of the base element; the less wide and the higher the element, the slower the growth. The main reason for this behaviour is **beam heating** [6] as the electron beam brings energy into the structures. This leads to locally increased temperatures entailing a higher precursor desorption and therefore a lower precursor coverage resulting in strongly reduced growth rates. The effect of these slowed down growth rates with increasing height is clearly visible in Fig. 3. To make up for these changing growth conditions, we developed a height correction from experimental calibration data where the dwell times are adjusted depending on the element width and the distance between growth front and substrate to reach layers of h ≈ 1 nm. This way, we lowered the deviations from the target height to < 3 % (compared to differences of > 90 % between pillars and 1 µm wide walls without correction).

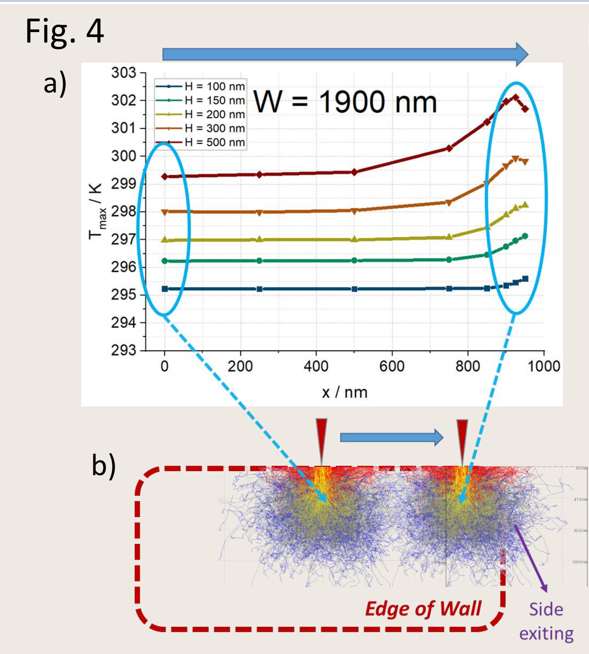
Temperature Compensation

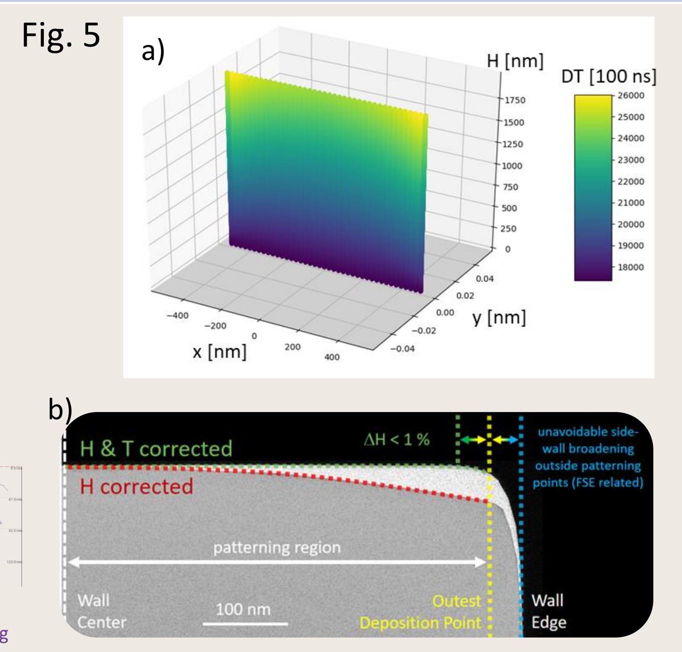
Additional to achieving accurate central heights, we then focused on improving the shape stability of the deposited elements and make up for morphological deviations occurring due to the fact that the growth conditions also depend on the position within the built layer, which is again mainly caused by beam heating. Based on finite difference temperature simulations (see example in Fig. 4a) we developed a model consisting of two exponential functions. The first includes the heat dissipation, the second a temperature decay in the edge regions. This decay derives from side exiting of electrons which then do not contribute to the heating process (compare electron trajectories in Fig. 4b). The temperature compensation effectively adjusts the individual deposition times (dwell times) at each patterning point according to this temperature behaviour (Fig. 5a). This way, it is possible to correct walls of different dimensions with the same model function, giving the tool a generic component as required for true 3D nanoprinting. The shape improvements that were achieved for a vertical wall via temperature compensation are shown by means of a SEM image in Fig. 5b.

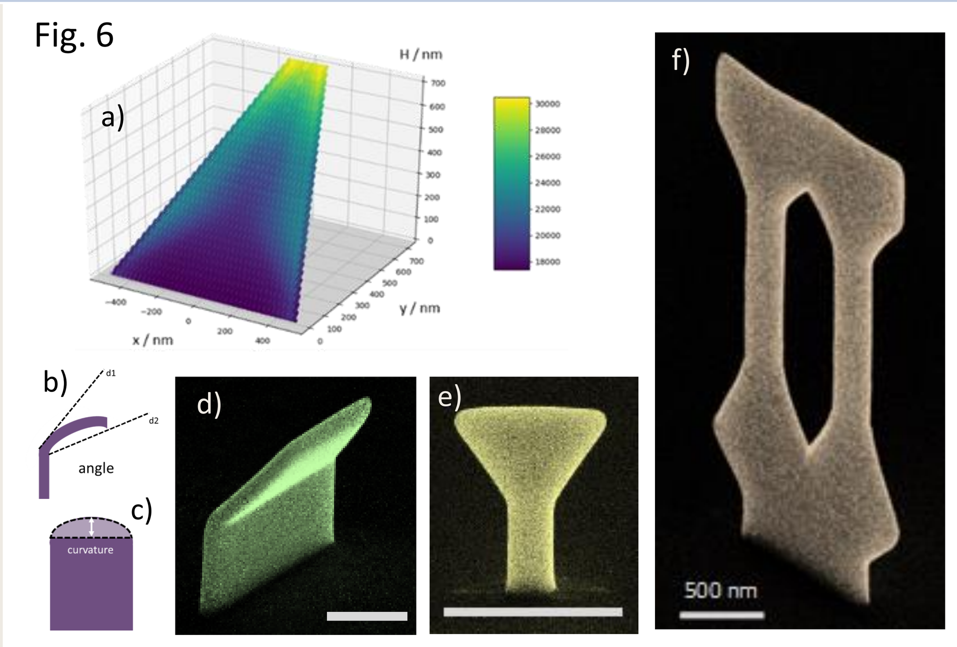
Advanced Structures

The modular Python compensation code was then further expanded to include inclined elements and trapezoid shapes (Fig. 6a). In first experimental tests without additional adjustments, the inclination extension showed promising results, both, in height as well as in shape stability. This was investigated by means of lateral as well as top curvature deviations from the intended shapes of inclined walls on top of vertical walls (Fig. 6b and Fig. 6c). The inclusion of an offset height, where the underlying structure before depositing a new element is taken into account, further allowed the extension to a "construction kit toolbox" where arbitrary elements can be stacked to create advanced architectures (Fig. 6d-f). There is, however, still room for improvement, especially for architectures with varying element widths, before reaching a universally applicable compensation tool.







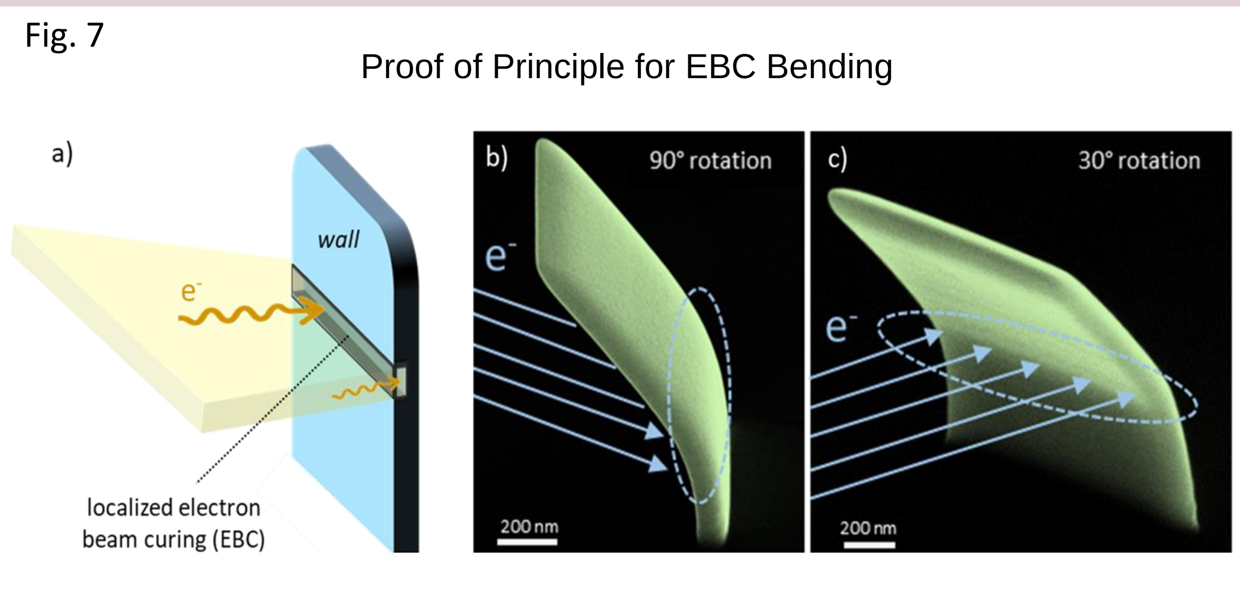


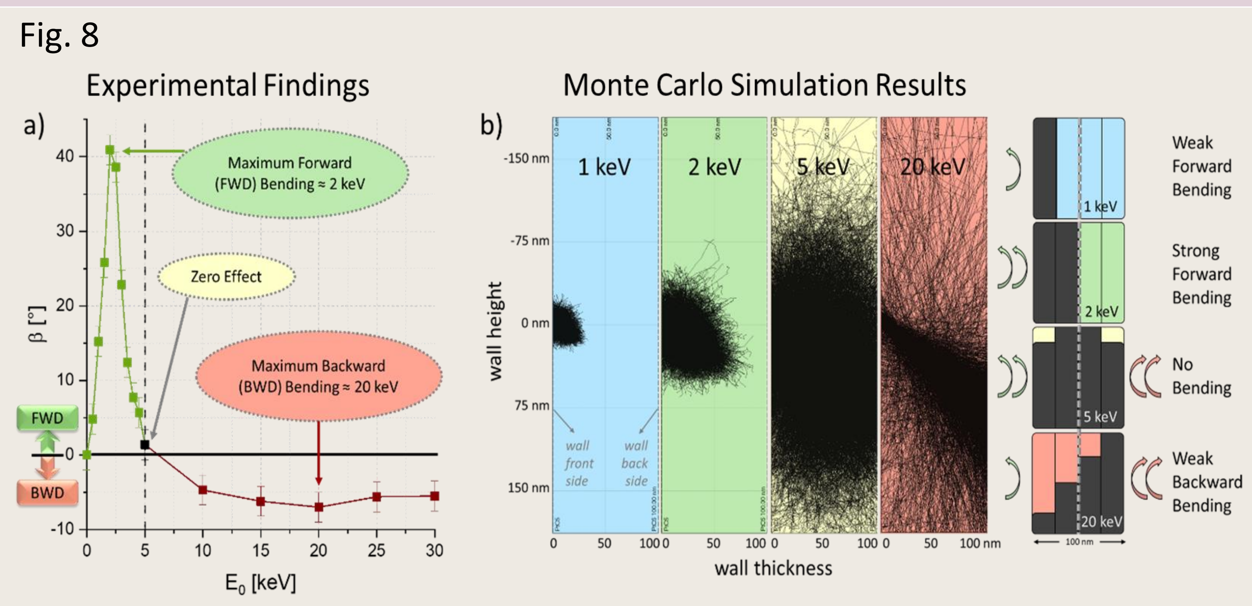
Controlled Bending of FEBID Structures Via Electron Beam Curing (EBC)

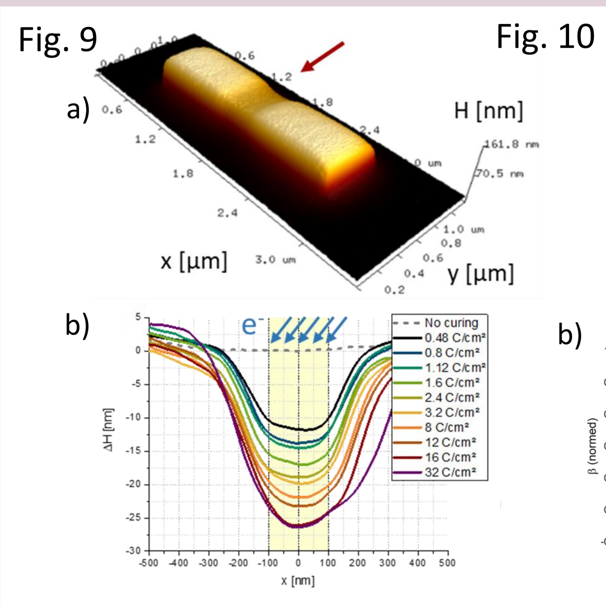
Electron beam curing, where a deposited structure is radiated again via electrons, this time without precursor gas present, was mainly used for post-processing entire FEBID structures in the past. Thereby incomplete dissociation of incorporated molecules can be reactivated, which presumably causes structural and volumetric changes. When 3D FEBID elements are only locally irradiated by electrons with a fitting parameter set, targeted bending via EBC becomes possible. Fig. 7a shows the schematic, Fig. 7b and Fig. 7c the proof of principle in the form of SEM images of spatially bent walls that were bent along a rectangular EBC strip, comparable to a paper seam.

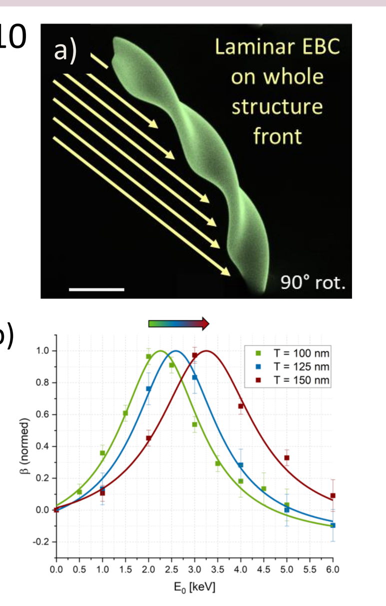
We investigated a variety of parameters to find ideal conditions for controlled bending. The primary electron energy during EBC was one of the parameters with the biggest influence on the bending effectiveness. As such, it was examined both experimentally as well as via Monte Carlo simulations. The experimental results for the bending angles (Fig. 8a) showed clear maxima for forward (green) and backward bending (red). The simulation results and additional schematics (Fig. 8b) confirm this behaviour and show that the bending strongly depends on the assymmetry in terms of electron interaction volumes and thereby electron beam cured regions through the wall thickness.

AFM studies for partially cured horizontal walls (Fig. 9) provide proof for the suspected volume loss due to EBC, which could thereby be identified as the main factor for the bending process. Fig. 10a shows an example for bending more advanced structures (vertical screw bent along curve) and thereby demonstrates how flexible this approach could be used in a target-oriented way to locally adapt existing FEBID structures. Yet, one has to be aware that the current element thickness has to be considered anytime (Fig. 10b).



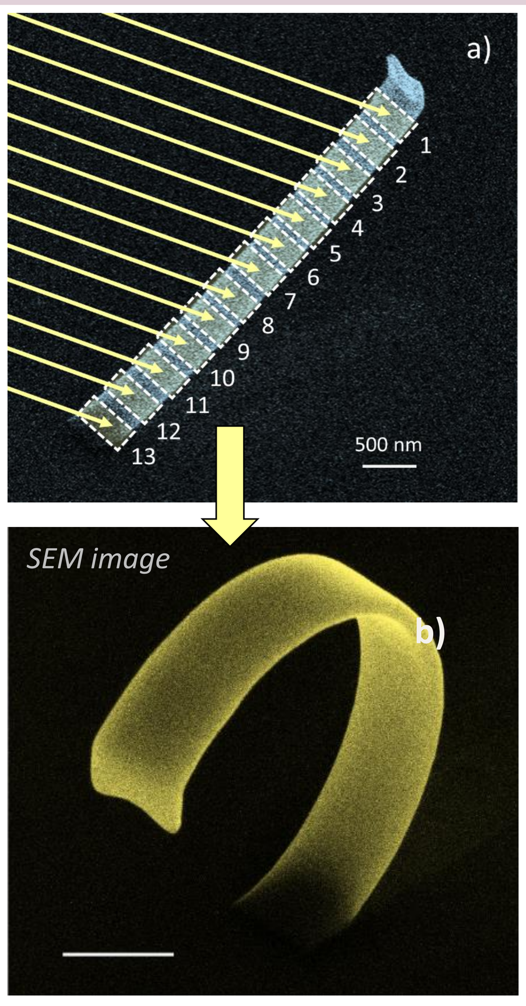






Conclusion

We strongly improved high-precision deposition of sheet-like 3D-nanostructures via FEBID by developing a Python compensation tool for temperature- and electron trajectory induced deviations [2]. It is built up in a modular way to include even more advanced structures in the future. We placed particular emphasis on building predictable, accurate and reproduceable structures via 3D nanoprinting that can be used in various future applications in research and development. We further applied localized EBC as morphological tuning tool for pre-existing 3D FEBID objects [5]. The study gives an insight into the mechanism, which is proposed as a combination of nano-grain growth and volume loss in agreement with experiments and simulations. While primarily used in terms of controlled morphological adaption (see advanced structure in Fig. 11), the structural changes also suggest the possibility to use it as a localized, functional tuning tool concerning mechanical, electrical or even thermal properties.



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