Expanding High-fidelity 3D-Nanoprinting - From Meshes toward Closed Structures

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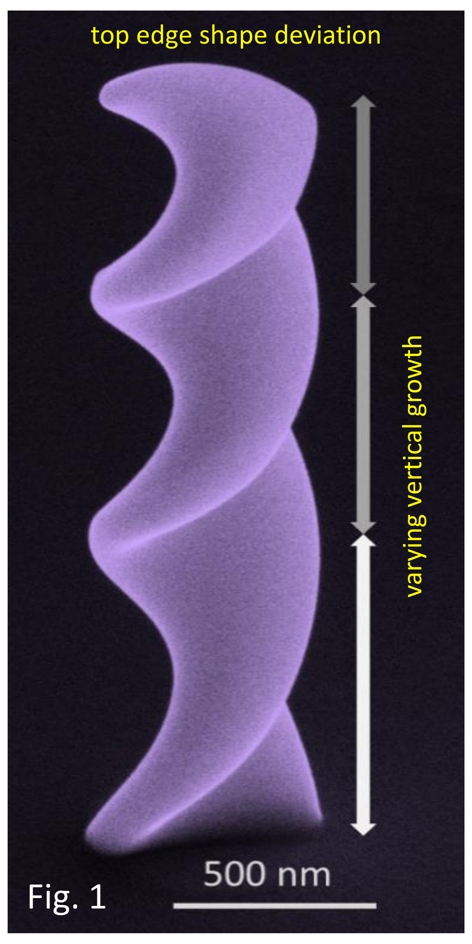

Fig. 1

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. With feature sizes below 100 nm on a regular basis and various possibilities in substrate and precursor materials, it is a highly flexible technique with numerous potential applications [1,2,3]. In the past, 3D-FEBID was mainly used for building mesh-like structures [4]. This project focuses on the expansion towards closed 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 [5].

Initial Point Pitch Adjustments

To perform the step from mesh-like to closed structures we first adjusted the step-size of the electron beam. When this so called point pitch (**PoP**) is chosen too small, unintended inclined depositions occur (Fig. 2a (red)). When it is too large, the single deposition points are clearly visible (Fig. 2a (yellow)). A medium step size (Fig. 2a (green)) results in a uniform growth, as intended. More detailed investigations in this range (Fig. 2b) showed increasing surface roughness starting from PoP = 30 nm. For this reason we chose **PoP = 25 nm** as our fixed point pitch for all further experiments for our settings of **5 keV** and **40 pA (≈ 25 % beam profile overlap)**.

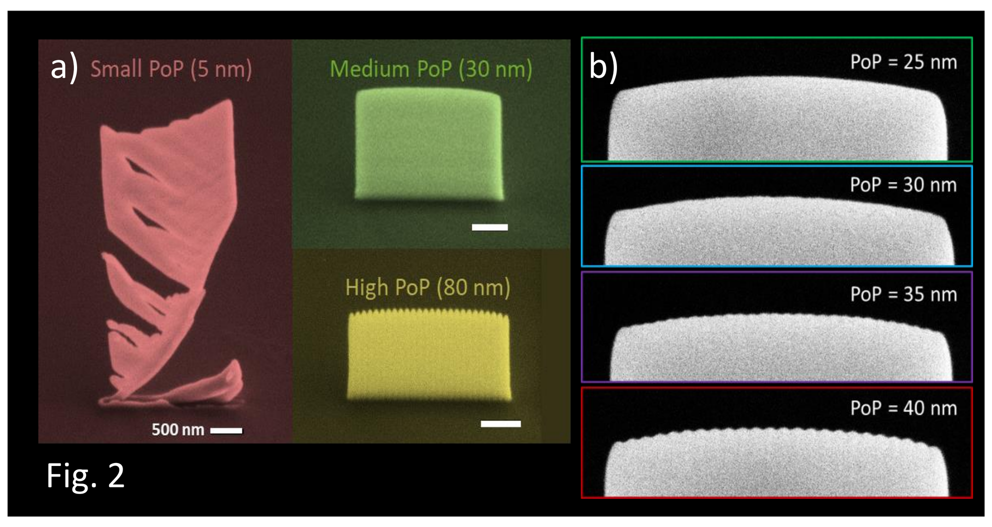

Fig. 2

Height Correction – Experimental Calibration

The main challenge in working with closed structures are the different growth rates depending on the element width. Fig. 3 shows the differences between vertical walls that were all built with the same total dwell times of TDT = 2 s (overall deposition times per xy pixel column). The growth increase from a point deposition (pillar) to a 1 µm wide wall increases by ≈ 94 %. Fig. 4 illustrates the varying incremental height growth rates (**iHGR**) for base elements of different dimensions. The iHGR not only depends on the width but also on the height of the base element, the higher the walls, the slower the growth. The main reason for this behaviour is **beam heating** [6] as the electron beam brings energy into the structure and in doing so the temperature is locally increased up to 70 °C (see Fig. 5). Higher temperatures entail a higher precursor desorption, therefore a lower precursor coverage leading to strongly reduced growth rates.

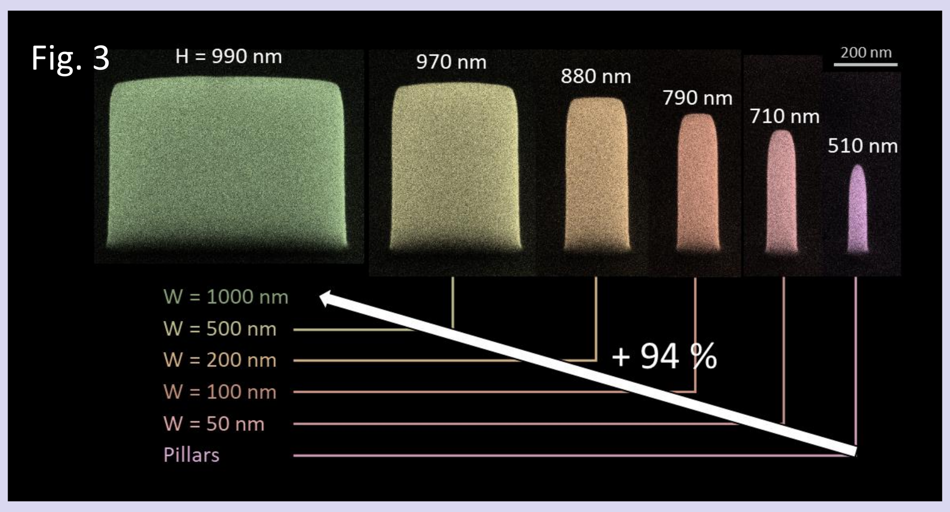

Fig. 3

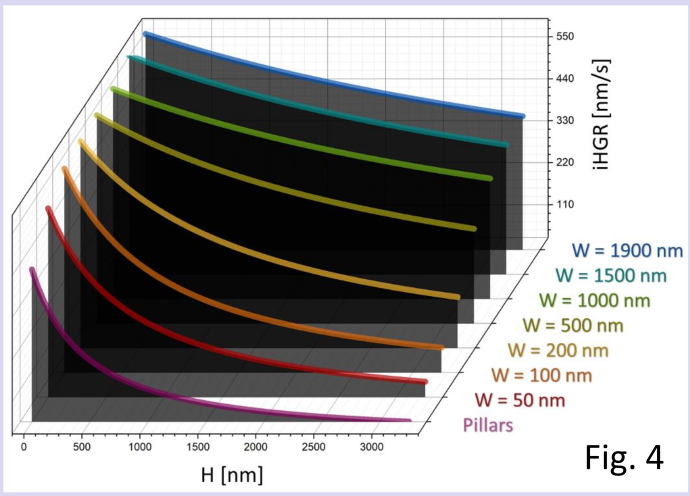

Fig. 4

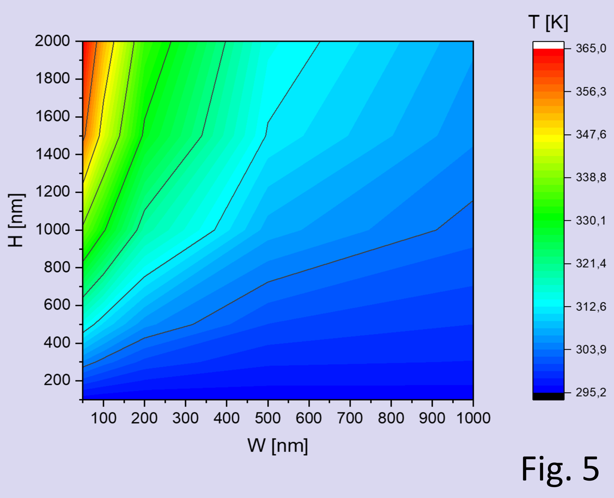

Fig. 5

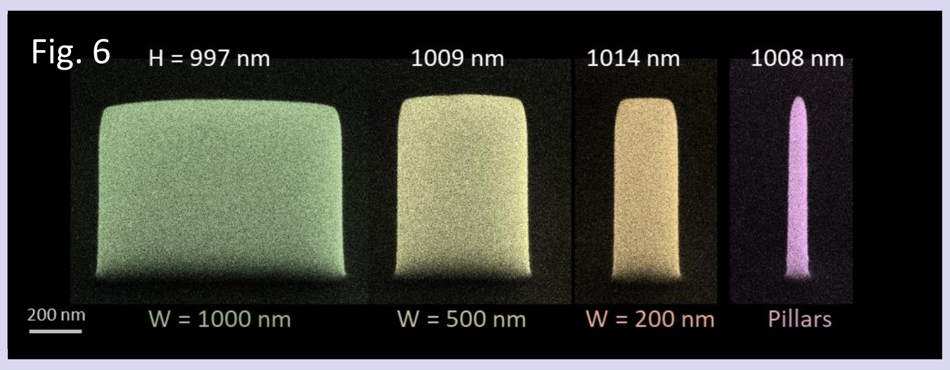

Fig. 6

To compensate for these deviations we introduced a height correction function through which we are now able to *fabricate individual layers with ≈ 1 nm thickness* with an *accuracy of < 3 %* (Fig. 6).

Temperature Compensation

To make up for the morphological deviations from the intended rectangular shapes (top edge curvature), we used finite element temperature simulations as shown on a representative wall for center and edge depositions (Fig. 7a). The maximal occurring temperatures when moving the electron beam along the wall surface are shown in Fig. 7b. The fitted functions are based on 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 (see Fig. 7c).

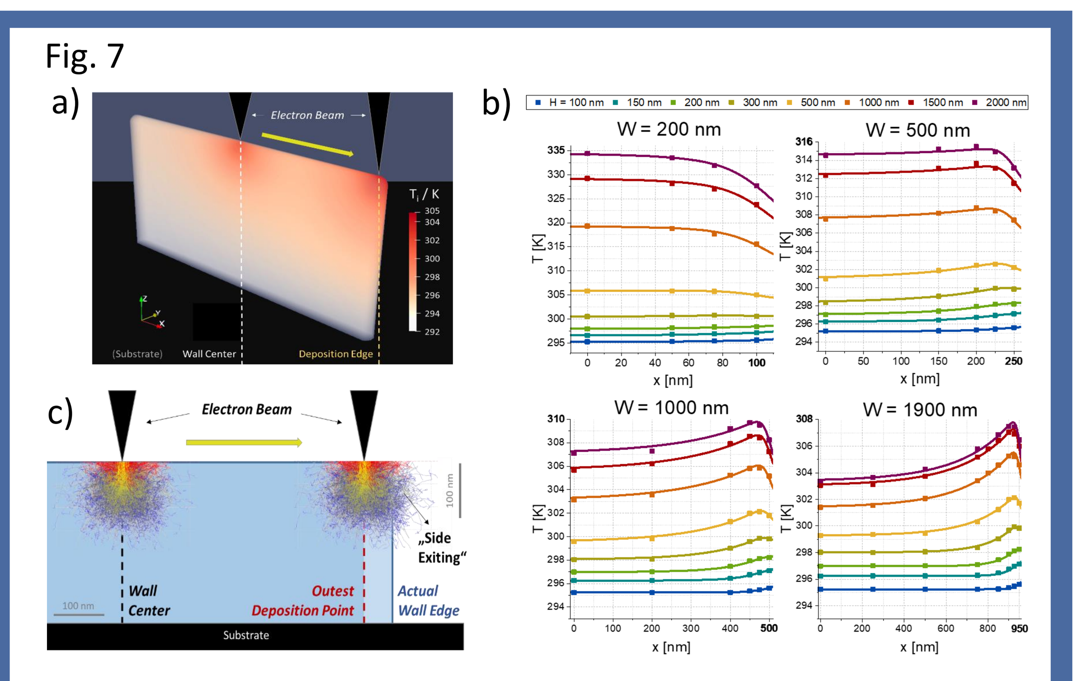

Fig. 7

The temperature compensation effectively adjusts the individual deposition times (dwell times) at each patterning point according to this temperature behaviour (Fig. 8). This way, it is possible to correct all kinds of different wall shapes (see Fig. 9) with the same model function, giving the tool a generic component as required for true 3D nanoprinting.

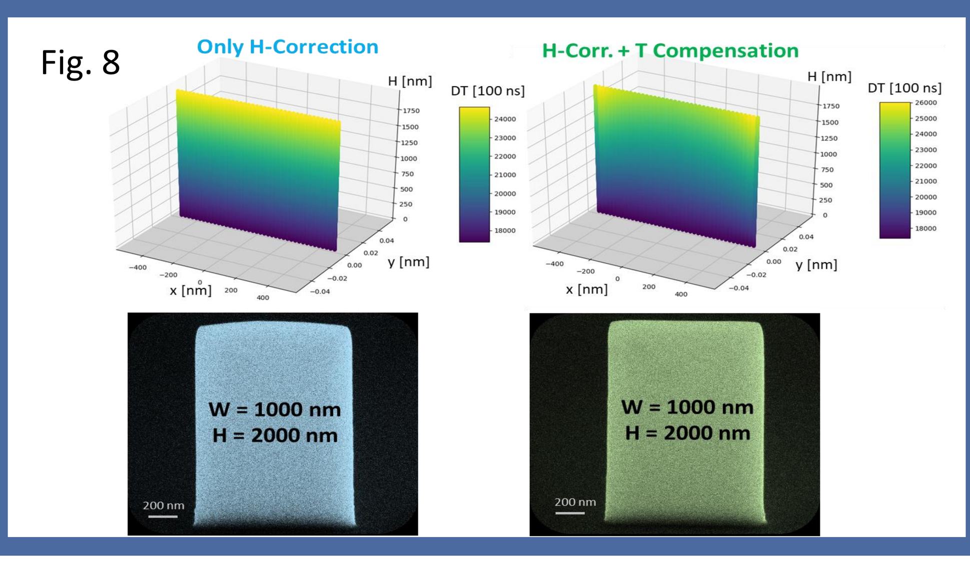

Fig. 8

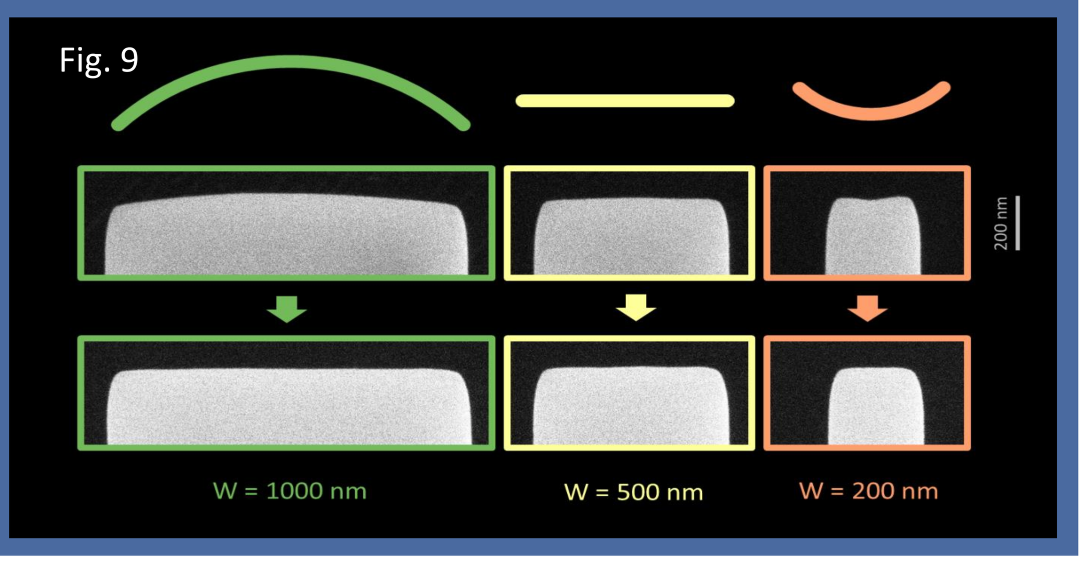

Fig. 9

Proximity Correction

On top of the aforementioned corrections we included the fact that not only primary electrons (**PE**) but also backscattered electrons (**BSE**) contribute to the deposition process (Fig.10). We included this by adding another correction function taking the Gaussian shapes of the electron distributions involved into account.

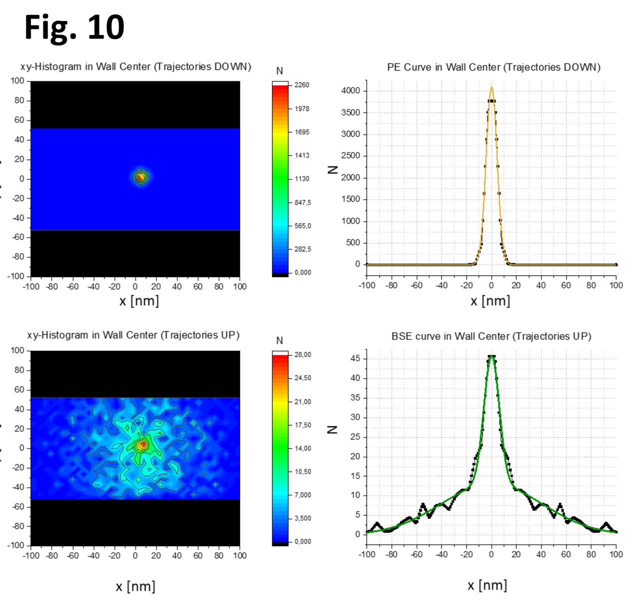

Fig. 10

The impact of the different compensations on vertical walls but also on more advanced structures, such as a three-turn screw, is depicted in Fig. 11-13.

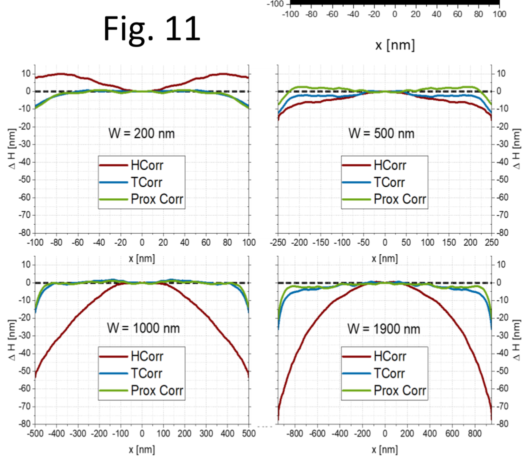

Fig. 11

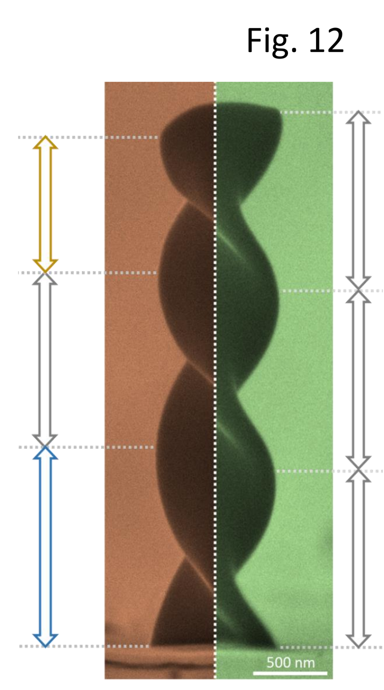

Fig. 12

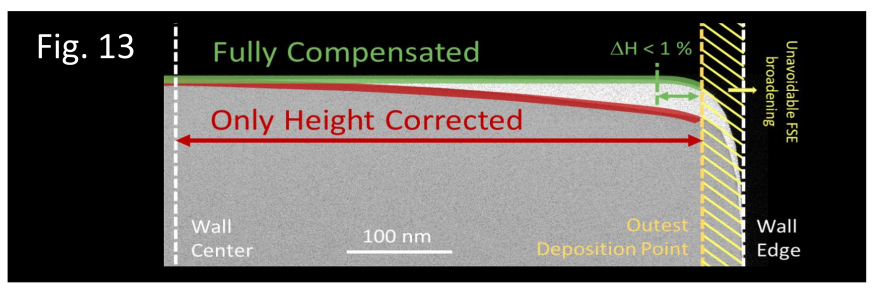

Fig. 13

Conclusion

We successfully took the first steps from mesh-like towards closed 3D-nanostructures by developing a Python compensation tool for temperature- and electron trajectory induced deviations [5]. 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.

References/ Literature

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