Expanding Capabilities of Focused Electron Beam Based 3D Nano-Printing:
From Meshes Towards Closed 3D Nano-Architectures

Anna Weitzer[a], Harald Plank[a,b,c]

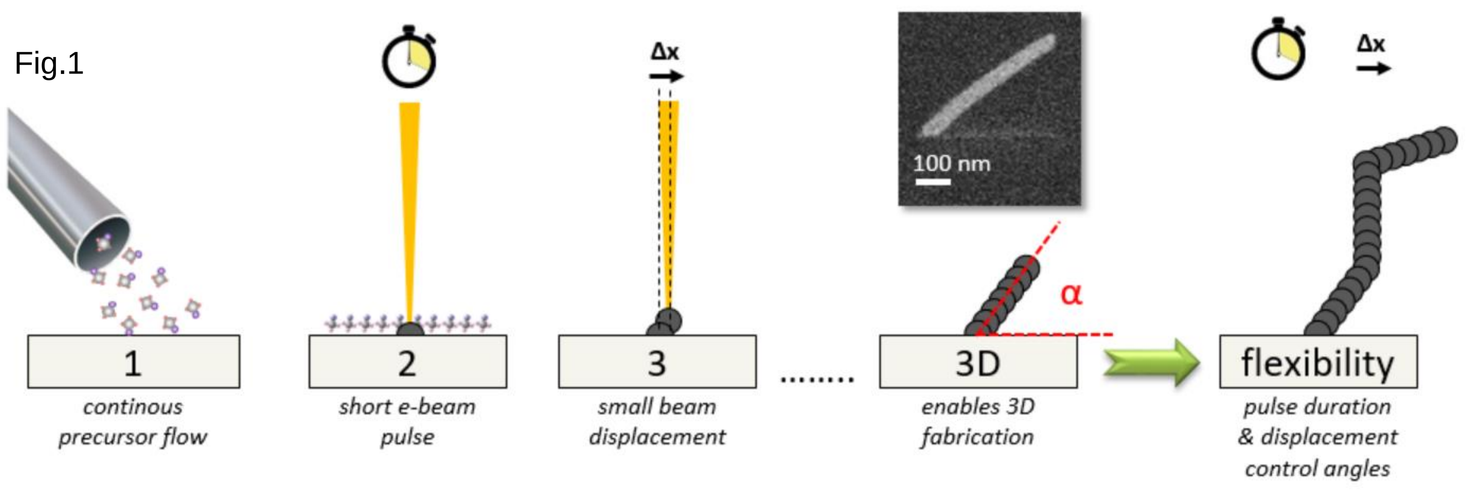
[a] Institute of Electron Microscopy and Nanoanalysis (FELMI), Graz University of Technology, 8010 Graz
[b] Christian Doppler Laboratory for Direct-Write Fabrication of 3D Nano-Probes (DEFINE), Graz University of Technology, 8010 Graz
[c] Graz Centre of Electron Microscopy, 8010 Graz

INTRODUCTION

Focused electron beam induced deposition (FEBID) is an aspiring technique for next-generation direct-write fabrication on the nano-scale. Based on previous research at our institute (e.g. [1] and [2]), this work aims on taking the next logical step from building mesh-like towards closed and even mixed 3D nano-architectures, such as flexibly shaped vertical walls, inclined blades and combinations of them into complex elements (see Fig.3-7). This opens up numerous possibilities as well as new challenges that will need further investigation in the future.

FEBID Basic Principle

Fig.1



1. A precursor gas (chemical preliminary stage of the target material) is streamed into the vacuum chamber, where it physisorbs onto, diffuses along and desorbs again from the surface.

2. A nanometer sized electron beam is exposed to the physisorbed precursor at a given position for a short pulse („dwell time"). The impact leads to a highly localized chemical dissociation and immobilization, which forms the final deposit.

3. The electron beam is moved by very small steps („point pitch") followed by another pulse (2), leading to vertically stacked but slightly displaced deposits: 3D lift-off. For larger angles, the dwell time has to be increased or the point pitch to be decreased.

As these 3 steps can be precisely controlled for any patterning point, 3D fabrication becomes possible, as demonstrated in detail for mesh-like structures[1,2].

Fig.3

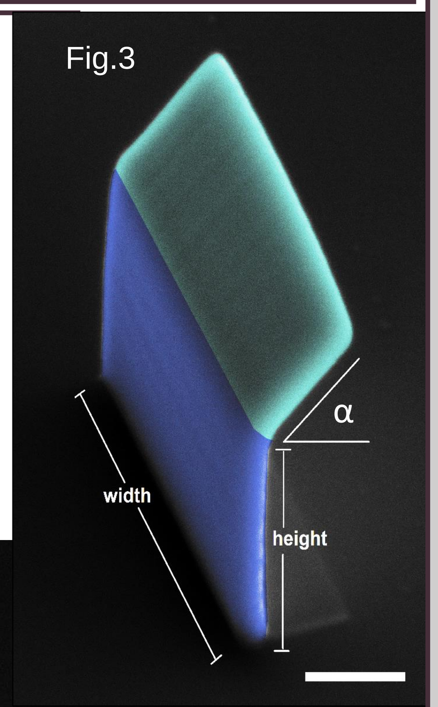


Fig.4

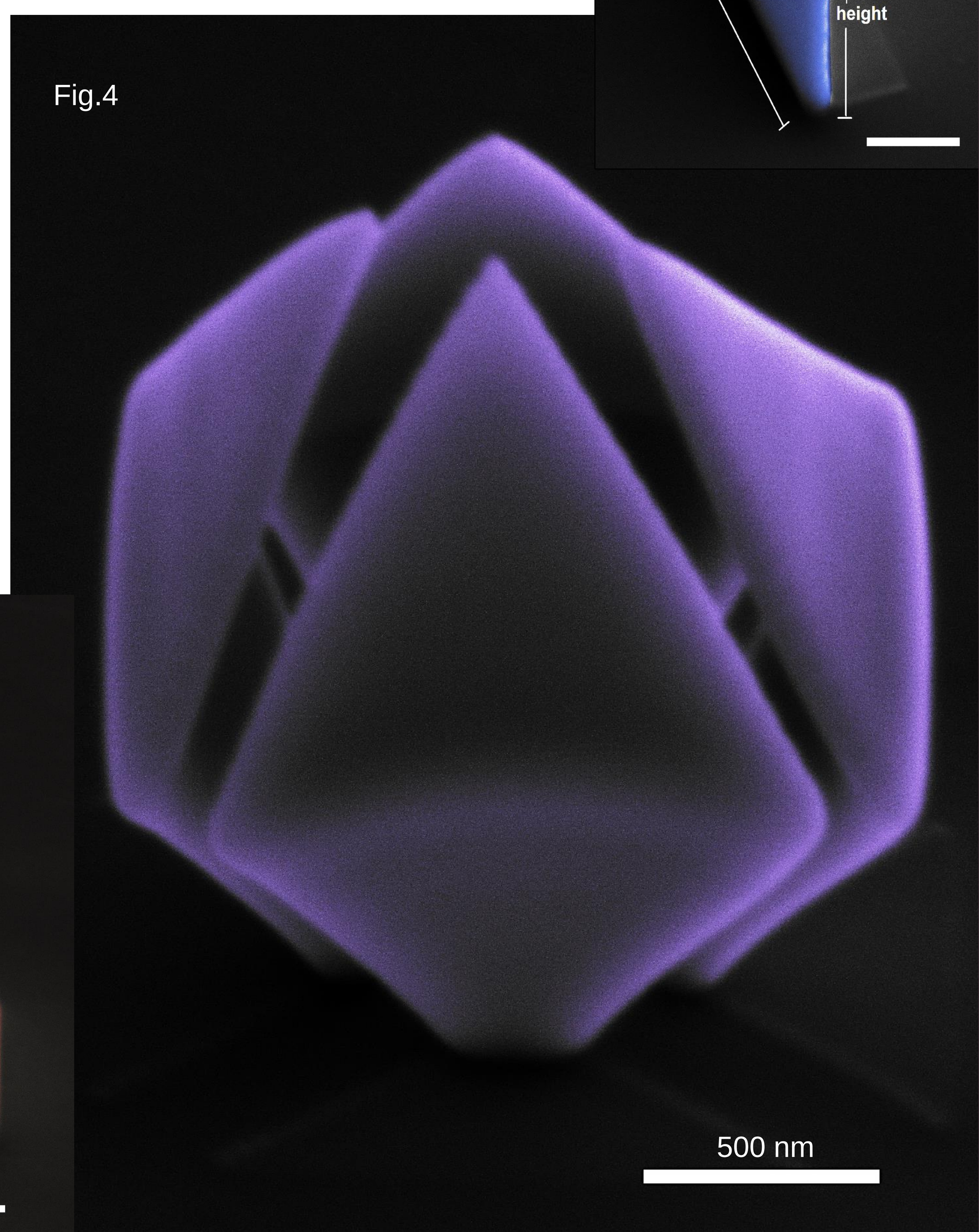


Fig.5

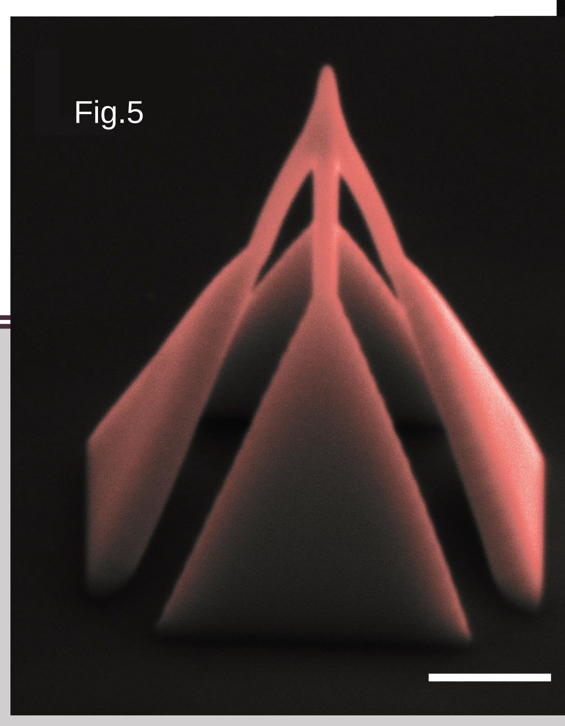


Fig.6

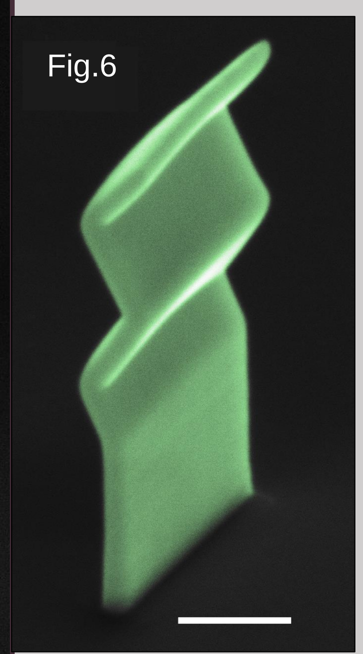
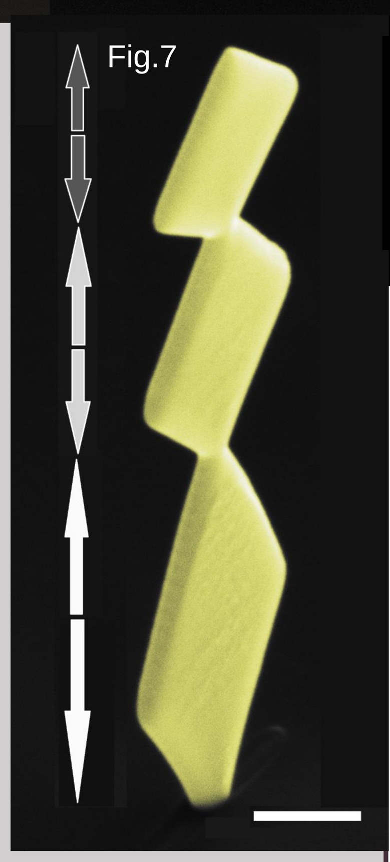


Fig.7



Direct-Write 3D Structures

2D Calibration

Fig.2a

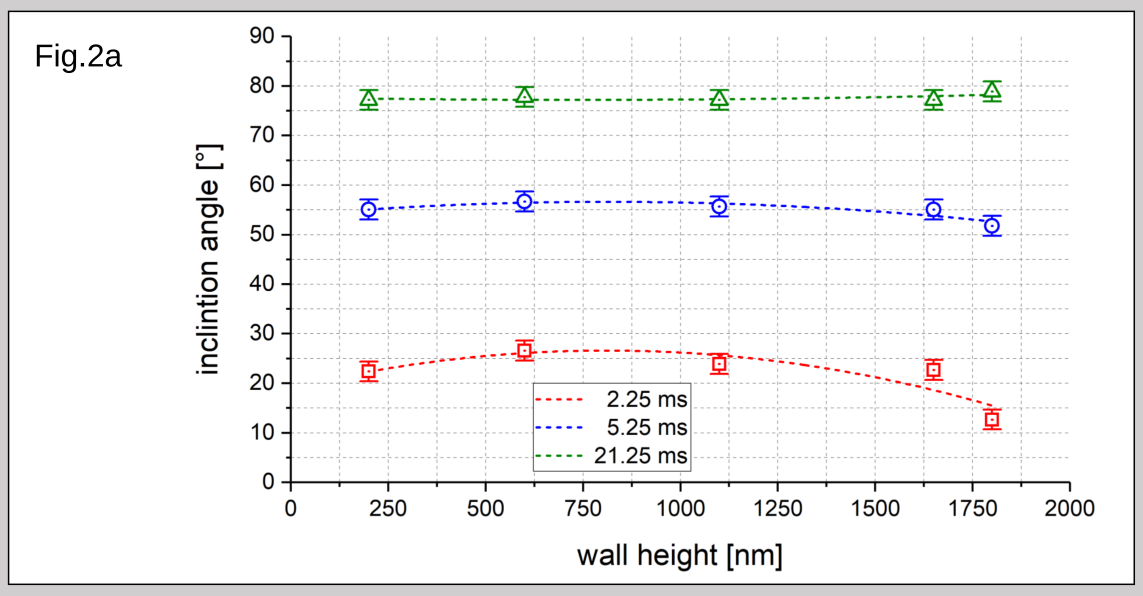
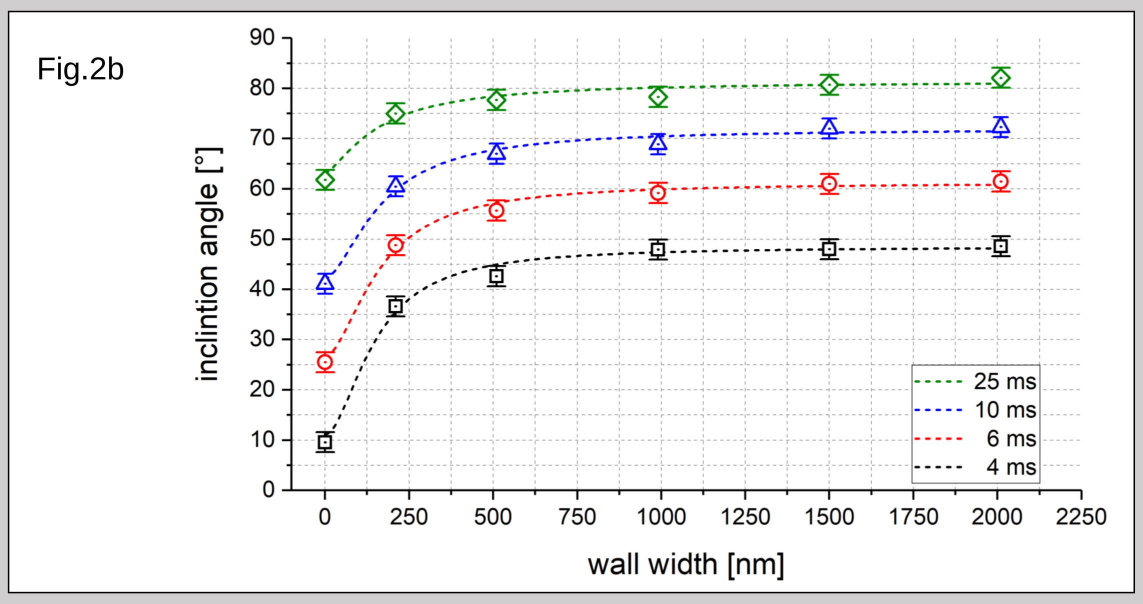


Fig.2b



To gain fundamental understanding of the behaviour of 2-dimensional nano-structures, systematic series of "Diving Boards" (vertical walls + inclined segments – called "Blades", see Fig.3) were designed, using a new pattern generating software we are currently developing and subsequently fabricated with a Quanta 3D FEG dual beam microscope. In more detail, we studied the implications of width and height of the built structures on finally arising inclination angles as input for correlated simulations (see below).

Figure 2 shows the dependency of the inclination angles from a) the width of the Diving Boards and b) the height of the base walls (for constant dwell times)

a) A strong influence of the structure width below 1 µm was found during these measurement series.

b) The influence of height only seems to play a minor role for 2D structures – in contrary to its influence on 1D structures[3].

Figures 3-7: Recolored SEM images of 3D structures fabricated at 5 kV and 58 pA using Pt-based precursor (scale bars are always 500 nm). Pattern file generation was done with a Python based code, currently under development at FELMI-ZFE.

Particularly noteworthy are the triangular structures (Fig.7), which can be fabricated within one object plane (shown here) or even in rotated fashion. This figure clearly shows the temperature effects by different diamond heights (for same exposure times) due to the bottleneck formation for heat diffusion. Fig.5 shows an example of a mixed structure combining mesh-like and two-dimensional elements. Finally, Fig.4 shows an example of a nearly closed 3D structure, which might be highly interesting for e.g. plasmonics or resonators.

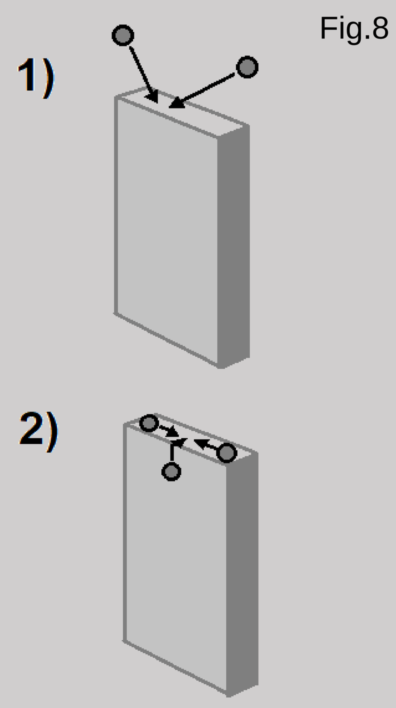
Temperature Effects

Once the electron beam impacts the new growth front of the 3D object, the local temperature rises very fast (lower µs scale), which has strong thermodynamic implications[3]:

a) Local Coverage:

The local precursor coverage is determined by two main effects (see Fig.8): 1) direct adsorption from the gas phase and 2) diffusive short range replenishment from surrounding regions (distance < 150 nm). Higher temperatures however, strongly decrease precursor residence times, meaning fast desorption, low coverage and by that reduced growth rates.

Fig.8



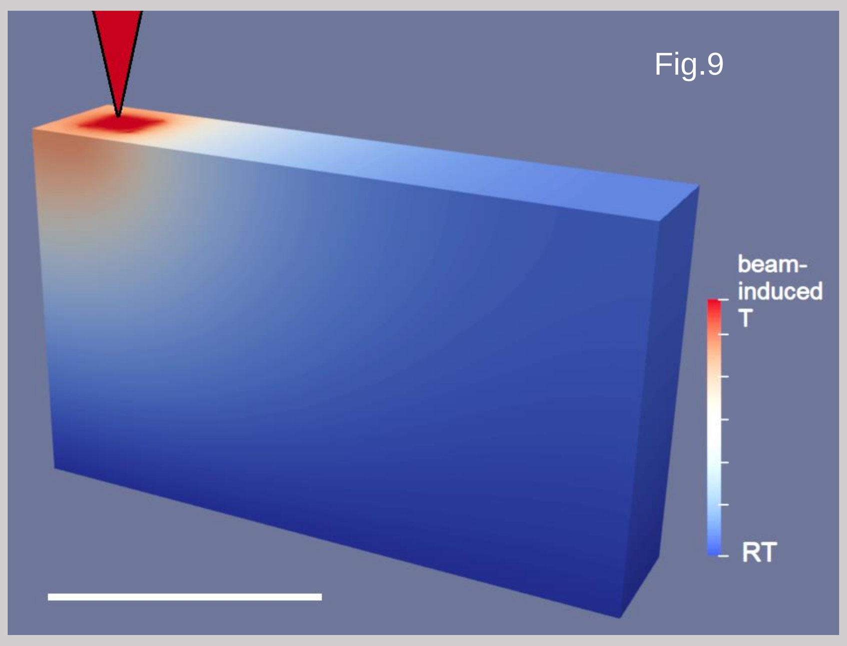
b) Geometry Depending Heating:

The complicated part of local beam heating is its strong dependency on the architecture and the dimension below the new growth fronts. The longer it takes to dissipate the heat, the higher the local temperatures at constant electron beam input power. For (semi-)closed structures this thermal situation can get quite complicated, as it depends on various parameters.

Simulations

For a better understanding of the temperature situation during FEBID, heat diffusion simulations were performed with OpenFOAM. This includes absolute temperatures in the impact region, its spatial distribution (see right) and its evolution during growth of closed, semi-closed and mixed 3D structures. The simulations will help to explain experimentally observed effects (see top right box) and to compensate for growth instabilities in an upfront way.

Fig.9



CONCLUSION

We performed systematic growth studies not only to get a comprehensive insight into the fundamental mechanisms during 3D FEBID but also to develop a general model for upfront compensation. This will lead to spatially precise, predictable and reproducible fabrication of even complex 3D nano-architectures as essential element on the route towards a generic 3D nano-printing technology for future applications in various fields of research and development.

ACKNOWLEDGEMENTS

Thanks to Prof. Ferdinand Hofer, Robert Winkler, Jürgen Sattelkow and Jakob Hinum-Wagner for the productive discussions and collaboration.
Financial support by Graz University of Technology is gratefully acknowledged.

REFERENCES/LITERATURE

[1] High-Fidelity 3D-Nanoprinting via Focused Electron Beams: Growth Fundamentals, Winkler et al., ACS App. Nano Mat. (2018), 1 (3), 1014.
[2] High-Fidelity 3D-Nanoprinting via Focused Electron Beams: Computer-Aided Design (3BID), Fowlkes et al., ACS App. Nano Mat. (2018), 1 (3), 1028.
[3] The Impact of Electron Beam Heating during 3D Nanoprinting, Mutunga et al., ACS Nano (2019), in revision.

Contact

anna.weitzer@felmi-zfe.at
harald.plank@felmi-zfe.at
www.felmi-zfe.at