Secondary Electron Emission during 3D Nanoscale Focused Electron Beam Induced Deposition

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Predictable and controlled three-dimensional nanoscale direct-write has recently been demonstrated using focused electron beam induced deposition (FEBID)[1-2]. This recent development builds on the pioneering work of Utke[3], Koops[4], Matsui[5] and others[6-7]. These early works demonstrated the ability to deposit suspended 3D nanowires using FEBID/FIBID effectively paving the way for the controlled 3D direct-write of mesh style objects. Three-dimensional plasmonic nanostructures[2] have already been demonstrated using the 3D FEBID design and exposure method[1].

The recent demonstration of 3D FEBID required a simulation component which was initially calibrated by conducting a simple physical morphology comparison between simulations and experiments. However, substrate current is also collected during FEBID and provides another data stream to further refine simulation precision. Specifically, the collected sample current contains key information regarding the emission of backscattered and secondary electrons (SE). Bret et al. have shown that suspended nanowires of variable angle yield a distinct sample current trace[8]. Curving nanowire deposition (demonstrated via FIB)[6] or exposure failure due to the loss of contact between the electron probe and growing nanowire[9] also produce unique signatures.

Secondary electron emission drives the deposition process. Thus, the SE surface emission profile must be known over the complex 3D object in order to accurately predict FEBID. For example, our current model of FEBID contains two parameters; (1) the fraction of primary electron energy converted into SE production and (2) the SE mean free path[1]. These variables can counteract leading to multiple solutions for a given 3D object. Initial results will be presented showing that the simulation can be tuned to simultaneously reproduce both the final 3D deposit shape and the sample current time evolution function (Figure 1). The elements of the SE model required for reproduction will be presented among such factors as SE surface reflection and SE reabsorption, which can be independently switched on or off using the simulation. The robustness of the solution will be tested by conducting a primary electron beam acceleration voltage study. The beam acceleration voltage strongly influences both the SE surface emission profile and the yield of SEs provided the robust metric needed to test an SE generation/emission model. Only through a precise understanding of SE activity during FEBID will it be possible to enforce dynamic feedback during FEBID growth to update the exposure sequence toward defect-free exposures.

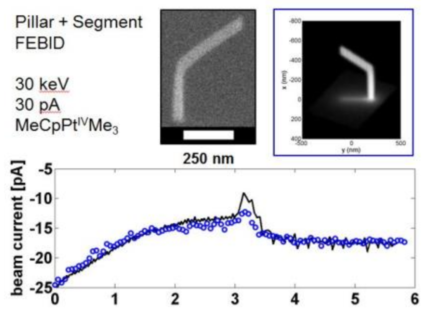

Figure 1: Vertical wire growth followed by the growth of a suspended segment: The acceleration voltage during deposition was 30 keV and the beam current was approximately 30pA. The Pt-C deposit was derived from the electron beam driven dissociation of the precursor $MeCpPt^{IV}Me_3$. Above: An SEM Image acquired at 52^o tilt of the wire and segment and the comparable result from simulation is shown on the right. Experimental data points of the sample current evolution during growth are shown in blue while the simulated result is shown as the black, continuous trace.

[1] Fowlkes, J. D.; Winkler, R.; Lewis, B. B.; Stanford, M. G.; Plank, H.; Rack, P. D., Simulation-Guided 3D Nanomanufacturing via Focused Electron Beam Induced Deposition. *ACS Nano* **2016,** *10* (6), 6163-6172
[2] Winkler, R.; Schmidt, F. -P.; Haselmann, U.; Fowlkes, J. D.; Lewis, B. B.; Kothleitner, G.; Rack, P. D.; Plank, H., Direct-Write 3D Nanoprinting of Plasmonic Structures. *ACS Applied Materials & Interfaces* DOI: 10.1021/acsami.6b13062
[3] Utke, I., *Nanofabrication Using Focused Ion and Electron Beams, Principles and Applications*. Oxford University Press: 2012.
[4] Koops, H. W. P.; Kaya, A.; Weber, M., Fabrication and characterization of platinum nanocrystalline material grown by electron-beam induced deposition. *Journal of Vacuum Science & Technology B* **1995,** *13* (6), 2400-2403.
[5] Matsui, S.; Kaito, T.; Fujita, J.; Komuro, M.; Kanda, K.; Haruyama, Y., Three-dimensional nanostructure fabrication by focused-ion-beam chemical vapor deposition. *Journal of Vacuum Science & Technology B* **2000,** *18* (6), 3181-3184.
[6] Kometani, R.; Warisawa, S.; Ishihara, S., The 3D nanostructure growth evaluations by the real-time current monitoring on focused-ion-beam chemical vapor deposition. *Microelectronic Engineering* **2010,** *87* (5-8), 1044-1048
[7] Gazzadi, G. C.; Frabboni, S.; Menozzi, C., Suspended nanostructures grown by electron beam-induced deposition of Pt and TEOS precursors. *Nanotechnology* **2007,** *18 (44)* 445709
[8] Bret, T.; Utke, I.; Hoffmann, P.; Abourida, M.; Doppelt, P., Electron range effects in focused electron beam induced deposition of 3D nanostructures. *Microelectronic Engineering* **2006,** *83* (4-9), 1482-1486
[9] Bret, T.; Utke, I.; Gaillard, C.; Hoffmann, P., Periodic structure formation by focused electron-beam-induced deposition. *Journal of Vacuum Science & Technology B* **2004,** *22* (5), 2504-2510