

Printing into Nowhere: Self-Formation of the Transition Region During Localized Electrochemical Copper Deposition onto a Partially Metallized Glass Substrate.

Ekaterina Shabratova,*^a Lisa Kirchhoff,^a Patrick Scheele,^a Katja Höflich^a

^a*Ferdinand-Braun-Institut (FBH), Berlin, Germany*

The continued miniaturization of electronic devices and the expansion of high-frequency technologies, for instance in the terahertz (THz) regime, require conductive microstructures with sub-millimeter dimensions that allow electromagnetic field-matter interactions to be precisely tailored [1]. However, their fabrication remains challenging: conventional microfabrication techniques, such as lithography, are inherently two-dimensional, while most metal additive manufacturing approaches rely on melting or sintering processes that limit geometric complexity, dimensional accuracy, and surface quality at the microscale.

FluidFM-based localized electrochemical deposition (LECD) offers a unique alternative by enabling the direct fabrication of complex three-dimensional (3D) copper microstructures with electrical conductivity approaching that of bulk copper [2]. In LECD, the substrate serves as the working electrode in an electrochemical cell, while a copper-ion-containing ink is dispensed through a hollow atomic force microscopy (AFM) cantilever with a 300 nm aperture. Under an applied potential, copper ions are locally reduced at the substrate surface, forming metallic copper. Once a voxel reaches the cantilever tip, an optical feedback system advances the tip to the next position, enabling precise control over the structure growth [3].

Despite these advantages, LECD is fundamentally limited by the requirement for an electrically conductive substrate, which must continuously supply electrons to the growth front during deposition. However, since electronic chips are typically based on semiconductor materials, whose electrical conductivity is often insufficient to sustain LECD, direct printing on chip architectures remains challenging. In this work, the feasibility of direct copper printing on partially metallized insulating substrates was investigated using gold-covered glass as a model system. An interesting growth behavior was observed: when the AFM cantilever was positioned above the insulating glass in proximity to the edge of a conductive pad, rather than directly above the pad itself, copper deposition spontaneously formed a conductive transition region bridging the gap between the pad and the cantilever. Once this bridge was established, the intended three-dimensional structure continued to grow normally.

The formation of this transition region is expected to follow the electric field lines present between the biased conductive pad and the cantilever, which in turn guide the copper ions toward the printing location. As a result, a metallic transition region is formed which ultimately provides an electrically conductive pathway from the metallized pad to the target position of the microstructure to be formed. This effect enables not only LECD beyond the boundaries of the initial conductive electrode but also potentially creates a “natural” electronic adiabatic transition region.

Acknowledgements

This work was supported by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) under project ID 576297090 “3D-@-6T”. Financial support by the German BMBF within the “Forschungsfabrik Mikroelektronik Deutschland (FMD)” framework under ref. 16FMD02 is gratefully acknowledged.

References

- [1] F. Matt et al., “Broadband Additively Manufactured Chip-Integrated Helical Antenna for 500–750 GHz,” IEEE International Symposium on Antennas & Propagation and USNC-URSI Radio Science Meeting, 2026.
- [2] P. Schürch et al., “Direct 3D microprinting of highly conductive gold structures via localized electrodeposition,” Mater. Des., vol. 227, p. 111780, Mar. 2023, doi: 10.1016/j.matdes.2023.111780.
- [3] G. Ercolano et al., “Multiscale Additive Manufacturing of Metal Microstructures,” Adv. Eng. Mater., vol. 22, no. 2, Feb. 2020, doi: 10.1002/adem.201900961.

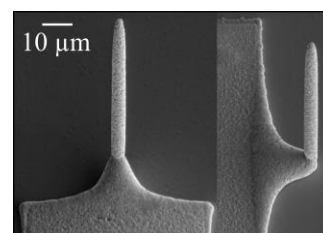


Figure 1. Scanning electron micrographs of the transition region obtained from two different perspectives.

* Corresponding author: Ekaterina.Shabratova@fbh-berlin.de; phone | 030-6392-58329