3D-Printed Nanoprobes in AFM: Transforming Surface Analysis with Multifunctional Nanoscale Precision

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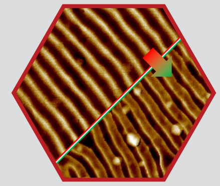

Atomic Force Microscopy Beyond Morphology

Atomic Force Microscopy (AFM) has long been a cornerstone in research and development, enabling detailed surface analysis across a wide range of materials from polymers, biomaterials, and soft biological samples to metals, semiconductors, ceramics, thin films, and advanced nanomaterials. Its unparalleled capability to capture topographical details down to atomic resolution has made AFM indispensable for researchers in fields as diverse as materials science, biology, and nanotechnology. However, AFM's potential extends far beyond basic surface imaging. Advanced modes, such as *Conductive AFM* (c-AFM), *Electrostatic Force Microscopy* (EFM), *Kelvin Force Microscopy* (KFM), *Magnetic Force Microscopy* (MFM), *Scanning Thermal Microscopy* (SThM), and others, open new frontiers by probing related properties of surfaces in parallel to 3D morphology. These functionalities transform AFM into a powerful correlative, multifunctional tool, unlocking a comprehensive understanding of material properties that are crucial for applications in fields spanning from material science to life-sciences in research, development, quality control, and failure analysis. As AFM continues to evolve through such instruments as Quantum Design's FusionScope® **[1]** or AFSEM®nano **[2]**, the development of precision-engineered AFM nanotips pushes these capabilities even further, enabling the exploration of complex interactions at the nanoscale with unprecedented accuracy and specificity.

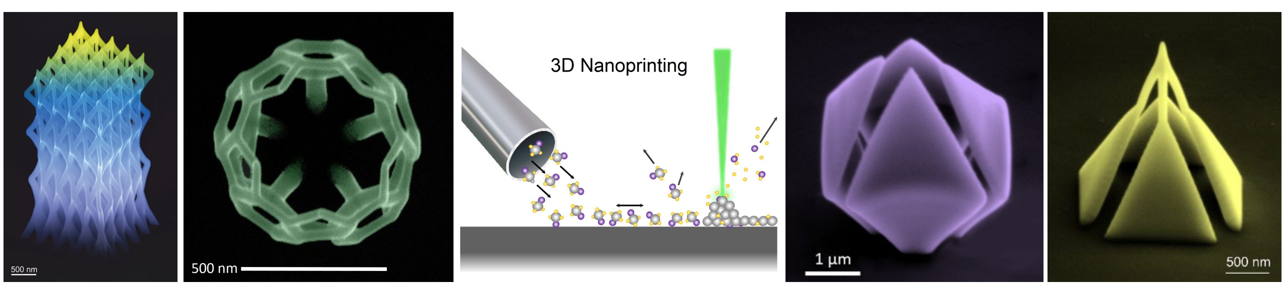

Figure 1:** 3D nanoprinting with focused electron beams enables precise, additive, direct-write fabrication offering unmatched design flexibility for on-demand fabrication of meshed and solid nanoscale structures on virtually any given surface such as cantilevers ([3]**, **[4]**, *and* **[5]***).*

The Challenges

Achieving the functional capabilities required for these advanced operation modes typically involves adding specialized coatings to the probe tip. These coatings – typically metals or magnetic materials – provide the necessary conductive (c-AFM), electrostatic (EFM, KFM), or magnetic properties (MFM). However, this functionalization approach presents significant challenges. First, there is the risk of delamination, where the coating detaches or deteriorates over time due to mechanical stress, thermal cycling, or chemical interactions. This deterioration can undermine the probe's functionality, resulting in unreliable data. Additionally, applying a coating inevitably increases the radius of the tip apex, clearly exceeding 25 nm, which reduces the achievable resolution and hampers the ability to capture and study fine surface details – an essential capability in the trend towards miniaturization. This trade-off between functionality and resolution is a fundamental limitation in many commercially available AFM tips.

Consequently, the ideal solution lies in the fabrication of all-metal nanoprobes with apex radii down to the sub-10 nm range, entirely eliminating the need for secondary coatings. Such probes not only provide the necessary functionality for advanced AFM modes but also maintain the high-resolution imaging required for nanoscale analysis, marking a transformative step forward in high-precision AFM applications.

3D Nanoprinting

To overcome the aforementioned limitations, *3D Nanoprinting* (3DNP) via *Focused Electron Beam Induced Deposition* (FEBID) offers a powerful and mature solution for creating high-performance and even multifunctional AFM nanotips. Over the past decade, this technology has advanced significantly, achieving levels of precision and reliability that were previously unattainable. This additive direct-write technology uses a focused electron beam to locally decompose precursor gases, depositing material with nanometer precision **[6]** and allowing for the fabrication of highly customized tip geometries and all-metal structures with apex radii down to the sub-10 nm range **[7]**. Hence, this approach eliminates the need for secondary coatings while enabling application-specific designs that maintain functional integrity and deliver superior resolution **[8]**.

FEBID-based 3DNP AFM probes – originally researched and jointly developed by worldwide known specialists from Graz University of Technology (Austria) – are robust, high-resolution AFM probes tailored to meet the demands of advanced imaging modes, making them an invaluable tool from cutting-edge nanoscale research to industrial development and quality control.

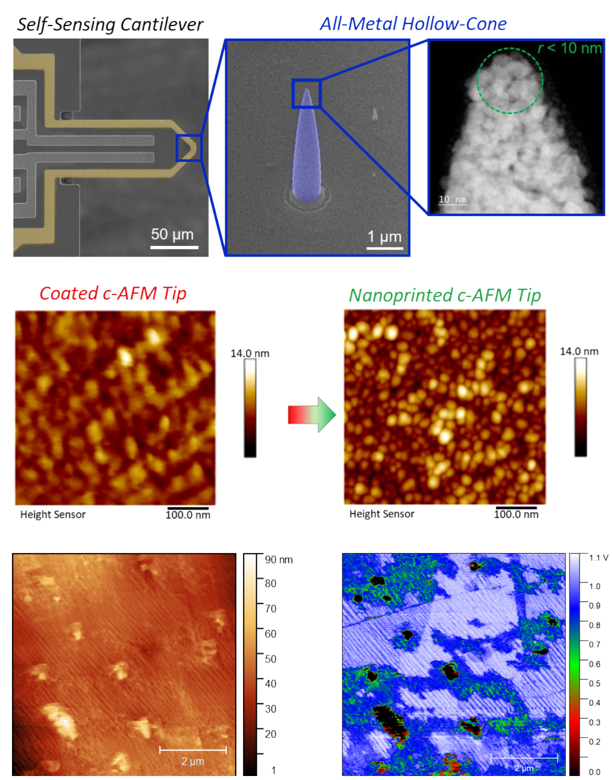

Figure 2: *All-metal Pt tip, produced by 3D nanoprinting directly at the electrodes of a pre-structured self-sensing cantilever. This process strongly enhances the achievable lateral resolution compared to traditionally coated tips, while enabling correlated current imaging* **[9]**.

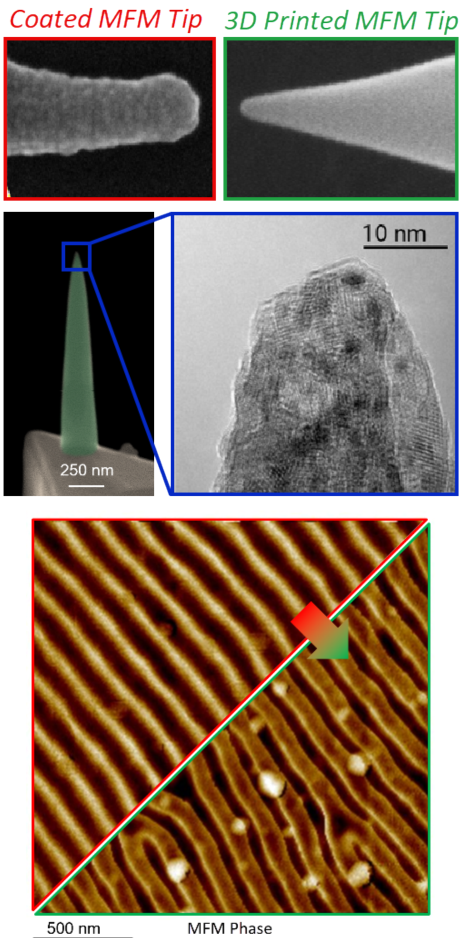

***Figure 3:** Based on 3D nanoprinting, the apex of all-metal magnetic tips is greatly reduced and reveals a highly crystalline, inner structure. Both together enable a superior lateral resolution, revealing previously hidden magnetic details* **[11]**.

Electric 3D Nanoprobes

The design and fabrication of all-metal AFM nanoprobes through FEBID-based 3DNP represents a breakthrough for advanced electric AFM applications. This approach utilizes a hollow-cone structure (Figure 2), combining mechanical rigidity with full electrical conductivity and apex sharpness of sub-10 nm which is key for achieving high-resolution imaging in c-AFM, EFM, or KFM. FEBID's two-step fabrication process includes precision deposition of platinum (Pt) materials using a focused electron beam, followed by a controlled purification step, transforming the deposited material into a robust, conductive all-metal Pt nanoprobe **[10]**. This process, refined over years, delivers reliable and reproducible nanoprobes with excellent mechanical rigidity, ensuring consistent performance even under demanding operational conditions relevant for c-AFM, which operates in contact mode. Altogether, these all-metal nanoprobes stand out as a reliable choice for high-precision electric AFM applications, offering a dependable solution for researchers who require fidelity and confidence while exploring nanoscale properties using the FusionScope or latest generation AFSEMnano scanners.

Magnetic 3D Nanoprobes

Pushing the boundaries of AFM for magnetic applications, FEBID-fabricated magnetic nanoprobes present an unprecedented leap in MFM technology. Created through a streamlined, single-step FEBID process, these Co_3Fe-based probes represent the pinnacle of nanoscale precision and performance. With a remarkably sharp sub-15 nm apex radius and an all-metal composition (Figure 3) , they deliver magnetic imaging that often outperform conventional options **[12]**. This unique combination of sharpness and stability produces a level of resolution, reliability, and clarity that allows researchers to uncover magnetic domains and structures with exceptional depth and detail. Tailored for demanding applications, these MFM probes not only satisfy but enhance the requirements of advanced nano-magnetism studies, offering FusionScope and AFSEMnano users an entirely new standard of imaging. Whether for pioneering research or precision industrial needs, these nanoprobes bring a transformative power to MFM, enabling researchers to capture and explore magnetic landscapes with unmatched fidelity and insight.

Next-Generation Thermal and Multifunctional Nanoprobes

At the forefront of AFM innovation, 3DNP nanoprobes are poised to unlock entirely new capabilities in SThM and multifunctional AFM applications. Designed for optimal thermal sensitivity by utilizing a nanoscale tetrapod thermistor as nanoprobe concept, they enable highly localized thermal mapping with fast response rates and low noise at room temperature **[13]**, making them ideal for capturing nanoscale heat distributions in advanced materials research. This thermal probing capability is coming soon to the FusionScope and stands ready to enhance its impact across a wide array of applications, offering users a tantalizing glimpse into the future of nanoscale thermal analysis.

In parallel, the ongoing development of our combined magnetic-conductive nanoprobes, denoted as MC-FUSION-Probes, will enable simultaneous MFM and c-AFM measurements within a single experiment. Printed from Co_3Fe, these unique probes seamlessly merge magnetic and conductive properties, allowing researchers to perform correlative imaging without the hassle of exchanging tips – an unprecedented advancement for fields requiring precise, complementary magnetic and electrical insights on challenging samples or unique areas of interest at the smallest scales. The integration of these patented next-generation probes with the FusionScope promises to bring correlative microscopy to a new level, empowering researchers with a toolset that combines unmatched versatility with unparalleled nanoscale fidelity.

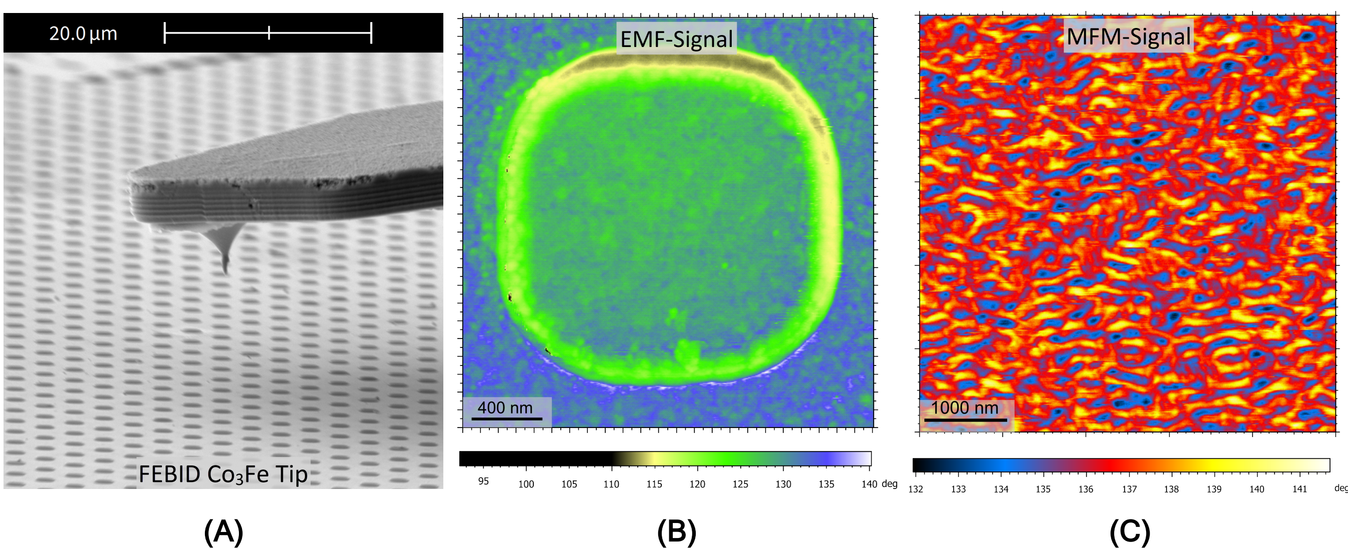

Figure 4: *First results of our combined magnetic-conductive nanoprobes. The Co_3Fe-tips can perform both EFM and MFM measurements with the same cantilever. This patented technology allows the fabrication of next generation cantilever probes.* ***(A)*** *FusionScope SEM image in Profile View showing the Co_3Fe-tip.* ***(B)*** *EFM measurement of aluminum disks on a gold substrate.* ***(C)*** *MFM image of Co/Pt multilayer structure.*

About the Author

Harald Plank is a professor at Graz University of Technology and Director of the “Christian Doppler Laboratory for Direct-Write Fabrication of 3D Nanoprobes”. His focus lies in research & development around “Functional Nanofabrication” with the aspiration of transferring basic research into industrially relevant applications. In addition, Professor Plank coordinates activities related to advanced microscopy for industrial services to support clients with complex material problems, time-sensitive challenges, or forensic analysis of patent infringements.

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