



MC Fusion Probes: 3D-Nanoprinted Co_3Fe Nanoprobes for Simultaneous Magnetic and Conductive AFM

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Atomic Force Microscopy (AFM) provides nanoscale access not only to surface topography but also to electrical, mechanical, thermal, optical, or magnetic properties. These advanced operation modes indispensably require functionalized probes, which are conventionally mostly produced by coating prefabricated tips. However, additional coatings inevitably increase the apex radius, reduce lateral resolution, and introduce the risk of wear or delamination. Three-dimensional nanoprinting by Focused Electron Beam Induced Deposition (3D FEBID) offers a direct-write alternative by fabricating monolithic functional nanoprobes directly on prefabricated cantilevers [1]. Previous work established electrically conductive all-metal probes with sub-10 nm apex radii [2] and highly crystalline Co_3Fe probes providing high-resolution, wear-resistant, and long-term-stable Magnetic Force Microscopy (MFM) performance [3].

Building on these complementary developments, we here introduce MC-Probes, a dual-functional nanoprobe architecture that integrates magnetic (M) and conductive (C) functionality within a single, coating-free Co_3Fe structure [4]. The objective extends beyond reducing measurement time: combining both functionalities in one monolithic probe architecture establishes the basis for spatially resolved magnetic and electrical characterization of identical nanoscale regions without uncertainties arising from probe exchange and relocation. The central integration challenge originates from the conflicting mechanical requirements of the two AFM modes. Conductive AFM (CAFM) operates in contact mode and generally benefits from compliant cantilevers, whereas MFM requires stable cantilever oscillation during tapping- and two-pass lift-mode operation.

MC-Probes are fabricated from an $\text{HCo}_3\text{Fe}(\text{CO})_{12}$ precursor using a mechanically robust α -pillar geometry with typical heights of approximately 3.5 μm and apex radii below 10 nm. The resulting material exhibits metal contents above 90 at.% and a predominantly nanocrystalline microstructure, directly providing both magnetic and electrical functionality without post-growth purification. Electrical characterization reveals a stabilized resistivity of approximately $2 \times 10^3 \mu\Omega \cdot \text{cm}$ and estimated total probe resistances of about 1-10 k Ω , comparable to commercial conductive probes. Systematic mechanical testing defines an overlapping operational window: reliable contact-mode operation is maintained up to cantilever spring constants of approximately 3-4 N.m⁻¹, while stable tapping-mode MFM is achieved down to approximately 2 N.m⁻¹. Functional performance is demonstrated under high-vacuum conditions in Quantum Design Microscopy's FUSIONScope™. CAFM measurements resolve individual graphene-layer steps and reproduce nominal resistor values with high accuracy, while MFM provides stable, high-contrast imaging of magnetic nanostructures. Correlative CAFM and MFM measurements on a custom $\text{SiO}_2/\text{Au}/\text{Co}_3\text{Fe}$ test structure further demonstrate electrical and magnetic characterization of the identical region of interest. Owing to the cantilevers currently available for the FUSIONScope™, these measurements still required two MC-Probes mounted on cantilevers individually optimized for contact- and tapping-mode operation. Nevertheless, the results validate the dual-functional probe architecture and establish the mechanical and functional basis for future single-cantilever integration.

By combining a suitable cantilever with an integrated multi-pass measurement sequence, MC-Probes acquire topographic, electrical, and magnetic information within a single workflow. Beyond CAFM and MFM, the concept is extendable to Kelvin probe force microscopy, electrostatic force microscopy, scanning spreading resistance microscopy, and related advanced electric modes. MC-Probes therefore represent an important step from single-purpose functional tips toward application-adaptive, multimodal nanoprobes for correlative AFM.

References

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