Stiffness, density and quality of high aspect ratio Cu/C nanostructures produced by focused electron-beam induced deposition

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With their maskless direct-write nanofabrication capabilities focused electron-beam (FEB) techniques will become increasingly important for device prototyping applications. Gas assisted FEB deposition and etching is used as an attach-and-release tool in electron microscope based nanomanipulation of individual nanostructures as well as a tool for functionalisation of AFM sensors. In view of these applications, characterization and control of the mechanical properties of FEB deposits is becoming a major issue.

FEB deposits often feature a composite structure, i.e. nanocrystalline (metal) grains embedded in a carbonaceous matrix. Evidently, the mechanical properties, such as stiffness, toughness, and adhesion must be determined experimentally since no data is available from template bulk materials.

From the combination of bending tests using *in situ* cantilever-based force sensing (Fig. 1) and modal vibration analysis (Fig. 2) we deduced Young's moduli and densities of FEB deposited pillars from the precursor $Cu(hfac)_2$. From several pillars deposited at 5 keV and 20 keV primary electron energy and otherwise equivalent conditions the average Young's modulus was 16 GPa and 25 GPa and the corresponding densities 1.9 g cm^{-3} and 3.9 g cm^{-3}, respectively. The measured density values compared well to measurements using a cantilever-based mass sensing approach.[2,3] The low stiffness (E_{Cu} = 130 GPa) can be associated to the carbonaceous matrix material since the Cu content of the deposits was measured to be in the order of 10 at.%.

From the phase relation at resonance the quality factors of the pillars were accurately measured in the order of 100 to 600 at room temperature in vacuum. These values are related to the intrinsic energy dissipation in the material. Multiple (polarized) resonance modes at frequencies related to each other by elliptical pillar cross-sections and pre-bent pillar shapes could be observed by top-view imaging of the vibrating structure (Fig. 3). To our knowledge these are the first systematic dissipation measurements in FEB deposited materials.

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[2] I. Utke, V. Friedli, J. Michler, T. Bret, X. Multone, and P. Hoffmann, *Appl. Phys. Lett.*, 88(3): 031906, 2006

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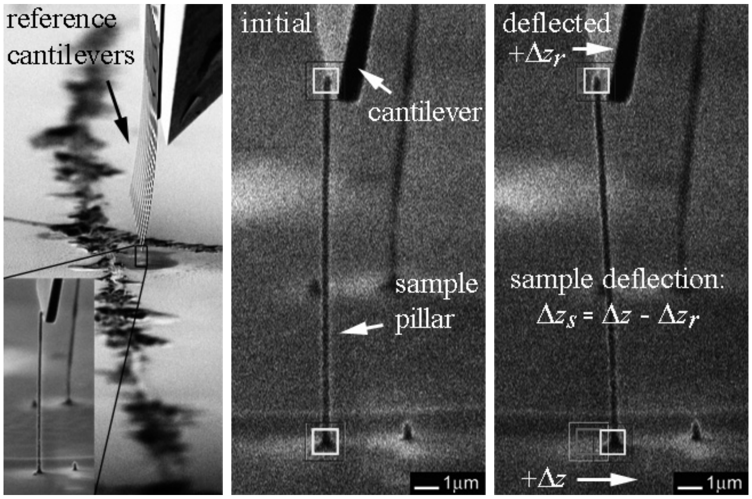

Fig. 1: *In situ* bending test to determine the Young's modulus via the force-deflection response of the sample pillar. The boxes mark the pillar base and tip position tracked by a cross-correlation image processing algorithm with < 20 nm resolution.

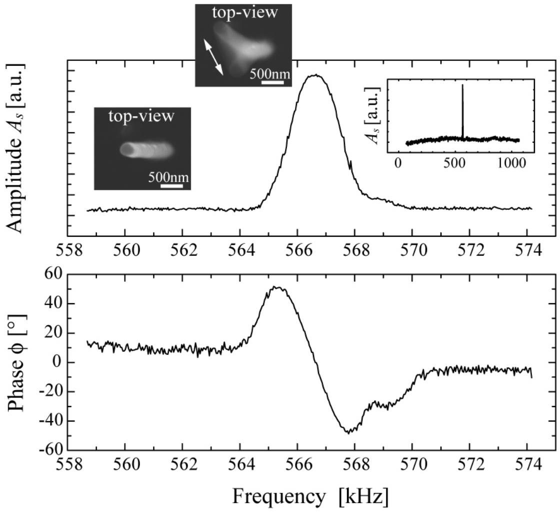

Fig. 2: *In situ* modal vibration analysis using the phase-locking technique: Fundamental mode amplitude and phase response of a FEB deposited pillar. Vibrations were induced by piezo-mechanical excitation and detected by the varying secondary electron signal through the interaction of a stationary electron beam with the oscillating structure.[1] The inset shows a wide spectrum of the amplitude response which locates the peak in the vicinity of 566 kHz.

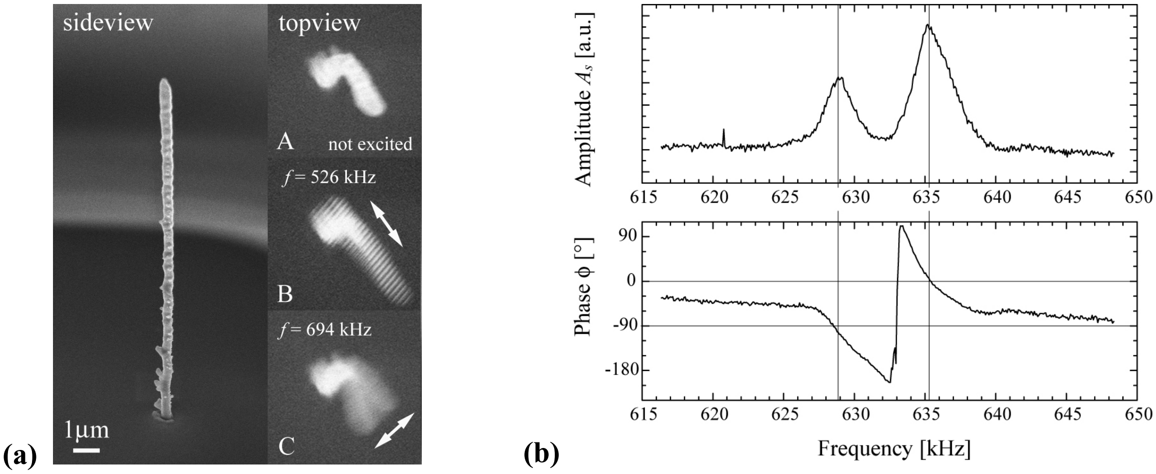

Fig. 3: (a) Illustration of the orthogonal polarizations of the vibrations of a FEB deposited pillar. (b) Polarized pillar vibrations have been detected by the secondary electron detection technique as a double amplitude peak and a 90° phase-shift between the two resonances.