High-Frequency Nano-motion Electron Imaging for Artificial Nanostructures

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Abstract – Development of future nanomechanical devices and sensors demands characterisation of fast movements, typically of sub-nanometre amplitude at MHz-GHz frequencies. We report on a novel approach to the visualization of nanoscale movements that is based on the detection of secondary electrons and photons emerging from the interaction of a focused electron beam with moving components of nano-objects, which may be actuated thermally or by external forces.

Photonic, Electronic, and mechanical devices grow ever smaller - some are now just a few tens of atoms in size with single-atom devices in prospect. This trend generates a need for increasingly sophisticated measurement and device characterisation tools. While conventional scanning electron microscopes (SEM) are normally used to study static objects, recent progress in nanotechnology demands new techniques for characterisation of fast nanoscale mechanical movements. Here, we present a new nanoscale dynamic SEM imaging technique (Fig. 1a) that is sensitive to movements at the sub-nanometre scale.

By way of demonstration, we consider the motion of rectangular cantilever arms (Fig. 1b) with well-defined (analytically described) modes of mechanical oscillation, manufactured by focused ion beam milling in a free-standing gold-coated silicon nitride membrane. The natural resonance frequency of a cantilever is first evaluated through the frequency domain analysis of scattered secondary electrons modulated by thermally-driven Brownian motion. In this frequency range, an alternating voltage is then employed to drive a piezo-transducer that induces controlled oscillatory displacement to the cantilever while a focused beam of electrons is raster-scanning across the sample. Amplitude and phase maps of the dynamic component of the secondary electron (SE) signal are recorded by a lock-in amplifier at the piezo transducer driving frequency in the manner of an SEM recording a static image, from which the mechanical mode shape of the cantilever can ultimately be derived.

Such maps are shown in Figures 1c and 1d for a cantilever driven at its fundamental in-plane oscillation frequency of 0.65 MHz. We observe *i.* no movement of the surrounding membrane or adjacent non-resonant (different length) cantilevers (amplitude zero; random phase); *ii.* a near-zero amplitude signal for most of the cantilever surface because over much of its surface area in-plane displacement does not change SE scattering; *iii.* a non-zero signal and locked phase along the edges of the beam, showing that it is moving, with maximum signal along the long edges of the beam (increasing with distance from the anchor point as would be expected); *iv.* Opposing π phase shifts along the two edges of the beam reflecting the differing signs of the SE signal gradient at these points. In this example, we record a maximal displacement ~60 nm with a displacement sensitivity of ~145 pm corresponding to the thermal noise floor in our system at the cantilever resonance frequency of 0.65 MHz. Notably, the dynamic displacement sensitivity/resolution is somewhat better than the several-nm static spatial resolution of the SEM. In summary, we have developed the dynamic nano-motion nanoscopy which can map the sub-nanometre scale movements in nanomechanical structures with nanometre spatial resolution and microsecond temporal resolution.

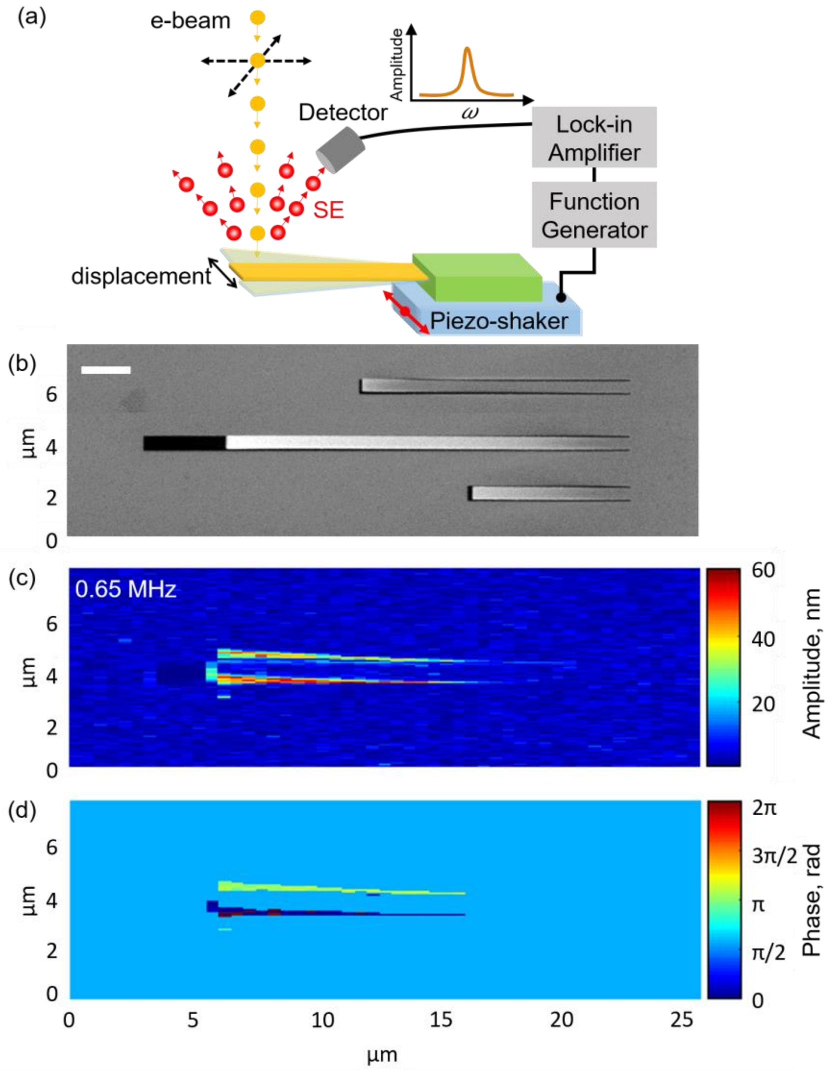

Figure 1. (a) System schematic for dynamic SEM nano-motion imaging. (b) Static secondary electron image of cantilevers cut into a free-standing membrane of 50 nm Si_3N_4 coated with 50 nm Au, scale bar 2 µm. (c, d) Nano-motion displacement amplitude (c) and phase (d) maps of the same area i.e. encompassing all three cantilevers obtained when the sample is driven by the piezo-transducer at a frequency of 0.65 MHz – the fundamental in-plane resonance frequency of the middle cantilever. In (d) points of random, un-locked phase are filtered out.