

Nanomotion Visualization through Cathodoluminescence

Toji Thomas¹, Eric Plum¹, Kevin F. MacDonald¹, and Nikolay I. Zheludev^{1,2}

1. Optoelectronics Research Centre, University of Southampton, Highfield, Southampton, SO17 1BJ, UK

2. Hagler Institute for Advanced Study, Texas A&M University, College Station, Texas, 77843, USA

The motion of nano/microscale objects can be detected and mapped via cathodoluminescence, with nanometric displacement sensitivity and spatial resolution, and MHz bandwidth.

Nanoscale motion is of growing technological importance and scientific interest, e.g. in relation to MEMS and NEMS devices, the properties of 2D and nanostructured materials, and fundamental studies of dynamics and the action of forces at the nanoscale. However, there are no routinely available techniques for mapping fast, complex motion at the nanoscale with high temporal and spatial resolution: Far field optical techniques are typically diffraction limited in their spatial resolution, while scanning probe and electron microscopies are constrained by very low frame rates. Here, we introduce a technique for hyperspectral motion visualization, based the detection of electron-induced light emission in an electron microscope, which provides for point measurements of motion with nanometric sensitivity and oscillatory mode mapping with $\sim$ few nm spatial resolution.

The measurement principle is illustrated in Fig. 1a. Conventional electron microscope images, in cathodoluminescent mode, are generated by raster-scanning a focused electron beam over an object and detecting the integrated, time-averaged, light emission intensity at each point. By instead recording the frequency spectrum of emission intensity at a given point, one can detect fast movements of the object – nanometric fluctuations of object position being captured as time-dependent fluctuations of light emission intensity. The technique relies upon the gradient dI/dy of the photon detection rate at the sharp edges of an object, yielding a value of minimum detectable displacement (with unitary signal-to-noise ratio) $\sim \sqrt{I/\tau} / (dI/dy)$ of order 1 nm for typical conditions of beam current and photons per electron yield and an integration time $\tau \sim 1$ s.

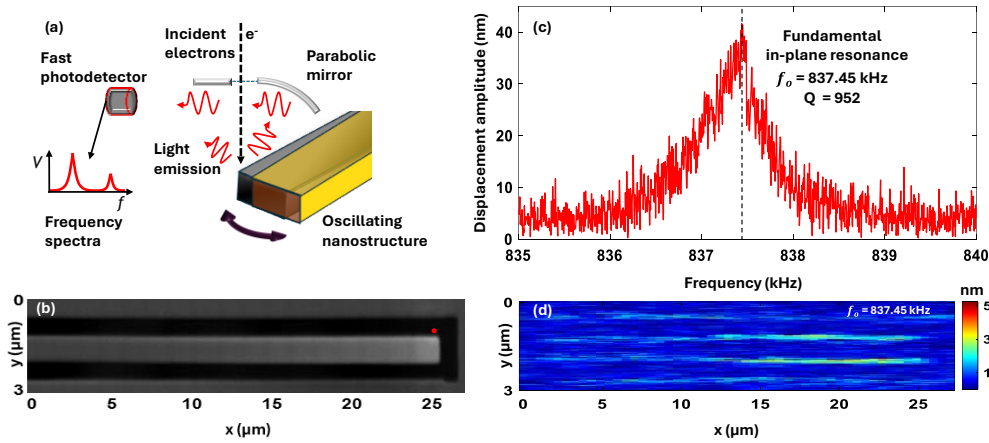


Fig. 1 Nanomotion imaging via cathodoluminescence. (a) Measurement principle: Nanostructural oscillation modulates the intensity of light emission generated by incident electrons striking or passing near to the target object. Light is directed to a fast photodetector by a parabolic mirror, for spectral analysis. (b) Scanning electron microscope image of a gold + gallium nitride coated nanocantilever employed as a test object. The red dot denotes the position of the incident electron beam for measurement of the cantilever's in-plane oscillation frequency spectrum. (c) Cantilever tip displacement spectrum [relative to its piezo-driven base] as a function of driving frequency. (d) Driven [y-direction] oscillation amplitude map of the cantilever at its resonance frequency.

Representative results are presented in Fig. 1 for a 25 μ m long, 800 nm wide cantilever fabricated by focused ion beam milling from a 150 nm thick gold + gallium nitride coated silicon nitride membrane (Fig. 1b), mounted on a piezo-actuator to drive in-plane oscillation. The spectrum of electron-induced light emission (converted to displacement amplitude – Fig. 1c) from a point near to the cantilever tip reveals the frequency (837.45 kHz) and mechanical quality factor (952) of the cantilever's fundamental in-plane oscillatory mode. With detection then locked to that frequency, oscillation amplitude can then be mapped as a function of position (Fig. 1d). Here, the intensity gradient-dependent nature of measurements is clearly seen, with movement not being resolved at points where there is no gradient along y (e.g. in the centre of the cantilever, and along the short edge at its tip).

Importantly, as light can be generated by electrons passing within a few nm of an object (by scattering the moving electron's evanescent field, c.f. Smith-Purcell radiation), as well as by direct impact, this approach offers the possibility of minimally perturbative measurements, i.e. involving energy exchange at the eV level of photons as opposed to the keV levels of secondary electrons, and potential means to probe/distinguish different mechanisms of free-electron interaction with nanostructures.