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G-mode – Full Information Capture Applied to Scanning Probe Microscopy

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Scanning Probe Microscopy (SPM) has spearheaded nanoscience and nanotechnology by unlocking the nanoscale world for exploration and manipulation. While substantial effort has been dedicated towards the development of better instrumental platforms and probes, opportunities related to signal processing and data acquisition in SPM have often been overlooked. Current SPM imaging and spectroscopy techniques use heterodyne detection methods such as lock-in amplifiers and phase-locked loops which compress the ~10 MHz information stream from the photodetector to ~ 1-10 kHz. Here, we discuss a fundamentally new approach to SPM called General-mode (G-mode) where we capture the complete broad-band response of the SPM probe at sampling rates of 4-100 MHz. Figure 1 compares the differences between the traditional heterodyne approach and the G-mode approach. G-mode enables exploration of the complex tip-surface interactions, spatial mapping of multidimensional variability of material properties and their mutual interactions, and imaging at the information channel capacity limit. The availability of the complete SPM probe response facilitates the application of various physical models, simultaneous multiresolution imaging at multiple frequencies, smart data compression, noise analysis, and novel spectroscopic methods. Here we present applications of the G-mode paradigm to spectroscopic imaging of ferroelectric and multiferroic materials.

Polarization switching in ferroelectric and multiferroic materials forms the basis for the next generation of electronic devices such as field effect transistors, and tunneling devices. The switching mechanisms in these materials are extremely sensitive to the local defects and structural imperfections at the micro and nanometer scale which have undesirable effects on ferroelectric domains. The SPM technique called Piezoresponse Force Microscopy (PFM) is the most popular method for probing electromechanical activity at the nanoscale since it provides insight into localized functionality of ferroelectric and multiferroic materials [1]. In PFM, an electric bias is applied to a conductive SPM tip in contact with a sample. The bias results in surface deformations that induce vibrations in the SPM probe which are measured at the SPM photodetector. In spectroscopic modes of PFM, the ferroelectric properties of material are explored via local hysteresis loop measurements, where electromechanical response is measured as a function of applied dc bias. However, current state-of-art PFM spectroscopy techniques suffer from serious compromises in the measurement rate, measurement area, voltage and spatial resolutions since they require the combination of a slow (~ 1 sec) polarization switching signal and a fast (~ 1 – 10 msec) measurement signal [2].

When applying G-mode to inspect the information content when imaging ferroelectric domains in the sub-switching regime, we observe that there is substantial information present in each of the eigenmodes of the SPM probe that are not captured in the traditional lock-in approach. We also extend G-mode to the spectroscopic mode of PFM where we combine the full cantilever response from G-mode with intelligent signal filtering techniques to directly measure material strain in response to the probing bias. Figure 2 shows the basic steps of this spectroscopic imaging technique. Our technique enables precise spectroscopic imaging of the polarization switching phenomena 3,500 times faster than currently reported methods. The improved measurement speed enables dense 2D maps of material response with minimal drift in the tip position. This technique will enable significant insight into nanoscale polarization dynamics and phenomena such as polarization fatigue or local wall displacements that remain difficult to study at the desired spatial and temporal scales, and are crucial for integration of ferroelectric nanostructures in future electronic devices. Besides PFM, G-mode can be applied to many other imaging and spectroscopy methods within and beyond SPM. By providing the complete and unbiased information, G-mode has the potential for truly quantitative probing local materials functionality [3].

References:

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[2] S. Jesse, *et al.*, Rev Sci Instrum **77** (2006), p. 073702.
[3] This research was conducted at the Center for Nanophase Materials Sciences, which is a DOE office of Science User Facility.

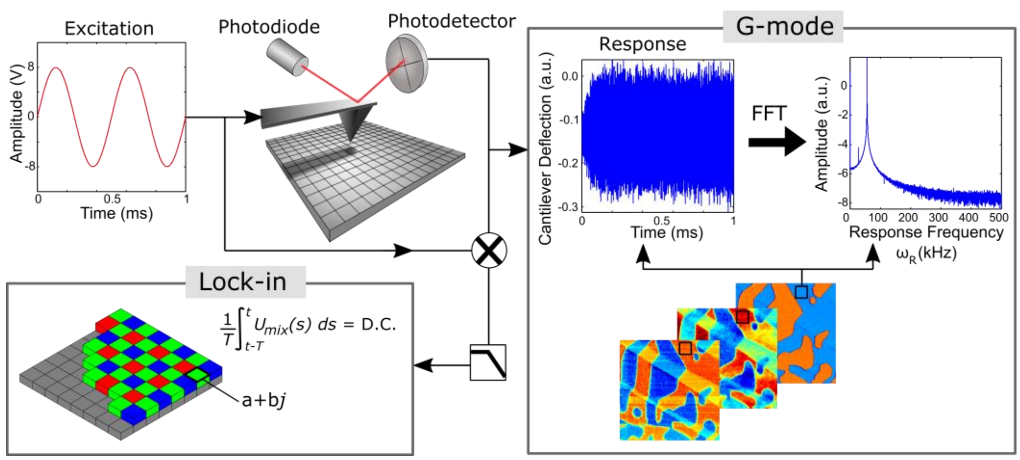

Figure 1. G-mode captures the complete raw signal from the photodetector thereby adding the time (or frequency) dimension for each spatial pixel. In contrast, the traditional lock-in paradigm integrates the product of the excitation and response signals over the time constant and produces a single pair (amplitude and phase) of values at each spatial pixel.

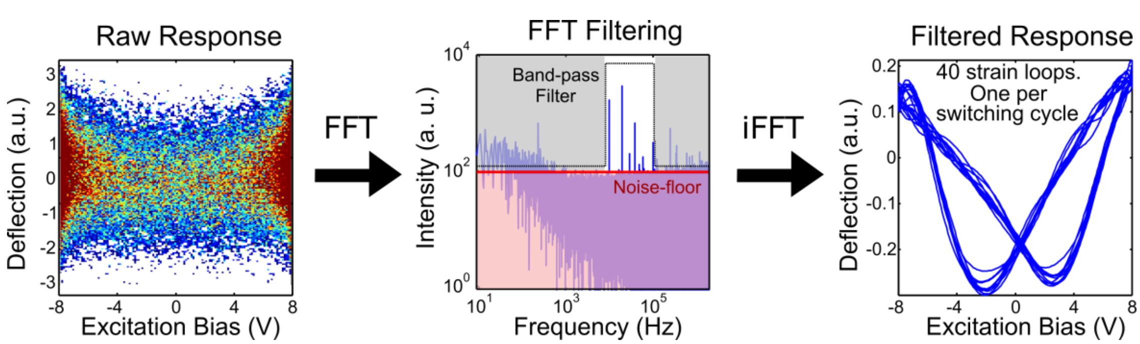

Figure 2. G-mode applied to spectroscopic PFM. The raw data from the photodetector is filtered in the frequency domain using adaptive noise thresholding and a band-pass filter to reveal multiple material strain loops.

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