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Getting to zero - quantitative electromechanical atomic force microscopy

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Since the very early days of atomic force microscopy (AFM), voltage modulation (VM) of AFM has been used to try to quantify a host of electronic, electrochemical and electromechanical functionalities across nanometer length scales. The critical importance of such information has resulted in the development of a plethora of VM-AFM techniques for exploration of either long or short-range forces. Of relevance for ferroelectrics, piezoresponse force microscopy (PFM) imaging and associated spectroscopies have effectively opened the door to the exploration of nanoscale ferroelectric properties. The rise of PFM, however, has also brought about claims of ferroelectricity in materials which were subsequently thought to be not ferroelectric,[1] even unlikely materials such as soda-lime glass. Explanations for the origins of these unexpected nanoscale phenomena have not been in short supply, including new material properties, surface-mediated polarization changes and/or spatially resolved behavior that is not present in bulk measurements. At the same time, it is well known that VM-AFM measurements are susceptible to numerous forms of crosstalk and despite efforts within the AFM community, a global approach for quantitative, crosstalk-free techniques remains elusive. In an effort to understand the true origins of the measured VM-AFM signals we demonstrate the presence of hysteretic ("false ferroelectric") long-range interactions between the sample and cantilever body and show that these are intrinsic to traditional VM-AFM detection methods. However, we show that with interferometric displacement sensor (IDS) [2] it is possible to separate the true tip motion from the cantilever dynamics. Using the IDS we have established a rapid and simple flagging routine of false piezo and ferroelectric responses and are able to demonstrate fully quantitative and repeatable nanoelectromechanical characterization. We attribute a lot of the observed unexpected hysteretic behavior to surface water, since it is ubiquitous in ambient conditions for even mildly hydrophilic surfaces and may explain the plethora of behaviors discussed above. Finally, we demonstrate that through using the interferometric approach allows for putting of quantitative limits on the electromechanical sensitivity. For example, we were able to show a $d_{eff} \leq 40$ fm/V for soda-lime glass using the IDS is much smaller than that implied by conventional VM-AFM measurements. These quantitative measurements are critical for a wide range of new devices ranging from mems actuators, memristor devices, energy storage and dynamic computer memory.

1. R.K. Vasudevan, et al., *Applied Physics Reviews* **4**, 021302 (2017).
2. A. Labuda and R. Proksch, *Applied Physics Letters* **106**, 253103 (2015).