Functional Material Properties of Oxide Thin Films Probed by Atomic Force Microscopy on the Nanoscale

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Scanning probe microscopy (SPM) has made tremendous progress characterizing functional thin films imaging the variation in material response on nanometer length scales. Especially the probing of electromechanical responses, i.e. the change in sample dimension under applied electric field, is well suited for SPM due to its high z-resolution. One field which benefitted a lot from SPM-based characterization are ferroelectric materials where piezoresponse force microscopy (PFM) is used to image and manipulate domains and extract polarization domain switching characteristics.

In recent years, many technical advances have been made in the field of SPM-based characterization based on electromechanical phenomena. This includes multi-frequency approaches and the development of new techniques, such as electrochemical strain microscopy. Despite the technical advances and the development of new AFM-based characterization techniques, the quantification of functional material parameters based on electromechanical phenomena is still elusive. The lack of quantitative and accurate measurement can lead to the misinterpretation of relevant material physics. Only if quantitative material parameters can be extracted, can a correlation of nanoscale structure-function relationships be derived.

The problem of quantification is two-fold. First, the slope of the cantilever is measured rather than the actual displacement of the sample. That means the shape of the vibrating beam is essential for the signal strength, especially in techniques utilizing contact resonance enhancement. This leads to strong variations in electromechanical response and different SPM cantilever cannot be directly compared. Here, we will demonstrate a software-based approach to extract quantitative cantilever displacements under consideration of beam contact dynamics. A correction factor is introduced to apply to experimental data to make the electromechanical response independent of the cantilever geometry. The second difficulty with quantification is the interpretation of the measured displacement and the extraction of the functional material parameters from the displacement. This is the most difficult task and can only be achieved through integrated experiment and theory and a deep understanding of the signal contributing mechanism. Ideally, electromechanical measurements are performed on a functional oxide, e.g. a ferroelectric material. The electromechanical response is then interpreted as only coming from the piezoelectric effect. In reality, many different phenomena can happen at the same time and it is difficult to separate different contributions. In order to separate the different contributions to the cantilever displacement it is important to conduct the correct experiments and to know how the individual contributions change with voltage, time, temperature, and cantilever properties. Only then, effective experiments can be planned and functional material parameters can be extracted. Here, we present efforts to follow this approach to extract quantitative material properties on the nanoscale of thin film oxides for various applications. This includes piezoelectric constants, dielectric tunability as well as electrostatic forces and activation energies of ionic transport.

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