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Research Statement

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My research focuses on developing a comprehensive quantitative framework for high resolution subsurface metrology using atomic force microscopy (AFM). This work is of notable interest because is one of few approaches for the non-destructive and non-invasive characterization of buried features with sub-micron dimensions. Methods for subsurface imaging with 3D reconstruction capabilities are critical in scaling down technologies and multiphases/multilayers materials.

AFM is traditionally known as a nanoscale instrument for surface topography and compositional contrast. However, it can investigate buried, subsurface objects. The underlying principle is the detection of interactions between an AFM probe and a sample, in the presence of an external wave or field that penetrates beneath the surface. The AFM is a newcomer to the field of subsurface imaging, in comparison to other available high resolution techniques like transmission or scanning electron microscopy. However, AFM offers significant advantages, such as i) operation over a wide range of environments, ii) broad materials compatibility, iii) low-energy of interaction, and iv) the ability to investigate local material properties. These make the AFM an essential characterization tool of materials/devices that cannot be studied otherwise.

The continuous development of novel nanomaterials and nanodevices generates a pressing need for innovative new metrology techniques, particularly at the sub-micron length scale. As an example, the Semiconductor Roadmap of 2015 has specifically identified interconnects, defect detection, and particle sizing related to nanoscale electronics as important metrology challenges. Advances in three-dimensional metrology is a key to understand the efficiency and performance (or lack thereof) of these systems. New tools capable of the detection of defects and analysis of interconnects covered by overlays are required to study the internal structure of nanodevices at different length scales.

Current and past research

My study of AFM started on a first visit to Purdue University as a research scholar. During this time, I joined Prof. Raman's lab, a well distinguished AFM research group. For the past five years, I have been on a learning journey about this versatile tool. My expertise is particularly in techniques related to the detection of electrostatic force interactions and local mechanical properties. I began investigating how AFM can be used as a subsurface imaging tool through electrical dynamic AFM techniques, such as electrostatic force microscopy (EFM) and Kelvin probe force microscopy (KPFM). These are based on long range electrostatic interactions between the AFM probe and the sample under the influence of an external electric field. A salient result of my initial work was the convincing demonstration of KPFM as a robust subsurface imaging technique. Prior to my efforts, KPFM was primarily used to generate surface potential maps. Now it is clear that KPFM can provide not only high-contrast subsurface mapping but also a quantitative depth profile of sample properties. I have also demonstrated an enhanced detection mode on KPFM that achieves high resolution subsurface imaging on a wide variety of embedded materials with different geometry and physical properties. As part of my research, I collaborated in a comparative study of KPFM with yet another quantitative subsurface technique based on the detection of local mechanical properties, known as contact-resonance AFM. This study lays out the advantages, limitations and disadvantages offered by each technique.

A quantitative interpretation of subsurface maps requires the implementation of numerical and computational methods. There is a lack of analytical solutions, due to the complexity of the geometry of the probe-sample system and sample heterogeneity. For this purpose, I have built a finite element model using Comsol Multiphysics, which mimics real experimental scenarios. This computational approach has become an indispensable tool for i) a deeper understanding of the physical principles behind the techniques, ii) a quantitative comparison between theoretical expectations and experiments and iii) a quantification of sample properties.

My final challenge as a graduate student is to develop a 3D non-destructive volume reconstruction technique (tomography). To be successful requires a clear understanding of the underlying mechanisms that contribute to the AFM sub-surface images. Secondly, the experimental observables (tip amplitude, frequency shift, etc.) need a quantitative interpretation. Lastly, a technique must be developed to generate a 3D representation with both spatial (x-y-z) and morphological information of subsurface features from a set of 2D maps. This requires the manipulation of experimental variables or conditions, for which there is not always an obvious procedure.

I am currently investigating a possible solution to this inverse problem. My proposed approach for 3D volume reconstruction involves the creation of a surrogate model based on numerical results obtained via parametric finite element computations and the acquisition of a set of experimental subsurface data. This non-destructive method can be used to estimate depth and size of the buried object, and in principle to estimate other relevant properties like stiffness or dielectric constant. So far, it has been validated using a fabricated calibration sample composed of nanoparticles (0D objects) buried under a thin polymer coating. The current state of the proposed model is still under evaluation.

Research goals

My ongoing research combines high-resolution subsurface imaging and quantitative 3D sample reconstruction, using dynamic AFM techniques and surrogate modeling. Imaging requires attention to relevant aspects such as spatial resolution, depth sensitivity, contrast enhancement, artifact identification and disentanglement of surface and subsurface information. 3D reconstruction is an inverse problem which requires a combination of computational modeling and large data processing.

I aim to make significant advances in the metrology needs at the micro and nanoscale. Without new developments, quantitative subsurface characterization and reconstruction using AFM-based approaches will not occur. I believe my work will have an impact on nanotechnology, especially with regard to the semiconductor industry in its race to reliable sub-10 nm designs and to the next generation of nanocomposites in materials science and engineering.