

Reference Materials to Enable Precise and Accurate Imaging with Electrical Scanning Probe Microscopes

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INTRODUCTION

Electrical scanning probe microscopes (eSPMs), such as the scanning Kelvin force microscope (SKFM), scanning capacitance microscope (SCM), or various scanning microwave microscopes (SMMs) are sensitive to the electric field between the sample and tip. Interpretation of measurements with these techniques can be confounded due to unknown tip shape and volume of interaction with the sample. Any two-terminal electrical measurement of electric field, capacitance, resistance, or inductance depends on the shape of the electrodes at each terminal. For simple one-dimensional metal-insulator capacitors, $C = \epsilon_0 \epsilon_i A / t_i$ where C is capacitance, ϵ_0 is the dielectric constant, ϵ_i the insulator dielectric constant, A is the device area, and t_i is the insulator thickness. For one-dimensional resistors, $R = \rho L / A$, where R is the resistance, ρ the material resistivity, and L the device length. Without knowing the device geometries, the material electrical properties (in these examples, ϵ_i and ρ) cannot be deduced regardless of how accurately the capacitance or resistance is measured. For complex electrode shapes varying in three dimensions, such as eSPMs, direct extraction of material properties is impossible without detailed information about the shape of the electrodes.

This work describes simulation, design and preliminary measurements of reference materials with precisely known geometries that will allow precisely calculable electric field gradients at a sub-micrometer scale to be generated. These structures have two intended uses: 1) as reference materials to determine the actual spatial resolution and accuracy of various eSPM techniques sensitive to electric field with different conductive tip technologies; and 2) as an electrical tip shape profiler. Electrical tip shape may vary significantly from physical tip shape. Knowledge of the electrical tip shape can then be fed back into image analysis software to improve the spatial resolution and accuracy of electric field measurements.

COMSOL MODEL OF ELECTRICAL SPMS

The COMSOL¹ MultiPhysics simulation software was used to simulate the electric field for candidate test structures. The COMSOL AC/DC Module combined with the RF Module allows simulation of high-frequency eSPMs such as SCM and SMM [1]. Many types of scanning probe microscope tips are integrated with conducting cantilevers and other conducting structures. For electrical measurements, all conducting parts of the probe assembly must be considered. We developed a complete COMSOL model of the SPM tip assembly to include the tip, the cantilever, the tilt of the cantilever with respect to the sample, and an arbitrary test structure (consisting of metal layers at defined bias voltages, ground planes, and dielectrics), Fig. 1. This model allows us to simulate the measured electrical potential between the defined test structure electrode and the defined probe electrode as a function of the terminal tip location.

¹Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the materials or equipment used are necessarily the best available for the purpose.

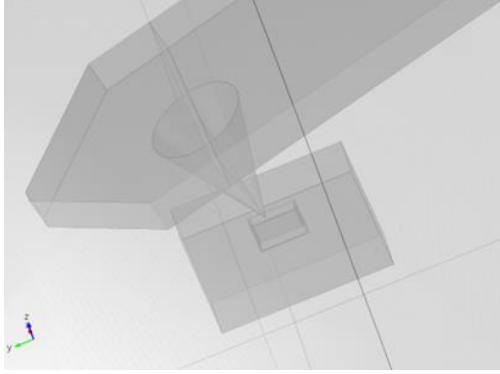


Figure 1: COMSOL generated image of the simulation geometry. A round base, conical tip (10 μm in height), the conductive cantilever, and a two-line test structure are shown.

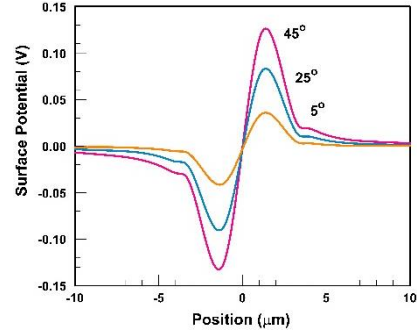


Figure 2: Simulated potential measurement across a test structure consisting of two lines, with the left line at negative potential and the right line at positive potential. The width of the response is related to the top cone width, while the slope of the response at the boundaries is inversely proportional to cone angle (5°, 25° or 45°).

A basic eSPM tip shape of a round cone is parameterized by the terminal tip radius, r_{tip} , the tip cone angle, Θ , the tip height (terminal tip to cantilever distance), h , and the top cone radius, r_{top} . For a perfect cone normal to the sample surface, the tip would be completely described by a single value of these four parameters (with $r_{\text{top}} = h \tan(\Theta)$). This model can be extended to simulate real eSPM tips that are not perfect cones (many are pyramidal), include some degree of asymmetry, and are used with their principle axis of symmetry tilted with respect to the sample surface. The physics of the tip-test structure interactions requires a dense mesh near the terminal tip, but also consideration of the long range contribution of all the parts of the test structure and the larger cantilever assemble. Many runs of the COMSOL model were require to determine a set of boundary conditions adequate to efficiently simulate the measurement while maintaining a realistic spatial domain and calculation time.

ELECTRICAL TIP PROFILER DESIGN STUDY

COMSOL simulations of the measured potential between a conical tip and simple test structures (generating an abrupt boundary in surface potential) revealed that both the cone angle and the top radius effect the measured surface potential in systematic ways, Fig. 2. The top radius broadens the measured response in direct proportion to the width of the tip as it crosses the boundary (Fig. 3a). Likewise, the slope of the response is inversely proportional to the cone angle at the point of maximum signal change (Fig. 3b). These results suggest a method of determining the tip parameters and asymmetry of an unknown tip from measurements on a test structure. If we consider the tip as an n-sided pyramid, with each side having an independent slope, then we can measure the width of the top of the pyramid and the slope of the side when that side cross the boundary in potential generated by the test structure. We suspect that most tips can be well characterized by four scans across the boundary with a 45° rotation between scans. While this approach will not be able to identify convex or concave tip sides, it will determine an equivalent tip shape (that is, the model tip parameters that produce a response equivalent to the tip under interrogation.) If the height of the tip is known by other methods, a complete equivalent tip shape can be determined and a figure of merit (measured field / actual field) for electrical profiling specified. The measured electrical tip parameters can then be used in a reverse model to deduce actual surface potential arising from structures whose geometry is not well known.

ELECTRIC FIELD MEASUREMENTS

The simulations have allowed us to design test structures capable of determining the electrical tip shape of eSPM tips. A simple biased line is sufficient if: 1) The line width is greater than the top radius of the tip, 2) regions beyond the active area are covered with a ground plane, and 3) spacing of the active region to the ground plane is kept small. From a practical viewpoint a square test structure is preferable. With his geometry, the desired four angles of attack can be acquired from two images, one with the cantilever sides orthogonal to the directions of scan and a second with the sample-cantilever geometry rotated by 45°. A series of designed square test structures using this approach are shown in Fig. 4. As a preliminary test of our model, we imaged a wide aluminum line [2] with SKFM using a Point Probe Plus conducting eSPM tip. These tips have a symmetric orientation (left-to-right across the cantilever) and an asymmetric orientation (front-to-back along the cantilever). Figure 5 shows two line scans

across the aluminum-to-oxide interface. When scanned with the symmetric tip profile parallel to the Al line, a symmetric contact potential difference response is obtained. When scanned with the asymmetric tip profile parallel to the Al line, an asymmetric response is obtained with the highly asymmetric side of the tip generating a kink in the CPD response as it passes over the Al-to-oxide interface.

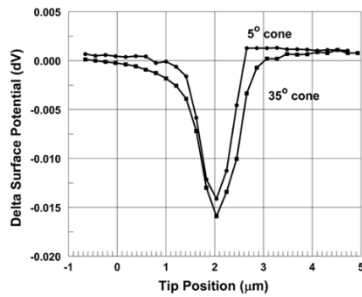


Figure 3a: Simulated potential measurement across a test structure consisting of a single biased line, surrounded by grounded planes on either side for conical tips with 5° and 35° cone angles. The broadening of the response provides a measurement of the tip cone radius.

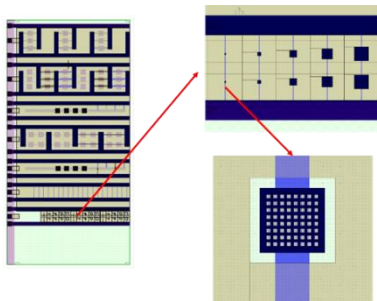


Figure 4: Section of test chip design with progressive enlargements showing the location of various sized 2-D electric tip profiler artefacts. Largest magnification shows buss structure, mid magnification shows different size 2D tip profilers, and highest magnification shows details of vias within a single profiler structure.

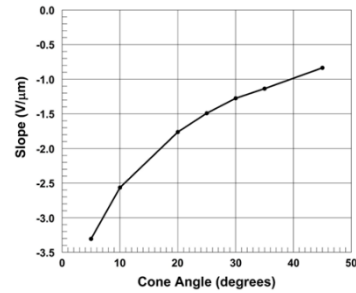


Figure 3b: Summary of the slopes at the boundary of simulated potential measurements across a test structure consisting of a single biased line, surrounded by grounded planes on either side for conical tips with cone angles of 5°, 10°, 20°, 30°, 35°, and 45°. Measured slope is proportional to cone angle.

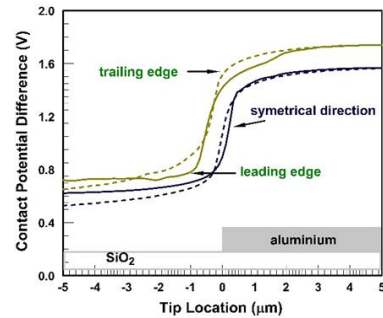


Figure 5: Measured surface potential across a biased metal line extracted from a SKFM image of a single metal line. The tip location data from the leading edge has been flipped and aligned with the trailing edge data for easier comparison. In the symmetric (purple lines) direction the tip (and the measured response) is broader. In the asymmetric direction, the response differs depending on whether the leading edge or trailing edge encounters the Al-to-SiO₂ boundary first. Symmetric data was offset for clarity.

CONCLUSIONS

In order to obtain accurate electric field based eSPM measurement results, or even to evaluate accuracy, it is necessary to have common calibration standards, ideally leading to SI traceability. COMSOL simulations show the electrical tip shape influences electric field based eSPM measurements in systematic ways. SKFM measurements with real tips on simple structures verify that such influences are real and can be experimentally measured. We have designed test structures that will amplify these effects and allow the tip electrical shape to be extracted.

REFERENCES

1. J. J. Kopanski, L. You, J. Li, J. Ahn, and Y. S. Obeng, ECS Transactions **72(2)**, pp. 131 -138 (May 2015).
2. L. You, J.J. Ahn, E. Hitz, J. Michelson, Y. Obeng, and J. J. Kopanski, Proc. 2015 IEEE Intl. Conf. Microelectronic Test Structures, pp. 235-239, Tempe, AZ (March 23-26, 2015).

KEYWORDS

Electric field measurement, scanning Kelvin force microscope, scanning probe tip profiler, reference materials