Electric Field Gradient Reference Material for Scanning Probe Microscopy

J. J. Kopanski, M. Fu[1], and L. You

National Institute of Standards and Technology
Nanoscale Device Characterization Division
Gaithersburg, MD 20899 USA

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 two-dimensional metal-insulator capacitors, $C = \varepsilon_0 \varepsilon_i A/t_i$ where C is capacitance, ε_o is the electric constant, ε_i the relative permittivity of the insulator, A is the device area, and t_i is the insulator thickness. For two-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, the accuracy of extracted material properties depends on having detailed information about the shape of the electrodes.

Any eSPM measurement of a spatially varying electric field at the surface of a sample has a large uncertainty due to the unknown details of the tip shape near the surface. We have designed an electric field gradient reference sample to provide an unambiguous known reference sample of transitions in electric field over small distances. Since all dimensions and materials of the reference sample are known, the electric field at the surface can be calculated precisely. This will allow the sources of error in the measured signal to be determined as a function of tip shape and measurement conditions. The reference also functions as a method of calibrating SKFM to improve its accuracy and to make calibrated measurements on unknowns.

E-GRAD REFERENCE MATERIAL DESIGN

We designed and built a test structure of 30 interdigitated buried metal lines that when biased will produce a stepped electric field across its length, Figure 1. Each set of three lines is connected to a polysilicon voltage divider that reduces the potential by a factor of 0.382 per stage. If the initial set of lines is biased at 10 V, voltages of 10 V, 3.820 V, 1.459 V, 552 mV, 213 mV, 81.3 mV, 31.1 mV, 11.9 mV, 4.53 mV, 1.73 mV, and 0.66 mV are produced down the structure. The interdigitated lines on the other side of the structure can be grounded, at a backing potential, or 180° out of phase with their opposing interdigitated lines. Structures with four line-to-spacing geometries were produced: 1.2 µm lines with 6.8 µm spacing, 3.2 µm lines with 4.8 µm spacing, 5.2 µm lines with 2.8 µm spacing, and 6.8 µm lines with 1.2 µm spacing. The lines are fabricated beneath an intermetal dielectric of approximately 1 µm thick. The region of the test structure with buried metal is covered by a metal cap that is exposed by the final bonding pad contact cut. This metal cap is removed post chip fabrication by etching.

[1] Mathew Fu contributed to this research as part of the NIST Summer Undergraduate Research Fellowship (SURF) program. He is currently an undergraduate student at Cornell University.

The SKFM typically produces images of the contact potential difference (CPD) between the conducting tip and a metallic surface. Our test structure has buried metal lines covered by a thin insulating layer. In this case, a contact potential cannot be defined as the oxide surface does not have a defined work function like a metal. This test structure effects the SKFM in two ways: through the geometrical capacitance between the metallic lines and metal tip which varies with probe height, z, and through the electrostatic force generated by the potential difference between the biased lines and the SKFM tip. The potential at the oxide surface from a voltage biased buried metal line will depend on the bias voltage, thickness of the insulating cover layer and its dielectric constant. When measured with SKFM this test structure will produce a force on the tip that is the product of the differential capacitance, dC/dz and the applied voltage, with the contact potential replaced by an effective CPD induced by the buried metal lines, Eqn. 1. Setting the amplitude, A, proportional to force F, we can separate the dC/dz component and the bias voltage component of the EFM response, Eqn. 2.

$$F = -\frac{dC}{dz}\left(V_{dc} - V_{CPD,eff}\right)V_{ac} \tag{1}$$

$$V_{CPD,eff} = \frac{A}{\left[-\frac{dC}{dz}V_{ac}G(\omega)\right]} + V_{dc} \tag{2}$$

Where *G(ω)* is the transfer function relating the force, *F*, and the resulting amplitude of oscillation, *A*. Detailed three dimensional simulations of the test structure are underway using COMSOL[2] MultiPhysics. Simulation will yield the expected electric field at the test structure surface and the potential difference measured with various tip shapes.

REMOTE BIAS ELECTROSTATIC FORCE MICROSCOPY

Biased, subsurface structures can be imaged with SKFM or electrostatic force microscopy (EFM) [1-2]. We found that the detection depth can be substantially improved, using a technique that we have dubbed remote bias induced EFM (RB-EFM). In RB-EFM, a set of synchronized ac with phase φ plus dc signals are sent to the adjacent sets of buried metal lines, instead of the cantilevered tip. An external ultra-high frequency lock-in amplifier (LIA) (Zürich Instrument, Zürich, Switzerland) was used to provide the excitation signals. To avoid interference with the atomic force microscope (AFM), the excitation near the cantilever second resonance was used. The amplitude and phase of the cantilever oscillation induced by the remote bias was measured from the AFM's position sensitive detector (PSD) signal fed back to the LIA as the input signal, using the frequency of the remote bias as the reference signal. One side of the interdigitated lines are biased in phase, while the other side is biased 180^{o} out of phase. This measurement scheme forces the tip oscillation to flip 180^{o} when scanned from one line to the next with an abrupt transition between the lines. Since for any line the adjacent lines are biased 180^{o} out of phase, the structure itself provides an active shield, allowing the effect of the central line on the cantilever to be isolated.

RESULTS

We report initial RB-EFM results here, obtained for a single set of lines biased at a series of discrete voltages (-5 V to +2 V), Figure 2. Each curve is an average of around 10 scans. The measured signal is proportional to the amplitude of cantilever vibration. The signal is forced to a minimum at the mid-point between adjacent lines by the change in phase in the driving signal between adjacent lines. As the dc bias on the lines is increased from -5 V to +2 V, the amplitude steadily decreases. Beyond +2 V, the signal reaches a minimum and begins increasing again with further increases in the dc bias. This is due to the effective contact potential difference induced by the buried metal lines. The RB-EFM response from the lines on the far ends of the test structure do not have a line biased 180^{o} out of phase on their far side, resulting in an enhanced response. Applying Eqn. 2, we can separate the dC/dz component (independent of dc bias), Fig. 3, and the effective CPD from the buried metal structures, Fig. 4. The dC/dz component is due only to the geometry of the metal lines and the SPM tip. The effective contact potential is inherently due to the

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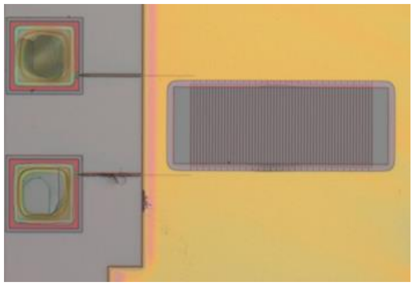
[2] Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the materials or equipment used are necessarily the best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

materials and any fixed charge of the buried structure. The applied dc bias affects the magnitude of the response. At the center of the line, the induced response scales linearly with the applied dc voltage.



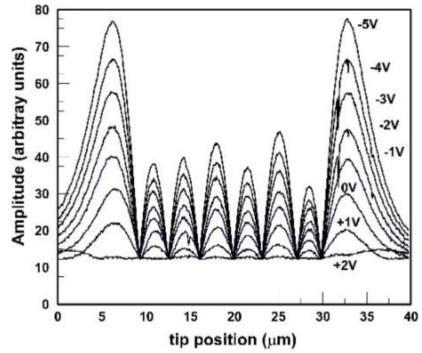
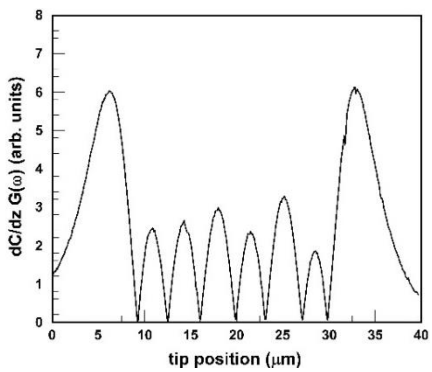


Figure 1: Photo micrograph of the prototype E-Grad Reference Structure. The area surrounding the active area is covered with a ground metal layer, hiding the voltage divider resistors from view.

Figure 2: RB-EFM amplitude measured for a single set of interdigitated lines at dc bias voltages increasing from -5 V to +2 V in 1 V steps.



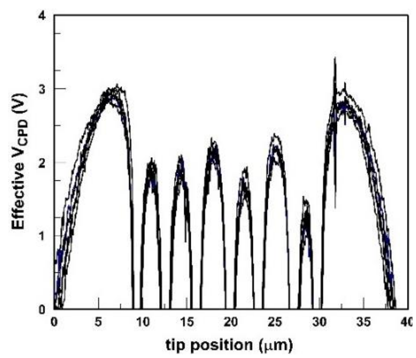


Figure 3: The geometrical component of the response (dC/dz), which depends on the tip to metal line capacitance only. Data is calculated by taking the slope of amplitude versus dc bias voltage at each tip position point from Fig. 2.

Figure 4: Effective contact potential difference at the test structure insulator surface due to the buried metal lines. Eight curves from each dc bias are plotted, approximately the same effective CPD is seen regardless of the dc bias.

CONCLUSIONS AND ONGOING WORK

We built and tested a candidate electric field gradient reference material. Preliminary measurements show that we can separate the geometrical effects due to dC/dz, the effects of the test structure materials and fixed charge as an effective contact potential, and the effects of applied dc bias voltages. Detailed measurements on the complete test structure with a variety of tips are underway. The width of the transition region will provide a measure of spatial resolution. By comparing the measured response for each tip to the expected electric field at the test structure surface, we can extract a figure of merit for a given tip geometry and measurement procedure.

REFERENCES

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2. J. J. Kopanski and L. You, Remote Bias Induced Electrostatic Force Microscopy for Enhanced Subsurface Imaging, in preparation.

KEYWORDS

Electric field, electrical scanning probe microscopy, eSPM, reference materials, standards for SPM.