Nanoelectronic Structural Information with Scanning Probe Microscopes

Joseph J. Kopanski, Lin You, Jung-Joon Ahn, and Yaw Obeng

Semiconductor and Dimensional Metrology Division, Physical Measurement Laboratory
National Institute of Standards and Technology (NIST)
Gaithersburg, MD 20899 USA
presenting authors email: joseph.kopanski@nist.gov

ABSTRACT

Scanning probe microscope (SPM) based methods to obtain subsurface structural information about nano-structured materials are described. A test structure chip containing structures to produce various surface electric field gradients, spatially varying capacitance structures, and surface magnetic field gradients is described. Buried metal lines with an applied potential from the test chip were imaged with scanning Kelvin force microscopy (SKFM). Buried metal lines that were electrically floating were imaged through their capacitance with the scanning microwave microscope (SMM). COMSOL Multiphysics simulations of the test structures and how they interact with the SPM tip are compared to the measured results. The paper concludes with a discussion of limitations and prospects for improved subsurface imaging with SPMs

Keywords: subsurface imaging, scanning microwave microscopy, SMM, scanning Kelvin force microscopy, SKFM

1 INTRODUCTION

Scanning probe microscopes (SPMs) have remarkable sensitivity to the surface. The atomic force microscope (AFM) can measure surface topography and the scanning tunneling microscope (STM) can interrogate the electrical density of states, both with atomic level accuracy. SPMs also have some ability to image sub-surface structures through the long range electromagnetic field. This paper describes the theoretical and practical basis for imaging metal lines buried beneath insulating layers and for imaging insulating regions or voids within metal using SPMs. Four techniques are discussed: scanning Kelvin force microscopy (SKFM) to image the potential of buried metal lines, scanning microwave microscopy (SMM) to image the capacitance of buried metal lines, magnetic force microscopy (MFM) to image the magnetic field from current carrying structures, and SMM to image voids in metals through the frequency dependence of the skin depth. A test chip, designed at NIST, and that contains buried structures to precisely produce electric potential and magnetic field variations at the surface to test the presumptions is described. COMSOL Multiphysics[1] simulations of the surface potential due to voltages applied to buried metal lines and RF simulations of reflected microwave signals from buried metal lines were conducted and are compared to some preliminary measurement results. The ability to obtain spatially resolved subsurface information with SPMs has multiple applications to electronics and nanotechnology. In integrated circuit technology, the back end of the line (BEOL) consists of all processes from the contacts to the transistors to the package and includes multiple levels of interconnect metallization and dielectric insulating layers. Likewise, emerging three-dimensional integrated circuits use complex interconnection schemes including through silicon vias (TSVs) filled with metal. The ability to detect electric and magnetic fields due to these buried conductors can be a powerful failure analysis diagnostic. The ability to non-destructively characterize buried interfaces of nanoelectronic devices and nano-structured materials could provide information that is not otherwise available.

2 NIST ELECTROMAGNETIC FIELD GRADIENT TEST STRUCTRUE CHIP

A key tool in developing and improving the subsurface imaging capabilities of SPMs is a target test chip that contains buried structures that can produce precisely calculable electric field and magnetic field distributions at the surface. We have designed and fabricated a test chip containing metal interconnect lines buried within an insulator at four discrete depths [1]. The buried metal lines can be biased to produce various patterns of electric or magnetic field that can be imaged at the surface with the appropriate SPM. The test chip has been designed so that the bonding pads are to one side, leaving clearance for the active regions to be probed with a cantilevered SPM probe. A printed circuit board allowing wire bonding to the test chip and electrical connection to the individual test devices has also been produced. By having a known potential

[1.] 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.

distribution we can evaluate the performance of different image modes. The test chip was fabricated by MOSIS using a 0.35 μm CMOS process from TSMC which includes four levels of metallization. Insulator and metal thicknesses were determined from imaging a polished cross-section in a scanning electron microscope.

The test chip contains eight variations of test patterns, some of which can be operated in both a potential and magnetic field mode. All structures contain variations of line width and combinations of metal 1 through metal 4. Test structures are connected between two 40-μm wide metal bus lines, separated by 80-μm, employing all four level of metal to produce a low resistance bus with very low loss along the bus. This ensures that structures along the bus all see essentially the same potential drop. Photos of a representative electric field test structure are shown in Figure 1a and magnetic field test structures in Figure 1b & 1c.

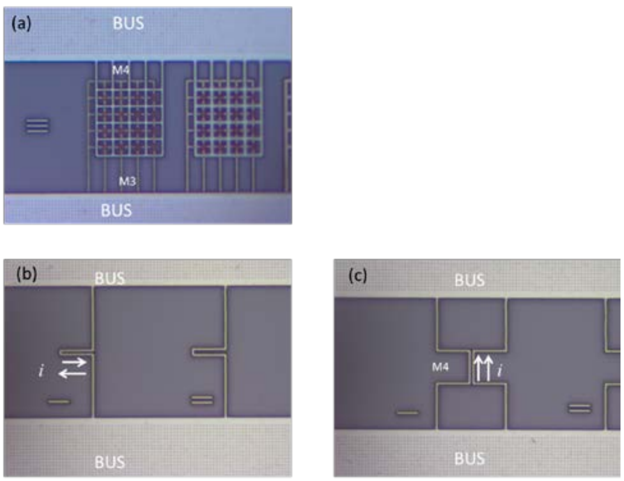

Figure 1 a) "Waffle" pattern electric field test pattern. b) Magnetic field test structure with opposing current flow. c) Magnetic field test structure with parallel current flow.

3 SCANNING KELVIN FORCE MICROSCOPY TO IMAGE BURIED POTENTIAL DISTRIBUTIONS

SKFM is an AFM based technique which uses an applied AC potential to induce oscillations of the cantilevered tip through capacitive forces [2]. A feedback loop is employed to null the oscillations and thereby provide a measure of tip-to-sample contact potential difference. If the work function of the tip is known, the work function or surface potential of the surface under examination can be deduced. SKFM should be able to produce subsurface images of biased buried metal lines from the potential at the surface of the insulator.

3.1 COMSOL Simulations

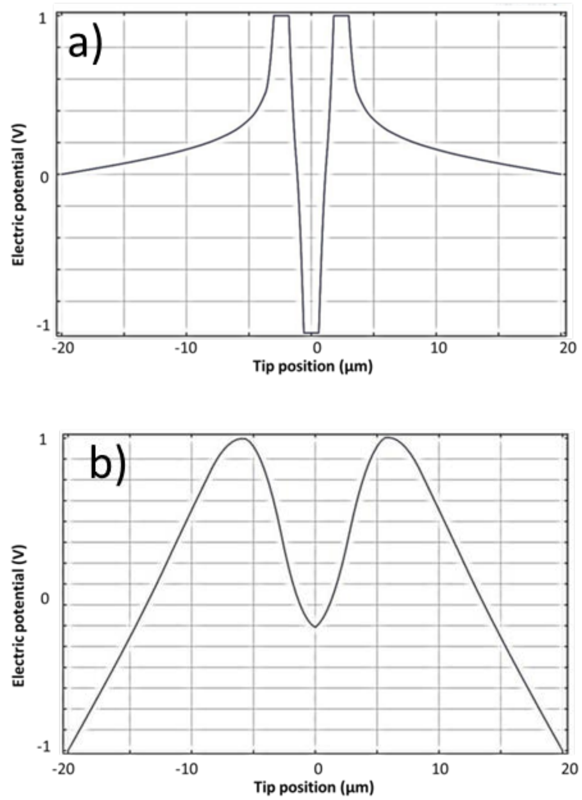

Figure 2: COMSOL simulation of the potential at the surface due to three metal lines, 1.2-μm in width, separated by 1.2 μm. The outer two lines are biased at +1 V and the inner line is biased at -1 V. a) metal lines on surface b) covered by an insulating layer 1.6 μm thick.

The surface potential distributions generated by various test structures from this chip have been simulated with the COMSOL Multiphysics software. Basic simulation geometry consists of three metal lines, 1.2-μm in width, separated by multiples of 1.2 μm. The lines are also separated and buried beneath an insulating layer (dielectric constant of 3.9) of varying thickness. COMSOL was utilized to simulate the potential at the surface of the insulator. This potential should be measurable with the scanning Kelvin force microscope. While quite sharp transitions in the surface potential are observed with an infinitely small test electrode, insertion of a probe with the shape of a real SKFM probe into the simulation substantially dampens the spatial resolution. The simulated conical tip has a 20 nm flat and a 15 degree cone angle. This result emphasizes the need for high aspect probes and advanced Kelvin force imaging to adequately resolve buried conductors within an insulating matrix. In Fig. 2a, the surface potential of these three metal lines on a planarized dielectric surface with the outer lines biased at +1 V and the middle line biased at -1 V is shown. The potential quickly reaches the applied value over the lines and the full 2 volts between lines is seen. In Fig. 2b, the lines are buried beneath an insulator of 1.6 μm thickness; the potential is smeared out relative to the no insulator case and the maximum difference in measurable potential is 0.6 V. COMSOL simulations show that lines buried beneath as much of 5 μm of silicon dioxide should still produce a surface potential of 5 mV when biased at 1 V, about the detection limit of amplitude-modulated SKFM.

3.2 SKFM Images of Buried Potential

Experimental results for a test structure similar to the simulation are shown in Fig. 3. Here we show the surface potential distribution on an area that has several parallel lines buried beneath the silicon dioxide. Here the lines are 2.4 μm wide and separated by 4.8 μm. The lines are covered by 600 nm of SiO_2 dielectric. Fig. 3(a) shows the AFM image of this area. Due to the manufacturing process, a residual 5 nm step can be found between the metal line buried areas and non-metal line buried areas. In 3(b), only slight surface potential contrast can be detected with SKFM. This confirms that all the metal lines are buried in SiO_2. Otherwise, a large potential contrast would be expected due to the significant electric properties difference between Al and SiO_2. In 3(c), the metal lines are alternatively biased with 1 V and -1 V. The additional electric fields vary the surface potential generating contrast nearly equal to the applied 2 V potential difference. Some potential leakage from the bus structures is also seen causing a small gradient in potential from the top to bottom of the image.

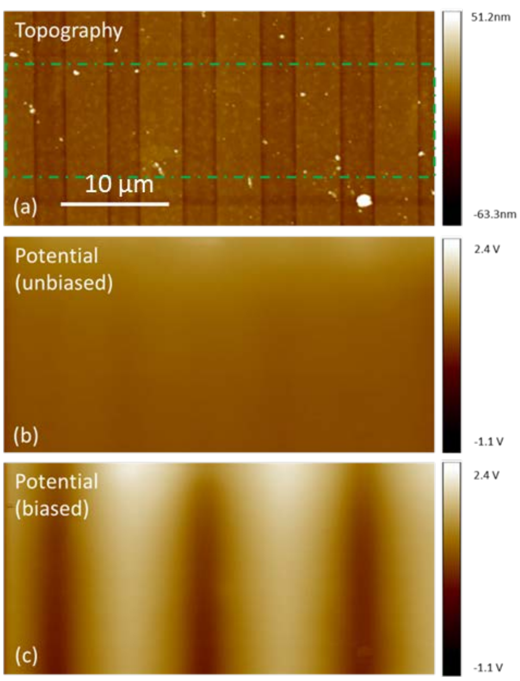

Figure 3 a) Surface topography of a set of buried metal lines beneath 600 nm of oxide. b) SKFM image of these buried metal lines without any applied bias. c) SKFM image of the lines with -1V and +1 V applied to every other line.

4 SCANNING MICROWAVE MICROSCOPY TO IMAGE BURIED CONDUCTIVE STRUCTURE

A new implementation of scanning microwave microscopy (SMM) has recently been introduced by Agilent (now Keysight Technologies). SMM measures the magnitude and phase of the S_{11} reflected high frequency signal (incident signal minus signal transmitted through the tip into the sample) through use of a vector network analyzer (VNA). The input to the VNA is a transmission line terminated by the tip-to-sample impedance. The terminal impedance will be some combination of frequency dependent resistances and capacitances. With additional electronics the SMM can also measure the dC/dV signal between the tip and sample. Through the capacitive coupling of the tip to conductive structures in an insulating matrix it should be possible to measure the dimensions and integrity of metallization within low-k dielectrics.

4.1 COMSOL Simulations

A simple model of the SMM, considers the cable connecting the tip and VNA as a transmission line with the tip and the underlying structure of the sample as the terminal impedance. A transmission line terminated by its characteristic impedance (50 Ω) will transmit the entire incoming signal (no reflection); while an open will reflect all the signal in-phase, and a short will reflect all the signal 180^o out of phase. Simply, an insulating substrate would be seen as a high terminal resistance, while a metallic substrate would be seen as a low resistance. Buried metallic structures, whether grounded or floating will contribute a capacitive component. Our buried test structures will produce a complex set of reflection parameters as a function of frequency, but we expect our buried metallic structures to increase the capacitance of the transmission line termination and thus be detectable in the phase of the signal reflected back to the VNA (relative to regions with no buried metal).

Imaging of electrically floating metal lines embedded within dielectric using the SMM utilizes a different physical mechanism than potential imaging with SKFM. To simulate this situation we used the high frequency module of COMSOL. A co-axial probe tip was used in the simulations terminated in a conical tip, similar in shape to the actual tip used in the SMM. Noise is due to the finite number of grid points used in the simulation. COMSOL simulations, Fig, 4 below, predict within a factor of two the observed contrast in the SMM.

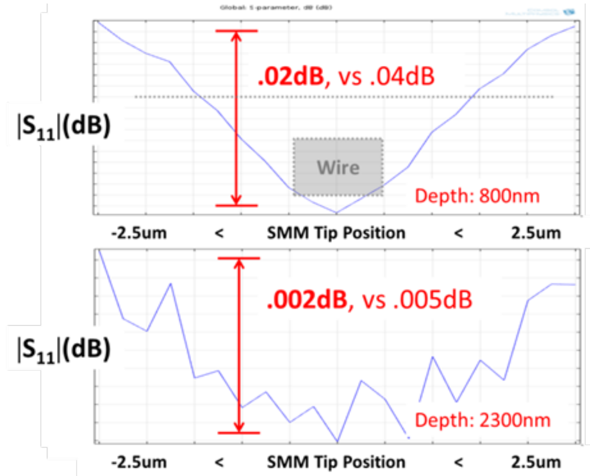

Figure 4: COMSOL simulation of the reflected SMM S_{11} signal due to an isolated metal line embedded within a dielectric. Here a 1-μm-wide line is simulated beneath either a) 800 nm or b) 2300 nm of dielectric. Simulated S_{11} is shown in bold and is compared to the actual measured S_{11}.

4.2 SMM Images of Buried Conductors

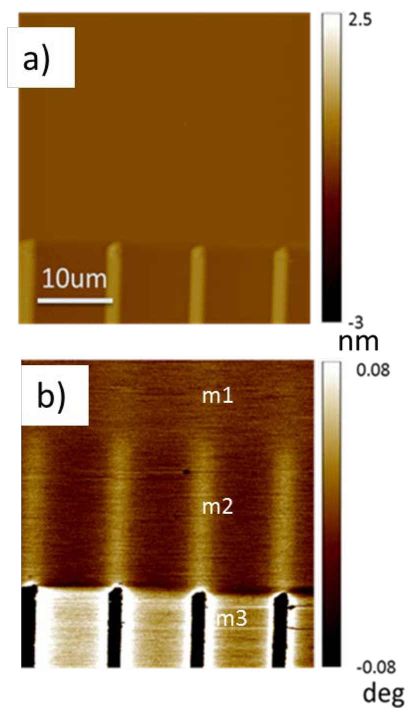

Figure 5 a) AFM topography image shows that M2 and M1 are totally buried within oxide and that there is no topography change above them. b) SMM phase images shows contrast from both the buried lines.

SMM images of electrically floating buried metal lines are shown in Fig. 5 [3-4]. In this structure, three metal lines at different depths are connected. The line at the bottom of the image is on the surface of the dielectric, the middle metal line is buried beneath 600 nm of dielectric, while the top metal line is buried beneath 2300 nm of dielectric. In Fig. 6a, the AFM measured topography shows the surface metal lines, but no contrast above the buried metal lines. In Fig. 6b, the SMM phase image shows the surface metal lines, but also detects the 600 nm deep lines and the 2300 nm deep lines.

5 OTHER SUBSURFACE IMAGING MODES

Two other modes of SPM with the potential to image subsurface structure are worth mentioning. Magnetic force microscopy, MFM, is capable of detecting the magnetic fields from currents in our buried metal test structures. A second distinct subsurface imaging mechanism for SMM utilizes the skin depth as a function of frequency [5]. Here images are acquired at different frequencies, with the primary component of the signal arising from a depth within the sample determined by the skin depth at that frequency. This technique should be able to detect buried voids within metals or composition variations within metallic structures. We are working to demonstrate subsurface imaging with both of these modes.

6 OUTLOOK

We have demonstrated subsurface image with SPMs using two distinct mechanisms: surface potential detection with SKFM and capacitance detection of electrically floating metal lines with SMM. Structures buried over 2 μm deep are detectable. Spatial resolution is limited by the tip aspect ratio with substantial signal generated from the tip side walls. We expected improvements in both sensitivity and spatial resolution as the SPM techniques are refined for the requirements of subsurface imaging and the availability of higher aspect ratio or co-axial tips. We expect SPM based subsurface imaging techniques to find increasing application to characterization of integrated circuits and nano-structured materials.

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