



Introduction to Scanning Microwave Microscopy

Application Note

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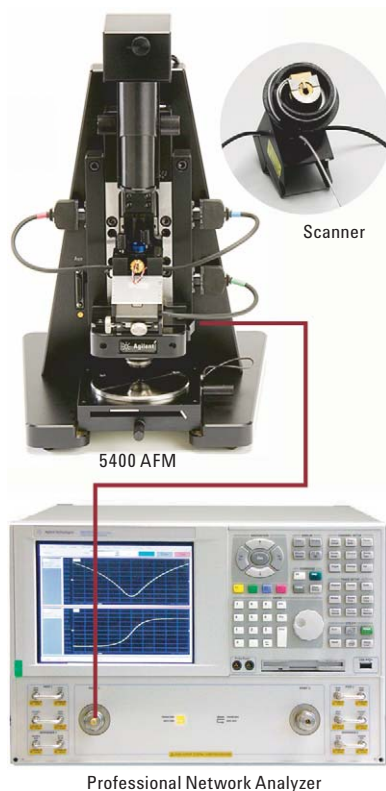


Figure 1. A scanning microwave microscope consists of an AFM interfaced with a professional network analyzer. Microwave is transmitted from the network analyzer through a matched resonant circuit to a conductive cantilever.

Introduction

Mapping materials physical properties, such as impedance, capacitance, dielectric constants, dopant density, etc., at the nanoscale is of great interest to both materials and semiconductor industries. Such mapping, however, usually is not as straightforward as topography imaging because, in many cases, these properties are related to buried structures not directly shown on the surface. It takes innovative approaches to “see through” and meanwhile achieve sufficient sensitivity and resolution.

With the invention of scanning tunneling microscopy (STM) and atomic force microscopy (AFM), a number of STM and AFM based techniques have been developed to probe materials properties. These include scanning near-field to scanning microwave microscopy (SMM), scanning capacitance microscopy (SCM), scanning spreading resistance microscopy (SSRM), electrostatic force microscopy (EFM), current-sensing (or conductive) AFM (CSAFM), and Kelvin force microscopy (KFM).¹ While each method carries its own pros and cons, SMM and SCM have shown most promising potentials in this field for both industrial applications and scientific research.

Using microwave as the medium, SMM measures electromagnetic interactions of the microwave from a sharp probe or aperture with the sample under test on a scale that is significantly less than the wavelength of the radiation.² STM or AFM based SMM typically uses a metal or metal-coated probe in-line with a coaxial resonator. Materials properties were obtained from the frequency shift and/or change of quality factor of the resonance.

The sensitivity and resolution, however, is very limited because of the small signal to background ratio.

AFM based scanning capacitance microscopy has been primarily applied to semiconductors, measuring two-dimensional dopant density.³ Operating at 915 MHz, commonly used SCM employs an RCA capacitance sensor that detects the capacitance-induced frequency shift. In fact, SCM measures changes of capacitance, rather than capacitance, caused by depletion of doped carries with a change of applied voltage, known as dC/dV, which correlates to the dopant density under certain conditions. This technique, however, is widely used in a qualitative manner for the lack of quantification process. Capacitance mapping is highly restricted due to the overwhelmed stray capacitance.

A new technique, scanning microwave microscopy or SMM, is introduced here. It integrates network analysis for microwave communications with high resolution AFM imaging. It is capable of mapping not only impedance, capacitance, dielectric constants of a variety of different materials, like what SMM does, but also dopant density of semiconductors like SCM. With a specially designed matched resonant circuit, its sensitivity and signal to noise ratio is significantly enhanced.

Setup

The scanning microwave microscope consists of an AFM⁴ interfaced with a vector network analyzer⁵, as shown in Figure 1. A microwave signal is sent directly from the network analyzer and

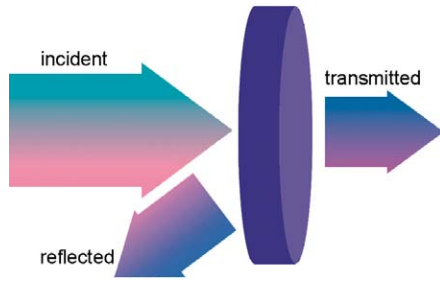


Figure 2. An optical analogy to microwave network analysis.

transmitted through a resonant circuit to a conductive AFM probe that is in contact with a sample being scanned. The probe also serves as a receiver to capture the reflected microwave from the contact point. By directly measuring the complex reflection coefficient from the network analyzer, known as S_{11} parameter, the impedance of the sample at each scanned point can be then mapped, simultaneously with the surface topography. A half a wavelength impedance transformer was placed directly across a 50Ω load to form a matched resonance circuit. Combined with enhanced peak detection, this circuit significantly increases the dynamic range and sensitivity of the impedance measurement. With a superimposed low-frequency modulation, changes of the capacitance as a result of depletion of carriers in a semiconductor sample, or dC/dV , can also be obtained at the same time with an ac mode controller containing digital lock-in amplifiers.

A new version of the PicoView software controls data acquisition of all channels, including topography from the AFM controller, amplitude and phase of the reflection coefficient from the network analyzer, and the dC/dV components from

the ac mode controller. The software saves all data in 32 bits, rather than 16 bits, widely used in other SPMs. That completely overcomes the limitations of data's dynamic range and resolution for extremely delicate measurements. With appropriate calibration standards, the system is capable of doing quantitative measurements on capacitance and dopant density.

Principle

Detailed theory of scanning microwave microscopy should consider both the electromagnetic interaction of the probe and the sample at the contact point and the transmission line theory for microwave network analysis. That is beyond the intended purpose of this article. A simplified picture can be understood using an optical analogy. As shown in Figure 2, when light strikes an object, some of the light is reflected from the object, and some passes through. By measuring the amount of light reflected and/or transmitted, optical properties of the object can be calculated. Applying the same principle for microwave of a few gigahertz, measurements of the incident and reflected, and/or transmitted waves can provide detailed information about the properties of the material under test.

The two-port professional network analyzer is capable of doing both reflection and transmission measurements. In the reflection mode (S_{11} measurement), the measured complex reflection coefficient Γ of the microwave from the contact point can be written as

$$\Gamma = \frac{V_{reflected}}{V_{incident}} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

where $V_{incident}$ and $V_{reflected}$ are the incident and reflected waves respectively, and Z_L and Z_0 are the impedance of the

sample under test and the characteristic impedance of the transmission line respectively. The maximum sensitivity of Γ is obtained at the resonance where the impedance of the sample under test matches the characteristic impedance, typically 50Ω . Near the resonance, the measured complex reflection coefficient directly correlates the impedance of the sample at the contact point. Small changes in the slightly mismatched impedance signal can be separated from the big background, resulting in a very high sensitivity. Under negligible variation of the resistance, the measured impedance signal then reflects changes of the capacitance of the sample at the contact point with appropriate phase offset. After calibration, the capacitance can be then obtained along with the surface topography.

Experiments

A few representative samples have been tried to test the capabilities of the scanning microwave microscope. All images were acquired in ambient. Both metallic Pt/Ir probes and Si cantilevers coated with Pt were used. The radius of curvature of the apex of those probes was typical 10 to 20 nm. Their nominal spring constants were estimated from 0.1 to 2 nN/nm.

Static random-access memory (SRAM) is commonly used to test the functionality of a scanning capacitance microscope. An SRAM unit cell consists of six metal-oxide-semiconductor field-effect transistors (MOSFETs or simply FETs) with four n-type FETs in a lightly doped p well and two p-type FETs in the next lightly doped n well. All dopant structures are under the top surface of an oxide layer.

Figure 3 is a typical SMM image of topography, capacitance, and dC/dV of an SRAM chip. Alternating p and n wells

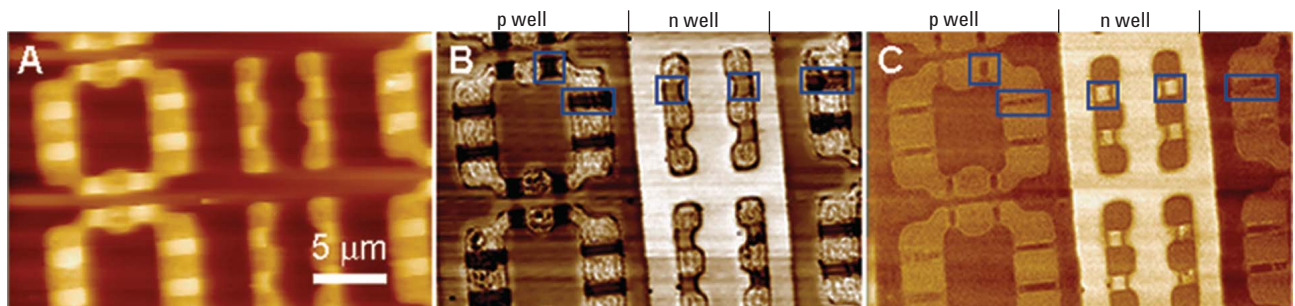


Figure 3. Simultaneous topography (A), capacitance (B), and dC/dV (C) images of an SRAM chip. Alternating lightly doped p and n wells are clearly identified in both capacitance and dC/dV images. Five of the six transistors in a unit cell are marked in B and C.

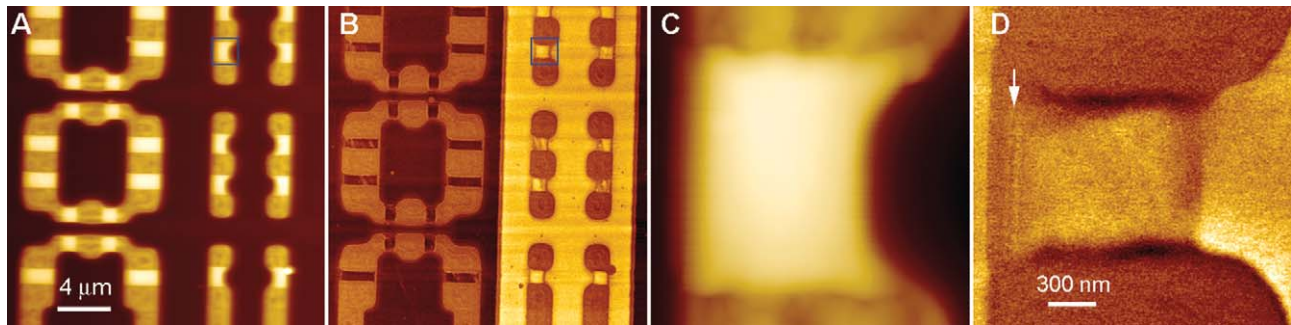


Figure 4. Topography (A and C) and dC/dV (B and D) images of SRAM. C and D are zoomed scans on one of the transistors in the n well marked in the blue square in A/B. A very fine line feature of 10 to 20 nm in width can be seen in the dC/dV image, as pointed in D, indicating high resolution capability of the scanning microwave microscope.

are clearly identified in both capacitance and dC/dV images with high contrast. For MOS structure, it is well understood that low dopant density results in a big change of capacitance at a fixed ac bias voltage, or high dC/dV.⁶ Five of the six transistors in a unit cell are marked in blue rectangles/squares. Most of the FETs in the p well demonstrated noticeable contrast on the capacitance image caused by the dielectric layer on the gates, as shown in Figure 3B. This characteristic of the gate dielectric capacitance was also observed on cross section images of MOSFETs using the SMM. The capacitance image of the FETs in the n well indicated that the dielectric layer on some of the gates had been damaged. The dC/dV image (Figure 3C), however, did not give any sign on the dielectric layer of the gates.

Figure 4 is another set of SRAM images intended to show the resolution of the microwave microscope. Zoomed scans on one of the n well transistors (blue marked in Figure 4A and B) are shown in Figure 4C (topography) and D (dC/dV). A very fine line feature in the range of 10 to 20 nm in width can be seen in the dC/dV image, as pointed in Figure 4D. The width matched

the approximate radius of curvature of the probe being used. This indicates that the scanning microwave microscope has the capability of achieving the resolution near the apex size of the AFM probe.

Dynamic random access memory (DRAM) stores each bit of data in a separate trench capacitor rather than a six-FET unit cell like SRAM. A DRAM chip was also imaged using the SMM. While the dC/dV image showed the ring structure of the dopant distribution on the side wall of a trench cell, consistent with previously published observations using an SCM, the capacitance image resolved a donut-shaped distribution in capacitance inside the wall of a trench cell.

SiGe based devices are relatively new compared to the pure Si based. They provide higher speed and performance. Figure 5 is a typical SMM image of a SiGe device containing a number of transistors. Both capacitance and dC/dV data clearly revealed the underneath dopant structures not shown in the topography image. Compared to Figure 5C (dC/dV), the capacitance image resolved some fine details inside broad dopant regions.

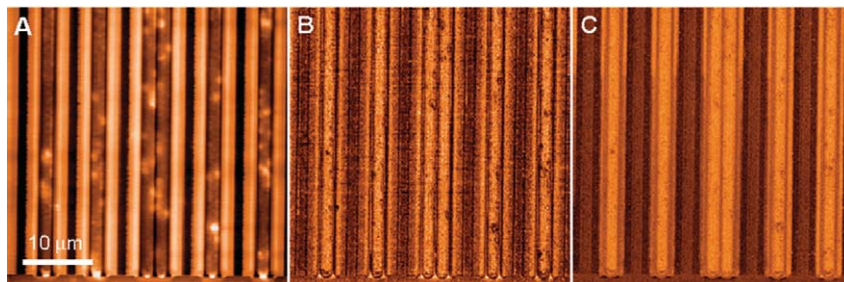


Figure 5 Simultaneous topography (A), capacitance (B), and dC/dV (C) images of a SiGe transistor device. Both capacitance and dC/dV images resolved the underneath dopant structures not seen in the topography.

Scanning microwave microscopy can be used not only on semiconductors, conductors, and dielectric materials to map capacitance, dopant density, and dielectric properties, but also on insulators and even biological samples to measure impedance. On insulators the complex reflection coefficient from the network analyzer reflects impedance variations at the contact point. Figure 6 shows such an example. The sample is made of dried bacteria cells of *geobacter sulfurreducens* on a gold substrate. The impedance data well correlated the features of the cells in the topography.

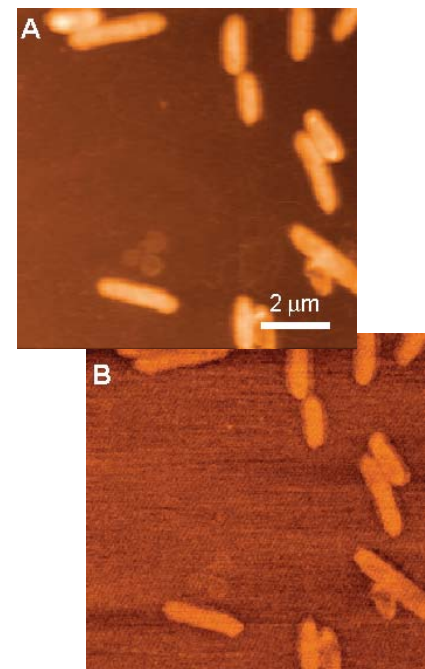


Figure 6 Topography (A) and the corresponding impedance (B) images of dried bacteria cells of *geobacter sulfurreducens* on a gold substrate. (Sample courtesy of N. Hansmeier, T. Chau, R. Ros, and S. Lindsay at Arizona State University.)

Conclusions

Scanning microwave microscopy is introduced. It combines sensitive impedance measurements from a vector network analyzer and a novel resonant circuit with high-resolution imaging of an AFM. It not only images impedance, capacitance, dielectric constants like what a traditional SMM does, but also measures different dopants for semiconductors like an SCM. It can be widely used on metals, semiconductor, dielectric materials, ferroelectric materials, insulators, and even biological materials to measure a variety of properties associated with slight variations in the electromagnetic interactions of different components of a sample with the incident microwave, statically or dynamically. Those properties can be under the surface not observable from the topography. As an introduction, preliminary data from a few representative samples have demonstrated that the scanning microwave microscope is capable of mapping materials properties at the resolution ultimately limited by the sharpness of the probe. More in-depth discussions and applications of this new technique can be found in future literatures.

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