Highly Sensitive Scanning Capacitance Microscope

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ABSTRACT

Emerging nanotechnology and biotechnology are in direct need of metrology tools with better than 10 –nm spatial resolution, capable of simultaneously measuring the topography and material properties of nano structures.

This paper describes a new approach for a Scanning Capacitance Microscope. The new instrument operates in the microwave frequencies range of 1.5 to 6 GHz in order to increase the measurement sensitivity over the existing solutions. We also employed a commercially available Vector Network Analyzer instrument (VNA) to achieve stable, repeatable and traceable measurements. The correlated SCM and AFM measurements are achieved through a sophisticated triggering to enable simultaneous and correlated characterization of the surface topography and material properties. We have solved the difficult and time consuming problem of SCM tip replacement, delivering the microwave stimulus to the tip, and shielding of the conductive cantilever through an innovative tip holder.

NANO SCALE CAPACITANCE MEASUREMENT CHALLENGES

The initial implementation of SCM was analogous to an STM in that the tip height was controlled by maintaining constant capacitance. The later generations of SCM have been based on an atomic force microscope (AFM) with a conductive tip; this provides a concurrent and essentially independent capacitance measurement. Figure1 shows a set up which is capable of concurrently measuring the topography and the capacitance of the SCM tip to the RF ground (i.e. corresponding to the dopant concentration) of a silicon chip. Up to now existing capacitance measurement apparati have been based on the RCA Video Disc capacitance sensor, and RF stimulus has been a UHF frequency at 915 MHZ coupled to detection circuitry through a resonant circuit. A highly tuned SCM employing the said architecture can detect a relative variation in capacitance in the range of 1E-18 F (atto-farad) around a total input capacitance of about 0.1 pF (pico-farad). The following are the short comings of that approach:

- Unrepeatable measurements.
- The conductive cantilever connection to the capacitance sensor is time consuming and labor intensive (i.e. silver paint).
- Difficult to develop a calibrated measurement.
- Lack of a robust RF shield to shield the conductive cantilever body to the sample causing stray capacitance.
- Lack of robust and repeatable RF ground.

We set out to mitigate these issues with a new approach that uses commercially available impedance measurement equipment.

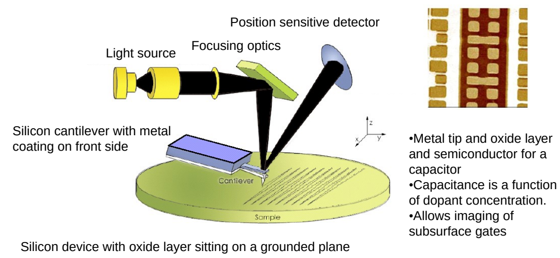

Figure 1: A typical SCM set up to measure silicon dopant profile.

VNA AS A MEASUERMENT ENGINE

Vector Network Analyzer (VNA) is used extensively to characterize RF and Microwave devices and networks. The VNA measurement science and calibration is well known and can be used as a key advantage for a repeatable and calibrated impedance measurement (i.e. capacitance).

VNA operates is two modes: Reflection Mode and Transmission mode. The reflection measurement mode is well suitable for measuring the tip\ sample capacitance to the ground, therefore it became the mode of measurement operation. Figure 2 shows the block diagram of the VNA in the reflection measurement mode. The operation of the VNA in a reflectometer mode can be summarized by referring to the figure 2.

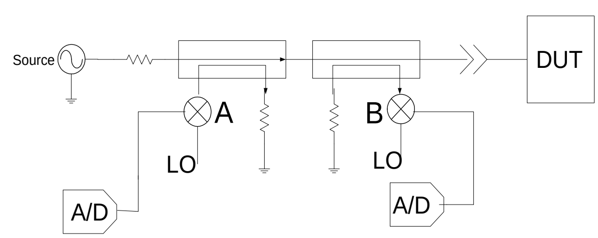

Figure 2: VNA in a Reflection Measurement Mode

Signals generated from the source travels down the transmission line as an incident wave. A small portion of the said incident wave couples through the first coupler and is down converted in the mixer A. This signal is digitized by the reference A/D converter (ADC) for further

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processing. The remaining incident waveform travels via the transmission line until it reaches the device under test (DUT). If the DUT impedance is that of the charactristic impedance of the transmission line (i.e. 50 ohms) the entire incident signal is absorbed by the DUT, therefore no reflection occurs. But if the DUT impedance is not the same as the impedance of the transmission line (i.e. 50 Ohms) some or the entire incident signal is reflected back toward the source. The said reflected signal is proportional to the impedance mismatch between the DUT and the charactristic impedance of the transmission line. If a reflection occurs, a portion of the said reflected signal couples through the second coupler and is down converted in the mixer B. This signal is digitized by the reflected wave A/D converter for further processing. The remaining reflected signal will reach the source and is absorbed by the source internal impedance, since this impedance is equal to the transmission line impedance (50 Ohms).The said digitized incident and reflected waveforms possess the information regarding the DUT impedance. This impedance (The SCM capacitance) can be extracted by means of the system DSP or processor using the well known calibration and measurement techniques.

VNA AS A SCM SENSOR

As explained previously a VNA in a refection coefficient mode can measure the impedance of a DUT, or in the case of the SCM the capacitance between the cantilever tip through the material under test to the RF ground. In a SCM measurement one starts from an initial capacitance that can be set by the operator; this could be at a set distance were the tip is above the sample, or where the tip and the sample are in contact. The size of the said capacitance is directly proportional to the size of the tip and inversely proportional to the distance between the tip and the ground. We set our design parameter to measure an initial capacitance of > 0.1 fF and capable of measuring 0.1 aF changes of the initial capacitance. This enables the use of 10 nm tip SCM cantilever.

Figure 3 shows a how a conductive cantilever tip is connected through a 50 Ohm transmission line to a VNA in reflection mode. S11 is the complex reflection coefficient and can be calculated by the following equation.

$$S_{11} = \frac{Z_L - Z_0}{Z_L + Z_0} \qquad \begin{array}{l} Z_L = \textit{load impedance} \\ Z_0 = \textit{source impedance} \end{array}$$

The magnitude of the reflection coefficient S11 is plotted in Figure 3. One can from the above equation and show that at extremely high and low impedances the magnitude of reflection coefficient approaches to unity and the sensitivity to the impedance changes drops dramatically figure 3 (graph flattens dramatically).

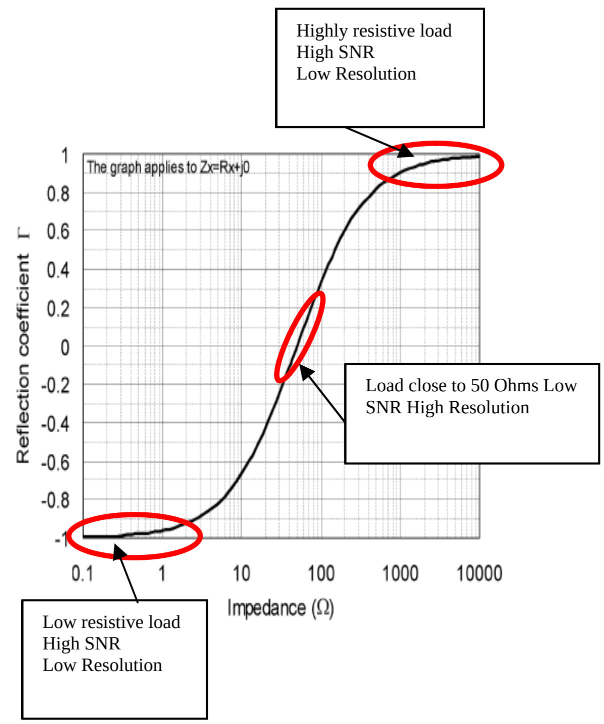

Figure 3: Magnitude of reflection coefficient verses the magnitude of the load impedance.

This dramatic decrease in the sensitivity and resolution makes it impossible to directly connect a conductive cantilever to a VNA and resolve the small changes in a small capacitor. For example the VNA can not distinguish between the load impedances of 10 and 20 pF in the reflectometer mode. The issue arises from the fact that the commercially available A/D converters have a limited resolution. For example a 14 bit ADC with a full range of 1 volt has 0.068836 mV of resolution and could only resolve the difference in refection coefficient between 300K and 400K Ohms. One can argue that with adding dither to the ADC and large averaging one can accomplish a very high resolution if a measurement is allowed to slow down drastically. Unfortunately the ADC non-linearity limits the potential resolution increase through dithering, Also one can not ignore the dramatic increase in the measurement time making the solution impractical. It is therefore impossible to measure the difference between 1 and 2 fF (change of 1 fF) because the difference in the magnitude of S11 is zero to 10 significant digits. Also the S11 phase difference between the 1 and 2 fF is 0.0551411703 degrees and is a very difficult measurement to perform. The design goal was to resolve capacitance changes of 0.1 aF which is a four orders of magnitude increase in sensitivity from the above example. In conclusion at the extreme load impedances (i.e. very small shunt capacitance) almost all of the incident waveform is reflected back to the source. SCM requires measuring a very small variation of a small capacitance; in the VNA reflectometer mode this translates to a small change of a large reflected signal, which is difficult to resolve with existing ADCs. Figure 4 shows the block diagram of a direct SCM measurement using a VNA.

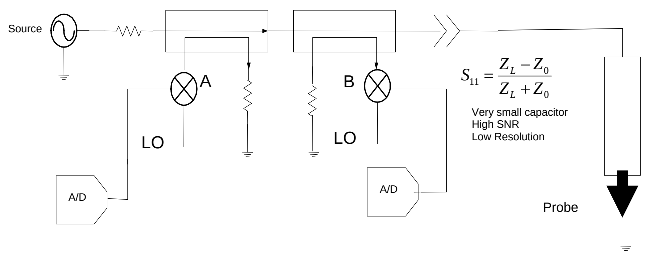

Figure 4: SCM cantilever is directly connected to the reflectometer

We have resolved the weakness of the ADC resolution by taking advantage of the VNA high sensitivity to the small changes of the reflected signal around the characteristic impedance (50 Ohm) shown in figure 3. We use a half wavelength impedance transformer to transfer the SCM capacitance and place it directly across an external 50 ohm load. Therefore the VNA in the reflectometer mode has the SCM capacitance in parallel with the 50 ohm load as a DUT. Since the SCM capacitance is very small the reflectometer operates very close to 50 ohm (matched) region of the measurement, where the sensitivity and resolution to the small changes of the impedance are high. This transformation physically transfers the electrical characteristics of the cantilever probe from the probe location (highly limited in physical volume) to a more manageable physical remote location. This allows space away from the immediate vicinity of the tip to design the electrical circuits to optimize the system performance. Figure 5 shows the block diagram of the transformed SCM tip in a VNA reflectometer mode.

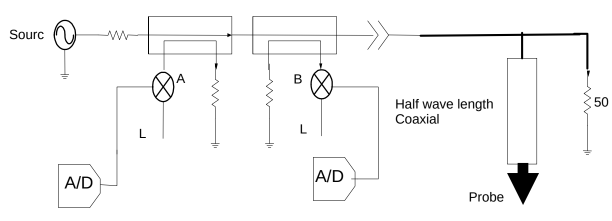

Figure 5: SCM probe transformation to 50 Ohm load.

We have modeled and simulated the said design using Agilent's ADS microwave simulator figure 6. This figure shows that the transformation of a highly reflective SCM probe of (10 fF) in combination with parallel 50 Ohm load generate a resonance structure. The VNA having the resonator as its load can resolve the minute changes in the SCM capacitance, since the changes of the said capacitance will shift the match and the resonance frequency of the resonator where the VNA is the most sensitive to the said changes. In the figure 6 the left graph is the smith chart and the right graph shows the return loss of the probe, half wavelength transformer and 50 ohm load combination.

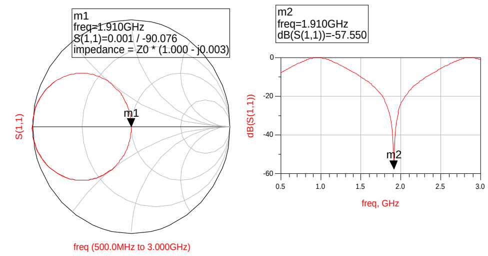

Figure 6: the simulation results of the transformer design

MECHANICAL DESIGN

A critical goal of the project was to deliver the microwave signal to the SCM cantilever such that it also solves the present difficulties of replacing the SCM tip. A microwave shield was added to SCM tip holder to shield the conductive body of the SCM cantilever from the surrounding environment. A robust and repeatable RF ground was added to help insure integrity and accuracy of the measurements. Also care was taken that the ground did not cause any measurable mechanical drag on the AFM scan. Figure 7 shows the mechanical implementation of the design.

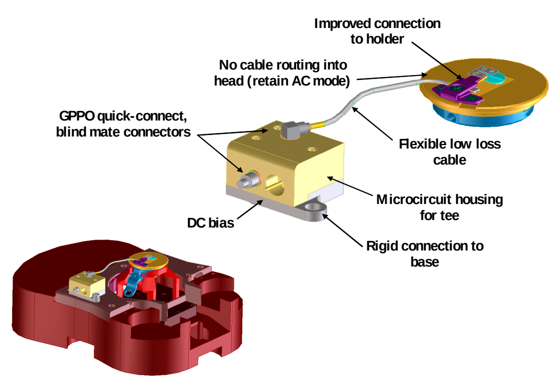

Figure 7: Mechanical design of the SCM cantilever holder and microwave matching network.

The measurement system employing Agilent VNA and Asylum Research AFM is shown in Figure 8. This clearly demonstrates the integration of two robust measurement systems capable of sensitive and repeatable SCM measurement.

Figure 8: The integrated SCM/AFM system

RESULTS

We scanned a SRAM with a metallization layer removed. The sample was lapped and fixed on a conductive substrate by means of silver paint. A concurrent AFM and SCM scan was preformed on the sample. The figure 9 shows the superimposed results of the AFM and SCM.

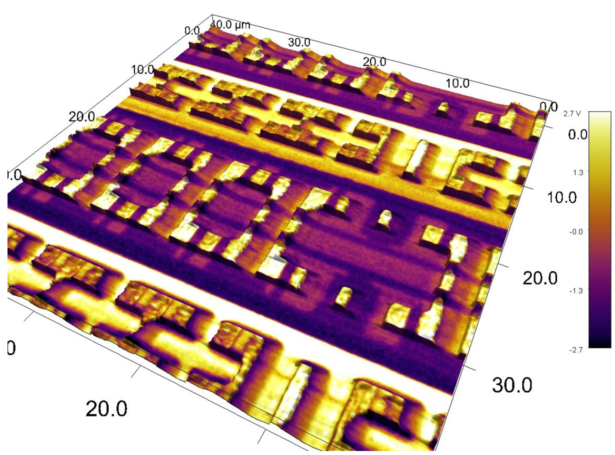

Figure 9: Superimposed AFM/SCM image of the SRAM

SUMMARY

We have developed a robust easy to use AFM/SCM platform. The platform is capable of sensitive, repeatable SCM measurement. The ease of use and the quick SCM tip replacement capability makes an ideal measurement system for scientist and engineers to use in the laboratories and the failure analysis settings.

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