Nanoscale electrical property evaluation using Scanning Microwave Microscopy (SMM)

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Abstract: Mapping electrical properties such as impedance, capacitance, dopant density, dielectric constants at the nanoscale is of great interest to both semiconductor and materials industries. Various measurement methods based on SPM technique have been developed to analyze the electrical properties. A new technique “Scanning Microwave Microscopy (SMM)” is introduced here. It integrates a network analyzer for microwave frequency communications with an AFM, and can do mapping of various electrical properties such as capacitance of sample surface. The sensitivity and quantification are enhanced by the use of electromagnetic wave of microwave frequency, and it is possible to measure not only dopant density like what SCM does but also impedance of dielectric materials and biological samples. In this paper, we show the principle of SMM, the advantages of custom solid metal probes as SMM standard probes, and SMM measurement results for failure analysis of SRAM and compound semiconductor.

Keywords: Scanning Microwave Microscopy, electrical property, dopant density, impedance, Scanning Capacitance Microscopy

1. Introduction

Scanning Capacitance Microscopy (SCM), Scanning Spread Resistance Microscopy (SSRM), Scanning Non-linear Dielectric Microscopy (SNDM), and Scanning Kelvin probe Force Microscopy (KFM) have been developed for electrical characterization at nanoscale based on Scanning Probe Microscopy (SPM). These technologies have been widely used for such applications as semiconductor devices. However, each technology has its advantages and disadvantages. Especially in the semiconductor field where downscaling is in progress, there are still many issues in terms of detection sensitivity, spatial resolution, quantitative performance, and stability. To solve such issues, Agilent Technologies, Inc. developed Scanning Microwave Microscopy (SMM) on the back of its established reputation in electronic and nanotechnology measurements.

2. System overview

As shown in Fig. 1, SMM consists of VNA: Vector Network Analyzer (Agilent Technologies, Inc. PNA Series) [1], AFM (Agilent Technologies, Inc. 5420 AFM/SPM) [2], and resonator (SMM Nosecone) including the probe. Electromagnetic waves of GHz order are sent from VNA to the conductive cantilever that is in contact with the sample surface via resonator circuit. This cantilever also functions as a receiver, and detects the reflected wave from the probe contact point. By measuring the Reflection Coefficient (S11 parameter) while scanning, SMM is capable of mapping the capacitance of the sample surface at the same time as acquiring topography. Since it can be combined with 5600 AFM/SPM, it can handle large samples such as 8-inch wafers [3].

Fig. 1, SMM system configuration
3. Features of the system
3.1 High resolution and quantitative performance

In analysis of physical property, network analyzers are used for various applications such as dielectric materials and semiconductors [4][5]. A high sensitivity to measure minute capacitance of aF (atto-farad) order is required when a network analyzer is combined with AFM for physical property analysis at nanoscale. While a network analyzer alone cannot achieve this, the measurement of minute capacitance can be achieved by the use of a resonator circuit that includes a probe called SMM Nosecone

S11 parameter is expressed by \((Z_L - Z_S)/(Z_L + Z_S)\). As shown in Fig. 2, the sensitivity is highest at around 50 Ohms [6] \((Z_L:\text{Impedance to be measured}, Z_S:\text{Characteristic impedance 50 Ohms})\).

However, the devices to be measured are not always at around 50 Ohms. Most of them have high impedance. As shown in Fig. 3, the impedance measurement of the entire range is realized by the resonator circuit which consists of the half wave-length coaxial resonator including the probe and of the parallelly-connected 50 Ohms resistor.

In addition, specially customized transmission lines enable even more resonance peaks. This not only increases the sensitivity substantially but also gives more freedom of frequency selection. The actual frequency sweep waveform is shown in Fig. 4.

![Fig. 4, Frequency sweep waveform (0.5 ~ 6 GHz)](image)

SMM specializes in minute capacitance measurements. Although capacitance measurements were only qualitative in the past, quantitative measurements of capacitance are made possible by the capacitance standard sample and the automatic calibration algorithm which Agilent is now developing in cooperation with NIST.

3.2 Dedicated Solid Metallic probe

SMM uses specially customized solid metallic probes (made of Pt) as standard, instead of metal coated probes that are generally used for electric measurements. While SMM is capable of measuring an absolute value of capacitance, the stray capacitance between sample and cantilever can be a significant cause of error. In order to reduce the impact of stray capacitance, the probe tip height is designed at about 100 um.

Since the probe is made entirely of Pt, the user does not need to worry about the abrasion of coating. Its lifetime is long, and the reproducibility is good.

3.3 Superior versatility

SMM is capable of measuring the capacitance of samples. In the case of semiconductor materials, it is possible to measure dC/dV.
simultaneously like the existing SCM by modifying the depletion region directly below the probe tip through application of AC voltage at the same time as microwave, thereby regarding it as capacitance. Fig. 5 shows the SRAM measurement data, Fig. 6 the SiGe device measurement data, and Fig. 7 the InGaP/GaAs hetero-junction bipolar transistor measurement data.

SMM can be used not only for semiconductor materials but also for ferroelectric materials such as PZT. In the case of ferroelectric materials, it is possible to perform SMM and Piezoresponse Force Microscopy (PFM) concurrently by scanning the sample while applying AC voltage like dC/dV measurements, thereby acquiring capacitance images and PFM images simultaneously. Fig. 8 shows the measurement data.

Fig. 8, Concurrent SMM + PFM of PZT thin film.

4. Application to semiconductor failure analysis

Lastly, SMM can be used for failure analysis of SRAM. Fig. 9 is an image of CCD optical microscope that is included in AFM. Fig. 10 is the measurement data of SMM. The capacitance image and dC/dV image clearly indicate that the 48th FET is defective.

Fig. 9, CCD optical microscope image of SRAM.
5. Conclusion

SMM is able to acquire capacitance images with high sensitivity and quantitative performance, while its performance in dopant density distribution measurements of semiconductors is comparable or superior to the existing SCM or SSRM. Furthermore, SMM can be applied to various analyses of physical property not only of semiconductors but also of dielectric, biological, and various other materials. In addition, SMM is expected to serve as the next generation tool for electrical characterization including the possibility of quantification by standard samples.

References