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De-embedding techniques for nanoscale characterization of semiconductors by scanning microwave microscopy

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ABSTRACT

The paper presents a methodology for de-embedding scanning microwave microscopy (SMM) measurements, mainly for semiconductor characterization. Analytical modeling, a parametric study and experimental verification are presented. The proposed methodology is based on the analysis of system response in the linear scale, instead of the dB scale commonly utilized in RF measurements, and on expressing the standard calibration capacitances per unit area. In this way the total measured capacitance is determined by the tip area which is then obtained as a result of the model fitting on the experimental data. Additional evaluation is performed by a straightforward experimental comparison with the usually adopted technique that is based on the electrostatic force microscopy approach curve method. The results obtained by the application of both techniques on the same tip during the same experiment were found to be in good agreement and moreover allowed a detailed discussion on the features of each one of the two methodologies. The paper provides also in this way useful knowledge for the potential users in order to choose the most appropriate technique according to the corresponding SMM application.

1. Introduction

Scanning microwave microscopy (SMM) is an experimental technique that aims to provide nanoscale level characterization and imaging offering simultaneously high resolution and high sensitivity measurements. This is achieved by applying a microwave signal, provided by a Vector Network Analyzer (VNA), to the device under investigation, through a tip [1–5]. In particular a relatively novel setup utilizes an Atomic Force Microscope (AFM) with a modified nosecone, using also a specially manufactured AFM/SMM tip, able to support microwave propagation up to its apex. The tip/sample system response on the incident microwave signal is also recorded by the VNA, providing in this way precise characterization arising from the combination of the VNA sensitivity with the AFM lateral resolution.

The demand for high sensitivity in SMM measurements is obtained by the proper matching of the high impedance tip/sample system with the VNA instrumentation requirements [6]. This can be achieved either by using an interferometric setup [7] or more commonly, as in the case presented below, implementing a shunt resistor and a resonator [8]. Both techniques demonstrated their ability to provide sub-fF sensitivity [7,8].

Regarding the lateral resolution of SMM, this is determined by the AFM tip apex dimensions and therefore is considered to be in the nanoscale. However besides that it should be noted that the accurate determination of the experimental lateral resolution of SMM measurements is not a trivial task. This is because in SMM beyond the contact point, there is also a microwave signal propagated through the tip. Accordingly the local tip/sample interaction may be determined, apart from the geometrical tip dimension, also by the presence of fringing fields around the edge of the tip. Moreover in most solid-state applications the AFM tip works in contact mode, therefore it is expected to gradually be deformed from its nominal shape. For these reasons the application of de-embedding methodologies on the experimental data is a critical step towards the enhancement of the SMM accuracy.

Up to date, SMM signals are mainly de-embedded based on the application of the electrostatic force microscopy (EFM) approach curve method [9]. Alternatively a new methodology recently demonstrated that, by using the dopant profile calibration procedure obtained by the correlation of the amplitude of S_{11} to the MOS system capacitance [10], de-embedding can also be achieved by modeling the SMM system response in the linear scale and implementing the concept of effective scanned area [11]; however beyond this preliminary study no further information is presently available in literature.

The present paper aims to present in details this new approach including the analytical modeling of the experimental setup with a parametric study. Also for the first time a straightforward experimental

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comparison between the two methodologies is presented. For this, both techniques have been applied within the same experiment, first on a new tip, and then on the same tip after purposely enlarged. Beyond these novel experimental data and based on the results extracted by the corresponding analysis, the features of each method are also discussed in details.

2. Background knowledge in brief

2.1. The EFM approach curve method

Estimation of the tip apex radius by the electrostatic force microscopy approach curve method is obtained [9] by fitting the capacitance acquired as a function of the tip to sample distance at a certain point. The total capacitance is considered to consist of three terms corresponding to the various parts of the cantilever, therefore

$$C = C_{apex} + C_{cone} + C_{Stray}. \quad (1)$$

The first term, C_{apex}, corresponds to the apex of the AFM tip and is given by

$$C_{apex} = 2\pi\varepsilon_0 r ln\left(\frac{h+\varepsilon_r z}{h+\varepsilon_r(r+z)-\varepsilon_r r sin\theta}\right). \quad (2)$$

The second comes from the contribution of the truncated cone part of the tip and is equal to

$$C_{cone} = \frac{2\pi\varepsilon_0}{\left(\ln\left(tan\frac{\theta}{2}\right)\right)^2}\left(z\ \ln\left(H\left(\frac{h}{\varepsilon_r}+z+r(1-\sin\theta)\right)^{-1}\right)\right. \\ \left. -\left(\frac{h}{\varepsilon_r}+r\left(1-\sin\theta^{-1}\right)\right)\ln\left(\varepsilon_r\left(\frac{h}{\varepsilon_r}+z+r(1-\sin\theta)\right)\right)\right). \quad (3)$$

The last term, C_{Stray}, from the cantilever can be defined as

$$C_{Stray} = c_{Stray} z + \text{const} \quad (4)$$

In the above equation r is the apex radius, H is the cone height, θ is the cone angle, z the tip to sample distance, h the dielectric thickness and ε_0 and ε_r the vacuum and dielectric permittivity respectively.

2.2. The MOS system capacitance

The methodology presented in the following section is based on the recording of the reflection coefficient for the microwave propagation, S_{11} on a silicon calibration sample with dopant profile. Such a sample is covered by native oxide and in contact with the metallic SMM tip on top, forms a Metal Oxide Semiconductor (MOS) capacitor. Therefore the standard capacitances used for the calibration procedure are based on the MOS system capacitance versus doping. For a MOS capacitor, working in the inversion regime the capacitance per unit area for the different doping levels can be quite accurately calculated by the following equation [12].

$$C_{MOS} = \frac{\varepsilon_{ox}}{d_{ox}+\frac{\varepsilon_{ox}}{\varepsilon_{sem}}W} \quad (5)$$

where W is the depletion layer width in inversion condition defined as

$$W = \sqrt{\frac{4\varepsilon_{sem}KTln\left(\frac{N_D}{n_i}\right)}{q^2 N_D}}. \quad (6)$$

In the above equations ε_{ox} and ε_{sem} are the oxide and silicon dielectric permittivity respectively, d_{ox} the oxide thickness, K the Boltzmann constant, T the absolute temperature, q the fundamental charge quantity and N_D and n_i the doping level and the intrinsic carrier concentration, respectively. Based on this the total capacitance can be defined as C = (area) × C_{MOS}.

3. The proposed methodology

The major features of the proposed methodology are two: expressing the standard capacitances per unit area and modeling the SMM setup using a circuital approach to analyze the system response in the linear scale, instead of the dB scale, commonly utilized in RF measurements. The total measured capacitance has been determined by the tip area. This is obtained by fitting the experimental results and therefore consists in an experimental estimation. The implementation of the linear scale for the assessment of S_{11} amplitude allows the straightforward extraction of important parameters from the experimental results as presented below, therefore it is an important step towards de-embedding. In contact mode, the SMM setup can be modeled using a circuital approach, in particular, for semiconductor samples, and for thin tips, where the tip/sample impedance is determined mainly by capacitive contribution. Under this condition the system is usually modeled as a properly terminated shunt capacitor (Fig. 1) [13,14]. Considering the quasi-static and localized nature of the dominant effects in the frequency range of 1–20 GHz, but also the design of the SMM setup, this aims to maintain the traveling of the waves through the different components by means of transmission lines, such an assumption can be adopted for our experimental procedure especially working at frequencies very close to the resonance frequencies (matched condition) provided by the λ/2 resonator, utilized to increase sensitivity.

Under these conditions, which represent the actual SMM operation, the reflection coefficient (expressed in the linear scale) measured by the VNA is

$$\Gamma = S_{11} = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{-i\omega CZ_0}{2+i\omega CZ_0} = -\frac{2i\omega CZ_0 + (\omega CZ_0)^2}{4+(\omega CZ_0)^2}. \quad (7)$$

So the reflection coefficient amplitude is expressed as

$$|S_{11}| = \sqrt{\left(-\frac{(\omega CZ_0)^2}{4+(\omega CZ_0)^2}\right)^2 + \left(-\frac{2\omega CZ_0}{4+(\omega CZ_0)^2}\right)^2}. \quad (8)$$

In the above equation Z_L and Z_0 are the load and characteristic impedance, in our case Z_0 is 50 Ω, C is the reflected capacitance and $\omega = 2\pi f$ with f being the SMM operation frequency.

The SMM capacitances formed by the nanometer scale tip and the semiconducting samples are in the order of fF or even less. Moreover SMM operates between 1 and 20 GHz, where the second order terms are expected to have minor contribution. Therefore, the amplitude of S_{11} is determined by the second term inside the square root of Eq. (8). In this case a linear relation between the measured amplitude and the reflective capacitance is expected. A parametric study presenting the relation between $|S_{11}|$ and C at different frequencies (under matched

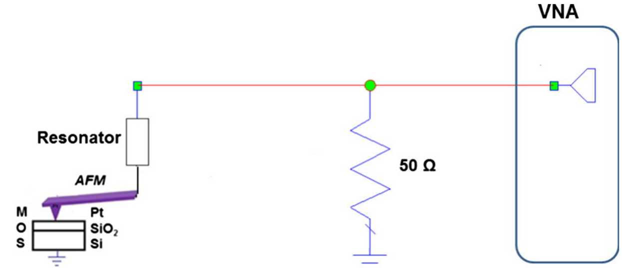

Fig. 1. Simplified schematic of the resistor/resonator SMM setup.