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Calibrated complex impedance and permittivity measurements with scanning microwave microscopy

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Abstract

We present a procedure for calibrated complex impedance measurements and dielectric quantification with scanning microwave microscopy. The calibration procedure works in situ directly on the substrate with the specimen of interest and does not require any specific calibration sample. In the workflow tip–sample approach curves are used to extract calibrated complex impedance values and to convert measured $S_{11}$ reflection signals into sample capacitance and resistance images. The dielectric constant of thin dielectric SiO$_2$ films were determined from the capacitance images and approach curves using appropriate electrical tip–sample models and the $\varepsilon_r$ value extracted at $f = 19.81$ GHz is in good agreement with the nominal value of $\varepsilon_r \sim 4$. The capacitive and resistive material properties of a doped Si semiconductor sample were studied at different doping densities and tip–sample bias voltages. Following a simple serial model the capacitance–voltage spectroscopy curves are clearly related to the semiconductor depletion zone while the resistivity is rising with falling dopant density from 20 $\Omega$ to 20 k$\Omega$.

The proposed procedure of calibrated complex impedance measurements is simple and fast and the accuracy of the results is not affected by varying stray capacitances. It works for nanoscale samples on either fully dielectric or highly conductive substrates at frequencies between 1 and 20 GHz.

Keywords: nanotechnology: calibration, complex impedance, dielectric constant, resistivity, scanning microwave microscopy

(Some figures may appear in colour only in the online journal)

1. Introduction

The advent of new nanoscale high speed materials and devices requires metrology tools enabling quantitative electrical characterization both at the nanoscale and at high frequency in the microwave range. Currently available electrical characterization techniques with nanoscale resolution include nanoscale impedance microscopy (NIM) [7–9, 13, 20, 22], electrostatic force microscopy (EFM) [1, 6, 11], scanning capacitance microscopy (SCM) [14, 19, 23], and scanning spreading resistance microscopy [4, 5] that usually operate only at low frequencies (below 1 GHz).

Scanning microwave microscopy (SMM) operates at high frequency in the GHz range and can detect the local changes of various materials properties like conductivity and dielectric constant. Different SMM designs like resonator SMM...
Figure 1. Schematics of the experimental set up, the calibration plane, and the calibration procedure. The conductive AFM-tip is connected to a vector network analyzer by a transmission line and impedance matching network (50 Ω shunt). The black box calibration procedure compares measured $S_{11}$ values with capacitance values measured at low frequencies by EFM during an approach curve in order to define the calibration parameters $\varepsilon_{00}$, $\varepsilon_{01}$, $\varepsilon_{11}$. From the approach curve also the tip geometry is extracted for the dielectric constant evaluation.

and transmission line SMM have been proposed [3]. The transmission line SMM we use in this work consists of an atomic force microscope (AFM) interfaced with a vector network analyzer (VNA) which covers a broad microwave frequency range of 1–20 GHz and enables the study of various material properties including calibrated capacitance [17], conductance [26], impedance [15], and dopant profiling [16]. The broad frequency coverage and selectivity of transmission line SMM gives it an advantage over the SCM that operates at a single frequency below 1 GHz and resonator SMM operating only at a fixed frequency determined by the geometry of the resonator cavity [18].

In order to obtain quantitative and reproducible measures of the intrinsic material properties a calibration of the SMM system is required. In the following we develop a systematic methodology to determine quantitative electrical properties of nanoscale samples from reflection $S_{11}$ measurements.

We first convert $S_{11}$ data into complex impedance data. Subsequently the impedance is used to determine quantitatively the dielectric constant at GHz frequencies. The calibration procedure works at every frequency between 1 and 20 GHz and takes into account the specific response of the VNA including connection cables and the specific geometry of the nanoscopic tip–sample system. Until today no such procedure is available that gives calibrated complex impedance and permittivity values in this frequency range. An additional advantage is that the calibration is done directly on the sample of interest without any need of a calibration sample.

The article is divided into the following sections: After the introduction in section 1 the experimental set up is detailed and the new calibration procedure that converts SMM $S_{11}$ data into capacitance and conductance is explained in section 2 for an oxide test sample. In section 3 the calibration is applied to SMM $S_{11}$ images resulting in calibrated capacitance and conductance images and the calibrated tip–sample capacitance is used to extract the intrinsic dielectric constant of silicon oxide. As another application the calibration is applied to a flat semiconductor dopant sample and capacitance–voltage spectroscopy curves are derived.

2. Experimental details

2.1. SMM set up

In the following we used a commercial transmission line SMM (Agilent Technologies, Chandler, USA) consisting of a standard 5600 atomic force microscope (AFM) interfaced with a 20 GHz vector network analyzer (VNA) both from Agilent. AFM tips made from solid platinum (Rocky Mountain Nanotechnology, USA) were used and measurements were carried out in dry atmosphere (RH < 5%). A sketch of the setup is shown in figure 1. The AFM-tip is used as a nanoscale imaging and microwave probe, enabling concurrent and correlated topography and microwave characterization of the material under test. The VNA measures the ratio of the incident and reflected signal at the tip, the so-called scattering $S_{11}$-parameter. The micrometric tip–sample system forms a low capacitance of a few fF (femto Farad), causing a high reflection coefficient and therefore loss of measurement resolution in the VNA. The matching of the transmission line and the measurement resolution has been remedied by a half-wavelength transformer connecting the conductive tip to a 50 Ω shunt resistor. This transforms the capacitance of the tip at the surface in parallel to the shunt 50 Ω resistor at the frequencies corresponding to the half wavelength of the transmission line [25]. For the length of the microwave cables used in our SMM good matching and therefore measurements with high S/N ratio can be obtained every ∼1 GHz. Since the admittance, $Y = G + j\omega C$, scales linearly with the frequency it is favorable for the S/N ratio to measure at high frequency.

2.2. Complex impedance calibration workflow

To convert the measured reflection coefficient $S_{11}$ into the complex impedance $Z = (Z = 1 / Y, Y = G + j\omega C, Y$ being the admittance, $G$ the conductance, $C$ the capacitance) we use the
one-port blackbox calibration that is an established method to calibrate the VNA and connection cables up to the device under test (DUT) [2, 15]. Here the DUT is the micrometric tip–sample system with the calibration plane located directly before the cantilever chip (see figure 1). For a given frequency the transfer function mapping the measured $S_{11}$ into the impedance plane is of the following form:

$$S_{11,m} = \varepsilon_{00} + \varepsilon_{01} S_{11,a}$$

(1)

$$S_{11,a} = \frac{Z_{in} - Z_{ref}}{Z_{in} + Z_{ref}}$$

(2)

where $Z_{ref} = 50 \, \Omega$ is the characteristic impedance of the VNA. The three complex parameters $\varepsilon_{00}$, $\varepsilon_{01}$, and $\varepsilon_{11}$ have to be determined with the measurement of three reference samples of known impedance. However, the electrical connection of three calibration standards at the place of the calibration plane (i.e. the AFM-tip) represents a technical challenge. The main reason is the stray capacitance from the AFM cantilever chip that leads to a varying signal and thus to an undefined calibration plane. The variable stray capacitance depends on the tip–sample distance and the macroscopic sample geometry. Thus, by exchanging between a calibration sample and the DUT the stray capacitance is not constant and the calibration is not valid and accurate anymore.

The approach we present here is to calibrate the system directly on the DUT by performing $S_{11}$-approach curves onto a bare and highly doped Si++ substrate shown in figure 2. The amplitude and phase of the $S_{11}$ signal is measured versus the tip–sample distance $z$ at a given frequency (here $f = 19.79 \, \text{GHz}$) (figures 2(a) and (b)). For metallic or dielectric substrates (i.e. non-lossy materials) the change in impedance is only capacitive and can be simultaneously measured at low frequency ($\omega = 2\pi f = 1.5 \, \text{kHz}$) by electrostatic force microscopy (EFM). In EFM the electrostatic force is detected at the second harmonic of the excitation potential $v(t) = V_0 \cos(\omega t)$ applied between tip and substrate. The relation between the electrostatic force, $F_{es}$, and the tip–sample capacitance, $C$, reads [10]:

$$F_{es} = \frac{1}{4} \frac{dC}{dz} V_0^2 \cos(2\omega t).$$

(3)

The electrostatic force can be converted into the voltage normalized force $dC/dz = 2F_{es,2\omega}/V_0^2$ that corresponds to the capacitance gradient with respect to the tip–sample distance, $z$, as shown in the inset of figure 2(e). Integrating this curve gives the desired tip–sample capacitance, $C(z)$ shown in figure 2(e), and the impedance $Z_{in}(z)^{-1} = Y(z) = i2\pi f C(z)$, respectively. Note that the $dC/dz$-curves have to be adjusted by a small offset to account for the stray capacitance from a part of the cantilever and chip that in contrast to SMM is not detected by EFM. Thus, by acquiring simultaneously EFM and $S_{11}$ approach curves we provide the defined calibration standards $Z_{in}(z)$ to calculate the complex parameters $\varepsilon_{00}$, $\varepsilon_{01}$, and $\varepsilon_{11}$. This is finally done by applying an optimization algorithm using equations (1) and (2) and the approach curves $S_{11,m}(z)$ and $Z_{in}(z)$ as input data.

The resulting calibrated conductance ($G$) and capacitance ($C$) curves obtained with the determined $\varepsilon$-parameters are shown in figures 2(d) and (e). Note that we plot the difference of $\Delta G$ and $\Delta C$ with respect to the value at a distance of $z = 800 \, \text{nm}$ in order to get rid of the stray capacitance offset.

Figure 2. Complex impedance calibration routine. Approach curves onto highly doped Si++ (black) and a 105 nm thick SiO$_2$ film (red): (a) $\Delta S_{11}$ amplitude; (b) $\Delta S_{11}$ phase; (c) complex $S_{11}$ plane; (d) conductance $\Delta G$ after blackbox calibration; (e) calibrated capacitance $\Delta C$ with integrated capacitance (blue); (f) calibrated admittance $Y$ in the complex plane. Insets in (a) shows the topography of the sample, in (e) the low-frequency $dC/dz$-EFM-curve. (Used tip 25Pt300B-RMN, measurement frequency $f_1 = 19.79 \, \text{GHz}$.)
The $\Delta G$-signal is nearly constant throughout the whole approach curve for both Si$^{++}$ and SiO$_2$ (figure 2(d)). While for Si$^{++}$ this is expected as it is set to zero in the calibration routine, the conductance is also zero for SiO$_2$ as it should be for a low loss material. In contrast to the conductance, the capacitance (figure 2(e)) rises linearly with the distance which can be attributed to contributions from the cantilever and the upper tip cone, as previously demonstrated using low-frequency scanning capacitance microscopy [7, 8, 13].

In figure 2(e), at close proximity to the sample surface the tip apex starts to sense the local electrical properties of the sample and the capacitance shows a nonlinear dependence with distance. The capacitance difference between the approach curves on Si and SiO$_2$ can be clearly observed in the contact region at $z = 0$ nm (400 aF for Si and 230 aF for SiO$_2$). In figures 2(c) and (f) the raw $S_{11}$ data and the calibrated admittance ($Y$) approach curves are visualized in the complex plane, respectively. In the raw reflection $S_{11}$ data the approach curves are oriented both in the real and imaginary part of $S_{11}$, while in the calibrated $Y$ plane the curves are oriented vertically and show only capacitive contributions and no variation in conductivity as expected from this sample. While thermal drift and changes in the lateral position can cause an offset in the raw $S_{11}$ data, the calibrated admittance difference data remains the same which indicates that the calibration remains valid even when the stray contribution varies.

3. Results and discussion

3.1. Capacitance and conductance imaging

Once the system has been calibrated with the approach curves the $S_{11}$-images can be converted into capacitance and conductance images. In figure 3 the raw $S_{11}$ amplitude and phase images of the Si$^{++}$/SiO$_2$ sample are shown as well as the calibrated conductance and capacitance images. As expected, the conductivity image does almost not show any contrast and the small difference is overwhelmed by the measurement noise as can be seen in the inset of figure 3(c).

But the capacitance image shows the same contrast (~200 aF) between Si$^{++}$ and SiO$_2$ as obtained from the approach curves in figure 2.

The $S_{11}$ images in figure 3 were acquired at two different frequencies (upper part $f_1 = 19.79$ GHz and lower part $f_2 = 19.90$ GHz) resulting in clearly different signals in the $S_{11}$ amplitude and phase images.

However, after calibration with two approach curves at $f_1$ and $f_2$ the capacitance image and conductance image give the same result (figures 3(c) and (d)) what verifies that the calibration procedure is consistent at different frequencies.

At this stage the calibrated images still contain nonlocal stray capacitance signals from the cantilever and the chip which vary linearly with the topography height, as explained elsewhere [7, 8, 13].

This topography crosstalk has been subtracted in each pixel by taking the slope from the capacitance approach curve far from contact (0.06 aF nm$^{-1}$) and multiplying it with the height as deducted from the topography image. Figure 4 shows the calibration results using a different sample of a thin SiO$_2$ staircase structure on a highly doped Si$^{++}$ substrate with a resistivity of 0.001–0.005 $\Omega$ cm. As obtained from the topography image (figure 4(a)) the height of the oxide stairs is $h = 26, 38, 48$ and 63 nm.

The $S_{11}$ amplitude and phase images (figures 4(b) and (c)) resolve the different oxide steps very well as can be also seen on the corresponding cross-section profiles.

Following the calibration workflow a single approach curve was acquired on the highly doped Si$^{++}$ and the conductance and capacitance images were calculated from the $S_{11}$ amplitude and phase images (figures 4(d) and (e)). The conductance image shows nearly no contrast as expected, whereas the capacitance image gives a clear contrast of ~22 aF for the first $\Delta h = 26$ nm stair and ~5 aF for the last $\Delta h = 15$ nm stair. The capacitances are already corrected for the step height.

3.2. Dielectric quantification

To extract the dielectric constant from the capacitance measurements an accurate approximation is necessary that takes also into account the nanoscopic AFM-tip geometry as previously described and verified using low-frequency capacitance microscopy [8, 13]. The AFM-tip over the thin dielectric film can be modeled as a truncated cone with spherical apex and cantilever. Each part of the tip contributes to the total
capacitance, but only the apex [8, 13] and cone [12] are sensitive to the local dielectric properties of the sample as shown in the following equations:

\[ C(R, \theta, H, c, c_{\text{stray}}, z, h, \varepsilon_r) = C_{\text{apex}} + C_{\text{cone}} + C_{\text{stray}} \] (4)

\[ C_{\text{apex}} = \frac{2\pi \varepsilon_r R}{(\log(\tan(\theta/2))^2) \log \frac{h + \varepsilon_r z}{R}} \] (5)

\[ C_{\text{cone}} = \frac{2\pi \varepsilon_r}{(\log(\tan(\theta/2))^2) \theta} \left( \frac{z \log \left( H \left( \frac{h}{\varepsilon_r} + z + R(1 - \sin \theta) \right) \right)}{\varepsilon_r} + \frac{1}{\varepsilon_r} \left( \frac{H}{\varepsilon_r} + R(1 - \sin \theta) \right) \right) \] (6)

\[ C_{\text{stray}} = c_{\text{stray}} + c \] (7)

where \( R \) is the apex radius, \( \theta \) the cone aperture angle, \( H \) the cone height and \( h \) and \( \varepsilon_r \) the thickness and dielectric constant of the thin film, respectively. The dielectric constant of the oxide can be determined either by acquiring \( S_{11} \) approach curves on the oxide staircase structure or directly from the \( S_{11} \) contact mode images in figure 4. In both cases the first step is to determine the tip geometry by acquiring an approach curve on the highly doped Si\textsuperscript{++} with a native oxide of \( h = 2 \) nm and \( \varepsilon_r = 4.3 \).

By fitting equation (4) to the Si\textsuperscript{++} approach curve we can determine the parameters \( R, \theta \) and \( H \) defining the overall tip geometry. Since the effect of the cone height and the cone angle is small we set it to the manufacturer nominal values of \( H = 80 \) nm and \( \theta = 10^\circ \). The only free fitting parameters are then the tip radius and the slope of the stray capacitance, resulting in \( R = [154 \pm 3] \) nm and \( C_{\text{stray}} = 0.03 \) aF nm\(^{-1} \) (cf figure 5).

In the first method we use the \( S_{11} \) approach curves on the various oxide steps to determine the dielectric constant (figure 5). The curves on the oxide steps were fitted with the tip radius extracted on the Si\textsuperscript{++} leaving the dielectric constant as the only free fit parameter. The dielectric constants were determined separately for each oxide step in order to investigate the accuracy of the method. While we expect the same nominal value of \( \varepsilon_r \approx 4 \) for each SiO\(_2\) step the resulting dielectric constants are \( \varepsilon_{r,26} = 3.9 \pm 0.2, \varepsilon_{r,36} = 4.3 \pm 0.4, \varepsilon_{r,48} = 6.6 \pm 0.9 \) and \( \varepsilon_{r,63} = 4.7 \pm 0.4 \) with a mean value of \( \varepsilon_r = 4.8 \pm 1.2 \). The extracted values are in relatively good agreement with the nominal value, however, they show some variability for the different oxide steps what might be related to the fact that we just perform a single point measurement in which local sample contamination, non-homogeneities and also noise/drift can influence the results.

In the second method we extract the dielectric constant of the oxide directly from the calibrated capacitance image (figure 5, inset). One of the advantages of SMM with respect to force sensing techniques like EFM is that it can measure the capacitance directly in contact with the sample (e.g. in contact mode or intermediate contact mode imaging). As one can see in figure 5 when measuring in contact (\( z = 0 \) nm e.g. for the black Si\textsuperscript{++} curve) the \( S_{11} \) capacitance signals (e.g. 80 aF) are significantly larger compared to the situation when the tip is lifted from the surface (e.g. 20 aF at \( z = 50 \) nm). Thus, also a larger signal difference is observed for the oxide steps making the extraction of capacitance and dielectric values more precise from contact mode images then from approach curves.
In the capacitance image the effect of the stray capacitance was very small as can be seen by the corrected profile (figure 5, inset, red line). The capacitance differences were calculated according to $\Delta C = C(h, s_1) - C(h = 2 \text{ nm}, s_4 = 4)$ what represents the difference with respect to the highly doped Si$^{++}$ with a thin native oxide layer. To increase precision a $\Delta C$ average was calculated for every oxide height shown in the profile of figure 5. Using equation (4) and the tip geometry extracted from the approach curve on Si$^{++}$ ($R = 154 \text{ nm}$, $\theta = 10^\circ$, $H = 80 \mu \text{m}$) the dielectric constants were calculated on the different oxide steps resulting in $\varepsilon_{1,26} = 4.0$, $\varepsilon_{1,36} = 4.1$, $\varepsilon_{4,48} = 3.5$ and $\varepsilon_{6,63} = 3.1$ with a mean value of $\varepsilon_i = 3.7 \pm 0.5$. The mean value is again in good agreement to the nominal SiO$_2$ value with a smaller standard deviation compared to the results from the approach curves. The main advantage of deriving the dielectric constant from the $S_{11}$ capacitance image is that several image points that are supposed to have the same dielectric constant can be averaged. The method is more precise on the images and the overall accuracy we obtain for extracting the dielectric constant is $\sim 20\%$.

### 3.3. Conductivity and capacitance of semiconductors

Doped semiconductor samples were used to check whether the proposed workflow can capture both a change in the sample resistivity as well as capacitance. Figure 6 shows measurements done on the cross-section of a flat Si-sample with differently doped areas (IMEC, Belgium). In contact mode imaging the tip-sample system forms a metal–oxide–semiconductor (MOS) interface where the electrical properties vary with respect to the different dopant densities. The tip–sample impedance can be either represented as parallel combination of capacitance and conductance as it has been done for all the measurements presented so far or, what is more instructive for this configuration, a series combination (figure 6, sketch). The raw $S_{11}$ images were converted for both equivalent circuits resulting in serial and parallel capacitance and conductance/resistance images. For the calibration the approach curve was taken on the area with the highest dopant density. As expected, both series and parallel capacitance images show a monotonic behavior with small capacitance values at low dopant densities and large capacitances at high dopant densities ($\Delta C \sim 1.3 \text{ fF}$). The highly doped semiconductor forms thereby a narrow depletion zone with large capacitance while low doping levels lead to an extended depletion zone with small capacitances [24]. With respect to the resistivity, the parallel conductance model shows a non-monotonic behavior, indicating that it is not useful to describe this type of sample with a parallel model in order to extract e.g. information on the dopant density. In contrast in the serial model the series resistance is clearly related to the bulk resistance of the Si and rises exponentially with falling dopant density. The difference in the serial resistance between high doping and low doping is $\Delta R = 17.1 \text{ k}\Omega$ and we are able to resolve variations in resistivity of $\sim 20 \Omega$.

The difference of the complex impedance between highly and low doped area is $\Delta Z = (17.1 - i6.4) \text{ k}\Omega$, with the imaginary part of 6.4 k$\Omega$ corresponding to $C = 1.4 \text{ fF}$ at $f = 19.1695 \text{ GHz}$.

![Figure 6. Complex impedance images of a cross sectional dopant semiconductor sample. Left column: Sketch of the flat Si-sample doped with increasing concentration of boron (red $5 \times 10^{19}$, orange $5 \times 10^{18}$, yellow $10^{18}$, green $7 \times 10^{16}$, blue $10^{16}$, purple $6 \times 10^{15}$ atoms cm$^{-3}$). The tip in contact with the semiconductor can be modeled as parallel or series combination of capacitance and resistance. Right column: The calibrated topography, capacitance and conductance/resistance for both equivalent circuits are shown. Electrical images were calculated from measured $S_{11}$ images taken at $f = 19.1695 \text{ GHz}$ and acquired in contact mode with $U_{dc} = -2 \text{ V}$ applied. (Used tip 25P300B-RM1.)](image-url)
the apex of the AFM-tip forming the MOS junction and not from cantilever based stray contributions. To further study the semiconductor properties, voltage spectroscopy curves were acquired (figures 7(d)–(f)). While the tip is in contact with the sample the tip bias was swept between −3 and +3 V. In figure 7(d) we plot the raw data in the complex $S_{11}$ plane with the thick lines representing the positive voltage from +3 to 0 V while the thin lines represent the negative part from 0 to −3 V. The raw $S_{11}$ data was converted into the resistive ($\Delta R_{\text{ser}}(U_{\text{dc}})$) and capacitive ($\Delta C_{\text{ser}}(U_{\text{dc}})$) contributions (figures 7(e) and (f)). The former represents the bulk resistance as well as the depletion layer resistance while the latter represents the oxide capacitance and the depletion layer capacitance. The strongest variation of the series capacitance with respect to the bias voltage can be obtained for the intermediate doping densities of $7 \times 10^{17}$ and $1 \times 10^{18}$ atoms cm$^{-3}$. This is in agreement with the simple expectation that at low doping concentrations ($6 \times 10^{15}–1 \times 10^{16}$) the depletion layer is much spread into the bulk and the SMM tip with the applied bias modulates only a fraction of the depletion layer capacitance. Detailed finite element simulations including the underlying semiconductor physics could proof the hypothesis. In contrast for high doping concentrations ($5 \times 10^{19}$) the depletion layer is too narrow and the overall capacitance is dominated by the native oxide rather than the depletion layer. Concerning the resistive behavior we find just a small variation with the applied bias voltage. Overall, for a quantitative understanding of the capacitance/voltage spectroscopy curves as well as the resistance/voltage curves at GHz frequencies more detailed models of the tip–sample interface need to be developed that can be compared to the experimental SMM data.

4. Conclusion

We present a simple and effective methodology to extract electrical properties from SMM reflection measurements. In the proposed calibration procedure the electrical response of the VNA is calibrated in a first step by simultaneously acquired electrostatic force and $S_{11}$-approach curves. Based on this calibration the $S_{11}$ amplitude and phase images are transferred in capacitance and resistance images. The topography crosstalk is subtracted from the capacitance image pixel by pixel resulting in capacitance values arising only from the local tip–sample interaction. From the capacitance image the dielectric constant is calculated with the tip geometry (i.e. the tip radius) extracted from the approach curves. The calibration approach curve should be performed on those areas of the sample that have low resistivity. This can be either fully dielectric substrates like glass or mica, or highly doped semiconductors or metallic substrates. One of the advantages of this methodology is that no extra calibration sample is required and no corresponding exchange of samples is necessary. The exchange of samples causes typically a large variation in the background stray capacitance which makes the calibration inaccurate. The methods presented here can be applied at every measurement frequency between 1 and 20 GHz and for any type of transmission line. The new calibration was shown on 20–60 nm thick dielectric SiO$_2$ films and the dielectric constant was extracted from $S_{11}$ images and from $S_{11}$ approach curves based on the evaluation of the capacitance signal. Due to the possibility of averaging we obtained a higher precision when the dielectric constant is determined from the SMM $S_{11}$ images. The extracted dielectric constant of SiO$_2$ at 19.81 GHz was $\varepsilon_r = 3.7 \pm 0.5$ with an accuracy of 20% which is in agreement with the nominal value at low frequencies.

Using differently doped semiconductor samples we showed that in addition of capacitance the SMM allows also to study quantitatively the resistive and conductive properties at the nanoscale. In the resistance images we were able to detect differences as small as 20 Ω and up to 20 kΩ, while the minimum values we can measure in the capacitance channel...
are around 1 aF which is currently the resolution limit of the Agilent SMM. The complex impedance difference we observed on the dopant sample is $\Delta Z = (17.1 - i6.4)$ kΩ.

In summary we showed that the SMM can measure quantitatively the real and imaginary part of the impedance within one scan at standard AFM imaging speeds (1 line s⁻¹). Depending on the model of the sample the real and imaginary part of the impedance can be translated into different quantities. For instance, the real part can be the loss of a material or the resistance of a device, while the imaginary part can be the permittivity of a material or the capacitance of a transistor. In future work semiconductor models are investigated in order to establish a better understanding of the physical processes that lead to complex impedance properties applied to dielectric films Nanotechnology 2012-ITN-317116, NANOMICROWAVE).

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