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Quantitative Scanning Microwave Microscopy: A calibration flow

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ABSTRACT

A procedure for doping concentration calibration using Scanning Microwave Microscopy (SMM) is presented. Calibration measurements are performed at a purpose-built sample comprising a wide range of doping concentrations of both n- and p-type implants at the sample surface. In order to evaluate the criticality of parameters affecting the measured signal, a transmission line model is used that takes into account the physical elements forming the evaluated network including modelling parameters for the tip-sample-interaction. Using a vertical DMOS sample a showcase flow for quantification is exercised and the attainable degree of accuracy is discussed.

1. Introduction

In the large variety of methods for characterizing semiconductor devices, the two-dimensional carrier profiling plays a major role since it helps detecting defects which are located e.g. in the active transistor area. Scanning Capacitance Microscopy/Spectroscopy (SCM/SCS), mainly used for carrier profiling, lacks from the disability to control the frequency of the used resonant circuit [1]. In order to overcome this, Scanning Microwave Microscopy (SMM) uses a transmission line coaxial resonator connected to a performance network analyser (PNA).[1] Here, a frequency signal between 1 and 20 GHz can be chosen such that the network is close to resonance, which results in a higher sensitivity and better controlled measurement conditions [2–4]. Moreover, the system design is built such that influences of stray capacitors and electrical instabilities are minimized which makes it easier to compare quantitative results of different samples.

In this paper, a Transition Line Model is presented, which takes into account the physical effective parameters for the MOS capacitor formed by the tip-sample system, like e.g. oxide thickness, tip radius and material, and majority carrier concentration [4,5]. The influence of these parameters on the model is discussed and compared to measurements on semiconductor samples. Furthermore, a new type of calibration sample is shown, which comprises several implant dose areas at the sample surface of both, n- and p-type, on one sample, as well as p–n-junctions of various levels, which can be used to calibrate the SMM system. A calibration flow is presented, which gives a guideline for determining quantitative carrier concentrations on unknown samples with an uncertainty of better than 50 per cent on small areas in the order of 100 nm.

2. Transition Line Model

The resonating circuit within the SMM is modelled using a circuitry of line segments shown in Fig. 1, where the tip-sample-interface is described by a MOS capacitor. In order to simulate an additional DC voltage applied to the system, a voltage source is included in series to the MOS capacitor. The software “Advanced Design System 2009” by Agilent is used to calculate the S_{11} parameter of the system which corresponds to the measured PNA signal. The differentiated calculated signal from the MOS capacitor corresponds to the dC/dV signal, which reflects the carrier concentration and is proportional to the measured dopant profile measurement module (DPMM) signal.

2.1. Variation of physical parameters

The MOS capacitor used in the transmission line model considers most of the influences of a real MOS capacitance. This is why a variation of majority carrier concentration, oxide thickness, and tip radius at various DC voltages offsets can be simulated to investigate those important parameters.

The signal increases with decreasing oxide thickness; for practical use, homogeneously grown native oxide is most preferred.

The signal increases with larger tip area, however, for practical use a trade-off between desired spatial resolution, S/N-ratio, and mechanical stability of the tip has to be found.

Majority carrier concentration: taking a real MOS-capacitor for modelling the tip-sample-interaction one obtains a behaviour that is non-monotonous over the whole range of carrier concentration

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[1] Here, a 5600LS AFM by Agilent combined with a N5232A PNA-L Microwave Network analyser is used.

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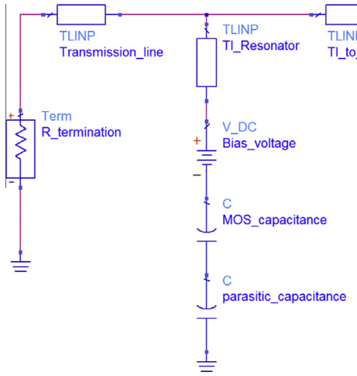

Fig. 1. Transmission line model used to describe the SMM network. The interacting area between tip and sample is modelled by the MOS capacitor shown.

between 10^{14} and 10^{20} cm^{-3} whereas the extreme value can be shifted by applying different DC bias values (see Fig. 2). This dependency can be explained considering the influence of the doping concentration not only on the MOS structure's ideal capacitance but also on the flat band voltage of the system [5].

2.2. Further measurement conditions influencing the system response

In order to minimize stray capacitance and charging of the sample while applying a bias offset it is crucial to ensure conducting adhesion of the sample to the chuck.

The used cantilever and tip material and radius determine the achieved resolution and measurement stability. Here, metal coated SiN cantilever tips are used (Nanosensors PtSi-FM-10). Full metal tips are not recommended since these tips suffer from fast degradation during scan, thereby changing the interaction behaviour and thus the calibrated value.

3. Calibration sample

Calibration samples currently available on the market (e.g. IMEC) usually consist of a series (up to five different carrier concentrations) of epitaxial grown layers. For SCM/SMM measurements a cross-section is performed, in this way forming a staircase of either n- or p-type-doped stripes [5].

Here, a new approach is chosen to design a calibration sample which can be accessed directly without preparation.[2] Using a mask stepping approach, up to twenty different implant steps have been performed on a low doped (10^{15} cm^{-3}) p-Si substrate forming ten n- and p-implant areas, each, with nominal majority carrier concentrations from 4×10^{15} to 1×10^{20} cm^{-3} in a stripe-shape design (see Fig. 3).

A set of larger areas, which can be used for Secondary Ion Mass Spectroscopy (SIMS) or Scanning Resistance Profiling (SRP) measurements has been created in the same process. Hence, a re-calibration is possible using methods with higher sensitivity but worse spatial resolution than SMM.

SIMS measurements performed show that the profiles are homogeneous within the tip-sample-interaction volume. Only at a depth of more than 200 nm from the surface, a significant decrease of the carrier concentration is found. The measured carrier concentrations are fairly close to the values intended as shown in Table 1, with the exception of the two highest p-type boron implant, where an elevation near the surface was observed. However, comparison to SRP measurement results indicates that the carriers near the surface might only be partially electrically active.

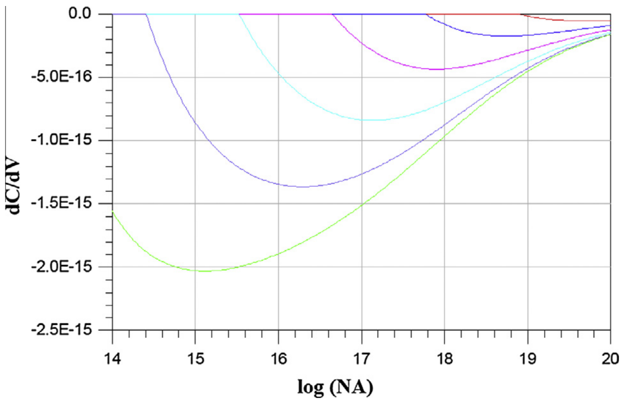

Fig. 2. Simulated dC/dV signal in dependence of carrier concentration for different DC bias values from 0 V (green) to −1 V (red) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Furthermore, an area where n- and p- type stripes are arranged in a cross-shaped manner is available, allowing for imaging of p–n-junctions of different kinds.

4. Calibration flow

For the quantification of carrier concentrations within an unknown sample, the following calibration procedure consisting of three main steps is used.

At first, the calibration sample is imaged using three different DC bias voltage values. The results obtained can be interpolated to gain the calibration curves for the dS_{11}/dV signal against doping concentration.

The second step is to measure the investigated sample using the same probe tip and applying the same three DC bias voltages which were chosen for the calibration curves. In order to ensure comparability of the results, the oxide layer of the samples should have a similar thickness and the connectivity of the substrates should be comparable.

Finally, the resulting values of the dS_{11}/dV Signal, observed at a sample location of interest, can be assigned to their corresponding values in the calibration curves. The interval matching for all three calibration curves leads directly to the interval for the doping concentration. Therefore, it is not necessary to have a monotonous behaviour of the relation between signal and majority carrier concentration over the complete investigated doping range. For a better accuracy, the result can be improved by fitting a linear approach through the measured values in the possible range.

A typical calibration flow can be seen in Fig. 4. The calibration sample is recorded three times with DC bias of −0.5 V,+0.5 V and +1.5 V (Fig. 4a). The same procedure is repeated with the device under test at the same conditions. The example in Fig. 4b shows a vertical DMOS transistor. The results are compared to the values of the calibration sample as shown in Fig. 4c. The intersection of the measured dC/dV signal at the region of interest with the corresponding calibration curve determines the carrier concentration. For a non-monotonous behaviour two intersection points and hence two carrier concentration values are possible using only one bias voltage. By comparison to the resulting values for the other bias curves, however, it is possible to obtain a defined value for the carrier concentration, and moreover to get a value for the accuracy of the measurement.

In the shown example, a linear fit was performed at the surrounding of the intersection (shown in Fig. 4d). As a possible doping range, a value between 2.1×10^{19} N_D/cm^3 and 3.9×10^{19} N_D/cm^3 for the n doped source implants marked in Fig. 4b, can be

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[2] Patent pending.

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