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Determination of doping type by calibrated capacitance scanning microwave microscopy

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ABSTRACT

The investigation of dopant distribution in discrete and highly integrated electronic devices is the main application of Scanning Microwave Microscopy in the semiconductor industry. To reliably determine the dopant type and the relation between differently doped areas within an electronic device, a calibration method based on the estimated complex impedance is introduced. The validation on differently doped silicon demonstrates that the method is able to simultaneously acquire accumulation and depletion capacitances. This enables the calculation of a 2D dopant type profile and furthermore provides a monotonic dependence of the measured capacitance on dopant density.

1. Introduction

The characterisation of semiconductor dopants plays an essential role in device development, failure analysis, and process monitoring. Scanning microwave microscopy (SMM) offers a score of different methods to probe the dopant type and density in state-of-the-art semiconductor devices [1,2,3]. However, the complexity of the SMM measurement still poses a challenge for the reliable and reproducible determination of dopant type and density within semiconductor devices. Previous methods do not acquire all relevant data in one image. Some require multiple scans on the sample under investigation as well as a comparison to a calibration sample [1]. Others are not able to identify the doping type [2], only the dopant density, while additional point scans are needed to test for dopant type [3]. Since for conventional scanning capacitance microscopy (SCM) and SMM, the used dC/dV and dS_{11}/dV signals, where S_{11} is the reflected part of the applied microwave signal, depend on the slope of the C-V behaviour. Therefore, no monotonic dependency on the dopant density is given, the dopant density relations cannot be easily determined. The SMM signal is based on the reflected part of the applied microwave. The SCM signal is obtained from the detuning of a resonance circuit. Both are not actual capacitance measurements. As this reflection respectively detuning is uncalibrated, the phase can switch and thus the dopant type cannot be determined on unknown samples. Hence, a reliable method for SMM is needed to simplify and speed up the estimation of dopant type and density in electronic devices.

In order to probe the dopant type within a semiconductor device by only one single scan on the region of interest, a different and improved calibration method is introduced here. It involves the capacitive accumulation and depletion behaviour of doped silicon probed by SMM.

2. Method and setup

The measurements were performed by the Keysight AFM 5600 LS system [4]. This equipment combines an atomic force microscope (AFM), equipped with a conductive metallic tip with a lock-in amplifier used to apply a modulation voltage between 200 Hz and 6 MHz to the cantilever in order to acquire electrostatic force microscopy (EFM) data. Furthermore a vector network analyser is used to apply the microwave signal from 10 MHz to 20 GHz to the cantilever and detect the SMM signal.

The reflected part of the microwave, i.e., the scattering parameter S_{11}, is calibrated with a fit of the capacitance signal revealing the complex impedance. This calibration, based on findings by Gramse et al. [5], is performed via a python script provided by Keysight Technologies. The script combines the simultaneously acquired EFM and S_{11} approach curves. The EFM data recorded during the approach are converted into a low frequency capacitance. Using an analytical model of the tip-sample interaction, the S_{11} data is fitted to the EFM capacitance. This fit provides the calibration parameters *e00, e01*, and *e11* [5]. Those parameters are used to calculate the complex impedance from the reflexion, which provides information on p- or n-type doping.

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The device under test, which is investigated by the measurement setup, is a metal oxide semiconductor structure, as schematically shown in Fig. 1 for a p-type semiconductor. It consists of the metal tip, the natively grown oxide and the doped silicon sample. The high frequency (HF) capacitance voltage (*C-V*) behaviour is plotted in an overlay. In the right half of the picture the depletion behaviour of the structure is demonstrated. When a positive voltage is applied to the tip, the positive charges are depleted from the semiconductor surface creating a space charge region. The space charge region gets larger with lower dopant density. Thus with decreasing dopant density the depletion capacitance decreases likewise [6].

The left part of Fig. 1 depictures the accumulation behaviour of the structure. Applying a negative bias to the tip, the positive charges are accumulated at the semiconductor surface. As there is no space charge region, the capacitance of the structure is nearly equal to oxide capacitance as long as the majority carriers can follow the microwave signal. At lower doping densities the accumulation capacitance decreases depending on dopant density and frequency [7].

The dS_{11}/dV signal, which is typically used in SMM measurements, depends on the slope of those *C-V* curves. Therefore very high and low dopant densities create the same signal.

In order to avoid the influence of reduced accumulation capacitance at a low dopant density level the sample capacitance was simultaneously measured for positive and negative tip bias. The subtraction of these two signals was used to determine the doping type.

For the validation of this method two different samples were scanned by SMM. The first one, the IMEC T8 sample, consists of stacked p-doped epitaxial layers ranging from 3.2×10^{16} cm^{-3} to 7.5×10^{19} cm^{-3} Atoms on top of a lowly p-doped substrate. The corresponding datasheet profile including the secondary ion mass spectroscopy (SIMS) and spreading resistance profiling (SRP) data is shown in Fig. 2a. For the scan, a mechanical cross section of the sample was prepared, where the sample was embedded and polished to the region of interest using a colloidal silica suspension as final polish. No further oxidation steps were performed.

The second sample is the Infineon dopant sample depicted in Fig. 2b. It contains 10 p-doped and 10 n-doped stripes ranging from 4×10^{15} cm^{-3} to 1×10^{20} cm^{-3} according to the simulation. SIMS measurements were performed to confirm the simulated values [1]. The sample substrate is p-doped with 1×10^{15} cm^{-3} Atoms. Since all doped stripes were accessible from the top of the sample, SMM was scanned on the surface.

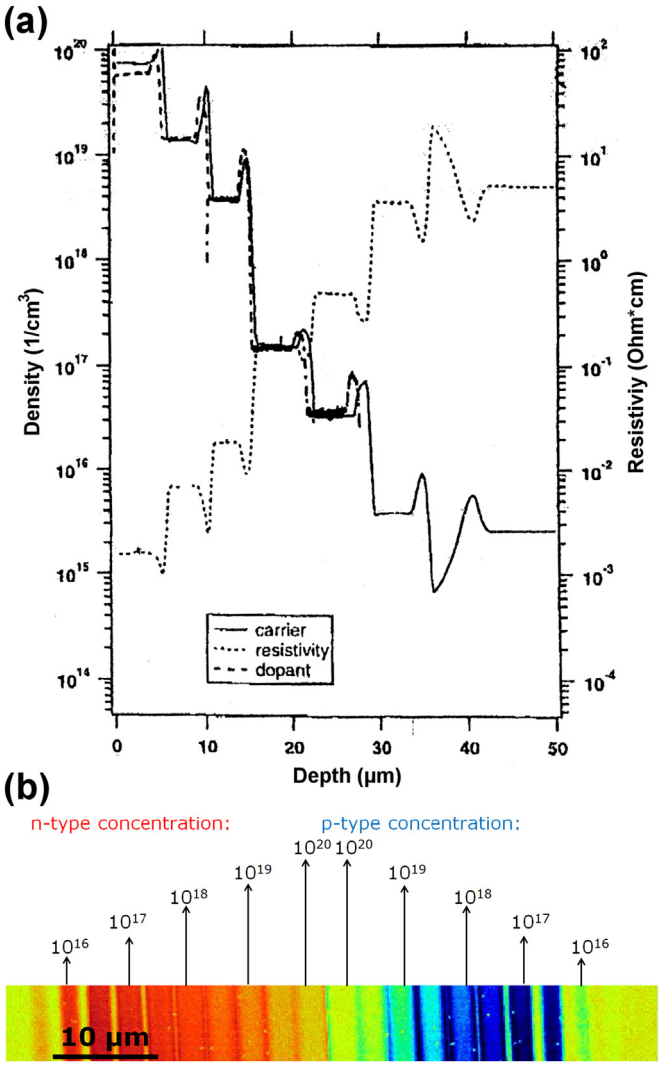

Fig. 2. Dopant densities and resistivities of IMEC T8 (datasheet reprint) (a) sample and SMM Re {dS_{11}/dV} image of Infineon calibration sample with corresponding datasheet values (b).

3. Results and discussion

3.1. Impact of dopant density and measurement frequency on SMM spectroscopy data

Spectroscopy measurements were performed on the IMEC sample (see Fig. 2a) to investigate the impact of the theoretical accumulation and depletion behaviour on the actual capacitance measured by SMM. The *C-V* spectra acquired at 4 GHz on differently doped epitaxial layers are shown in Fig. 3, where the DC tip bias was swept from −4 V to +4 V.

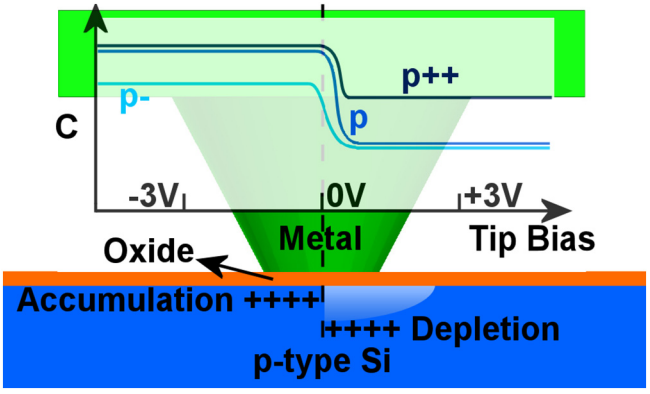

Fig. 1. Schematic of the SMM principle with the general accumulation and depletion behaviour in a p-type semiconductor and overlaid C-V curves.

At negative tip bias, the accumulation capacitance did not reach the oxide capacitance level for 3.2×10^{16} cm^{-3} boron atoms and below (pink and green curve). This effect is well known for highly resistive substrate in the MHz range [7], and affects the GHz SMM measurements of common dopant densities [3]. At low doping densities the majority carriers do not follow the high frequency signal properly causing the accumulation capacitance not to reach the oxide capacitance level anymore [3,7].

In contrast the depletion capacitance measured at positive tip bias scales with doping density down to 3.8×10^{15} boron atoms (all curves). This effect provides a solution to determine the relationship between different doping densities on the basis of depletion capacitance. Furthermore the difference between the accumulation at −3 V and the depletion capacitance at +3 V, which is significant down to at least 3.2×10^{16} cm^{-3} boron atoms (pink curve), can be used to decide on p- or n-doping over a wide density range.

3.2. Distinction of dopant type by differential capacitance

The differential measurements performed on the IMEC sample (dopant profile in Fig. 2a) with 4 GHz and 19 GHz are shown in Fig. 4. Fig. 4a

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