Determination of dopant density in Infineon SCM calibration sample by scanning microwave microscopy (SMM)

Introduction

This application note is a follow up on a preceeding application note for SMM measurements of a capacitance standard sample[1]. The present application note contains all neccesary information but the application note on SMM capacitance calibration can be used as additional reference.

Scanning microwave microscopy (SMM) is a scanning probe technique, which measures local tip-sample microwave impedance, deduced from the S11 parameter. This impedance depends on local electrical properties of the sample, such as dielectric constant (ε), conductivity (σ) and carrier density (n). These properties are of extreme importance in designing semiconductor devices. Similar measurements are possible with Scanning Spreading Resistance Microscopy (SSRM), but this method is normally using diamond tips and high tip forces to cut through a silicon oxide layer, which damages the sample surface. Apart from that, SSRM cannot distinguish the type of dopants in the sample – *n* or *p*, the dependence of current vs. dopant density is non-monotinic and the calibration of SSRM measurements is difficult. Another alternative method is Scanning Capacitance Microscopy (SCM), which has similar difficulties with determining dopant type and density.

In this application note we used SMM to study a silicon SCM calibration sample, made by Infineon, containing both types of dopants – *n* and *p* and a range of dopant densities between $4{\cdot}10^{15}$ – 10^{20} cm^{-3} for both types with 10 distinct regions of densities for each type (20 regions in total). A schematic of the sample is shown in Fig. 1. This sample is well studied by different groups[2].

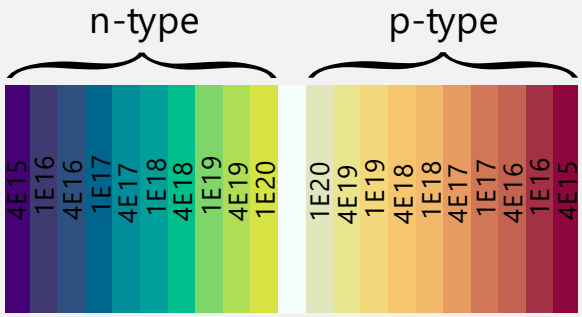

Figure 1. Schematic representation of a region of interest in an Infineon SCM calibration sample made of silicon. The area consists of 20 regions with different doping: 10 for each dopant type (*n* and *p*). With dopant densities in the range $4{\cdot}10^{15}$ - 10^{20} cm^{-3}. Exact dopant densities for each region are indicated in the sketch. The width of each line is 2.5 µm, the total width is of the area

For sample characterisation we have used two different SMM modes. First is the S11 measurement, where the microwave signal has only one frequency for the emmision and detection. This mode has been described in the application note on SMM measurements of capacitance standards. The second measurement is a so-called dS/dV measurement, which we will describe below.

dS/dV measurement

The S11 measurement is prone to topography cross-talk since every change of height is also a change of cantilever-

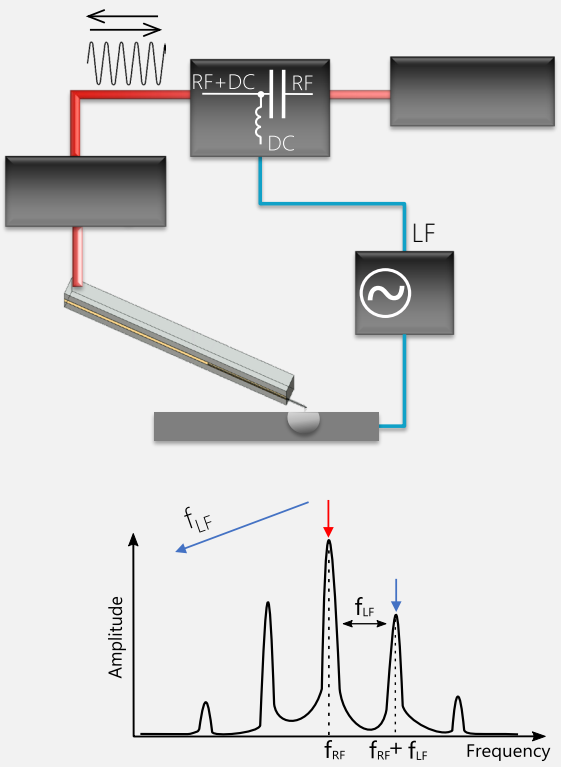

Figure 2. (a) Schematic of a dS/dV measurement: a low frequency bias voltage (LF) is applied between the probe and the sample. The non-linear behavior of the tip-sample contact causes frequency mixing between the RF and the LF signals. (b) The frequency spectrum has now peaks on both sides of the main RF tone. The detector is working on the frequency of the mix-product, i.e. $f_{RF}+f_{LF}$.

sample capacitance. In semiconductor materials, an AC voltage bias can modulate the dopant density in the sample under the tip, and therefore the S11 signal. This is called the dS/dV measurement, which yields similar information to the conventional dC/dV measurement in SCM. The dS/dV is less affected by topography, but it only works for semiconductors. Another advantage of this method is that it yields information about the type of the dopants via phase change. In the dS/dV case, low frequency (LF) AC voltage is applied between the tip and the sample, and non-linearity in tip-sample interaction is causing frequency mixing between RF and LF waves, giving rise to sidebands (Fig. 2).

The signal detection on the sideband frequency can be done in several ways – for example down-mixing this signal back to the LF frequency, and measuring it with a lock-in amplifier. Alternatively, one could set the receiver to work on a frequency a few MHz away and do digital mixing and filtering on an FPGA. The disadvantage of dS/dV method is the same as with the dC/dV measurement – amplitude of the signal is non-monotonic with the dopant density, therefore the combination of S11 and dS/dV measurements is best for a complete analysis.

Theoretical background

The determination of dopant density in semiconductors by SMM (or SCM) is based on measurement of tip-sample capacitance. This capacitance is formed by the metallic tip of the SMM, the oxide below the tip and the semiconductor. It is a metal oxide semiconductor contact (MOS). The tip sample capacity consists of the the capacity C_i of tip and oxide in series with the so-called depletion capacitance C_{dep} in the semiconductor. The depletion capacity forms when a voltage is applied between the SMM tip and the semiconductor. The depletion capcity is a consequence of the applied electric field and charge carrier diffusion in the semiconductor. The electric field either attracts or repells electric charges from the surface whereas the diffusion counteracts on this force[3]. This C_{dep} is a function of carrier density (Eq. 1):

$$C_{dep} = \pi R^2 \sqrt{\frac{\varepsilon_0 \varepsilon_r n e^2}{k_B T}} \qquad (1)$$

In this case the equation for the total capacitance would be (Eq. 2):

$$C_{tip} = \frac{C_{dep} C_i}{C_{dep} + C_i} \qquad (2)$$

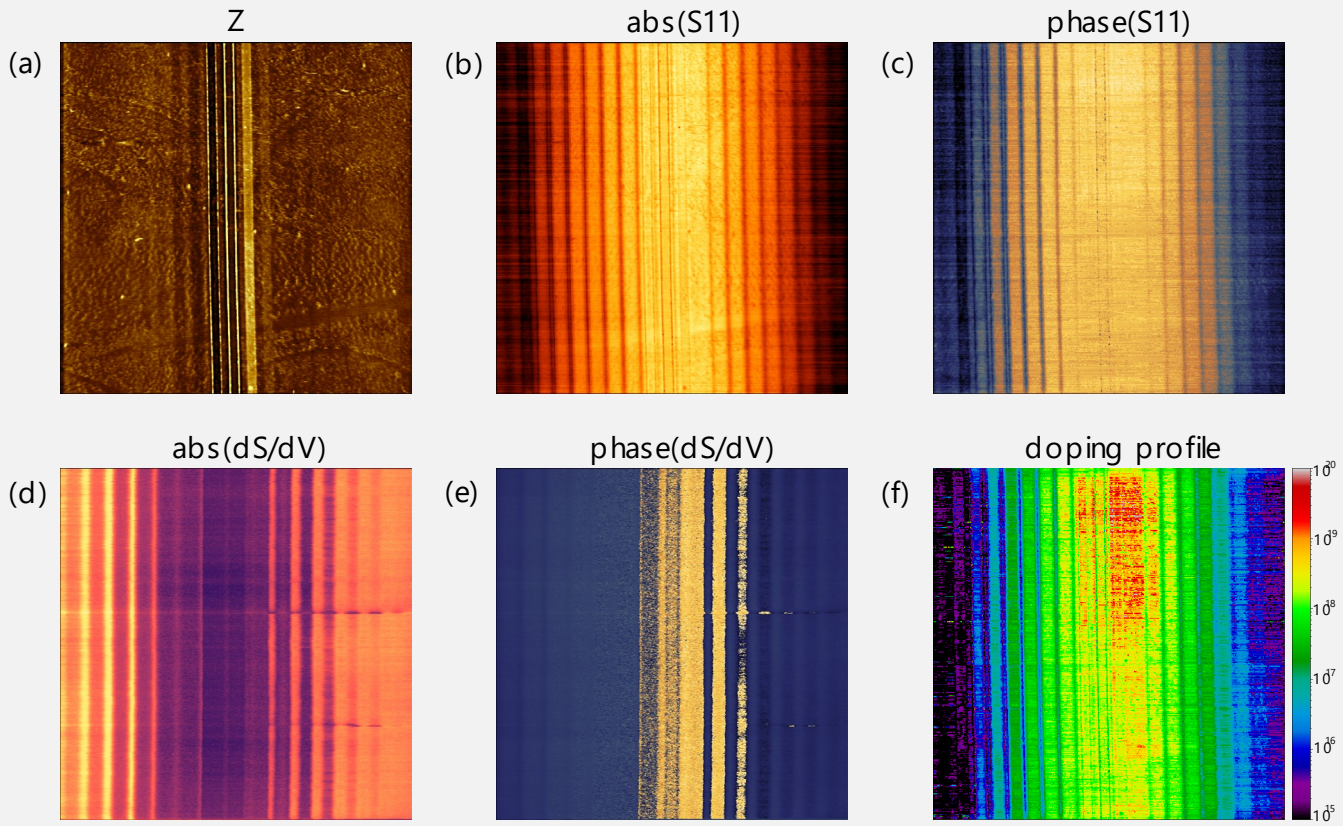

Figure 4. Experimental data of the S11 (b,c) and dS/dV (d,e) measurements of Infineon SCM calibration standard sample. The difference between the S11 and dS/dV can be clearly seen. The amplitude of S11 signal (b) is monotonically increasing with the carrier density, while the dS/dV signal (d) has largest amplitude in the middle of the range (10^{16}-10^{18} cm^{-3}). Phase signal of the dS/dV carries information about the type of dopants – n or p. The doping profile (f) was calculated from the S11 measurement (b,c).
Image size (a,b,c,f): 50 x 50 μm^2, (d,e): 35 x 35 μm^2.

The calibration protocol[4] that we have used here is the same as in the case of the capacitance standard sample (see the corresponding application note[1]). Except in the former case the C_{dep} was constant and the C_i was varying due to different sizes of gold dots. In the present study, the C_{dep} is varying in different regions and C_i is assumed to be constant all over the area of the measurement and depends only on the tip dimensions. C_i calculation is identical to the one in the previous application note. While tip dimensions are included in the calculations, one can avoid characterizing the tip by using regions of "known" dopant densities.

Calibration procedure

The measurement data of the S11 parameter and the dS/dV measurement of the Infineon SCM sample are shown in Figs. 4a-e. For calibration we have selected 3 areas in the sample where the dopant density was assumed to be known – 10^{16}, $4*10^{17}$ and $4*10^{19}$ cm^{-3}. Using Eq. 1-2, we then calculated tip-sample capacitances in these areas, which were found to be 1.3, 3.4 and 4.7 aF correspondingly, assuming a tip radius of 15 nm. After that, the calibration protocol[1,4] was applied to calculate the capacitance map of the full scan area. From the capacitance map we have calculated the map of dopant densities (Fig. 4f). As can be seen from Figs. 4b,c the S11 measurement

bears no information of the type of dopants. This information can be obtained from the phase of the dS/dV measurement (Figs. 4d,e). Another difference between the S11 and the dS/dV measurements is that while the amplitude of S11 signal is monotomically increasing from low to high dopant densities, the amplitude of the dS/dV is reaching its maximum in the middle of the range of densities (10^{16}–10^{18} cm^{-3}).

Conclusion

SMM measurement is a powerful tool in studying semiconductor samples. It yields information about carrier concentration and carrier type. For a complete study, different modes of SMM, i.e. S11 and dS/dV have to be used.

References

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