sMIM Measurement of Planar Doping Calibration Sample

Scanning microwave impedance microscopy (sMIM) is an emerging electrical mode for scanning probe microscopy (SPM). We apply the technique to the profiling of dopants in semiconductor samples with sub-micron spatial resolution. In this document we demonstrate the practical application of sMIM for measuring a doping calibration sample with a range of doping concentrations from $10^{15}$ to $10^{20}$ atoms/cm$^3$ for both N-type and P-type carriers. In this document we show high contrast imaging of the sample using sMIM dC/dV phase and amplitude simultaneously with sMIM-C contrast. The sMIM-C is monotonic with doping concentration unlike conventional SCM or dC/dV, which allows for a direct interpretation of low doped compared to high doped areas qualitatively by using the sMIM-C contrast and a way to apply the calibration sample to make quantitative measurements.

Calibration Sample Description

PrimeNano measured a commercially available planar doping calibration sample from Infineon, Munich. The sample has various structures for investigating doping levels and P-N junctions. In Region B, shown in Figure 1, the calibration sample has 20 doped stripes in a 50µm repeating pattern. Each repeating pattern has 10 p-type stripes and 10 N-type stripes on a P-type substrate. The Figure 1 b) shows the SIMS measurements for the P-type region and c) for the P-type region [1].

![SIMS depth profiles of B implants (p-type)](image1)

![SIMS depth profiles of P implants (n-type) showing nearly homogeneous profiles in upper 200nm](image2)

Figure 1. Planar doping sample from Infineon with SIMS calibration of 10 p-type and 10 n-type doping regions from $10^{15}$ to $10^{20}$ atoms/cm$^3$. Region B is highlighted where the sample is calibrated.
sMIM measurements of Doping Calibration Sample

A doping calibration sample, commercially available from Infineon [2], is measured using a commercial AFM in contact mode and a 2 pass (lift mode) scan. The 1st image is taken in contact to the surface and the 2nd image is scanned 100’s of nm’s above the surface using the same path as the contact 1st pass. The 2nd pass is used as a reference for the sMIM at a constant height above the surface and used to removed drift, any stray capacitance, and set a relative reference for the calibration sample [3]. In Figure 2 we show the height image (a) and sMIM-C image (b) after background subtraction of the reference surface. The height shows a polished surface with some markers in the center of the doped structure, for centering the feature in the SPM optics. The sMIM-C image shows the contrast representing the doped stripes. The average sMIM-C profile (c) shows the steps representing the different doping levels. The center of the figure is where the both the N-type and P-type doping have the highest doping levels, and both progressively have lower doping towards the edges.

The images in Figure 3 show the calibration sample using ScanWave’s SCM equivalent, dC/dV Amplitude (a) and dC/dV Phase (b). The dC/dV images...
have a non-monotonic response to the doping, making it more challenging to use these data sets towards quantification of doping. The Amplitude profile (c) shows for both the N-type and P-type sections of the sample the peak response at the middle doping ranges $10^{17}$ atoms/cm$^3$ for 0V DC bias offset. The Phase profile (d) shows the P-type substrate and region of stripes compared to the N-type stripes. The lock-in signal for the dC/dV images show high contrast and quality for the full range of doping concentrations across the calibration feature.

**sMIM-C vs Doping Calibration**

sMIM-C has a monotonic response to the log doping which makes it an ideal method for converting sMIM to units of log doping. By using the sample available from Infineon, where a verified reference measurement such as SIMS is used to independently measure the doping levels for each stripe feature for both N & P extract the average sMIM-C profile. The sMIM values for each step are given in relative units of mV. By plotting the sMIM-C values for each step in mV to the known SIMS doping level of each stripe, we can make a plot and from that a conversion equation for sMIM-C to units of log doping. Figure 4 shows an example of such a plot made from the Infineon calibration sample. The graph shows that the N- & P-type regions are plotted separately and align very closely over the range of doping. This calibration applies for the specific probe used to image the sample and the same probe needs to be used on an “unknown” for the calibration to be valid. Adjustments can be made for changes in the probe tip size.

![Figure 4. Graph of sMIM-C values in depletion plotted for each doped stripe from the Infineon calibration sample vs SIMS value shown in Figure 1.](image)

Figure 5 shows an example of a NMOS power device from Linear Technologies where the scale has been calibrated so the contrast scale displays the color in units of log doping [5]. The calibration shown in this specific example was done using IMEC doped staircase calibration samples, a N-type, T8, and P-type, T9, standards [6] using a similar methodology to that described previously. to the device measured using ScanWave to first

![Figure 5. Example of a NMOS power device displayed after calibration in units of log doping.](image)
acquire the calibration data then in sequence the device data. The image is scaled in the physical units as a post process step.

Summary

ScanWave electronics integrated onto a commercial SPM provides a high-resolution imaging and measurement tool for semiconductor applications. Combining sMIM-C with the dC/dV phase and Amplitude images provide a richer visualization of the device structure’s materials variations to interpret relative doping of a device or feature. The images are acquired simultaneously providing high sensitivity to a large range of doping concentration $<10^{15}$ to $>10^{20}$ atoms/cm$^3$ for both N-type and P-type carriers.

Quantitative doping results are presented demonstrating that sMIM-C can be used as a method for quantitative measurements of dopant concentrations on semiconductor devices with nanoscale spatial resolution. The methodology is applied using a planar doped reference sample with P-type and N-type doped regions. The same calibration methods can be applied using cross-section calibration samples. Calibration of sMIM-C is based on the linear relationship to the log of doping concentration over a useful range.

References