Scanning Microwave Microscopy (SMM)

Over the last few decades, the drive to miniaturize electronics has increased the demand for nano-electrical characterization methods. Understanding the local electronic material properties, such as conductance, dielectric constant, local capacitance and dopant density is critical for research and development of the semiconductor and microelectronics industries.

Atomic force microscopy (AFM) has been a key technology used to correlate topographical structures with local electronic properties at the nanoscale. Techniques such as conductive atomic force microscopy (C-AFM) and Kelvin probe force microscopy (KPFM) allow for the measurements of local currents and electric surface potentials while scanning capacitance microscopy (SCM) maps the capacitance or local carrier density. Scanning microwave microscopy (SMM) is unique in revealing buried structures that are prevalent in multilayered modern integrated circuits (ICs). These measurements are essential for applications in failure analysis, simulation of device performance, and optimization of semiconductor manufacturing processes.

Scanning microwave microscopy

SMM is a scanning probe technique that measures the interactions of a microwave between a sharp tip and the sample. The ratio between the power sent to the tip and the power received after being reflected at the tip-sample contact is expressed in the microwave reflection coefficient (S11 parameter). The S11 parameter is used to infer the tip-sample microwave impedance. The microwave impedance yields information about the local capacitance that can be used to determine the dielectric constant and the dopant density.

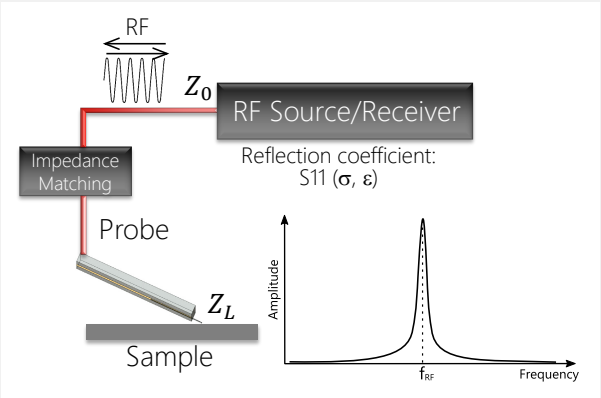

Figure 1. A schematic of a typical SMM setup: RF source/receiver electronics send the RF wave with impedance Z_0 through the transmission line to the probe (red). The sample-probe impedance is Z_L. The impedance matching circuit works as an "anti-reflection" medium between the low impedance Z_0 and high impedance Z_L. There is only one frequency peak (f_{RF}) in the spectrum and the amplitude and/or phase are tracked during scanning of the surface.

One of the main shortcomings of SCM, a technique similar to SMM, is that dopant density measurements are largely qualitative and can not be applied to materials other than semiconductors. In contrast, SMM can be used to measure a range of materials including dielectric materials and metals[1], since it does not solely rely of the modulation of the depletion capacitance in the sample. Additionally, SMM operates at higher frequencies, leading to better sensitivity and the high precision electronics allow for calibrated and absolute measurements. While extraction of numerical data is possible analytically in SMM, in practice, calibration samples keep the experiment from quickly become complex.

A typical SMM setup consists of a radio frequency (RF) wave source and a receiver working at a few GHz (Fig. 1). In a pure S11 measurement, the transmitter and receiver

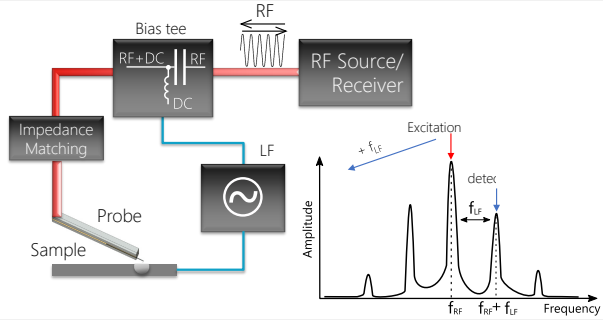

Figure 2. Schematic of a dS11/dV measurement: a low frequency bias voltage (LF) is applied between the probe and the sample. The non-linear behavior of the tip-sample contact causes frequency mixing between the RF and the LF signals. The frequency spectrum exhibits sideband peaks on both sides of the main RF tone (plot). The frequency of the mixed product, i.e. $f_{RF}+f_{LF}$, is used for detection of dS11/dV

both work on the same frequency, and only one main tone (or frequency) is observed in the frequency spectrum. The signal is transferred to and from the cantilever via a low loss coaxial cable. Because the typical port impedance is 50 Ω and the tip-sample contact impedance is much higher, an matching circuit is usually required.

Once the RF electromagnetic wave leaves the coaxial cable, it starts radiating into free space. This can cause topographic cross-talk in the S11 measurement. In semiconductor materials, an AC voltage bias can modulate the dopant density in the sample under the tip, and therefore the S11 signal. Tracking the change of S11 relative to the change of the bias voltage (similar to lock-in amplification) minimizes topographic cross-talk. This is called the dS11/dV measurement, which yields information that is similar to the conventional dC/dV measurement in SCM. dS11/dV only works on semiconductors. To realize this measurement, a low frequency (LF) modulation is applied between tip and sample. The non-linearity in the tip-sample interaction causes frequency mixing between the RF and LF waves. Hence, it gives rise to sideband peaks on both sides of the main tone (Fig. 2). The detection of the sideband signal is performed by mixing the signal back down to the LF frequency and demodulating it using a lock-in, or by directly measuring amplitude and phase of the sidebands. The latter is preferred as it eliminates 1/f noise.

SMM measurements

Applications of SMM include measuring dopant densities and failure analysis in semiconductor devices. We demonstrate an example of each:

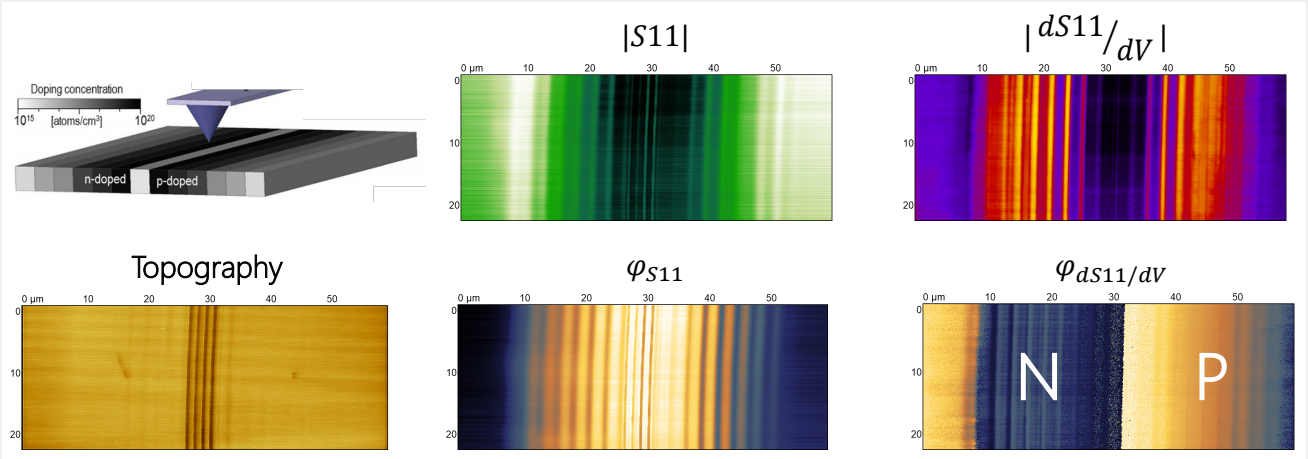

Figure 3. An S11 measurement (amplitude and phase) and a dS11/dV measurement (amplitude and phase) of an Infineon SCM calibration sample. Clear contrast between the regions of different dopant density can be observed in both the S11 and the dS11/dV measurements. The dS11/dV measurement indicates polarity and the type of the dopant – n or p – can be determined. The schematic image of the sample is taken from Ref. 2.

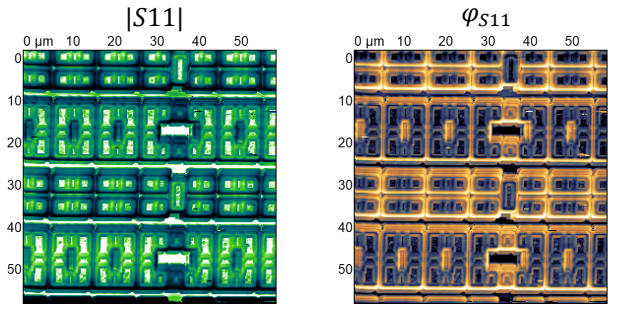

Figure 4. An S11 measurement (amplitude and phase) of a SCM sample, demonstrating high contrast between the areas of different doping levels.

Figure 3 shows the S11 measurement of the Infineon SCM calibration sample and good contrast can be observed on dopant densities in the range of 10^{15}-10^{20} 1/cm^3. The dS11/dV measurement provides complementary data and the type of the dopant (n or p) can be observed in the phase image. The raw data in the SMM measurement is uncalibrated, and the calibration procedure has to be applied to the measured data to extract quantitative values for the capacitance, resistance, and the material parameters. Detailed description of calibration procedures for SMM can be found in literature[2,3].

Another sample that exhibits structures with clear differences in dopant type and concentration is a semiconductor SRAM chip. Figure 4 shows an SMM measurement of a device where device faults or relative changes in dopant concentration could be identified to evaluate device performance or potential sites for failure.

Conclusion

SMM is a modern alternative to SCM that does not rely on the use of resonant circuits, to measure the S11 parameter or the microwave reflection coefficient. SMM is applicable to materials beyond semiconductors including dielectrics and metals. Calibration isn't required for many key applications such as for instance fault detection in the semiconductor industry. Still, when using relatively simple calibration procedures, analytical calculations become possible, and material properties can be determined quantitatively.

References

1. J. Hoffmann et al., Appl. Phys. Lett. 105 (2014) 013102
2. Brinciotti *et al.*, *Nanoscale* **7** (2015) 14715
3. Hoffmann J., *et al.*, IEEE-NANO (2012)

Contact information

Nanosurf AG
Gräubernstr. 12-14
4410 Liestal
Switzerland
info@nanosurf.com
www.nanosurf.com