Manipulating and Characterizing with Nanorobotics: In-situ SEM technique for Centimeter and Millimeter Waves

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***Abstract*—Combining Scanning Electron Microscopy (SEM) and Microwave Microscopy is resulting in a hybrid microscope with multi-sensorial features. Parallelized measurements in the micro- and mm-wave region and manipulation of micro- and nano-scaled objects will be possible. Nanorobotic positioning stages with end-effectors inside the vacuum chamber of this microscope are controlled by an open-source automation software framework which also obtained live data and images of a Vector Network Analyzer (VNA) and the SEM.**

I. INTRODUCTION

SMART tools to investigate, manipulate and transport materials small objects and even systems in the nanoscale range are required. Imaging, characterizing and handling in an automated manner [1] is up to now an unknown approach in the field of micro- and mm-wave research. High repeat accuracy to the regions of interest to positioning precisely the local scanning probe lead to the use of automation strategies [2].

20 years ago a Scanning Tunnel Microscope was combined with a microwave resonator [3] and are now commercially available as so called Scanning Microwave Microscopes (SMM). Imaging and characterizing complex electric properties of different nanomaterials are possible [4] [5]. Working with a Scanning Microwave Microscope a built-in optical CMOS-Camera is helping to guide the user to the area or region of interest but only in a coarse positioning manner. With known SMM´s the scanning measuring process cannot be observed under closer surveillance with higher lateral resolution. Blunted cantilever tips reduces the imaging quality after some surface scans. To overcome most of the mentioned difficulties we propose an in-situ SEM technique by combining a Scanning Electron Microscope and a Scanning Microwave Microscope (SEM^2). This new high-frequency instrument is based on our open-source OFFIS Automation Framework (OAF) for Nanorobotics.

II. SETUP

This instrument consists of three parts: An Atomic Force Microscope (AFM) inside a SEM, the SMM and the control hard-and software based on OAF.

A combined AFM/SEM based on the laser deflection principle were firstly described in [6]. Nowadays companies, like Nanonics Imaging Ltd., Danish Micro Engineering A/S or Attocube Systems AG are selling commercial products of laser-based AFM for the integration into a SEM. But these instruments are only designed for conventional AFM-based surface analysis inside a SEM. Resulting in methods leading to the usage of one cantilever for one method and no possibility to use additional microwave signals as an additional scanning sensing method in vacuum.

The SEM^2 proposed here is own-build and based on a ZVA24 VNA from Rhode&Schwarz. Figure 1 shows the general building blocks. The system control software-framework has a modular design and enables Python™ scripted automation of various sensor and actuator components.

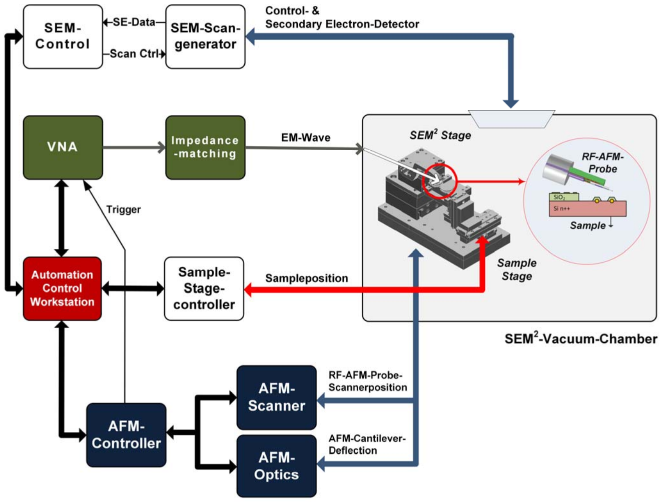


Fig. 1. Block diagram of the SEM^2-System. The probing and sample setup is situated inside the vacuum chamber on the right side.

The microwave signal coming out of the VNA port is guided through a RF-AFM-Cantilever tip in contact mode to the surface of the sample. A PCB as a holder for the conductive RF-AFM-Cantilever was simulated, optimized by Ansoft HFSS™ in the GHz range, built and integrated into the SEM^2 (figure 2).

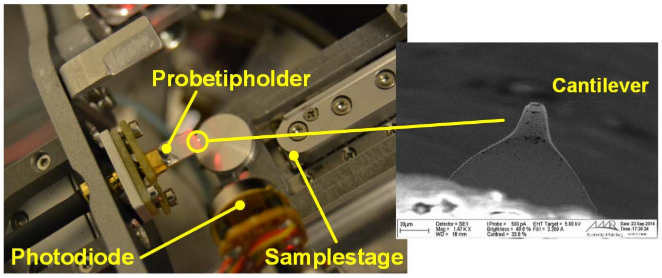


Fig. 2. Left: Close-up photo of the setup with RF-AFM-Probetipholder and sample stage in a Zeiss/LEO 1450 SEM; Right: SEM top view image of the probe tip

III. NANOROBOTIC CONTROL

Most AFM and SMM system providers deliver proprietary software that do not allow any modification and improvement of the equipment especially the automation and synchronization of different control processes. The University of Oldenburg issued the OFFIS Automation Framework (OAF)

[7] as open-source that is tailored for automation of nano-robotic processes, like characterization and manipulation, i.a. in the vacuum chamber of scanning electron microscopes. The software-framework has a modular design and enables Python™ scripted automation of various sensor and actuator components. Central components of this framework are software tools for visual process control, object recognition and tracking. This image processing components are specifically optimized for processing noisy image data as they are common by SEM. By means of this open-source software-framework, the so-called “OFFIS-Automation-Framework”, complete nano-technologic characterization and assembly sequences were realized. For example, the realization of fully automated selecting and mounting of exchangeable and customizable scanning probe tips onto standard AFM cantilevers during the EU-funded project “NanoBits”.

The software structure of the whole instrument based on OAF is divided into the frontend and backend. The frontend interacts with the user via the Graphical User Interface (GUI) (see Figure 3). In the backend, which is divided into the three parts Vision, Automation and Telecontrol, the whole automation process take place. With the scripting language Python™ all the positioning control, the gathering of the measurement data from the AFM and VNA and the acquisition of the SEM live images are done. The individual so called “RC-Units” (Remote Control-Units) are the connecting soft-ware parts responsible for each measurement data producing hardware, like the VNA or AFM but also for the nanoposi-tioner from Physik Instrumente GmbH. and SmarAct GmbH used here. In “Telecontrol” operating mode the user control the setup manually.

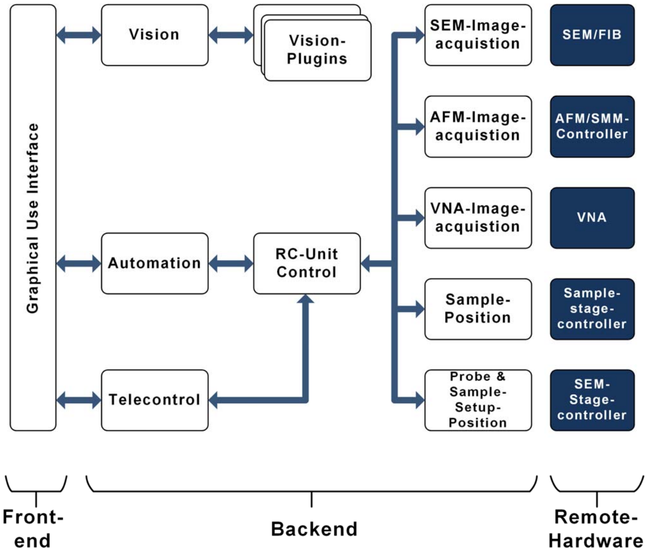
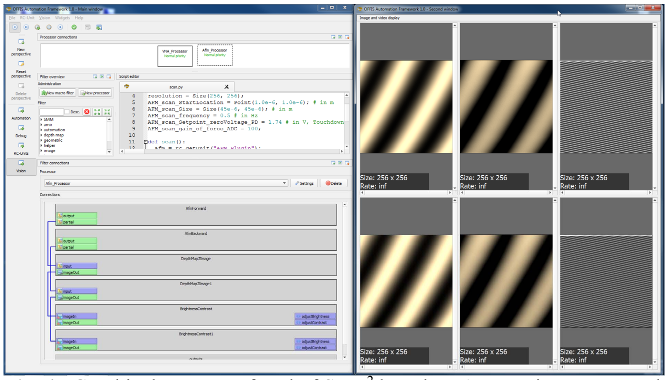


Fig. 3. Software structure of SEM^2 based on Automation Framework OAF

In figure 4 the GUI of the hybrid microscope control is shown. Automation and vision control scripts are running as own processes and can be changed on-the-fly during measuring or scanning. To simplify the software testing, especially the synchronization of the VNA and the self-designed AFM-controller, a Sample-Under-Test-Simulator for up to 14GHz was built. This was based on a microwave-PIN-modulator controlled by an open-source Arduino™-Microcontroller. This simulator moves the matching point in different manners, sinusoidal or trapezoidal, around 50 Ohm with variable repetition frequencies of up to 2Hz resulting in varying S11 magnitude and phase, seen in the right part of fig.4. The simultaneously acquired SEM live image isn´t shown here, but this is also done with the automation backend of the software framework.



```
resolution = Size(256, 256);
AFM_scan_StartLocation = Point(1.0e-6, 1.0e-6); # in m
AFM_scan_Size = Size(45e-6, 45e-6); # in m
AFM_scan_frequency = 0.5 # in Hz
AFM_scan_Setpoint_zeroVoltage_PD = 1.74 # in V, Touchdown
AFM_scan_gain_of_force_ADC = 100;

def scan():
  afm = rc.getUnit("AFM_Plugin");
```

Fig. 4. Graphical User Interfaced of SEM^2 based on Automation Framework OAF. Left: Automation and Vision control; Right: Reflection Coefficient S11-Magnitude, S11-Phase and AFM Deflection; Top right: SMM Forward scan; Bottom right: SMM Backward scan.

IV. SUMMARY

Work in progress of a scanning microwave microscope inside a SEM based on Nanorobotics control was shown. Automation strategies will be introduced in future works.

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