

PROJECT FINAL REPORT



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1. Final Publishable Summary

1.1. Executive Summary

Advances in micro-, nano-, and biotechnology put increasing demand on nanoscale microscopy and characterization. Atomic force microscopy (AFM) is one of the highest resolution microscopy methods used in this area. The FALCON project focused on a new sensor technology for the detection of the cantilever deflection for fast all-electric cantilever, and make them suitable for a much broader range of applications in air, liquid and even high-vacuum environment.

While traditional AFMs use optical detection of the cantilever sensor and yield very high resolution images they are difficult to automate and the integration into demanding environments (liquid, high-vacuum) is not straight forward or in many cases not feasible. This project aimed at removing these limitations for a large area of attractive AFM applications such as analysis in material science and biological applications. The innovative concept is based on a novel 3D nano-printing method used for the fabrication of nanogranular tunnelling resistors (NTR) that are used as strain sensors for measuring the cantilever deflection. This method, the so-called focused electron-beam-induced deposition (FEED) is a mask-less direct writing technique that allows the fabrication of the NTR sensors on almost any surface with nanometre precision.

The aim of this demonstration project was to prove the viability of our novel self-sensing NTR-cantilever technology for applications with specifications and performance superior to commercially available conventional piezoresistive or optical cantilevers. In order to achieve the ambitious goals, the main objectives of the FALCON project included:

1. The establishment of a fast- and cost-effective NTR-cantilever fabrication cycle that allows the integration into the cantilever process on wafer level. Therefore, a commercial SEM was upgraded to an industrial NTR fabrication tool that was used for a first NTR-cantilever batch production.
2. Performance verification of NTR-cantilever and evaluation of results in order to test the performance for market relevant applications. This included the development of a dedicated test-facility.
3. Development of Prototype AFM upgrade modules for existing AFM systems that allow the end-users an easy and cost-efficient upgrade of their existing systems in order to use self-sensing cantilevers.
4. Market studies and business plan that describes the main aspects of the total business planning for the successful commercialization of the FALCON cantilever. In addition, describing the vision and strategy alongside sub-plans to cover marketing & sales, finance, operations, human resources as well as IPR and legal aspects.

The project consortium consisted of 3 SME's – SCL, NANOSS, AMGT – and is the follow-up of the ALBICAN² project. The main objective of this joint project of 3 high-tech SMEs was to further strengthen their position in the global market of MEMS (micro-electro-mechanical systems) based sensors. This project allowed the SMEs to develop the novel all-electric FALCON cantilevers for atomic force microscopy. By combining their

² ALBICAN – “High-speed all electric bio-cantilever”

[FP7-SME-2011, research for SMEs, grant agreement no: 286146, project coordinator: SCL-Sensor.Tech GmbH], project partners: AMGT, Nanoss, Anfatec and RTD-partners Ecole Polytechnique de Lausanne (LBNI), Johann Wolfgang Goethe University Frankfurt (GU-Nano) and Technical University Vienna (VUT)

technologies and based on the results of the project, this project prepared the basis for a successful market introduction of the NTR cantilevers for attractive AFM applications.

1.2. Summary description of project context and objectives

In atomic force microscopy (AFM) a sharp tip on a micro-fabricated cantilever is scanned over a surface to generate a 3D-representation of the sample surface topography, up to atomic resolution. The cantilever can measure the topography of the sample through a mechanical interaction of the cantilever tip with the sample surface. In order to achieve the extremely high resolution of the AFM, the cantilever deflection needs to be measured extremely precise. This is traditionally done by measuring the angle of reflection of a laser beam focused to the back of the cantilever. Figure 1 shows a schematic representation of a tapping mode AFM system with optical read-out.

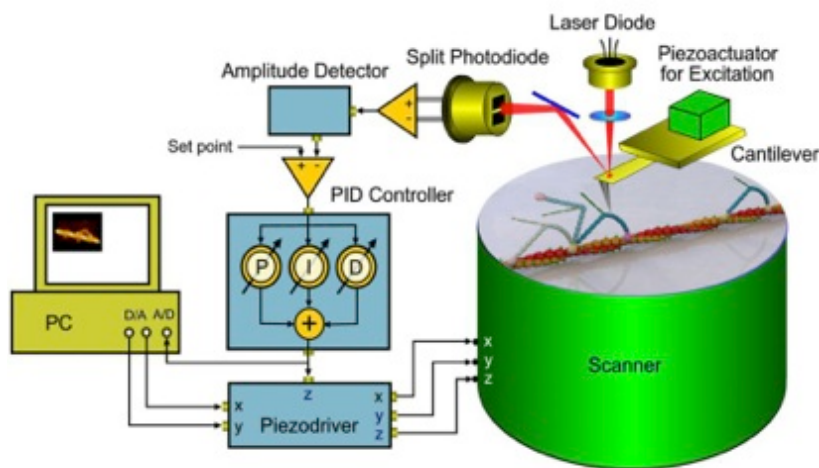


Figure 1: Schematic presentation of a tapping mode AFM system using optical read-out (image taken from Ando, Nanotechnology 23(6):062001 (2012))

Miniaturization has been the driving force of the success of micro-technologies over the last decades. In the field of atomic force microscopy, the miniaturization of AFM cantilevers has led to rapid development in recent years towards higher imaging speeds. While the potential of high-speed AFM is only starting to be exploited, it has become clear that a further increase in imaging speed will be required to make a truly drastic impact in science and technology. For this even smaller and faster cantilevers will be needed. Such cantilevers will be too small to be detected with conventional (optical) means since the cantilevers are of the same size (or smaller) as the best achievable laser spot sizes.

The FALCON project is the follow-up of the ALBICAN project and focuses on a novel technology for high-speed AFM cantilevers, enabled by a new technology for the detection of the cantilever deflection using nanogranular tunnelling resistors (NTR). This new technology allows the fabrication of much smaller, thinner and thereby faster cantilevers usable for high-speed AFM.

Nanogranular materials can be deposited with unprecedented precision and flexibility using focused electron-beam-induced deposition (FEED). This technique is a mask-less bottom up process that can be used for fabrication of micro- and nano-structures. It is based on the beam-induced dissociation of a (metal-) organic precursor gas that is introduced locally to a substrate via a gas-injection system (Figure 2). By using the FEED process thin cantilevers (up to a factor of 10 thinner than conventional Silicon self-sensing cantilevers) can be fabricated with nanometre thin NTR sensor elements. The high lateral resolution of the FEED technique makes

structure formation well below 100 nm possible, therefore enabling a tremendous downsizing of cantilever structures.

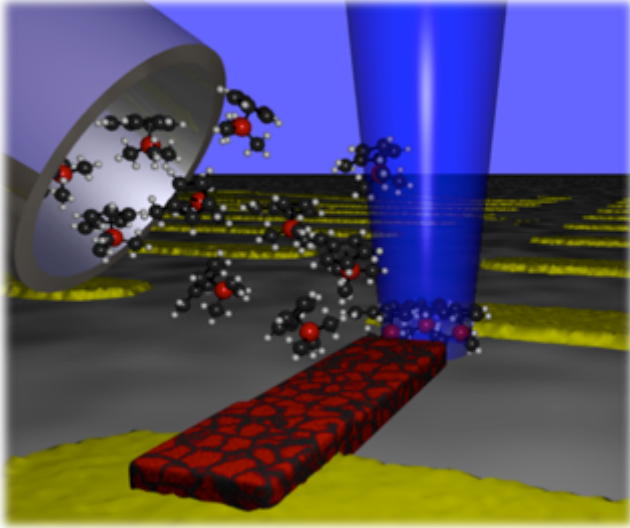


Figure 2: Schematic representation of the FEBID process. The electron-beam of a SEM is scanned over a substrate thereby dissociating precursor molecules supplied by the needle of a gas-injection system.

The aim of this demonstration project is to prove the viability of our novel self-sensing NTR-cantilever technology high-speed applications with specifications and performance superior to commercially available conventional piezoresistive or optical cantilevers. This will allow a breakthrough improvement in self-sensing cantilever performance and enable a new generation of high-speed AFM initiating completely new designs of combinations of AFM and other microscopy techniques (e.g. SEM, optical). Based on the extremely promising results generated in the course of the ALBICAN project, where we were able to measure biological samples, e.g. Collagen fibres, using the novel NTR-cantilevers (see Figure 3 for details) all pre-requirements are given for realization of our ambitious goals.

In order to achieve this goal, and generate all prerequisites for a market introduction of the novel all-electric cantilevers for high-speed applications the following project objectives are addressed:

- **Establish a fast- and cost-effective NTR-cantilever fabrication cycle**
Develop a process strategy for the automated NTR production that allows the integration into the cantilever process on wafer level. Afterwards implement the process strategy for upgrading of a commercial SEM to an industrial NTR fabrication tool and use it for NTR-cantilever prototype production.
- **Performance verification of NTR-cantilever and evaluation of results**
Verification of NTR-cantilever performance that will help the SMEs to highlight the distinct advantages of the NTR-technology compared to conventional optical and piezoresistive cantilevers. In order to test the performance of the NTR-cantilever prototypes a test-facility is necessary that enables the usage of ultra-small cantilevers in combination with high scanning speeds.
- **Development of Prototype AFM upgrade module**
Development of a set of dedicated upgrade modules for existing AFM systems, that allow end-users an easy and cost-efficient upgrade of their existing systems in order to use self-sensing NTR-cantilevers.
- **Market studies and Business plan**
The SMEs will generate a business plan describing the main aspects of the total business planning for the successful commercialization of the FALCON cantilevers. It will describe vision and strategy alongside sub-plans to cover marketing & sales, finance, operations, human resources as well as IPR and legal aspects.

In the first phase of the project a dedicated know-how transfer from ALBICAN RTD partners to the FALCON SMEs took place concerning NTR sensor deposition, cantilever fabrication and AFM development. In addition, the main focus was the development of the process strategy for the fully automated NTR deposition on the

wafer level. A detailed description of the needed process steps concerning hardware and software was developed and all necessary steps for a successful implementation were identified. In addition, a first business plan for the successful market introduction after the end of the FALCON project was created that addresses market research, competition study, and financial and legal plans. The Dissemination activities in the first reporting period addressed the promotion of the FALCON project on several international conferences, training activities between the project partners, and management of intellectual property.

In the second phase of the project the fully-automated NTR deposition process was implemented and demonstrated on wafer level. The FALCON FastScan upgrade package was developed and tested that enables a seamless integration of self-sensing Cantilever in already existing AFM systems (Keysight 55xx-series). In addition, test-customers were approached that provided critical user feedback of the FALCON NTR-cantilever performance for high-vacuum as well as bio-applications. The business plan was updated and finalized addressing market research, competition study, and financial and legal plans. The Dissemination activities addressed the promotion of the FALCON project on several international conferences and fairs.

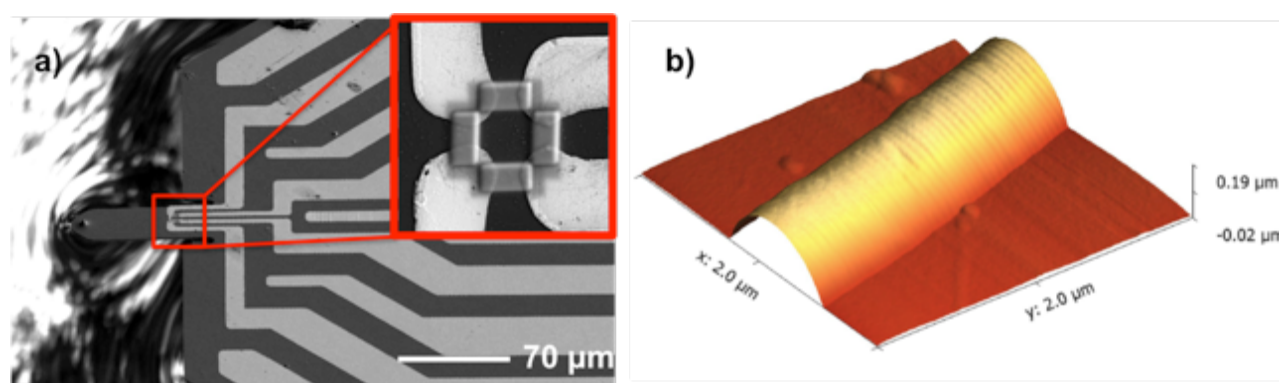


Figure 3: (a) SEM image of an ALBICAN NTR-cantilever with dimensions $70 \times 30 \times 1 \mu\text{m}^3$. The inset shows the bending edge of the cantilever including the NTR sensor elements deposited in a full wheatstone bridge assembly. (b) AFM image of a collagen fiber taken with the NTR-cantilever.

To communicate the project results to the general public a dedicated website has been created for the FALCON project (URL: <http://falcon.freesponsible.info>). The website serves as a platform where general information about the FALCON project is given. Furthermore, the scientific background concerning nanogranular tunnelling resistors, the preparation via focused electron-beam-induced deposition and the application for high-speed imaging using atomic force microscopy in liquids is explained.

The achieved results provide allow the FALCON consortium to fabricate self-sensing NTR-cantilever on wafer level. Market relevant applications concerning AFM measurements in air, liquid, and even high-vacuum could be realized. These new cantilever products will provide benefits complementary to the small optical readout cantilevers such as easier operation and easier integration into other analytical tools such as optical microscopes or SEMs. In addition to this, the developed technologies can be used to further miniaturize the cantilevers to sizes far beyond the sizes that were previously possible (due to the optical detection limit that is currently used in high speed AFMs). This will allow completely new approaches for research into ultra high speed AFMs in the future.

FALCON Project Consortium:

SCL-Sensor.Techn. Fabrication GmbH (<http://www.sclsensortech.com>)

R&D and production expertise of cantilevers with optical and electrical read-out. Application expertise in fast AFM.

NanoScale Systems GmbH (<http://www.nanoss.de>)

R&D and production expertise of the novel NTR-technology for applications in AFM, bio-chemical sensing, and MEMS/NEMS applications.

AMGT Technology OOD (<http://www.amg-t.com>)

R&D expertise in prototyping of various MEMS/NEMS structures with embedded piezoresistors. Front-end implementation of the developed cantilevers for NTR integration. Back-end processing of AFM sensors.

1.3. Description of the main S&T results/foregrounds

1.3.1. Automated NTR production process for integration into the cantilever production on wafer level

Main Objectives:

The main objectives of WP1 were:

- Development of a process strategy for the NTR fabrication on wafer level
- SEM Philips XL40 adaption for NTR sensor element fabrication
- Implementation of FEBID process for NTR sensor element fabrication
- Fully automated NTR batch fabrication
- Performance verification of NTR fabrication process

Description of Work:

The system used for the development of the automation sequence is a Tescan Lyra FE-SEM. The following hardware and SEM-Parameters and where used during the development and testing:

- Robotic stage (SmarAct System) which consists of three linear axes allowing an operational range of 21 x 21 x 21 mm
- 5 kV beam energy for the deposition of NTR
- PC6 (about 1.6 nA) beam current for the deposition of NTR
- All depositions are done with a platinum precursor³.

The final development of the automation and its final assessment is performed on wafer pieces offered by AMG-T. The entire wafer is FIB treated by OFFIS to get a final electrode design of the blank electrodes as depicted in Figure 4. Overall, 136 electrode structures were prepared. The wafer carrying stubs are mounted on the robotic stage. A vertical alignment of the wafer's columns to the robotic axis is done by eye-control only. No additional alignment measures are necessary.

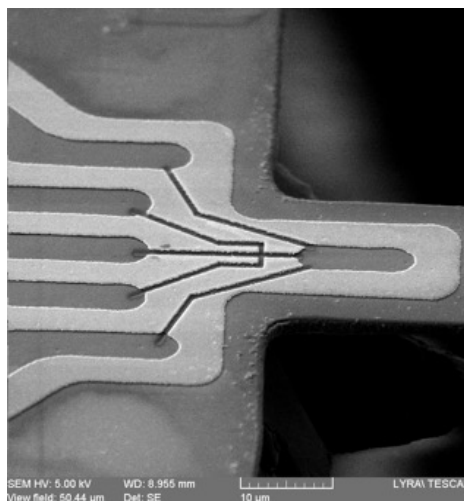


Figure 4: Example of the FIB treated electrode structure resulting in the final electrode design.

³ Trimethyl(methylcyclopentadienyl)platinum(IV)

Developed Scan Generator (SG)

The developed SG is a hardware prototype (developed by OFFIS) allowing for controlling the SEM beam and acquiring images using an analog SEM interface. The scanner has two main connectors:

1. A micro-USB port for the communication to the control PC. This connection has to be directly to one of the PC USB Ports. An interfacing USB HUB can cause major signal delays resulting in malfunctions of the hardware.
2. A Sub-D 25 connector for the analog connection to any SEM.

The SG offers two different operational modes: The “image acquisition mode” works very similar to conventional build-in methods of image acquisition; the point list mode allows to set the electron beam in patterns which can be defined by the user. Simultaneous image acquisition is not possible during the latter mode.

Software

The scanner can be operated by an additional PC only. A library and an application for Windows is available. Furthermore, static C++ libraries and header-files are available allowing for the development of own software.

The developed automation sequence, which is presented in the following section uses the supported open source development framework “OFFIS automation framework”⁴.

The standalone application for Windows allow to connect to the scanner and to call all operations. Image acquisition, point list loading and execution, and controlling of all accessible parameters. Acquired images are displayed in the application as well. Before a point list can be executed, it has to be loaded to the scanner.

Implementation of FEBID process for NTR sensor element fabrication:

The automation sequence is diverted into 5 different fundamental steps as depicted in Figure 5.

Initialization: during the initialization, the software connects to the HW units SG and robotic stage and sets them to operational mode. Subsequently, a calibration method is called to acquire a geometrical description of the wafer, which speeds up all subsequent positioning steps, in particular the indexing.

Indexing: the automated indexing starts with the first electrode. Subsequently, the sequence processes firstly all positions within a column and secondly all rows using the expectancy matrix and the linear position estimator.

Depositing: The automated deposition process uses all validated and stored positions of the indexing sequence. The SG performs point list based scans in order to deposit tungsten. The deposition process is interrupted by a drift detection and correction after several seconds. This drift correction is performed by scanning a region of interest with the same geometrical properties as an enveloping square of the NTR deposition.

⁴ <https://github.com/OFFIS-Automation/Framework>

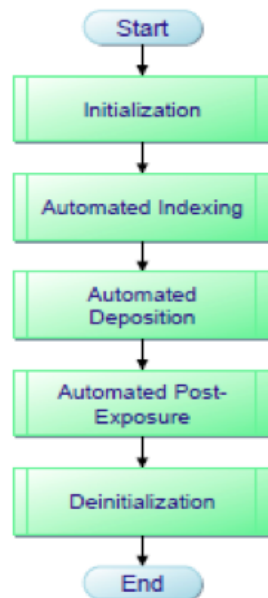


Figure 5: Sequence of the fully automated NTR deposition process.

Post-Exposure: the post exposure is performed in the same way as the depositing process, except the GIS has been closed manually by the operator in advance.

Deinitialization: the deinitialization stops the communication to the HW devices and stops the automation sequence.

Performance verification:

The assessment of the entire automation sequence is based on the provided wafers with cantilever and electrode structures. The wafer is separated into four quarters to meet the geometrical criteria of the robotic setup. The automation sequence is developed on different quarters and wafer samples, while the demonstration and evaluation is done with different runs with up to 27 samples. The 27 samples on the wafer were in 7 rows and 5 columns.

The expectancy matrix is crucial and speeds up the entire process on wafer level. Using the expectancy matrix avoids this navigation time completely and reduces the process time to necessary steps only. The calibration of the wafer (detection cantilever positions, centering, focusing, calculation of wafer plane) takes overall an average of 110 seconds (max 128 seconds, min 89). This value depends on the rotation of the wafer and hence the amount of required searching loops.

The indexing of all electrode structures is reliable. 27 structures could be found. The algorithm detected 27 usable structures in an average time of 13 seconds per structure. 81% (22) of these structures were found immediately using the trained position prediction without additional search loops. The remaining 19% (5) structures were found successfully using search loops within an average time of 26 seconds.

The searching time for electrode structures which are not findable (no structure on wafer despite indication by expectancy matrix) is 61 seconds.

The overall success rate and average detection time is 100% and 15 seconds (min 11.5 seconds; max 27.9 seconds), respectively.

The deposition process was performed on all 27 cantilevers. The average process time for the automated deposition process is 129.3 seconds per structure and this includes the actual FEBID time of 120 seconds. Hence, the time share of the automation is 9.3 seconds per cantilever.

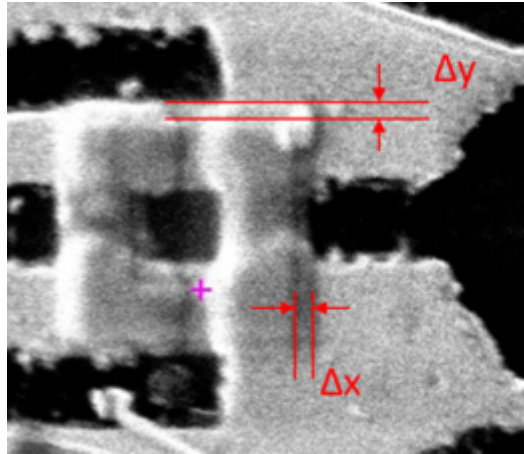


Figure 6: NTR deposition and its precision: The deviation in x and y is less than 200 nm:

Investigation of the failed depositions indicate, that the drift correction can become a disruptive measure instead of optimizing the process: the appearance of the electrode structure changes during the deposition. The template matching based algorithms cannot follow this changes and results in misdetections of the correct position. In success cases in contrary, the drift correction keeps the deposition centered with a maximal deviation of less than 200 nm (cf. Figure 6).

The process and time for the post-exposure routine is the same as for the deposition process, just with closed GI system and larger beam current. Problem is the drift correction as less important, since no deposition is applied and the appearance of the sample doesn't change. Hence, the success rate of the post-exposure can be assumed as 100%.

In conclusion, the presented strategy, development and implementation proof the feasibility and capabilities of automation for NTR deposition. The developed HW offers an operation performance which fulfils all criteria to perform a reproducible process as characterized by research. The proposed automation sequence is proven to work on medium runs without any distortions and process time and success rate are already adequate for a serial process, since a daily throughput close to hundred pieces is realistic.

Summary:

A dedicated process strategy for the upgrade of a commercial SEM to a fully automated NTR fabrication tool was developed in WP1. The implementation of this process strategy will enable the FALCON consortium to establish a cost-effective and competitive NTR fabrication platform. Documented in detail in Deliverable 1.1 *"Detailed upgrade protocol for automated NTR deposition"*.

The main tasks were the implementation of the developed process strategy. This meant an adaption of dedicated SEM for NTR sensor element fabrication, the implementation of the FEBID process, the realization of a fully automated NTR batch fabrication, and the performance verification of the NTR fabrication process (Task 5). The work and all the results were documented in detail in Deliverable 1.2 *"Demonstration of fully automated NTR sensor element deposition on test-wafer"*.

1.3.2. NTR cantilever prototype production

Main Objectives:

The main objectives of WP2 were:

- Define target specifications for NTR cantilever prototypes, incl.: optimization of the vertical structure of the cantilevers; material parameters of the cantilever's sub-layers; optimize the electrode layout; tuning the resonance frequency and control of Q-factor
- Fabrication of cantilever prototypes for target applications, incl.: design of dedicated test structures and specified cantilevers; conduct of process integration experiments for incorporation of NTR sensor elements; fabrication of specified cantilever structures, etc.
- Characterization and test of NTR cantilever prototypes, incl.: determine optimal tapping amplitude values, current and voltage levels, etc. specific conditions for measurement and exploitation of cantilevers with NTR.

Respectively, Deliverable 2.1 "Fabrication of 4 different NTR cantilever prototypes" proves that a fabrication of sufficient variety and sufficient number of cantilevers for NTR deposition needed for implementation of the project, has been provided for the project implementation.

Description of Work

Usability of the NTR-enabled devices depends critically on the electrical and mechanical characteristics of the self-sensing MEMS. For this purpose the know-how for manufacturing of cantilevers, incl. the one generated in the research project ALBICAN (FP7-SME-2011-BSG, GA#: 286146), has been used and further developed by AMGT and was transferred to the project partner SMEs SCL and NANOSS within the duration of the project.

Define target specifications for NTR cantilever prototypes

Analyses of the influence of each material parameter on overall cantilever performance and usability in potential AFM application have been implemented. Particularly, it has been shown that initially targeted bio-applications require very "soft" cantilevers which are in strong conflict with the sensitivity of the strain sensors exploiting NTRs. Thus, novel approach to demonstrate the NTR superiority over existing analogues has been considered.

- a) Material parameters of NTR and cantilever's sub-layers

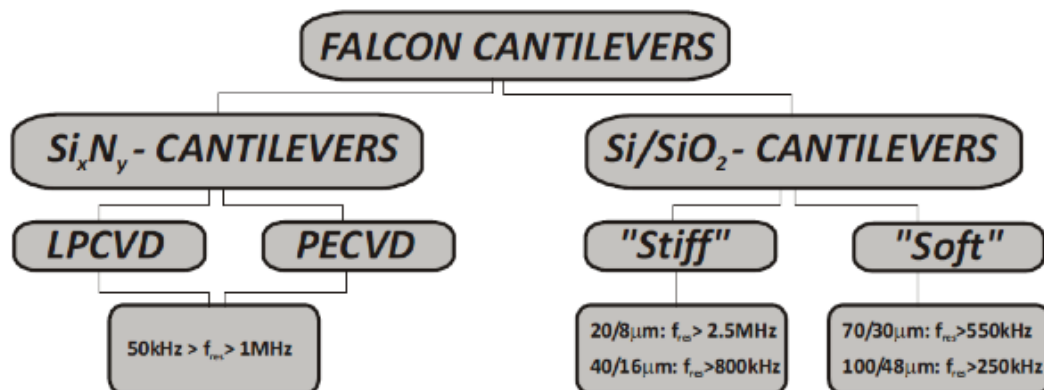


Figure 7: Cantilever Material Options

Two cantilever materials – Si/SiO₂ and Si_xN_y have been preferably used, as shown in the Figure 7. By means of numerical calculations, the influence of material parameters on overall cantilever performance has been

analyzed. Besides, it was experimentally found that FIB-cut metal electrodes on PECVD Si_xN_y layers reveal very low insulation resistance. Despite series of dedicated experiments have been triggered, it was found that PECVD Si_xN_y layers have a limited application when FIB-cutting method is exploited for metal patterning.

b) Vertical structure of the cantilevers – optimization for target applications

Since lithography equipment with limited patterning performance has been exploited in the project, a complex vertical structure of the cantilevers was the only compensating option. Patterned structures are located one-above-the-other, thus multilayered cantilevers – Si/SiO_2 , $\text{Si}_x\text{N}_y/\text{SiO}_2$, etc. have been created. Alternative techniques for cantilever materials' deposition have been experimentally studied incl. spin-on deposition from zol-gel solutions.

c) Electrode structure (layout) for targeted applications

For achieving high resonance frequency and low spring constant small-size cantilevers have been developed. The layout of the smallest cantilever enabled with four sensing resistors and an electrothermal actuator, is demonstrated in Figure 8 (left). Metal patterning takes place in two stages: first, the overall layout is shaped with optical photolithography and after that, the metal structure is further processed by FIB-cutting as demonstrated in the left figure. The overall size of the cantilevers: $40\mu\text{m} \times 16\mu\text{m}$. Besides, these AFM sensors are provided with a second cantilevered structure also called “foreground”. The length \mathcal{L} and the thickness of the foreground structure define its resonance frequency.

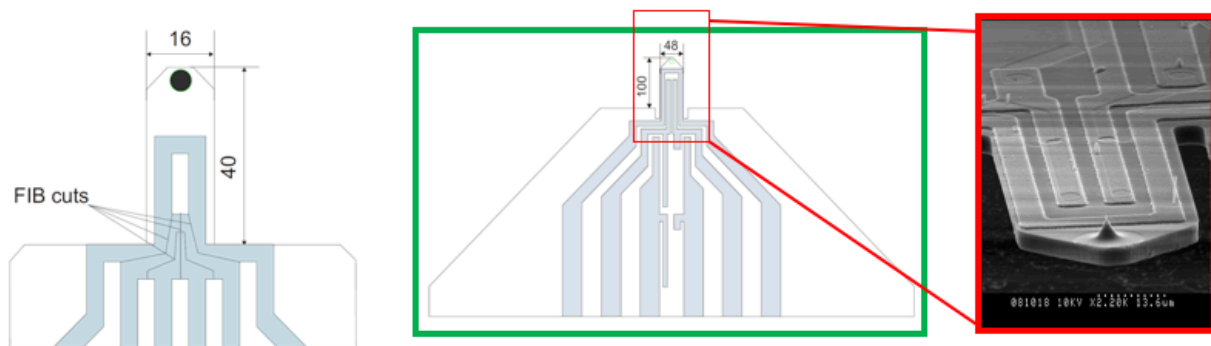


Figure 8: Layout of electrodes of dedicated FALCON cantilevers: (left) $40 \times 16\mu\text{m}$, (right) $100 \times 48\mu\text{m}$.

In order to control the Q-factor in vacuum application of NTR cantilevers, a thermo actuator is needed. The layout of electrodes of a cantilever having size $100/48\mu\text{m}$ is illustrated in Figure 8 (right). This layout represents the smallest cantilever with two self-sensing resistors (NTR) resolved by the available photolithography equipment in AMGT and without FIB-cut.

d) Control of resonance frequency

Since the length and width of the cantilevers are defined by the geometry of the masks for photolithography, the only variable parameter is the cantilever thickness. Respectively, a method for controllable tuning the thickness by a dry blank etching on the rear side of the wafers has been developed and experimentally verified.

e) Control of cantilever Q-factor

Target the vacuum applications of AFMs depends critically on means for Q-factor control on the cantilevers, thus additional structures for electro-thermal actuation have been integrated on above mentioned cantilevers. The layouts of both thermo actuators are shown in Figure 8.

f) Tip sharpness

Providing sharp tips with RIE at fabrication of self-sensing AFM cantilevers is an extremely tough problem to solve – more that 90% of the yield loss is due to the bad tip sharpness. Thus a concept of: i) optical microscope monitoring the pre-etched test patterns ii) for each tip size, a specific modification of RIE process by hardware means, has been developed.

Fabrication of cantilever prototypes for target applications

For fabrication of each type of the above mentioned of AFM cantilevers, a dedicated set of masks for photolithography has been used. These masks comprise patterns in every layer of both above mentioned cantilever device and test structures, as displayed in Figure 9.

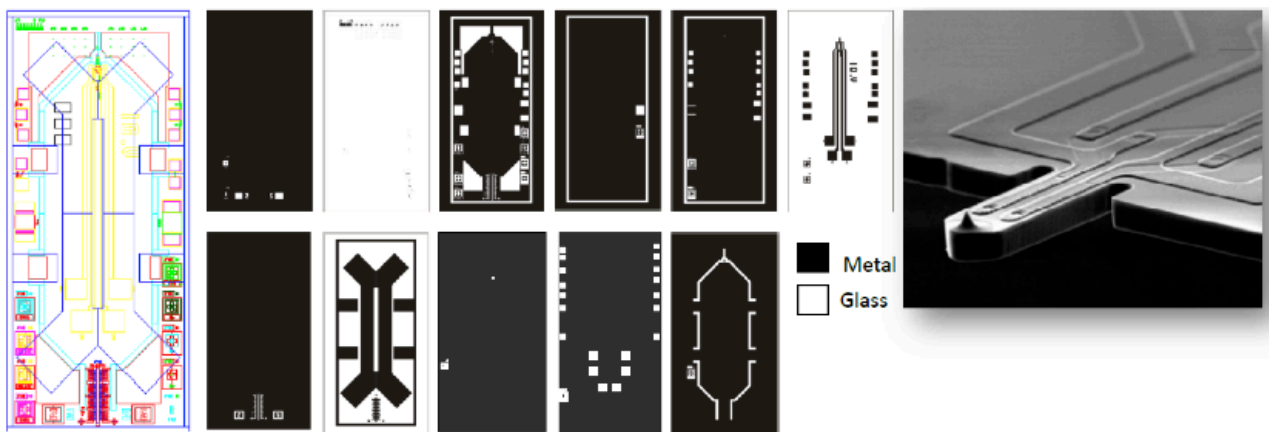


Figure 9: Breakdown of the layout of the cantilever in masks for photolithography.

Besides aimed performance of the cantilevers, the usability of cantilevers having a length of less than 100 μm , has been boosted by providing them with a second cantilevered structure, also called “foreground” shown in Figure 10. Respectively, a new process sequence for shaping the foreground by means of wet etching in KOH solution has been developed.

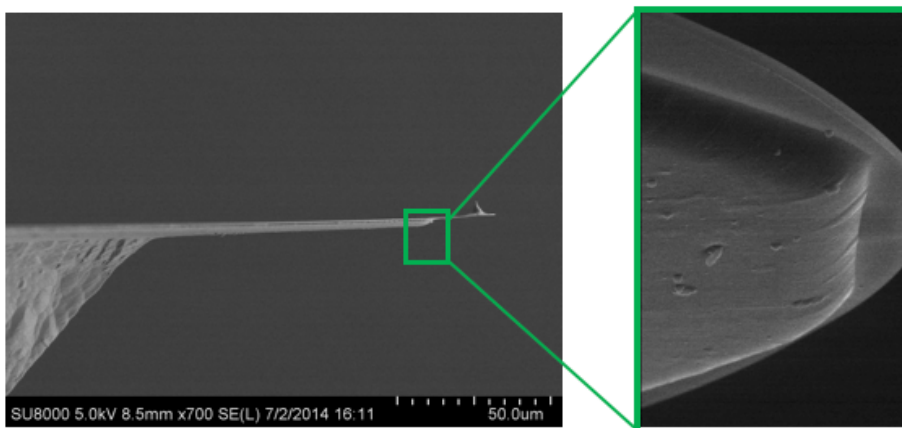


Figure 10: Si_xN_y cantilevers with a P^+ second cantilever structure foreground.

During the research within ALBICAN project, it was found that due to very low supply voltages used with NTR-enabled cantilevers, there's no need of passivation layers. Also, it was found that passivation with PECVD harms the NTR performance. Since a dominating number of the targeted applications of NTR cantilevers are considered to be related to vacuum applications, experiments with passivation layers have been abandoned.

Strategy of mass manufacturing of NTR enabled AFM cantilevers

In order to secure efficient mass manufacturing of AFM cantilevers for NTR enabling, it was experimentally validated the options for:

- Tuning of the cantilever parameters. Having the cantilevers with above mentioned patterned structures, the parameters can be tuned on wafer level, to achieve the optimal performance as requested per specific application.
- Metal patterning. Double step metal patterning: by optical lithography and FIB cutting has been considered as most promising method. To reduce the FIB processing time, an optimized layout of the metal pattern has been designed.

Tip sharpness. The tip sharpness is the key the cantilevers' yield. By unconditional deposition (Figure 11) of NTR and tip-apex in one FIB-process, a yield of 90% can be achieved.

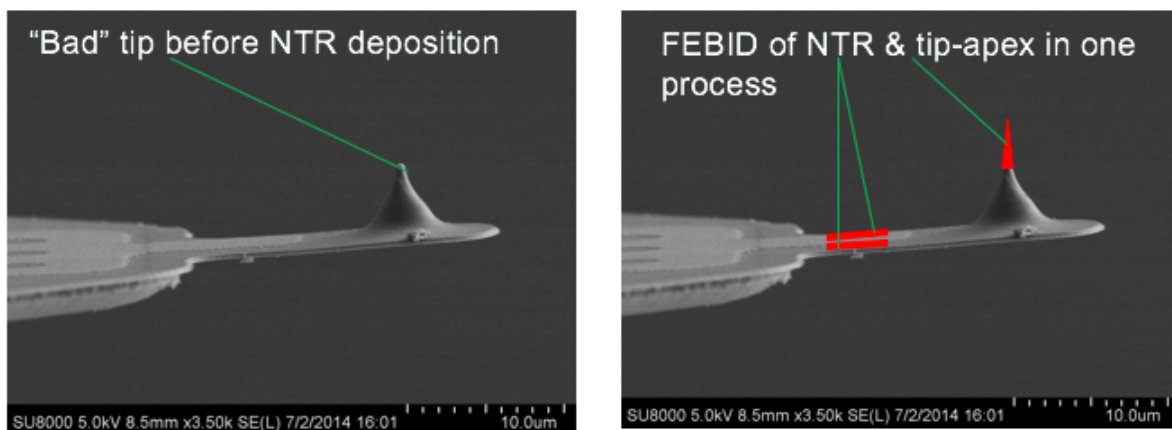


Figure 11: Shaping the tip-apex with FEBID - exploiting the same HW&SW as for NTR deposition.

Additional works in WP2 have been focused on preparation of optimized structures on wafer-level to achieve automated NTR deposition, to reduce the cost of fabrication and to improve further the tip-to-sample accessibility. Technical detail are confidential, and respectively, not disclosed here.

Summary & Results

AFM cantilevers having four different layouts were available for NTR deposition:

- 100/48 μm ($250\text{kHz} < f_{\text{res}} < 700 \text{ kHz}$)
- 70/30 μm ($550\text{kHz} < f_{\text{res}} < 1.4\text{M kHz}$)
- 40/16 μm ($800\text{kHz} < f_{\text{res}} < 3.0\text{MHz}$)
- 20/8 μm ($2.50\text{MHz} < f_{\text{res}} < 4.5\text{MHz}$)

These cantilevers have been prototyped on different substrates/layers, thus, a sufficient number of cantilevers for NTR deposition have been prototyped for project implementation.

1.3.3. High-speed Bio-AFM test-facility

Main objective:

The main objective of this work package was the setup of a dedicated test facility for the NTR cantilever prototypes. In addition, application notes were produced that highlight the advantages of the FALCON self-sensing cantilever technology.

Description of Work:

Test-System for NTR cantilever

For the test-system for the FALCON self-sensing cantilever a new cantilever holder as well as a new read-out electronic and a switch-box was developed. Figure 12 shows the AFM head with the new cantilever holder. The main focus of the new design was:

- Electrical integration of a first stage pre-amplifier unit directly next to the Cantilever, at the beginning of the flexible PCB
- Mechanical Re-designing to improve the mechanical high frequency performance, in order to achieve:
 - Enhanced stability of Cantilever / CL-holder coupling
 - Better damping of resonances
 - Adaptation to new mechanical mounting and alignment situation

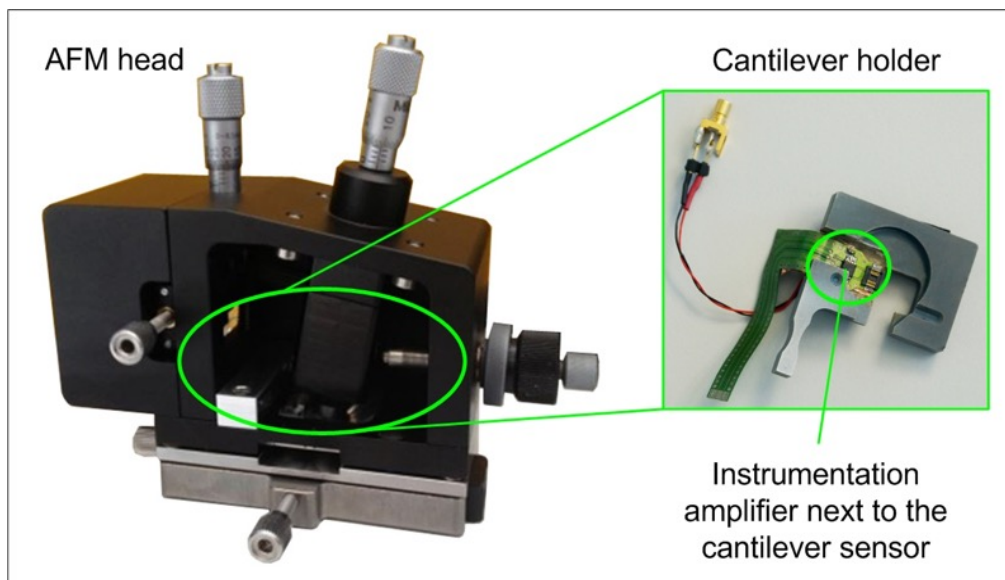


Figure 12: AFM head for optical and electrical read-out. The instrumentation amplifier was integrated next to the cantilever sensor for noise reduction.

In addition, a new read-out electronic was developed. The main goal was to bring the full performance of the NTR sensors to the AFM controller. The procedure was to create a fully adapted, NTR – dedicated solution (not only a re-parameterized read-out for classical piezoresistive cantilever sensors).

During designing electrical read-out circuit, the main focus was:

- Better adapting to NTR resistor behaviour (higher drift-compensating range, different impedance adjustment)
- Further reduction of noise and better high frequency performance:

- Development and Integration of the first pre-amplification (pre-readout) unit directly next to the cantilever, at the beginning of the flexible PCB.
- Re-designing the main PCB (for adapting to the outsourced first pre-amplification stage)

The switch-box was developed, enabling switching between optical and electrical read-out of the cantilevers, for means of comparison, evaluation and adjusting of the data interpretation and presentation. The switching point is located between the AFM head and the AFM base (see Figure 13).

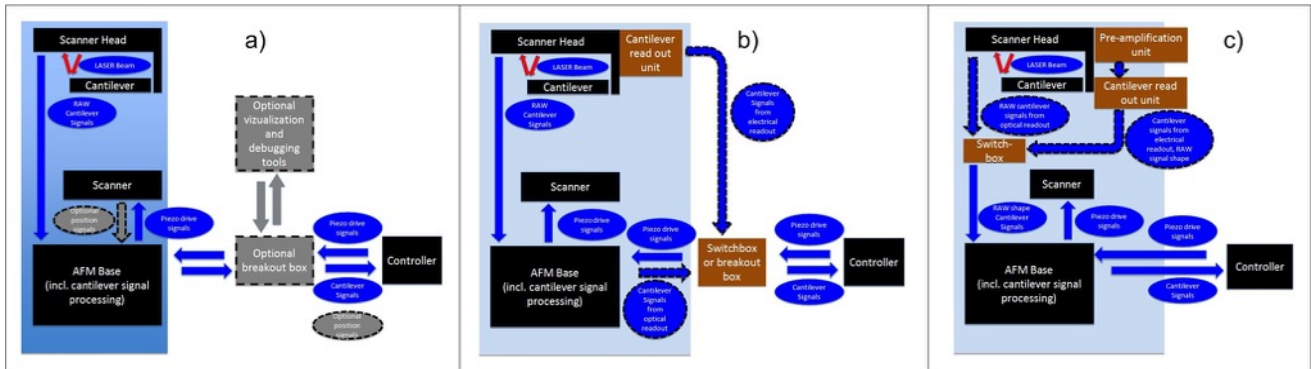


Figure 13: Cantilever signal readout path configuration options: a.) Original AFM including designated optional features b.) Setup enabling switching between optical and electrical cantilever readout (ALBICAN version) c.) Setup enabling switching between optical and NTR electrical cantilever readout, switching in raw cantilever signal path (dedication FALCON version).

The NTR test-system can perform an imaging speed of 20 lines/s with 90% undistorted scan image surface in air and vacuum. It is therefore well prepared to distinguish the differences between NTR and classical (PR) electrical read-out cantilevers (both advantages and disadvantages within their optimal parameter operation window). Exemplary measured resonance curves of two different NTR-cantilevers are shown in Figure 14.

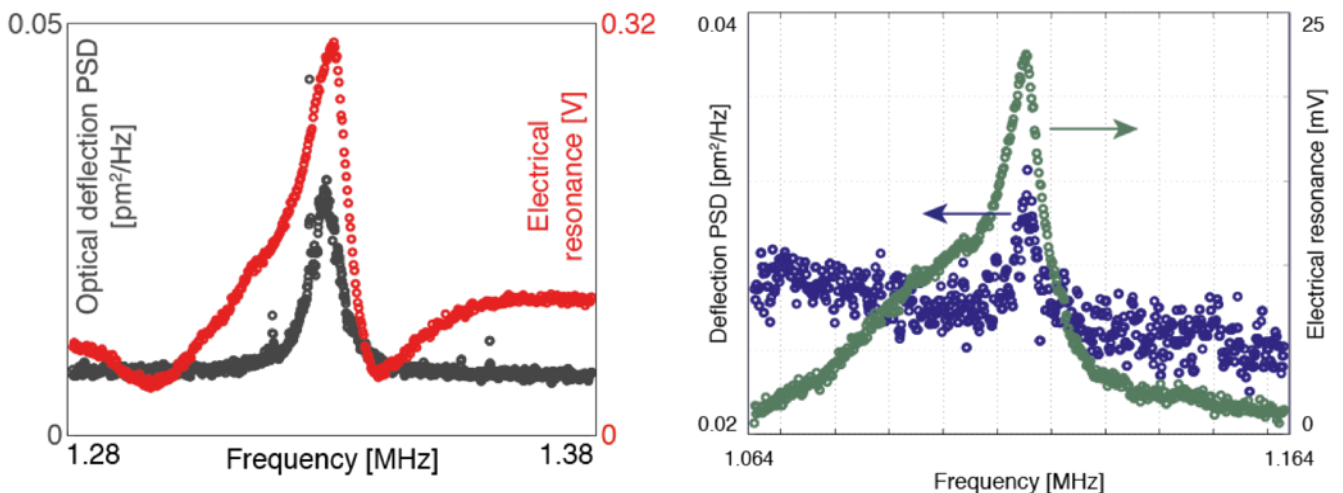


Figure 14: Measured Resonance curves for two different Si_3N_4 -cantilevers. For each cantilever the resonance frequency using optical detection as well as measuring the electrical signal from the NTR sensor elements was used. The resonance frequency for the left measurements was $f_{\text{res}} = 1.32$ MHz. For the measurements shown on the right side a resonance frequency of $f_{\text{res}} = 1.11$ MHz was observed.

Application studies:

In order to identify and select 1-2 applications based on input from test-customers that demonstrate the advantages of the FALCON self-sensing cantilevers two different applications have been addressed:

1. Correlated Microscopy in high-vacuum environment

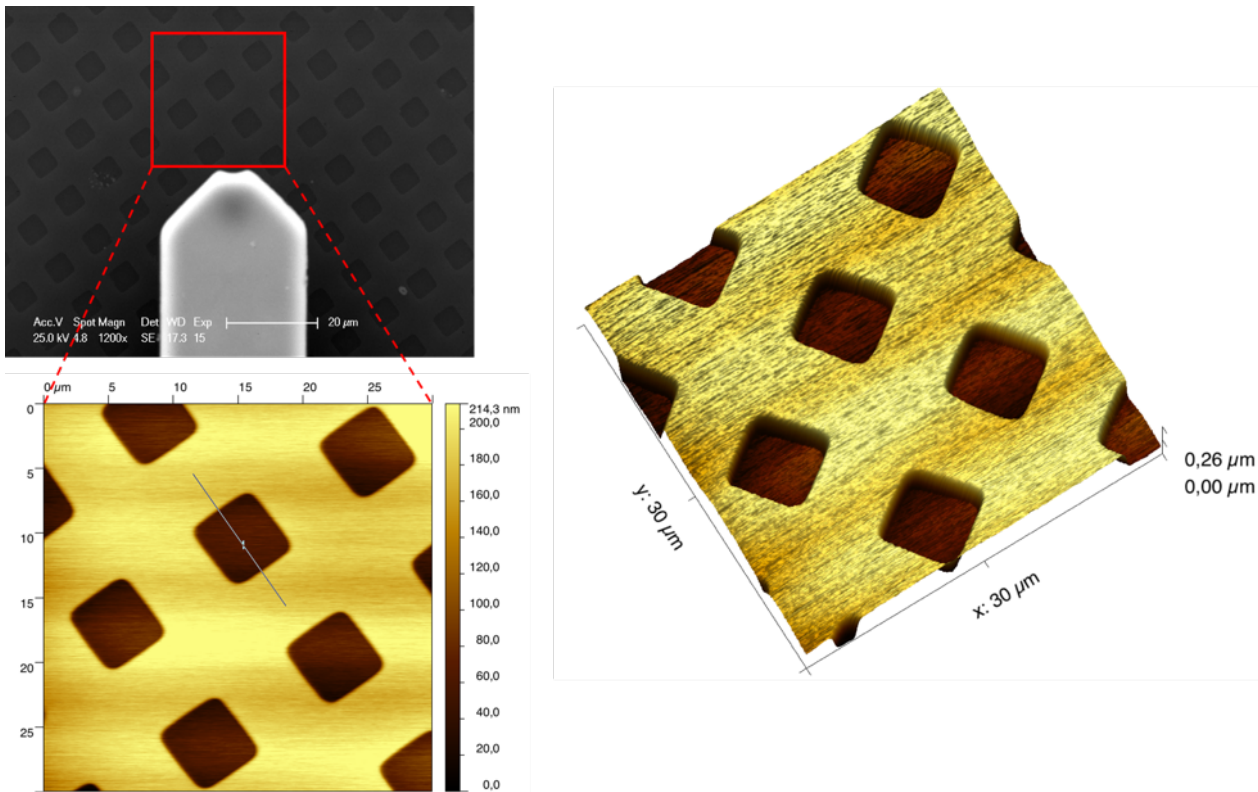


Figure 15: (Top Left) SEM image of NTR Self-Sensing Cantilever inside the SEM above the test-grid. (Bottom left) Correlated AFM image using the NTR cantilever on exactly the marked area in the SEM image. (Right) 3D representation of the test-grid structure measured in high-vacuum environment.

To demonstrate the advantages of the NTR Self-Sensing Cantilever we have used them in a first application for correlated microscopy in a high-vacuum environment inside a scanning electron microscope (SEM). For that we used the existing AFSEM™ of the company GETec Microscopy Ltd. The AFSEM™ is an AFM developed for easy integration into high-vacuum environment especially for integration into SEMs. The AFSEM™ only works with self-sensing cantilevers that require no optical read-out. The NTR self-sensing cantilever are therefore ideally suited for working with the AFSEM™ microscope. Figure 15 displays a correlated measurement inside the SEM. First the area of interest can be identified using the SEM image. Afterwards the cantilever can be positioned exactly on the desired area and the AFM image can be taken. This enables a correlated image using both the SEM and the AFM. Therefore, the additional information from the AFM measurement (topography, phase, ...) can be used to analyze the sample.

The usage of the NTR Self-Sensing Cantilevers for high-vacuum applications has the great benefit that no optical detection of the cantilever deflection is necessary. This enables a much easier integration into the high-vacuum host system. In addition, it allows for a much faster operation time since the time-consuming optical alignment can be circumvented and starting the AFM measurements can be performed within minutes.

2. FALCON cantilever in air & liquid environment for bio-applications

To demonstrate the advantages of self-sensing small & soft cantilevers we have integrated the self-sensing technology into a commercial available AFM system by developing a FALCON FastScan AFM upgrade module for a Keysight 5500 AFM (former Agilent). This AFM has a world-wide installed base and is mainly used for measurements on biological samples in liquid. It offers a variety of imaging modes like contact, tapping, force modulation, phase imaging mode, etc., and is therefore an optimal AFM system for usage of the FALCON self-sensing cantilever.

The complete FALCON FastScan AFM upgrade module is shown in Figure 17. It consists of a scanner nose upgrade, a pre-amplifier and a switch-box. The upgrade module allows the usage of self-sensing cantilevers using electrical read-out. Therefore, no optical detection is needed for AFM imaging. This brings great advantages for measuring biological samples especially in non-transparent liquids (e.g. blood). In addition, the self-sensing cantilever are more stable in terms of drift that allows long-term measurements without the need of a constant re-alignment of the laser beam. In order to demonstrate the potential of the usage of the self-sensing cantilevers in combination with the FALCON FastScan upgrade module, AFM in a non-transparent liquid have been performed. In Figure 16 Figure 19 the used setup is shown. A standard calibration grid was inserted into a bowl of milk and afterwards measured using self-sensing piezo-resistive cantilevers in combination with the FALCON upgrade module. As can be seen in Figure 19 right the grid can be perfectly imaged in non-contact mode even in the non-transparent liquid environment.

Summary:

We could demonstrate to attractive applications for market relevant applications using the self-sensing NTR cantilevers. One is the usage of the NTR cantilevers in high-vacuum environment. Here the benefits are:

- No optical alignment needed due to self-sensing measurement
- Fast operational time → AFM is ready in a few minutes
- Self-sensing cantilever technology allow an easy integration into high-vacuum host system (especially SEMs)
- True correlated microscopy is possible (Combination of SEM image and AFM image at exactly the same spot)

In addition, we demonstrated the application of the FALCON FastScan upgrade package in air and liquid environment. Here the benefits are

- Usability of self-sensing cantilever in non-transparent liquids (e.g. blood) for bio-applications
- Higher stability concerning drift (long-term measurements are possible)
- Potential for further optimization using passivation techniques

In summary, we could demonstrate the usability of the NTR self-sensing cantilever in air, liquid, and high-vacuum environment. This opens the road for a range of market relevant applications.

1.3.4. FALCON FastScan AFM upgrade module

Main objectives:

The main objective is a tested prototype of a final FALCON FastScan AFM (atomic force microscope) upgrade module. The usability of small & soft self-sensing cantilevers (NTR - nanogranular tunnelling resistor as well as piezo resistive cantilevers) in one of a world-wide installed modern AFM system with the following advantages should be demonstrated:

- No speed limitation due to cantilever bandwidth
- No laser light on the sample

Description of Work:

To demonstrate the advantages of self-sensing small & soft cantilevers we have integrated the self-sensing technology into a commercial available AFM system by developing a first prototype FALCON FastScan AFM upgrade module for a Keysight 5500 AFM (former Agilent). This AFM has a world-wide installed base and is mainly used for measurements on biological samples in liquid. It offers a variety of imaging modes like contact, tapping, force modulation, phase imaging mode, etc., and is therefore an optimal AFM system for usage of the FALCON self-sensing cantilever.

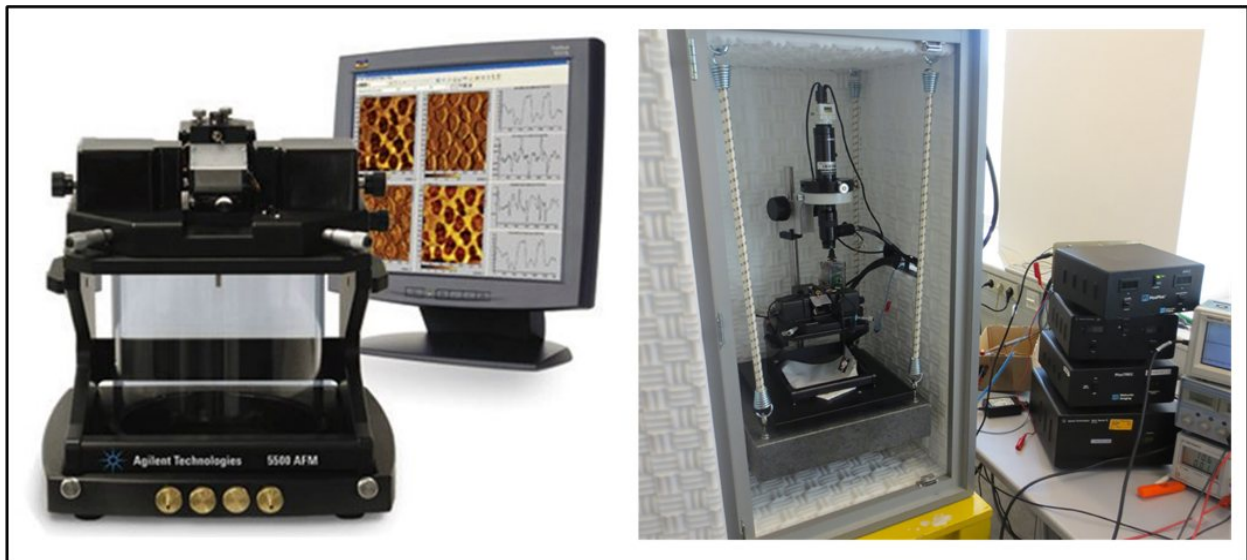


Figure 16: Keysight 5500 AFM situated at the test customer in Linz. The NTR self-sensing cantilever upgrade package was integrated into this AFM for imaging in air and liquid environment.

One of these systems is located at a partner from our scientific network (JKU, Johannes Kepler University in Linz, Austria). JKU uses various Keysight AFMs mainly for bio and life sciences analysis. Figure 16 displays the Keysight AFM system at JKU with the already installed first prototype FALCON upgrade package for imaging with the self-sensing cantilevers developed in course of the FALCON project.

The upgrade package consists of 3 main parts that are displayed in Figure 17:

1. Newly designed AFM scanner nose
2. Post-amplifier box
3. Final switch box



Figure 17: Key components for the FALCON upgrade module: (a) Newly designed AFM scanner nose upgrade for a Keysight 5500 AFM. (b) Post-amplifier box for the FALCON upgrade module. (c) Final Switch box for the FALCON upgrade module.

AFM scanner nose including read-out electronics

In order to be able to work with the FALCON self-sensing cantilevers the new cantilever holder including a read-out electronic for self-sensing cantilever was developed (see Figure 17a). The most important design requirements for the scanner nose upgrade in order to use the FALCON self-sensing cantilevers are:

- Optical and self-sensing imaging opportunity with the same nose
- Tip – sample positioning system using existing CCD camera system
- Self-sensing measurements in liquid and
- An integrated amplification stage for low noise measurements

The final design allows selecting between 0.5 and 2V low noise voltage supply for the Wheatstone bridge. The 0.5V supply is preferred for the NTR cantilevers and necessary for performing measurements in liquid environment. 2V Wheatstone bridge supply is preferred in dry state using piezo resistive self-sensing cantilevers for increased sensitivity. The new instrumentation amplifier allows adjusting the deflection signal amplification via an external wired resistor. The same board can be used for an acoustic excitation or a thermal excitation nose just by replacing a wire jumper in form of a 0 Ohm resistor. A main requirement during PCB design was using a soft and small flex part for the cantilever connector to fit through the hole of the nose and to be afterwards sealed, protecting the electronics during operation in liquid. The new board design combines the rigid equipped part with the flexible connector part in a multilayer board.

Post-Amplifier Box for FALCON upgrade module

The measured sensor signal must be amplified as soon as possible after the readout from the sensor chip to avoid noise pickup or to keep the signal noise ratio as high as possible. Therefore, we have integrated the first amplification stage inside the small nose. The second stage was placed outside the scanner but directly on the AFM base as a post-amplifier.

For the final post-amplifier the following optimization steps and re-designs have been included:

- Variable amplification between 1 and 100
- Optimized PCB design to fit into smaller new housing
- Usage of micro D-Sub-9 connectors

The post-amplifier exhibits a variable amplification which can be adjusted between 1 and 100 and is equipped with an optional low pass filter. It is directly connected to the standard cables of the Keysight system without the need of changing the standard hardware. The amplifier has been rerouted for an optimized PCB board

perfectly fitting to a new housing. The micro D-Sub 9 connectors are surface mounted to reduce the wiring length for all needed signals for optimized signal to noise ratio. Figure 17b displays the final Post-Amplifier Box for the FALCON FastScan upgrade module.

Switch box for Upgrade Module

The third needed newly developed hardware, the switch box, is placed between the stage and the AFM's head electronic box (HEB). The main function of the switch box is to select between the optical and the new self-sensing mode. Furthermore, the power supply and the offset voltage for the pre-amplifier are connected via the switch box.

For the final switch box the following optimization steps and re-designs have been included:

- Redesign of external connectors
- Redesign of all hardware
- Easy switching between optical and self-sensing

In the new design the signal splitting and the external connectors are PCB surface mounted and not wire connected to reduce the noise. In addition, the supply voltage for the self-sensing cantilever hardware is now taken from an original Keysight breakout box whereby a redesign of the whole hardware from +/- 6V to +/- 15V was necessary. The deflection output of the switch box is connected to the original Keysight MAC-II or MAC-III box using their lock-in amplifier to drive the AFM with the self-sensing cantilever deflection signal. To switch between optical and self-sensing intermittent contact mode just software settings are necessary. Using the Keysight AFM in combination with self-sensing cantilever in contact mode is possible but requires a change in the HEB, where a circuit path needs to be opened and switch between optical and electrical contact mode has to be placed at the HEB. Figure 17c shows the final switch box developed for the final upgrade module.

Test imaging

After assembly and first electrical pre-testing and characterization of all final upgrade package components (nose with pre-amplifier, post-amplifier, and switch box), all parts were integrated into the Keysight AFM system. An in depth characterization of the AFM performance of the final upgrade package was performed using a standard calibration grating. AFM images using self-sensing cantilevers were performed in contact mode, tapping mode using either external piezo-actuation or tapping with self-actuated heater structure.

Figure 18 displays AFM images recorded in air at ambient conditions using contact mode (a), tapping mode with external piezo-actuation (b), and tapping mode with self-actuation (c). All different modes were also performed in liquid environment using de-ionized water for contact mode (d), tapping mode with external piezo-actuation (e), and tapping mode with self-actuation (f). This test images clearly show the capability of the final upgrade package to use self-sensing cantilever on all Keysight 5x00 AFM series both in ambient conditions as well as in liquid environments. Therefore, a completely new market segment for the FALCON cantilevers can be addressed.

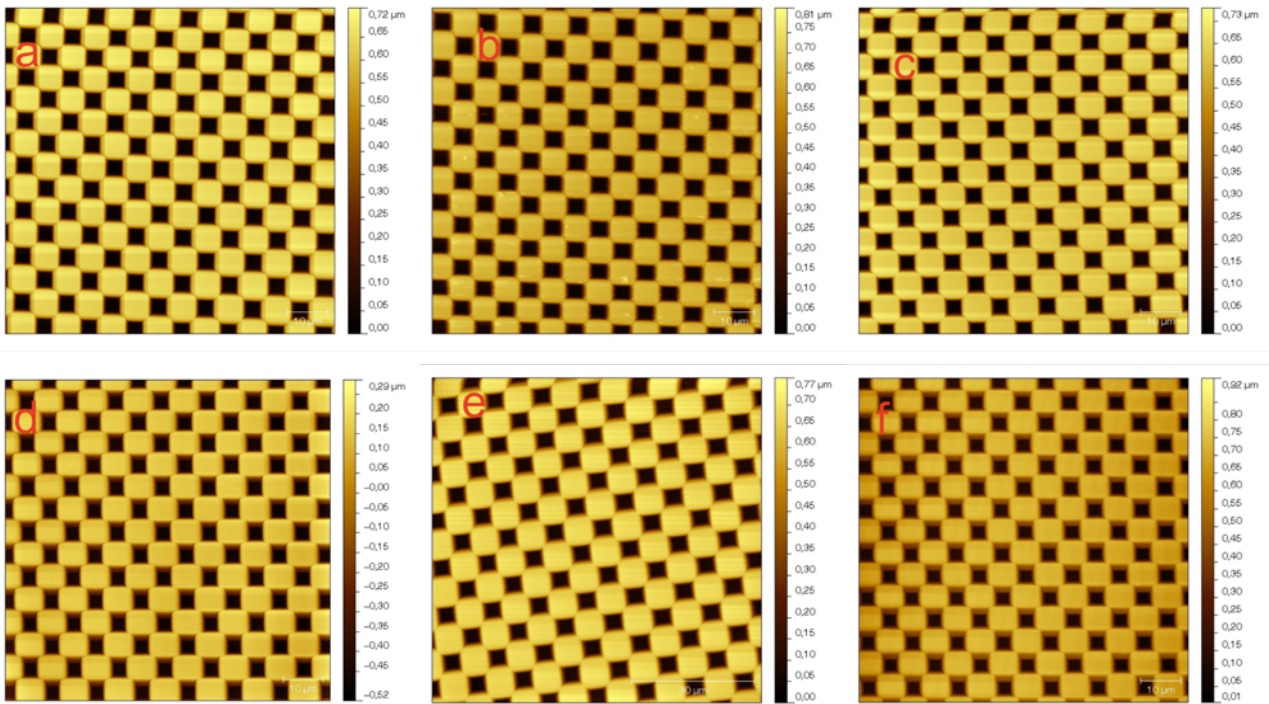


Figure 18: AFM image of a calibration grating. Upper row shows contact, tapping with piezo and tapping with heater in dry state (a-c), the second row shows the corresponding images in de-ionized water.

1.3.5. Test Customers

Main Objectives:

The main objective of this work package was to achieve test-cooperations with dedicated AFM users that will use the self-sensing cantilever prototypes with their lab-equipment. In addition, 2 critical test-customer reports that include a detailed test-protocol, fault analysis and suggestions for improvements were wanted.

Description of Work

Choice of Test Customers

The Institute of Biophysics at the Johannes Kepler University Linz as one of the world leading Institutes in atomic force microscopy (AFM) and former project collaborator of SCL.SensorTech was been chosen as test costumer for bio applications using self-sensing cantilevers. They mainly perform AFM imaging on biological samples (cells, proteins, DNA, ...) in ambient conditions as well as in deionized water and physiological buffers. JKU is expert in molecular recognition force microscopy (MRFS), where interaction forces between single molecules are measured and the energy landscape of these interactions can be investigated and topography and recognition imaging (TREC) where in addition to a topographical image a corresponding receptor distribution map is recorded. As former project partner, they are highly interested in self-sensing cantilevers for bio imaging, MRFS and TREC. In addition, JKU is in close collaboration with Keysight and equipped with several Keysight bio-AFM's perfectly suited to perform characterization of self-sensing cantilevers and test them on hot topics in life science.

GETec Microscopy Ltd is a high-tech start-up focusing on developing of special atomic force microscopes (AFM) dedicated to a seamless integration into other host systems such as scanning electron microscopes (SEM). The modular AFM concept is based on "all electric cantilevers" allowing a very compact design (AFSEM™, www.getec-afm.com). Therefore, correlated microscopy of exactly the same sample spot can be performed almost simultaneously. The FALCON cantilever are interesting for GETec since they provide a higher flexibility concerning cantilever properties for integration into high-vacuum environment.

Short summary of test customer report JKU Linz

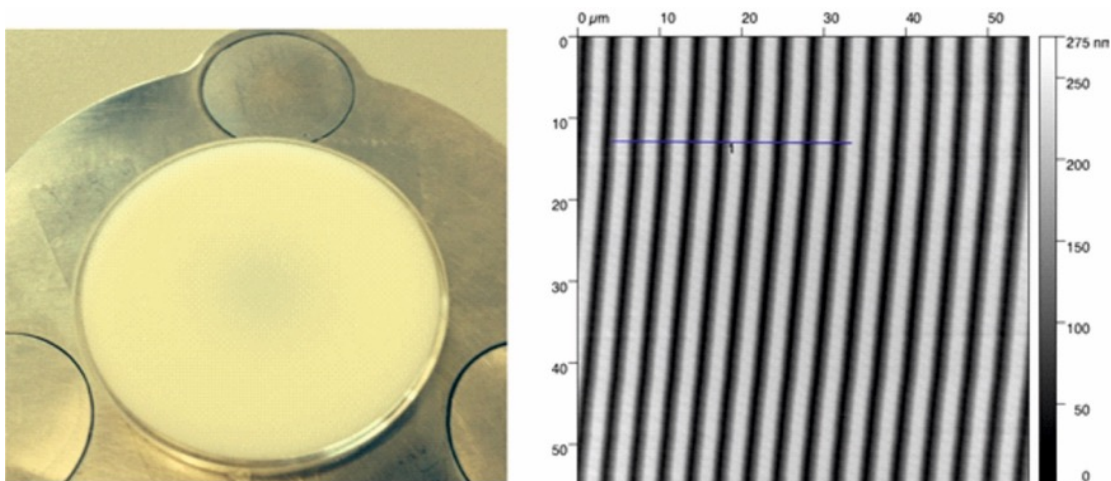


Figure 19: A calibration grid in milk (left side) and the corresponding AFM image recorded in tapping mode using a self-sensing cantilever.

JKU Linz served as a test-customer with the main focus on testing the self-sensing cantilevers in combination with the developed FALCON self-sensing add-on kit (see details in Deliverable 4.2). The test included an in depth cantilever characterization, imaging in liquid environment (see Figure 19), and a comparison of optically AFM imaging and electrical imaging using the FALCON upgrade module for biological samples (see Figure 20).

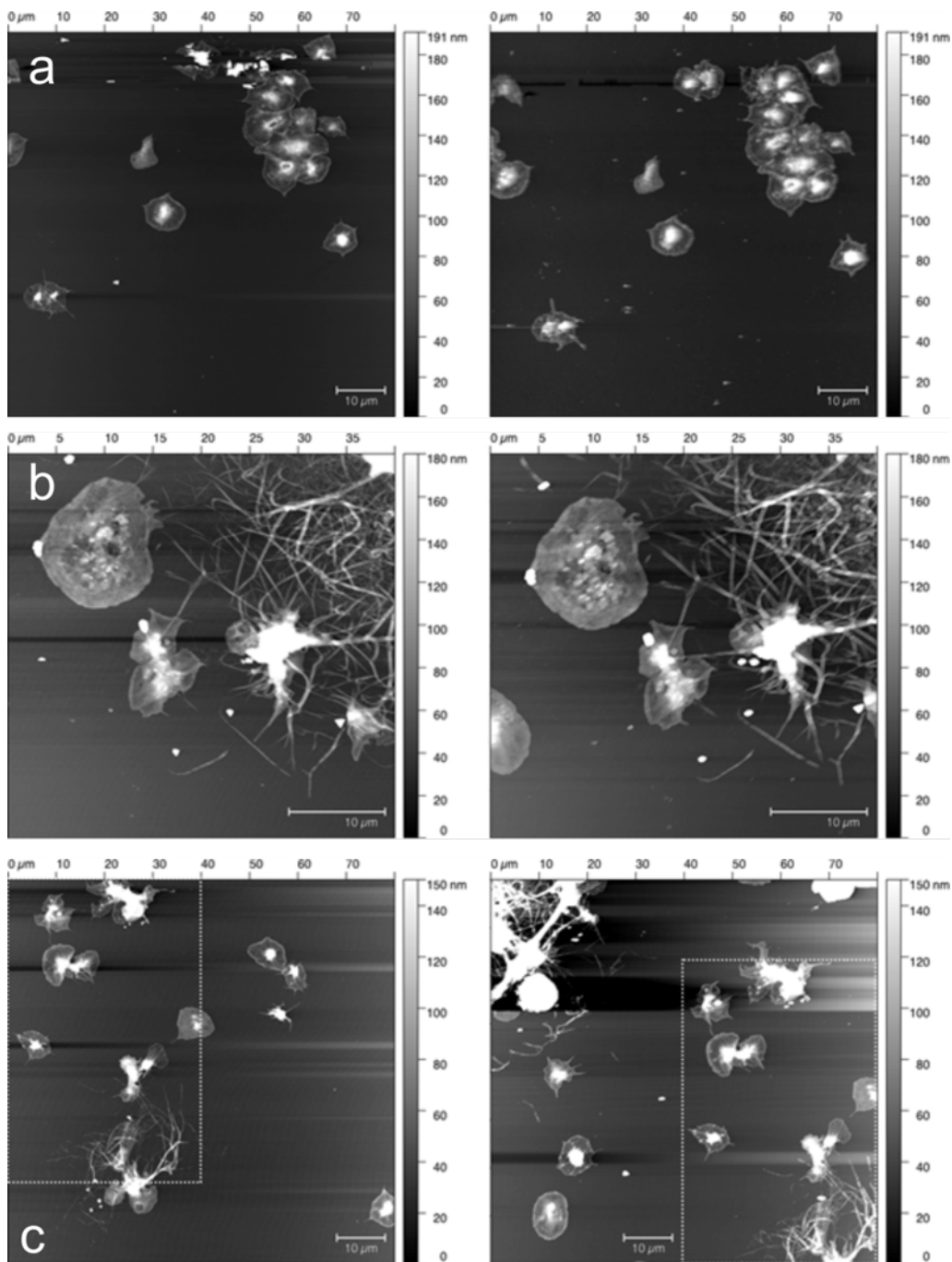


Figure 20: The left column shows the images recorded with optical readout, the right column images with electrical readout using self-sensing cantilevers. In line (a) a platelet sample after 3 minutes of incubation and in line (b) with 5 minutes incubation times is shown. (b) already shows a much higher activation and crosslinking then (a). From column (a) and (b) it can be seen that die resolution is worse compared to the optical images because of a larger tip radius. The marked areas in the images in line (c) mark for the same sample position. Here the tip resolution is comparable as the self-sensing cantilever tip seems to be as sharp as the optical one being in a range of 10-30 nm due to the manufacturer.

Short summary of test customer report GETec Microscopy Ltd

GETec Microscopy served as a test-customer with the main focus on testing NTR self-sensing cantilever in combination with their product AFSEM™ that enables correlated microscopy inside a SEM in high-vacuum environment. The test included also an in depth cantilever characterization and imaging in high-vacuum environment inside a Philips XL30 SEM.

Figure 21 shows the NTR self-sensing cantilever inside the SEM above the test-grid sample structure that was imaged in high-vacuum environment. In Figure 22 the obtained AFSEM™ images of the test-grid structure inside the SEM are shown.

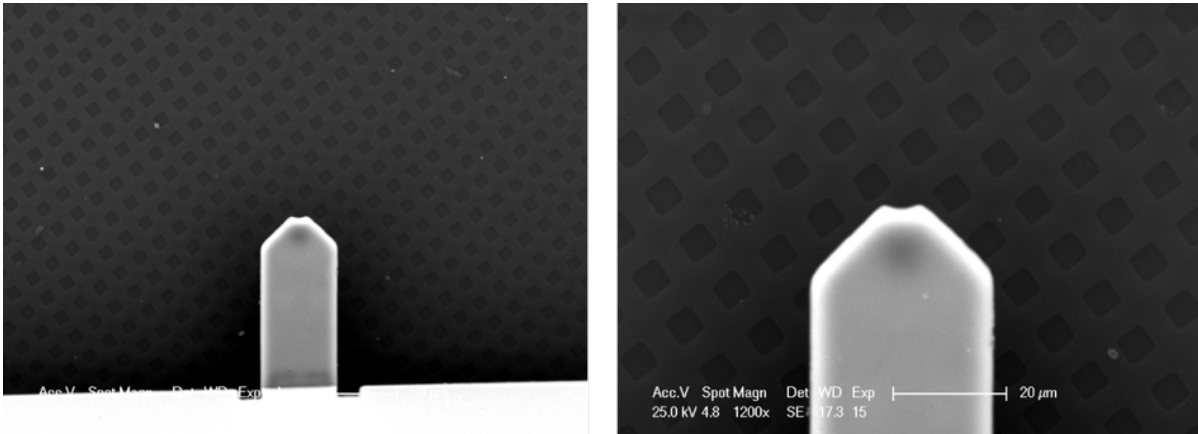


Figure 21: (Left) SEM image of the NTR Self-Sensing Cantilever inside the SEM. In the background the used test-grid can be seen. (Right) Zoom in image of the NTR Cantilever and the test-grid structure.

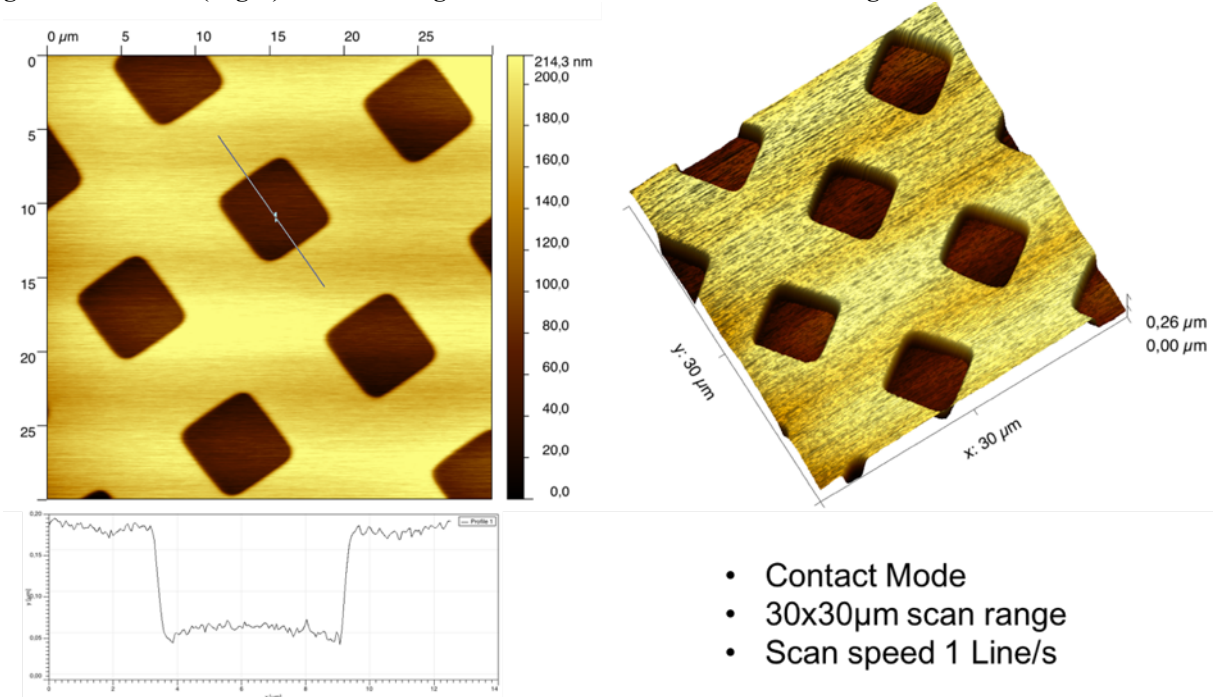


Figure 22: AFSEM™ images of test-grid structure in high-vacuum environment inside a Philips XL30 SEM system.

1.3.6. Business Plan

In the Business Plan the future FALCON product range has been established. It consists in the first run of four different types of NTR self-sensing cantilever. These cantilevers address a wide range of resonance frequencies and spring constants that are important for different market relevant applications. The range for resonance frequencies addressable with the NTR self-sensing cantilevers ranges from 90 kHz up to 3600 kHz. The spring constants ranges from 0.15 N/m to 140 N/m. This enables the usage of the novel NTR cantilever for applications in liquids as well as high-vacuum applications (the two key markets for our NTR cantilever). In addition, our future product range includes a FALCON Upgrade Kit that is a dedicated development for the complete Keysight 5x00 AFM series and allows an easy and user-friendly integration of the NTR self-sensing cantilever. This allows a direct targeting of the Keysight user base.

NTR self-sensing cantilever (Type NTR-L20-XXX)

Description:

The type NTR-L20-xxx cantilever series addresses applications in high-vacuum and air. The high resonance enable high scanning speeds. The wide range of available spring constants make this cantilever usable for tapping mode as well as contact mode applications.

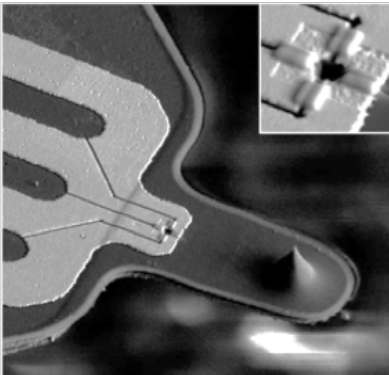


Figure 23: NTR Self-Sensing Cantilever Type NTR-L20-XXX.

Tip Specification		
Type	NTR-L20-F1200	NTR-L20-F2400
Radius (tip apex)	< 15 nm	
Height	4...7 μm	
Material	Silicon/Si-Nitride/EBD	
Cantilever Specification		
Resonance frequency	700...1800 kHz	1800...3600 kHz
Spring constant	0.5...8 N/m	8...62 N/m
AFM mode	Tapping mode	Various applications
Length	$20 \pm 2 \mu\text{m}$	
Width	$8 \pm 1 \mu\text{m}$	
Shape	Rectangular	
Material	Silicon/Si-Nitride/...	
Deflection Sensing	NTR full bridge	
Actuator	External Shaker	
Electrical connections	Bonded to small PCB with connector	

NTR self-sensing cantilever (Type NTR-L70-XXX)

Description:

The type NTR-L70-xxx cantilever series addresses applications in high-vacuum, air and fluid environment. The available low spring constants make this cantilever usable even for soft samples for biological applications in fluid environment.

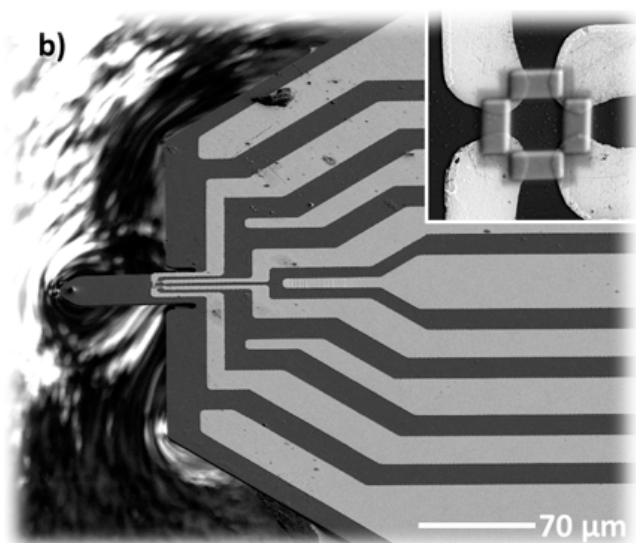


Figure 24: NTR Self-Sensing Cantilever Type NTR-L70-XXX

Tip Specification		
Type	NTR-L70-F200	NTR-L70-F600
Radius (tip apex)	< 15 nm	
Height	4...7 μm	
Material	Silicon/Si-Nitride/EBD	
Cantilever Specification		
Resonance frequency	90...300 kHz	300...900 kHz
Spring constant	0.15...5 N/m	5...145 N/m
AFM mode	Contact & Tapping mode	Various applications
Length	70 ± 2 μm	
Width	30 ± 1 μm	
Shape	Rectangular	
Material	Silicon/Si-Nitride/...	
Deflection Sensing	NTR full bridge	
Actuator	External Shaker	
Electrical connections	Bonded to small PCB with connector	

FALCON Upgrade Module

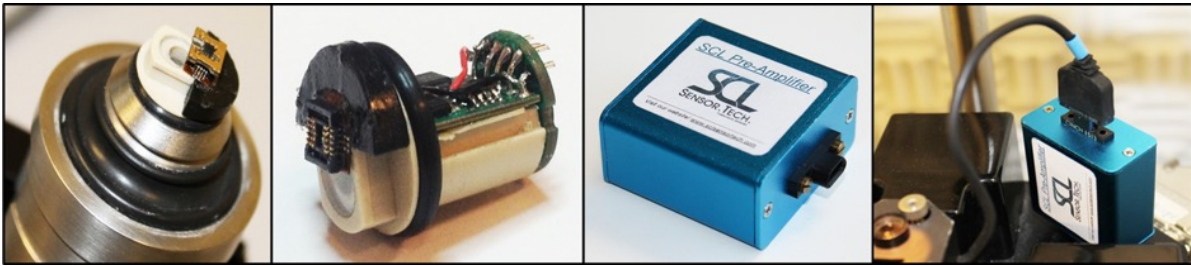


Figure 25: Upgrade kit for Keysight AFM (cantilever holder “nose”, pre-amplifier and signal splitter box (see below))

Description

The self-sensing add-on kit enables a user to work with self-sensing cantilevers on a Keysight 5x00 AFM series. This combines the benefits of a conventional bio AFM with the advantages of a laser free deflection detection using SCL’s self-sensing cantilevers. The add-on can be used without changes to the original AFM hardware for imaging in intermittent contact mode. The self-sensing cantilever add-on kit consists of a cantilever holder plug-in module for self-sensing cantilevers (nose), a pre-amplifier, a signal splitter box, cables and 10 self-sensing cantilevers. The nose contains an adjustable low noise instrumentation amplifier and a fixed reference voltage for the Wheatstone bridge of 2.048V for high sensitivity measurements or 0.5 V for measurements in de-ionized water. For driving the cantilever a nose implemented piezo or a heater of a SCL PRSA cantilever can be used (mechanical or thermal excitation). The deflection signal is amplified (adjustable from 1x to 100x) and filtered before it is wired to the lock-in amplifier of the Keysight AFM MAC-box. The hardware is powered via the Keysight break-out box or an external power supply unit and is connected via the signal splitter box. The whole system is plug-and-play able and only the cantilever holder has to be changed for electrical or optical readout.

Dimensions (l x w x h)	
nose	48 x 28 x 1.6 mm
signal splitter box	52 x 28 x 7 mm
post-amplifier	46 x 36 x 18 mm
Electrical Pre-Amplifier Specifications	
Operation voltage V_s	+/-15 V (from Keysight breakout box)
Gain, voltage amplification	10...10.000x
Bandwidth	$f_{3dB} = 2,5 \text{ MHz @ } 2\text{mV}_{pp}$ sine input signal
external offset voltage range	$(V_s^-) +0.5 \text{ V to } (V_s^+) -0.5 \text{ V}$
Output impedance	50 Ohm
Input impedance	3 GΩ 6 pF
Wheatstone bridge supply voltage	0.51 V or 2.048 V (voltage reference)
Slewrate output stage	27 V/μs
Connectors and cables	
Input connector (cantilever side)	FFC 8 Pin
Output connector	Header Connector 8 Pin
Input FFC cable	FFC, 8 pol, length: 152 mm
Output cable	shielded flexible cable, l = 1 m, open ends



The table below describes the sales forecast for the NTR-Cantilever products developed within the FALCON project. The forecast is based on the following market trends and observations:

- We got a very positive response from potential customers at the presentation at the conference in Linz last February
- We succeeded in starting negotiations with Keysight to promote the new upgrade kit together to their established userbase. A joint marketing effort could speed up the market penetration significantly. A visit of Keysight to Vienna is agreed upon for coming Mai.
- We see a strongly growing market demand for using self-sensing cantilevers in experimental research systems for applications apart from AFM: e.g. conductivity measurements on nanowires or mechanical measurements on Graphene.

The market response to the M&S-cooperation with AGAR started in November last year shows that this channel has a worldwide reach, indeed (e.g recent orders from China and USA)

This forecast shows that

- This business will give a positive cashflow contribution from the start of selling these new products.
- The costs of the 3 consortium partners for the development of this technology and for the products – taking into account the costs and the funding in ALBICAN for the 3 partners – will be recovered by end of 2018.
- The additional sales by these products will account for more than 30% of the sales by current products of the 3 partners from 2019 onwards.

These expected results clearly show that the decision in 2011 to invest into this highly innovative and therefore high-risk project was a commercially justified decision. It has to be stated that this decision would have been not taken without the FP7-funding and especially would not have been technically feasible without the cooperation and contributions by the scientific partners of ALBICAN.

Significant Results:

An updated Business Plan has been formulated that includes a detailed description of the future product range, a market analysis and an updated plan for the market introduction of the novel NTR self-sensing cantilever.

1.4. The potential impact and the main dissemination activities and exploitation results

The potential impact on the European scale

The AFM technology is based on the investigations of Gerd Binnig and Heinrich Rohrer carried out 1981 at the IBM Research Laboratory in Rüschlikon, Switzerland. For this investigation both received the Nobel Price for Physics in 1986.

Based on these developments a whole industry has been started, leading to a market volume about estimated 500 Million EUR in 2013. This market is served by some 5 major players (e.g. Bruker (Previously Veeco), Oxford Instruments (previously Asylum Research), Agilent, JPK) and many minor suppliers. Within this market the cantilevers are essential consumables and determine to a high extent the performance of the instruments. Such instruments find applications in practically all material related investigations and developments today. The application areas are numerous such as:

- Chemistry
- Coatings
- Microstructures
- Physics
- Semiconductors, LEDs
- Materials Science
- Life Science

In particular, the upcoming area of Bioscience and Life Science is looking for specific investigations to be carried out with improved AFMs in the area of

- Molecular Elasticity
- Protein Folding
- Polymers
- DNA Interatomic/Molecular bonds
- Receptor-ligand bonds
- Colloidal forces
- Adhesion
- Nanoindentation
- and more...

The FALCON self-sensing NTR cantilevers will address both application areas. In the first area it will allow more sensitive investigations in shorter times with smaller cantilevers. For the material science as well as the bio- and life science area they open the whole field with AFM imaging in high-vacuum environment as well as of soft material in liquids at high speeds.

With such improved research and investigation tools all these high tech areas in Europe will benefit, because they will have earlier access than other groups outside Europe. Therefore, Europe's nanomaterial research will gain an additional competitive advantage.

The expected impact on the SMEs

The current product of self-sensing cantilevers of SCL is based on conventional piezo-resistive sensor technology. Figure 26 shows such a cantilever bonded onto a small PCB with a micro-connector. With an adapter module hosting in addition an integrated preamplifier these cantilevers can be used directly in the AFM systems of the 5 main global AFM vendors. The new FALCON NTR-based small cantilever will be fully compatible with the existing connector and adaption module. Therefore, they are usable at least in 50% of the installed AFM base.

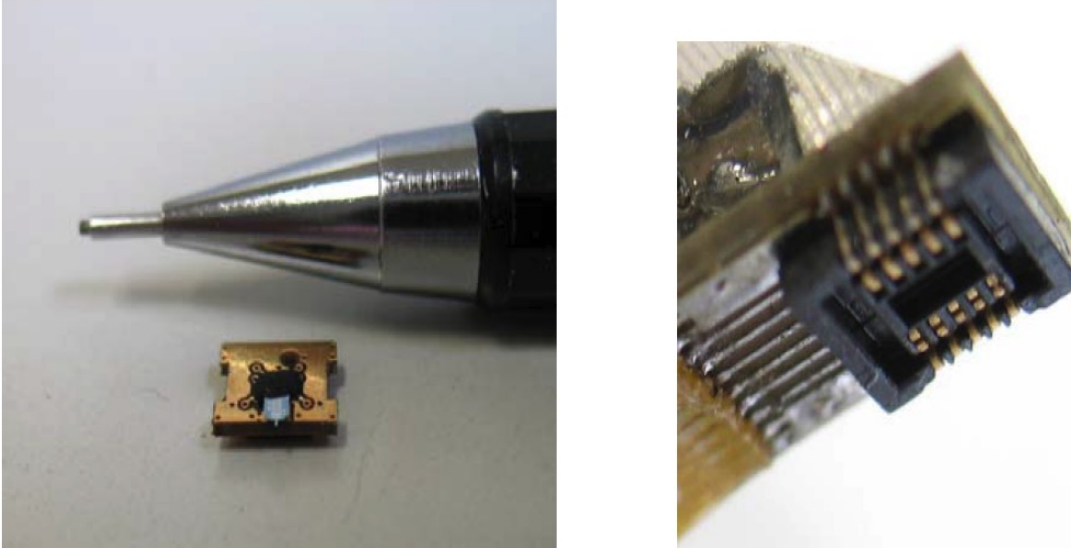


Figure 26: Pictures of the current self-sensing cantilevers with the connector for easy mounting of the cantilever into the AFM head.

Benefit for NANOSS

The main benefit for Nanoss will be the development of a new market for NTR self-sensing cantilevers using its unique and patented FEBID-NTR technology. This new application of its technology forms one of its key elements of NANOSS chief company strategy on promoting and establishing a new industrial measurement standard of force sensing devices on the nanometer scale. Its unique NTR technology, which overcomes the limitations of both the classical optical methods and traditional piezoresistive sensors, enables the company to act as a worldwide supplier for manufacturers of AFM and other high-end analytic devices.

This project demonstrates the key USPs (Unique Selling Propositions) and benefits which come along with the sensors provided by NANOSS:

- Independency from substrate materials allows the implementation of new sensor concepts on a wide range of materials and surfaces such as glass, polymers, metals, etc. and therefore ensures flexibility and adaptiveness compared to traditional silicon based manufacturing techniques.
- Manufacturing of very small sensor components with dimensions below 100 nm and highly sophisticated 3-dimensional structures enables NANOSS to provide solutions for completely new products and novel applications beyond the AFM-business case (e.g. in Nanoanalytics, Gas- and Bio-sensing, pressure sensors etc.).
- Conventional (top-down) production techniques for integrated sensors (e.g. piezoresistors) require clean room environment, photo masks and expensive silicon semiconductor equipment, respectively. In contrast to these conventional techniques the NANOSS technology is based on a direct structuring (bottom-up) approach. This approach drastically simplifies conventional lithography and therefore

allows new adaptive rapid prototyping techniques. It also has a huge impact on cost reduction and production efficiency since investments in machinery and costs of maintenance can be reduced at least by a factor of 10 with the NANOSS technology.

NANOSS expects as a direct outcome of this cooperation further joint developments for novel NTR based MEMS and NEMS devices with the other SME partners.

Benefit for AMGT

AMGT strategy is to focus further on development of a large number of MEMS devices with force/displacement feedback, for different applications. Besides AFM sensors, the company develops dedicated compliant micro-devices with force/ displacement operation capability in the range of more than four orders of magnitude. The NTR-enabled technology will provide a common approach to overcome the limitations of current (“classical”) piezoresistive sensors, rendering the company to become an internationally recognized supplier of self-sensing MEMS, incl. AFM sensors. The key Unique Selling Propositions and benefits which come along with the sensors with NTR are as follows:

- Extending the self-sensing function on new classes of micro-devices and microsystems. Self-sensing feedback will be added to both: devices made of nonsilicon substrates as well as to silicon devices with non-sufficient self-sensing components; NTRs will be especially useful in hybrid micro-systems applications.
- Manufacturing of application specific devices in very small volume by tailored modification of sensor components, beyond AFM-compatible applications: for advanced studies and for highly specific and limited-in-volume applications.
- Fast prototyping of force/displacement sensors with NTR elements – by using the ready templates and established NTR-enabling protocol, prototyping of devices with (extra) feed-back options will be available in a max two days.
- AMGT will become a competitive provider of wide range of advanced products and services based on low-cost and high added value NTR technology, after its licensing.

Benefit for SCL

The business model of SCL is based on the role of a trend setter in highly innovative cantilevers for emerging applications. This allows competing successfully with the main cantilever suppliers without price damping, which is not affordable for an SME. The results of the FALCON project significantly broadens the SCL expertise and technology base as well as the international R&D network – both in academia and industry. This is the best basis for the future plans to expand the current product range with completely new AFM cantilevers such as functionalized cantilevers, where the cantilever tip will be “functionalized” with specific molecules. This will make the cantilever “intelligent”. This means that the cantilever will not only react directly to sample surface morphology, but also to different chemical compositions. This means that the AFM cantilever develops to a “chemical sensor”. The technology of NTR cantilevers is a prerequisite for these future product developments.

1.4.1. Main dissemination measures

The dissemination of the ALBICAN project results started right from the beginning of the project and actions will still continue. The main dissemination activities during the lifetime of the ALBICAN project included:

- Development and setup of the project specific website
- Publications in scientific journals
- Attendance and oral presentations at international conferences and fairs
- Training activities and meetings of the ALBICAN partners
- Promotion activities and workshops

Setup of project specific website

The FALCON project website was implemented and can be found online (URL: <http://falcon.freesponsible.info>). It informs interested visitors about the project and gives a basic introduction to the fabrication techniques that are used.

The FALCON website (URL: <http://falcon.freesponsible.info>) is set up using the publishing tool WordPress. The website serves as a platform where general information about the FALCON project is given. Furthermore, the scientific background concerning nanogranular tunneling resistors, the preparation via focused electron-beam-induced deposition and the application for high-speed imaging using atomic force microscopy in liquids is explained.



Figure 27: Welcome page of the FALCON website.

Main Dissemination Activities, meetings and customer visits:

During the course of the FALCON project scientific experts and users of the NTR deposition technology have been invited to our production and show room facilities in order to spread our results and roadmap for market entry. The following meetings have been held during the project:

- Formal and un-formal visits to the facility of AMG-T, incl. the group led by Mr. Prof. Siegfried Selberherr - TU Vienna, April 30th, 2014 and the Delegation from IMEC, Belgium led by Dr. Jo De Boeck, Senior Vice President and Corporate Technology Officer, May 22nd, 2014
- Visit of scientists from JKU Linz to SCL led by Dr. Andreas Ebner: Presentation of self-sensing cantilever technology and of the FALCON FastScan upgrade package
- Visit to the facility of a top equipment supplier EVG: Presentation of self-sensing cantilever technology, July 21st, 2015.



Fig. 1. Photo taken during the presentation at Electronica 2014 conference in Sofia, May 15, 2014



Fig. 2. Photos taken during the visit of the group from IMEC, Belgium – (left) Explanation of the currently running projects (FALCON – the right most on the slide); (right) Discussion with Dr. De Boeck on applicability of self-sensing bulk micromachined cantilevers for non-AFM measurements

The activities and meetings of the FALCON partners during the FALCON project are summarized in the table below. In order to keep all partners up to date in the daily operational work of the relevant work packages,

discuss solution strategies for emerging problems and plan the next necessary steps, regular bi-monthly video Skype conferences have been scheduled. The high degree of participation in the video Skype project meetings reflected the deep involvement of all partners— members of all three project partners participated in each Skype meeting. Extensive and specific minutes of the meetings with the main emphasis on the action points agreed upon in the meetings documents the continuous project progress and the cooperation between all partners.

Besides the Skype meetings, several in person meetings were organized. The FALCON project kick-off meeting took place in Langenlois, Austria (2013-11-14/15) with all project members participating. Additionally, a 2nd full project meeting took place at AMGT in Botevgrad, Bulgaria (2014-04-28/29) in order to discuss the project progress and necessary next steps. The third project meeting was held in Darmstadt (July 16th-17th, 2014) where the progress of project implementation vs. challenges analyses, have been done. A full day STEERING BOARD MEETING of FALCON project, was held after the review meeting in Brussels (2014-09-12). Besides regular issues, the concept of most effective distribution of NTR cantilevers fabrication in a shared process between AMGT and SCL, has been formally discussed. The fourth project meeting has been organized in Vienna (July 8th-9th, 2015), where the progress in achieving the Deliverables and MS has been discussed and reported in the minutes of the meeting.

Efficient dissemination of the knowledge between the partners took place by several bi- and tri-lateral visits (see table below for details). Also, oral presentations were scheduled to disseminate the results of the FALCON project to the outside world. The unique features of the NTR-technology and advertise the FALCON cantilevers have been communicated to the leading experts in the scientific community.

Bi-Monthly	Skype meeting with all project partners <u>Aim:</u> Presentation of results, definition of work schedule, discussions concerning experimental problems and possible solutions
11/2013	2 Day kick-off meeting in Langenlois, Austria with all three partners
12/2013	Ch. Schwalb (NANOSS) and E. Fantner (SCL) visit AMGT in Botevgrad (Bulgaria) <u>Aim:</u> Analyze the existing SEM and equipment needed for successfully upgrading the Philips XL40
04/2014	2 nd full project meeting at AMG-T in Botevgrad (Bulgaria) with all project partners <u>Aim:</u> Detailed discussions on project progress and necessary next steps
07/2014	3 rd full project meeting at AMG-T in Darmstadt (Germany) with all project partners • <u>Aim:</u> Reports on project progress and necessary next steps; dedicated meeting with OFFIS
08/2014	Ch. Schwalb (NANOSS) visits SCL in Vienna (Austria) <u>Aim:</u> AFM training and joint experiments
08/2014	3days visit of Tobias Strunz (SCL) to AMGT <u>Aim:</u> XL-40 and Cantilever technology know-how transfer to SCL
08/2014	Ch. Schwalb (NANOSS) and E.J.F. (SCL) visits JKU Linz Prof. Hinterdorfer Institute for Biology (Austria) <u>Aim:</u> Planning of first experiments at test-customer site
09/2014	Steering Board meeting after interim report meeting in Brussels with all project partners
09/2014	3days visit of Peter Ziger (SCL) to AMGT <u>Aim:</u> XL-40 and Cantilever technology know-how transfer to SCL
10/2014	Visit of Dr. Ch. Schwalb (NANOSS) to (OFFIS) in preparation of NTR sensor elements run by MB
12/2014	Un-formal resolution on reallocation of NTR deposition facility from AMGT (Botevgrad) to SCL (Vienna)
2015/Q1	Workshop at SCL for MEMS/NEMS applications
2015/Q2	Direct NTR deposition knowledge transfer from NANOSS to SCL by employment of Dr. Ch. Schwalb

2015/Q2+Q3	Direct NTR deposition knowledge transfer from NANOSS to OFFIS by Dr. Alexander Kaya
07/2015	4 th full project meeting at SCL in Vienna (Austria) with all project partners <u>Aim:</u> <ul style="list-style-type: none"> • Discuss project progress and necessary next steps Preparation of FALCON final report
2015/Q3	Experiments Dr. Ch. Schwalb with Dr. Michael Leitner on bio samples
2015/Q3	Experiments Dr. Ch. Schwalb with Dr. Michael Leitner on vacuum applications

Oral/Poster Presentations:

During FALCON project, related results have been presented at the following events:

- V. Stavrov (AMG-T) made an oral presentation of current FALCON project results at Second National Congress in Physics, November 2013, Sofia, titled: V. Stavrov, P. Vitanov, G. Stavreva, "Self-sensing Microcantilever Sensors for Advanced Applications",
- V. Stavrov (AMG-T) made an oral presentation, titled: "3D Position sensors with Self-sensing Detection", at National Conference Electronica 2014, Sofia, May 15, 2014, pp. 5-25(invited talk)
- 2014, July, 22-24.: Christian Schwalb (Nanoss) had an oral presentation at the 5th FEBID workshop in Frankfurt, Germany, titled: "New pathways for ultra-small MEMS/ NEMS force sensor systems using nanogranular metals"
- 2014, Sept, 7-10: Vladimir Stavrov (AMG-T) presented a poster at the Eurosensors 2014 in Brescia, Italy, titled: "MEMS sensors for mm-range displacement measurements with sub-nm resolution"
- 2014, Sept., 09-10: Ernest J. Fantner (SCL) presented a poster at the International Microscopy Congress in Prague (IMC 2014) – titled: "Beyond Current SEM-AFM Solutions: A Highly Flexible in-situ AFM for Correlated Microscopy in Micromechanical Testing"
- 2014, Nov. 30 to Dec 5, Boston: Prof. Georg E. Fantner (EPFL), presented oral talk at the Material Research Society fall meeting, titled: "Nanoscale Calorimetry Reveals Higher Stability of Cholesterol Induced Nanoscale Domains in Lipid Bilayer and Multi-Frequency AFM in the MHz Regime"
- Alexander Deutschinger, Ernest J. Fantner (SCL), presented a poster, titled: "Self-sensing AFM cantilevers for bio AFM applications", at XVII annual Linz Winter-Workshop 2015, Jan. 30 - Feb. 2, 2015 (poster)
- Rodrigo Pacher Fernandes (Nanoss) had an oral presentation at TechConnect World/National Innovation Summit & Showcase (June 14-17, 2015), Washington, D.C., U.S.A., titled: "Novel 3D-Printing on the Nanoscale for Tailored Sensors and Electronics"
- Alexander Kaya (Nanoss) presented a poster at TechConnect World/National Innovation Summit & Showcase (June 14-17, 2015), Washington, D.C., U.S.A., titled: "How Micro Sensors influence Science & Technology and "Fast All-Electric Cantilever for Bio-Applications"
- 2015, June 8-9: Dr. Ch. Schwalb(SCL) made an oral presentation at the Nanoforum Workshop in Linz, Austria, titled: "Self-Sensing Cantilevers for Nanoanalytics and Characterization of Nanostructures"
- 2015, June 21-24: Prof. Georg E. Fantner (EPFL) presented an invited talk in the International Scanning Probe Microscopy Conference (ISPM), Rio de Janeiro, Brazil, titled: "Time resolved atomic force microscopy imaging of biological processes".
- 2015 Nov. 30th – Dec. 5th: Dr. Ch. Schwalb and Dr. Ernest J. Fantner (SCL) attended the MRS fall meeting in Boston, USA. Oral presentation titled "Correlated AFM & SEM Microscopy of Nanostructured Materials"

Publications

The project team had plans to publish the project results in noted journals until the end of the project coordinated with the communication plan, taking into account the IPR and competition aspects. A joint manuscript with the leading experts from the ALBICAN consortium entitled "Additive rapid prototyping of

nanogranular strain sensors for micro- and nanomechanical resonators" has been submitted to the Journal Nature Nanotechnology on March 12th, 2015. The manuscript highlights the project results from the ALBICAN project and gives an outlook on the FALCON project goals. The consortium members were regret to get a negative decision of the reviewers and a modified paper entitled "3D printing of nanogranular tunnelling strain sensors on sub-micrometer cantilevers for next generation high-speed atomic force microscopy" (reference number: NCOMMS-15-19666), has been submitted to Nature Communications on October 4th, 2015. The manuscript review is taking place, currently.

Exploitation of results

The detailed plan for the use and exploitation of foregrounds is explained in depth in chapter 2.

1.5. Address of the project public website and relevant contact details

Project specific website

Project website address: <http://falcon.freesponsible.info>

Contact Details

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