Final report

Sensing with single atoms

Leibniz-Institute: Leibniz Institute of Surface Engineering (IOM)
Reference number: SAW-2015-IOM-1
Project period: 01.03.2015-28.02.2018
Contact partner: Dr. Jürgen W. Gerlach

Initial questions and aim of the project

The project addresses the questions of how to gain nanometric access to the local properties of small objects by using sensors as small as possible, consisting of a few atoms only. The highly sophisticated preparatory instrument used for this purpose is the implantation of single ions.

Aim of the project was to develop a freely selectable arrangement of sensors based on quantum mechanical effects (NV centers in diamond). A prerequisite for this was the development of a unique system to implant single ions with high local precision. This includes in particular the development of a novel means to detect and count single ions.

Progress of the work in the project including deviations from the initial concept, scientific failures, problems in the organization of the project or in the technical realization

The work was conducted at the IOM Leipzig in the Leibniz Joint Lab “Single Ion Implantation” as well as at Leipzig University. The Leibniz Joint Lab is a mutual laboratory of both the IOM Leipzig and Leipzig University (Felix Bloch Institute for Solid State Physics, Nuclear Solid State Physics Division, Prof. Dr. J. Meijer). Its purpose is to provide the opportunity for scientific and technical efforts in the field of single ion implantation as well as to develop applications for single ion implantation.

The project included the following work packages:

AP1: Development and setup of a gas ion source for single ion implantation purposes

AP2: Realization of a system for single ion implantation

AP3: Development of a sensor array for a microwave spectrometer

AP4: Development of a sensor array for nanometric magnetic resonance tomography meant for tomographic characterization of single macromolecules

AP5: Exploitation and transfer

The gas ion source (from SPECS), initially meant for the system for deterministic single ion implantation, proved to be not sufficient enough for this highly advanced application and the required highly-sensitive single ion detection. Instead, an electron beam ion source (from DREEBIT) was identified to be the better candidate for this purpose because of its ability to produce highly charged ions from a variety of selectable gases, which makes a fly-by detection using image charges much more feasible. Nonetheless, the SPECS gas ion source was successfully used in a separate setup to investigate the principle of image charge detection of small bunches of ions (described later on in detail). Based on these results, a big step towards deterministic single ion implantation was made.

In the course of the work on the project, it became clear that - despite the achievements already made in the first part of the project - the aim of deterministic the single ion implantation could be approached but not finally reached within the time frame of this project. The technical challenges were too manifold to solve them all in time. Thus, the tasks within the work packages AP3 and AP4 were worked on to partially great success by using statistical single ion implantation as well as broad beam ion implantation. Exploitation and transfer of the results of the project are in ongoing progress.

Description of obtained results and discussion regarding the relevant state of research, possible perspectives of applications and possible follow-up projects

The efforts in the first work packages to develop and realize a system for deterministic single ion implantation are described in the following, as well as the results of sensing with structures produced by statistical single ion implantation.

Construction of the system for deterministic single ion implantation

The (high vacuum) system for deterministic single ion implantation, as sketched in Fig. 1, consists of several main sections (key sections) which can be separated by vacuum valves. In these main sections the following processes are to be realized: (i) generation of ions, (ii) counted detection of single ions in fly-by geometry, as well as (iii) controlled local implantation of the detected and counted single ions into the surface near region of a chosen sample.

The generation of ions with single or multiple charge is realized with a (rental) electron beam ion source (EBIS) (Dresden-EBIS by Dreebit GmbH, Großröhrsdorf, Germany) [Zsc08, Sch09]. This specific type of ion source, operable with different working gases, provides the unique opportunity to generate ions of different species with high charge states - up to completely stripped ions - in a working pressure region below 10^{-8} mbar. This extraordinary low pressure results in similarly low pressures in the other main/key sections of the system. As a consequence, the mean free paths of the generated ions in the system are long, reducing the probability of ion collisions with residual gas molecules outside the ion source.

The energetic ions leaving the ion source must first pass an ExB filter (Wien velocity filter), which allows selecting ions of a specific charge state at a specific kinetic ion energy (see example in Fig. 2). Next, the ion beam is collimated by two displaceable pinhole apertures, so that the ions move into the adjacent single ion detector exactly along the axial direction of the ion column with a well-defined, small beam divergence as well as beam diameter.

The detection of single ions with this sophisticated detector, where ions are detected in fly-by geometry by passing undisturbed through the detector itself, enabling the detection as well as counting of passing ions, will be described in detail in the following subchapter.

Those single ions, which were allowed to pass and were counted already before they reach the sample to be modified, enter the ion optics column of a system for laterally nm-precise ion implantation. This commercial system is a nanofocus ion beam workstation (ionLiNE by Raith GmbH, Dortmund, Germany) which is equipped with a laser interferometer controlled high-precision sample stage. This allows, on the one hand, to approach every chosen location on a sample in order to implant a single ion as laterally precise as possible (precision of a few nm) into this location. On the other hand, the implantation depth of the single ion is defined by the mean projected range which can be chosen by adjusting the kinetic energy of the ion.

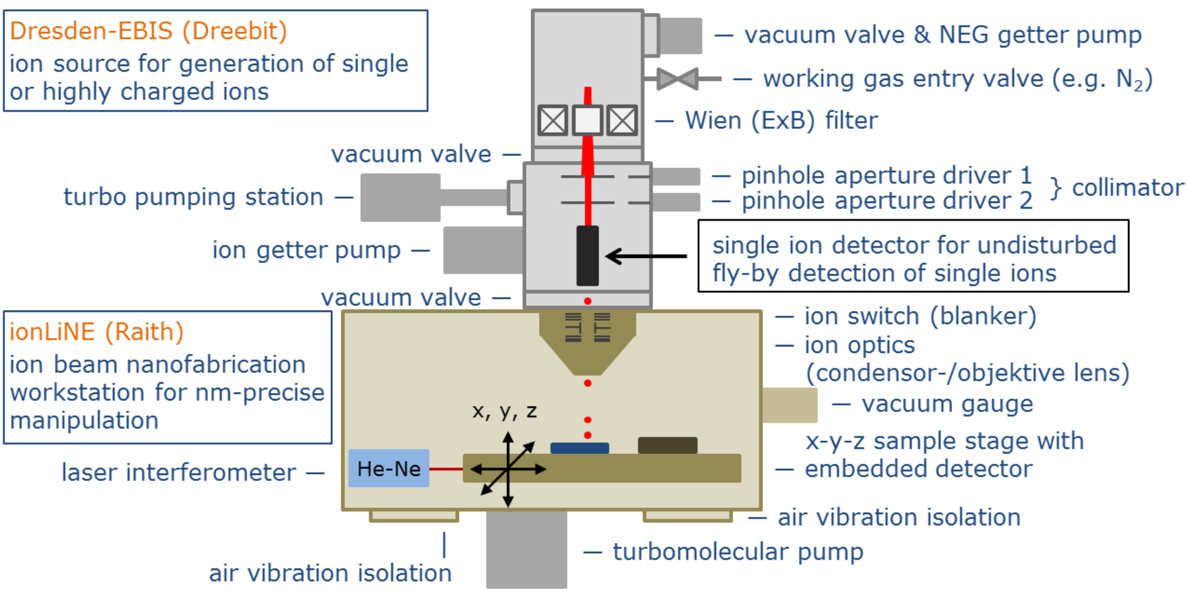

Figure 1: Schematic of the system for deterministic single ion implantation.

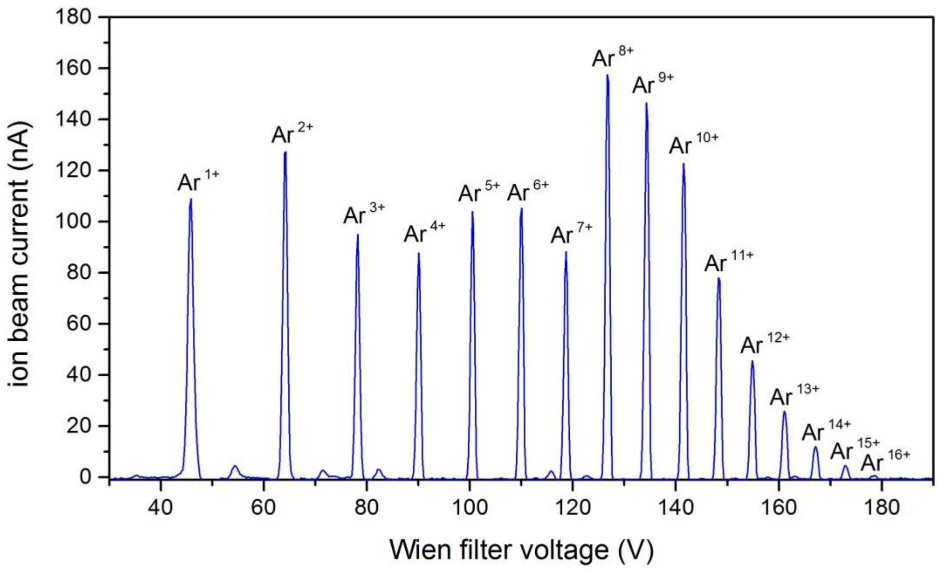

Figure 2: Yield of Ar ions with single and multiple charges from the EBIS in dependence of the Wien filter voltage, measured with a Faraday cup at the position of the fly-by single ion detector inside the system for deterministic single ion implantation.

The actual setup of the single ion implantation system, located in the Leibniz Joint Lab „Single Ion Implantation" at the IOM in Leipzig, is shown in Fig. 3. The commercial nanofocus ion beam workstation ionLiNE is originally meant for operation with a liquid metal ion source in order to produce a focused ion beam (FIB) of Ga ions. Instead, the present system was equipped with a purpose-built experimental ion column (Fig. 4), the EBIS with the Wien filter being mounted on top of the column. In this ion column the fly-by single ion detector is to be situated together with the cooled detector electronics. A solid-state reference single ion detector can be embed-ded in a modified sample holder, placeable on the sample stage inside the nanofocus ion beam workstation. Thus, as a figure of merit single ions detected and counted by the fly-by detector can be detected a second time by the reference detector, confirming the fly-by detection

Figure 3: Overview photograph of the system for deterministic single ion implantation as built in the Leibniz Joint Lab "Single Ion Implantation" located at the IOM in Leipzig.

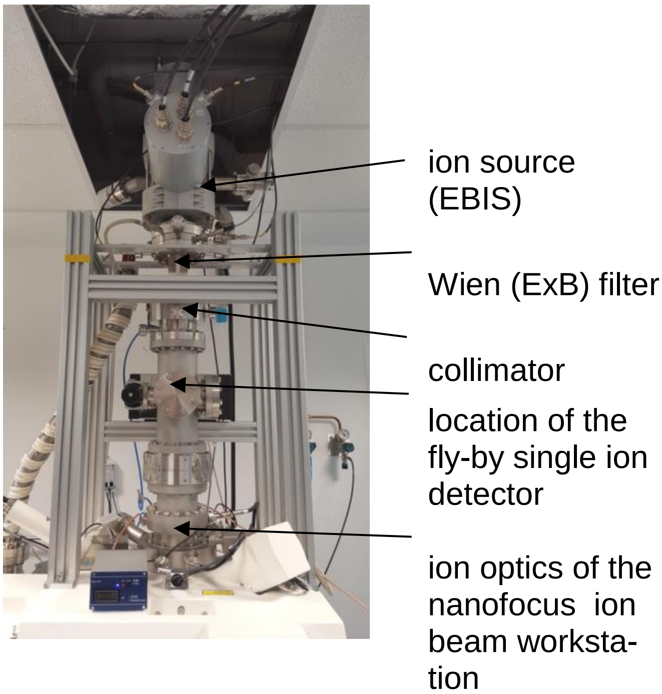

Figure 4: Purpose-built experimental ion column placed above the ion optics of the ionLiNE workstation instead of the original Ga ion source.

The system for deterministic ion implantation, in particular the realization of the fly-by single ion detector, is to be completed and finalized in an already accepted follow-up project (SAB project, Sächsische Aufbaubank). This will make the system ready for application oriented basic research in the Leibniz Joint Lab „Single Ion Implantation". Furthermore, the finalized system can be made available/usable to other groups and possible new cooperation partners in Germany and abroad.

The concept of image charge detection

Within quantum technology, the functionalization of individual atoms is gaining increasing importance. Here, atoms can act as switches, single photon sources, sensors or even qubits for quantum information processing [Dol13, Gae06, Cai13, Loh11]. The fabrication of such devices, however, is hampered by a significant technical challenge, the placing of individual atoms at specific locations at the nanoscale. Ion implantation is ideally suited for this purpose when combined with the ability to count each individual atom that is placed into the substrate material – this variant is termed *deterministic ion implantation*. Without this ability of counting, the probability of success is 37% only for one atom, dictated by Poisson statistics. Laying down ten individual atoms would then only be successfully achieved with a probability of $(0.37)^{10}$ = 0.0048%, i.e. only one out of 21,000 devices would be fabricated correctly.

Several approaches have been used to detect and count individual atoms in the implantation process: (i) detection of secondary electrons emitted upon ion impact into the substrate [Shi05] or (ii) detection of charge carriers generated in the substrate upon ion impact [Jam17]. Both approaches have the inherent disadvantage that the ion detection requires the implantation of the ion. Consequently, the detection efficiency must effectively be 100% for successful deterministic ion implantation. This demand is a serious technical and physical challenge that cannot be expected to be achievable at the low ion energies required for spatially precise implants. At the same time, “false positives”, i.e. the pretended detection of an ion that in fact was not present at all, must be avoided.

Within this project, a new concept for detecting single ions has been developed. The concept is based on detecting the image charge of an ion induced on a set of metallic electrodes as the ion passes along (see Figure). A similar approach has been demonstrated for the mass spectrometry of large molecules, called Charge Detection Mass Spectrometry – CDMS, where a detection limit of six elementary charges was recently demonstrated [Pie15]. Our approach is new in that it seeks to reach preferably one elementary charge sensitivity and requires only one passage of the ion through the detector with negligible influence of the image charge generation on the ion trajectory and energy. The latter is required to maintain the low emittance of the EBIS, a prerequisite for the ion to be focused by the ion optical system into a nanometre-sized spot.

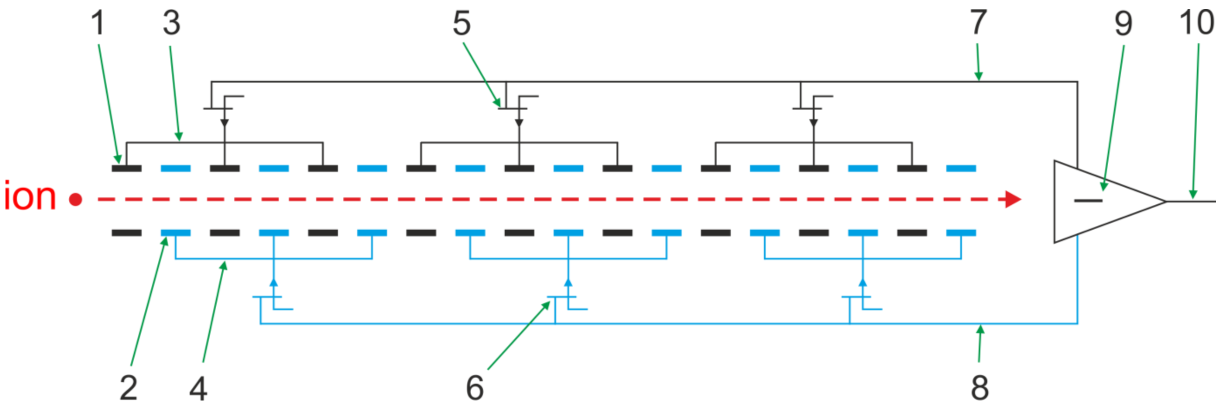

Figure 5: Schematic cross sectional view of the electrode array used for single ion detection. Two sets of metallic rings (1,2) are interdigitated to produce an alternating signal during ion passage. For this purpose, groups of electrodes are combined (3,4) and connected to cryogenically cooled FET transistors (5,6). The transistor outputs of these groups are combined again (7,8) and fed into a differential amplifier (9) to produce the output signal (10).

A patent on this concept with the title “Apparatus for detecting individual charged particles and material processing system having such an apparatus“ has been filed with the international number WO 2016/174177 A1 with Leibniz Institute of Surface Engineering (IOM), University of Leipzig and Max Planck Society as inventors.

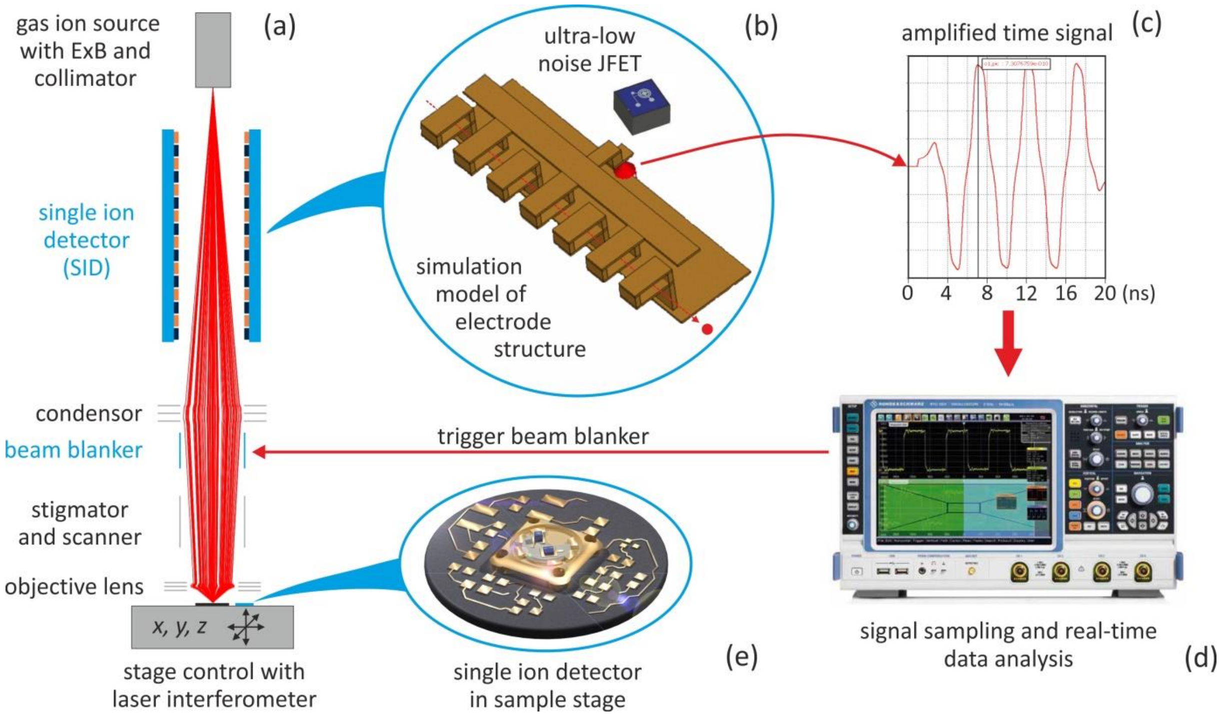

Figure 6: (a) Schematic of the FIB system equipped with the SID, (b) electrode structure used for simulation of the detector's response to an ion passage, (c) the amplified signal is fed into a sampling oscilloscope (d) that provides a trigger for the beam blanker, (e) the trigger settings for the SID are optimized with the help of a single ion detector mounted in the sample stage.

The single ion detector (SID) with electrode array will be positioned between the EBIS ion source with collimator and the ion optics of the Raith FIB column as shown in Figure 6(a) so that the array is traversed by the ions on their way to the substrate. The main advantage of such a configuration is that the ion detection is independent from the ion implantation itself. When combined with a beam blanker downstream, this allows detector operation with less than 100% detection efficiency, for example, to avoid "false positives" due to electronic noise. Only in case of successful ion detection, the drifting ion is allowed to pass the beam blanker and will be implanted. In the case the detection signal was too low compared to the electronic noise, the ion will pass the detector unnoticed and be discarded at the beam blanker.

The feasibility of this single ion detection concept is supported by time-resolved simulations of the image charge generation during ion passage performed at the Ferdinand-Braun-Institut für Höchstfrequenztechnik (FBH) in Berlin which indicate that a signal-to-noise ratio SNR > 1 can be expected for the electrode structure shown in Figure 6(b), when 67 of these structures are combined to form a ~15 cm long electrode array that is traversed by a single-charged ion of 1.34×10^5 m/s velocity (corresponds to 1.3 keV N^+, 2.9 keV P^+ or 19 keV Bi^+). In the setup on which these simulations are based, the 200 MHz signal of ~1 µs duration produced by the ion is amplified by ultra-low noise cryogenically cooled electronics, filtered with a 1 MHz bandpass to limit noise contributions and fed into a Rohde & Schwarz sampling oscilloscope (Figure 6(d)) with ample real-time data analysis capabilities to produce a trigger pulse upon ion detection. It has to be pointed out, that in the above simulations only the thermal noise from the electrode structure is taken into account, but no noise contributions from the amplifiers. Experimental investigations of the image charge detection presented below nevertheless show the feasibility of the approach, at least for ions of higher charge states.

Experimental image charge detection of ion bunches

To investigate the principle of image charge detection in practice, an experimental test set-up was devised [Räc18]. To make an image charge signal measurable, the signal-to-noise ratio is the most important limitation. To increase the signal amplitude, bunches of ions can be used instead of single ions. Considering the Shockley-Ramo theorem [Sho38; Ram39] the signal should be proportional to the number of charges. The noise can be decreased, if it is possible to repeat a measurement and average over single acquisitions. Noise that is purely statistical in nature decreases with a factor proportional to the square root of the number of measurements. The test set-up combines both of these capabilities. A schematic of the experimental set-up is shown in Fig. 7(a). A Specs IQE 12/38 ion source produces a continuous beam of Argon or Nitrogen ions with kinetic energies up to 5 keV. The beam blanker can be biased on one plate to deflect the ions. The potential is switched off and on within a few nanoseconds with a Behlke HV switch. In this way, small bunches can be transmitted through the aperture at a defined point in time. The ions pass through the image charge detector and eventually collide with the Faraday cup, which is used to measure the constant beam current. The image charge detector (ICD) itself consists of a set of copper tubes with a diameter and length in the order of millimeters. In the course of the project, different versions of ICD prototypes were developed and tested. In Fig. 7(b), the two most important outcomes, ICD1 and ICD2, are shown. ICD1 uses a self-designed printed circuit board and an Amptek A250 charge-sensitive pre-amplifier, which is placed in a case close to the electrodes inside the vacuum chamber. ICD2 is contained in a larger case, allowing for more electrodes to be used. The pre-amplifier is an improved version, using the A250 with a Peltier-cooled input JFET for superior noise performance. Different numbers of electrodes have been used in the experiments. Figure 7(c) shows three different configurations of the prototype ICD2. A specific configuration is connected to the preamplifier for the respective type of experiment. The signal electrodes are connected to the pre-amplifier. Its output is read out with a Rohde & Schwarz RTO oscilloscope.

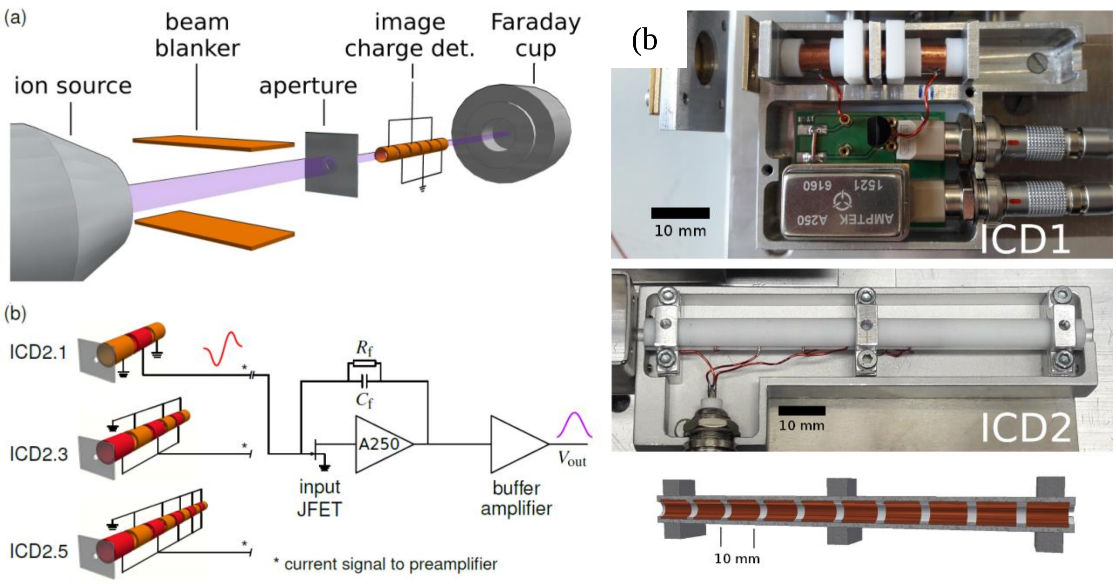

Figure 7: (a) Schematic of the experimental set-up for image charge detection of ion bunches. (b) Image charge detector prototype configurations ICD2.1 (1 signal electrode), ICD2.3 (3 sign. el.), ICD2.5 (5 sign. el.) and the preamplifier circuit common to all three.

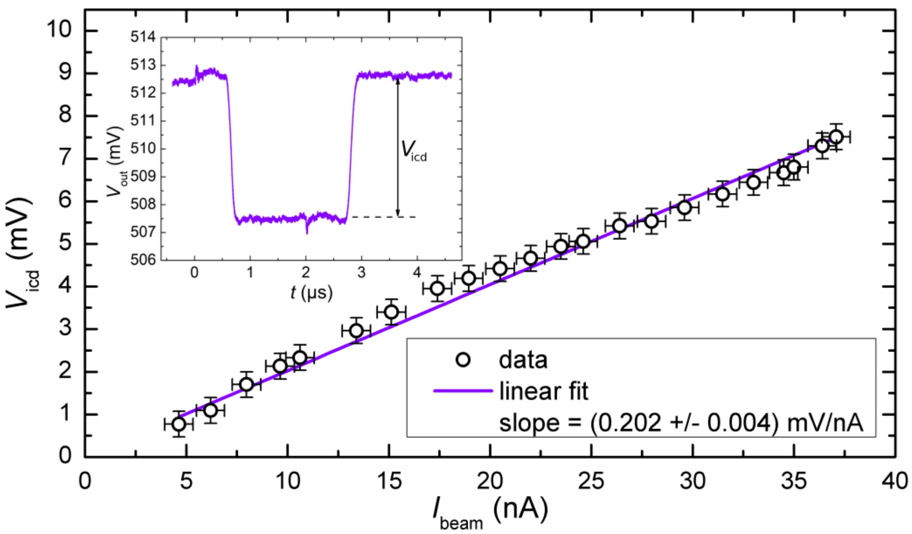

Figure 8: Linear calibration of the output signal in dependence on the ion beam current of ICD2.1.

An important initial result confirming the Shockley-Ramo theorem is shown in Fig. 8. The inset graph shows the time trace of the pre-amplifier output of ICD2.1. To reduce the noise level, 100 acquisitions were averaged. The continuous ion beam is interrupted for 2 µs. The resulting step height V_{icd} is proportional to the ion beam current (main graph in Fig. 8), meaning that it is proportional to the effective image charge, or the number of charges inside the signal electrode.

If more than one electrode is connected to the preamplifier input (e.g. three for ICD2.3), a single short bunch induces a signal in each electrode. For short bunches, the resulting peaks in the time domain were analyzed to extract the time-of-flight. Since the distance between the electrodes is known, the velocity of an ion can be calculated. This has been done for different kinetic energies and ion species. Effectively, this measurement is a way to perform non-destructive mass spectrometry, or to confirm the known parameters of ion bunches.

The next step towards the detection of a single pass of charges is the transfer of the analysis from the time to the frequency domain. Figure 9 (inset graph) shows a time signal of ICD2.5. The five signal electrodes give rise to five clearly separated maxima for ion bunches that are shorter than the space between two signal electrodes. By applying a Fourier transform to this signal (Fig. 9, main graph), the periodic repetition of the electrode signals give rise to a peak. The peak frequency depends on the spacing of the electrodes and the ion velocity. Again, values for Nitrogen and Argon ions at different kinetic energies match theoretically calculated frequencies.

Instead of measuring unknown parameters of charged particles, deterministic ion implantation seeks to take into account all that is known to be able to detect a signal from a single pass through the detector. In the Fourier analysis of ICD2.5, the frequency is known and the criterion for detection is a threshold that the FFT amplitude needs to overcome at that frequency. In this kind of experiment, only two outcomes are possible per trial: detection or not. If a signal is correctly detected, this is called a true positive. If in a trial no signal is present, because of the absence of ions, this is called true negative. Random statistical fluctuations of electrons in the preamplifier circuit give rise to noise in the spectrum. It can therefore happen, that a component of this noise is strong at the probed frequency and causes a detection although no real ion signal is to be measured. This is called a false positive. Finally, if a true signal is not detected, it is called a false negative.

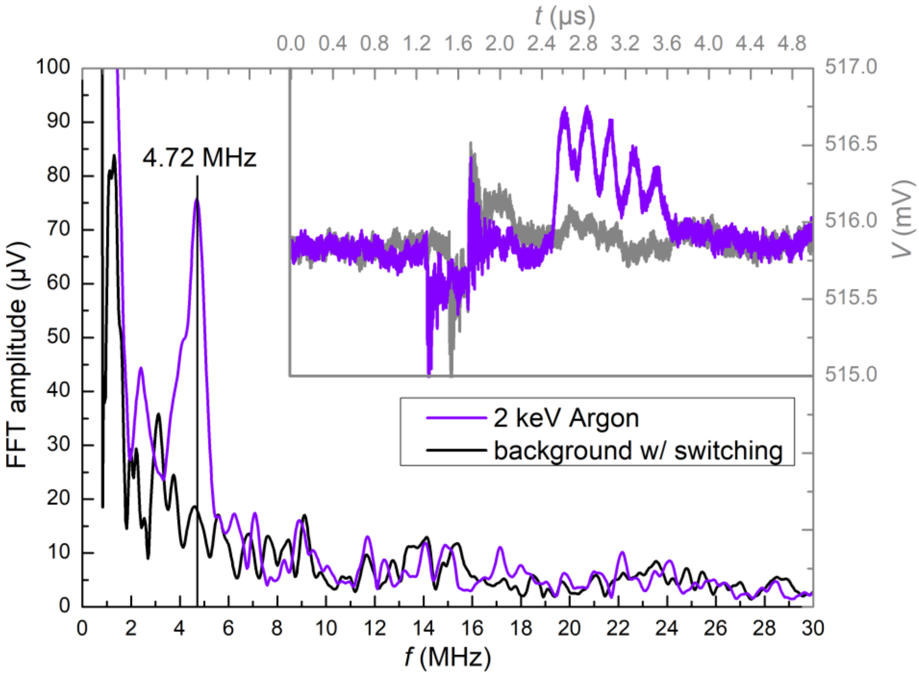

Figure 9: Time signal (inset graph) and its FFT spectrum (bottom left) for 2 keV Argon ion bunches, shown together with the background spectrum (black/grey line) without ion bunch, averaged over 100 acquisitions.

In a deterministic ion implantation experiment false negative detections are less problematic than false positives. A false negative merely means that an available ion is not used, or the implantation rate is lower. In contrast, a false positive results in a missing ion at an implantation spot. Therefore, it is important to optimize a detection scheme to be able to avoid false positives.

In the case of ion bunches, the ion beam current was reduced, so that a single bunch comprised less than 1000 elementary charges. Then, a threshold at the expected frequency was chosen and 10000 ion bunches were directed through the detector ICD2.5. For every pass of an ion bunch, a single acquisition without averaging was taken and a detection was counted, if the signal surpassed the threshold in its Fourier transform. The number of detections divided by 10000 gives the true positive rate. The same measurements were repeated, but with the ion beam turned off. The resulting fraction of detections gives the false positive rate. The results of such a measurement are given in Tab. 1.

Threshold (µV)	True positive rate (%)	False positive rate (%)
150	92	1.7
175	76	0.3
200	51	0.05
225	26	0 in 10^4

Table 1: Detection and false positive rates for different thresholds set in the live FFT of single acquisitions with and without ion bunches, respectively.

The results show, that even at low signal-to-noise ratio, a threshold can be found, that makes false positive detections highly improbable. The true positive rate decreases as well, but to a still tolerable value. As long as it stays in the same order of magnitude, this is not restricting the feasibility of implanting deterministically.

Single ion implantation and sensing with structures created by single ion implantation

The single-ion implantation designed in this project combines, on the one hand, the local introduction of atoms (AP1) and, on the other hand, the countability of the introduced atoms (AP2). Especially the latter turned out to be very difficult. However, a new patented method based on a pre-detection technique by image charge measurement seems to be very promising. Pre-detection has great advantages compared to the previous post-detection systems - such as secondary electron detection, because it allows to reduce false negative signals. However, image charge detection of one electronic charge is very challenging. We could make a large number of improvements but this aim of the project could not yet been successfully completed within the time frame of the project due to significant technical difficulties. The applications (AP3 and AP4) could therefore not yet be achieved by means of deterministic ion implantation. Instead, we used statistical single ion implantation as well as broad beam ion implantation to investigate the work packages AP3 and AP4.

The realization of the package AP3 was developed in close cooperation with the research group of the Thales company in France and it got international approval, because this methods are not only applicable for radar applications, the detection and spectroscopy of weak microwave (>GHz) signals is of pivotal importance for a large number of key areas of modern technology, including wireless communication, navigation and medical imaging. The transition frequency of NV centers in diamond can be tuned across the 1-100 GHz range. Absorption of even a single photon could be detected by readout of a single spin. A NV based spectrum analyser is new with the promise of instantaneous monitoring of the radio frequency spectrum in the application frequency range from 2 GHz to 20 GHz, with simultaneous analysis of up to 50.000 frequency channels and with a microwave sensitivity lower than 100 µW. The sensor works at room temperature and is solid-state. Such performances are a breakthrough in the field of spectrum analysis where present analog devices require sweeping a local oscillator and thus cannot address the complete spectrum at the same time, whereas the digital counterpart based on analog to digital converters have a bandwidth-dynamics product limited by the performance of current electronics. This method is patented by THALES and ULEI, patent FR-14/02429 (2014).

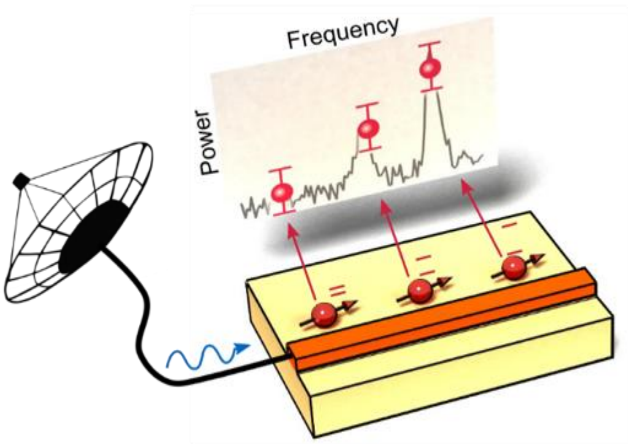

Figure 10: Quantum spectrum analyzer. Spins in a sensor chip are tuned to ascending transition frequencies, exploiting e.g. the spatially varying Zeeman shift in a magnetic field gradient. An incoming signal excites only those spins resonant with the signal frequency. Parallel readout of all spins by a camera provides a single-shot measurement of the signal spectrum.

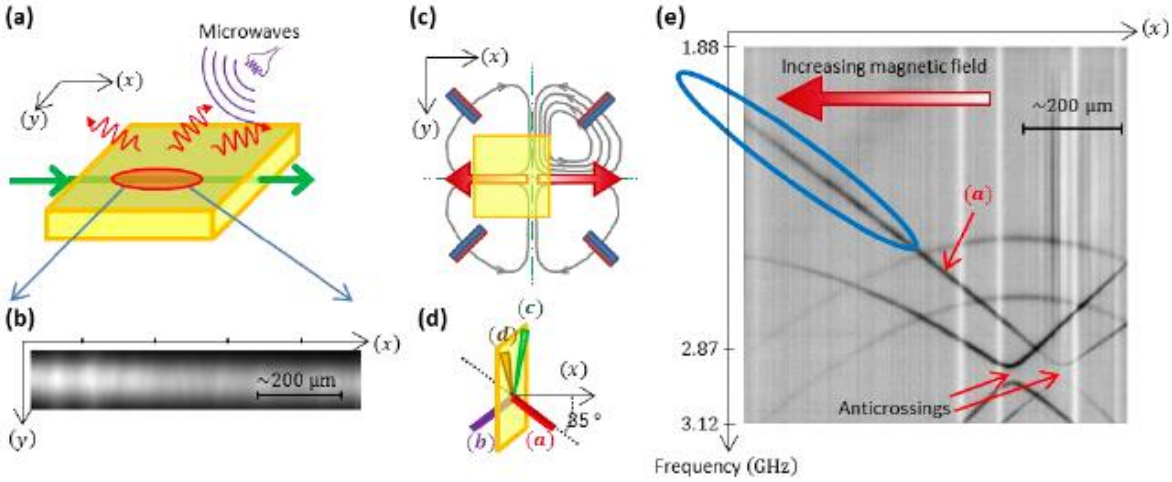

Figure 11: (a) A CVD diamond plate (yellow) holds NV centers in its volume. It is pumped by a laser beam (green arrow). The induced red photoluminescence is collected through a standard optical microscope (not represented here) and monitored by a digital camera. (b) typical image of the monitored photoluminescence. (c) The diamond is submitted to a magnetic field gradient along the (x) direction generated by an assembly of four magnets. The horizontal green dashed line indicates the plane in which the magnetic field is included. In particular, the field is aligned with the red arrow and is zero in the center of the square. In this area, the magnetic gradient is also aligned with that direction. (d) The four crystallographic axes (a), (b), (c) and (d) are represented relatively to the facets of the diamond plate. The magnetic field is aligned with (a), with an angle with axis (x). (e) The normalized photoluminescence, obtained from the raw images, is plotted as a function of the position along the (x) axis and of the microwave frequency. ESR lines are detected by a drop of the photoluminescence. Their frequencies are linked to the projection of the magnetic field along the crystallographic axes (a), (b), (c) and (d). The spectra represented in Fig. 12 were performed in the area delimited by the blue oval [Chi15].

Figure 11 shows the principal procedure of the method. Here, NV centers are introduced by ion implantation in a diamond and exposed to a magnetic field gradient. A microwave of a certain frequency can now attenuate the photoluminescence of the NV centers if the transition of the line shifted by the Zeeman effect is achieved. As a result of the magnetic field gradient, each location in the diamond is assigned a specific frequency. The method thus allows a large frequency range to be detected simultaneously. Thales wants to use this process for the development of new radar systems [Chi15].
This preliminary work carried out within the framework of this project also served to establish a joint project "Microsens" start at 10.2017 within the framework of the EU flagship quantum technology. In addition to Leipzig and Thales, this project also includes groups from Munich, Ulm and Paris. Additionally, these results served to develop a new magnetic sensor. This sensor is based on the same principle and is being developed to market readiness within the framework of a BMBF project "DiaQuantFab" (projected start 10.2018). Among others, the companies: CIS (Erfurth), Ballhuff (Neuhausen), EcoDiamanond (Kavelsdorf) and Nanoanalytics (Ilmenau) are involved. The goal is to provide a magnetic sensor with production costs below 5 euros for the mass market. Here, the performance is achieved by 3 orders of magnitude compared to conventional sensors.

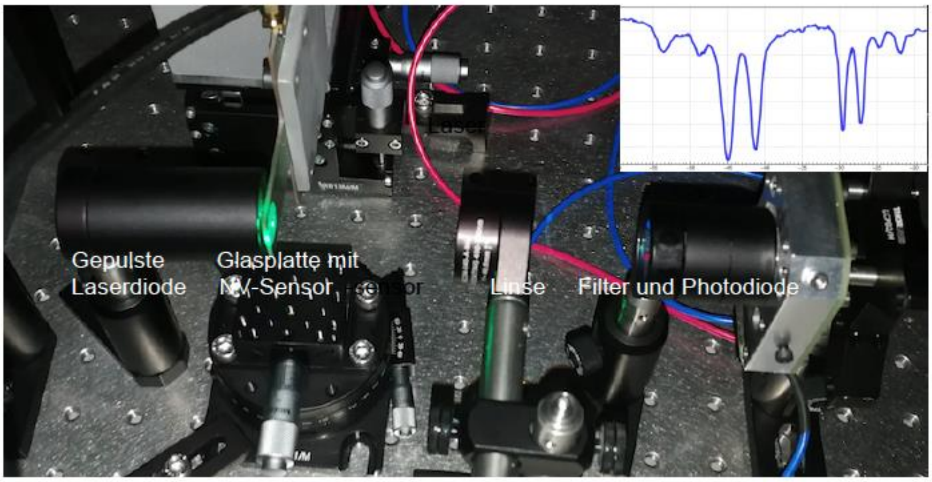

Figure 12: Implementation of a NV-based calibration-free magnetometer to demonstrate the principle of a sensor for industrial use utilizing a simple laser and photodiodes. To make the system applicable for an industrial use, the structure has to be miniaturized and adapted to the desired specifications. The signal of the photodiode shown in the spectrum corresponds to the expected result according to the physical model described above. The detected minima correspond to the transitions of the triplet state from m = 0 to m = 1 or m = 0 to m = -1. The second line pair results from NV centers in a different orientation. There are four orientations in the crystal. A magnetic field leads to a shift of these lines, which varies depending on the NV orientation: The distance between the two line pairs is different. It is thus possible to measure a complete vector field with only one sensor. In addition to the about 3 orders of magnitude higher resolution thus the orientation of the magnetic field can be determined. If the photodiode is replaced by a CCD chip, a local determination of the magnetic field without movement is possible. This can be used to zero a length measuring system without moving the system. This would be a great time saver for many applications (e.g., CC milling). In cooperation with several companies, in particular Ballhuff and CIS, this detector is to be made ready for the market.

The goal of AP4 was to switch single NV centers to obtain a tomographic method to detect and investigate single large bio molecules at the surface of a diamond plate. In order to investigate the switching properties we create planar pip- or pin-structures in diamond. NV centers became dark without any disturbing electron spin, if they were switched in the NV+ state.
To fulfil this task, the single NV center has to be switched from NV- to NV0 and finally to NV+ charge state by changing the Fermi level. In a pip-structure the Fermi level can be tuned by an applied voltage, thus a switching of the charge state became possible.
In order to prove the basic idea of switching NV-centers by an applied voltage, we investigate in-plane pip-structures in diamonds. The creation of these specific structures was performed by masked ion implantation. We used 30 keV phosphorus ions to create the n-type and boron ions to create the p-type structures. Fig. 13(a) shows the implanted structures to realize a pip structure. The intrinsic area is in the range of 5-20 µm (Fig. 13(b)). In this i-area we implant individual NV centers (Fig. 13(c)). This experiments shows that whereas the switching from NV- to NV0 is possible (Fig. 14a), the transition from NV0 to NV+ is very difficult. It might be that the NV0/NV+ transition level is very deep, close to the valence band that electrons are already released during readout by means of the green laser. This means that the NV center may be switched in a NV+ state but cannot be stabilized. Although this goal has not yet been achieved, the results are very promising, so it was possible to estimate a local determination of the Fermi level. This unexpected result is very important for the investigation of diamond-based high power devices in the future.

During the setup of the new system, we developed a new type of nanoapertures [Sch17] and found a new method to create NV centers by electron irradiation [Bec17]. Thus, during the project three publications in the highly cited Nature family journals could be achieved.

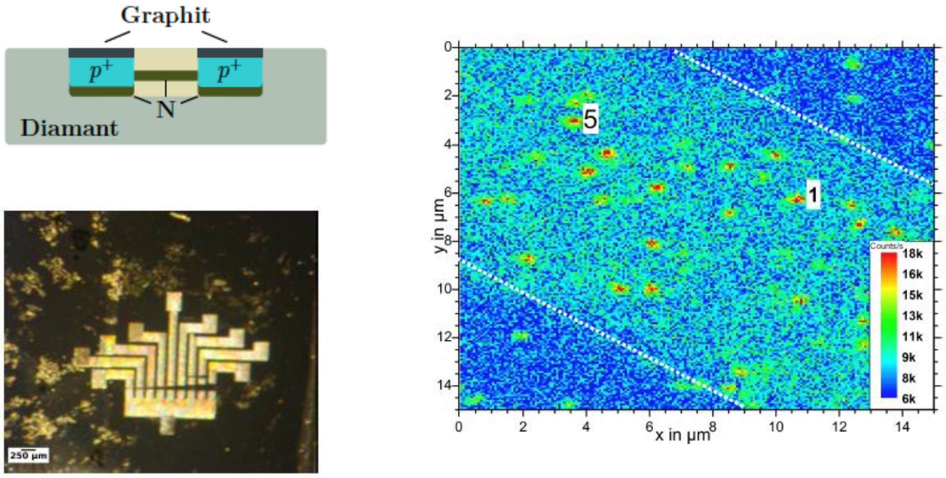

Figure 13: (a) Example of an in-plane pip structure in diamond produced by ion implantation. (b) image of the gold contacts to the p structures, in the gaps are the intrinsic areas. (c) confocal image of the intrinsic area with different NV centers.

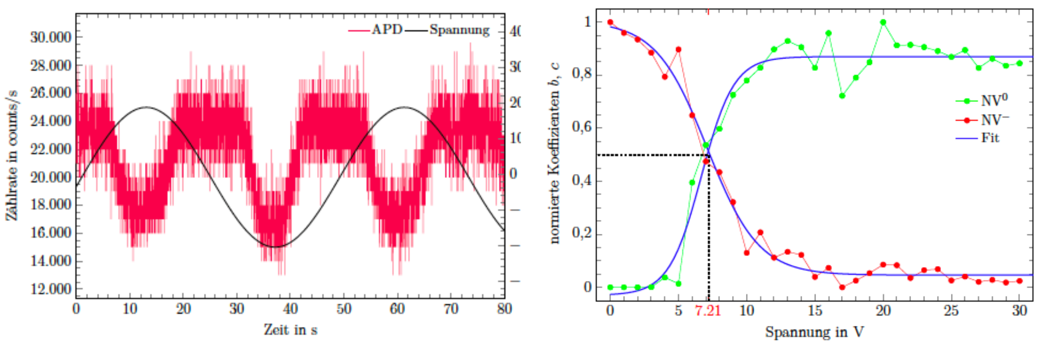

Figure 14: (a) Switching of the charge state of a single NV center from NV- to NV0 (red) in comparison to the appled voltage (black curve). (b) Occupation of the charge states depending on the applied voltage of a single NV-center. The distribution corresponds to the Fermi function and allows to determine the local Fermi level. By measuring different NV-centers a 3-dimensional distribution of the Fermi level became possible.

References

[Bec17] S. Becker et al., *Sci. Rep.* **8** (2017) 32.

[Cai13] J.M. Cai et al., *Nature Physics* **9** (2013) 168.

[Chi15] M. Chipaux et al., *Appl. Phys. Lett.* **107** (2015) 233502.

[Dol13] F. Dolde et al., *Nature Physics* **9** (2013) 139.

[Gae06] T. Gaebel et al., *Nature Physics* **2** (2006) 408.

[Jam17] D.N. Jamieson et al., *Mater. Sci. Semicond. Process.* 62 (2017) 23-30.

[Küp17] Johannes Küpper, Master Thesis, Leipzig University (2017).

[Loh11] A. Lohrmann et al., *Appl. Phys. Lett*. **99** (2011) 251106.

[Pie15] E.E. Pierson et al., *J. Am. Soc. Mass Spectrom*. **26** (2015) 1213.

[Räc18] P. Räcke et al., *Sci. Rep.* **8** (2018) 9781.

[Ram39] S. Ramo, *Proc. IRE* **27** (1939) 584-585.

[Sch09] M. Schmidt et al., *Rev. Sci. Instrum.* **80** (2009) 063301.

[Sch17] C. Scheuner et al., *Sci. Rep.* **7** (2017) 17081.

[Shi05] T. Shinada et al., *Nature* **437** (2005) 1128-1131.

[Sho38] W. Shockley, *J. Appl. Phys.* **9** (1938) 635-636.

[Zsc08] G. Zschornack et al., *Rev. Sci. Instrum.* **79** (2008) 02A703.

Statement if results of the project can be economically exploited and if such an exploitation is in progress or to be expected; details on possible patents or industry cooperations

Regarding the instrumentation side, during the work within the frame of the project the contact to Raith GmbH as well as Dreebit GmbH was close and steady. Future cooperation with these companies in follow-up projects in the field of single ion implantation and sensing is very probable. Taking into account the high risk of the project, a final success, rather unexpected by companies, will make the commercialization the more probable. As is usually the experience, companies are careful unless the success is already at hand.

A patent on this concept with the title "Apparatus for detecting individual charged particles and material processing system having such an apparatus" has been filed with the international number WO 2016/174177 A1 with Leibniz Institute of Surface Engineering (IOM), University of Leipzig and Max Planck Society as inventors:

Jürgen W. Gerlach, Jan Meijer, Sébastian Pezzagna, Bernd Rauschenbach, Stephan Rauschenbach, Daniel Spemann

Apparatus for detecting individual charged particles and material processing system having such an apparatus, WO 2016/174177 A1, PCT/EP2016/059565

As for the sensing side, the already established cooperation with companies working in this field will be continued and fortified.

Contributions of possible cooperation partners in Germany or abroad to the results of the project

Ferdinand-Braun-Institut für Höchstfrequenztechnik (FBH), Berlin, Germany: Analysis regarding detection of single charges (signal intensity and noise in image charge detection)

Dr. S. Rauschenbach, Max Planck Institut für Festkörperforschung Stuttgart, Germany (now: Oxford University, UK): Discussions and intellectual contributions to the above mentioned patent on detection of individual charged particles

List of theses from the project

Paul Räcke, dissertation, Leipzig University, will be submitted in 2019.

List of publications

M. Chipaux, L. Toraille, C. Larat, L. Morvan, S. Pezzagna, J. Meijer, T. Debuisschert,
Wide bandwidth instantaneous RF spectrum analyzer based on nitrogen vacancy centers in diamond,
Appl. Phys. Lett. **107** (2015) 233502, DOI: 10.1063/1.4936758

C. Scheuner, S. Jankuhn, J. Vogt, S. Pezzagna, C. Trautmann, J. Meijer,
Nanometer collimation enhancement of ion beams using channeling effects in track-etched mica capillaries,
Sci. Rep. **7** (2017) 17081, DOI: 10.1038/s41598-017-17005-w

S. Becker, N. Raatz, St. Jankuhn, R. John, J. Meijer,
Nitrogen implantation with a scanning electron microscope,
Sci. Rep. **8** (2018) 32, DOI: 10.1038/s41598-017-18373-z

P. Räcke, D. Spemann, J.W. Gerlach, B. Rauschenbach, J. Meijer,
Detection of small bunches of ions using image charges,
Sci. Rep. **8** (2018) 9781, DOI: 10.1038/s41598-018-28167-6.

T. Herzig, P. Räcke, N. Raatz, D. Spemann, J.W. Gerlach, J. Meijer, G. Cassabois, M. Abbarchi, Sébastien Pezzagna,
Creation of quantum centers in silicon using spatial selective ion implantation of high lateral resolution,
IEEE Conf. Proc. (IIT 2018) (submitted)

List of talks

Daniel Spemann, Jürgen W. Gerlach, Stephan Rauschenbach, Bernd Rauschenbach, Jan Meijer
Concept of single ion detector for deterministic ion implantation at the nanoscale.
22. International Conference on Ion Beam Analysis, Opatija, Croatia, 15.-19.06.2015.

Daniel Spemann, Jürgen W. Gerlach, Stephan Rauschenbach, Bernd Rauschenbach, Jan Meijer
Concept of single ion detector for deterministic ion implantation at the nanoscale.
Workshop Ionenstrahlen & Nanostrukturen, Heidelberg, 22.-24.07.2015.

Daniel Spemann
Implantation of counted single ions.
Autumn School, Faculty of Physics and Geosciences, University of Leipzig, 28.09.-02.10.2015.

Daniel Spemann, Jan Meijer, Jürgen W. Gerlach, Paul Räcke, Susann Liedtke, Stephan Rauschenbach, Bernd Rauschenbach
Concept of deterministic ion implantation at the nanoscale.
XXIII. Erfahrungsaustausch Oberflächentechnologie mit Plasma- und Ionenstrahlprozessen, Mühlleithen, 15.-17.03.2016.

Daniel Spemann, Jan Meijer, Jürgen W. Gerlach, Paul Räcke, Susann Liedtke, Stephan Rauschenbach, Bernd Rauschenbach
Invited: *Concept of deterministic ion implantation at the nanoscale.*
International Conference on Electronic Materials (ICEM2016), Singapore, 04.-08.07.2016.

Daniel Spemann, Jan Meijer, Jürgen W. Gerlach, Paul Räcke, Susann Liedtke, Stephan Rauschenbach, Bernd Rauschenbach
Concept of deterministic ion implantation at the nanoscale.
Seminar ECMP, School of Physics, The University of Melbourne, Australia, 11.07.2016.

Daniel Spemann, Jan Meijer, Jürgen W. Gerlach, Paul Räcke, Susann Liedtke, Stephan Rauschenbach, Bernd Rauschenbach
Invited: *Deterministic ion implantation for engineering arrays of atoms at the nanoscale.*
Autumn School and BuildMoNa Module T4, Faculty of Physics and Geosciences, University of Leipzig, 19.09.2016.

Daniel Spemann, Paul Räcke, Jan Meijer, Jürgen W. Gerlach, Bernd Rauschenbach
Current status of the deterministic ion implanter of the Leibniz Joint Lab at IOM.

XXV. Erfahrungsaustausch Oberflächentechnologie mit Plasma- und Ionenstrahlprozessen, Mühlleithen, 19.-23.03.2018.

Paul Räcke, Daniel Spemann, Jürgen W. Gerlach, Bernd Rauschenbach, Jan Meijer
A concept for deterministic ion implantation by image charge detection.
21st Int. Conf. on Ion Beam Modification of Materials (IBMM 2018), San Antonio, Texas, USA, 24.-29.06.2018.

Paul Räcke, Daniel Spemann, Nicole Raatz, Robert Staacke, Jürgen W. Gerlach, Bernd Rauschenbach, Jan Meijer
Invited: *A concept for deterministic ion implantation by image charge detection*.
16th Int. Conf. on Nuclear Microprobe Technology and Applications (ICNMTA 2018), Guildford,
Surrey, UK, 08.-13.07.2018.

List of posters

Paul Räcke, Daniel Spemann, Franz-Josef Schmückle, Wolfgang Heinrich, Susann Liedtke, Jürgen W. Gerlach, Bernd Rauschenbach, Jan Meijer
Novel concept for deterministic ion implantation at the nano-scale.
DIADEMS Summer School, Cargèse, Corsica, 26.04.-06.05.2016.

List of press releases and media reports

Press release of the public relations office of the IOM Leipzig on the IOM web page (www.iom-leipzig.de) about the SAW project "Sensing with single atoms".

Press release of the public relations office of the IOM Leipzig on the IOM web page (www.iom-leipzig.de) about the visit of Min. Dr. Stange at IOM Leipzig and of the Leibniz Joint Lab "Single Ion Implantation".