1 Explanation of the work carried out

Task number & title *excluding the uptake and exploitation task (JRPs & JNPs only) & management & coordination tasks*	**Task end date in Annex 1**	**Actual task completion date**	**Status:** *inactive, on schedule, delayed to..., or completed*	**Explanation of the work carried out in each task in this reporting period**	
				Summary of the progress towards the aim of each task in this reporting period	**Explain any issues affecting the completion of the tasks (eg describe the cause of delays / deviations etc. and any knock-on effects)**
1.1:Developing a process for controlled ion implantation in diamond	August 2022		Delayed to February 2023	**Activity A1.1.1. Completed** **Activity A1.1.2**. **Completed** The delivery of the requested parts for the process chamber installation was finalised September 2022. The results on the testing of the implanting facility has been carried out and one research paper is in preparation. Charge sensitive preamplifiers have been purchased to achieve single ion sensitivity with tens of keV sensitivity. The initial plan of developing a cryogenic system was intended to increase the readout electronics sensitivity. During the development of the irradiation chamber this plan was reconsidered as it was deemed probable that the cryogenic operation would not only require an articulated setup, but also it would generate further issues related to induced mechanical vibrations on the sample. As an alternative route, a careful study of the different classes of readout electronics was performed. It was estimated that with cryo-genic operation @ 70K it is expected a reduction of the noise floor of a factor 5 with respect to RT sensitivity in controlled implantation regime (100Hz). For standard pre-amplifiers (with a nominal noise floor of 10%) this would allow to reach approx 2% sensitivity. **Activity A1.1.3**. **Completed.** During the installation of the ion scattering chamber, UniTO performed preliminary ion implantation campaigns at external facilities for ensemble and individual colour centres fabrication. EU Radiate Transnational access has been exploited to this purpose. Ion implantations of different regions in the range of 10^{10}-10^{17} cm^{-2} fluence and 10 keV – 2 MeV range have been performed on >10 regions of four separate samples and annealed in the 750-1000 °C range. 6 additional regions were implanted with 10^13-10^15 cm^-2 at the UNITO implanter following the completion of A1.1.2. All fluences below 10^{17} cm^{-2} resulted to be suitable for the formation of NV centres on 14 regions all of which with bright PL luminescence, as verified by PL measurements. The 10^{17} cm^{-2} fluence was exploited to feed activities in A4.1.2, performed in parallel.	The previously reported delays in the delivery of the purchased material are still affecting the implantation campaigns at UniTO. While alternative facilities have been exploited for sample fabrication, the lack of the facility availability is a bottleneck for sample distribution to the partners throughout WP1-WP2 activities. To compensate for this delay several activities of WP2 started ahead of schedule (A2.2.4, A2.3.1, A2.3.3, A2.3.4) and A2.2.2 has been completed ahead of schedule.

				Activity A1.1.4. TUBITAK has resumed the implantation campaign as of December 2022 on the second batch of N-rich type-Ib diamond substrates. After finishing the optical and structural characterization of the first batch of implanted diamond samples, they were annealed at 800-850 C in a high vacuum chamber. The samples are being characterized again after the implantation in order to investigate the annealing effects. The second batch of samples will be implanted in the second week of January 2023 following the pre-implantation characterization. **Activity A1.1.5.** The activity depends on at least a partial completion of A1.1.2 to explore the actual nanoscale resolution of the implantation facility, thus it could not start in due time. UniTo has started exploring the availability of external facilities to perform nanoscale ion implantation during the finalization of the internal ion irradiation chamber. As mitigation the activity was performed in parallel to the implanter installation exploiting external facilities. A regular pattern of Ge ions implantation (100 nm spot size, 3 um spacing) was fabricated and characterized in confocal PL microscopy . Nanopatterned samples are in preparation on the basis of the aforementioned characterization. Expected completion of the activity in M21.	
1.2:Metrological tools for the characterisation of single-atom systems	May 2024		On Schedule	**Activity A1.2.1** TUBITAK will perform photoluminescence spectroscopy on the samples that have been implanted within A1.1.4 after the characterisation of the samples via XRD, Raman and FT-IR spectroscopies. Then, the samples will be shared with the activity partners for confocal PL mapping. The activity has been resumed as the Helium Ion microscope is functional again after flood gun and turbomolecular pump repairs. The samples have been characterized by scanning Raman and scanning Photoluminescence measurements at three different stages, before implantation, after implantation and annealing. We have measured photoluminescense peaks of zero phonon lines for neutral (NV^0) and active (NV^-) centers at 575 nm and 638 nm respectively. New batch of samples will be implanted in the first week of March in order to confirm the repeatability of the pre- and post-implantation processes. Then these samples will be measured using scanning PL and Raman following the annealing. Then the samples will be shared for advanced optical characterizations such as $g^{(2)}$ correlation measurements. The activity was delayed due to malfunctions in the Helium ion microscope and supply chain issues but now it is resumed and ongoing. **Activity A1.2.2 Completed.** XRD characterization of the samples were completed and no significant change was observed between pre- and post-implantation results. This indifference is attributed to small implantation area which did not lead to detectable difference in the XRD signal. Raman and photoluminescence results	A1.2.1: The activity has been delayed for flood gun and turbomolecular pump repairs. A1.2.4: TUBITAK has finished setting up its scanning confocal PL and Raman measurement system. TUBITAK will measure the samples that will be forwarded by QNAMI and INRIM from the activity A1.1.5.

				however revealed the impact of the implantation as these results were measured in the local implanted area unlike XRD which was taken from the whole sample. The samples were characterized using high resolution XRD (HRXRD) technique at several stages, (i.e. before and after implantation, before and after annealing) but the XRD results did not show a significant change between before and after measurements. This result is attributed to small signal to noise ratio since the implanted area is very small (in the order of microns) compared to X-Ray spot on the sample (in the order of millimetres. Therefore, we have concluded that normal or HRXRD is not suitable for the investigation of single atom limit implantation studies. This activity is considered as **completed** since the investigation planned and promised in the project proposal was done. **Activity A1.2.3** A sample provided by UNITO with active colour centres implanted in nanodimensions on silicon wafer was characterized at PTB in collaboration with INRIM. The characterization was performed in terms of its photoluminescence and spectral characteristic of photon emission. No zero phonon line was observed. Moreover, due to the high background, no monophoton emission (g2(0)) could be measured. New samples with lower background will be developed by UNITO and TUBITAK, which will be characterized again at PTB. New colour centres will be implanted in diamond samples with less background in order to achieve single photon emission. These samples will be characterized again at the PTB. **Activity A1.2.4** Activity has started. Preliminary PL maps acquired in non nanostructured samples. **Activity A1.2.5** Activity not started **Activity A1.2.6** Activity not started	
1.3: Investigation of alternatives to diamond materials and NV centres	May 2024		On Schedule	**Activity A1.3.1 Completed.** Implantation campaigns were performed by UniTO at several irradiation facilities for the fabrication of alternative colour centres. Experiments included the implantation of several ion species, including Pb, Ge, Mg, Sn, and Mn. The PL characterisation of the afore-mentioned impurities has evidenced the formation of optically active defects for each of the afore-mentioned species. A systematic characterisation has been done on the 2 most promising color centers (MgV and Sn, 2 research papers were published). **Activity A1.3.2** PTB has delivered the first batch of hBN samples to TUBITAK. Following the initial characterization and first implantation results, PTB will decide on the next batch of samples. TUBITAK has started characterising the hBN samples. Implantation will be performed after the characterizations are finished. **Activity A1.3.3 completed** UNITO finalised the acquisition of Si and SiC wafers. Ion implantation campaigns for the formation of defects ensembles has been performed. A3.2.3 has determined that the centers were successfully implanted. This activity is related only to implantation.	A1.3.2 The delay in the activity was caused by the Helium ion microscope repair as it was the case for A1.2.1. The optical characterization part of A1.2.3 was done but Helium ion implantation recently resumed. Therefore the delay occurred. However the activity is resumed and ongoing now.

				Activity A1.3.4 Preliminary characterization of a diamond sample with Sn ion implantation was started. Unfortunately, from photoluminescence mapping it was observed that the sample was too dirty (probably graphene), thus no implanted region was visible. UNITO will provide a new cleaner sample for its characterisation, which includes the micro-photoluminescence measurement, spectral characteristic and single-photon emission. Moreover, characterisation on h-BN implanted samples (A1.3.2) will be performed next. **Activity A1.3.5** Activity not started	