Publishable Summary for 20IND05 QADeT
Quantum sensors for metrology based on single-atom-like device technology

Overview

In 2018 the global market for magnetic sensors alone was €1.7 billion. Quantum sensors (QS) could potentially revolutionise any area where accurate sensors are required and the development of metrology for these is one of the four aims of the EU's Quantum Flagship agenda. The scale-up and commercialisation of QS requires independent and rigorous testing for the new devices and systems. This project aims to develop a new class of single-atom-like QS devices, together with techniques for their characterisation. It will define optimal methods to assess reproducibility in the production and characterisation of QS systems. These new devices promise to provide nanoscale high-sensitivity measurements of properties such as electro-magnetic fields, temperature and stress, allowing European NMIs to develop the infrastructure and reliable standards for the emerging QS technology sector.

Need

Despite the wide potential use of quantum technologies in quantum-computing, -communications and -sensing, their commercialisation has been identified as one of Europe's biggest industrial challenges. Most of the immediately foreseen applications for QSs target high-precision devices and niche applications rather than mass-market applications. New test and validation methods need to be developed for the independent, rigorous testing of new quantum devices and systems in order to be able to bring them to market. This requirement has been cited by a significant number of early quantum adopters and companies (e.g. Bosch, Thales, Qnami, NVISION, MUQUANS, AOSENSE), which are looking at exploiting Quantum Technology (QT). They need the quality of their prototypes, and subsequently of their commercial devices, to be ensured. Tools need to be developed to assess the performance and the reliability of these devices. Furthermore, in the field of material development, standardisation would be beneficial. Material development is key for all devices based on solid-state sensors in order to build reproducible and reliable components.

Traditionally, negatively charged Nitrogen-Vacancy (NV) centres in diamond (or other suitable materials) are used as QS materials, however more recently novel optically active centres in diamond (and other suitable materials) have been identified as a better way to develop nanoscale magnetic field, electrical field and temperature sensors. Single-atom-like systems (SALS) involving 'ion implantation' where a charged atom is magnetically 'fired' at the vacancy in the substrate, have the potential to measure several physical quantities with unprecedented spatial resolution and high sensitivity, and these need to be investigated and characterised. The goal is a 'deterministic' ion implantation process where it is possible simultaneously to control the number of implanted ions, their accurate nano-positioning, and their optical activation with unit probability. Although significant effort in this field exists in Europe, there are currently no facilities available at European NMIs with the capability to create single-atom-like QSs realised via deterministic ion implantation, whether based on diamond or other materials. There is currently a lack of effective techniques for realising nanoscale QSs including standardised synthesis processes to produce material with reproducible performance and quality, as well as reproducible techniques for the production and measurement of the QS including their optical activation, modelling and traceability.

These needs are in line with the objectives and the scope of the EURAMET European Metrology Network for Quantum Technologies (EMN-Quantum). By providing reliable material, high creation efficiency and device qualification, these results will ultimately lead to marketable QS products and help the EU achieve its quantum goals.

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Objectives

The overall objective of the project is to foster the development of QSs for metrology based on single-atom-like device technology.

The specific objectives of the project are:

1. To develop single-atom-like systems in diamond or other suitable materials, e.g., silicon carbide (SiC), silicon (at different ion energies in the 20 keV - 50 keV range) and 2D materials (ion energies in the 15 keV - 30 keV range), using controlled ion implantation, aiming at a deterministic placement of individual emitters with a spatial resolution below 500 nm in a single-ion regime, and to develop the associated metrological capabilities to support this.
2. To develop robust and accurate QSs using controlled implantation based on NV centres in diamond (or other suitable materials) for the measurement of magnetic fields, electric quantities, temperature, and stress (as well as other possible physical observables of interest). In addition, to metrologically compare the sensitivity of these QSs with state of art nitrogen-vacancy (NV)-based sensors.
3. To investigate the possibility of developing QSs for the measurement of magnetic fields, electric quantities and temperature via deterministic controlled ion implantation based on novel defects in diamond (including promising complexes based on Si, Ge, He, Sn, Pb and other impurities) and in other suitable materials.
4. To develop reliable methods for the production (e.g. conventional and non-conventional annealing in the 600 °C - 1200 °C temperature range) and measurement of single-atom-based sensor devices, including modelling their behaviour via tight-binding methods. In addition, to develop the necessary traceability chains for such single-atom-based sensors in the photon flux regime of 10^7 - 10^8 photons per second (approximately in the 600 nm - 900 nm wavelength range).
5. To facilitate the take up of the knowledge, technology and measurement infrastructure developed in the project by the measurement supply chain, standards developing organisations (ISO, CEN) and end users (quantum sensing, computing, and communications).

Progress beyond the state of the art

In order to support the development of the 2nd quantum revolution and to boost the commercialisation of smaller and more sensitive sensors, there is a strong need for certified tools for their characterisation, testing and validation, as this is limiting the development of QTs. This project addresses this issue as follows:

1) exploiting an ion beam irradiation implanting facility targeted at single ion delivery, based on the accurate control of the beam position as well as a real-time, number-resolved feedback on the impact of ions on the target substrate, in combination with a systematic study aimed at the optimisation of the centre's activation by annealing processes, and investigating the possibility to fabricate SALS-based sensors in host materials other than diamond such as Si, SiC and 2D materials (e.g. h-BN);

2) developing robust and accurate magnetic field, electric quantities, temperature and stress NV-based QSs (and also prototypes for industrial application, by using a dedicated setup for their characterisation (and comparison with state-of-the art sensors) featuring novel techniques for reaching high sensitivity (based on, e.g., lock-in detection, multi-pulse decoupling techniques for magnetometry and environmental EM-noise-insensitive thermometry);

3) investigating alternative non-NV-based (based on, e.g. Si, Ge, He, Sn, Pb and other impurities in diamond) and non-diamond-based (based on e.g. Si, SiC, h-BN, etc.) QSs and comparing them with state-of-the-art sensors;

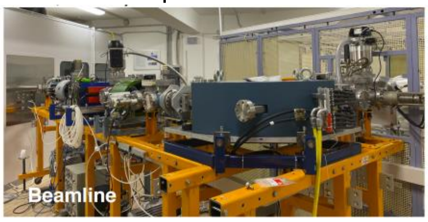
4) identifying reliable methods for the optical activation of the SALSs upon ion implantation, with support by the theoretical modelling of single-atom via tight-binding methods and with a strong interplay between the modelling activities with the experimental activities on controlled ion implantation and providing traceability of the new sensors to radiometric standards.

Results

The following is the list of the expected and preliminary results for each JRP objective:

Objective 1: Development of single atom-like systems aiming at deterministic ion implantation with metrological control (target spatial resolution below 500 nm)

The main expected result towards meeting this objective is the development of SALSs, also by the realisation of a dedicated implanting facility and the development of techniques targeting controlled ion implantation. The combination of these technical solutions, together with a systematic study aimed at the optimisation of the centre's activation by annealing processes, will pave the way towards the definition of a fully deterministic ion implantation process (targeting a spatial resolution below 500 nm). Controlled fabrication of SALSs will be assessed by the concurrent development of techniques based on the optical and structural characterisation of the sample. This will be a crucial step towards the standardisation of material production and characterisation techniques. Diamond samples with suitable properties have been identified. The implanting facility has been finalised in September 2022 and ion implantation campaigns have been performed.



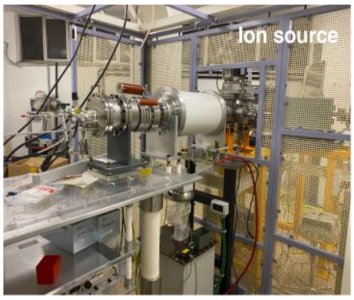


Fig. 1: Multi-elemental ion implanter installed at the Solid state physics lab of UNITO during the project.

In parallel, the possibility to fabricate SALS-based sensors in host materials other than diamond (i.e. a high-potential, vastly unexplored research field) such as Si, SiC and 2D materials such as hexagonal Boron Nitride (h-BN), is being investigated.

In particular, concerning 2D materials, a study on engineering Multicolour Radiative Centres in hBN Flakes by Varying the Electron Beam Irradiation Parameters has been performed.

Objective 2: Development of robust and accurate Quantum Sensors using controlled implantation based on NV centres

The setup for the characterisation of the sensors, that were developed specifically for the project is complete. The facility is equipped with a single-photon sensitive confocal microscope (compatible with ODMR measurements), lock-in amplifiers, Helmholtz coils, and pulsed excitation. Preliminary Lock-in testing and pulsed ODMR measurements have been performed.

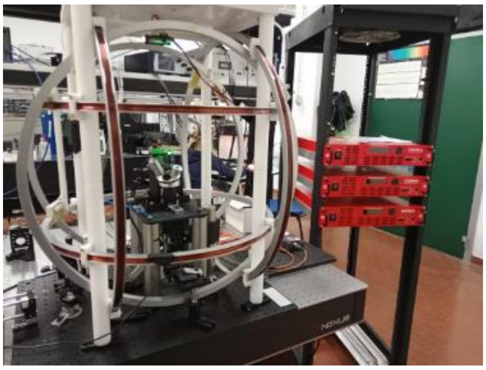


Fig. 2: Photo of the facility targeted for the characterisation of quantum sensors developed in the project, featuring single-photon-sensitive confocal microscopy, ODMR capabilities, Helmholtz coils, pulsed excitation.

Several activities are ongoing, and several important results have been achieved, including: NV-based biological sensing, RF NV sensors, high-Speed Wide-Field Imaging of Microcircuitry Using Nitrogen Vacancies in Diamond, quantum sensing under extreme pressure with Nitrogen-vacancy magnetometry up to 130 Gpa, and photoconductive detection of electronic spin resonance through graphitic planar electrodes.

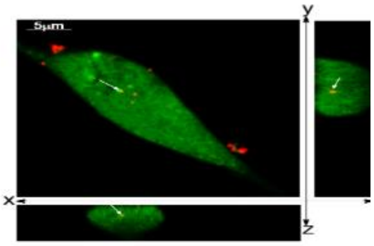


Fig. 3: Nanodiamond NV quantum sensors for intra-cell thermometry

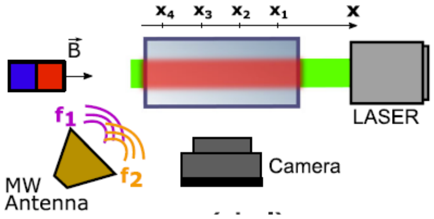


Fig. 4: RF NV signal analyser (developed by THALES)

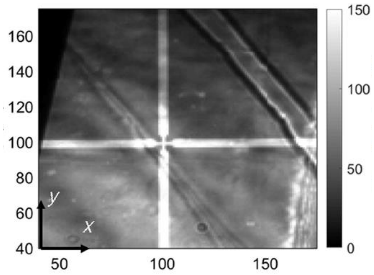


Fig. 5: High-Speed Wide-Field Imaging of Microcircuitry Using Nitrogen Vacancies in Diamond

Objective 3: Investigation of feasibility for Quantum Sensors based on novel defects

In the context of the investigation of the sensors based on alternatives to NV-centres and diamond material, implantation of several ion species has started in diamond and also ion implantation campaigns for the formation of defects ensembles on recently acquired Si and SiC wafers has been performed.

Among the most notable results, the spectral emission dependence of tin-vacancy centres in diamond from thermal processing and chemical functionalisation, magnesium-vacancy centres, Ge-V Quantum Emitters in Single-Crystal Diamond upon Ion Implantation and HPHT Annealing and their use for realisation of bright SPSs exploiting solid immersion lens, and optical properties of SiV and GeV colour centres in nanodiamonds under hydrostatic pressures up to 180 Gpa have been investigated.

In parallel, a user-friendly high flux single photon quantum dot source in a compact He-flow cryostat was designed and developed. The source consists of an InAs quantum dot embedded in GaAs. An initial characterisation was performed at cryogenic temperature.

Objective 4: Development of reliable methods for the production and measurement of single-atom-based sensor devices

The results related to this objective are divided into three lines of research. The first is focused on the development of post implantation activation techniques for the SALSs that will be used as quantum sensors. The activities related to this task are running in parallel with the activities on implantation reported in the frame of Objective 1. In particular a new paper is under revision concerning activation techniques for telecom emitters. The second task is related to the development of empirical tight binding code for the computation and modelling of single atoms. This task is ongoing but the first results are available concerning the modelling of the electronic and optical properties of III–V quantum dots. Recently a work was published on PRB about GaAs quantum dots under quasiuniaxial stress. Finally, the last task is related to the traceability of the radiometric standards of the developed sensors. Concerning this task, measurements on the absolute responsivity of a silicon detector at 930 nm using low photon flux sources have been performed. Preparations are ongoing to achieve lower uncertainties in responsivity at a lower photon flux of 1-100 million photons per second traceable to a cooled PQED detector in the spectral range of interest (600 nm - 900 nm) with an uncertainty of < 1 % both in the free-beam and in the fibre-coupled (multi-mode) configurations. A joint paper is in preparation.

Impact

To promote the uptake of the quantum sensing techniques, and to share the insights generated throughout the project, results were shared broadly with scientific and industrial end-users. 22 papers were published (plus 3 submitted) in international journals (listed in the next section), including high-profile papers in *Light Science and Applications*, *Advanced Science*, *ACS Photonics*, and *Physical Review Letters*, etc. 83 presentations were made at conferences, including *CIM 2021 (20th International Metrology Congress)*, *Hasselt Diamond Workshop 2022*, *32nd International Conference on Diamond and Carbon Material*, *SPIE Optics + Photonics 2022*, *Single Photon Workshop 2022*, etc. 4 training activities were performed. Furthermore, during the project, 23 various dissemination outputs were produced, among which: one PhD was presented in the metrology program at Politecnico di Torino (open to the general public), one seminar on the fabrication and characterisation of solid-state quantum emitters at INRIM (scientific audience), 5 M. Sc. and 2 B. Sc. thesis presentations, the online workshop “Quantum Lectures 2022 ad memoriam of Carlo Novero”, the organisation of a Special Session inside CEWQO 2023 conference in Milan, Italy (July 2023), etc.

Impact on industrial and other user communities

The developed QSs are expected have an impact in industrial fields such as physics, nanotechnology, medicine, mobility, biology, data storage and processing. The results will prompt the technological development of quantum sensing and the development of reliable techniques for the characterisation of QS materials and prototypes enabling more accurate measurement of physical observables ranging from electromagnetic quantities, temperature, pressure, force, etc. with nanoscale spatial resolution for e.g. biological applications and nanotechnology. The techniques developed are expected to provide reliable common ground for material and device qualification and the developed sensors could also become commercial products themselves.

The advances in both ion implantation manufacturing and in the standardisation of low fluence or single ion delivery techniques can represent enabling technologies for advanced large scale manufacturing not only of quantum devices at the nanoscale, but also for nanotechnology and semiconductor devices.

To increase the impact of the project towards the industrial community, an article has been submitted to the Italian trade journal “TUTTO MISURE”(industrial readership) (accepted, to be published in October).

Impact on the metrology and scientific communities

The possibility to systematically build quasi-atomic scale sensors with high sensitivity and efficiency affects the current status of quantum metrology, providing as a direct consequence, an increased measurement capability for several physical observables (e.g. electromagnetic quantities, temperature, pressure, force, etc.) with high sensitivity and extreme spatial resolution. This will be of great impact in the measurement science community in several fields, such as medical imaging. The fabrication and characterisation methods developed in SALSs will also lead to the manufacturing of solid-state Fock state sources. This will enable the development of quantum processors based on boson sampling and photonic quantum walks, as well as offering a central resource to boost quantum-enhanced techniques such as quantum radar and sub-shot-noise imaging.

One of the most recent developments in this context is the activity related to the traceability of the radiometric standards of the developed sensors at a photon flux of 1-100 million photons in the spectral range of 600 nm - 900 nm with an uncertainty of < 1 %.

Impact on relevant standards

The work in this project targets standard ways to characterise quantum sensing devices with different techniques and equipment. However, the development of standardisation in this area is at an early stage. In order to identify any new standardisation needs emerging from the QT community, CEN-CENELEC has created a Quantum Technologies Focus Group (FGQT). Several project partners are members of this FGQT and through them the project is contributing to quantum sensing and metrology standardisation efforts, in particular in drafting of a document, the” FGQT Quantum Technologies Standardization Roadmap”, published in 2023. This effort has also led to a joint publication titled “Towards European Standards for Quantum Technologies” in EPJ Quantum Technology. Following this initiative, a new Joint Technical Committee of CEN/CENELEC (JTC-22) dedicated to the standardisation of quantum technologies, including consortium members, kicked off in March 2023.

Longer-term economic, social and environmental impacts

This project contributes to the growth and consolidation of the QT market by potentially offering new types of QSs based on diamond and other materials, which can lead to a number of long term societal and economic benefits, e.g. in the fields of: disease diagnosis and treatment (via medical imaging), environment (through optimised battery consumption), optimised wireless communications, new job opportunities. QSs will be at the heart of the Quantum internet of Things with a strong transformative effect on society in the long term.

This project supports the development of applications of QS technologies that can lead to concrete marketable products, such as a multi-purpose magnetometer and an NV-based RF sensor.

QSs are expected to take a significant part in the large sensor market. This includes sensors for bio-medical applications. In the field of current sensing for automotive applications, the world market size amounts to 100 M€, and 3 axis magnetometers account for 350 M€ of worldwide revenue.

Having a non-invasive magnetic imager such as the NV-centre magnetic imager will open a market of about 2 million € to 5 million € per year for the next 5 to 10 years. These are conservative numbers of course; if the price and usability of the resulting instrument is impacting the innovation quality of the material science, the figure can easily be multiplied by 10.

Driven by 5G communications development, the microwave devices market should reach 11.86 billion US$ by 2024.

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This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	01 June 2021, 36 months	
Coordinator: Paolo Traina, INRIM Tel: +390113919246 E-mail: p.traina@inrim.it Project website address: https://qadet.cmi.cz/		
Internal Funded Partners: 1. INRIM, Italy 2. Aalto, Finland 3. CMI, Czechia 4. DFM, Denmark 5. PTB, Germany 6. TUBITAK, Türkiye	External Funded Partners: 7. DTU, Denmark 8. ENS Paris-Saclay, France 9. Qnami, Switzerland 10. SQ, Denmark 11. Thales, France 12. UNITO, Italy	Unfunded Partners: -
RMG: -		