Selected Research Topic number: **SRT-n01**
Version: 1.0

Title: Normating colour-centre-based quantum sensing technology towards industrial application and standards

Abstract

The proposed research aims to build on the JRP 20IND05 QADeT to develop standardised techniques for the creation and characterisation of quantum sensors based on Nitrogen-Vacancy (NV) centres in diamond (the highest TRL solid state atomic-scale sensor) for nano-scale, high sensitivity sensing of EM fields, temperature or dynamic quantities (e.g. pressure, etc.). It will address the need for standardisation in this area expressed by the CEN-CLC Focus Group on Quantum Technology (FGQT) and will be performed in synergy with FGQT and the upcoming JTC-22. The long-term goal is to disseminate these sensors into industry and market, fostering a fast uptake of novel solid-state solutions, including colour centres in other bulk or 2-D semiconductor materials (e.g. Si, SiC, hBN, InP).

Keywords

Quantum technology, single-atom systems, colour centres in diamond, quantum sensors, Controlled ion implantation.

Background to the Metrological Challenges

This project addresses the necessity to provide standards for quantum technologies and, in particular, for solid state quantum sensors. This technological field has a recognised level of maturity as well as being recognised as an emerging key requirement for industrial applications by CEN/CENELEC Focus Group on Quantum Technologies (FGQT) in the recently developed roadmap about quantum-technologies and their standardisation needs. In particular the current version of this document contains a section "5.2 Color centers in (nano)diamonds and other crystals (e.g. SiC)". In this it underlines that: "*there are not standards related to NV-center based sensors*". The roadmap goes on to say that a "*Lack of standards for quantum sensor industry is commonly seen as a barrier to market acceptance of new relevant products. The standardisation will help multiple industries in the quantum technology sector. The existence of a standard that stakeholders can adhere to would therefore significantly de-risk further investments in the market*."

A number of standardisation needs were highlighted in the FGQT roadmap concerning NV based sensors. In the area of material standardisation this covers host material assessment through referenced methods for the characterisation of material properties. This includes the technique of synthesis of the base material, native defect concentration, spatial distribution, lifetime, doping technique, type, density, lateral position and depth of implanted colour centres and photoluminescent properties (photon flux, spectrum, autocorrelation properties).

For Magnetometry/sensing this includes figures of merit for sensitivity, environmental working conditions (e.g. temperature, pressure, external electromagnetic fields), optical excitation power, power density, bias magnetic field (amplitude, orientation) and biocompatibility.

In the area of microwave engineering this includes standards related to microwave power & polarisation, geometry of the antenna delivering the microwave, contrast and linewidth of the ODMR resonance dip, and excitation pulse sequences.

Finally for device standardisation this includes performance of colour centres in quantum sensing and imaging as well as quantum computing and simulation, and consistent characterisation methods.

Following the works of FGQT, a dedicated technical committee (JTC-22) was launched in March 2023. Concurrently, part of the above-mentioned gaps are starting to be addressed by NMIs. In particular, current EMPIR 20IND05 QADeT joint research project is contributing by providing reproducible techniques for the creation and characterisation of atom scale quantum sensors either based on colour centres (NV centres or otherwise) in diamond or in other host materials (e.g. Si, SiC, hBN, etc.). This will indicate paths to traceability of these measurements to the SI units and, most importantly, create a fruitful synergy among the partners of the consortium (constituted by NMIs, key players companies in the QT field and Academia) and channelling the needs of the various research or industrial realities in agreement with an expanding network of relevant stakeholders.

NV-based quantum sensors QADeT are extremely promising as highly sensitive nanoscale probes for EM field as well as temperature or pressure, by virtue of the optically detected magnetic resonance (ODMR) scheme, *i.e.,* spin state detection at room temperature with optical readout. This sensor has found particular interest in biosensing application and in the engineering of novel devices. Among all the related experiments, sensitivities as low as 15 pT/Hz^(1/2) for magnetometry and below 1 mK/Hz^(1/2) for thermometry have been demonstrated,

In parallel, the features of alternative defects in the diamond lattice that were previously explored as optical active centres (such as Si, Ge, He, Sn, Pb) have been investigated more deeply and, in the last few years, this scenario has widened to include e.g. point defects based on F, Mg, etc. These emitters, in some cases showing peculiar performance, such as narrower emission linewidth with respect to NV centres, can potentially be exploited as sensors.

Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The JRP shall focus on the development of traceable measurement and characterisation methods for quantum sensing technologies necessary to support standardisation in devices based on colour centres in diamond.

The specific objectives are

1. To define referenced methods and standards for NV-based sensor's material certification, covering properties like e.g., doping, native defects concentration or position of colour centres. Development of standardised methods for infrastructure characterisation, including the definition of measurement procedures and figures of merit. Standardise characterisation methods of individual device performance in terms of key performance parameters. This will include methods for sub-micron localisation (spatial resolution <500 nm) of point defects and for quantification of their formation yield (Formation yield >10 %) via controlled ion implantation in diamond via 3D confocal mapping.
2. To identify and validate standard procedures for robust sensing techniques for non-NV sensors/ single photon emitters (e.g. novel defects in diamond, point defects in Si, SiC, 2D materials (hBN), semiconductor quantum dots (InP), etc.). This will include the development of a benchmarking with respect to NV sensors, in terms e.g. of contrast, brightness, emission wavelength.
3. To explore the extension of the current techniques to include methods for enhanced performance of sensors based on colour centres in diamond. This will include squeezed light excitation for reduction of pump noise level, coupling of the photoluminescent sensors to photon-collection-enhancing structures, machine-learning based protocols to optimise the performance based on the specific signal being measured and feasibility study on synchronous detection of PL and electric-activity in biological samples (e.g. tests of background PL emission of Multi-Electrode Arrays).
4. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs/DIs), standards developing organisations (CEN-CLC, CEN/CENELEC FGQT and JTC-22) and end users (industry, sensor manufacturers, calibration facilities) and EMN Quantum.

The proposed research shall be justified by clear reference to the measurement needs within strategic documents published by the relevant Regulatory body or Standards Developing Organisation or by a letter signed by the convenor of the respective TC/WG. EURAMET encourages proposals that include representatives from industry, regulators and standardisation bodies actively participating in the projects. The proposal must name a "Chief Stakeholder", not a member of the consortium, but a representative of the user community that will benefit from the proposed work. The "Chief Stakeholder" should write a letter of support explaining how their organisation will make use of the outcomes from the research, be consulted regularly by the consortium during the project to ensure that the planned outcomes are still relevant and be prepared to report to EURAMET on the benefits they have gained from the project.

Proposers should establish the current state of the art and explain how their proposed research goes beyond this. In particular, proposers should outline the achievements of the EMPIR project 20IND05 QADeT and how their proposal will build on this.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 1.0 M€ and has defined an upper limit of 1.3 M€ for this project.

EURAMET also expects the EU Contribution to the external funded beneficiaries to not exceed 30 % of the total EU Contribution across all selected projects in this TP.

Any industrial beneficiaries that will receive significant benefit from the results of the proposed project are expected to be beneficiaries without receiving funding or associated partners.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the 'end user' community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the "end user" community (e.g. letters of support) is also encouraged.

You should detail how your JRP results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies,
- Facilitate improved industrial capability or improved quality of life for European citizens in terms of personal health, protection of the environment and the climate, or energy security,
- Transfer knowledge to the quantum technologies sector.

You should detail other impacts of your proposed JRP as specified in the document "Guide 4: Writing Joint Research Projects (JRPs)"

You should also detail how your approach to realising the objectives will further the aim of the Partnership to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically, the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work.

Time-scale

The project should be of up to 3 years duration.

Additional information

[1] 005 CEN SECT-FGQT Normative Call 2023 (metpart.eu)