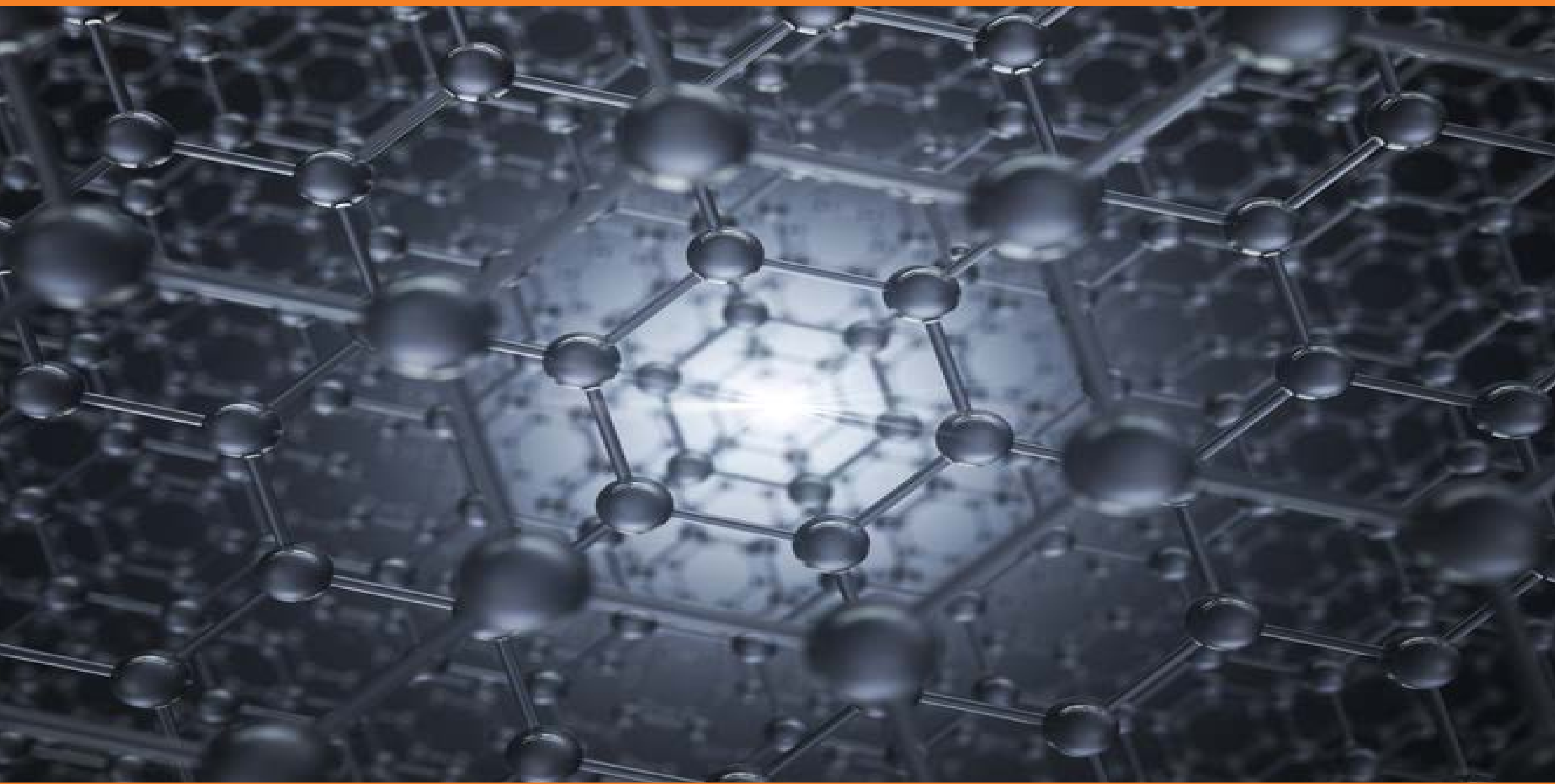
European Metrology Programme for Innovation and Research

Delivering Impact



Enhancing European metrology for practical quantum sensors based on diamond

The European Commission's Quantum Strategy aims to make Europe a global leader in quantum technologies by 2030. At the quantum level electrons, photons and atoms exist in multiple states simultaneously. This strange phenomenon opens the possibility of new sensors with vastly enhanced performance. To progress beyond the protype level however these require new metrology to ensure their reliability.

Europe's National Measurement Institutes working together

The European Metrology Programme for Innovation and Research (EMPIR) has been developed as part of Horizon 2020, the EU Framework Programme for Research and Innovation. EMPIR funding is drawn from 28 participating EURAMET member states to support collaborative research between Measurement Institutes, academia and industry both within and outside Europe to address key metrology challenges and ensure that measurement science meets the future.

Challenge

At the quantum level, fundamental particles have counterintuitive properties. They can exist in multiple states simultaneously, a phenomenon, termed "superposition" (electrons or photons can be both "1" and "0" at the same time), or be correlated in a nonclassical way, no matter how far apart they are (the so-called "entanglement"). The quantum state is fragile and the minimum interaction of the particle with the environment can alter it ("decoherence"). Quantum sensors (QS) exploit this sensitivity to external influences to make equally supersensitive measurements in areas including medical diagnosis, navigation, or environmental monitoring.

One form of QS is based on randomly implanting atoms into synthetic diamonds. If implantation occurs next to an empty space in the diamond lattice, a "colour centre" is created. When interacting with its environment it emits light encoded with information, acting as a sensor for external influences such as magnetic and electric fields. Implantation of nitrogen atoms creates nitrogen-vacancy (NV) centres, however, the performance these QS is highly dependent upon the location of the nitrogen which can affect its spectral stability or, if near the surface, decoherence time. Other atoms, such as silicon or germanium, have demonstrated superior spectral stability but standardised techniques for realising nanoscale QSs, including synthesis processes to produce material with reproducible performance and quality, were lacking.

Solution

During the QADeT project, the University of Torino - in collaboration with external colleagues of Italian Fondazione Bruno Kessler - employed a custom ion implantation process with alignment techniques. A focused ion beam implanted germanium ions (Ge^{2}+) with sub-100 nm precision into a high purity diamonds distributed into sets of 10 x 40 arrays. The arrays were subsequently overlapped with nanopillars fabricated by project partner QNAMI, with the aim of trapping GeV colour centres into the 300 nm tip of each pillar. To tightly control the position and depth of Ge^{2+} ions beam energy ranges of 35 keV and 70 keV were used. GeV centres could now be studied in combination with nanopillars acting as optical waveguides. Results indicated up to 33% of the fabricated nanopillars contained single photon emitters, providing an 8-fold increase in photoluminescence signal-to-background ratio, a considerable improvement on the current state of the art. Furthermore, pre- and post-characterisation indicated that the nanopillar fabrication process did not affect the quantum properties of the GeV centres.

Impact

QNAMI is a world leader in quantum sensor technology and in the development of quantum sensing and imaging applications, providing analytical solutions for applications in nanotechnology, spintronics and failure analysis. Due to this expertise, the company was asked to join QADeT to produce a range of samples at their Quantum Foundry facility, including the manufacturing of optical waveguides in the form of nanopillars. Through the work performed, longstanding questions concerning diamond fabrication were answered, further expanding the knowledge QNAMI has in fine-tuning ion implantation for specific quantum applications. This will be translated into improved products for their customers and, in time, their own such as the ProteusQ, the first NV microscope for analysing magnetic materials at the nanoscale.

Controlled ion implantation and characterisation methods are essential steps for developing practical and stable QS. The diamond nanopillars developed, for example, act as "waveguides" for incorporation into practical quantum applications, including photonic chips for quantum computers.

The development of target Ge^{2+} ion implantation will serve as a basis for expanding the use of diamond-based QS in a wide variety of fields, including physics, data storage and diagnostic imaging.

This is one of the very first instances where, through the effort of QADeT, newly developed tools to realise practical QS by the metrological institutes exist to take these beyond the prototype stage, allowing Europe to meet its quantum goals. Work continued in the follow-up project NoQTeS.

Developing the foundation for practical quantum sensors in Europe

The QADeT project:

- developed a dedicated facility with real-time monitoring of sample position and alignment and performed ion implantation with the best possible nano scale resolution (< 50 nm) using germanium ion species in a high purity diamond sample with nano patterned nanopillars.
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- developed metrological tools for characterising single-atom systems created by implantation, including Raman Spectroscopy and photo-luminescence measurements.
- used nanodiamond QS to measure subcellular temperature variations in cultured rat hippocampal neurons.
- investigated alternatives to diamond materials and NV centres including the use of colour centres in silicon and silicon carbide wafers emitting at 1278 nm and 1219 nm, respectively.
- developed a Quantum Diamond Signal Analyser for detecting radio frequency signals from 25 GHz down to 1 MHz with a millisecond temporal resolution and a large dynamic range.
- performed Implantation campaigns for the fabrication of alternative colour centres including lead, germanium and magnesium, in the keV energy range.

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Paolo Traina

INRiM, Italy
p.traina@inrim.it

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