NV Diamond Materials for Quantum Systems

Based on a QED-C workshop
December 2023

QED-C

PREFACE

- The Quantum Economic Development Consortium (QED-C) aims to enable and grow the quantum industry. Toward this goal, QED-C undertakes activities to identify enabling technology gaps and strategies to fill those gaps.
- An enabling technology, NV diamond materials have properties that are being exploited for various quantum-based applications.
- This report on the opportunities and challenges for scaling up the practical application and commercialization of NV diamond materials for quantum systems is based on a virtual QED-C workshop held December 4, 2023 and on additional expert input. BCG provided analysis of the quantum markets and private sector activity.
- Thank you to the organizing committee members (listed below) for their valuable contributions. BCG is acknowledged for support in preparing this report.
  - Lina Mechat, BCG
  - Cassia Naudet-Baulieu, BCG
  - Elina Kasman, Great Lakes Crystal Technologies
  - Krishnan Thyagarajan, SRI International
  - Dogan Timucin, SRI International
  - Frank Torres, SRI International
  - Celia Merzbacher, SRI International

DRAFT

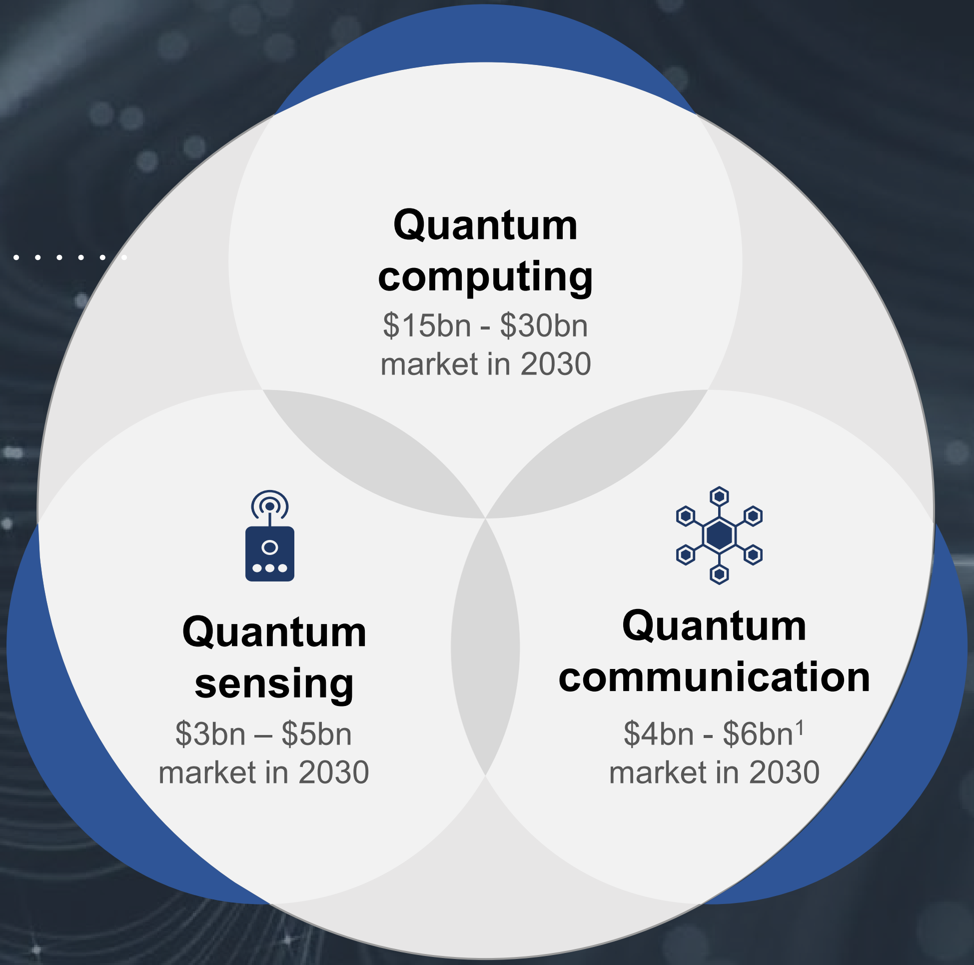
OUTLINE

- Overview
- Roundtable
- Material and processing
- Markets and end-users
- Policy and standards

OVERVIEW

Quantum technologies are expected to enable significant markets by 2030

$22bn - $41bn
global quantum technology market in 2030



370
Companies involved[2]

1,600
Patents granted[2]

$2bn
Raised by start-ups[2]

1. Without Post-Quantum Cryptography; 2. 2022 figures– Sources: Pitchbook; Dealroom; The Quantum Insider; Polaris Market Research; Global Information (GII); and BCG analysis

NV diamond is being most actively developed for quantum sensing applications

	Quantum computing	Quantum communication	Quantum sensing
NV diamond This technology leverages nitrogen vacancy defects in diamond crystal controlled by light	☆	☆☆	☆☆☆
Superconducting quantum device Used as the most sensitive devices for measuring or amplifying different physical quantities and are hotly tipped as very promising candidates for the implementation of a quantum computer	☆☆☆	☆	☆☆☆
Photonic device Leverage the quantum nature of light on photonic chip devices or for quantum communication in optical fibers or in free-space	☆☆☆	☆☆☆	☆☆☆
Trapped ions Single (or array of) ion(s) trapped and manipulated using electric and magnetic fields to store and process quantum states	☆☆	☆☆	☆
Neutral atoms Similar to trapped ion technology, here the atoms are neutrals and controlled by optical laser beams	☆☆	☆☆	☆

Activity[1]
- ☆ Low
- ☆☆ Medium
- ☆☆☆ High

1. Activity is measured by the number of startup players, public laboratory research and public grants; Source: BCG analysis

NV diamond materials for quantum applications face obstacles

Quantum sensors and quantum computers based on NV diamond are being developed by several companies.

However, there are barriers to scaling up, including:

- Materials and processing challenges
- Demonstration of applications with a “quantum advantage”
- Standards and policies that promote rather than hinder innovation

This report is based on a QED-C roundtable, expert inputs, and analysis by BCG.

ROUNDTABLE

ROUNDTABLE AGENDA

An industry-driven, virtual roundtable was held Dec 4, 2023

Participation was by invitation only

Followed Chatham House Rule

01	Introduction	Celia Merzbacher	SRI
02	NV diamond materials: Current state of the art	Danielle Braje	MIT Lincoln Laboratory
03	Quantum computing based on NV diamond	Neil Wester	Quantum Brilliance
04	Quantum sensing based on NV diamonds	Connor Hart	Quantum Catalyzer
05	Quantum standards landscape	Barbara Goldstein	NIST National Institute of Standards and Technology U.S. Department of Commerce
06	Breakouts – Facilitated discussions among groups of 6-8 participants		
07	Discussion – Breakout reports and discussion of findings & recommendations		

WORKSHOP PARTICIPANTS

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BREAKOUT QUESTIONS

Materials	▪ What materials properties/performance do quantum system developers require? ▪ What properties of NV diamonds need to be improved—i.e., what are the gaps between commercially available materials and what quantum developers need/want? What are the barriers to making these improvements? ▪ What are alternative materials to NV diamond? What are the advantages/disadvantages of each?
Processing	▪ What are the methods of fabrication? Are they reproducible and scalable? ▪ Are there gaps in testing/metrology methods?
Markets	▪ What is the market today for NV diamond materials (including all applications)? ▪ Which quantum applications are likely to lead to large-volume markets in the next 5-10 years? Longer term?
Policies	▪ In addition to technology/materials barriers, what other barriers exist to the use of NV diamond materials in quantum-based applications? ▪ Are there policies that needed or are creating bottlenecks to commercialization? ▪ What industry standards are needed?
Research	▪ What R&D is needed to advance diamond for quantum applications?

MATERIAL & PROCESSING

NV centers have interesting properties making the technology suitable for quantum sensing and quantum computing

NV centers are the substitution of two carbon atoms by a nitrogen and a vacancy in the diamond crystal lattice. NV centers are a stable defect that provides a two-level system for quantum operations.

Predictable behavior

- Measurements can be tied to fundamental constants
- Strong and stable diamond structure
- Long coherence time over a wide range of temperature

Miniaturization

- No vacuum or cryogenics are required
- Millimeter-scale sensors
- No narrow-linewidth laser required
- Mature semiconductor processes

Engineered system

- High sensitivity
- High spectral range (DC to GHz)
- High spatial resolution
- Compatible with biological systems
- Tunable material properties

Source: QED-C Dec 2023 workshop; BCG analysis

Ability to customize NV centers enables a range of applications

Properties can be tailored…

- Coherence time
- Isotopic chemistry
- Crystal quality
- Geometry
- NV/N ratio
- Nitrogen concentration

…to meet the diverse needs of applications

- Magnetometry
- Memory
- Widefield magnetic imaging
- Surface profiling
- Quantum compouting
- Single photon scources
- Quantum communications.

Among others…

NV diamonds have been widely studied and fabricated but scaling up for commercialization faces several pain points

Substrate	Diamond growth and doping	Processing	Characterization	Fabrication
Technologies				
• Diamond seeds for chemical vapor deposition • Other seeds for heteroepitaxial-grown diamond	• Chemical vapor deposition of N-doped artificial diamond • Vapor deposition of high purity artificial diamond followed by nitrogen ion implantation	• Electronic irradiation to create vacancies • Annealing	• Raman • Birefringence • EPR • Quantum coherence • Surface roughness	• Reactive ion etching • Deposition • Integration with electro-optic and microwave components for control and readout • Packaging
Pain points				
× Seed quality × Seed/substrate availability × Disorder/defects/variability in substrates × Manufacturability/volume production	× Nonuniform diamond structure × Control of ion and vacancy implantation × Control of NV:N concentration × Nonuniform doping within and across devices × Isotopic variability	× Material functionalization limitations × Surface preparation	× No uniform characterization methodology to support material development × No specification standards × R&D equipment is complicated	× Fabrication- and packaging-induced damage × Processes not automated × Commercial suppliers not optimized to meet quantum requirements × Hardware not optimized for NV diamond

Source: QED-C Dec 2023 workshop; BCG analysis

Materials-based challenges must be addressed to unlock full commercial potential of NV centers

Material performance

High variability

Reproducibility of physical properties needs improvement.

Few suppliers meet stringent requirements

Suppliers who can meet stringent materials requirements such as isotopic purity are limited.

Process of fabrication

Unfit equipment

Equipment for fabrication and characterization are not specifically designed for and do not meet the needs of NV center manufacturers.

Manual processing

Scaling will require significant process automation.

Scaling vs quality

Lack of volume

Research-scale production allows tailoring of material properties but cannot achieve high volume, low cost and fast turnaround.

Lack of quality

Commercial suppliers focus on serving the broadest possibly customer base at the cost of meeting application-specific requirements.

Source: QED-C Dec 2023 workshop; BCG analysis

MARKETS AND END-USERS

Quantum sensing is likely to be the first widespread commercial application of NV centers

Quantum sensing
NV diamond applications for quantum sensing have been emerging in the past decade

Time to market
Commercial applications are already deployed for niche markets, including for research

Quantum communication
Multi-qubit nodes that provide quantum memory for the network

Time to market
Prototypes are being developed and demonstrated in the laboratory

Quantum computing
Early-stage development of NV diamond platforms for quantum computing

Time to market
Prototypes are being developed and demonstrated

Source: BCG analysis

NV diamonds are used in various quantum sensing applications

Quantum magnetometers	Quantum thermometers	Quantum frequency sensing
How it works		
Quantum magnetometers are used to detect small variations or levels of magnetism with high spatial accuracy. A collection of NV centers can increase the sensitivity.	NV-center based quantum thermometers enable temperature measurements with an accuracy of a few mK and high spatial resolution.	Quantum frequency sensing identifies the microwave frequencies present in the environment. They can reach high precision and large bandwidth.
Main alternative technologies		
SQUID, atomic vapors, fluxgate, GMR and Hall Effect technologies	Bulk diamond, liquid crystal, infrared Raman and green fluorescent protein	Fast Fourier, neutral atom, optical frequency combs
Illustrative applications		
Battery charging, semiconductor manufacturing, navigation, biomedical imaging	Semiconductor manufacturing, medical treatment and diagnosis	Telecommunications

Illustrative players

Great Lakes Crystal Technologies, NVision, QDTI Quantum Diamond Technologies, Microsoft, Southwest Sciences incorporated, Qnami, Universität Stuttgart, Quantum Catalyzer, Thales, SBtech, Sensorix (A member of QED-C), Lockheed Martin, Zurich Instruments, universität ulm, Harvard John A. Paulson School of Engineering and Applied Sciences, element six (De Beers Group), Massachusetts Institute of Technology, Quantum Brilliance, MIT Lincoln Laboratory, Zabre

Source: BCG analysis

Research and defense customers may be willing to pay more but markets are small. Consumer electronics and automotive markets could be large but will require the NV diamond industry to scale up

Research

- Microscope for magnetic material properties
- Molecule and cell characterization

Defense

- Spectral analyzer
- Intercept communications
- Non-GPS navigation for defense application (e.g., missiles, drones)

Healthcare

- Medical diagnosis and treatment (e.g., drug development)
- Room temperature MRI
- Analyze brain activity

Consumer electronics

- Quality control process for semiconductor, integrated systems and batteries manufacturing

Automotive

- Non-GPS navigation applications trickled-down from defense and aviation use cases

Lower time to market

Larger market size

In addition to technical challenges, market growth faces a "chicken & egg" problem

Demand & customers

Small market

Today, the market for NV diamond material for quantum systems is small, mostly driven by research labs and small-scale industrial applications.

Uncertain demand forecast

Growing demand from early customers in the defense & security sector remains uncertain.

Supply & market structure

Lack of incentive for suppliers

Small current market and difficulties to meet the tough requirements of quantum developers makes suppliers reluctant to invest in development.

Supply chain pressure

The supply of NV diamonds for quantum are limited, and those companies also face supply chain issues.

Case for change

Cost of adoption

NV diamond must demonstrate significant business advantage (performance, costs savings, etc.) to compete with incumbent technologies.

Awareness and trust

Lack of general knowledge and awareness of NV diamond technology leads to difficulties in explaining the benefits.

Source: QED-C Dec 2023 workshop; BCG analysis

STANDARDS & POLICY

Standards organizations are starting to assess quantum sensing

Standardization is a process

Assess standardization readiness

Define existence and maturity of the three following dimensions: market, technology and community

Define standardization strategy

Define the level of standardization required to accelerate adoption: identify priority elements to standardize, and determine appropriate standard format, mechanism and target timeline

Measure impact

Define and control metrics and trends expected to be fueled by standard definition and promotion

Organizations leading in quantum standards development relevant to sensing

International Organization for Standardization

International Electrotechnical Commission

Joint Technical Committee (JTC-Q) formed in Q4 2023 to create a focal point for international quantum standardization

CEN CENELEC

4 working groups formed in Q1 2023 built on the CEN / CENELEC[1] standardization roadmap

Current initiatives

- No standards for NV-center based sensors[1]
- ISO / IEC establishing a roadmap activity to be carried forward into the new JTC-Q
- CEN-CENELEC identified pre-normative gaps and standardization needs for color centers in (nano)diamonds, across materials, infrastructure and device standardization
- US published a National Standards Strategy for Critical and Emerging Technologies[2], including quantum

1. CEN-CENELEC Focus Group on Quantum Technologies (FGQT) – Standardization Roadmap on Quantum Technologies; Source: BCG analysis
2. https://www.whitehouse.gov/wp-content/uploads/2023/05/US-Gov-National-Standards-Strategy-2023.pdf

Policies and strategies are taking shape

Public funding

Technology protection

Public Private Partnerships

- Government agencies are exploring quantum sensing for mission-related applications including defense, navigation, border protection, biomedicine and energy systems.
- Regulatory controls on quantum technologies with national security implications are being considered.[1]
- Quantum industry groups worldwide are focused on commercialization of quantum. For example, QED-C has assessed quantum sensing use cases and quantum sensor needs for environmental and vacuum packaging.[2]
- Public investments help de-risk technologies and defray non-recurring engineering costs.

1. E.g., Export Controls for Quantum Computers and Advanced notice of proposed rulemaking on outbound investments from U.S. to countries of concern
2. See QED-C reports on Quantum sensing use cases and Environmental and vacuum packaging for quantum sensors.

Policies are needed that address bottlenecks to innovation and commercialization

Technology protection

Uncertain control of technology

Current restrictions, e.g., around magnetometers and microwave generators exports make industry fear new restrictions on NV center value chain.

Obtaining IP rights

Universities are incentivized to protect IP created by their researchers, leading to highly fragmented IP. Developers may have to negotiate licenses with multiple institutions which is costly and inefficient.

Standardization

Necessity to align on standards

Standards should enable the whole supply chain: from encouraging suppliers to comply with standards to creating confidence among end-users.

Standardization timeline

Stakeholders need to engage in standardization at the appropriate time to ensure smooth technology innovation.

Public funding

Targeted public funding

Public investments are needed to de-risk technologies and to bridge the gap as markets emerge and private investors step in. Investment in and access to infrastructure and capital equipment is needed.

Limitations of public customers

Government entities (e.g., DoD) can support smaller scale applications, but large-scale adoption will require commercial uptake.

Source: QED-C Dec 2023 workshop

SUMARY OF FINDINGS

Materials and processing

While properties of NV diamond materials are highly customizable, the ability to reproducibly manufacture materials at scale to meet the needs of quantum system developers is challenged by material variability and inadequate processing & characterization capabilities.

Markets and end-users

Markets for quantum sensors based on NV diamond materials are small, primarily in research settings and defense applications, and developers are not incentivized to invest in R&D. Reaching mass markets such as automotive is challenged by limits on performance and production and by the cost of displacing the incumbent technology.

Standards and policy

While there are no standards for NV center-based sensors yet, standards developers are establishing roadmaps and assessing needs. Meanwhile, industry fears regulation of technology and restriction on NV diamond fabrication and applications.

RECOMMENDATIONS

Recommendations may be most appropriately addressed by government, private investors, or through a public-private entity like QED-C.

- Develop scalable manufacturing processes for reliable fabrication of NV diamond that meets requirements of quantum system developers
- Establish standard methodologies for specification and comparison of performance and properties that meet the requirements of quantum system developers
- Develop tools for automated characterization
- Improve quality, size, and production of seeds and substrates
- Develop packaging techniques that do not impact NV centers
- Develop processes and materials that are compatible with semiconductor processing
- Government agencies should use existing mechanisms, such as SBIR and QED-C, to fund research to address the gaps identified in this report

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