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*Letter*

# Quantum Sensing Can Already Make a Difference. But Where?

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## Abstract

Quantum sensing technology is already providing value and potential use cases can shape multiple industries. There are four core technologies with promising applications—solid state spins, neutral atoms, superconducting circuits, and trapped ions—which have sensing capabilities across a broad range of physical properties, including magnetic fields, electric fields, rotation, temperature, gravity, time, and pressure. Which quantum sensing technology and implementation type to use depends on the use case, as they measure different properties and are best suited to specific environments. This paper discusses the potential and current applications of the abovementioned quantum sensing technologies through varied use-case studies. They are presented around four specific industries and along different time horizons, emphasizing the need for further development and enhancement that can be achieved over the conventional counterparts. The full power of quantum sensors is not yet known, but they have the potential to create an entire new ecosystem if researchers, start-ups, and industry leaders work together to explore their applications and get them out of the lab. Here, the paper outlines necessary actions and possible avenues for the stakeholders to realize this potential across academia and industry.

**Keywords:** Quantum sensing technology, Quantum Sensors, Quantum sensing use cases, Quantum sensing market, Quantum sensing ecosystem.

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## 1 Introduction

The world is seeing an increasing demand for high-precision measurements and data for critical applications. Quantum sensors have the potential to meet this need by applying quantum properties for enhanced performance, such as greater sensitivity, higher spatial resolution, and the ability to operate in extreme and harsh conditions (Aslam, 2023; Crawford, 2022). At scale, quantum sensors could monitor geologic activity (Antoni-Micollier et al., 2022) to avert climate disasters, detect biomarkers in just a drop of blood (Aslam, 2023; Savage 2021), or enable longer-lasting batteries for electric vehicles (EVs) (Debuisschert, 2021). Similarly, quantum sensors have the potential to be small and lightweight, such as fitting on a helmet or belt, to measure vital signs after extreme events or patients on the operating table. Quantum sensors may also open up new use cases where existing measurement devices do not currently exist, for example, in the harsh environments of outer space or within a nuclear fusion reactor.

Today's quantum sensors already provide value in some use cases. However, the technology and its applications are still emerging, with further development needed. While quantum sensing is more mature than other quantum technologies, such as computing and communication, there is a chasm between what has been achieved in academic labs and what is being pursued in industry and business for critical applications like those mentioned above.

Looking forward, the quantum sensing market has great potential. Current market estimations project quantum sensing to reach \$0.7 billion to \$1.0 billion by 2030 at a CAGR of 10 to 15 percent. By extrapolating based on assessing use cases, we expect this market to grow to between \$1 billion and \$7 billion by 2040, disrupting industries relying on sensor technology (McKinsey, 2023; Yole Intelligence, 2021). Perhaps most exciting is that the technology could lead to an entirely new ecosystem that observes what once was unobservable — thereby providing unique new data sets across many sectors of the economy, which can then be used to train AI algorithms for wide-ranging applications. Uncovering e.g., a new depth of precision measurement signals and data in the biomedical space not only allows a better understanding of the in-vivo situation but may create the foundation to eventually develop more targeted treatments.

While quantum sensors offer a great deal of promise, there is still a long development road ahead though many are beyond a research project. Currently, many high-impact applications have yet to be demonstrated in the field or made to work at scale. So, looking forward, what will a commercial disruption by quantum sensors look like? Where do quantum sensors have the most potential to outperform current technologies, which are quite effective in many areas? Where can quantum sensors open up completely new applications and markets?

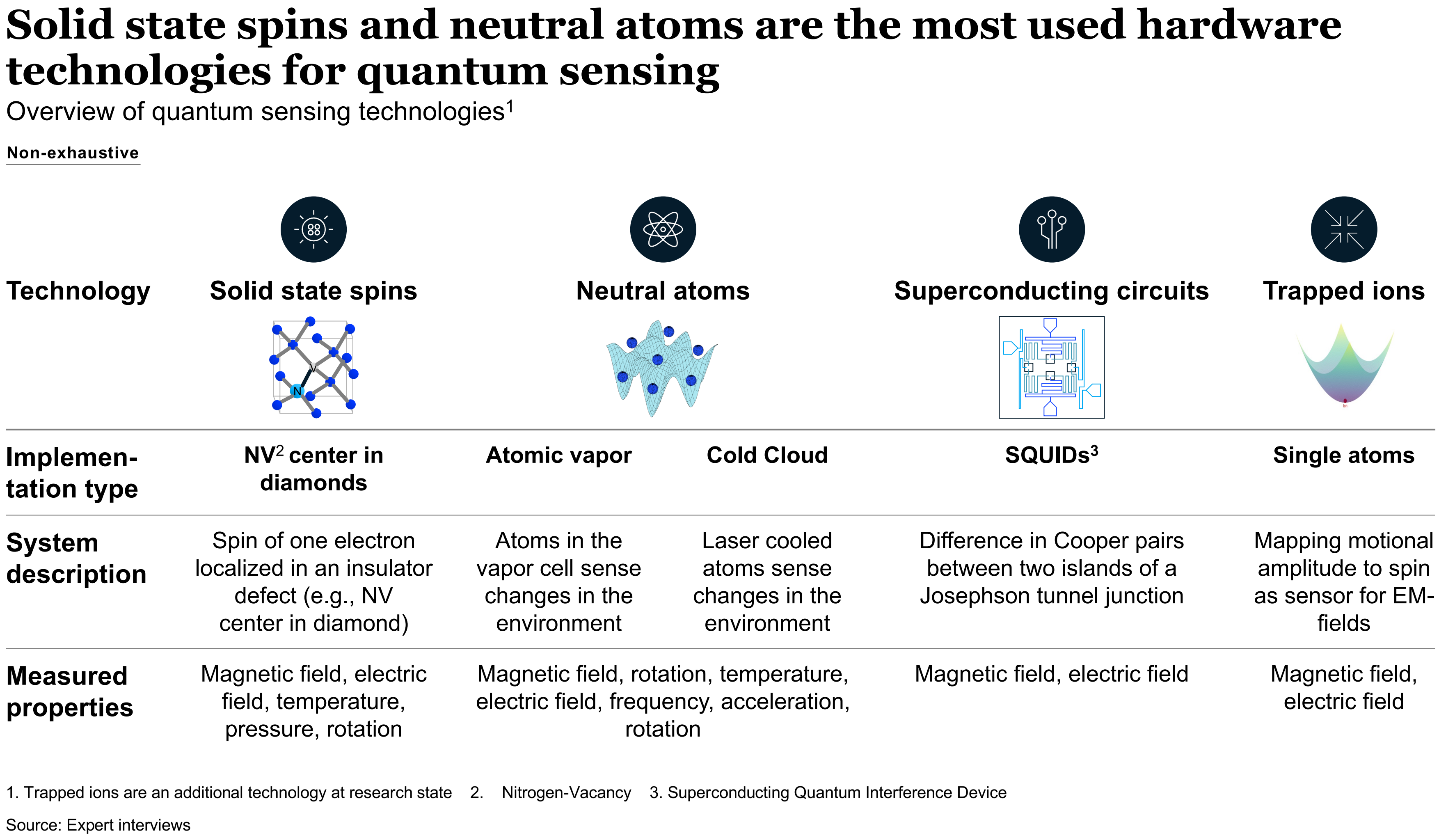
This potential becomes tangible when looking at specific use cases. While the highest impact applications will emerge over time, in the short term, we see at least four types of use cases where this technology is commercially viable: imaging and diagnostics in the life sciences, navigation without GPS, fault analysis in microelectronics, and underground measurements for mapping tunnels, buried objects, and resource extraction.

Below, we provide an overview of these opportunities, summarize industry and business needs, note how quantum sensors can be applied to meet those needs, and highlight the specific quantum sensing technologies best suited to each.

## 2 Quantum sensing technologies

We chose four core quantum sensing technologies: solid-state spins, neutral atoms, superconducting circuits, and trapped ions (Figure 1). These technologies have sensing capabilities across a broad range of physical properties, including magnetic fields, electric fields, rotation, acceleration, temperature, gravity, time, and pressure (Degen et al., 2017, Savage 2021). Such quantum sensors bring ultimate sensitivity and precision to measurements, for example, biomagnetism, currents flowing in integrated circuits, gravity detecting underwater pipe leaks, and the temperature of tiny organisms. Additional technologies, such as photonics, could also be used for sensing applications, but there are currently few applications for which photonics are a suitable platform.

The particular use case informs what quantum sensor to use, as each use case will require certain measurement properties and operational environments. For example, when measuring gravitational or electromagnetic fields for navigation, sensors must correct for environmental noise, have low drift, and be able to sense vector fields in order to get the most accurate reading, making



## Solid state spins and neutral atoms are the most used hardware technologies for quantum sensing

Overview of quantum sensing technologies[1]

**Non-exhaustive**

| **Technology** | **Solid state spins** | **Neutral atoms** | | **Superconducting circuits** | **Trapped ions** |
|---|---|---|---|---|---|
| **Implementation type** | **NV[2] center in diamonds** | **Atomic vapor** | **Cold Cloud** | **SQUIDs[3]** | **Single atoms** |
| **System description** | Spin of one electron localized in an insulator defect (e.g., NV center in diamond) | Atoms in the vapor cell sense changes in the environment | Laser cooled atoms sense changes in the environment | Difference in Cooper pairs between two islands of a Josephson tunnel junction | Mapping motional amplitude to spin as sensor for EM-fields |
| **Measured properties** | Magnetic field, electric field, temperature, pressure, rotation | Magnetic field, rotation, temperature, electric field, frequency, acceleration, rotation | | Magnetic field, electric field | Magnetic field, electric field |

1. Trapped ions are an additional technology at research state 2. Nitrogen-Vacancy 3. Superconducting Quantum Interference Device

Source: Expert interviews

**Figure 1.** Solid state spins and neutral atoms are the most-used hardware technologies for quantum sensing.

neutral atom and quantum diamond sensors the best fit (Childress et al., 2014; Debuisschert, 2021).

## 3 Where quantum sensing can make a difference today

Looking at the above four areas where quantum sensors show the most near-term promise, we compiled a long list of use cases based on discussions with experts from academia and industry. Further, we grouped them based on when we believe they will begin to provide commercial impact (Figure 2). While the use cases are still emerging, already a selection show great promise for offering industry and business leaders new solutions to the challenges they face today.

### 3.1 Signal detection in life sciences

Quantum sensors should allow for more precise and practical localization of magnetic signals from the human body, e.g., from the brain and heart (Quantum Flagship, 2022). Currently, doctors detect such signals using conventional MEG, MRI, and MCG technology, which provides limited information about the location of the signal source within the organ of interest (Childress, 2014). Furthermore, conventional detectors are bulky and fragile; require the use of expensive cryogenics; and measurements must be performed in special shielded rooms or chambers to reduce the effect of ambient magnetic noise.

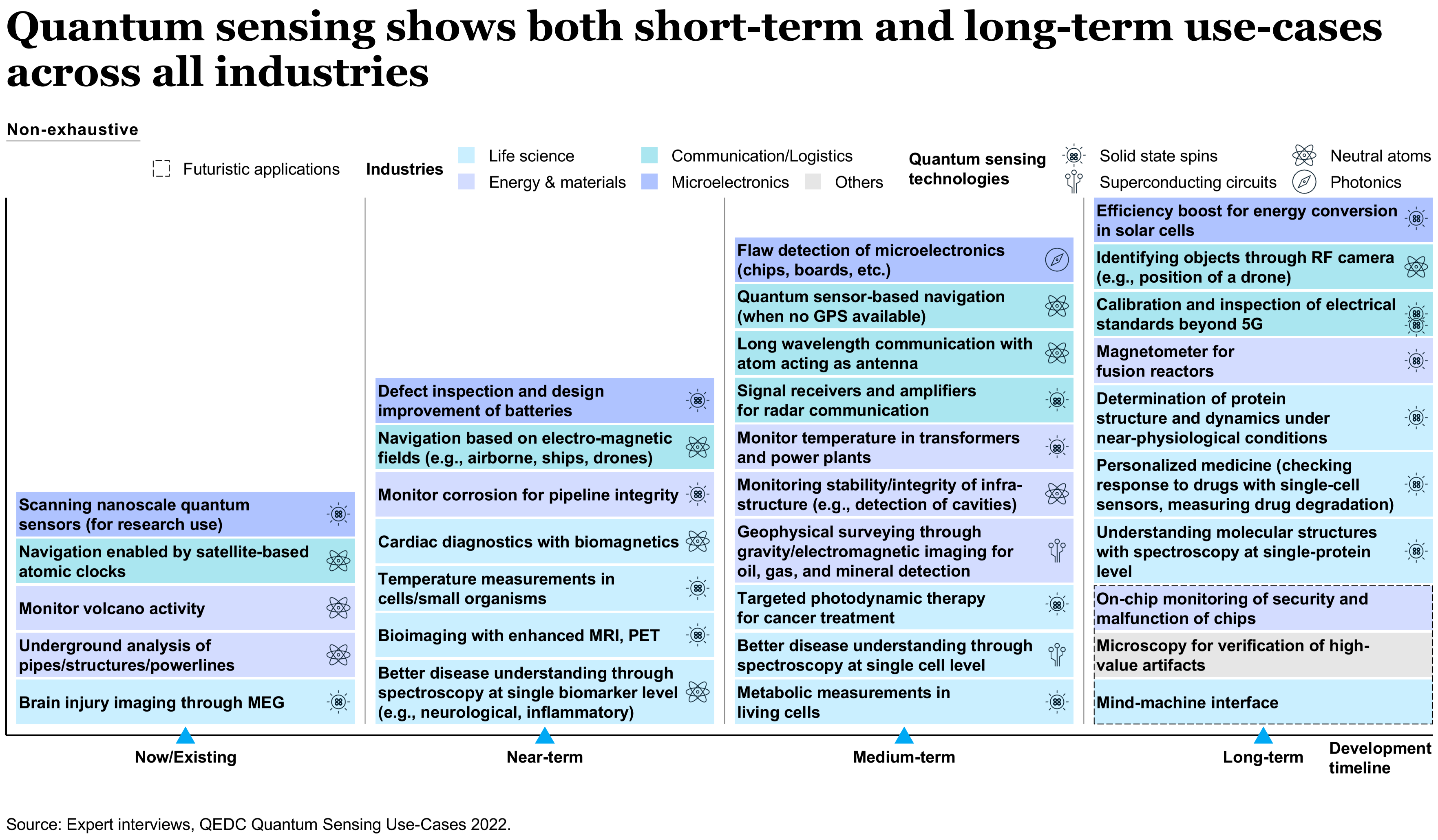
By contrast, quantum biosensors could take measurements via a lightweight helmet or belt that is placed on a patient (Aslam et al., 2023). The technology would consist of an array of several small sensors (each about 1 cm in size), e.g., using neutral atoms or defects in diamonds. This array of quantum biosensors would rapidly determine the spatial location of a magnetic signal within a human body to within a few millimeters. With further development, these quantum biosensors should also be able to operate under ambient conditions, i.e., without cryogenics and a shielded room. Likely, a small, wearable quantum bio-sensor system that is operable under ambient conditions will be available within the next five years. Scalable, low-cost production of such sensors will require a steep ramp-up of manufacturing capabilities.

Similar applications will arise across the life sciences as the technology advances. In the near term, we will see applications in bioimaging for research and in spectroscopy and microscopy for molecular analysis; in the long term, these sensors could be used in medical imaging and diagnosis and to analyze drug and compound effectiveness (Aslam et al., 2023; Levine et al., 2019).

### 3.2 Navigation without GPS

Quantum sensors, such as neutral atom or diamond magnetometers, can provide enhanced navigation capabilities for a wide range of vehicles and platforms, independent of the availability of GPS satellite signals and even in the presence of environmental noise (Stray, 2022).

There is an urgent need for better navigation for autonomous and other vehicles if GPS satellite signals are not available, e.g., in cluttered or shielded/screened environments, underwater, underground, within or between buildings, or when the GPS system has been compromised. Currently, when there is no GPS available for a short period, inertial measurement units can be used to infer location related to an initial known position and heading. There are various grades of commercially available inertial measurement units, based on conventional magnetometers and gyroscopes, ranging from those for civilian use, such as in cell phones, to defense applications, such as navigating ships or even submarines. However, such conventional technology is limited in performance, requires regular recalibration, and can produce significant navigation errors.



**Quantum sensing shows both short-term and long-term use-cases across all industries**

**Non-exhaustive**

⬚ Futuristic applications

**Industries**: 🟦 Life science; 🟦 Energy & materials; 🟦 Communication/Logistics; 🟦 Microelectronics; ⬜ Others

**Quantum sensing technologies**: Solid state spins; Superconducting circuits; Neutral atoms; Photonics

**Now/Existing**
- Scanning nanoscale quantum sensors (for research use)
- Navigation enabled by satellite-based atomic clocks
- Monitor volcano activity
- Underground analysis of pipes/structures/powerlines
- Brain injury imaging through MEG

**Near-term**
- Defect inspection and design improvement of batteries
- Navigation based on electro-magnetic fields (e.g., airborne, ships, drones)
- Monitor corrosion for pipeline integrity
- Cardiac diagnostics with biomagnetics
- Temperature measurements in cells/small organisms
- Bioimaging with enhanced MRI, PET
- Better disease understanding through spectroscopy at single biomarker level (e.g., neurological, inflammatory)

**Medium-term**
- Flaw detection of microelectronics (chips, boards, etc.)
- Quantum sensor-based navigation (when no GPS available)
- Long wavelength communication with atom acting as antenna
- Signal receivers and amplifiers for radar communication
- Monitor temperature in transformers and power plants
- Monitoring stability/integrity of infra-structure (e.g., detection of cavities)
- Geophysical surveying through gravity/electromagnetic imaging for oil, gas, and mineral detection
- Targeted photodynamic therapy for cancer treatment
- Better disease understanding through spectroscopy at single cell level
- Metabolic measurements in living cells

**Long-term**
- Efficiency boost for energy conversion in solar cells
- Identifying objects through RF camera (e.g., position of a drone)
- Calibration and inspection of electrical standards beyond 5G
- Magnetometer for fusion reactors
- Determination of protein structure and dynamics under near-physiological conditions
- Personalized medicine (checking response to drugs with single-cell sensors, measuring drug degradation)
- Understanding molecular structures with spectroscopy at single-protein level
- On-chip monitoring of security and malfunction of chips
- Microscopy for verification of high-value artifacts
- Mind-machine interface

Source: Expert interviews, QEDC Quantum Sensing Use-Cases 2022.

**Figure 2.** Quantum sensing shows both short-term and long-term use cases across all industries.

Using quantum sensors will require much less frequent calibration of inertial measurement units, reducing the accumulated drift error and improving navigation accuracy over time. For example, quantum magnetometers have drift less than 100 pT over the course of a year, compared with drifts of several nT over the course of a few hours for a conventional flux-gate magnetometer. Alternatively, quantum sensors can be used to navigate based on preexisting maps of the Earth's gravity and crustal magnetic fields. In these applications, quantum sensors are one to two orders of magnitude more sensitive than conventional technology. Multi-modal quantum magnetometers could be even more robust by combining highly sensitive optically pumped magnetometers or OPMs (based on neutral atoms) with highly stable diamond vector magnetometers using nitrogen vacancy (NV) quantum defects, which have natural directional calibration due to their crystal structure.

Further development is needed for quantum navigation sensors to be sufficiently compact, robust, and low-cost enough for widespread use on vehicles and other mobile platforms. Nonetheless, recent successful field tests of prototype quantum navigation systems by several companies suggest that NV-diamond sensors may be commercially ready within the next two years while OPM systems may be ready in the next five years (QED-C, 2022). With ongoing investment for development, such quantum sensor technology could soon be in ships, cars, and drones. Long term, this technology could be implemented in self-driving vehicles and defense applications.

## 3.3 Functional analysis of microelectronics

Quantum sensors can also improve the detection of flaws and operational states in microelectronics through noninvasive diagnostic imaging of electrical currents and magnetization in such systems. In the near term, this technology could be used to achieve higher sensitivity in functional analysis of various types of microelectronics, ranging from electric vehicle (EV) batteries to computer chips, as well as aid the design of next-generation integrated circuits (ICs) using 3D architectures.

Consider the semiconductor chip fabrication process: one aspect of quality control is ensuring the magnetic memory bits' feature size is well below 100 nm. Existing test measurements are performed by connecting electrical probes to memory points and checking their electric performance — but only at the end of the production process. In contrast, quantum magnetic sensors could analyze individual points in the memory at earlier stages of the production process — before chip metallization, packaging, and dicing — greatly benefitting future chip design and quality control. In addition, imaging of vector magnetic fields generated by electrical currents in operating devices, combined with AI analysis of these images, can be used for diverse applications such as: fault detection in integrated circuits (ICs) and EV batteries (to name a few); identification of malicious circuitry, Trojans, or side channel attacks in ICs; counterfeit chip detection; and as an aid in the development of next generation ICs (Levine, 2019). Magnetic fields pass through most materials, and thereby provide a powerful window into microelectronic device structure and function, much like functional MRI (fMRI) in the biomedical sciences.

NV-diamond sensors are particularly well suited to these applications, as they offer minimally invasive vector magnetic imaging with high spatial resolution, good sensitivity, and wide field-of-view (Debuisschert, 2021). The first tabletop-size NV-diamond products for microelectronics analysis are already available — a result of a recent surge in quantum sensing start-ups — with commercial applications to date mostly in chip research, IC fault analysis, and EV battery quality control. Beyond near-term use in fault analysis in semiconductors and batteries, this technology could also be used in the longer term for in-line metrology in semiconductor chip and EV battery fabrication, later expanding into general electronics and replacing many analysis instruments in defense.

## 3.4 Underground measurements and other harsh environments

Finally, we see applications for quantum sensors in underground and other extreme or harsh environments, where this technology can offer more robust and precise measurements, e.g., of magnetic and gravitational fields (Bongs et al., 2023).

For example, accurate magnetic and gravitational maps of the ground beneath the Earth's surface can help identify faults and locate minerals, oil, and buried objects (Crawford, 2021) or even associated flows, e.g., of water (Bongs et al., 2023). To create such accurate readings, devices would need to be compact — fitting, for instance, into the wing of a drone aircraft or the trunk of a vehicle traveling in underground tunnels or on the Earth's surface (Stray, 2022). Conventional devices cannot easily distinguish a measured magnetic or gravitational field from environmental noise, such as from the drone or vehicle where the sensor is placed, thus providing limited information to inform mathematical models used to model the sub-surface environment.

Quantum sensors are highly sensitive – neutral-atom based sensors such as or atomic vapor magnetometers or gradiometers allow to sense even very weak vector magnetic fields and gravitational gradients, increasing the resolution of drone maps from 100 m to 10 m. These devices, for instance, measure shifts in atomic resonance lines to provide highly sensitive measurements. And by looking at vector gradients as opposed to scalar gradients, these sensors can derive more advanced and custom compensation algorithms for reducing the effect of environmental noise and customized pulse sequences to filter out various sources of noise (Bongs et al., 2023).

The first of these quantum sensors are already being used to detect gravitational changes induced by volcanic processes (Antoni-Micollier et al., 2022). For them to work at scale, improvements are needed to minimize the effects of vibrations and sharp maneuvers that can stop the sensors from functioning. Longer term, these sensors and others based on NV-diamond could be used to detect magnetic fields from buried pipes and power lines, monitor the temperature in electrical transformers and power plants, and serve as magnetometers to help control fusion reactors.

# 4 Looking forward: Taking quantum sensing to the next level

The potential of quantum sensors reaches far beyond the use cases detailed above. It is possible to speculate about where future high-impact use cases will be — for instance, quantum sensors might enable nuclear magnetic resonance (NMR) spectroscopy and MRI of single biological cells and even individual proteins, with transformative possibilities for human health. Much as the full potential of 20th-century technology based on quantum effects, such as semiconductors, only became clear over several decades, quantum sensors could create completely new opportunities that cannot be foreseen.

Today, some quantum sensors are still too large, heavy, and expensive or are built on a bespoke basis. Thus, broad commercial impact will depend on further development to reduce device size, weight, and power (SWAP) and improve fabrication cost-efficiency (Bongs et al., 2023). But these advancements are within reach. With smart investment, industry leaders could accelerate the commercialization of quantum sensors to integrate them into the technology ecosystem, opening the door to diverse use cases such as those outlined above, and providing large new data sets for AI training and application.

## 5 Main takeaways: Quantum sensing at a glance

The following actions will be important in order to harness quantum sensing and see its potential realized.

### 5.1 Embrace short-term and long-term value

Quantum sensing is a lucrative emerging market. Near-term applications could generate commercial value even sooner than quantum computing applications. The potential for scaling quantum sensing technology is significant because the technology can disrupt several industries (as discussed above) and explore new territories. Investment is needed to advance the technology, generate continued value, and fully explore newly emerging sensing use cases. There is value that can be captured now and even more value can be unlocked in the long run. Many small and medium markets sum to big economic value.

### 5.2 Integrate into existing technologies and form a new ecosystem

We see an emerging ecosystem beyond current sensors. Quantum sensors can observe what once was unobservable with conventional technology, opening possibilities for new insights. Already, there are dedicated quantum sensing hardware and early AI algorithms for data analysis. For the greatest impact in the short term, quantum sensors must be integrated into existing technologies and infrastructure. In the longer term, as the technology becomes broadly adopted, quantum sensors could provide unique, large data sets for training of AI algorithms with wide-ranging impact. To unlock this impact, a well-developed ecosystem can take an important role. Innovation clusters emerge at several locations around the globe. While this is a great opportunity and an important step, there are also major challenging that need to be overcome such as the need for interdisciplinary coordination. An orchestrator can take a central role here to set up a clear strategy and connect the respective stakeholders of the ecosystem, e.g., research institutions, start-ups, and industry players working collaboratively on sensing use cases.

### 5.3 Educate talent in quantum sensing

Quantum sensing requires a wide range of expertise and specific capabilities. There is a risk for the market growth mentioned at the beginning of the article to outpace talent growth. A gap between talent and market growth may act as a bottleneck for the quantum sensing industry. Therefore, specific training profiles are needed, combining engineering with quantum knowledge to familiarize industry leaders with quantum sensing and its potential. This includes both enabling the learning of quantum sensing relevant skills after graduation and training experienced professionals to acquire relevant skills.

### 5.4 Adopt a new mindset

Much current thinking focuses on using quantum sensors to improve existing applications; but there are limits in device cost and sizing, as well as competition with existing technology. Thus, there is a need to pursue disruptive, forward-looking ideas that push beyond existing applications — for example, exploring the possibilities for quantum sensors in extreme environments where existing technology cannot operate. Companies should be bold and explore new ground.

### 5.5 Close the gap between research and industry

For their part, industry players will need to be proactive and approach quantum sensing researchers, while researchers need to think beyond the lab to potentially new and exciting opportunities. Start-ups will also play a key role in advancing quantum sensor technology and pursuing novel applications, but patient, visionary investment is needed. Partnerships and collaboration between these three actors could pave the way to close this gap and unlock value. Applying existing research results from research labs to dedicated use cases in industry is one of the key next steps for quantum sensing to thrive.

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## Appendix: background on expert interviews

We conducted interviews with ten experts in the field of quantum sensing to reflect first-hand perspectives on the most promising applications of various quantum sensing technologies. We interviewed experts with a broad range of backgrounds, covering both industry and academia as well as representing companies and research institutions from North America and Europe.

- University professor focusing on precision measurement and quantum sensing (North America)
- University professor in the field of physical and chemical spectroscopy (Europe)
- Chief technology officer of a startup building quantum imaging microelectronics (North America)
- Senior scientists in the field of quantum sensing of a venture incubator (North America)
- Founder of a start developing quantum clocks and navigation technology (North America)
- Founder of startup pursing magnetic measurements based on quantum sensor (North America)
- Founder of a startup active in electromagnetic measurements with quantum sensor (North America)
- Founder of a startup commercializing biomarker detection with nanodiamonds (North America)
- Founder of startup focusing on quantum microscopy (Europe)

## Biographies

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