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Towards Scalable Quantum Sensors: Interface Electronics for Quantum Sensors

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Contents

Towards Scalable Quantum Sensors: Interface Electronics for Quantum Sensors

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ABSTRACT

This monograph presents the emerging field of second-generation quantum sensing, which leverages phenomena such as superposition and entanglement, thereby offering measurement sensitivities far surpassing classical methods. In our discussion, we emphasize its potential to revolutionize various scientific and technological domains. Starting with a foundational overview of quantum sensors, distinguishing them from quantum computing and communication technologies, we then highlight the relative maturity of quantum sensing, especially in room-temperature operations, which positions it closest to market adoption.

The main part of the monograph is dedicated to solid-state defects, particularly nitrogen-vacancy (NV) centers in diamond, which have emerged as promising candidates for scalable quantum sensors. The unique optical and spin properties of NV centers are explored in detail, emphasizing their

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possible applications in fields such as biomedical imaging, materials science, and semiconductor inspection. We delve into the technical aspects of integrating NV centers with conventional electronic and photonic systems, discussing the challenges and innovations in electronic interface circuits, photonic integration, and system-level integration technologies.

Additionally, we examine gas-based quantum sensors, particularly those utilizing Rydberg atoms, which offer high precision due to their long coherence times. The challenges of integrating gas-based sensors, compared to their solid-state counterparts, are also briefly discussed.

Overall, the monograph underscores the potential of second-generation quantum sensors, particularly those based on NV centers, to be the first scalable, high-volume quantum devices on the market, with applications spanning various fields due to their high sensitivity and room-temperature operation.

1

Introduction and Motivation

Quantum technology is a young, thriving field of research that combines fundamental concepts of quantum physics with practical aspects of engineering to develop novel technologies. Quantum effects such as entanglement between photons or the discrete energy states of atoms are used to develop innovative approaches to communication, sensor technology, simulation, or computing that have no equivalent in the realm of classical physics. Quantum technologies, therefore, offer numerous opportunities for new applications in industry and society. The immense potential of quantum technologies is undisputed and quantum technologies are classified as one of the technologies of the future by both leading companies and political decision-makers [35]–[37].

The term quantum technologies generally covers the areas of quantum computing – including quantum simulation – quantum communication, and quantum sensing. These three areas are at very different stages of development, as outlined in the following paragraphs.

Quantum computing harnesses the principles of superposition and entanglement to perform certain computations at speeds unattainable by classical computers [28]. This paradigm shift is poised to revolutionize fields such as cryptography, optimization, and complex system simulations. Quantum computers can solve specific problems exponentially faster than their classical counterparts, potentially breaking cryptographic codes and simulating quantum systems for drug discovery and material science. However, the realization of scalable, fault-tolerant quantum computers remains a significant challenge, with practical, widespread deployment still years, if not decades, away [7].

Quantum communication utilizes quantum entanglement and quantum key distribution (QKD) to enable ultra-secure communication channels. By leveraging the fundamental properties of quantum physics, it ensures that any eavesdropping on the communication can be detected, providing an unprecedented level of security. This technology holds immense promise for safeguarding sensitive information for governmental applications as well as the finance and healthcare sectors. While significant strides have been made, including the successful demonstration of satellite-based QKD [9], the infrastructure required for a global quantum communication network is still under development. Here, one major challenge is the realization of so-called quantum repeaters. While in classical communication systems, a repeater is essentially an amplifier that boosts the signal strength, the non-cloning principle of quantum mechanics prevents a straightforward signal amplification. Instead, quantum repeaters are small quantum computers (so-called quantum registers) implementing a quantum memory and the possibility to perform quantum operations on the quantum states in the memory. The message is then transmitted by entangling quantum states of the quantum memories of neighboring quantum repeaters. Since the quantum registers require only a small number of qubits (around ten), it is currently believed that quantum communications can find its way into the market at a shorter time scale than quantum computing.

Quantum sensing employs quantum physics to achieve measurement sensitivities far beyond classical capabilities. Utilizing quantum phenomena such as squeezed states, entangled photons, and superposition, quantum sensors can detect minute changes in physical quantities with extraordinary precision. Importantly, virtually all quantities are accessible via suitable quantum sensors, rendering quantum sensing an interesting alternative for various fields, including medical imaging, navigation, environmental monitoring, and fundamental science experiments.

Unlike quantum computing and quantum communications, quantum sensing devices can provide a quantum advantage using a single qubit and are, in general, easier to develop and deploy, with several practical applications already approaching market readiness. Here, one key advantage of quantum sensors is the fact that – depending on the quantum sensor – a quantum advantage can be achieved at room temperature, removing the need for cryogenic cooling and, thereby, providing much faster entries to (potentially) much larger markets.

Among the three quantum applications explained above, quantum sensing stands out as the closest to market adoption. The relatively lower complexity and immediate applicability of quantum sensors make them a tangible option for near-term integration into existing technologies and systems. The rapid progress in this field, in combination with the substantial benefits of enhanced sensitivity and precision, positions quantum sensing as the quantum technology most likely to see widespread commercial use in the near future.

Therefore, this monograph will primarily focus on quantum sensing, providing a self-contained overview from its principles to state-of-the-art implementations of scalable quantum sensors. Here, we will focus on the integration technologies that are required to design and manufacture such scalable quantum devices, placing our main emphasis on the electronic integration of quantum sensors.

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