Color centers in diamond from single-photon emission to sensing applications

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Abstract

Quantum metrology is one of the foundational elements of emerging quantum technologies, playing a central role in applications ranging from secure communication to high-precision sensing. Among these, quantum sensing is rapidly gaining attention due to its ability to exploit quantum coherence and entanglement to achieve sensitivities beyond classical limits. One particularly promising platform for quantum sensing is based on nitrogen-vacancy (NV) centers in diamond, which offer a unique combination of quantum coherence, optical addressability, and biocompatibility.

This thesis explores the potential of quantum sensing using NV centers in nanodiamond (ND) for nanoscale thermometry in biological systems, with a particular focus on probing temperature at the intracellular level. Understanding temperature dynamics inside living cells is a fundamental challenge in modern biology and medicine, as thermal processes are closely related to cellular functions, metabolic activity, and pathological states. However, conventional thermometry techniques struggle to provide the spatial and temporal resolution needed in such complex environments, such as the single-cell interior.

NV centers exhibit spin-dependent photoluminescence that is sensitive to temperature, even at the nanoscale. By embedding these quantum sensors in NDs and developing experimental protocols for their optical interrogation, we investigate the feasibility of performing localized temperature measurements in biologically relevant environments.

While significant challenges remain, our work demonstrates key steps toward the realization of intracellular quantum thermometry. In particular, we highlight the robustness and biocompatibility of ND-based sensors, and their potential for mapping thermal variations with high spatial resolution.

Moreover, the prospect of functionalizing NDs to target specific organelles or cellular structures adds an exciting dimension to future developments, potentially enabling organelle-specific thermometry. Even though this kind of advancement is still a future perspective, these possibilities suggest that quantum sensing tools could be useful in many areas of life sciences, justifying the potential interest in the investigation described in this thesis.

In addition to biological thermometry, this thesis also addresses other experimental directions. The first concerns the optimization of ND processing through oxidation and irradiation-based treatments, aimed at enhancing the properties of NV ensembles while reducing ND size. These improvements are essential to increase sensitivity and reduce variability in sensing applications. The second direction

focuses on the comparative study of germanium-vacancy (GeV) color centers under different post-annealing conditions. By analyzing the fluorescence lifetime, saturation power, and excitation efficiency of individual GeV emitters, I provide quantitative metrics for assessing their performance as alternative quantum probes. Moreover, a joint collaboration with the Czech Metrology Institute is reported, presenting the characterization of a custom calibrated detector developed for the mesoscopic regime.

In summary, this thesis reports on my research activity during my PhD at Istituto Nazionale di Ricerca Metrologica (INRiM), ranging from material optimization to integrated bio-sensing applications. The results contribute to the growing intersection between quantum metrology and biophysics, offering practical insights into how diamond-based quantum sensors can be engineered, calibrated, and deployed for probing nanoscale temperature variations in living systems.