Practical Applications of Quantum Sensing: A Simple Method to Enhance the Sensitivity of Nitrogen-Vacancy-Based Temperature Sensors

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(Received 23 December 2019; revised manuscript received 3 March 2020; accepted 21 April 2020; published 22 May 2020)

Nitrogen-vacancy centers in diamond allow measurement of environment properties such as temperature, magnetic and electric fields at the nanoscale level, of utmost relevance for several research fields, ranging from nanotechnologies to biosensing. The working principle is based on the measurement of the resonance frequency shift of a single nitrogen-vacancy center (or an ensemble of them), usually detected by monitoring the center photoluminescence emission intensity. Albeit several schemes have already been proposed, the search for the simplest and most effective one is of key relevance for real applications. Here we present a continuous-wave lock-in-based technique able to reach high sensitivity in temperature measurement at microscale or nanoscale volumes (4.8 mK/Hz$^{1/2}$ in μm^3). Furthermore, the present method has the advantage of being insensitive to environmental magnetic noise that in general introduces a bias in the temperature measurement.

DOI: 10.1103/PhysRevApplied.13.054057

I. INTRODUCTION

Reliable techniques for high-sensitivity nanoscale sensing, eventually exploiting the peculiar properties of quantum systems [1,2], are of absolute importance for several applications ranging from nanotechnology to biophysics. Among them, of particular interest are the innovative approaches to local temperature sensing. These include scanning probe microscopy [3,4], Raman spectroscopy [5], and fluorescence-based measurements using nanoparticles [6,7] and organic dyes [8]. For example, fluorescent polymers and green fluorescent proteins have recently been used for temperature mapping within a living cell [9]. However, many of the existing methods have drawbacks such as poor temporal and spatial resolution, low signal-to-noise ratio, instability in fluorescence emission, and limited operation time. In this perspective, negatively charged nitrogen-vacancy N-V centers in diamond have attracted increasing attention thanks to their unique sensing capabilities [1,10,11]. Sensing techniques based on N-V centers in diamond can be implemented at room temperature; they are also the only technique suited for operating in extreme-pressure conditions [12]. Furthermore they have already been applied inside living cells [13], a feature that makes them ideal sensors for nanoscale bioapplications. By taking advantage of the biocompatibility [14] or anyway of the absence of substantial effects on cell functionality [15], neuronal cells can be grown directly on diamond surfaces [16] or nanodiamonds can be internalized within the cellular body through endocytosis [15]. Thanks to the small dimensions of nanodiamonds, the mapping of temperature fluctuations up to a sensitivity of 200 mK/Hz$^{1/2}$ and at length scales as small as 200 nm is possible in living cells when being integrated with optical microscopic imaging techniques [17,18]. Thus, among other sensing applications, N-V-based thermometry is attracting increasing interest [19–28].

Considering the ground triplet state, the degenerate $m_s = \pm 1$ spin states in the absence of an external magnetic field are separated from the $m_s = 0$ state by the zero-field splitting (ZFS) parameter, $D \sim 2.87$ GHz at room temperature, due to spin-spin interactions in the orbital structures of the N-V. The ZFS parameter depends on the lattice spacing, which is strongly influenced by the local temperature. For instance, when the local temperature increases, the distance between the localized spins at the N-V center increases, lowering the spin-spin interaction and reducing D_{gs}. The ZFS parameter nonlinearly depends on temperature [20], under ambient conditions the temperature dependence being $c_\tau = dD_{gs}/dT \approx -74$ kHz/K [19].

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