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Photo-physical properties of He-related color centers in diamond

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Diamond is a promising platform for the development of technological applications in quantum optics and photonics. The quest for color centers with optimal photo-physical properties has led in recent years to the search for novel impurity-related defects in this material. Here, we report on a systematic investigation of the photo-physical properties of two He-related (HR) emission lines at 535.2 nm and 559.7 nm (as measured at a temperature of 25 K) created in three different diamond substrates upon implantation with 1.3 MeV He^+ ions and subsequent annealing. The spectral features of the HR centers were studied in an "optical grade" diamond substrate as a function of several physical parameters, namely, the measurement temperature, the excitation wavelength, and the intensity of external electric fields. The emission lifetimes of the 535.2 nm and 559.7 nm lines were also measured by means of time-gated photoluminescence measurements. The Stark shifting of the HR centers under the application of an external electrical field was observed in a CVD diamond film equipped with buried graphitic electrodes, suggesting the lack of inversion symmetry in the defects' structure. Furthermore, the photoluminescence mapping under 405 nm excitation of a "detector grade" diamond sample implanted at a He^+ ion fluence of $1 \times 10^{10}\,cm^{-2}$ enabled us to identify the spectral features of both the HR emission lines from the same localized optical spots. The reported results provide an insight into the structure of He-related defects in diamond and their possible utilization in practical applications. *Published by AIP Publishing.*
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Color centers in diamond are appealing physical systems for application in emerging quantum technologies. In recent years, growing interest in this research field led to the discovery, investigation, and fabrication of several classes of impurity-related defects.[1–6]

The formation of optically active defects in diamond upon He implantation followed by annealing in vacuum was recently reported.[7] The spectral features of these defects consisted of two narrow emission lines at 536.5 nm and 560.5 nm at room temperature and a phonon sideband in the 572–630 nm spectral range. Following their initial observation in cathodoluminescence (CL),[8,9] their optical activity was investigated in both photoluminescence (PL) and electroluminescence (EL).[7,10]

The need of understanding the possible formation of stable optically active centers, whose current (and still tentative) attribution is based on He incorporation in the diamond lattice, motivates a further investigation of their optophysical properties. More specifically, the centers have so far been attributed to the He-vacancy complex,[11] and density functional theory calculations demonstrated that both this structure and the interstitial He defect could result in stable complexes in the diamond lattice.[12] Apart from this limited body of works, a systematic set of experimental results on the opto-physical properties of He-related (hereafter referred to as HR) centers is still missing. Such results would be of significant interest, as He implantation has been widely exploited for the fabrication of diamond-based optical micro-structures,[13–15] under the implicit assumption of its chemical inertness in the diamond crystal. The understanding of the formation process and the emission properties of HR color centers could therefore enable us to either exploit them as possible single-photon emitters or to identify a suitable strategy to mitigate their undesired presence.

In this letter, we present an extensive characterization of single crystal diamond samples incorporating HR centers, with the purpose of gaining a deeper insight into their optophysical properties. Their PL spectral features were investigated as a function of temperature, excitation wavelength, and intensity of external electrical fields. Additionally, single-photon-sensitive PL confocal microscopy of a diamond substrate containing HR centers at very low densities enabled their preliminary mapping, thus providing indications on the spatial distribution/correlation of HR emission lines from the same complexes.

The reported measurements were performed on a set of three He-implanted samples: a type-IIa synthetic single-crystal "optical grade" diamond plate ($3 \times 3 \times 0.3\,mm^3$ in size) by ElementSix (Sample #1); a single-crystal diamond film grown at the laboratories of University of Rome "Tor Vergata" on a commercial high-pressure high-temperature (HPHT) Ib diamond substrate (Sample #2); a type-IIa "detector grade" diamond plate by IIA Technologies (Sample #3) with a nominal substitutional N concentration of <1 ppb.

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