Eur. Phys. J. Plus (2025) 140:614
https://doi.org/10.1140/epjp/s13360-025-06537-0

THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

Development of a novel light and ion beam induced luminescence (LIBIL) setup for in-situ optical characterization of color centers in diamond

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Received: 20 December 2024 / Accepted: 7 June 2025

Abstract In this work, development of the new laser and ion beam-induced luminescence experimental end-station has been presented. To systematically test the capabilities and limitations of the newly developed setup, ionoluminescence and iono-photoluminescence measurements were performed on a type IIa optical grade and a type Ib nitrogen-rich diamond. By comparing and analyzing the obtained spectral response, it was shown that the speed of luminescence quenching has a non-trivial dependence on the ion beam current. Additionally, it was demonstrated that some spectral feature characteristics of the negatively charged nitrogen-vacancy color center have been observed only during iono-photoluminescence measurements. This demonstrates that the unification of two separate steps, ion implantation, and optical characterization could yield new insights into dynamics of color center formation.

1 Introduction

Color centers in diamond are crystalline defects that are responsible for imparting color to an otherwise transparent crystal. Although studied for decades, in recent years, interest in them has surged due to their potential applications in quantum sensing and quantum computing [1]. One such defect, the nitrogen-vacancy (NV) color center, exists in two optically active charge states: negatively charged (NV^-), and neutral (NV^0) [2]. The NV^- center is especially interesting due to its reported photostability, and ability to optically initiate, manipulate, and measure its spin state with high fidelity at room temperature [3–5]. This makes it a promising candidate for quantum network qubits. Beyond quantum information processing, NV^- centers offer numerous quantum metrology applications, such as: magnetometry [6], electrometry [7], barometry [8], and thermometry [9].

Synthetic diamonds can be made using two different procedures: high temperature and high pressure (HPHT) and chemical vapor deposition (CVD). In HPHT diamond growth, crystals are generated by dissolving a carbon material (i.e. graphite) with a flux of molten metal (usually iron, nickel or cobalt). The carbon is then deposited on a substrate containing diamond seed crystals in a specialized press generating pressures of around 6 GPa and temperatures of 1500 °C [10] replicating the conditions of natural diamond growth. CVD, on the other hand, is a method that uses a carrier gas (usually a hydrogen-methane mix) to transport constituent elements (carbon) onto a heated substrate containing nucleation centers (i.e., diamond seeds) [11]. Both of these methods allow for the creation of single crystal diamonds with controlled concentrations of impurities (down to a few ppb).

Ion implantation is a technique in which different ion species are used to irradiate solid targets which modifies their physical, chemical, and electrical properties. It is a well known technique in the semiconductor industry for the incorporation of dopants in a material [12]. Ion implantation offers many advantages for defect engineering over incorporation of defects during growth. Ion beams can be focused down to nanometer sized spots [13], allowing for laterally resolved color center creation. By tuning the ion energy, it is possible to precisely define the penetration range of ions in a material, allowing for precise longitudinal placement of color centers. Furthermore, by selecting the implanted ion species it is possible to create color centers with varying optical properties [14]. Finally, precise ion counting systems allow for well-defined determination of defect concentration [15]. The ion microprobe setup, having all the capabilities mentioned above, is an ideal choice for defect engineering by ion implantation [16].

Ionoluminescence (IL) or ion beam induced luminescence (IBIL) is an ion beam analysis (IBA) technique employed for material investigation [17–19]. When an ion beam strikes a material, it transfers energy to the electron system through electronic stopping interactions. This energy excites electrons in the material, and as they return to their ground state, they release the energy in the form of visible light (if other shell electrons are excited). The wavelength of the emitted light depends on the material's properties-for

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Published online: 01 July 2025