Fabrication and characterization of quantum emitters in silicon for quantum technology applications

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In recent decades, due to the presence of photoluminescence and electroluminescence from various optically active point defects, silicon has demonstrated the potential to integrate photon-emitting components with CMOS technology, despite its indirect band gap. However, it was only in 2020 that the first demonstration of single-photon emission in the infrared range and at cryogenic temperatures from the so-called G center was demonstrated, sparking renewed interest in luminescent centers within silicon for the development of next-generation technologies in the second quantum revolution. This result offered an enticing perspective to develop single photon sources emitting at telecom wavelengths. Moreover, these sources can be implemented in a host material with the highest available degree of maturity in processing and mass production, including industrially available techniques for manufacturing integrated photonics chips. The development and implementation of a complete silicon photonics integrated circuit for quantum computing applications would enormously benefit from the development of an industry-compatible deterministic single-ion implantation technique, allowing the manufacturing of monolithic devices equipped with multiple indistinguishable photon sources. In this regard, an introductory discussion on single-photon sources as building blocks of quantum photonic technology aims to describe color centers in solid-state platforms and provides the theoretical framework underpinning the experiments discussed. The addressed research questions are then contextualized through an overview of some of the significant optically active defects identified from the mid-70s up to the present, with a particular focus on the single-photon sources identified in silicon following the first demonstration in 2020. From the perspective of the concrete realization of second-quantum revolution devices, the core activity of this Dissertation is then discussed with a detailed description of the adopted methods to address the main manufacturing challenges in the realization of a well-established fabrication protocol for silicon-based quantum emitters. The ion-matter interaction mechanisms are discussed, along with the application of the ion implantation technique as a reliable industry-compatible fabrication technology for the realization of color centers. The role of radiation damage during the introduction of specific impurities into the crystal lattice is accurately investigated both in diamond, as a pioneering material in quantum technologies, and in silicon. An in-depth study in diamond shows that, with high-temperature implantations it is possible to increase the vacancy density threshold required for the irreversible conversion of the diamond to a graphitic phase, thus enabling the achievement of higher-density ensembles, which constitutes a great advantage in the realization of quantum-enhanced sensing protocols. On the other hand, the focus on the radiation-induced intrinsic defects dynamics in silicon reveals an effective approach for the realization of recently discovered intrinsic interstitial quantum sources, named W centers. The use of single-photon sensitive microscopy at cryogenic temperatures enables the optical characterization of the emitters under study. In particular a systematic characterization of carbon-implanted high-purity silicon substrates enables the examination of the effects of post-implantation thermal treatment in the formation of intrinsic silicon defect complexes generated by the introduction of extrinsic atomic species. Along with the radiation damage, the delivery of single impurities and their conversion into stable single-photon sources are extensively covered. For the first fabrication challenge, the Ion Beam Induced Charge technique (IBIC) is explored as a post-detection technique for deterministic implantation. Notably, an experiment with a custom Si photodiode micromachined via FIB milling is proposed where the device is exploited as an integrated beam diagnostic tool for the real-time assessment of the beam spot size of the probe beam. The information on the size of a 2MeV Li+ ion micro-beam takes advantage of the spatial correlation between the induced charge pulse amplitude and the micro-structures through Charge Collection Efficiency (CCE) measurements. In contrast to the main techniques commonly adopted by the scientific community and based on the imaging of patterned standards, the proposed approach allows the qualification of the ion beam by the CCE mapping of the very same target of the ion beam analysis, avoiding possible limitations in the accuracy of the beam size estimation. Moreover, numerical simulations based on the Shockley-Ramo-Gunn model are carried out for data analysis, validating the interpretation of the experimental results as originating from the effects of the charge implanted during the FIB micromachining on the measured charge induction. Finally, the controlled activation of silicon color centers is explored. In contrast to statistical activation approaches based on conventional Rapid Thermal Annealing processes reported so far, a novel approach consisting of an ns heat transient in the annealing step, thus offering a practical off-equilibrium pathway for the occurrence of competitive processes in the formation of defective complexes in silicon is discussed. The interpretation of the experimental results, together with the strong non-stationarity of the technique, is then validated through a finite element analysis, which highlights the radically different defect engineering possibilities compared to conventional longer thermal treatments, thus paving the way to the direct and controlled fabrication of emitters embedded in integrated photonic circuits and waveguides.