Isotopically Resolved Focused Ion Beam Systems for Quantum Technologies

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Focused ion beam (FIB) technologies are rapidly emerging as powerful tools for deterministic nanoscale materials engineering, enabling new approaches to the fabrication and control of quantum materials and devices. In this work, we present recent advances achieved using the Platform for Nanoscale Advanced Materials Engineering (P-NAME) [1], a system designed to deliver precise ion implantation and nanoscale modification for next-generation quantum technologies. By integrating a new generation of stable ion sources, the platform now provides access to 18 isotopically resolved ion species and clusters, significantly expanding the range of materials engineering capabilities available for fundamental studies and device fabrication.

A key capability enabled by this development is deterministic single-ion implantation with detection efficiencies approaching 100% [2]. This allows controlled doping with spatial resolutions below 20 nm, an essential requirement for the scalable fabrication of quantum devices. Using this approach, we have uniquely created and imaged pairs of ^{121}Sb and ^{123}Sb ions substitutionally doped into silicon, an architecture relevant for the formation of coupled qudit systems. For the first time, we directly measure the separation of Sb–Sb dopant pairs created through molecular implantation, revealing an average spacing of approximately 2 nm [3]. These results demonstrate the ability to engineer atomic-scale dopant configurations with unprecedented spatial precision.

Importantly, these implantation processes are compatible with in-situ isotopic enrichment of silicon to extremely low ^{29}Si concentrations (<2 ppm) [4,5] within the same instrument. Such enrichment is critical for improving the coherence properties of spin-based quantum systems by suppressing noise from natural abundant nuclear spins in ^{29}Si. Recent measurements of ensembles of doped ions in highly enriched silicon confirm the expected improvement in electron spin coherence, highlighting the potential of this approach for scalable silicon-based quantum technologies. Furthermore, our enrichment methods have recently enabled the fabrication of high-purity silicon-on-insulator ($Si/SiO_2/Si$) films with full epitaxial regrowth as well as oxidation of the enriched area to produce enriched SiO. Detailed electron microscopy studies provide new insight into the regrowth mechanisms involved in this process and nanoSIMS is used to confirm the enrichment levels achieved.

Beyond silicon platforms, we demonstrate the broader versatility of nanoscale ion beam engineering across multiple quantum material systems. In diamond, ion implantation has been used to create tin-vacancy (Sn-V) colour centres [6], producing spatially controlled single-photon emitters with potential applications in quantum communication and sensing. Similarly, nanoscale ion beam doping has been applied to enhance the spintronic performance of nanowire lateral spin-valve devices, illustrating how targeted atomic modification can directly influence spin transport properties. We have also demonstrated the ability to dope individual epitaxial quantum dots, enabling controlled tuning of their photonic characteristics.

Together, these studies highlight the broad applicability of deterministic ion implantation across diverse materials platforms relevant to quantum information processing, spintronics, and integrated photonics.

Overall, this presentation will provide an overview of the P-NAME platform and its capabilities for deterministic nanoscale ion implantation and localized materials engineering. We will highlight recent breakthroughs across silicon, diamond, and photonic material systems, while outlining future directions for the field. Particular emphasis will be placed on emerging opportunities in nanofabrication, single-ion implantation, localized property engineering, and multimodal characterization, illustrating how focused ion beam technologies can play a transformative role in the development of next-generation quantum devices.

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